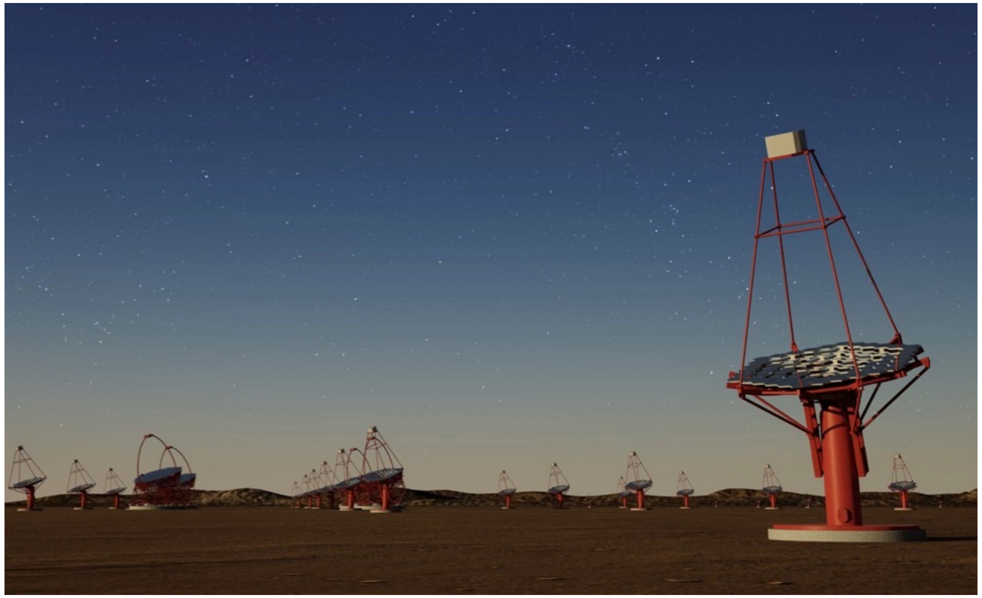
Gamma-ray dark matter searches



Gabrijela Zaharijas

Centre for Astrophysics and Cosmology,

University of Nova Gorica, Slovenia

ISAPP school 2021, Madrid

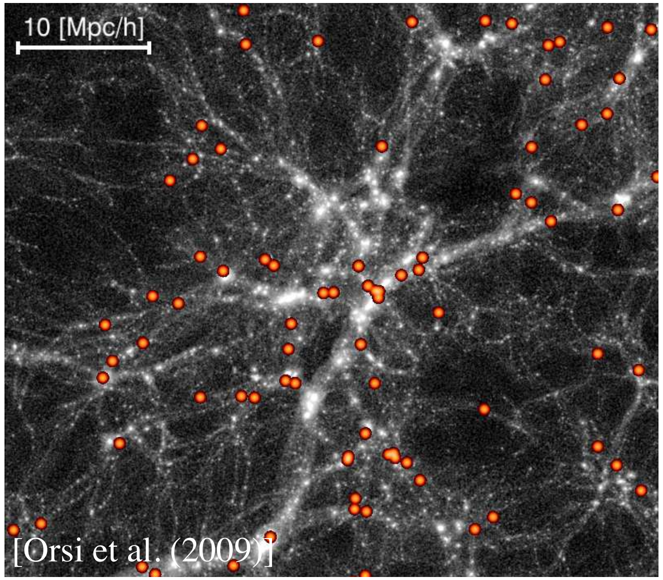
Work at the University of Nova Gorica, Slovenia

Member of the Fermi LAT since 2008

Member of the CTA since 2014

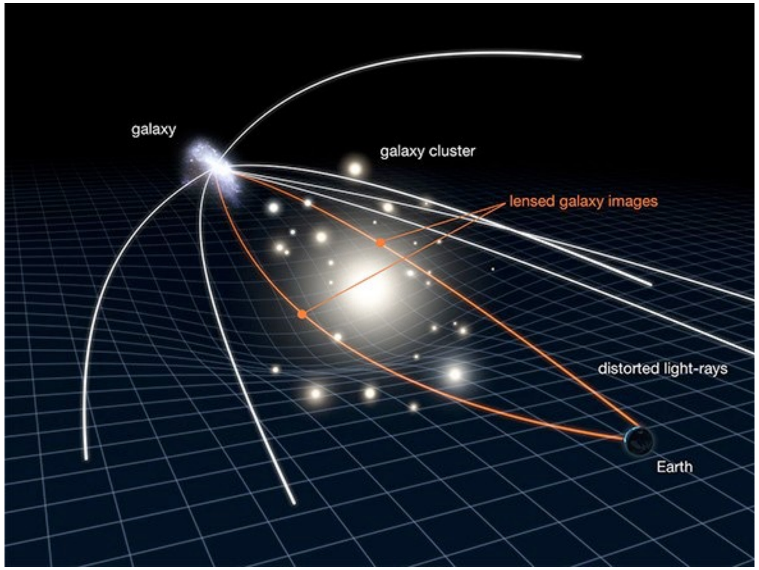
Dark matter is an essential building block of the Standard Model of Cosmology

large scale structures



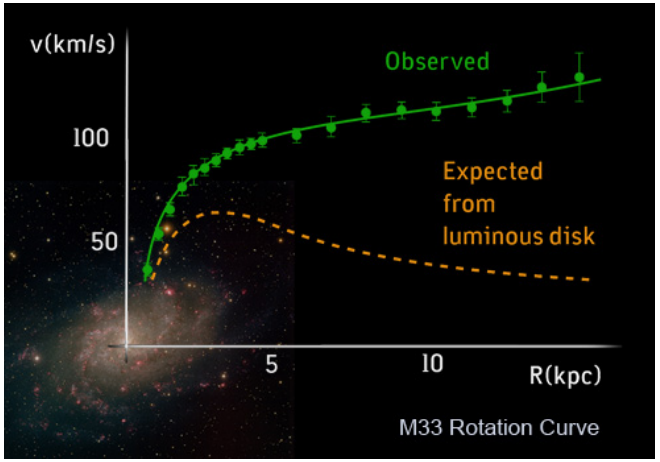
10s Mpc

clusters of galaxies



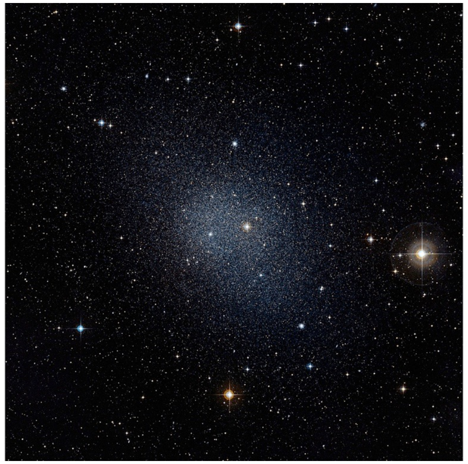
Mpc

Milky Way-sized galaxies



10s kpc

dwarf galaxies



<~ kpc

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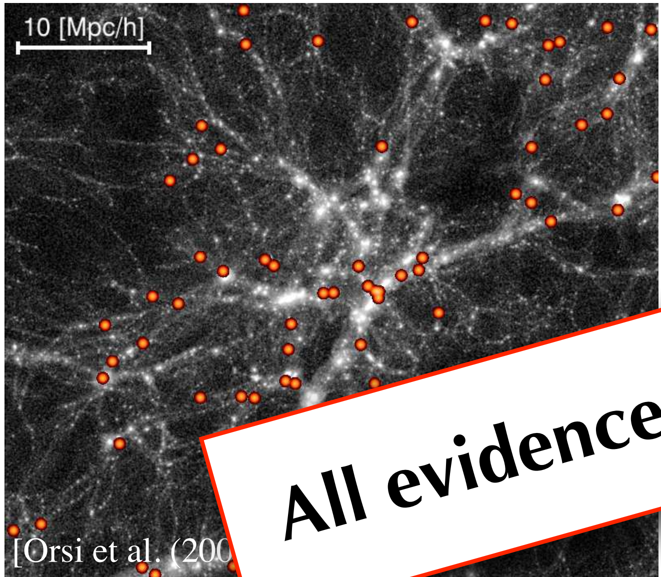
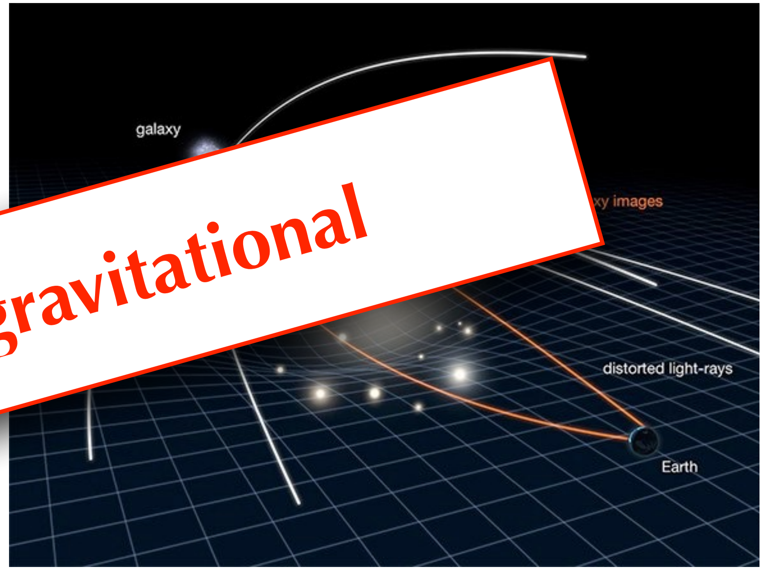


10s Mpc

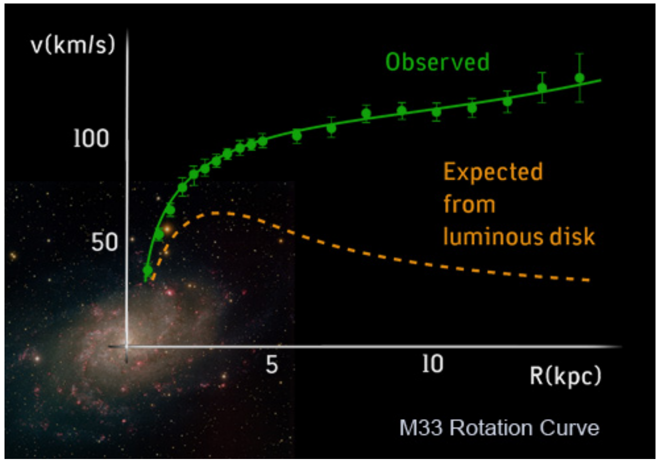
clusters of galaxies



Mpc

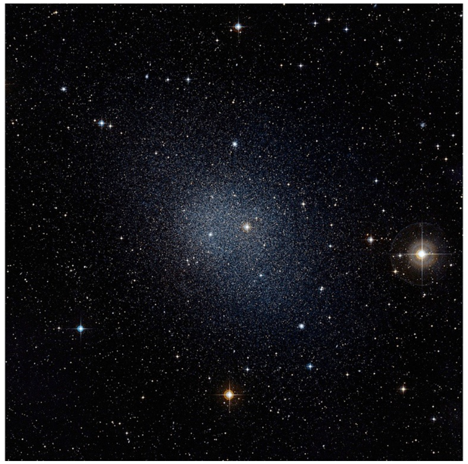
All evidence so far is gravitational

Milky Way-sized galaxies



10s kpc

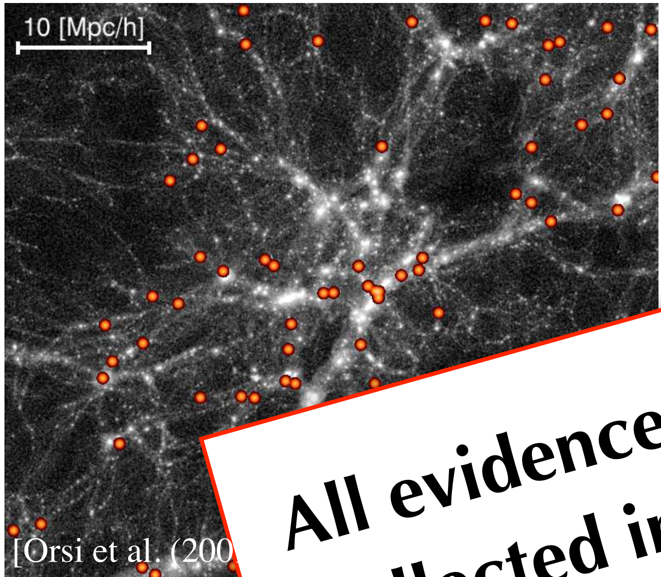
dwarf galaxies



<~ kpc

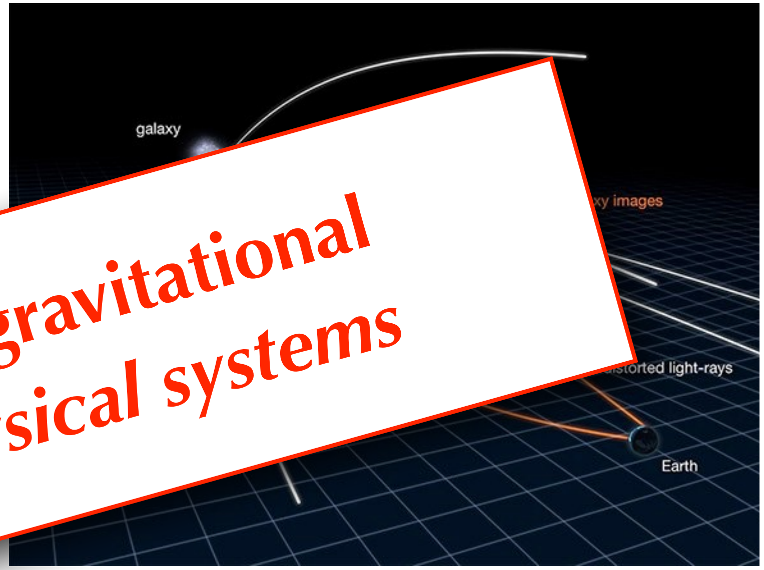
Dark matter is an essential building block of the Standard Model of Cosmology

large scale structures



10s Mpc

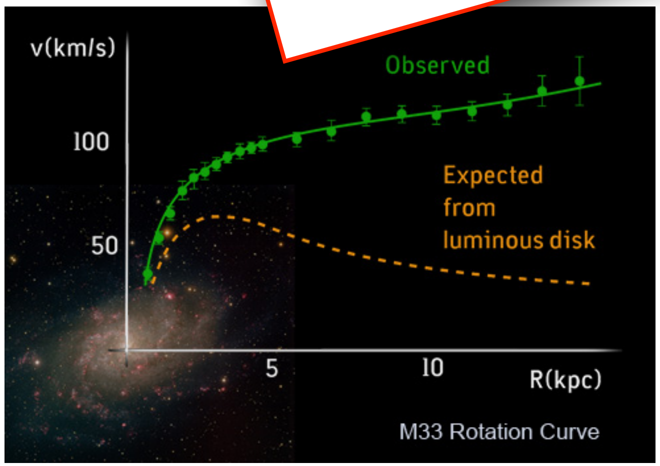
clusters of galaxies



Mpc

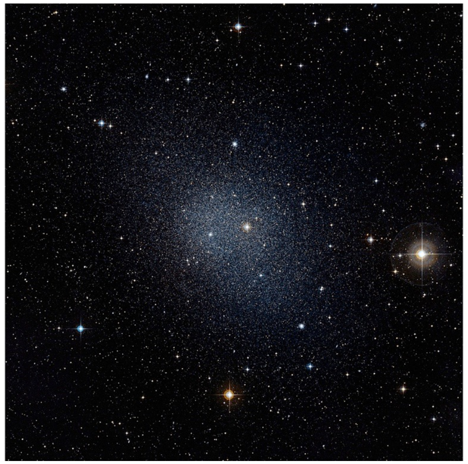
All evidence so far is gravitational
Collected in astrophysical systems

Milky Wa



10s kpc

dwarf galaxies



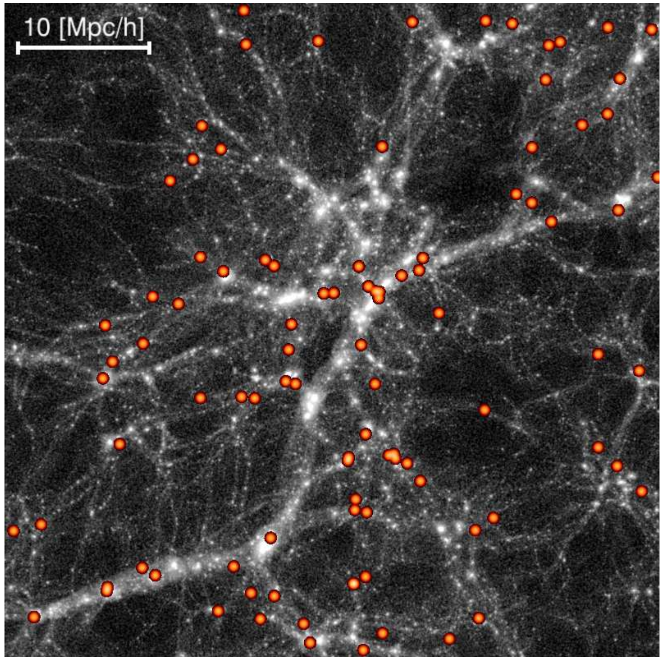
<~ kpc

'**Astrophysical**' dark matter search:

Serach for:

- **non gravitational signatures** of DM (new forces, interactions with SM) - '*indirect*' DM detection
- Or **use gravity** to determine its properties (mass, self-interaction…)

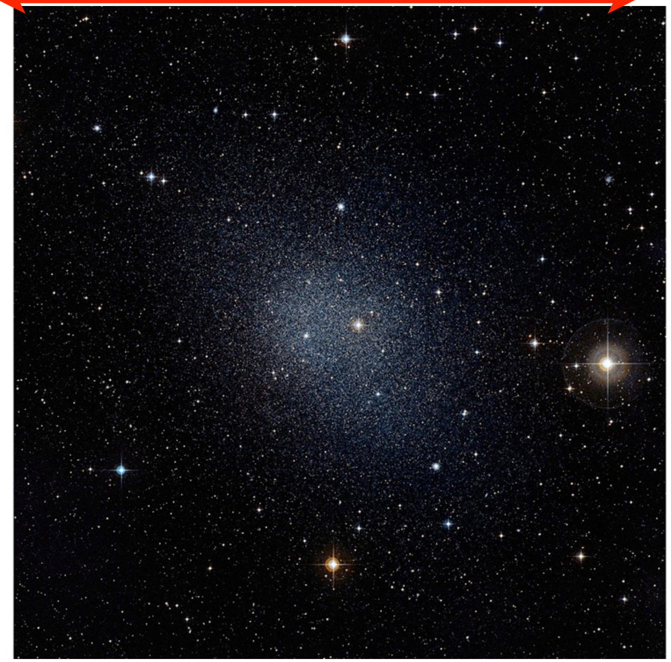
large scale structures



100s Mpc

…

dwarf galaxies



<~ kpc

‘**Astrophysical**’ dark matter search:

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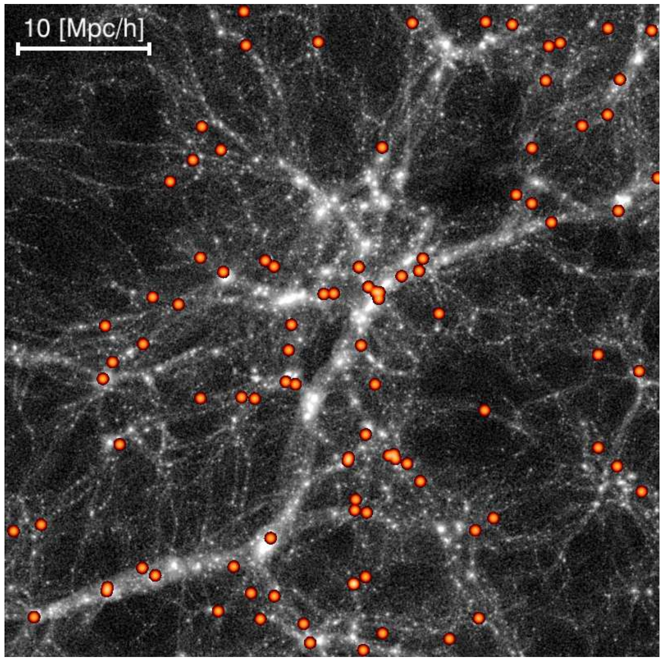
Zavala’s talk

large scale structures

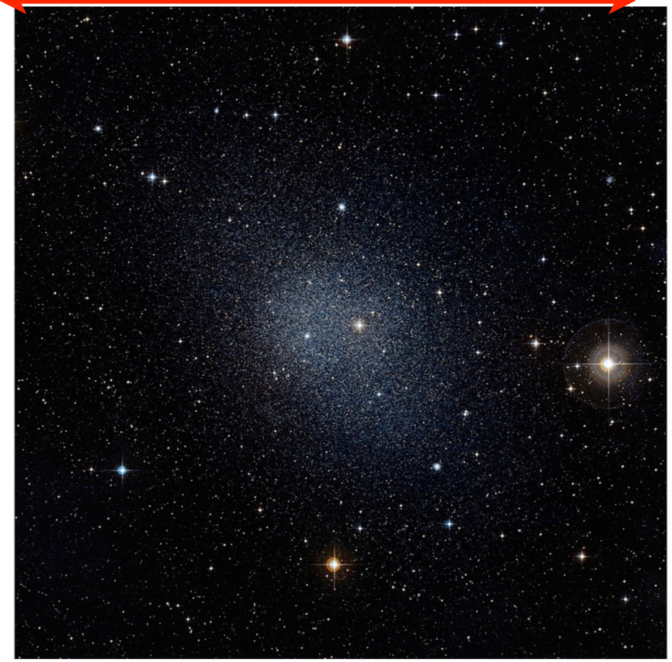
100s Mpc



…

dwarf galaxies

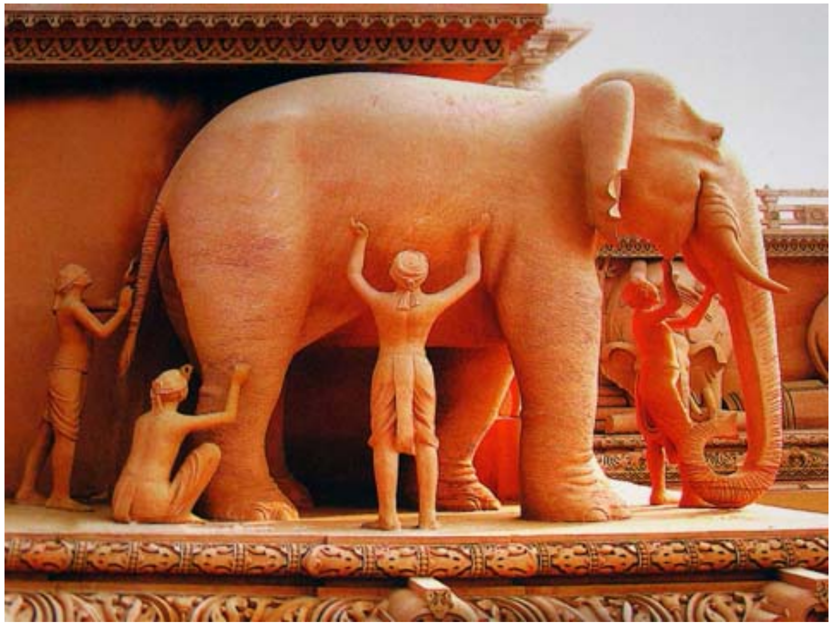
<~ kpc



The ‘big’ picture

- Why indirect searches?
  - direct detection and collider searches are cleaner environments with ‘controlled’ backgrounds
- **Essential:**
  - to search for DM **remotely**/in places where it was **discovered**
  - In some cases, direct **link to early universe physics**
  - ideally: detect it in the Lab AND astrophysical objects

    —> **multiple handles** on its properties.



The ‘big’ picture

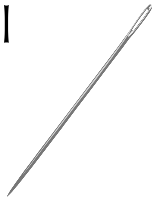
Astrophysical experiments:

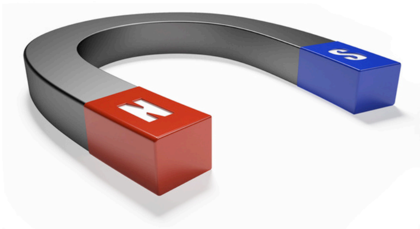
- plus:
  - multipurpose experiments (rich scientific program, beyond DM)
- minus:
  - different exp priorities,
  - not optimized for DM searches
  - ‘backgrounds’ are astrophysics not a ‘controlled’/lab system

The 'big' picture

(most of) the astro-signal we measure DOES NOT look like the one expected from DM.

Challenge:
look for an uncertain signal swapped in the uncertain backgrounds.



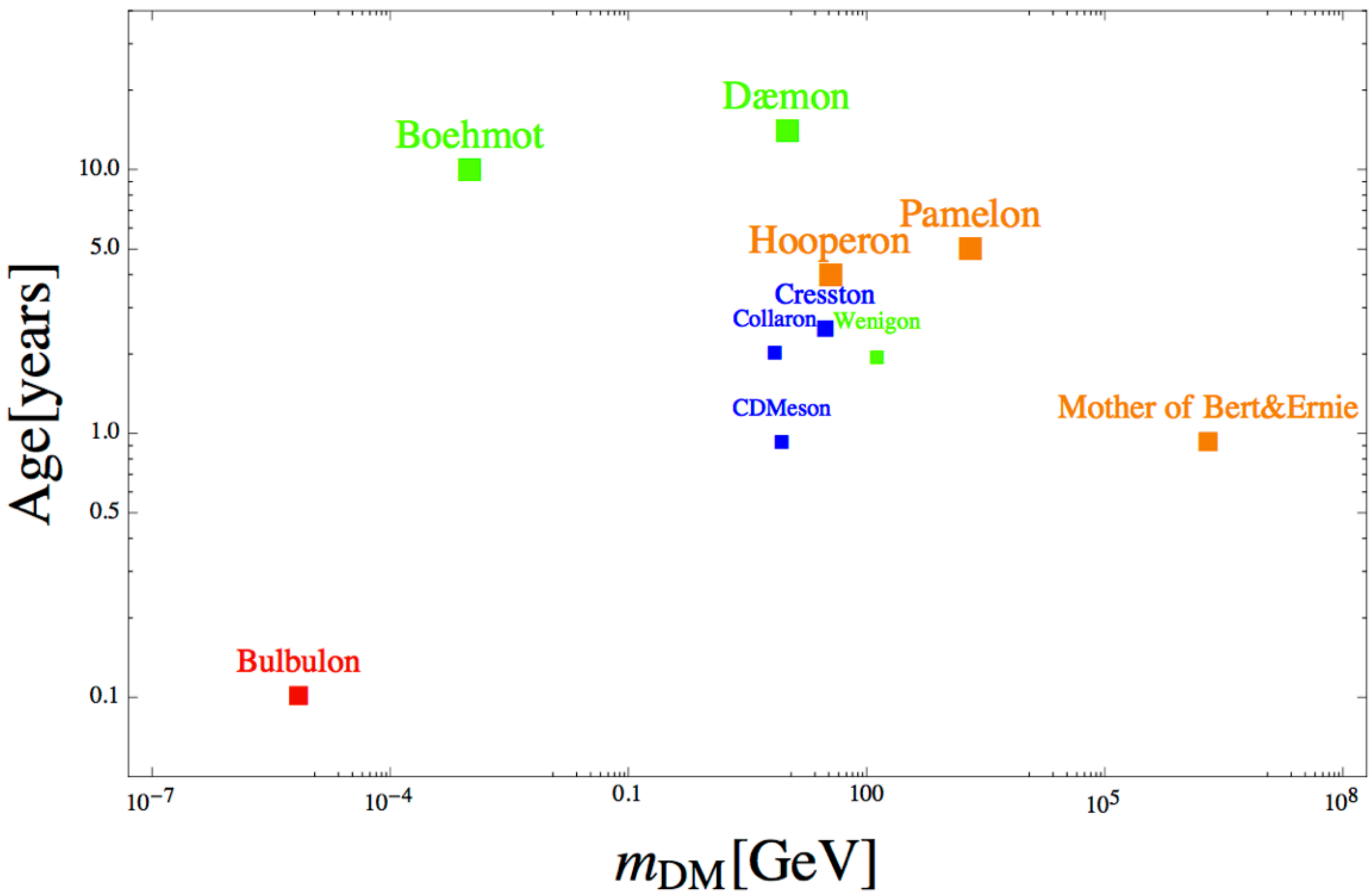


[J. Siegal-Gaskins talk@Sackler colloquium 2012]

The ‘big’ picture

Detection?

- given the complexity of astrophysical phenomena and experimental challenges it happens relatively often to stumble upon curious **signal hints**.



[RESONAANCES blog, cca 2015]

The 'big' picture

Detection strategies:

A) look for ***smoking guns***:

➡ **'zero' astro backgrounds, but need luck** -- expected signals (for vanilla DM) low

B) or, learn astrophysics :) and try again

Outline

1. DM model space that CAN be tested with gamma-rays
2. Experiments & data analysis techniques
3. Wish list, targets
4. Astro backgrounds
5. Examples:
    - WIMPs
    - ALPs
    - (PBHs)

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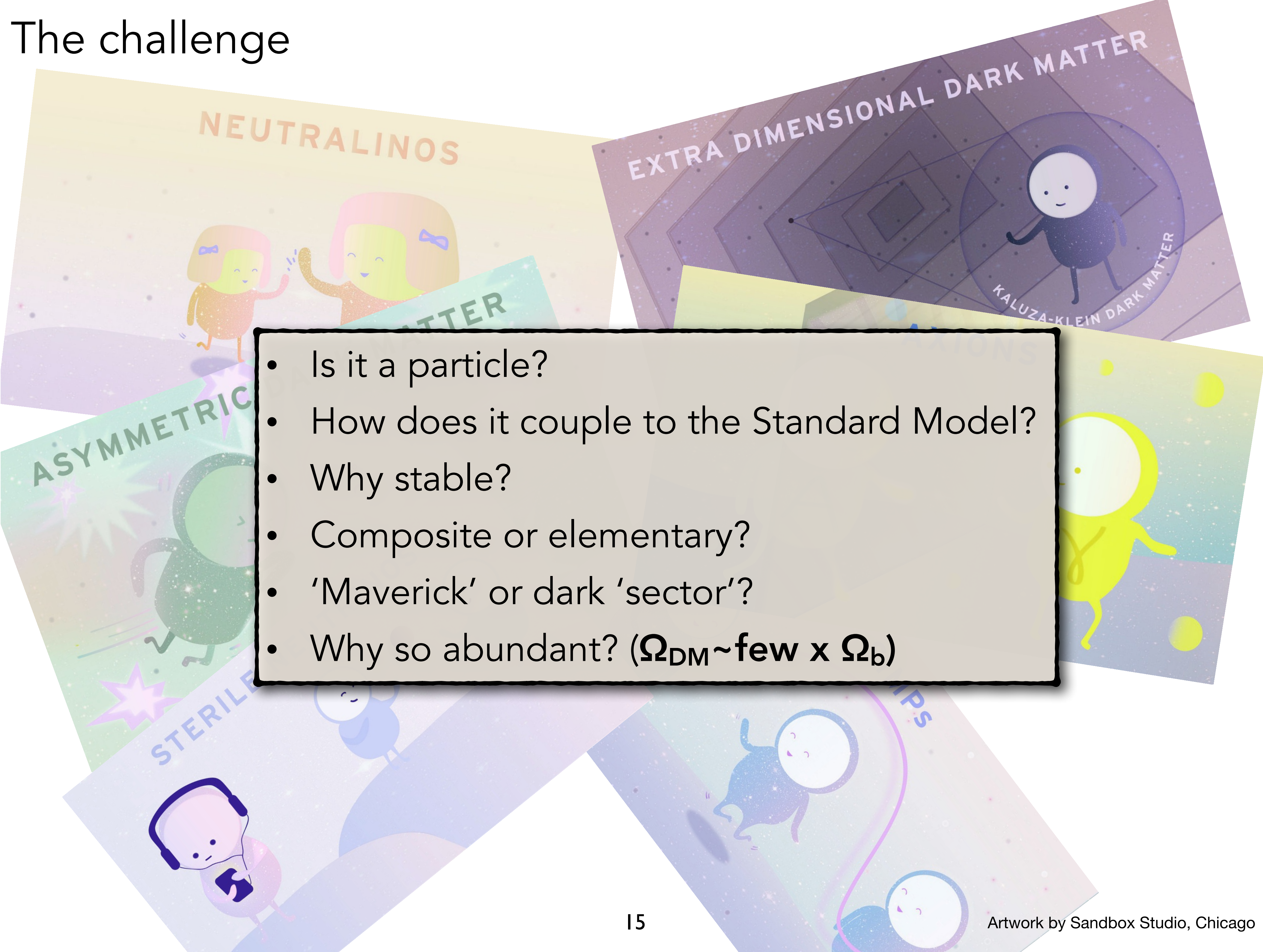
The challenge



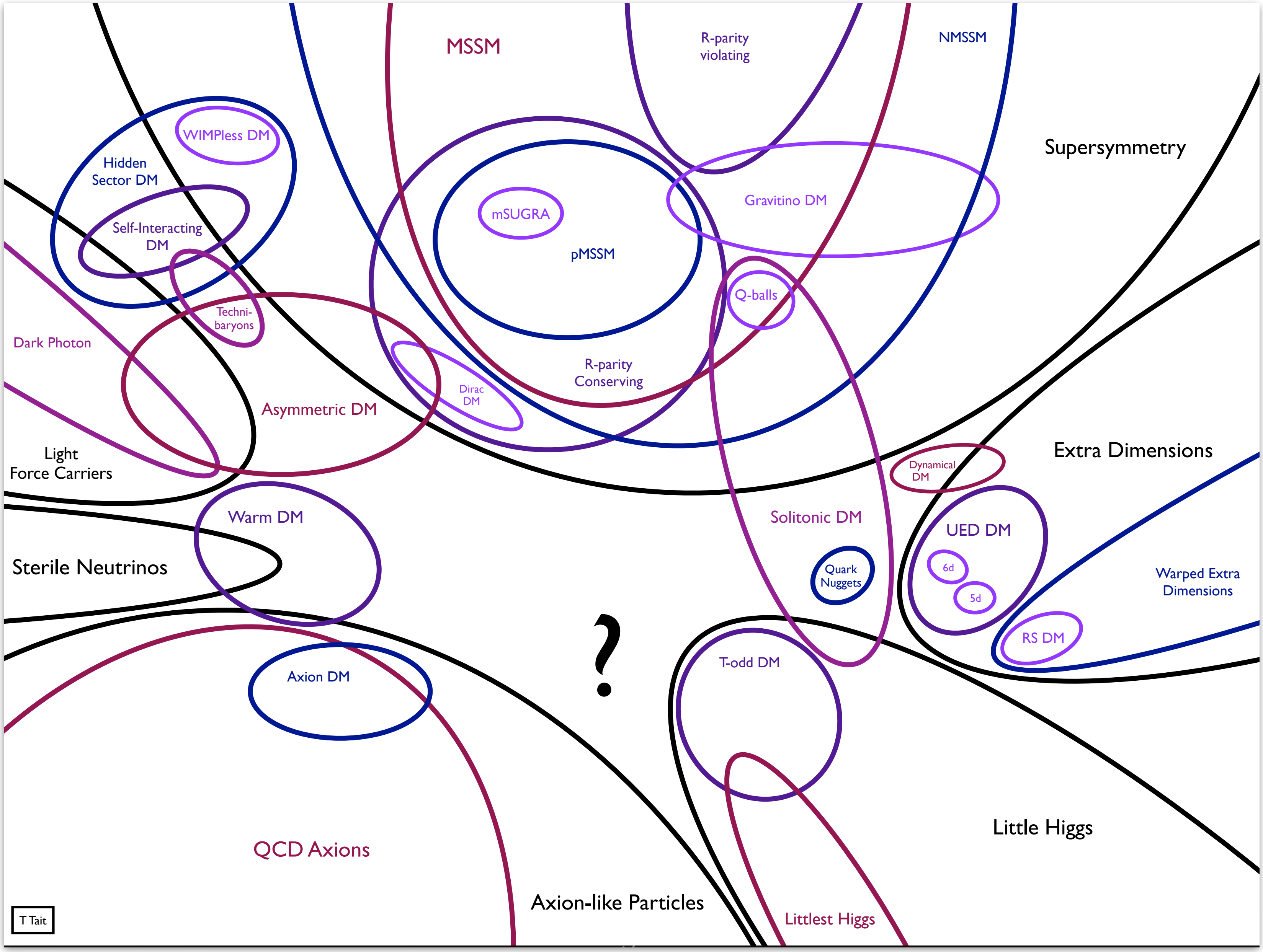
- Is it a particle?
- How does it couple to the Standard Model?
- Why stable?
- Composite or elementary?
- ‘Maverick’ or dark ‘sector’?
- Why so abundant? (**Ω_{DM}~few x Ω_b**)

Artwork by Sandbox Studio, Chicago

Particle dark matter models

A theorist's 'landscape'

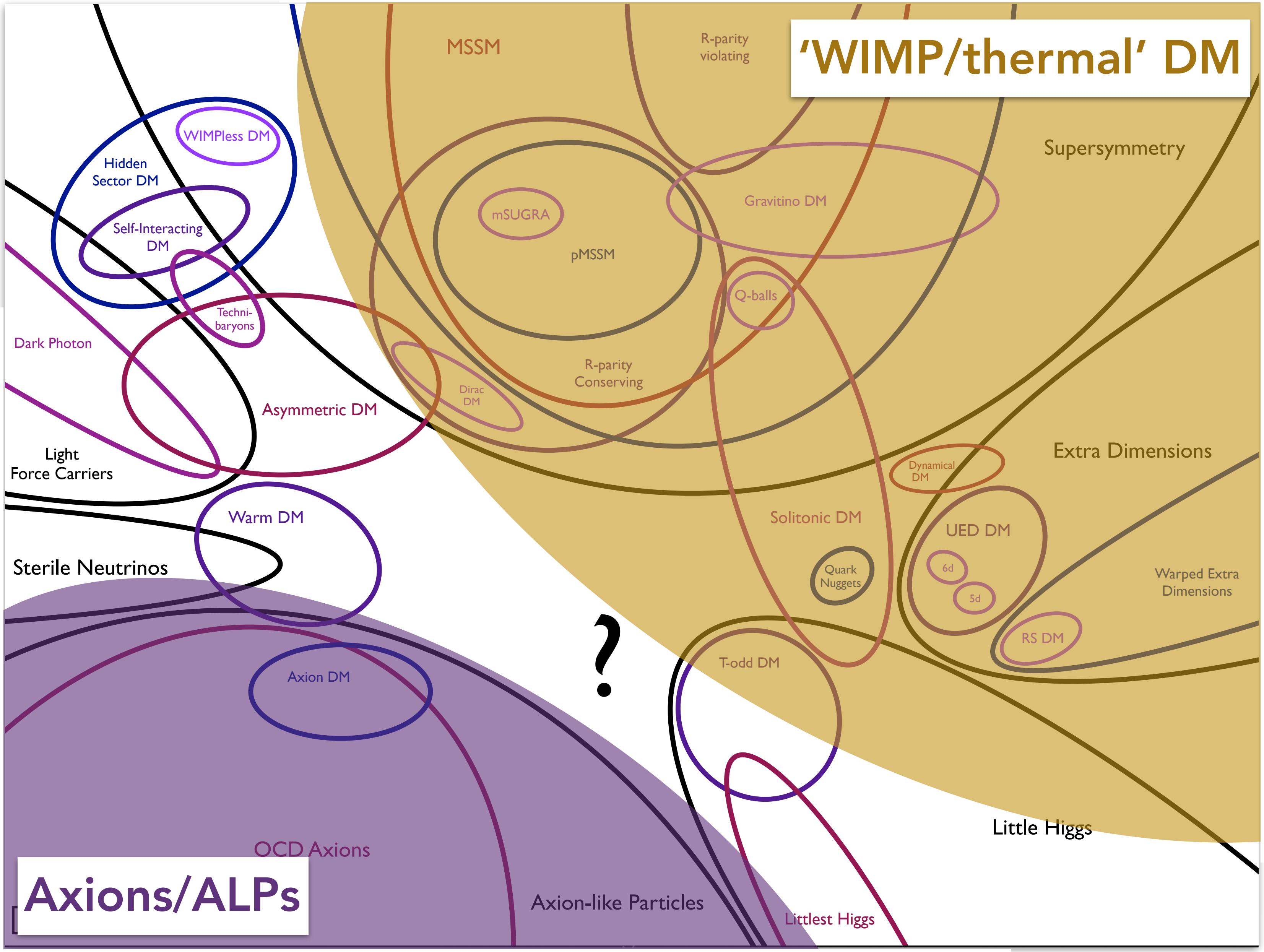
Laura's talk



Credit: T. Tait

Particle dark matter models

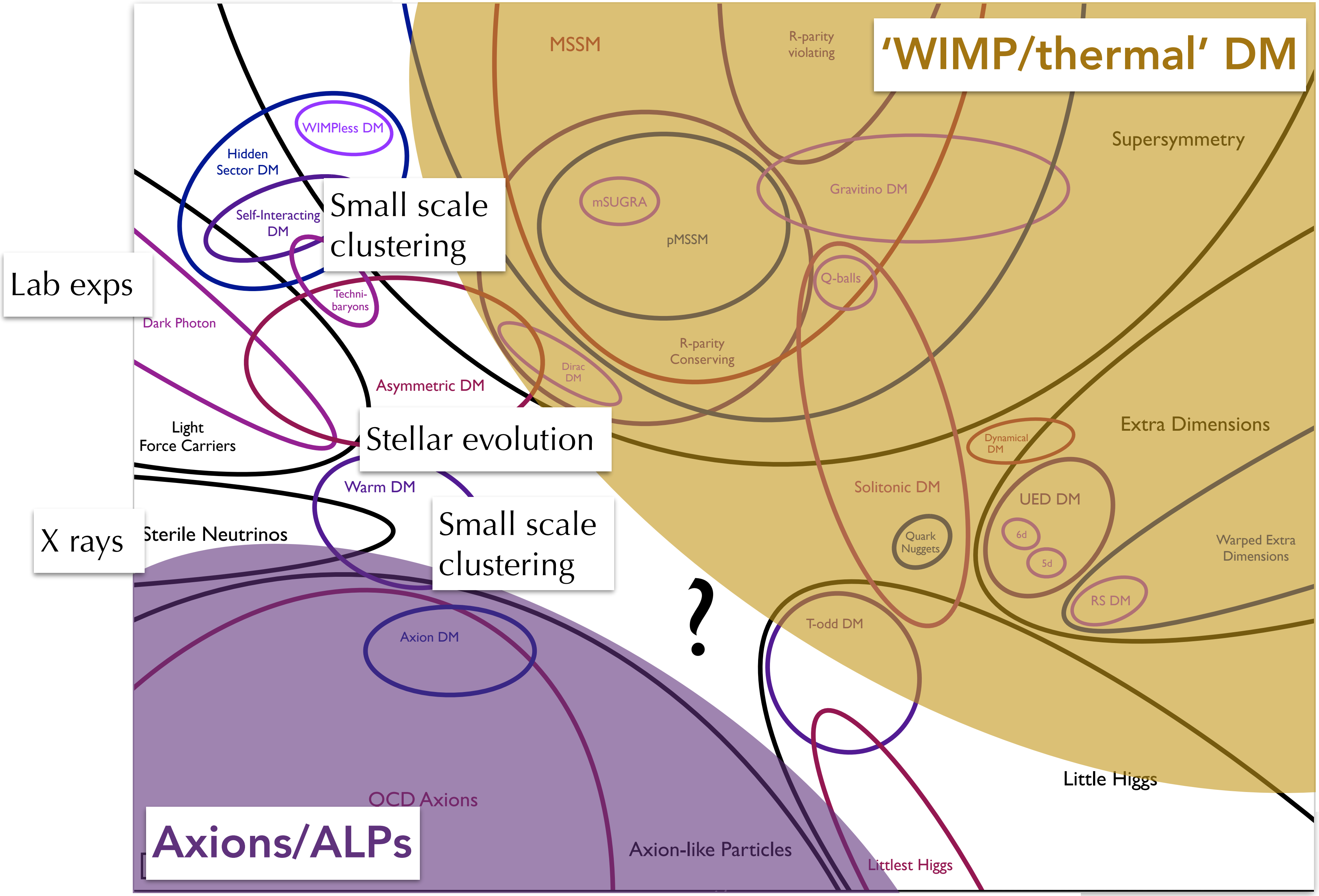
Landscape in terms of (astrophysical) signatures



Credit: M. Meyer

Particle dark matter models

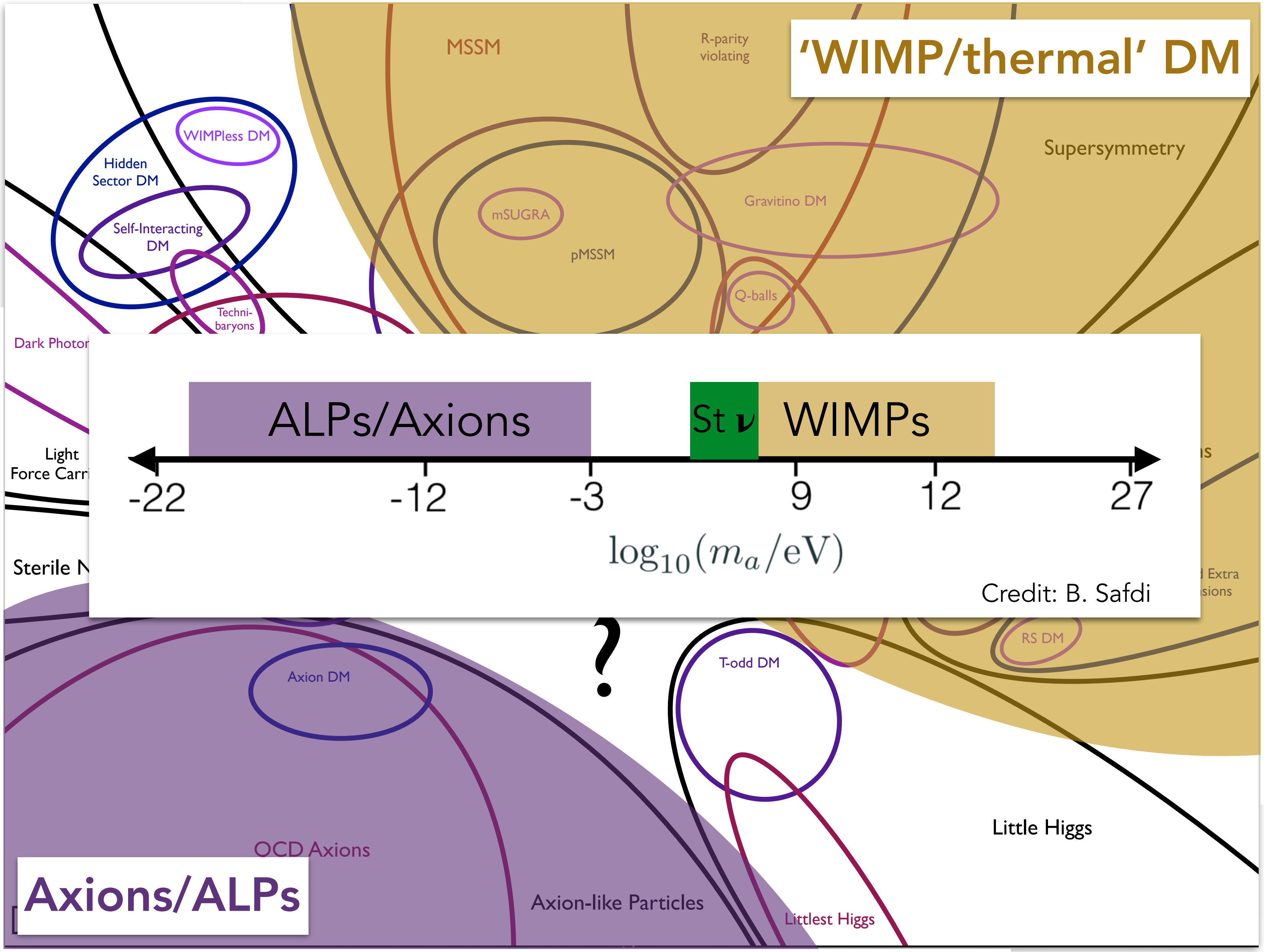
Landscape in terms of (astrophysical) signatures



Credit: M. Meyer

Models

Landscape in terms of (astrophysical) signatures

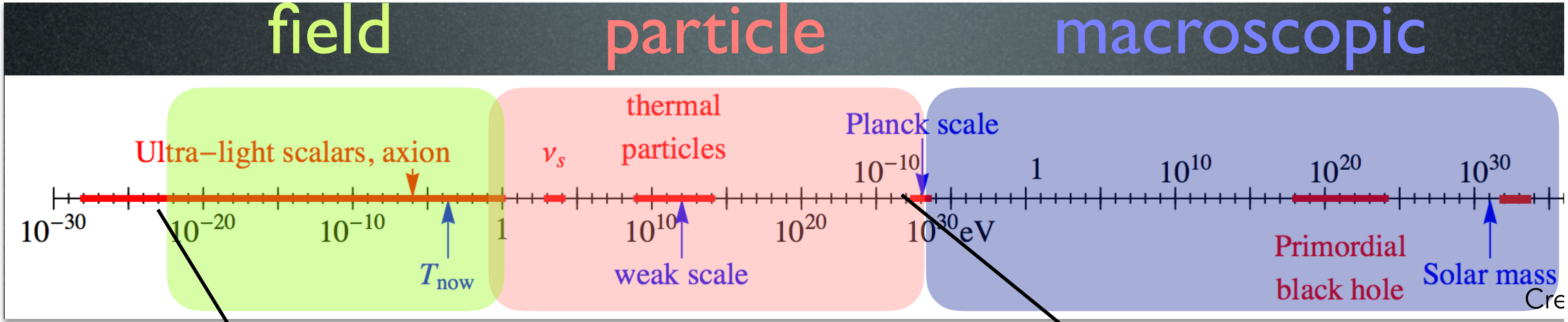


Credit: M. Meyer

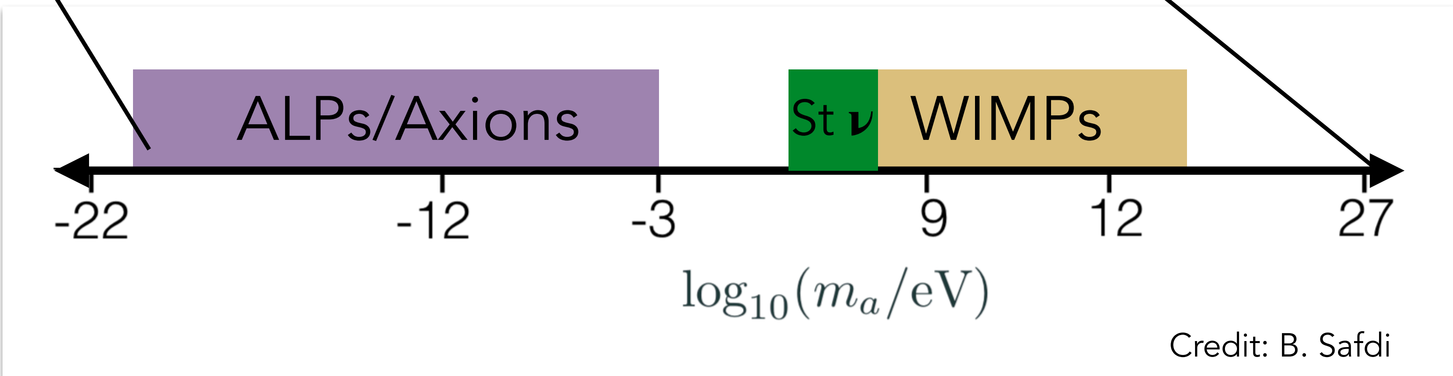
Models

Landscape in terms of (astrophysical) signatures

Macroscopic objects?



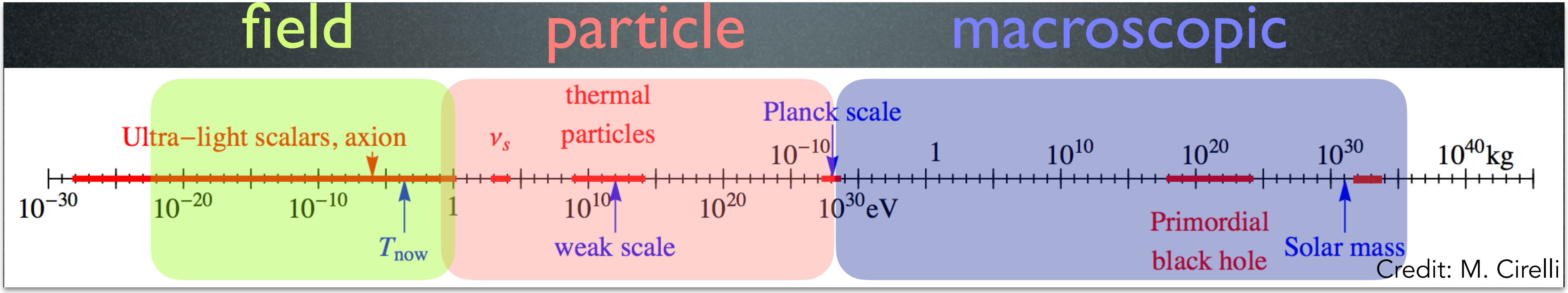
90 orders of magnitude…



Models

Landscape in terms of (astrophysical) signatures

Macroscopic objects?



Credit: M. Cirelli

90 orders of magnitude…

Search under 'theory' lamppost

Outline

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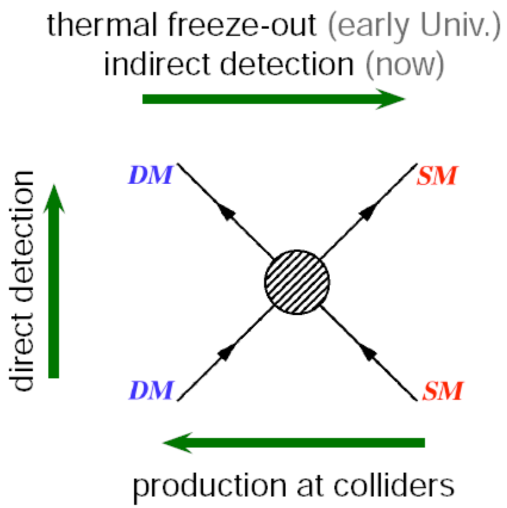
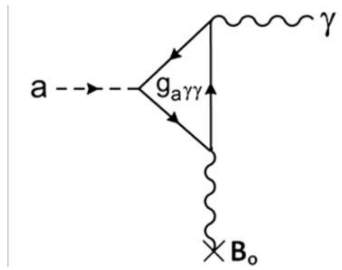
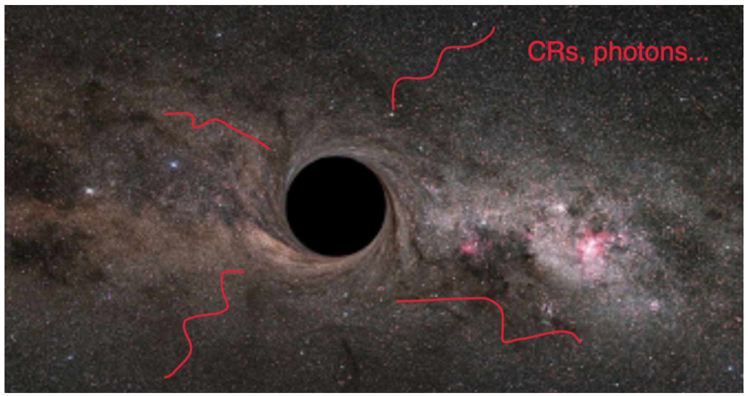
Search strategy & tools



decay

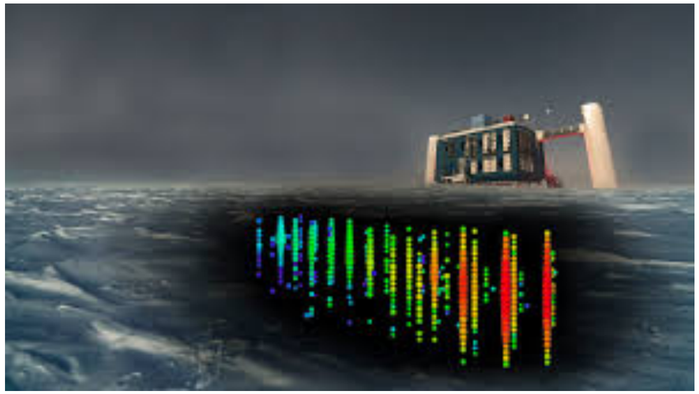
@ $\mathcal{O}(M_Z)$





γ

ν



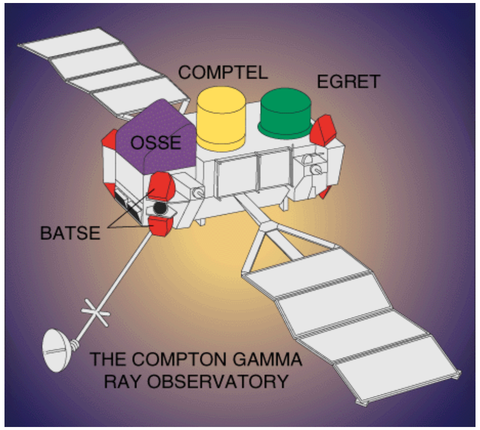
$e^{\pm}$, $p^{\pm}$ D^{-}

Gamma rays

Doro's talk

atmosphere is not transparent to gamma rays → ***satellites***

EGRET ***1991-2001***



Fermi LAT ***2008-***

AGILE ***2007-***

→ ***or ground based:***

i) Imaging Atmospheric Cherenkov Telescopes

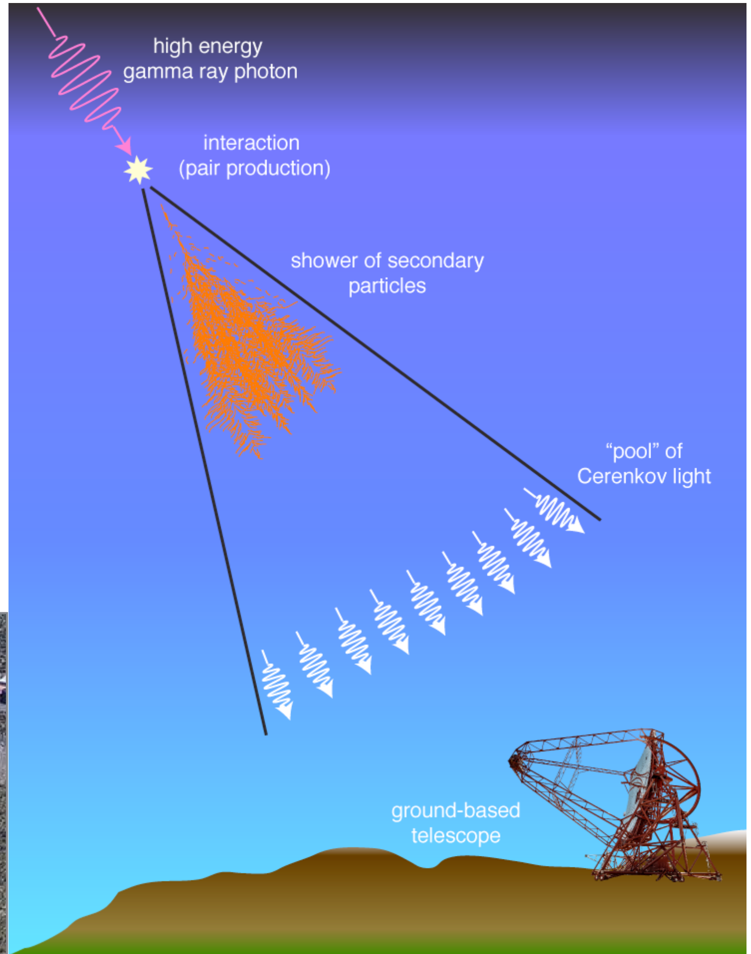
WHIPPLE 10m (1968-2013) - the beginning of γ ray astronomy

H.E.S.S. (2002 -), ***MAGIC*** (2004 -), ***VERITAS*** (2007 -)

ii) Air shower arrays ('buckets of water')

MILAGRO (2001-2008)

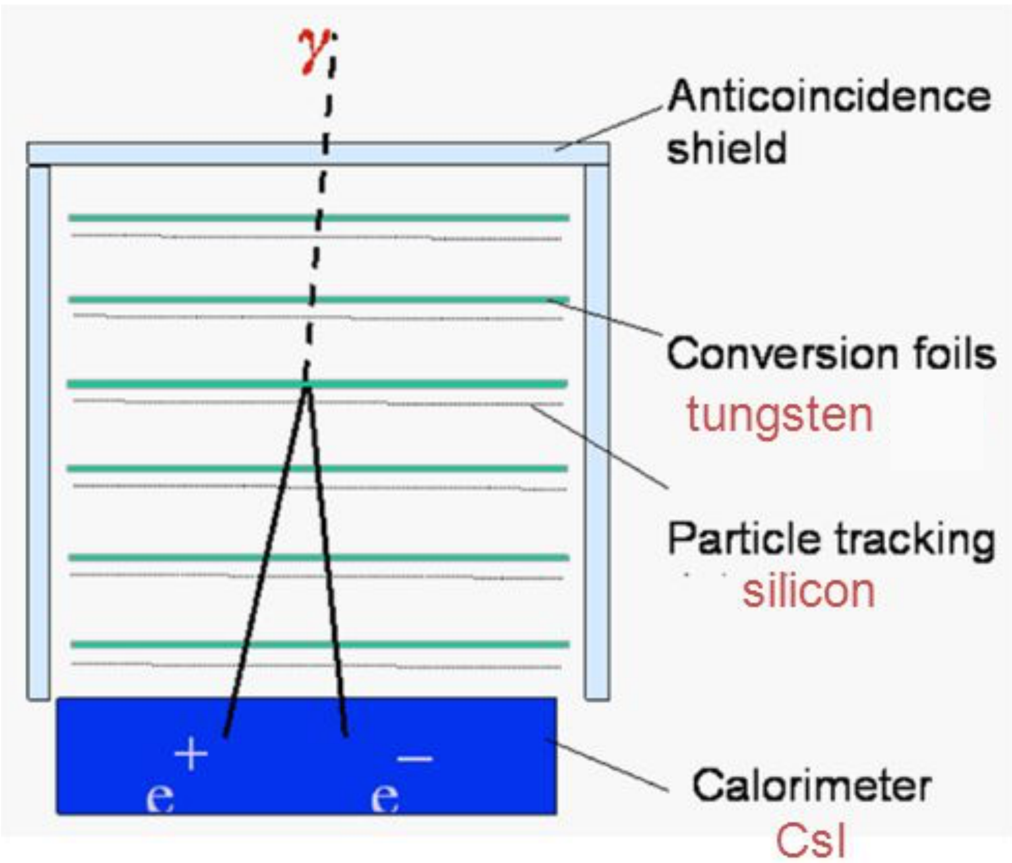
HAWC (2010 -)



Fermi LAT

Launched 11 June 2008 - 13 years!

Data public within 24h and actively used by the community



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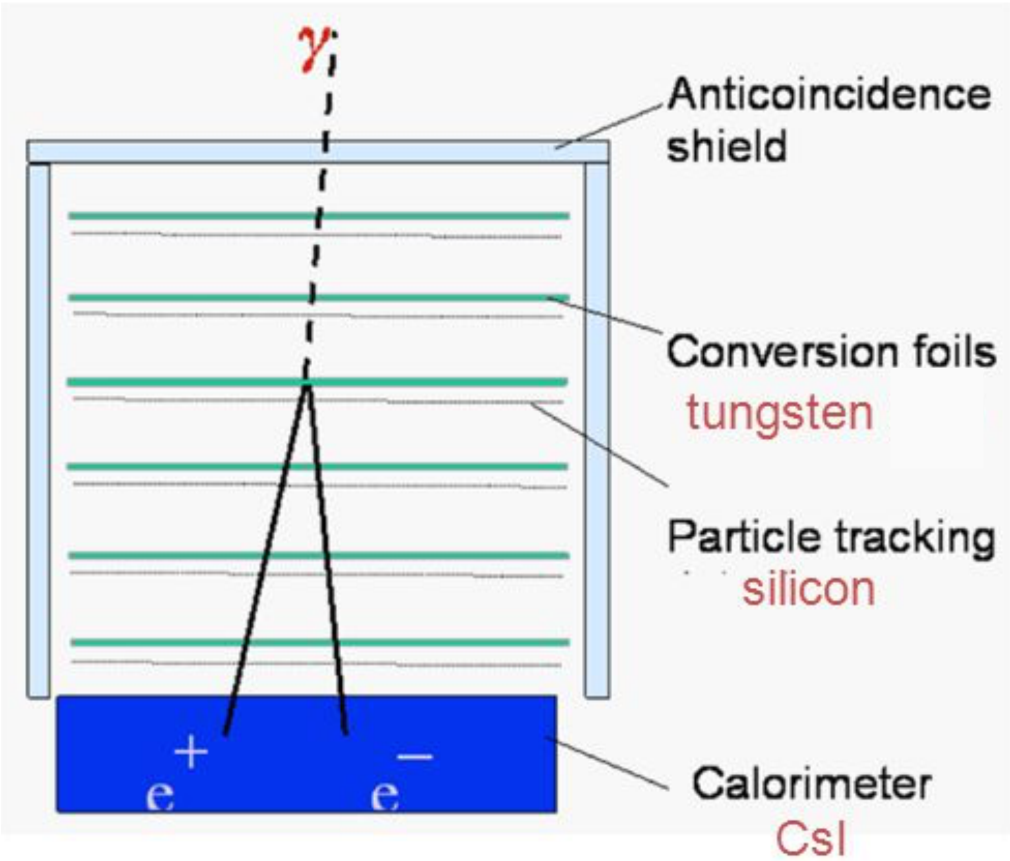
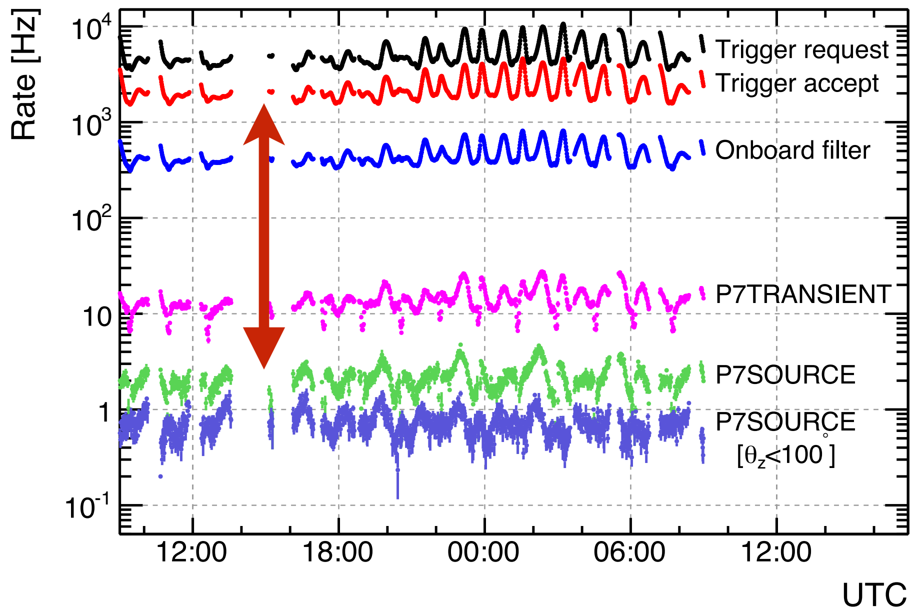


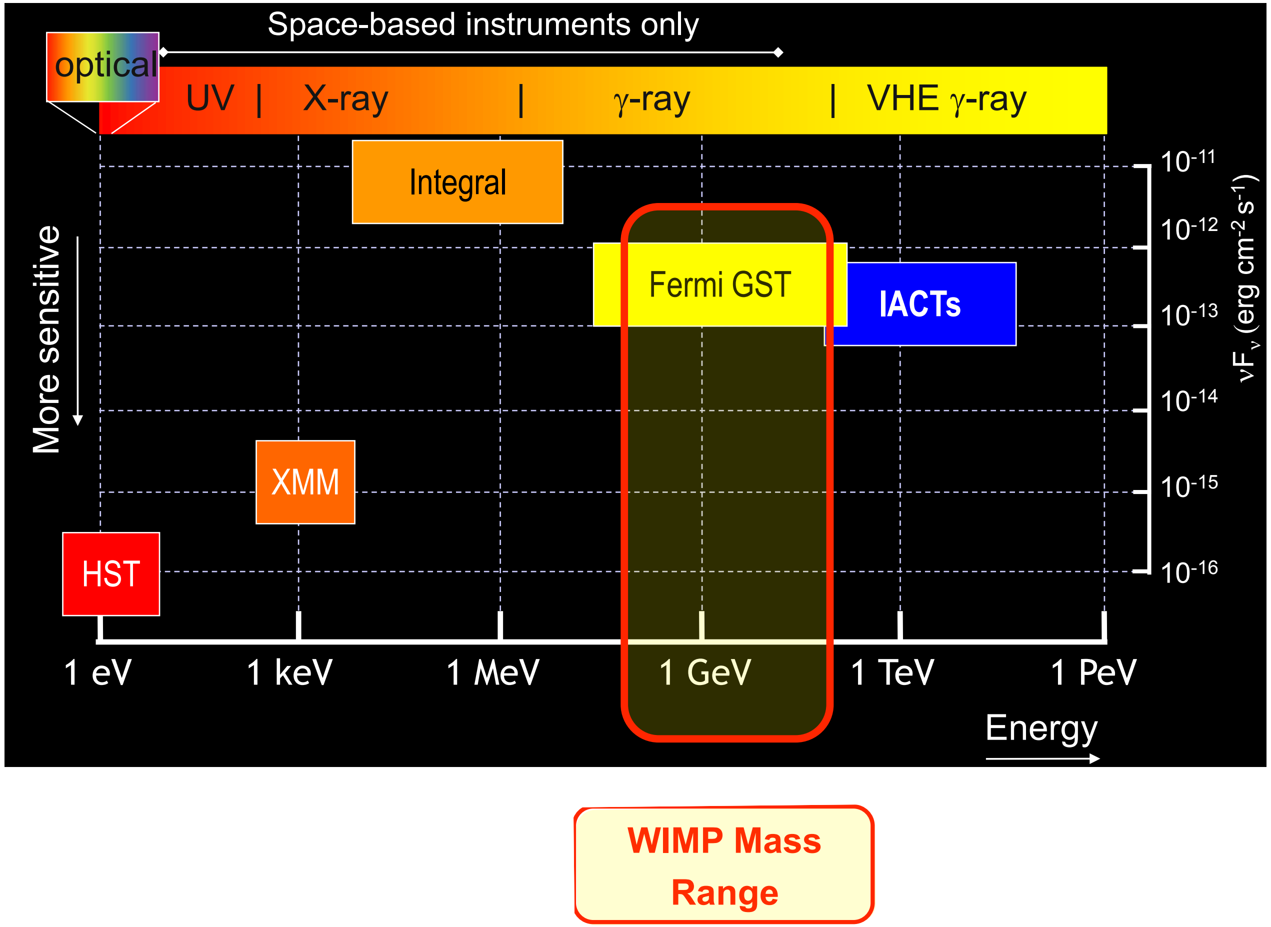


Challenge:
flux of charged CRs >>> the γ-ray flux

Fermi LAT

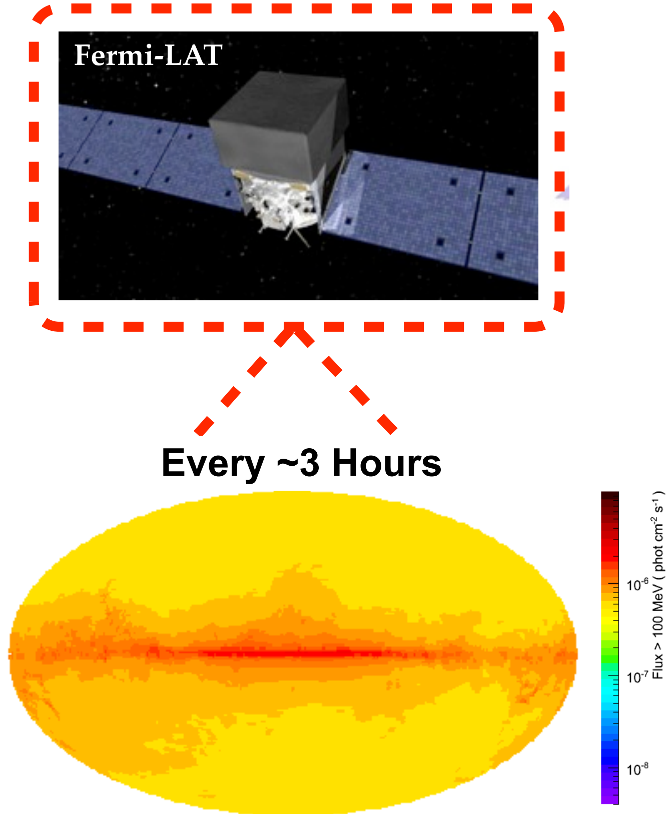
anticipated as a *'dark matter discovery tool'*

i) Energy range: 20 MeV to >300 GeV @ $\mathcal{O}(M_z)$



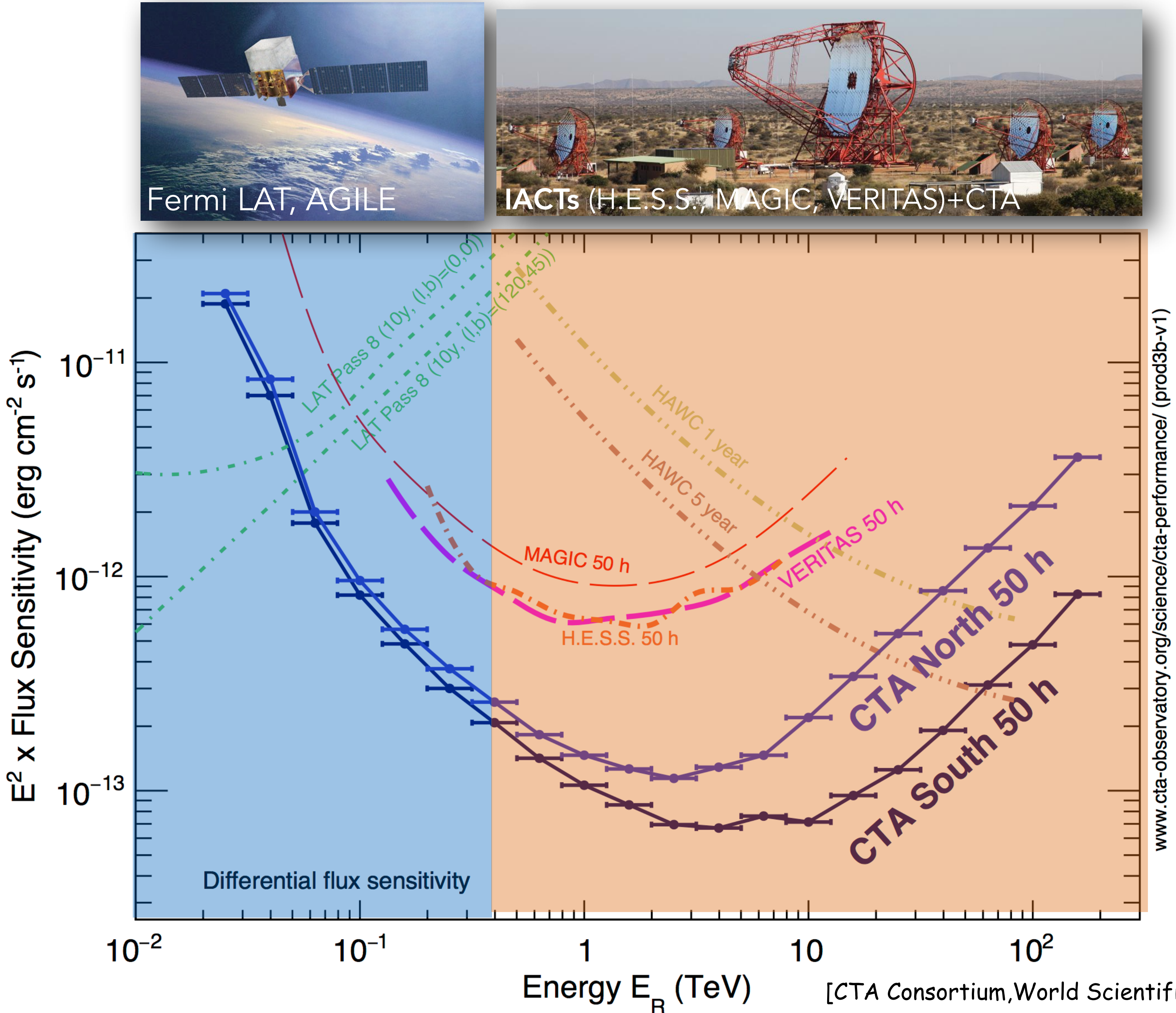
ii) Large field of view:

20% of the sky at any instant!



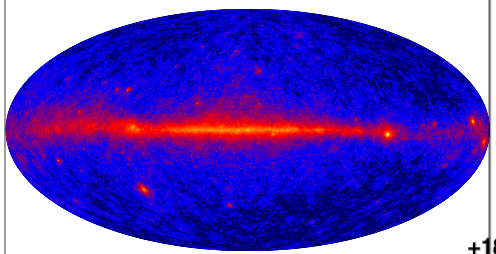
iii) Limited charged CR contamination (anti-coincidence detector)

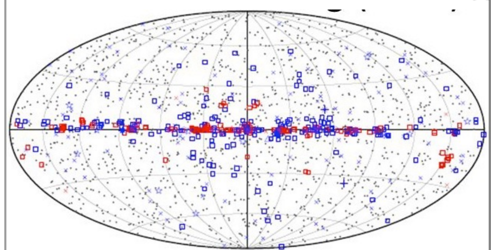
Gamma rays - the full picture

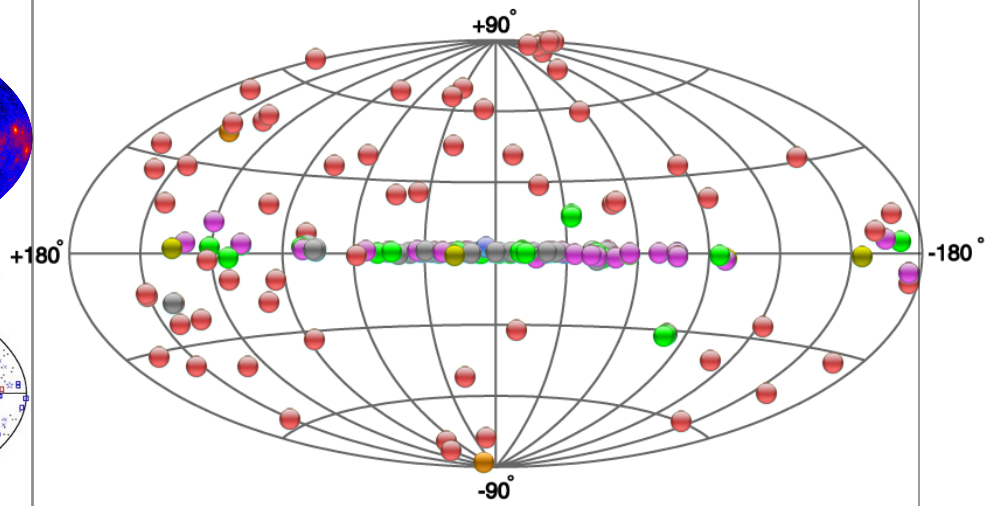


[CTA Consortium,World Scientific (2019), 1709.07997]

Gamma rays - the full picture







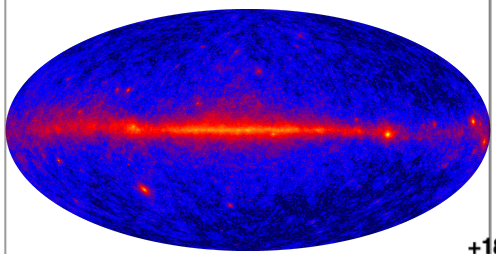
Fermi LAT:

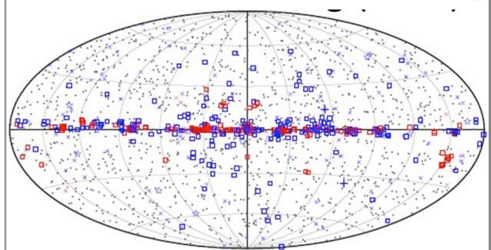
- **Large FoV (whole sky)**
- **Negligible CR**

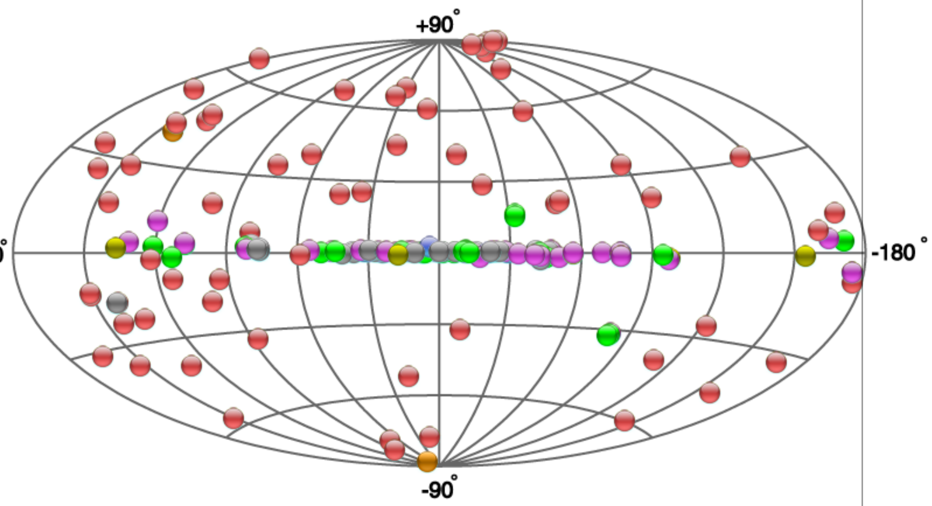
IACTs are pointing telescopes:

- **Small FoV**
- **Significant CR contamination**
- **Better energy and ang resolution**

Gamma rays - the full picture







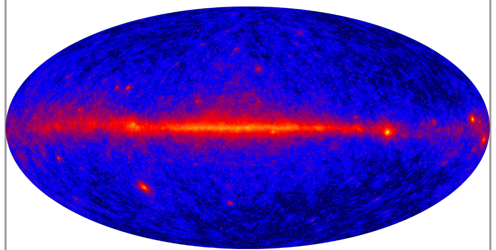
Fermi LAT:

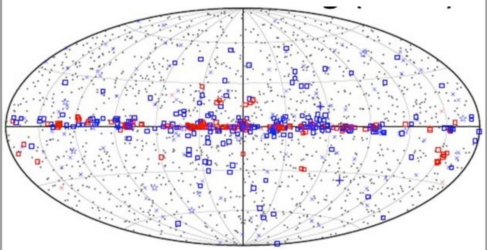
- **Large FoV (whole sky)**
- **Negligible CR**

Water Cherenkov:

- **Larger FoV**
- **Significant CR contamination**
- **Worse energy and ang resolution**

Gamma rays - analysis techniques

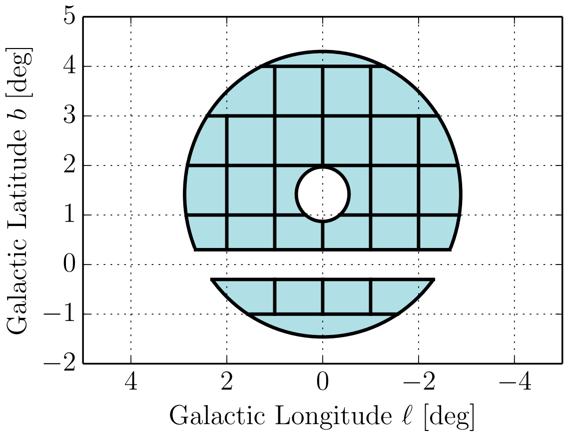




Fermi LAT:

- **Large FoV (whole sky)**
- **Negligible CRs**

Typical: **'Template based' likelihood fitting**



Poisson likelihood:

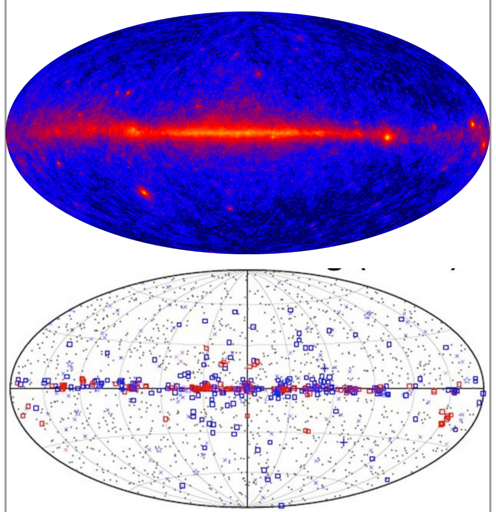
$$\mathcal{L}\left(\boldsymbol{\mu}|\boldsymbol{n}\right) = \prod_{i,j} \frac{{\mu_{ij}}^{n_{ij}}}{n_{ij}!} \exp(-\mu_{ij}).$$

model data

model $$\mu_{ij}(A^{\chi}, A_i^X) = A^{\chi}\mu_{ij}^{\chi} + \sum_X A_i^X \mu_{ij}^X \,.$$

DM Astro components

Gamma rays - analysis techniques



Fermi LAT:

- **Large FoV (whole sky)**
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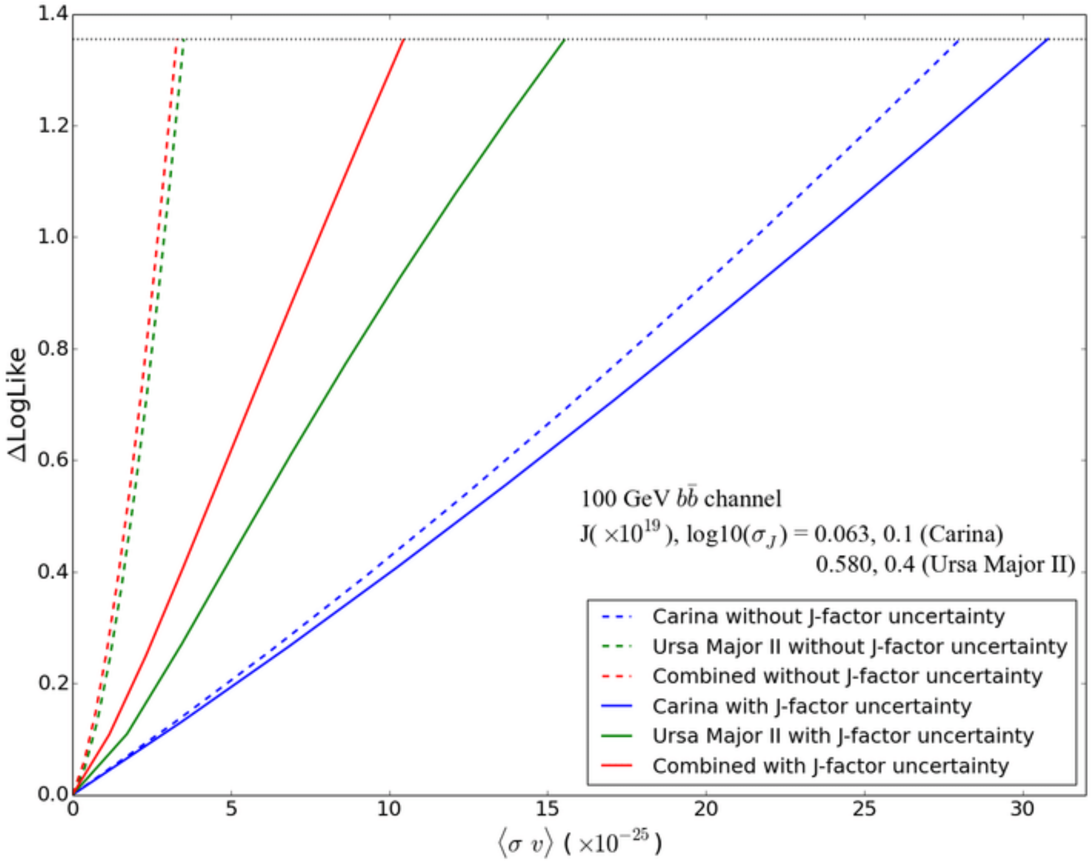
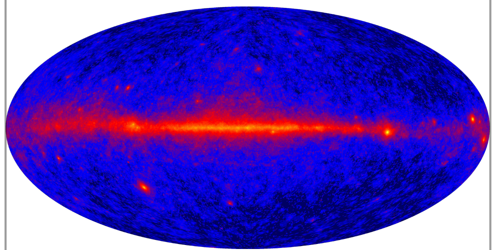
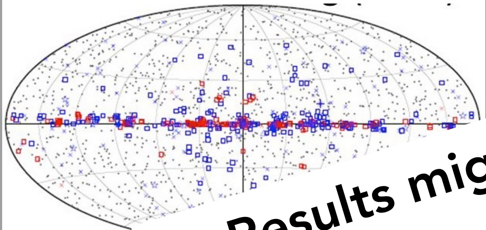


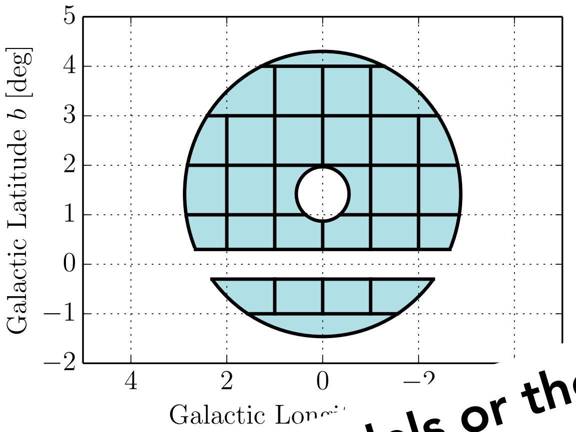
$$\mathrm{TS}(A_\chi) = \min_{\{A_i^X\}} \left(-2 \ln \left[\frac{\mathcal{L}(\boldsymbol{\mu}(A^X, A_i^X) | \boldsymbol{n})}{\mathcal{L}(\hat{\boldsymbol{\mu}} | \boldsymbol{n})} \right] \right)$$

Gamma rays - analysis techniques





Typical: 'Template based' likelihood fitting technique



Poisson likelihood:

$$\mathcal{L}(\boldsymbol{\mu}|\boldsymbol{n}) = \prod \frac{\mu_{ij}{}^{n_{ij}}}{} \quad (-\mu_{ij}).$$

data

- **Results might depend on input models or the amount degrees of freedom - estimate of systematic uncertainties critical**

$$\mu_{ij}(A^\chi, A_i^X) = A^\chi \mu_{ij}^\chi + \sum_X A_i^X \mu_{ij}^X \, .$$

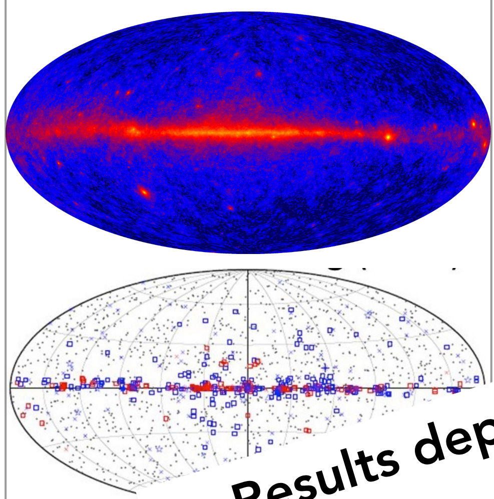
DM

Astro components

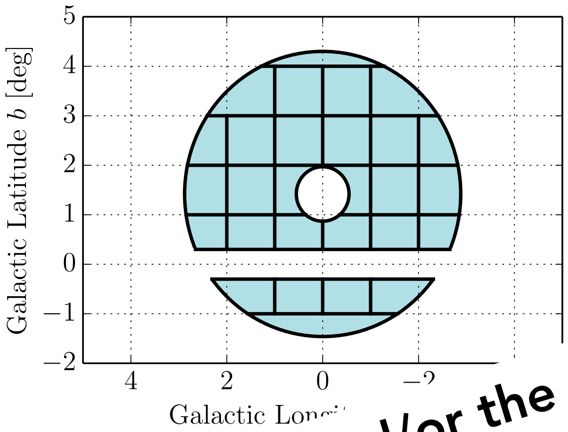
Fermi

- **Large FoV (whole sky)**
- **Negligible CRs**

Gamma rays - analysis techniques



Typical: 'Template based' likelihood fitting technique



Poisson likelihood:

$$\mathcal{L}(\boldsymbol{\mu}|\boldsymbol{n}) = \prod \frac{\mu_{ij}{}^{n_{ij}}}{\ldots} \ldots (-\mu_{ij}).$$

data

- Results depend on input models and/or the amount degrees of freedom - estimate of systematic uncertainties critical

$$\mu_{ij}(A^\chi, A_i^X) = A^\chi \mu_{ij}^\chi + \sum_X A_i^X \mu_{ij}^X \, .$$

'Covariance matrix'

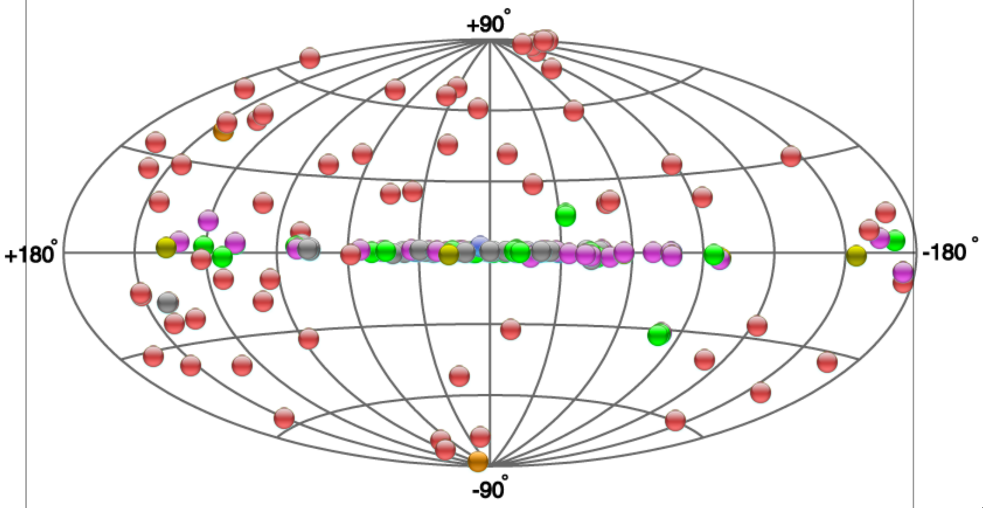
$$\mathcal{L}(\boldsymbol{\mu}|\boldsymbol{n}) = \prod_{k=1}^{\mathcal{N}} \frac{\mu_k^{n_k}}{(n_k)!} e^{-\mu_k} \times \exp\left[-\frac{1}{2}\Delta B_k \sum_{l=1}^{\mathcal{N}} \left(K^{-1}\right)_{kl} \Delta B_l\right]$$

ΔBk - perturbations in different background templates, k

Fermi …:

- **Large FoV (whole sky)**
- **Negligible CRs**

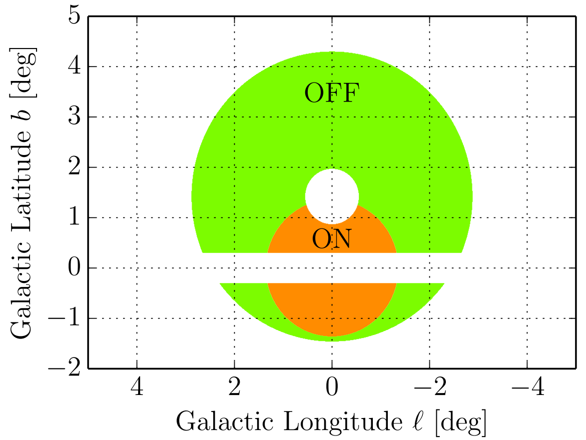
Gamma rays - analysis techniques



IACTs are pointing telescopes:

- **Small FoV**
- **Significant CR contamination**
- **Better energy and ang resolution**

Traditionally 'ON/OFF' technique

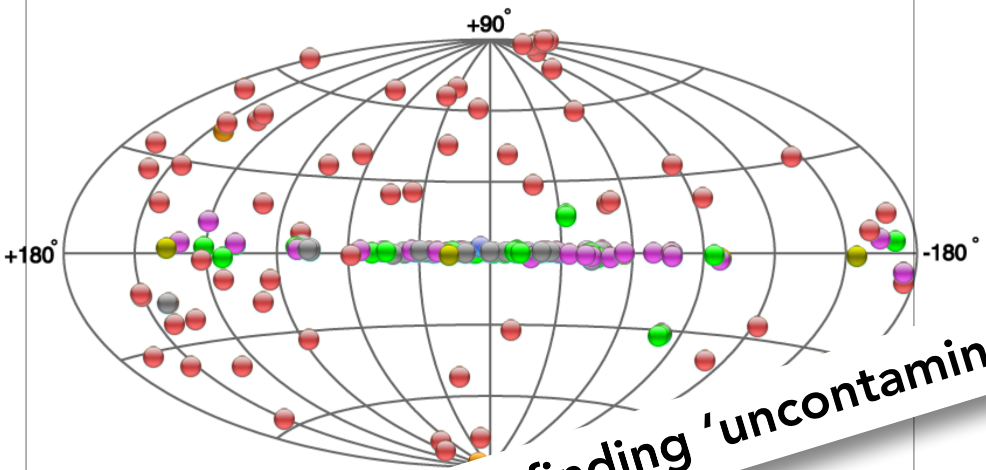


Backgrounds measured, not modelled

$$\mathcal{L}(M_{\rm DM}, \langle\sigma v\rangle) = \prod_{ijk} \mathcal{L}_{ij}\left(\mathbf{N}^{\rm S}_{\mathbf{k}}, \mathbf{N}^{\rm B}_{\mathbf{k}}, \kappa_{\mathbf{k}} \,|\, \mathbf{N}^{\rm ON}_{\mathbf{k}}, \mathbf{N}^{\rm OFF}_{\mathbf{k}}\right)$$

$$= \prod_{ijk} \frac{\left(N^{\rm S}_{ijk}+\kappa_{ijk}N^{\rm B}_{ijk}\right)^{N^{\rm ON}_{ijk}}}{N^{\rm ON}_{ijk}!} e^{-(N^{\rm S}_{ijk}+\kappa_{ijk}N^{\rm B}_{ijk})} \times \frac{\left(N^{\rm B}_{ijk}\right)^{N^{\rm OFF}_{ijk}}}{N^{\rm OFF}_{ijk}!} e^{-N^{\rm B}_{ijk}}$$

Gamma rays - analysis techniques



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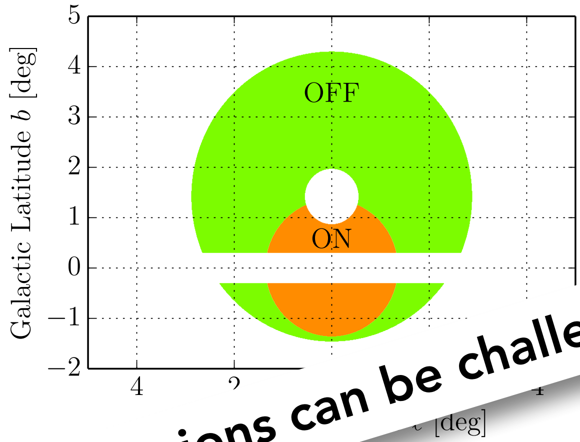


- However, finding 'uncontaminated' OFF regions can be challenging

ckgrounds measured not modelled

$$\mathcal{L}(M_{\rm DM},\langle\sigma v\rangle) = \prod_{ijk} \mathcal{L}_{ij}\left(\mathbf{N}^{\rm S}_{\mathbf{k}}, \mathbf{N}^{\rm B}_{\mathbf{k}}, \kappa_{\mathbf{k}} \,|\, \mathbf{N}^{\rm ON}_{\mathbf{k}}, \mathbf{N}^{\rm OFF}_{\mathbf{k}}\right)$$

$$= \prod_{ijk} \frac{\left(N^{\rm S}_{ijk}+\kappa_{ijk}N^{\rm B}_{ijk}\right)^{N^{\rm ON}_{ijk}}}{N^{\rm ON}_{ijk}!} e^{-(N^{\rm S}_{ijk}+\kappa_{ijk}N^{\rm B}_{ijk})} \times \frac{\left(N^{\rm B}_{ijk}\right)^{N^{\rm OFF}_{ijk}}}{N^{\rm OFF}_{ijk}!} e^{-N^{\rm B}_{ijk}}$$

Outline

1. DM model space that CAN be tested with gamma-rays
2. Experiments & data analysis techniques
3. Wish list, targets
4. Astro backgrounds
5. Examples:
    - WIMPs
    - ALPs

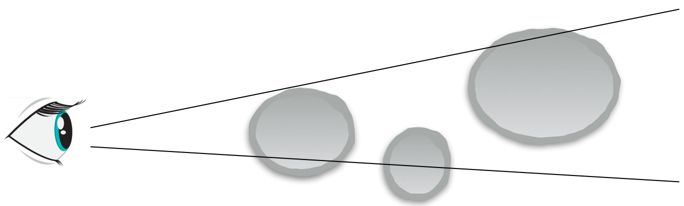
The signal

$$\boxed{\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma}} \sim$$

how likely the interaction (annihilations, decays, conversions)

how many photons produced PER interaction

How many DM particles/objects are there along the L.O.S.



The signal

Francesca's talk

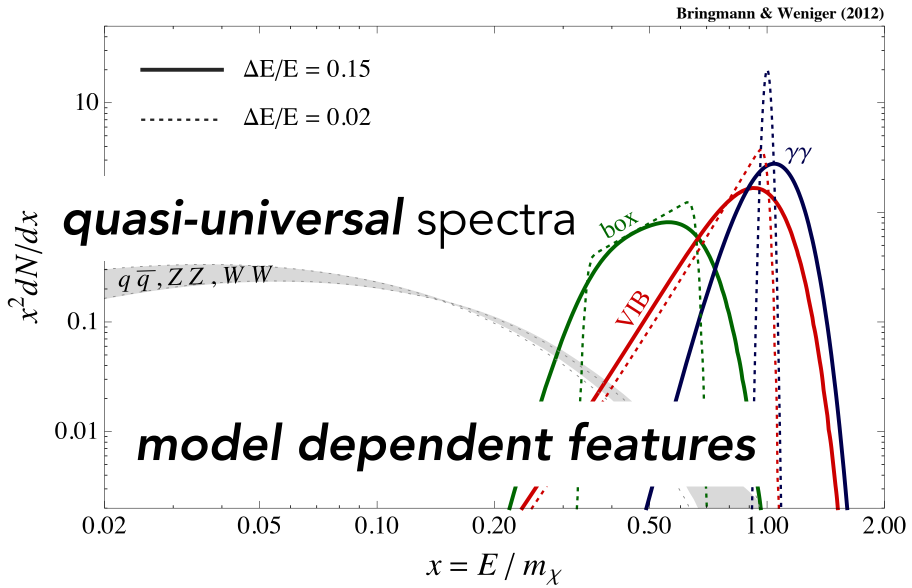
In the case of WIMPs

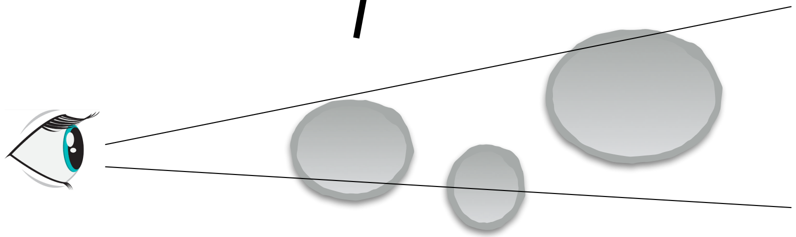
particle physics **cosmology**

$$\boxed{\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma}} = \boxed{\frac{1}{4\pi}\;\frac{(\sigma_{\rm ann} v)}{2\, m_\chi^2}} \;\mathrm{X}\; \boxed{\sum_i \mathrm{BR}_i \frac{dN_\gamma^i}{dE_\gamma}} \;\mathrm{X}\; \boxed{\int_{\Delta\Omega} d\Omega \int_{\rm los} ds\, \rho^2(s,\Omega)}$$

flux of SM particles

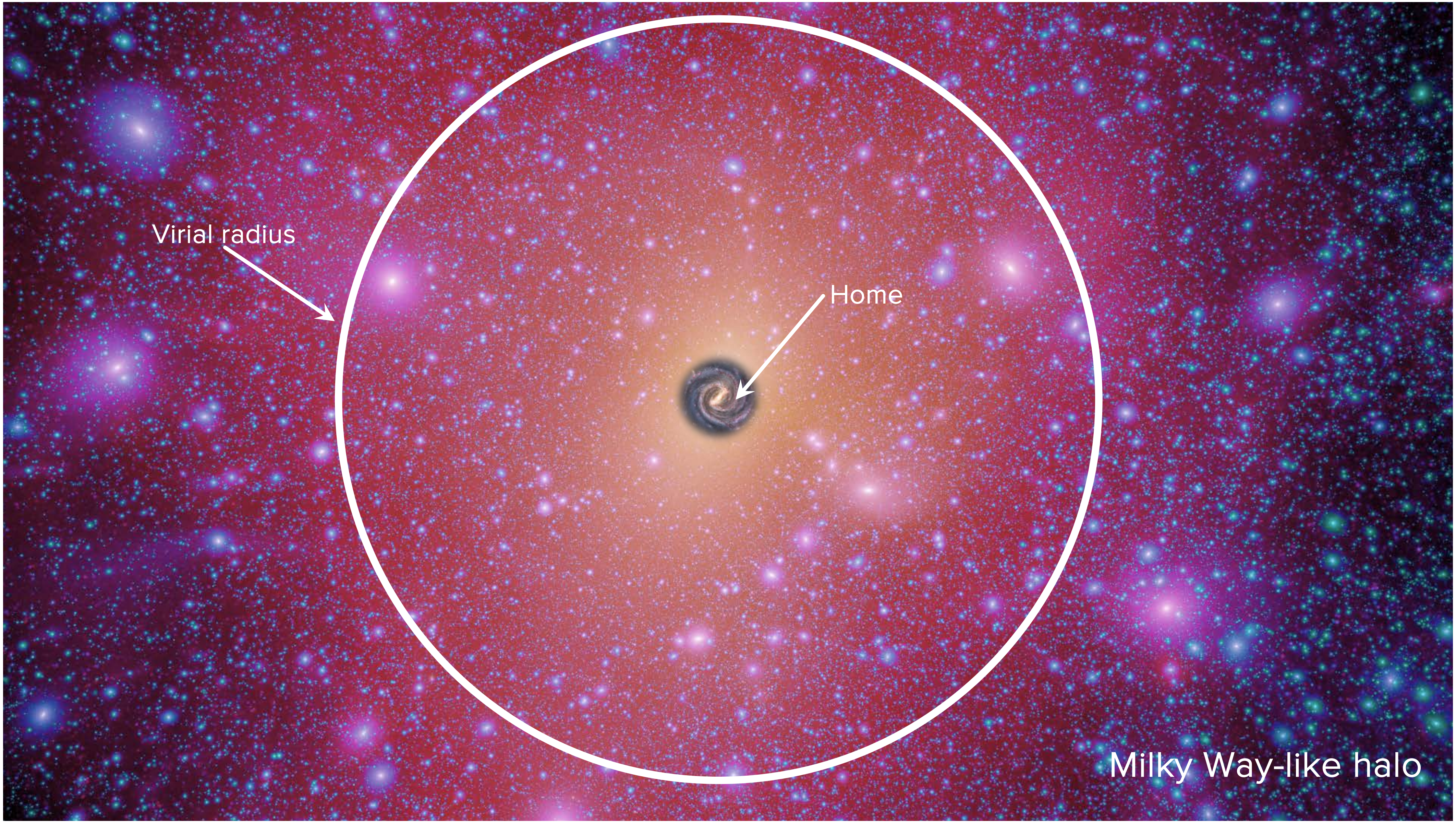
per DM annihilation





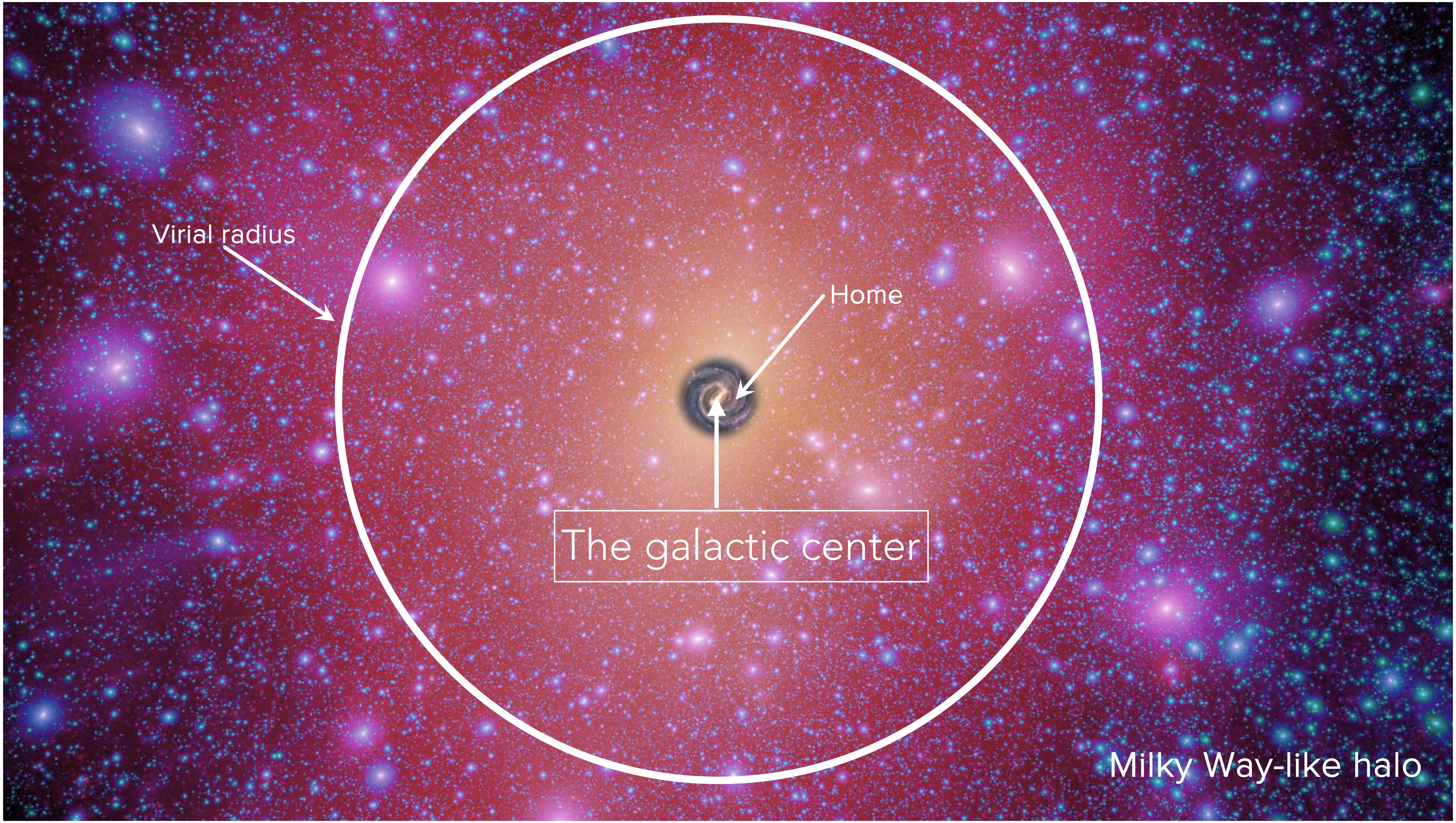
Where to look

Celine's, Moritz's + talks



Credit: J. Coronado-Blazquez

Targets



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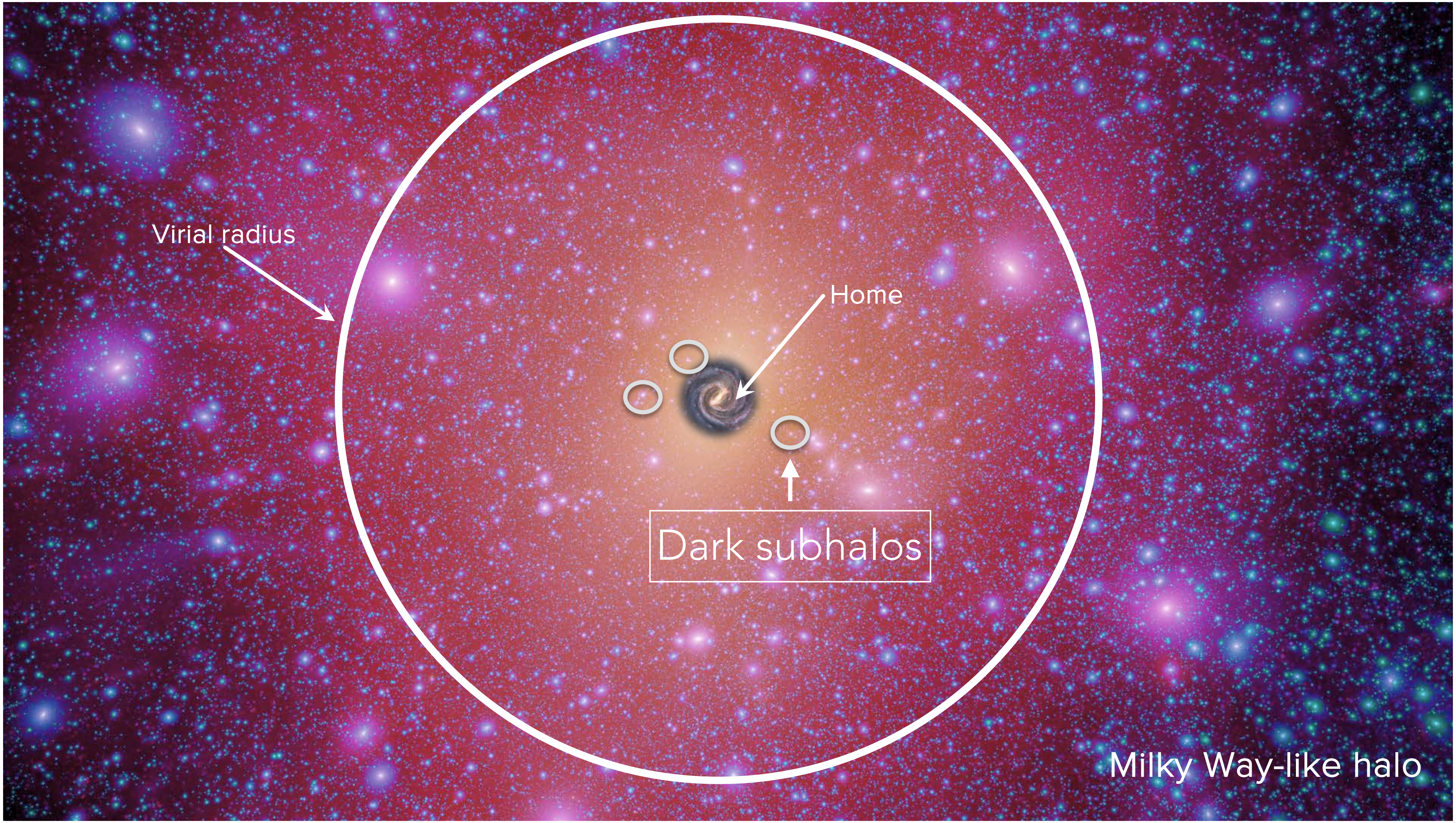
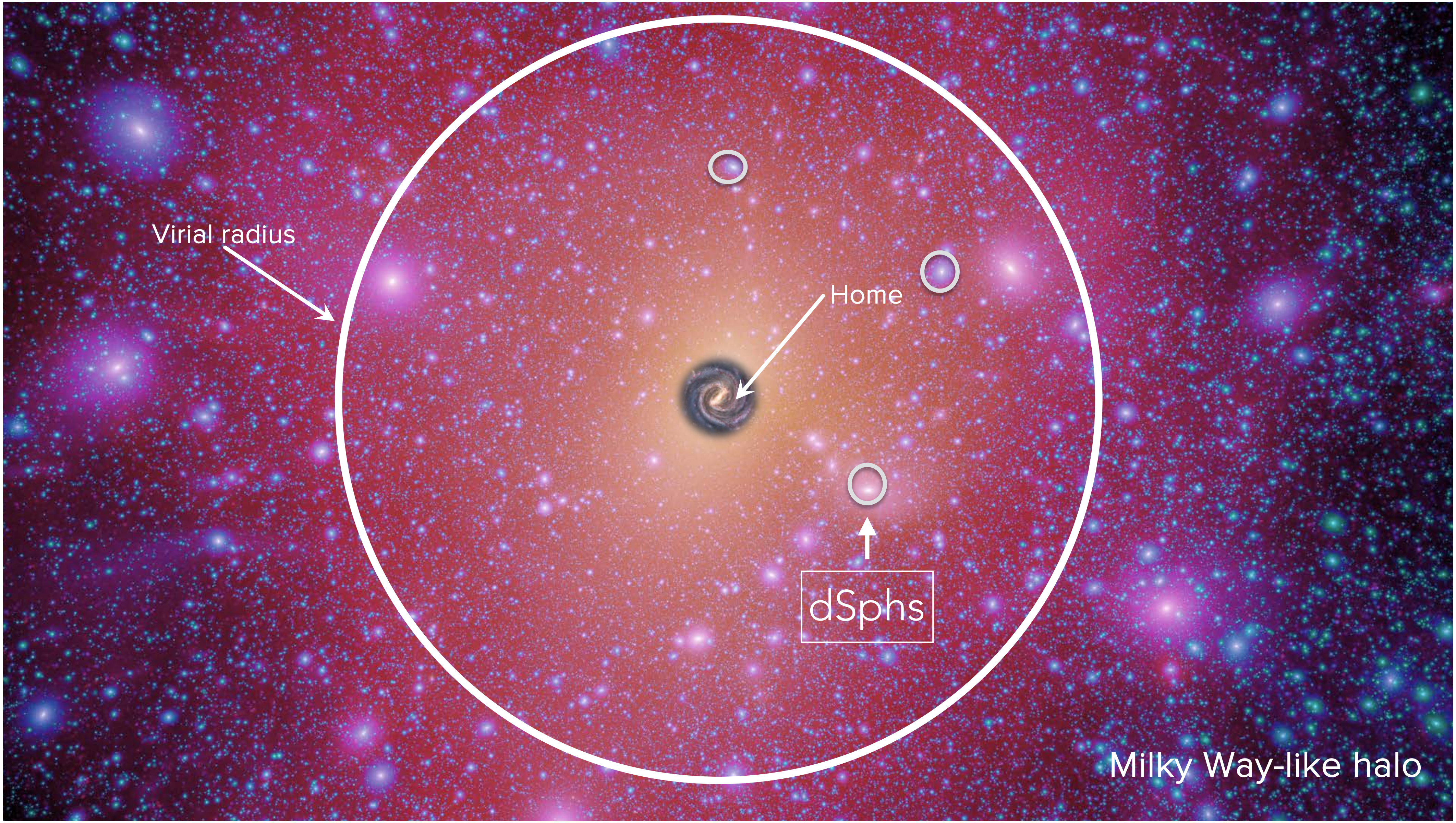
Targets



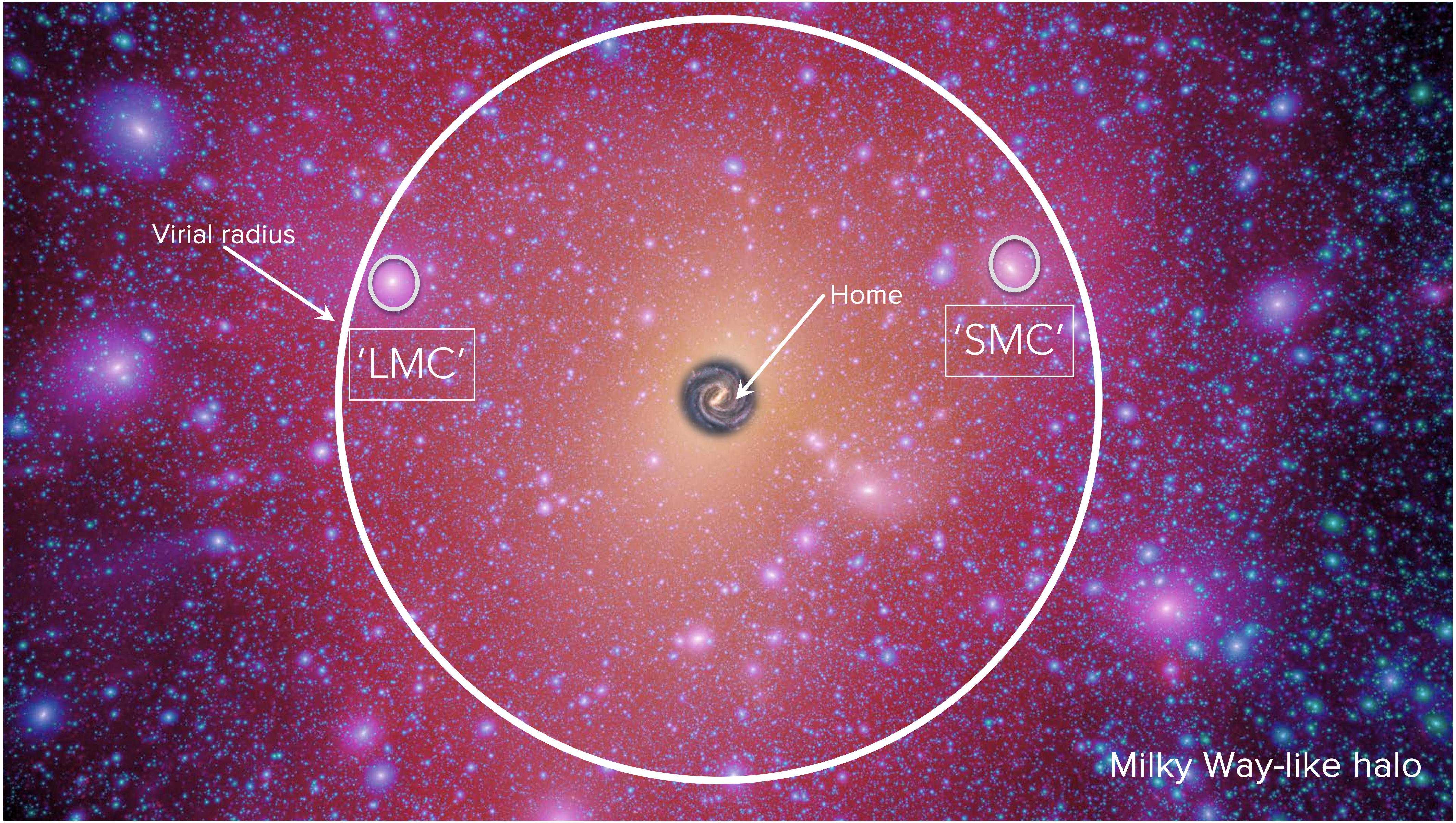
Credit: J. Coronado-Blazquez

Targets



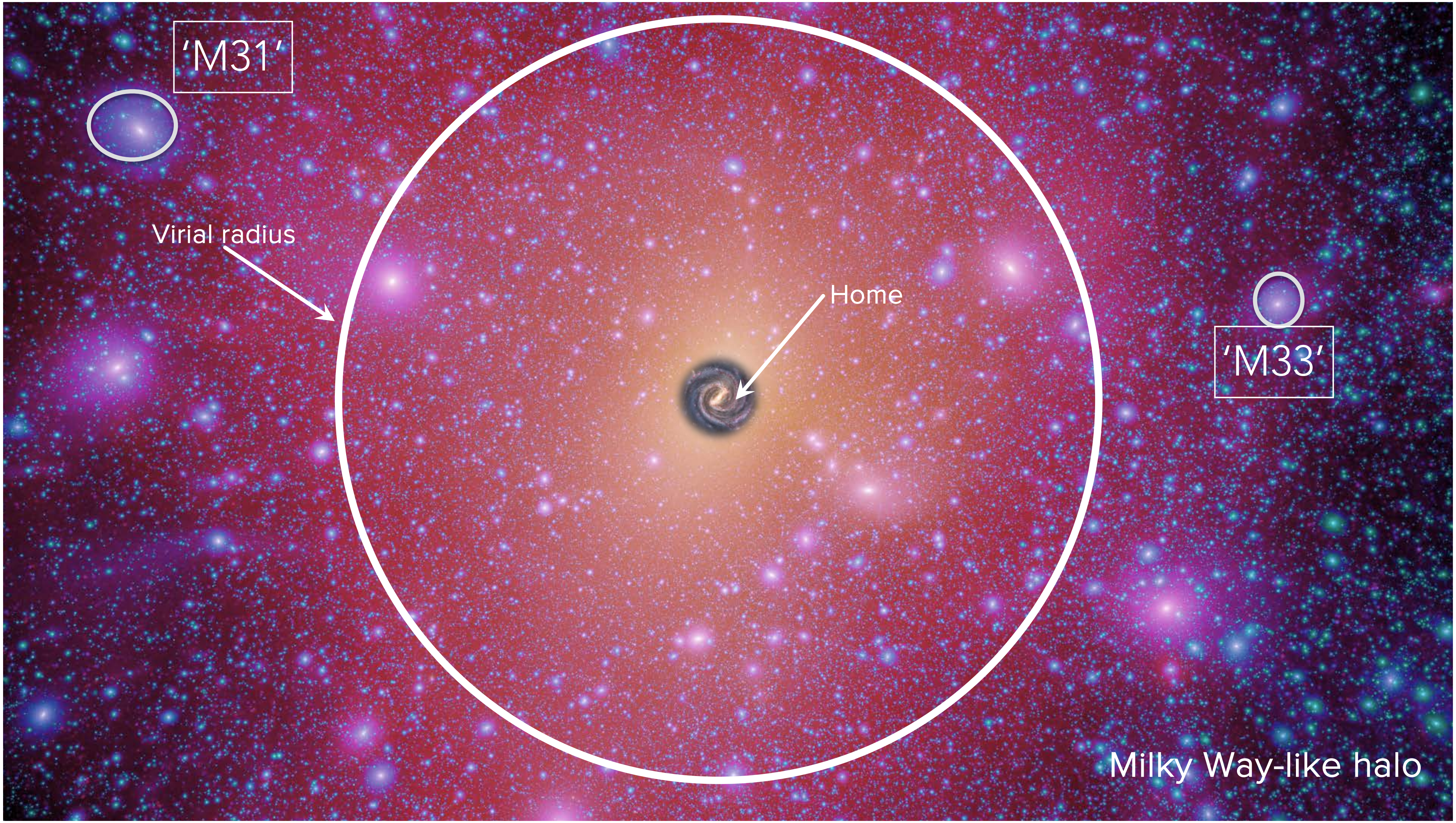
Credit: J. Coronado-Blazquez

Targets



Credit: J. Coronado-Blazquez

Targets



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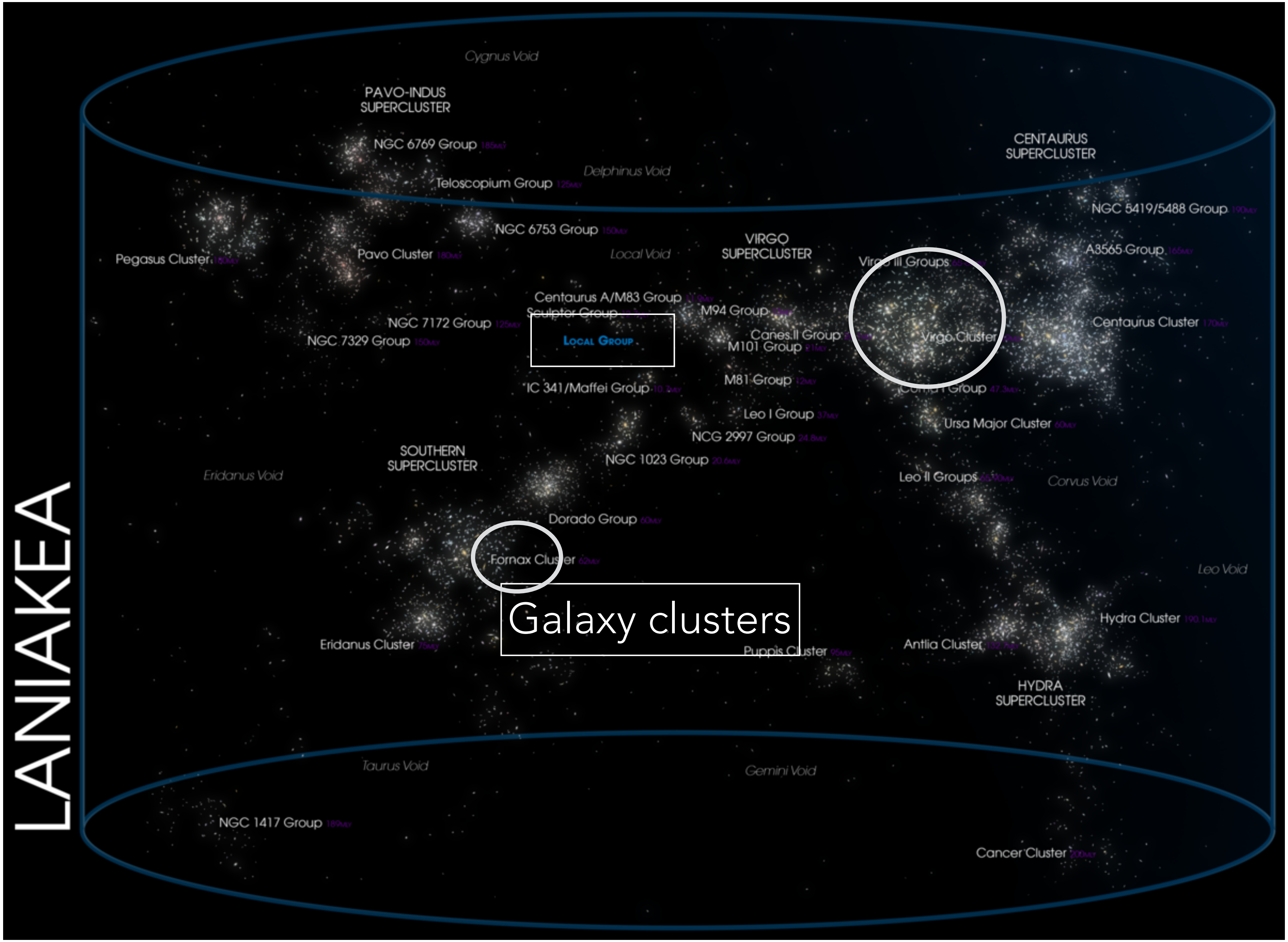
Targets


LANIAKEA
Cygnus Void
PAVO-INDUS SUPERCLUSTER
NGC 6769 Group
Teloscopium Group
Delphinus Void
CENTAURUS SUPERCLUSTER
NGC 5419/5488 Group
NGC 6753 Group
Pegasus Cluster
Pavo Cluster
Local Void
VIRGO SUPERCLUSTER
A3565 Group
Centaurus A/M83 Group
Sculptor Group
M94 Group
NGC 7172 Group
Local Group
Canes II Group
M101 Group
Virgo Cluster
Centaurus Cluster
NGC 7329 Group
IC 341/Maffei Group
M81 Group
Leo I Group
Ursa Major Cluster
NCG 2997 Group
SOUTHERN SUPERCLUSTER
NGC 1023 Group
Eridanus Void
Leo II Groups
Corvus Void
Dorado Group
Fornax Cluster
Leo Void
Galaxy clusters
Hydra Cluster
Eridanus Cluster
Puppis Cluster
Antlia Cluster
HYDRA SUPERCLUSTER
Taurus Void
Gemini Void
NGC 1417 Group
Cancer Cluster

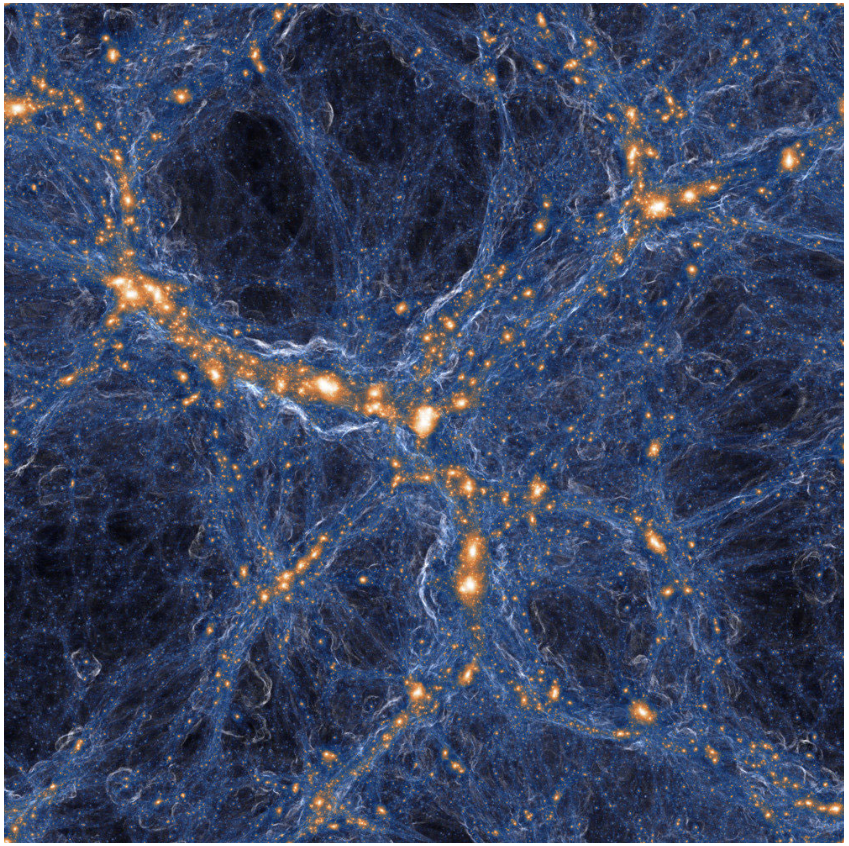
Targets

Together with analysis of individual targets, target ***assembles*** can be used in various statistics frameworks:

— cumulative extragalactic signal

— angular anisotropies

— cross-correlations between gamma ray maps and DM tracer maps (weak lensing, galaxy catalogues..)

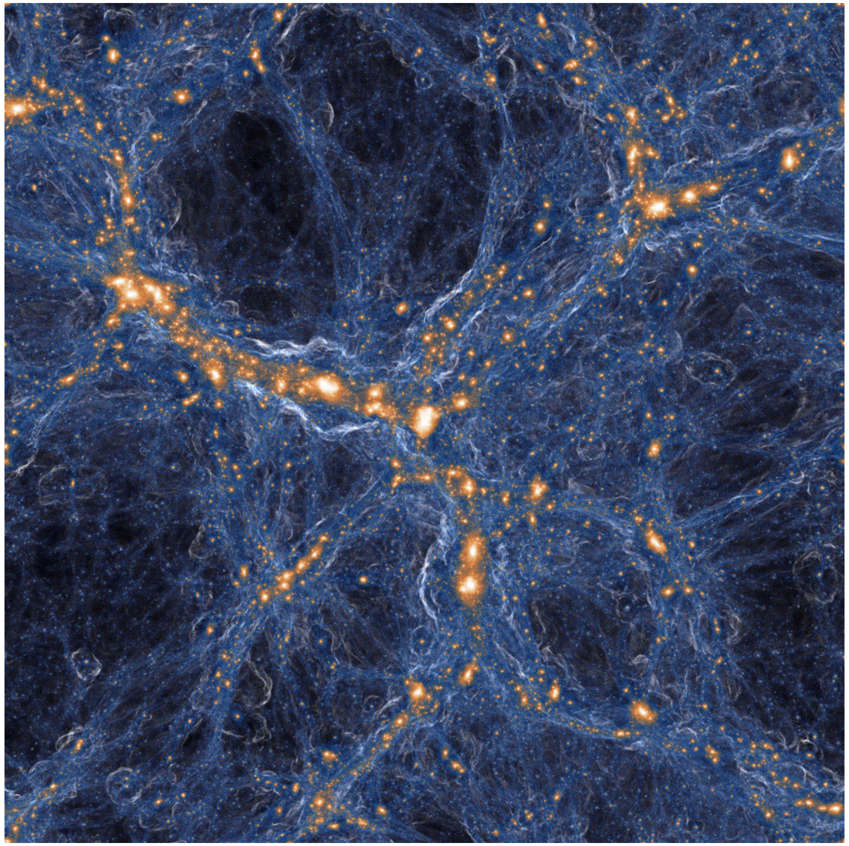


[TNG100 simulation]

Elephants in the room

DM density distribution **poorly constrained on small scales**!

Critical because signal is usually DOMINATED by small scales (e.g. center of our Galaxy) or by annihilation in small halos (which are the most concentrated)



[TNG100 simulation]

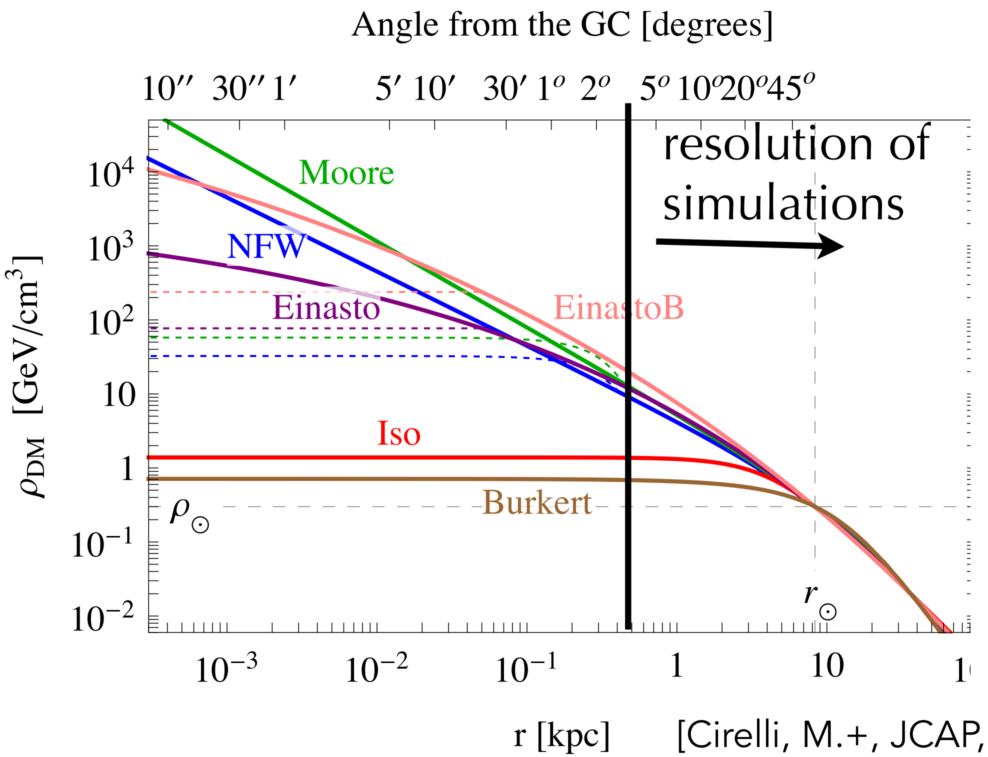
Elephants in the room

Gustavo's talk

N-body simulations: issues 01

- ***limited resolution-> small distances and small masses unresolved.***

recall for WIMPs signal~ $\int_{\Delta\Omega} d\Omega \int_{\text{los}} \mathrm{d}s\, \rho^2(s,\Omega)$



[Cirelli, M.+, JCAP, 2011]

(sub)halos resolved down to >~10^5 M_{sol}.

WIMPs could produce halos as small as 10^{-6} M_{sol}.

Elephants in the room

Annalisa's talk

N-body simulations: issues 02

- ***baryonic feedback*** baryons can dominate gravitational potential iat small scales
- Challenge - simulations need to cover a large span of scales

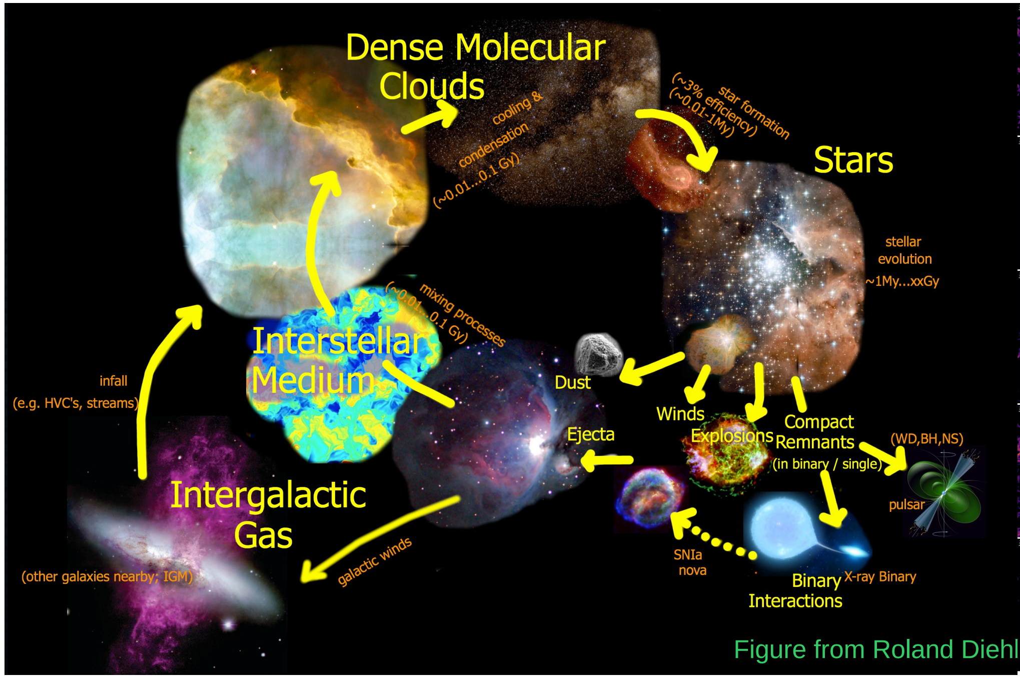
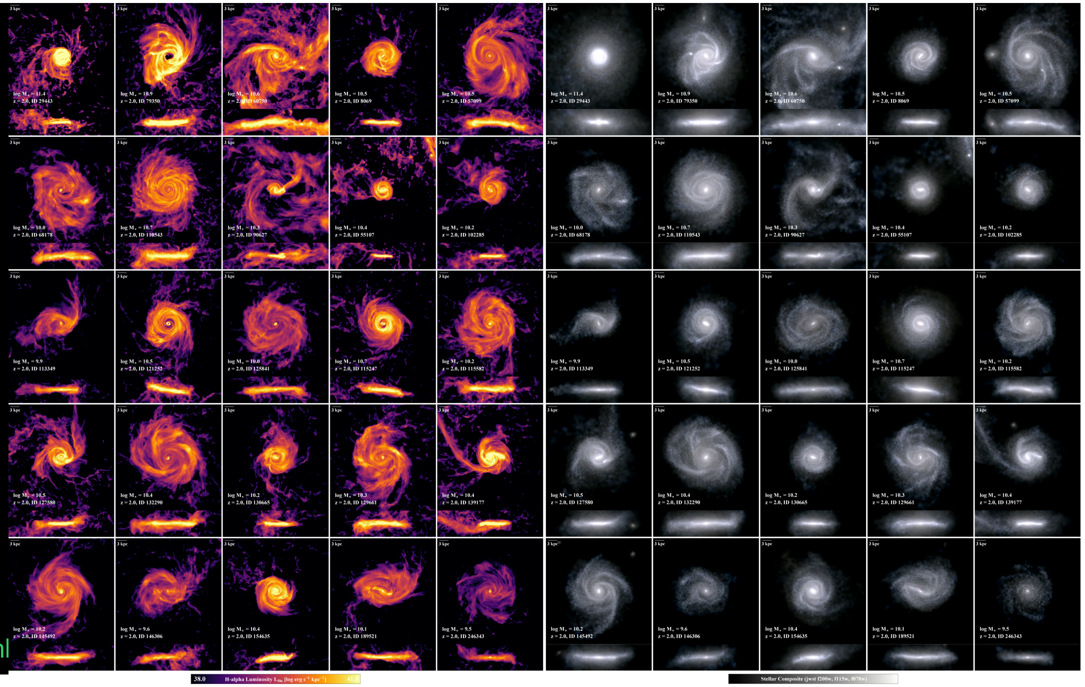


Figure from Roland Diehl



[TNG simulation]

A number of simulations recover realistic disk Galaxies (great progress!), but still a number of open issues

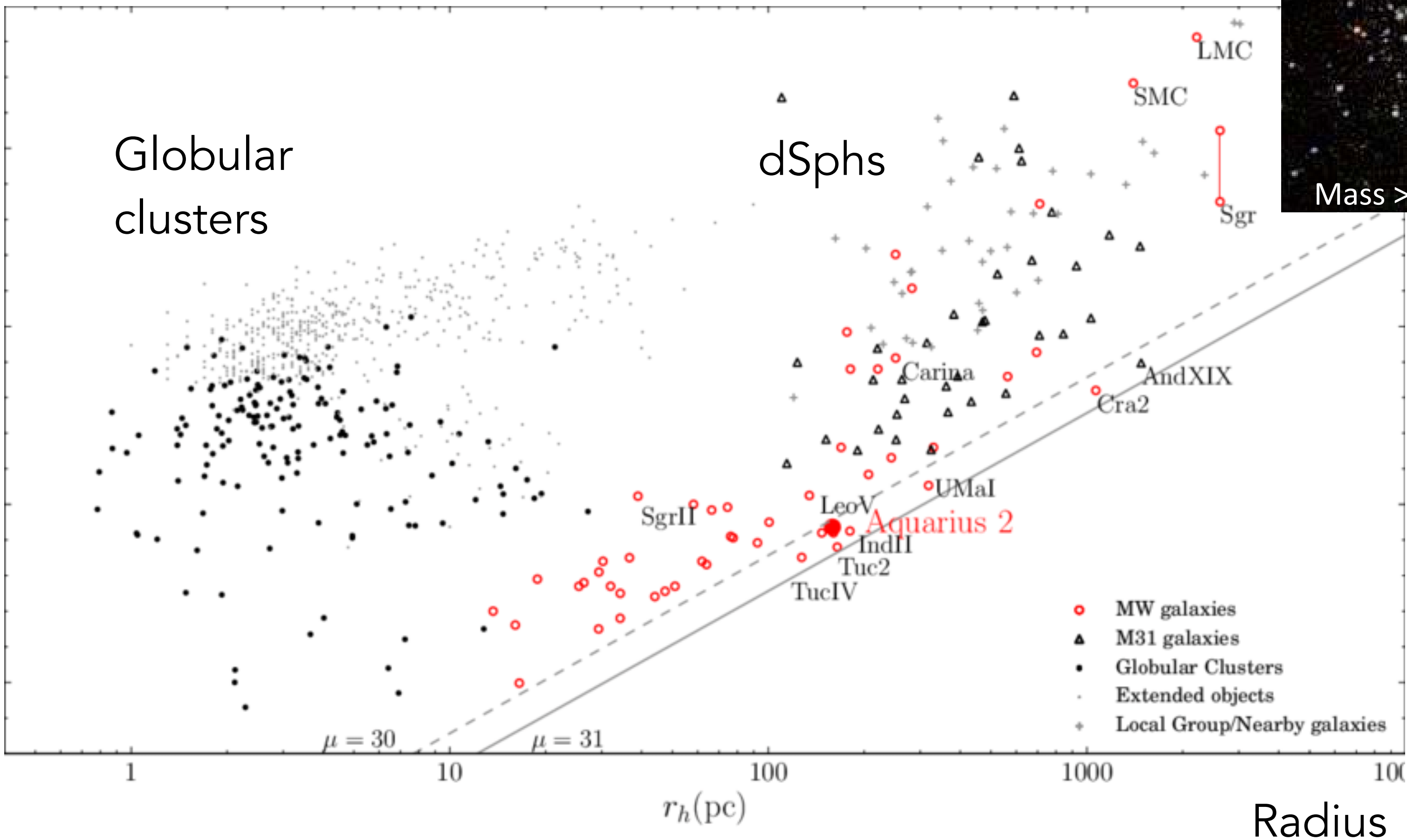
Elephants in the room

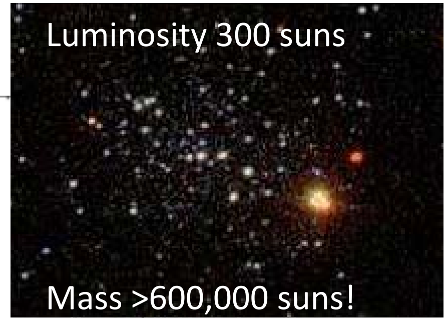
Observations:

different approach is to ***measure*** motion of stellar objects to determine the gravitational potential of DM. For example:

- ***dwarf spheroidal Galaxies:*** the smallest DM halos (10^8, 10^9 Msol) that host stars

Brightness





Radius

Elephants in the room

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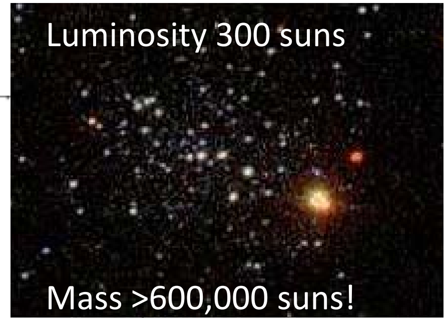
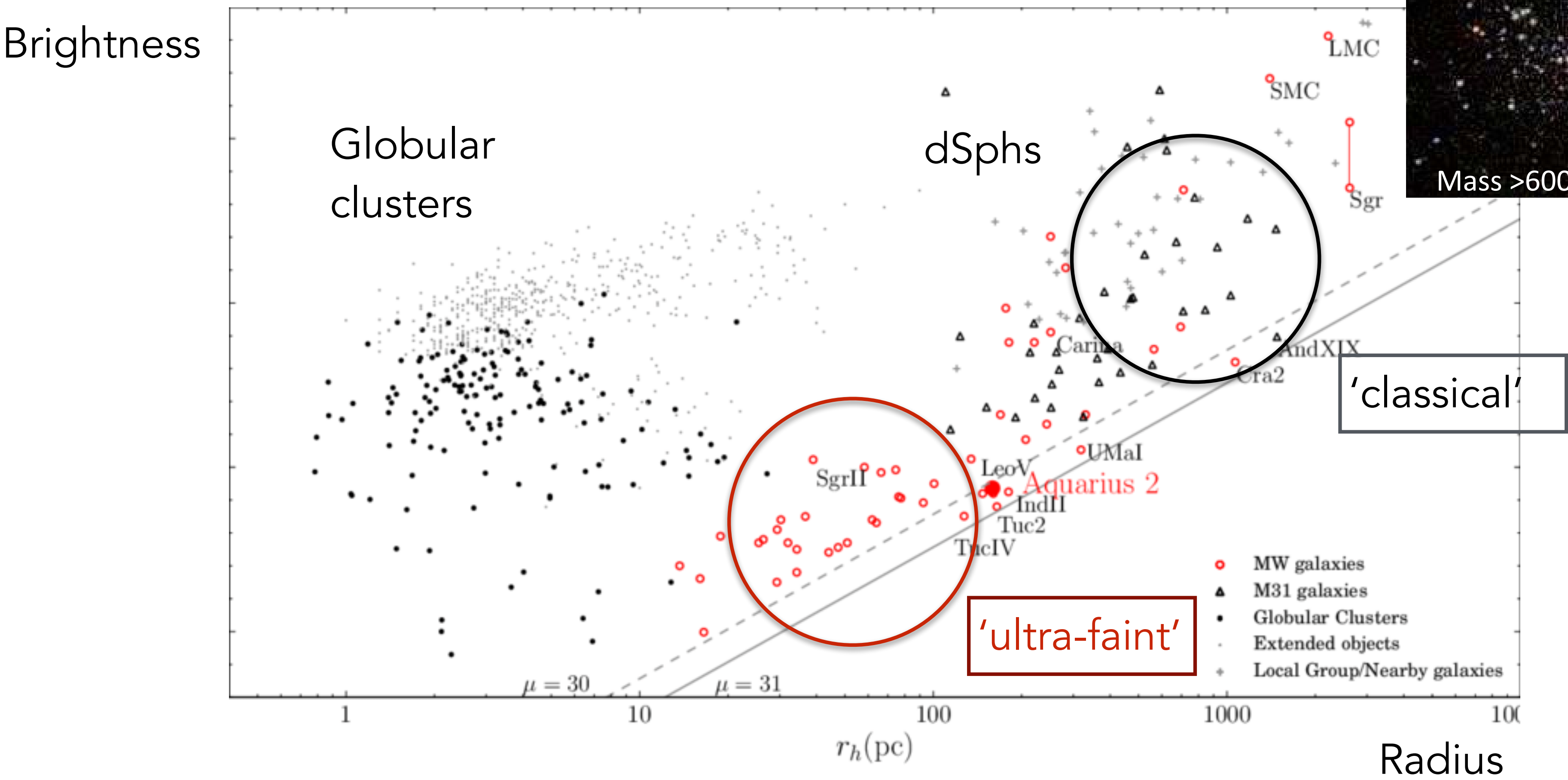


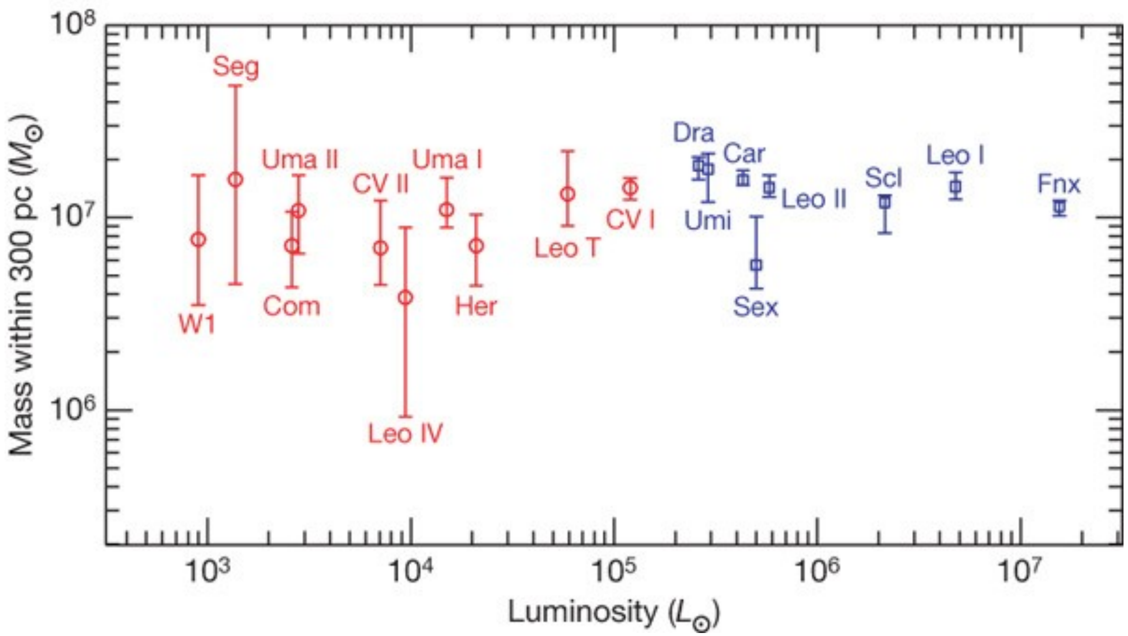


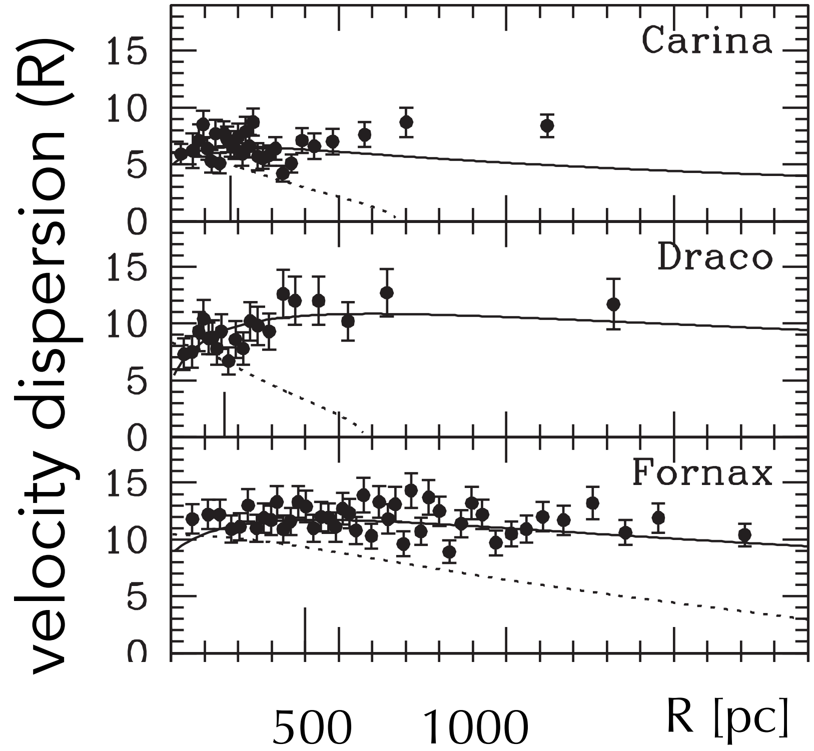
Elephants in the room

Observations:

different approach is to ***measure*** motion of stellar objects to determine the gravitational potential of DM. For example:

- ***dwarf spheroidal Galaxies:*** Assuming virialization, each population traces the gravitational potential, and we can use the **spherical Jeans equation** to link the measured velocity dispersion and the dSph gravitational potential





[Walker+, 2007]

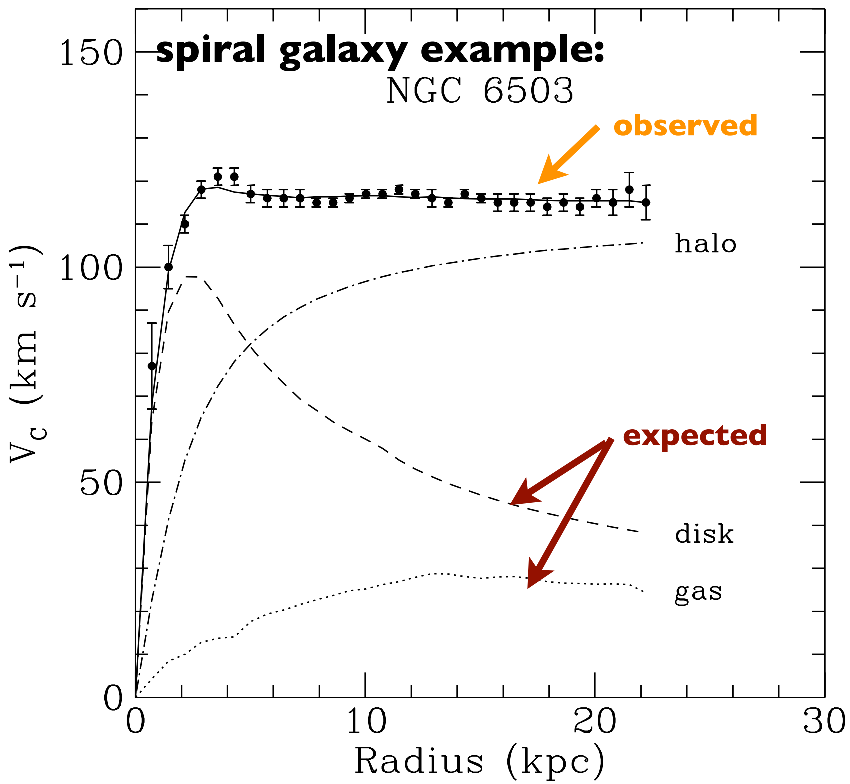
Elephants in the room

Observations:

a different approach is to ***measure*** motion of stellar objects to determine the gravitational potential of DM. For example:

- ***Galactic rotational curves:*** relate circular velocity to the total enclosed mass

$$G_N m_\odot \frac{M(r<R)}{R^2} = m_\odot \frac{v^2}{R}$$



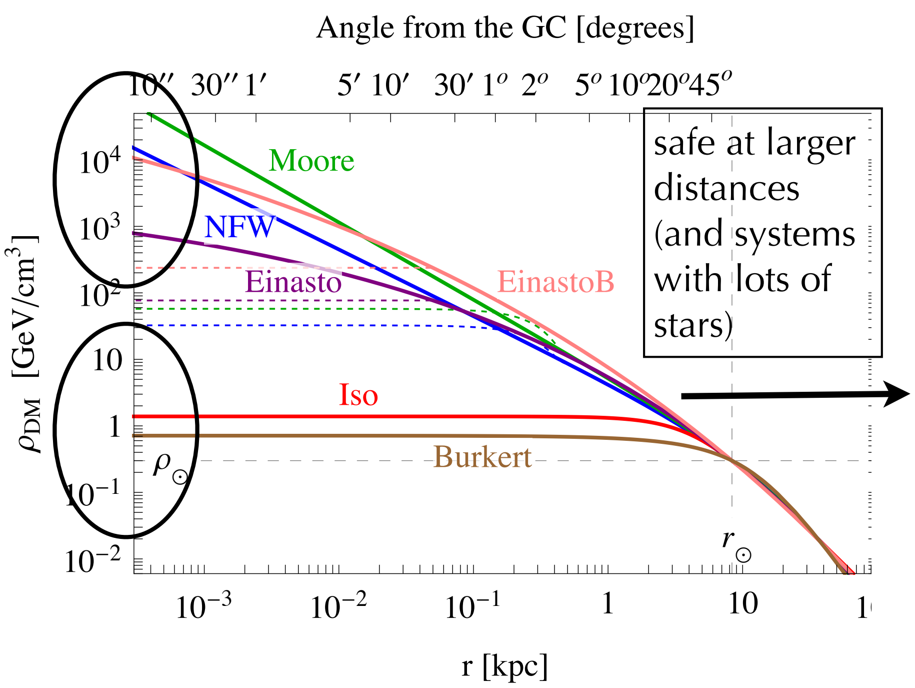
The signal: Dark matter distribution

Observations:

However, similarly to the N-body simulations:

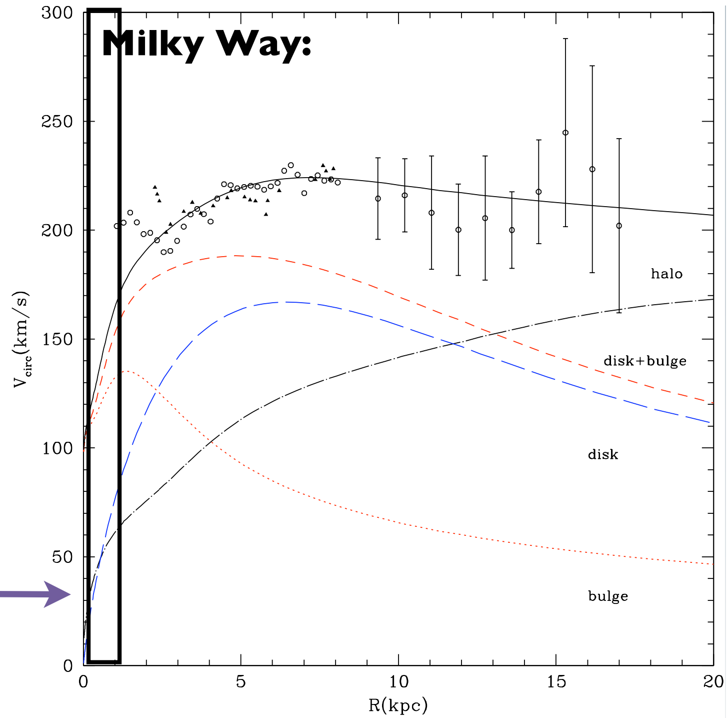
- **small (sub)halos** have few or NO stars and
- in the very **centers of halos** gravitational potential is usually dominated by baryons, or hard to determine.

➡ **Considerable uncertainties remain!**



[Cirelli, M.+, JCAP, 2011.]

DM contribution subdominant



[Klypin.+, Apj, 2002.]

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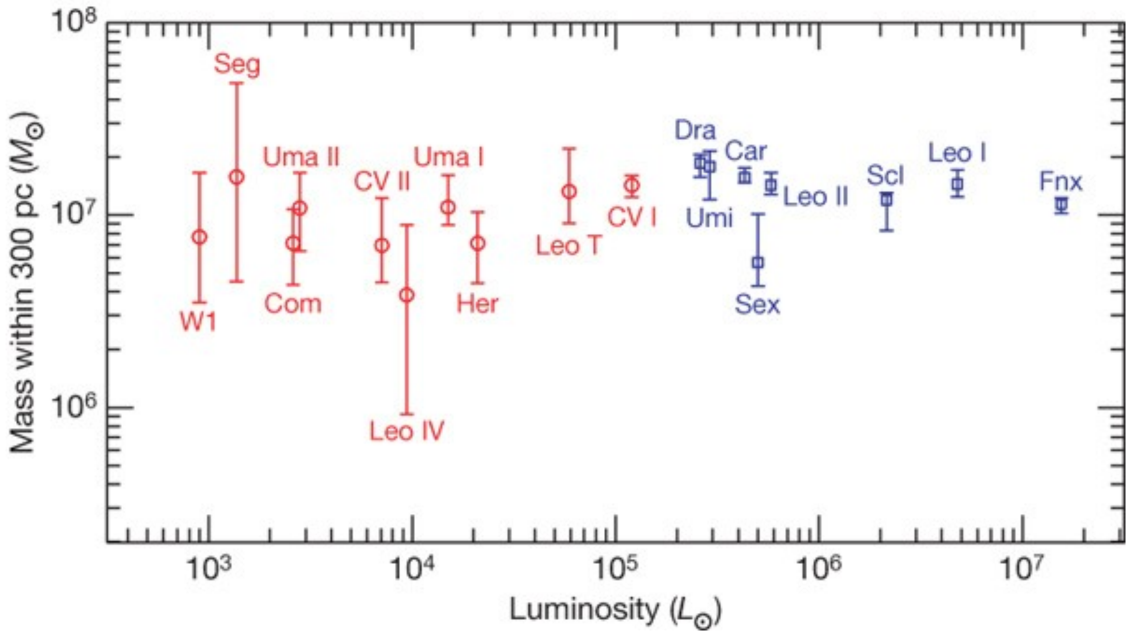

Uncertainty on total mass (total J-factor) are dominant when targets are observed 'from outside'

The signal: Dark matter distribution

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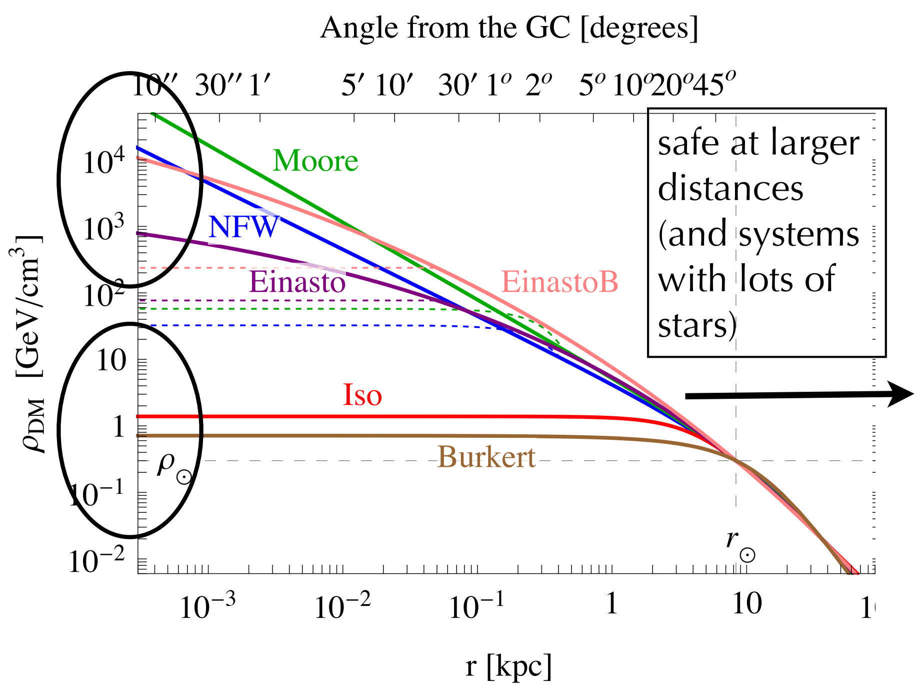


[Cirelli, M.+, JCAP, 2011.]

Uncertainty on density distribution dominant when we observe central regions from within, or with high res instruments

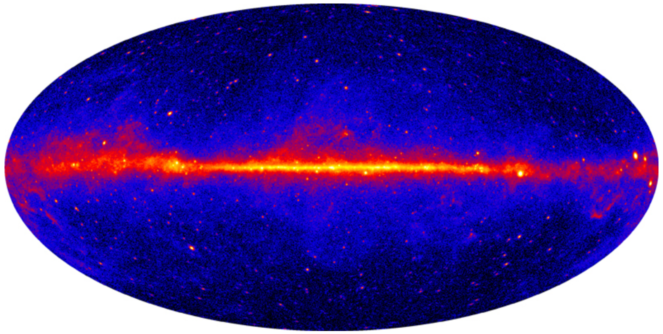
Outline

1. DM model space that CAN be tested with gamma-rays
2. Experiments
3. Wish list, targets
4. Astro backgrounds
5. Examples:
    - WIMPs
    - ALPs

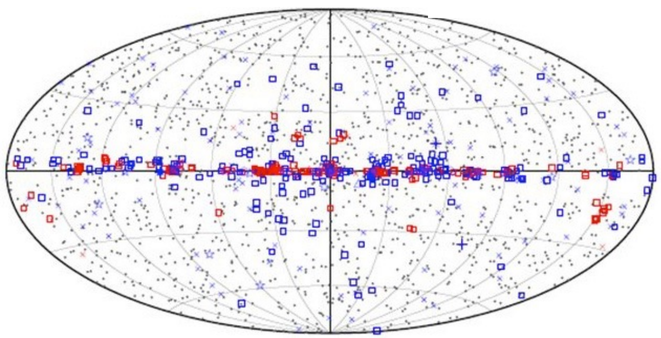
The Fermi sky

Daniele's talk

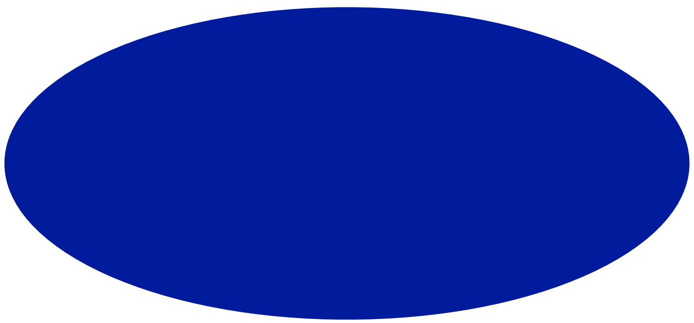
Diffuse emission from our Galaxy



Point sources



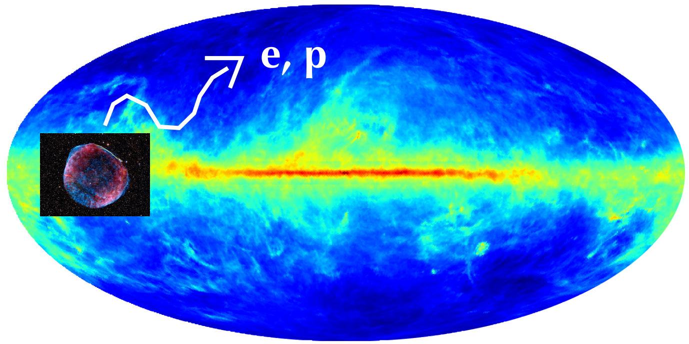
Isotropic emission

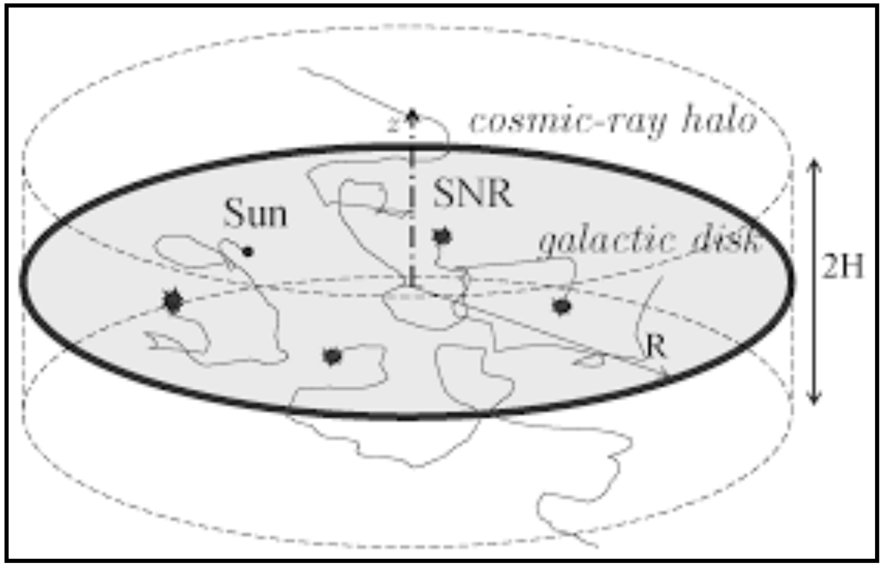


90% of the LAT photons!

cosmic rays+**interstellar medium**

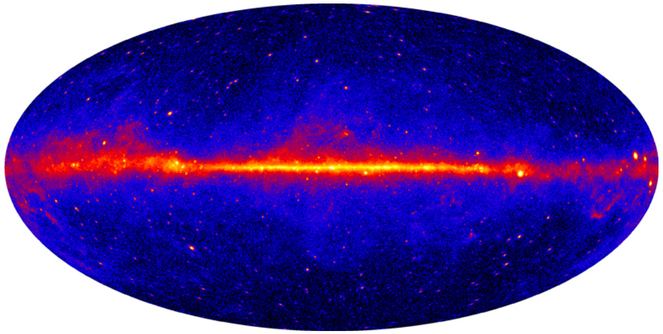
→**gamma rays parameters**: distribution of sources, magnetic fields, gas, injection spectra...



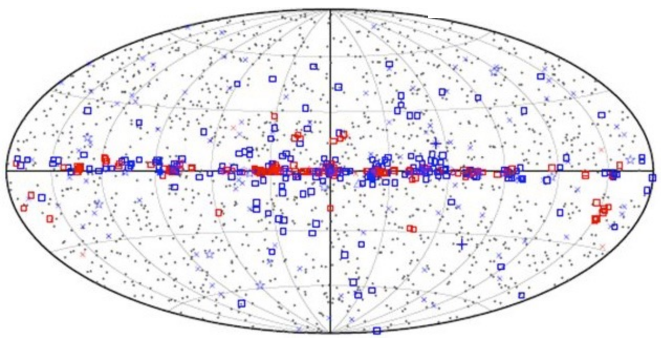


The Fermi sky

Diffuse emission from our Galaxy



Point sources



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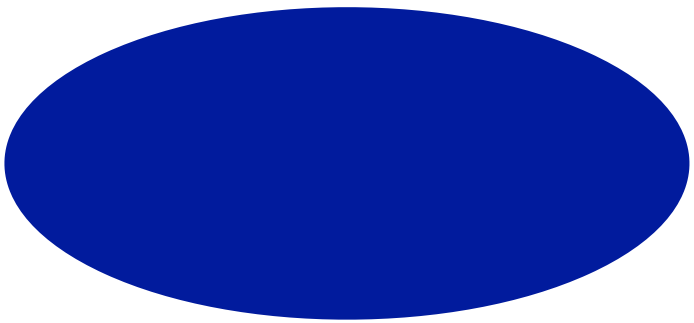

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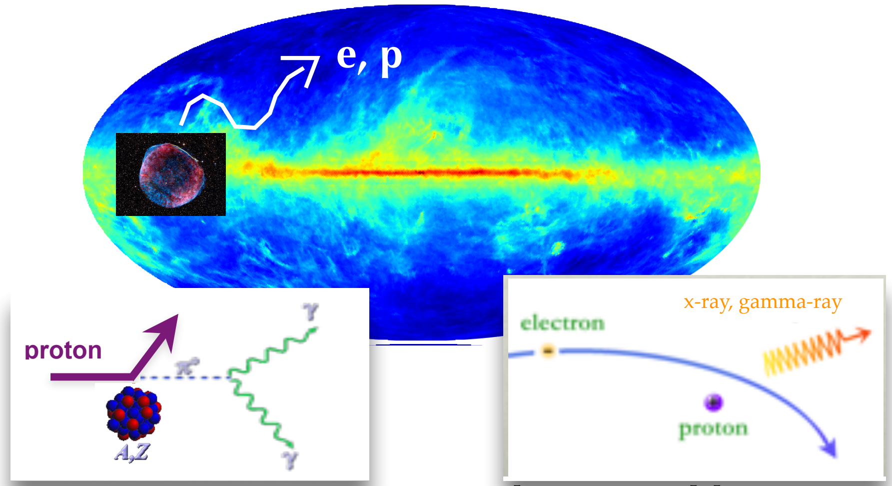
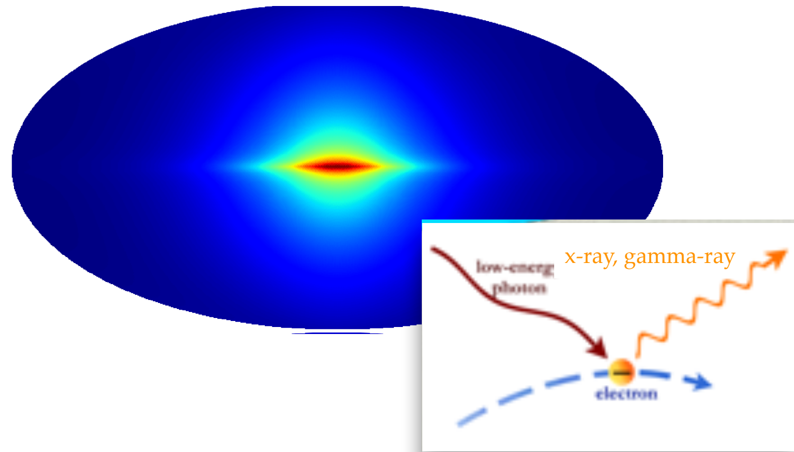


π^0 decay **bremsstrahlung**

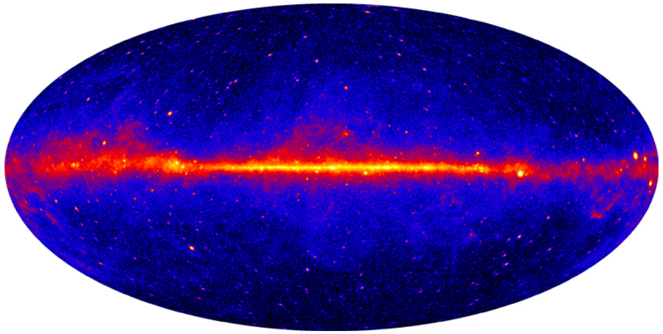
+



inverse Compton

The Fermi sky

Diffuse emission from our Galaxy



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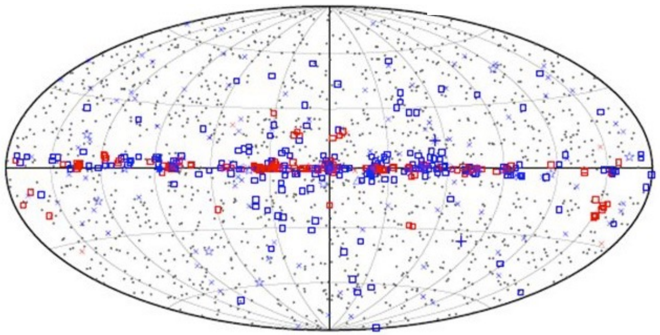
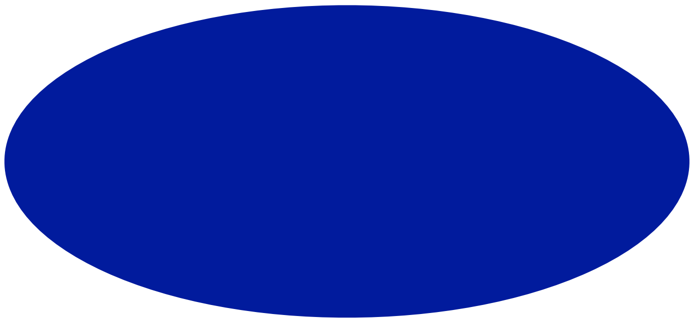


Isotropic emission



90% of the LAT photons!

cosmic rays+interstellar medium

→**Challenges:** distribution of sources, magnetic fields, gas, CR injection spectra… poorly known

— source distribution from tracers (SNRs, PSRs - poorly constrained themselves)

— gas densities from atomic transition lines - 3D reconstructions

— IC: ISRF hugely unknown

— Galactic magnetic fields…

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p)$$ sources (SNR, nuclear reactions...)

diffusion $$+\vec{\nabla}\cdot[D_{xx}\vec{\nabla}\psi - \vec{V}\psi]$$ convection

diffusive reacceleration $$+\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}\right]$$

E-loss $$-\frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3}p\,\vec{\nabla}\cdot\vec{V}\psi\right]$$ convection

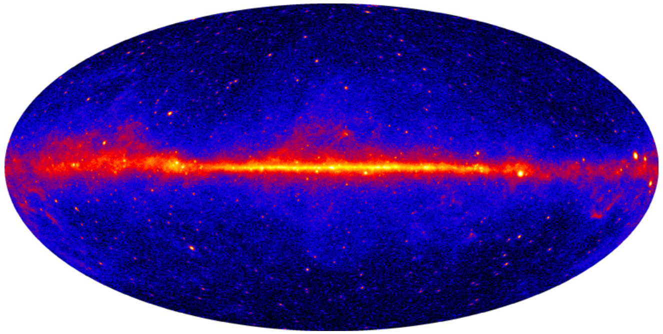
fragmentation $$-\frac{\psi}{\tau_f} - \frac{\psi}{\tau_d}$$ radioactive decay

$\psi(\mathbf{r},p,t)$ – density per total momentum

Sophisticated numerical solvers: GALPROP, DRAGON…

The Fermi sky

Diffuse emission from our Galaxy



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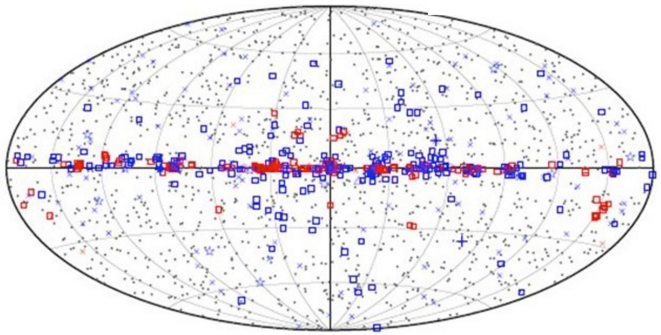

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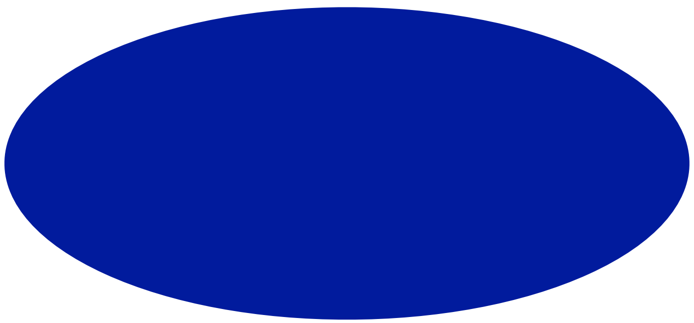
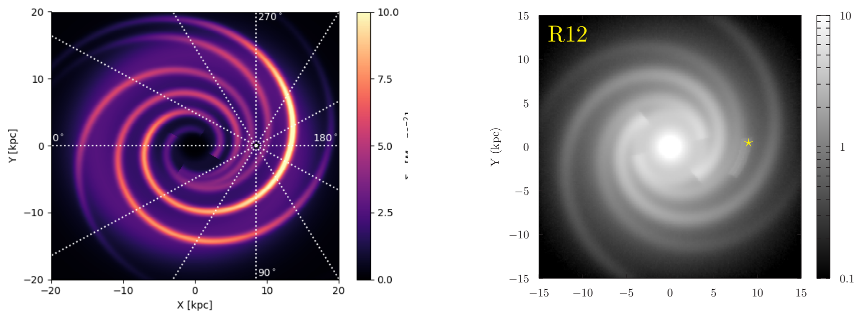


90% of the LAT photons!

Sophisticated numerical solvers: GALPROP, DRAGON/HERMES…

Include 3D gas and ISRF distributions,

time dependent CR source distribution +



$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p) \quad \text{sources (SNR, nuclear reactions...)}$$

$$\text{diffusion} \quad + \vec{\nabla}\cdot[D_{xx}\vec{\nabla}\psi - \vec{V}\psi] \quad \text{convection}$$

$$\text{diffusive reacceleration} \quad + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}\right]$$

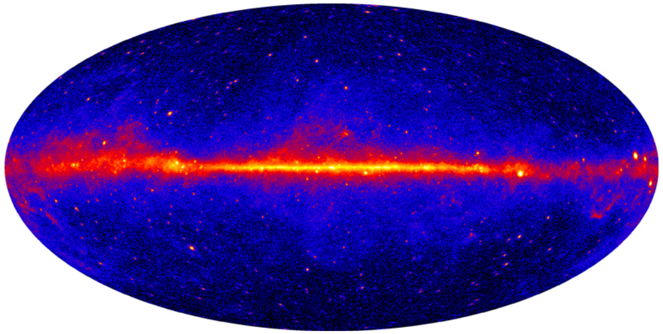
$$\text{E-loss} \quad - \frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3}p\vec{\nabla}\cdot\vec{V}\psi\right] \quad \text{convection}$$

$$\text{fragmentation} \quad - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_d} \quad \text{radioactive decay}$$

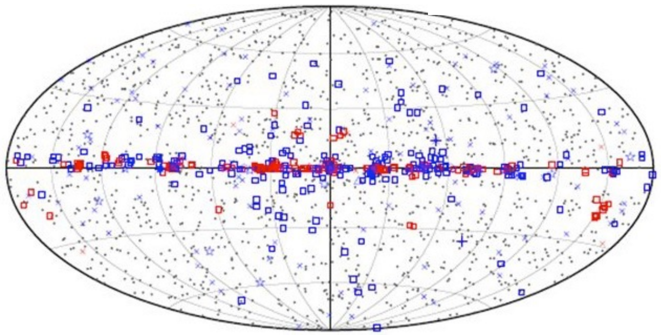
$\psi(\mathbf{r},p,t)$ – density per total momentum

The Fermi sky

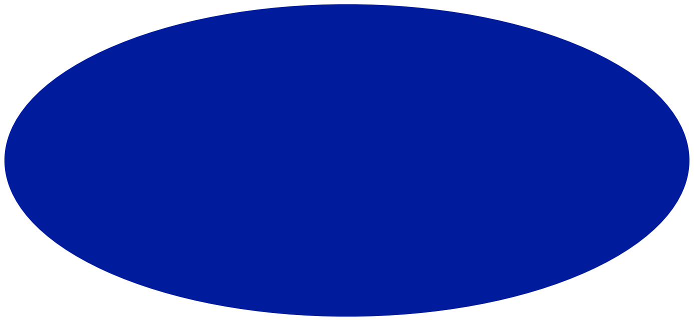
Diffuse emission from our Galaxy



Point sources



Isotropic emission

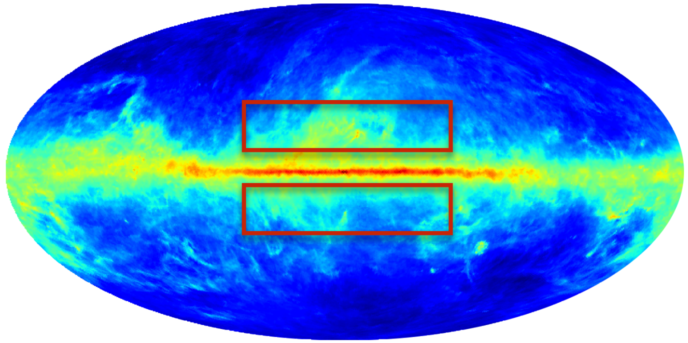


90% of the LAT photons!

cosmic rays+**interstellar medium**

→**Challenges for DM search**

Diffuse emission **'bulgy'** morphology degenerate with DM.



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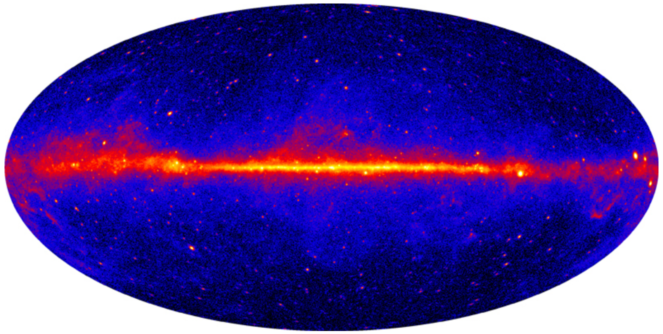

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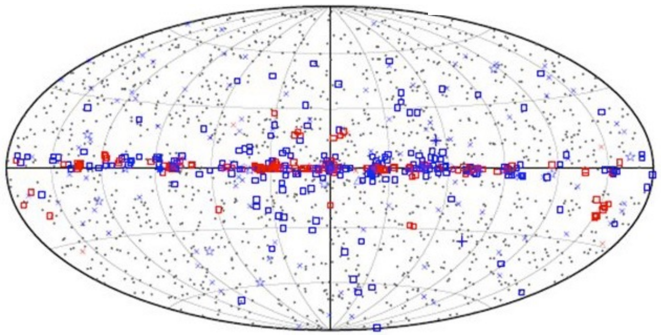

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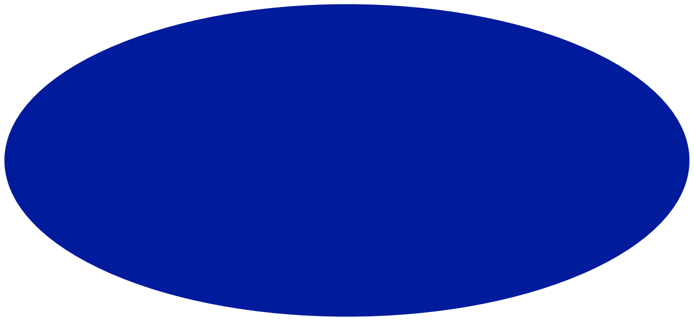

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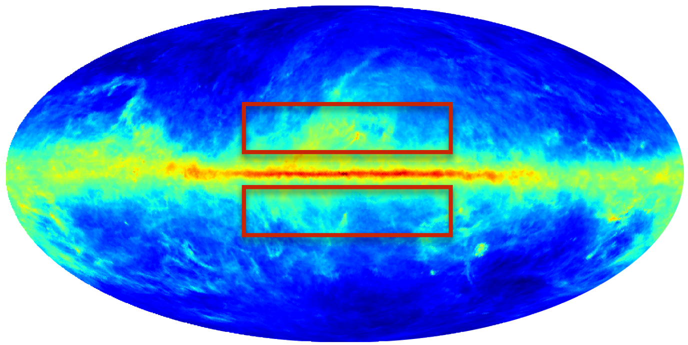
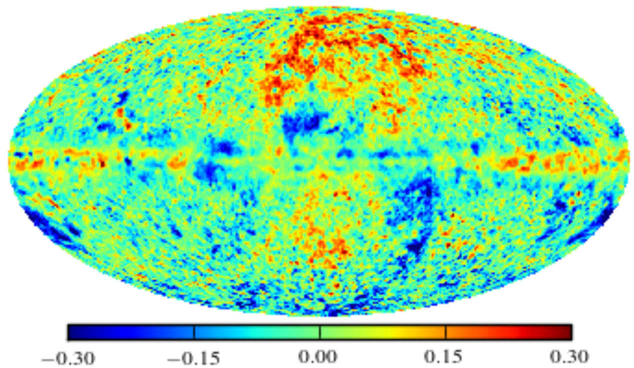


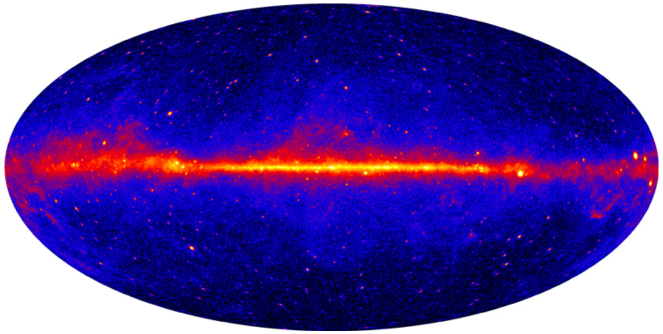
Residuals are not 'flat', many small scale structures remain



[Ackermann, 2012]

The Fermi sky

Diffuse emission from our Galaxy



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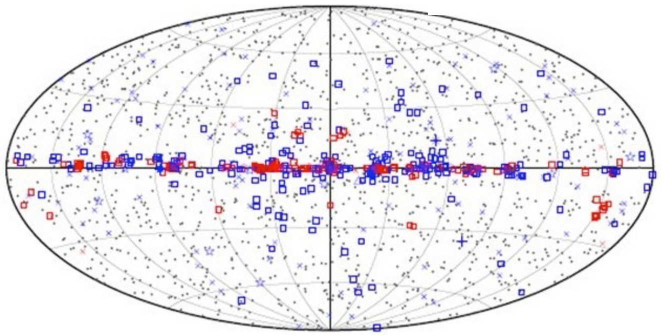

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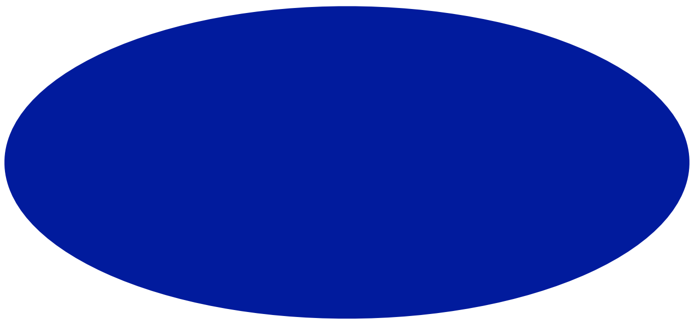

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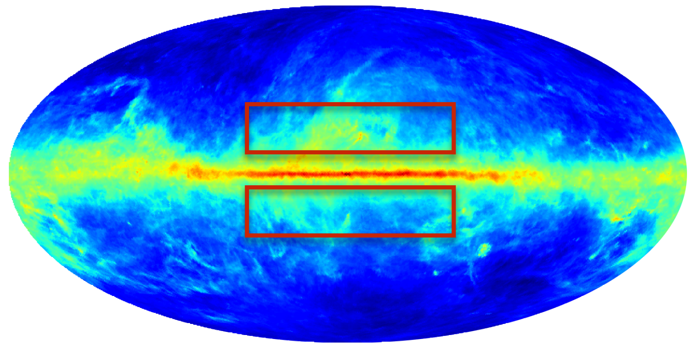
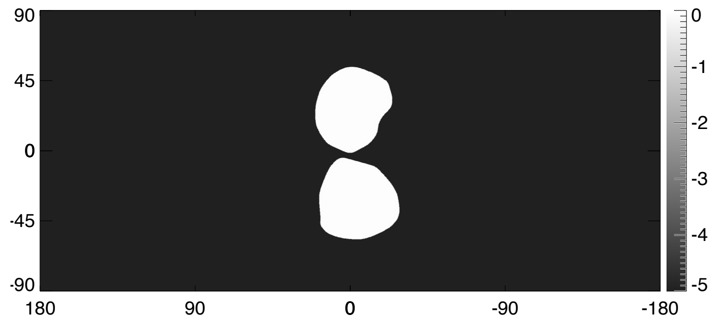


+ **Fermi bubbles** are 'right on the spot' and highly uncertain



[Su+, 2012]

The Fermi sky

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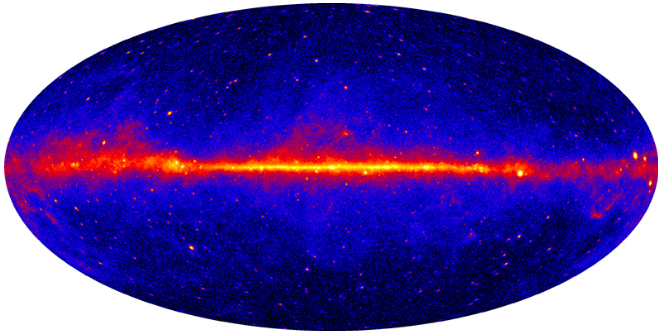

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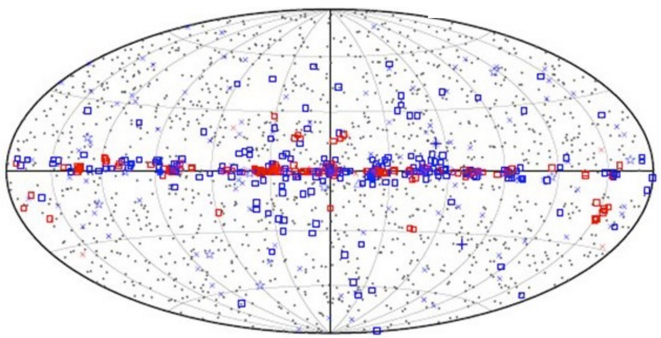

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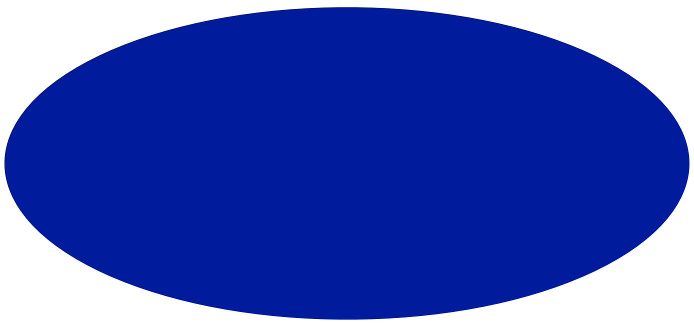


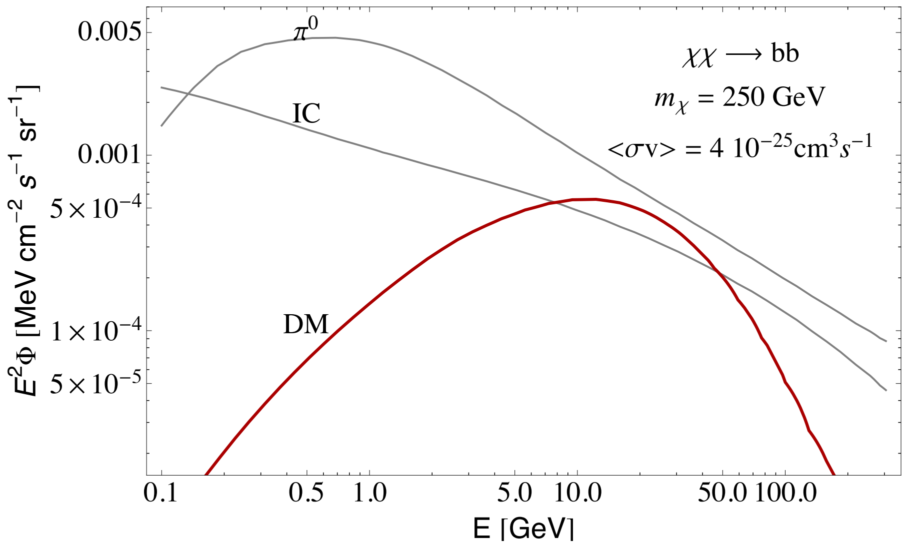
90% of the LAT photons!

cosmic rays+**interstellar medium**

→**Challenges:** distribution of sources, magnetic fields, gas, injection spectra…

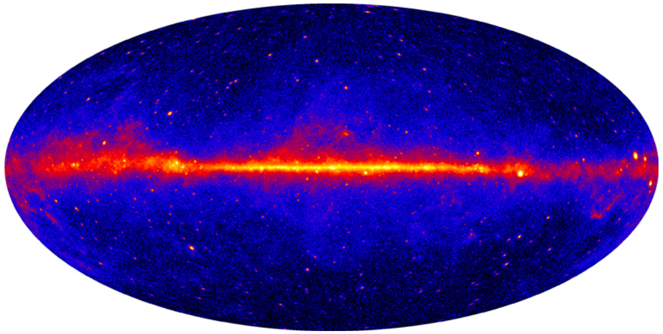
Diffuse emission **'bulgy'** morphology degenerate with DM.

PL spectrum also significantly degenerate with Galactic DM signal



The Fermi sky

Diffuse emission from our Galaxy



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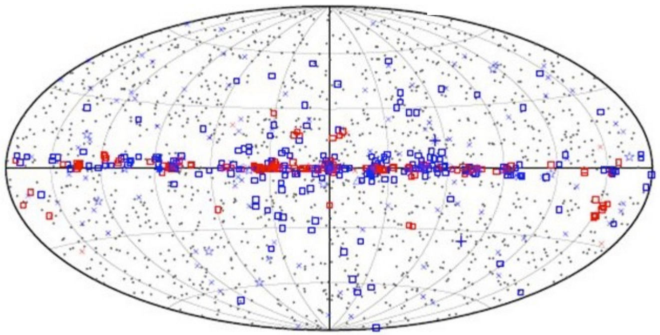

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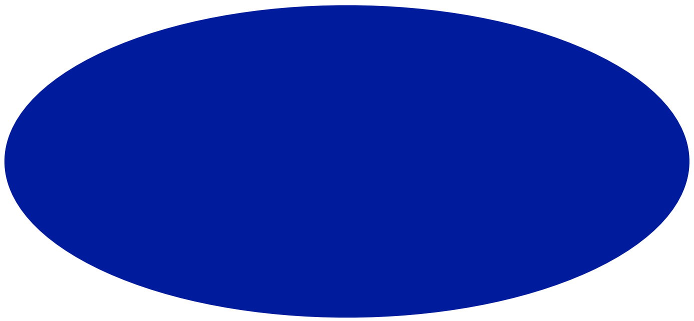
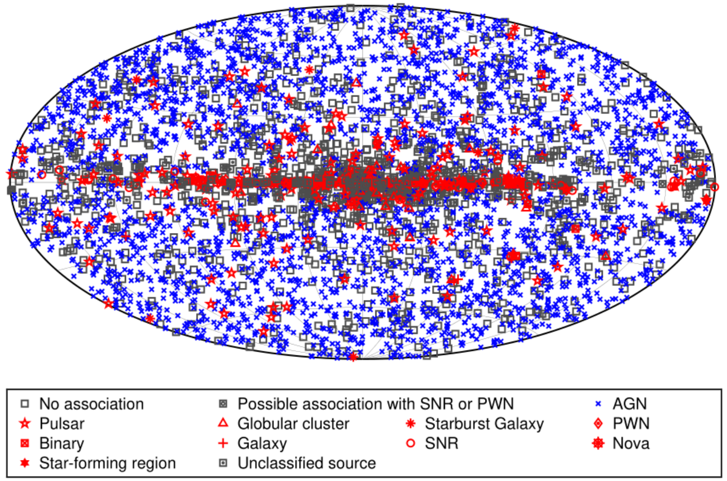
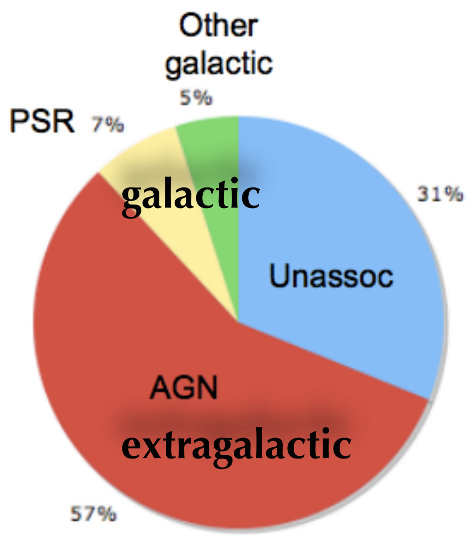


Fermi 4FGL catalog
>~5000 sources!



https://fermi.gsfc.nasa.gov/ssc/data/access/lat/8yr_catalog/

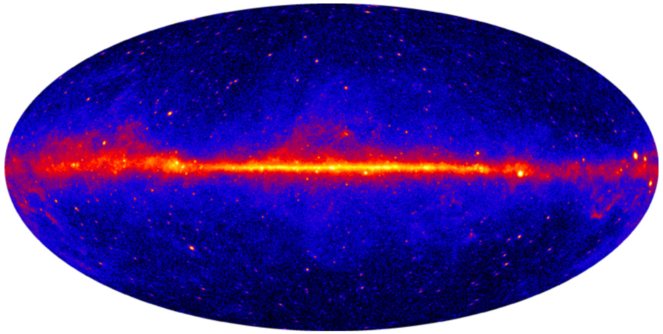
galactic: PSRs, PWNs, SNR, Nova, Globular clusters…



extragalactic: AGNs (BLLacs, FSRQs), star forming galaxies

The Fermi sky

Diffuse emission from our Galaxy



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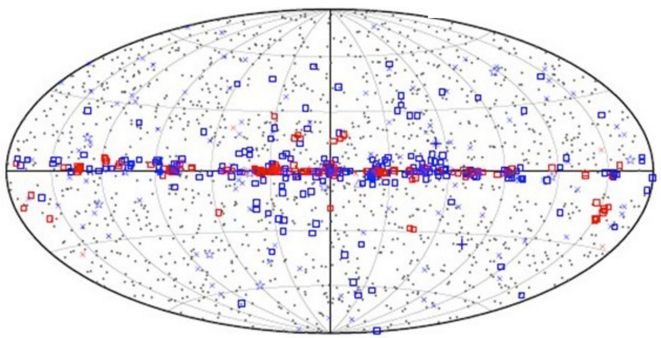

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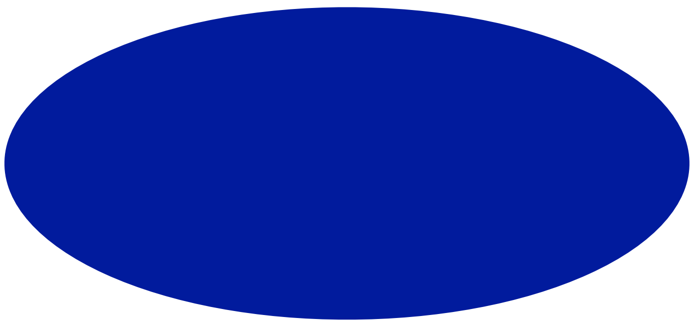

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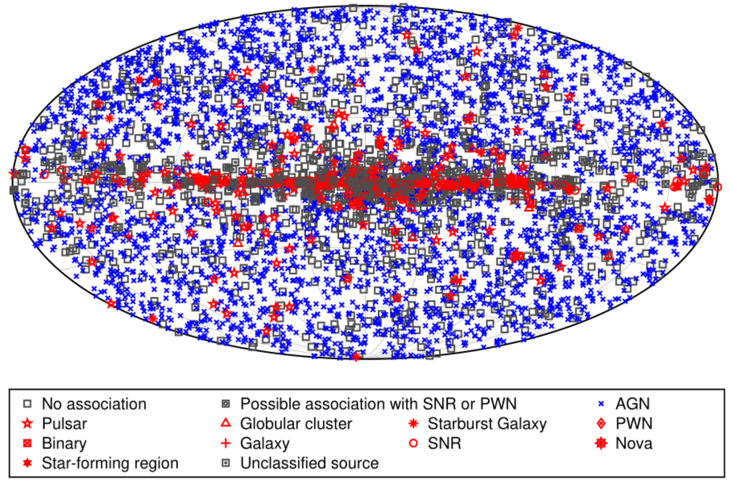

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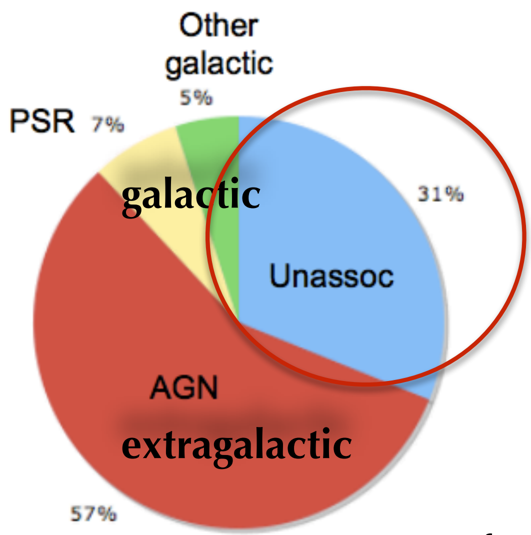

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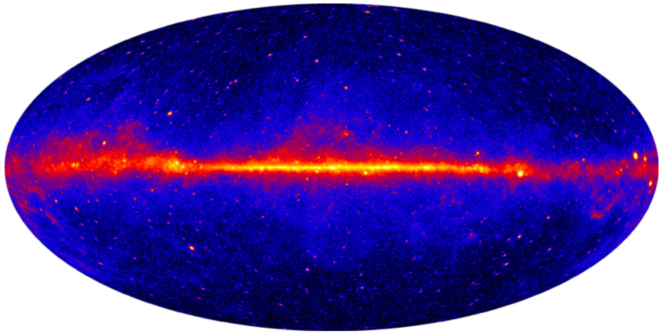
The Fermi sky

Diffuse emission from our Galaxy



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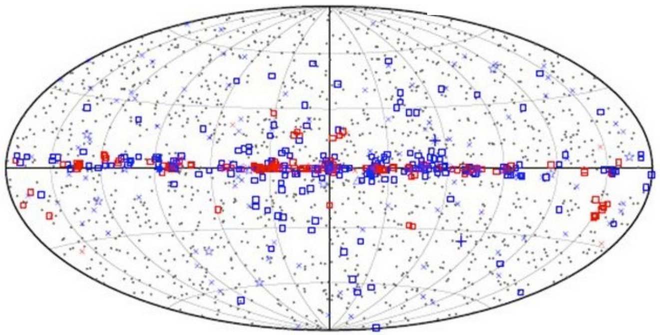

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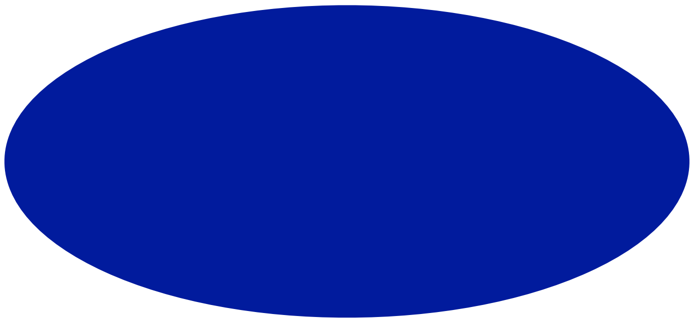
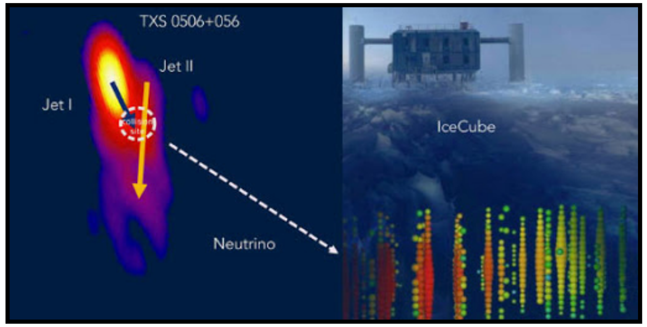
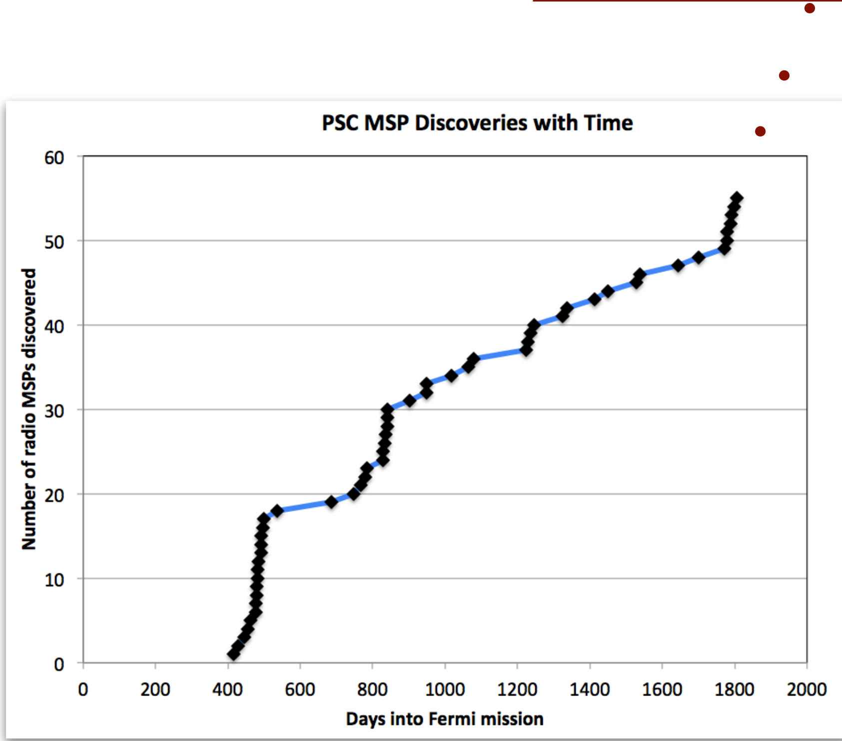


AGN and PSR revolution in the last decade!

AGNs and multi wavelength

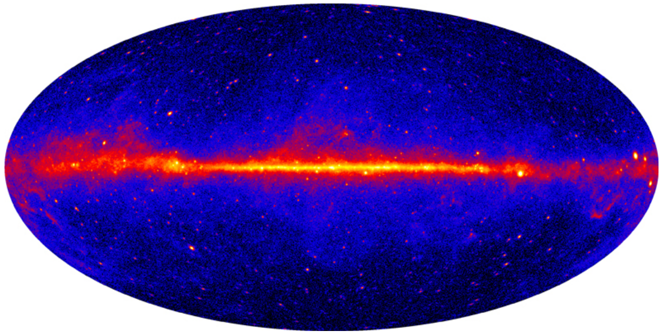


PSRs and our galaxy + MSPs! (5k days, ~250PSRs)



The Fermi sky

Diffuse emission from our Galaxy



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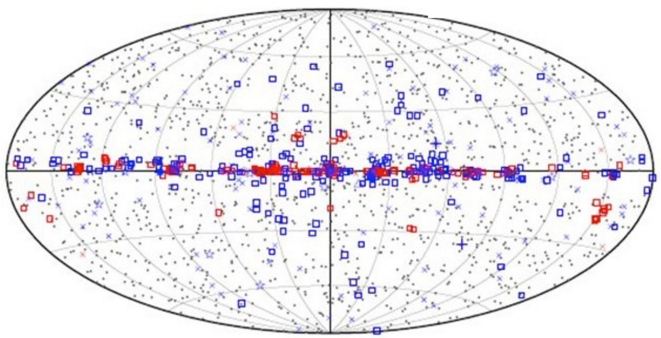

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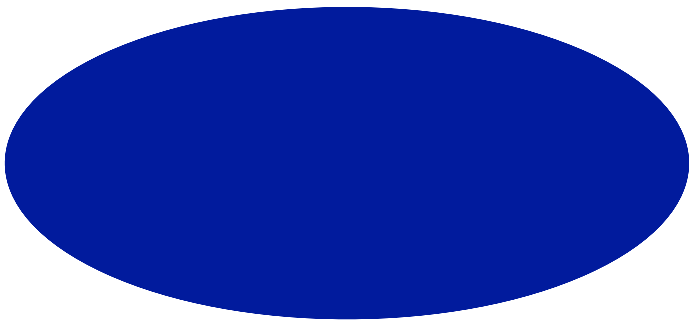
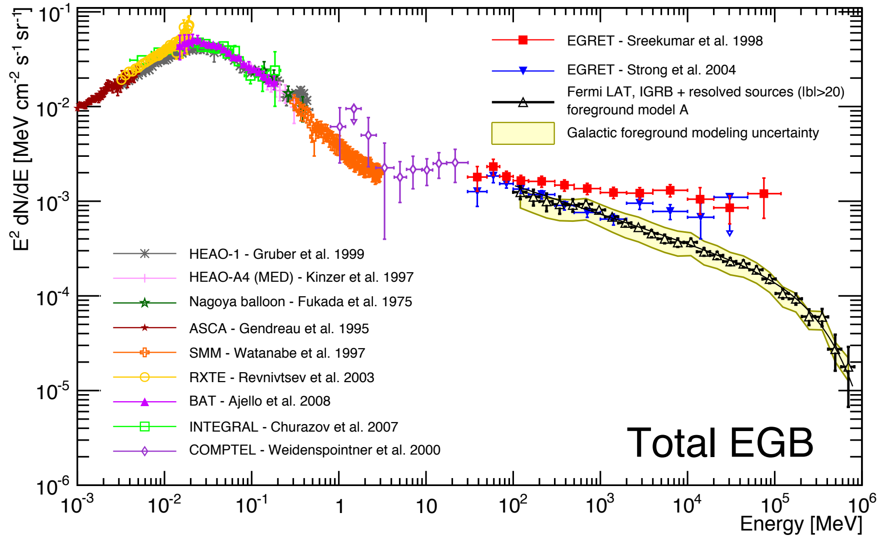


dominates at high latitudes

origin not yet fully understood

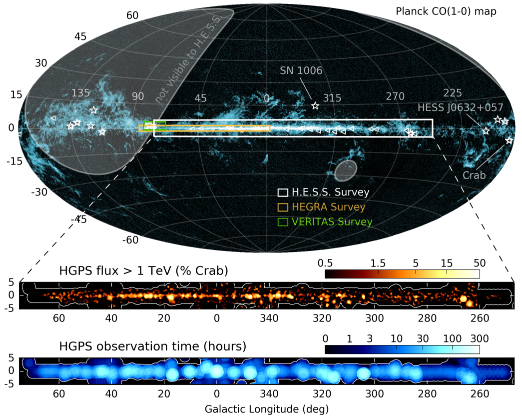


guaranteed contribution: faint (not individually resolved) extragalactic sources

[Ackermann+, ApJ799, 2015)]

The TeV sky

Diffuse emission from our Galaxy



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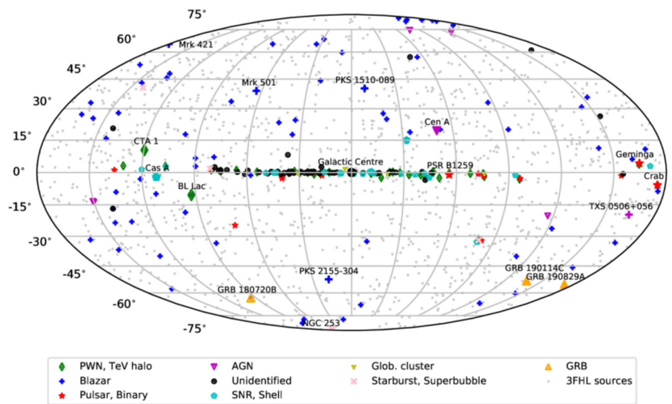

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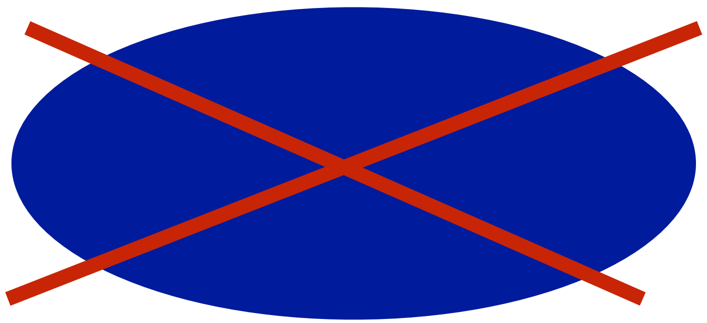
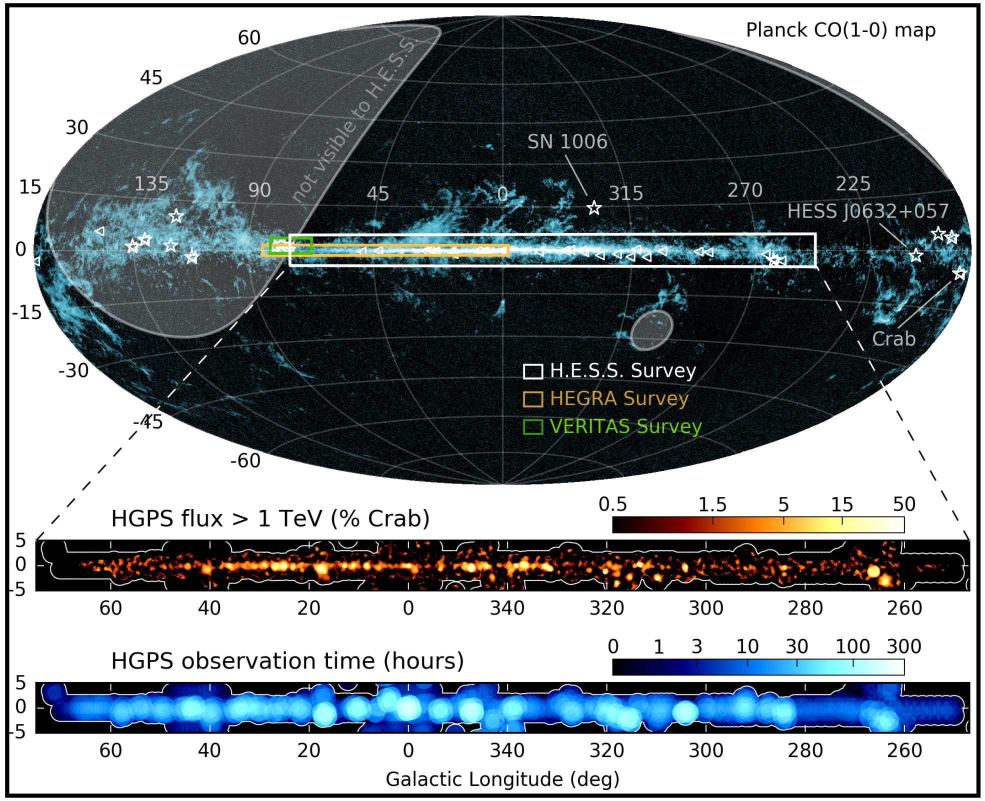


Ground based telescopes performed survey observations of extended regions:

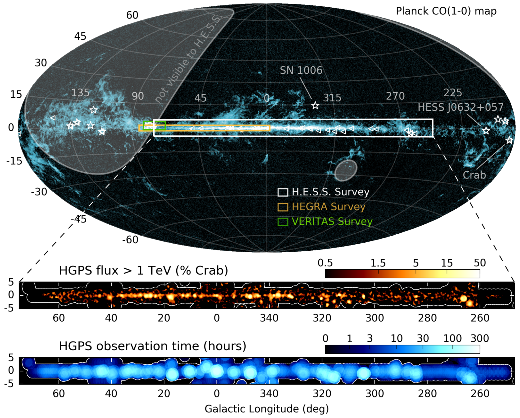


Cumulative diffuse emission detected along the plane

[H.E.S.S. Galactic Plane Survey]

The TeV sky

Diffuse emission from our Galaxy



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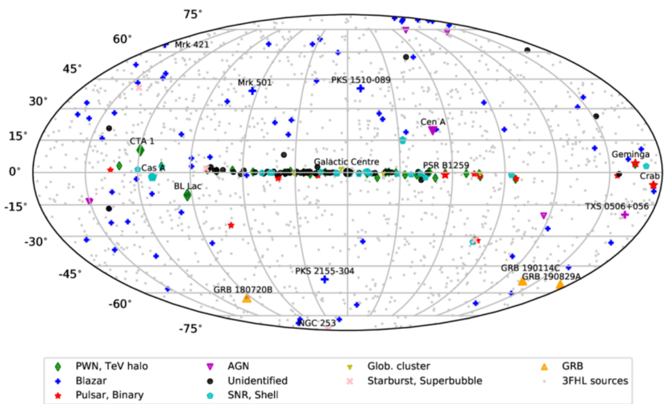

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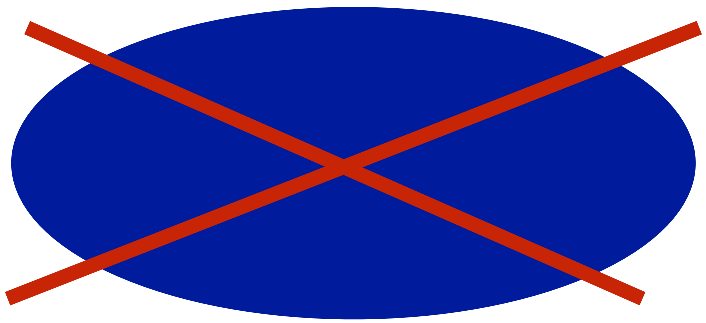

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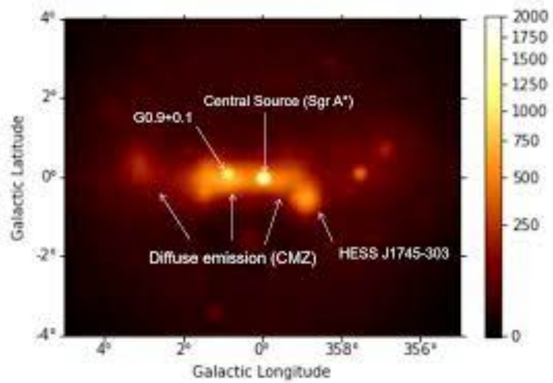
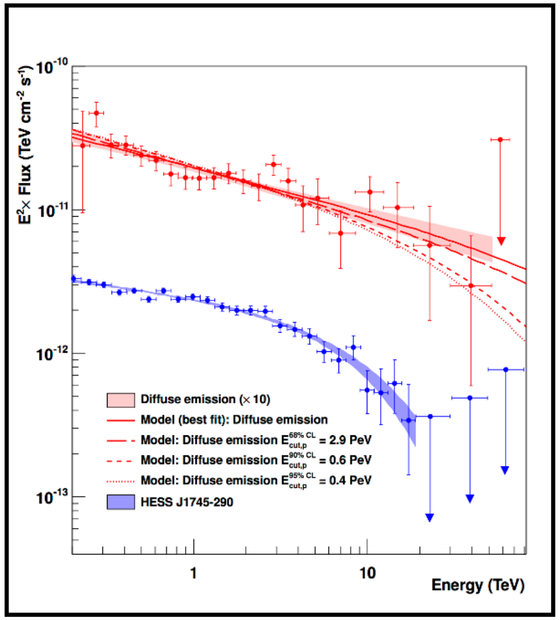


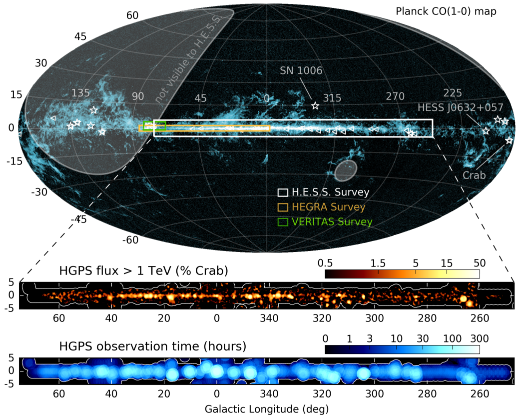
Diffuse emission in the Galactic center ridge region detected by HESS.
It follows the gas distribution, indication of pion component. Hard spectrum - a PeVatron source!



[Aharonian, 2016]

The TeV sky

Diffuse emission from our Galaxy



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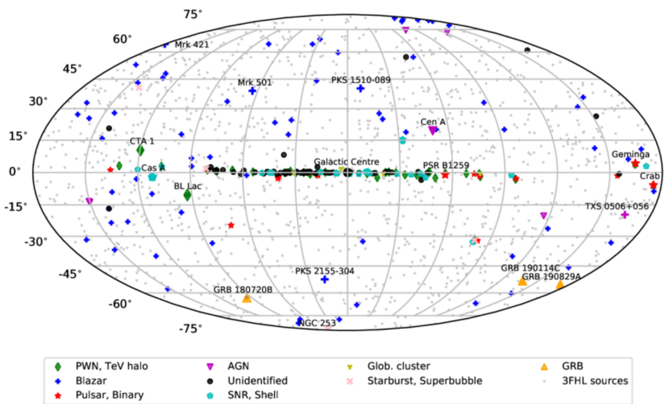

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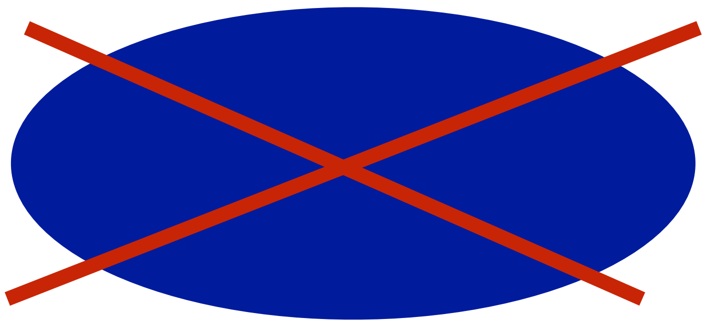

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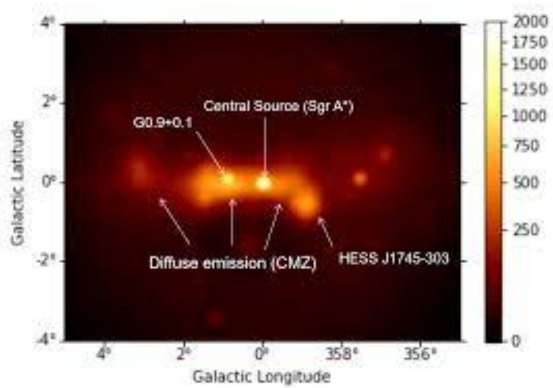

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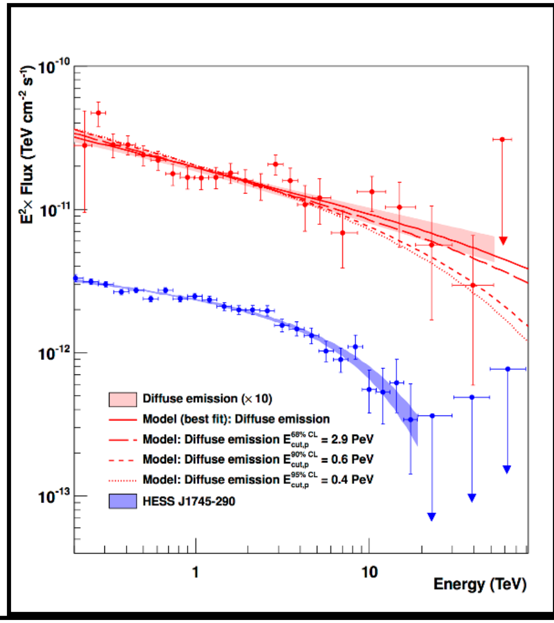


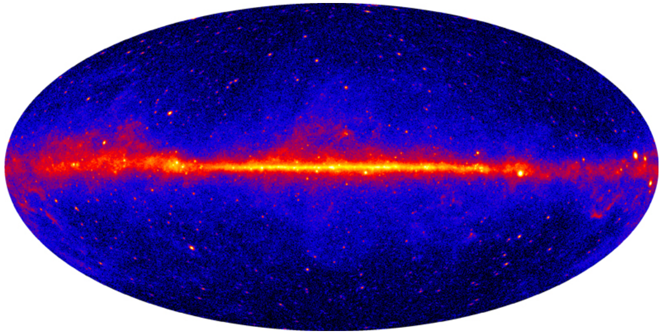
still not much is known about the diffuse emission at TeV energies in the Galactic plane…

Morphology energy dependent - crucial information

[Aharonian, 2016]

The TeV sky

Diffuse emission from our Galaxy



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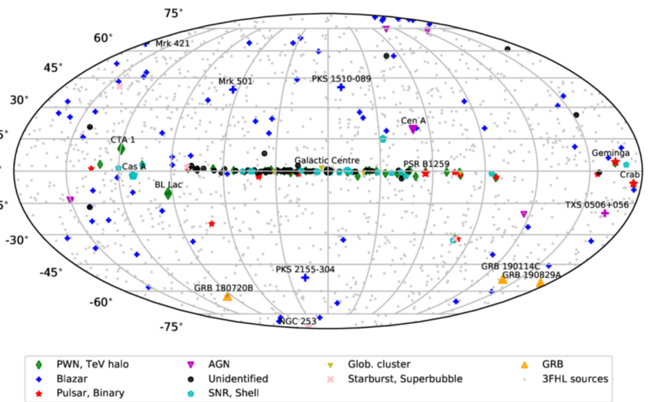

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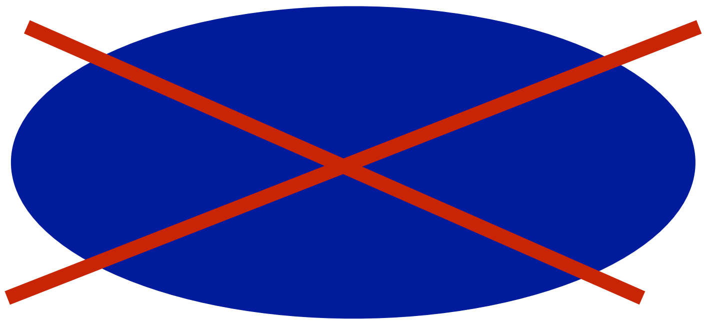
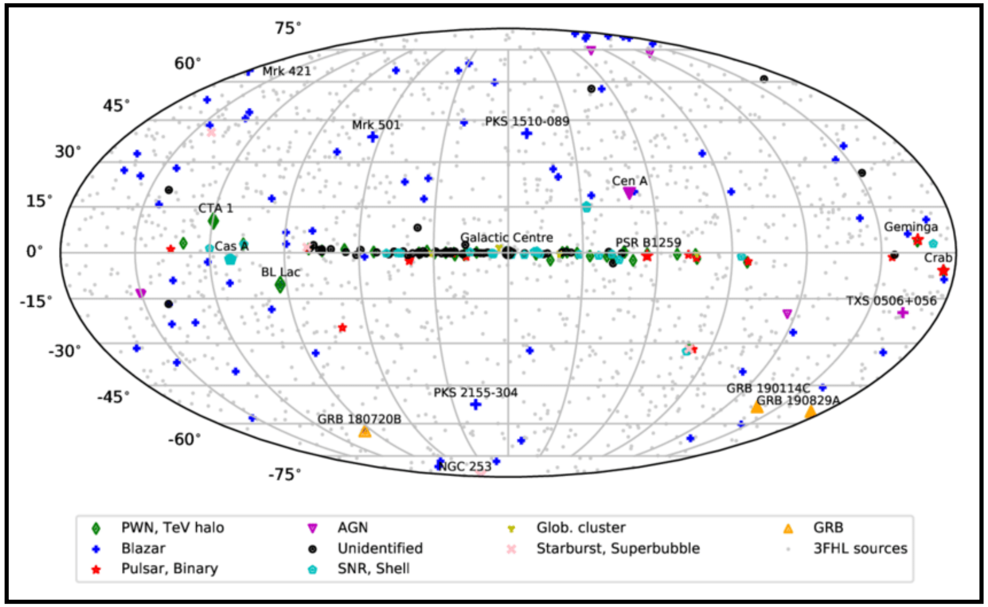


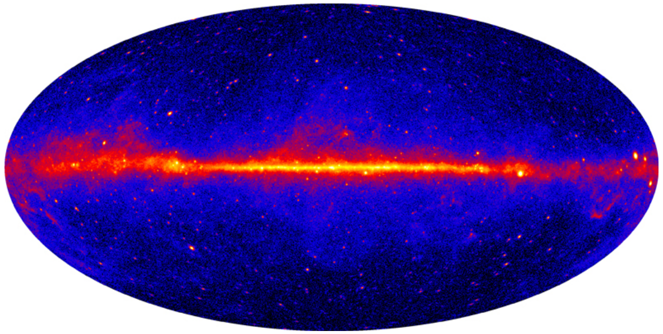
Hundreds of sources
Significant portion of galactic sources is extended (PWNs, SNRs etc)



[TeVCat, mid 2019]

The TeV sky

Diffuse emission from our Galaxy



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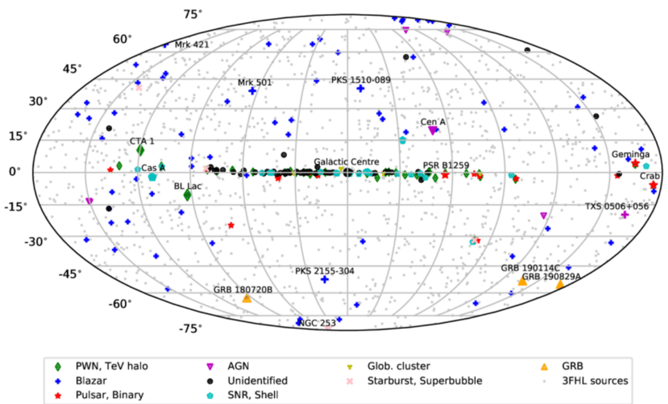

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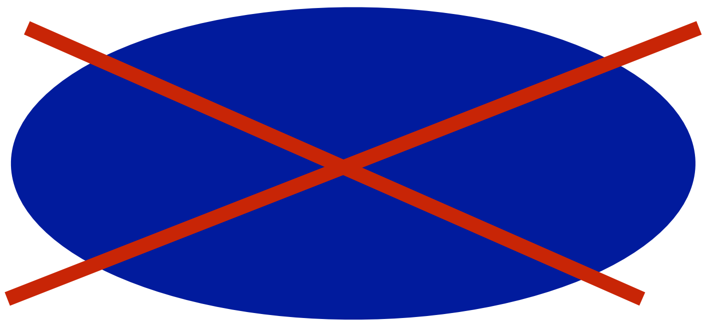
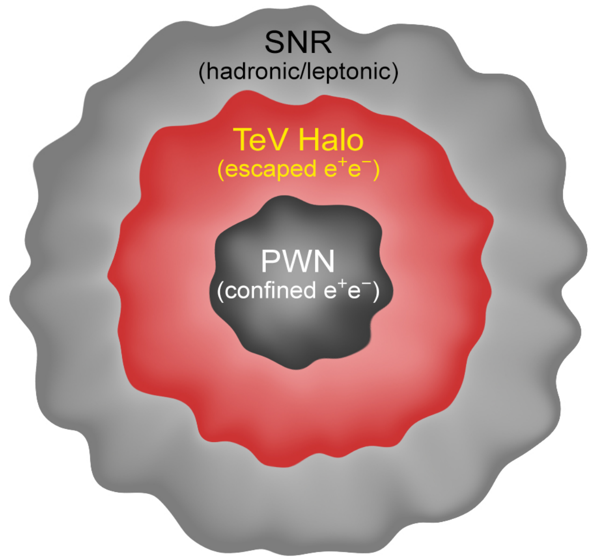


New source classes - pulsar halos



[Sudoh+, 2019]

New powerful ways to probe electron population in our galaxy and the CR diffusion properties!

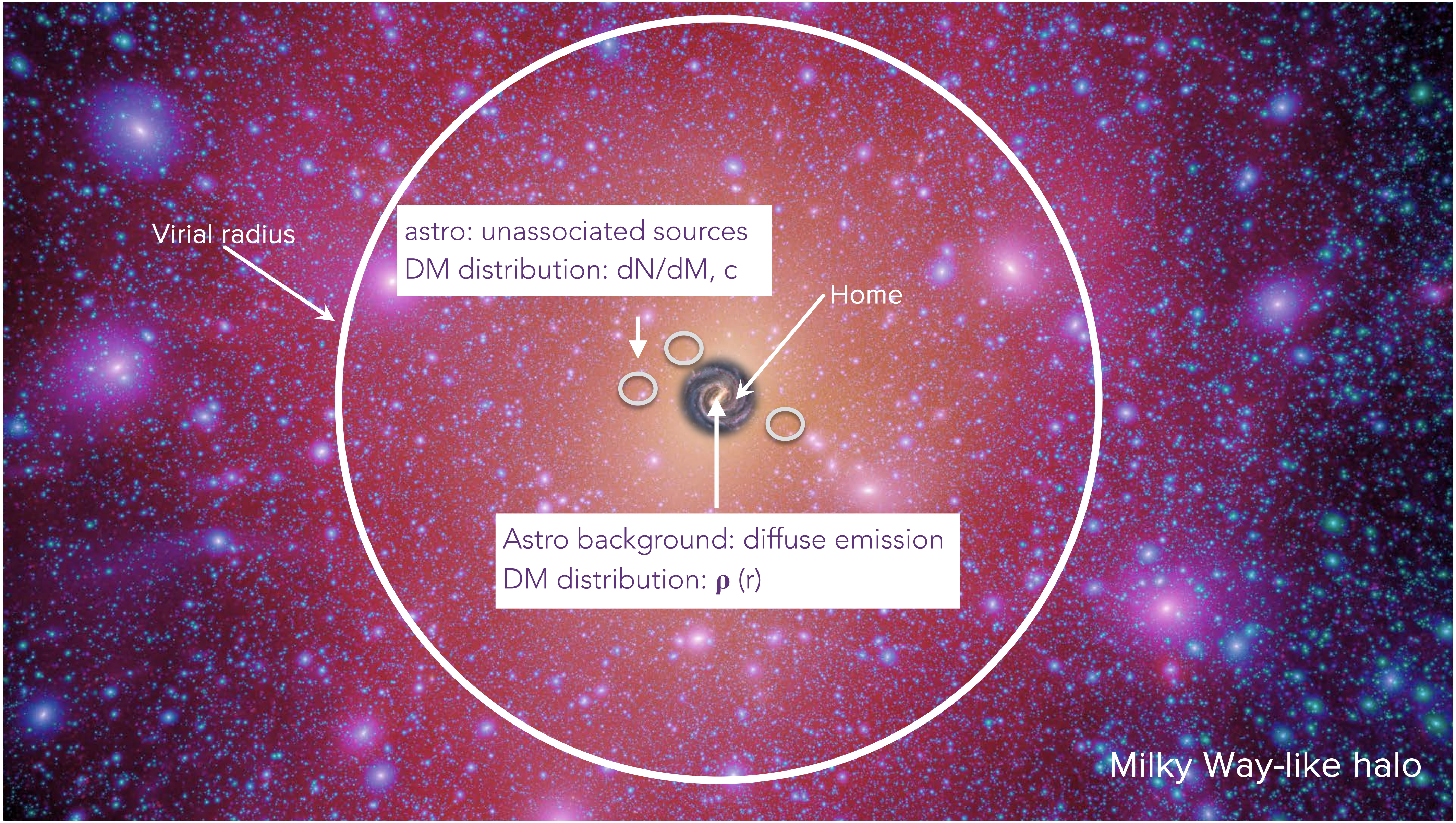
Also a new classes of extended sources, formidable background for close by DM halos

Main challenges:

— **complex astrophysical backgrounds**

— **DM distribution often poorly constrained**

— **instrumental limitations**



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Outline

1. DM model space that CAN be tested with gamma-rays
2. Experiments
3. Wish list, targets
4. Astro backgrounds
5. Examples:
    - WIMPs - an example of DM detection in a crowded region of the GC
    - ALPs - an example of smoking gun signature
    - PBHs - an example of gamma rays excluding a significant portion of parameter space.

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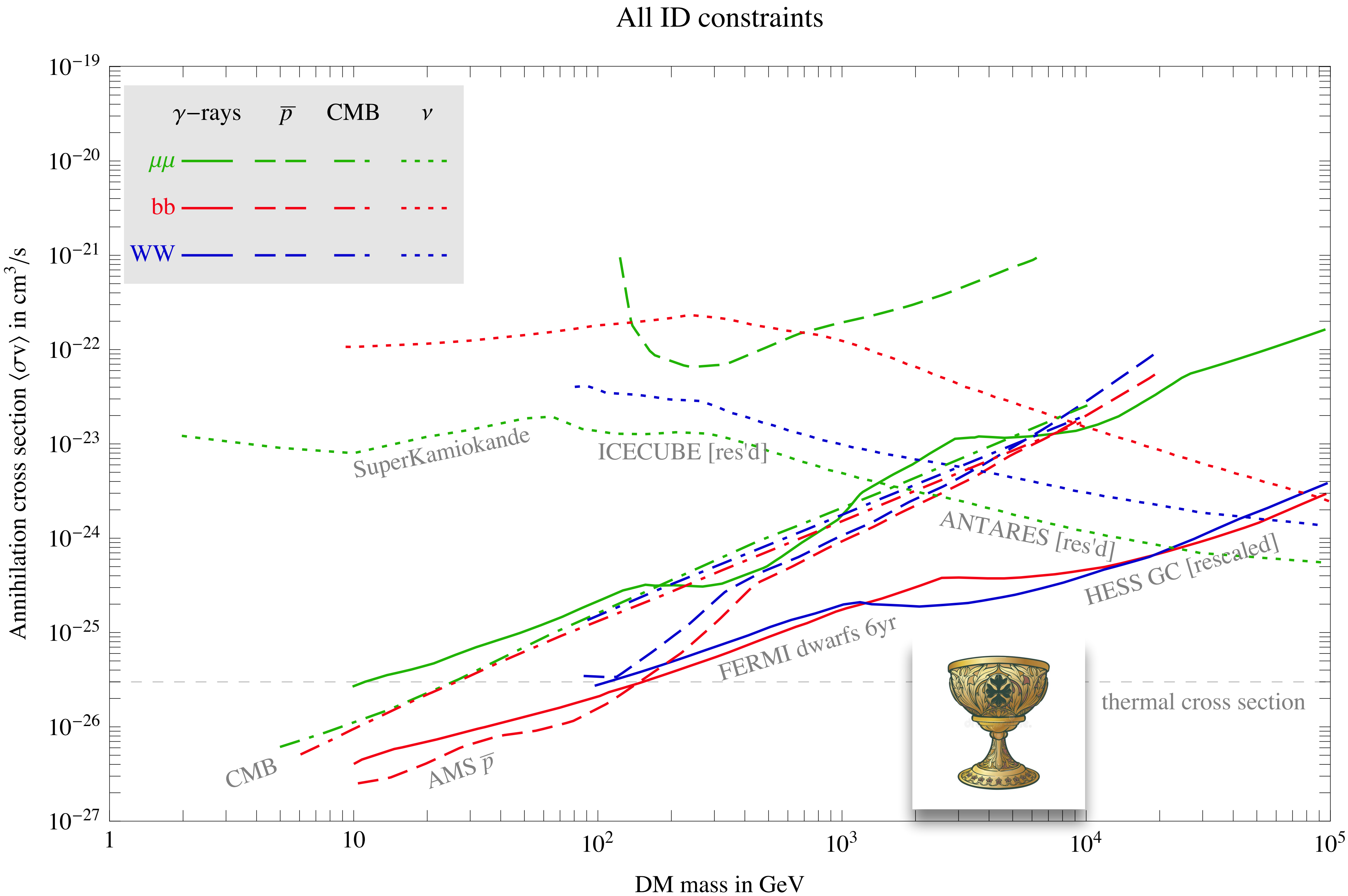
A 'darling' example of the school

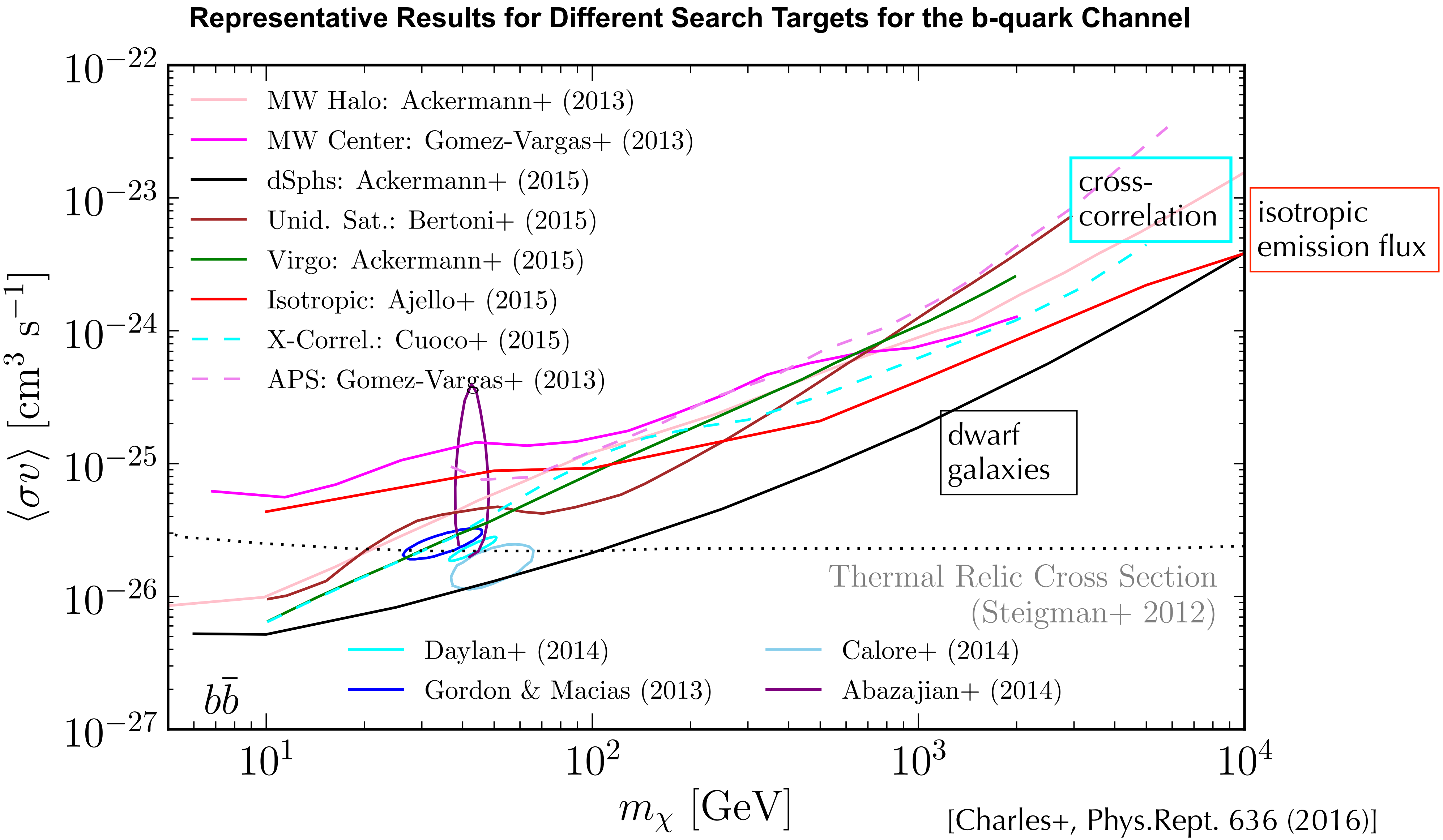
WIMPs - all ID messengers



M. Cirelli, A. Strumia, J. Zupan to appear

WIMPs - all gamma ray limits (cca 2016)

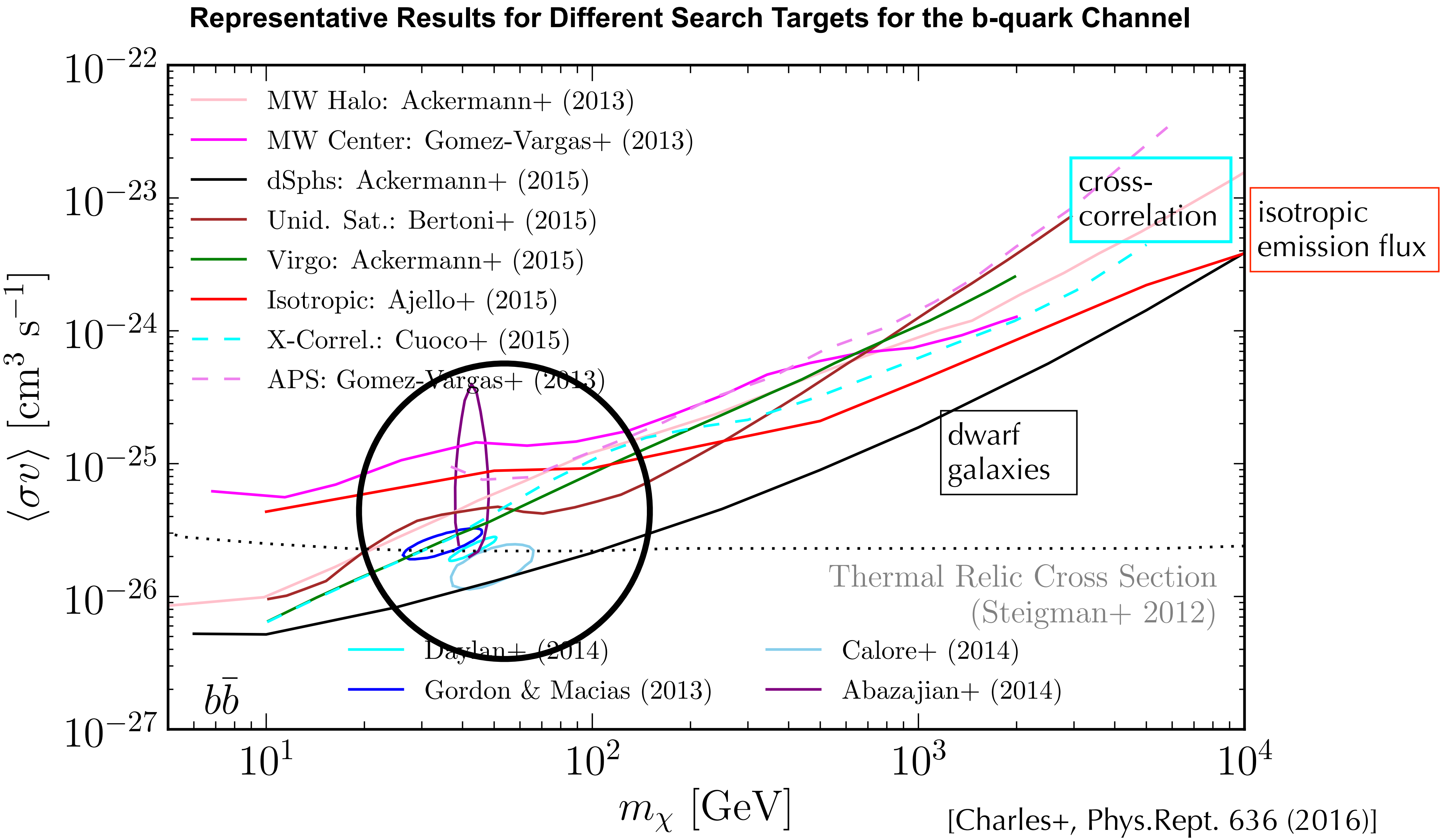
Many analysis approaches (Francesca's talk)



[Charles+, Phys.Rept. 636 (2016)]

WIMPs - all gamma ray limits (cca 2016)

Will focus on Galactic center -> for the rest F. Calore's lecture

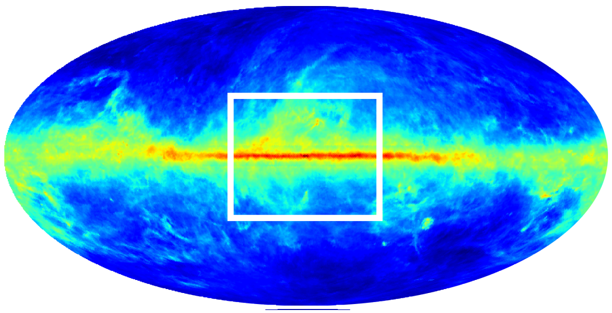


[Charles+, Phys.Rept. 636 (2016)]

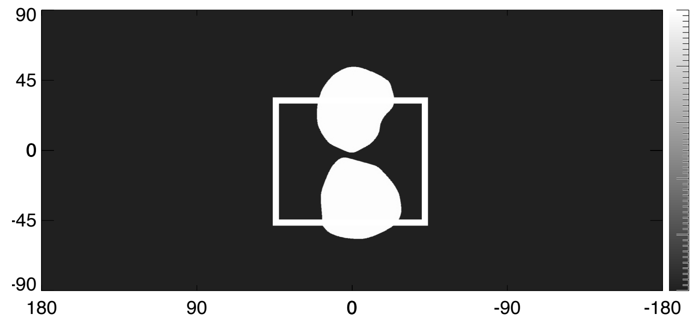
DM search in the inner Galaxy

general approach

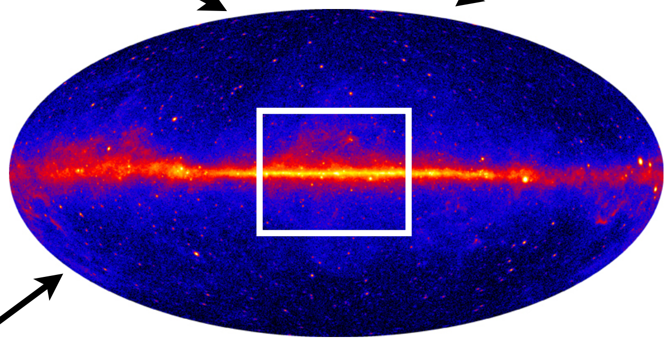
apply ***template fitting*** procedure to the inner ~<20 deg with addition of the FBs



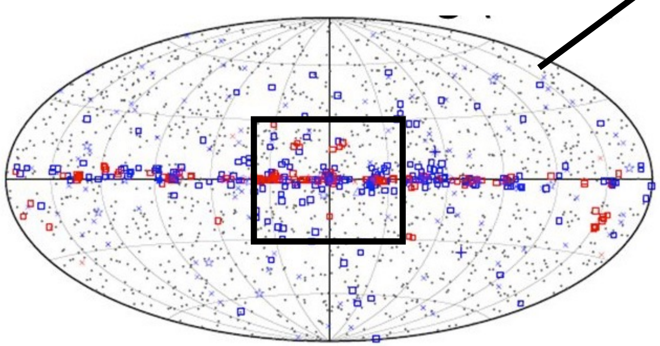
model(s) of the diffuse emission



uniform-brightness template for the Fermi Bubbles



LAT data



point sources from the catalog

$$\mathcal{L}\left(\boldsymbol{\mu}|\boldsymbol{n}\right) = \prod_{i,j} \frac{{\mu_{ij}}^{n_{ij}}}{n_{ij}!} \exp(-\mu_{ij}).$$

$$\mu_{ij}(A^X, A_i^X) = A^X \mu_{ij}^X + \sum_X A_i^X \mu_{ij}^X \,.$$

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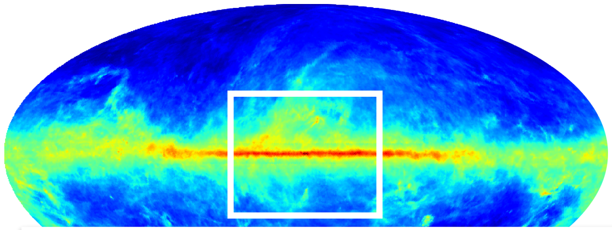
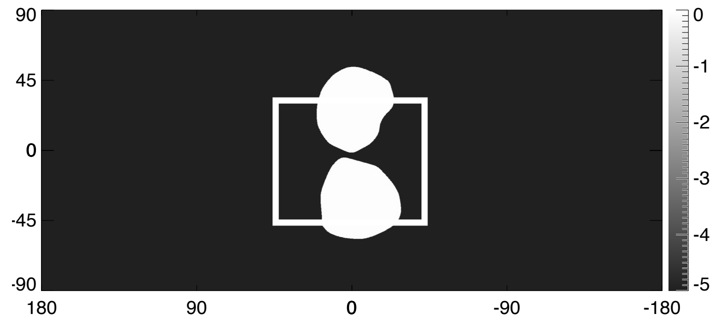


Devil is in details…

At least two philosophies:

— start from a set of ‘**physical’ astro models** and estimate systematics from the range of results

— allow as much as possible **freedom** to a given astro model, **within chosen priors** (swordfish)



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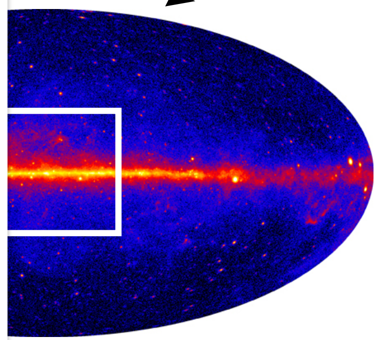

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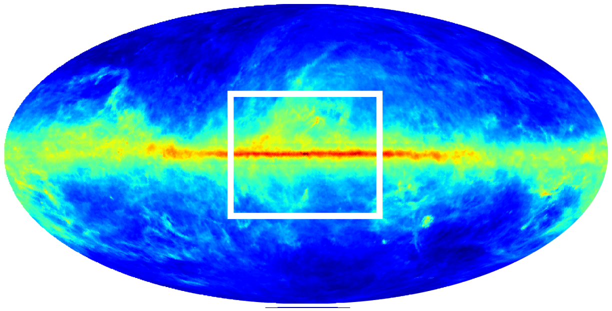

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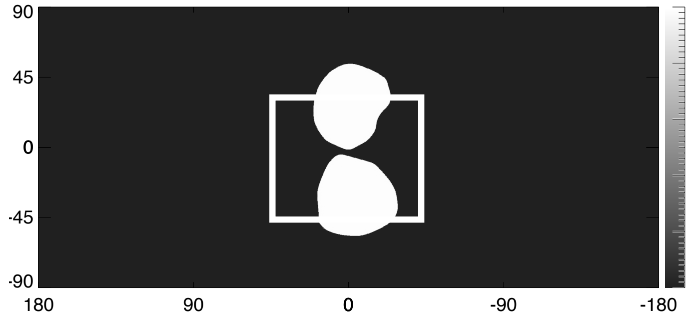

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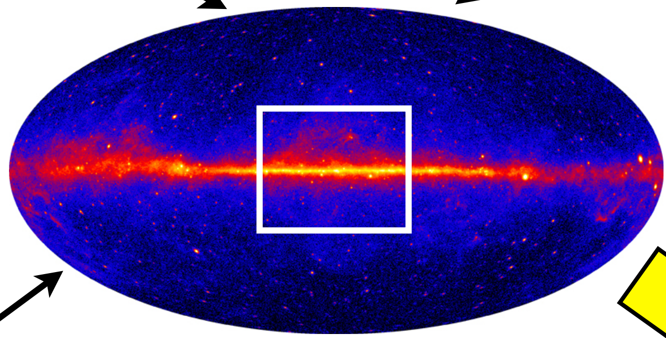

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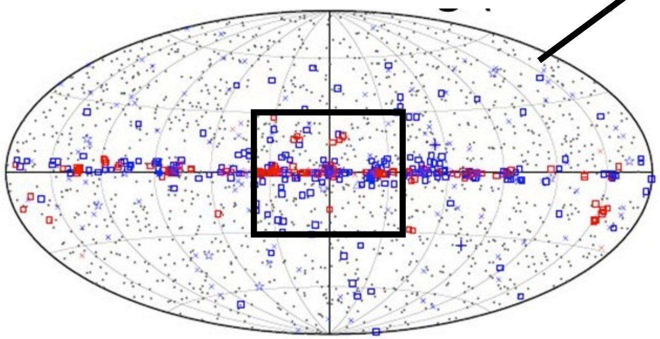

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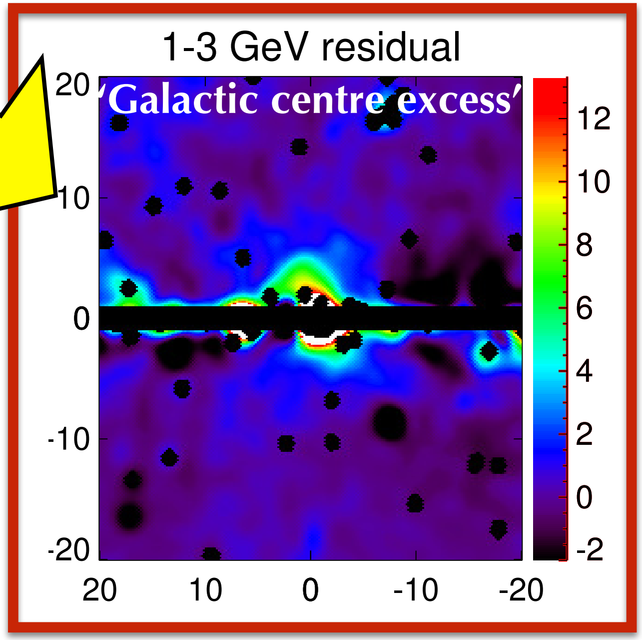
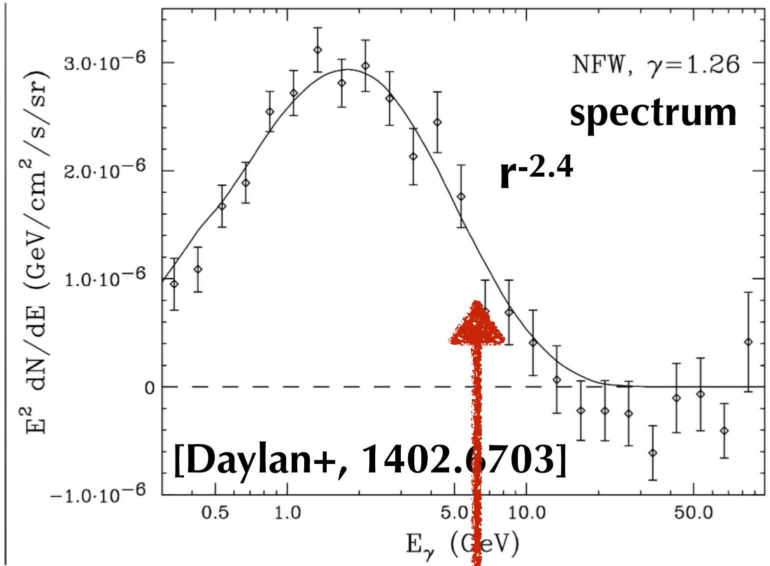
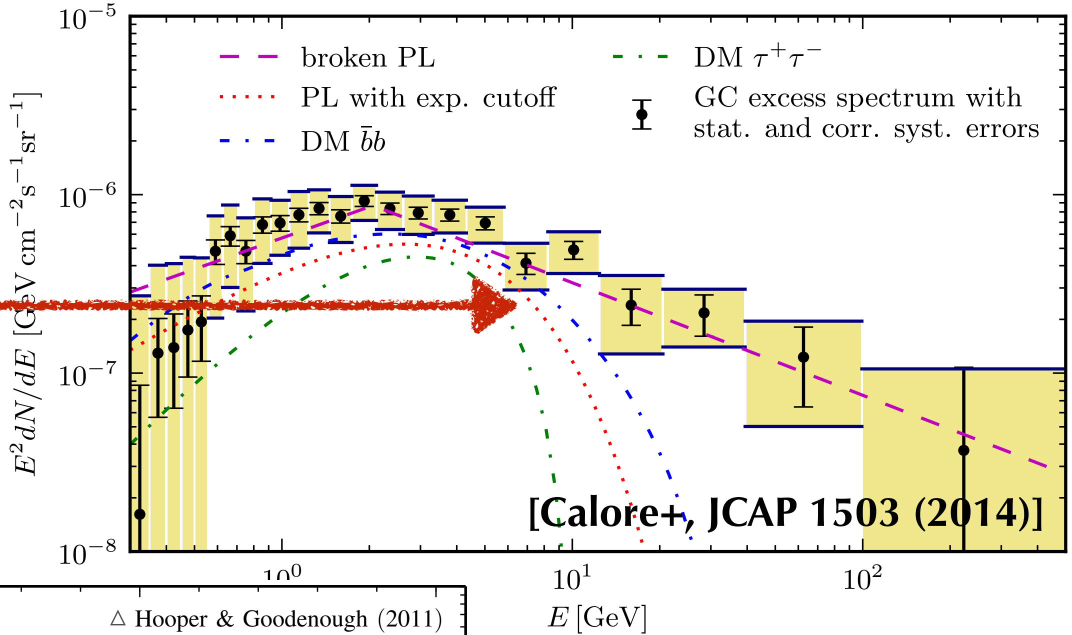


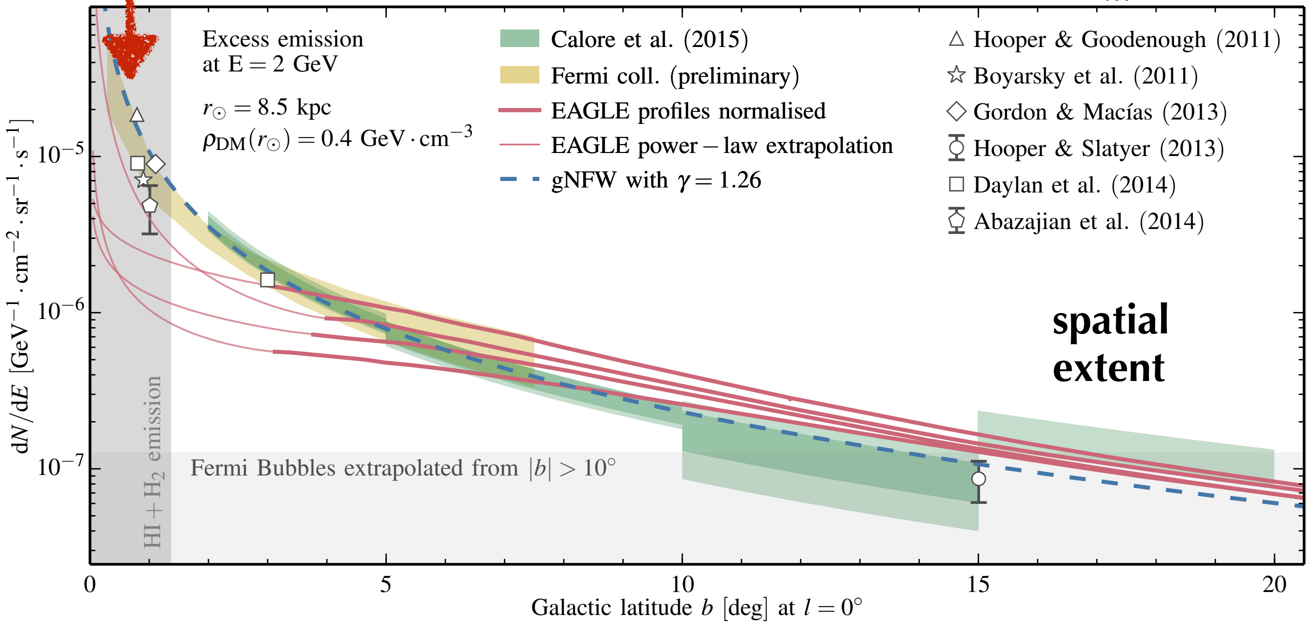
Many works reaching similar results: Vitale & Morseli (2009), Goodenough & Hooper (2009), Hooper & Goodenough (2011, PLB 697 412), Hooper & Linden (2011, PRD 84 12), Abazajian & Kaplinghat (2012, PRD 86 8), 1207.6047, Hooper & Slatyer (2013, PDU 2 118), 1302.6589 Gordon & Macias (2013, PRD 88 8) 1306.5725 Macias & Gordon (2014, PRD 89 6) 1312.6671, Abazajian et al. (2014, PRD 90 2) 1402.4090, Daylan et al. (2014) 1402.6703, 1407.5583 1407.5625 1410.1527

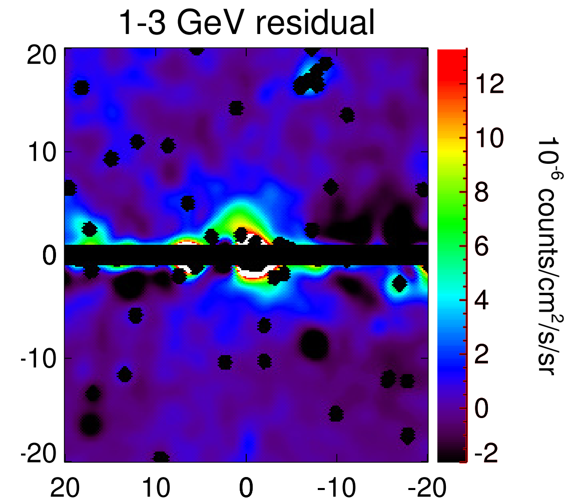


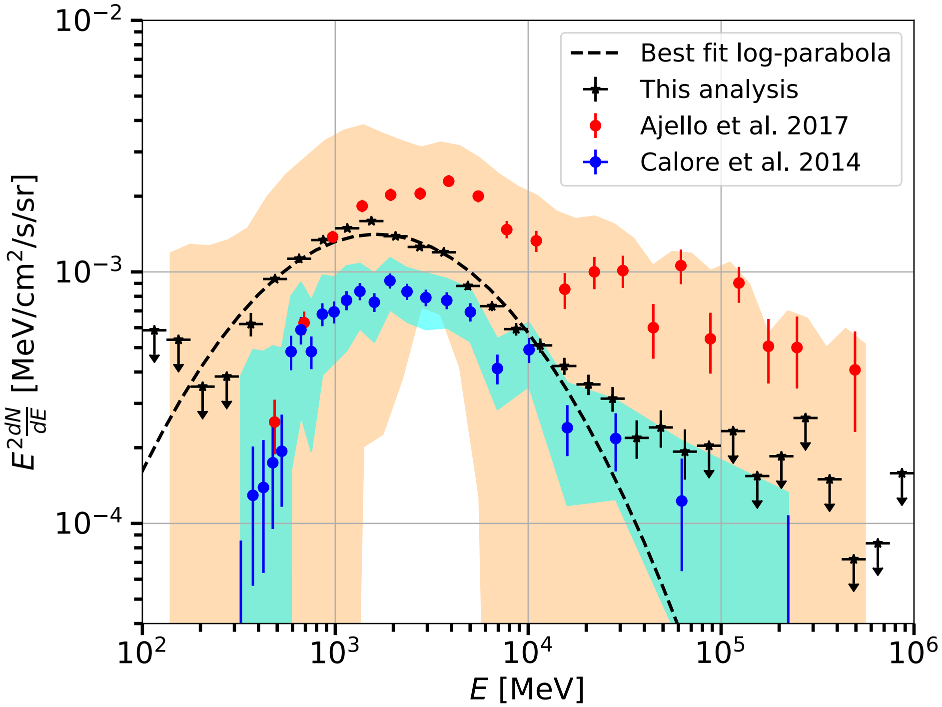
DM spectral fits

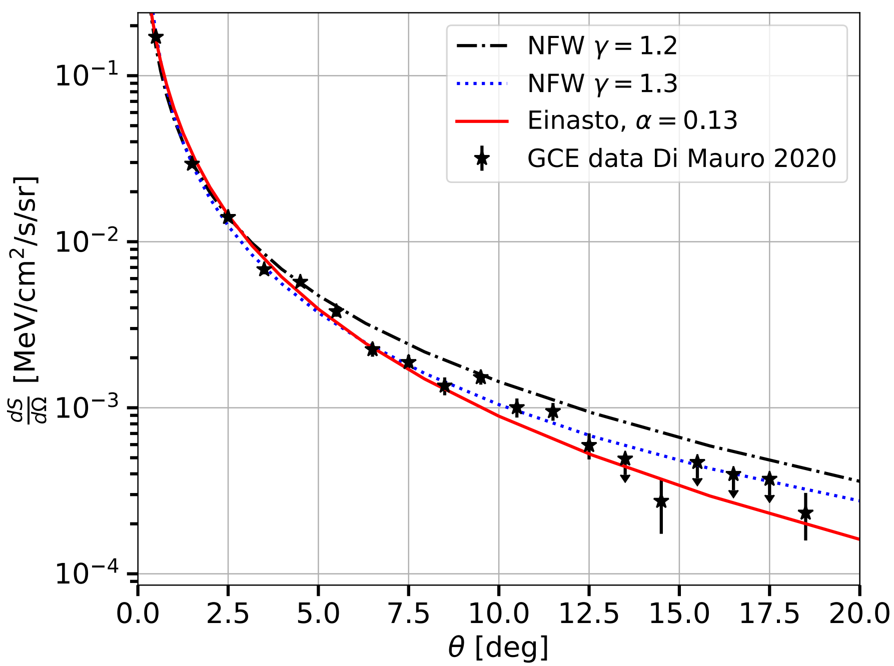


DM morphology









Systematic uncertainty estimates [Ackermann+, ApJ 2017]

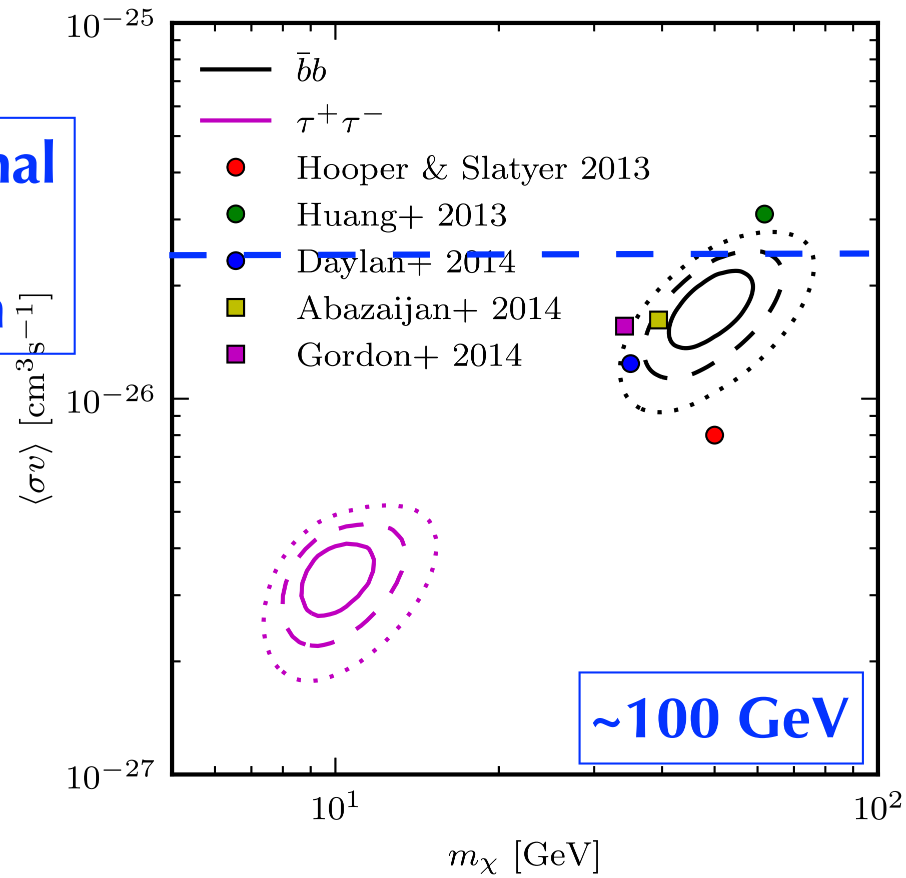
- GALPROP model parameters variations
- Alternative gas maps (softer GCE spectrum < 1GeV)
- Include additional sources of CR electrons near the GC (Gaggero+2015, Carlson+2015 ; GCE reduced)
- data driven template of the Fermi Bubbles

[diMauro+, ApJ 2021]

Could it be dark matter?

Right on the spot where WIMP DM is supposed to be!

~thermal cross section



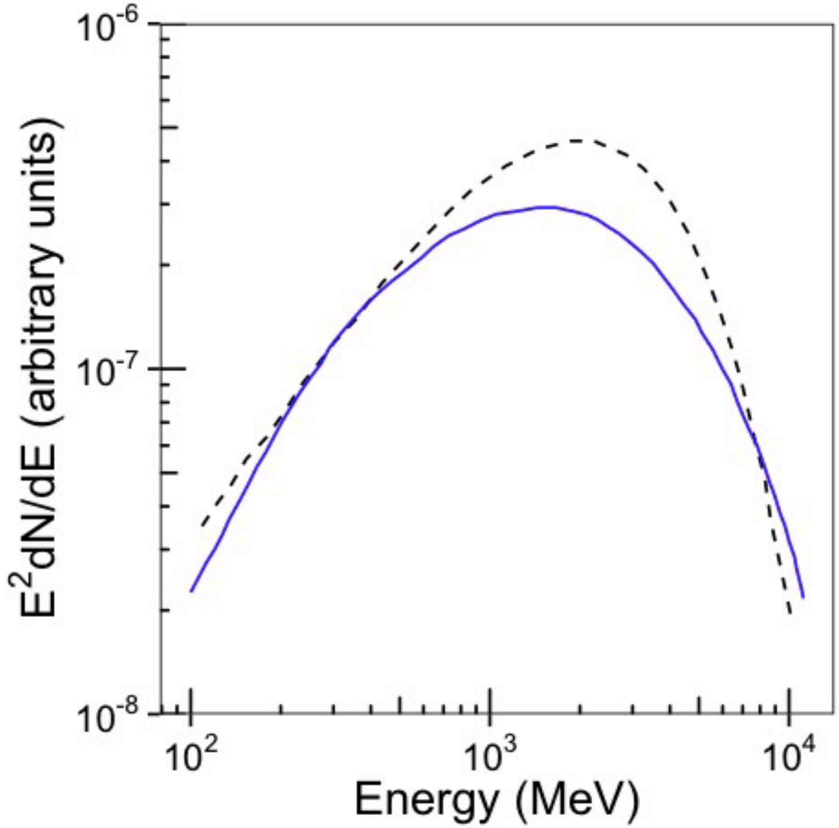
γ

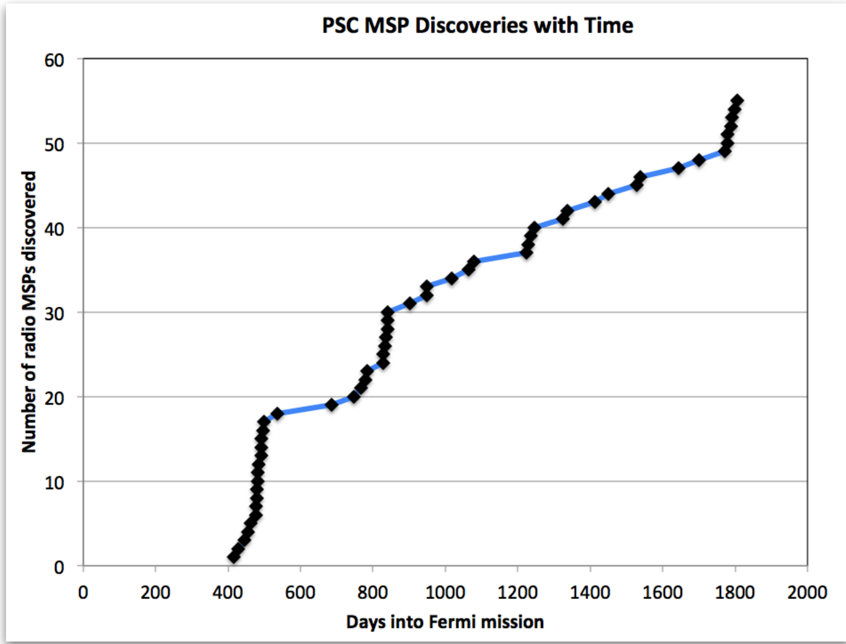
Thermal cross section & <~100 GeV & at the Galactic center

Spatial distribution close to the predicted NFW profiles.

Or…

Spectral twins: Pulsar/DM Annihilation (30 GeV bb channel)





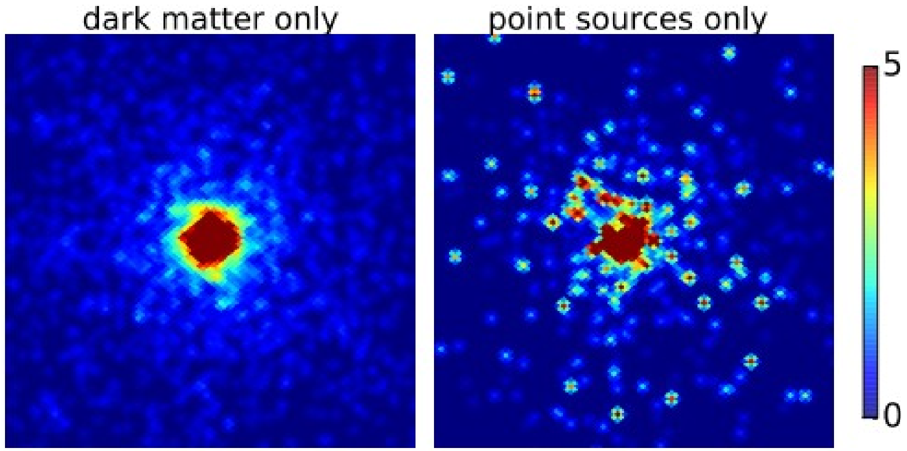
Baltz et al (2007)

The origin of the GCE — current status

Evidence that the signal is due to pulsar is strengthening:

— **statistical properties of photo counts** suggest that GCE is of a 'point source' origin

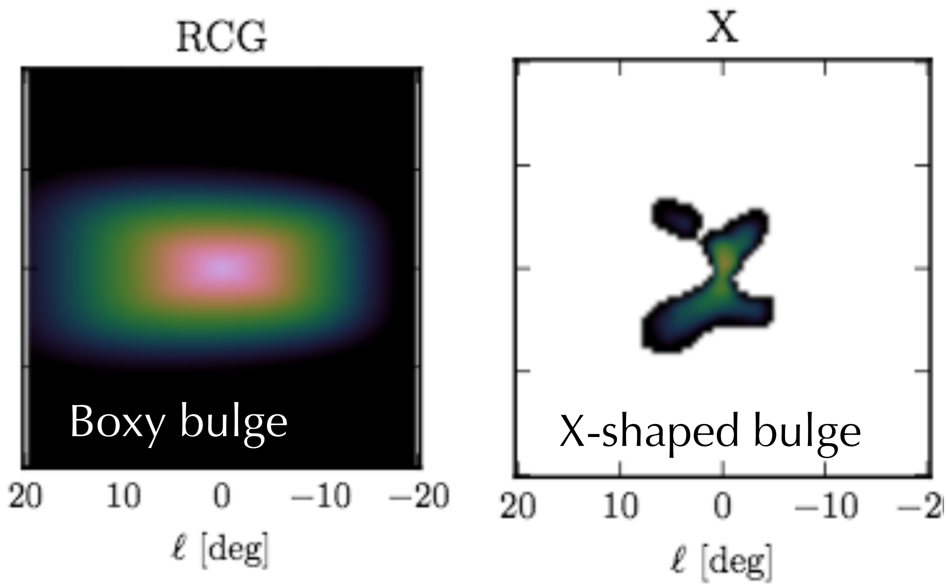
(Bartels+, PRL (2016), Lee+, PRL (2016))



(Credit: Lee+ 2014)

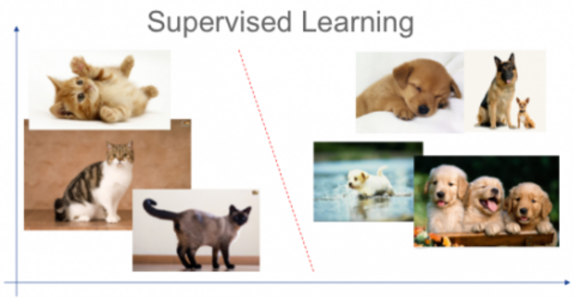
— evidence of **GCE tracing stellar densities**

(Bartels+, 1711.04778; Macias+, Nature Astronomy (2018))



— **Machine learning techniques** could also be usec

(Caron+, JCAP(2017))

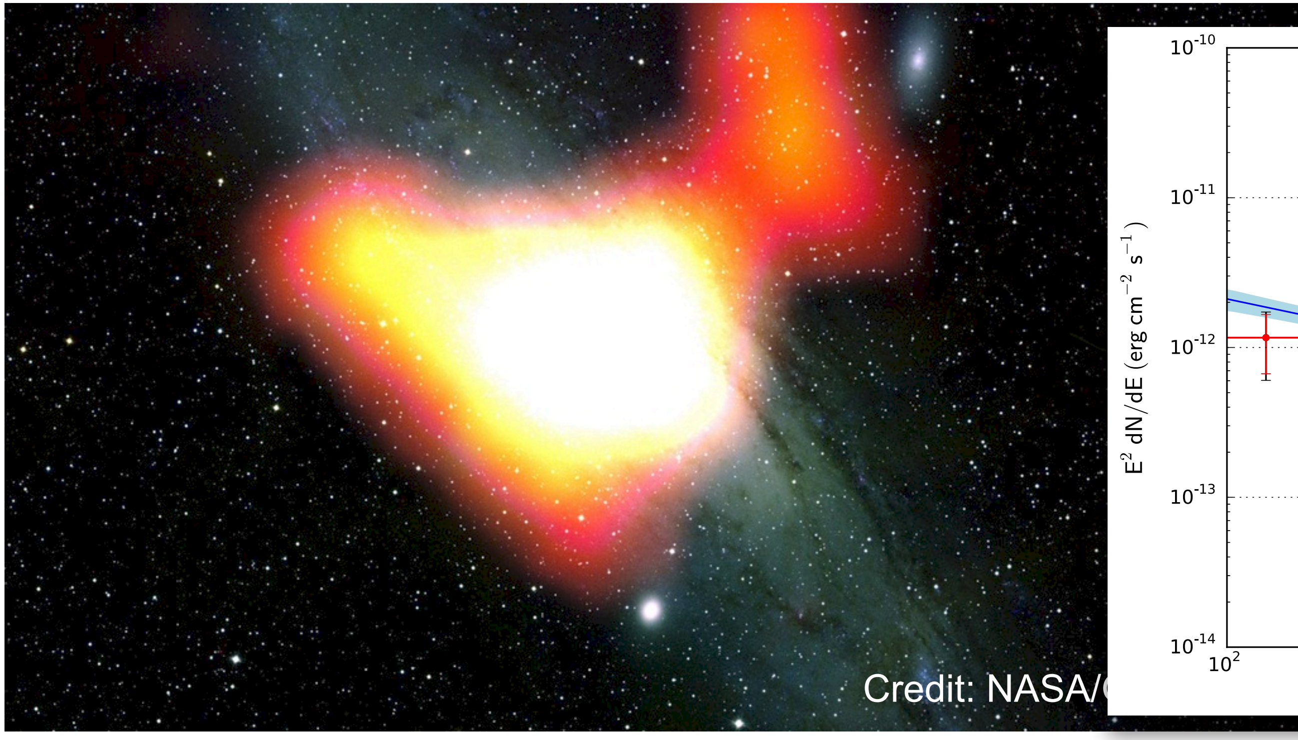


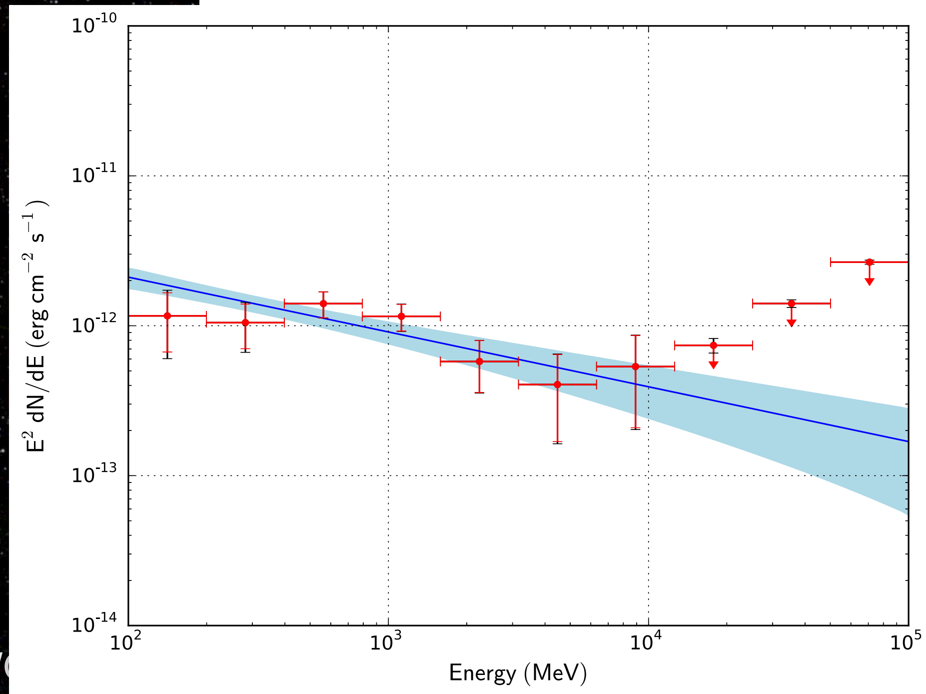
Deep neural networks

Multi-target - M31

M31 - 'sister' galaxy of the MW
The extended gamma-ray emission observed recently from M31 bulge region

- Main facts
    - Emission confined to inner regions (R<5kpc)
    - Not correlated with interstellar gas and star formation sites
    - Galactic disk not detected

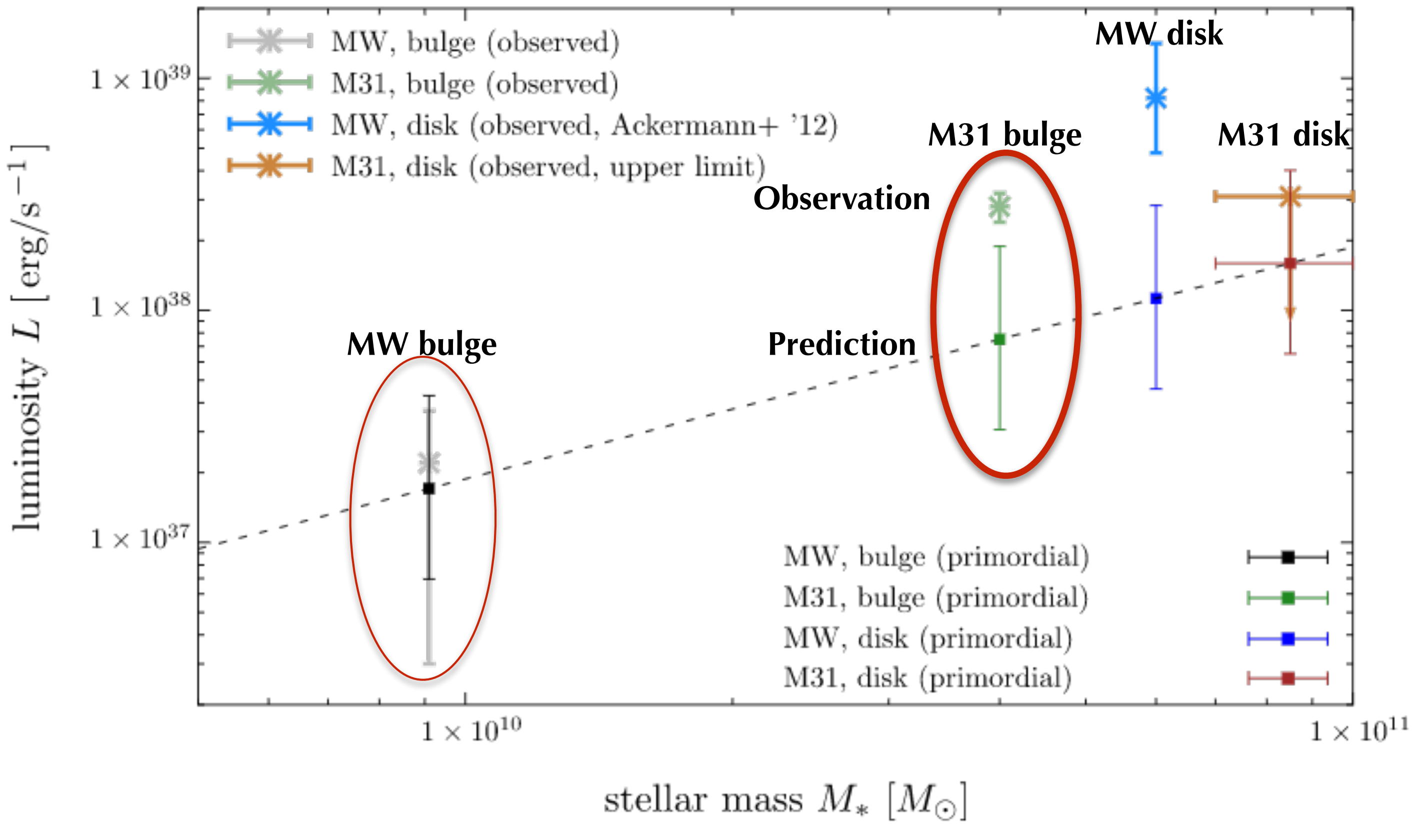




[Ackermann+, ApJ (2017)]

Multi-target - M31

Origin of the M31 emission?
MSPs could explain it, though they slightly (factor of ~2) under predict it (Eckner+, ApJ (2017))



[Eckner+, ApJ (2017), 1711.05127
Bartels+, 1711.04778]

Additional source components?

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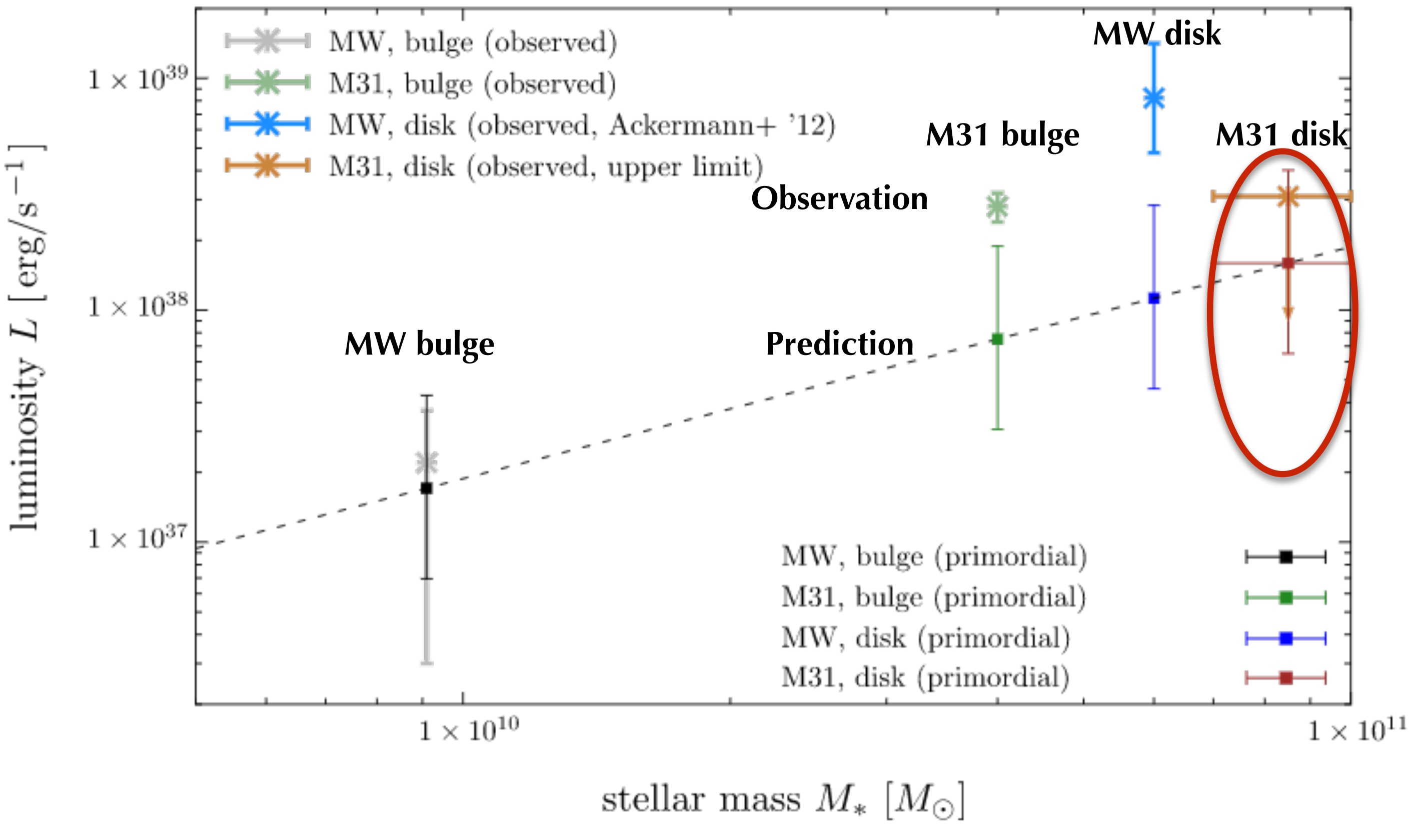


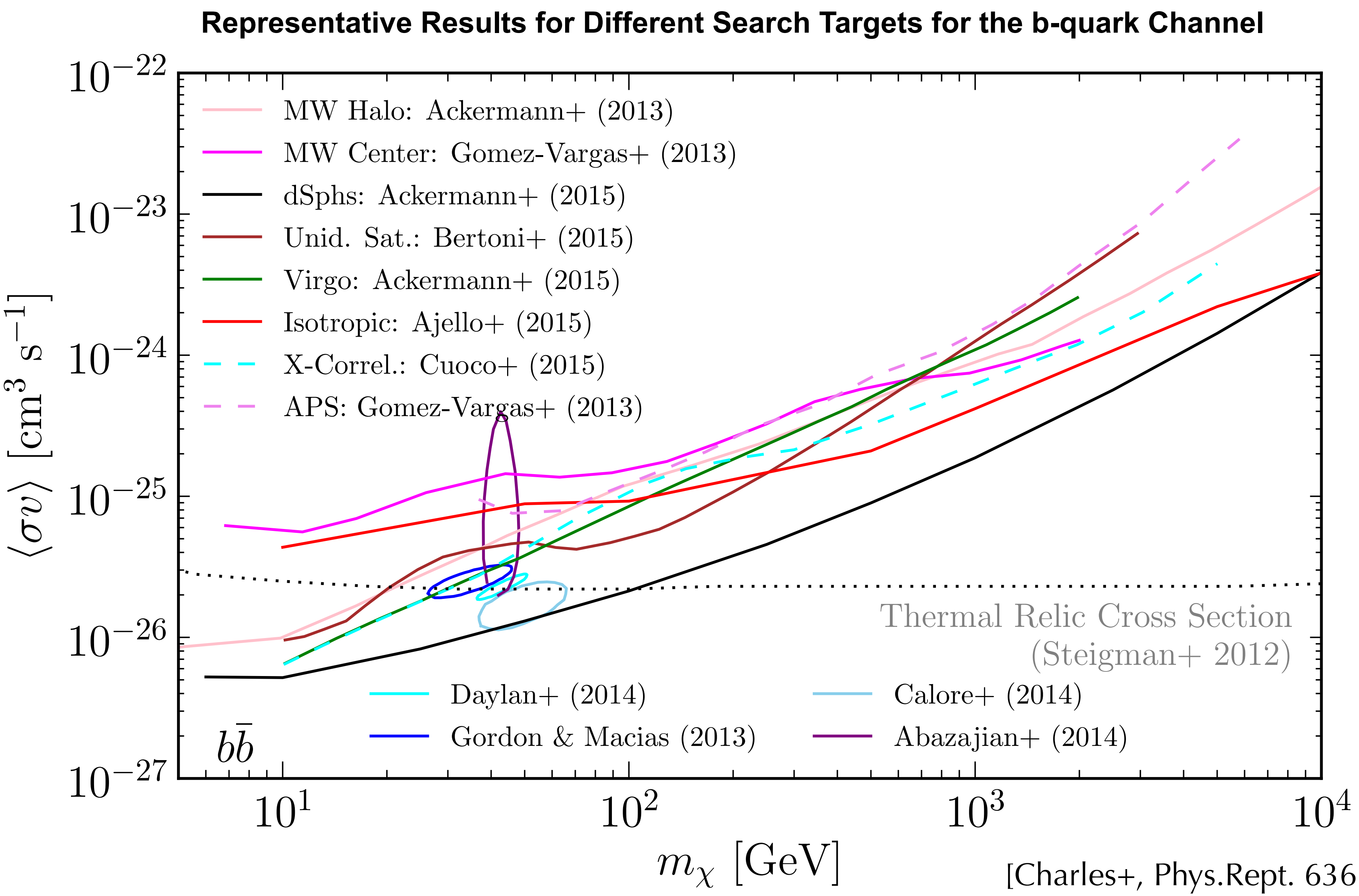
[Eckner+, ApJ (2017), 1711.05127
Bartels+, 1711.04778]

If pulsars, M31 disk might be at the verge of discovery…

Additional source components?

Multi-target - dSPhs

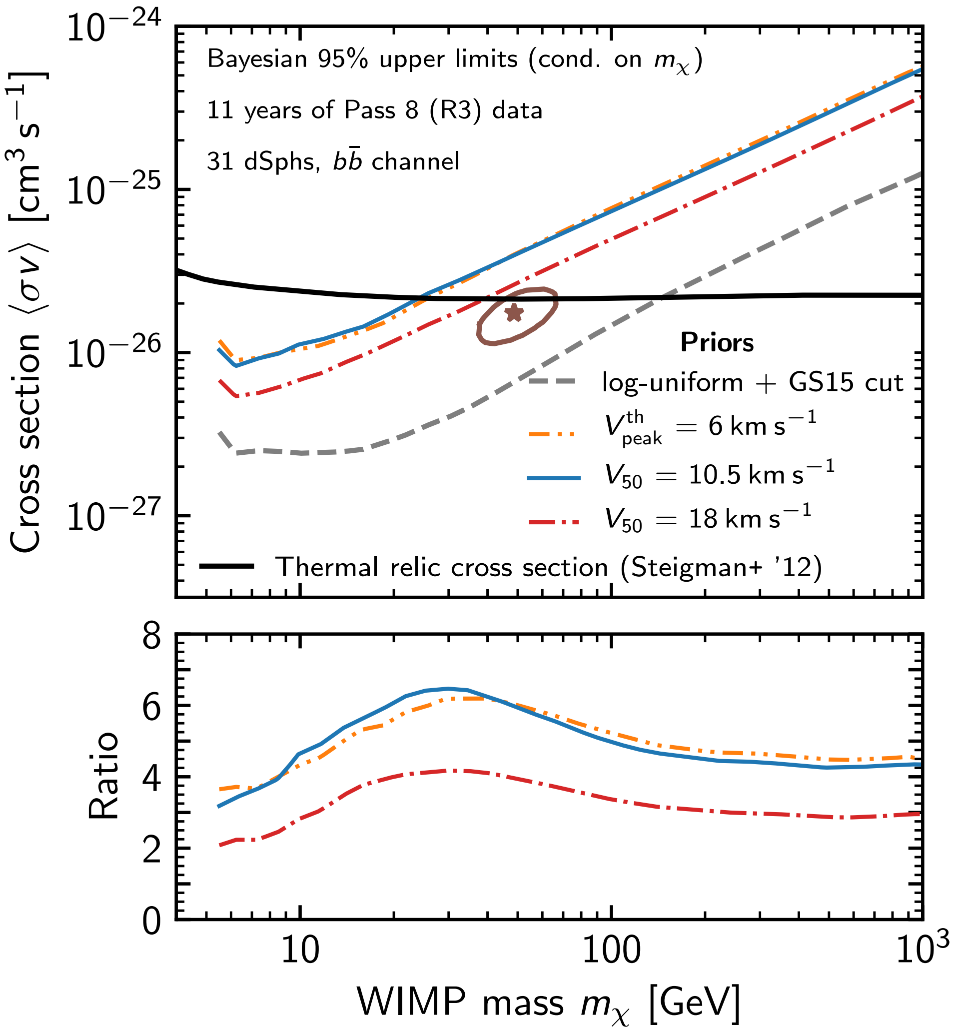
dSphs - limits in tension with GCE

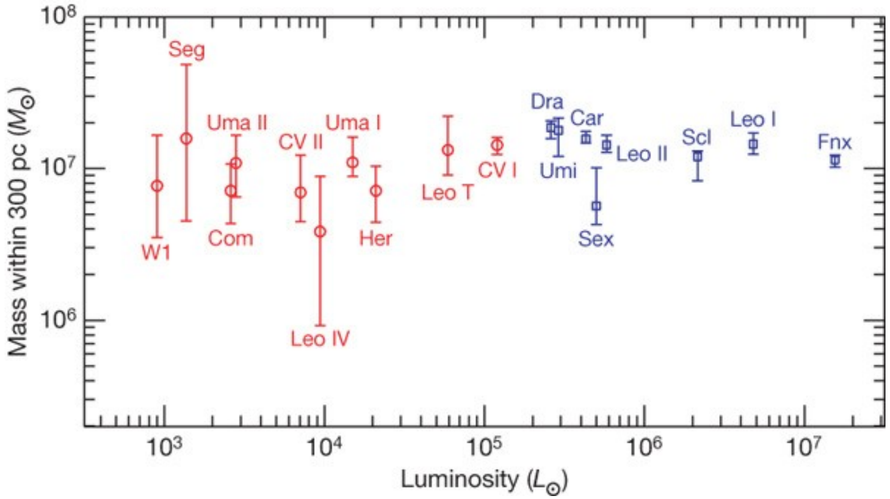


[Charles+, Phys.Rept. 636 (2016)]

Multi-target - dSPhs

dSphs - unclear if at present they **exclude** the DM interpretation of the GCE





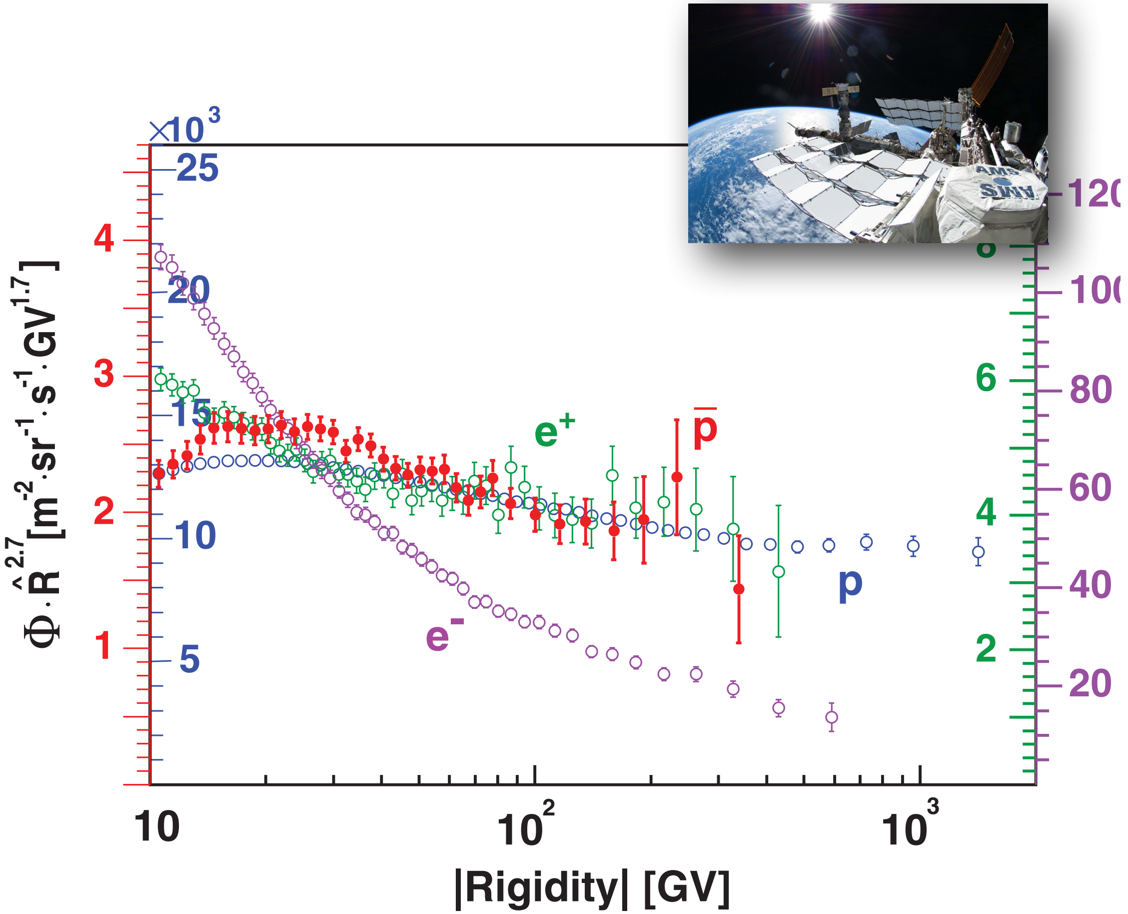
traditionally, **uniform priors for both logrs and logps** adopted
But, such uniform priors **ignore theoretical and numerical simulation results** that predict the frequency distributions of subhalo parameters.

[Ando+ (2002), …]

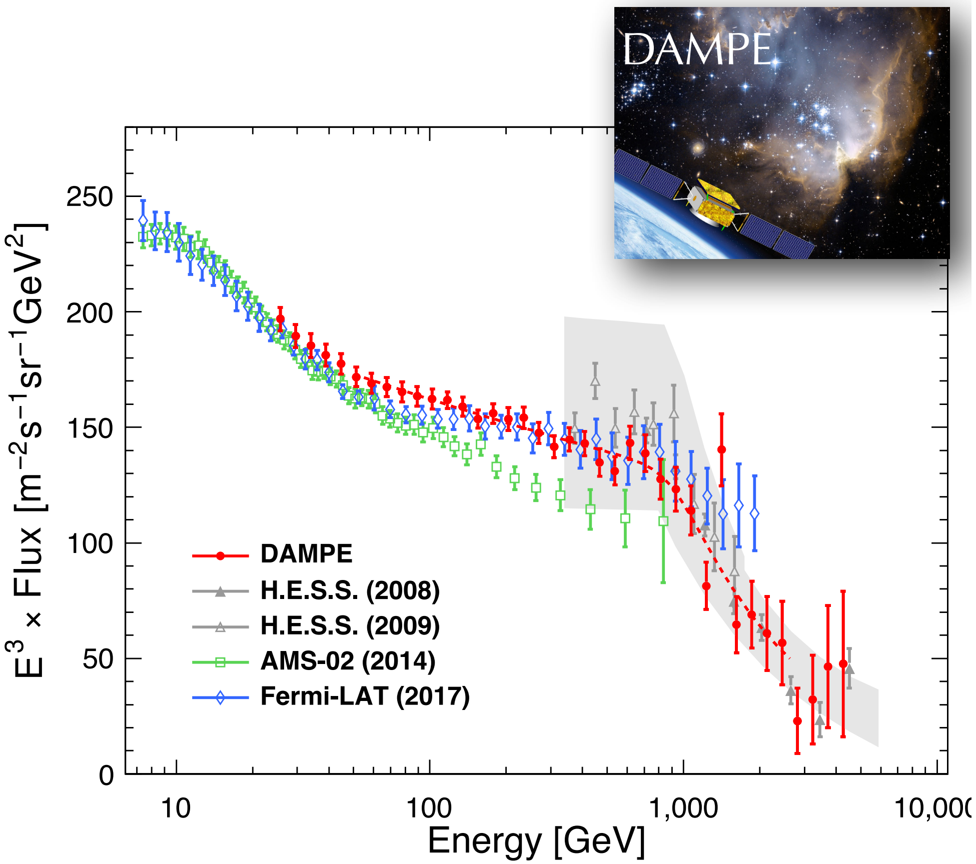
Multi-messenger - antiprotons

Antiprotons - one of the most sensitive probes of new physics

PAMELA, AMS-02, DAMPE… measured CR fluxes with exquisite precision and reaching <~ TeV energies.
Challenge the 'Standard model' of CR propagation in the Galaxy



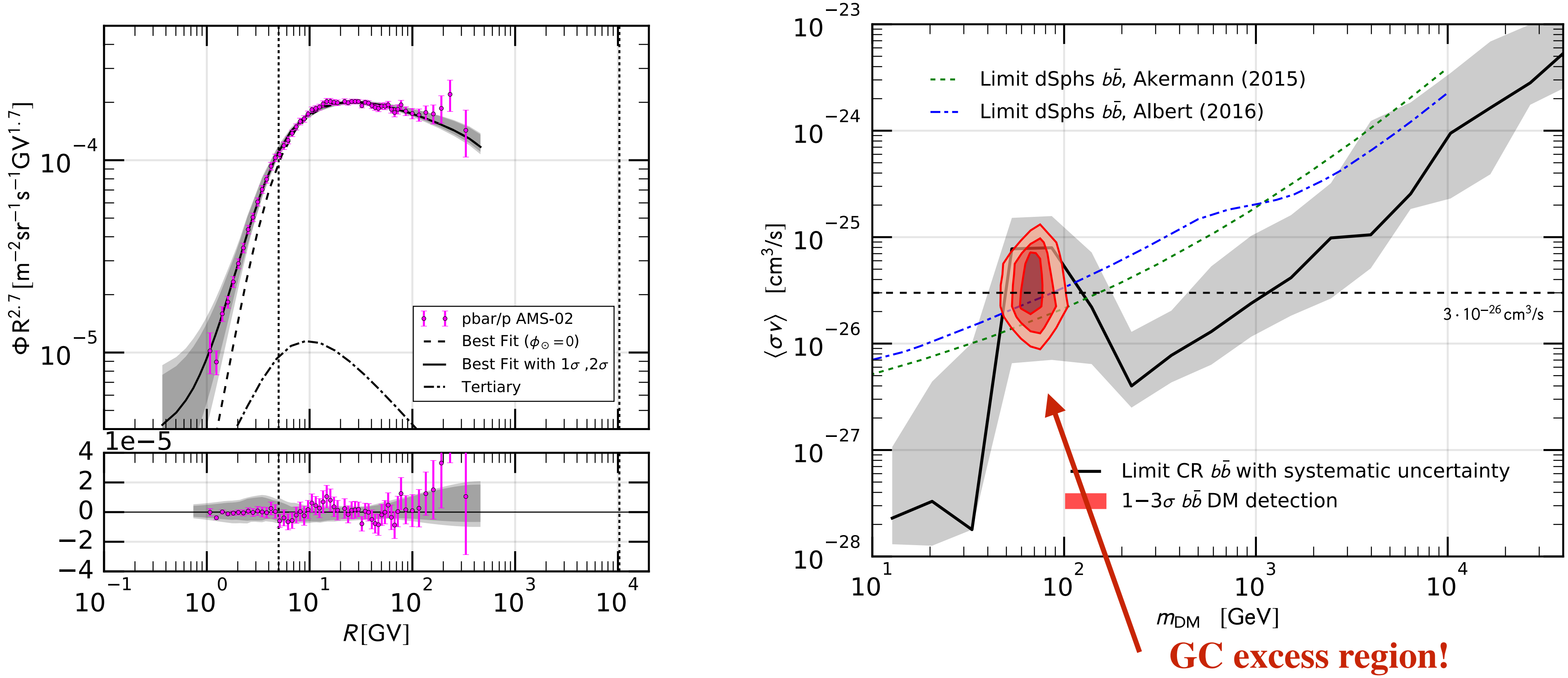
[Aguilar+, PRL117 (2014)]



[Ambrosi+, Nature552 (2017)]

Multi-messenger - antiprotons

Antiprotons - one of the most sensitive probes of new physics
— p spectra measured exquisitely well
— anti-p produced as secondaries, with the proton spectra as the source term
Simultaneous fit to p and He spectra (constrain propagation parameters) + DM component



[Cuoco+, PRL 118(2016), Gielsen+, JCAP1509 (2015), …]

However, uncertainty in solar modulation, pp x-section, …

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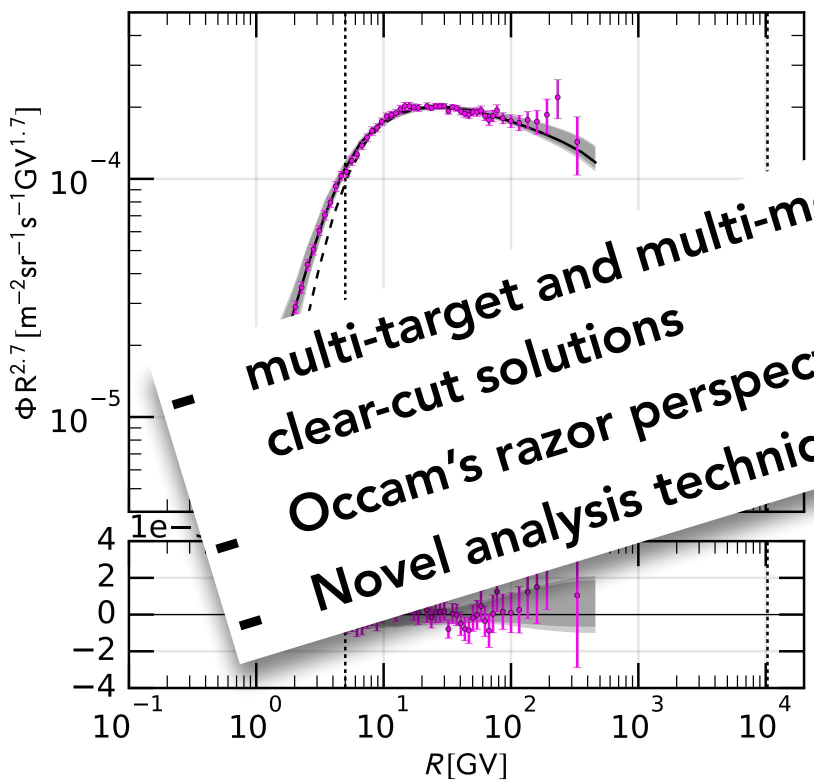
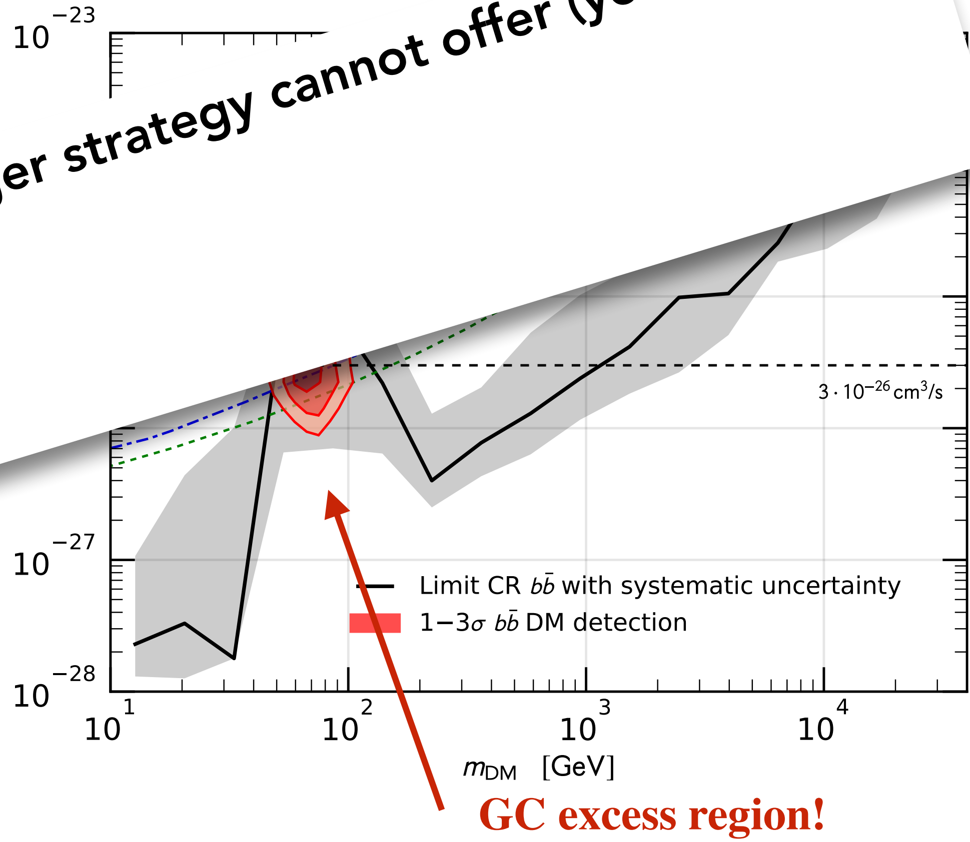


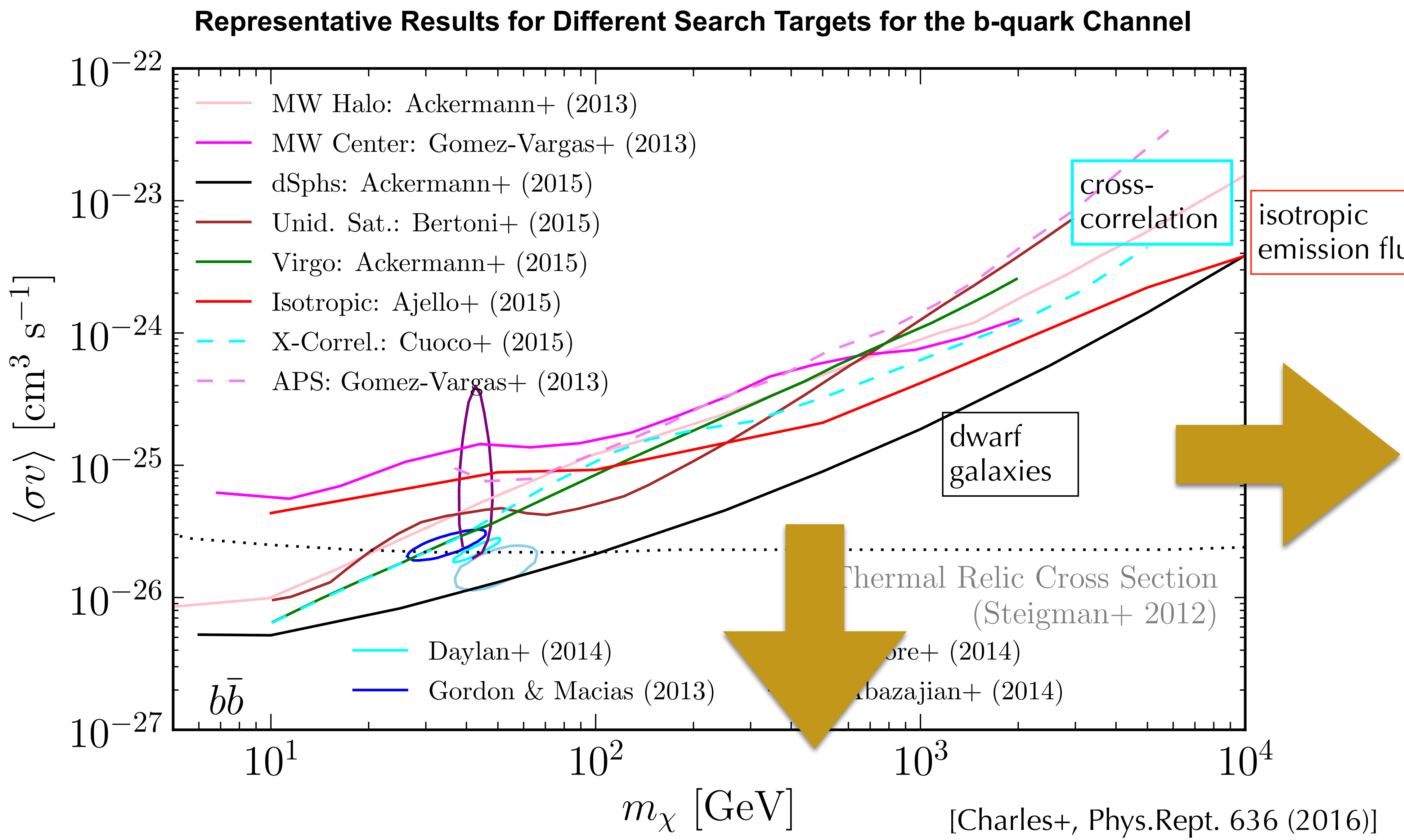


- multi-target and multi-messenger strategy cannot offer (yet) robust clear-cut solutions
- Occam's razor perspective?
- Novel analysis techniques?

[Cuoco+, PRL 118(2016), Gielsen+, JCAP1509 (2015), …]

However, uncertainty in solar modulation, pp x-section, …

WIMPS - frontiers



[Charles+, Phys.Rept. 636 (2016)]

WIMPs - frontiers

Heavy DM ?

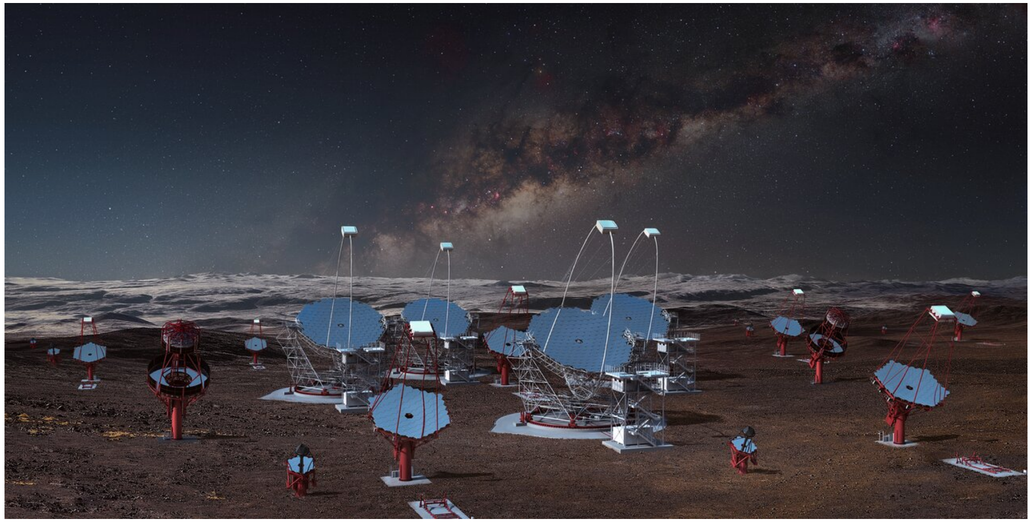
multi-TeV DM IS vanilla WIMP —> important part of the parameter space

weak force as a long-range force:

— Sommerfeld enhancement

— Bound state formation enhancement

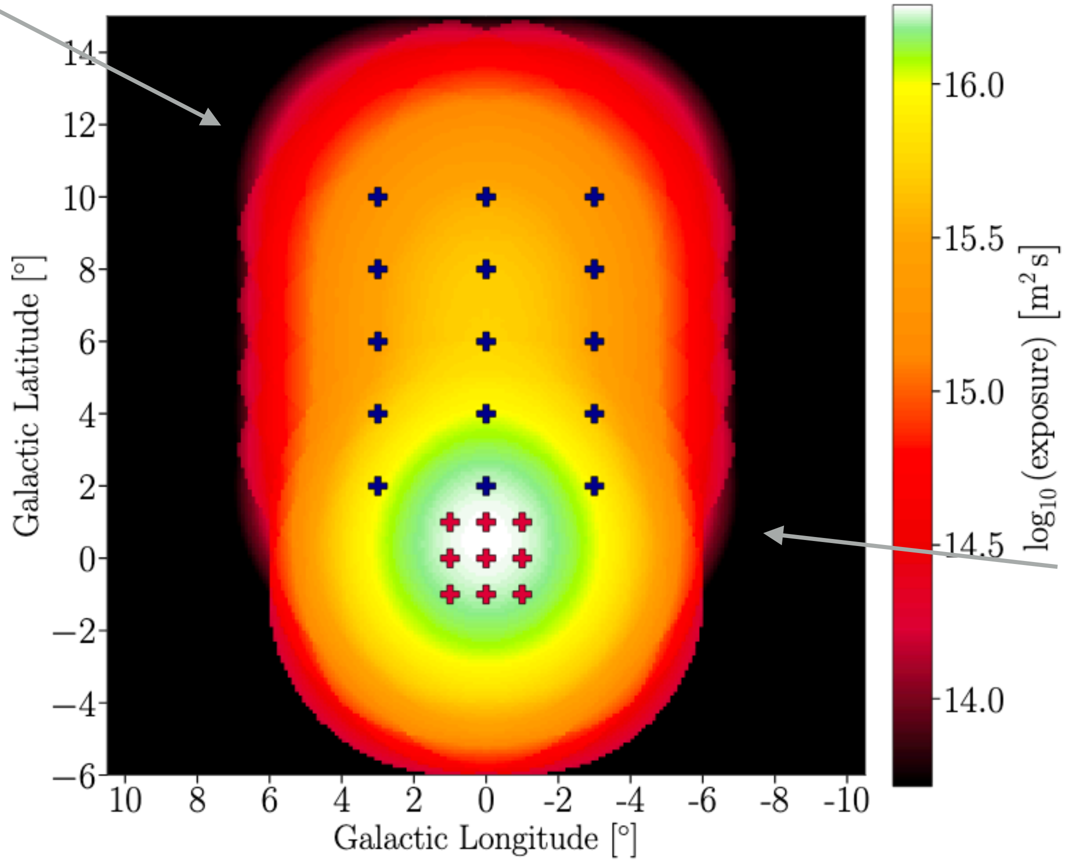
Galactic center with CTA



Cherenkov telescopes are

'pointing', but…

Extended survey: additional 300 hours (relevant for cored DM profiles!)



Galactic center survey: 525 hours over first 10 years

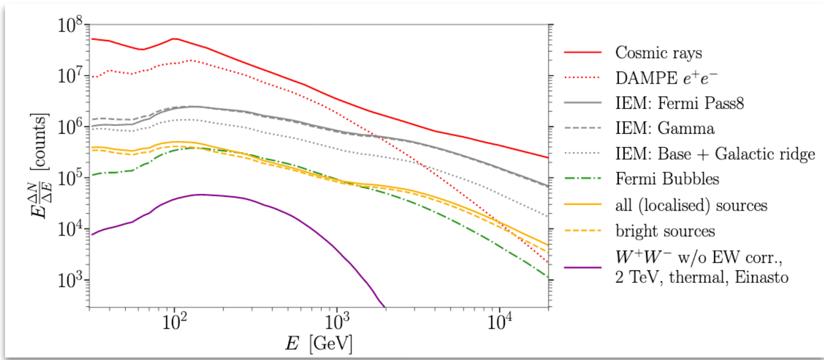
[Archaryya+, 2020]

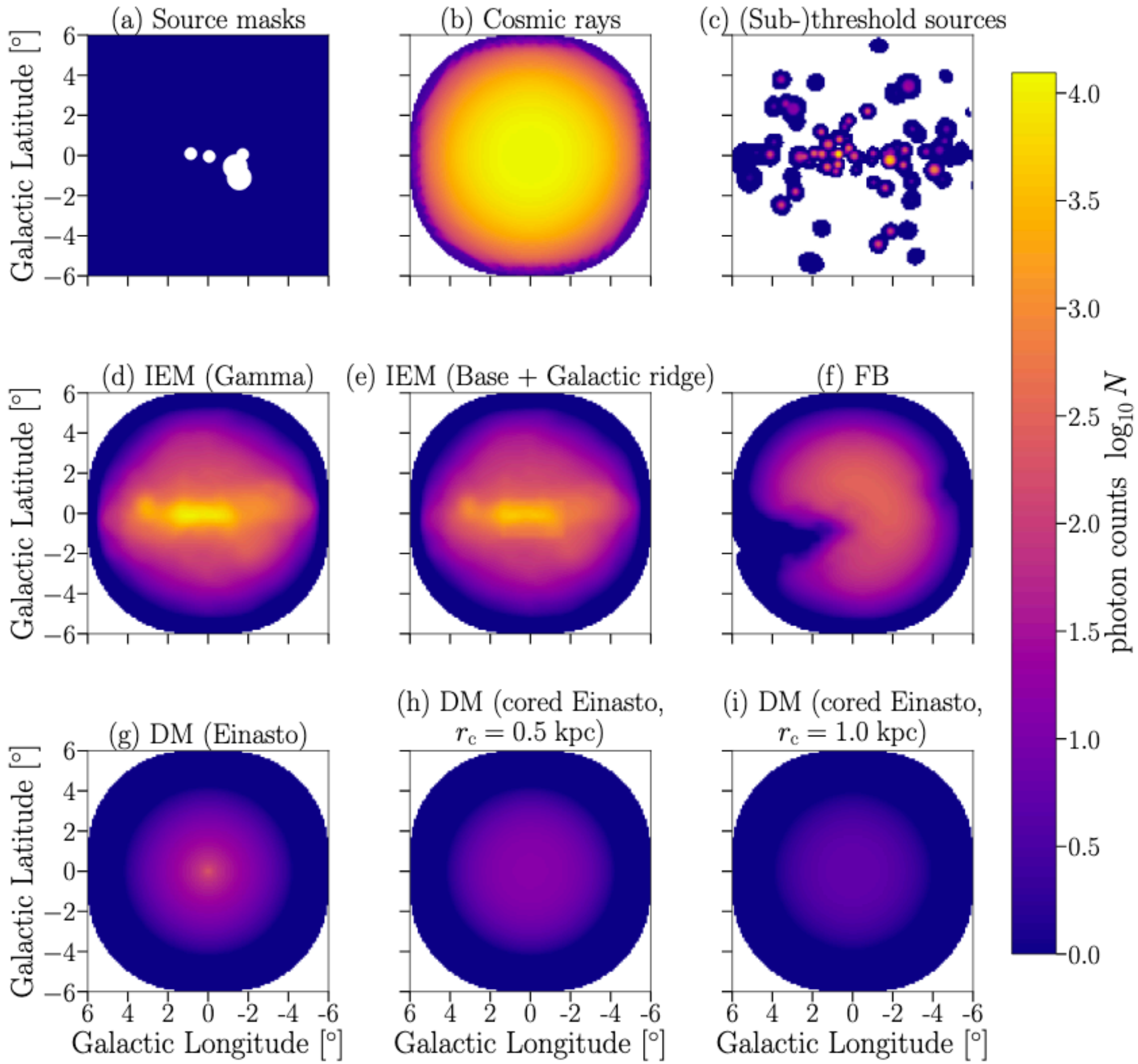
Galactic center with CTA

CTA analysis techniques

ON/OFF analysis
unfeasible for GC (no
good OFF region)

—> FULL 3D TEMPLATE ANALYSIS





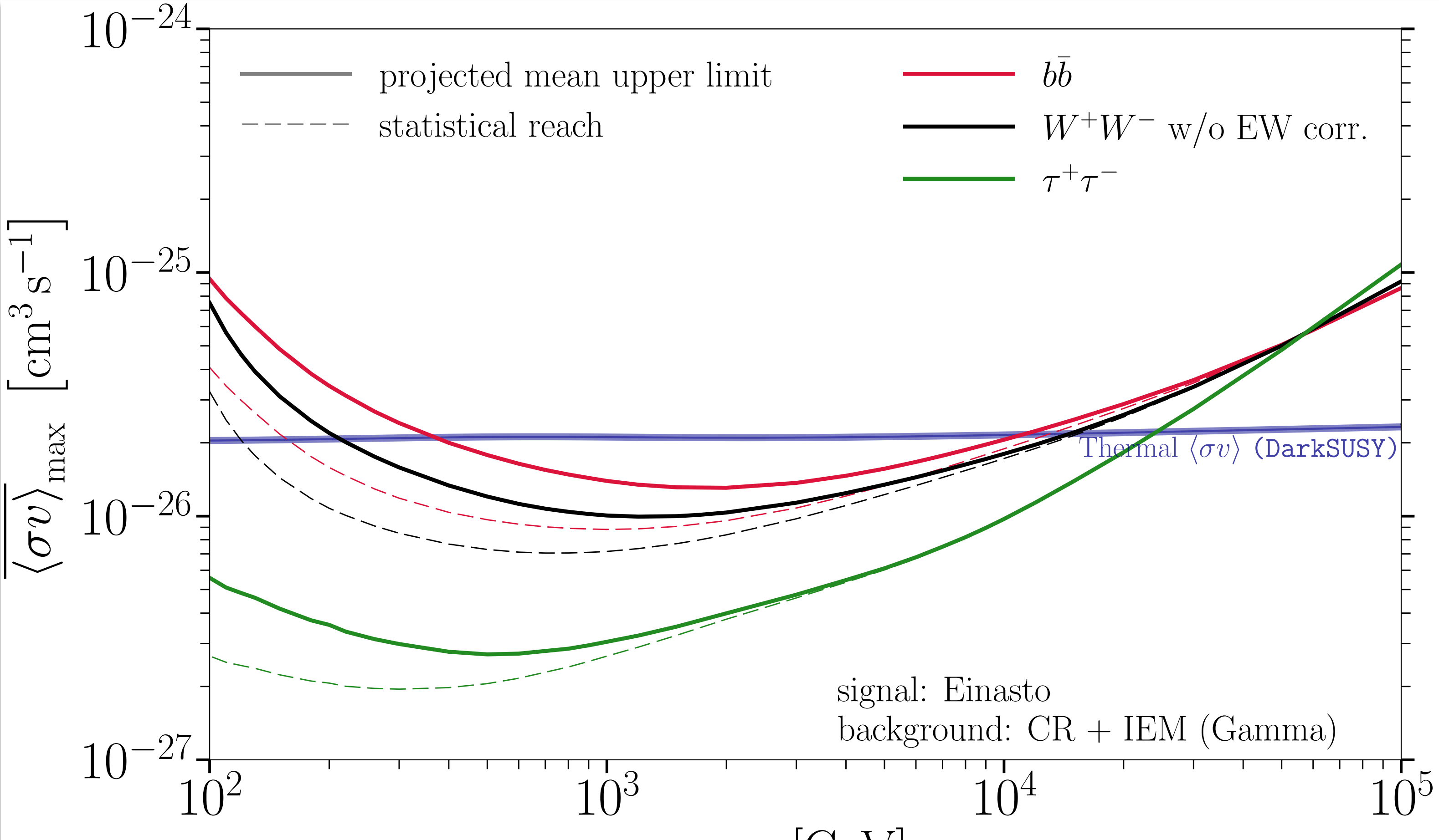
[Archaryya+, 2020]

Galactic center with CTA

Likelihood analysis for sensitivity includes:

- systematic uncertainties
- astro backgrounds

—> CTA expected to probe thermal annihilation cross section between 100s of GeV and tens of TeV



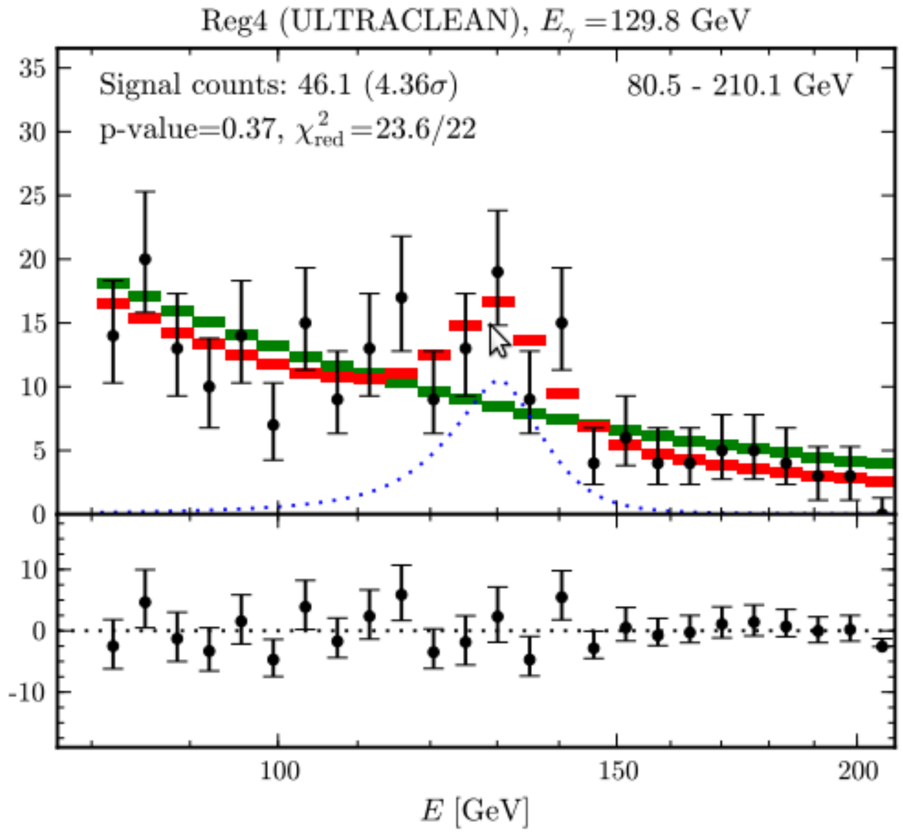
[Archaryya+, 2020]

Outline

1. DM model space that CAN be tested with gamma-rays
2. Experiments
3. Wish list, targets
4. Astro backgrounds
5. Examples:
   - WIMPs - an example of DM detection in a crowded region of the GC
   - **ALPs - an example of smoking gun signature**
   - PBHs - an example of gamma rays excluding a significant portion of parameter space.

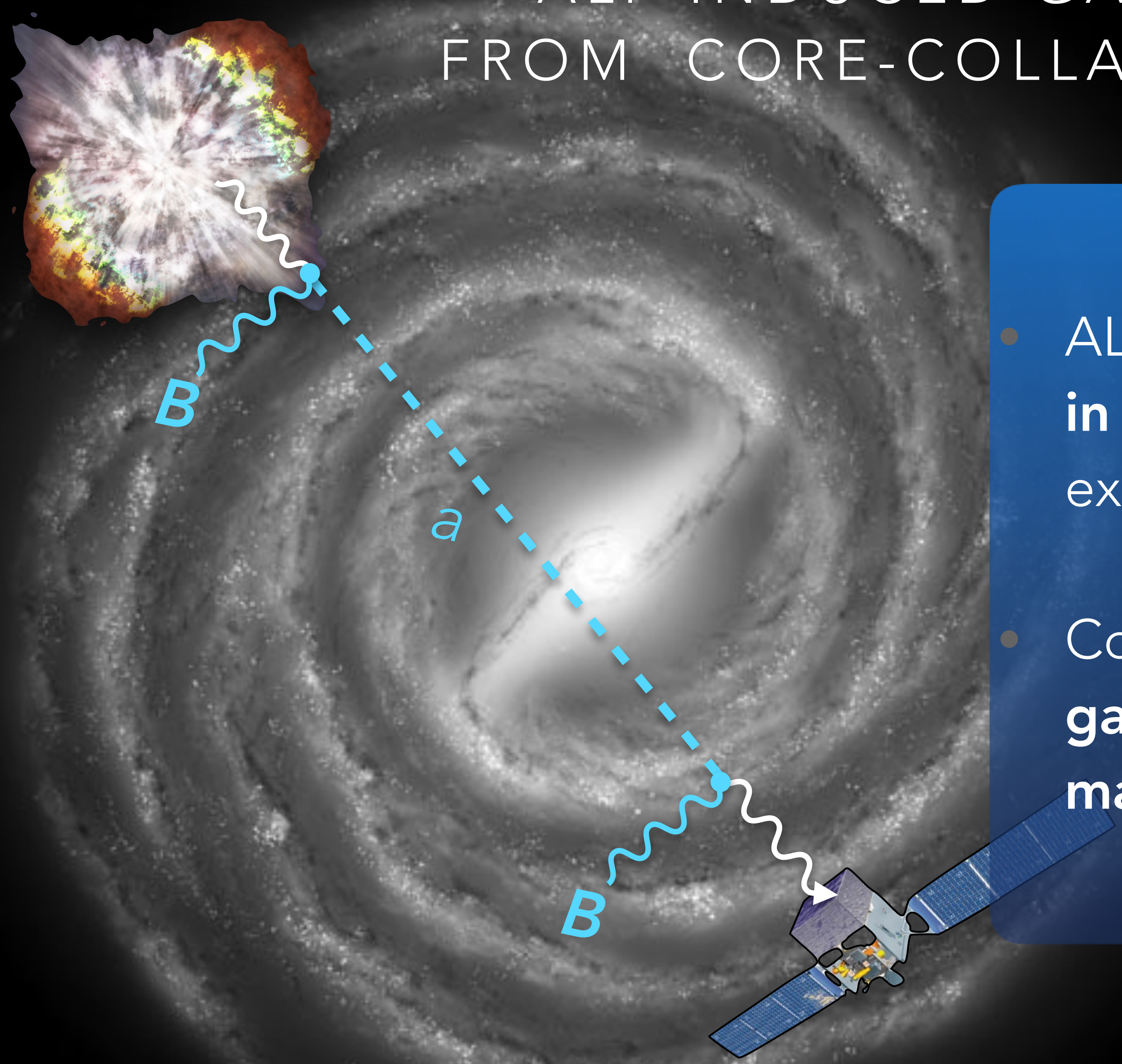
Smoking guns

Spectral features



Targets with no gamma emitters (except DM)

ALP INDUCED GAMMA-RAY BURSTS FROM CORE-COLLAPSE SUPERNOVAE



- ALPs would be **produced in a core-collapse SN** explosion
- Could **convert into gamma-rays in Galactic magnetic field**

[credit M. Meyer]

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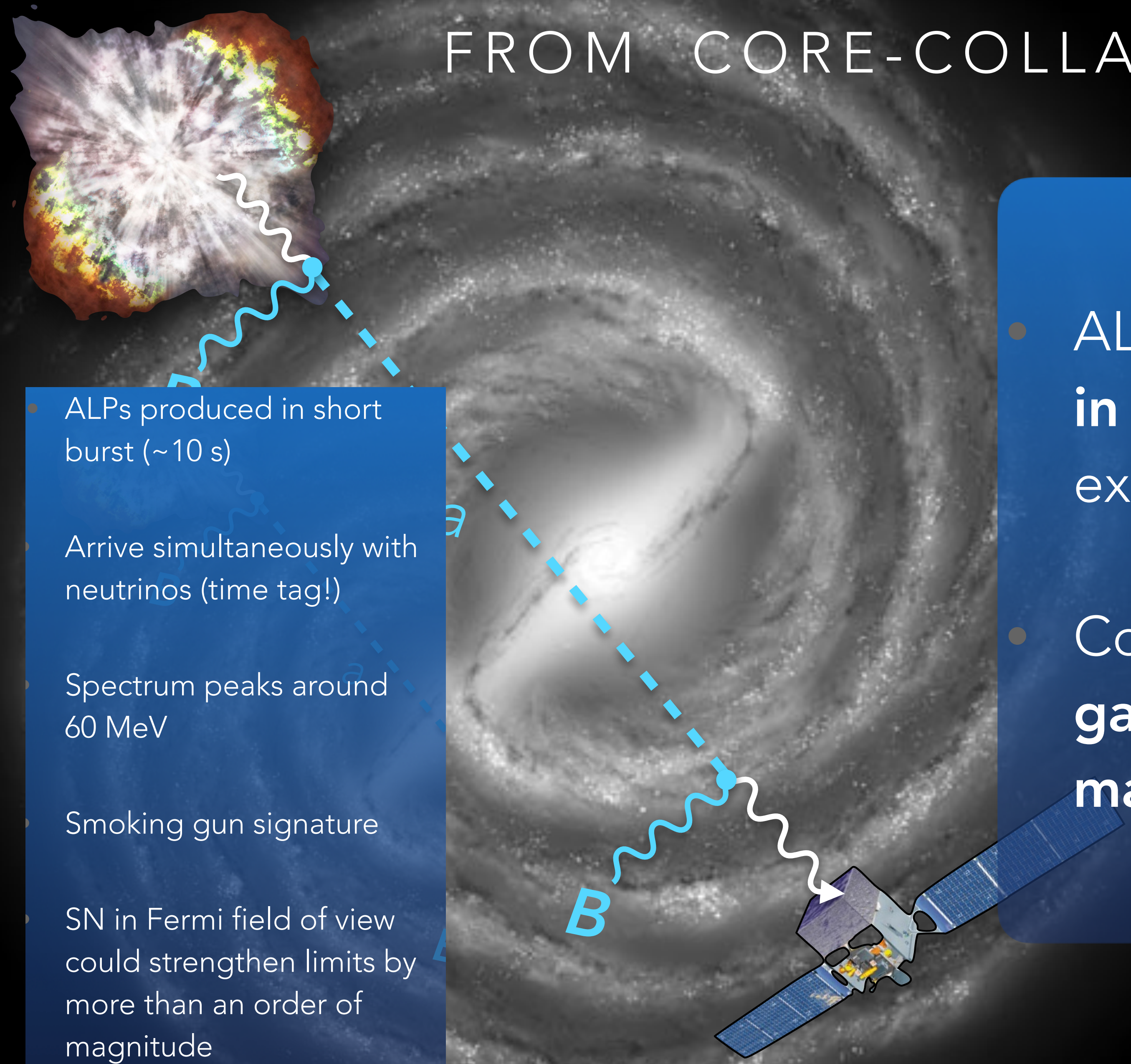

- ALPs produced in short burst (~10 s)
- Arrive simultaneously with neutrinos (time tag!)
- Spectrum peaks around 60 MeV
- Smoking gun signature
- SN in Fermi field of view could strengthen limits by more than an order of magnitude [**MM** et al. PRL 2017]

[credit M. Meyer]

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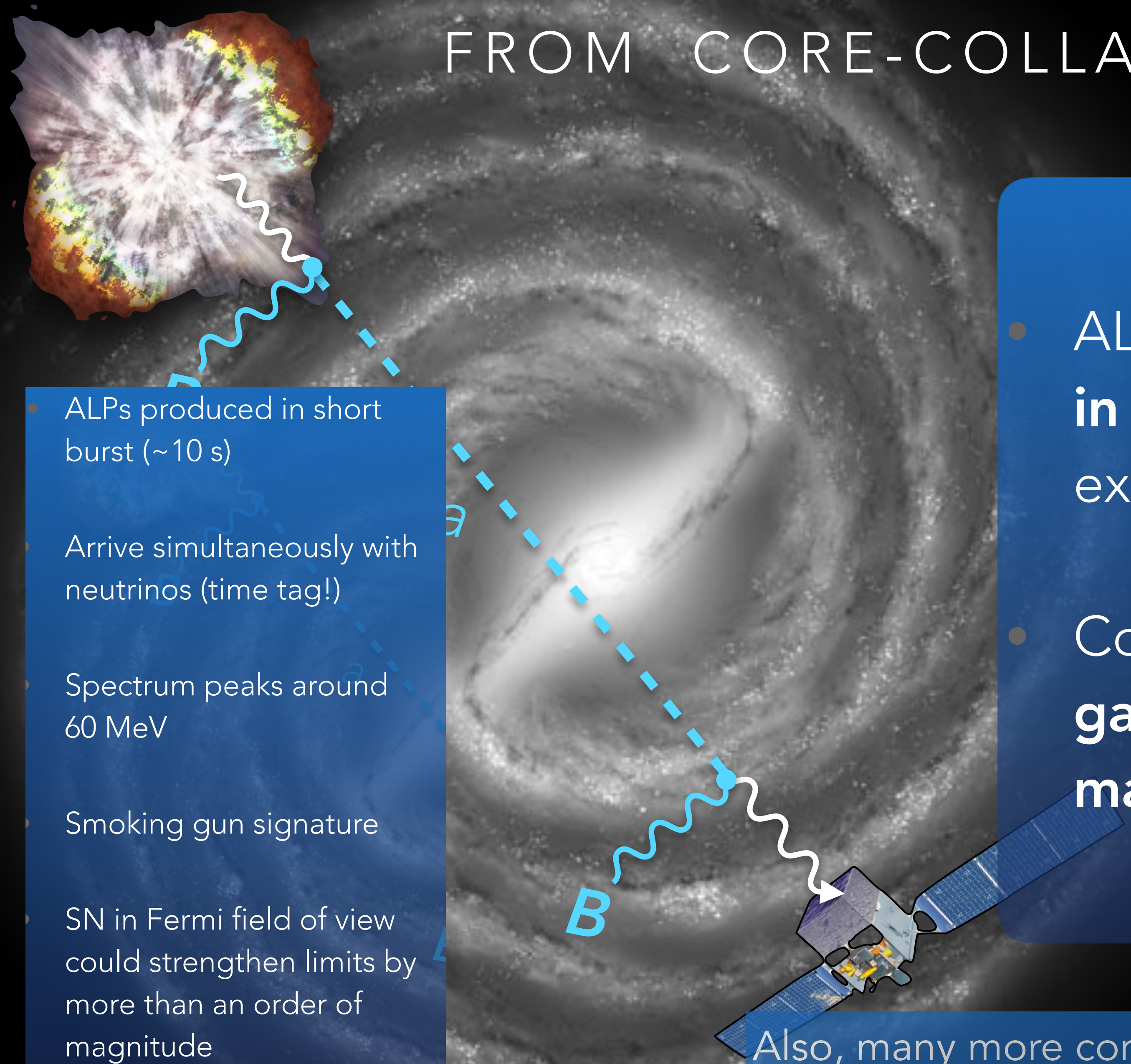

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- ALPs would be **produced in a core-collapse SN** explosion
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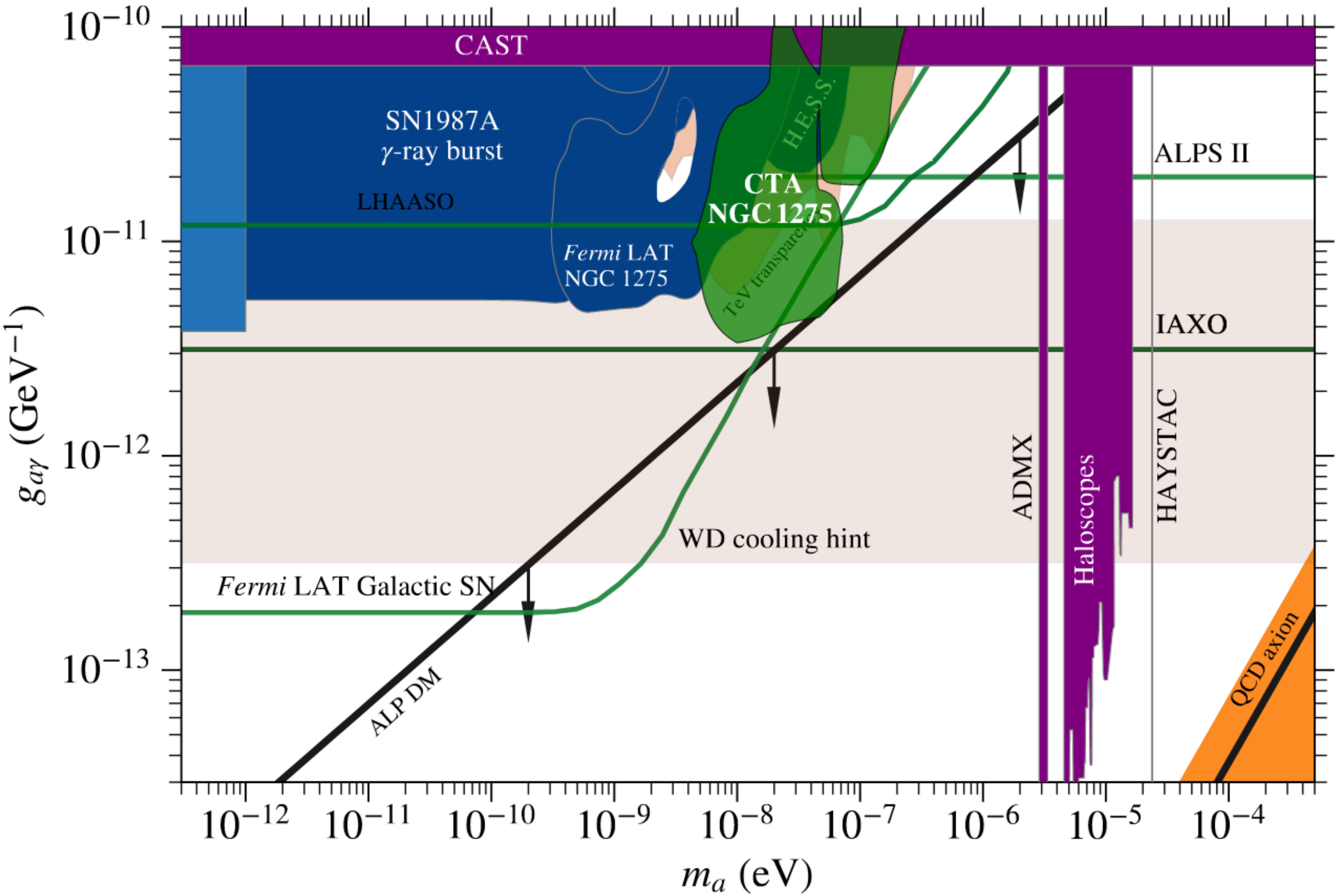
Also, many more core collapse SNe will be discovered in close-by galaxies with on-going surveys and the Rubin observatory! [Meyer+, PRL, 2020]



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PBHs

Black holes are called primordial when they are **formed by density perturbations** during the early stage of the expansion of the Universe.

Their initial mass scales with the time *t* elapsed since their creation after the Big Bang.

$$M(t) \approx 10^{15}\ \mathrm{g} \times (t/10^{-23}\ \mathrm{s})$$

Due to the **Hawking–Bekenstein radiation** PBHs evaporate in a time

$$\tau \approx 400\ s \times (M/10^{10}\ \mathrm{g})^3$$

PBHs in the last stages of their lifetime at the current epoch were created at a time close to the Big Bang, with an initial mass of order **10^{15}g**.

PBHs

Gamma-ray emission from PBHs could contribute to the extragalactic gamma-ray diffuse background via the cumulative emission over cosmic ages, with a photon spectrum peaking at 100 MeV at present days (constraints by EGRET and Fermi LAT)

In addition to this observable, the theory predicts an explosive final stage for each black hole with a flash of very-high-energy gamma rays, reaching TeV energies (HESS).

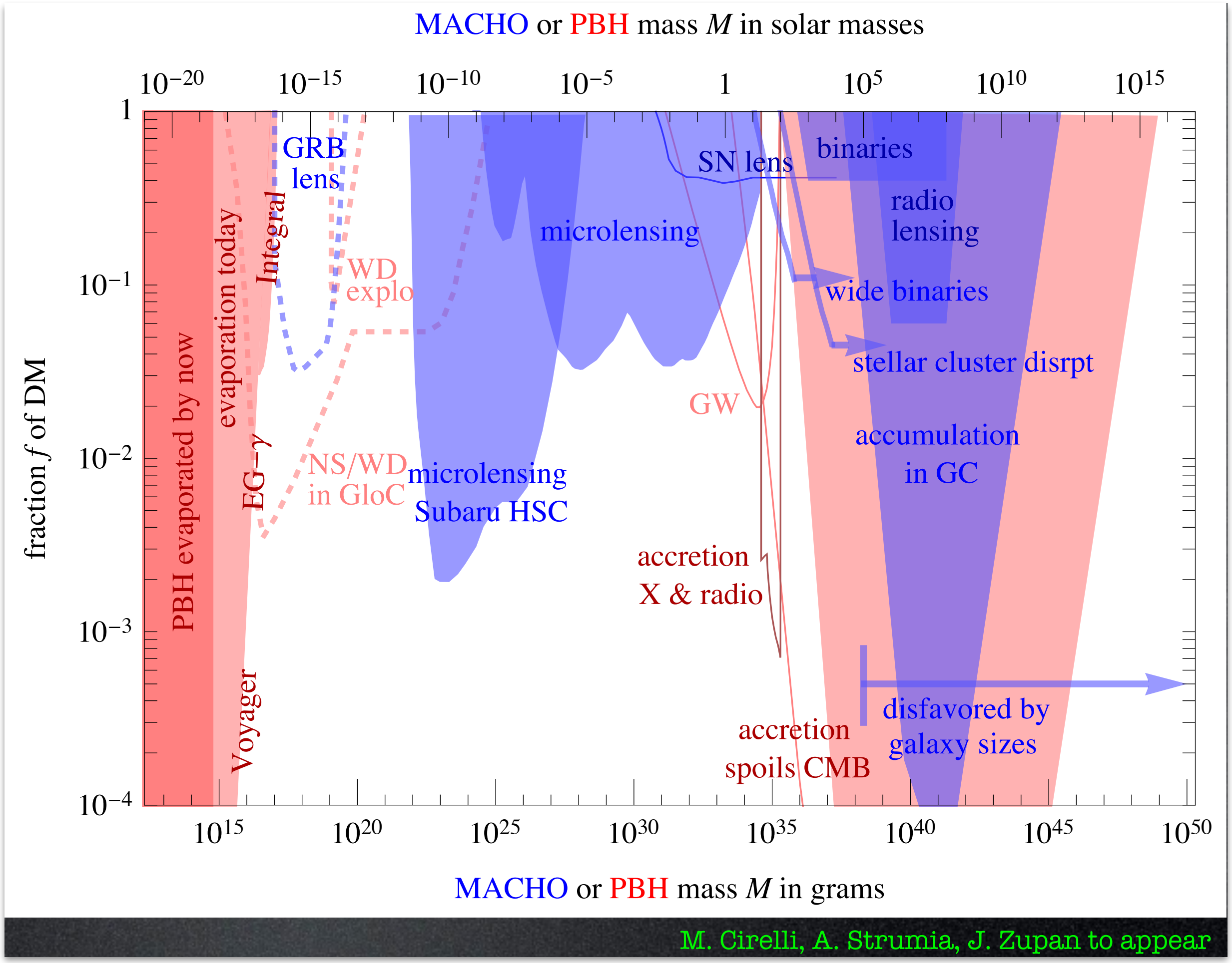
$$T = \frac{1}{8\pi G_N M}$$

rate

$$\frac{dM}{dt} \simeq -5 \times 10^{25} f(M) \left(\frac{\mathrm{g}}{M}\right)^2 \mathrm{g/s}$$

spectrum

$$\frac{dN}{dt\,dE} = \frac{27}{2\pi} \frac{G^2 M^2 E^2}{e^{E/T} + 1}$$



Summary

Life is hard

But field is mature and growing + astrophysics is exciting :)

— a range of well thought strategies that can be applied to variety of systems

Future:

- Advances from astro theory (Pulsar halos? Galactic PeVatrons?)
- New analysis techniques (Christoph's talk!)
- New Experiments (CTA + MeV gap + Vera Rubin Observatory +…)

Summary

Life is hard

But field is mature and growing + astrophysics is exciting :)

— a range of well thought strategies that can be applied to variety of systems

“The hardest thing of all is to find a black cat in a dark room, especially if there is no cat.”

— **Confucius**