Dark Matter Update

Graciela Gelmini - UCLA

U.S. DEPARTMENT OF ENERGY | Office of Science DE-SC0009937

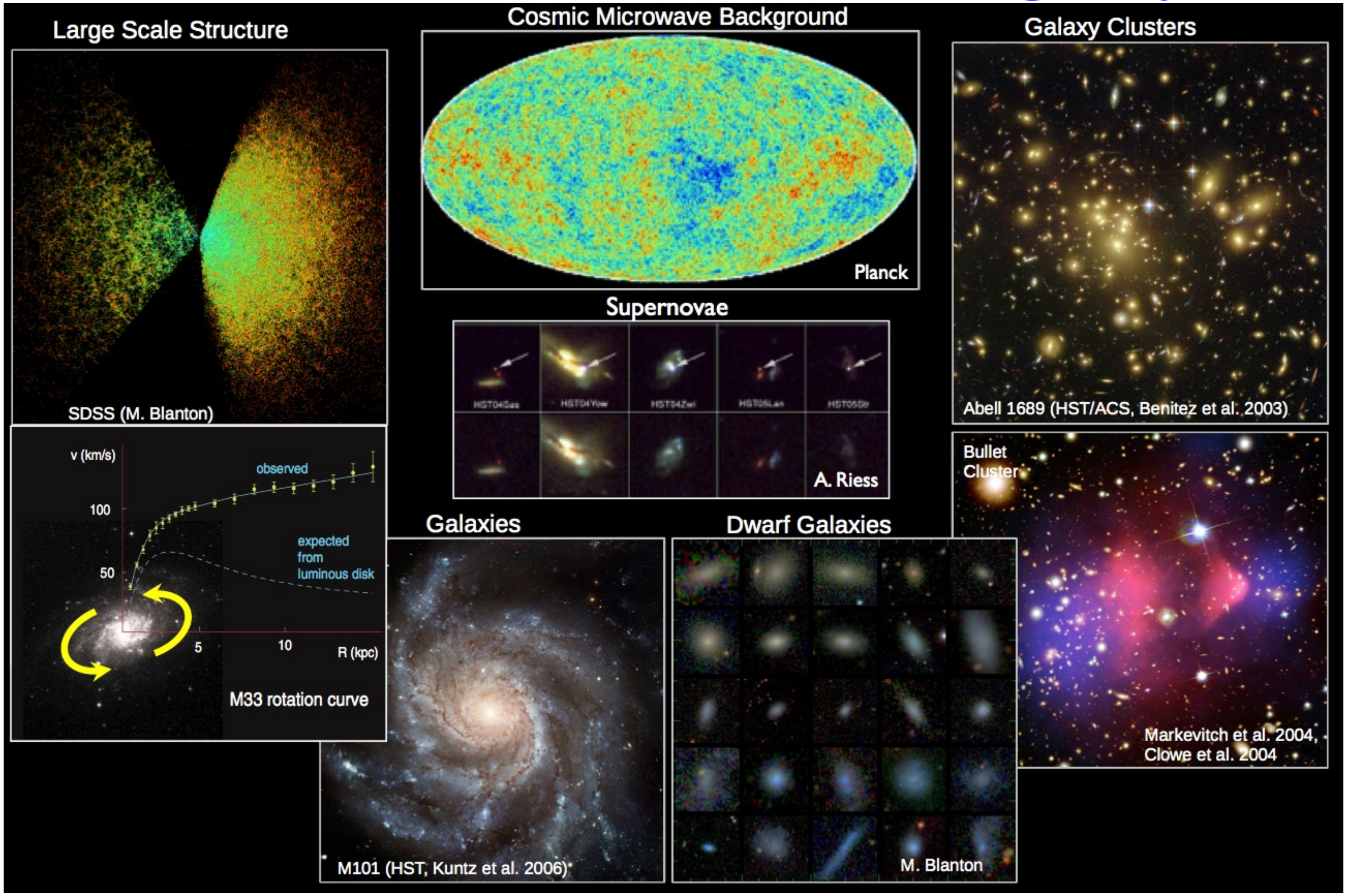
Christmas Workshop, IFT, Madrid, Dec. 11-13, 2019

Content:

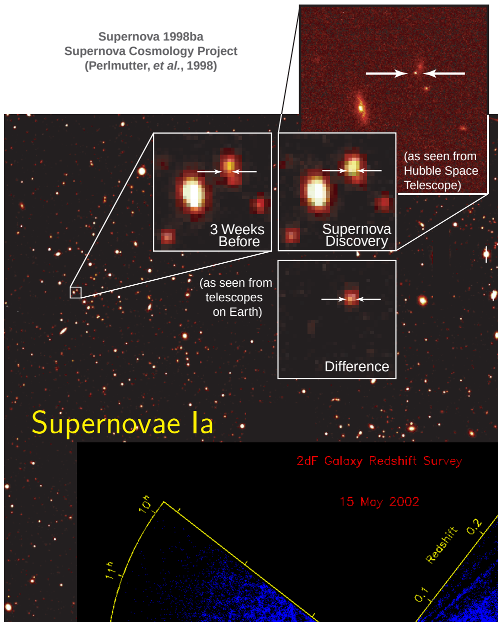
- **Dark Matter: What are we looking for?**
- **WIMPs dead or alive?**
- **Direct DM detection efforts:** well stablished and the new ideas
- **Indirect DM detection:** positron excess? the GC GeV excess?
- **Short comments on accelerator DM searches**

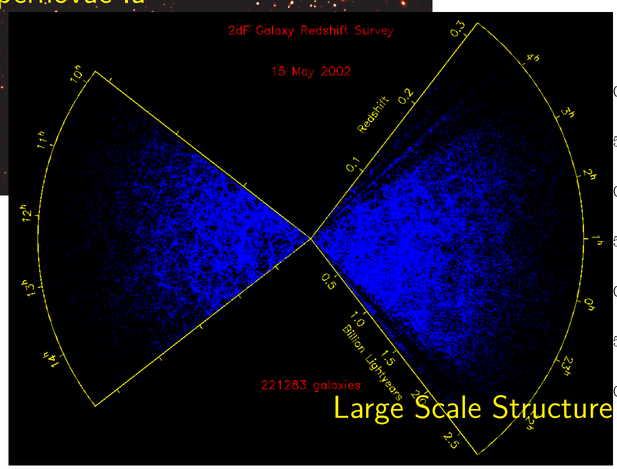
(Disclaimer: idiosyncratic choice of subjects-not complete lists of citations.)

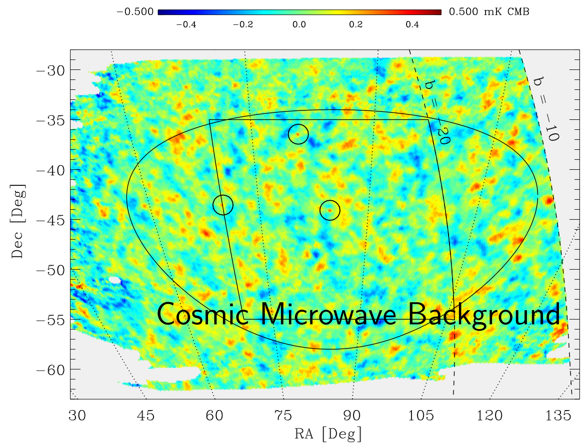
DM dominates all structures from dwarf galaxy scales on

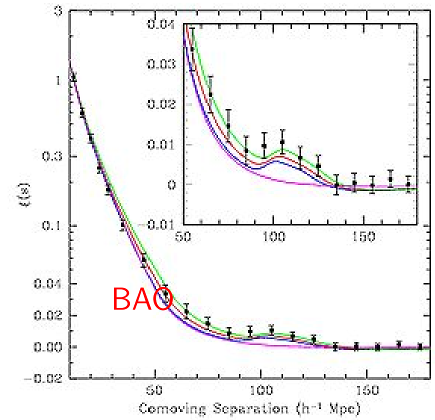


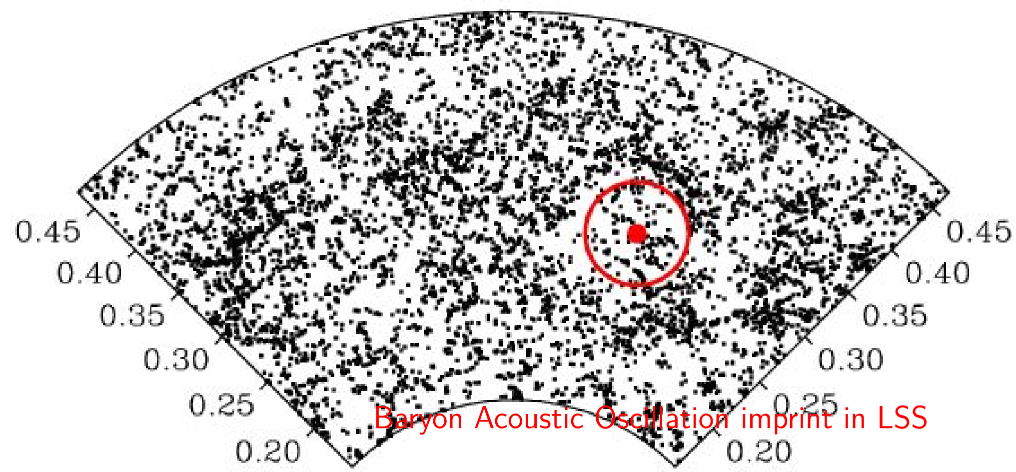
At the largest scales



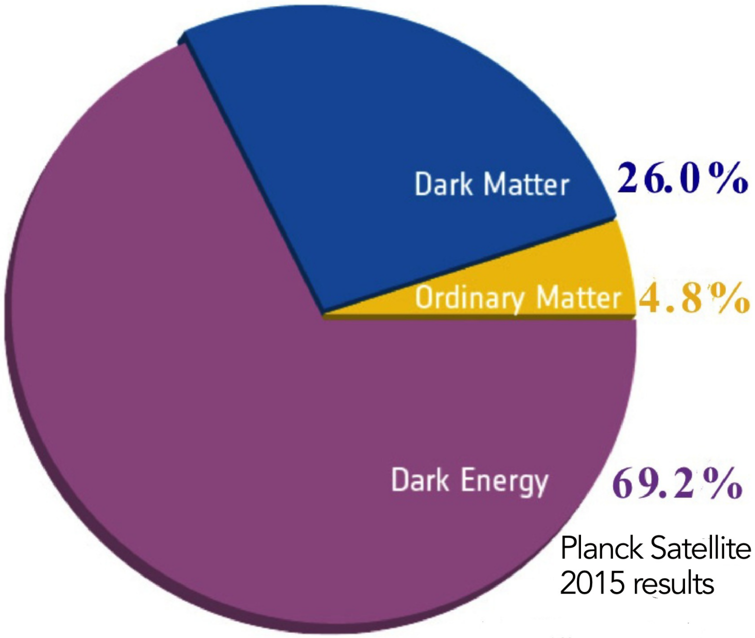


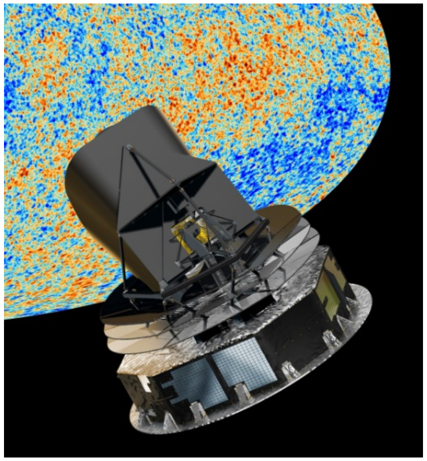






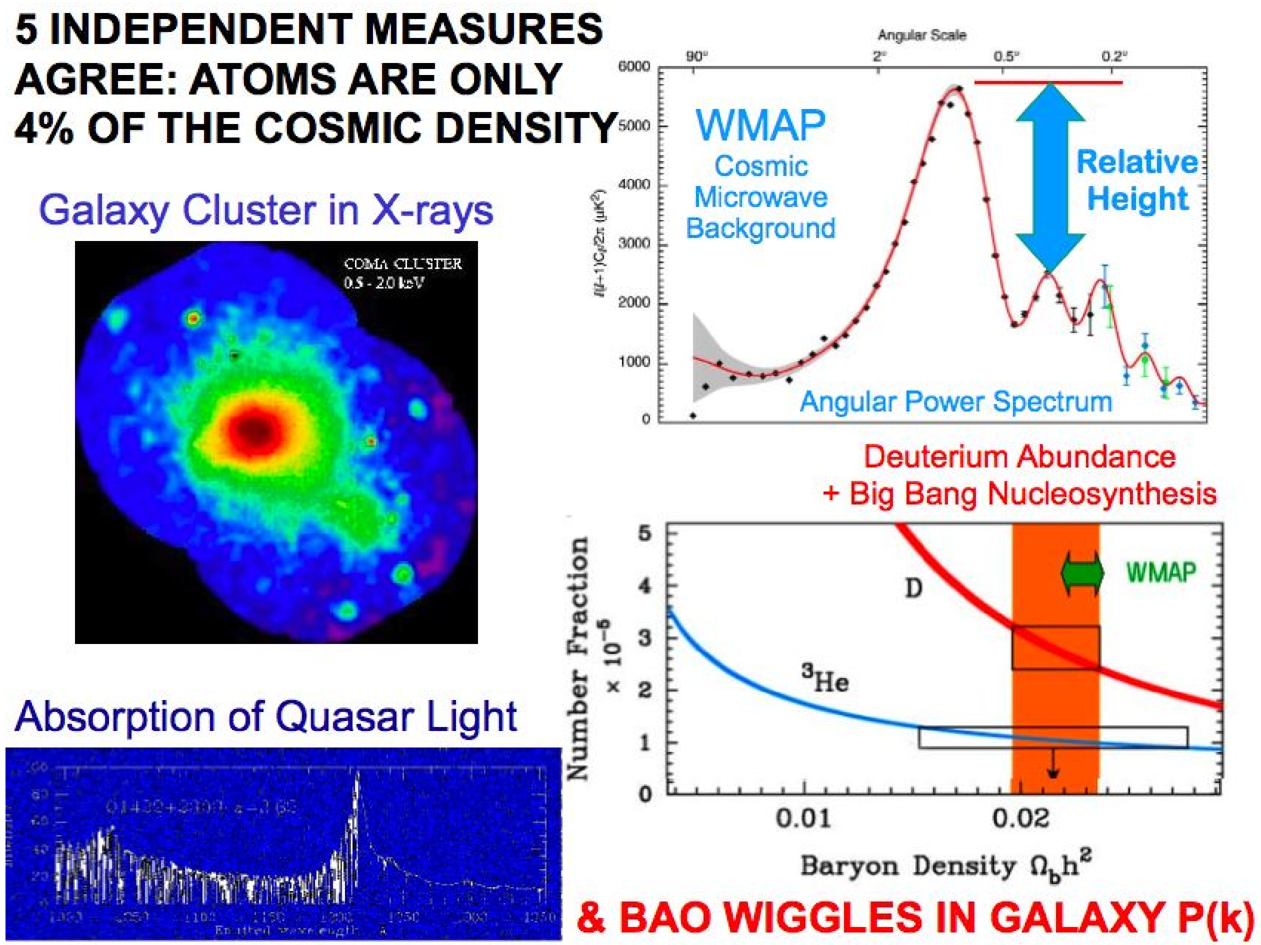
At the largest scales: the “Double-Dark” model





“DARK ENERGY” 69% (with repulsive gravitational interactions)
“MATTER” 31% (with usual attractive gravitational interactions- forms gravitationally bound objects) and most of it is **“DARK MATTER” 26%**

Our type of matter is only $< 5\%$.... Fig: from J. Primack 2010



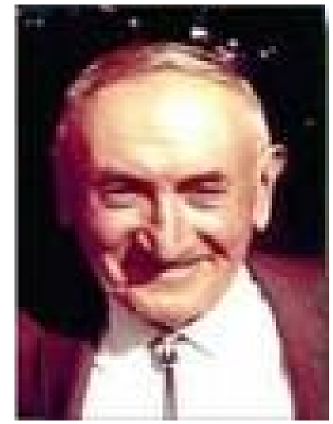
The Dark Matter problem has been with us since 1930's,

Fritz Zwicky, Helvetica Physica Acta Vol6 p.110-127, 1933

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)



Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

On page 122

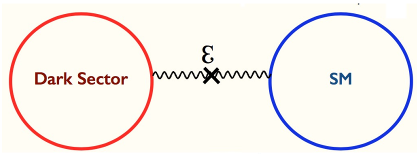
gr/cm³. Es ist natürlich möglich, dass leuchtende plus **dunkle (kalte) Materie** zusammengenommen eine bedeutend höhere Dichte ergeben, und der Wert $\bar{\varrho} \sim 10^{-28}$ gr/cm³ erscheint daher nicht

After 80 years, what do we know about DM?:

- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- DM is non-baryonic and is not observed to interact with light**

i.e. it is either neutral or with a very small electromagnetic coupling such as:

"Millicharged DM" Unbroken U$_{dark}(1)$ hidden gauge symmetry that would give rise to bound states "kinetic coupling" $\varepsilon F_{\mu\nu} F^{\mu\nu}_{dark}$



Diagonalized gauge boson kinetic terms: em photon $A_\mu (J^\mu_{em} + \varepsilon g J^\mu_{dark})$
(g is U$_{dark}(1)$ coupling). Holdom 1986 , Burrage et al 0909.0649
which can be part of "Atomic DM", with dark protons and dark electrons forming dark atoms or "Mirror DM" whose Lagrangian is a copy of that of the SM, but for the mirror particles,

or "electric or magnetic dipole DM", or"anapole DM"

What we know about DM:

- **1- Attractive gravitational interactions and lifetime $>> t_U$**
- **2- DM is non-baryonic and is not observed to interact with light**
- **3- So far DM and not modified dynamics + only visible matter**

After 2013, no proposed "alternative to Dark Matter" explained the CMB anisotropy spectrum and the BAO

From any theory that claims to "replace Dark Matter" we should ask for its prediction of the matter power spectrum and the CMB angular power spectrum
(stop discussing endlessly only about galaxy rotation curves!)

Eloquently expressed in Dan Hooper's talk "In Defense of Dark Matter" - KITP 4/30/2018- in debate with Eric Verlinde ("emergent gravity" is a theory without cosmology)

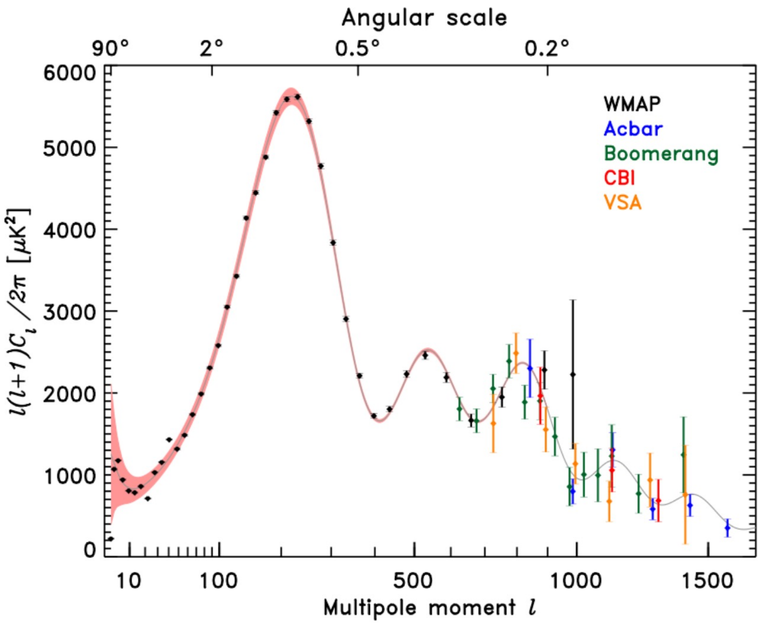
CMB Anisotropies Angular Power Spectrum

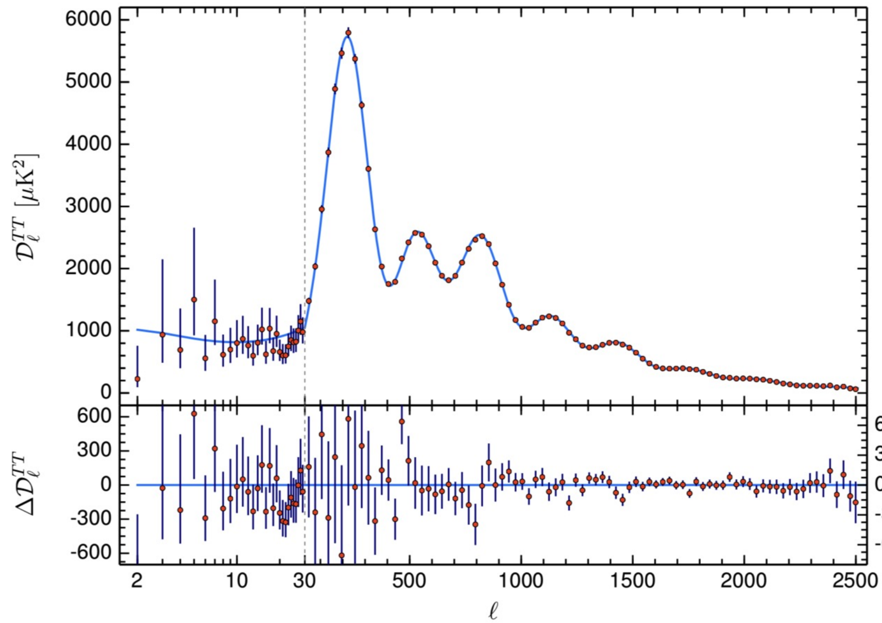
C_ℓ defines the T-T auto-correlation function ($P_\ell(\theta)$: Legendre Polynomial)

$$C(\theta) = \langle \frac{\delta T}{T}(\hat{n}_1)\frac{\delta T}{T}(\hat{n}_2)\rangle = \frac{1}{4\pi}\sum_\ell (2\ell+1)C_\ell P_\ell(\theta)$$

Before Planck: Only 3 peaks of the TT angular power spectrum observed

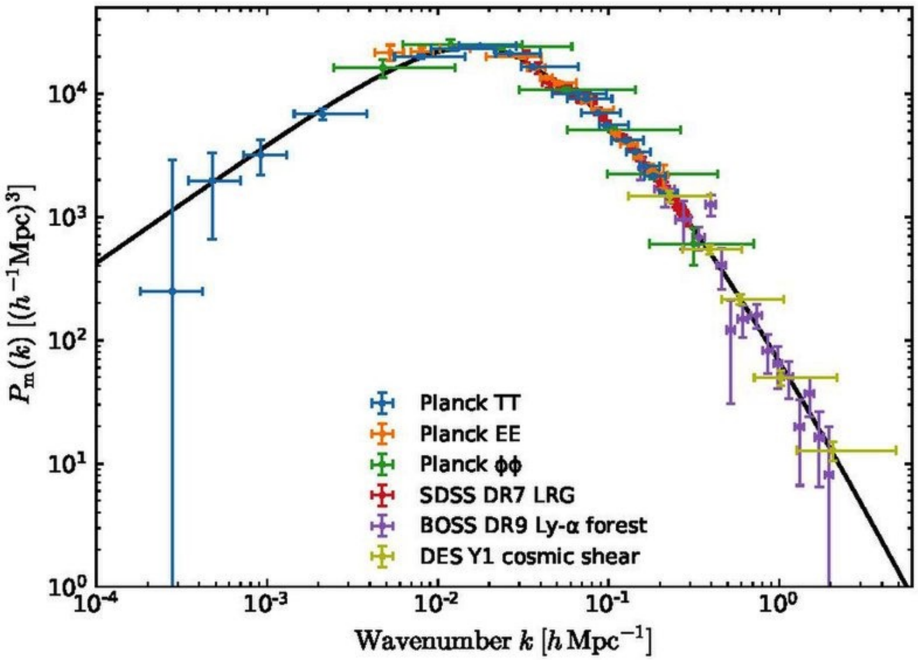
After Planck: 7 TT peaks, E-modes, precision parameter determination.





Matter Power Spectrum $P(k)$ (SDSS 2005, BOSS 2012)

$$\frac{\delta\rho}{\rho}(\vec{x}) = \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}\,, \qquad \langle \frac{\delta\rho}{\rho}(\vec{x_1})\, \frac{\delta\rho}{\rho}(\vec{x_2}) \rangle = \int \frac{d^3k}{(2\pi)^3} P(k)\; e^{i\vec{k}\cdot(\vec{x_1}-\vec{x_2})}$$



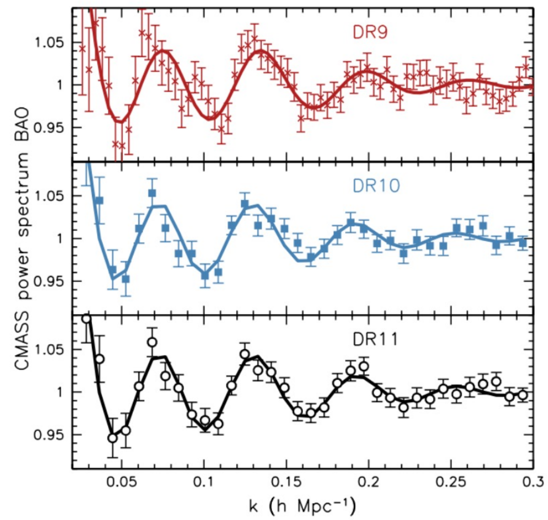
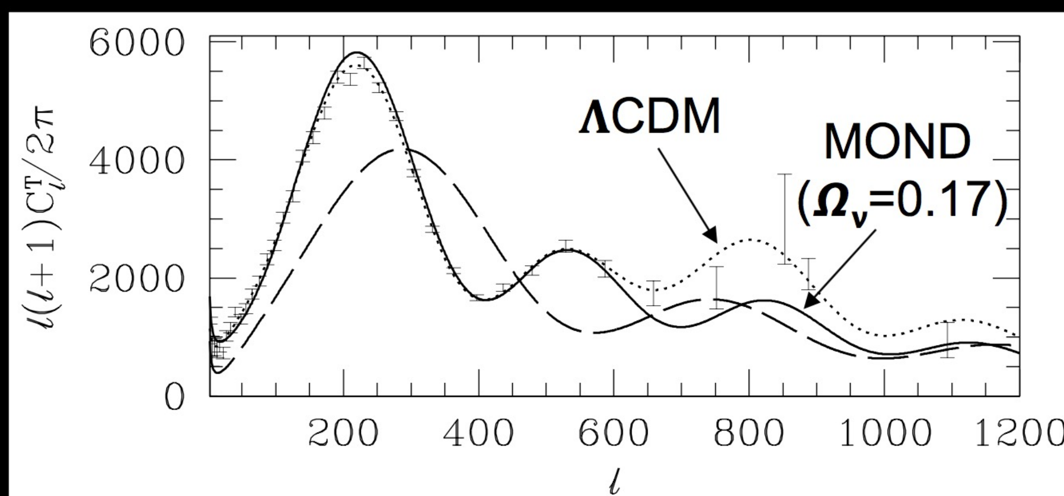


Figure 16. The CMASS BAO feature in the measured reconstructed power spectrum of each of the BOSS data releases, DR9, DR10, and DR11. The data are displayed with points and error-bars and the best-fit model is displayed with the curves. Both are divided by the best-fit smooth model. We note that a finer binning was used in the DR9 analysis.

Dan Hooper talk- KITP 4/30/2018 "In Defense of Dark Matter"-in debate with Eric Verlinde

What The CMB Really Tells Us About Dark Matter and Modified Gravity

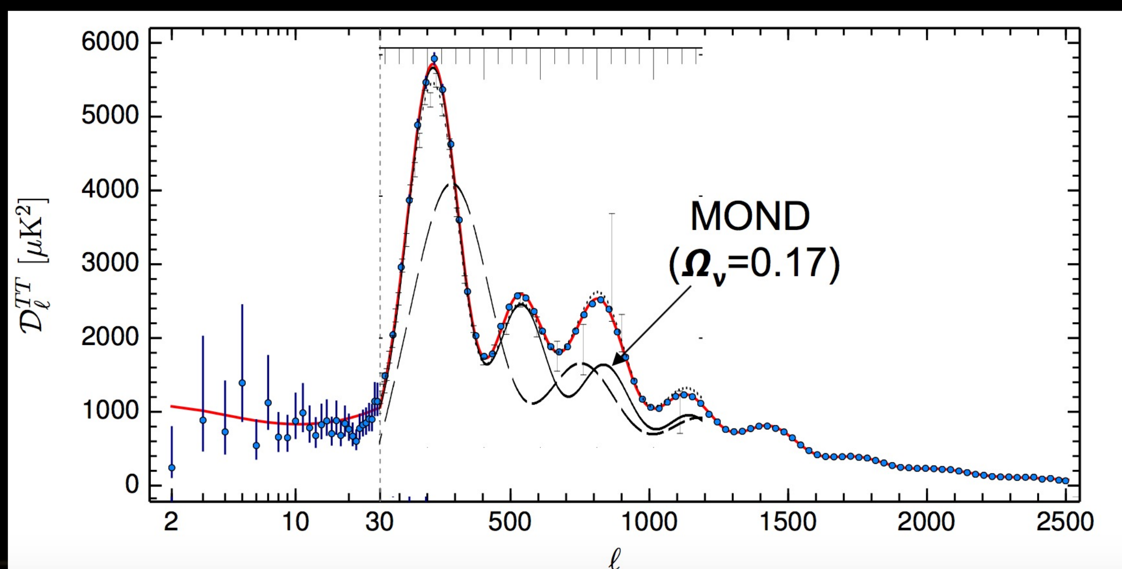
- Here is an example, (as calculated within TeVeS), Skordis et al. (2005)
- At the time, this was marginally consistent with the data (if one allows for ~2 eV neutrinos), but cannot accommodate modern CMB measurements



Dan Hooper talk- KITP 4/30/2018 "In Defense of Dark Matter"-in debate with Eric Verlinde

What The CMB Really Tells Us About Dark Matter and Modified Gravity

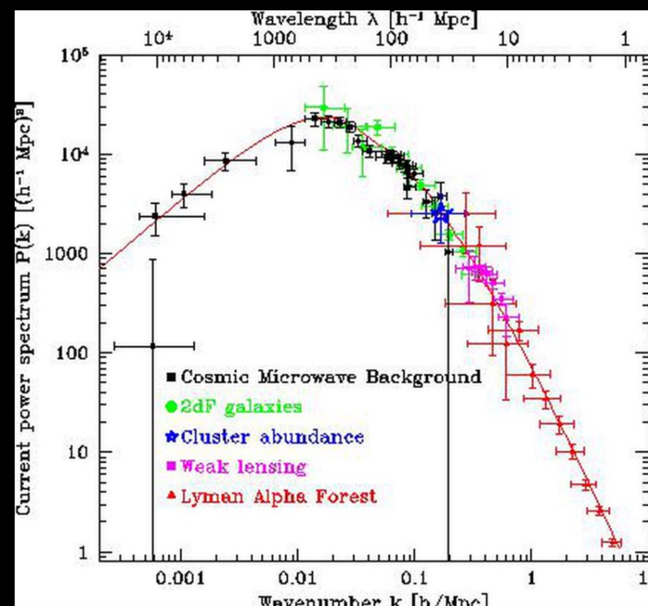
- Here is an example, (as calculated within TeVeS), Skordis et al. (2005)
- At the time, this was marginally consistent with the data (if one allows for ~2 eV neutrinos), but cannot accommodate modern CMB measurements



Dan Hooper talk- KITP 4/30/2018 “In Defense of Dark Matter”-in debate with Eric Verlinde

Matter Power Spectrum

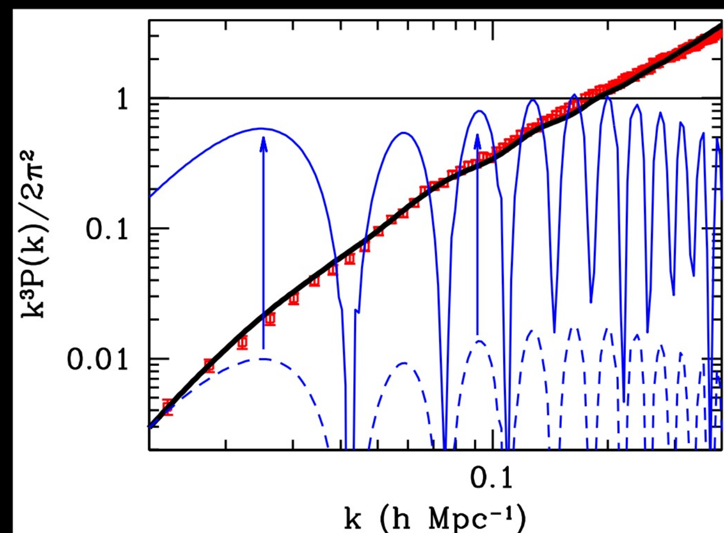
- If you look closely, you can see small wiggles in the matter power spectrum, resulting from baryon acoustic oscillations (BAO)
- These BAO are small in standard ΛCDM cosmology, because they are suppressed as baryons fall into the potential wells formed by dark matter – only a few percent of the primordial oscillations survive



Dan Hooper talk- KITP 4/30/2018 “In Defense of Dark Matter”-in debate with Eric Verlinde

Matter Power Spectrum

- If you look closely, you can see small wiggles in the matter power spectrum, resulting from baryon acoustic oscillations (BAO)
- These BAO are small in standard ΛCDM cosmology, because they are suppressed as baryons fall into the potential wells formed by dark matter – only a few percent of the primordial oscillations survive
- In a universe without dark matter, however, these oscillations should be *much* larger
- Even if structure growth is somehow enhanced through modifications of gravity, without dark matter, BAO should be ~30 times larger than observed



Dodelson (2011)

What we know about DM:

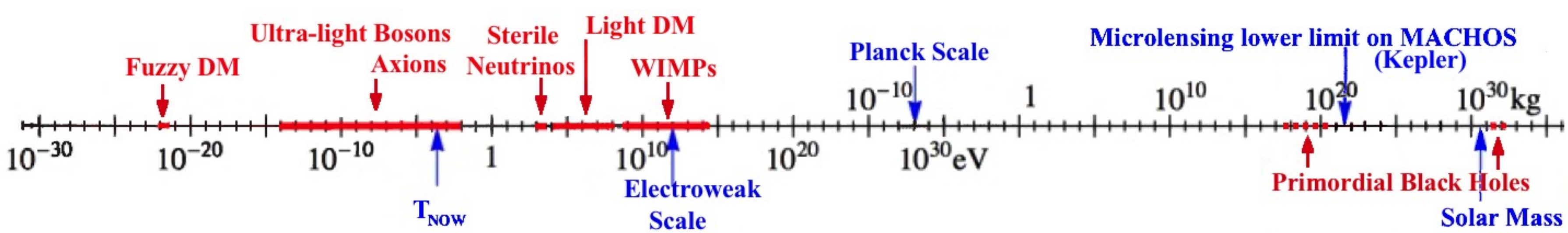
- **1- Attractive gravitational interactions and lifetime $>> t_U$**
- **2- DM is non-baryonic and is not observed to interact with light**
- **3- So far DM and not modified dynamics + only visible matter**
- **4- The bulk of the DM must be nearly dissipationless but ≤10% of it could be dissipative.**
- **5- DM has been mostly assumed to be collisionless, but huge self interaction upper limit $\sigma_{\rm self}/{\rm m} \leq$ 2 barn/GeV= 10^{-24} cm^2/GeV**
  (by comparison e.g. ^{235}U-neutron capture cross section is a few barns!)
  Self Interacting DM (SIDM) just below limit (WIMPs: σ_{DM-p} <10^{-46}cm^2/10GeV)

- **6- The mass of the major component of the DM has only been constrained within some 90 orders of magnitude.**

10^{-31}GeV$\leq$**M** $\leq 10^{-10} M_\odot = 10^{47}GeV= 2\ 10^{20}$kg (window $\simeq 10 M_\odot = 10^{58}$GeV??)

Lower limit:"Fuzzy DM", boson with de Broglie wavelength 1 kpc Hu, Barkana, Gruzinov, 2000

Upper limit on MACHOS (Massive Astrophysical Compact Halo ObjectS): Moniez 0901.0985, Yoo, Chaname, Gould, ApJ**601**, 311, 2004; Griest, Cieplak and Lehner 1307.5798, Niikura *et al.* 1701.02151



Problem with MACHOS: how would they form? Could be Primordial Black Holes

Dark Matter: could be Primordial Black Holes (PBH)?

PBH are a hypothetical type of black hole not formed by the gravitational collapse of a large star but in an early phase transition, before BBN (thus non-baryonic)
Zel'dovich and Novikov, 1966; Hawking, 1971; Carr and Hawking, 1974

Many limits exclusively applying to BH:
- $M > 10^{15}$g $= 6 \times 10^{38}$ GeV, lighter would have evaporated by now
- $M > 10^{17}$g or evaporating BH would have been observed (by EGRET and Fermi)
- 5 10^{17}g$< M < 10^{20}$g excluded by non-observation of "femtolensing" of GRB 1204.2056

Revised: wave effects (wavelength larger than Schwartzschild radius) and finite source size effects
- 10^{16}g$< M < 10^{22}$g excluded- its accretion in stars would destroy compact remanent 1209.6021
- 3 10^{18}g$<M<$ 5 10^{24}g excluded- its accretion in n stars in GC would destroy them (NS limit) 1301.4984 Revised: required a too high density in GC1807.11495
- $M >$ 100 $M_\odot$= 2 10^{35}g excluded by absence of CMB spectral distortions 0709.0524

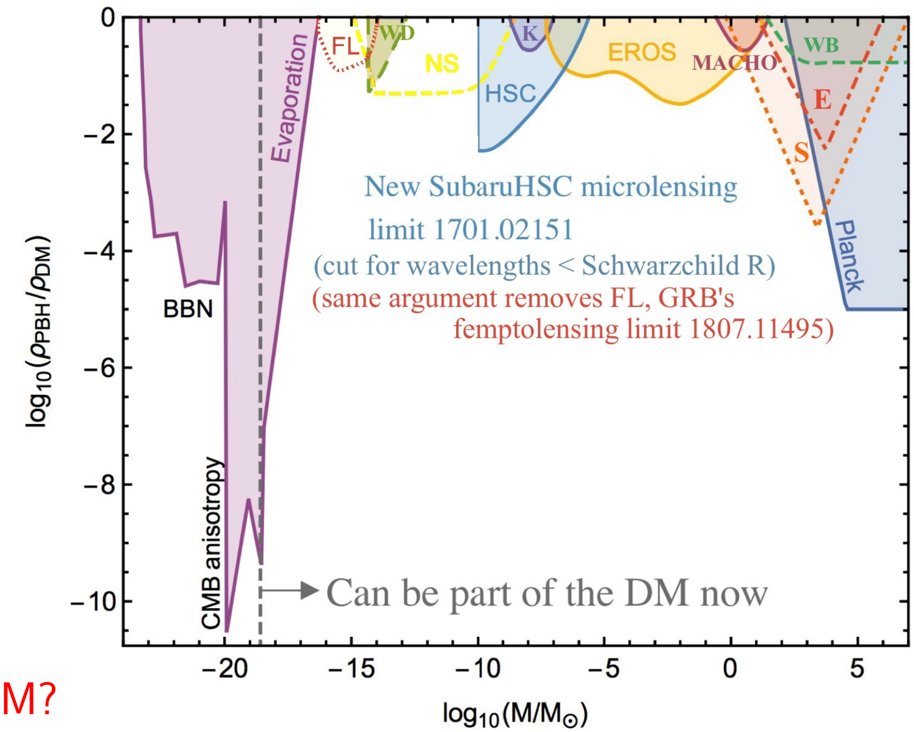
Many limits revised after LIGO's BH-BH mergers events! Bird etal. 1603.00464, Clesse&Garcia-Bellido 1501.07565, 1603.05234

Could Dark Matter be Primordial Black Holes (PBH)?

compilation of bounds on PBH DM density fraction f for single mass PHB (dashed limits can be avoided with special assumptions)

Carr, Tenkanen and Vaskonen 1706.03746 + modified

($M_\odot = 10^{57}$GeV)

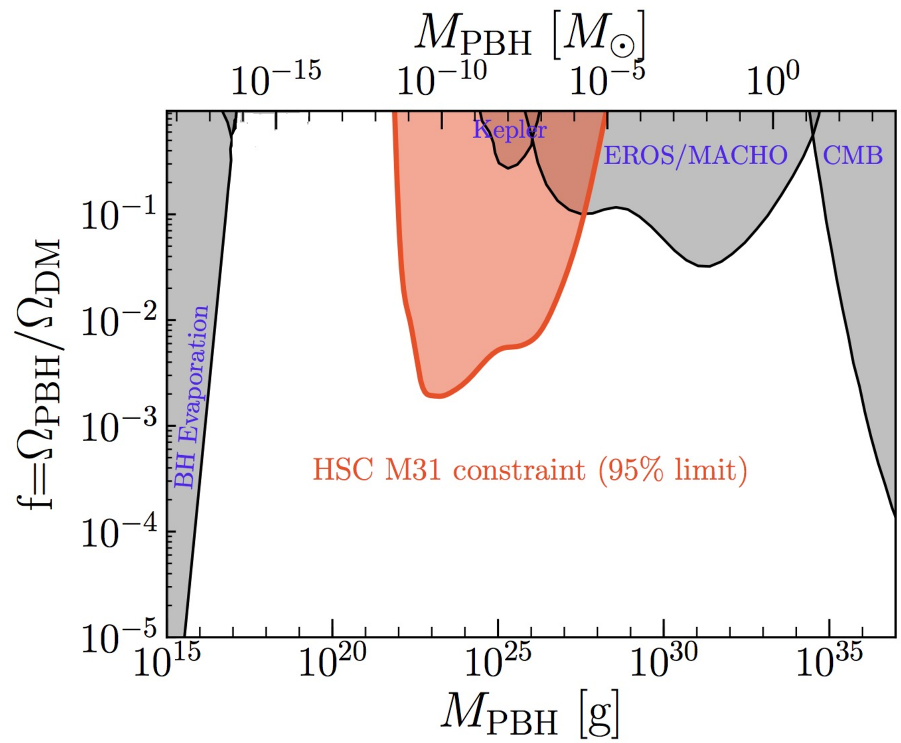


Could LIGO BH ∼10's $M_\odot$ be most of the DM?

Bird etal. 1603.00464, Clesse&Garcia-Bellido 1603.05234, 1501.07565; and before the LIGO events Frampton 0905.3632, Frampton, Kawasaki, Takahashi &Yanagida 1001.2308

Could Dark Matter be Primordial Black Holes (PBH)?

compilation of bounds on PBH DM density fraction f for single mass ($M_\odot = 10^{57}$GeV)



New Subaru/HSC camera limit Niikura et al. Nat. Astron. **3**, no. 6, 524, 2019 (1701.02151)
They also have a candidate PBH event consistent of a PBH of mass 10^{-7} $M_\odot$.

What we know about DM:

- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- DM is non-baryonic and is not observed to interact with light**
- **3- So far DM and not modified dynamics + only visible matter**
- **4- The bulk of the DM must be nearly dissipationless**
- **5- DM has been mostly assumed to be collisionless, but huge self interaction upper limit** $\sigma_{\rm self}/{\rm m} \leq$ **barn/GeV**
- **6- Mass within 90 orders of magnitude.**
- **7- The bulk of the DM is "Cold" or "Warm"**(Non-relativistic or almost when dwarf galaxy core size structures start to form, $T \sim$ keV)
  "Double-Dark" model works well with CDM or WDM above galactic scales, distinction at sub-galactic scales.

"Double-Dark" model works well with CDM or WDM above galactic scales, distinction at sub-galactic scales

Fig: from Tegmark ("Standard model" with ΛCDM: with Cold DM)

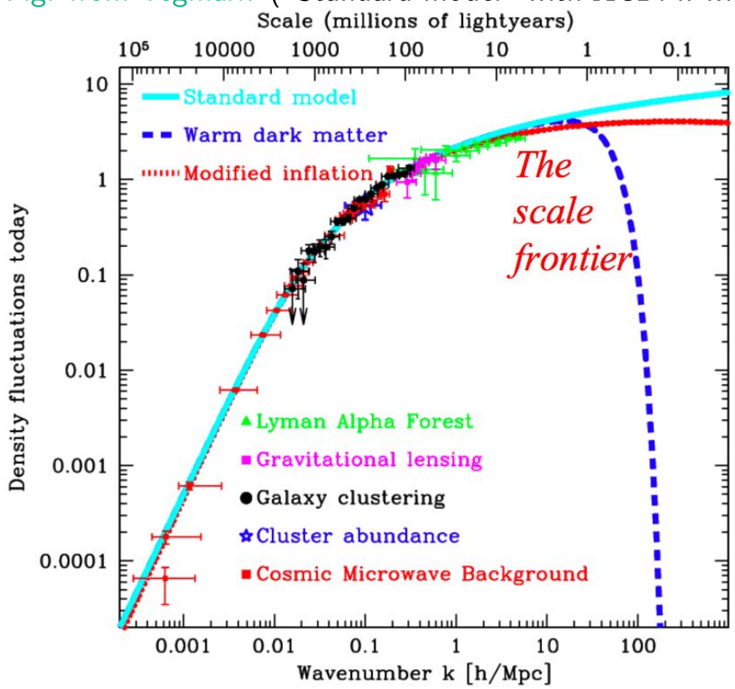
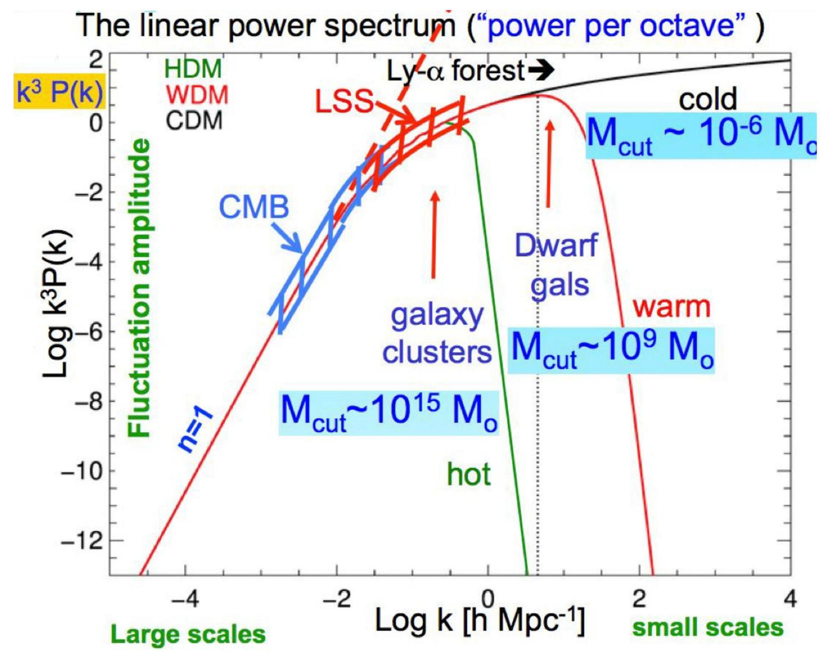
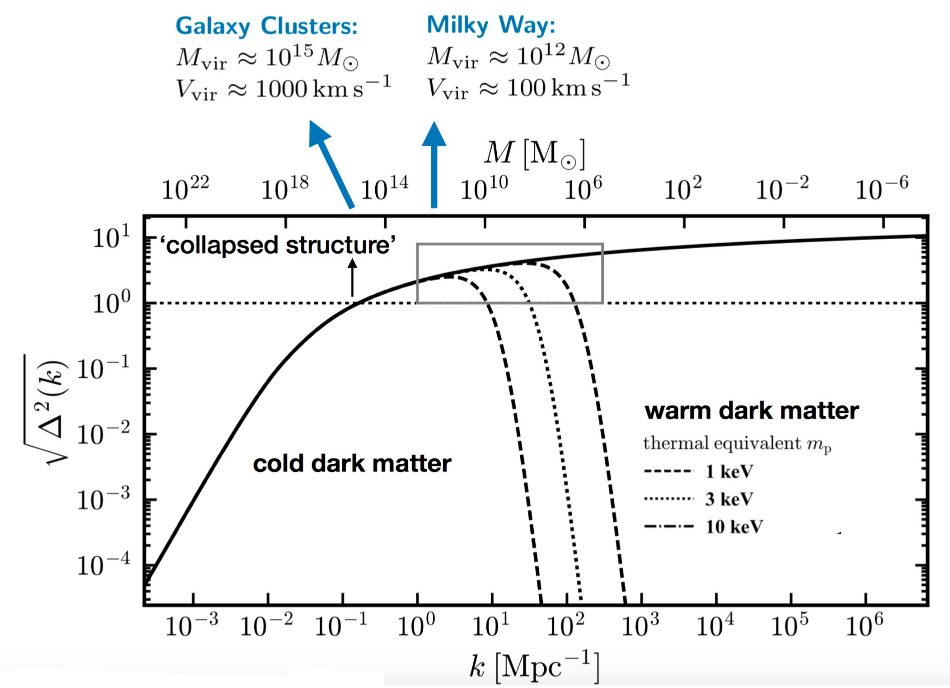


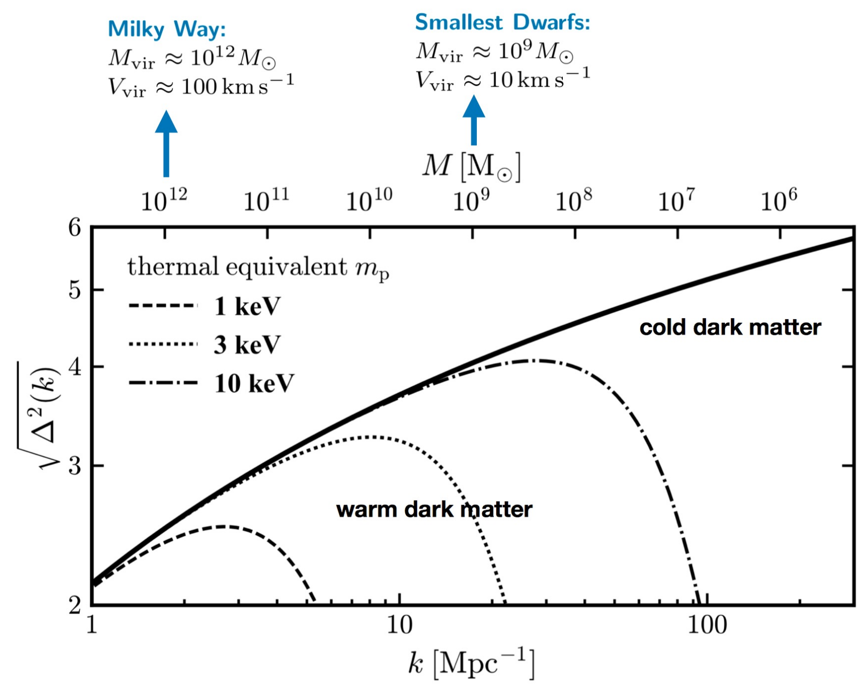
Fig: from Carlos Frenk



Distinguishing CDM-WDM-SIDM-mixed DM and baryonic effects at sub-galactic scales is where most of the structure formation simulations and observational efforts are directed at present.

"Double-Dark" model works well with CDM or WDM above galactic scales, distinction at sub-galactic scales Figs: from James Bullock, Boylan-Kolchin, ARAA, 2017





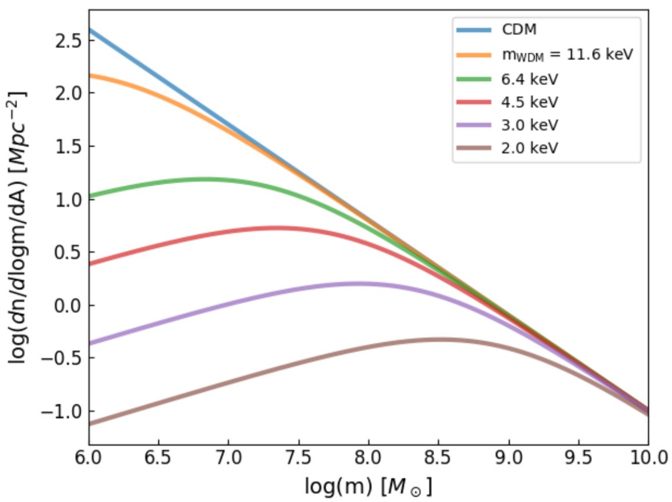
If it has a thermal spectrum, $\bar{E} \simeq 3T$, WDM requires $m \simeq$ keV

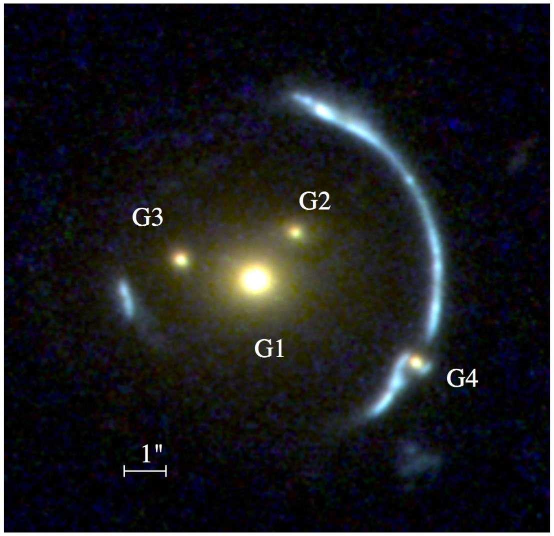
Distinguish CDM-WDM with strong gravitational lensing

Two ways to measure the abundance of 10^6 to 10^9 M$_\odot$ subhaloes (Review by Zavala, Frenk 1907.11775)

- 1) Use flux-ratio anomalies seen in some multiply-lensed quasars. From 7 of them, got an upper limit on the mass fraction in 10^6- 10^9 M$_\odot$ compatible with CDM, so m$_{WDM}$ >3.8 keV (95%CL) (Hush et al 1905.04182)- 11 were studied to get limits on mass-concentration (Gilman et al 1909.02573)

- 2) Small distortions of Einstein rings and large arcs. So far observed M> 10^8 M$_\odot$, but could reach 10^7 M$_\odot$ (Vegetti et al 1002.4708, Vegetti et al 1405.3666, Despali et al 1907.06649)





RIGHT: G4 is a10^{10} M$_\odot$ satellite galaxy of the lensing galaxy G1 (Vegetti et al 1002.4708)

What we know about DM:

- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- DM is non-baryonic and is not observed to interact with light**
- **3- So far DM and not modified dynamics + only visible matter**
- **4- The bulk of the DM must be nearly dissipationless**
- **5- DM has been mostly assumed to be collisionless, but huge self interaction upper limit** $\sigma_{\rm self}/\mathbf{m} \leq$ **barn/GeV**
- **6- Mass within 90 orders of magnitude.**
- **7- The bulk of the DM is Cold or Warm** (NR or quasi when $T \sim$ keV)
- **8- Particle DM requires Beyond Standard Model physics**

  In the SM, only neutrinos are part of the DM, but Hot DM

  Particle DM candidates must have the right relic density.
  Caveat: the computation of the relic abundance and velocity distribution of particle DM candidates produced before $T \simeq 5$ MeV depend on assumptions made regarding the thermal history of the Universe.

Particle DM requires BSM physics, but which?
The scope of DM particle models has changed with time:

- 1980's: DM candidates were an afterthought. Models proposed exclusively to solve problems in Standard Model such as SUSY, Technicolor, Peccei-Quinn symmetry, neutrino masses - which also contain DM candidates (WIMPs, axions, sterile neutrinos)

- 1990's: DM candidates were mandatory. Models required to have a DM candidate in SM extensions.

- Since 2000's: DM model independent of the SM. Models made to fit DM hints and/or predict novel DM signals and experiments to detect them, without regard for completion of the SM (but may have implications for colliders e.g. search for light mediators, displaced vertices...)

Leads to all types of DM interactions, to "dark sectors" seen through "portals" i.e. very small couplings (with photons, with neutrinos, with the Higgs....)

Some members of the particle DM candidates zoo

- WIMPs "Weakly Interacting Massive Particles": have close to weak order interactions with the SM particles.

Models: Started with massive SM neutrinos in 1970's, then in 1980's to lightest particle carrying a conserved charge in most BSM UV complete models (SUSY, composite models,"Little Higgs" models, Inert Doublet models...): LSP (Lightest Supersymmetric Partner- R parity), Lightest Technibaryon, LKP (Lightest KK Particle) or LZP (in Warped SO(10) with Z3), LTP (Lightest T-odd heavy γ in Little Higgs with T-parity), LIP (Lightest Inert Particle)... in dark sectors too

Production: reach thermal equilibrium via 2 DM$\rightarrow$2 SM interactions and freeze-out, or in the decay of another WIMP (SuperWIMP scenario)

Mass: GeV to 100 TeV

- FIMPs, "Feebly Interacting Massive Particles" (or "Frozen In Massive Particles"): have interactions of order much weaker than weak, very small couplings Hall, Jedamzik, March-Russell & West, 0911.1120...; see e.g. Bernal, Heikinheimo, Tenkanen, Tuominen &Vaskonen 1706.07442, ...

Models: moduli/modulinos of string theory compactifications with mass generated by the weak-scale SUSY breaking, right-handed sneutrino in Dirac neutrino models within weak scale SUSY (which requiere a coupling $\sim 10^{-13}$), GUT-scale-suppressed interactions, DM with small kinetic mixing coupling to the SM, DM though a Higgs portal...

Production: never reach thermal equilibrium, freeze-in as DM or freeze-in and decay to the DM

Mass: sub eV to 100's TeV

- SIMPs, "Strongly Interacting Massive Particles": Old 1990's SIMPs had strong interactions with the SM particles! Did not survive.

Revived in 2014 as strongly SELF interacting but very weakly coupled to the SM Hochberg, Kuflik, Volansky & Wacker, 1402.5143; Kuflik *et al* 1411.3727; Choi & Lee 1505.00960; Lee&Seo 1504.00745; Bernal&Chu 1510.08527; Bernal, Garcia-Celt& Rosenfeld 1510.08063; Hochberg, Kuflik &Murayama 1512.07917.... Ho, Toma &Tsumura,1705.00592

Models: could be e.g. a pseudo-Nambu-Goldstone bosons of a strongly coupled confining hidden sector, with kinetic mixing with the SM (photon or Z' or Higgs portal)

Production: reach thermal equilibrium and freeze-out in the dark sector due to 3→2 or 4→2 DM to DM interactions- assumes kinetic equilibrium of dark and visible sectors so they have the same temperature

Mass: 100 keV - 10's MeV (they are "Light DM" LDM)

- PIMPs, "Planckian Interacting Massive Particles":
assume new physics comes only at the Planck scale M_P Garny, Sandora & Sloth 1511.03278

Models: effective couplings of DM in a hidden sector connected only with gravitational order interactions to the SM.

Production: soon after a very high T reheating inflationary period-many variations

Mass: most typical close to M_P

(Similar to GIMPs, "Gravitationally Interacting Massive Particles" in a particular Kaluza-Klein model Holthausen & Takahashi 0912.2262)

- Axions and ALPs, "Axion-Like Particles":

The axion is the pseudo-Goldstone boson of a spontaneously broken axial U(1) global symmetry introduced by Peccei and Quinn in 1977, U(1)$_{PQ}$ to solve the strong CP problem of QCD (Weinberg and Wilczek in 1978 realized the PQ model predicted an axion).

The original axion was soon rejected experimentally. So the "invisible axion" models were proposed (Kim- 1979, Shifman, Vainshtein, Zakharov (SVZ)-1980 and Dine, Fischler, Srednicki-1980 and Zhitnisky-1981 (DFSZ)

ALPs are other hypothetical pseudo-GB (among which Majorons and familons...)

Production: as a boson condensate or radiated from axion topological strings

Axion DM mass: 10^{-4} to 10^{-10} eV (for ALPs is very model dependent but light)

- WISPs, "Weakly Interacting Slim Particles (WISPs)": a combined name for axions/ALPs (spin zero) and dark (or hidden sector) photons (spin 1).

Still others:

“Dynamical DM (DDM)”, dark sector with a vast number of particle species whose SM decay widths are balanced against their cosmological abundances- shorter lived has smaller densities Dienes &Thomas 2011,

“Mirror DM”, from a hidden “dark” copy of the SM- could or not interact via kinetic mixing Blinnikov & Khlopov 1982, Kolb, Seckel &Turner 1985, Foot, Lew %Volkas 1991....

WIMPZILLAS, heavy particles created during reheating after inflation) Kolb, Chung & Riotto 1998,

Q-balls, non-topological solitons created as a fragmentation of a scalar condensate) Kusenko 1997, Kusenko &Shaposhnikov 1997,

Sterile neutrinos...(in simplest models produced via freeze-in of active-sterile flavor oscillations)

Strong diversified program of DM searches

Direct detection: attempts to detect energy/momentum deposited in collisions of DM particles within a detector with several target materials and strategies (mature background-free multitonne experiments with Xe and Ar, Ge/Si crystals, axion cavity searches, new ideas for lighter particles e.g. SENSEI, CASPER, ABRACADABRA...)

Indirect detection: attempts to detect annihilation or decay DM products in the dark halos of our galaxy and others with multi-messenger approach (with exceptions, due to astrophysical uncertainties may be a confirmation but not a discovery of DM)

Accelerator searches: attempt to produce DM particles or their mediatos at LHC, DUNE, fixed target...(if DM candidate discovered, will need to confirm is DM)

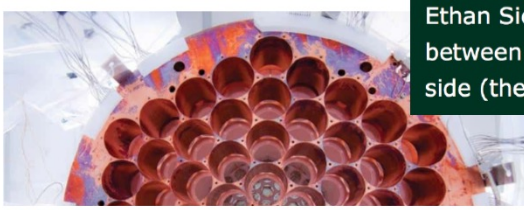
for WIMPs, sub GeV DM, axions/ALPs/ WISPs, sterile neutrinos,...
for all types of interactions, production models, mass ranges...
Very vibrant field, will continue to be so for many years to come

ARE WIMPS DEAD?

Dark matter no-show puts WIMPs in a bind

SPACE 30 October 2013

By Lisa Grossman



50,667 views | Feb 22, 2019, 02:00am

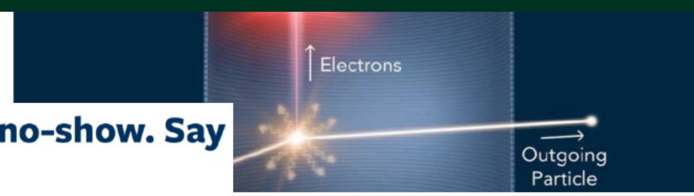
The 'WIMP Miracle' Hope For Dark Matter Is Dead

Ethan Siegel Contributor
Starts With A Bang Contributor Group
Science

saturday, february 23, 2019 ...

Rumors of the WIMP miracle's death have been greatly exaggerated

Ethan Siegel has shown us another example of the profound difference between careful scientists on one side and zealous activists on the other side (the side where he sadly belongs) when he wrote



MACHOs are dead. WIMPs are a no-show. Say hello to SIMPs.

By Robert Sanders, Media relations | DECEMBER 4, 2017

Tweet

The intensive, worldwide search for dark matter,
find an abundance of dark, massive stars or scad
new candidate is slowly gaining followers and ob

WIMPs on Death Row

Posted on July 21, 2016 by woit

One of the main arguments given for the idea of supersymmetric extensions of the standard model has been what SUSY enthusiasts call the "WIMP Miracle" (WIMP=Wea
Interacting Massive Particle). This is the claim that such SUSY models include a stable very massive weakly interacting particle that could provide an explanation for dark mat

The rumors of WIMPs death are greatly exaggerated!

What are WIMPs? When in doubt...consult Wikipidia

Weakly interacting massive particles

From Wikipedia, the free encyclopedia

"WIMPs" redirects here. For other uses, see WIMPS (disambiguation).

Weakly interacting massive particles (**WIMPs**) are hypothetical particles that are thought to constitute dark matter. There exists no clear definition of a WIMP, but broadly, a WIMP is a new elementary particle which interacts via gravity and any other force (or forces), potentially not part of the standard model itself, which is as weak as or weaker than the weak nuclear force, but also non-vanishing in its strength. A WIMP must also have been produced thermally in the early Universe, similarly to the particles of the standard model according to Big Bang cosmology, and

Agree with 1st two sentences- but WIMP not necessarily produced thermally...

What are WIMPs? WIMP name invented in 1985 by Steigman and Turner

June 1985 M. Turner's lectures:

WIMP	MASS	T_{WIMP}/T	λ_{FS}(Mpc)
Neutrino	light	$(4/11)^{1/3}$	40 Mpc/(m/30eV)
Axion	10^{-5}eV	$< 10^{-14}$	$< 10^{-5}$Mpc
Axino/RH Neutrino/Light Gravitino	keV	1/4	1 Mpc
Heavy Neutrino/ LSP	GeV	1	10^{-5}Mpc

The scale 1 Mpc corresponds to a galactic scale. The relationship of λ_{FS} to the galactic scale neatly divides the WIMPs into three categories: (i) Cold, $\lambda_{FS} << 1$ Mpc -- the characteristic damping scale is much smaller than a galactic scale, and galactic-sized perturbations survive freestreaming; (ii) Warm, $\lambda_{FS} \approx 1$ Mpc -- the characteristic damping scale corresponds to a galactic scale; (iii) Hot, $\lambda_{FS} >> 1$ Mpc -- only perturbations on scales much larger than a galactic scale survive freestreaming. Almost all of the WIMPs fall into the category of cold dark matter. Only the neutrino is a hot WIMP. At present there are a couple of warm dark matter candidates -- a 1 keV gravitino, 1 keV right-handed neutrino, or a 1 keV axino (supersymmetric partner of the axion).

What are WIMPs? WIMP changed meaning very fast

Ann. Rev. Nucl. Part. Sci. 1988. 38: 751–807

DETECTION OF COSMIC
DARK MATTER

Joel R. Primack and David Seckel

Santa Cruz Institute for Particle Physics, Ur
Santa Cruz, California 95064

Bernard Sadoulet

Physics Department, University of Californi

CONTENTS

1. INTRODUCTION ....
1.1 *How Much DM Is There?* ....
1.2 *Arguments That DM Is Nonbaryonic* ....
1.3 *Nonbaryonic DM Candidates* ....
2. WEAKLY INTERACTING MASSIVE PARTICLES....................
2.1 *Motivation for and Properties of WIMP Candidate*
2.2 *Interaction Rates of WIMPs with Ordinary Matte*
2.3 *Direct Detection by Nuclear Recoil* ....
2.4 *Indirect Detection by Annihilation* ....
2.5 *Present Constraints and Future Prospects* ....
3. AXIONIC DARK MATTER...
3.1 *Motivation* ....
3.2 *Cosmological and Astrophysical Constraints* ....
3.3 *Detection by Conversion to Photons in Laboratory*
3.4 *Theoretical Uncertainties* ....
4. LIGHT NEUTRINOS...

However WIMP not restricted to 1 to 100 GeV in mass

"Thermal WIMPs"

Standard calculations: start at $T > T_{f.o.} \simeq m_\chi/20$ and assume that

- WIMPs **reach equilibrium** while

Universe is radiation dominated

- **No particle asymmetry**
- Chemical decoupling (freeze-out) when $\Gamma_{ann} = \langle\sigma v\rangle\, n \leq H$,
- **No entropy change** in matter+radiation

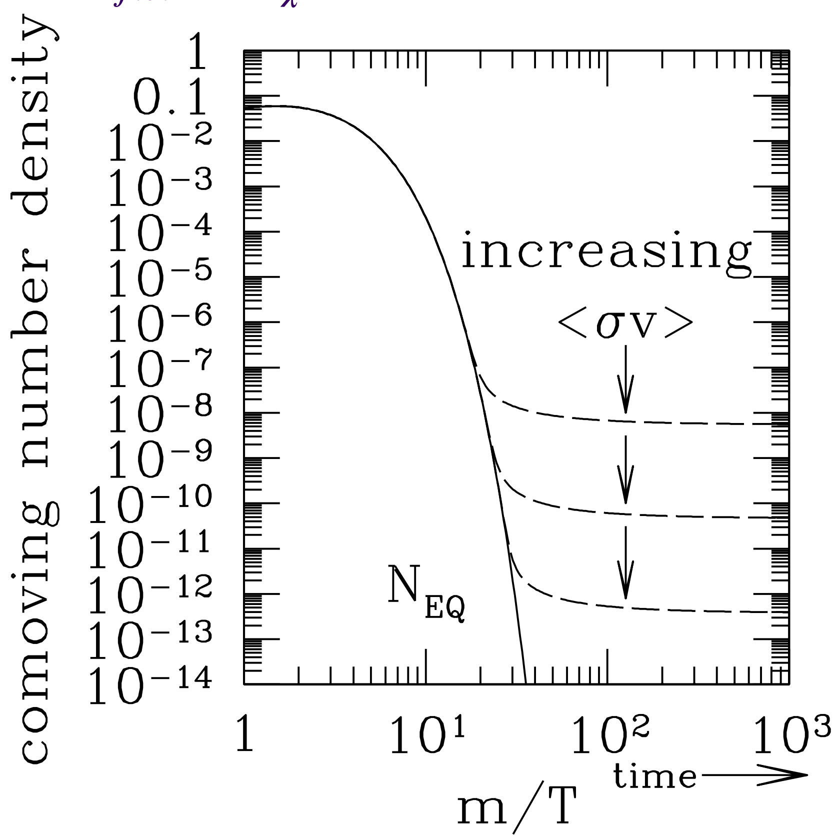
$$\Omega_{std} h^2 \approx 0.2\, \frac{3\times 10^{-26} cm^3/s}{\langle\sigma v\rangle}$$

Weak annihilation cross section

$\sigma_{annih} v \simeq G_F^2 m^2 \simeq 3\times 10^{-26} cm^3/s$

$m \simeq$ GeV is enough to get

$\Omega = \Omega_{DM} \simeq 0.2$! "WIMP Miracle"



Are WIMPs dead ?

- Are WIMPs coupled to the W/Z bosons dead? Mostly- not entirely e.g. "Minimal DM": need $T_3 - Q\ \theta_W = 0$, i.e. $T_3 = 0$ (i.e. $Y = Q - T_3 = 0$), possible for triplets, quintuplets... Cirelli, Fornengo, Strumia, hep-ph/0512090

- Are "WIMP miracle" WIMPs dead? NO, but constrained...
  Indirect detection: $m > 20$ GeV if annihilate in s-wave "GeV-Scale Thermal WIMPs: Not Even Slightly Dead", Leane, Slatyer, Beacom and Ng,1805.10305 No limits if annihilate in p-wave

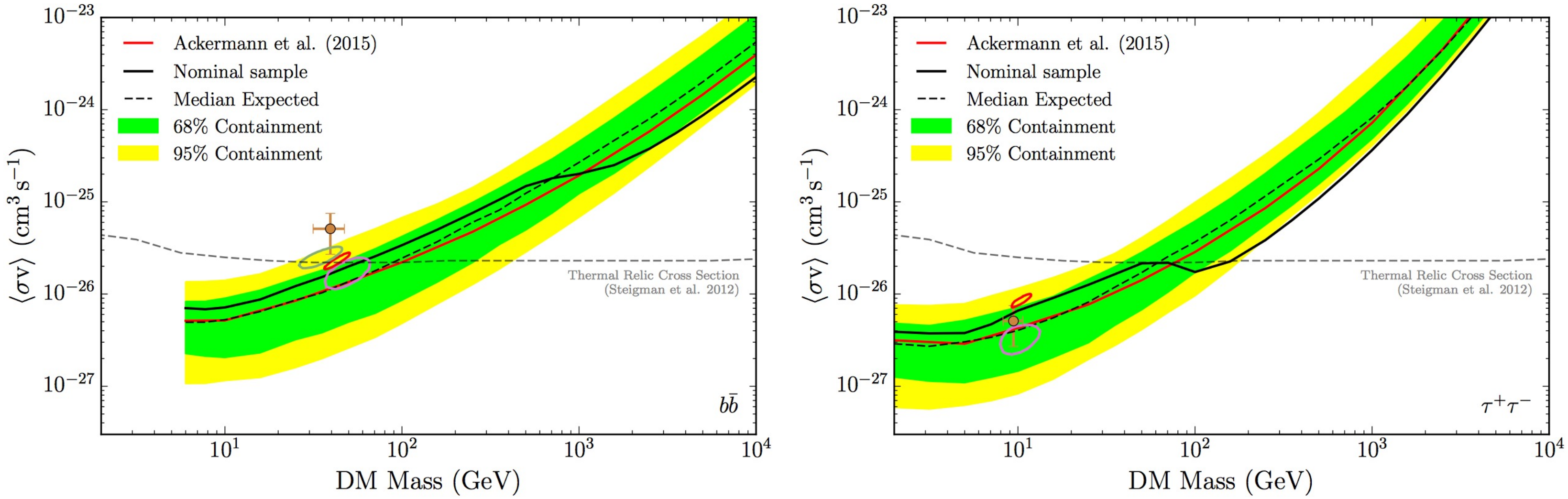
- Why consider only "WIMP miracle" WIMPs? NO REASON......

- Are SUSY WIMP models dead? NO, many rejected many not...

- Must WIMPs be produced thermally? NO, not necessarily...

Upper limit on "WIMP miracle" from Fermi ST

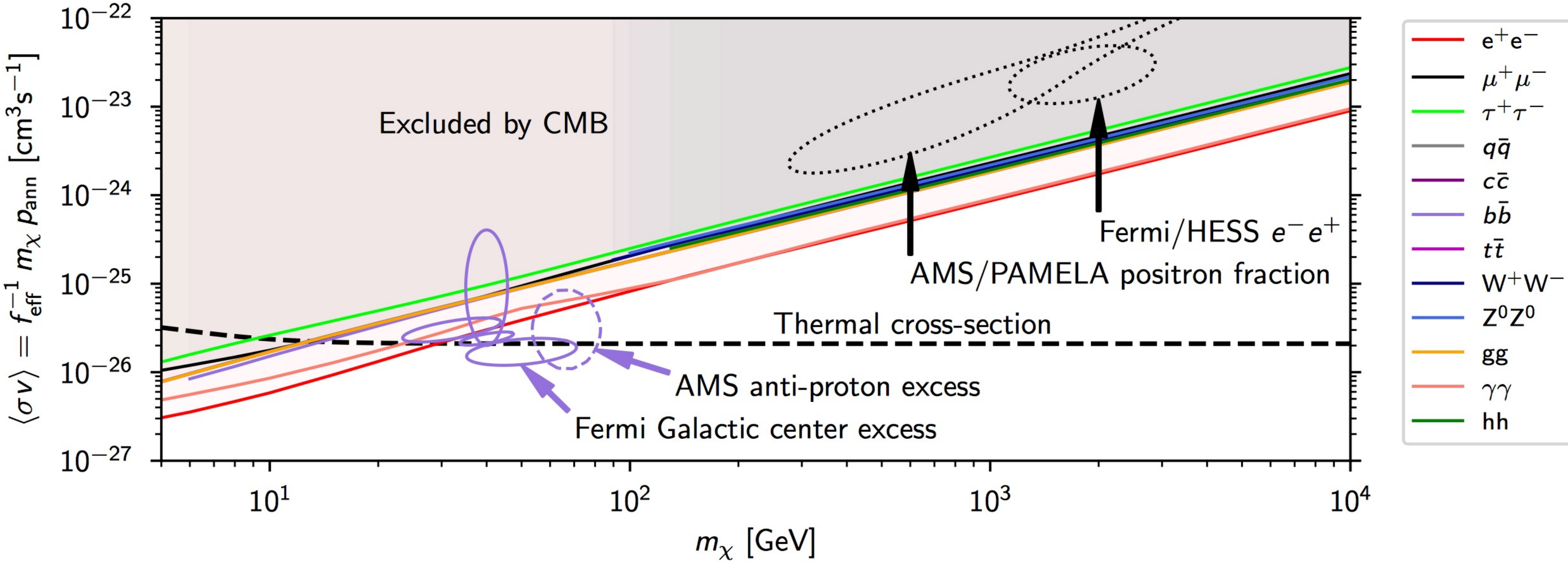
95% CL upper limits, 6 y of Fermi-LAT and DES - 15 stacked dwarfs 1611.03184



Shown are model for the GC excess. They are in tension with the upper limit.

"WIMP miracle" annihilation at decoupling cannot be smaller than the benchmark annihilation cross section ($< \sigma_{annih} v > \simeq 2 \times 10^{-26}$ cm^3/s).

CMB limits on DM annihilation cross sections Planck 2018, 1807.06209



DM annihilations which would heat up the Universe close to recombination would leave an imprint in the CMB- Limits due to the total electromagnetic power injected, so they extend to lower masses too.

Indirect limits on “WIMP miracle” cross sections

1- FermiLAT observations of stacked dwarf galaxies
Constrain annihilation at present of DM particles bound to galactic haloes

2- CMB anisotropy precision measurements (Planck and others)
Constrain DM annihilations (or decays) at recombination or after

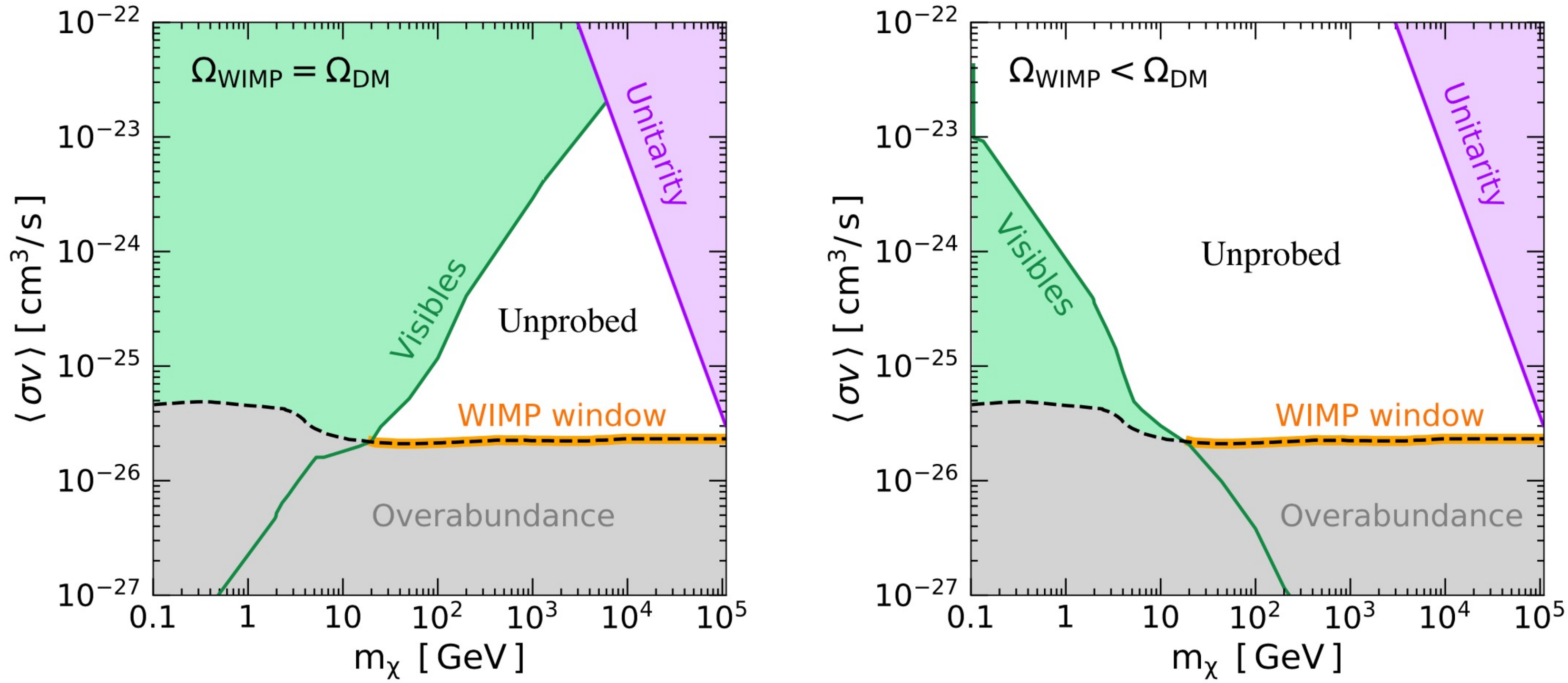
3- Positron spectrum measured by AMS-02 (more precise that earlier measurements) Constrain annihilation at present of DM particles close to Earth

They all imply $< \sigma v >< 3 \times 10^{-26}$ cm^3/s for WIMP $m < O(10)$ GeV (exact limit depends on annih. mode). This rejects thermal WIMPs $m < O(10)$ GeV if annihilation is in s-wave:$< \sigma v >$ is v independent.
Not constraining for p-wave annihilation: $< \sigma v >\sim v^2$, because at freeze-out $v \simeq c/3$ and v is much smaller at recombination and within galaxies

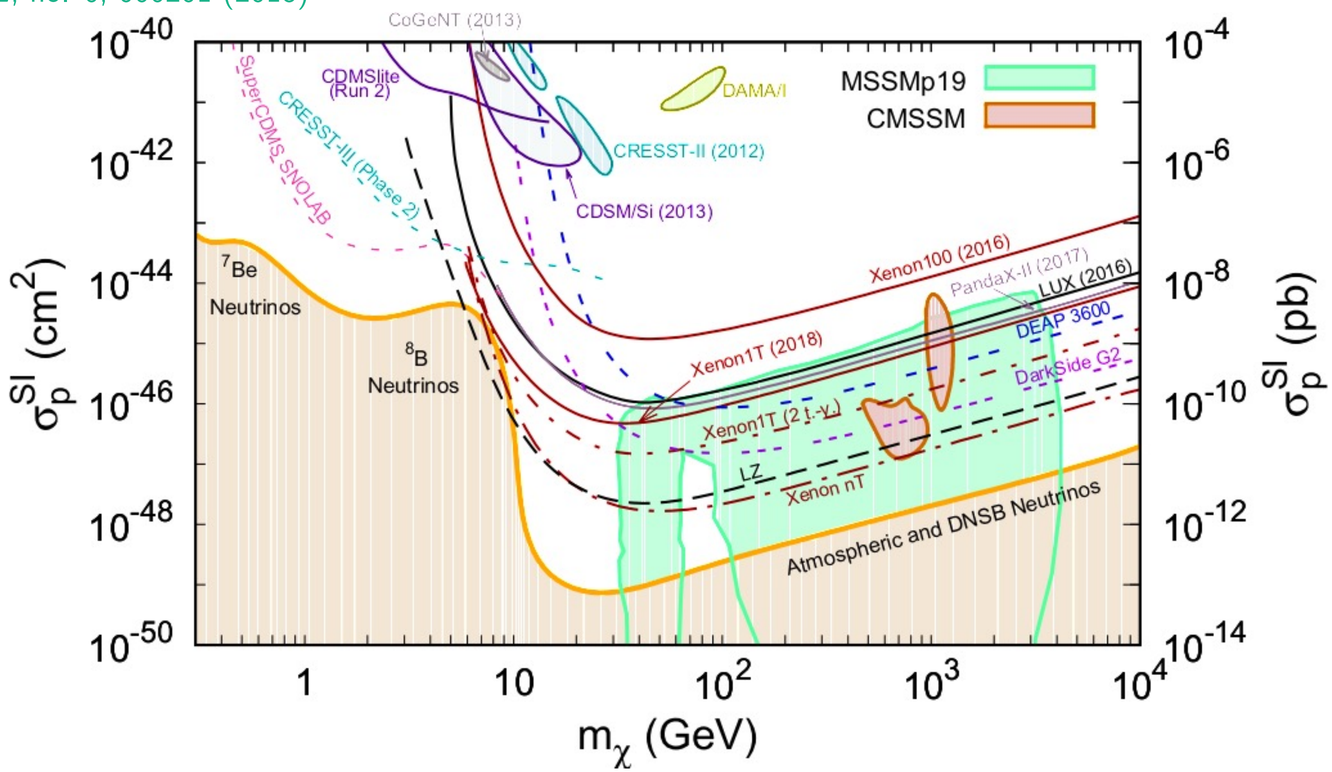
Indirect limits on s-wave "WIMP miracle" cross sections

"GeV-Scale Thermal WIMPs: Not Even Slightly Dead" Leane, Slatyer, Beacom and Ng,1805.10305

s-wave 2→2 annihilation, standard cosmological history, conservative limits



Neutralino models to be found in DD! Roszkowski, Sessolo and Trojanowski, Rept. Prog. Phys. **81**, no. 6, 066201 (2018)



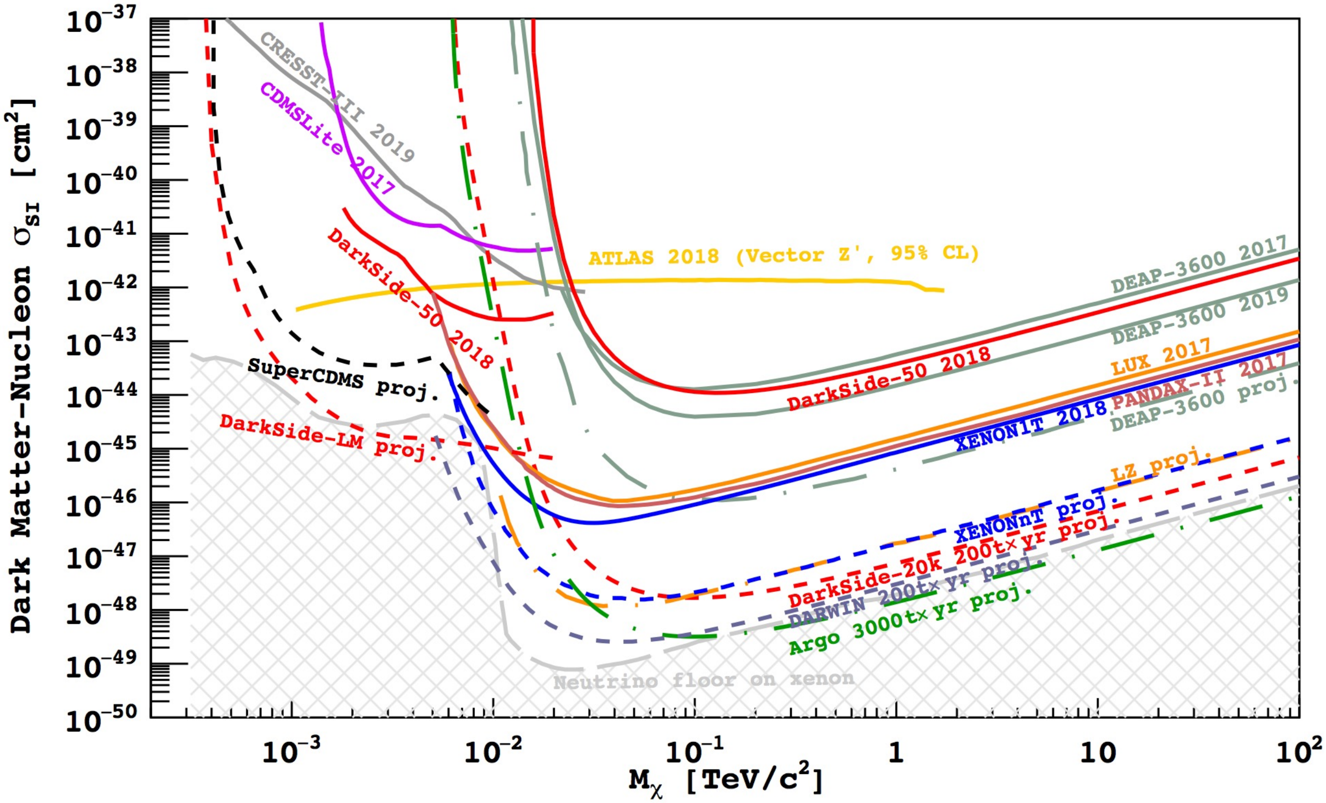
SUSY "light vanilla" models rejected by LHC- but those remaining could be seen in DD. Green region allowed (notice tend to be heavy WIMPs)

WIMP direct detection experiments

DAMA clearly sees an annual modulation at 12.9σ, DM or instrumental?
“Global NaI(TI) Collaborative Effort”: COSINE:KIMS (52 kg) and DM-Ice (55 kg), in YangYang Lab. (S Korea), ANAIS (112 kg), in Canfranc Lab. (Spain) and SABRE (50 kg) in two sites, Gran Sasso Lab. (Italy) and Stawell Lab., Australia
Very important to check in the Southern Hemisphere!
First results presented this summer by ANAIS reject modulation at the $\simeq 1.8\sigma$ level- more statistics needed (3σ in 2.5 y) and COSINE-100 no modulation but statistically limited still.

XENONnT (5.9T-2020), LZ (5.6T-2020), DarkSide20T 2022 (later GADMC 300T?), SuperCDMS-SNOLAB (was at Soudan, up to 400kg of Ge and Si, 2021) maybe later merge with EDELWEISS III (30kg) and CRESST III into EUREKA?, PandaX-II (0.5T running, later PandaX-III nT?), PICO 60 (running, later PICO-250?)?, DARWIN(30T)?, ... and Directional Direct DM detectors (CYGNUS)... Light DM detectors...

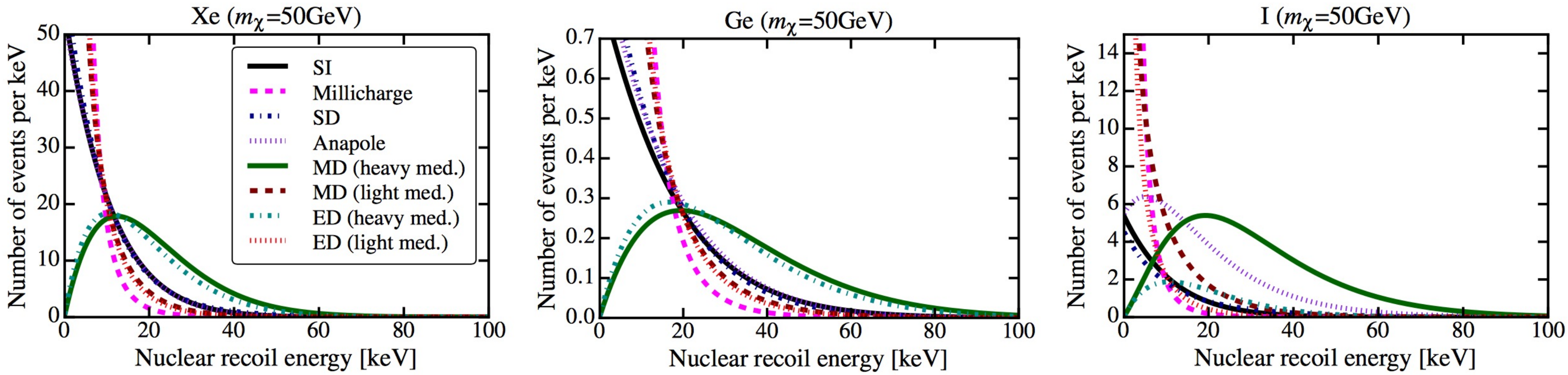
Future of Direct Detection and its neutrino floor (Fig from E. Aprile-Cosmic Controversies 2019 **This is for Spin-Independent interactions**



Future of Direct Detection and its neutrino floor

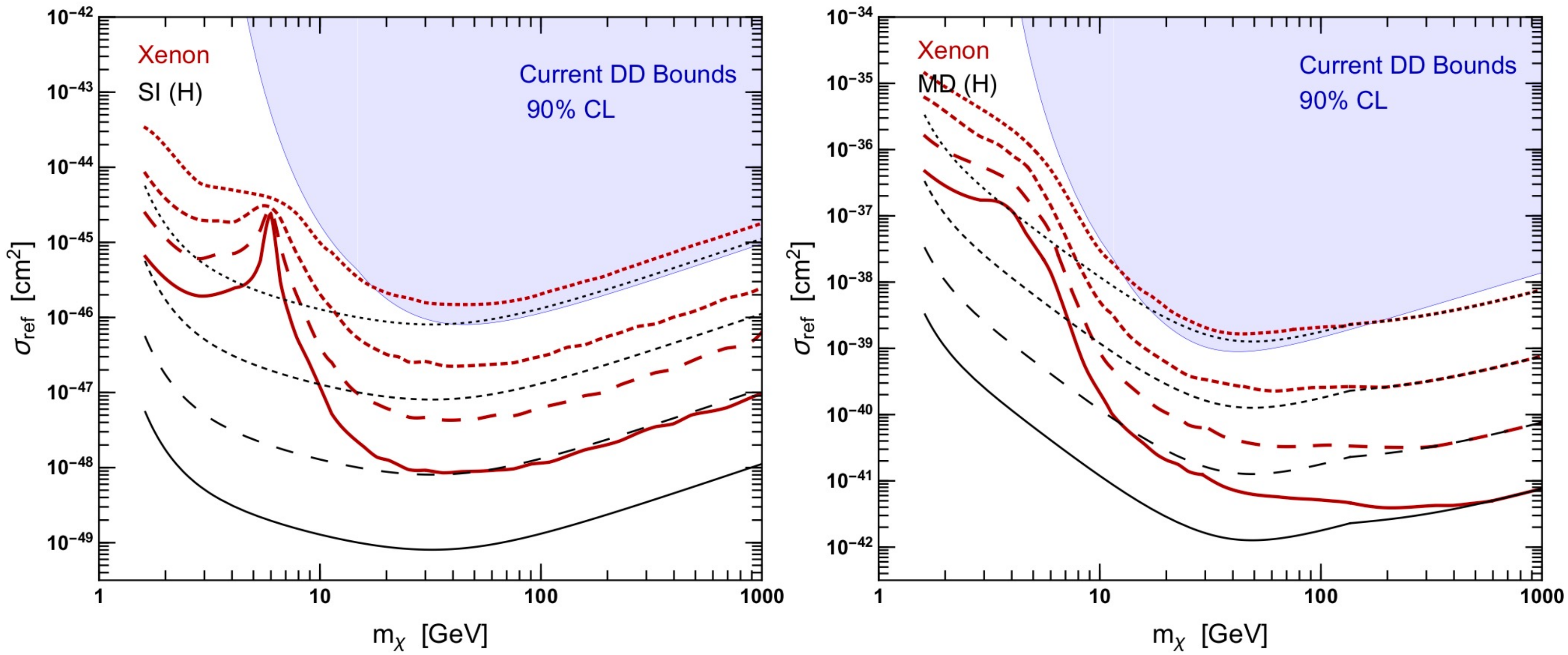
Consider all types of WIMP interactions
Differential rates can be very different than for SI

Fig. from Gluscevic, Gresham, McDermott, Peter and Zurek 1506.04454



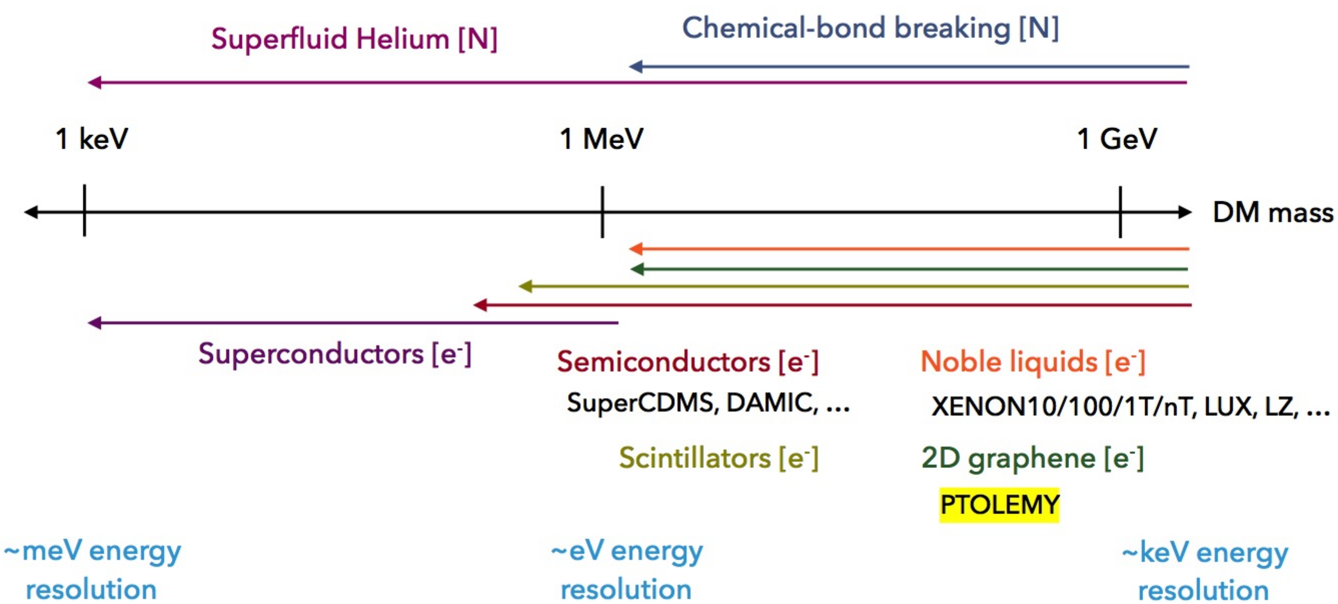
Future of Direct Detection and its neutrino floor The relevance of the neutrino floor depends on the WIMP interaction, e.g. SI, Magnetic Dipole

Gelmini, Takhistov and Witte, 1804.01638



The Xe discovery limit of heavy q^x (q is the momentum exchanged) interacting DM is not affected by the neutrino floor (for exposures $\leq$ 100 tonne y) but require experiments to extend the energy range and change their data analysis!

Diversify into unexplored domains light DM, dark photons and other light mediators, boosted DM. ("Dark Sector Workshop"1608.08632; "U.S. Cosmic Visions: New Ideas in DM" 3/2017- KITP 2018 workshop "HEP at the Sensitivity Frontier", "Multi-Channel Direct Detection of Light Dark Matter" 1910.08092, 1910.10716) e.g. for sub-GeV Light DM direct detection



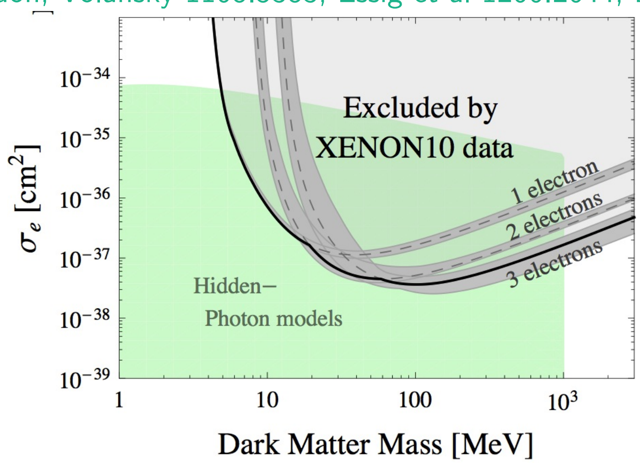
Scattering off e [e$^-$] or inelastic scatt. on nuclei [N] (γ emission in nuclear recoil, breaking chemical bonds in molecules/crystals, multi-phonon processes in superfluid He or insulator crystals)

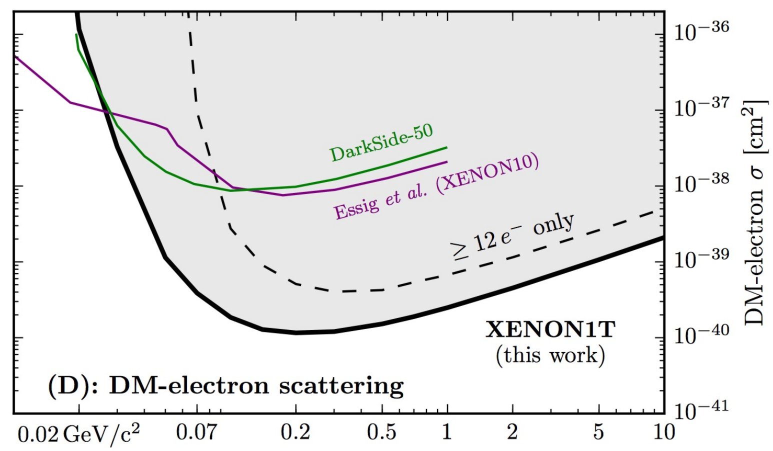
Sub-GeV DM

$m \simeq$ keV to 0.1GeV<< M of nuclei, the maximum energy imparted in an elastic collision with the whole nucleus is below threshold for most experiments ($E_{thres} > 0.1$ keV)

$$E_{max}^{elastic-Nuclei} \simeq 20eV \left(\frac{m}{100MeV}\right)^2 \left(\frac{10GeV}{M}\right)$$

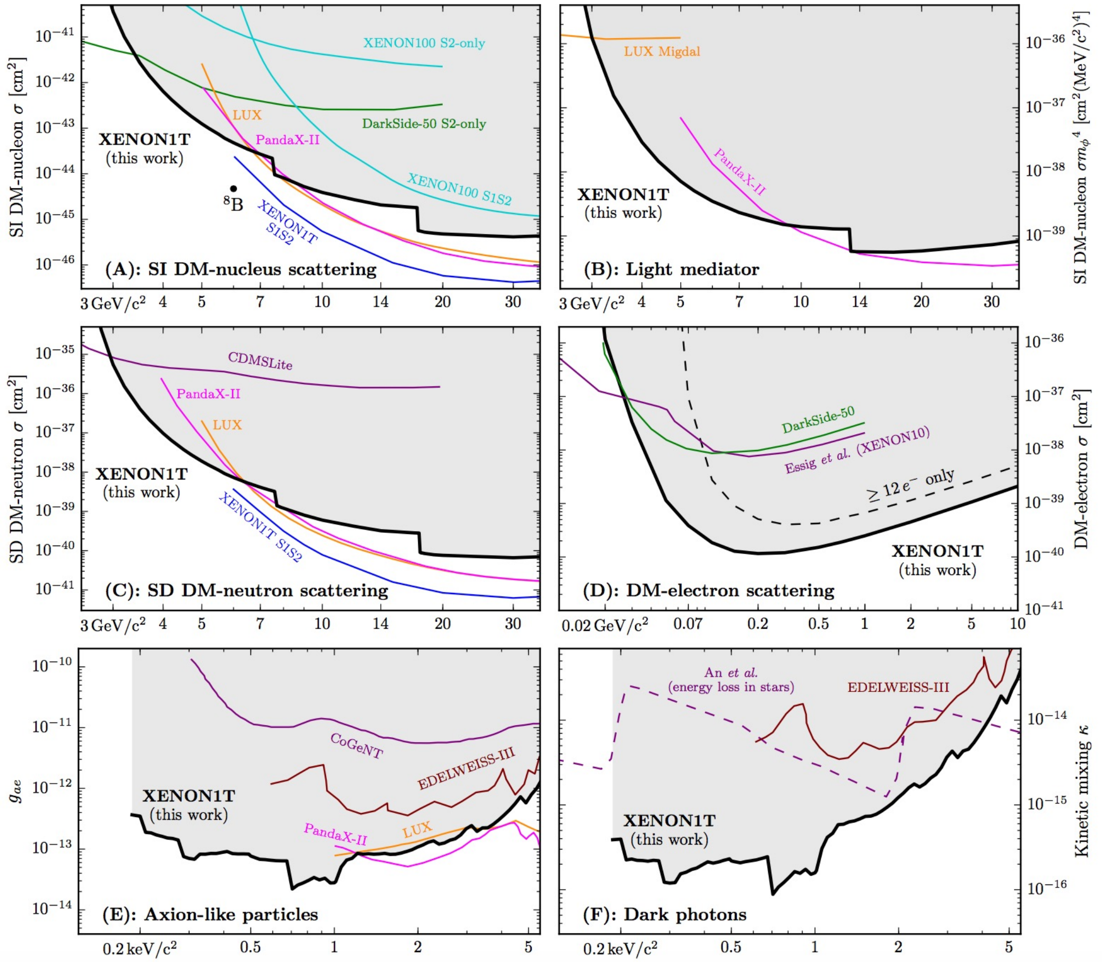
but Light DM could deposit enough energy, 1 to 10 eV, interacting with electrons (electron ionization, electronic excitation, molecular dissociation...) Bernabei et al. 0712.0562; Kopp et al 0907.3159; Essig, Mardon, Volansky 1108.5383; Essig et al 1206.2644; Batell, Essig, Surujon 1406.2698; XENON1T 1907.11485



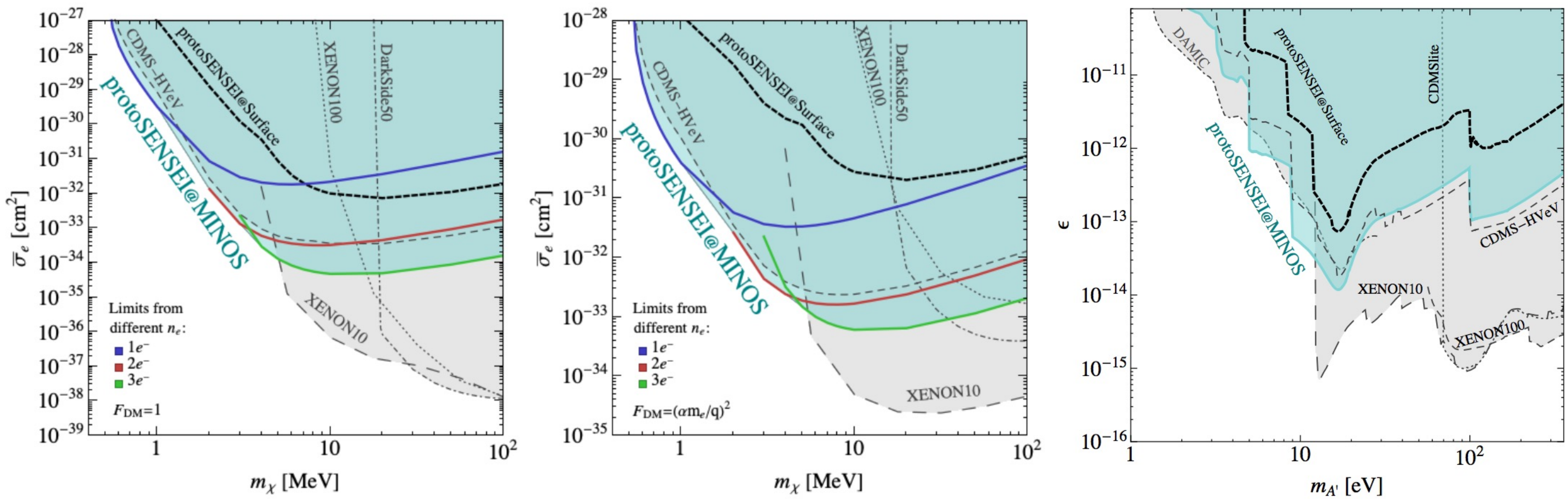


Graciela Gelmini-UCLA

New limits on Light DM S2 (ionization) only analysis XENON1T 1907.11485



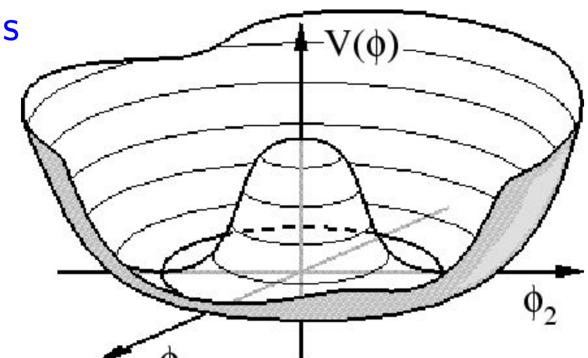
SENSEI "Sub-Electron-Noise Skipper CCD Experimental Instrument" 0.1g at Fermilab. LEFT: direct-detection constraints on 1-100 MeV DM interacting with electrons, exposure 0.177g-days 1901.10478



RIGHT: limit on dark photon with kinetic mixing ε

SENSEI-100 g at SNOLAB (funded, 2020), DAMIC-M: 1 kg at Modane (funded, 2023), a 10 kg Skipper-CCD (planned, longer term), for eV to GeV DM

AXIONS Only viable solution proposed so far: augment the SM to make the Lagrangian invariant under a global chiral symmetry $U(1)_{PQ}$ (Peccei-Queen 1977) spontaneously broken at a high scale f_a, whose Goldstone boson is the AXION a (Wilczek 1978, Weinberg 1978)

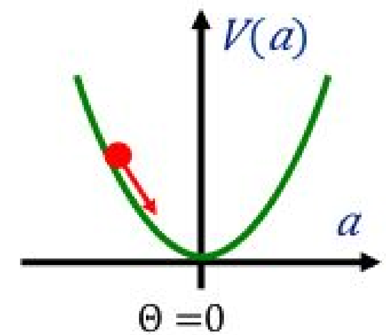


so that now

$$\bar{\theta} + \frac{< a >}{f_a}$$

Effects of the QCD anomaly generates an explicit breaking of $U(1)_{PQ}$, thus a potential for the field a,

$$V_{eff} \sim cos\left(\bar{\theta} + \frac{< a >}{f_a}\right) = cos(\theta)$$

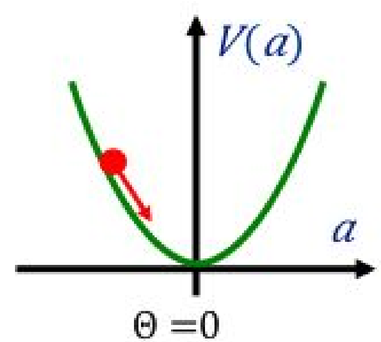


whose minimum is at $< a >= -f_a/\bar{\theta}$, i.e. $\theta = 0$ thus the Lagrangian in terms of $a_{phys} = a - < a >$ no longer has a CP violating θ-term. CP - symmetry is dynamically restored

AXIONS as CDM In the coherently oscillating field scenario, present QCD parameters and temperature dependent m_a imply (Bae, Huh & Kim, 0806.0497)

$$\Omega_a h^2 = 0.195\ \theta_i^2 \left(\frac{f_a}{10^{12} GeV}\right)^{1.184} = 0.105\ \theta_i^2 \left(\frac{10\mu eV}{m_a}\right)^{1.184}$$

θ_i is the initial value of a in our patch of the Universe.
If inflation happens after the PQ symmetry spontaneous breaking, there is only one value



If axions account for the whole of the DM $\Omega_a h^2 = 0.11$

$$\theta_i = 0.75 \left(\frac{10^{12 GeV}}{f_a}\right)^{0.592} = 1.0 \left(\frac{m_a}{10\mu eV}\right)^{0.592}$$

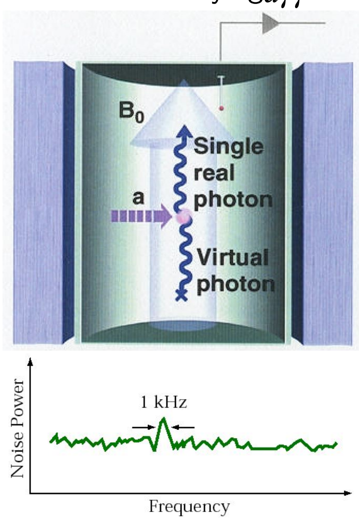
$\theta_i \simeq 1$ implies $f_a \simeq 10^{12}$ GeV "classic window"
$\theta_i < 1$ implies $f_a > 10^{12}$ GeV " anthropic window" (e.g. $f_a \simeq 10^{16}$ GeV for $\theta_i \simeq 0.003$)

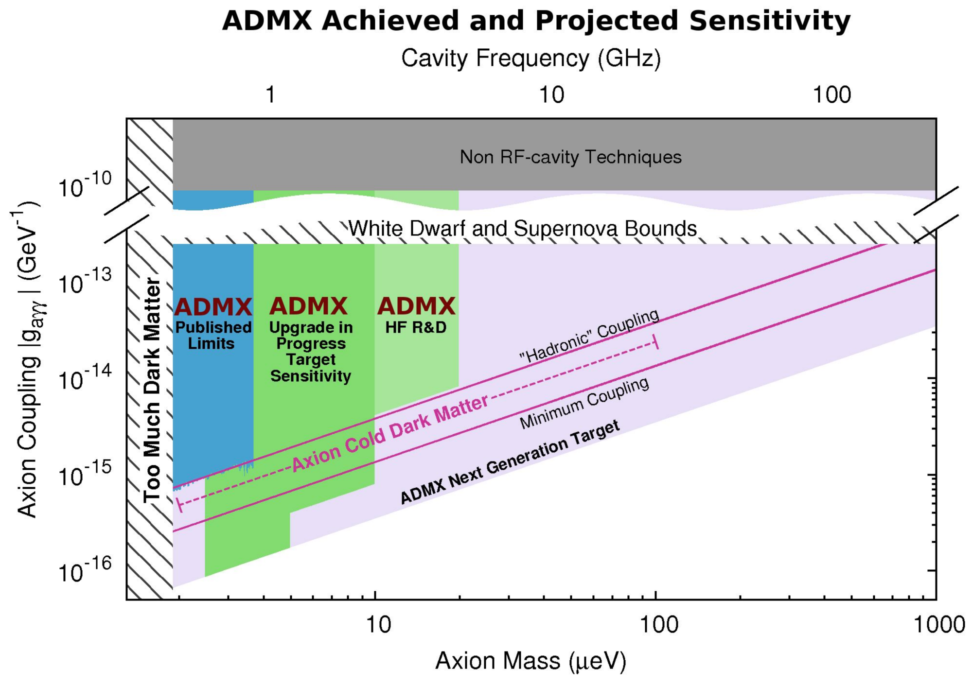
But also AXIONs could be a subdominant component of the CDM.

Direct searches of very Light DM: AXIONS as CDM using the axion coupling to photons (model dependent) (Sikivie 1983) Axion DM exp (ADMX) best experiment for the "good CDM candidate range" 1μeV $\leq$ m ≤ 1 meV New results 1910.08638

ADMX (Axion DM eXperiment)

Microwave cavity: $g_{a\gamma\gamma}$



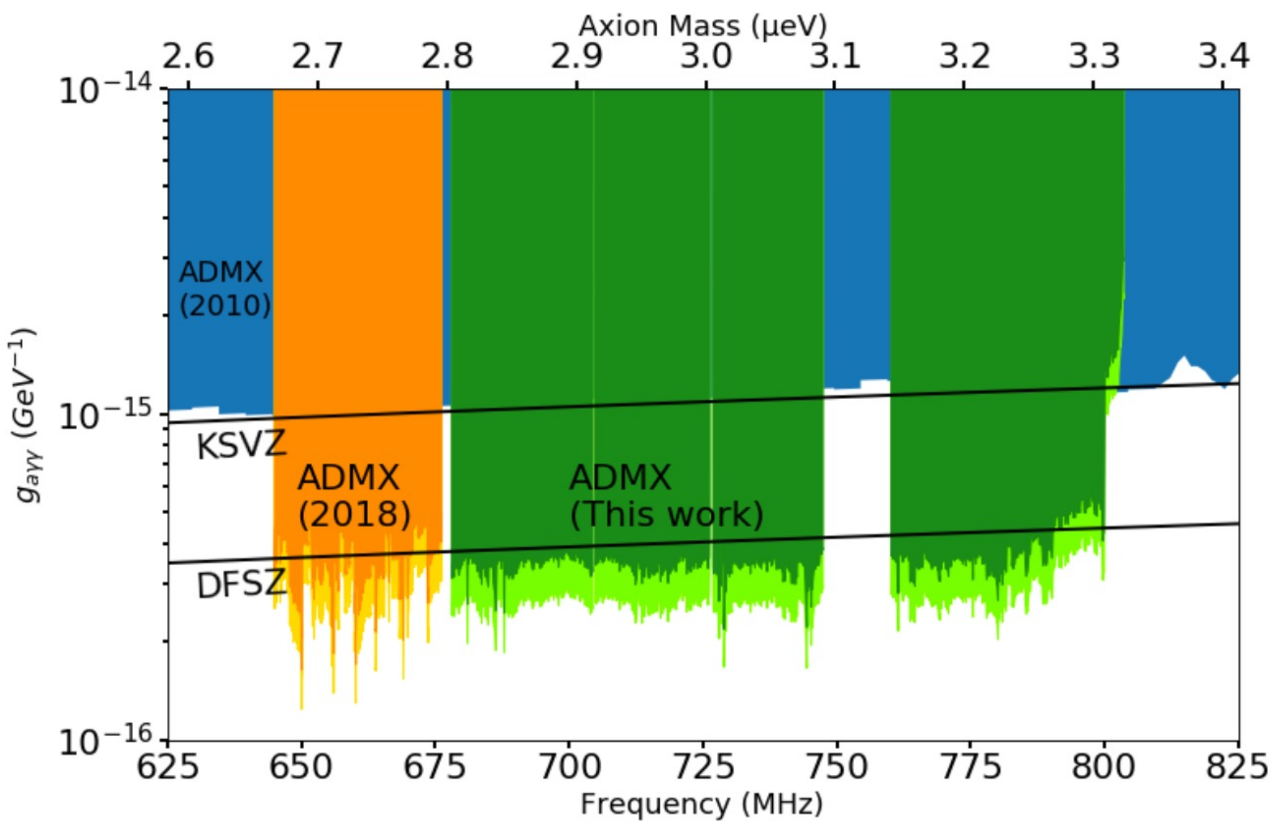


ADMX G2- will explore 2 to 40 μeV axion mass in 6 years of operation- started in 2017

Other new searches: with cavities at KAIST, Korea; new methods "dielectric haloscope" in MADMAX (40 to 300μeV axion mass), CASPER and ABRACADABRA ($<.\mu$eV)...

ADMX G2 New results 1910.08638

90% confidence exclusion on axion-photon coupling



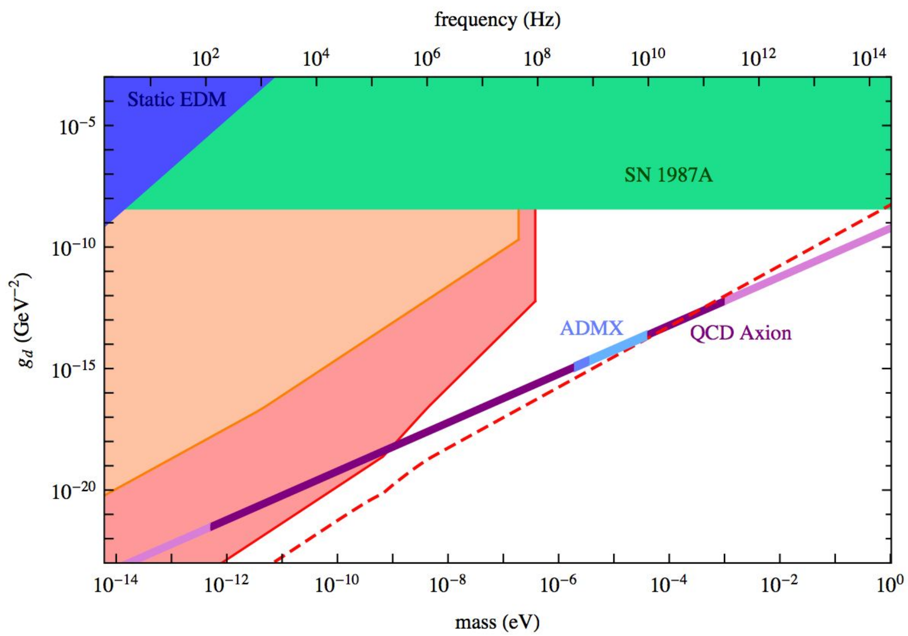
MADMAX Magnetized Disc and Mirror Axion Experiment: in R&D, based on axion-photon conversion at the transition between different magnetized dielectric media, within a 10 T magnetic field, ∼80 r=10cm dielectric discs implies a 10^5 amplification, for $m_a \sim 40 - 400\mu$eV- Prototype in construction- Munich, Hamburg

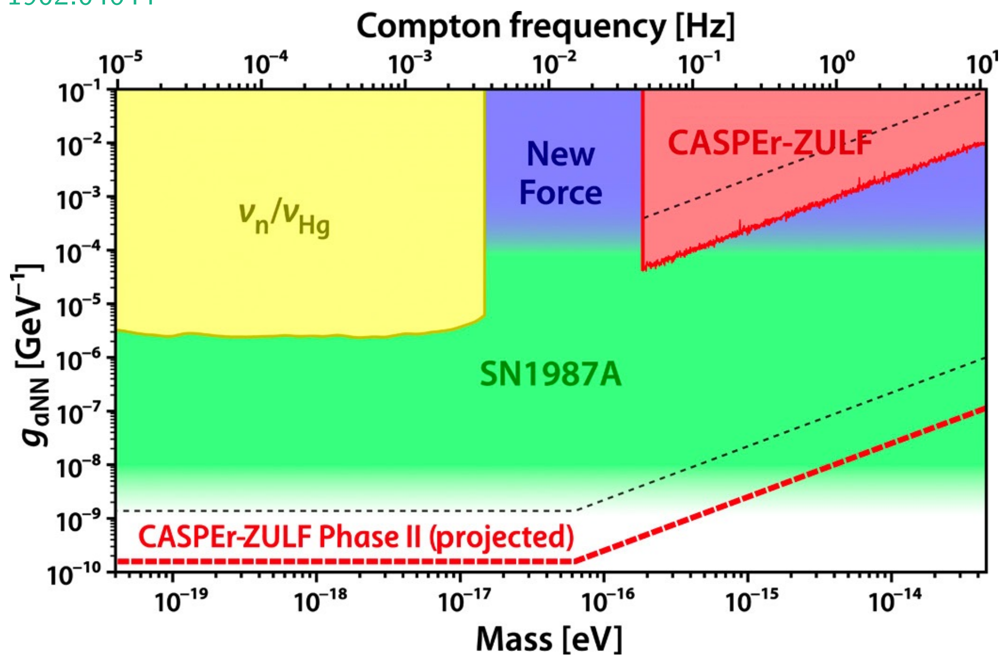
CASPEr Cosmic Axion Spin Precession Experiment: axion coupling to gluons- measure a time varying electric neutron moment as the axion field oscillates. Recall $d_n \sim \theta$ and $\theta(t) = a(t)/f_a$. For kHz-GHz, precession of nuclear spins in electric fields changes the magnetization of a sample of material, which could be observed with precision magnetometry, Mainz (Graham & Rajendran 1101.2691, 1306.6088, 1306.6089)

ABRACADABRA "A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-Field Ring Apparatus": new idea for axion dark matter via interaction with a toroidal magnetic field- now 10cm prototype at MIT - in study a 1m scale ABRACADABRA-75cm (Kahn, Said, Thaler 1602.01086, Ouellet et al 1810.12257)

AXIONS as CDM: CASPEr (Cosmic Axion Spin Precession Experiment)

LEFT from Budker, et al 1306.6089, RIGHT from Garcon et al 1902.04644

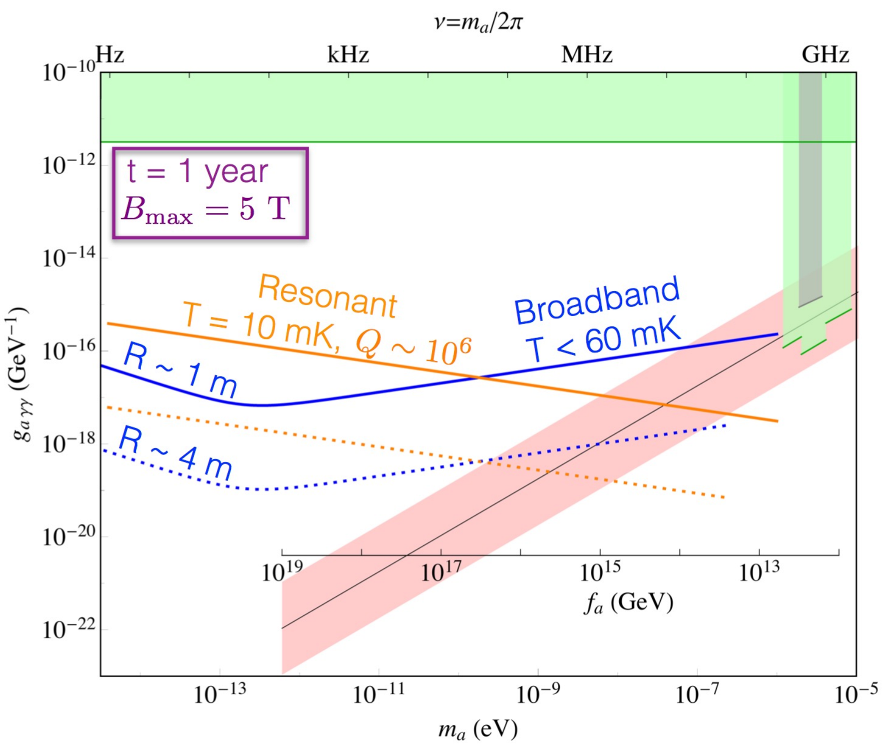


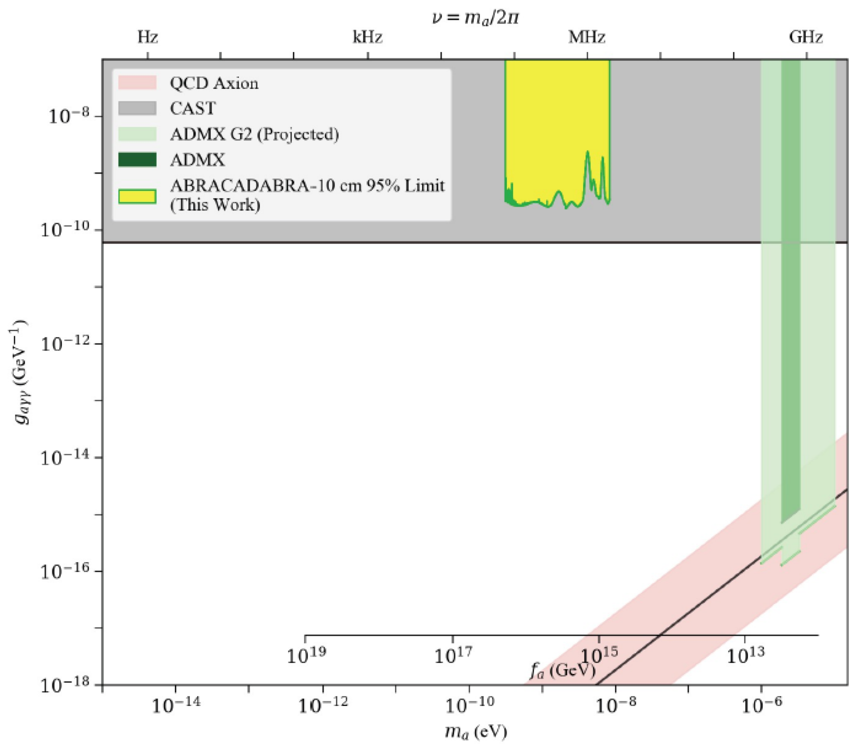


LEFT:Solid pink and orange: sensitivity regions for phase 1 and 2 proposals, set by magnetometer noise, red dashed line: limit from magnetization noise-

RIGHT: recent limits on light ALPs with Zero to Ultra Low Field (ZULF)

ABRACADABRA (A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus) (Kahn, Said, Thaler 1602.01086, Ouellet et al 1810.12257)





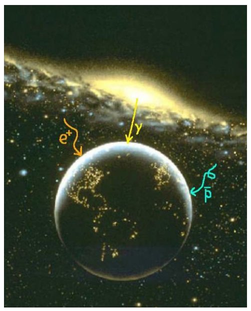
LEFT: expected sensitivities- RIGHT: actual limit of R=10 cm prototype

Indirect detection through γ and anomalous cosmic rays

Main detectors: PAMELA, AMS, Fermi ST, HESS, VERITAS, CANGAROO, MAGIC

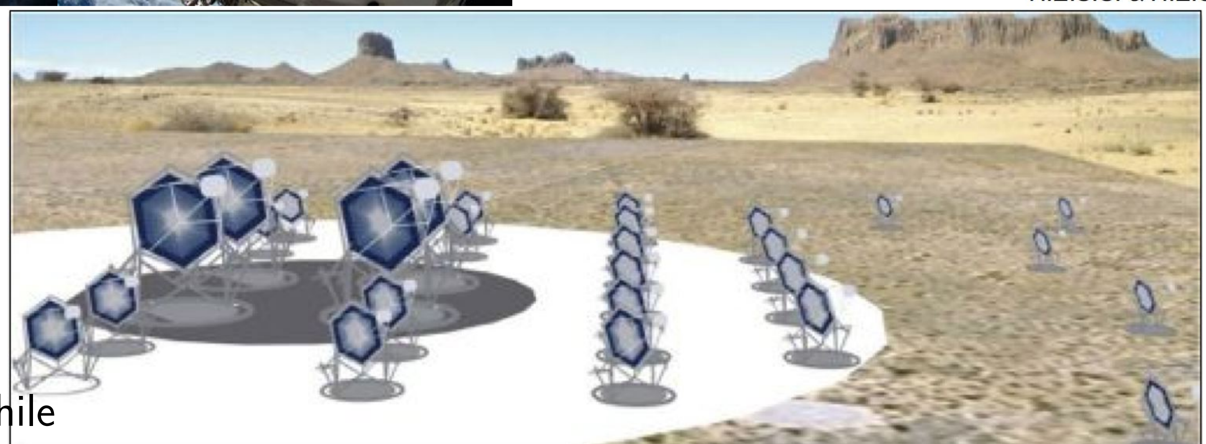
Look for an excess of γ, e^+, $\bar{p}$ over expected, and a bump at $E \sim m$

(Fig. from G. Gondolo) PAMELA AMS



Fermi-LAT (Fermi Large Area Telescope)

H.E.S.S. & H.E.S.S.-2

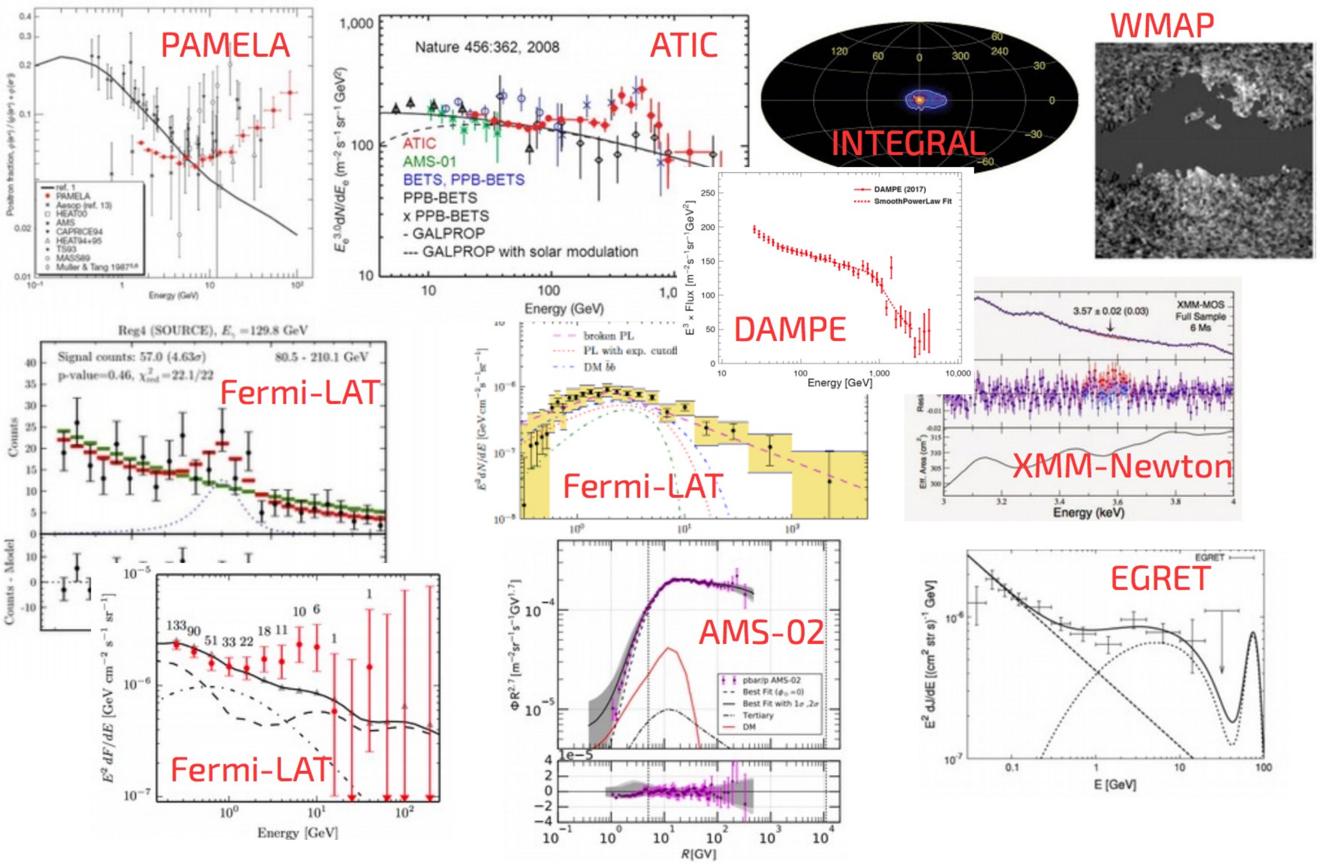


2015 in La Palma and Chile

CTA (Cherenkov Telescope Array)

Fig. from C. Weniger

Some signal claims of recent years



PAMELA 10-100's GeV e^+ excess

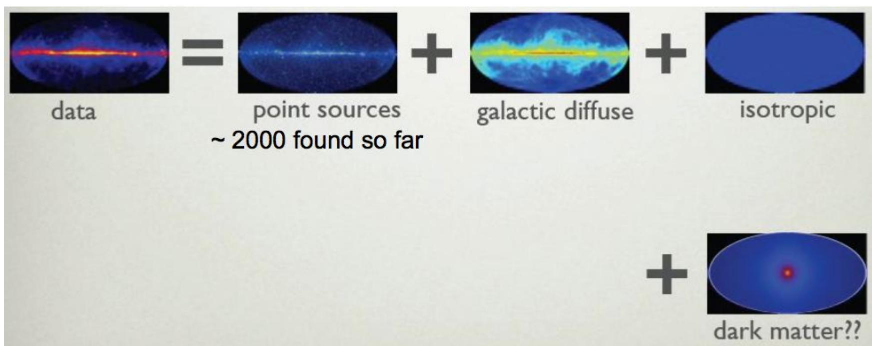
Confirmed by the Fermi Space Telescope-LAT in 2013 and AMS (Alpha Magnetic Spectrometer) as of 2016

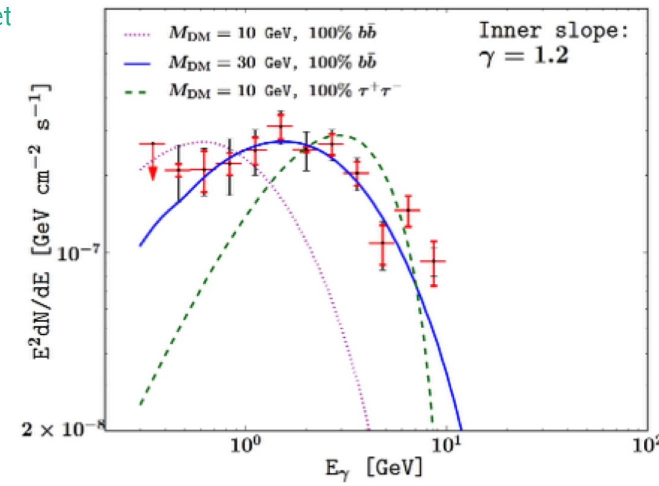
In 2017, HAWC first measurements 1702.02992 of the very high-energy (multi-TeV) γ-ray emission from the Geminga and Monogem pulsars- show they inject a flux of e^+ into the local interstellar medium as necessary to account for the observed e^+ excess. Confirmed from Geminga with 10 y of Fermi-LAT data Di Mauro, Manconi, Donato 1903.05647

This strongly favors nearby pulsars as the origin (Hooper, Cholis, Linden, Fang 1702.08436, Di Mauro, Manconi, Donato 1903.05647)

Galactic Center GeV excess in Fermi-LAT data

GeV γ's from extended region at the Galactic Center and Inner Galaxy. From annihilation of DM with m =7-10GeV into $\tau^+\tau^-$ or 30-45GeV into $q\bar{q}$? Goodenough& Hooper 0910.2998, Hooper& Goodenough 1010.2752, Hooper& Linden 1110.0006; Hooper 1201.1303; Abazajian& Kaplinghat 1207.6047, Hooper etal 1305.0830, Macias& Gordon, 1306.5725, Abazajian et al. 1402.4090, Dayland et al. 1402.6703, Cholis, Hooper& Linden 1407.5625, Calore, Cholis& Weniger 1409.0042, Bartels, Krishnamurthy& Weniger 1506.05104, Lee et Fermi-LAT 1511.02938 and 1704.03910, ...





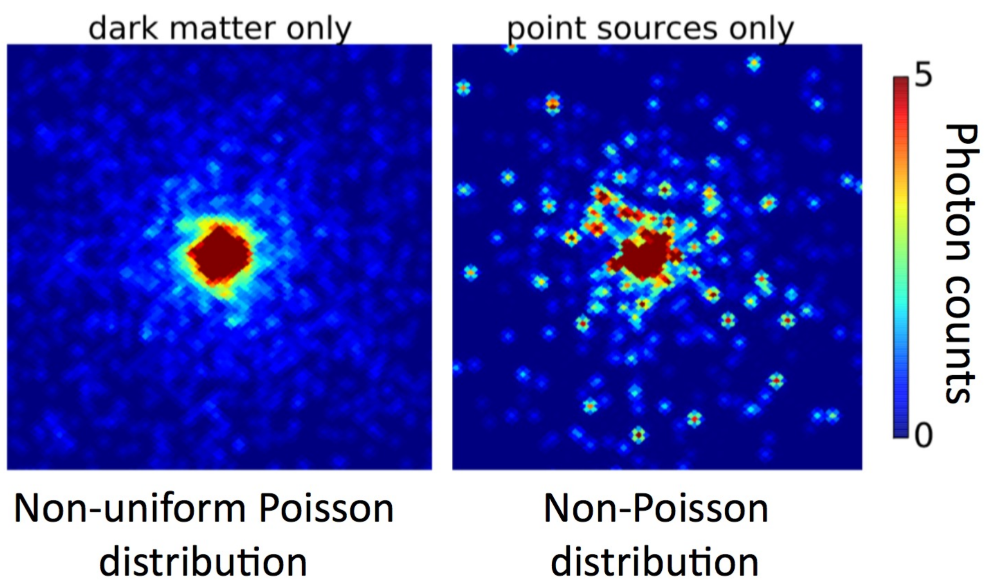
Extended spherically symmetric GC excess in GeV's gamma rays! Confirmed by many groups..

DM annihilation or astrophysical? Unresolved millisecond pulsars

Potential astrophysical sources of the GC excess:

- Unresolved millisecond pulsars Abazajian 1011.4275, Bartels, Krishnamurthy & Weniger 1506.05104

Differences in the statistics of the photon counts can be quantified - tentative evidence of an unresolved point source population found Lee et al 1506.05124, Bartels et al 1506.05104 or small scale structure of the diffuse background? Horiuchi, Kaplinghat & Kwa 1604.01402



Still jury is out on the origin of the GC excess:

- "DM Strikes Back": Statistical evidence suggested that the GC excess originates from point sources. But, unmodeled sources in the Fermi Bubbles can lead to a DM signal being misattributed to point sources Leane and Slatyer 1904.08430, PRL 123, 241101, Dec. 11, 2019

- GC excess traces the stellar over-density of the Galactic bulge ("Boxy Bulge" due to the bar in our galaxy), so no more room for DM Macias et al 1901.03822

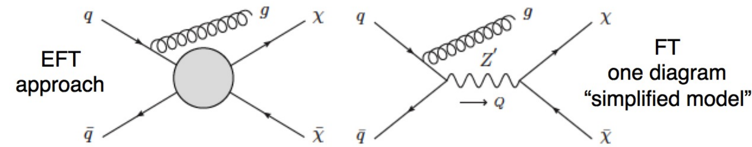
- Evidence of the GeV excess from Andromeda? 7.6 y of Fermi-LAT data shows evidence for an extended 1-100 GeV γ-ray excess from the outer dark halo of Andromeda, with radial extension 120 200 kpc from the center, consistent with the same model that explains the GC excess as a dark matter annihilation signal. A large population of millisecond pulsars is not expected to be present in the outer emission region Karwin, Murgia, Campbell and Moskalenko, 1903.10533

but given the large astrophysical uncertainties this could constitute at most a corroboration of a discover of DM somewhere else

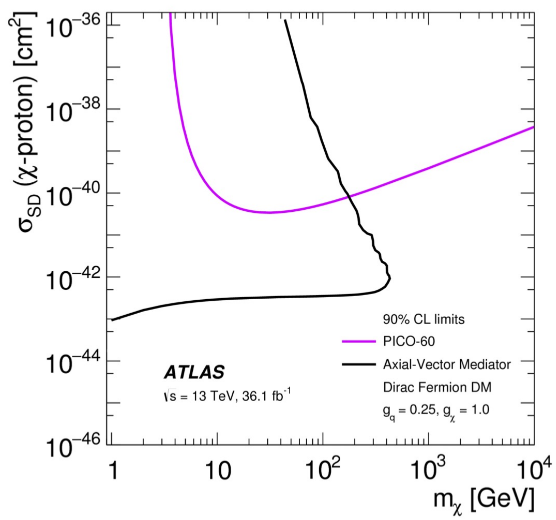
Searches at accelerators: colliders and fixed target experiments

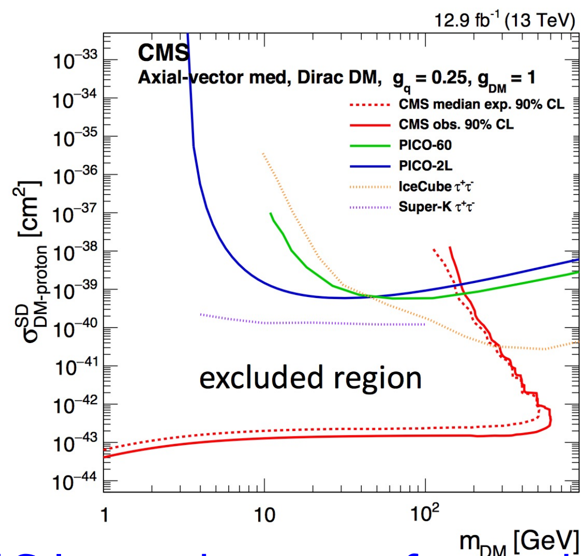
- Search for the DM itself, as missing momentum in collisions (in effective filed theory couplings, simplified models and specific complete particle models)
- Search for the possible mediators of the DM particles
- Search for whole hidden sectors very weakly coupled (via a "portal") to known particles, such as the Higgs, gauge bosons, neutrinos
- An enormous amount of different DM models with different phenomenologies need to be considered
- This makes an evaluation of the relic density difficult and this is necessary to compare with direct and indirect searches (assuming the DM particle is stable)
- A signal produced by a particle escaping the detectors with lifetime $\simeq 100$ ns cannot be distinguished from one with lifetime $> 10^{17}$ s as required for DM particles.

"Simplified models" A mediator of mass M coupled to the DM particle of mass m and to quarks with couplings g_q and g_{DM} (4 parameters)



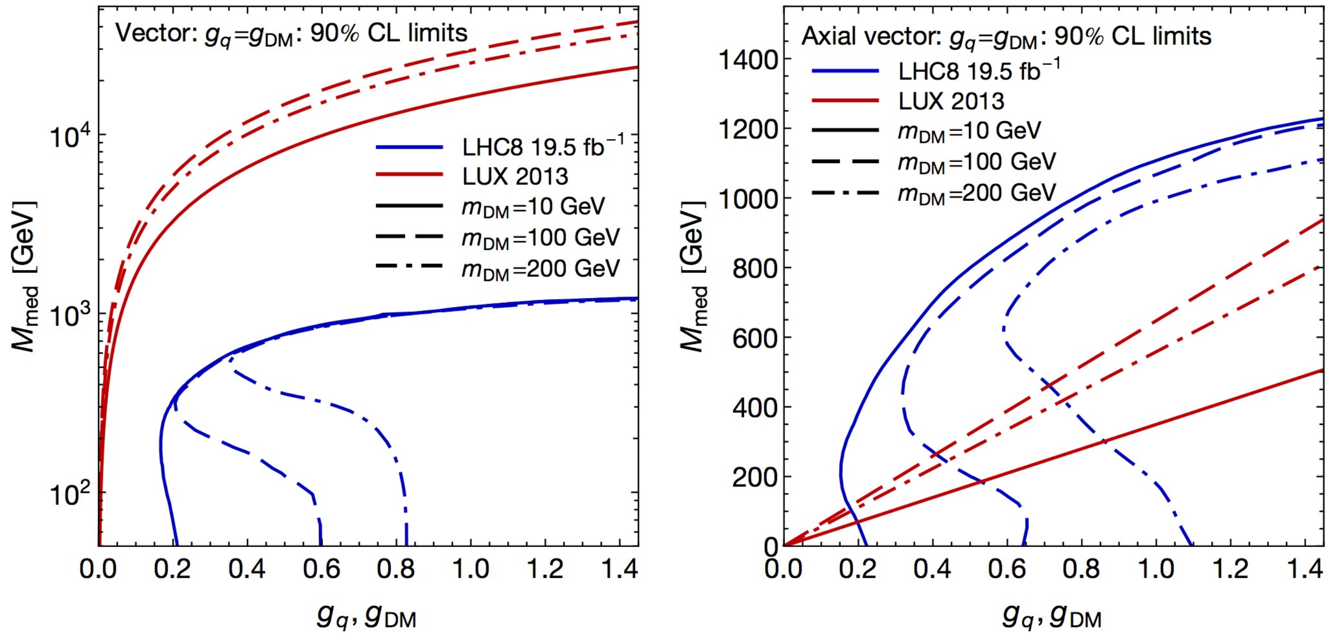
Axial vector mediator g_q=0.25, g_{DM}=1.0





LHC and direct detection limits: The LHC limits disappear fast with smaller g_{DM} and g_q, while the direct detection limits do not- they depend on the scattering cross section $\sim (g_{DM}\ g_q/\ M^2)^2$.

Simplified Models "Mono" searches limits Buchmuller, Dolan, Malik and Mc Cabe, 1407.8257



If couplings are $\simeq$ 0.1 or less LHC limits disappear. E.g. $g_q = g_{DM} < 0.1$

FASER (ForwArd Search ExpeRiment) Ariga et al 1811.12522

Approved by CERN in March 2019- to start in 2021, to look for decay products of light, very weakly interacting long-lived exotic particles which would escape the ATLAS detectors (dark γ, dark Higgs, B-L gauge bosons, heavy neutral leptons, ALPs).

The 5m $\times$ 20cm detector is aligned with the collision axis in ATLAS, in a service tunnel 480 m away from the collision point.

MATHUSLA

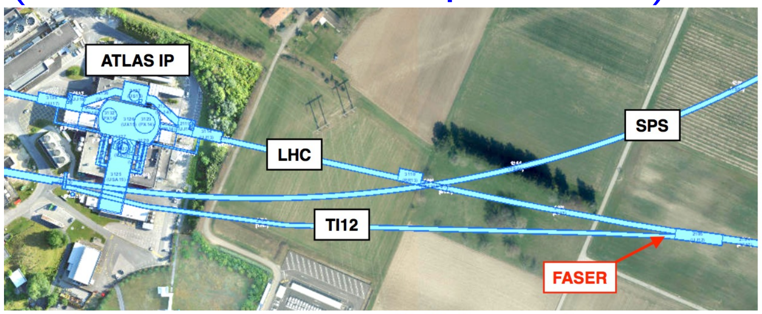
(MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles)1811.00927

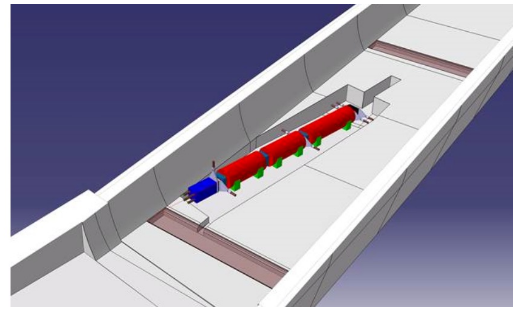
Proposal for a (200m)$^2\times$ 20 m surface detector above the CMS or ATLAS at 150 m of the IP to detect displaced vertices from long-lived particles.

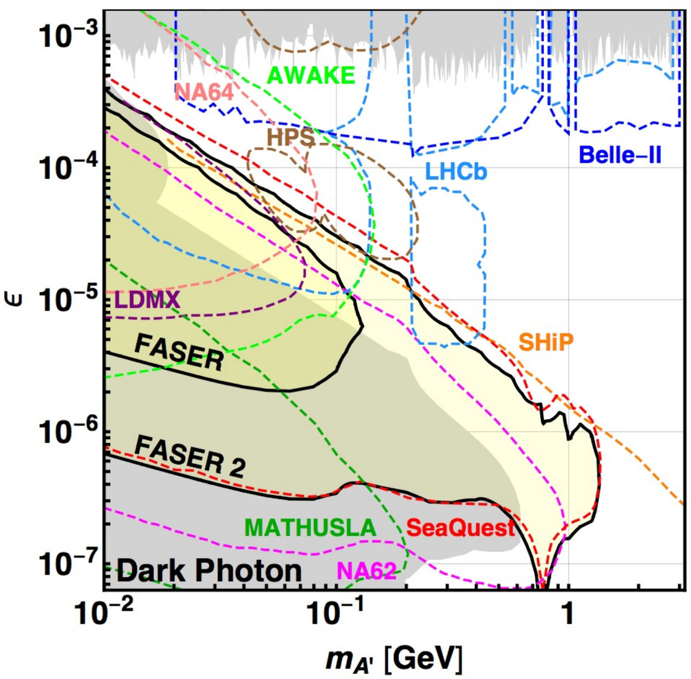
SHiP (Search for Hidden Particles) 1504.04956 , 1504.04855

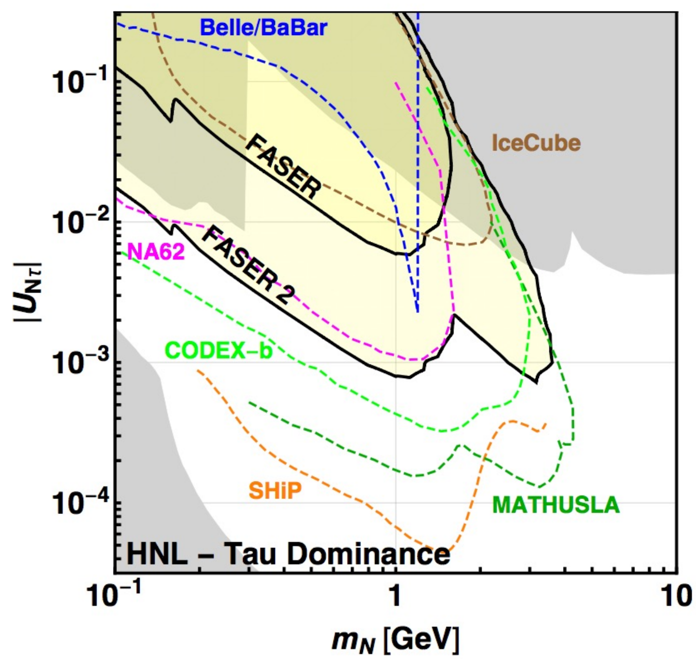
Proposal for new fixed target experiment using the SPS beam with 10^{20} protons on target.

FASER (ForwArd Search ExpeRiment) Ariga et al 1811.12522









DM searches at other accelerators

- Mono-photon+missing momentum at e^+e^- colliders analogous to LHC searches
- Electron (E137, BDX)and Proton Beam Dump (LSND,MiniBooNE, SeaQuest, NOvA, DUNE) Experiments
- Missing Energy (LDMX)/momentum (NA64) at fixed target experiments

Experiment	Machine	Type	E_{beam} (GeV)	Detection	Mass range (GeV)	Sensitivity	First beam
Future US initiatives							
BDX	CEBAF @ JLab	electron BD	2.1-11	DM scatter	$0.001 < m_\chi < 0.1$	$y \gtrsim 10^{-13}$	2019+
COHERENT	SNS @ ORNL	proton BD	1	DM scatter	$m_\chi < 0.06$	$y \gtrsim 10^{-13}$	started
DarkLight	LERF @ JLab	electron FT	0.17	MMass (& vis.)	$0.01 < m_{A'} < 0.08$	$\epsilon^2 \gtrsim 10^{-6}$	started
LDMX	DASEL @ SLAC	electron FT	4 (8)*	MMomentum	$m_\chi < 0.4$	$\epsilon^2 \gtrsim 10^{-14}$	2020+
MMAPS	Synchr @ Cornell	positron FT	6	MMass	$0.02 < m_{A'} < 0.075$	$\epsilon^2 \gtrsim 10^{-8}$	2020+
SBN	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \sim 10^{-12}$	2018+
SeaQuest	MI @ FNAL	proton FT	120	vis. prompt	$0.22 < m_{A'} < 9$	$\epsilon^2 \gtrsim 10^{-8}$	2017
				vis. disp.	$m_{A'} < 2$	$\epsilon^2 \sim 10^{-14} - 10^{-8}$	
Future international initiatives							
Belle II	SuperKEKB @ KEK	e^+e^- collider	~ 5.3	MMass (& vis.)	$0 < m_\chi < 10$	$\epsilon^2 \gtrsim 10^{-9}$	2018
MAGIX	MESA @ Mami	electron FT	0.105	vis.	$0.01 < m_{A'} < 0.060$	$\epsilon^2 \gtrsim 10^{-9}$	2021-2022
PADME	DAΦNE @ Frascati	positron FT	0.550	MMass	$m_{A'} < 0.024$	$\epsilon^2 \gtrsim 10^{-7}$	2018
SHIP	SPS @ CERN	proton BD	400	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-12}$	2026+
VEPP3	VEPP3 @ BINP	positron FT	0.500	MMass	$0.005 < m_{A'} < 0.022$	$\epsilon^2 \gtrsim 10^{-8}$	2019-2020
Current and completed initiatives							
APEX	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.06 < m_{A'} < 0.55$	$\epsilon^2 \gtrsim 10^{-7}$	2018-2019
BABAR	PEP-II @ SLAC	e^+e^- collider	~ 5.3	vis.	$0.02 < m_{A'} < 10$	$\epsilon^2 \gtrsim 10^{-7}$	done
Belle	KEKB @ KEK	e^+e^- collider	~ 5.3	vis.	$0.1 < m_{A'} < 10.5$	$\epsilon^2 \gtrsim 10^{-7}$	done
HPS	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.015 < m_{A'} < 0.5$	$\epsilon^2 \sim 10^{-7}$**	2018-2020
NA/64	SPS @ CERN	electron FT	100	MEnergy	$m_{A'} < 1$	$\epsilon^2 \gtrsim 10^{-10}$	started
MiniBooNE	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-9}$	done
TREK	K^+ beam @ J-PARC	K decays	0.240	vis.	N/A	N/A	done

Outlook

DM searches are advancing fast in all fronts, direct and indirect detection, searches at accelerators, astrophysical observations and modeling.... many possibilities, many different searches. Lots of data necessarily lead to many hints, so far not corroborated... Hopefully at some point several of them will point to the same DM candidate.