ISAPP
2021

International School on AstroParticle Physics

MAD$^{(\gamma)}$

Gamma rays to shed light on dark matter

21 - 30 June

ONLINE EVENT

GAMMA-RAY ASTRONOMY

A story of travelers

Part 1. Theory

'Gamma rays to shed light on dark matter'
ISAPP School 2021, 21-30 June

Michele Doro (University of Padova, michele.doro@unipd.it)

Program

- Who am I?
- What is gamma?
- Cosmic rays and gamma-rays
- Acceleration of cosmic rays
- Generation of gamma rays
- Nice gamma-ray targets
- Gamma-ray postcards
- Instruments (Monday's lecture)

Who am I

Michele Doro

Associate Professor of Experimental Particle Physics at
Dipartiment of Physics and Astronomy (DFA) of the University of Padova

- Courses: Experimental Physics, Physics
- Mail: michele.doro@unipd.it. *Write me if needed!*
- http://www.pd.infn.it/~mdoro, http://unipd.academia.edu/MicheleDoro

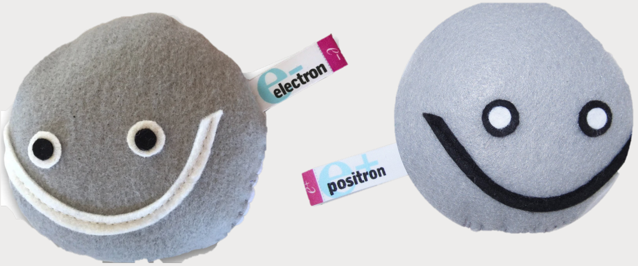
MAGIC telescopes!

cta cherenkov telescope array

SWGO The Southern Wide-field Gamma-ray Observatory

Trinity

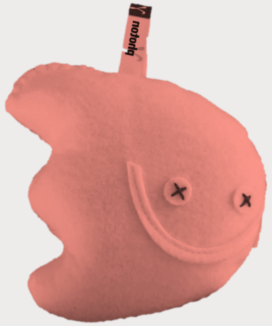
Travellers (and a disclaimer)



the electron and the positron

the PROTON

the neutrino



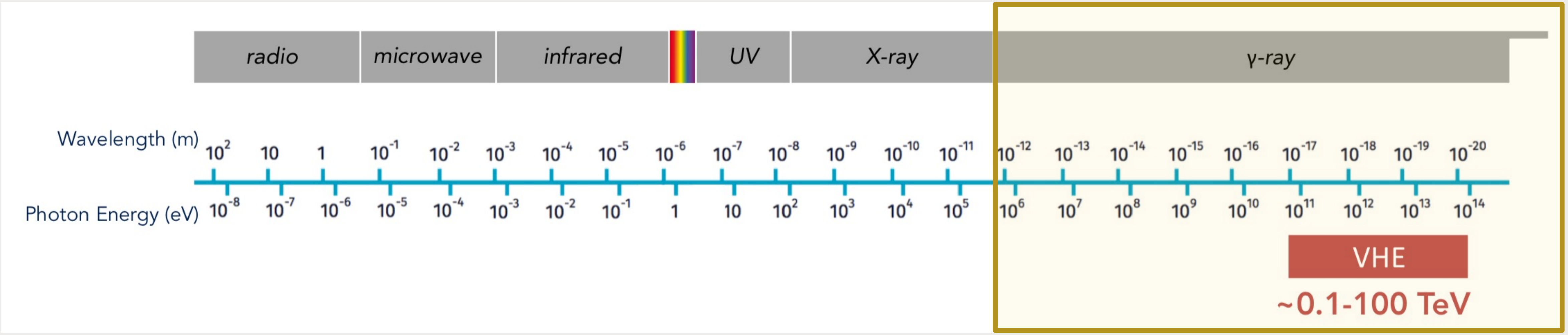
ze scary gamma ray

Weak photons

- To try and fix concepts, we will try and get helped by analogies to travel…but our will be an truly **cosmic travel**

- DISCLAIMER: wide topic!
  - *Structured as seminar, not lecture*
  - *Some books recommended*

Gamma-rays



- A photon of 1 TeV has
  - *A wavelenght of* $1.25\ 10^{-18}\ m$
  - *A frequency of* $2.4\ 10^{-26}$ *Hz*
  - *An energy of* $1.6\ 10^{-7}$ *J = 1.6 erg*

- Photon flux dN/dE in astrophysics best expressed as

$$E^2 \frac{dN}{dE} = \nu F_\nu\ [erg\ cm^{-2} s^{-1}]$$

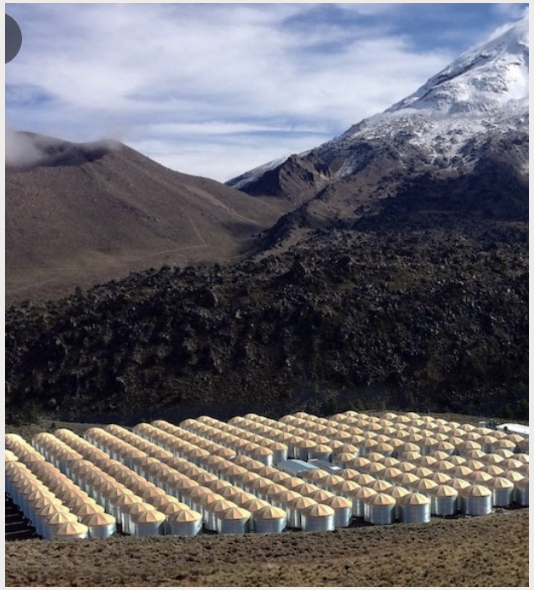
Spectral energy distribution (SED)

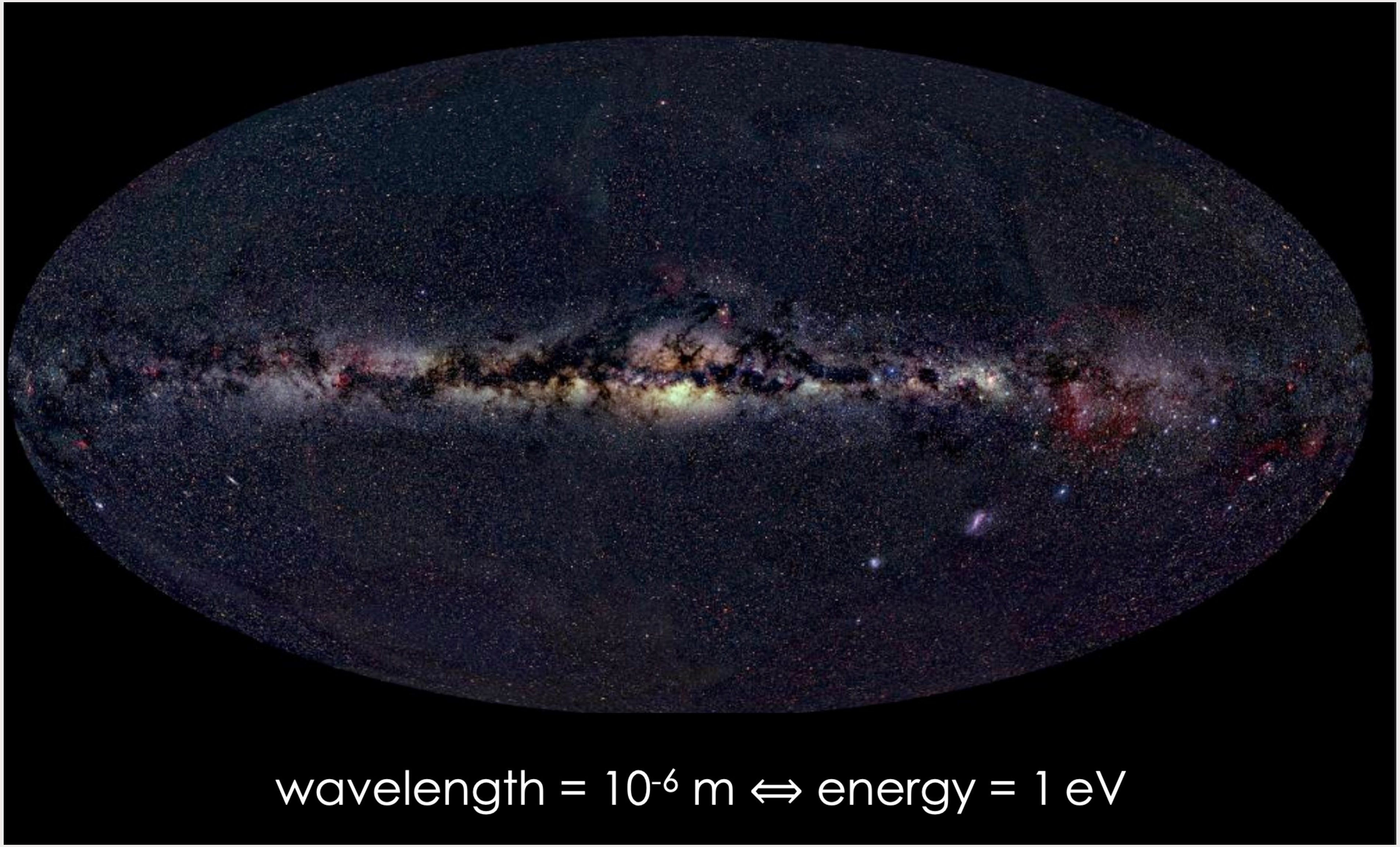
Gamma Ray (Cosmic-ray) Nomenclature

	Range	Type	Detection mec.	Experiments
LE	< 30 MeV	Balloon	Compton Effect	
HE	30 MeV–30 GeV	Satellite	Calorimeter	EGRET, Fermi
VHE	100 GeV–30 TeV	Ground	Atm.–Cherenkov	Whipple, HEGRA (past) **MAGIC**, HESS, Veritas
UHE	30 TeV–30 PeV	Ground	Water–Cherenkov	Milagro
EHE	> 30 PeV	Ground	Atm. Fluorescence	Hires, Auger

- Classification more related to experimental technique (see Monday's lecture!)

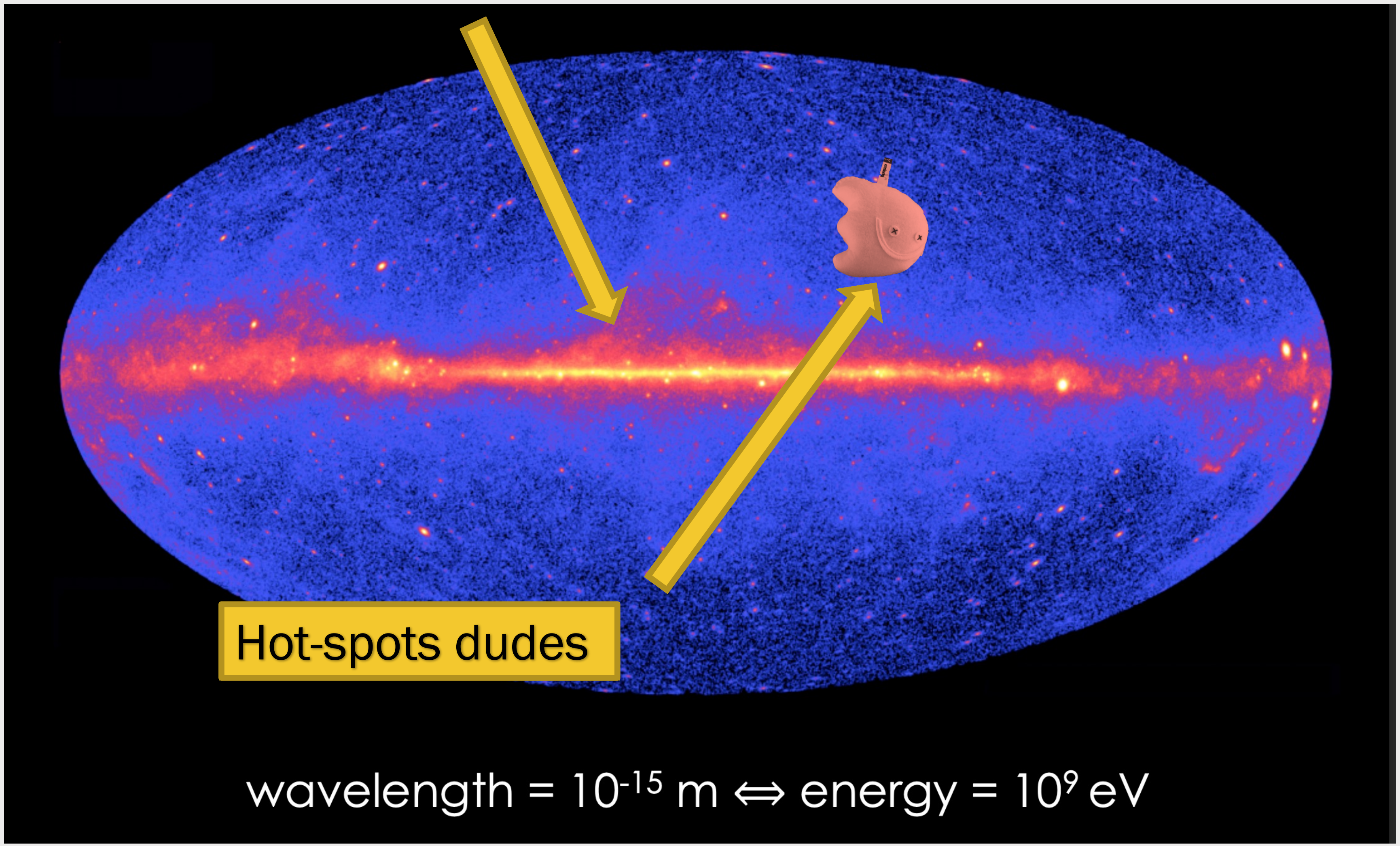


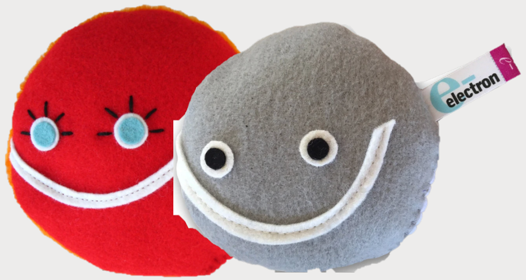


"The Universe as *we see it"* [humans]

Big Party There (Galactic Plane)

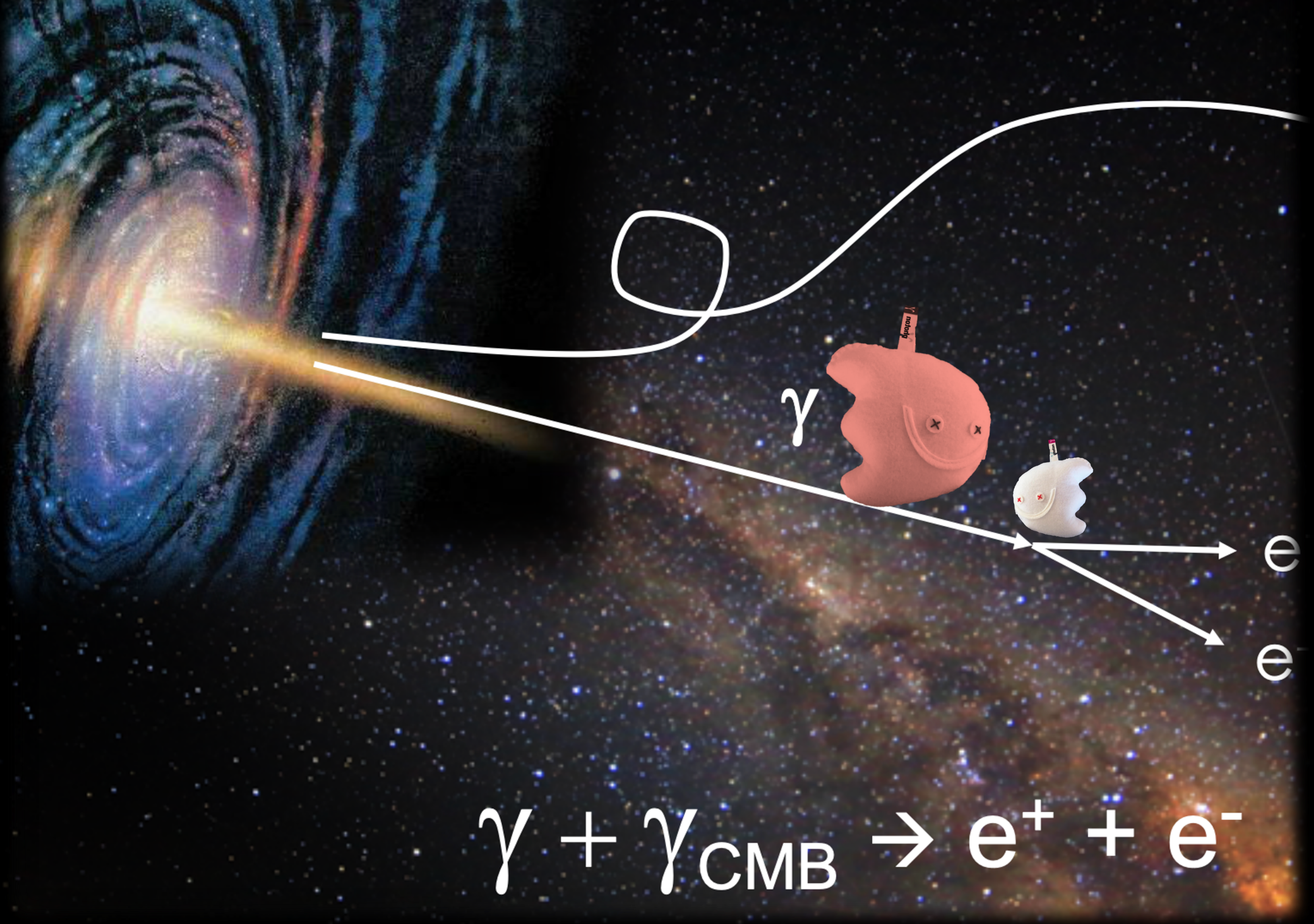




“The Universe as we see it”

“Know a fun fact about highest energy gamma rays?”

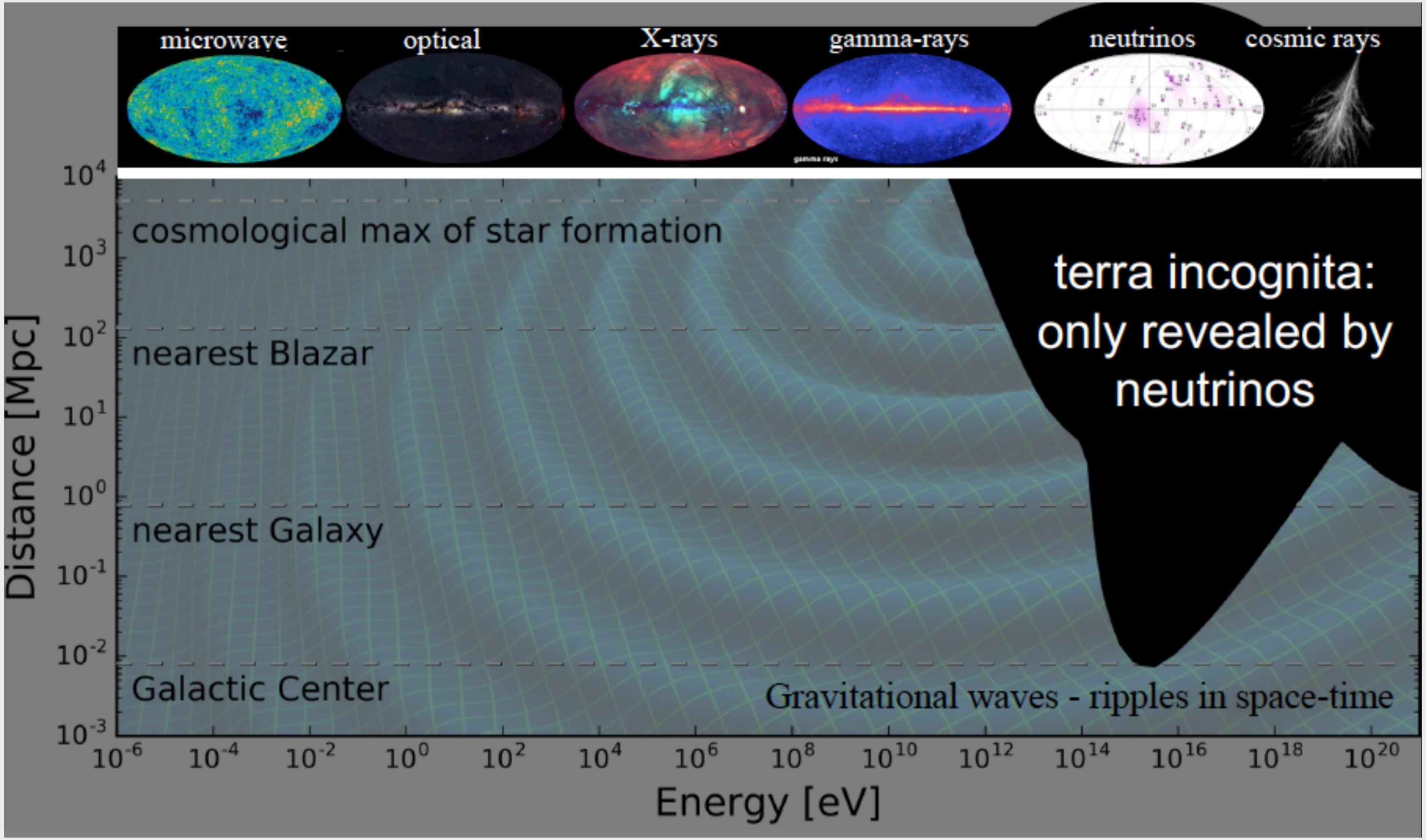
The opaque Universe



"I took too many energ(etic bars)"

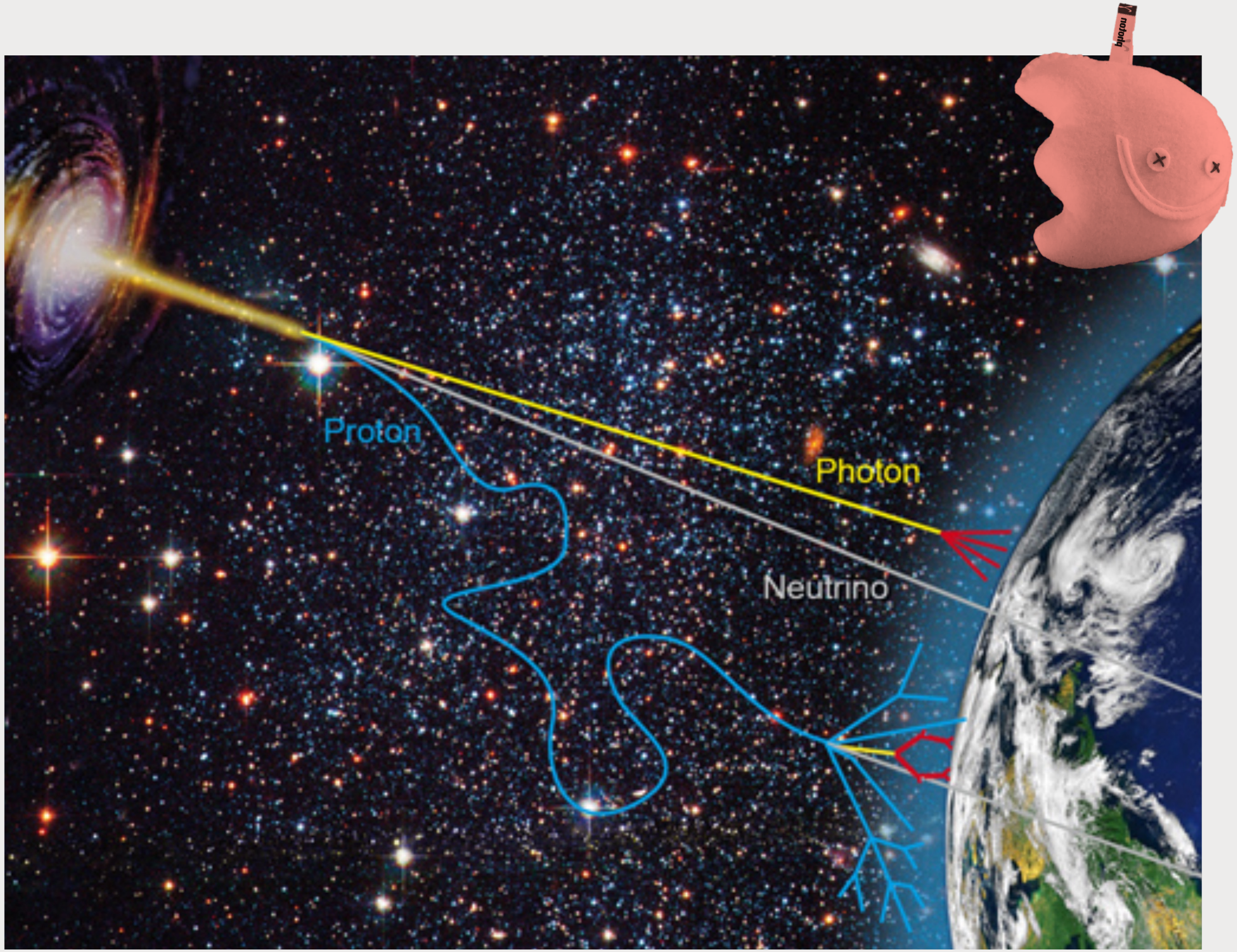
[The high energy gamma]

"I travelled where you'll never do"
[the neutrino]



(the neutrino)

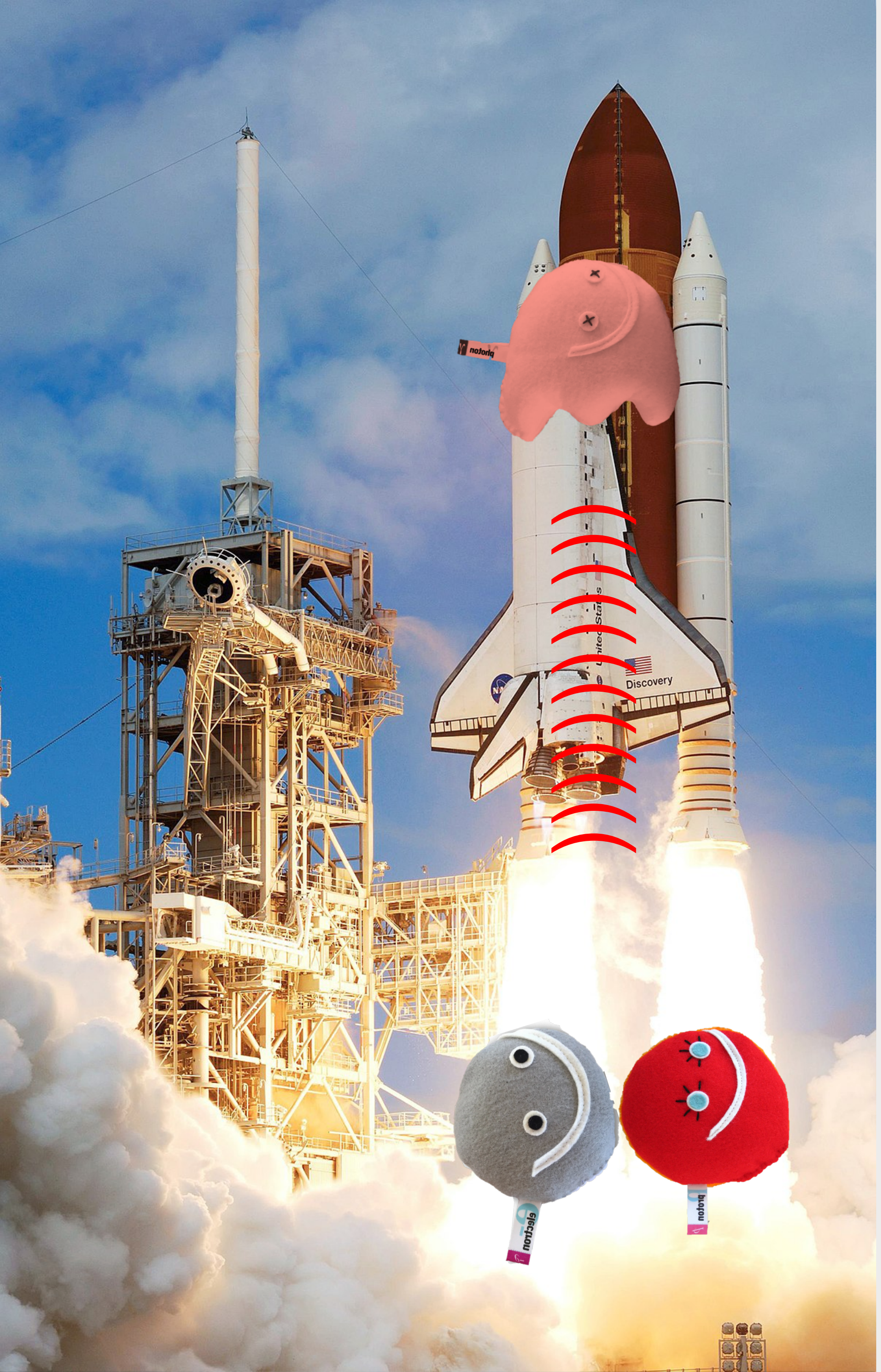
- "Just leave me alone, you'll never catch me"



Importance of being gamma

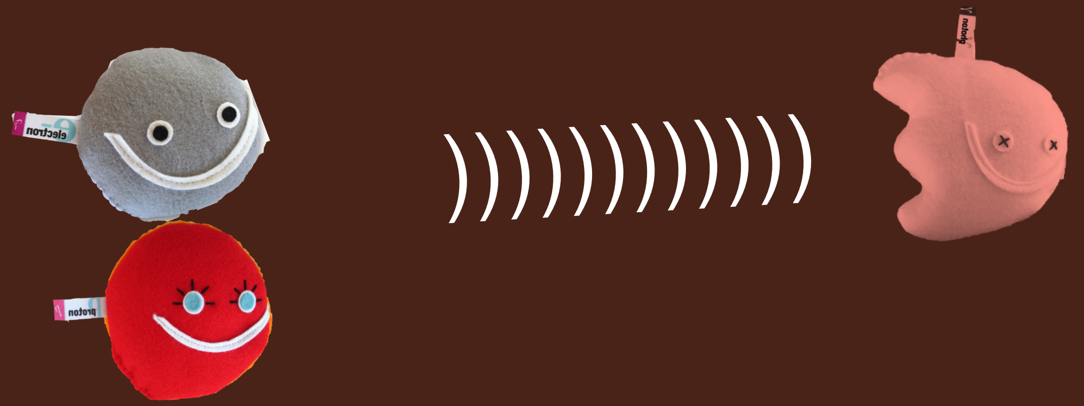
- You are a straight traveller about the galaxies. Who cares about those B-dudes
- Don't get absorbed in the way by low-energy photons!

I like to listen to gamma-ray travel stories, they have a lot to say!

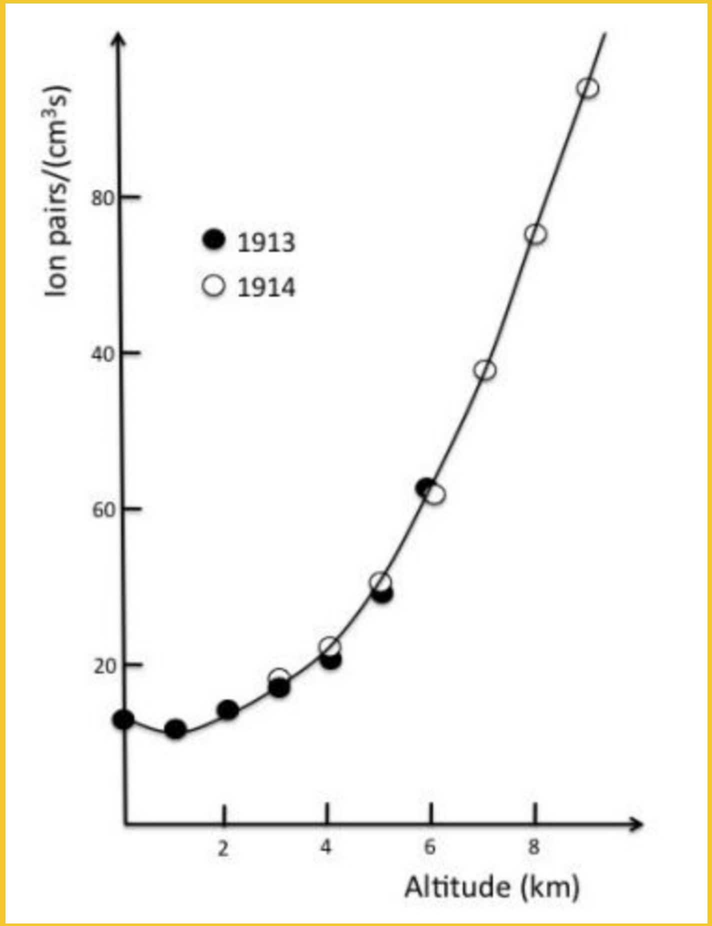


GAMMA RAYS and COSMIC RAYS

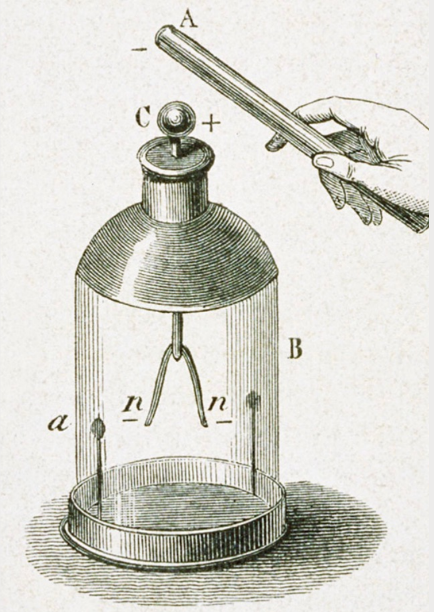
The journey of gamma-rays is very much connected to the journey of COSMIC RAYS



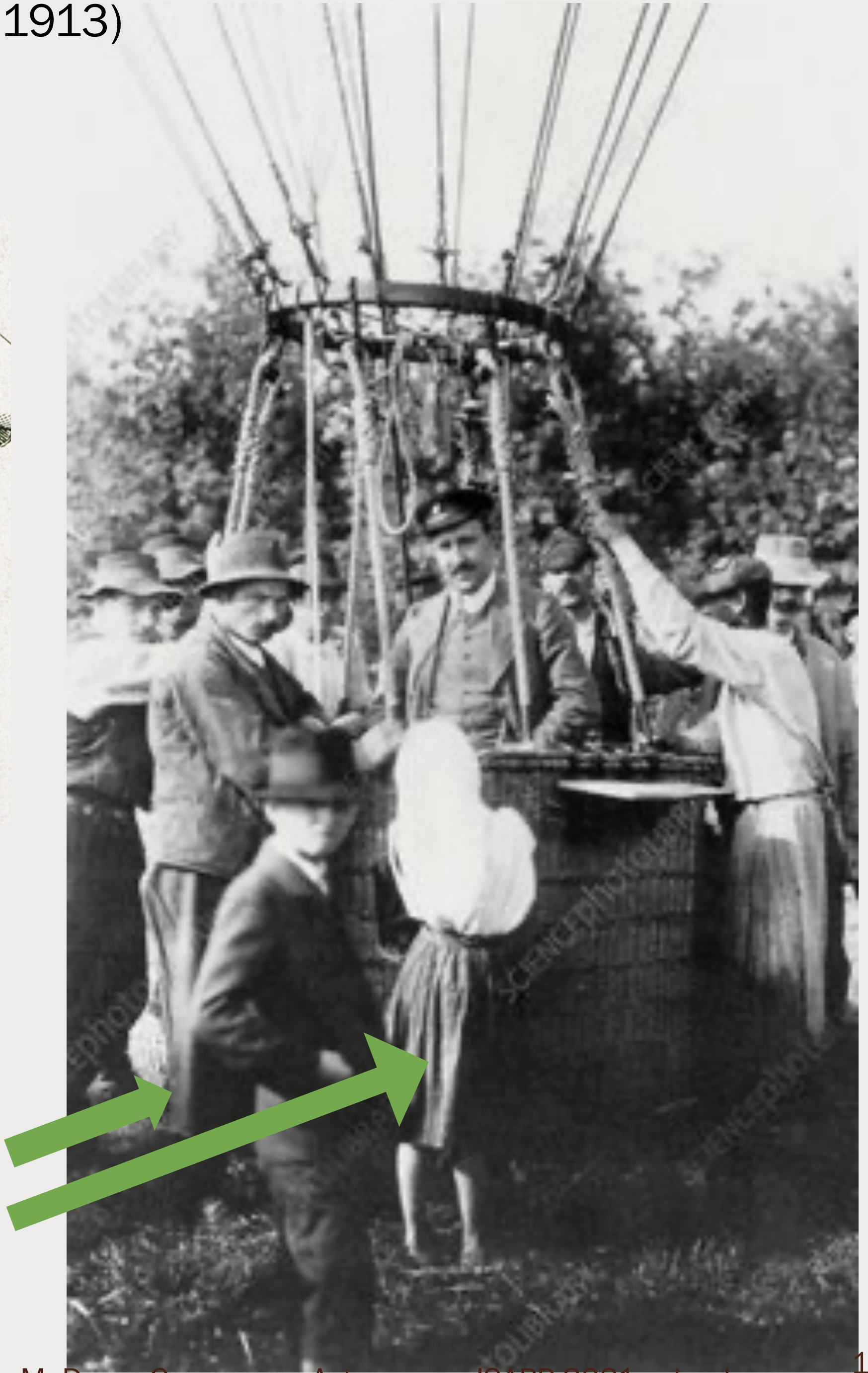
The *Cosmic Ray Spectrum*



Victor Hess (1913)



Electroscope's discharges



Hess's PhD Students!

The amazing *Cosmic Ray Spectrum*

- 19 orders of magnitude in energy
- 32 orders of magnitude in flux

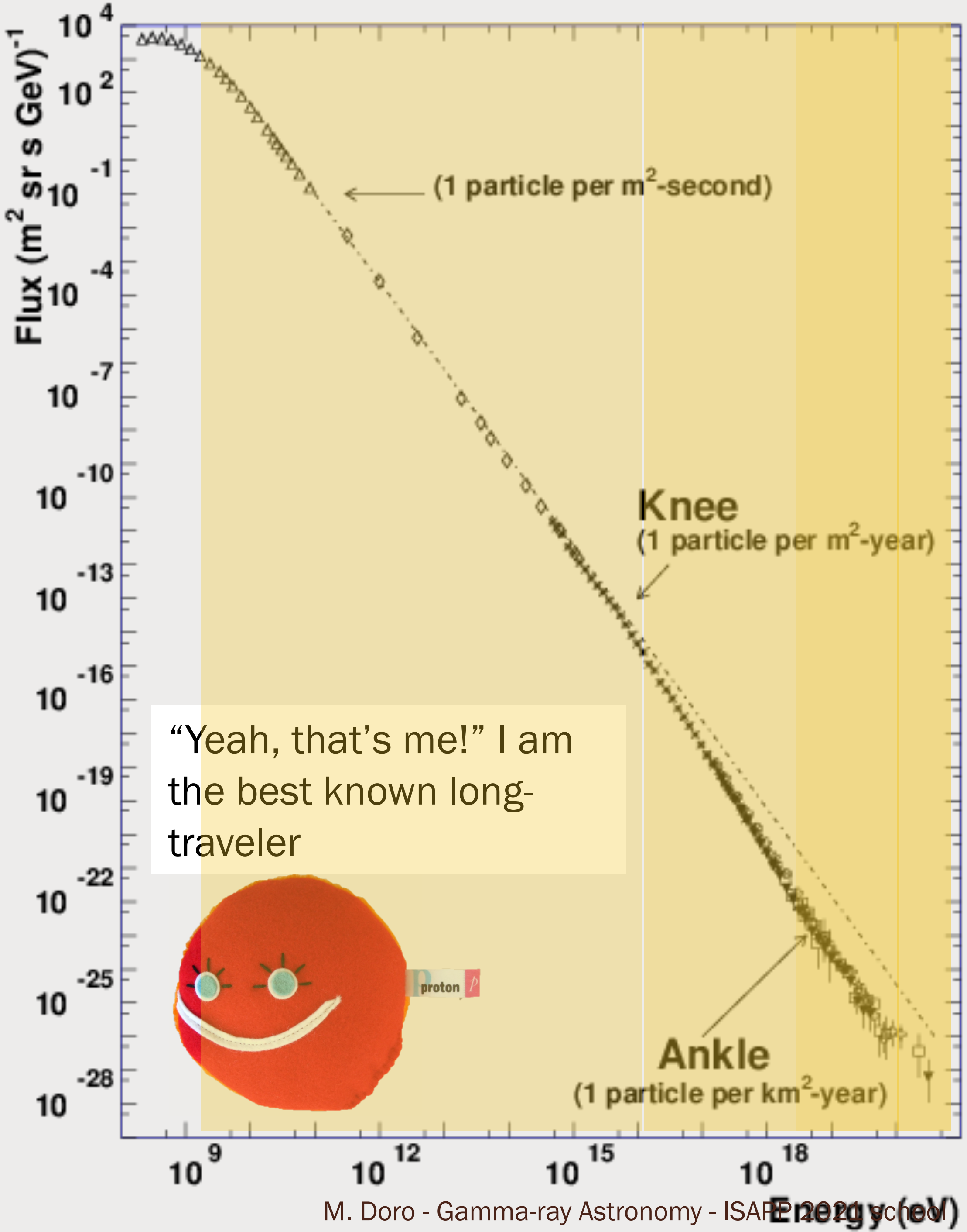
Particle energy (eV)	Particle rate ($m^{-2}s^{-1}$)
1×10^9 (GeV)	1×10^4
1×10^{12} (TeV)	1
1×10^{16} (10 PeV)	1×10^{-7} (a few times a year)
1×10^{20} (100 EeV)	1×10^{-15} (once a century)

$$N(E)\,\mathrm{d}E = \mathrm{const} \cdot E^{-2.7}\,\mathrm{d}E \qquad E < E_{\mathrm{knee}} = 10^{16}\,\mathrm{eV}$$

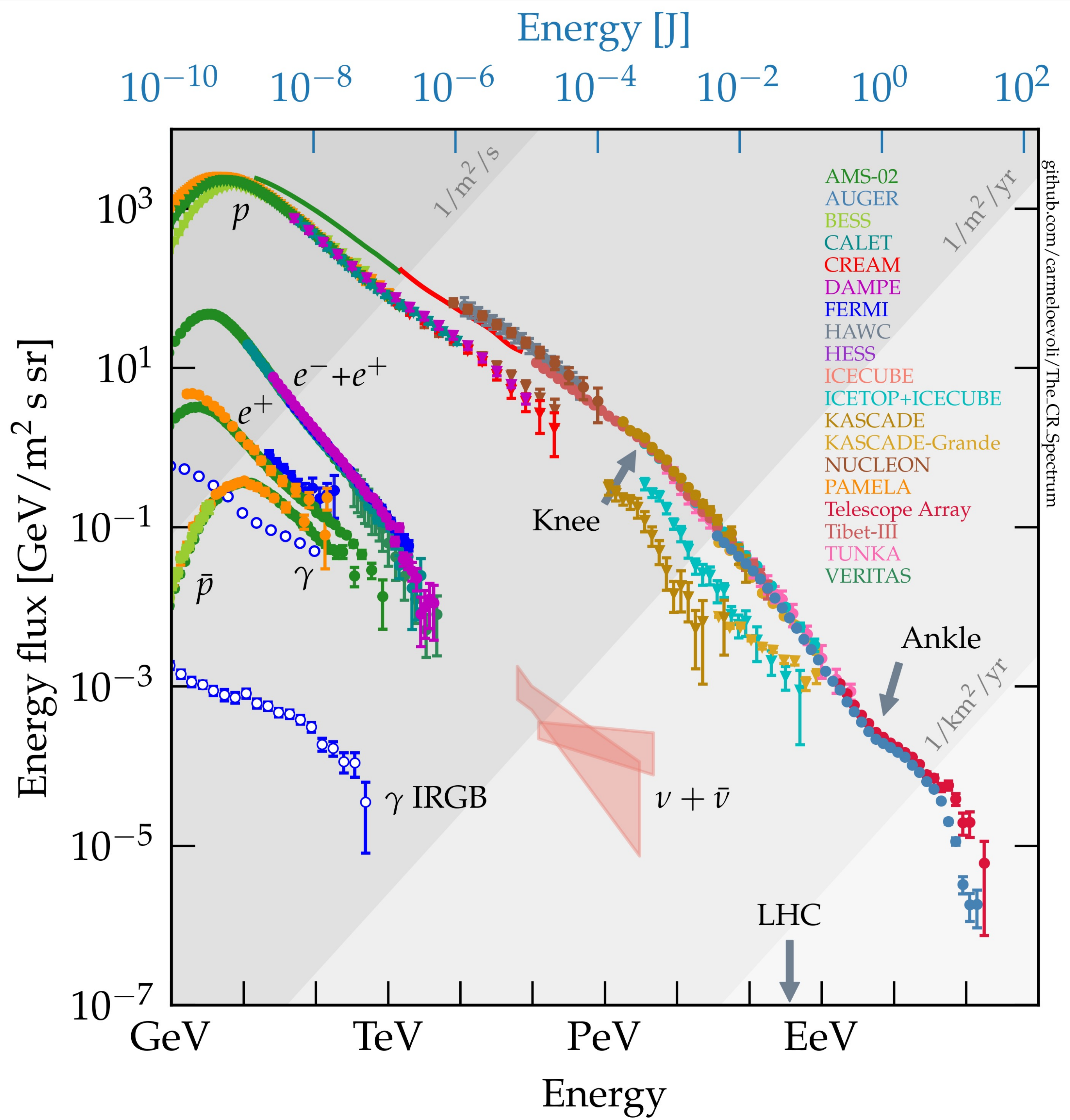
$$N(E)\,\mathrm{d}E = \mathrm{const} \cdot E^{-3.0}\,\mathrm{d}E \qquad E_{\mathrm{ankle}} > E > E_{\mathrm{knee}}$$

$$N(E)\,\mathrm{d}E = \mathrm{const} \cdot E^{-2.69}\,\mathrm{d}E \qquad E_{\mathrm{GZK}} > E > E_{\mathrm{ankle}}$$

$$N(E)\,\mathrm{d}E = \mathrm{const} \cdot E^{-4.2}\,\mathrm{d}E \qquad E > E_{\mathrm{GZK}} = 4 \times 10^{19}\,\mathrm{eV}$$

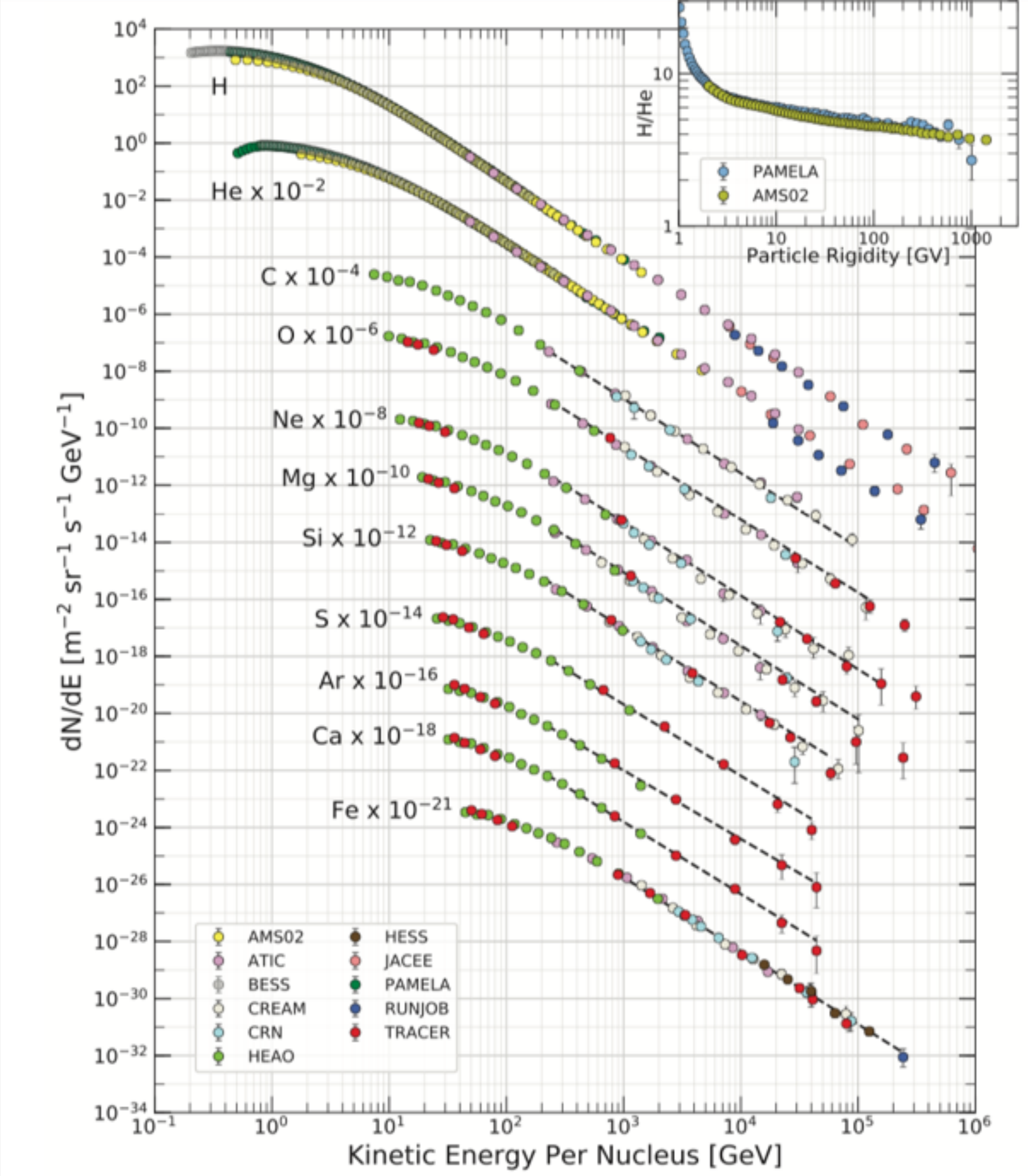


"Yeah, that's me!" I am the best known long-traveler



A crowded space!

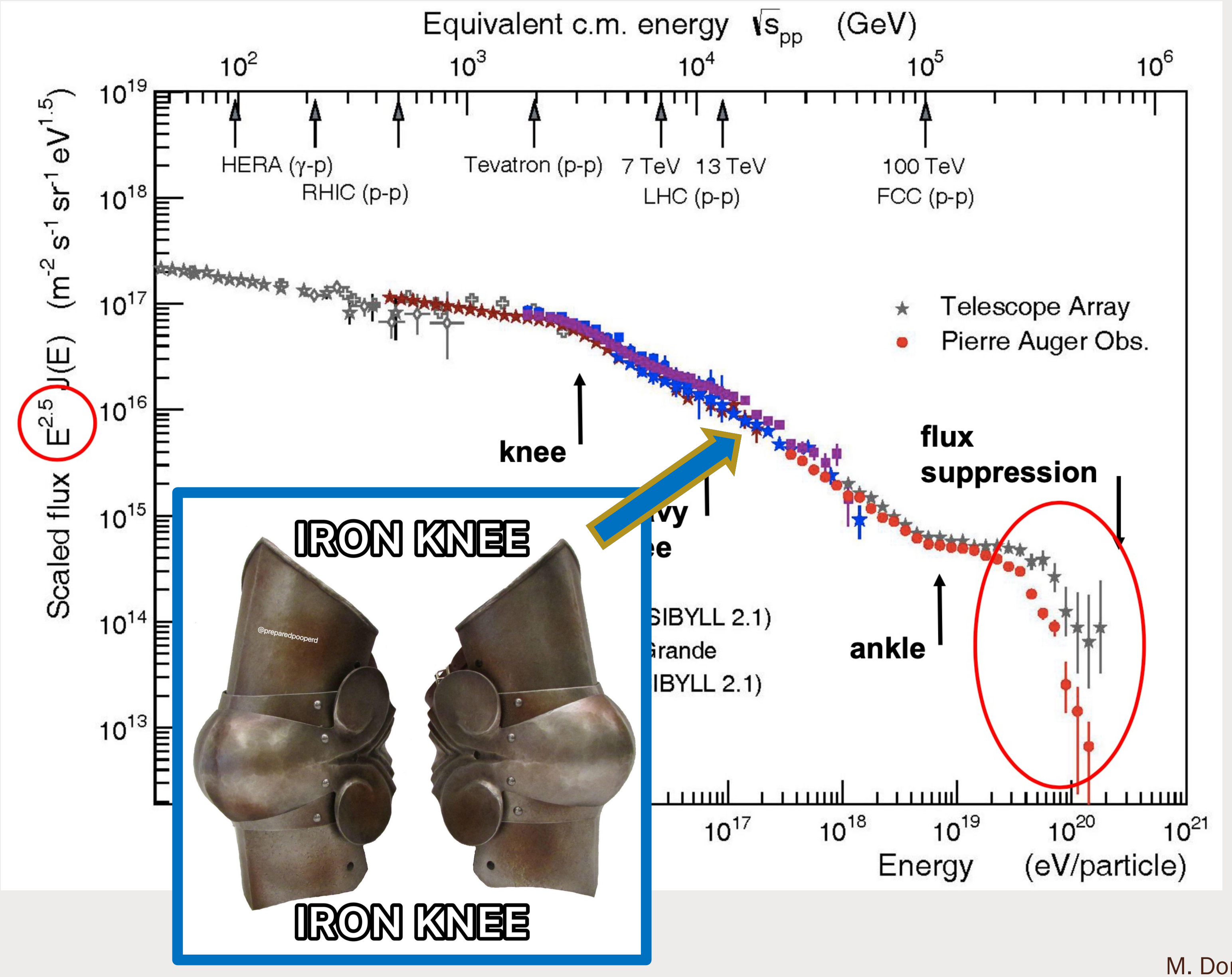
- Travellers:
  - *Protons and antiprotons*
  - *Heavier cosmic rays,*
  - *Electrons, positrons*
  - *Gammas*
  - *neutrinos*
- Experiments!
- Spectral features!



Heavier nuclei

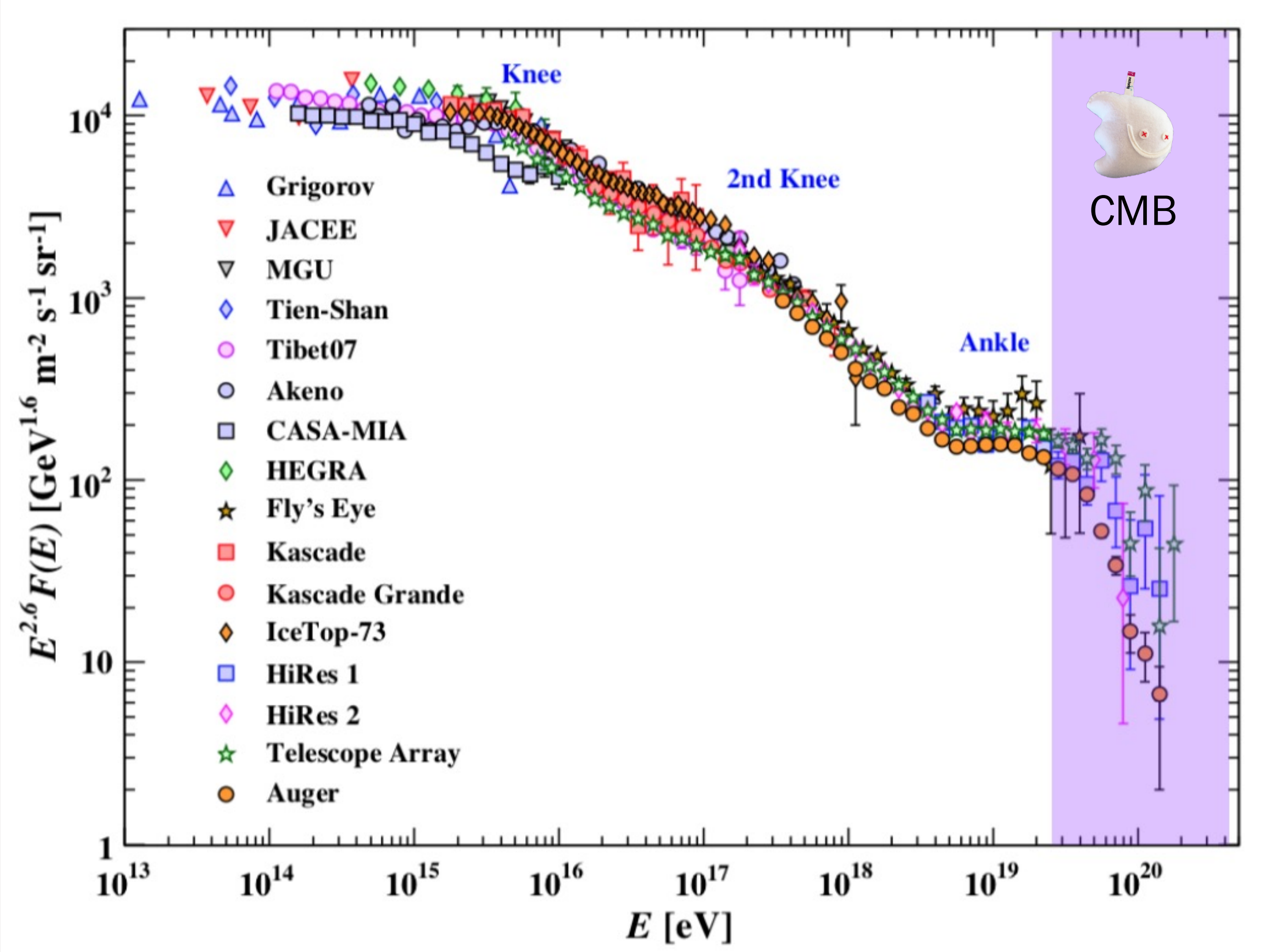
- Idrogen and iron nuclei observed to the larger energies!

Knees, iron knee



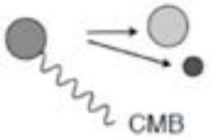
- Details show the imprint of different particle
- Cosmic rays have a iron knee!

The high energy end

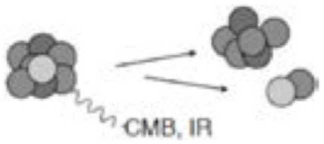


"When I travel too fast, I hit those damned CMB photons, they are everywhere"

$$p + \gamma_{CMB} \to p + \pi^0$$
$$\to n + \pi^+$$
$$\to p + e^+ + e^-$$

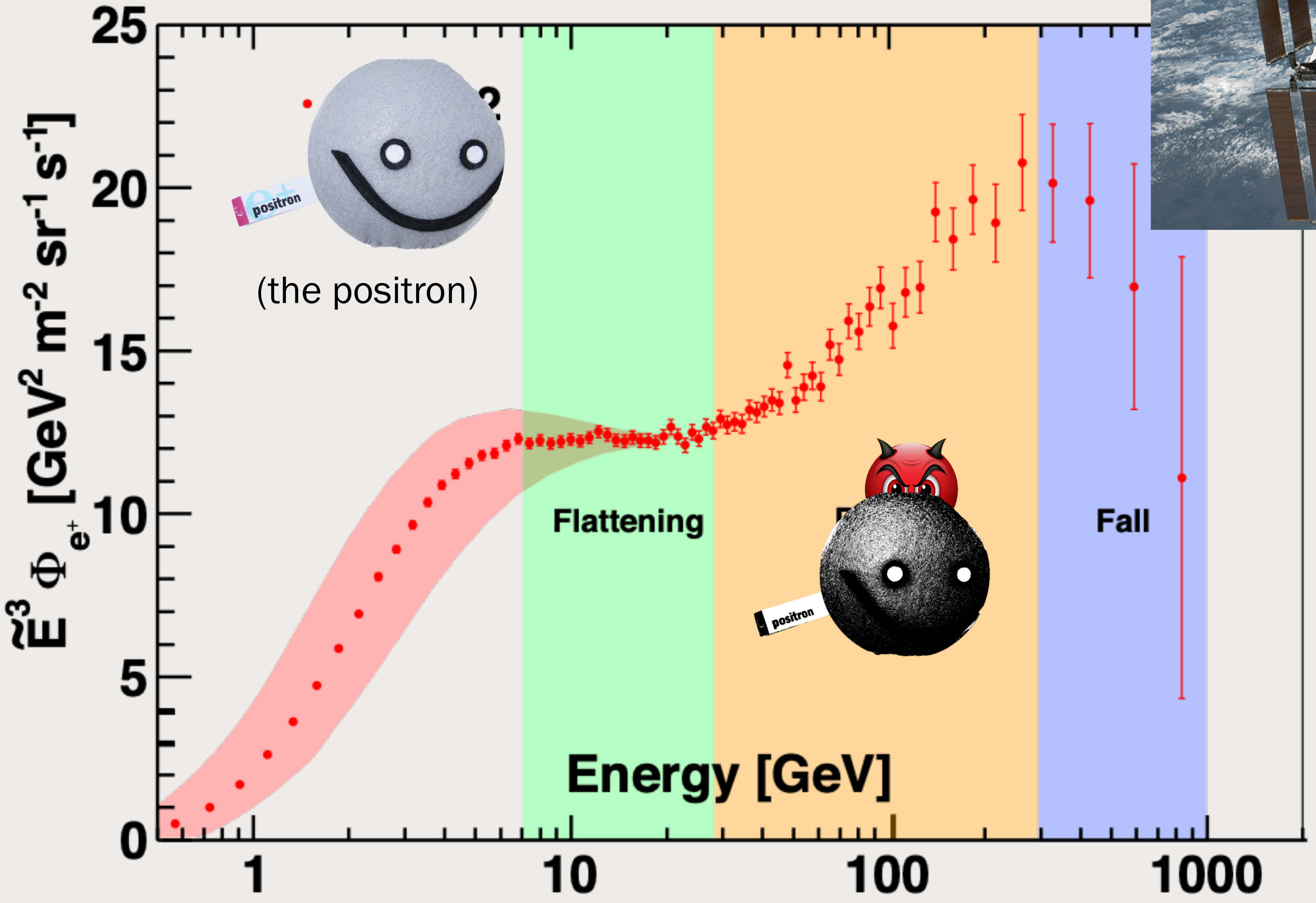


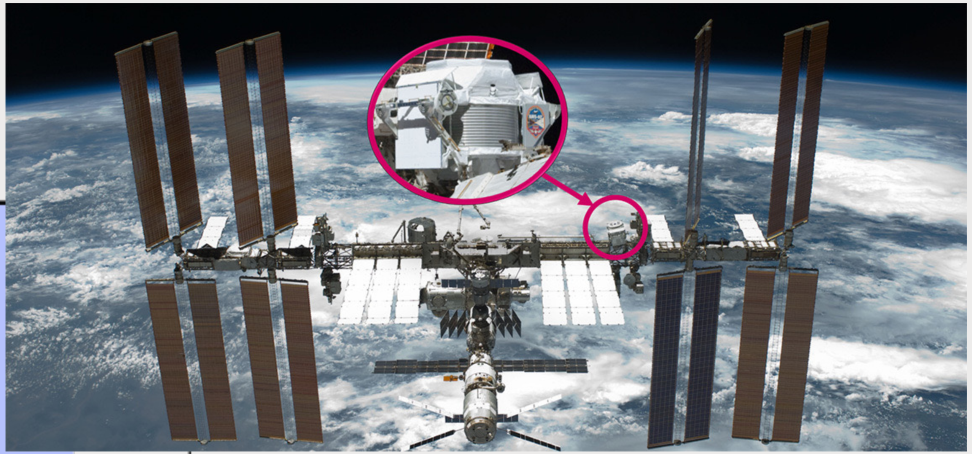
$$A + \gamma_{CMB} \to (A-1) + n$$
$$\to (A-2) + 2n$$
$$\to A + e^+ + e^-$$



- Greisen-Zatsepin-Kuz'min (GZK) cutoff

Anomalies

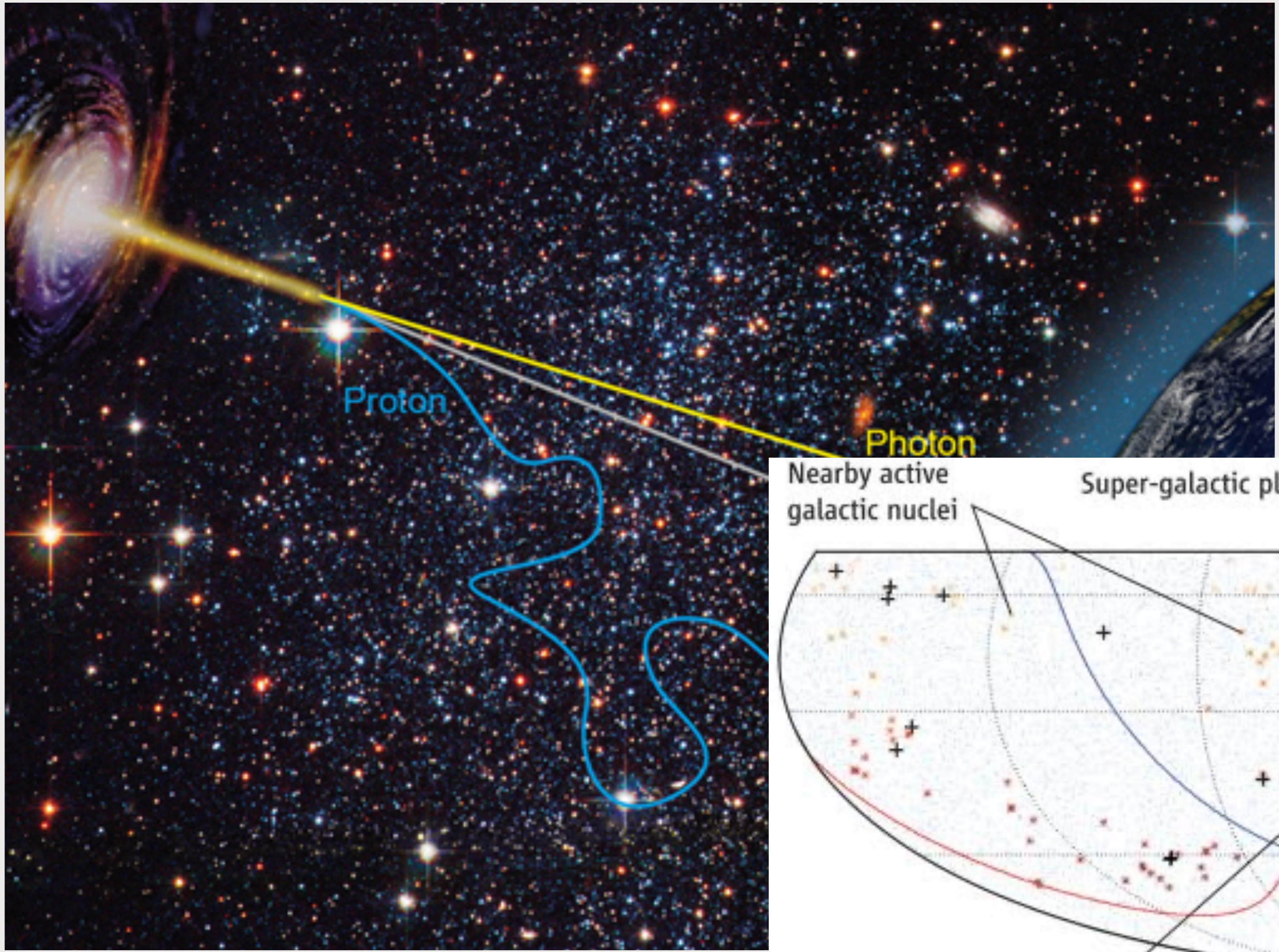


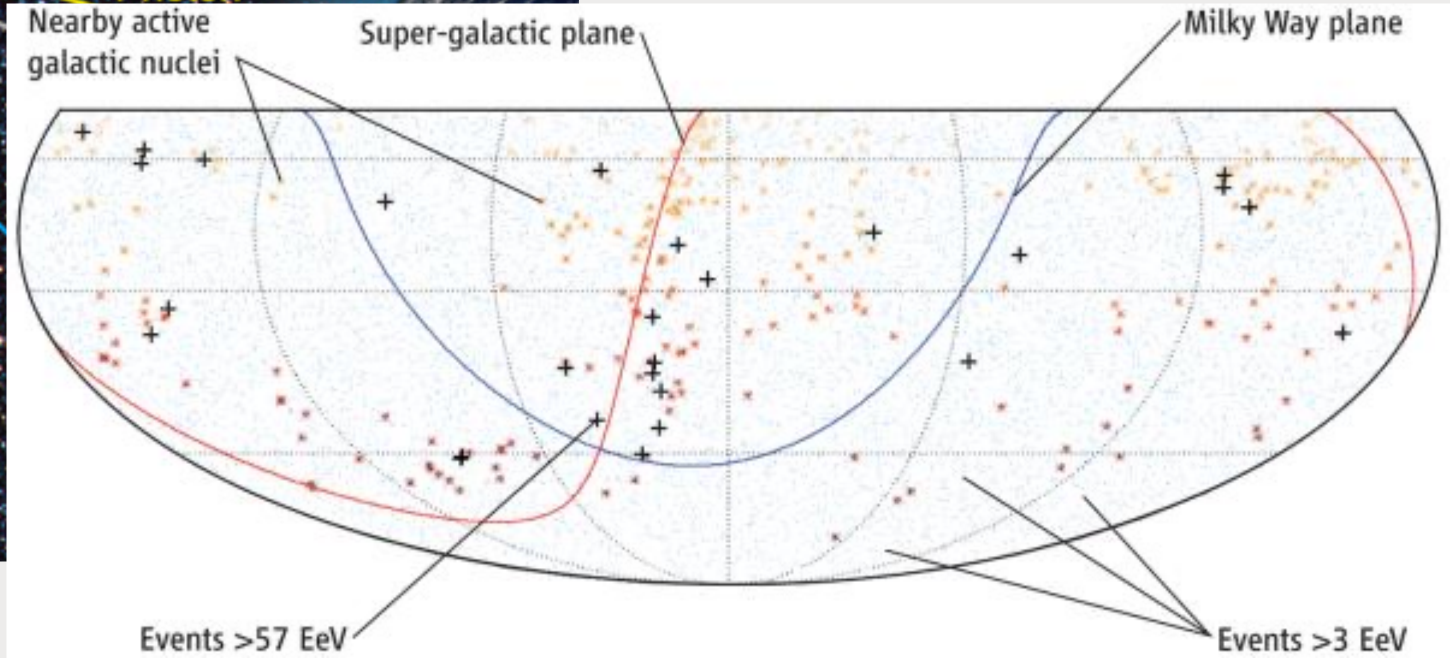


Positrons are produced via cosmic ray spallation of carbon and oxygen

https://ams02.space/physics/towards-understanding-origin-cosmic-ray-positrons

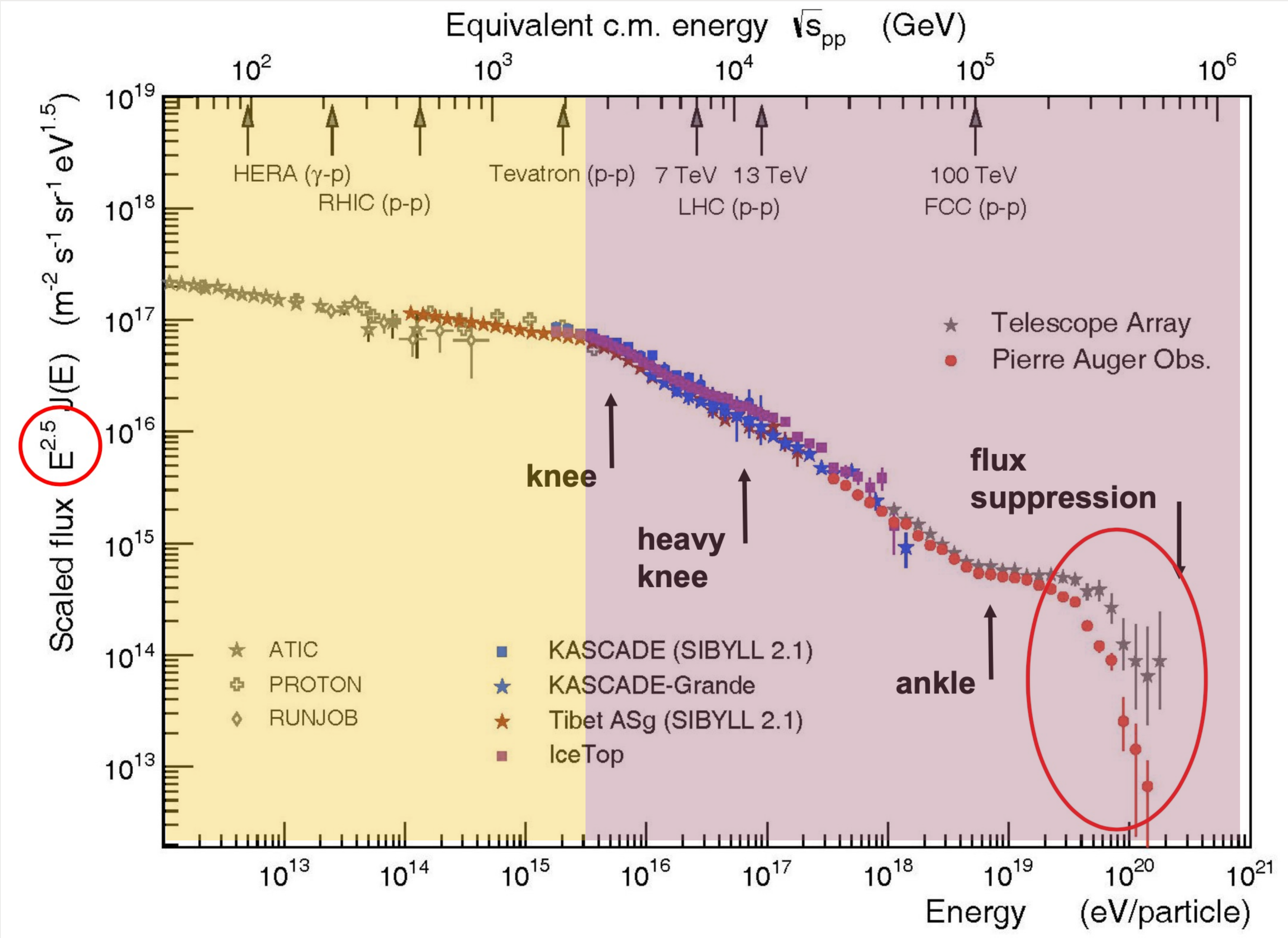
Passport please





- Only recently found association of UHE CR with nearby Extragalactic Objects
- Auger *Science* 09 Nov 2007:
  Vol. 318, Issue 5852, pp. 938-943

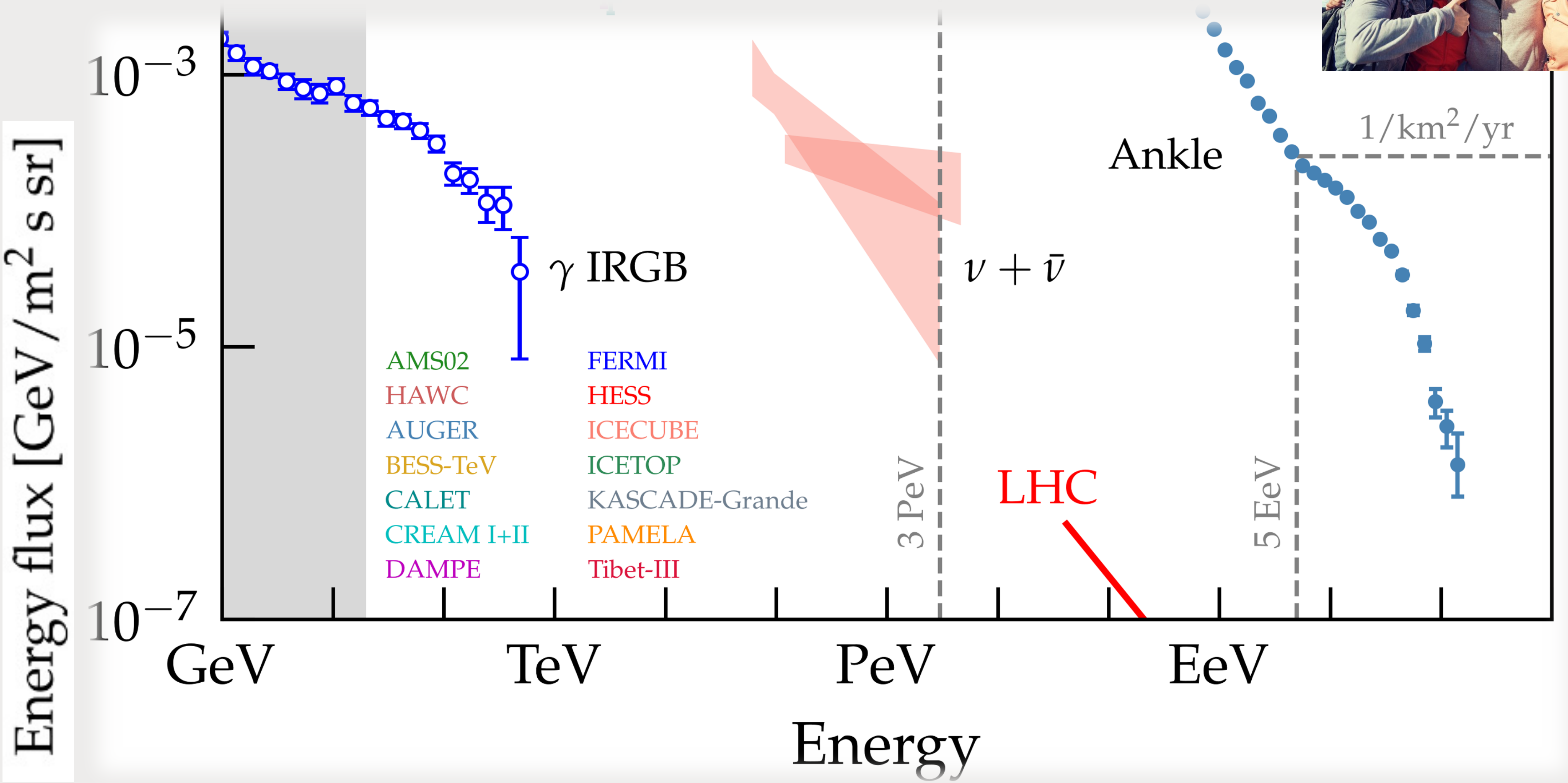
Tell us where you're from



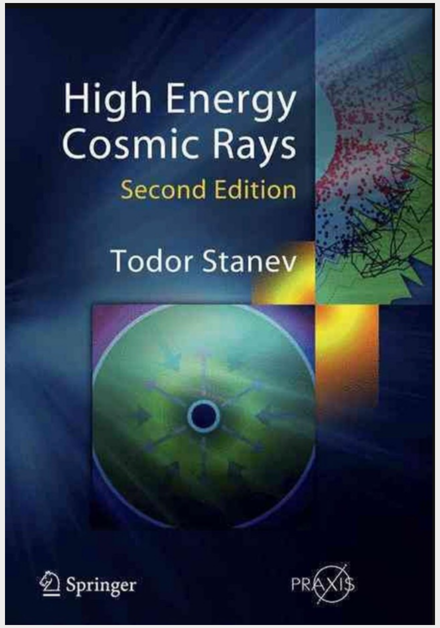
GALACTIC

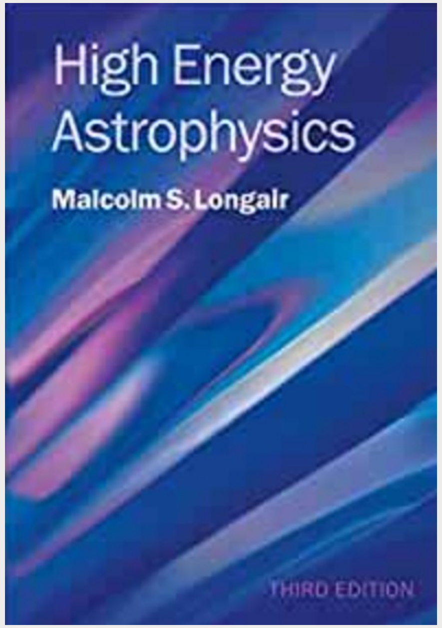
EXTRAGALACTIC

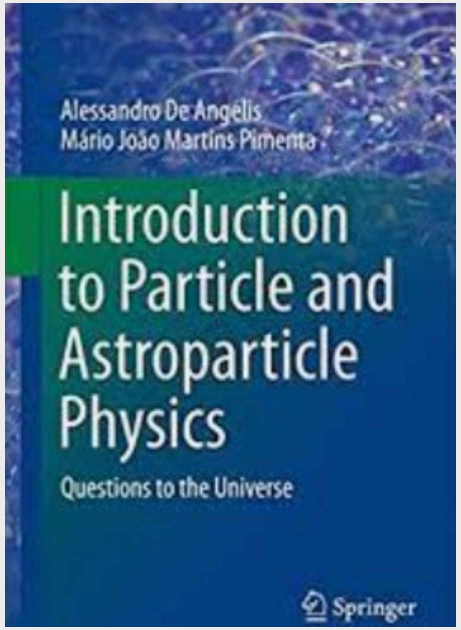
Are you also from?

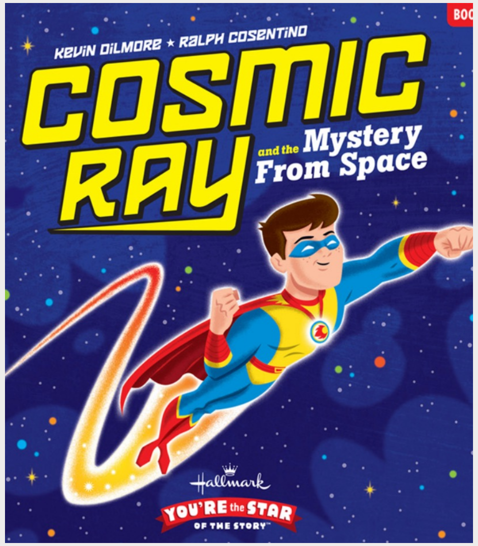


References, e.g.

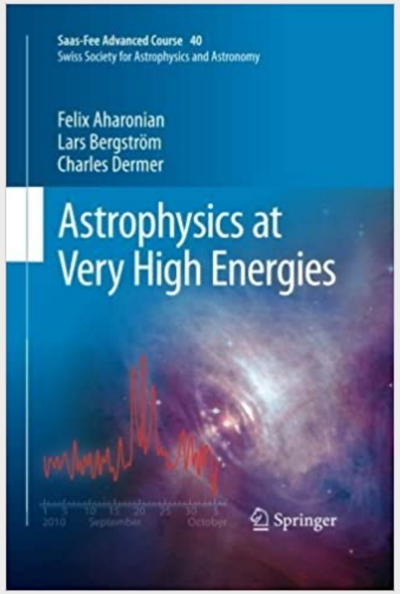


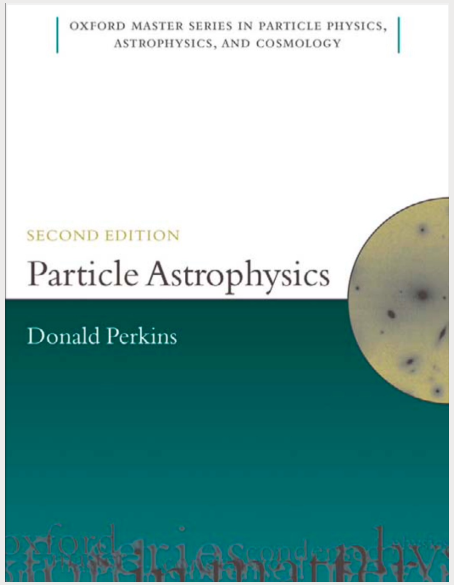


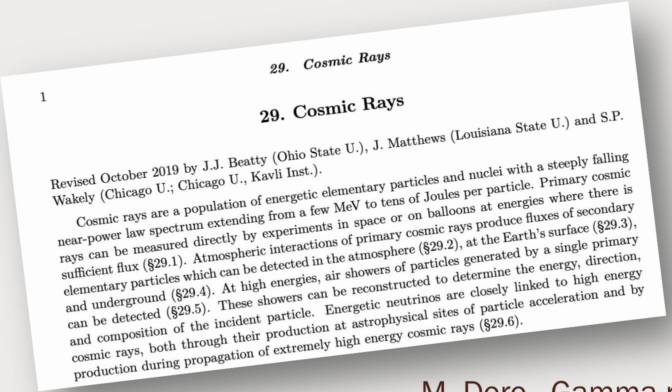




For family and friends







29. Cosmic Rays

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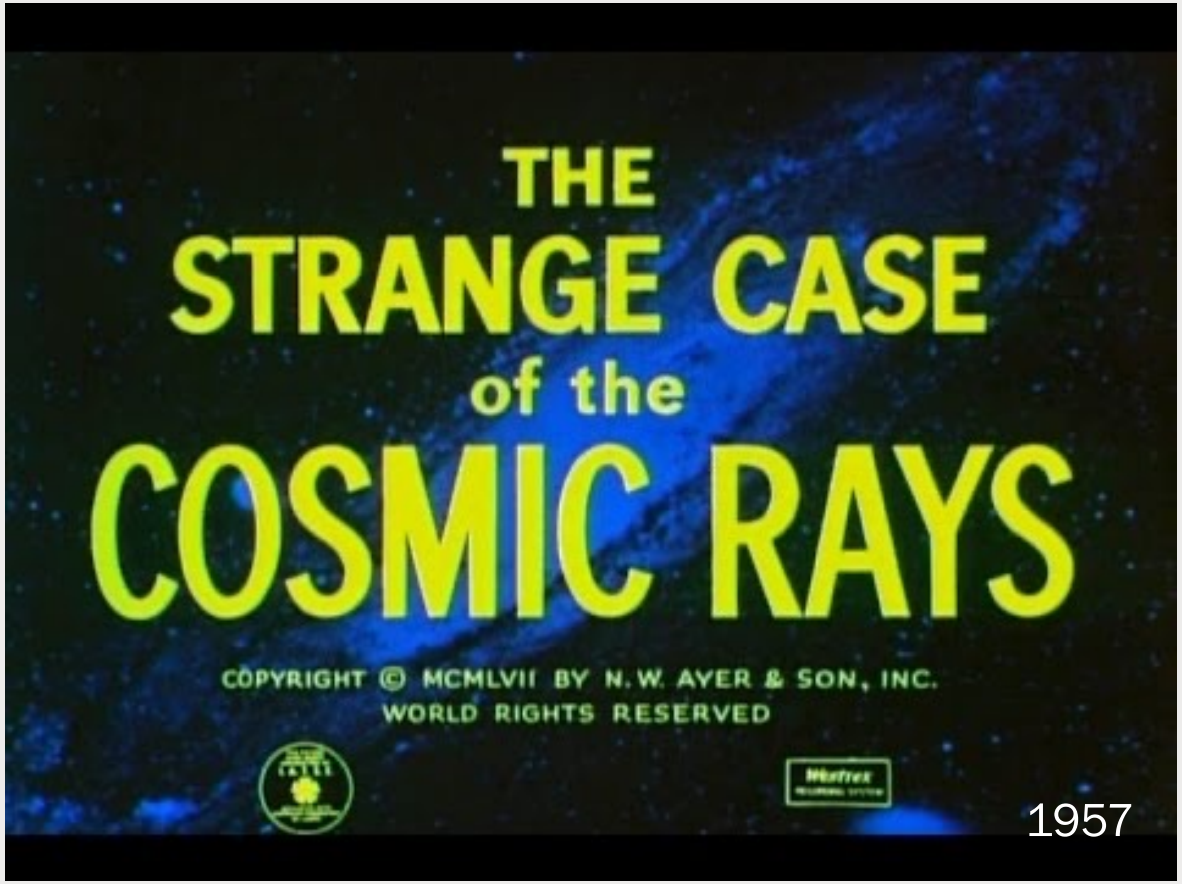
29. Cosmic Rays

Revised October 2019 by J.J. Beatty (Ohio State U.), J. Matthews (Louisiana State U.) and S.P. Wakely (Chicago U.; Chicago U., Kavli Inst.).

Cosmic rays are a population of energetic elementary particles and nuclei with a steeply falling near-power law spectrum extending from a few MeV to tens of Joules per particle. Primary cosmic rays can be measured directly by experiments in space or on balloons at energies where there is sufficient flux (§29.1). Atmospheric interactions of primary cosmic rays produce fluxes of secondary elementary particles which can be detected in the atmosphere (§29.2), at the Earth's surface (§29.3), and underground (§29.4). At high energies, air showers of particles generated by a single primary can be detected (§29.5). These showers can be reconstructed to determine the energy, direction, and composition of the incident particle. Energetic neutrinos are closely linked to high energy cosmic rays, both through their production at astrophysical sites of particle acceleration and by production during propagation of extremely high energy cosmic rays (§29.6).

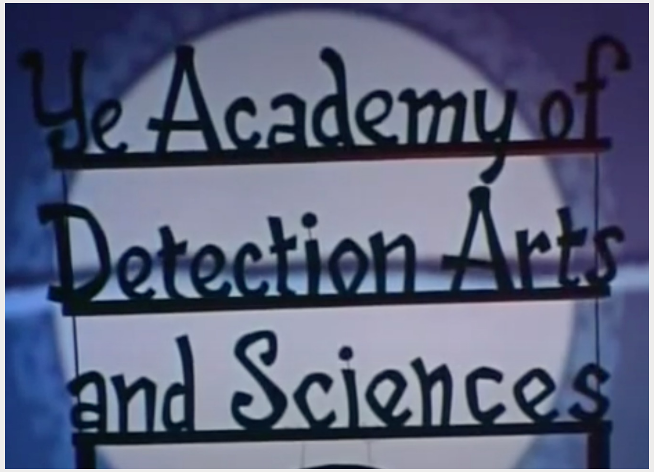
Particle Data Group (PDG) biannual reviews



1957

“Wanna see an out-of-this-world true detective story?...”


The scientists

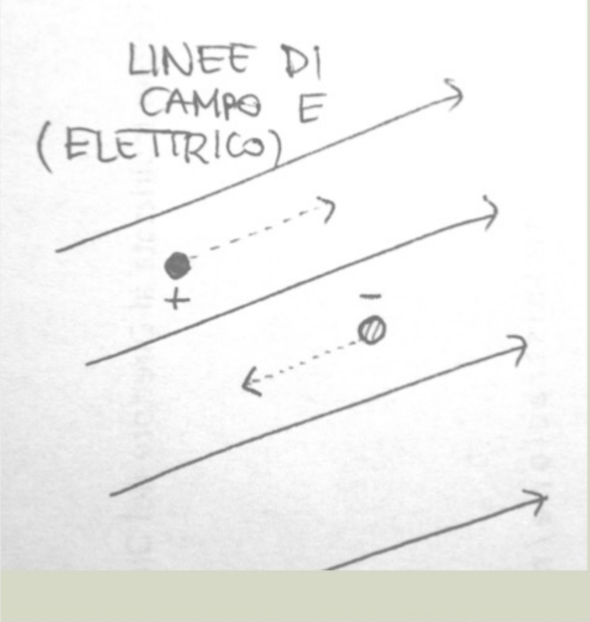


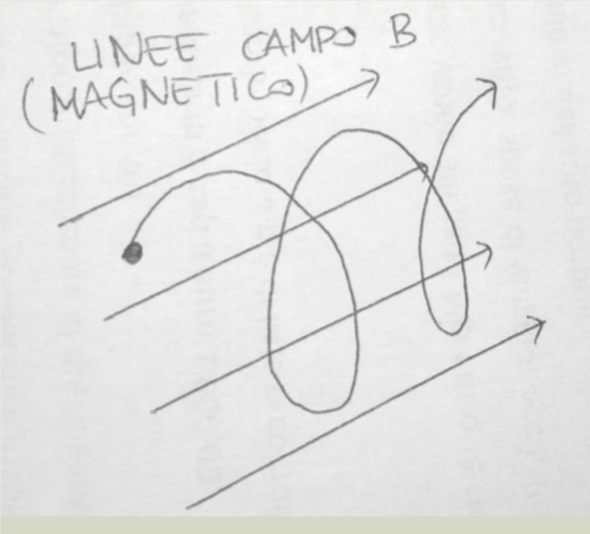

C. Dickens E. Allan Poe F. Dostoevsky

https://www.youtube.com/watch?v=tPuvuRrJy7M

How to fuel up for a long interstellar travel?

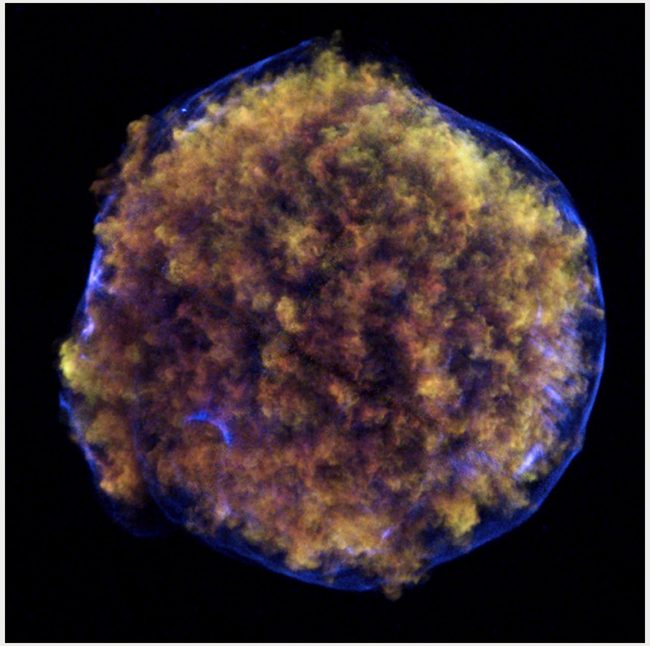
How to accerelate a particle



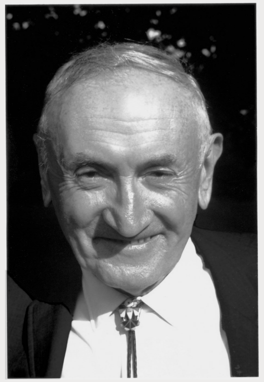


- Electric field
  - *It is easy to accelerate, but E field quickly neutralized*
  - *May work if few charges around*
- Magnetic field
  - *Permanent magnetic field do not accelerate*
  - *Variable magnetic fields → variable electric fields → acceleration*

Not only acceleration



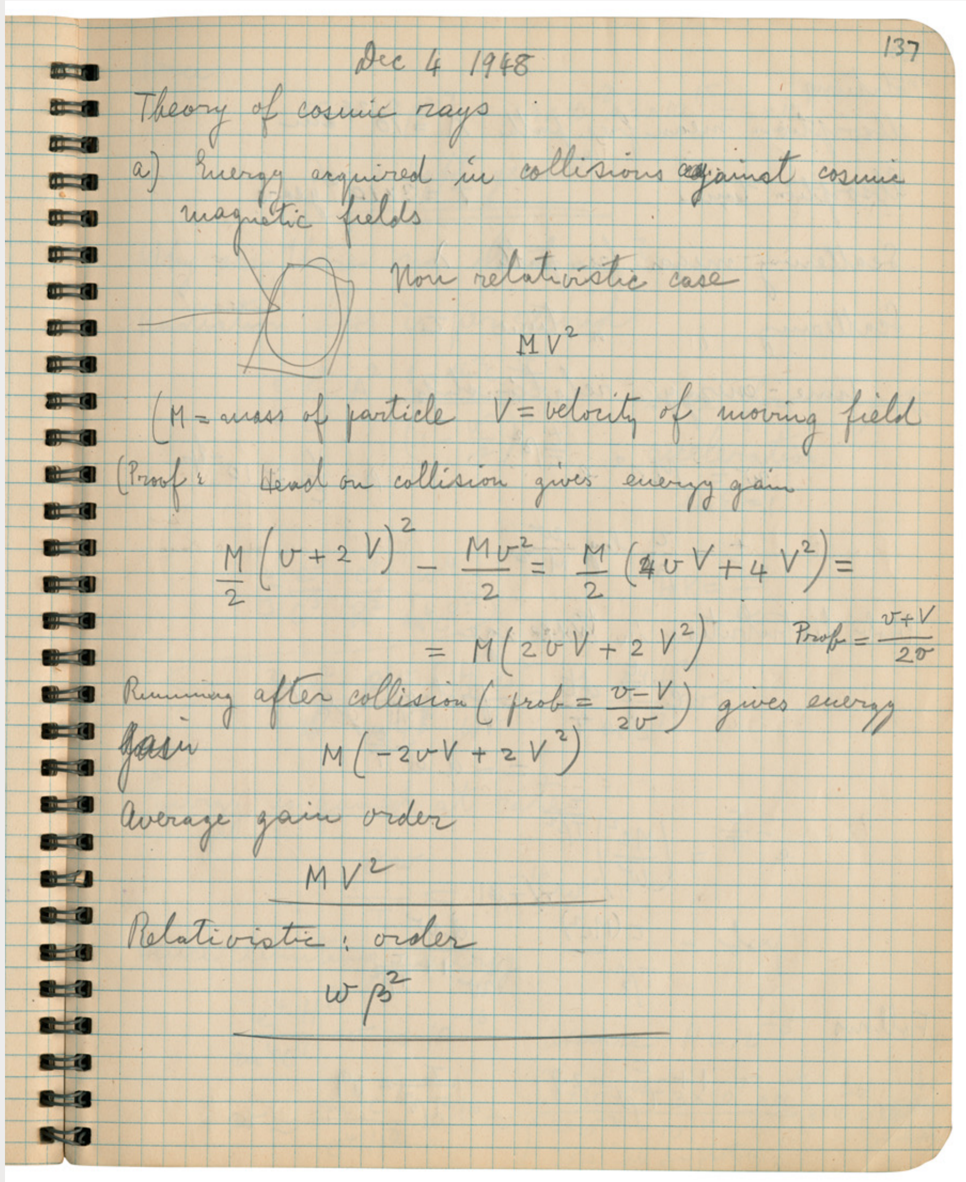
This is not a jellyfish



Ptitsyna+ 0808.0367

- Geometry:
  - *the accelerated particle should be maintained within the object during the acceleration process;*
- Power and emissivity:
  - *the source should be able to provide the necessary energy for the accelerated particles;*
  - *the density and power of sources must be enough to account for the observed UHECR flux;*
- Radiation and interaction losses:
  - *within the accelerating field the energy gained by a particle should be no less than its radiation energy loss;*
  - *the energy lost by a particle due to its interaction with other particles should not be greater than its energy gain;*
- 1933 Zwicky and Baade simplest conjecture: *"The largest explosions we know are in stellar endlife bursts, that's where CR are from"*

1948 Fermi



Dec 4 1948 137

Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields

Non relativistic case

MV^2

(M = mass of particle V = velocity of moving field

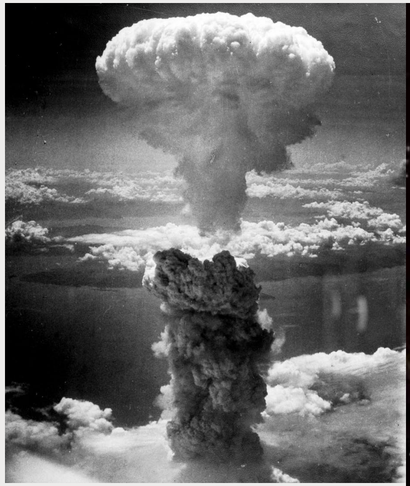
(Prob: Head on collision gives energy gain

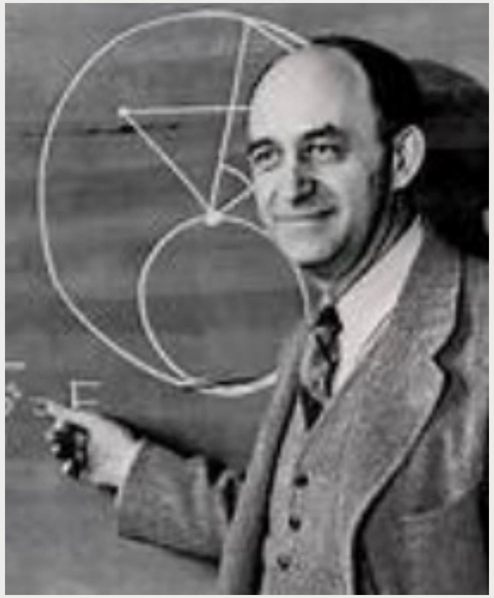
$$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV+4V^2) = M(2vV+2V^2) \qquad \text{Prob} = \frac{v+V}{2v}$$

Running after collision (prob $= \frac{v-V}{2v}$) gives energy gain $M(-2vV+2V^2)$

Average gain order MV^2

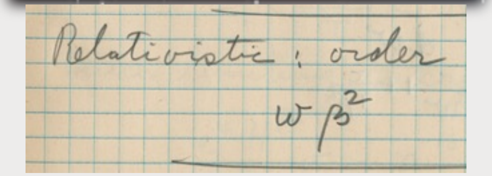
Relativistic: order $w\beta^2$

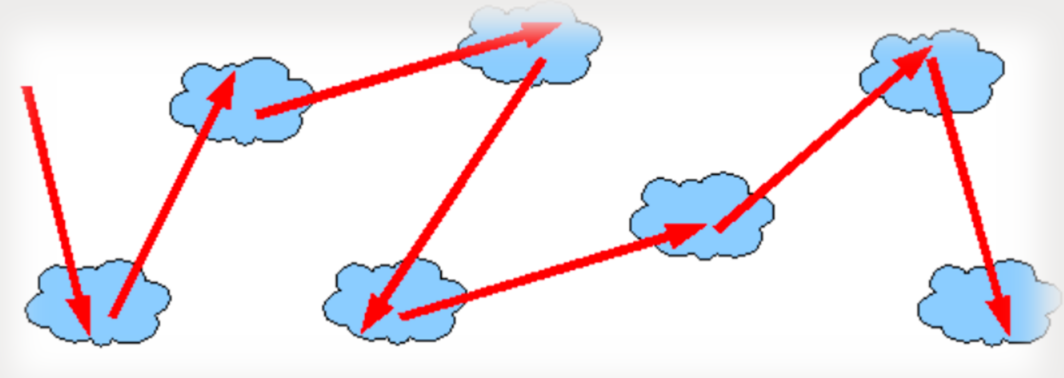




- There must be great atomic bombs in the sky
- Expanding shells of material with charged particle and magnetic fields
- Charged particle around get stochastic acceleration by bumping into those shells

2nd order Fermi acceleration





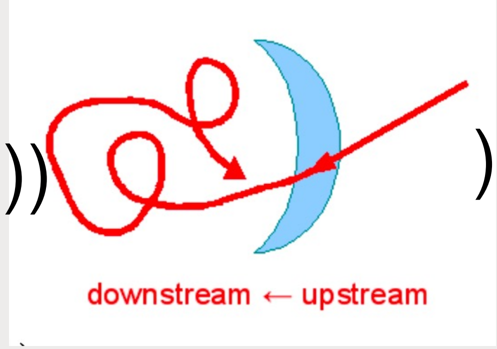
- Charged particle in a shock wave make stochastic collisions with a moving ionized blob of material (cloud) with magnetic fields embedded
- Cloud act as scatterer
- By computing probability, at each encounter:

$$\left\langle \frac{\Delta E}{E} \right\rangle \approx \frac{4}{3}\left(\frac{v}{c}\right)^2$$

Not efficient: since $\beta = \frac{v}{c} \sim 10^{-4} - 10^{-2}$

Fermi 1st order: diffusive shock acceleration

)))))



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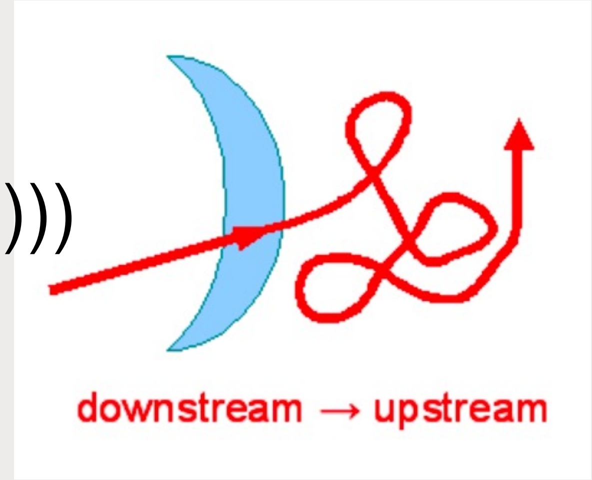


Linear dependence! And considering particle velocity distribution:

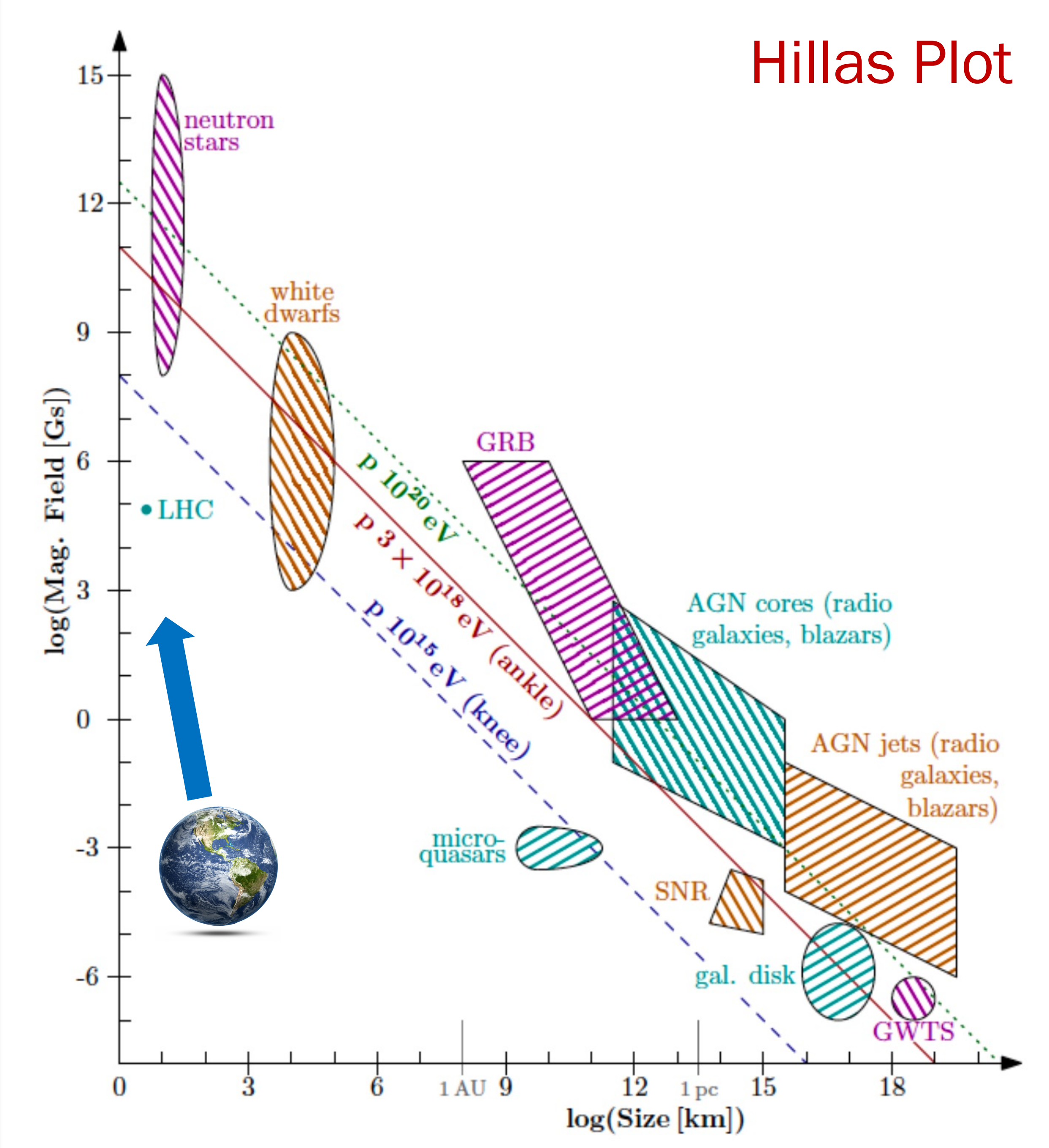
$$\frac{dN_\gamma}{dE} = \left(\frac{E}{E_0}\right)^{-\Gamma}$$

with $\Gamma \sim -2.5$

Wait: is the cloud that random?

- In the shock, a shock front is formed that expand faster that sound speed
- Upstream material is swept up by the (magnetized) shock front, when downstream, it can be randomly scatterer back to the front
  - *Particle trapped in magnetic mirrors upstream-downstream*
- By counting probability now

$$\left\langle\frac{\Delta E}{E}\right\rangle \approx \frac{4}{3}\frac{v}{c}$$



Fuel at Magnetic fields station

- The maximum energy of a particle q escaping a region with B at distance R is

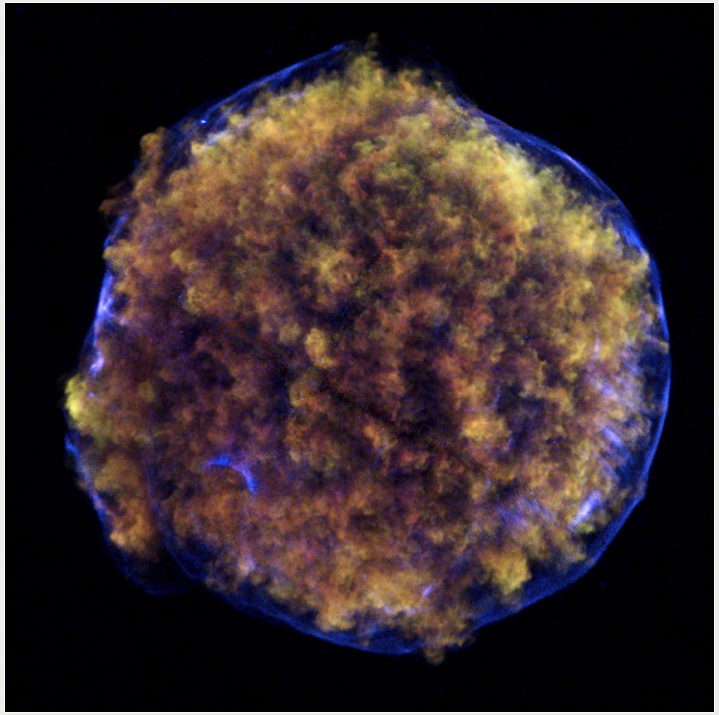
$$\varepsilon_{max} = qBR$$

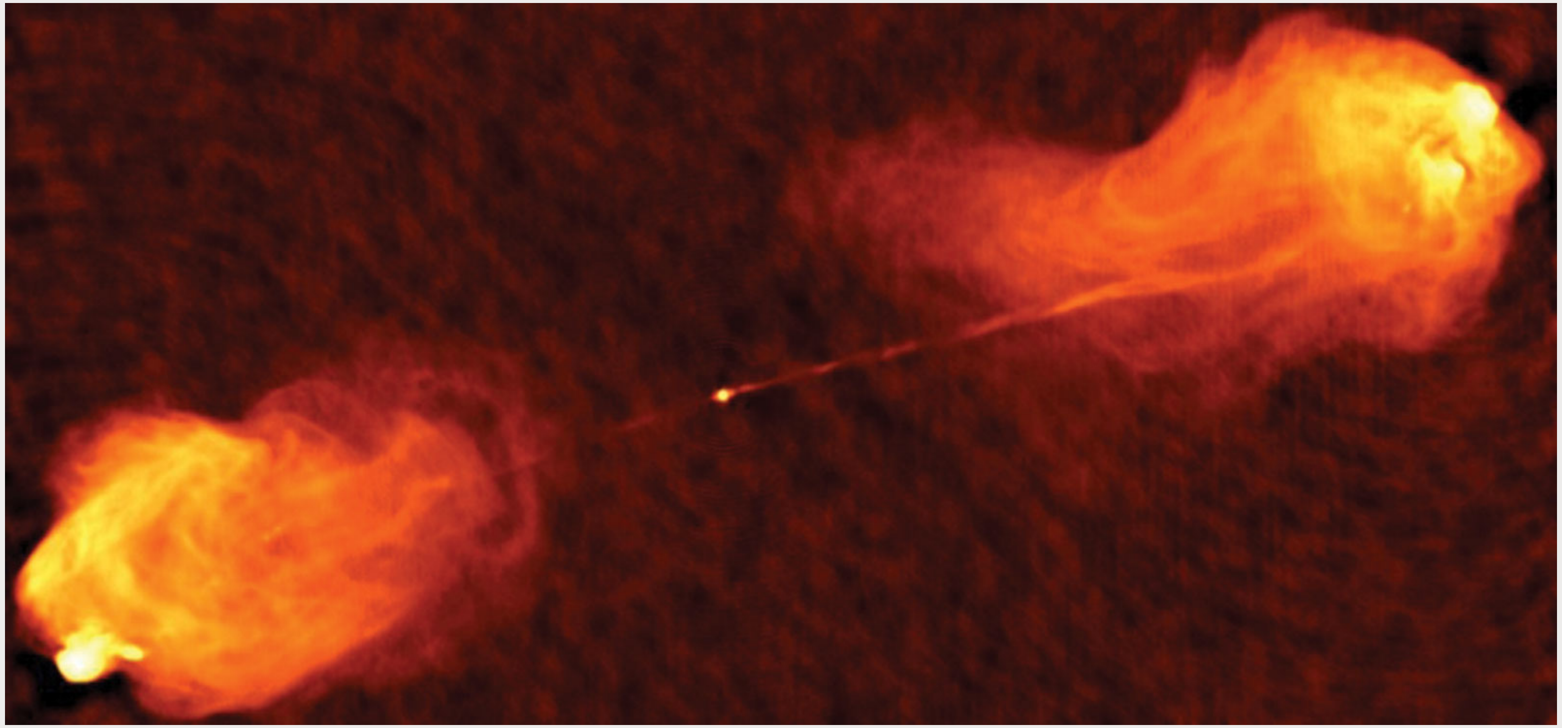
[Hillas Criterion]

- Shaded regions includes losses

M. Hillas

Diffusive Acceleration in jets too





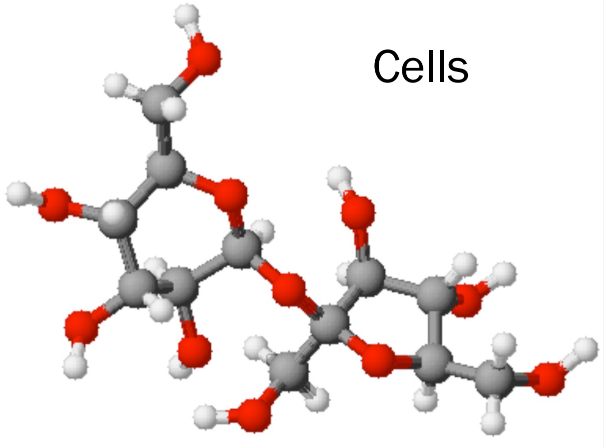
- Universe displays great booms (stellar explosition, BH matter conversion)
  - *Shocks are formed that lasts k-M years*
- Diffusion of particles around the shocks generate slow-but-steady acceleration

Energy conversion efficiency

$$\eta = \frac{\Delta E}{\Delta m c^2}$$

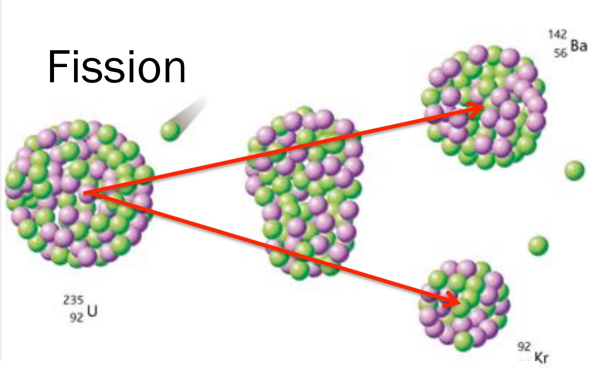
Credit: Gabriele Ghisellini

$$\eta = \frac{mgh}{mc^2} = \frac{980 \times 10^4 \,(h/100\text{ m})}{9 \times 10^{20}\text{ erg}} \sim 10^{-14}$$

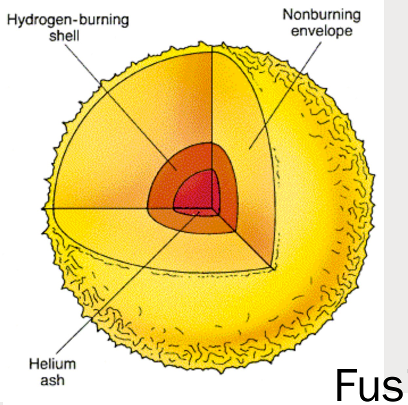


Sugar saccharose $C_{12}H_{22}O_{11}$

$$\eta = \frac{E}{mc^2} = \frac{1.6 \times 10^{11}\text{erg}}{9 \times 10^{20}\text{ erg}} = 1.8 \times 10^{-10}$$



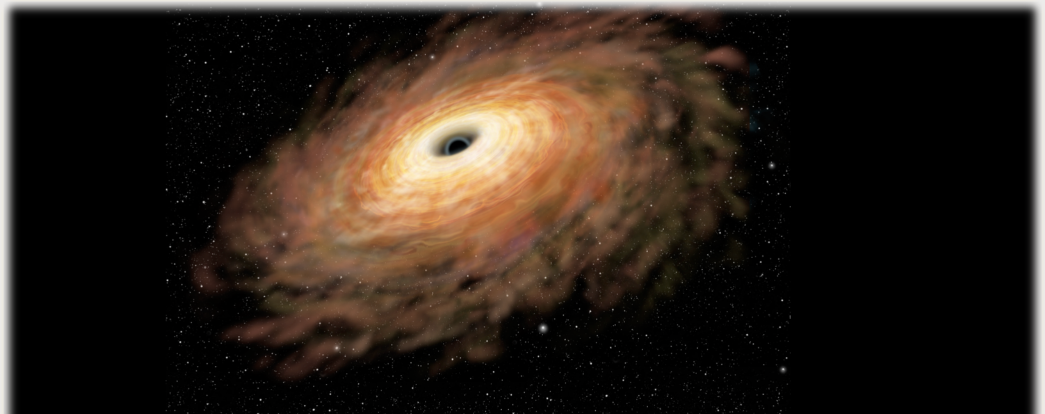
$$\eta = \frac{E}{mc^2} = \frac{0.2 \times 10^9\text{eV}}{235 \times 9.4 \times 10^8\text{ eV}} \sim 9 \times 10^{-4}$$



Fusion

$$\eta = 0.008 \times 0.1 \sim 8 \times 10^{-4}$$

$$\eta = \frac{mv^2}{2\,mc^2} = \frac{(v/c)^2}{2} = 4 \times 10^{-15}$$



$$\eta = \frac{1}{2}\frac{GM\,m}{R\,mc^2} = \frac{R_g}{2R}$$

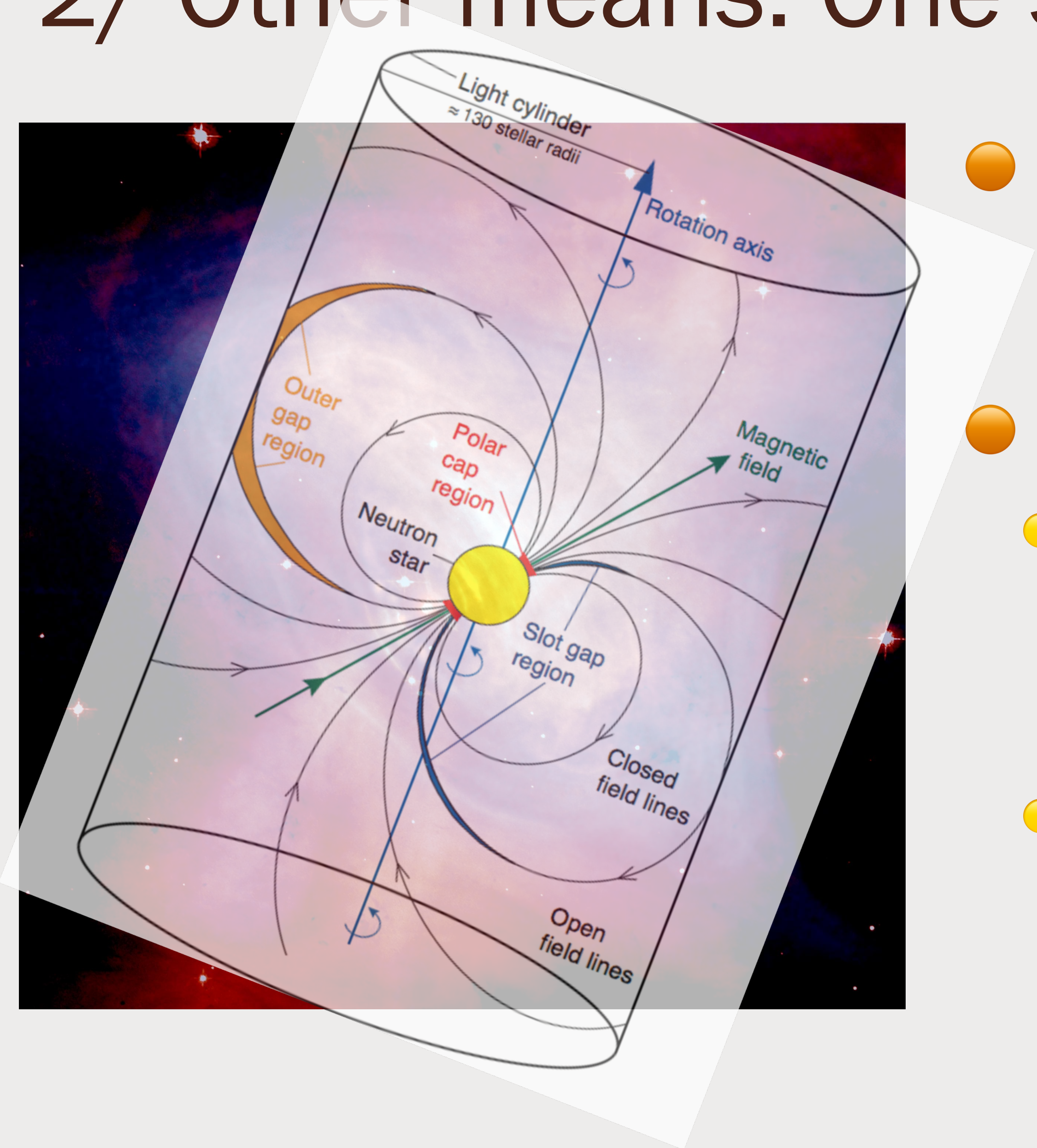
(Newton)

$R_{min} = R_g$ for max spin

η = 0.1 up to 0.3 for accreting Kerr

(Thorne 1974)

2/ Other means: One shot acceleration



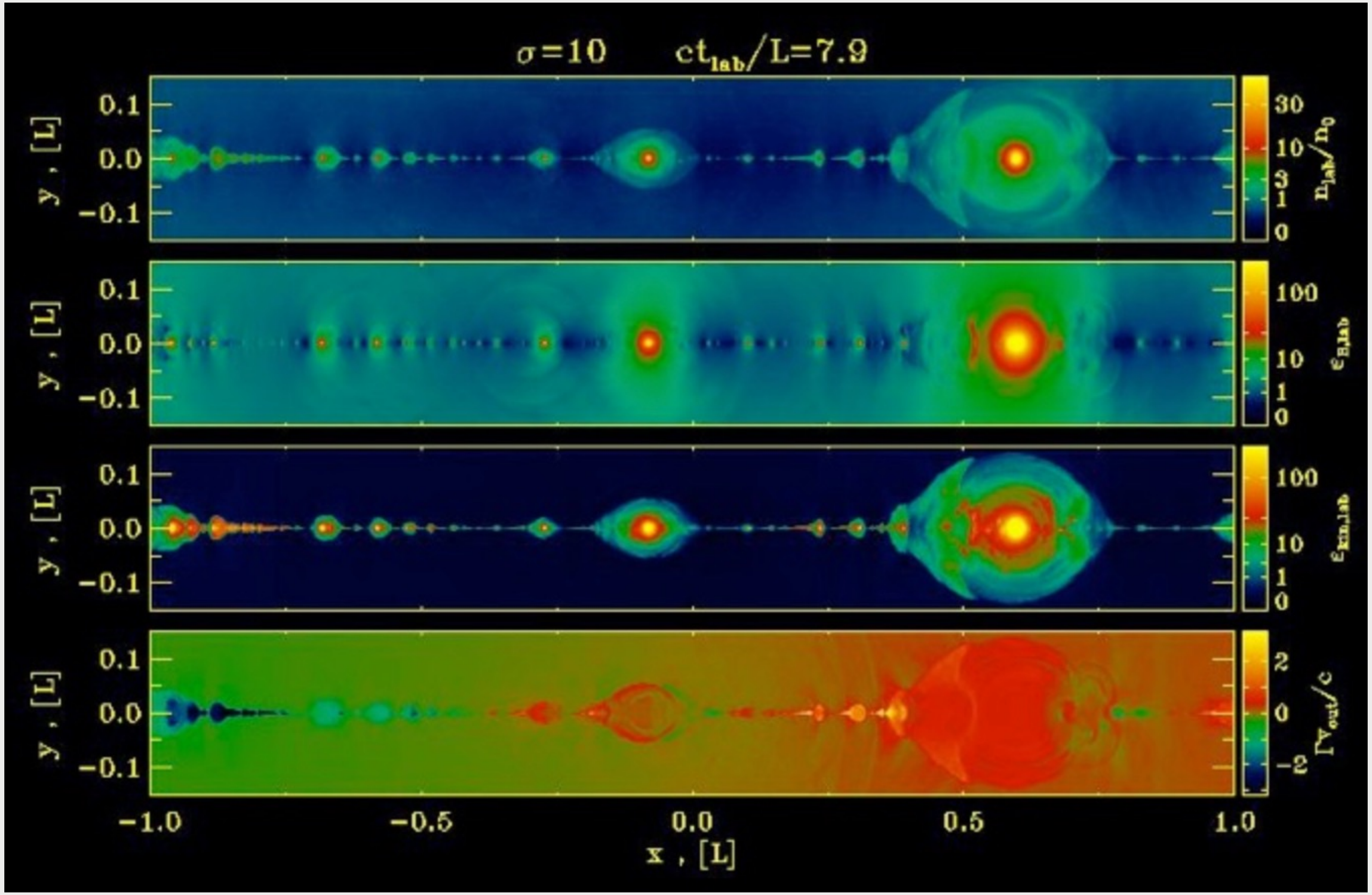
- A particle is accelerated in a continuous way by an ordered E field
- Maximum energy
  - *curvature-dominated losses*

$$\varepsilon_c = \frac{3^{1/4}}{2} \frac{m}{q^{1/4}} B^{1/4} R^{1/2}$$

  - *Synchrotron dominated losses*

$$\varepsilon_s = \sqrt{\frac{3}{2} \frac{m^2}{q^{3/2}}} B^{-1/2}$$

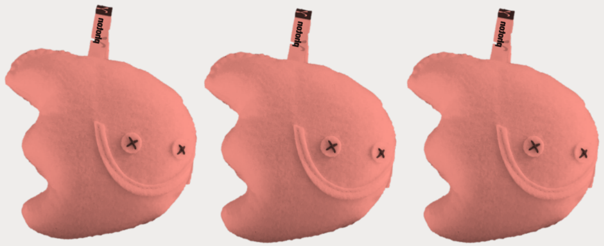
3/ Other means: Magnetic reconnection



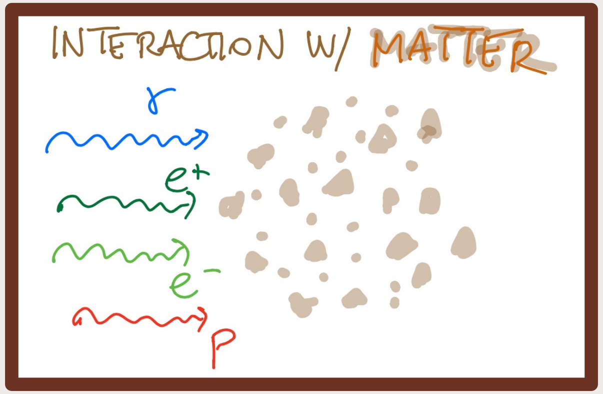
Zenitani & Hoshino 2001 Sironi & Spitkovsky 2014

- Occasional flips in the field polarity of the accretion flow
- Instabilities in ultrarelativistic jets,
- A few regions may exist where the field direction reverses over microscopic plasma scales, triggering magnetic reconnection.

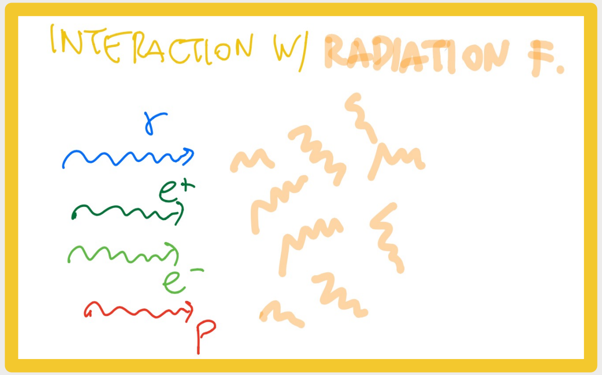
GENERATION OF HE GAMMA-RAYS



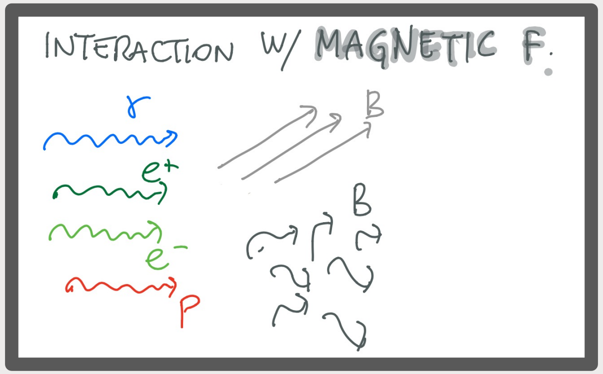
Radiative and collisional processes



- Pion decays from
- Electron bremmshtralung
- Positron annihilation

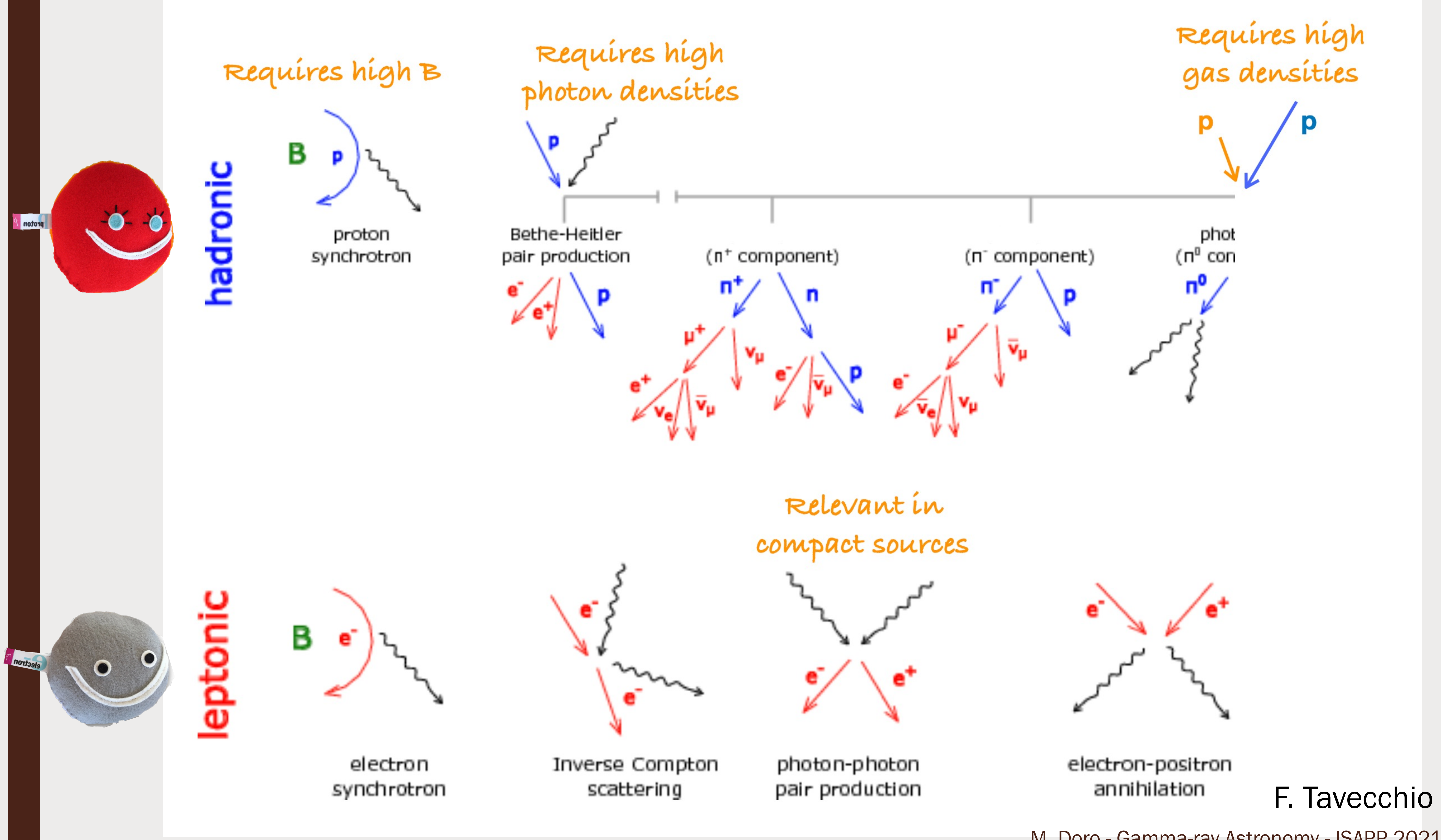


- Pair production
- Inverse Compton
- Photoproduction



- Synchrotron radiation

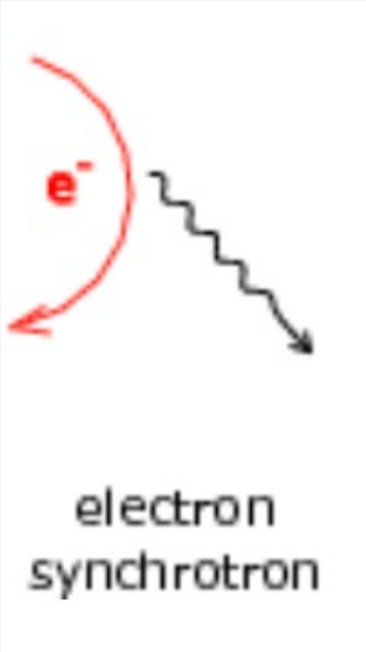
Leptonic or hadronic?



F. Tavecchio

1/ Leptonic gamma ray generation

- Electrons are easily found in all astrophysical environments, and easy to accelerate (although they also cool rapidly or get absorbed)
- Magnetic fields are also everywhere (see Hillas plot)



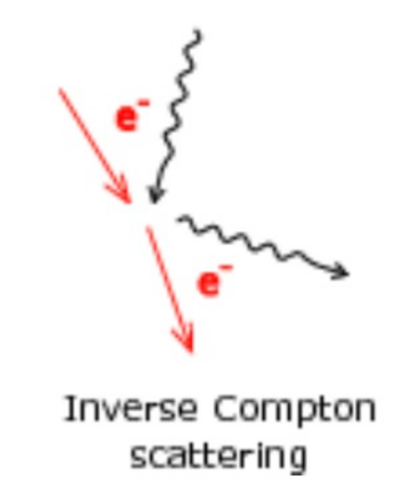
Synchrotron radiation

- The acceleration (centripetal) around magnetic field lines allows radiation of photons with

$$-\frac{dE}{dt} \sim 2.6 \frac{keV}{s} \left(\frac{Zm_e}{M}\right)^4 \left(\frac{E}{1keV}\right)^2 \left(\frac{B}{1G}\right)^2$$

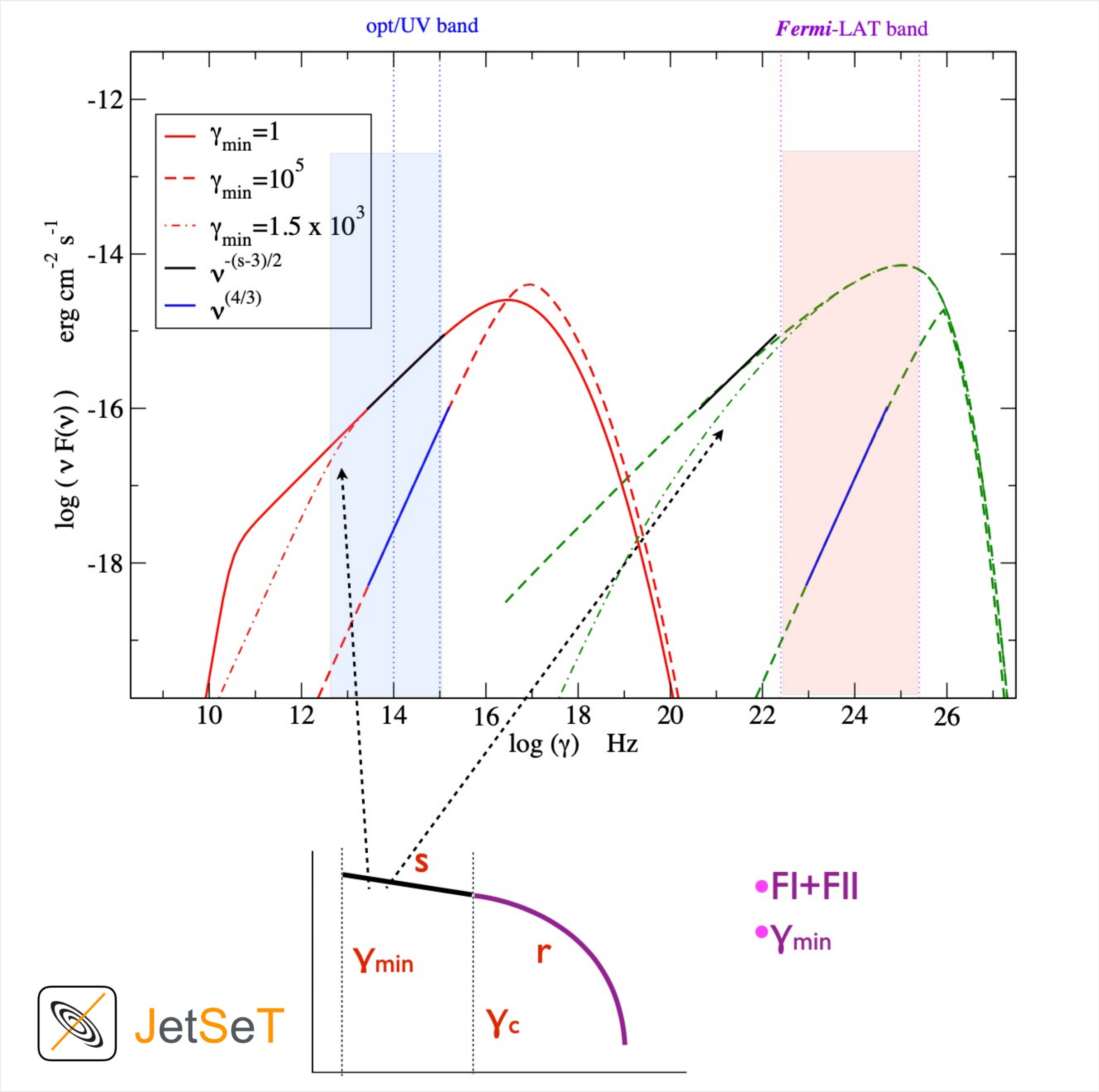
- Proton synchrotron only in very strong B

+ Inverse and Self Synchrotron Compton



- Compton scattering:
  - *A photon of energy E transfer energy to low energy electron*
  - *The scattered photon has* $E' < E$
- In astrophysical environment, normally the opposite situation
  - *A lot of high energy electrons*
  - *A lot of low energy photons*
- Inverse compton:
  - *A high energy electron transfer energy to a low energy photons*
  - *The scattered photon has* $E' > E$
- Can reach energy of TeV
- Low ambient photons can be synchrotrhon photons generated by the eletrons (self-synchrotron compton, SSC)

Family travelers (S+IC=SSC)



- You take a parent population of electron
- Take a model of 'astrophysical region'
- Predict
  - *Synchrotron bump*
  - *IC bump*
- Peaks are correlated!
  "Orphan" flare not expected
- Spectral shape informative of particle distribution!

Jet Model builders

- Several very mature jets builder and fitter with awesome tutorial = you can self-teach

JetSeT

Jets SED modeler and fitting Tool

Andrea Tramacere

https://jetset.readthedocs.io/

νF_ν

AGNpy

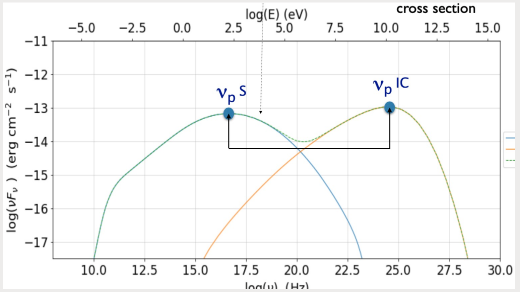
Cosimo Nigro

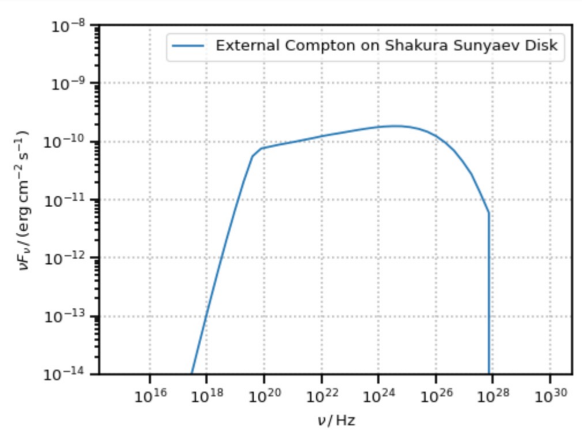
https://agnpy.readthedocs.io/

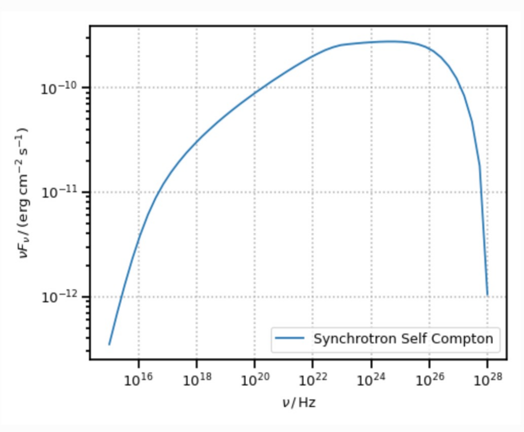
naima

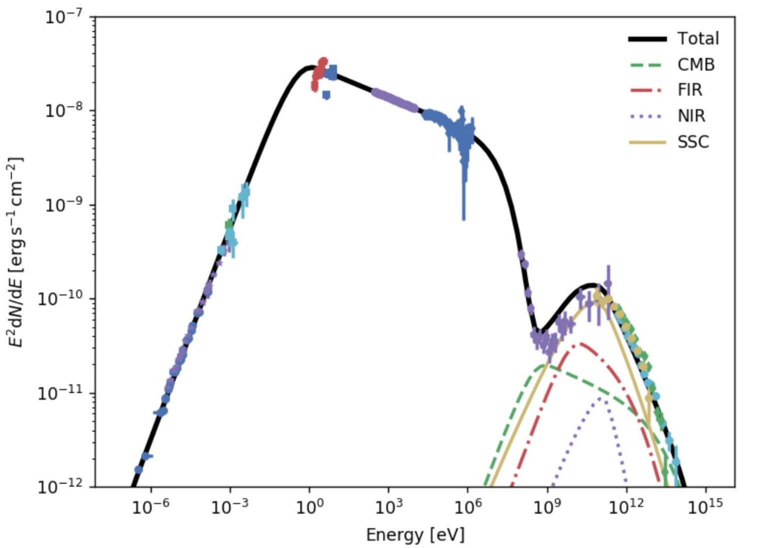
Python package for computation of non-thermal radiation from relativistic particle populations and MCMC fitting to observed spectra

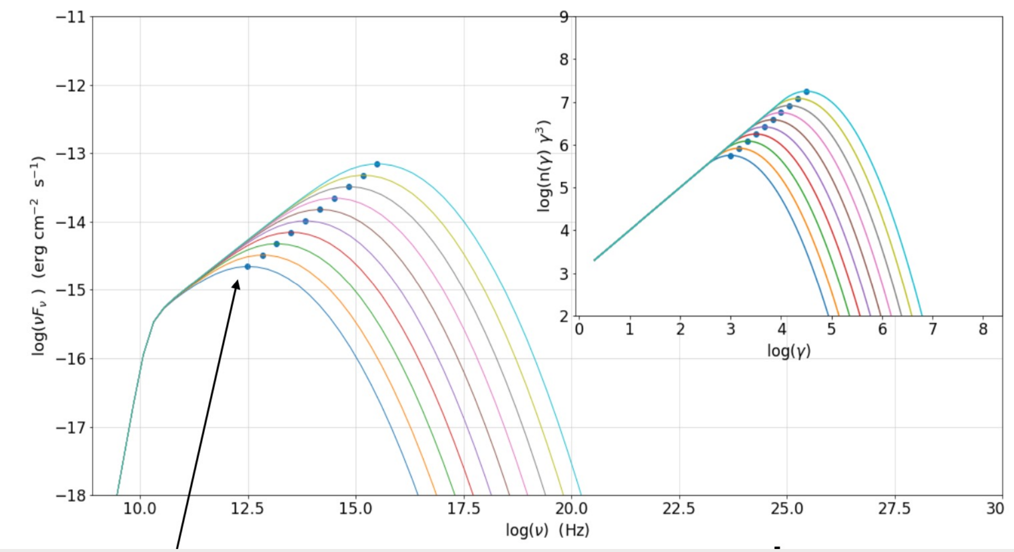
https://naima.readthedocs.io/



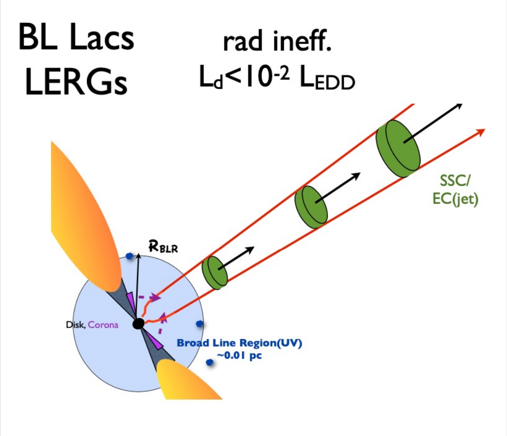


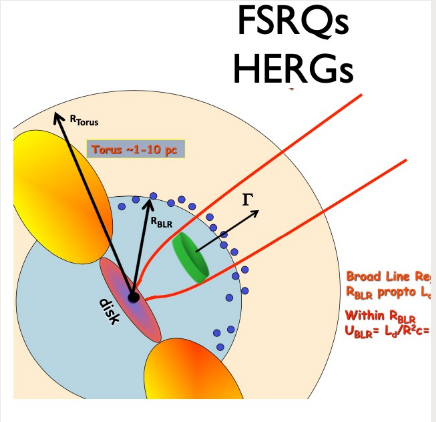




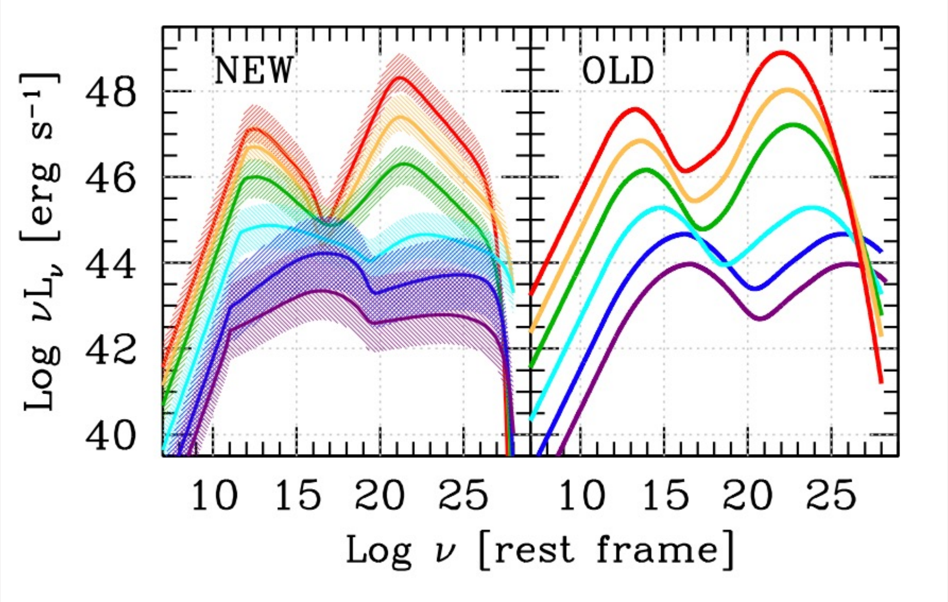


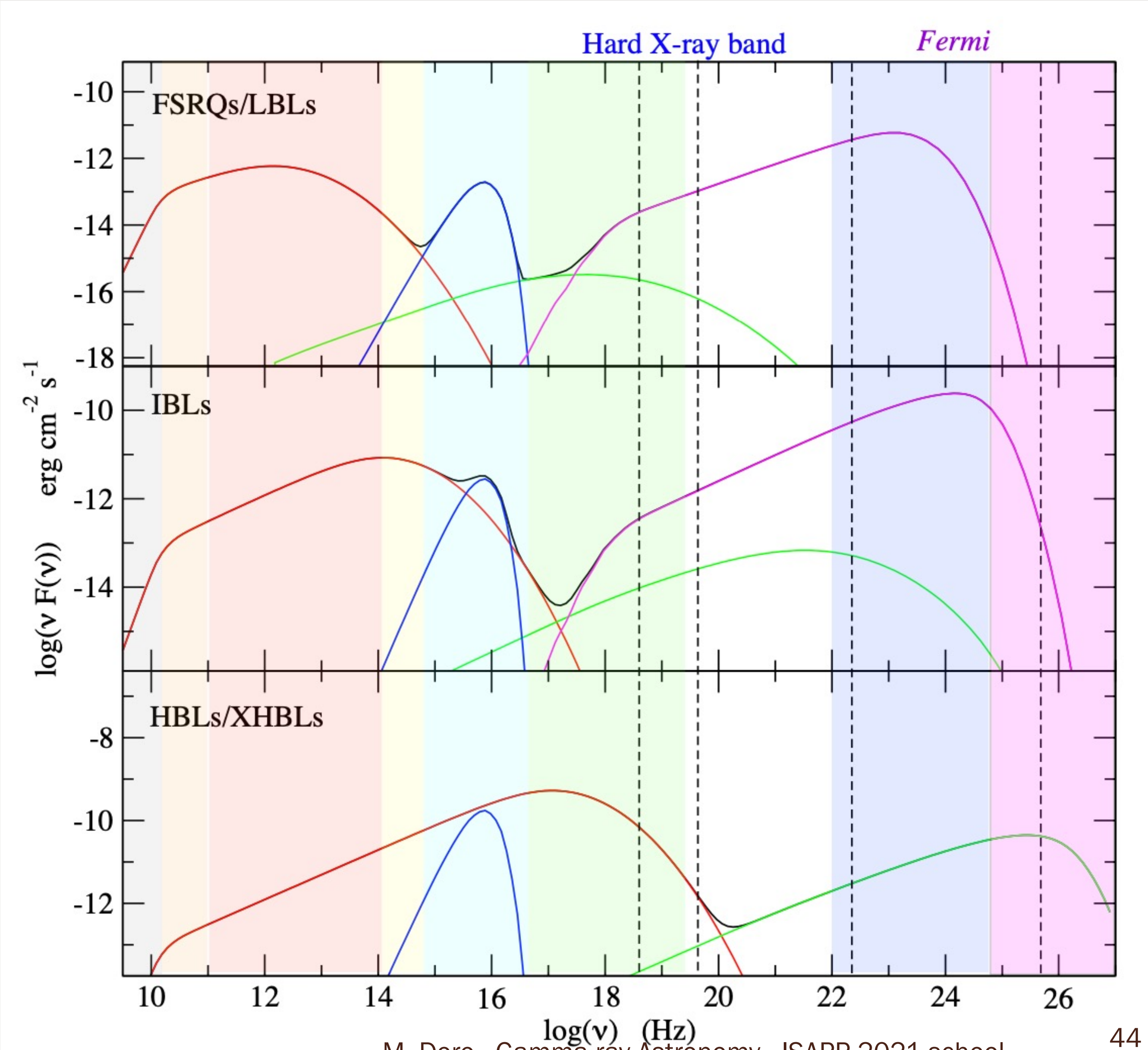
Not that clear after all





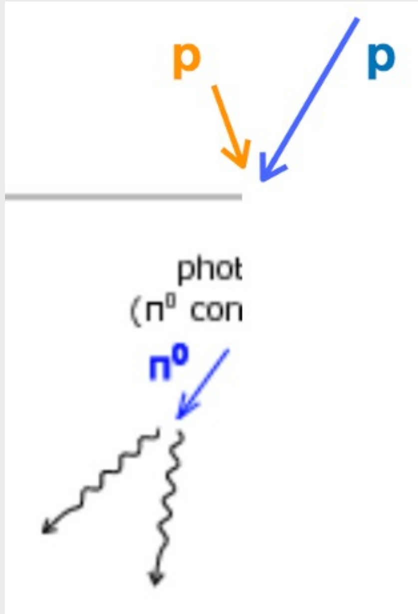
Evolution one into another





2/ Hadronic gamma ray model

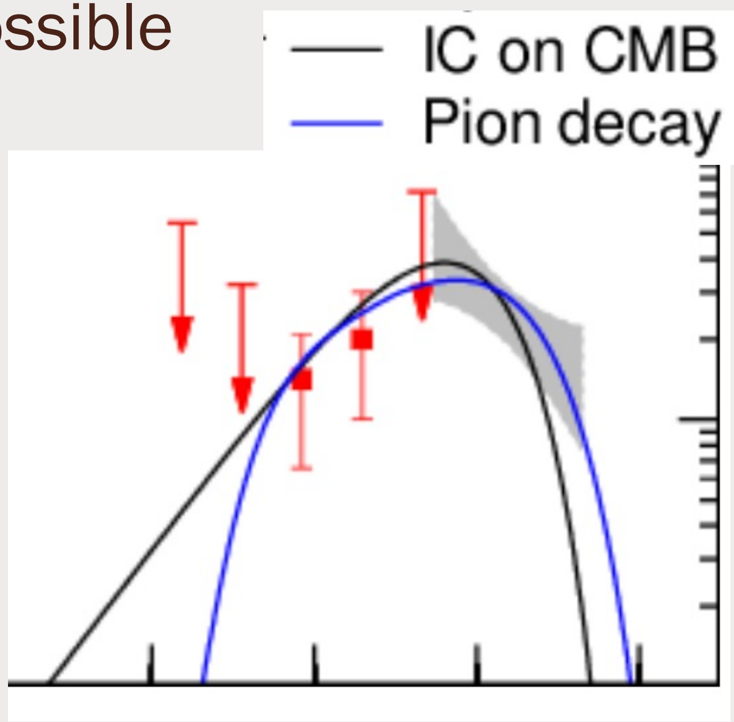
- A lot of cosmic rays around, but
  - *it takes time to accelerate them,*
  - *They diffuse*
  - *So you may not find them where you want them*
- Main process is pion decay, photoproduction also possible



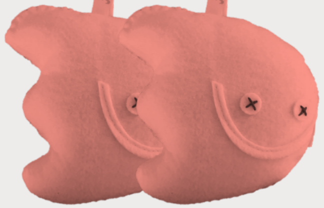
Pion decay

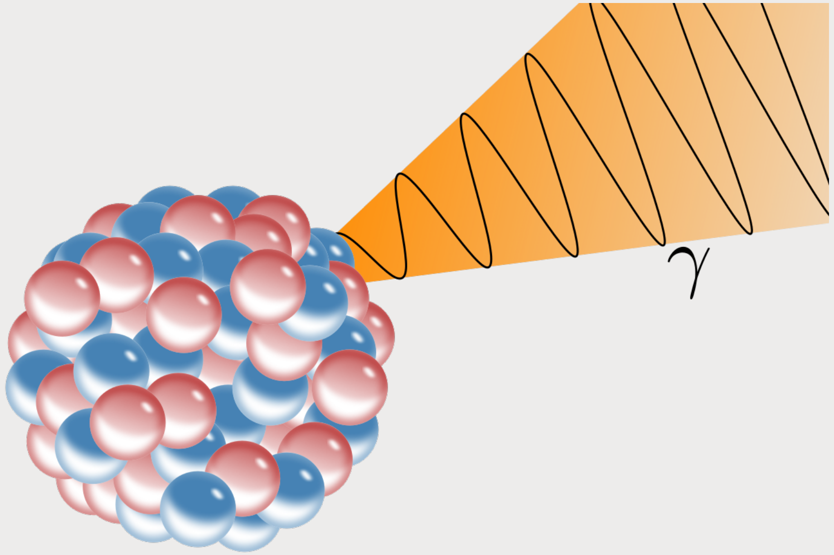
$$\sigma_{Ap} \sim A^{2/3} \sigma_{pp};\ \sigma_{pp} \sim 30\, mb$$

- The photons from neutral pion decays have energies larger than for synchrotron

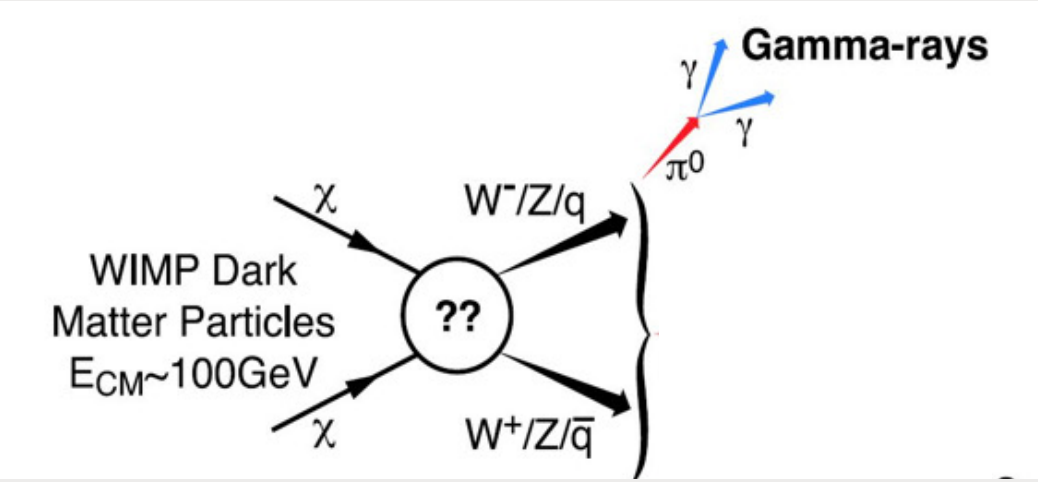


3/ Other mean to get

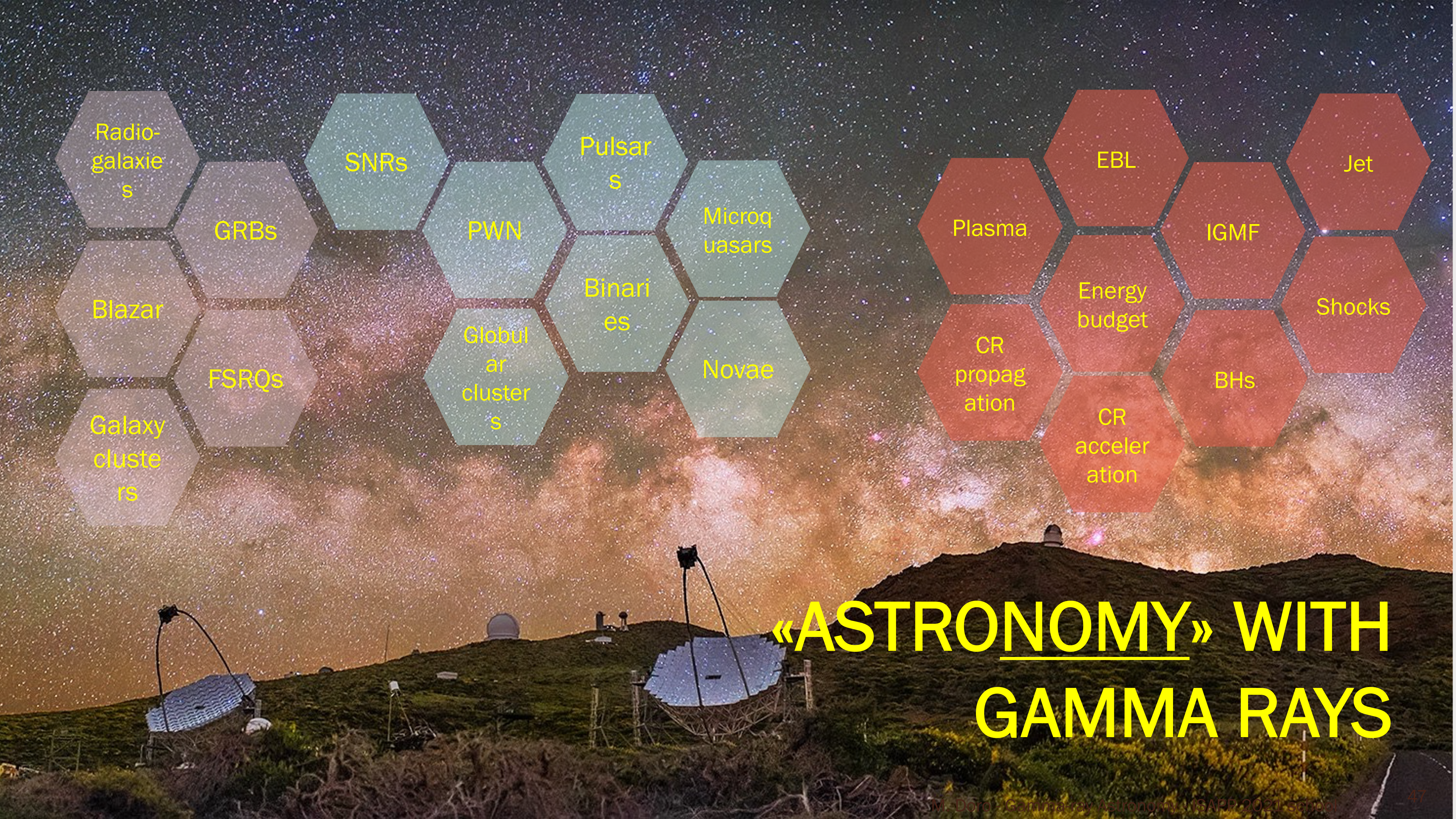




- Nuclear processes
  - *De-excitation of target nuclei leads to keV-MeV lines*
    - 4.4 MeV from 12C
    - 6.1 MeV from 16O
    - 0.85 MeV from 56Fe

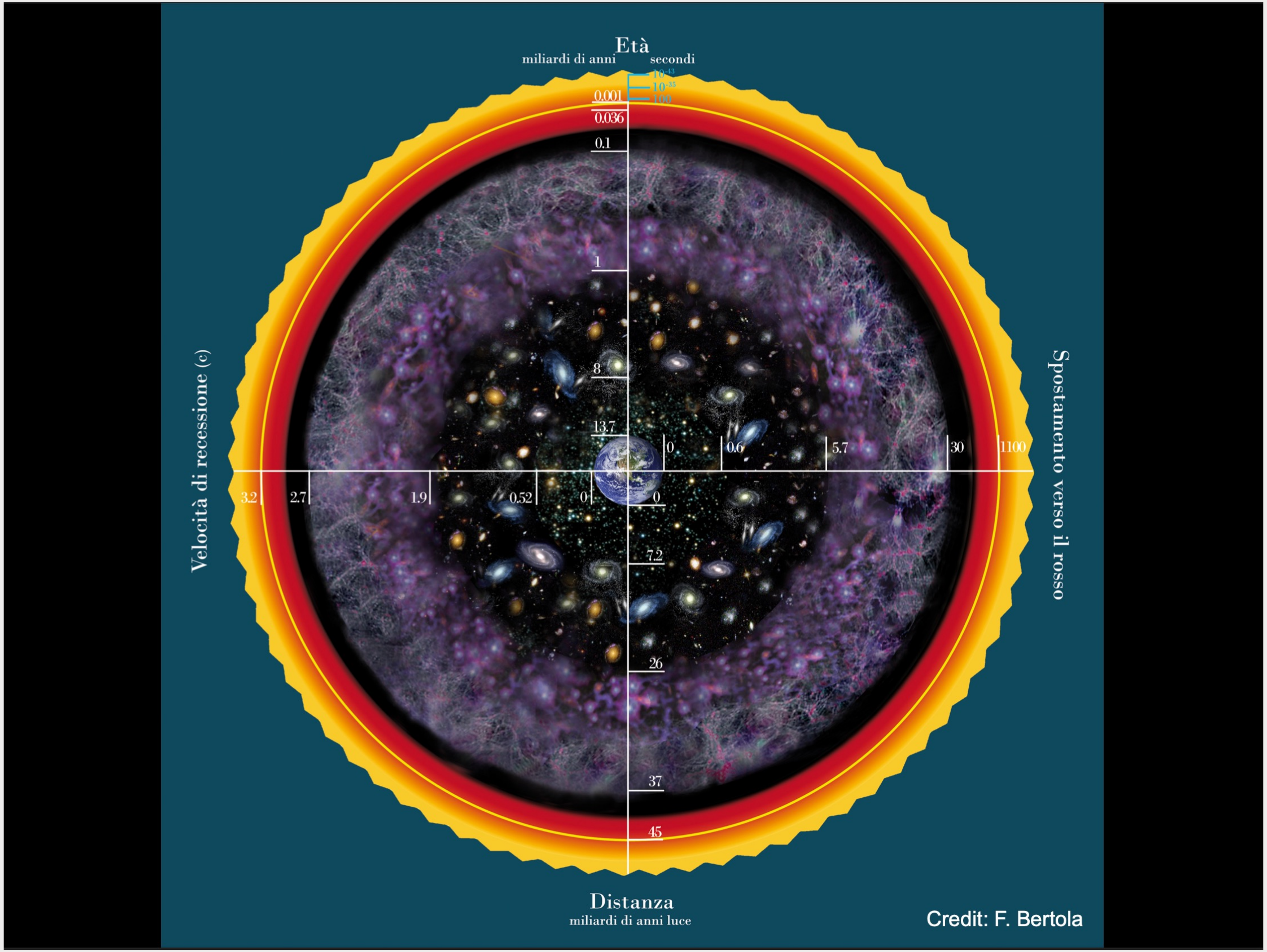


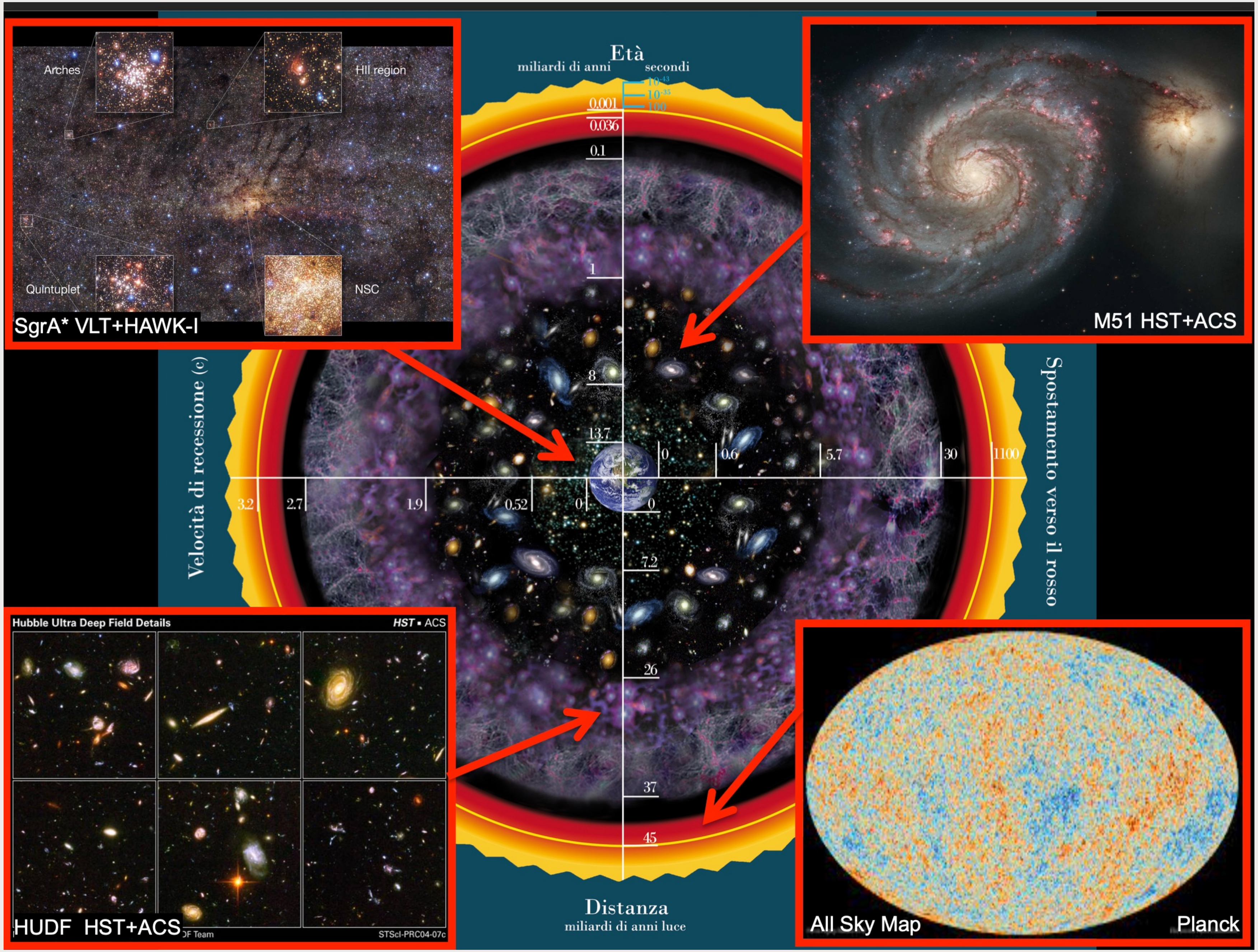
- Dark matter and other new physics fields



«ASTRONOMY» WITH GAMMA RAYS

Where are you?



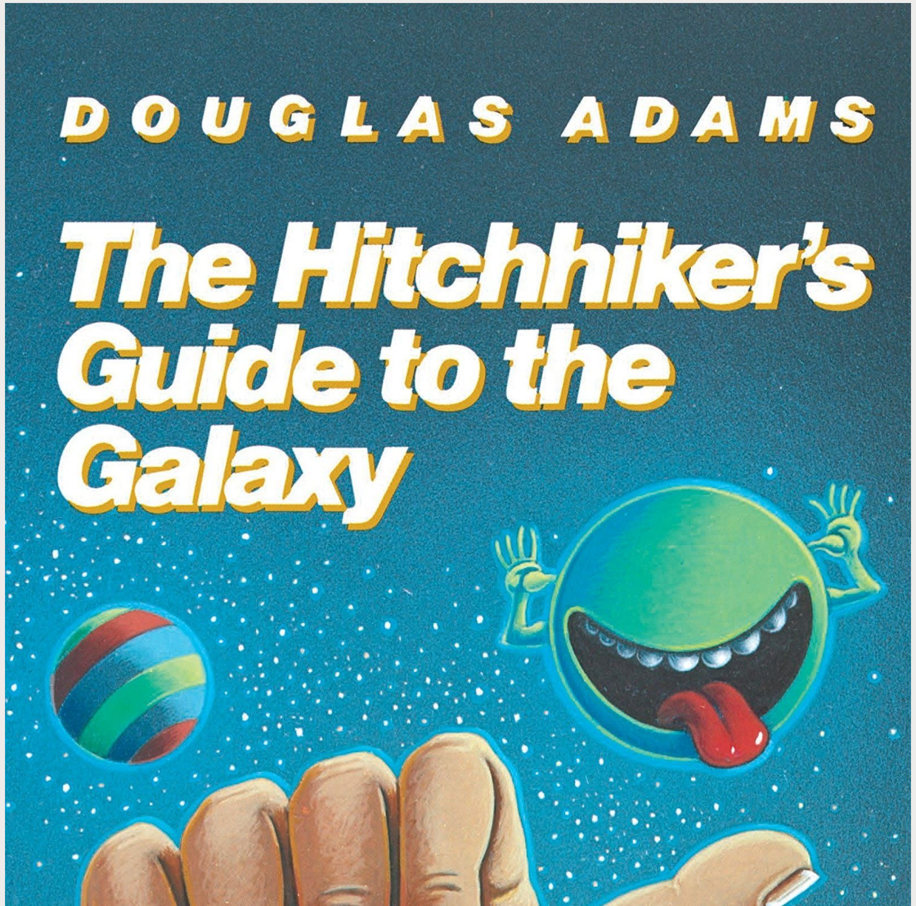


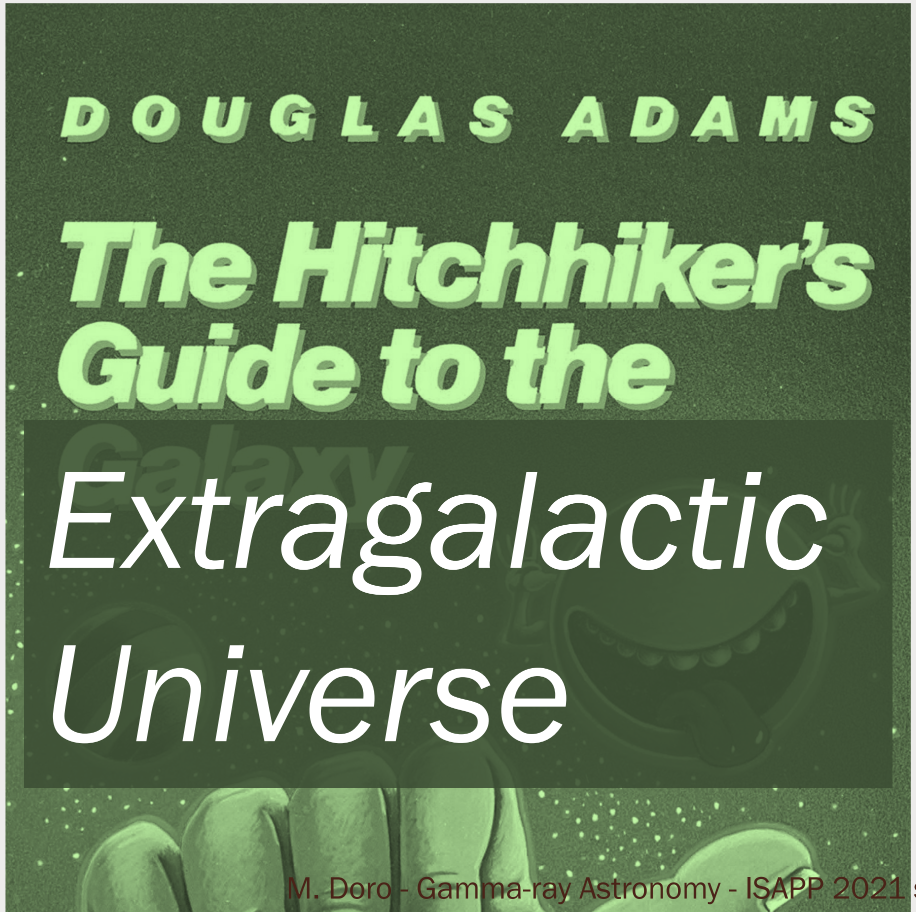
Where are you?

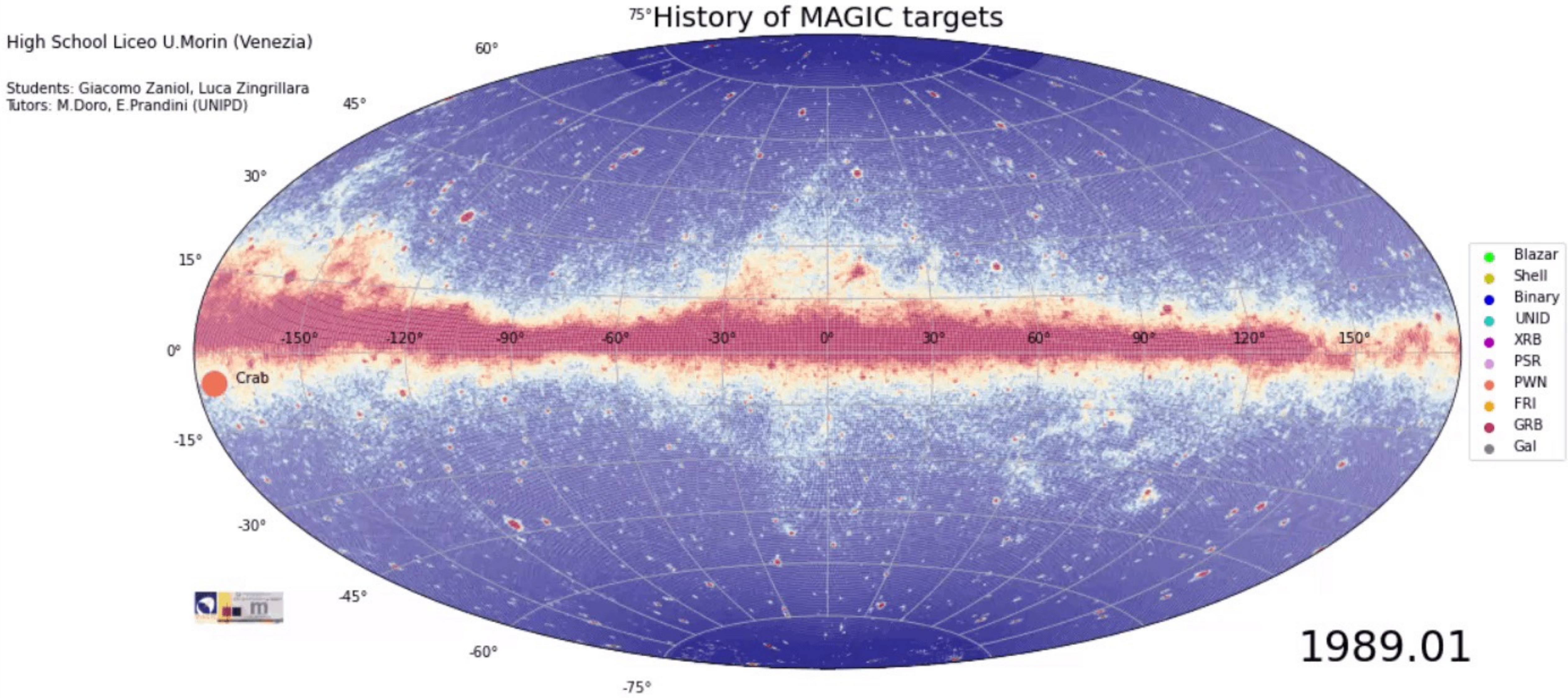
- In the extragalactic space?
- In the intergalactic space?
- Around a compact object?
- Close to a SMBH?
- Close to a binary system?
- Close to a Gamma-Ray Burst?

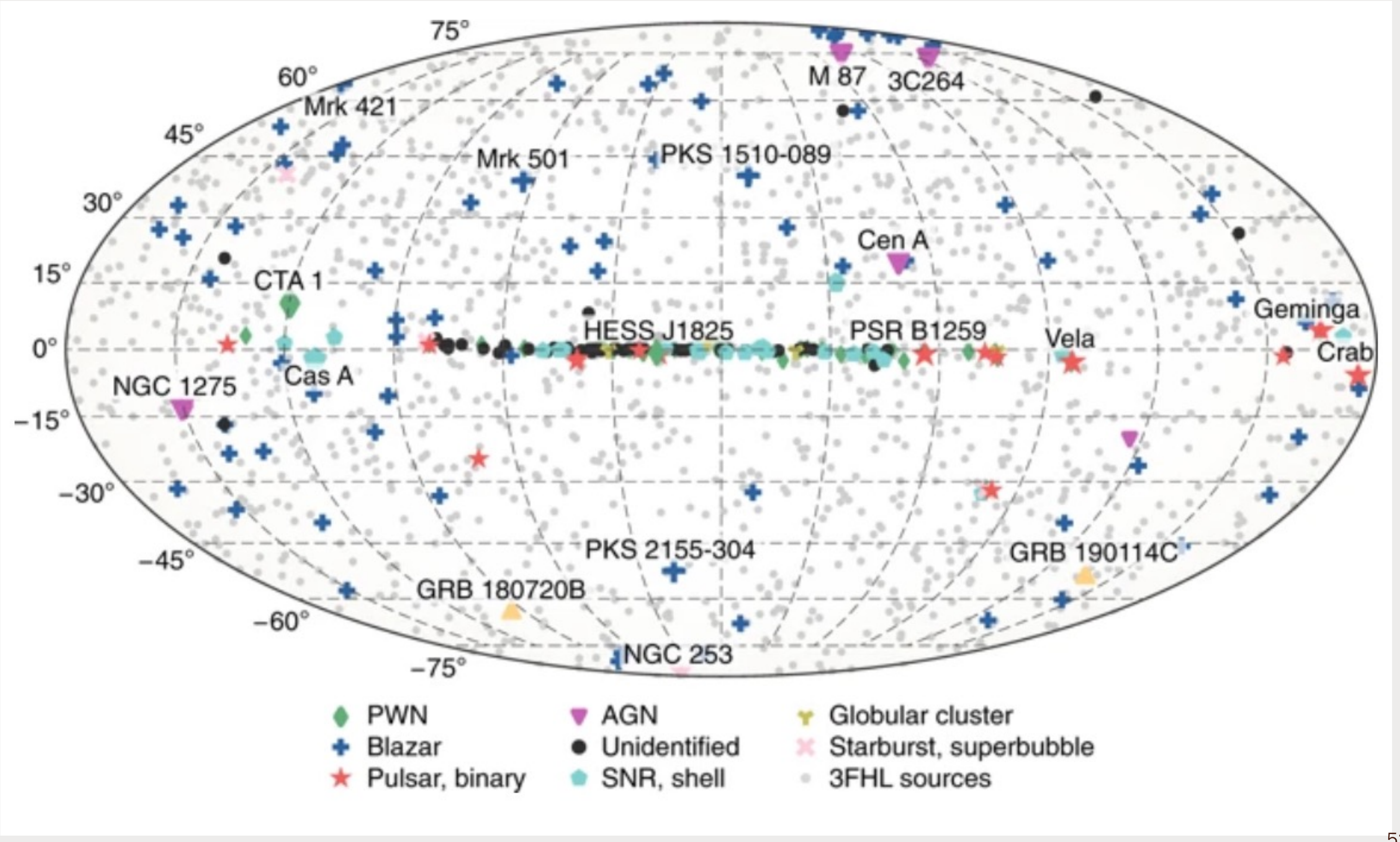
Neighborhood and definitely not

10^{-4} pc	1 -10 kpc	10 -100 kpc	1 Mpc	50 Mpc	1 Gpc
Sun	Nearby stars Binary Systems MW center	MW Satelite Galaxies	Closest galaxies Andromeda	Closest Cluster Virgo	Farthest TeV emitter



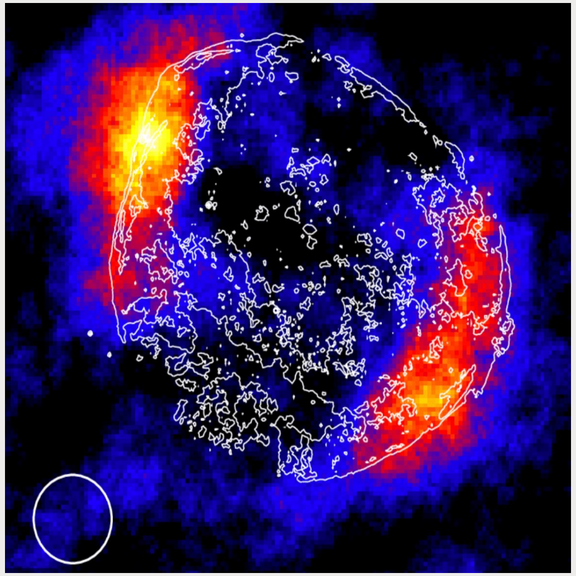



History of MAGIC targets
High School Liceo U.Morin (Venezia)
Students: Giacomo Zaniol, Luca Zingrillara
Tutors: M.Doro, E.Prandini (UNIPD)
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°
Crab
Blazar
Shell
Binary
UNID
XRB
PSR
PWN
FRI
GRB
Gal
1989.01


75°
60°
45°
30°
15°
0°
−15°
−30°
−45°
−60°
−75°
Mrk 421
Mrk 501
PKS 1510-089
M 87
3C264
Cen A
CTA 1
HESS J1825
PSR B1259
Vela
Geminga
Crab
Cas A
NGC 1275
PKS 2155-304
GRB 190114C
GRB 180720B
NGC 253
PWN
Blazar
Pulsar, binary
AGN
Unidentified
SNR, shell
Globular cluster
Starburst, superbubble
3FHL sources

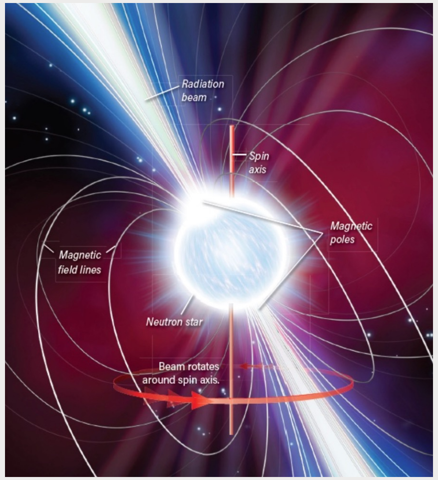
Galactic GeV-TeV emitters

- Connected to the death of a star



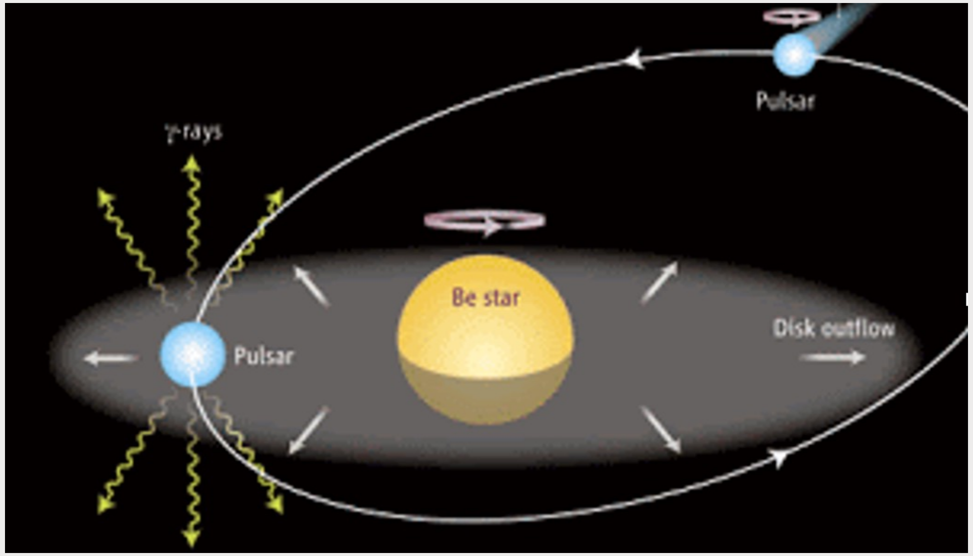
Supernova Remnant

Pulsar Wind Nebula

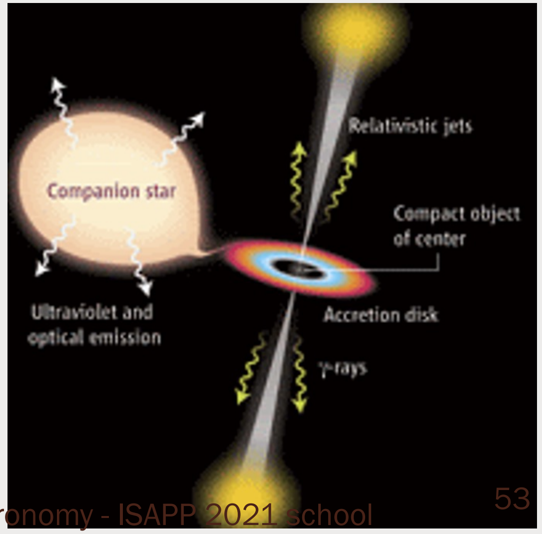


Pulsar

- When stars are too alive

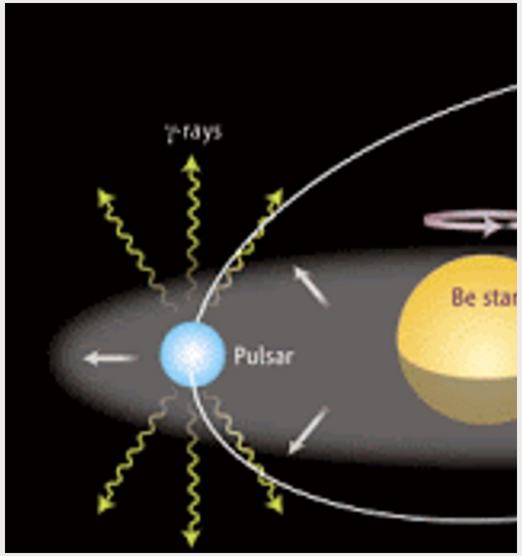


Binary Pulsar



Microquasar

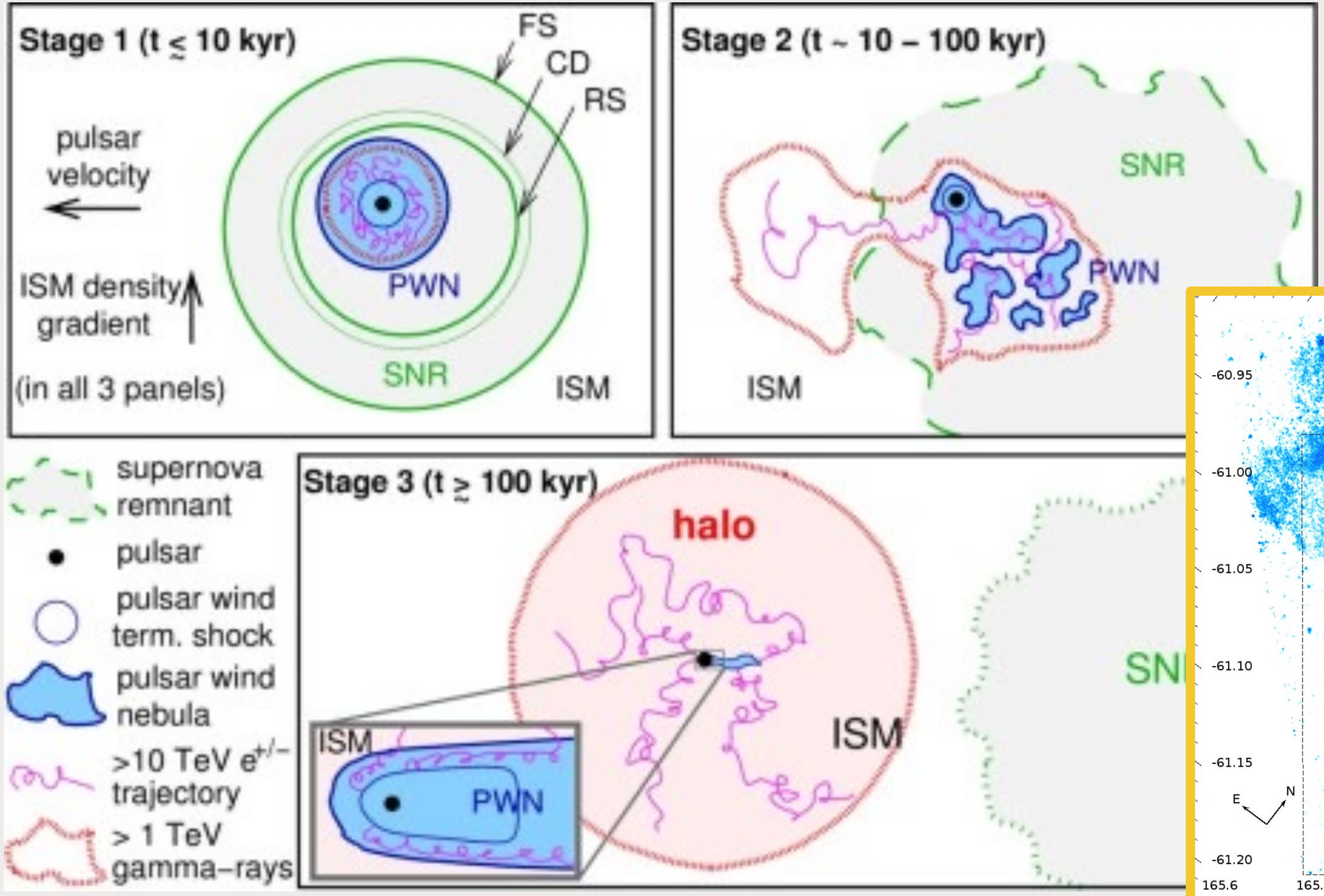
Stellar endproducts

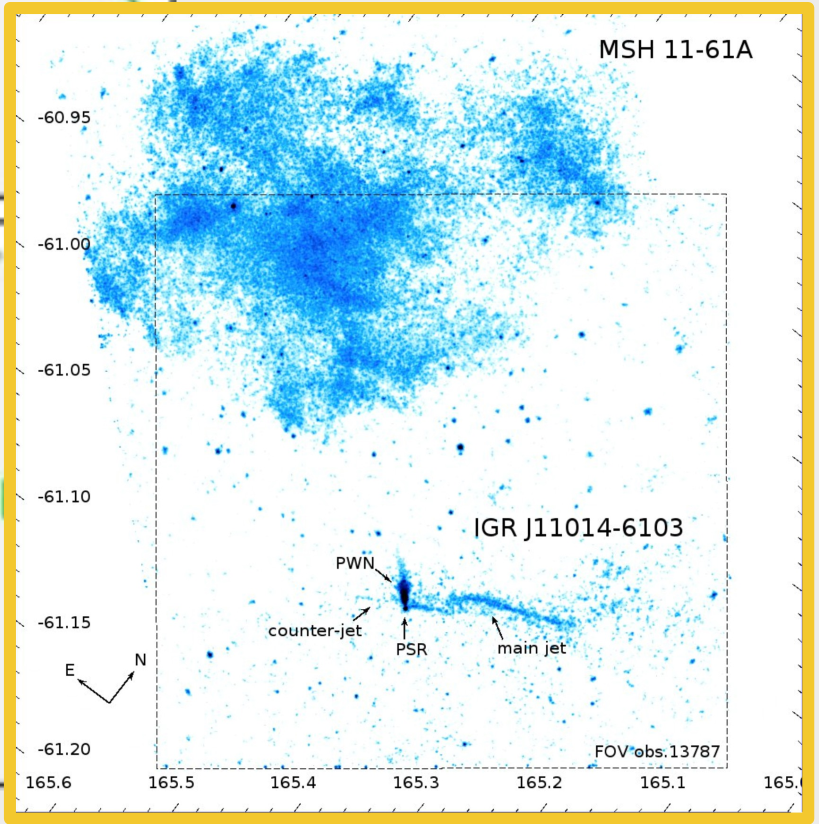


- End of some stars life: **supernova boom**
  - ***Core-Collapse*** *(Type Ib,Ic,II): lack of hydrogen, contraction, rebound and explosion*
  - ***Type Ia:*** *accretion on white dwarf in companion system above a critical mass (standard candles, see Zavala's talk at this school)*
- Neutron stars
  - *Rotation of the order of 1 ms*
  - *Magnetic fields of the order of* 10^{12} *G*
- Ejecta
  - *Magnetic fields of the order of* $0.01 - 1\ mG$
  - *3-10k km/s ejecta*
- In all cases, winds of accelerated particles
- Surely leptonic gammas, but also hadronic gammas

SNR and PWN

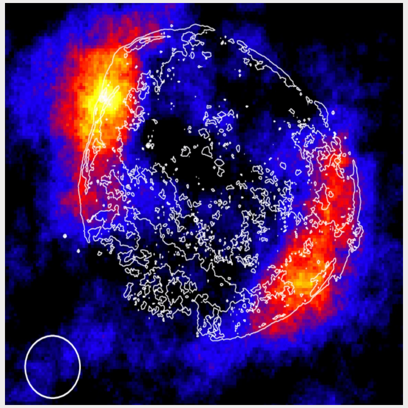
G. Giacinti



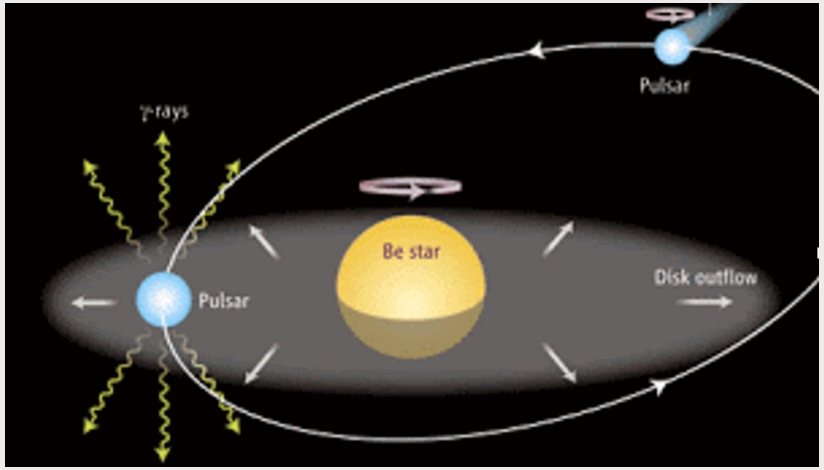


- Winds
  - *SNR*
  - *PWN*
  - *Composite*
- Pulsar can leave its remnants

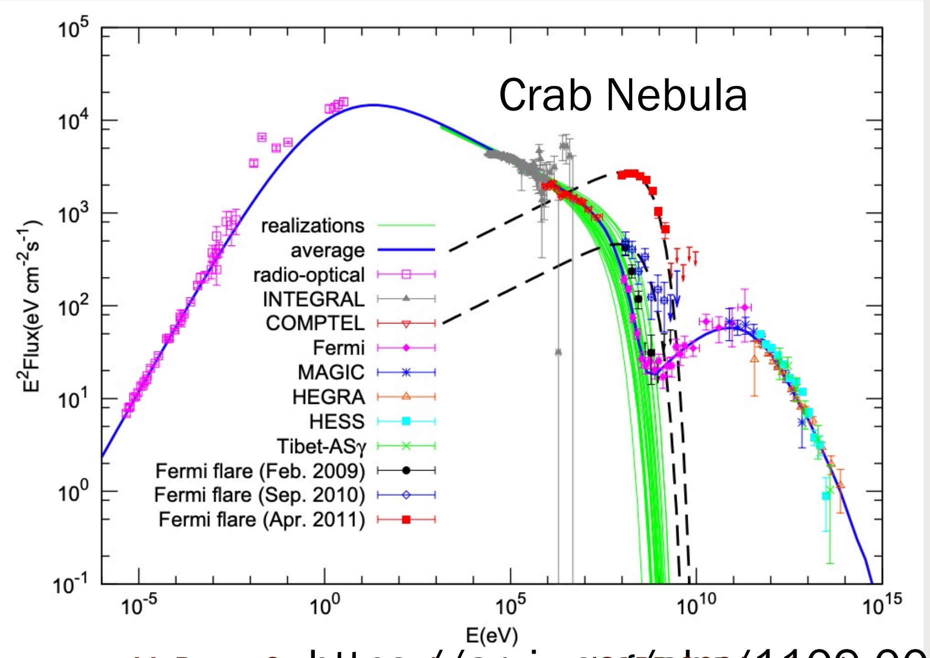
Strong particle winds generate shocks



1. Kinetic energy of ejecta (winds) create shocks
2. Shock front embed turbulent magnetic field
3. Shock accelerate upstream cosmic rays (Fermi mechanism)
4. Gamma-rays through inverse compton (leptons) with external photons (EIC) or synchroton-generated photons (SSC) or pion decay (protons)



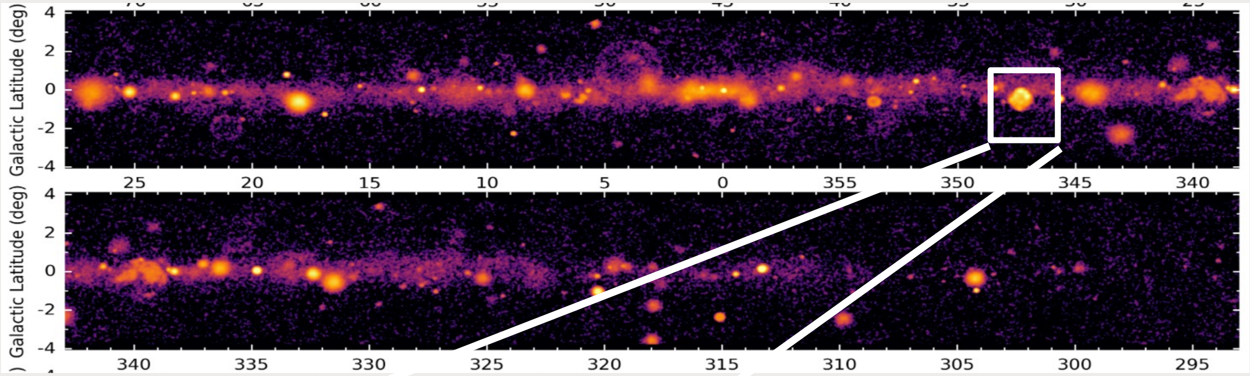
Maximum energy $E_{max} \sim 300\ Z\ TeV$

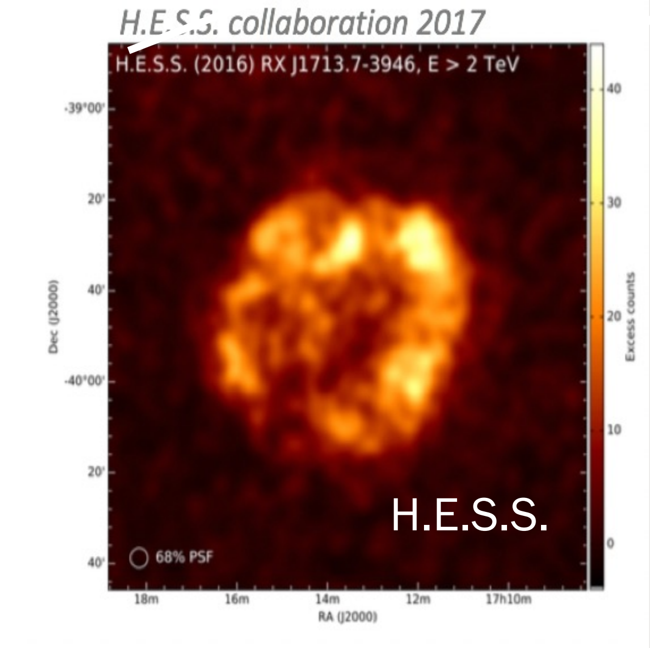


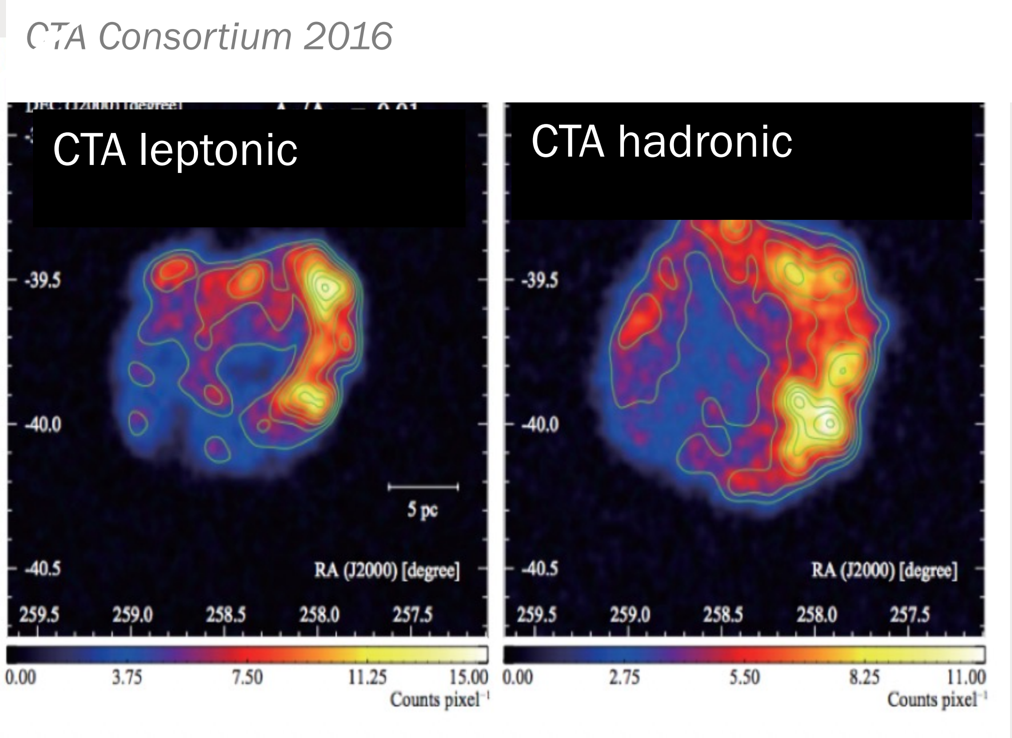
https://arxiv.org/abs/1109.0075

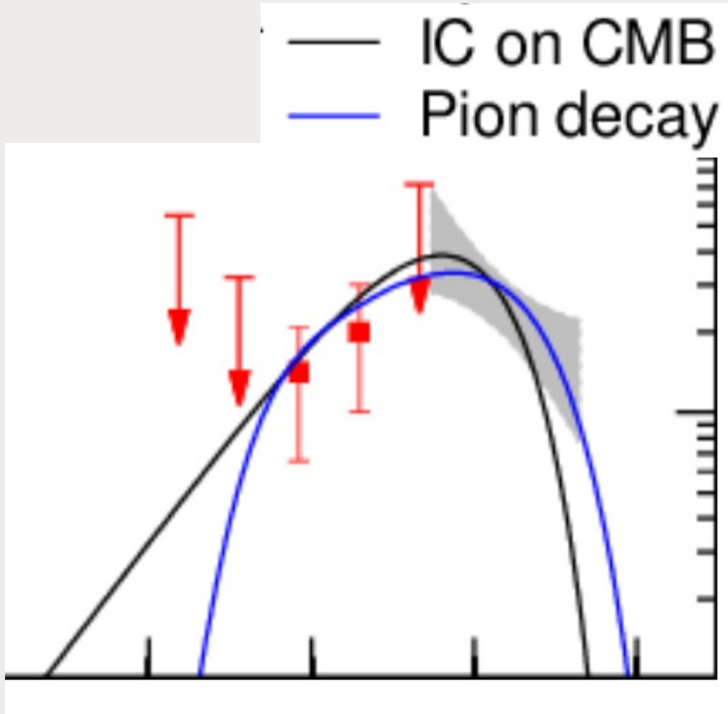
SNR RXJ1713

- Parent particles determines morphology and spectrum

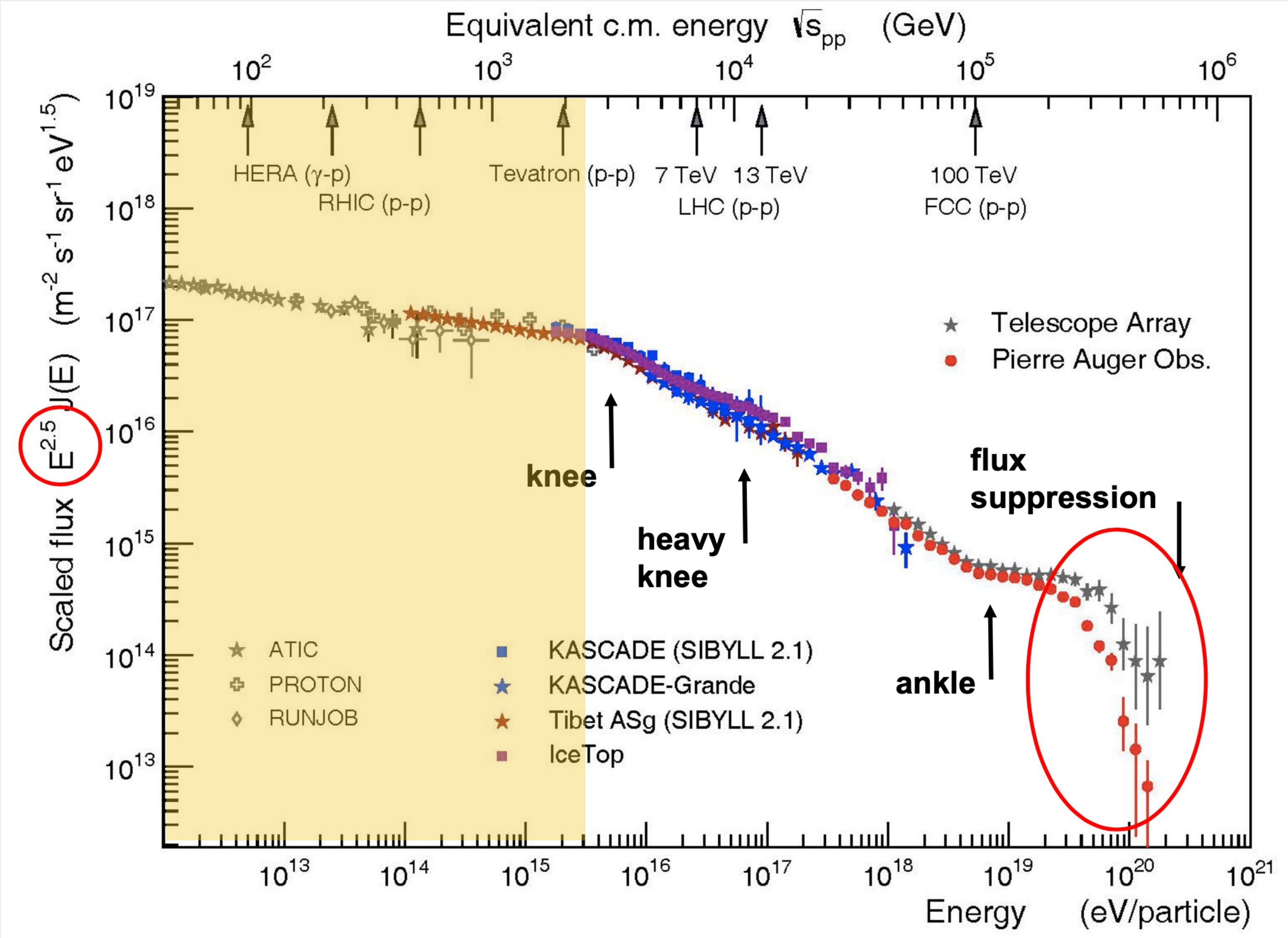








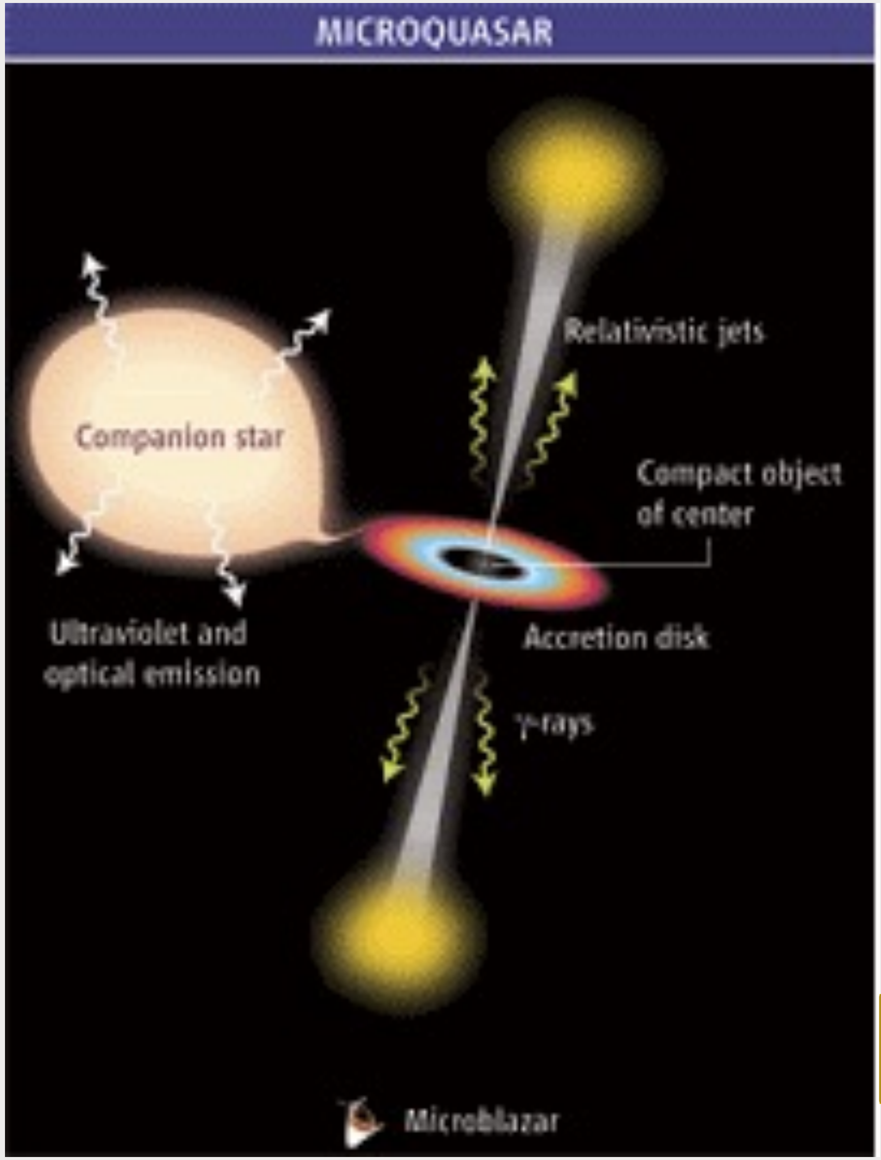
Here comes the galactic CR



GALACTIC

- In 1000 years of expansion, considering time to accelerate, SNR can give CR protons Maximum energy $E_{max} \sim 300\ Z\ TeV$
- Explain
  - *Knee (proton)*
  - *Heavy knee (nuclei)*

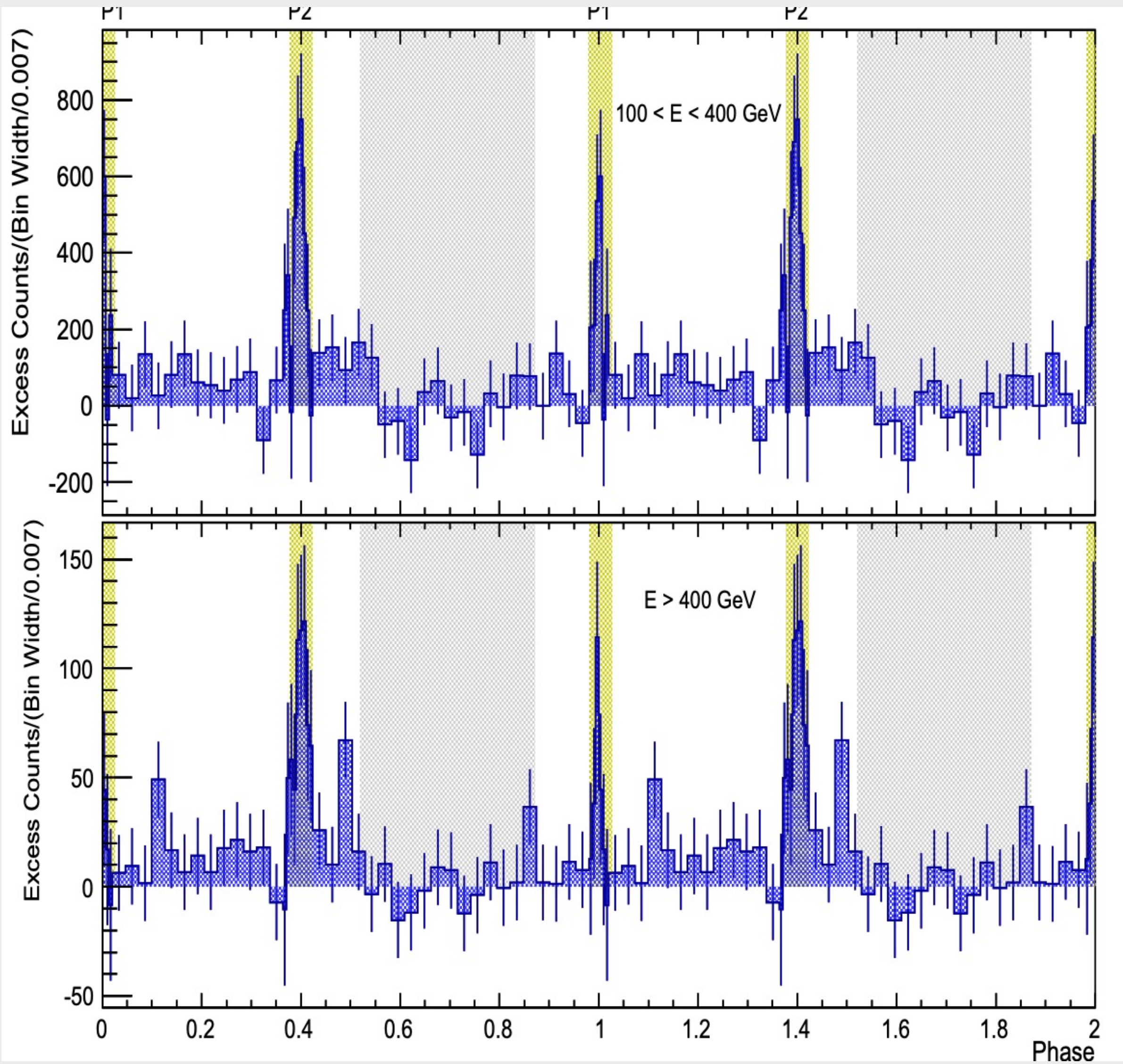
Ultrarelativistic galactic jets



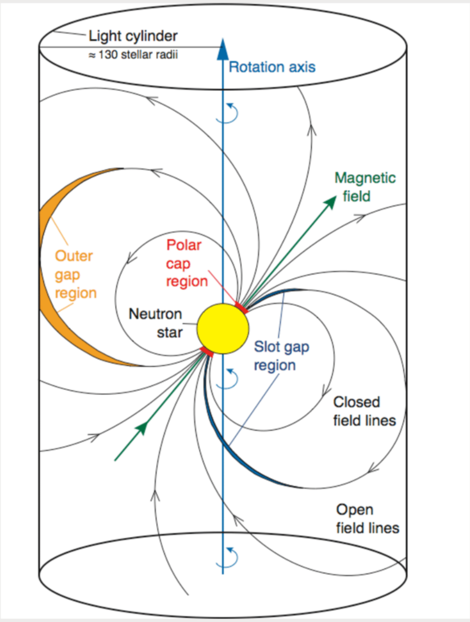
1. Kinetic energy of infall material & rotating BH spin power generate ultrarelativistic jet
2. Particle acceleration within jets (shocks, encounter with clouds (knots))
3. Gamma—ray emission through Inverse Compton with external photons (EIC) or synchroton-generated photons (SSC)

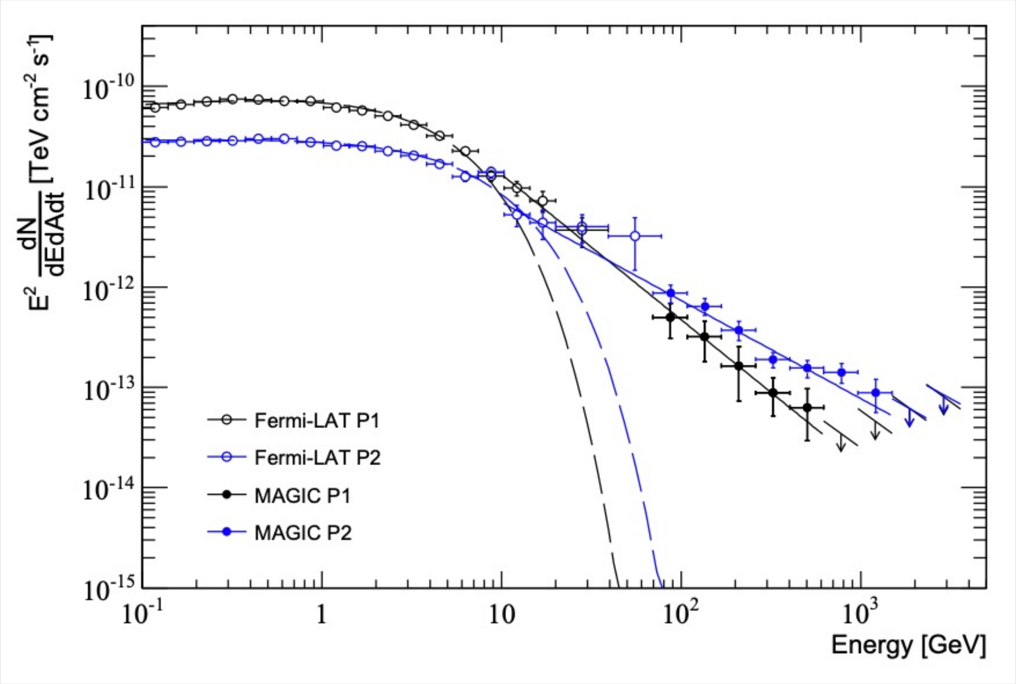
Beatiful jets that can be switched ON and OFF

Pulsars



Pulsed emission

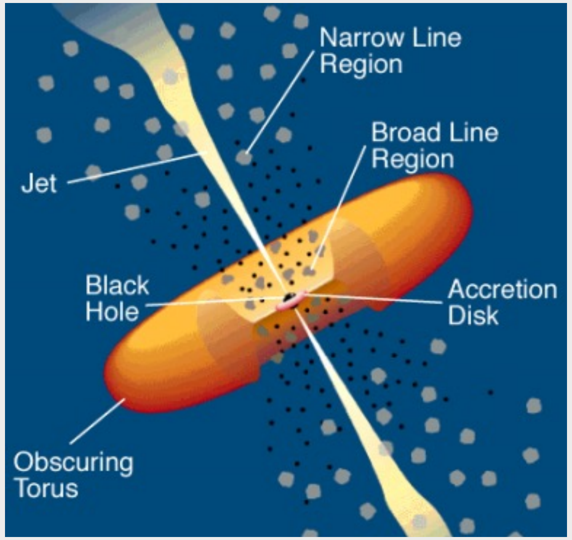


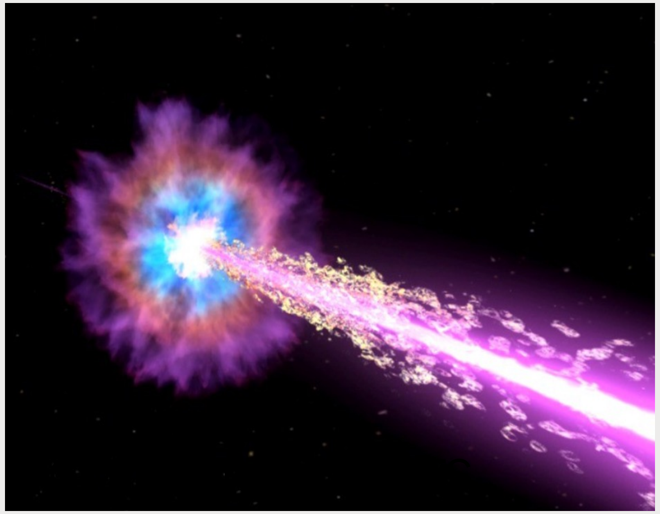


[MAGIC Coll] Astron.Astrophys. 585 (2016) A133

Extragalactic GeV-TeV emitters

- Connected to the ultrarelativist jets & BHS





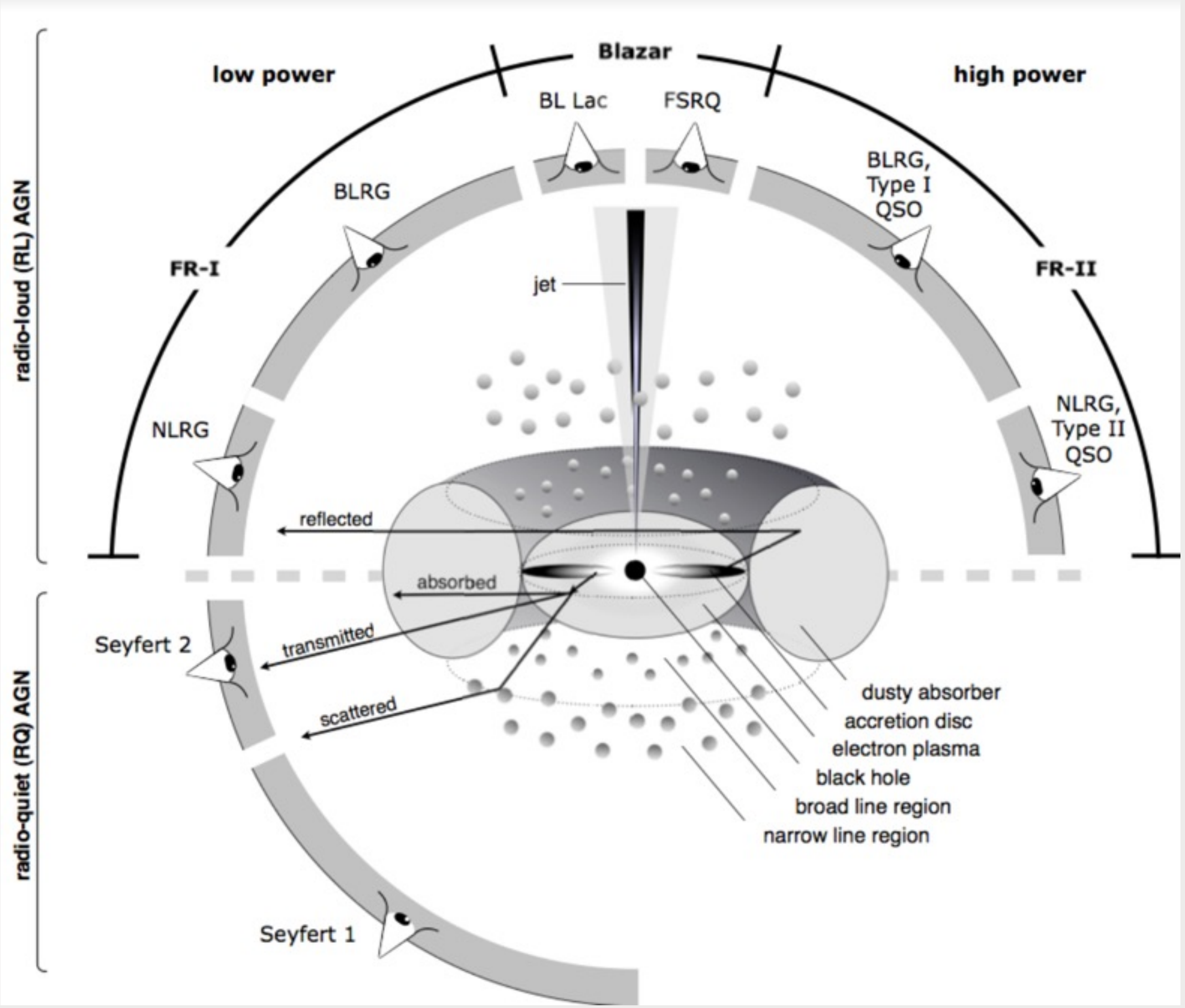
ACTIVE GALACTIC
NUCLEI

RADIO
GALAXIES

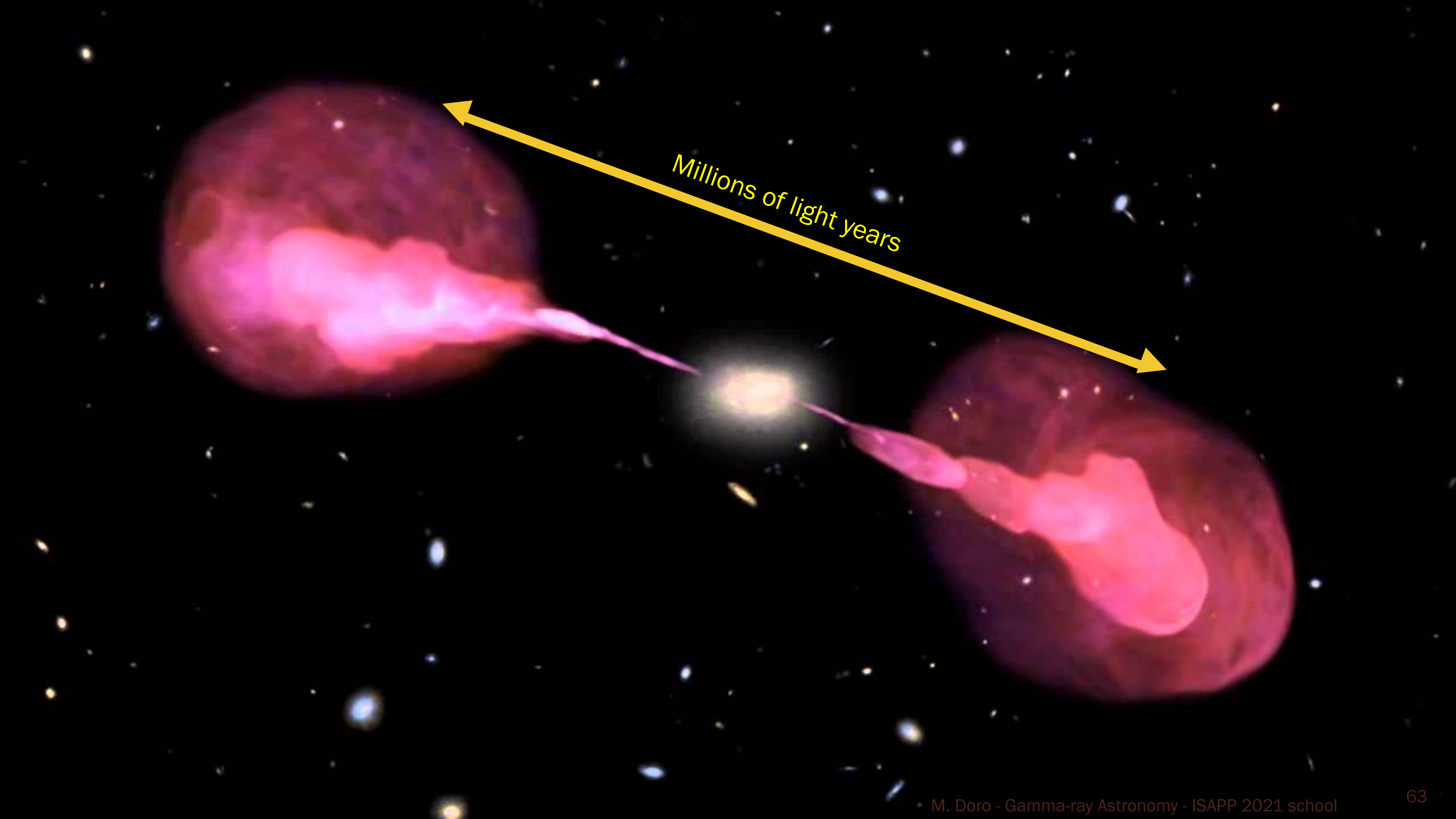
- Intense activities (winds)

STAR-BURST GALAXIES

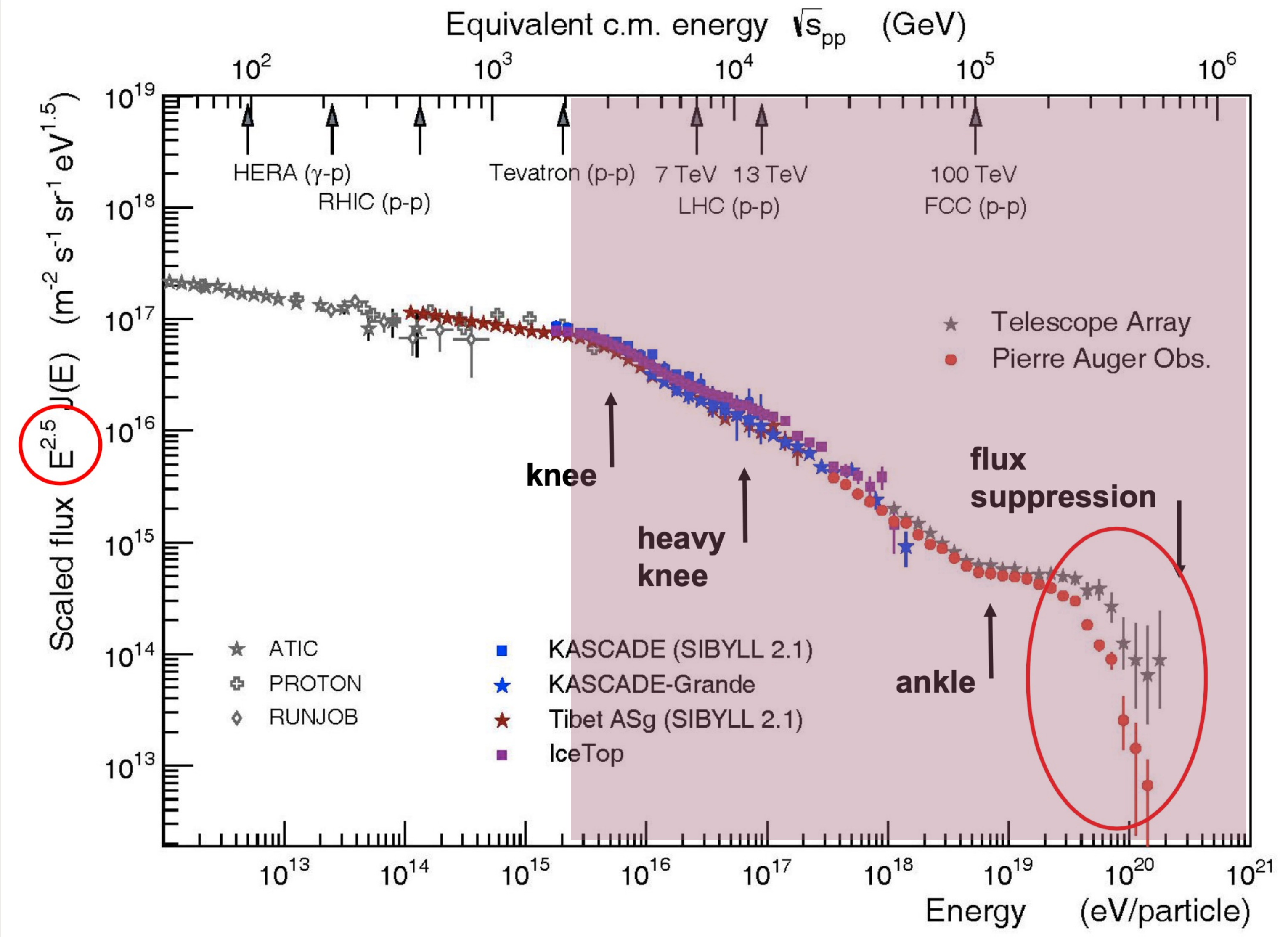
Model of Active Galactic Nuclei



- A supermassive BH $10^6 - 10^{10}\ M_\odot$
- In 1% of cases AGN
  - *Strong (rotationg) accretion disk*
  - *A dusty torus*
- (10% of AGN) Ultrarelativistic jets
  - *0.01 pc width*
  - *Mpc length*
- According to the view angle: different spectra
  - *Blazar: If eye is aligned to jet, you can see very faraway AGN because of strong Doppler boost*
  - *Quasar: one can see BH and the torus*
  - *Radio galaxy: BH is hidden, observed the jets*

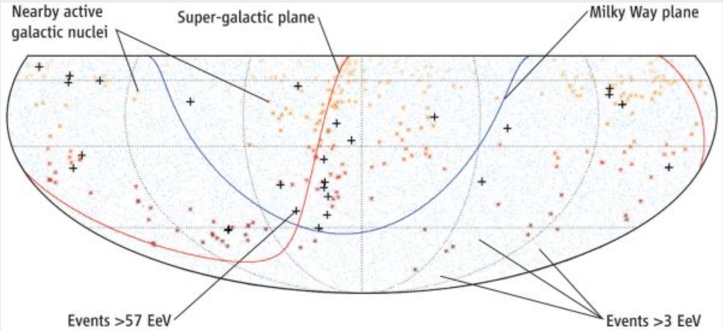

Millions of light years

Here comes the galactic CR



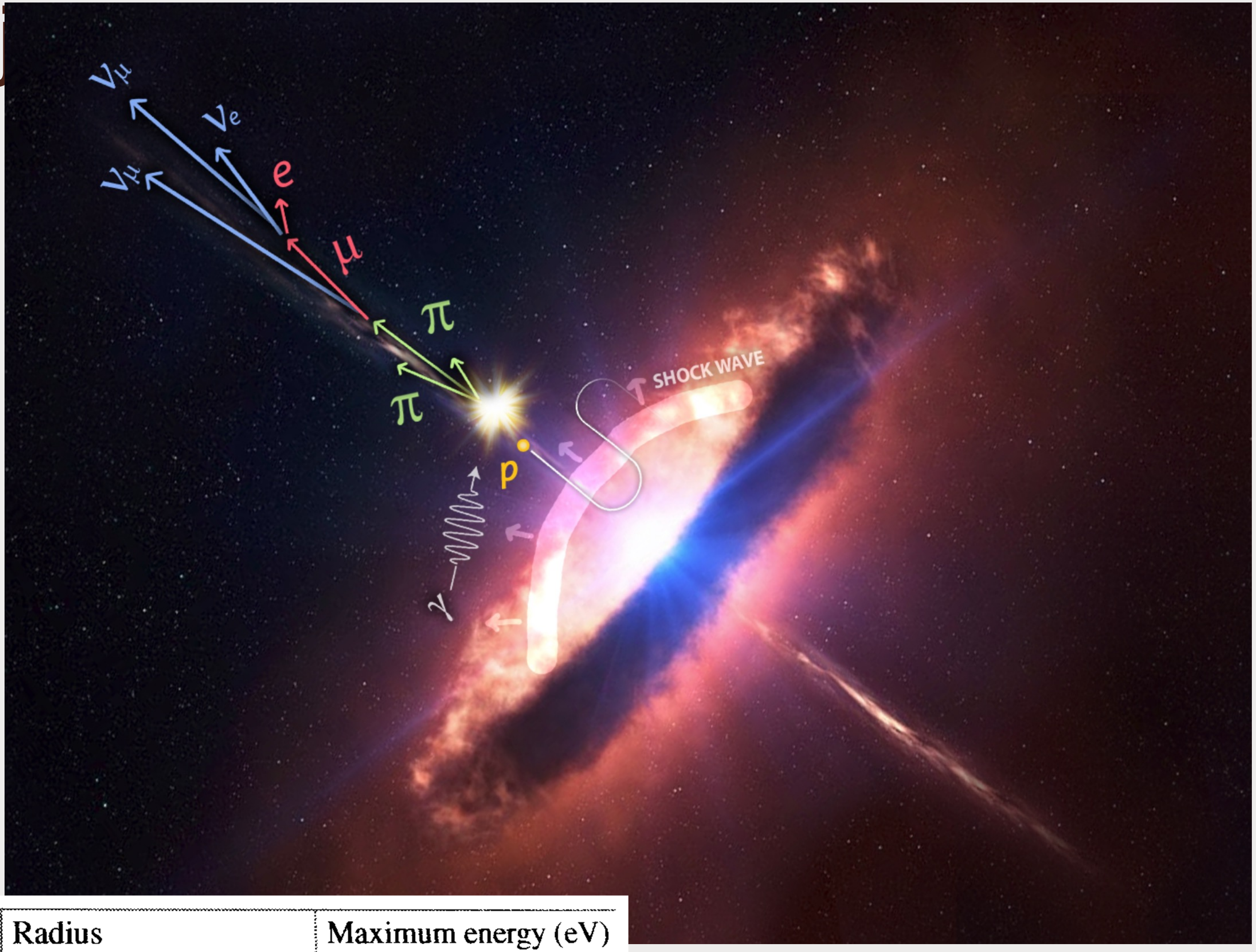
EXTRAGALACTIC

- AGN are valid booster
- Only recenty validated experimentally (Auger)



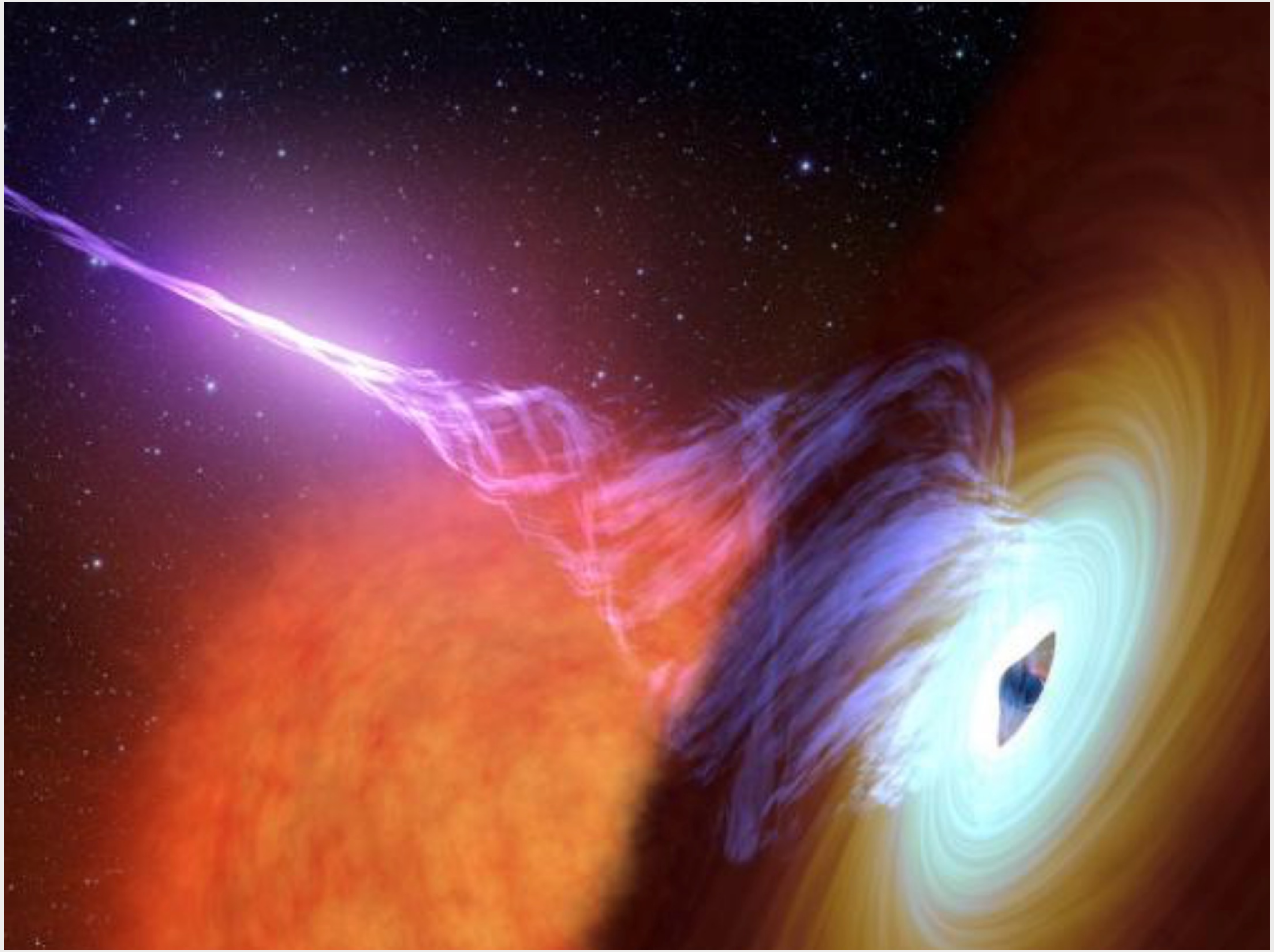
Ultrarelativistic j

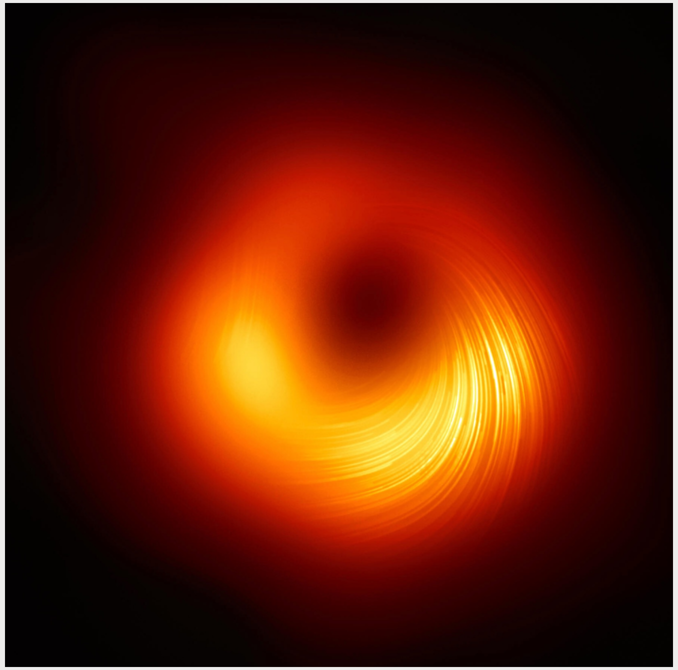
- AGNs can accelerate particle via diffuse stochastic acceleration up to 10^{21} eV



Source	Magnetic field	Radius	Maximum energy (eV)
SNR	30 μG	1 pc	3×10^{16}
AGN	300 μG	10^4 pc	$>10^{21}$
GRB	10^9 G	10^{-3} AU	0.2×10^{21}

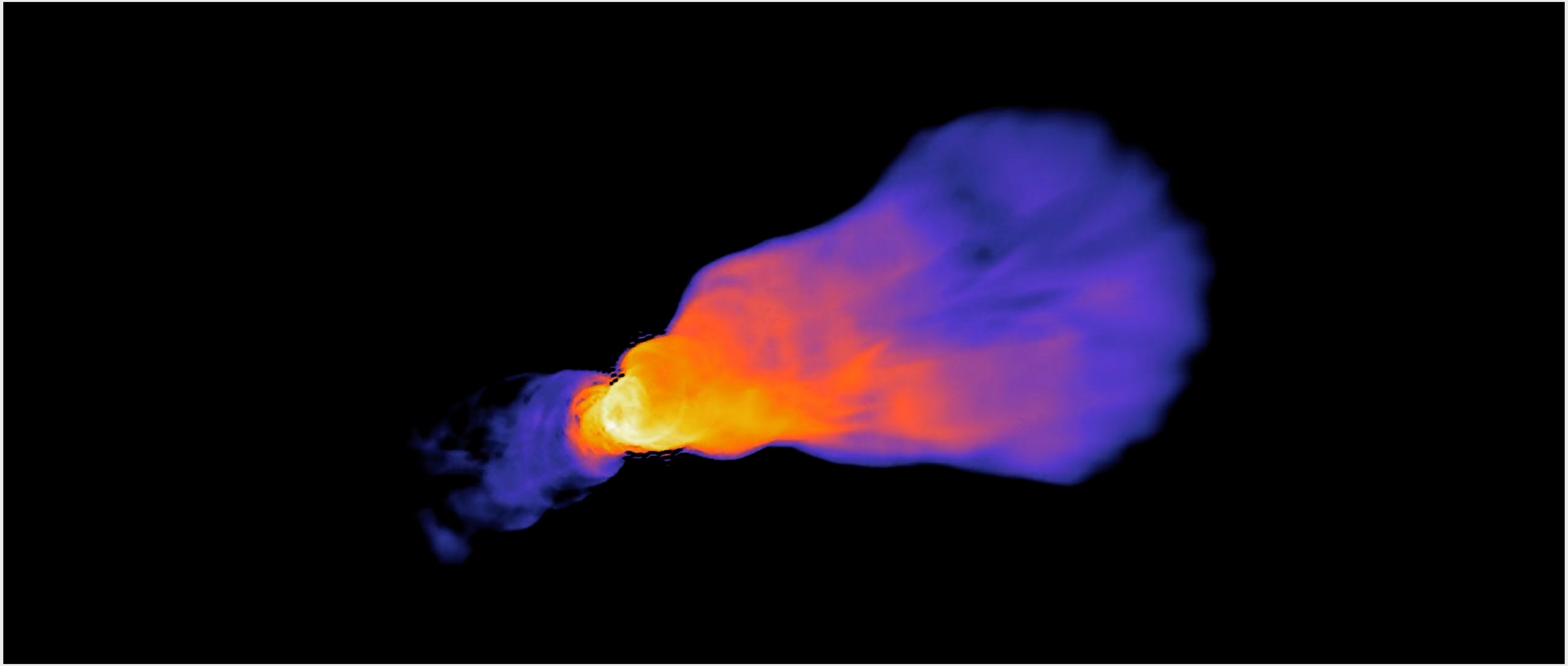
Ultrarelativistic jets mechanism





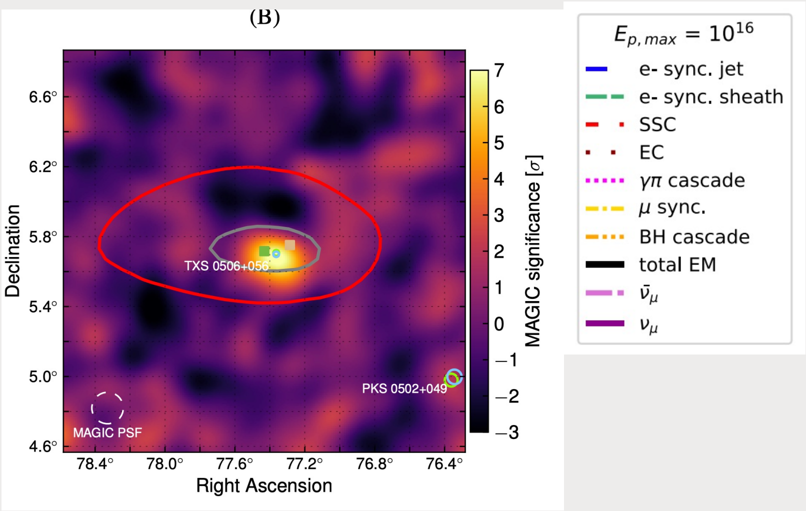
- Very recently released second (polarized!) image of M87 BH
- https://eventhorizontelescope.org/blog/astronomers-image-magnetic-fields-edge-m87s-black-hole

Engine Powering Black Hole Energy Beams

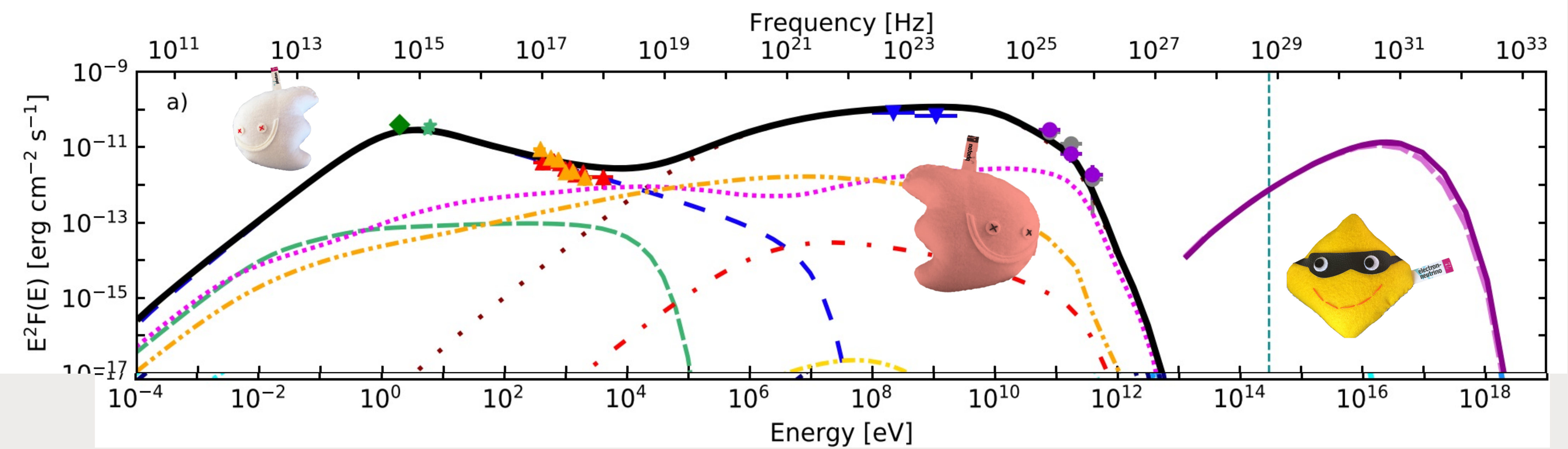


Simulations are catching up with physics, expect results soon!

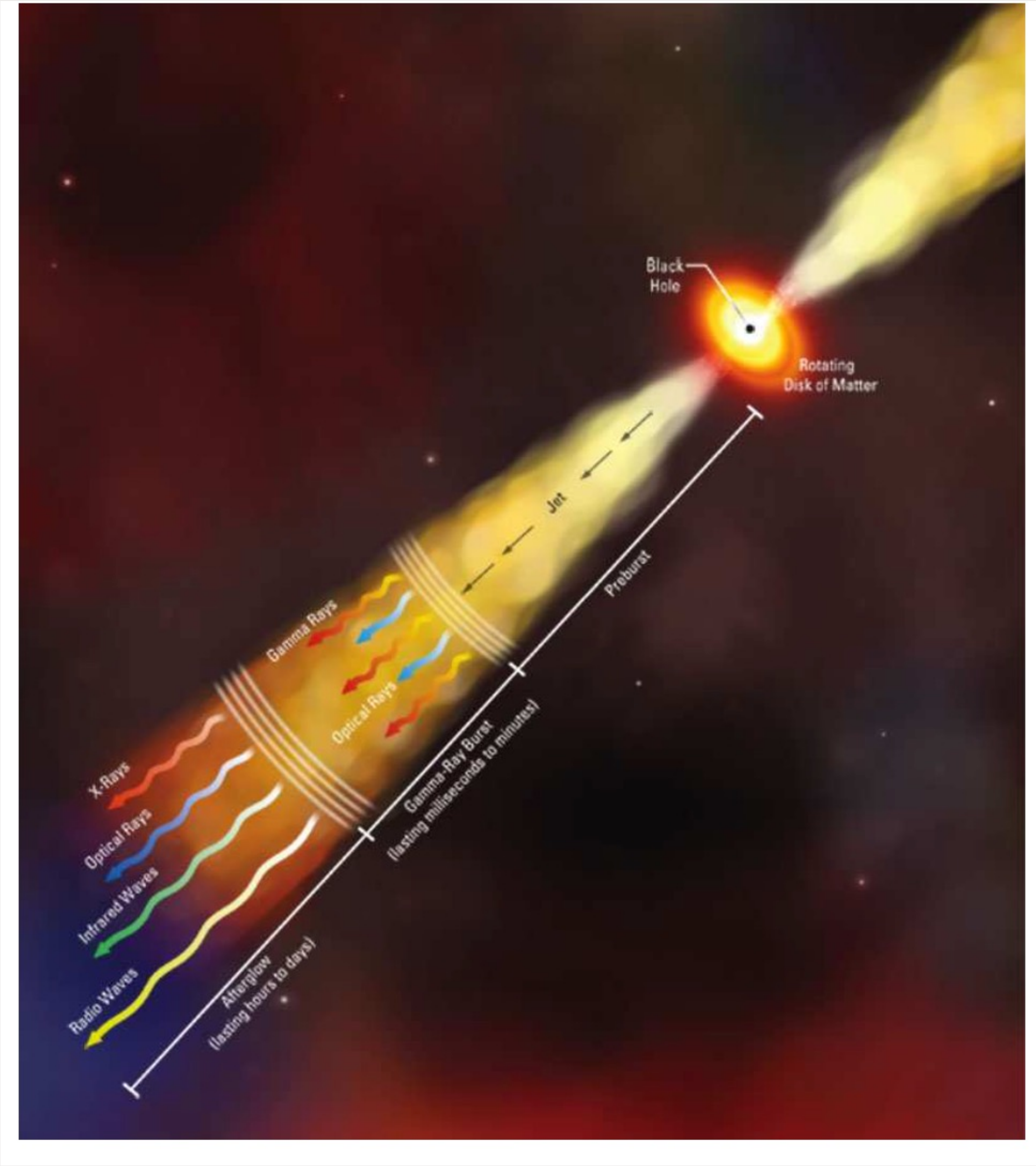
TXS 0506: multimessenger astronomy!



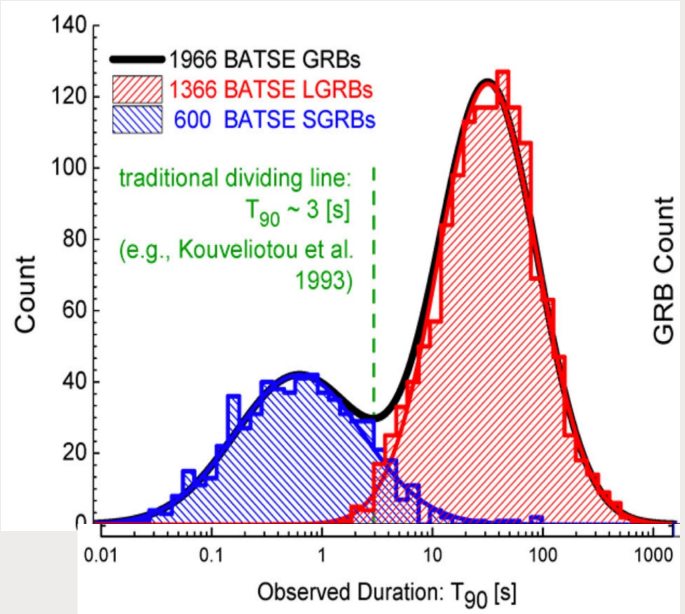
- On 2018, a neutrino with energy ~290 TeV was detected in coincidence with the BL Lac object TXS 0506+056 during enhanced gamma-ray activity
- A new messenger!



Gamma Ray Bursts

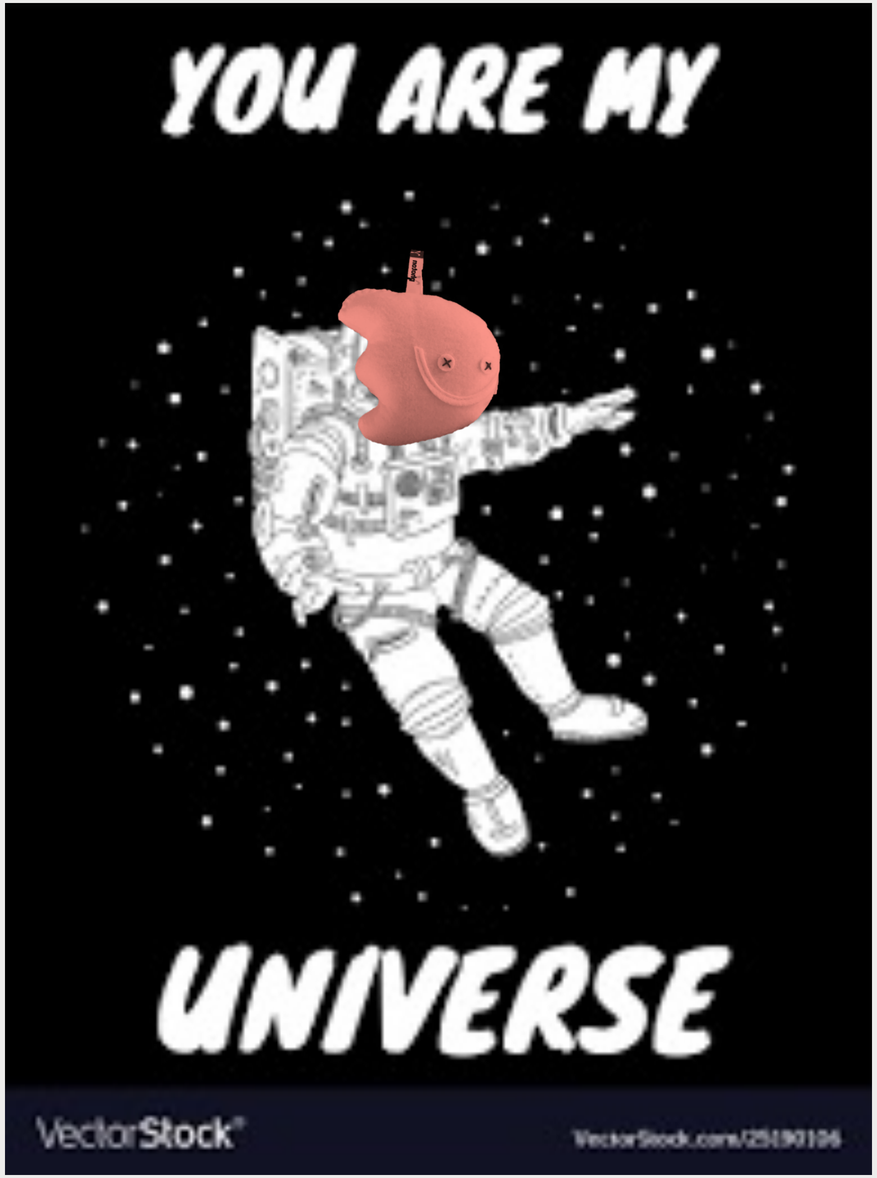


- Sudden outburst of radiation at all wavelengths
- Up to 10^{53} erg s^{-1}
- Convert into energy a mass of $10^{-3}\ M_{\odot}$ in matter of seconds
- Two populations
  - *Long duration*
  - *Short duration*

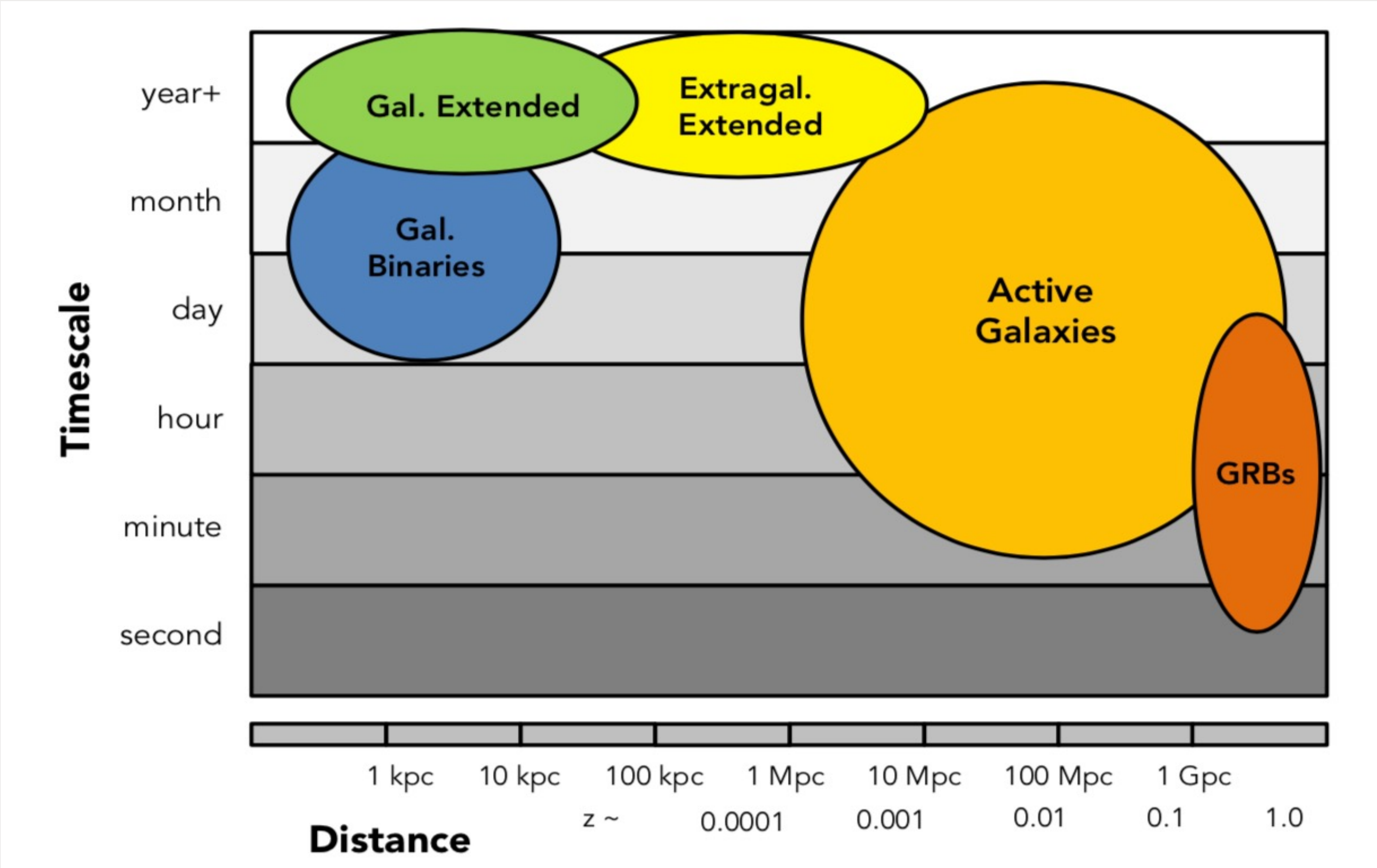


MNRAS 451, 126-143 (2015)

Postcards facts from gamma-ray Universe
(if time allows)

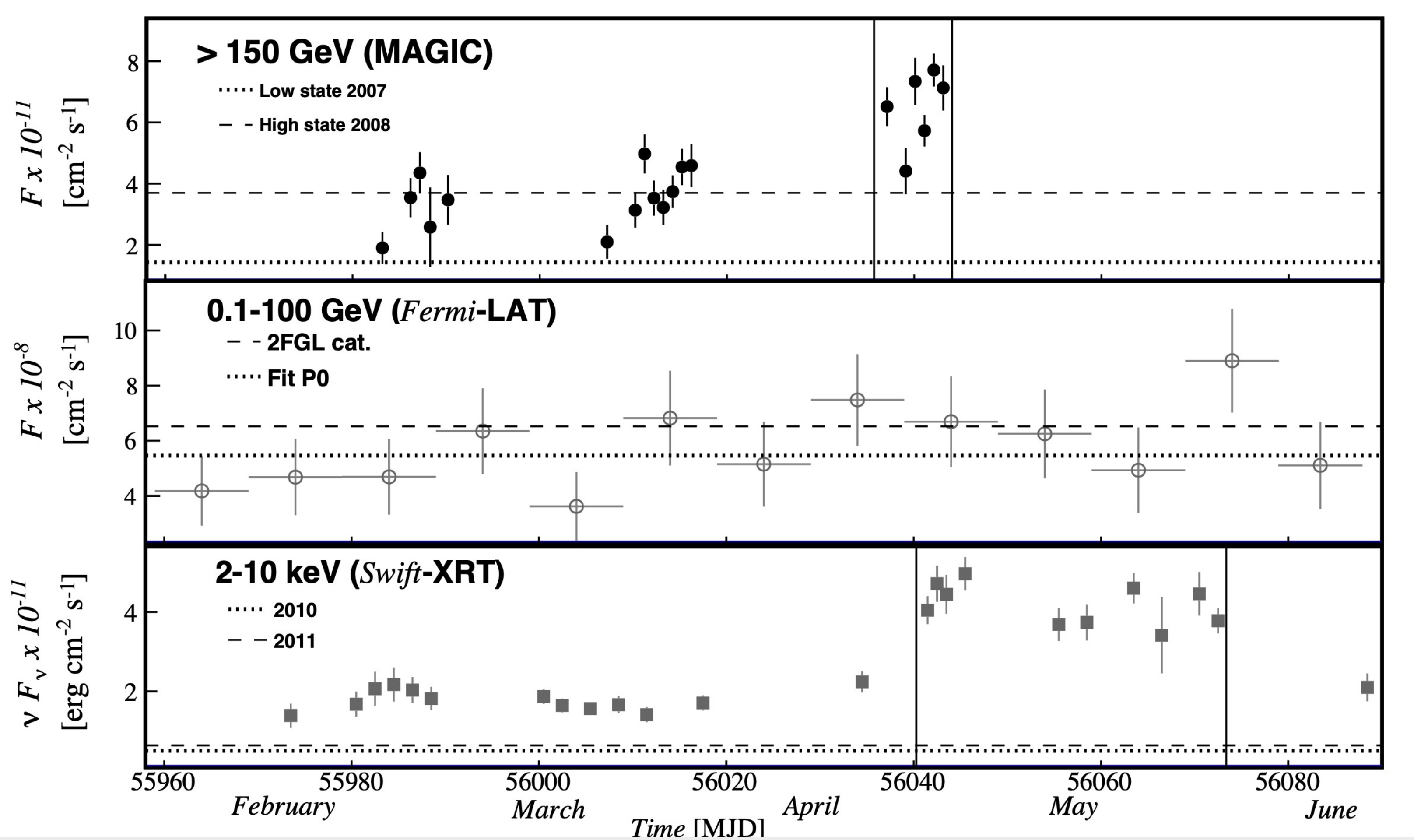


Temporal variability



J. Hinton

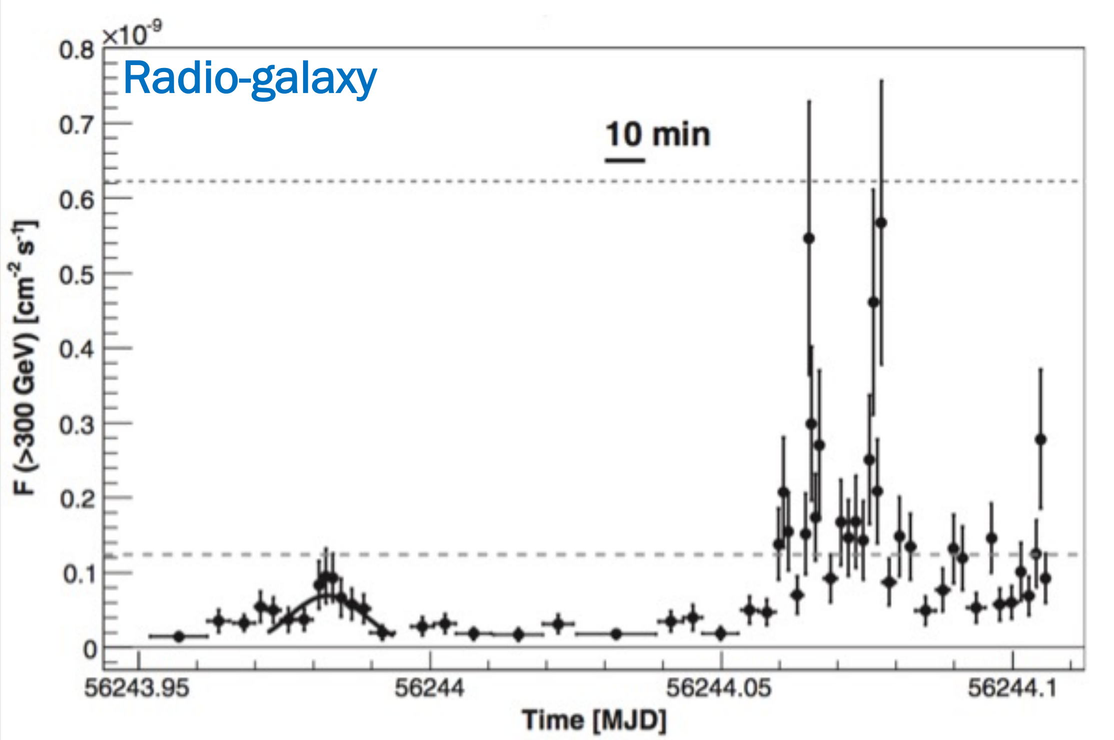
1/ Strong variability



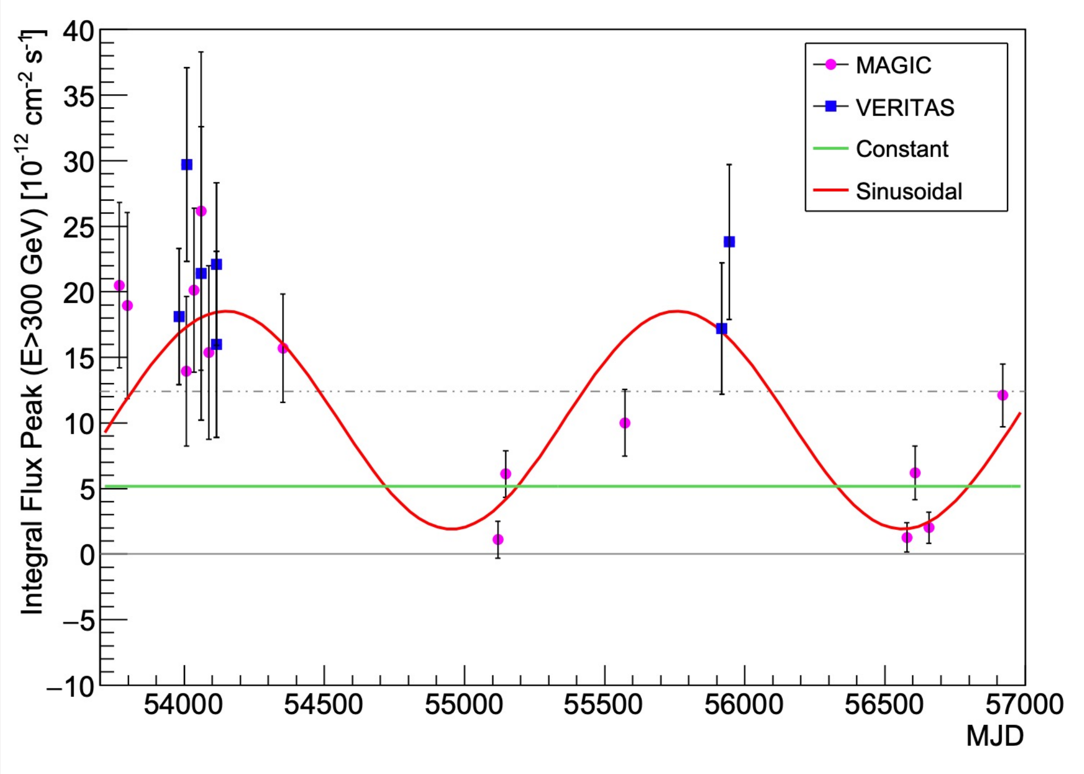
[MAGIC Coll] Mon.Not.Roy.Astron.Soc. 450 (2015) 4, 4399-4410

- Most non-thermal signatures are EXTREMELY variable
  - *Hint of acceleration region size*
  - *Sharp probe of physics (even new)*
- Wind crossing, molecular clouds encounters...

Fast and slow variability



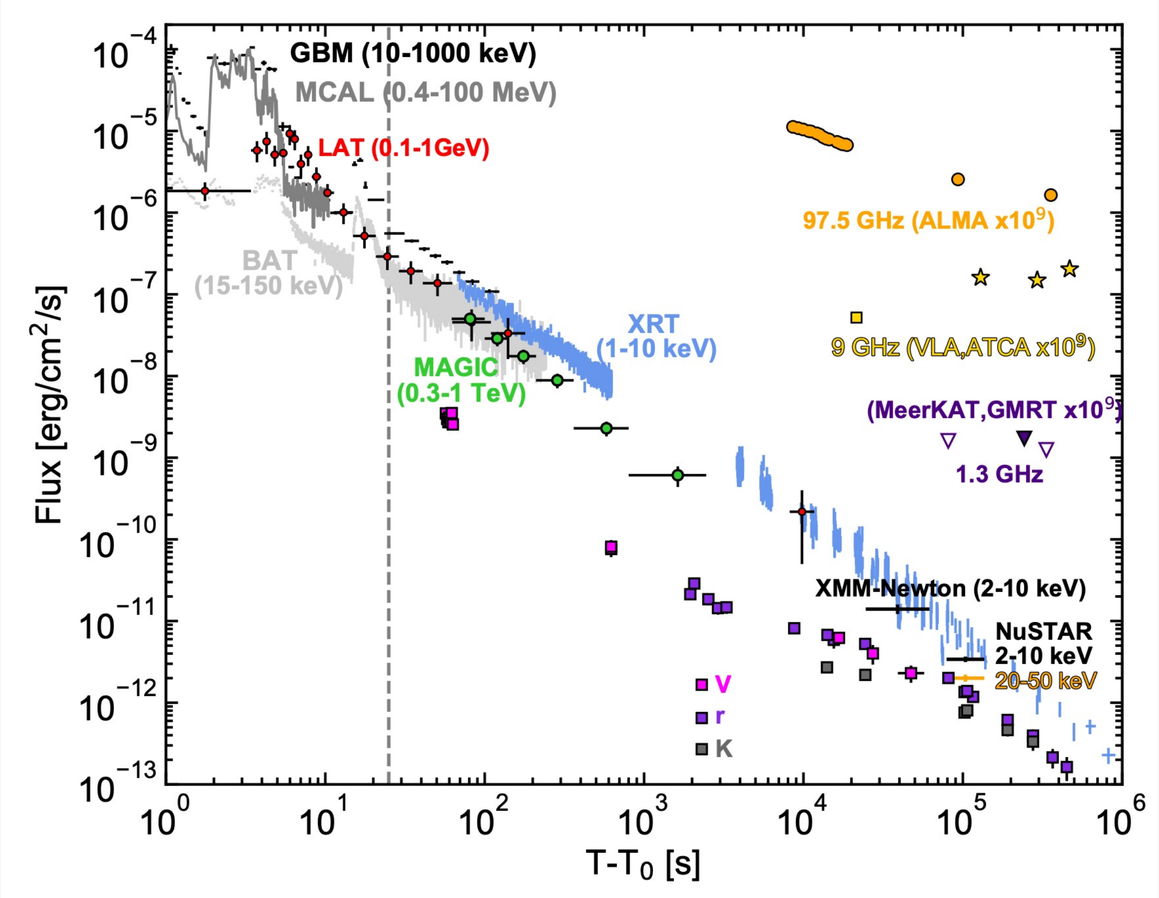
IC310. Doubling time 4.8 min

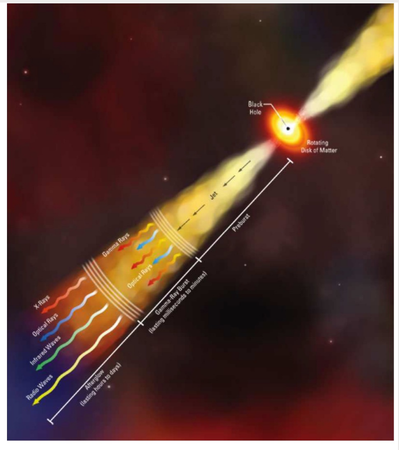


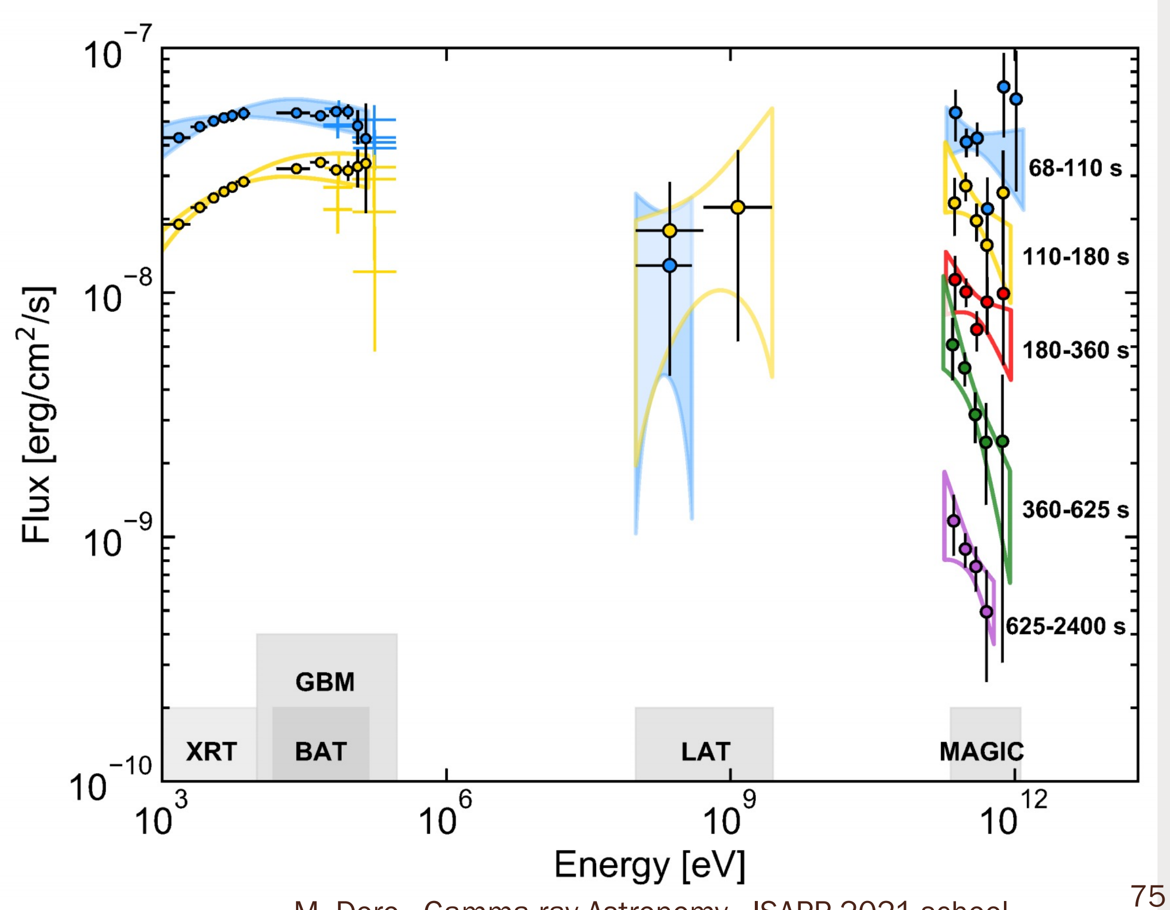
[MAGIC] Astron.Astrophys. 591 (2016) A76

- Fast variability: shocks, sudden status change
- Slow: binary encounters, variation over cosmic times

Temporal Evolution at High Energies

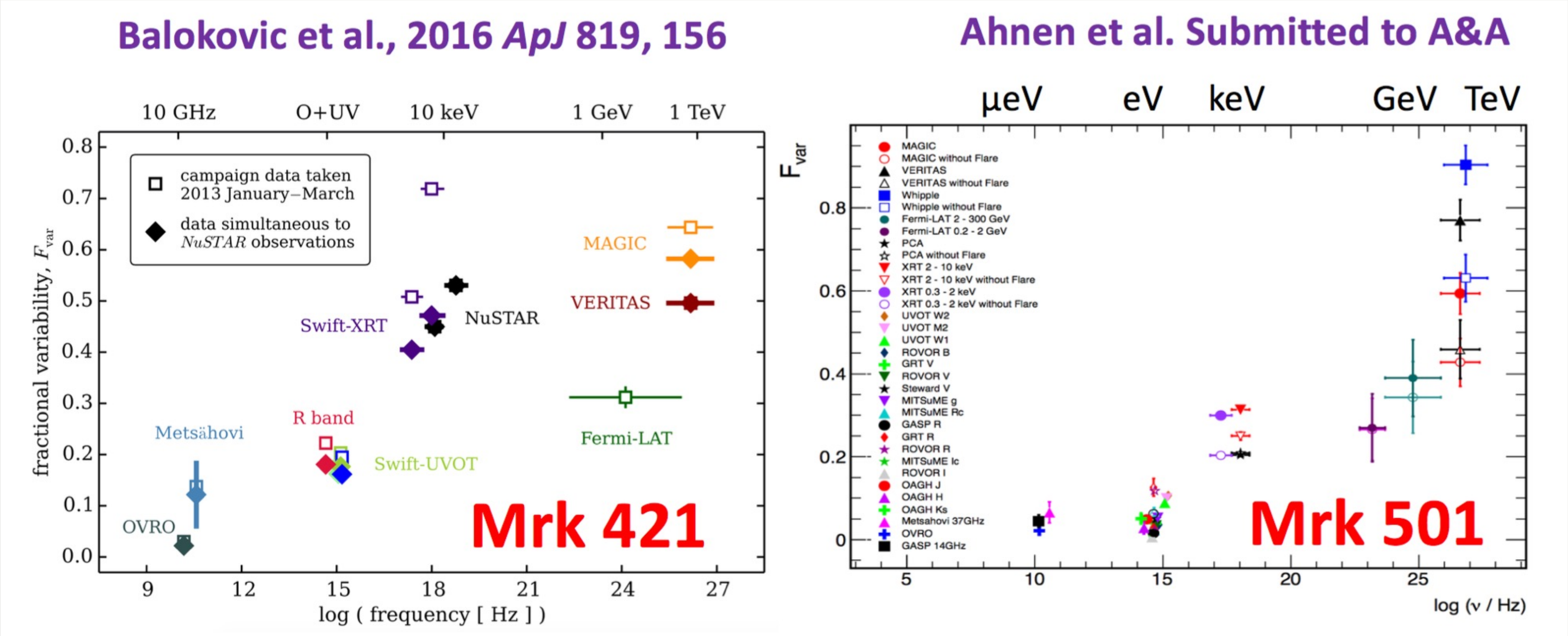






Nature 575 (2019) 7783, 459-463
Nature 575 (2019) 7783, 455-458

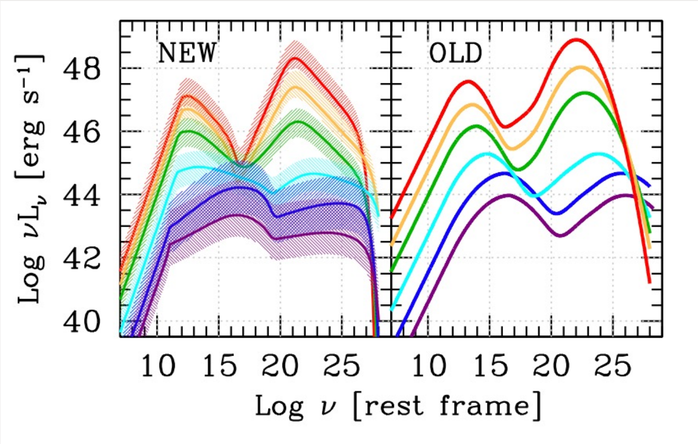
Fractional variability

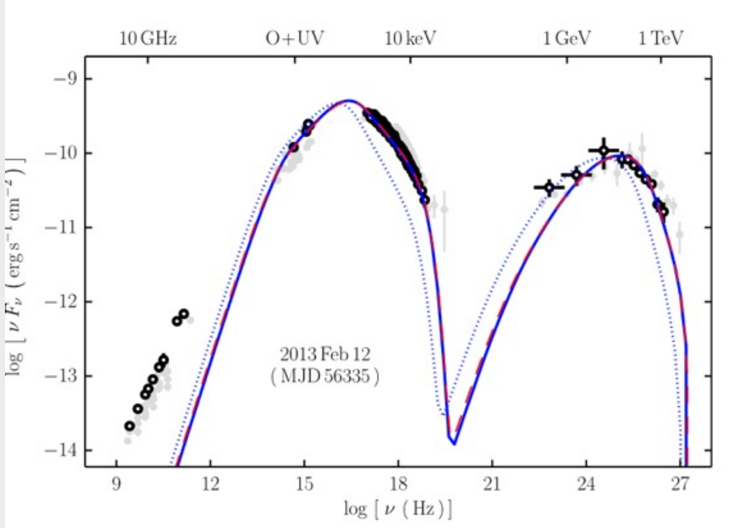


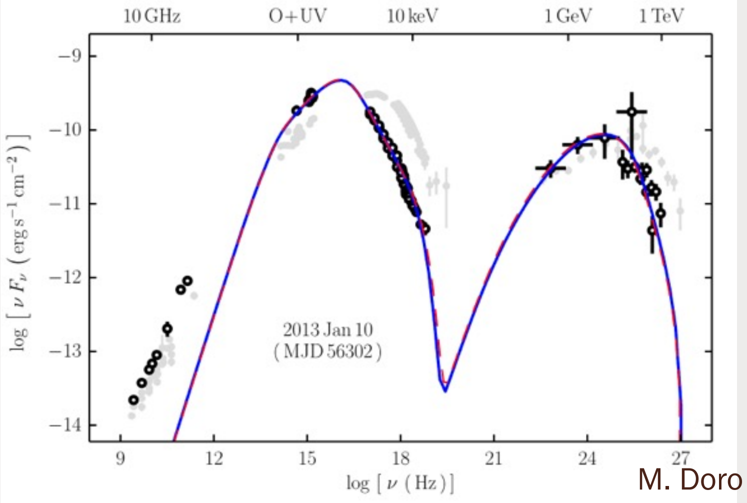
- Fractional variability requires large coverage, but guarantees connection between two bumps:
  - *Information on particle populations, acceleration efficiency…*

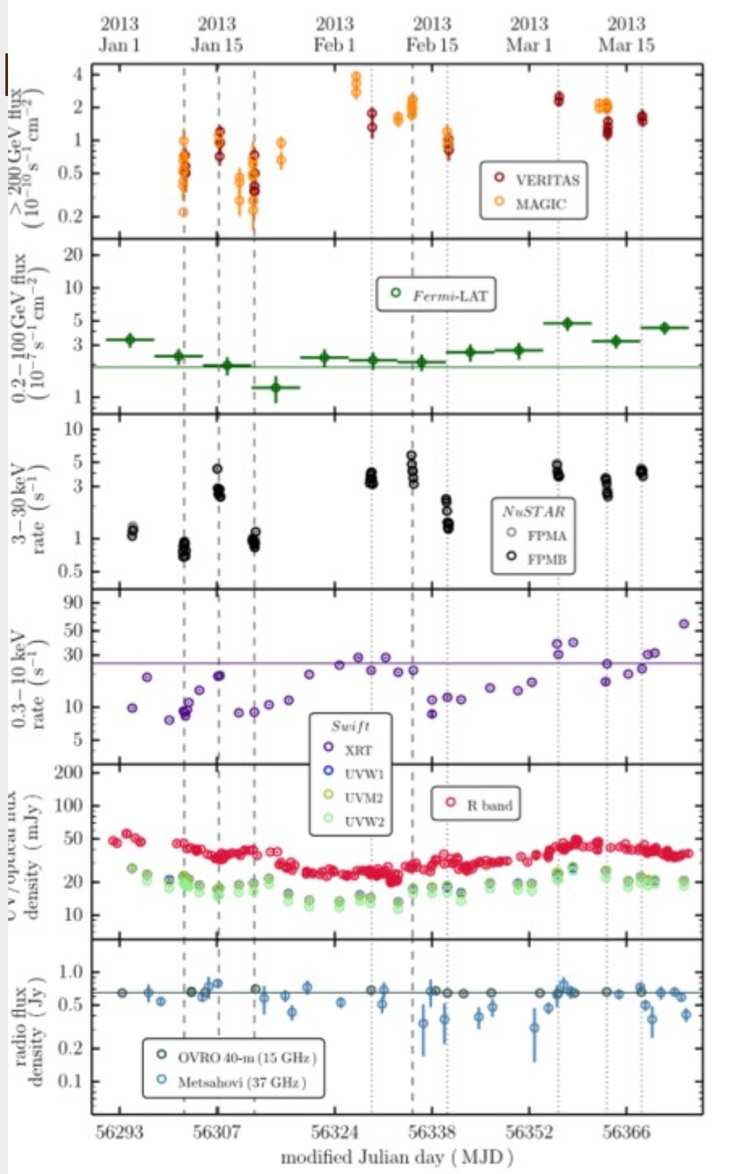
2/ Large projects: Multi-wavelength/multi-year

- The importance of multi-w campaign has become utter, l
several monitoring campaigns + ToO.







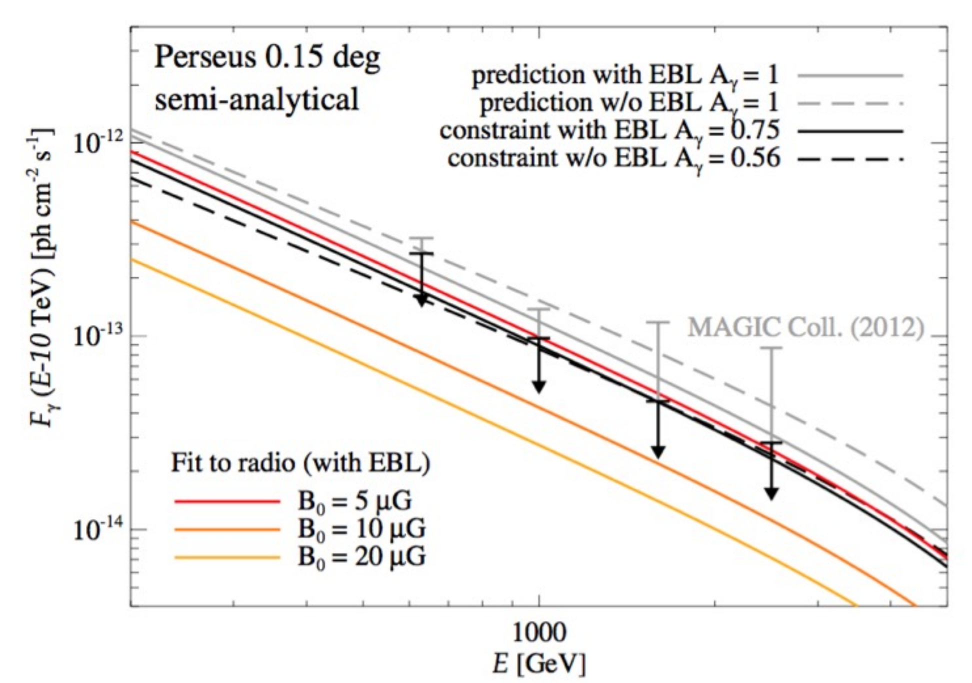


Astrophys.J. 819 (2016) 156

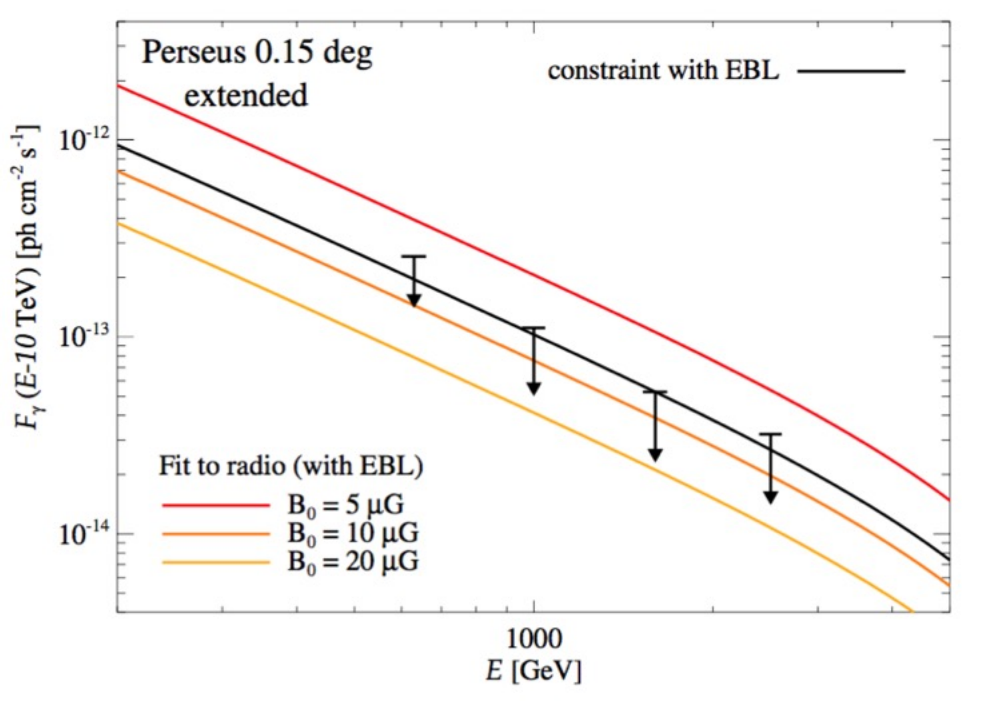
3/ Energy budgets in galaxy cluster

- Galaxy clusters are expected to show a diffuse gamma-ray emission due to the interaction of accelerated CR with the ambient intracluster medium
- Perseus is a cool-core clusters, brightest in X-ray→optimal lab

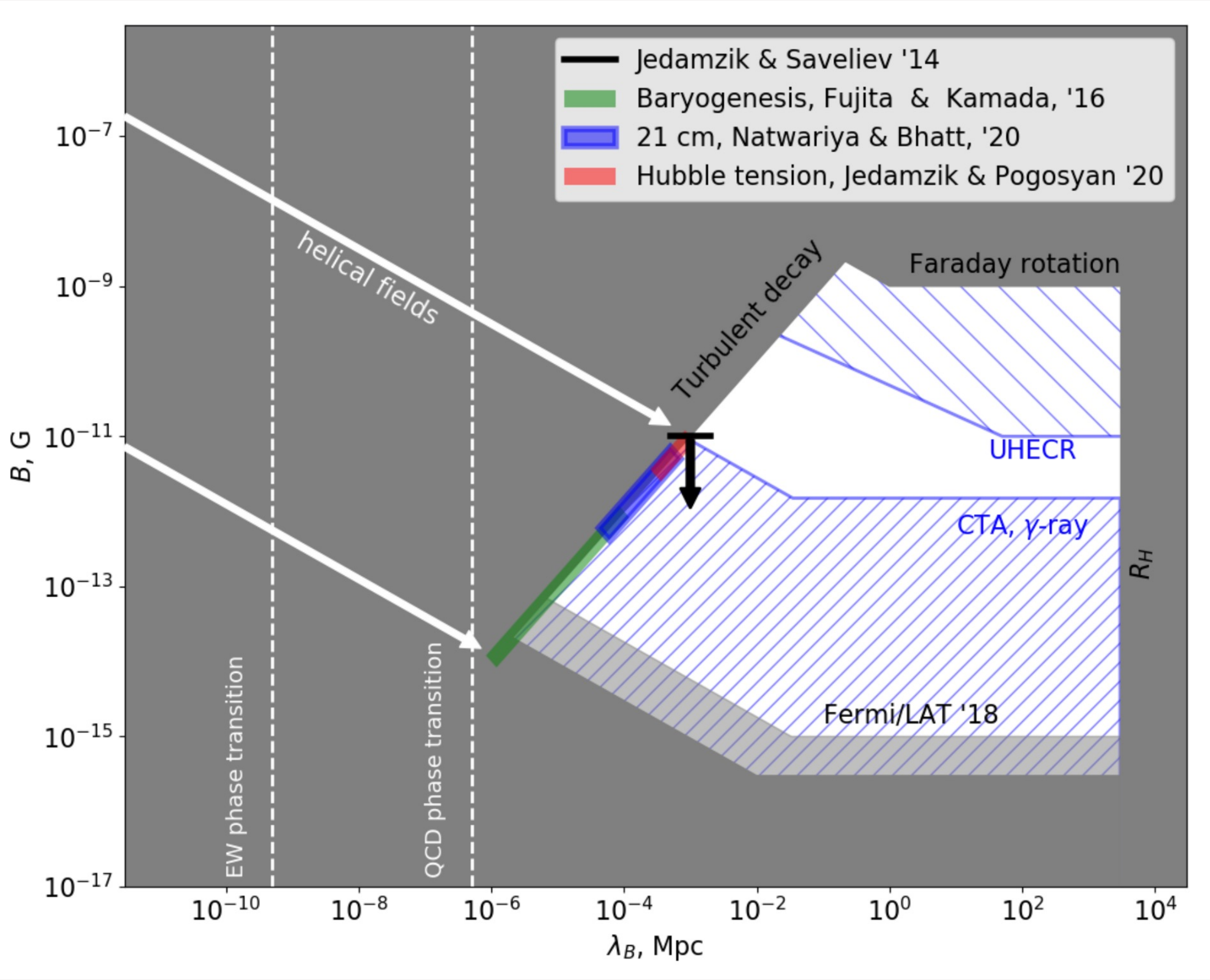
Q1: What fraction of the energy dissipated in structure formation shocks goes into particle acceleration ?



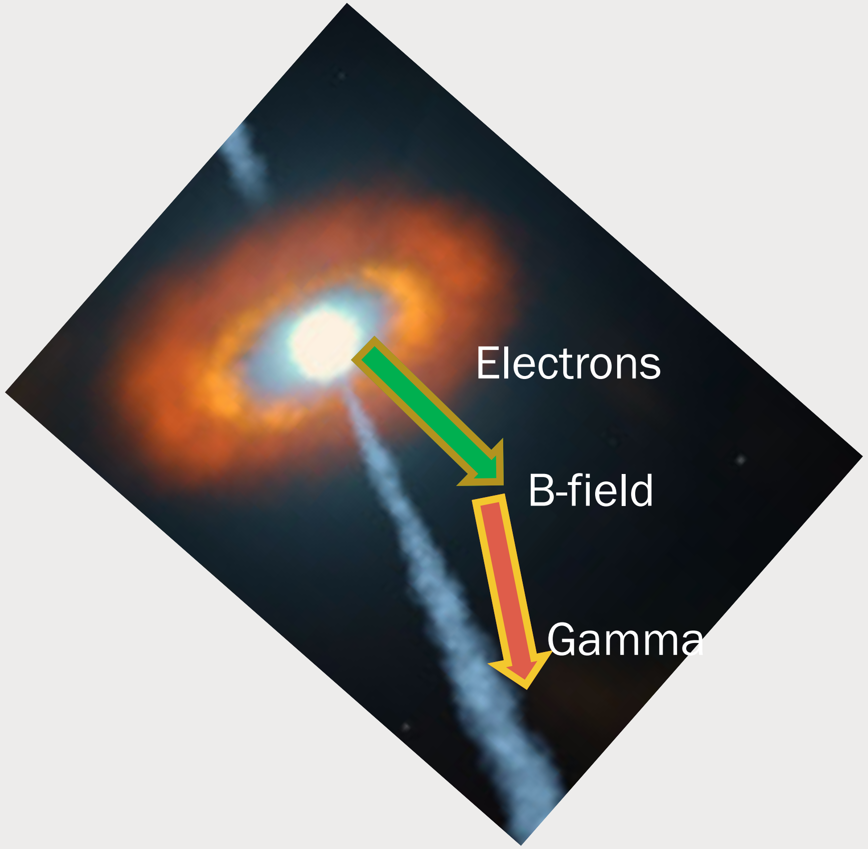
Q2: how intense is the magnetic fields that produce the observed sync-emission from secondary electrons?



4/ Probes of magnetic fields



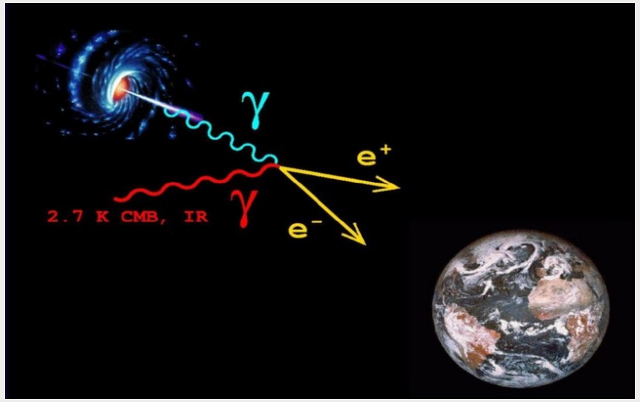
Astrophys.J. 906 (2021) 2, 116

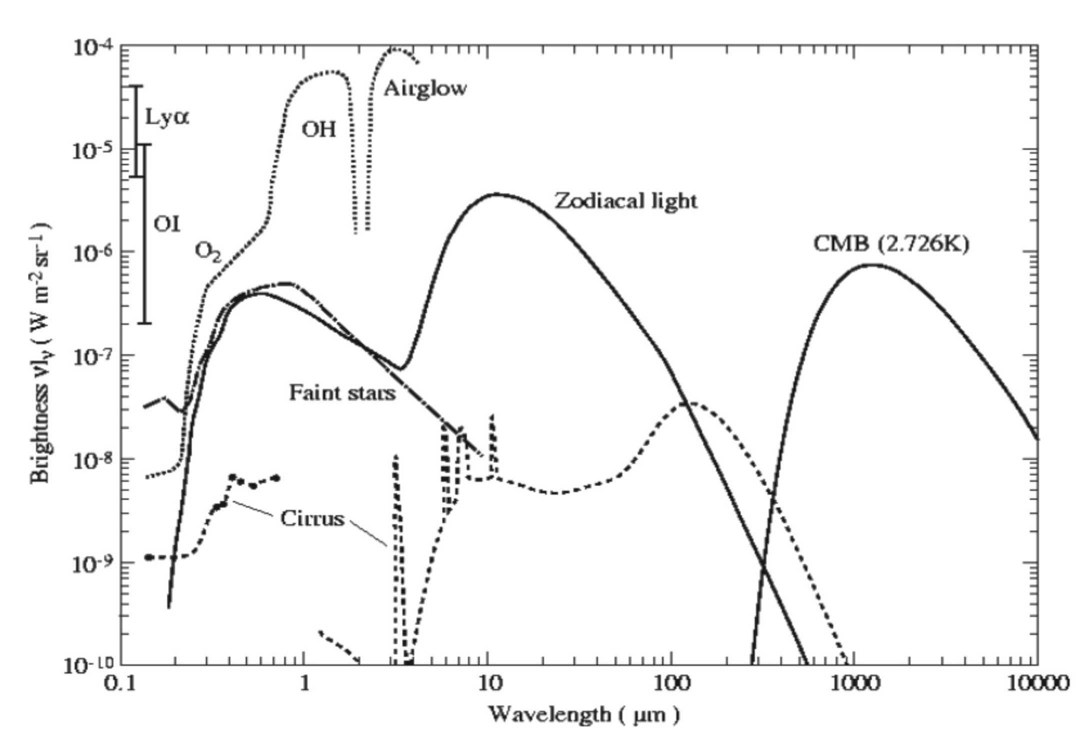


- Gamma-rays from synchrotron haloes around blazars

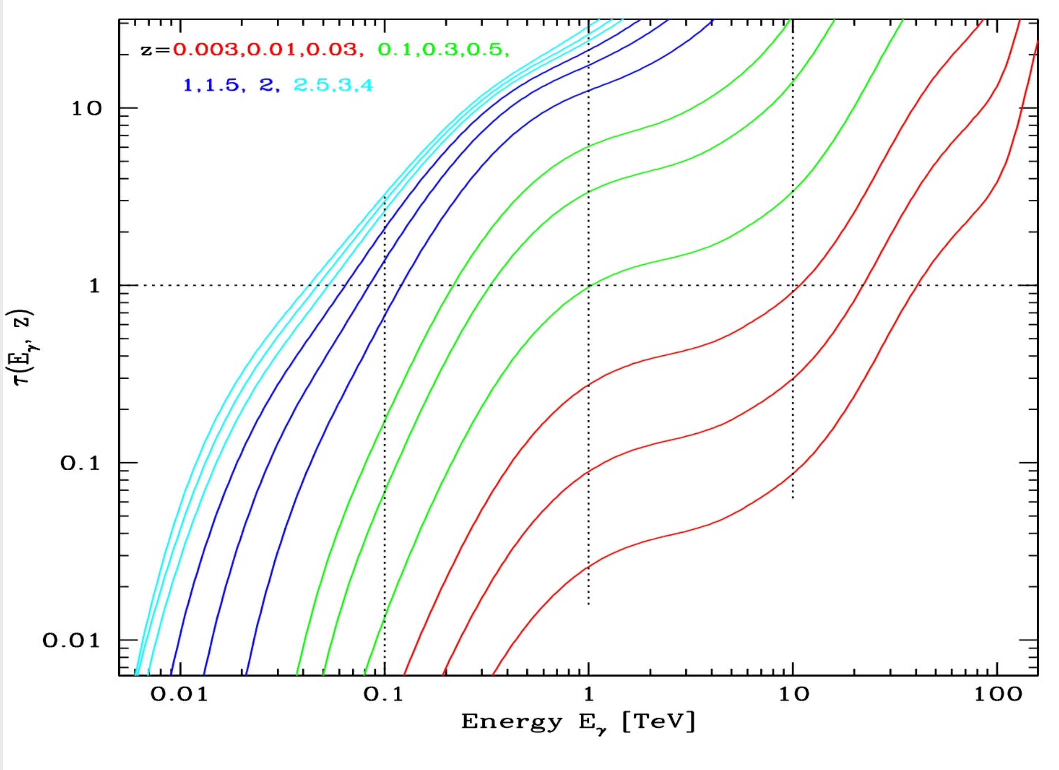
5/ EBL

- Extragalctic Background Light: light emitted from star and galaxies since early times, also absorbed and reprocessed permating the Universe
- Leave an imprint on blazar spectra, that probes the 'thickness' of the Universe





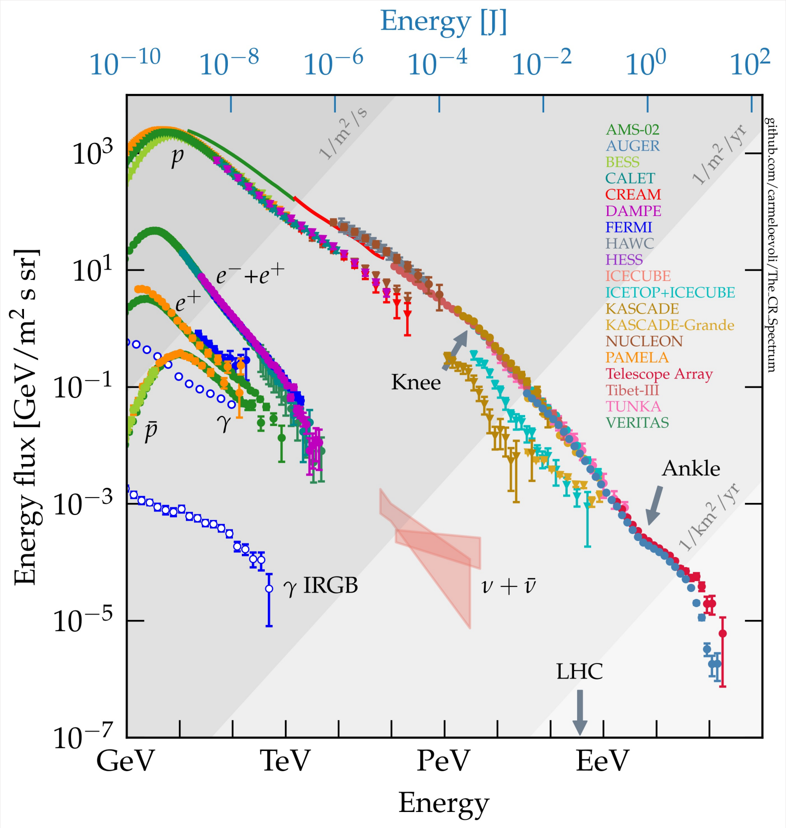
Leinert et al A&AS, 127, 1

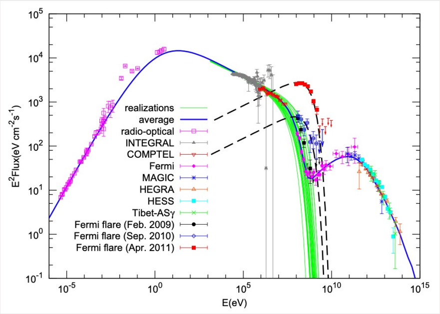


A. Franceschini Universe 7 (2021) 5, 146

CONCLUSIONS
TAKE HOME MESSAGES

Take home messages

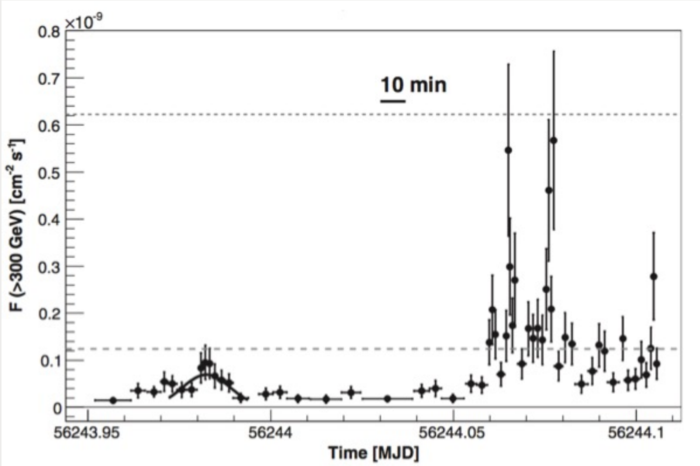


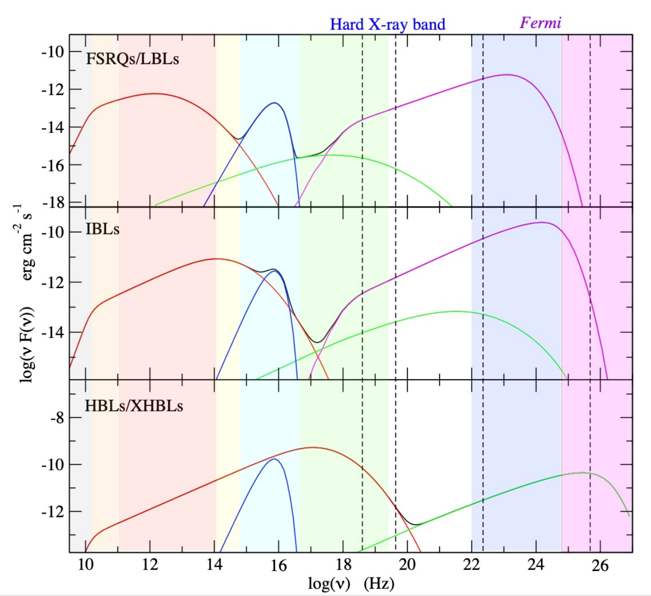


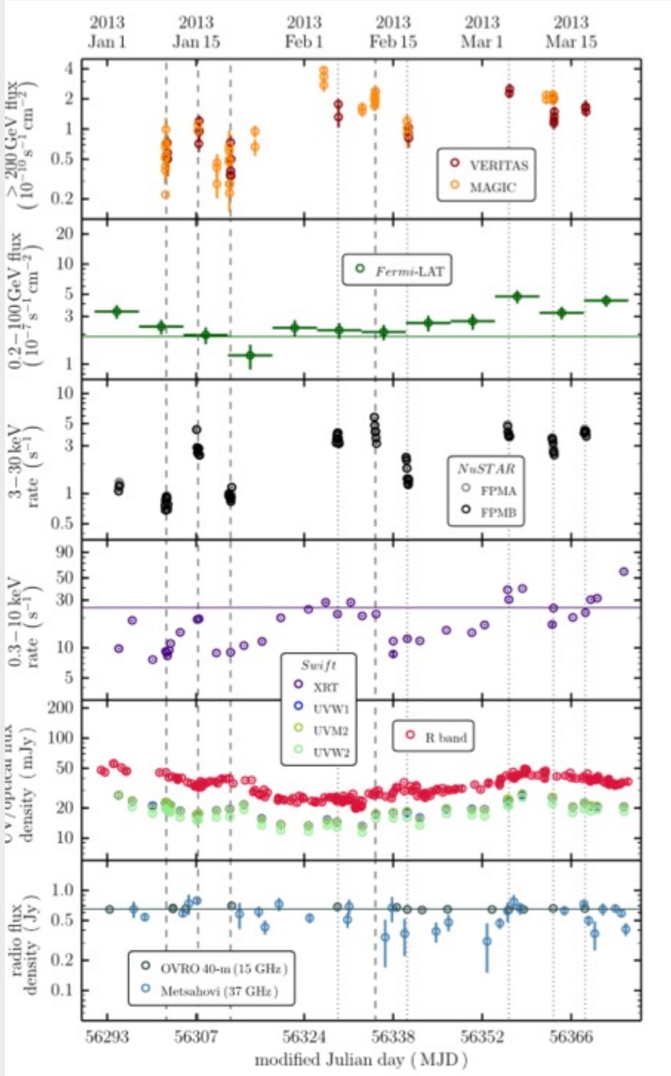
The amazing cosmic ray spectrum entails a world of physics phenomena

- From galactic to extragalactic
  - *Galactic: SNR?!*
  - *Extragalactic: AGN?!*
- Electron, positrons, proton, antiprotons, cosmic ray nuclei
- Accelerations mechanism requires mostly varying magnetic fields
- Charged particle radiate gammas
  - *Leptonic IC*
  - *Hadronic Pion decay*
- Energy density of diffuse neutrinos, hadrons and gammas very similar

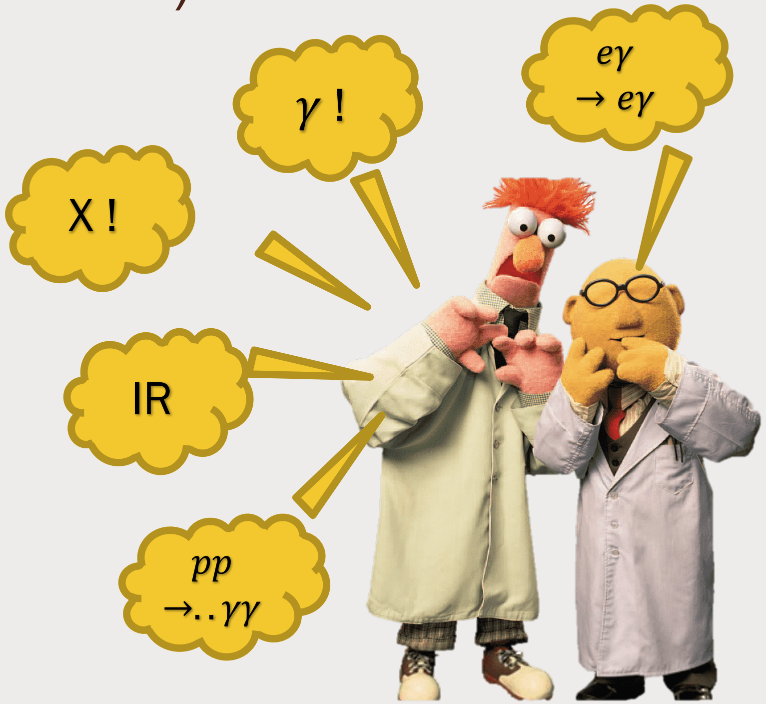
Gamma-ray physics/astrophysics/astroparticle







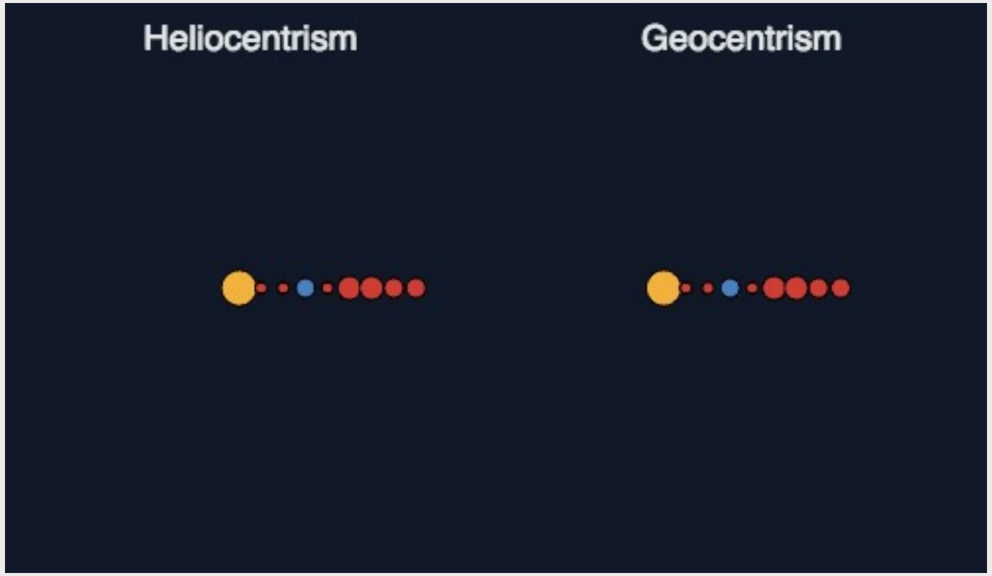
- It is a transient sky!
- A physical knowledge of the target require a strong astronomical knowledge (from radio to X)



Gamma-ray revolutions

- Revolution every 10 years (cf. Aharonian)
  - *TeV sky 2000 (MAGIC, HESS, VERITAS)*
  - *GeV sky 2010 (AGILE, FERMI-LAT)*
  - *PeV Sky 2002 (LHAASO, HAWC)*
- More revolutions
  - *GW+gamma (2017)*
  - *Neutrino+gamma (2018)*
- **More on Monday lecture!**

Are they close to solving the CR puzzle?



Hope you enjoyed our trip so far! **Thanks**