GAMMA-RAY ASTRONOMY

A story of travelers

Part 1. Theory

‘Arqus Twinning’ Bergen-Padova 2022

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

Program

- What is a gamma ray?
- Cosmic rays and gamma-rays
- Acceleration of cosmic rays
- Generation of gamma rays
- Nice gamma-ray targets

Pt 2. Instruments (Tuesday lecture)

- Many travellers
  - *Particles*
  - *Radiation*

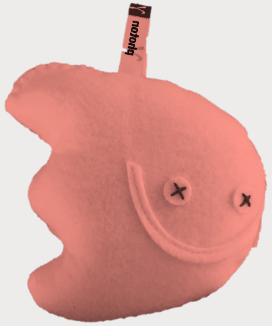
- To try and fix concepts, we will try and get helped by analogies to travel…but our will be an truly **cosmic travel**

Travellers (and a disclaimer)

the electron and the positron

the PROTON

the neutrino

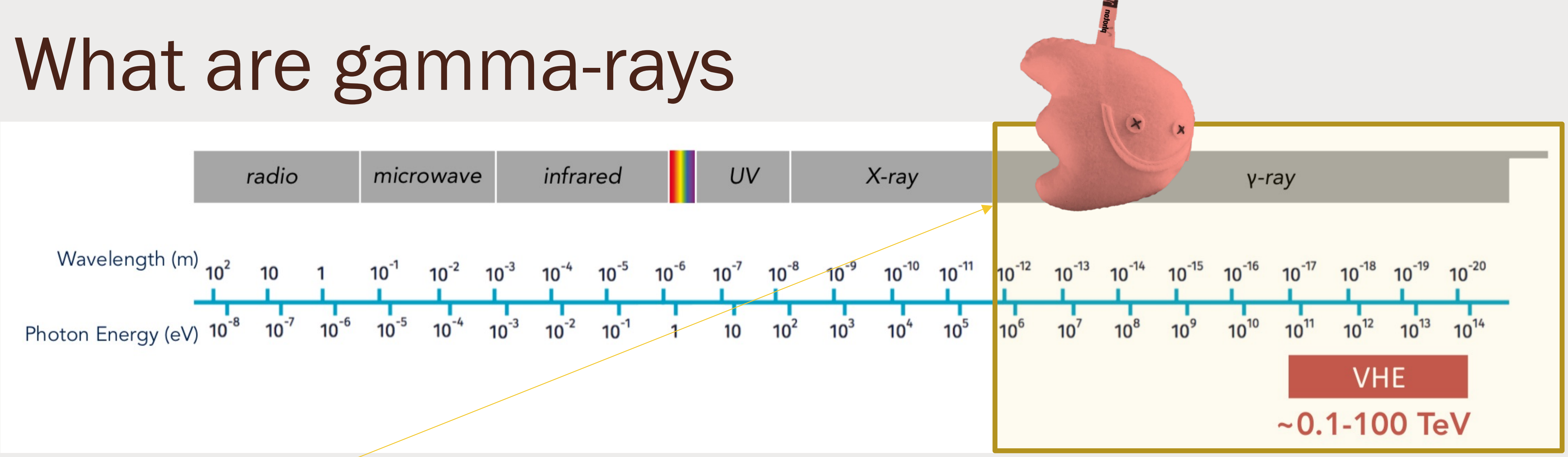


ze scary gamma ray

Weak photons

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

What are gamma-rays



- Minimum energy is the pair production threshold E=0.511 MeV (electron mass)
- A photon of 1 TeV has
  - *An energy of* $1.6 * 10^{-7}$ *J = 1.6 erg*
  - *A wavelength of* $1.25 \; * 10^{-18}$ m
  - *A frequency of* $2.4 \; * 10^{-26}$ Hz

- Photon flux dN/dE in astrophysics best expressed energy flux (differential):

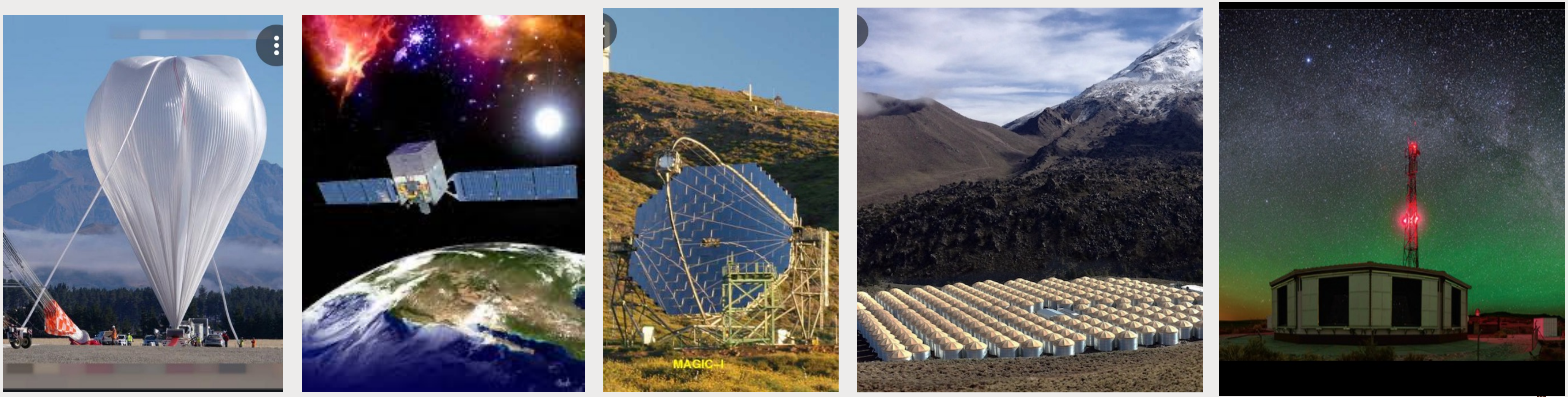
$$E^2 \frac{dN}{dE} = \nu F_\nu \; [erg\ cm^{-2} s^{-1}]$$

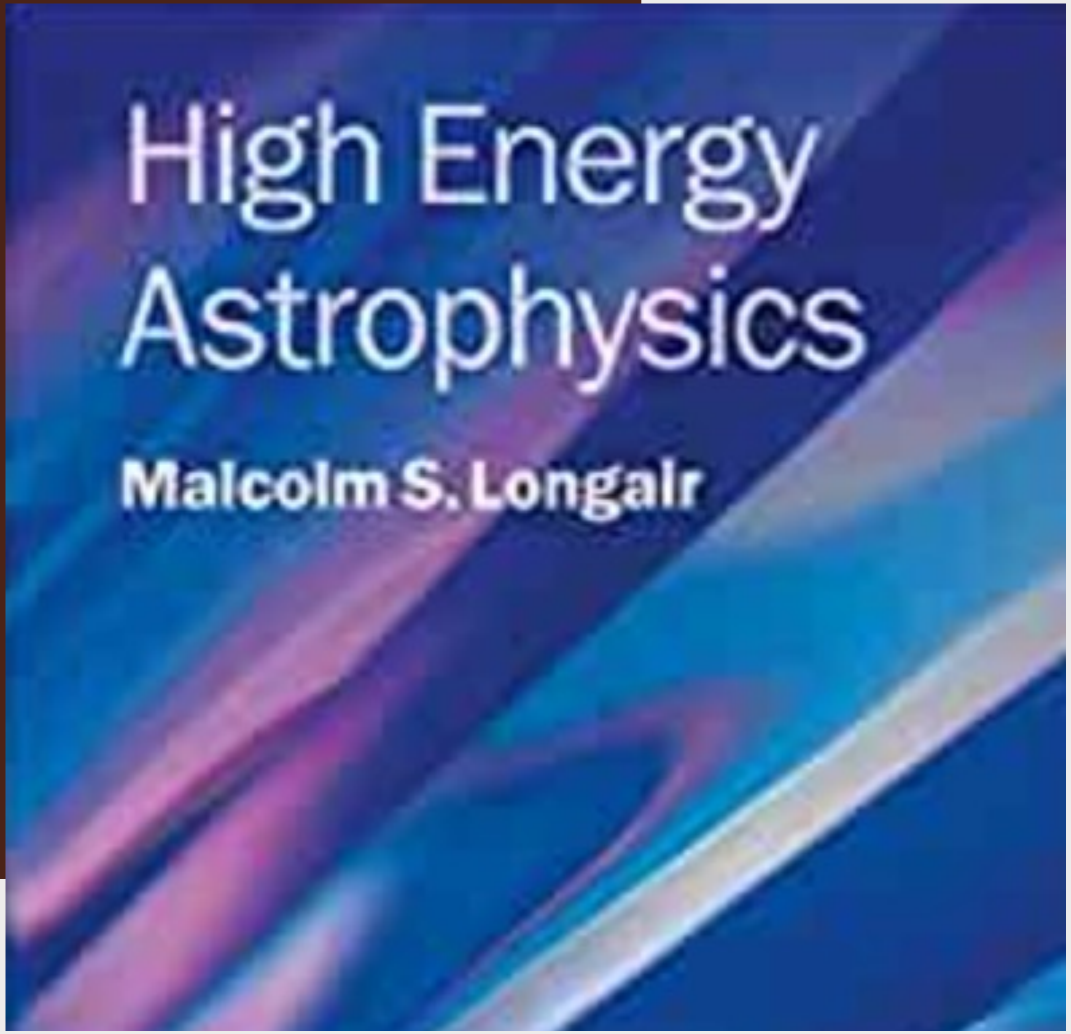
Spectral energy distribution (SED)

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

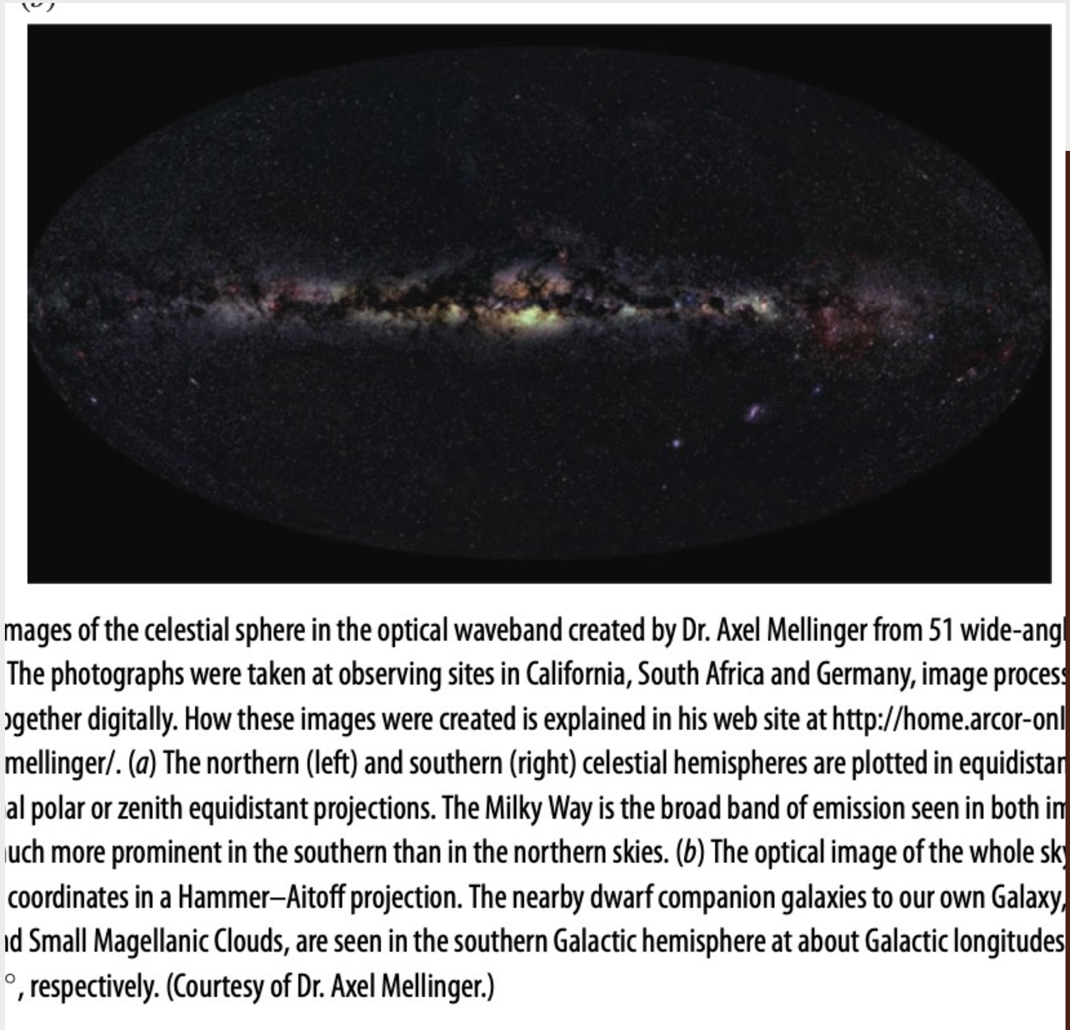
- Classification more related to experimental technique (see next lecture!)





High Energy Astrophysics

Malcolm S. Longair



mages of the celestial sphere in the optical waveband created by Dr. Axel Mellinger from 51 wide-angl
The photographs were taken at observing sites in California, South Africa and Germany, image process
ogether digitally. How these images were created is explained in his web site at http://home.arcor-onl
mellinger/. (*a*) The northern (left) and southern (right) celestial hemispheres are plotted in equidistan
al polar or zenith equidistant projections. The Milky Way is the broad band of emission seen in both im
uch more prominent in the southern than in the northern skies. (*b*) The optical image of the whole sky
coordinates in a Hammer–Aitoff projection. The nearby dwarf companion galaxies to our own Galaxy,
d Small Magellanic Clouds, are seen in the southern Galactic hemisphere at about Galactic longitudes
°, respectively. (Courtesy of Dr. Axel Mellinger.)

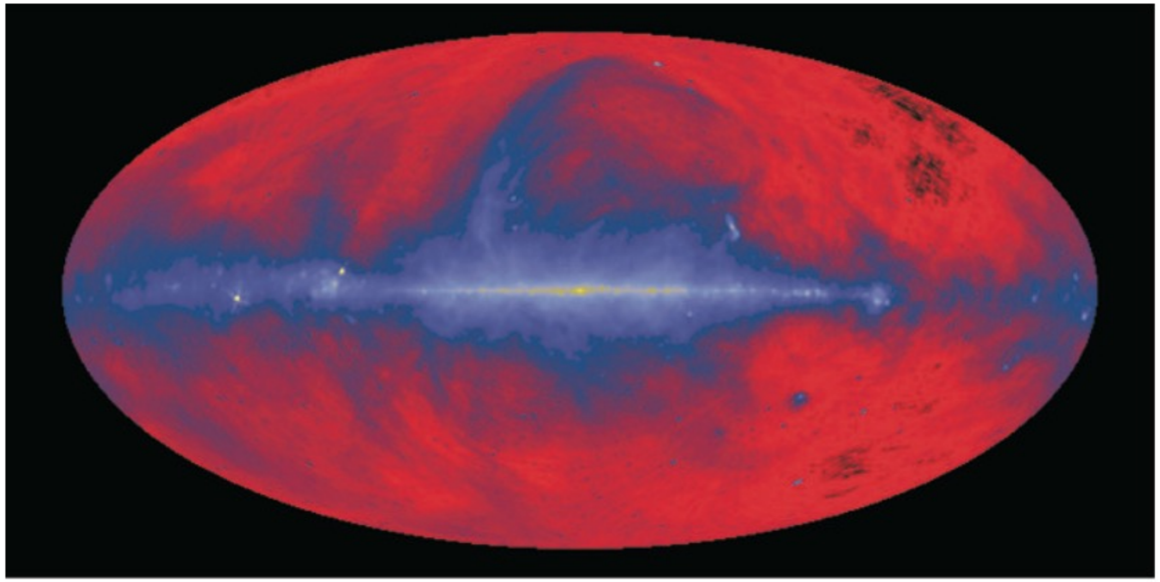


Fig. 1.9 Images of the celestial sphere at a radio frequency of 408 MHz in a Hammer–Aitoff projection. This image is dominated by the radio emission of relativistic electrons gyrating in the interstellar magnetic field, the process known as *synchrotron radiation*. The radiation is most intense in the plane of the Galaxy but it can be seen that there are extensive 'loops' and filaments of radio emission extending far out of the plane. (Courtesy of Max-Planck-Institut für Radioastrotiomie, Bonn.)

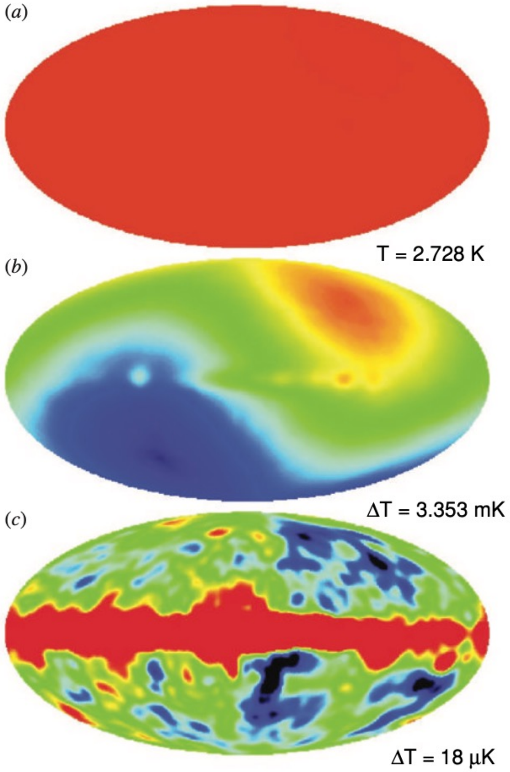


Fig. 1.6 Maps of the whole sky in Hammer–Aitoff projections in Galactic coordinates as observed at a wavelength of 5.7 mm (53 GHz) by the COBE satellite at different sensitivity levels. (*a*) The distribution of total intensity over the sky. (*b*) Once the uniform component is removed, a dipole component associated with the motion of the Earth through the isotropic background radiation is observed, as well as a weak signal from the Galactic plane. (*c*) Once the dipole component is removed, radiation from the plane of the Galaxy is seen as a bright band across the centre of the picture. The fluctuations seen at high Galactic latitudes are a combination of noise from the telescope and the instruments and a genuine cosmological signal. At high latitudes, an excess sky noise signal of cosmological origin amounts to $30 \pm 5 \mu K$ (Bennett *et al.*, 1996).

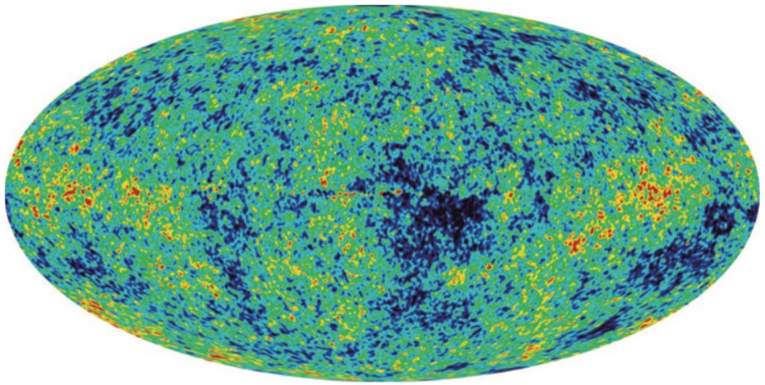


Fig. 1.7 A map of the whole sky in Galactic coordinates as observed by the WMAP satellite at millimetre wavelengths (Bennett *et al.*, 2003). The angular resolution of the map is about 20 times higher than that of Fig. 1.6*c*. The emissions due to Galactic dust and synchrotron radiation have been subtracted from this map.

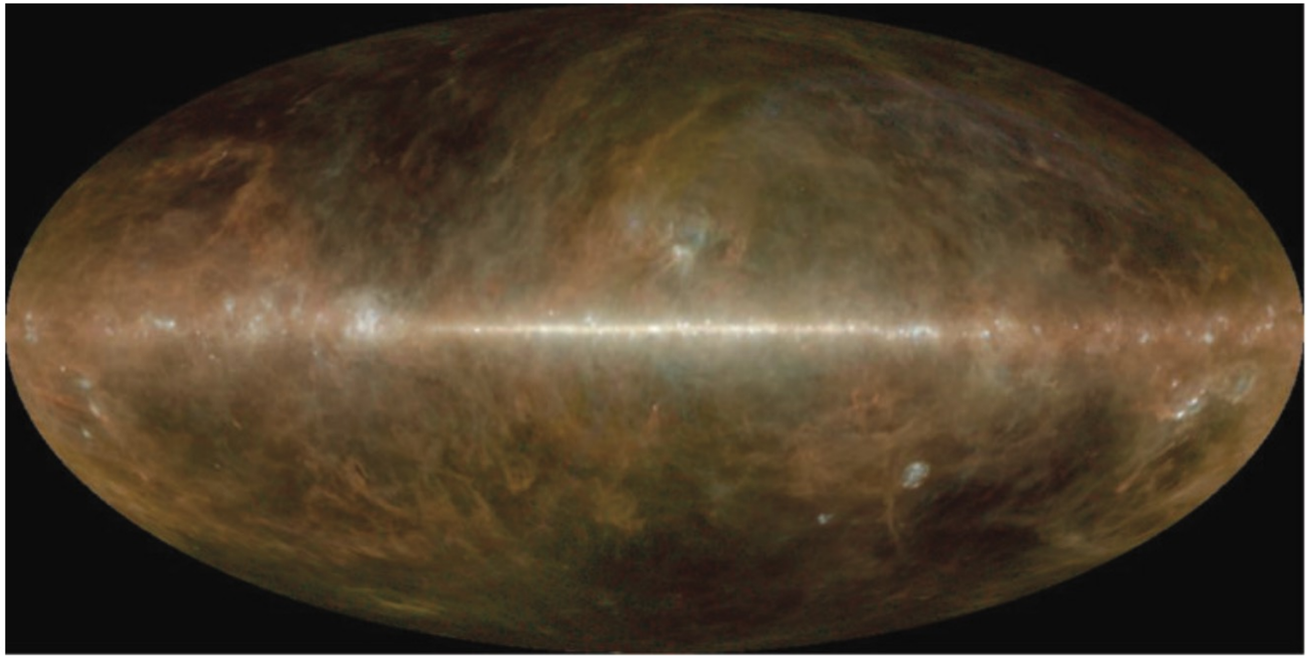
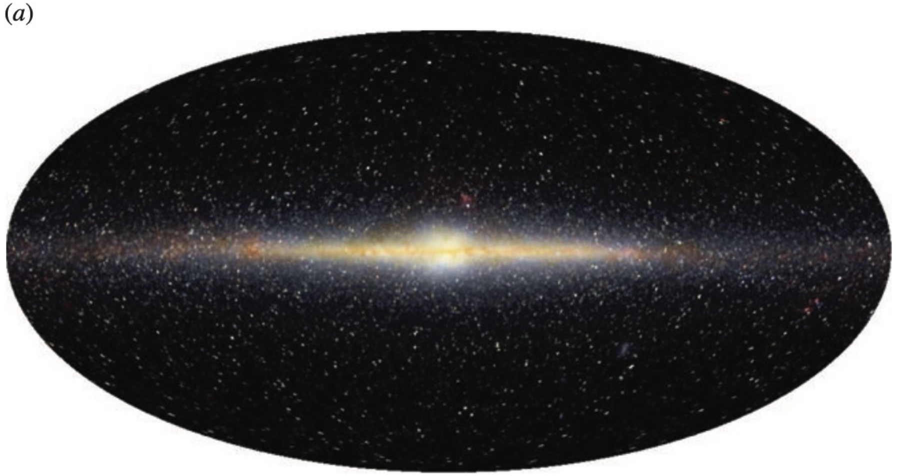


Fig. 1.5 A composite image of the celestial sphere in the far-infrared waveband in a Hammer–Aitoff projection. The observations were made with the DIRBE instrument of the COBE satellite and were made at 60 μm (blue), 100 μm (green) and 240 μm (red). Zodiacal light due to sunlight scattered by interplanetary dust has been removed from this image. (Courtesy of Edward Wright and the COBE Science Team.)



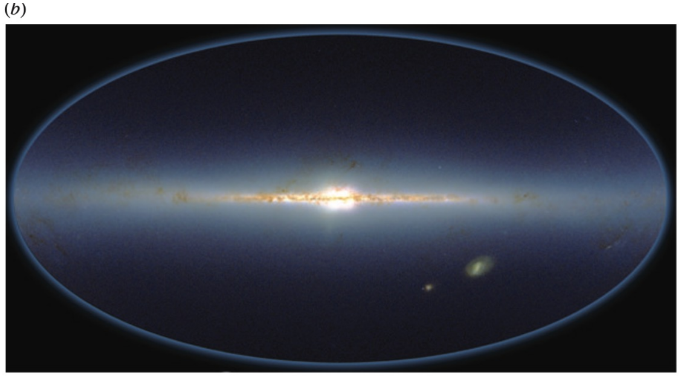


Fig. 1.4 Images of the celestial sphere in the near-infrared waveband. (*a*) A false-colour image of the near-infrared sky as observed by the DIRBE instrument of the Cosmic Background Explorer (COBE). Data at 1.25, 2.2 and 3.5 μm are colour-coded blue, green and red, respectively, in a Hammer–Aitoff projection. (Courtesy of NASA and the COBE Science Team.) (*b*) The structure of the Galaxy determined by the distribution of almost 100 million stars detected in the 2MASS sky survey. (Courtesy of the 2MASS Science Team and IPAC.)

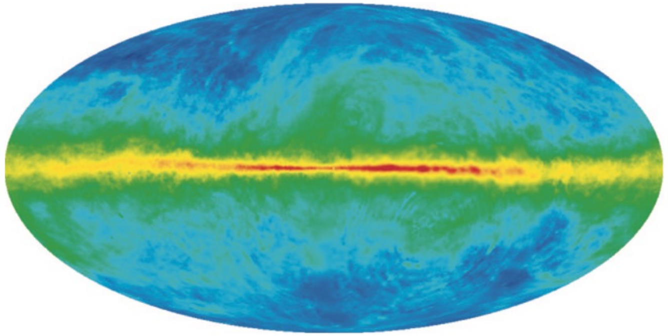


Fig. 1.11 A map of the whole sky in Galactic coordinates in the 21-cm line of neutral hydrogen. (Courtesy of the LAMBDA progamme of GSFC of NASA.)

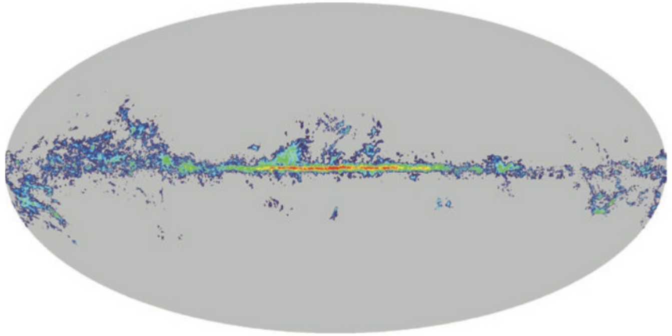


Fig. 1.8 A map of the whole sky in Galactic coordinates in the carbon dioxide molecule CO. (Courtesy of the LAMBDA progam of GSFC of NASA.)

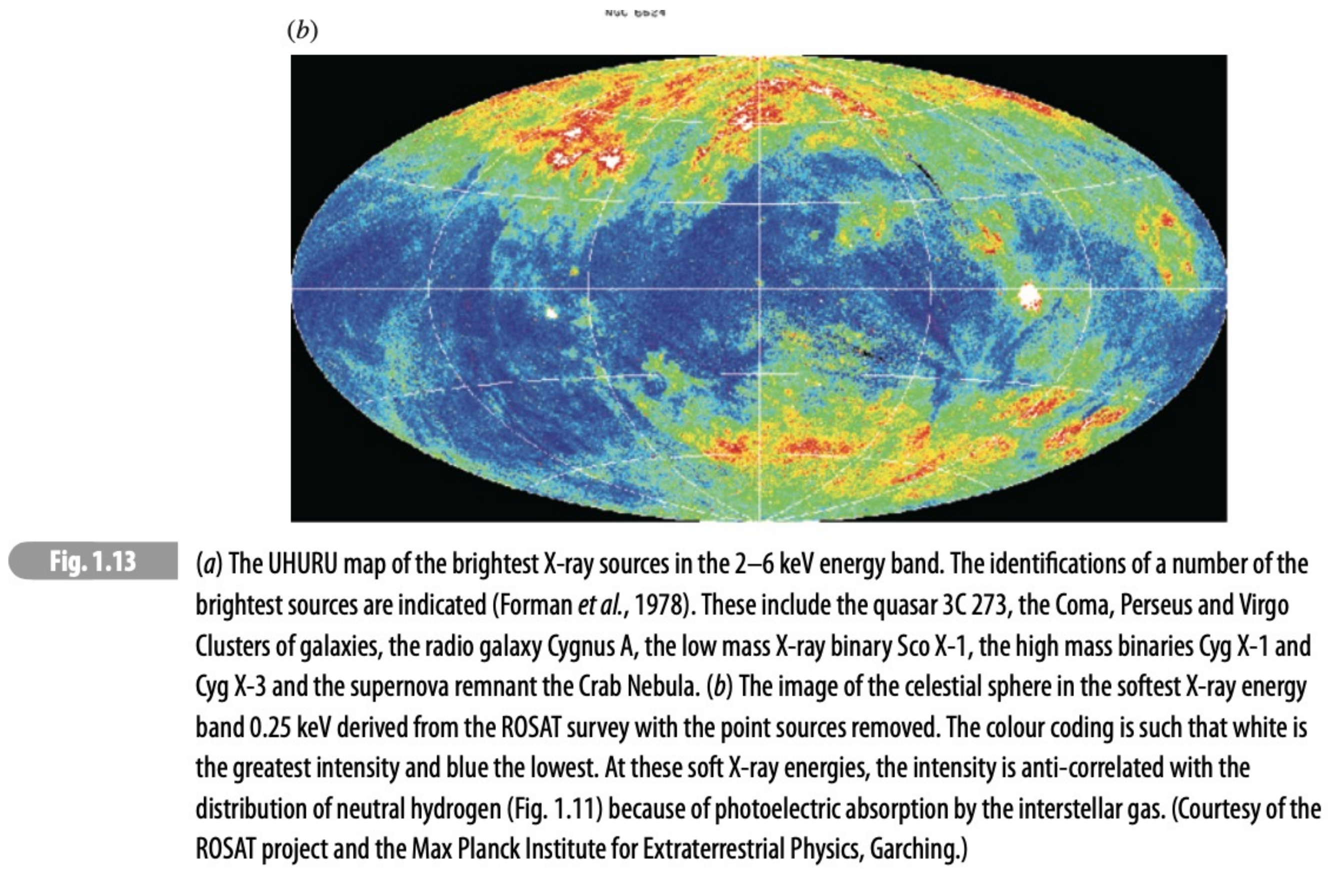


Fig. 1.13 (*a*) The UHURU map of the brightest X-ray sources in the 2–6 keV energy band. The identifications of a number of the brightest sources are indicated (Forman *et al.*, 1978). These include the quasar 3C 273, the Coma, Perseus and Virgo Clusters of galaxies, the radio galaxy Cygnus A, the low mass X-ray binary Sco X-1, the high mass binaries Cyg X-1 and Cyg X-3 and the supernova remnant the Crab Nebula. (*b*) The image of the celestial sphere in the softest X-ray energy band 0.25 keV derived from the ROSAT survey with the point sources removed. The colour coding is such that white is the greatest intensity and blue the lowest. At these soft X-ray energies, the intensity is anti-correlated with the distribution of neutral hydrogen (Fig. 1.11) because of photoelectric absorption by the interstellar gas. (Courtesy of the ROSAT project and the Max Planck Institute for Extraterrestrial Physics, Garching.)

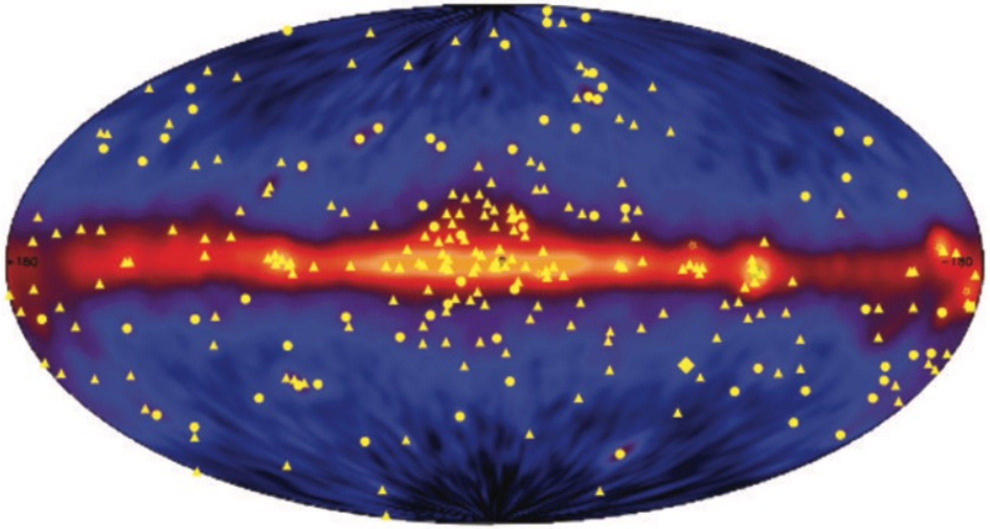
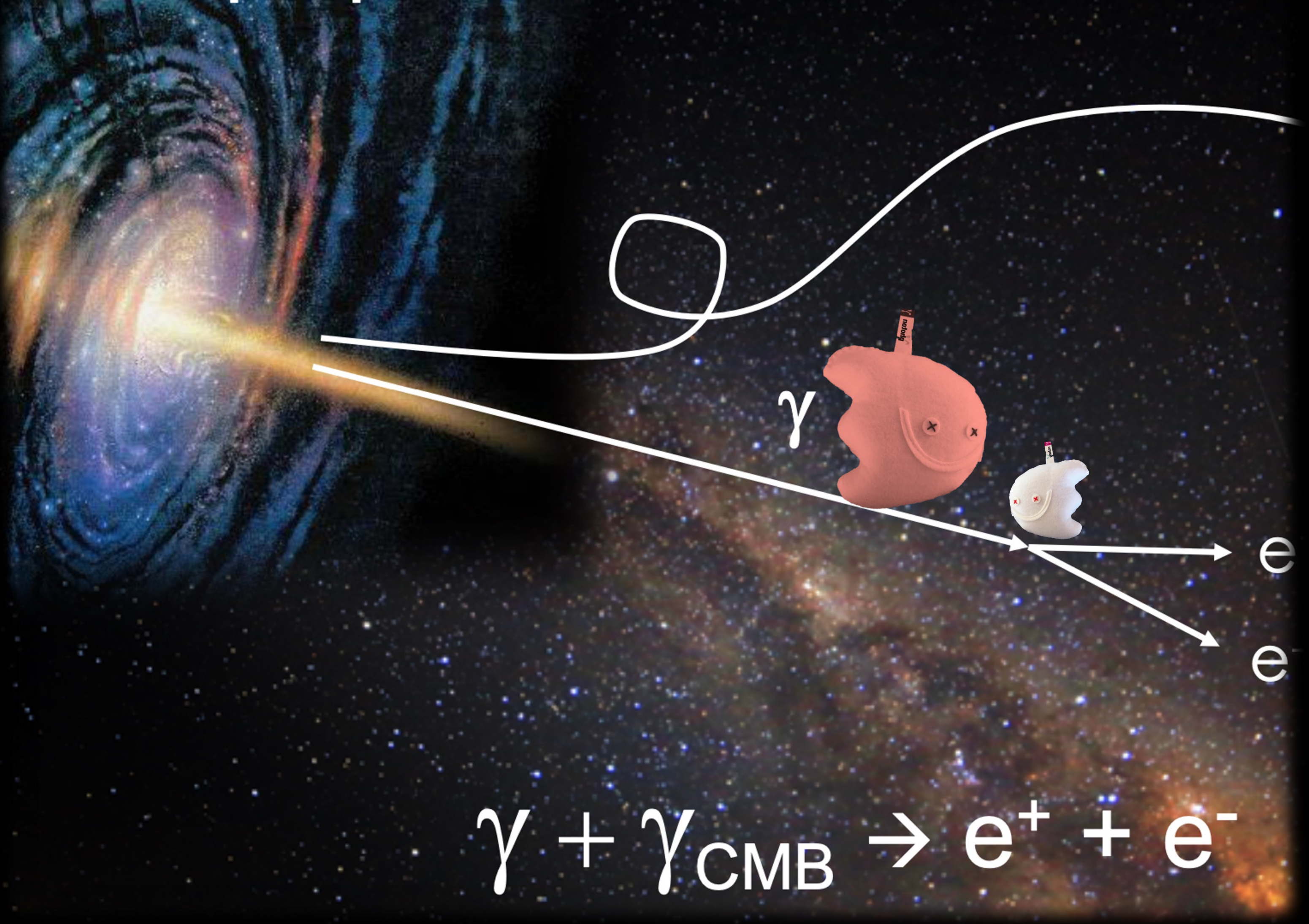


Fig. 1.14 An image of the celestial sphere at γ-ray energies $\varepsilon \geq 100$ MeV in a Hammer–Aitoff projection from observations made by the EGRET instrument of the Compton Gamma-Ray Observatory (CGRO). The emission from the plane of the Galaxy consists of diffuse γ-ray emission from the interstellar gas, most of it associated with γ-rays produced by the decay of neutral pions, π^0, generated in collisions between cosmic ray protons and nuclei and the interstellar gas. The yellow symbols show the distribution of discrete sources detected in the all-sky survey: circles are active galactic nuclei; five-point stars are pulsars; squares are solar flares; the diamond is the Large Magellanic Cloud; and the triangles are unidentified sources. (Courtesy of NASA and the EGRET science team.)

The opaque Universe



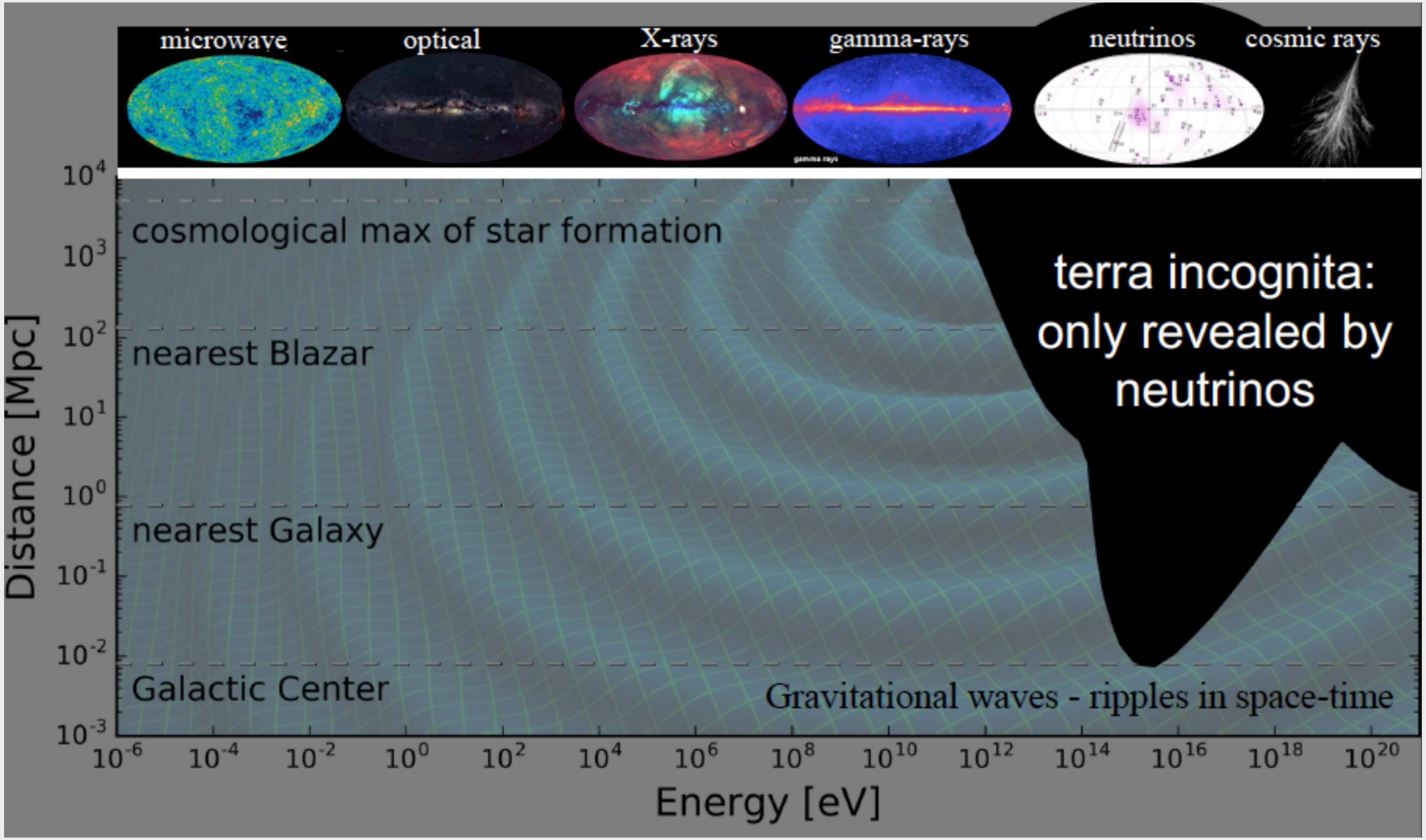
$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

My Universe

[The high energy gamma]

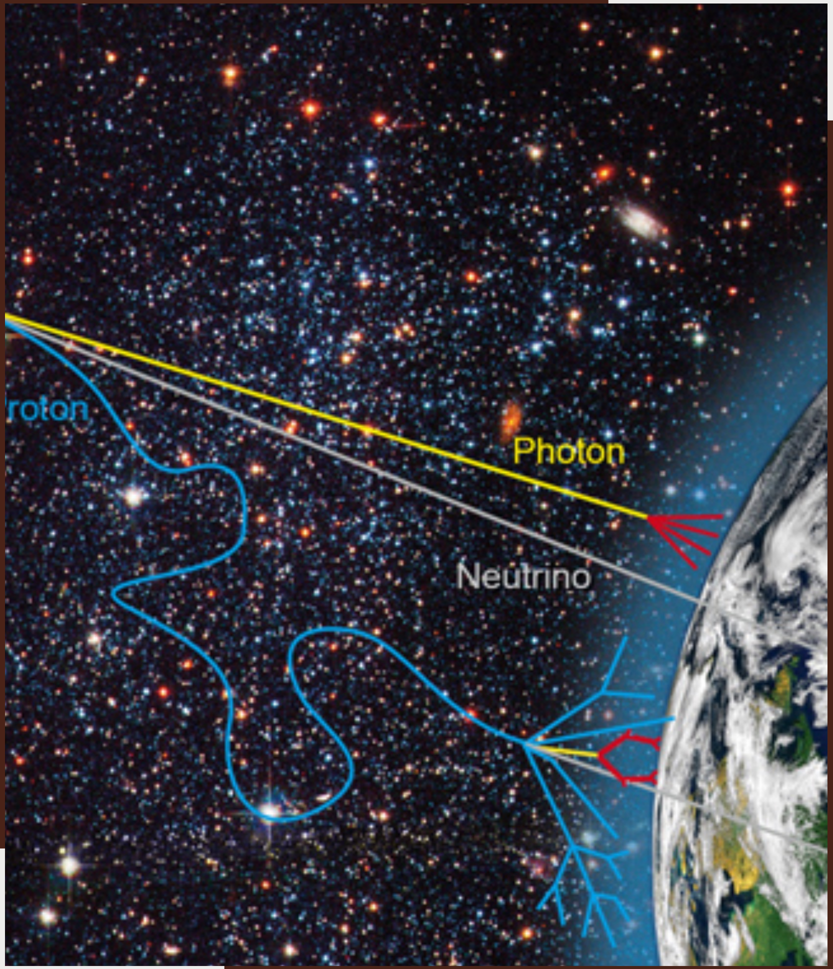
"I travelled where you'll never do"

[the neutrino]



(the neutrino)

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



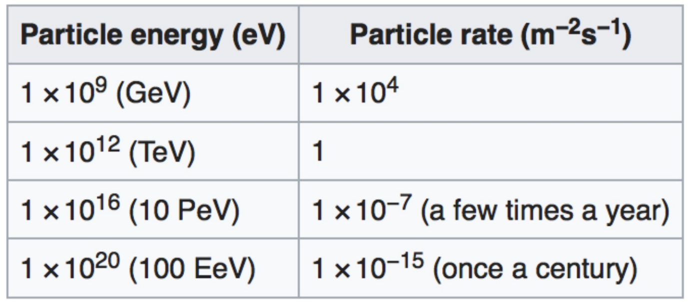
THREE DIFFERENT TRAVELLERS

Only two are straights travellers, which ones?

COSMIC RAYS

A gamma-rays started left home always with a cosmic ray companion

The amazing *Cosmic Ray Spectrum*



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)

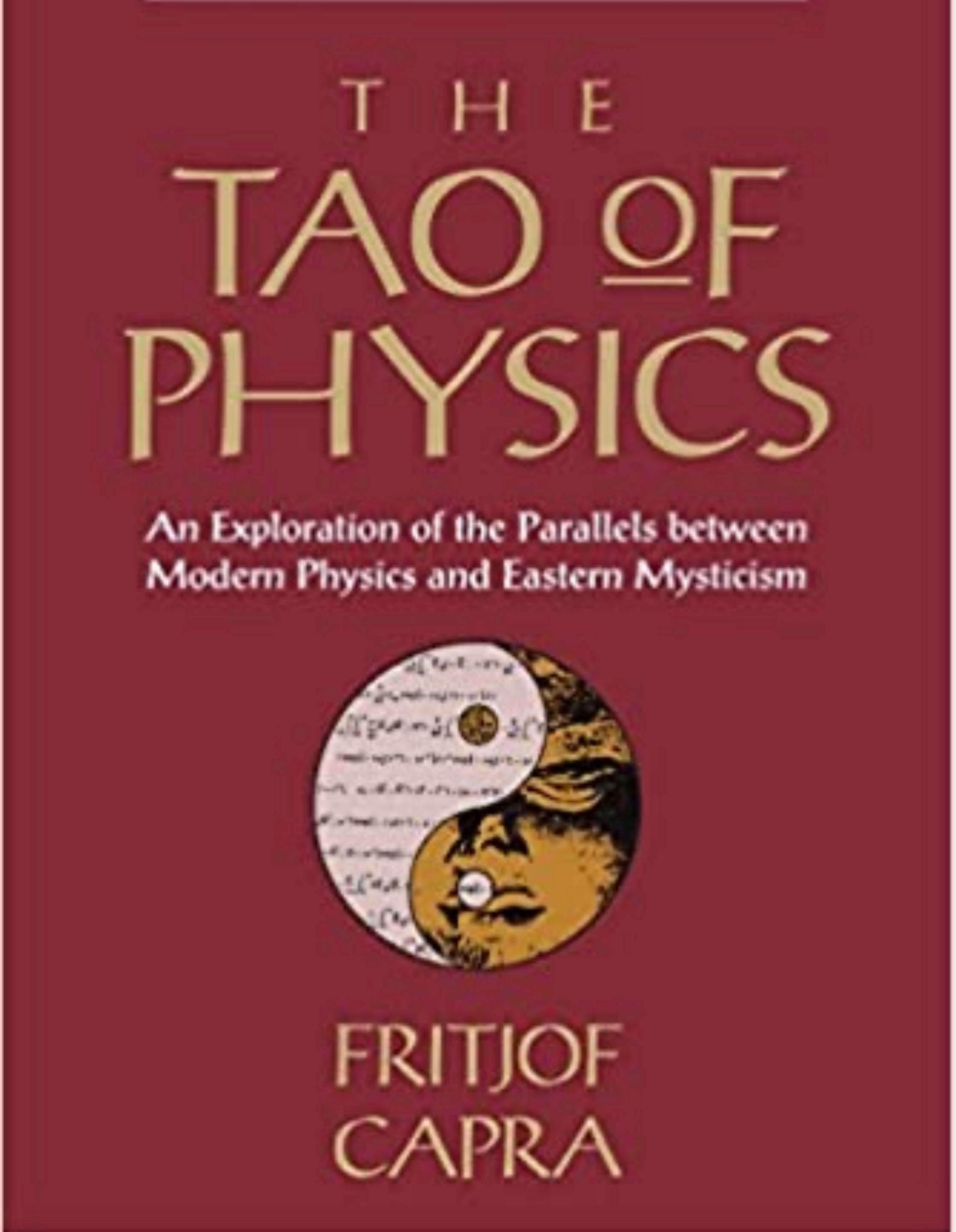
- 19 orders of magnitude in energy
- 32 orders of magnitude in flux

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

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

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

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

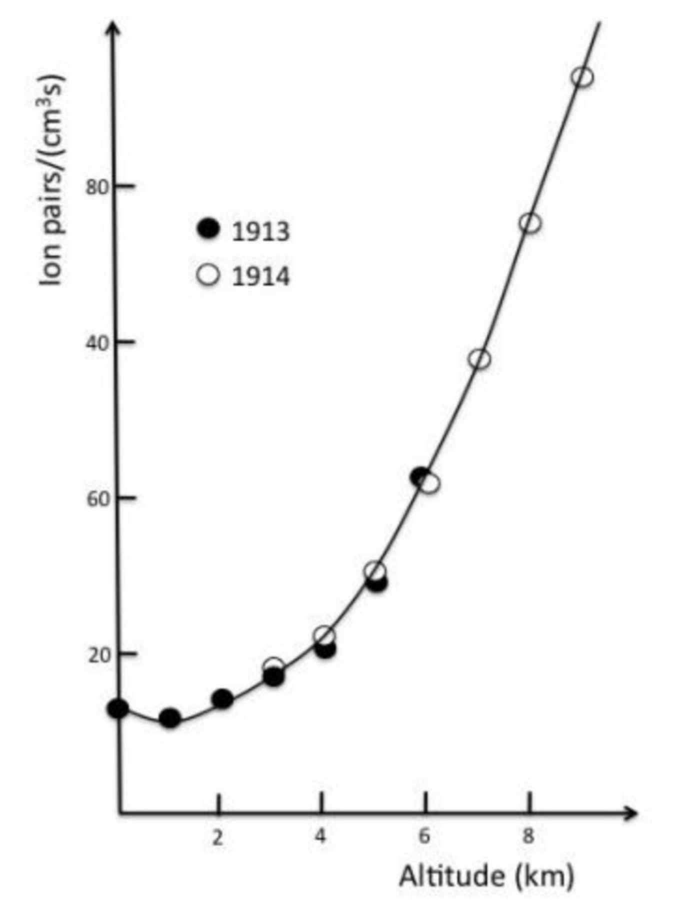


THE
TAO OF
PHYSICS

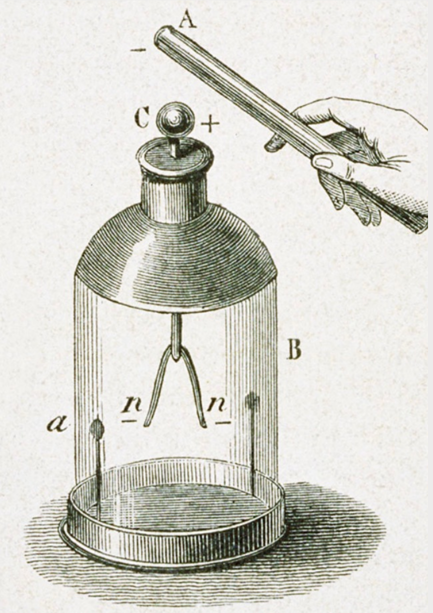
An Exploration of the Parallels between
Modern Physics and Eastern Mysticism

FRITJOF
CAPRA

The *Cosmic Ray Spectrum*

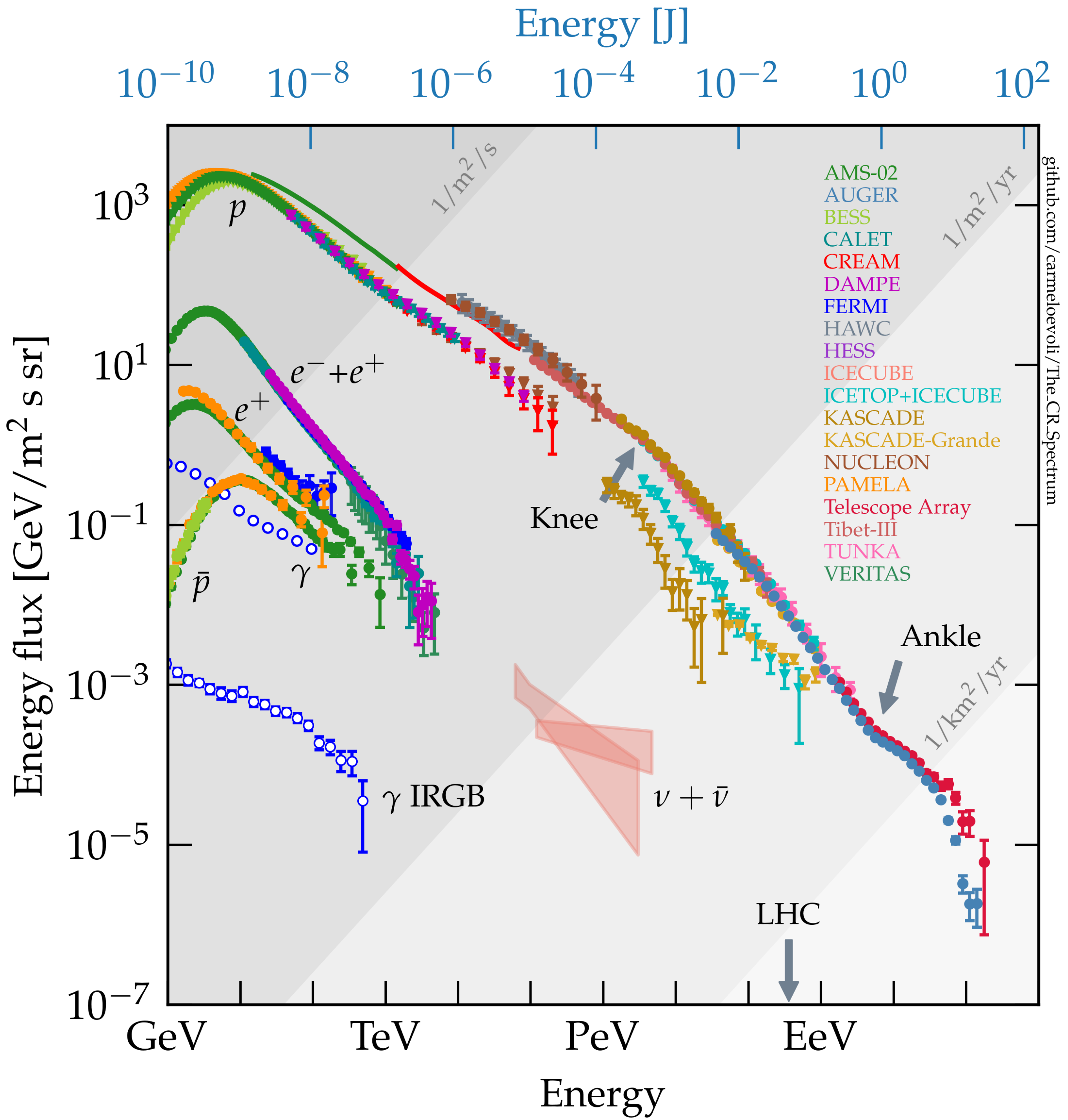


Victor Hess (1913)



Electroscope's discharges

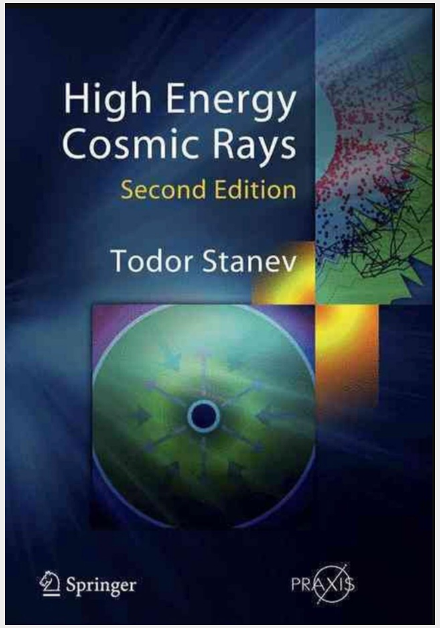
Hess's Students?

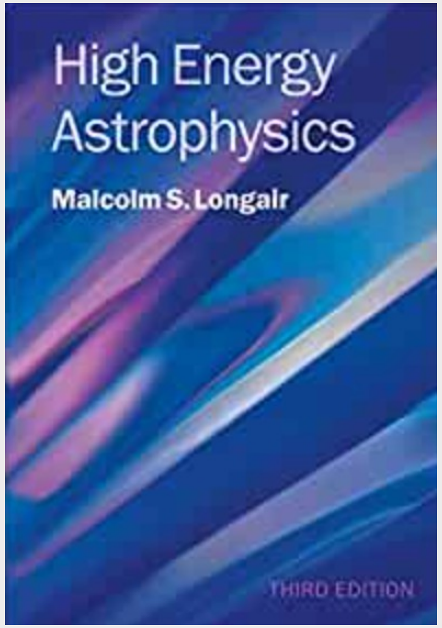


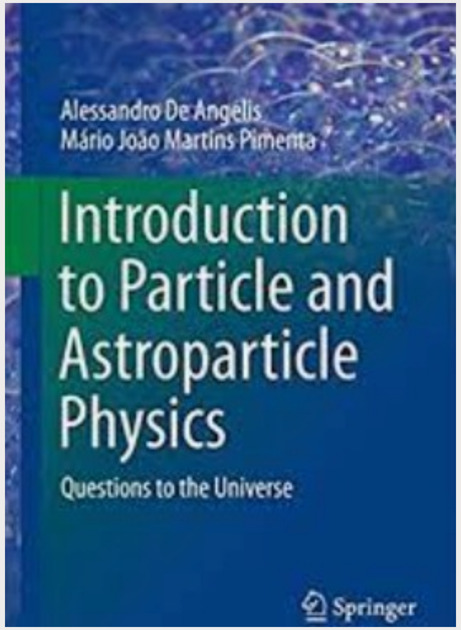
A crowded space!

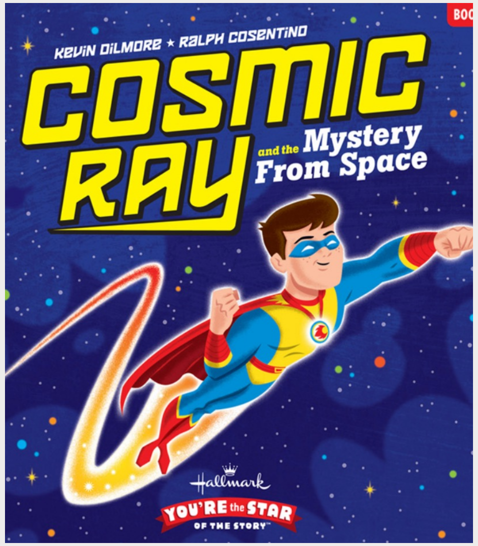
- Travellers:
  - *Protons and antiprotons*
  - *Heavier cosmic rays,*
  - *Electrons, positrons*
  - *Gammas*
  - *neutrinos*
- Experiments!
- Spectral features!

References, e.g.

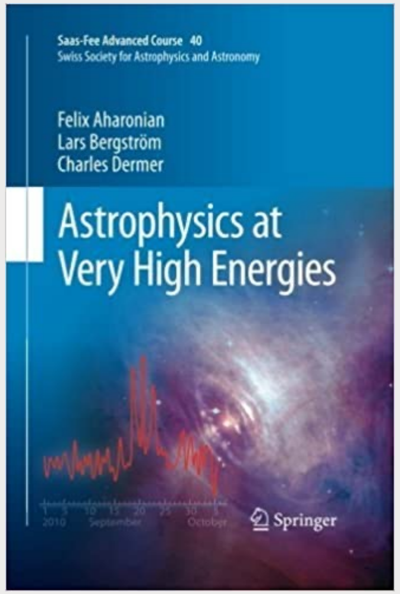


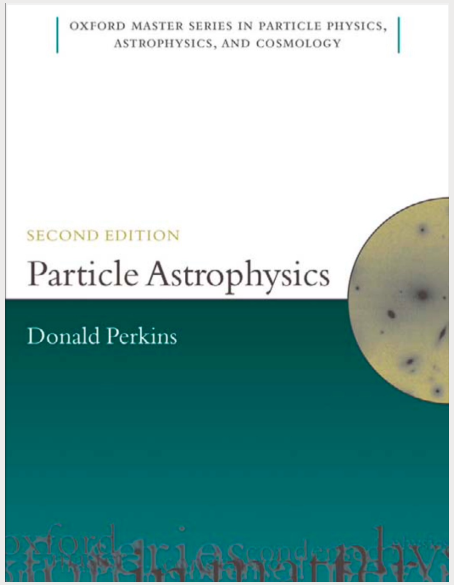


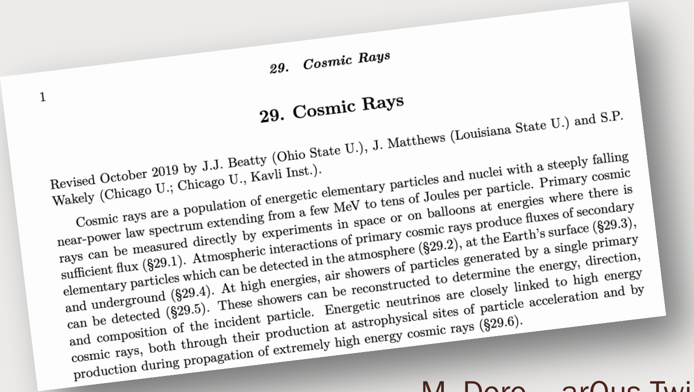




For family and friends







29. Cosmic Rays

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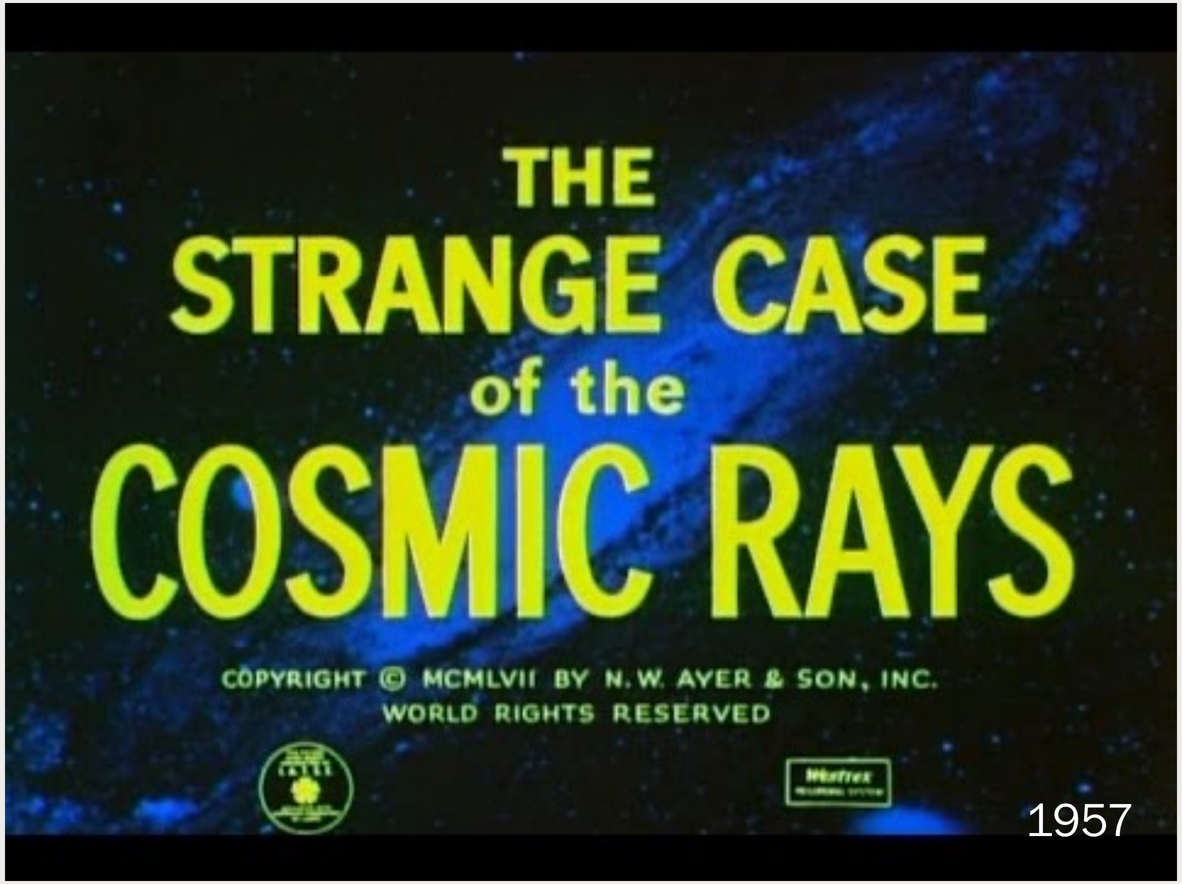
29. Cosmic Rays

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.).

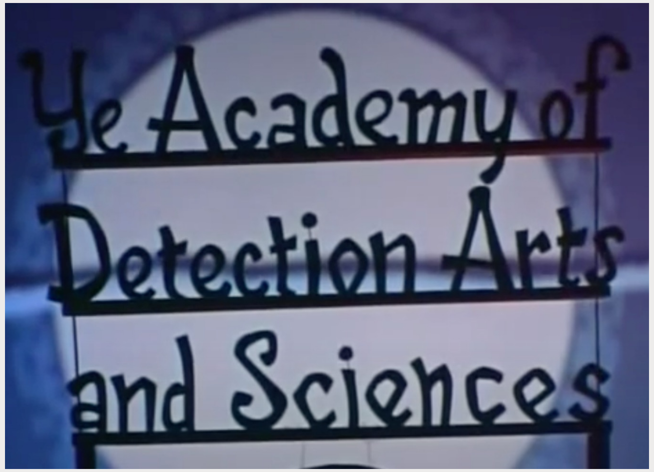
Cosmic rays are a population of energetic elementary particles and nuclei with a steeply falling near-power law spectrum extending from a few MeV to tens of Joules per particle. Primary cosmic rays can be measured directly by experiments in space or on balloons at energies where there is sufficient flux (§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

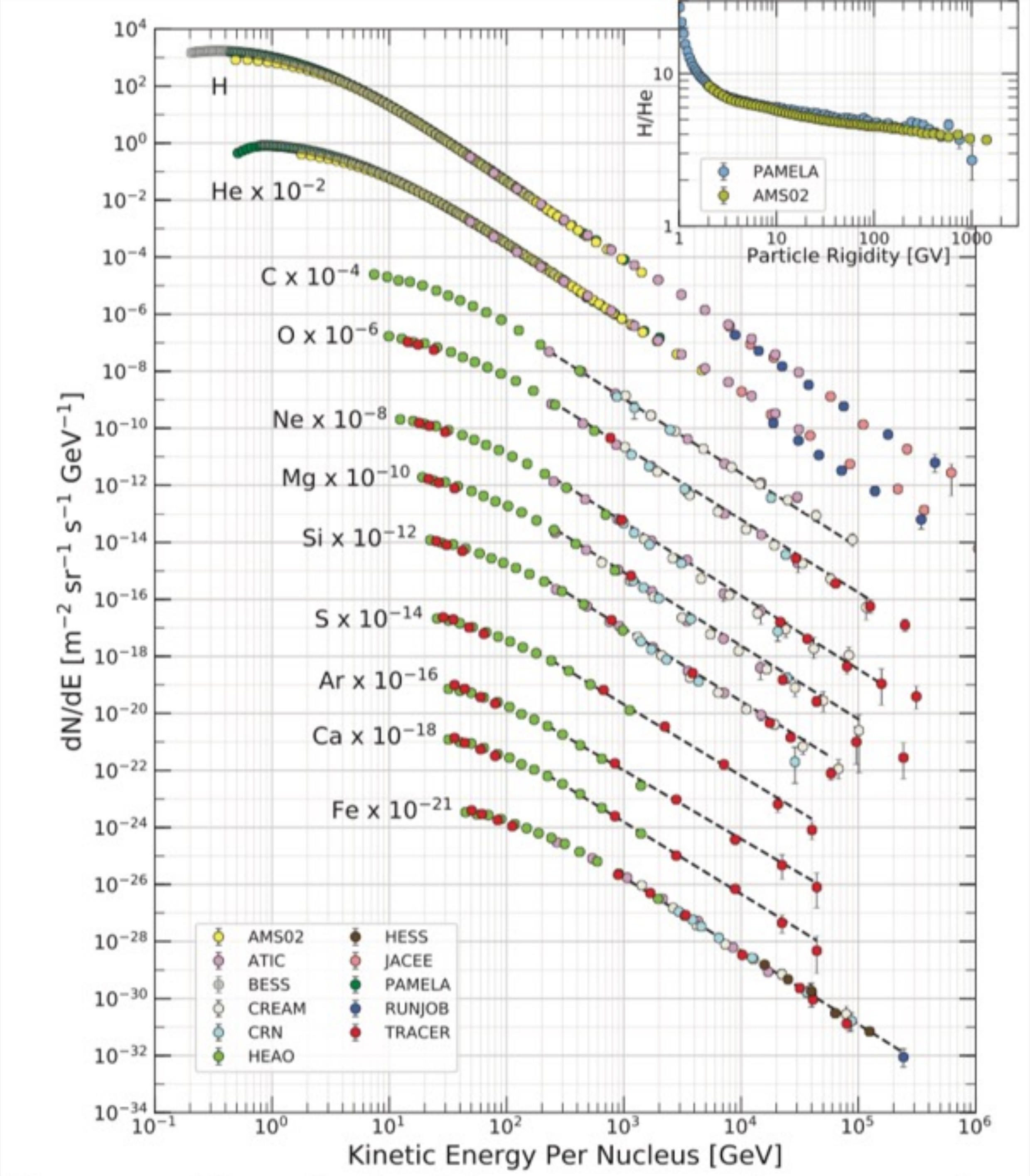
The scientists



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

C. Dickens E. Allan Poe F. Dostoevsky

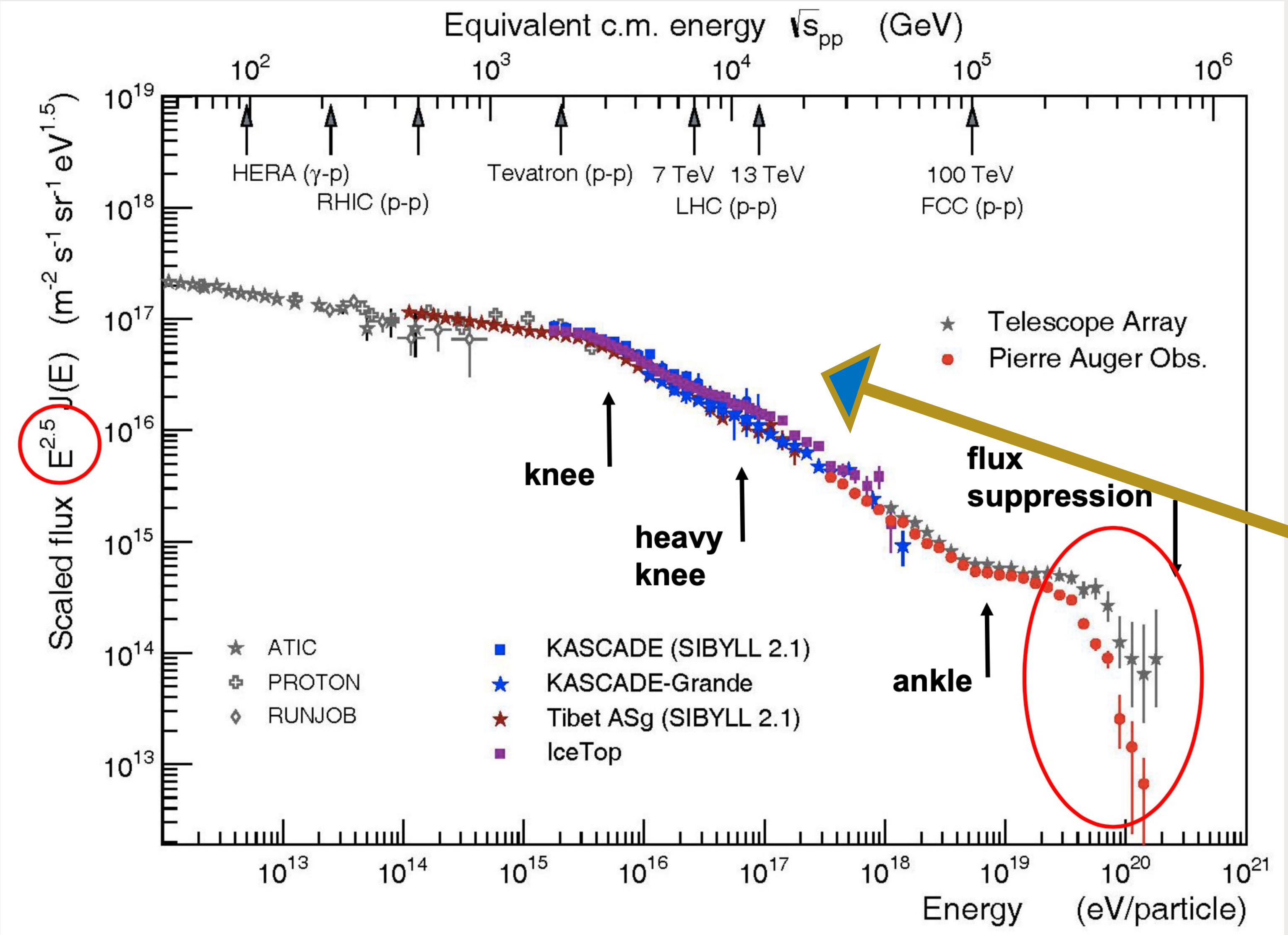
https://www.youtube.com/watch?v=tPuvuRrJy7M



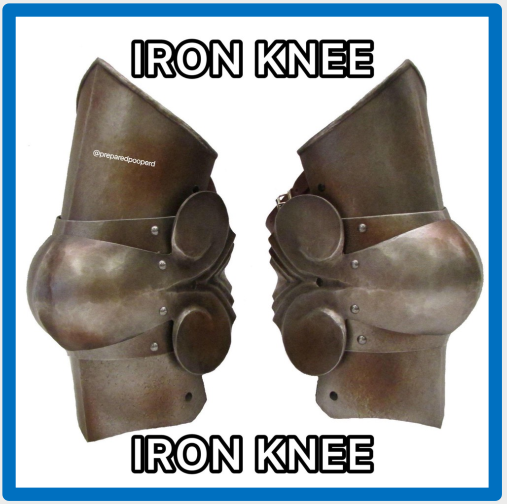
Heavier nuclei

- Idrogen and iron nuclei observed to the larger energies!

Knees, iron knee

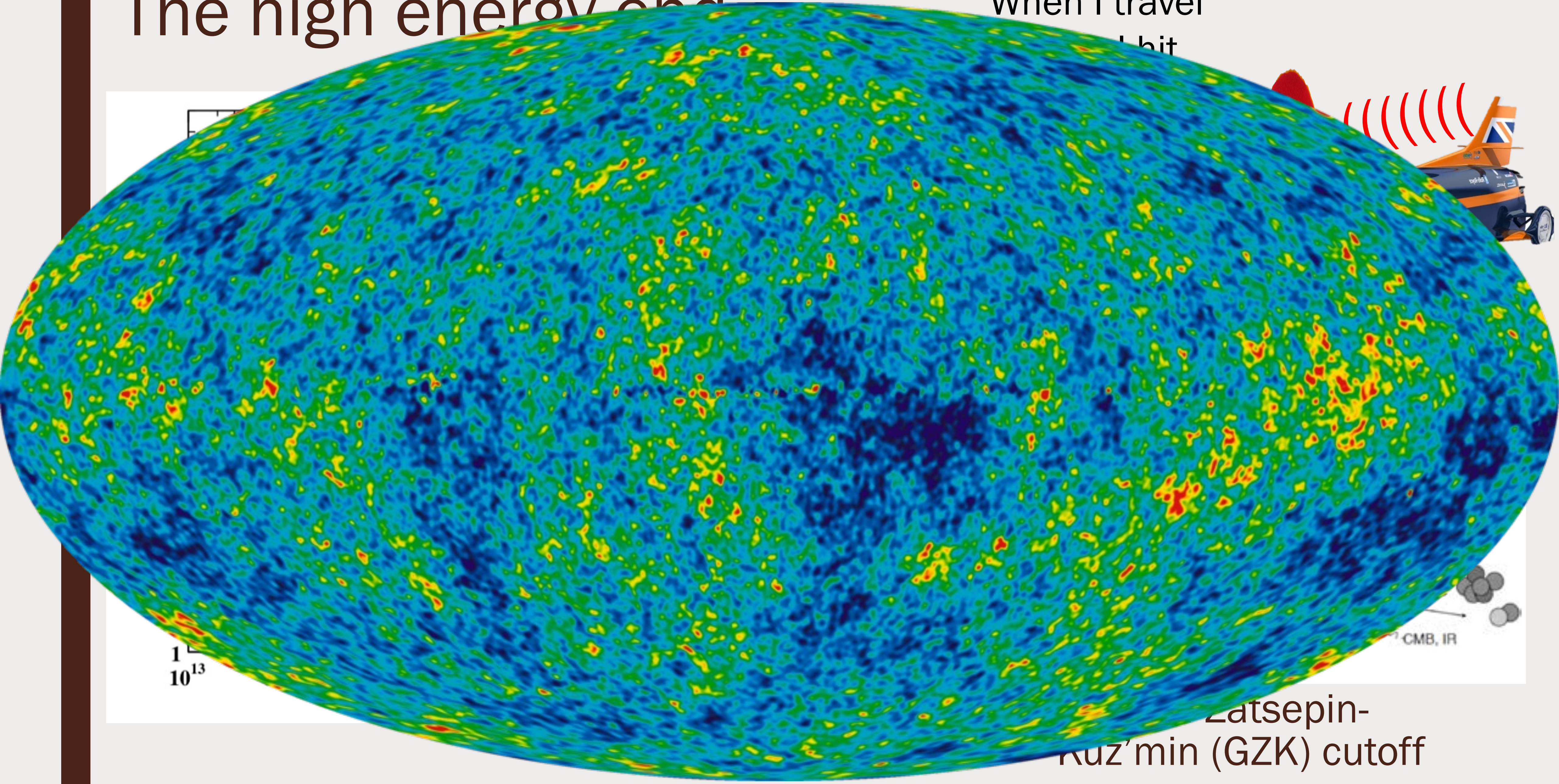


- Details show the imprint of different particle
- Cosmic rays have a...



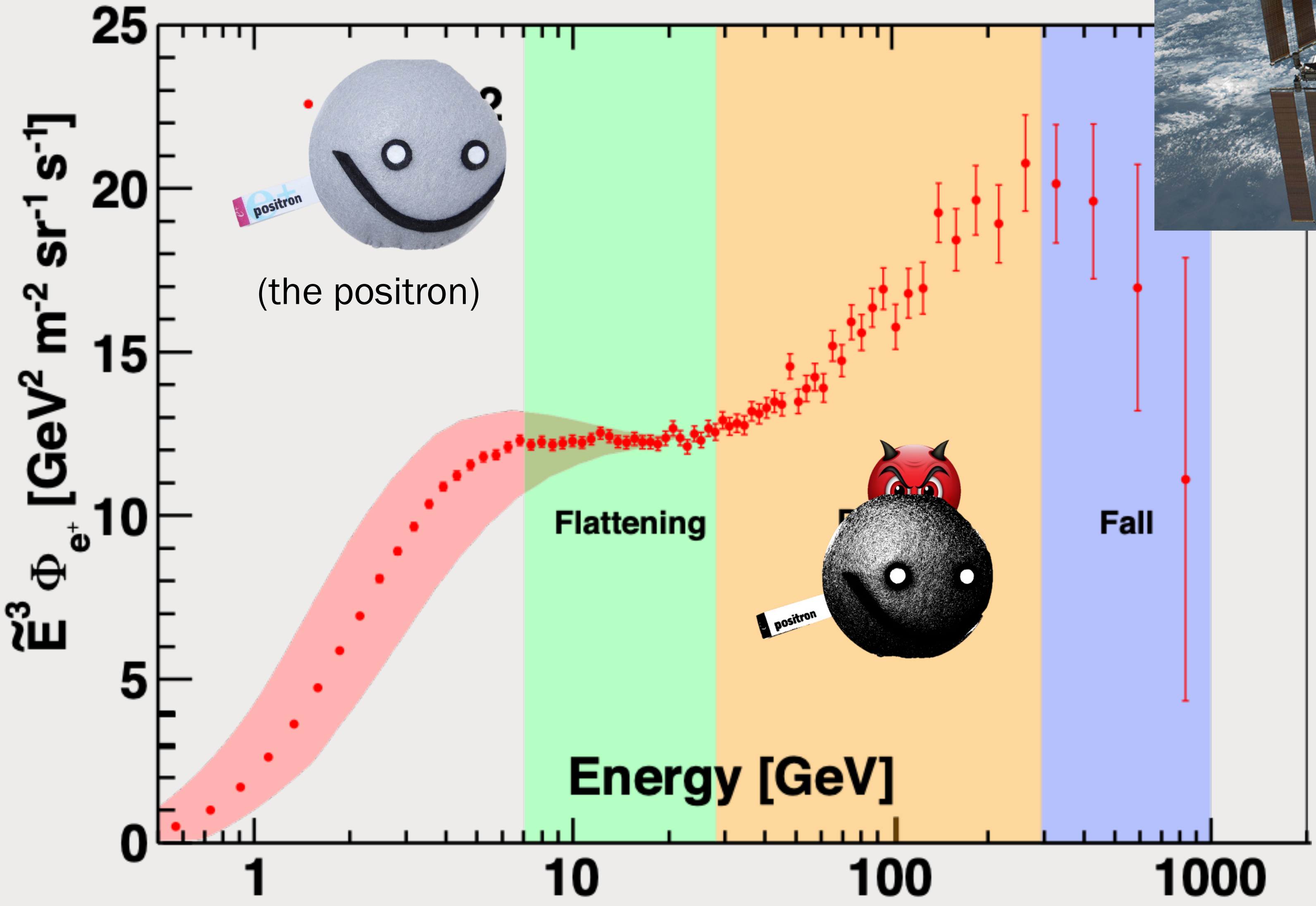
The high energy end

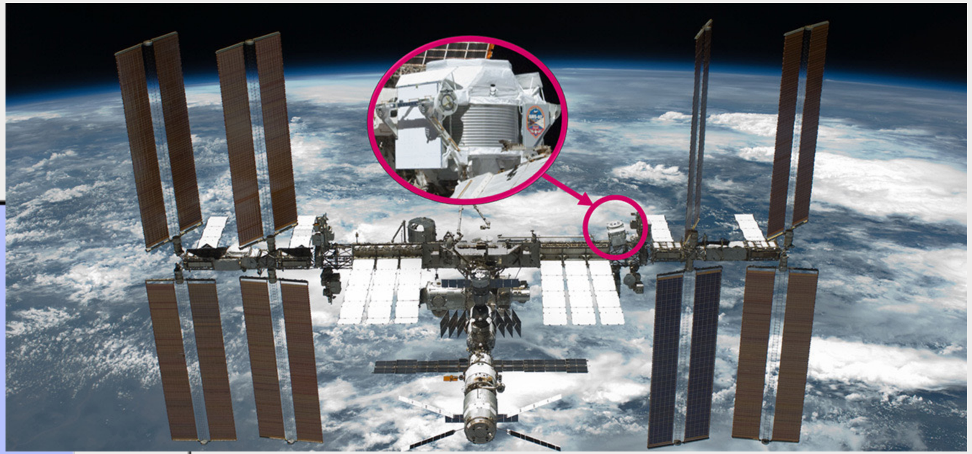
“When I travel
l hit



Zatsepin-
Kuz’min (GZK) cutoff

Anomalies

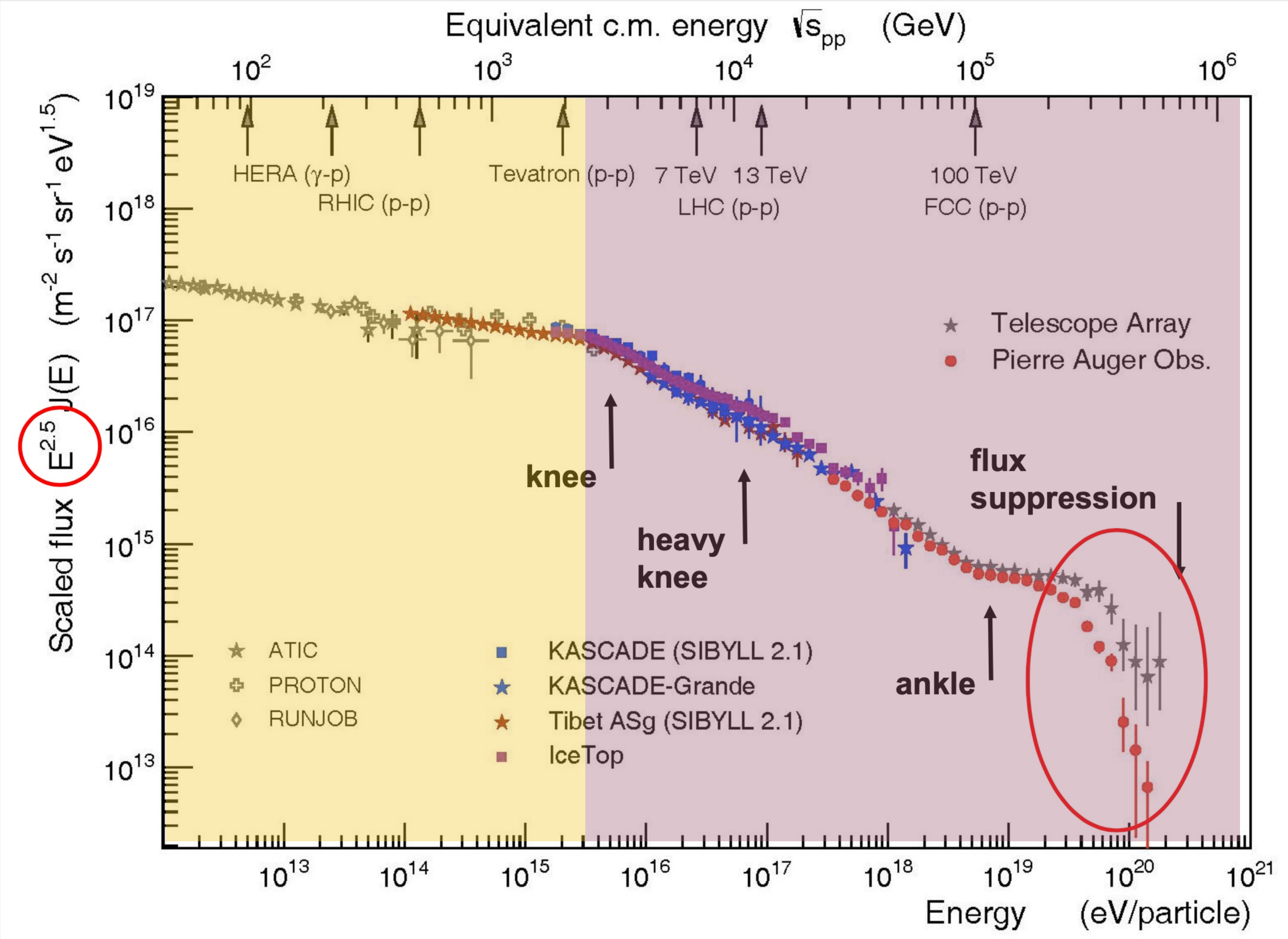




Positrons are produced via cosmic ray spallation of carbon and oxygen

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

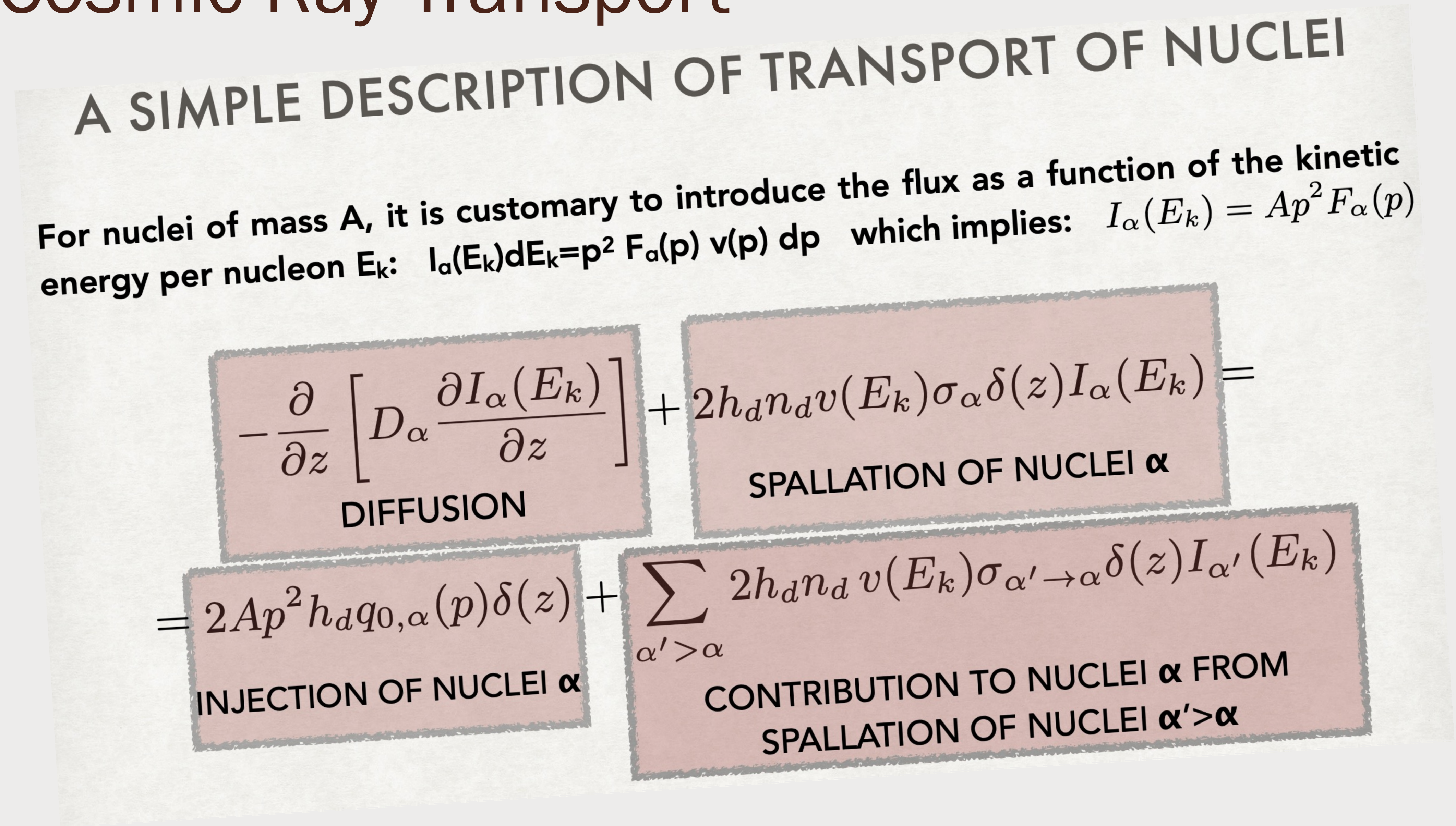
Tell us where you're from



GALACTIC

EXTRAGALACTIC

Cosmic Ray Transport



A SIMPLE DESCRIPTION OF TRANSPORT OF NUCLEI

For nuclei of mass A, it is customary to introduce the flux as a function of the kinetic energy per nucleon E_k: $I_\alpha(E_k)dE_k=p^2 F_\alpha(p)\, v(p)\, dp$ which implies: $I_\alpha(E_k) = Ap^2 F_\alpha(p)$

$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{\partial I_\alpha(E_k)}{\partial z}\right] + 2h_d n_d v(E_k)\sigma_\alpha \delta(z) I_\alpha(E_k) =$$

DIFFUSION

SPALLATION OF NUCLEI α

$$= 2Ap^2 h_d q_{0,\alpha}(p)\delta(z) + \sum_{\alpha'>\alpha} 2h_d n_d\, v(E_k)\sigma_{\alpha'\to\alpha}\delta(z) I_{\alpha'}(E_k)$$

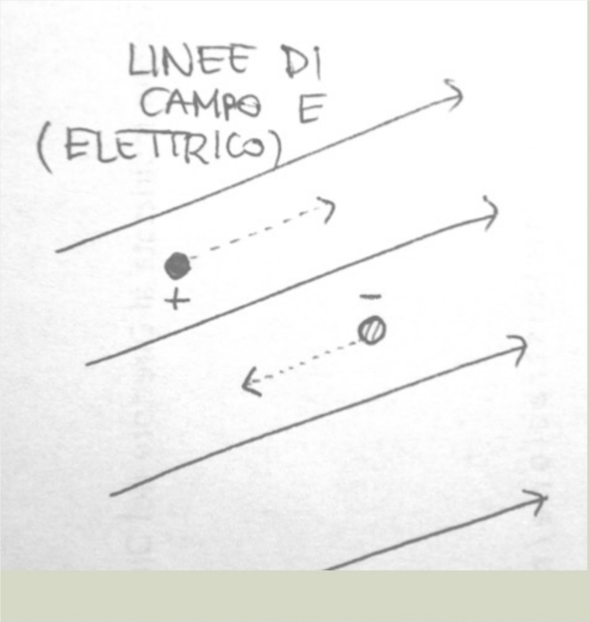
INJECTION OF NUCLEI α

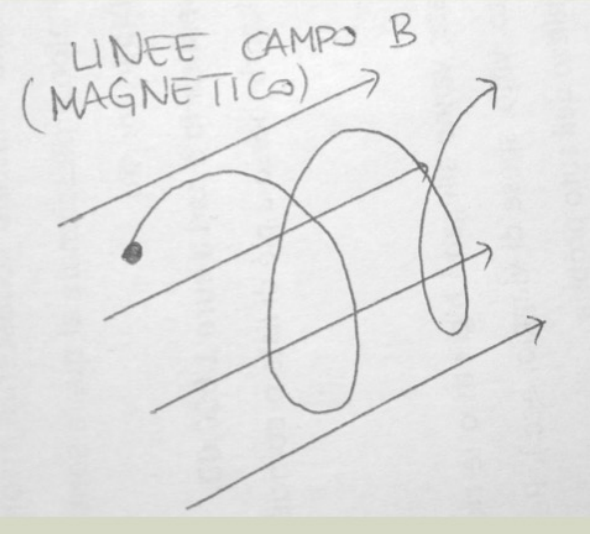
CONTRIBUTION TO NUCLEI α FROM SPALLATION OF NUCLEI α'>α

How to fuel up for a long interstellar travel?

COSMIC RAY ACCELERATION

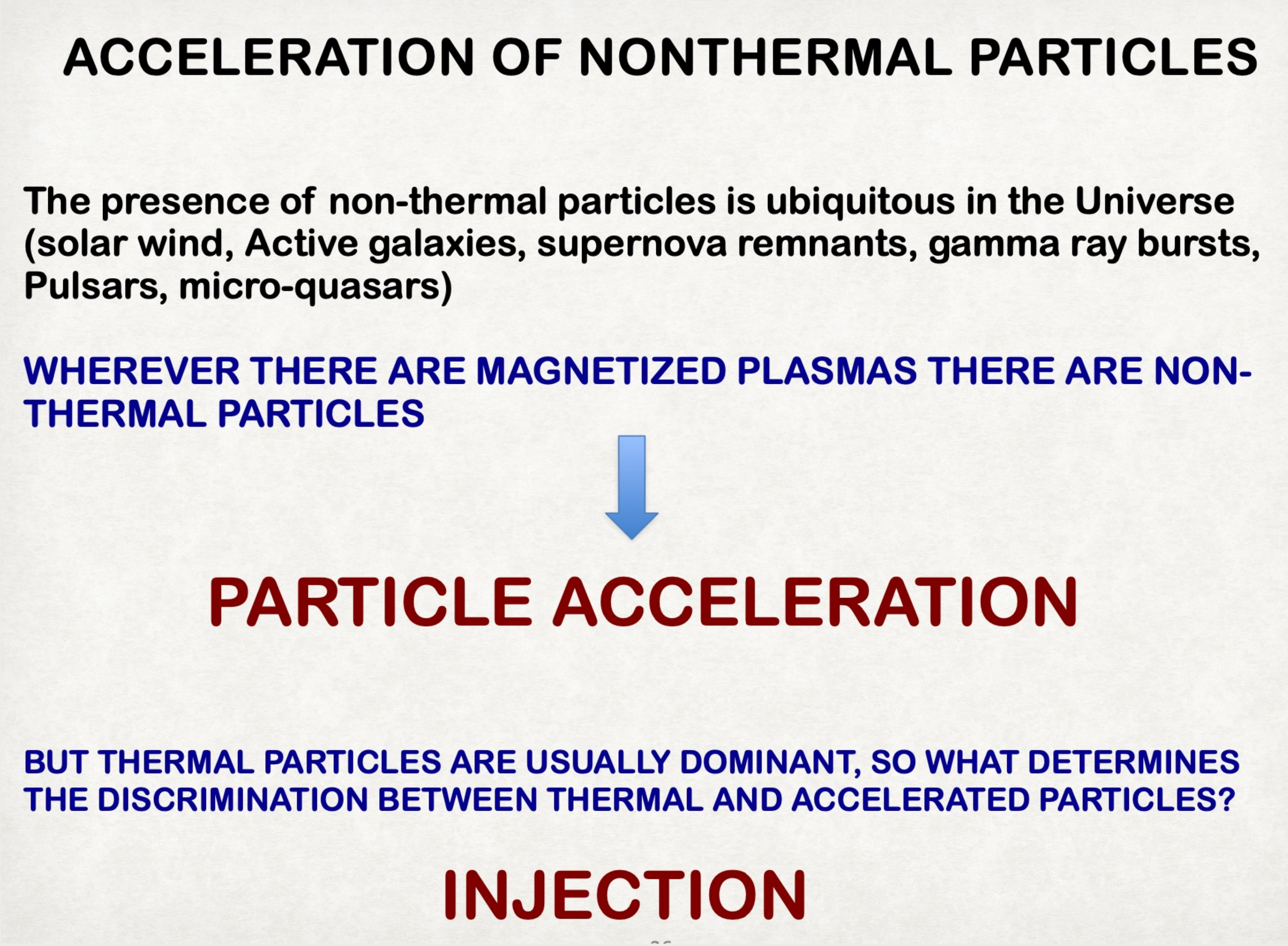
How to accelerate a charged particle?





- 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 or moving magnetic fields → variable electric fields → acceleration*

We need to find strong E and B in the Universe!



ACCELERATION OF NONTHERMAL PARTICLES

The presence of non-thermal particles is ubiquitous in the Universe (solar wind, Active galaxies, supernova remnants, gamma ray bursts, Pulsars, micro-quasars)

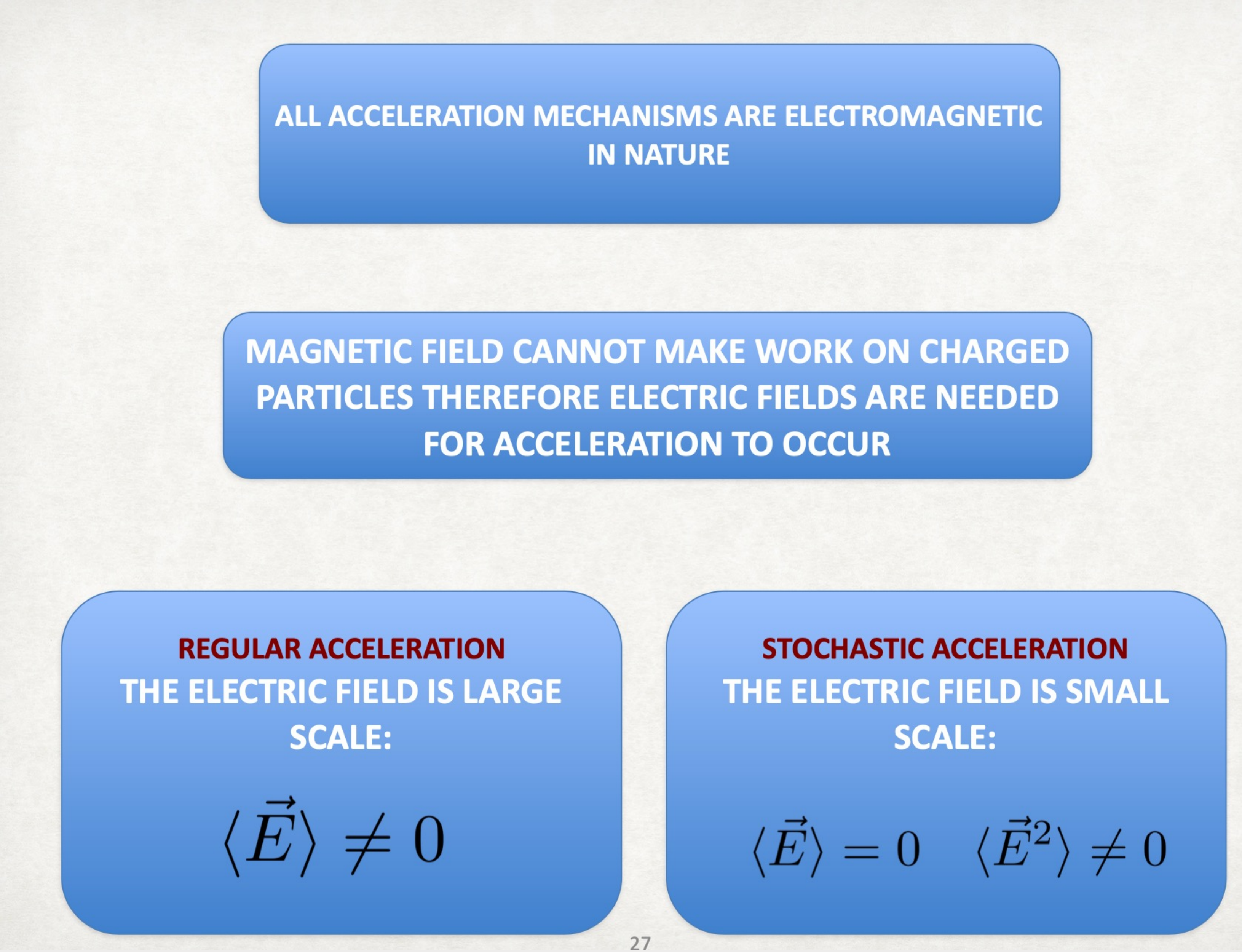
WHEREVER THERE ARE MAGNETIZED PLASMAS THERE ARE NON-THERMAL PARTICLES

↓

PARTICLE ACCELERATION

BUT THERMAL PARTICLES ARE USUALLY DOMINANT, SO WHAT DETERMINES THE DISCRIMINATION BETWEEN THERMAL AND ACCELERATED PARTICLES?

INJECTION



ALL ACCELERATION MECHANISMS ARE ELECTROMAGNETIC IN NATURE

MAGNETIC FIELD CANNOT MAKE WORK ON CHARGED PARTICLES THEREFORE ELECTRIC FIELDS ARE NEEDED FOR ACCELERATION TO OCCUR

REGULAR ACCELERATION

THE ELECTRIC FIELD IS LARGE SCALE:

$$\langle \vec{E} \rangle \neq 0$$

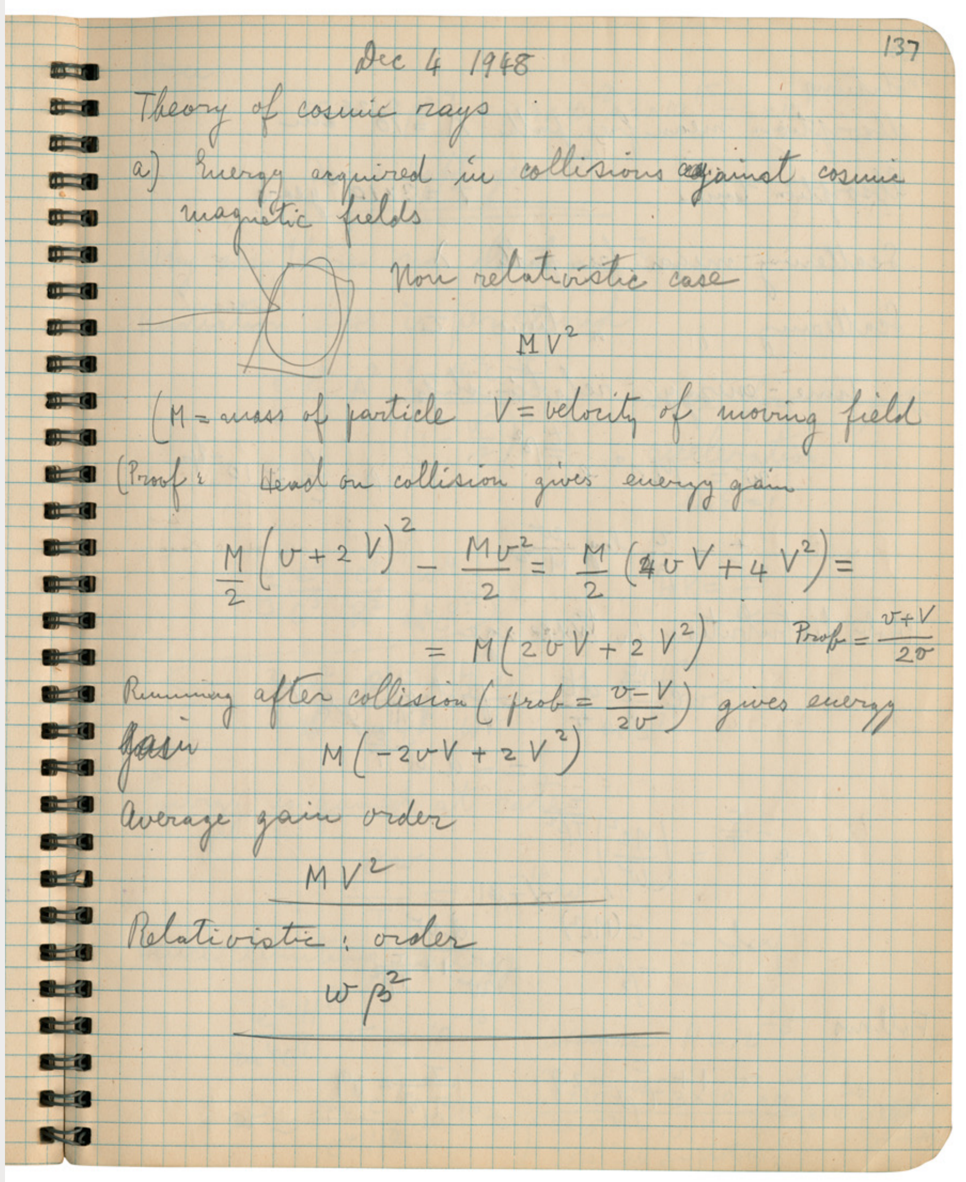
STOCHASTIC ACCELERATION

THE ELECTRIC FIELD IS SMALL SCALE:

$$\langle \vec{E} \rangle = 0 \quad \langle \vec{E}^2 \rangle \neq 0$$

27

1948 Fermi



137

Dec 4 1948

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

(Proof: 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 ($\text{prob} = \frac{v-V}{2v}$) gives energy gain

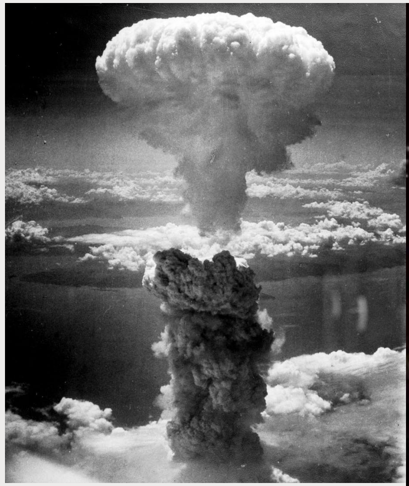
$$M(-2vV+2V^2)$$

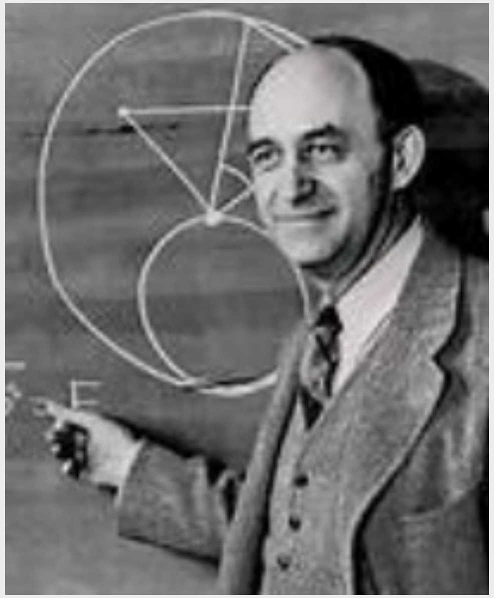
Average gain order

MV^2

Relativistic: order

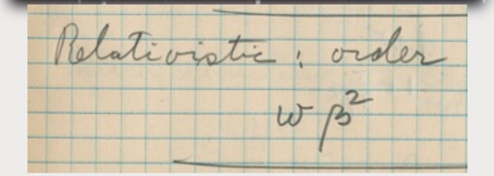
$w\beta^2$





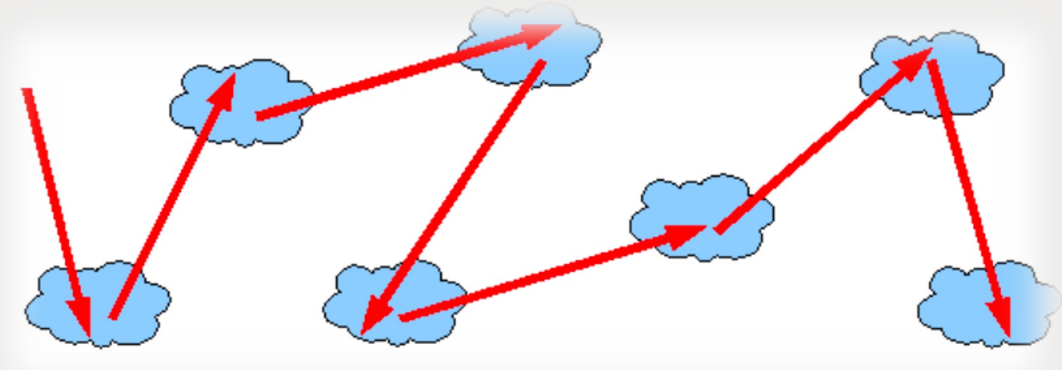
- There must be great atomic bombs in the sky
- Expanding shells of material with charged particle and magnetic fields
- Charged particle around get stochastic acceleration by bumping into those shells

2nd order Fermi acceleration



Relativistic : order

$\omega \beta^2$

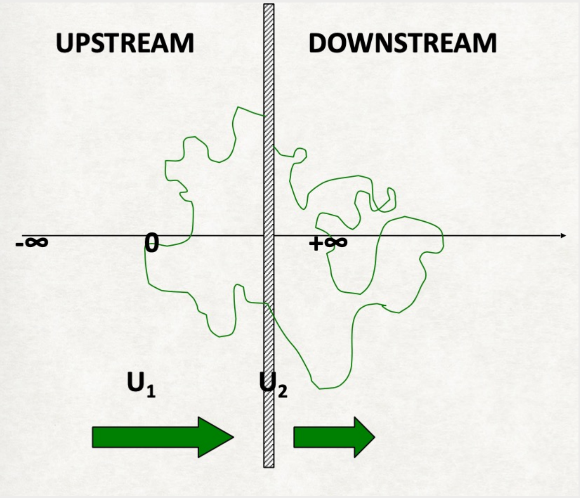


- Charged particle in a shock wave make stochastic collisions with a moving ionized blob of material (cloud) with magnetic fields embedded
- Cloud act as scatterer
- By computing probability, at each encounter:

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

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

Fermi 1st order: diffusive shock acceleration



Wait: is the cloud that random?

Linear dependence! And considering particle velocity distribution:

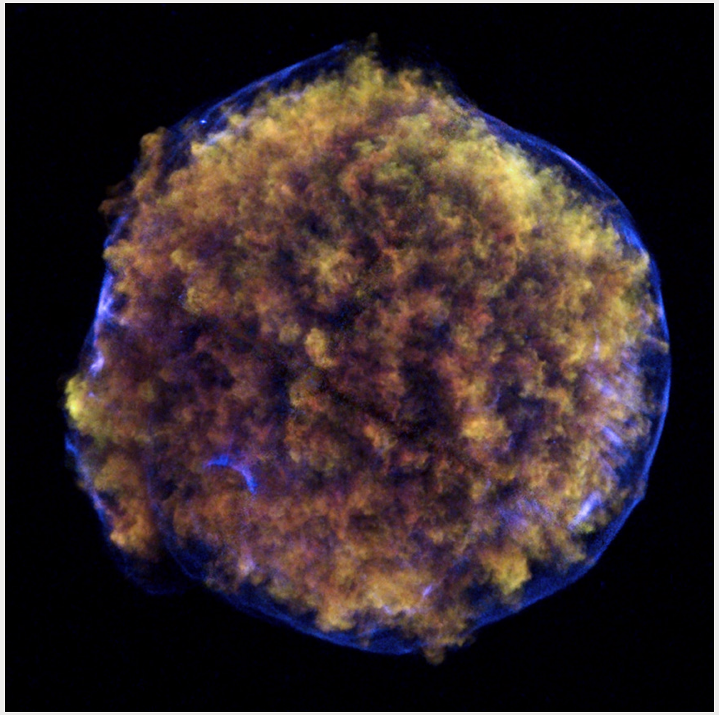
$$\frac{dN_\gamma}{dE} = \left(\frac{E}{E_0}\right)^{-\Gamma}$$

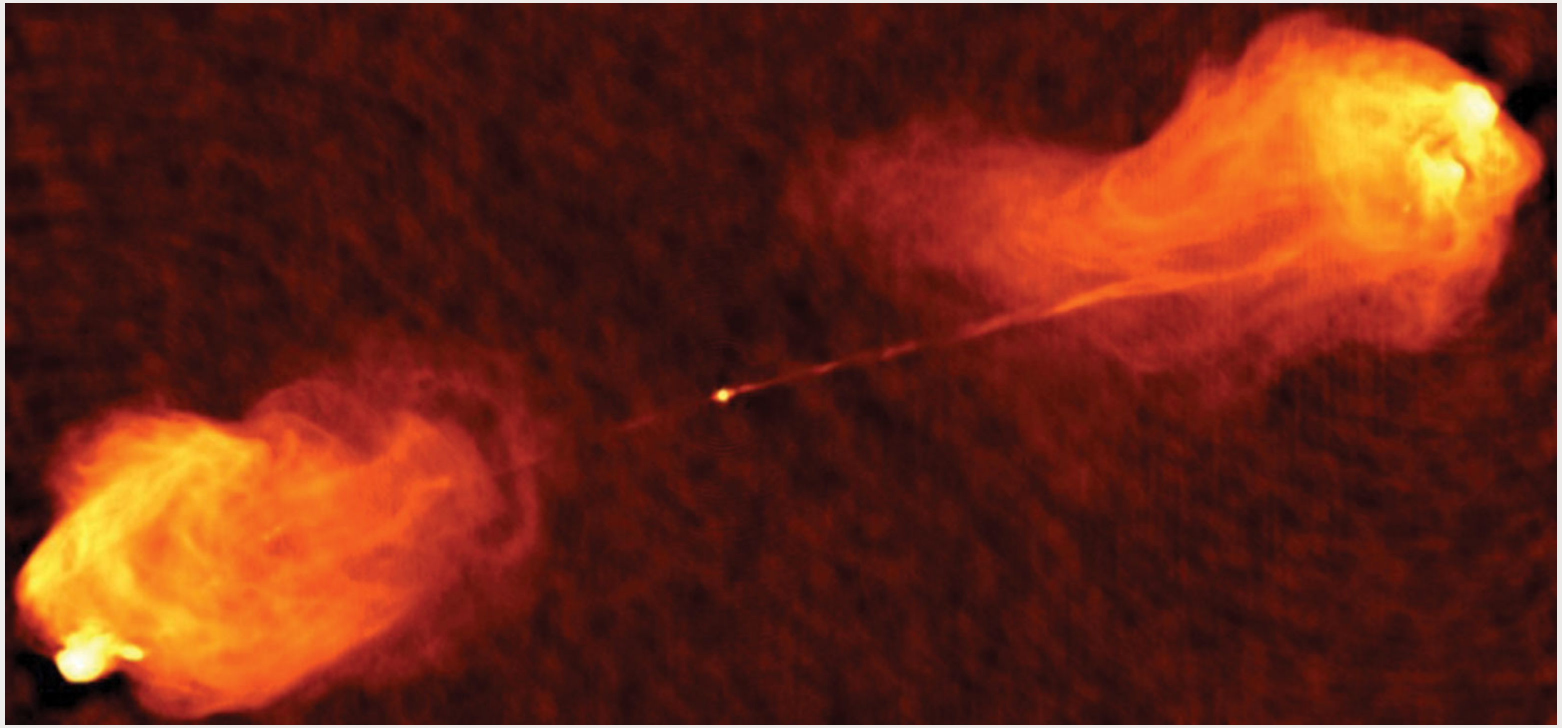
with $\Gamma \sim -2.5$

- 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

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

Galactic and Extragal Diffusive Acceleration





- 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

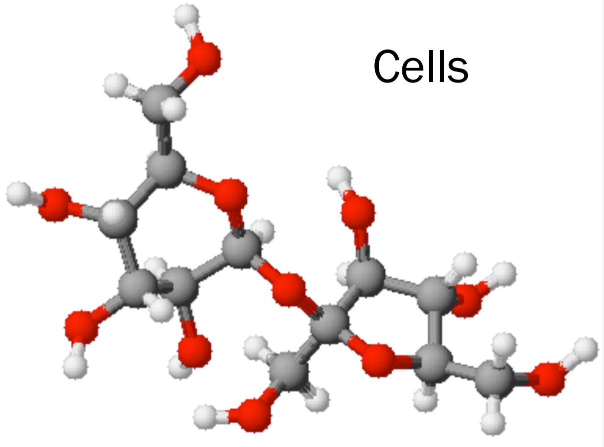
Energy conversion efficiency

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

Credit: Gabriele Ghisellini

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

Cells

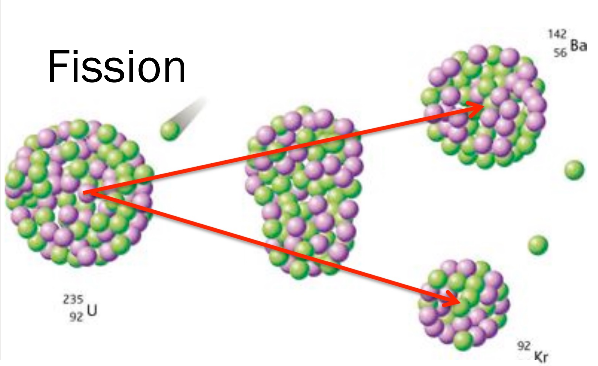


Sugar saccharose $C_{12}H_{22}O_{11}$

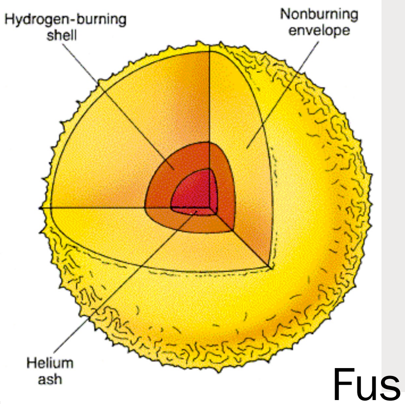
$$\eta = \frac{E}{mc^2} = \frac{1.6\text{x}10^{11} erg}{9\text{x}10^{20}\ erg} = 1.8\text{x}10^{-10}$$

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

Fission

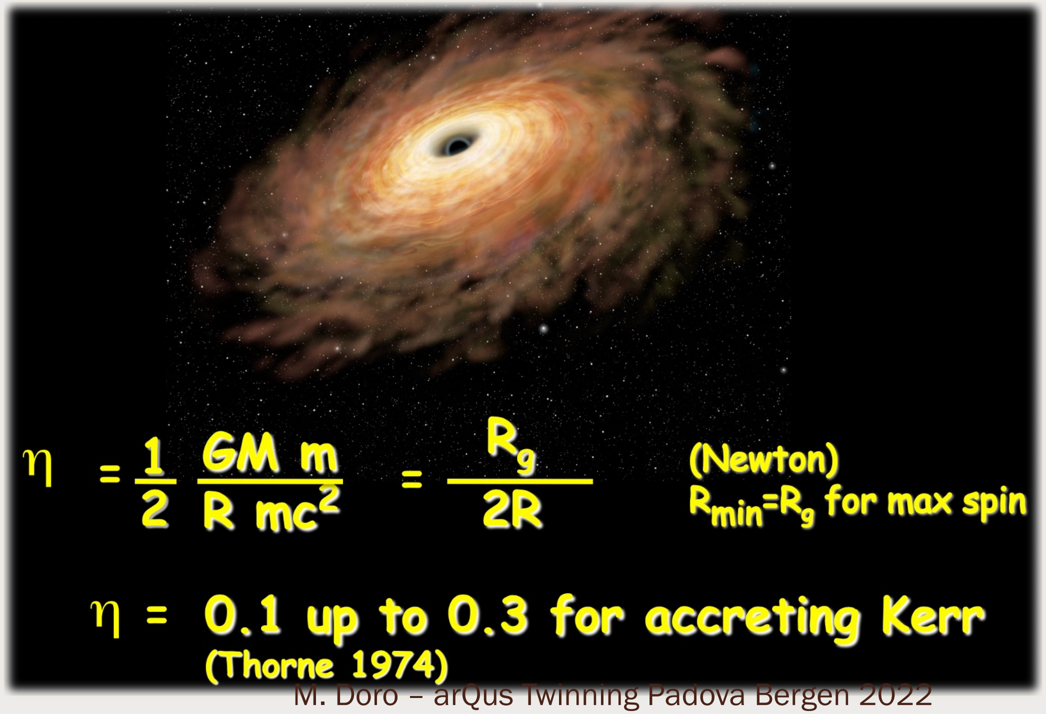


$$\eta = \frac{E}{mc^2} = \frac{0.2\text{x}10^9 eV}{235\text{x}9.4\text{x}10^8\ eV} \sim 9\text{x}10^{-4}$$



Fusion

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

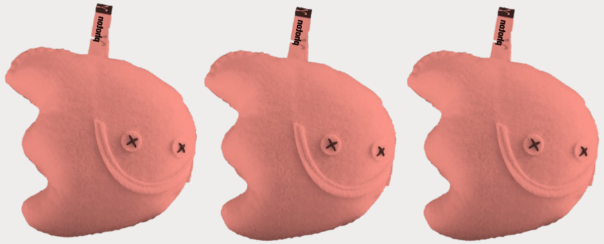


$$\eta = \frac{1}{2}\frac{GM\ m}{R\ mc^2} = \frac{R_g}{2R}$$

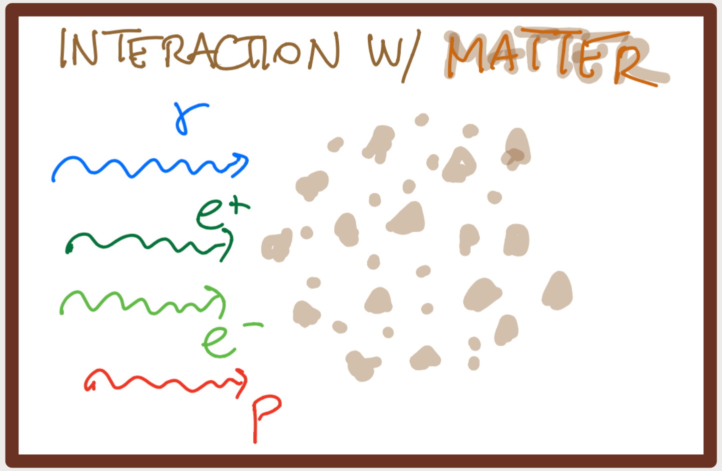
(Newton)
$R_{min}=R_g$ for max spin

η = 0.1 up to 0.3 for accreting Kerr
(Thorne 1974)

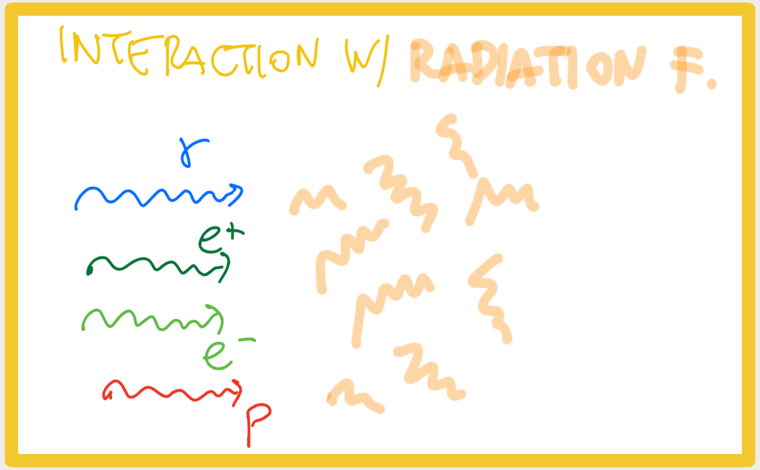
HOW TO GENERATE THE GAMMA-RAYS



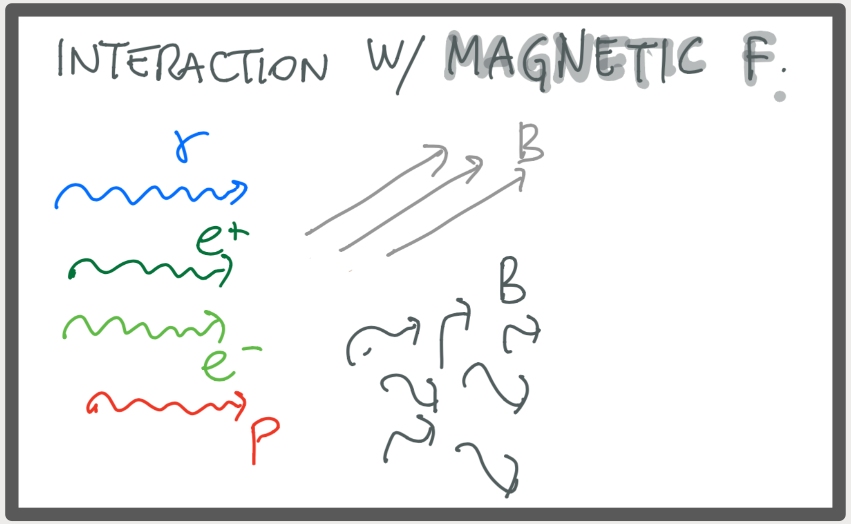
Radiative and collisional processes



- Pion decays from
- Electron bremmshtralung
- Positron annihilation

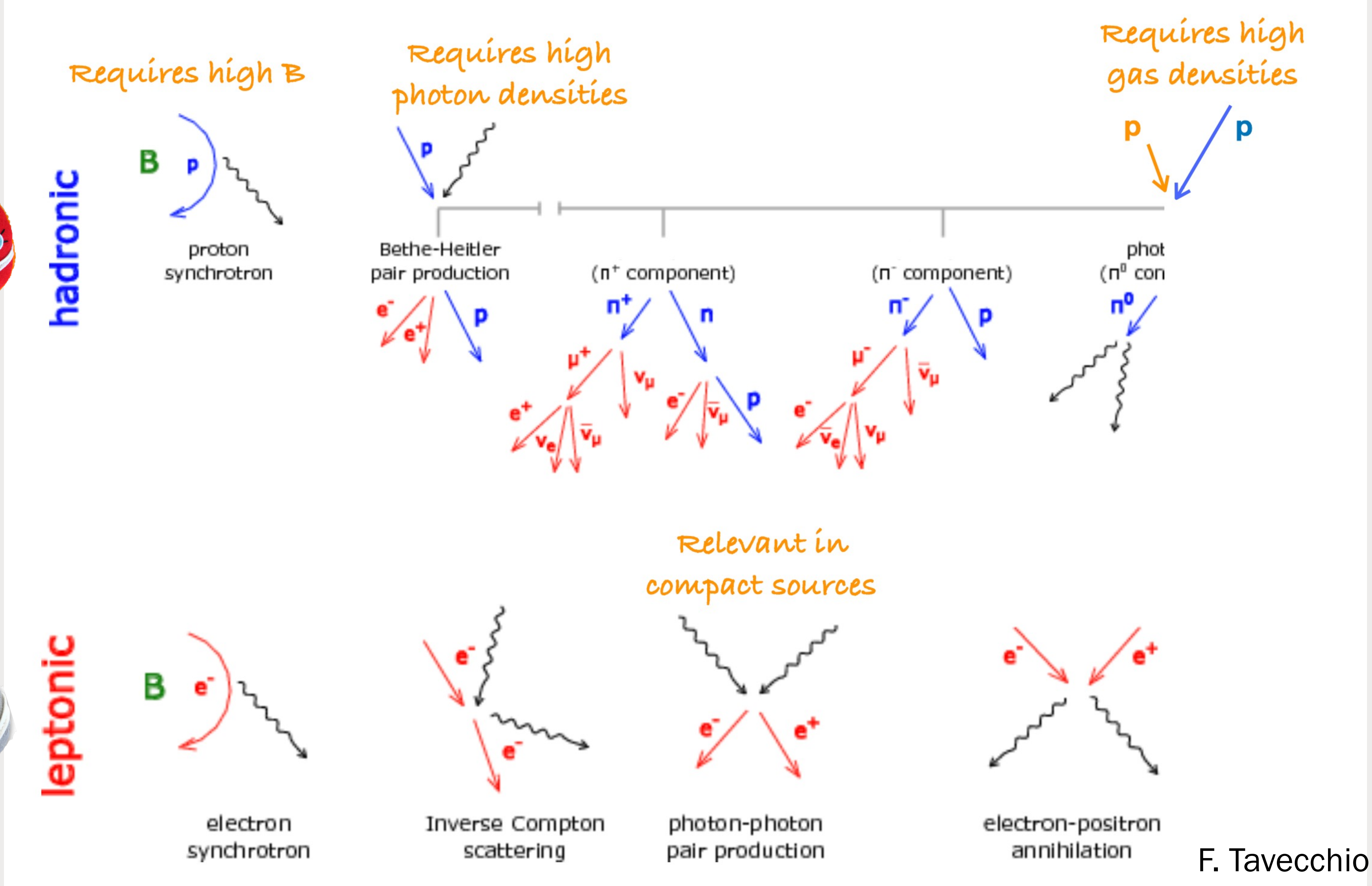


- Pair production
- Inverse Compton
- Photoproduction



- Synchrotron radiation

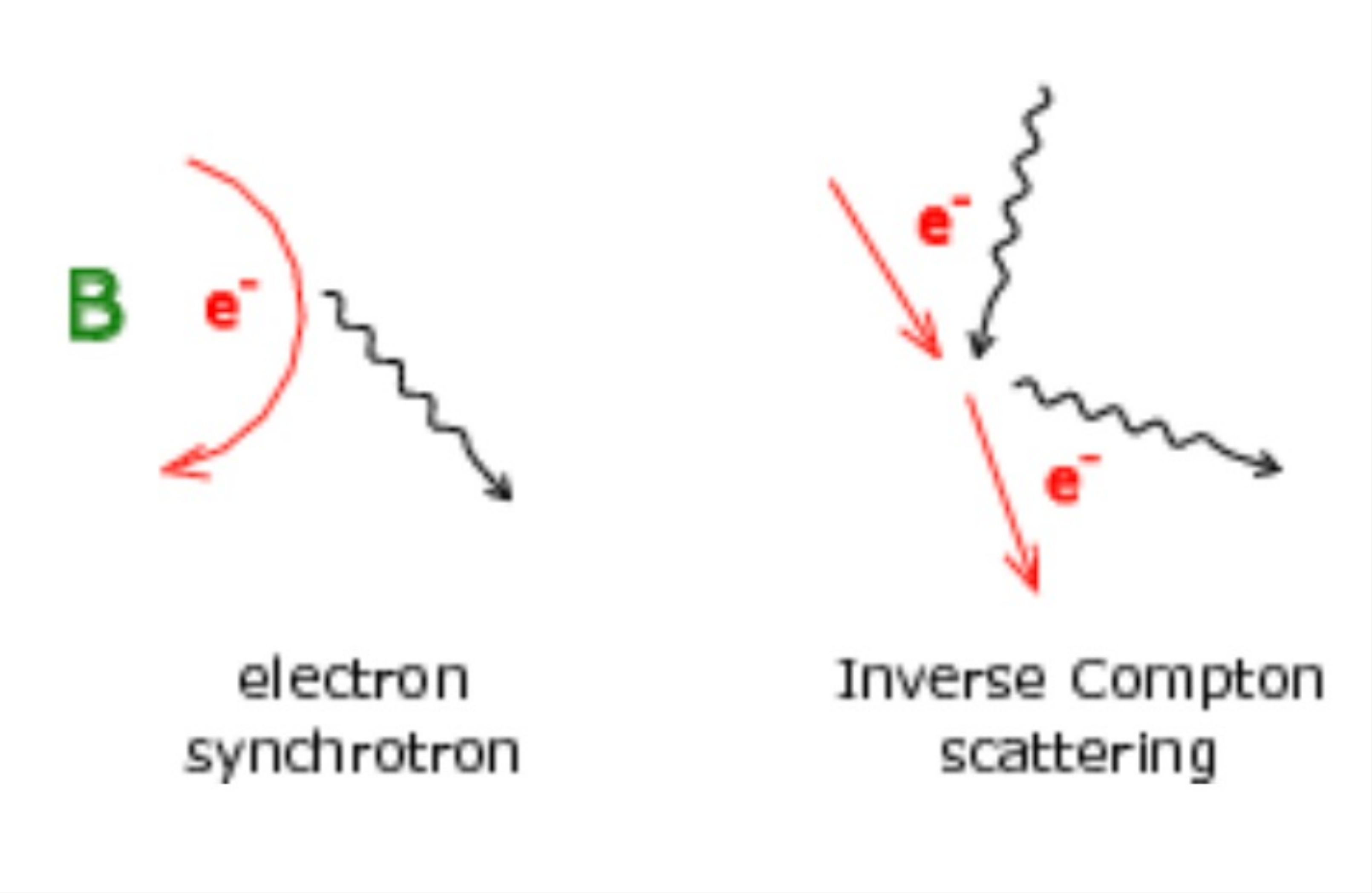
Leptonic or hadronic?



F. Tavecchio

The most common leptonic processes

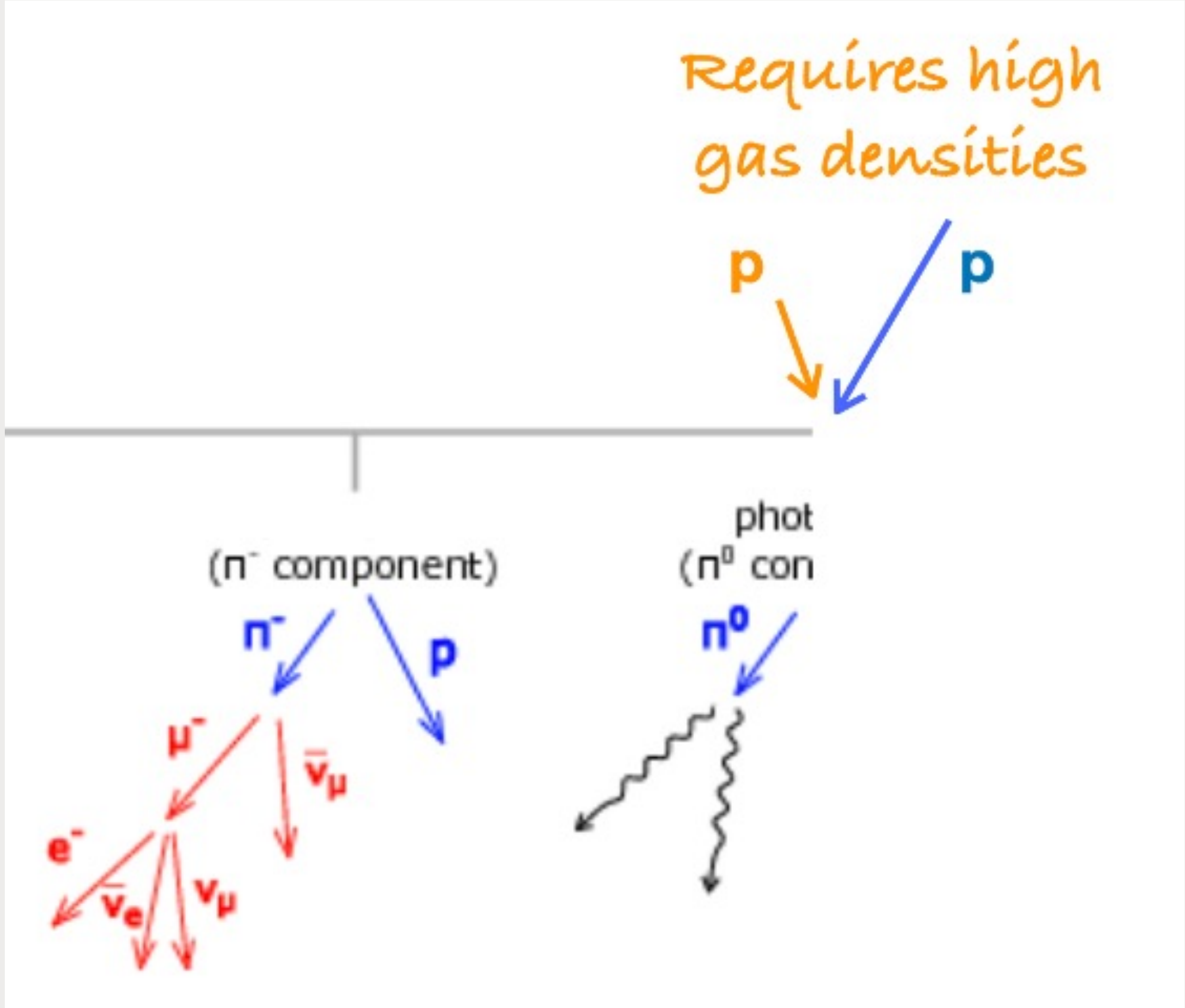
leptonic

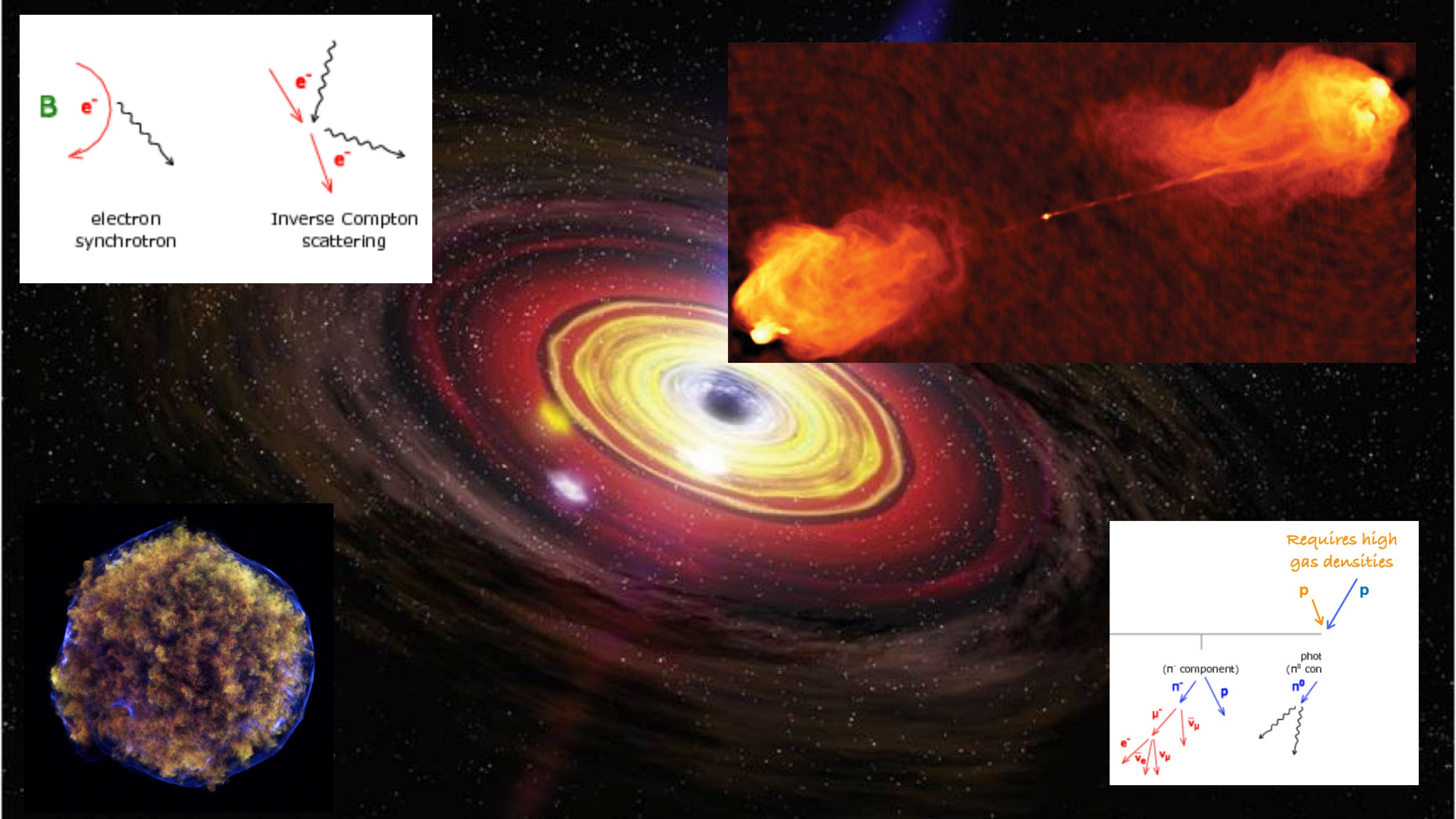


electron synchrotron

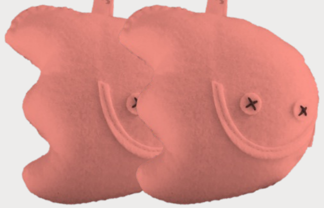
Inverse Compton scattering

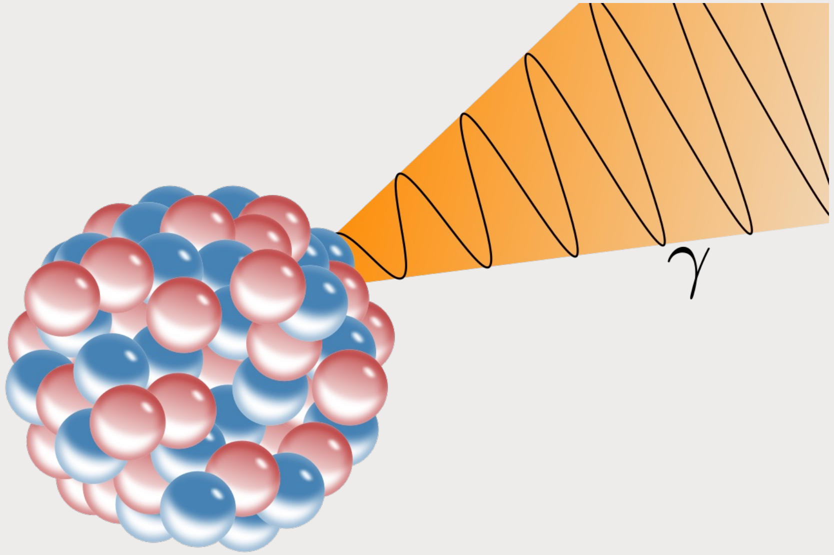
The most common hadronic process


Requires high gas densities

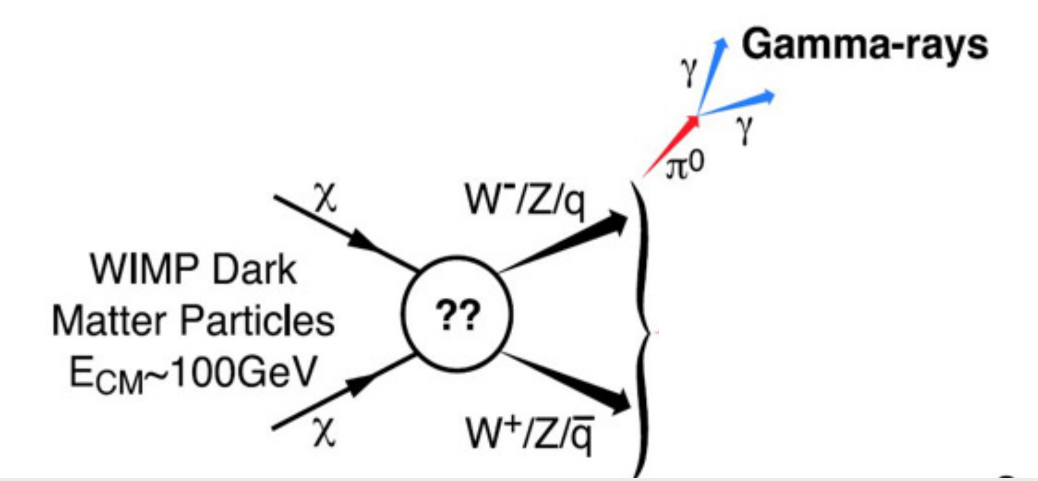

B
e⁻
electron synchrotron
e⁻
e⁻
Inverse Compton scattering
Requires high gas densities
p
p
(π⁻ component)
phot
(π⁰ con
π⁻
p
μ⁻
ν̄μ
e⁻
ν̄e
νμ
π⁰

Other means to get

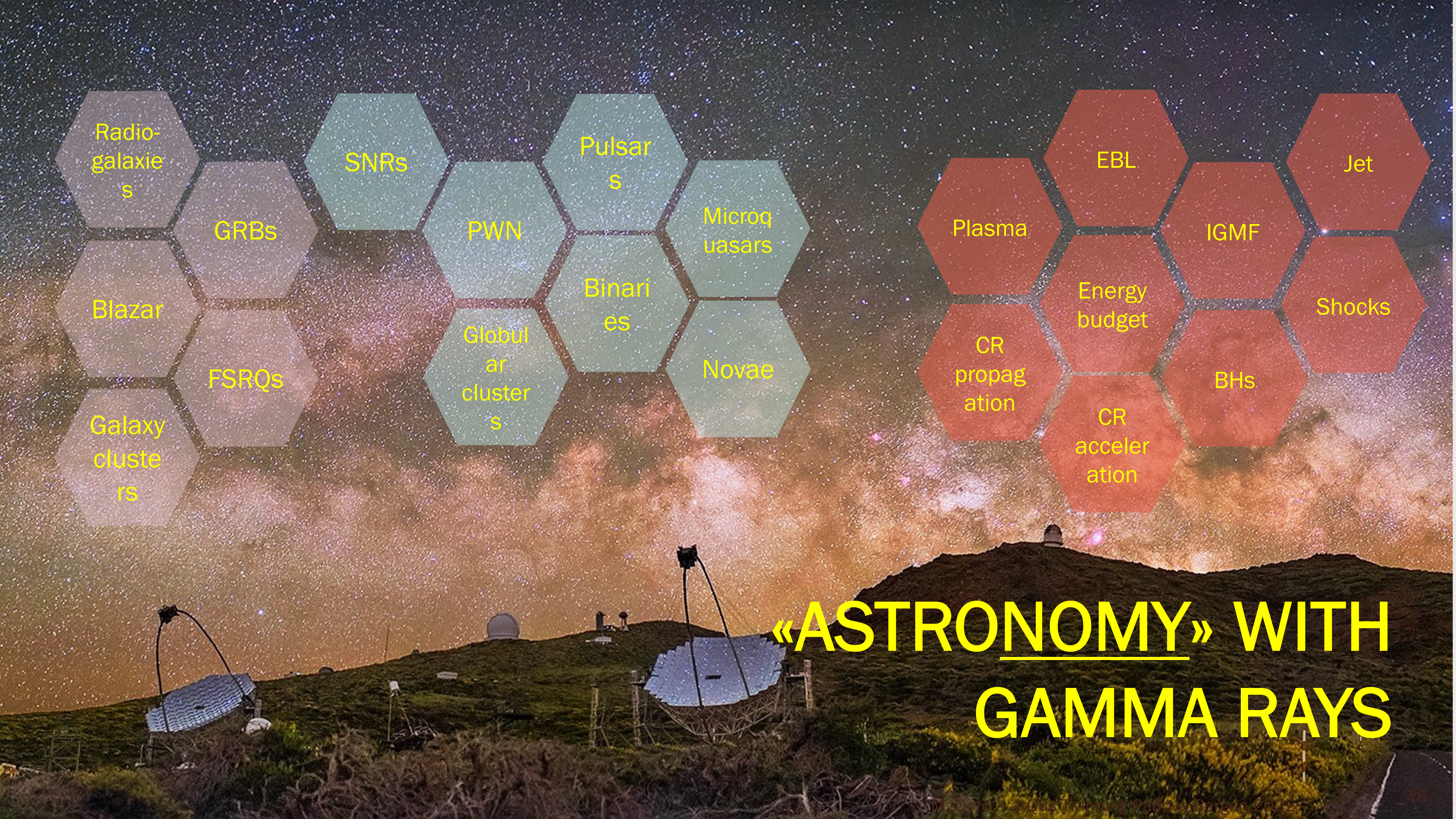




- Nuclear processes
  - *De-excitation of target nuclei leads to keV-MeV lines*
    - 4.4 MeV from 12C
    - 6.1 MeV from 160
    - 0.85 MeV from 56Fe



- Dark matter and other new physics fields



Radio-galaxies

GRBs

Blazar

FSRQs

Galaxy clusters

SNRs

PWN

Pulsars

Microquasars

Binaries

Globular clusters

Novae

Plasma

EBL

IGMF

Jet

Energy budget

Shocks

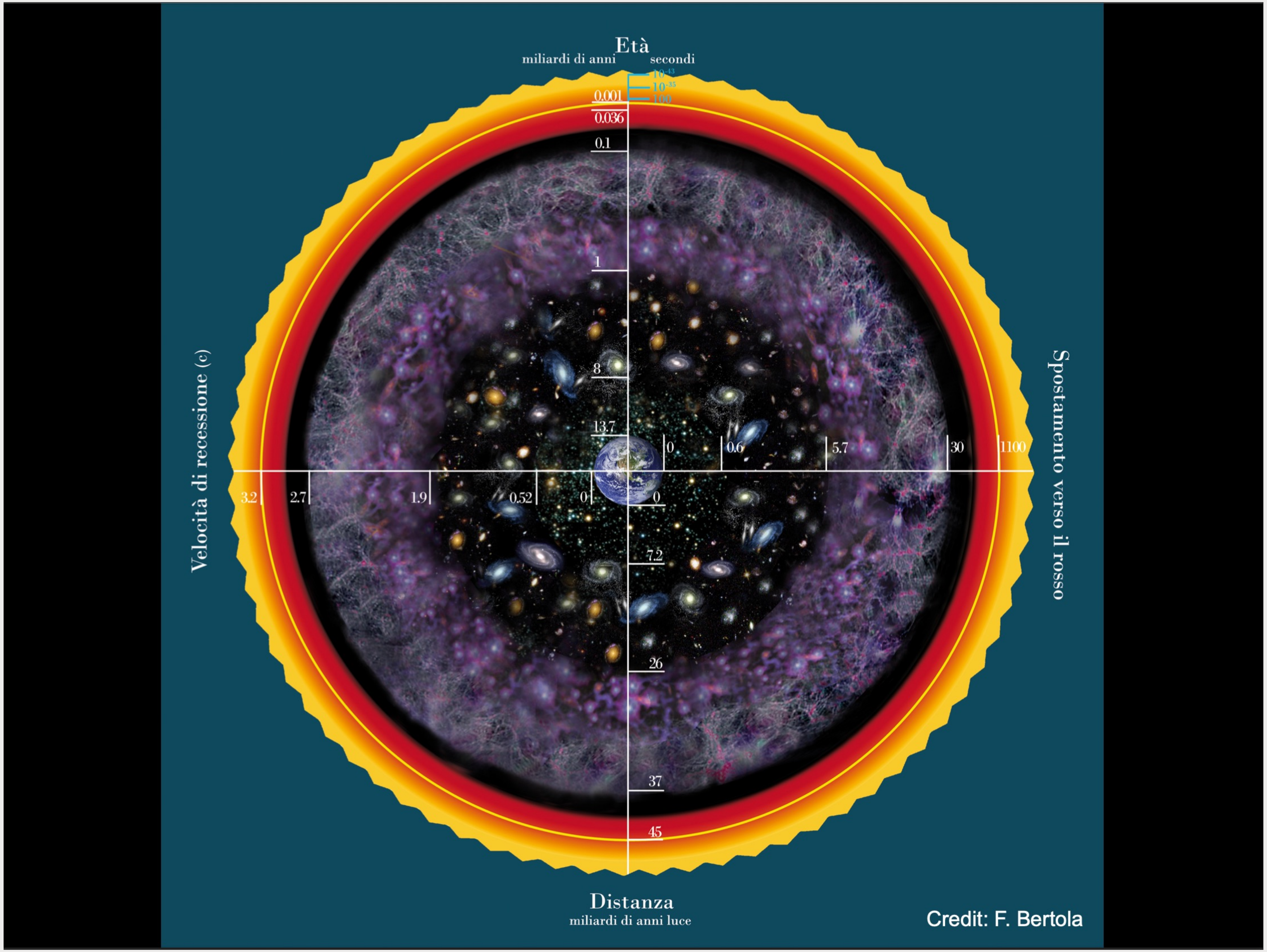
CR propagation

CR acceleration

BHs

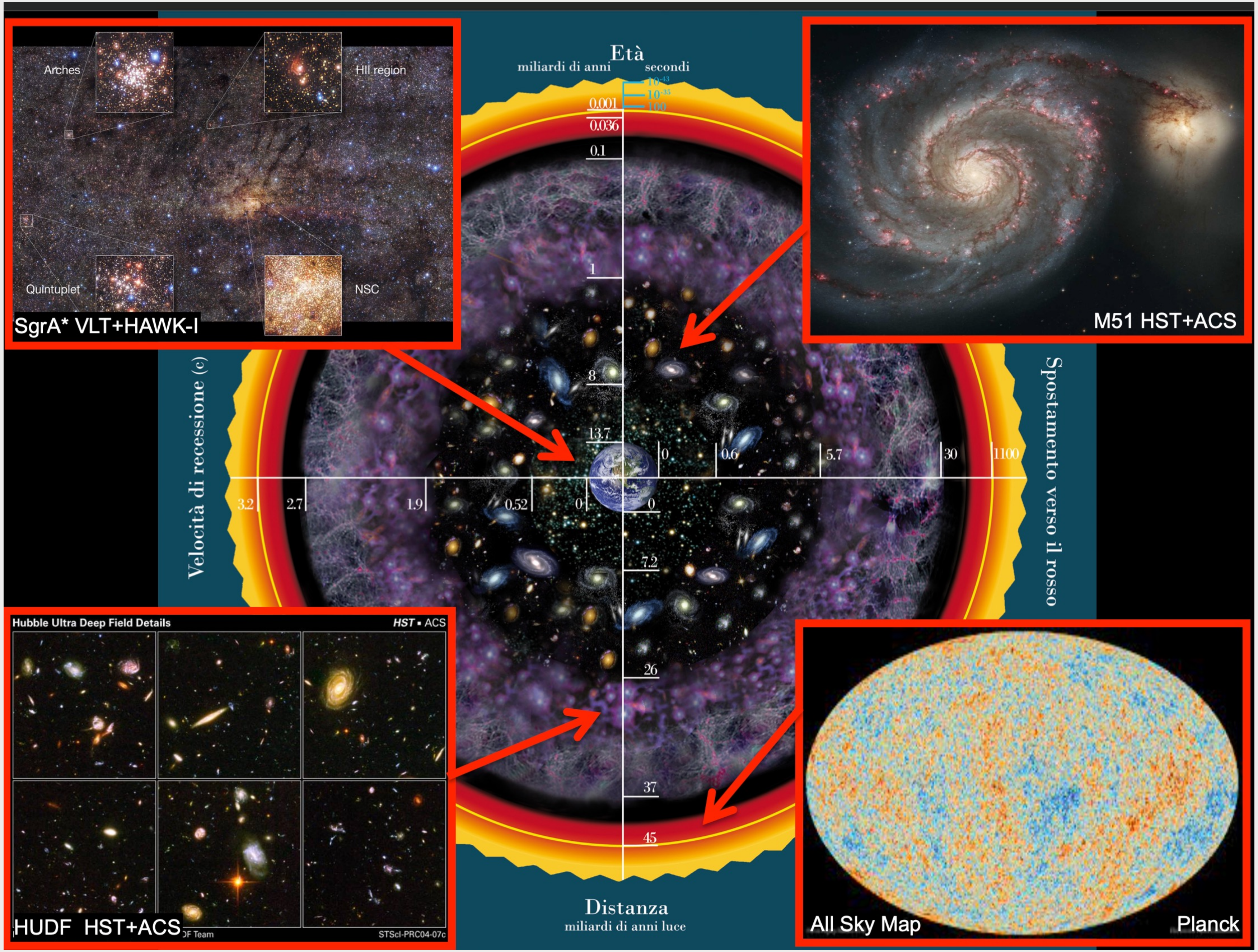
«ASTRONOMY» WITH GAMMA RAYS

Where are you?



Credit: F. Bertola

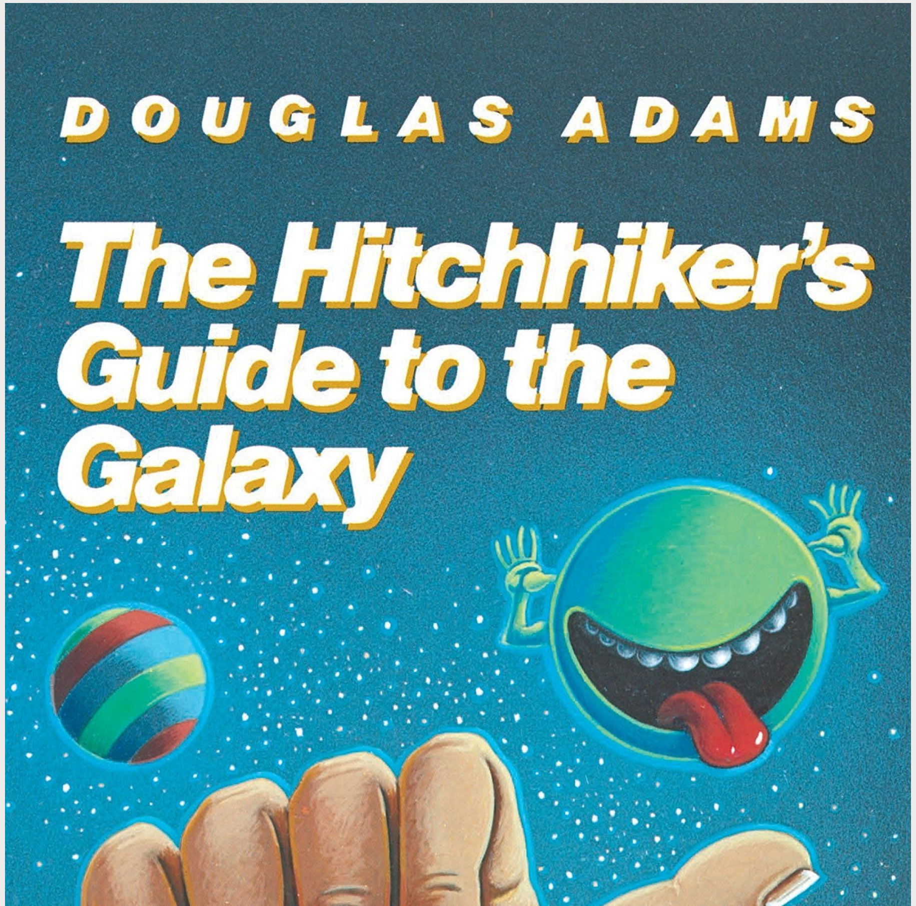
Where are you?

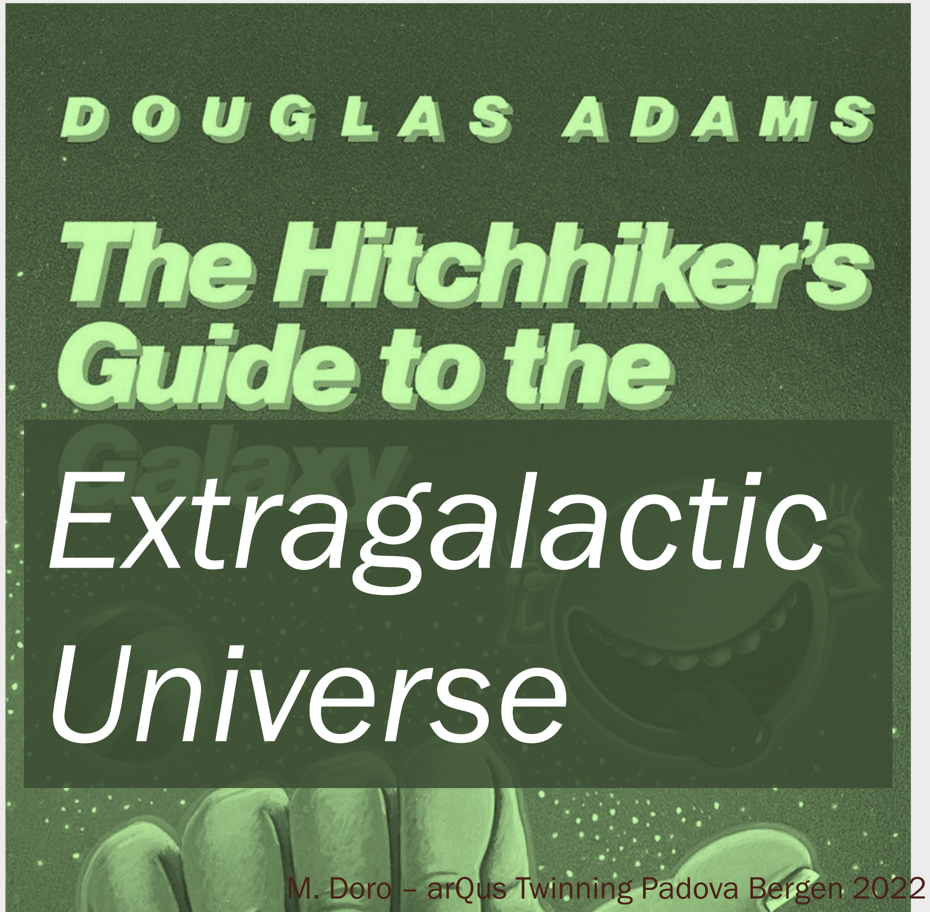


- In the extragalactic space?
- In the intergalactic space?
- Around a compact object?
- Close to a SMBH?
- Close to a binary system?
- Close to a Gamma-Ray Burst?

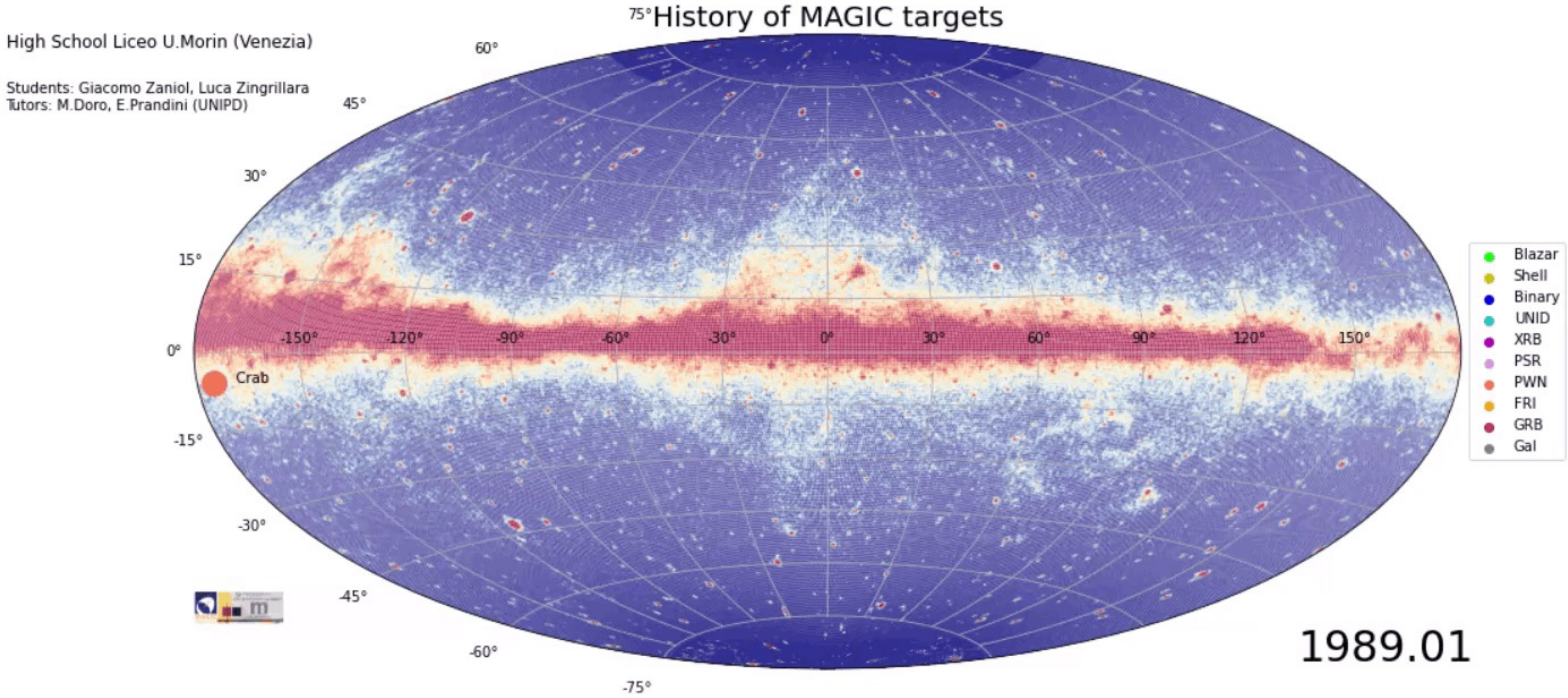
Neighborhood and definitely not

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



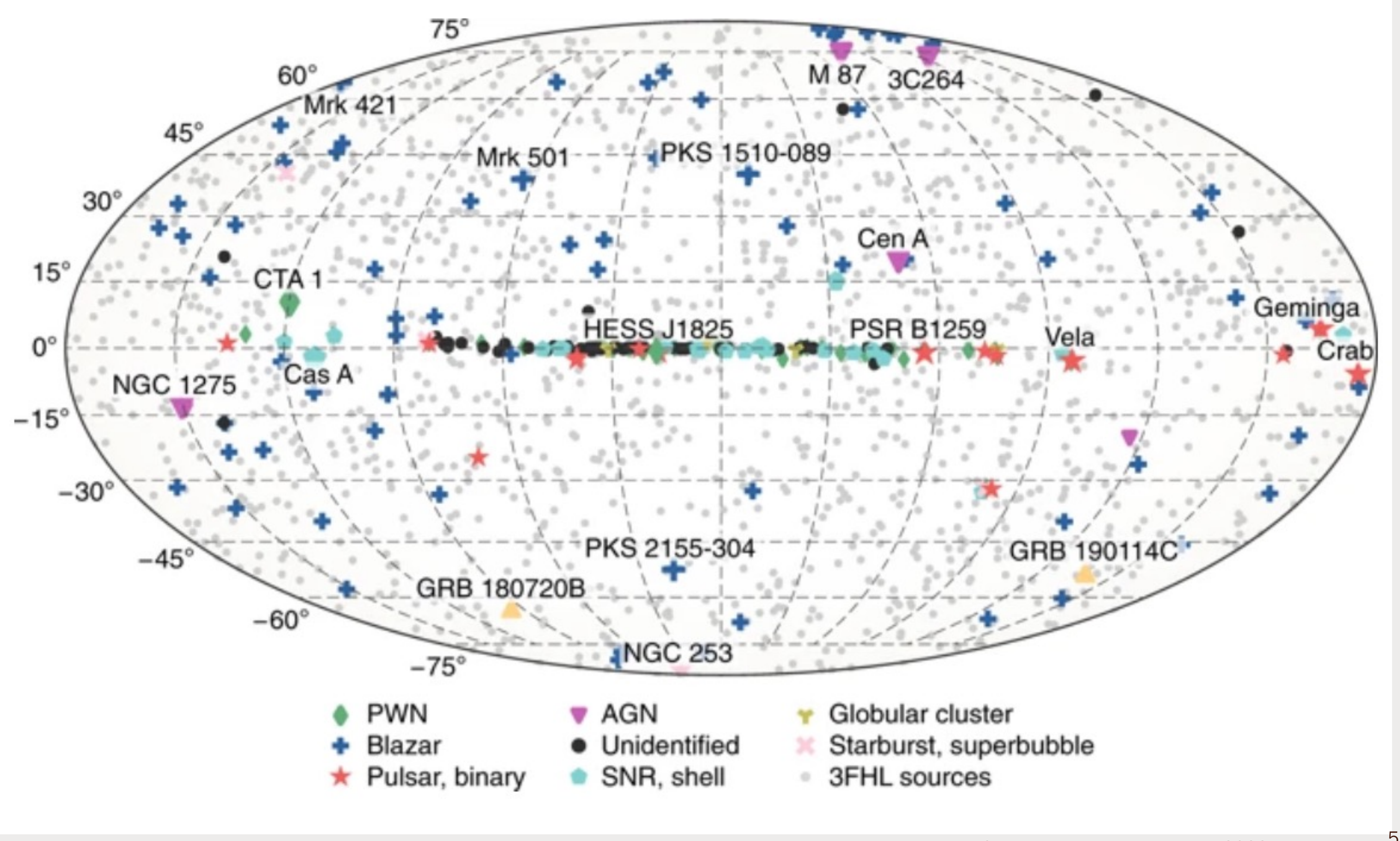


Extragalactic Universe


History of MAGIC targets

High School Liceo U.Morin (Venezia)

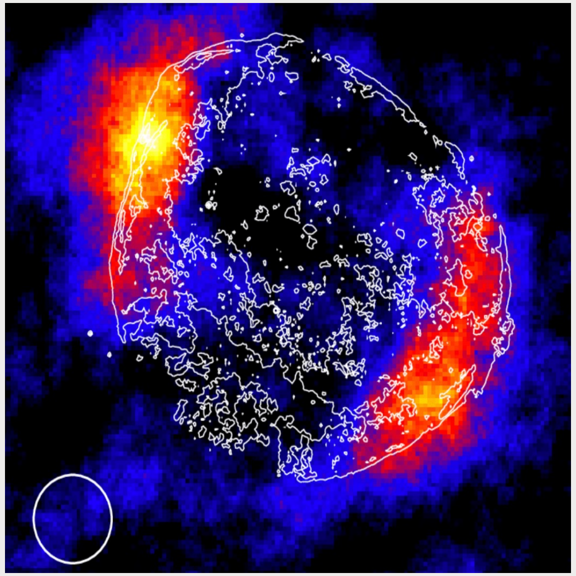
Students: Giacomo Zaniol, Luca Zingrillara
Tutors: M.Doro, E.Prandini (UNIPD)


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

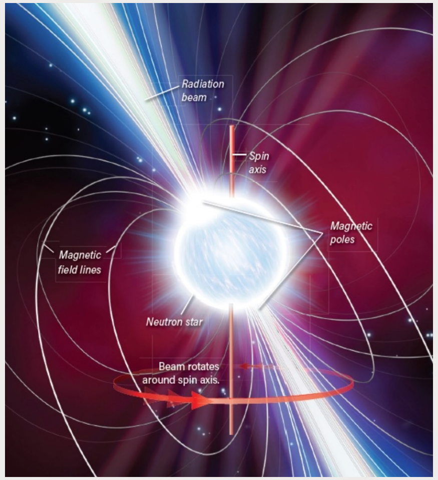
1/ Galactic GeV-TeV emitters

- Connected to the death of a star

Supernova Remnant

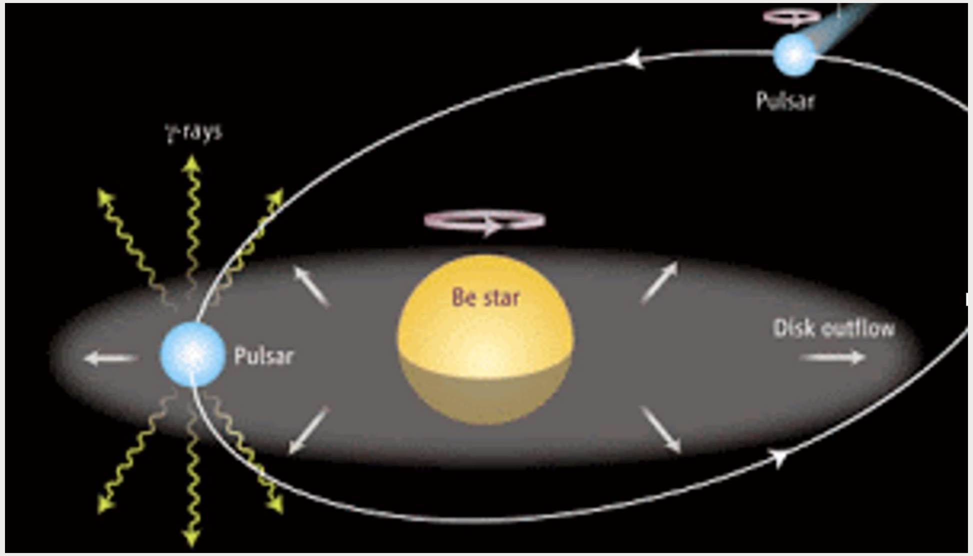


Pulsar Wind Nebula

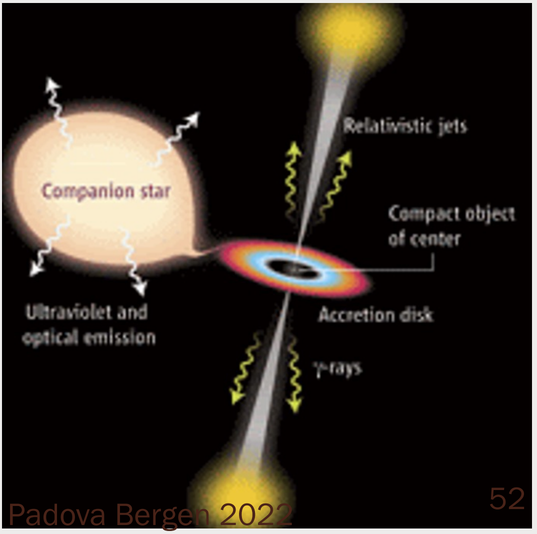


Pulsar

- When stars are too alive

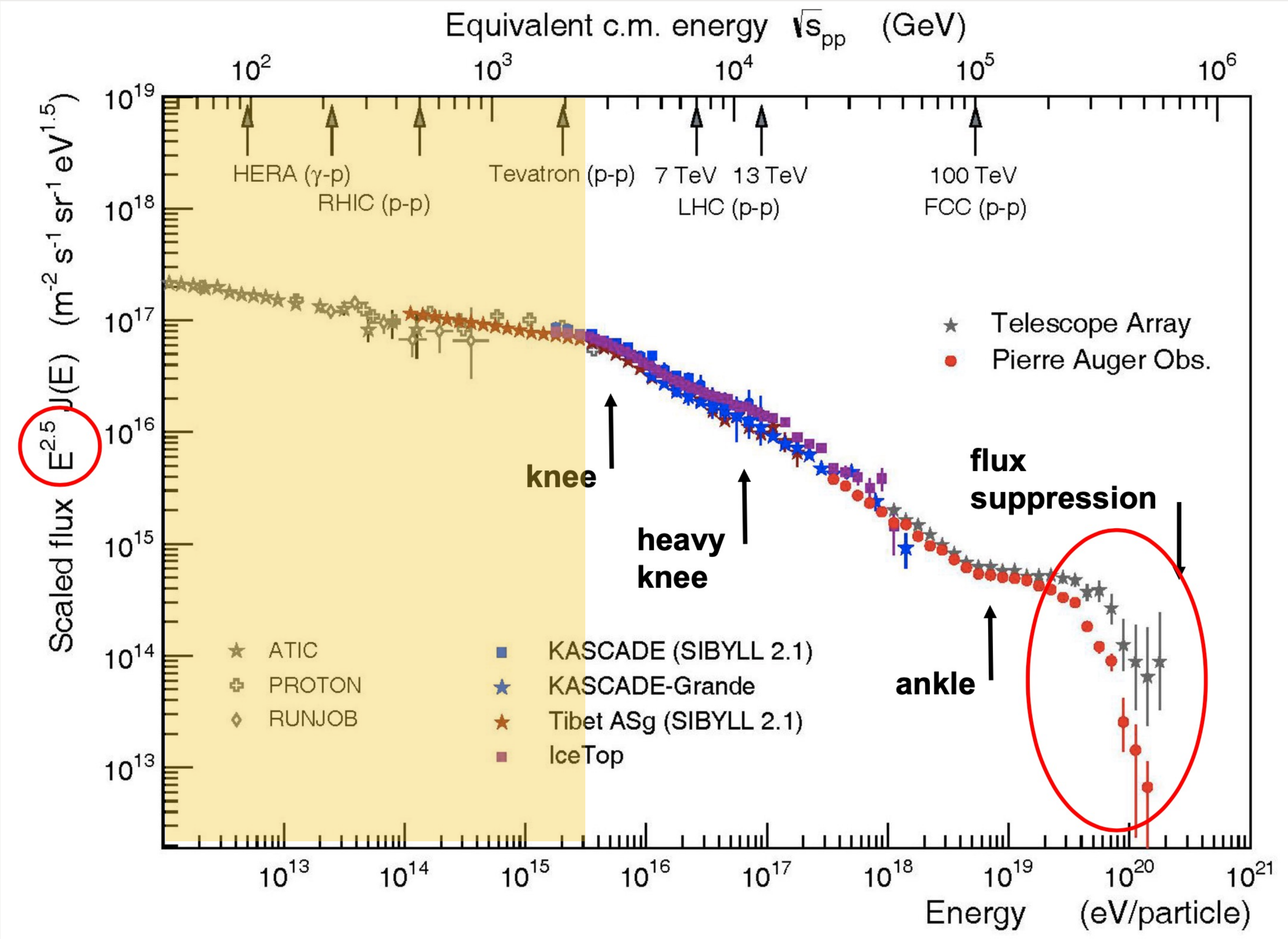


Binary Pulsar



Microquasar

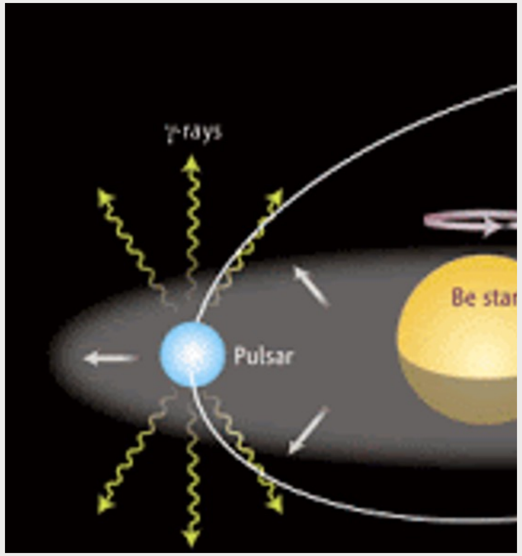
Here comes the galactic CR



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)*

Stellar endproducts

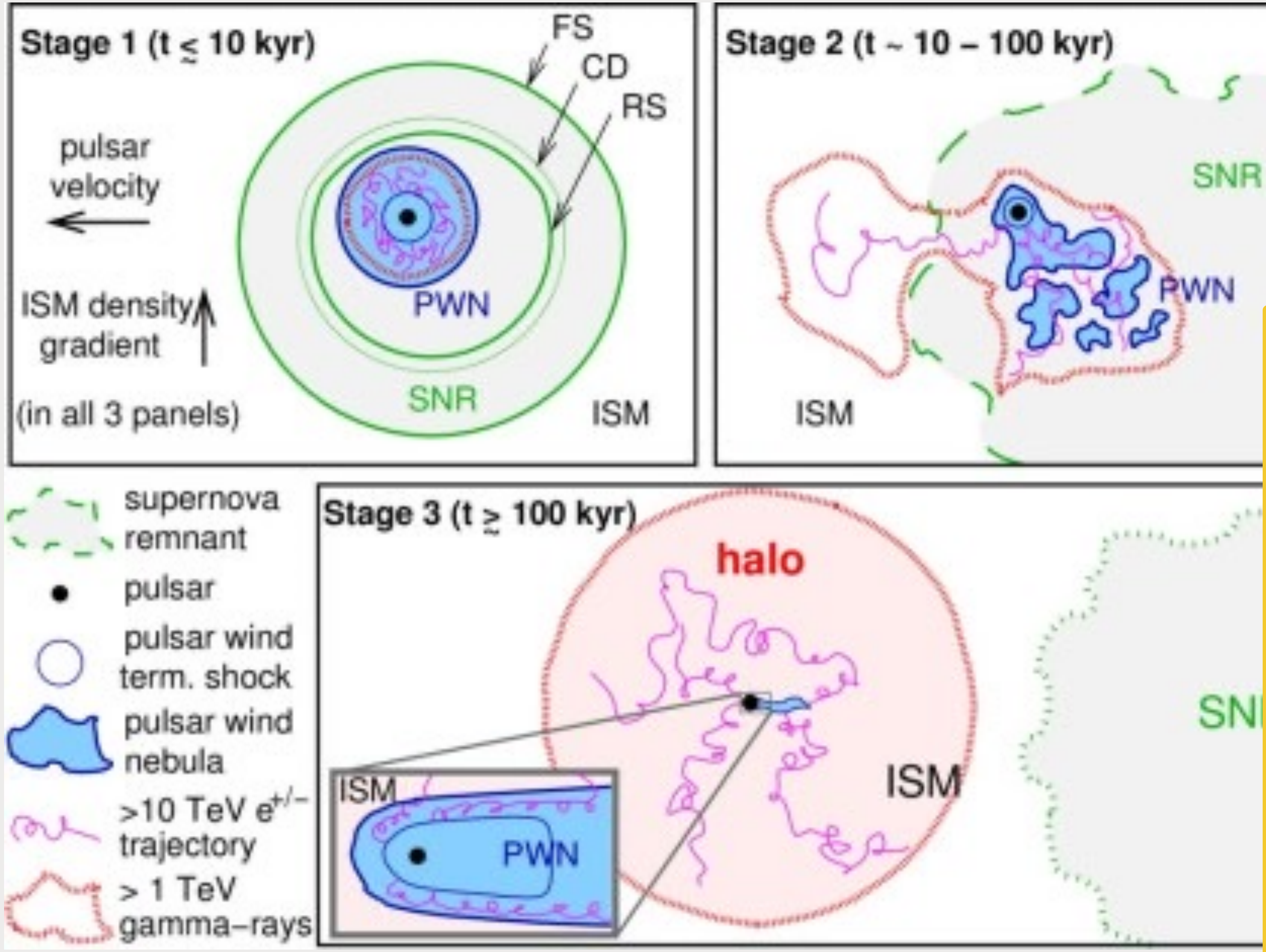


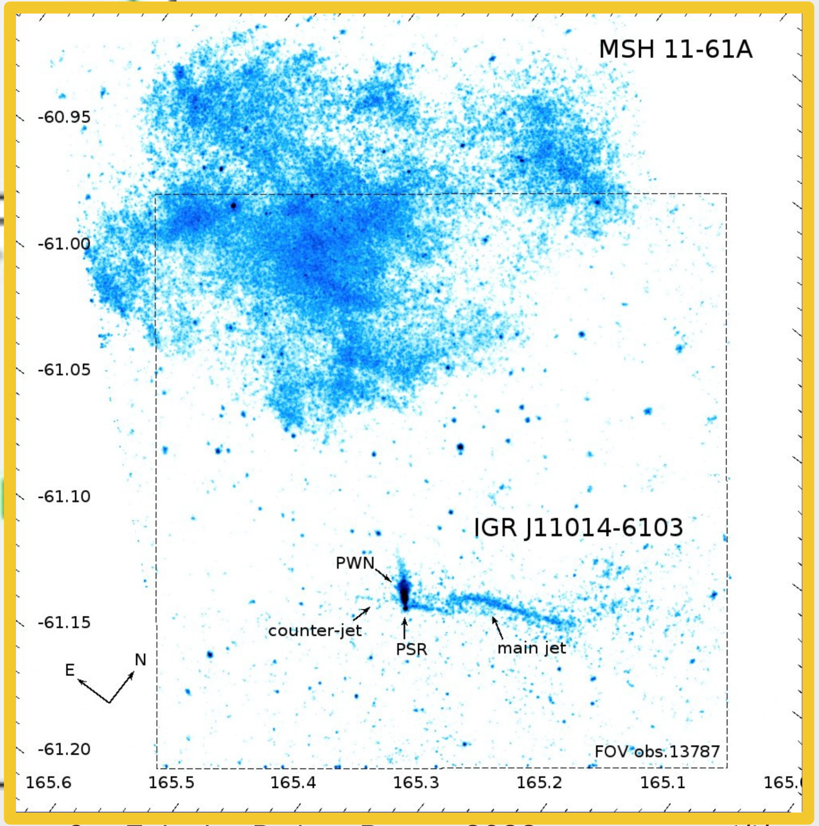
- End of some stars life: **supernova boom**
  - ***Core-Collapse*** *(Type Ib,Ic,II): lack of hydrogen, contraction, rebound and explosion*
  - ***Type Ia:*** *accretion on white dwarf in companion system above a critical mass (standard candles, see Zavala's talk at this school)*
- Neutron stars
  - *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

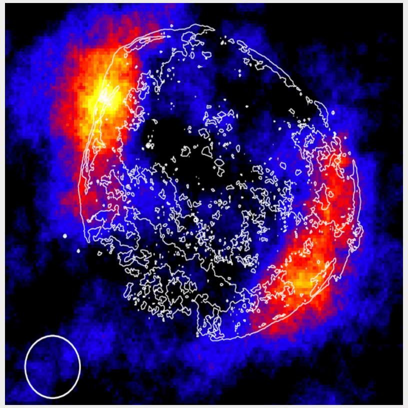
G. Giacinti



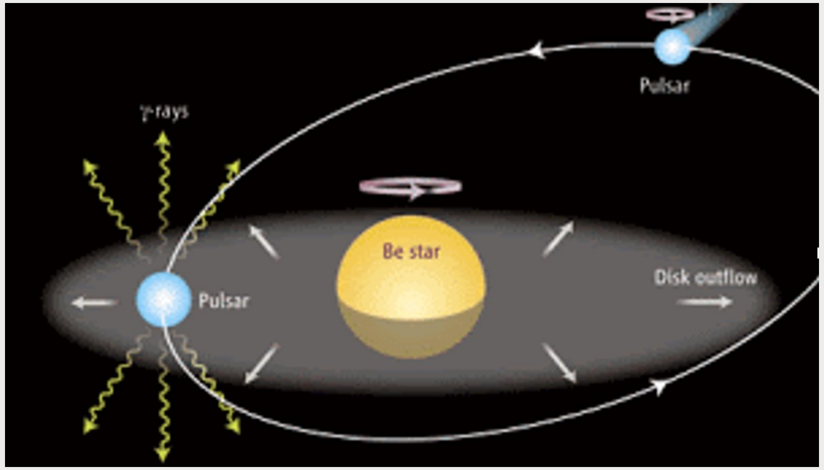


- Winds
  - *SNR*
  - *PWN*
  - *Composite*
- Pulsar can leave its remnants

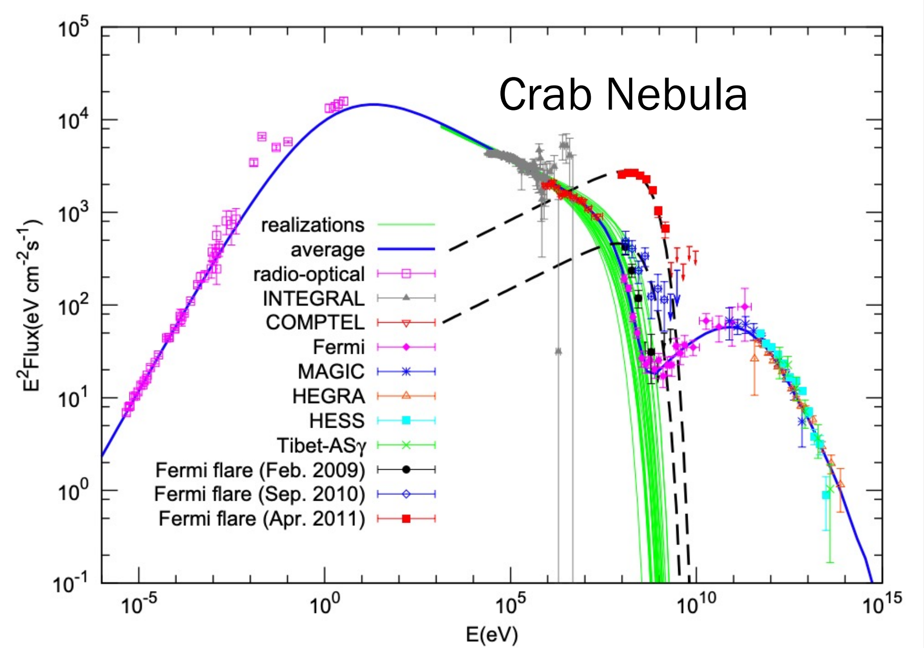
Strong particle winds generate shocks



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)



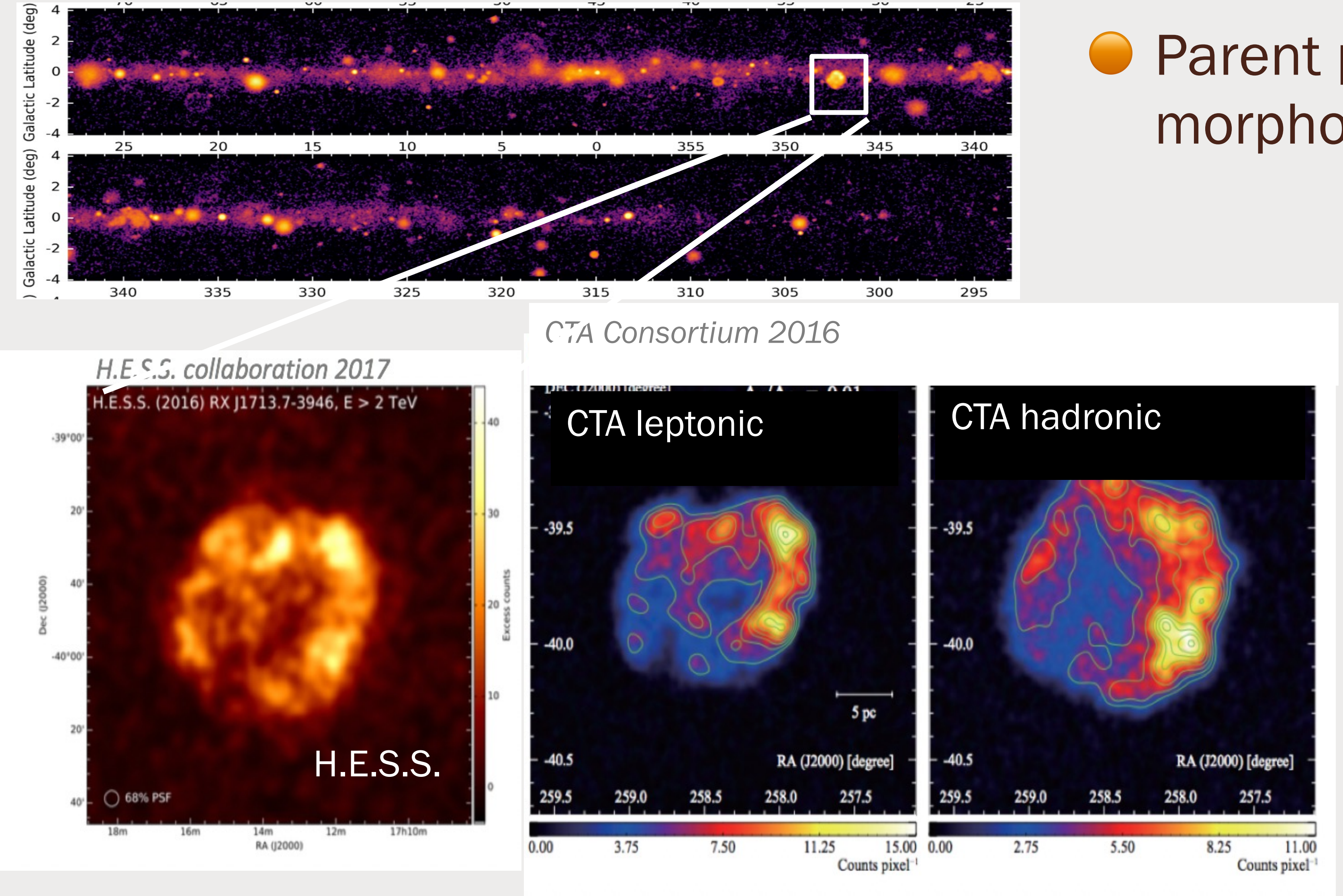
Maximum energy $E_{max} \sim 300\ Z\ TeV$



https://arxiv.org/abs/1109.0075

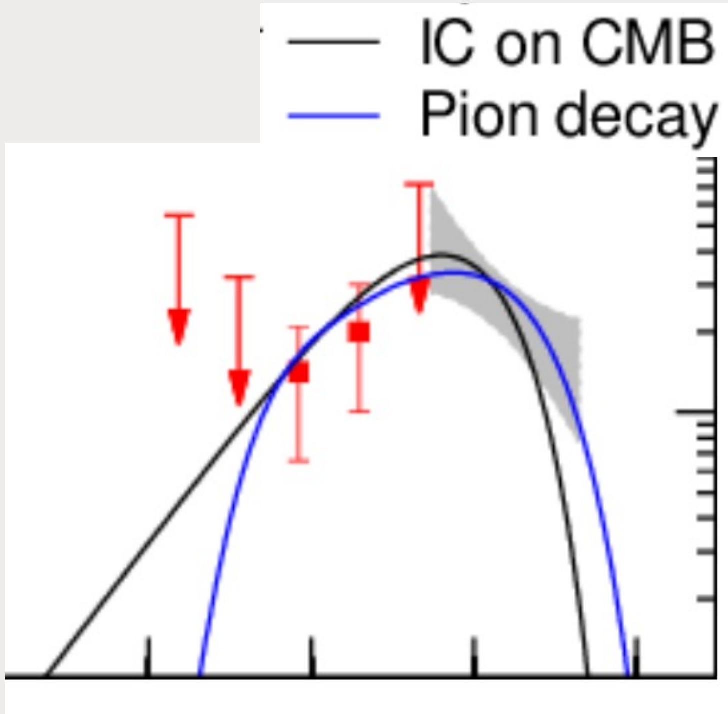
SNR RXJ1713

- Parent particles determines morphology and spectrum

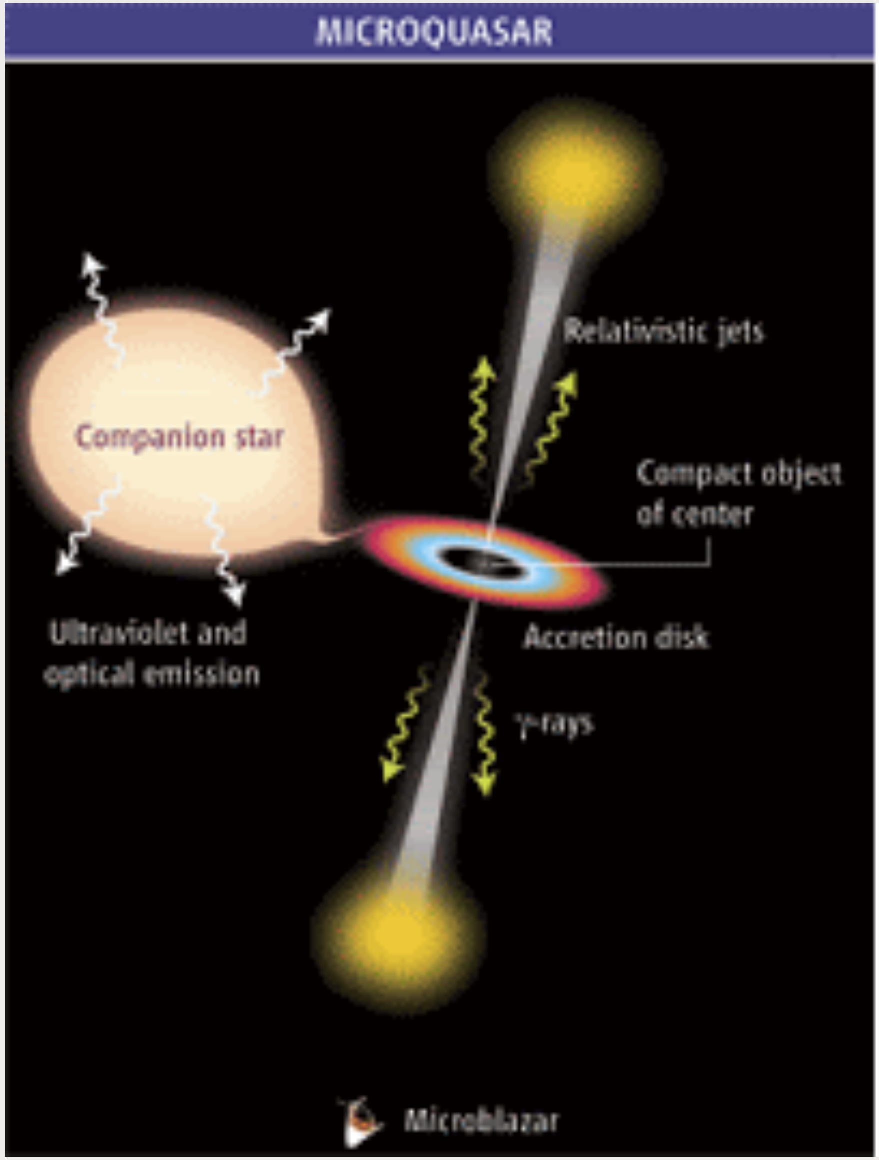


H.E.S.S. collaboration 2017

CTA Consortium 2016



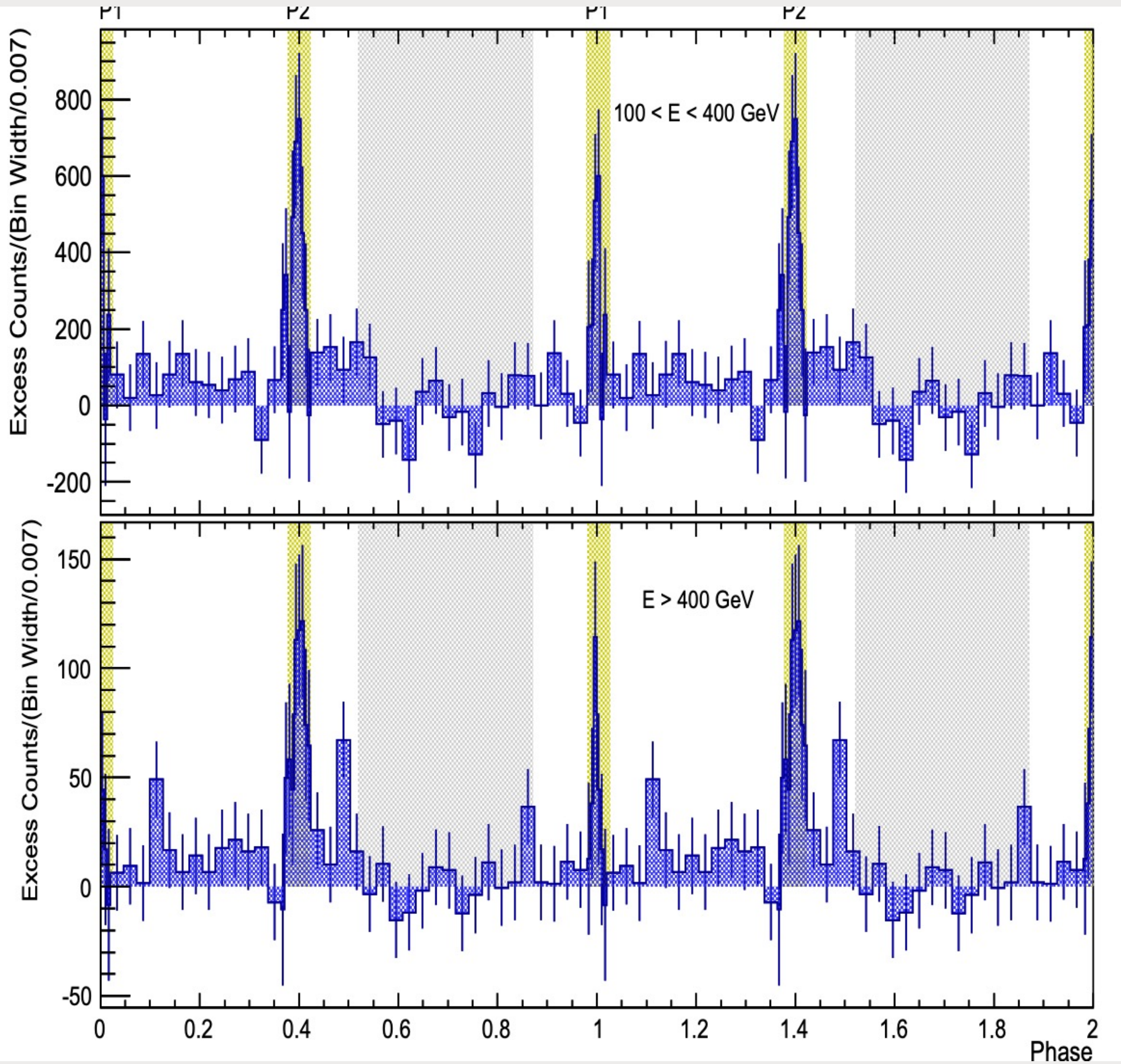
Ultrarelativistic galactic jets



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)

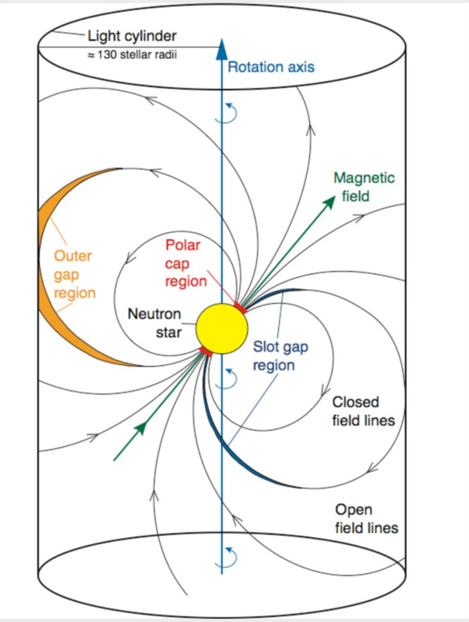
Beatiful jets that can be switched ON and OFF

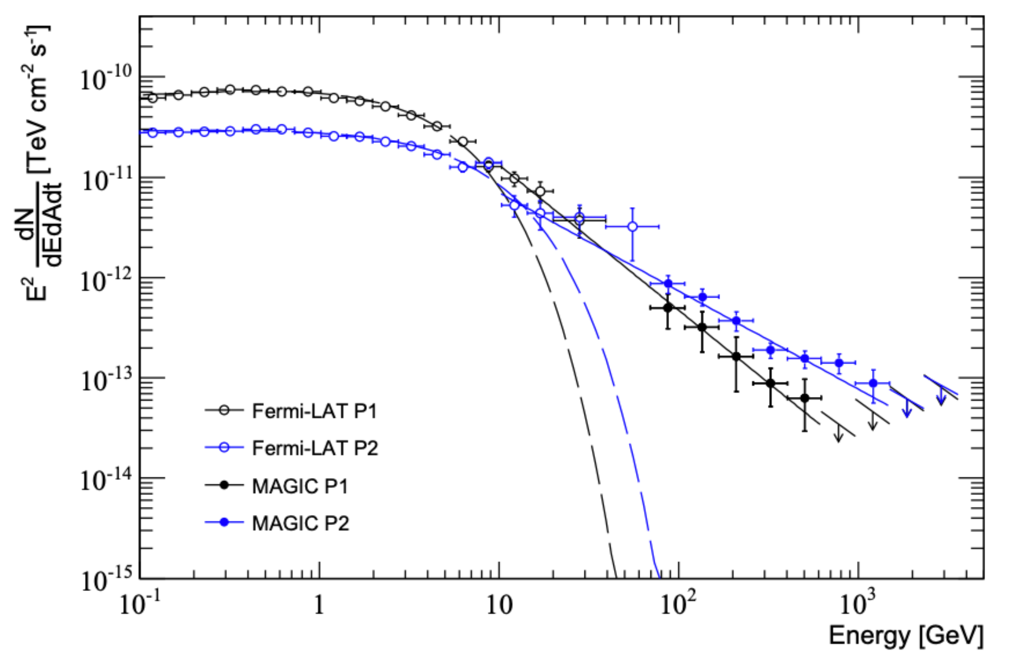
Pulsars



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

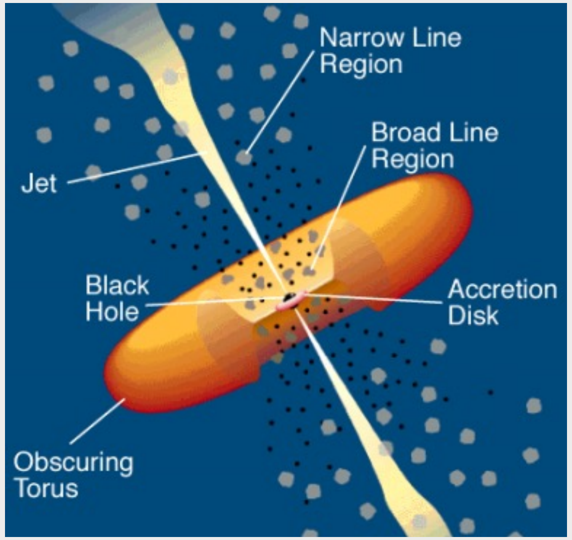
Pulsed emission



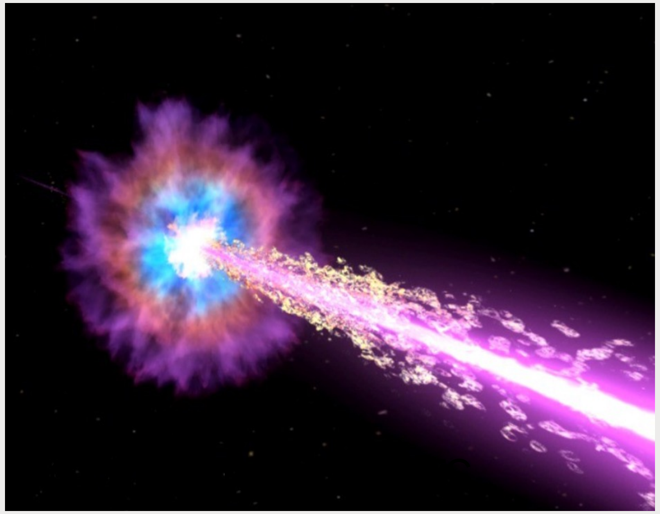


2/ Extragalactic GeV-TeV emitters

- Connected to the ultrarelativist jets & BHS



ACTIVE GALACTIC NUCLEI

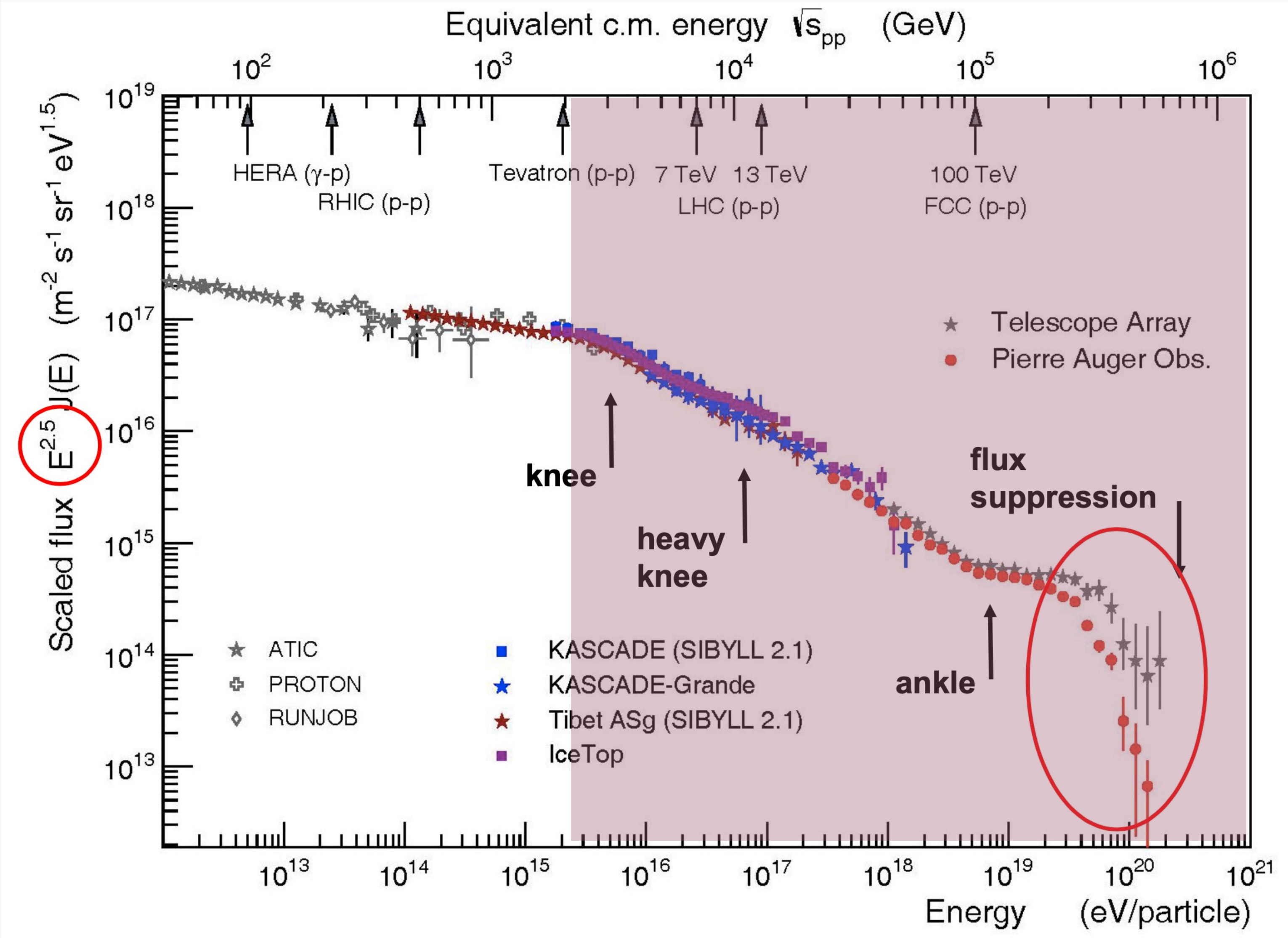


RADIO GALAXIES

- Intense activities (winds)

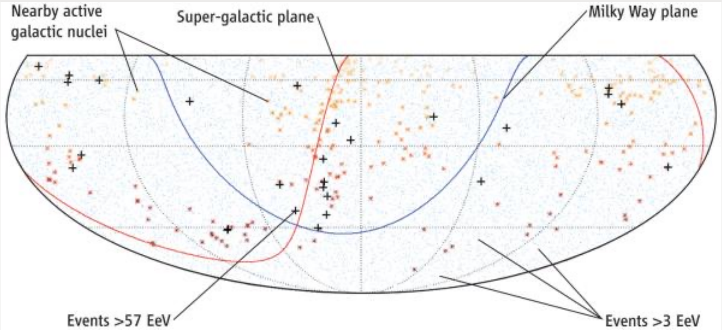
STAR-BURST GALAXIES

Here comes the galactic CR

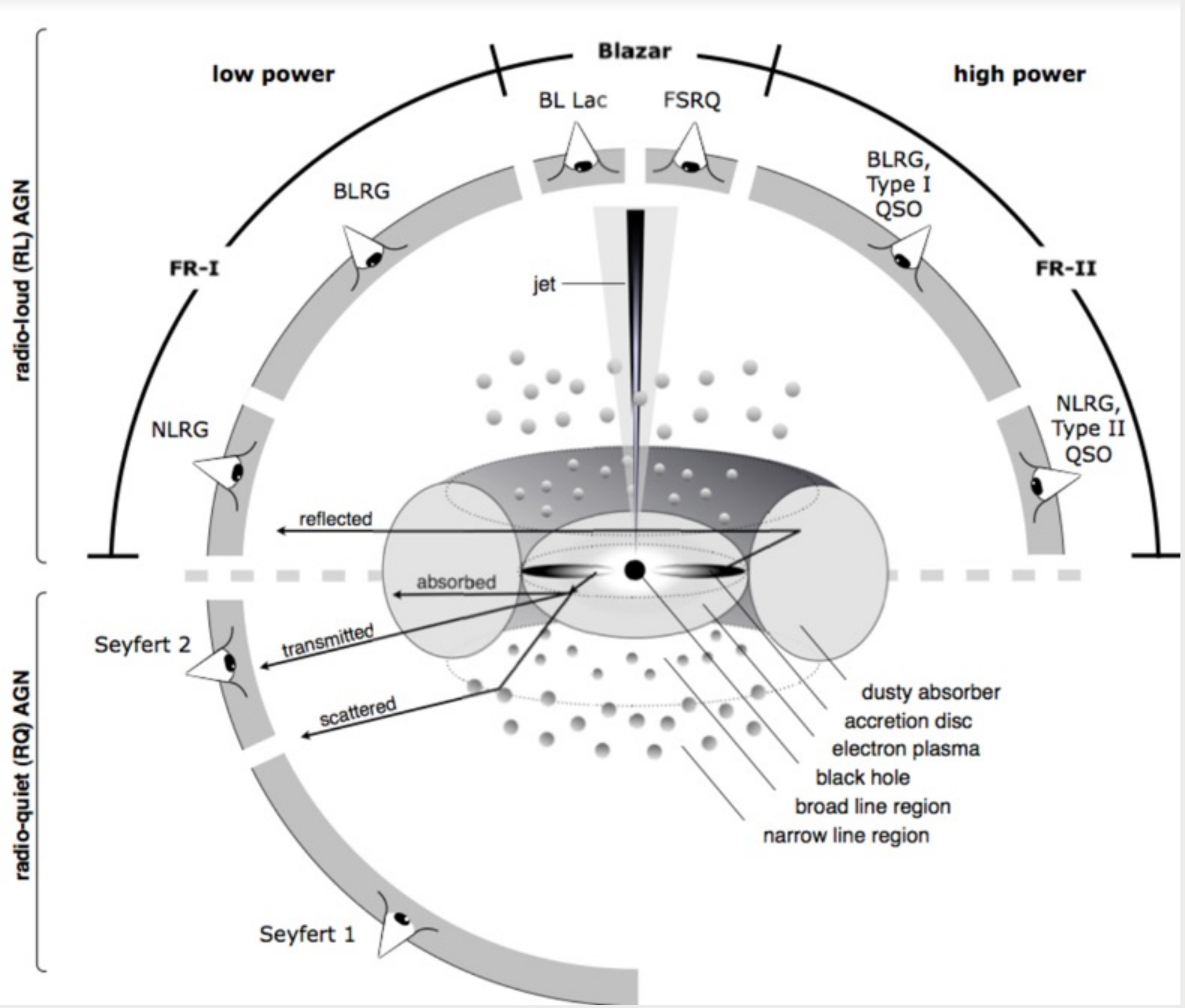


EXTRAGALACTIC

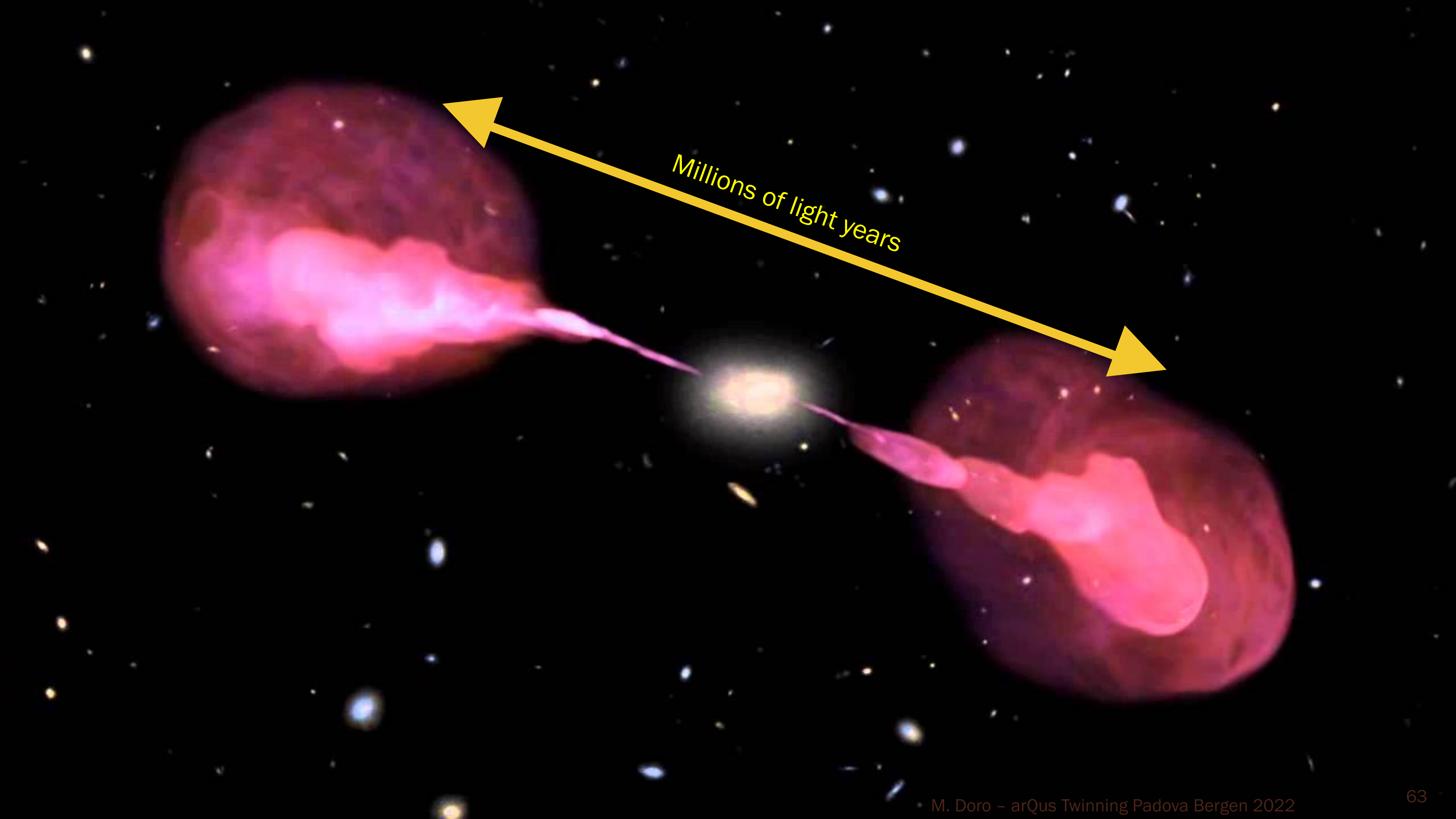
- AGN are valid booster
- Only recenty validated experimentally (Auger)



Model of Active Galactic Nuclei

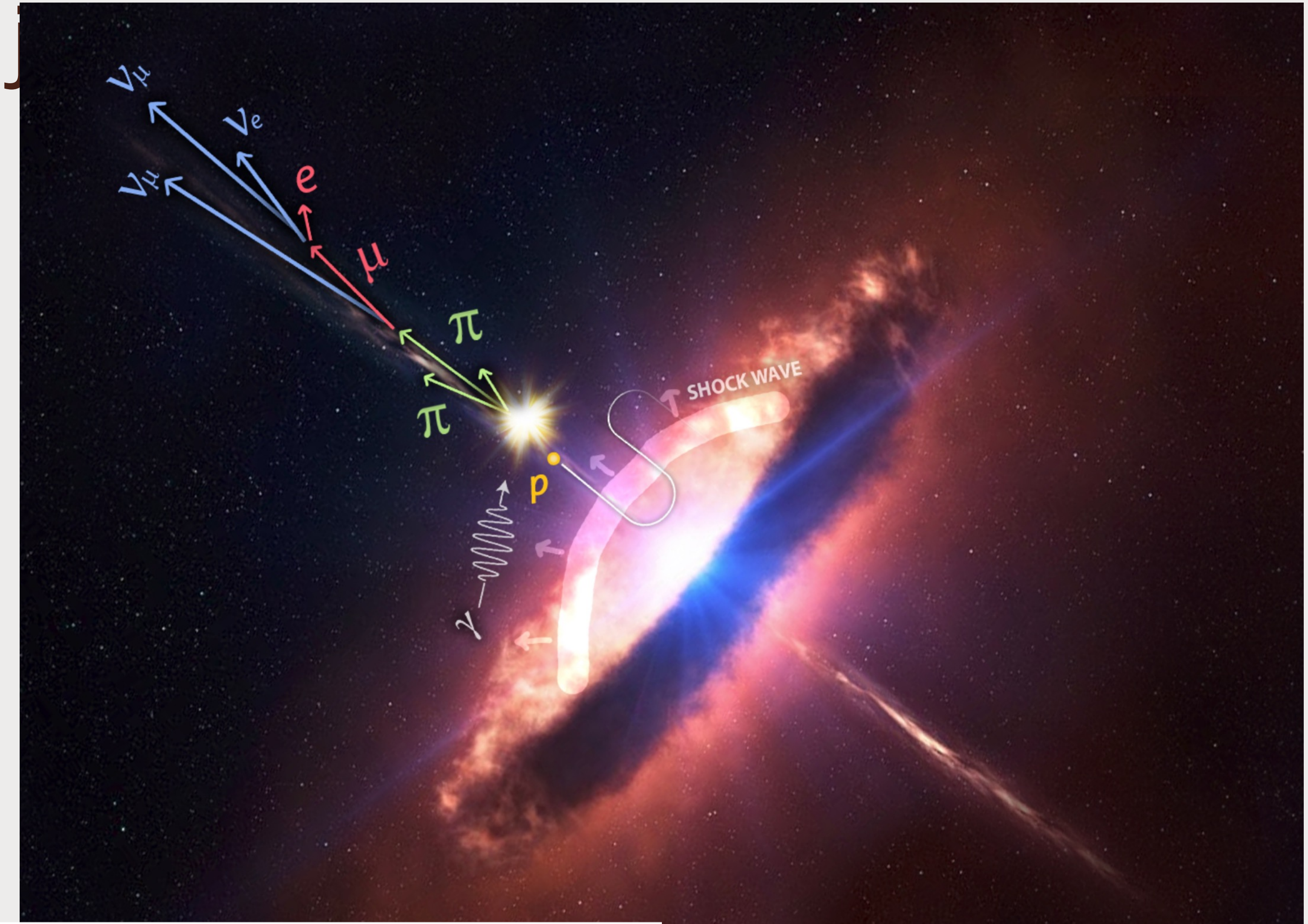


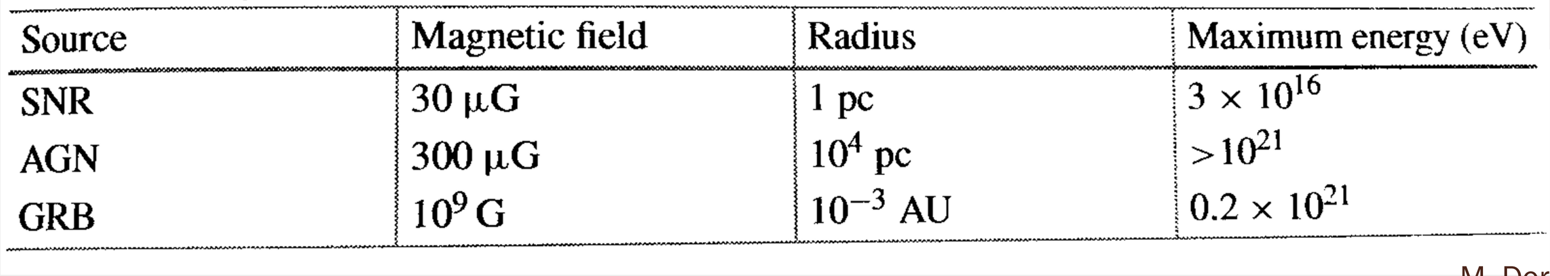
- A supermassive BH $10^6 - 10^{10}\ M_\odot$
- In 1% of cases AGN
  - *Strong (rotationg) accretion disk*
  - *A dusty torus*
- (10% of AGN) Ultrarelativistic jets
  - *0.01 pc width*
  - *Mpc length*
- According to the view angle: different spectra
  - *Blazar: If eye is aligned to jet, you can see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

Ultrarelativistic j

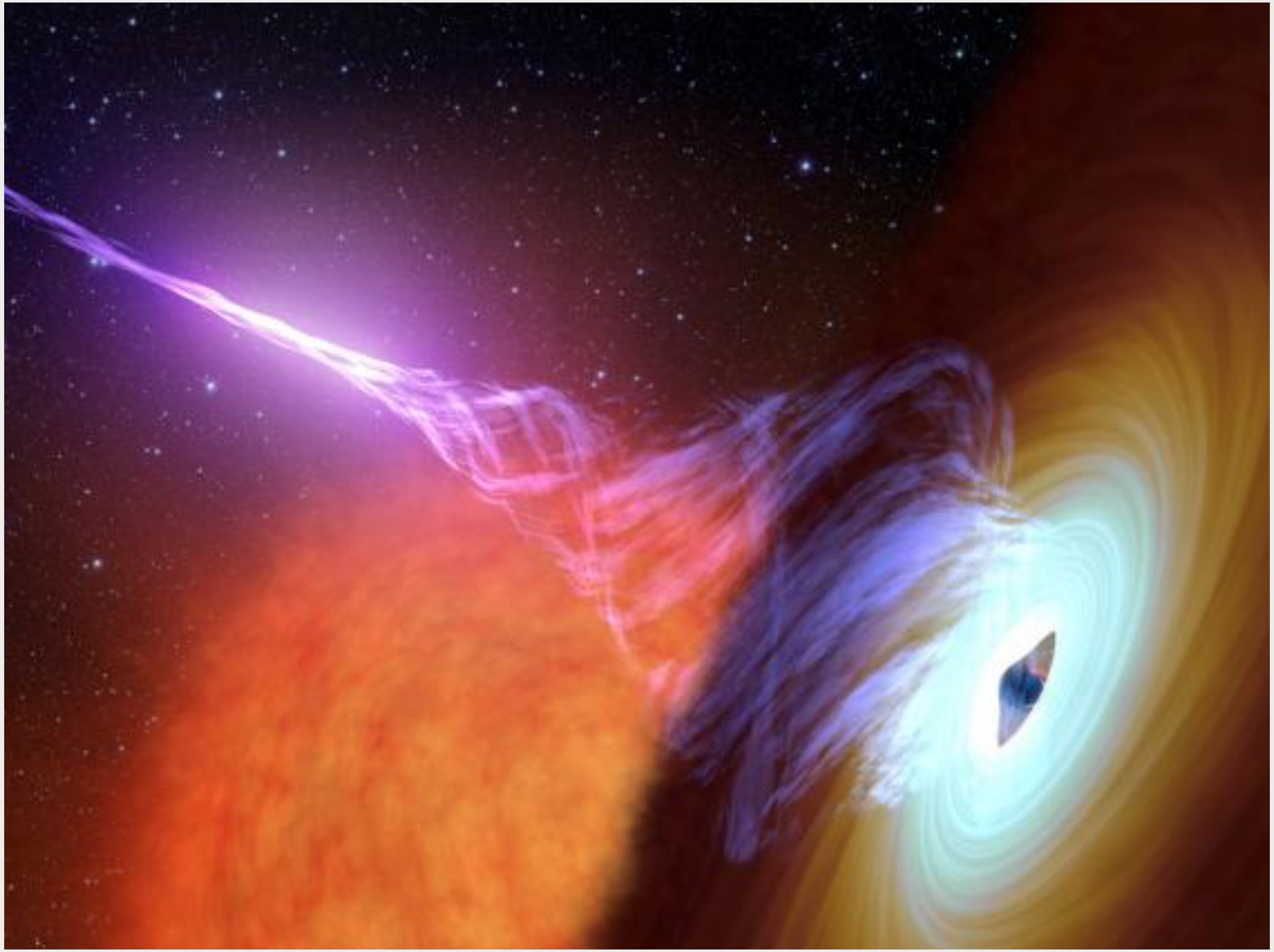
- AGNs can accelerate particle via diffuse stochastic acceleration up to 10^{21} eV

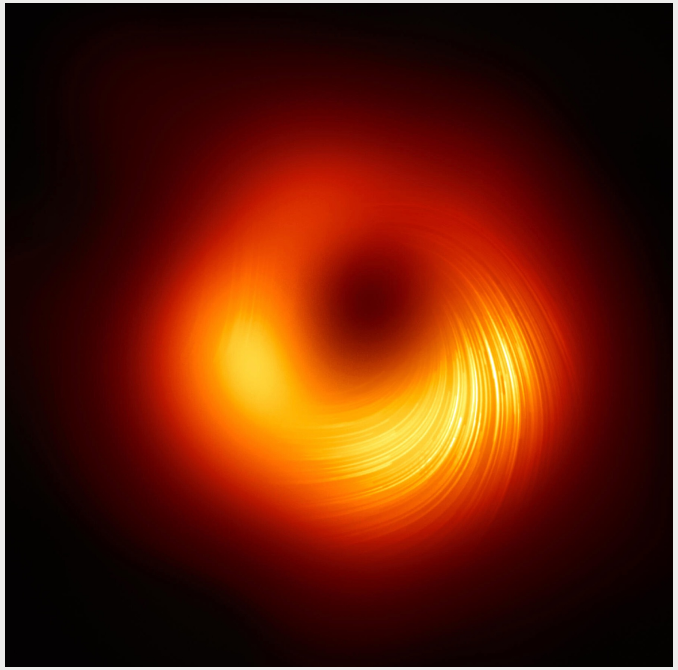




Source	Magnetic field	Radius	Maximum energy (eV)
SNR	30 μG	1 pc	3×10^{16}
AGN	300 μG	10^4 pc	$>10^{21}$
GRB	10^9 G	10^{-3} AU	0.2×10^{21}

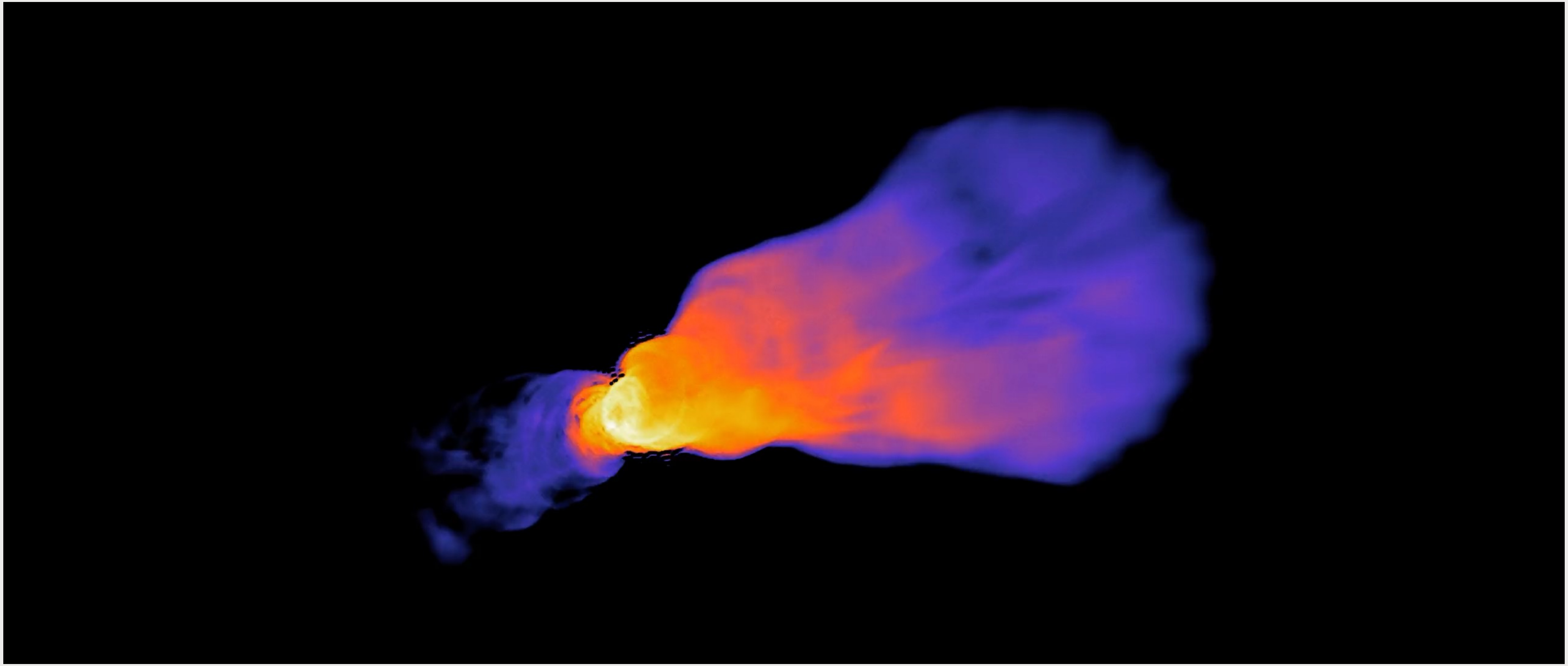
Ultrarelativistic jets mechanism





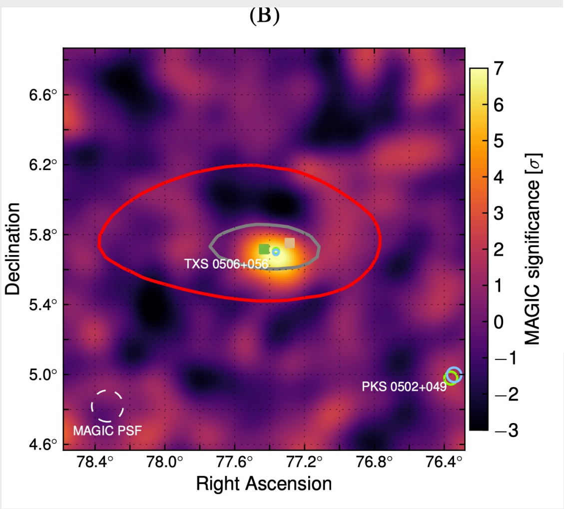
- Very recently released second (polarized!) image of M87 BH
- https://eventhorizontelescope.org/blog/astronomers-image-magnetic-fields-edge-m87s-black-hole

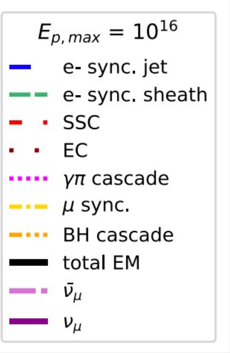
Engine Powering Black Hole Energy Beams



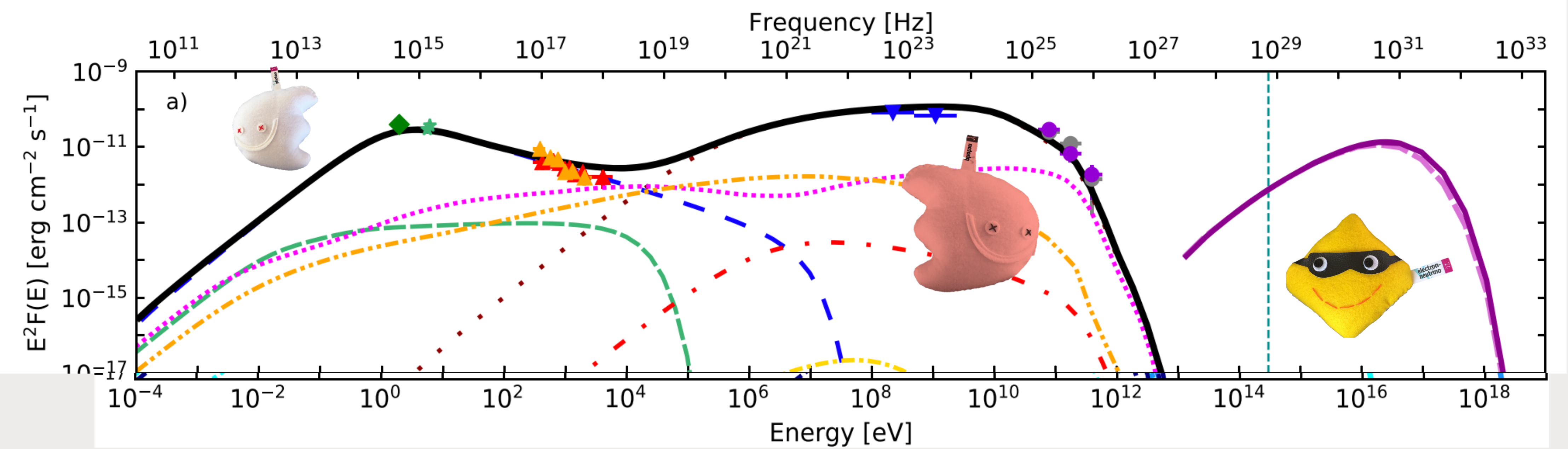
Simulations are catching up with physics, expect results soon!

TXS 0506: multimessenger astronomy!

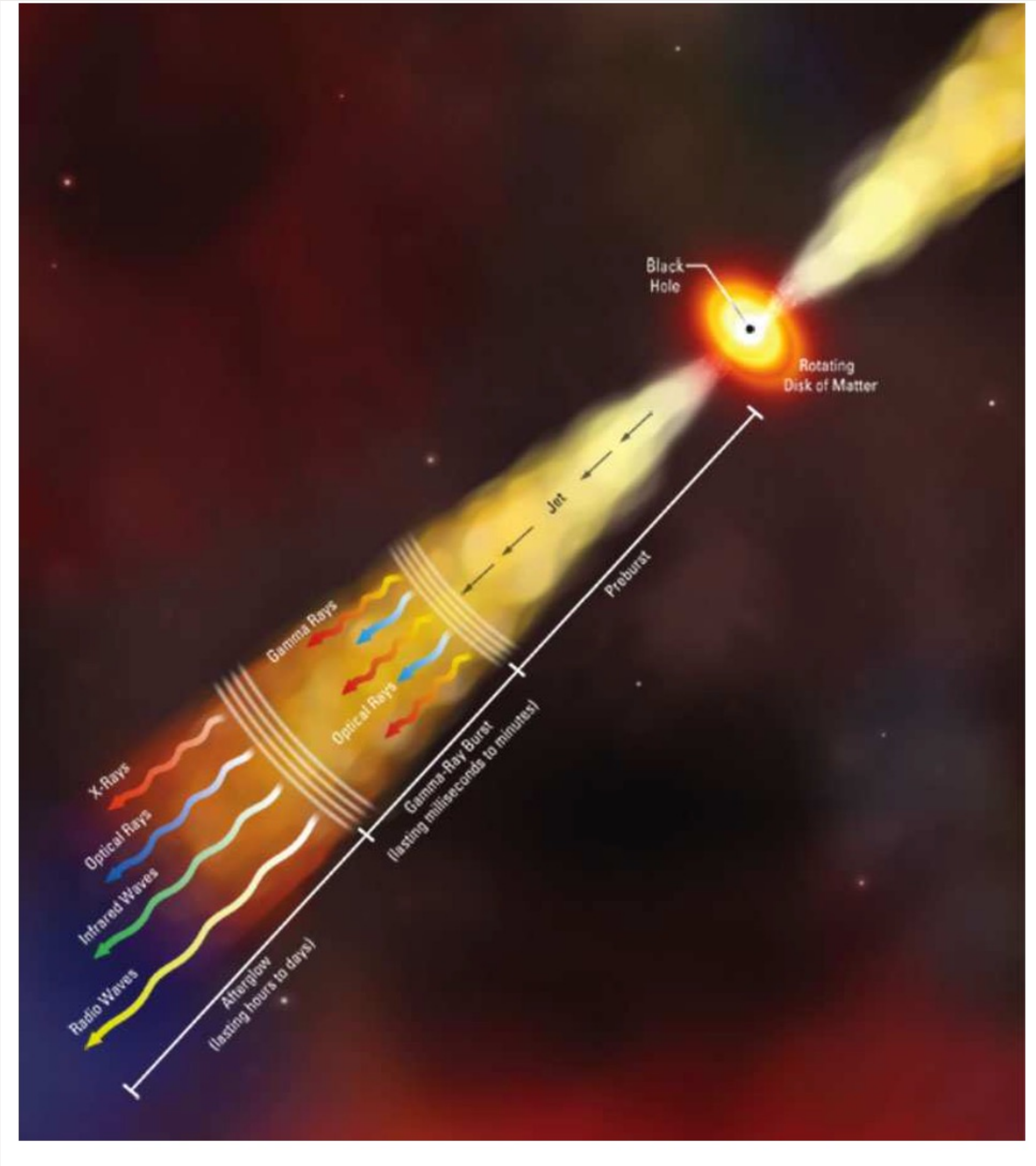




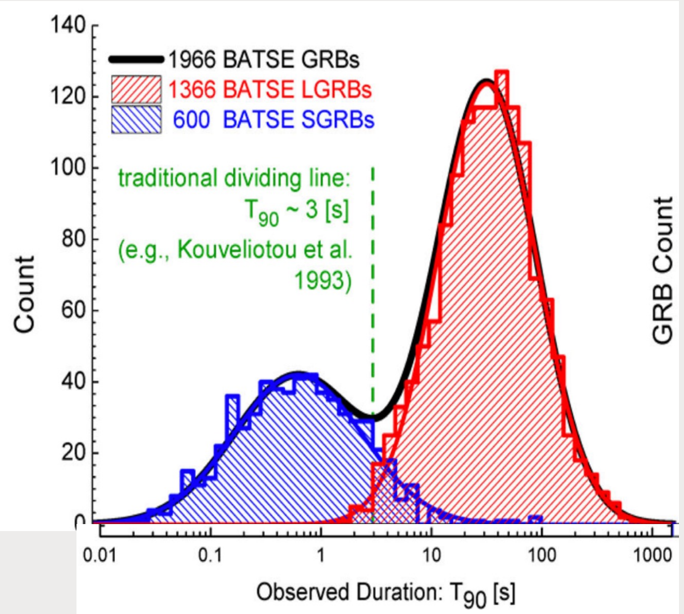
- On 2018, a neutrino with energy ~290 TeV was detected in coincidence with the BL Lac object TXS 0506+056 during enhanced gamma-ray activity
- A new messenger!



Gamma Ray Bursts



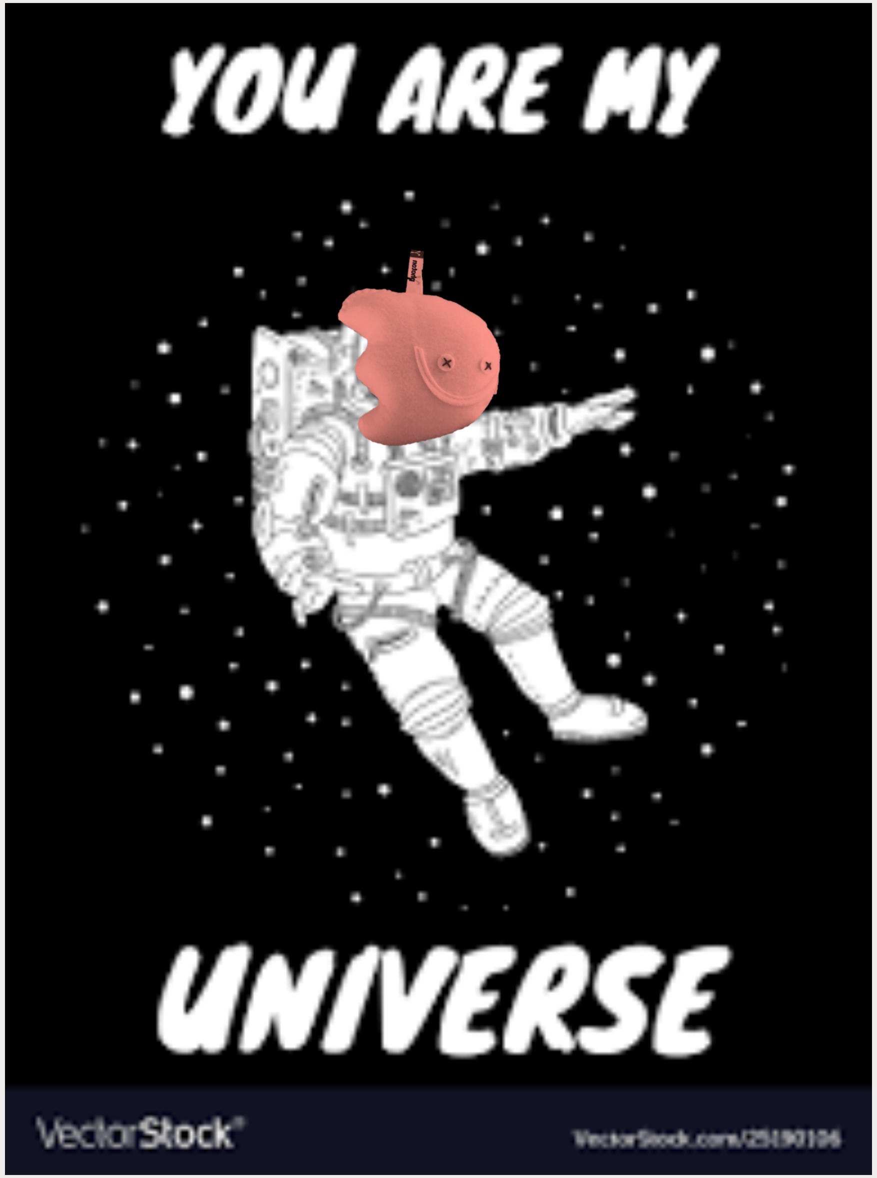
- Sudden outburst of radiation at all wavelengths
- Up to 10^{53} erg s^{-1} (Sun is 10^{26} erg s^{-1})
- Convert into energy a mass of 10^{-3} $M_\odot$ in matter of seconds
- Two populations
  - *Long duration*
  - *Short duration*



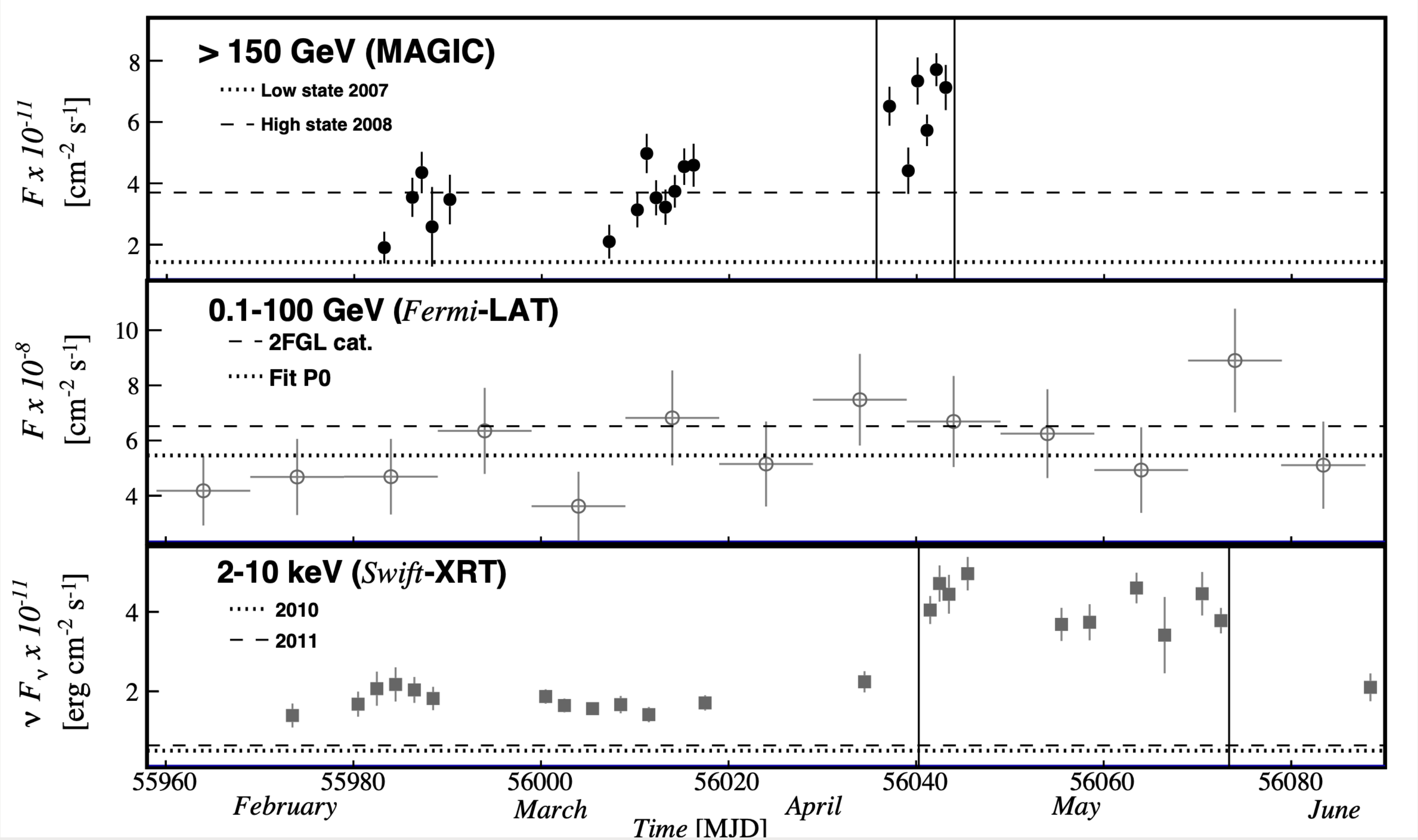
MNRAS 451, 126–143 (2015)

Postcards facts from gamma-ray Universe

(if time allows)



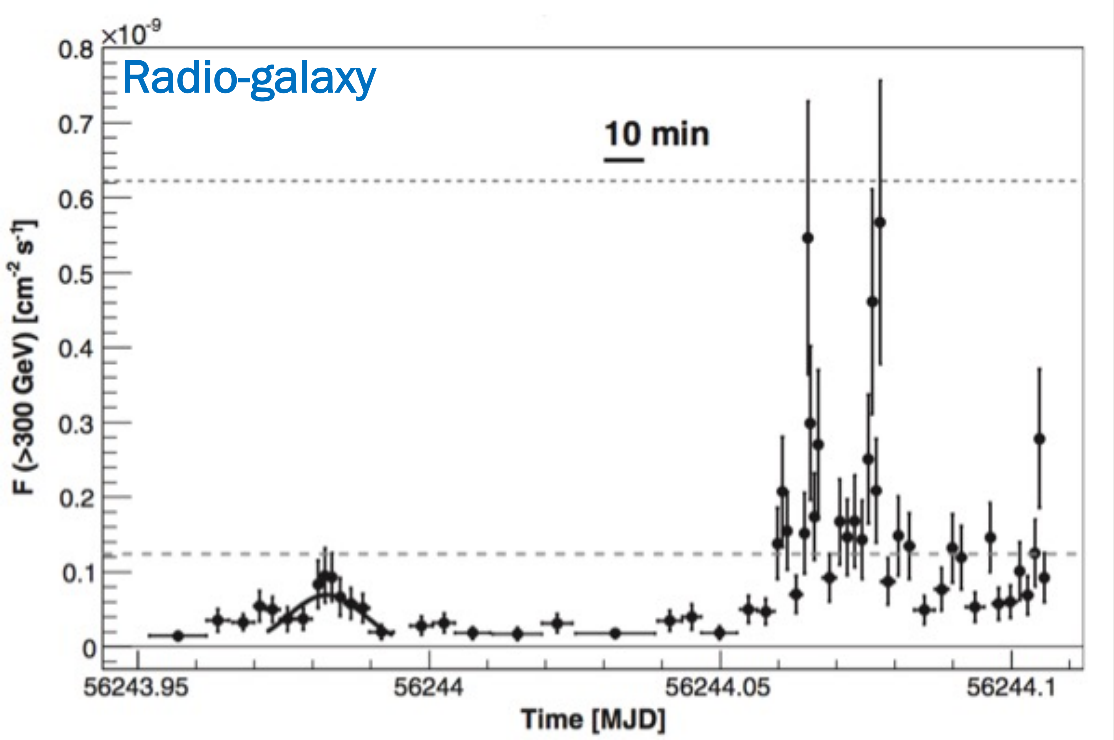
1/ Strong variability



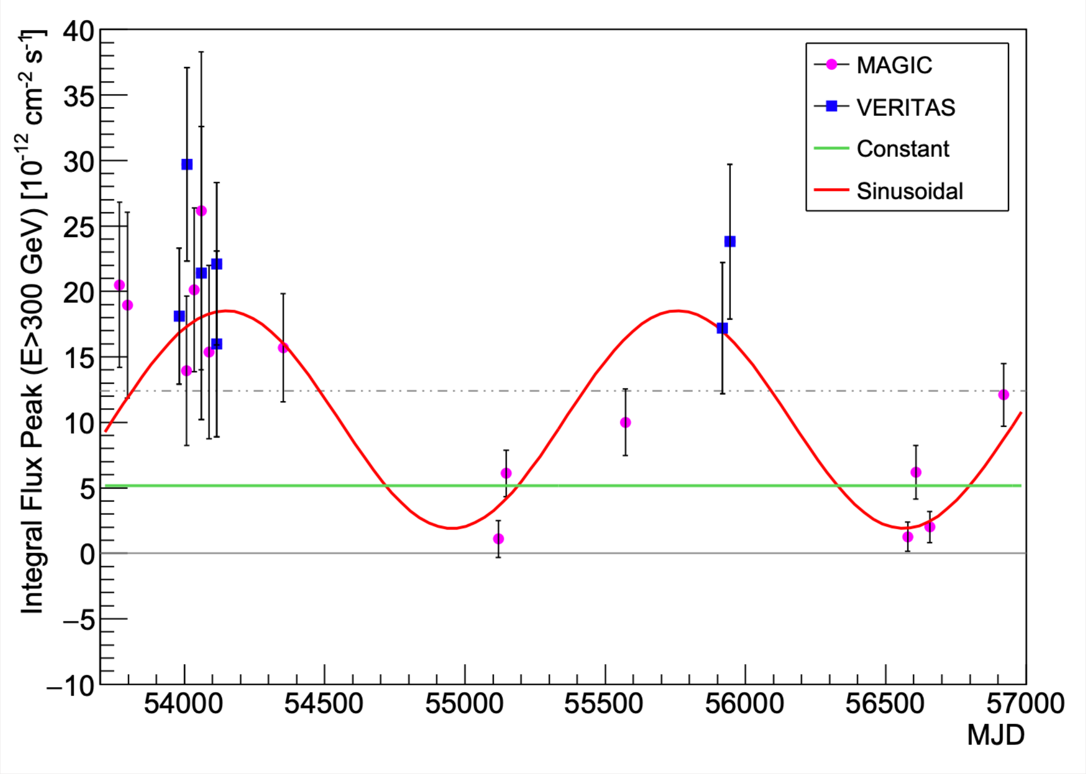
[MAGIC Coll] Mon.Not.Roy.Astron.Soc. 450 (2015) 4, 4399-4410

- 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



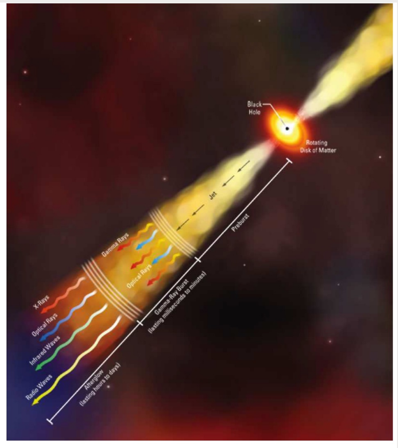
IC310. Doubling time 4.8 min

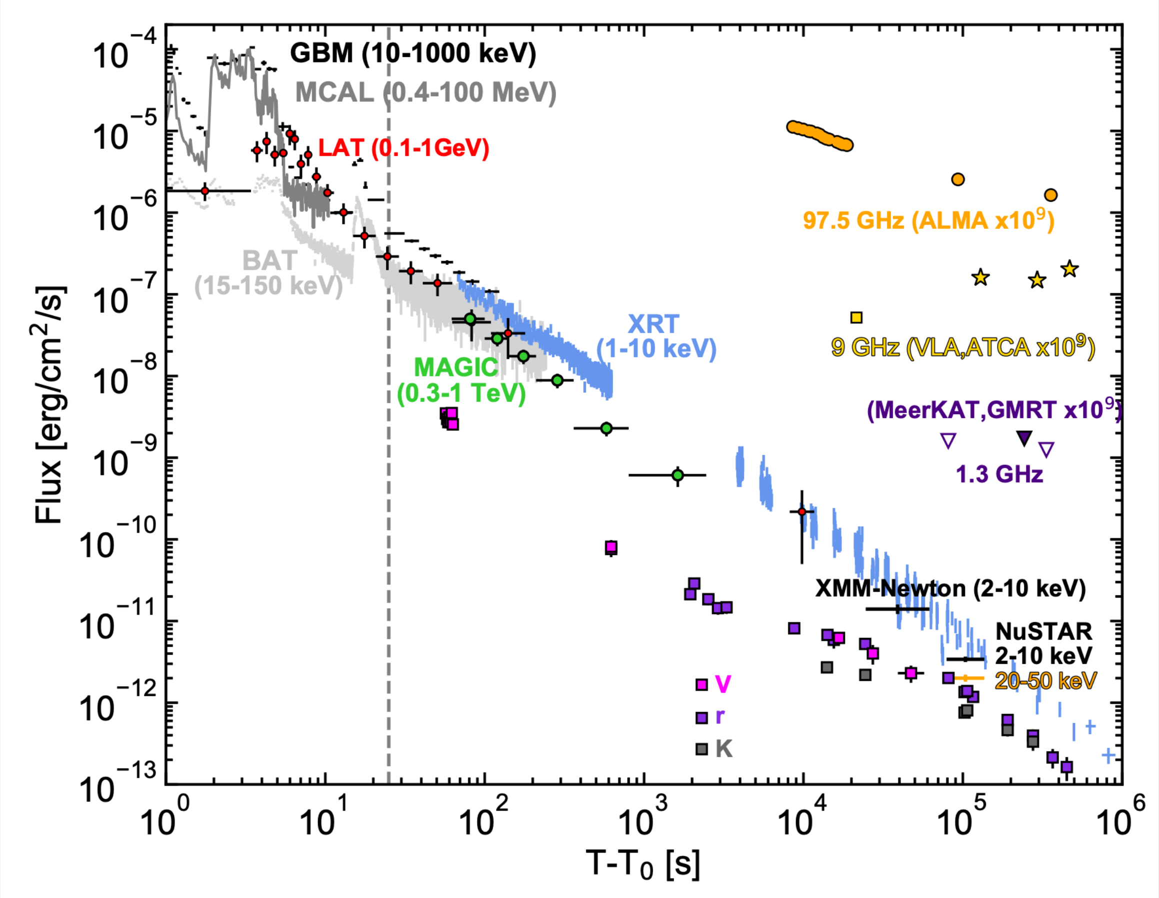


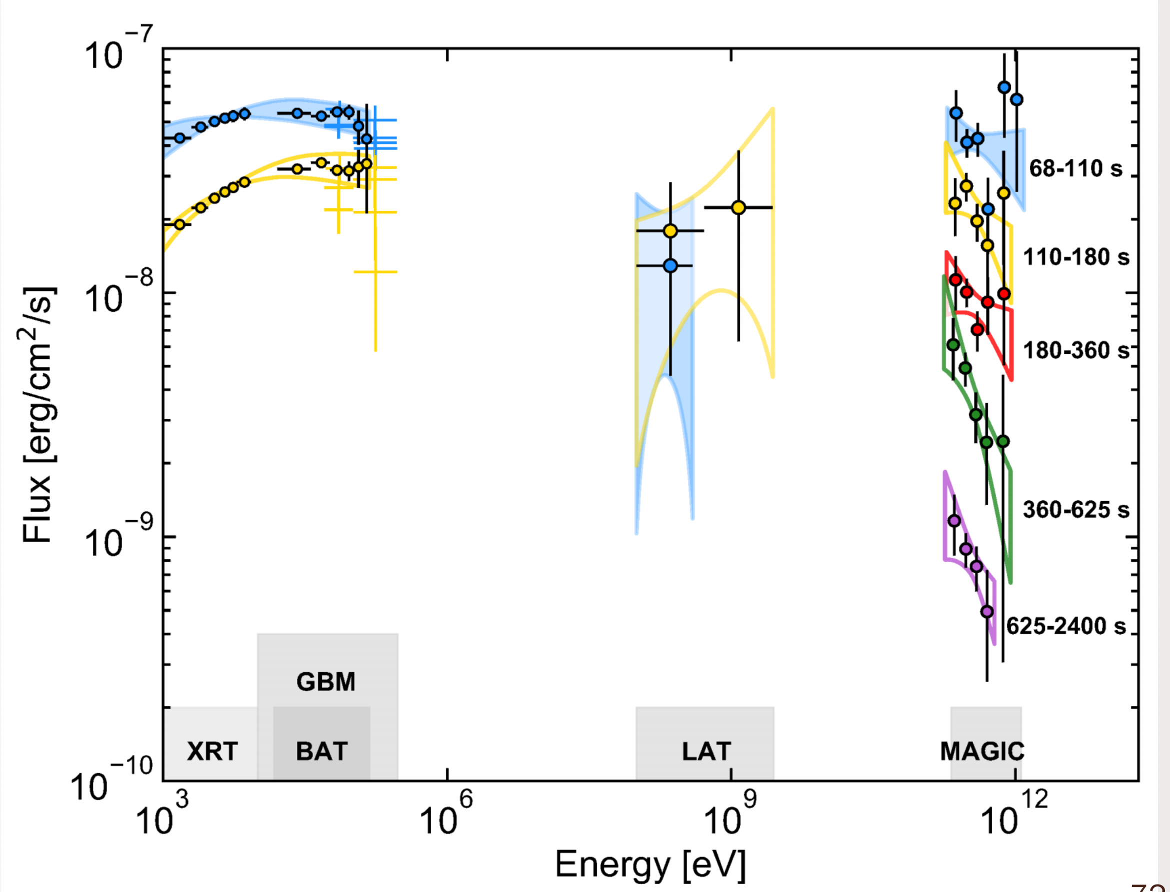
[MAGIC] Astron.Astrophys. 591 (2016) A76

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

Temporal Evolution at High Energies



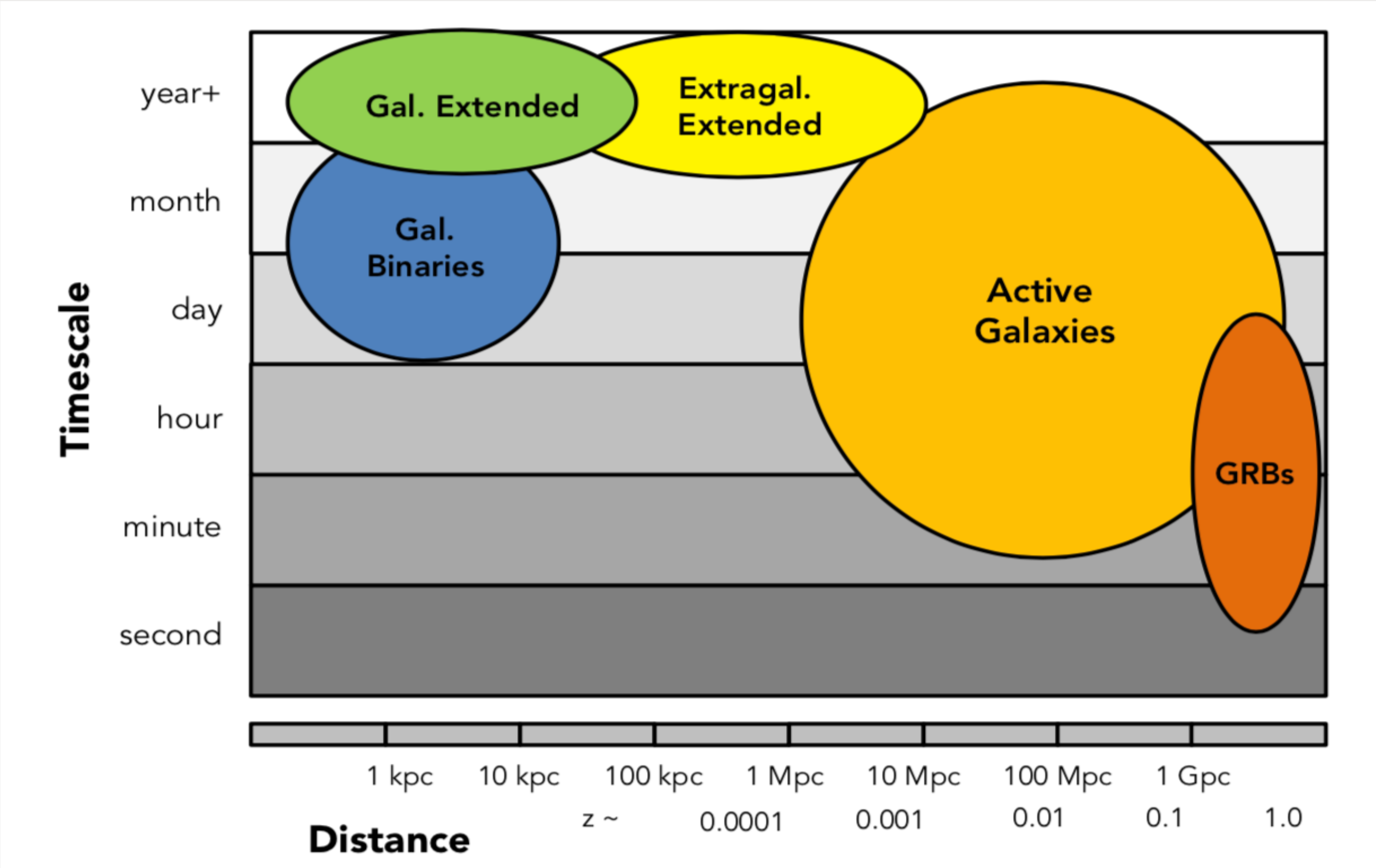




Nature 575 (2019) 7783, 459-463

Nature 575 (2019) 7783, 455-458

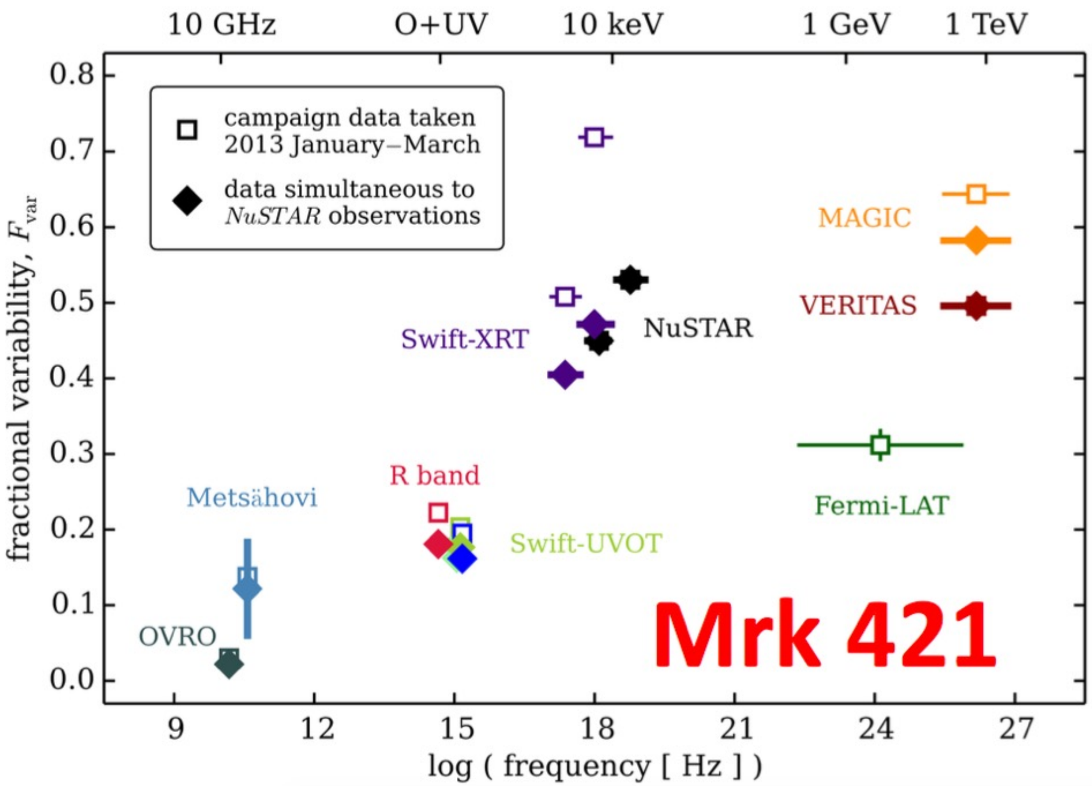
Temporal variability



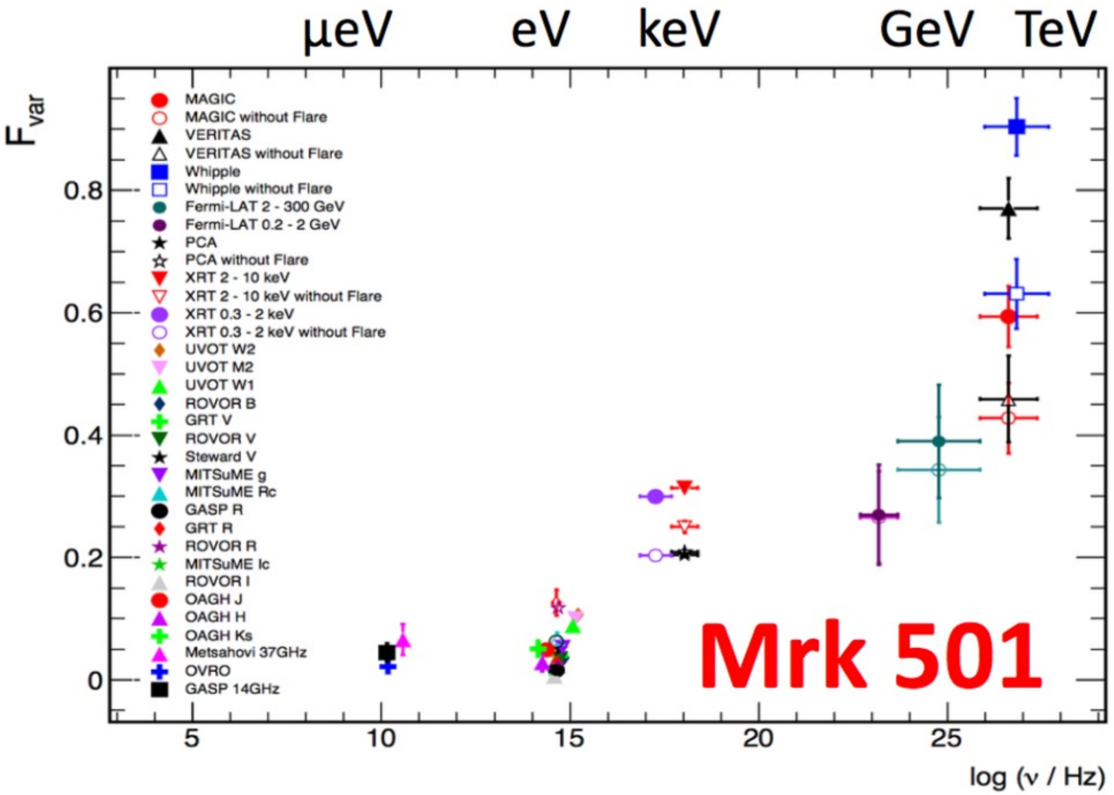
J. Hinton

Fractional variability

Balokovic et al., 2016 *ApJ* 819, 156



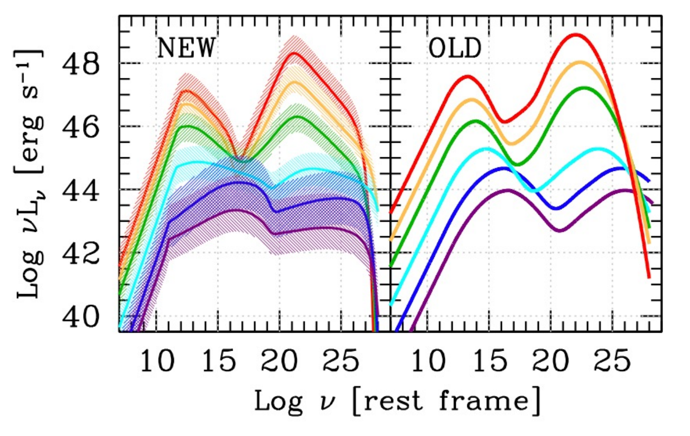
Ahnen et al. Submitted to A&A

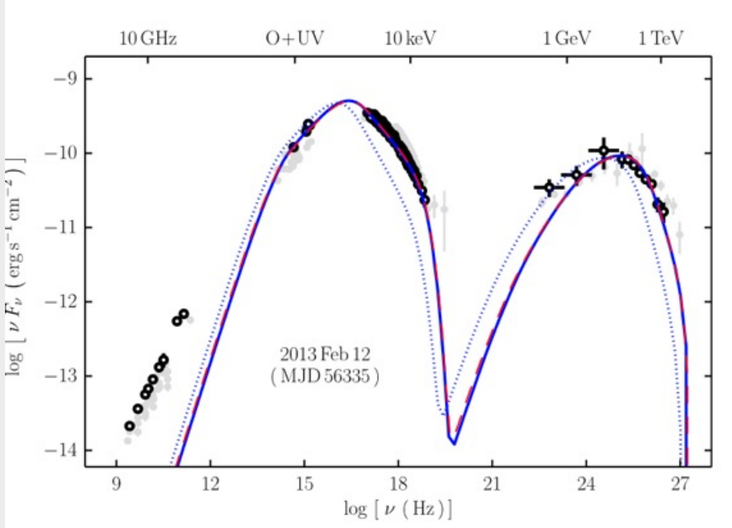


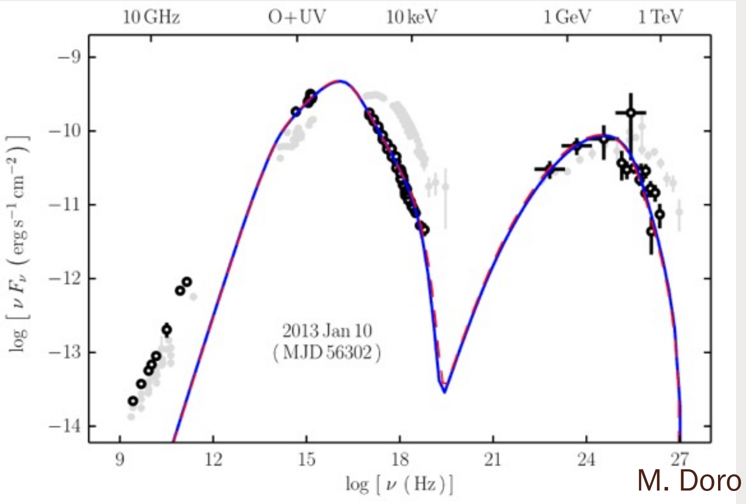
- Fractional variability requires large coverage, but guarantees connection between two bumps:
  - *Information on particle populations, acceleration efficiency…*

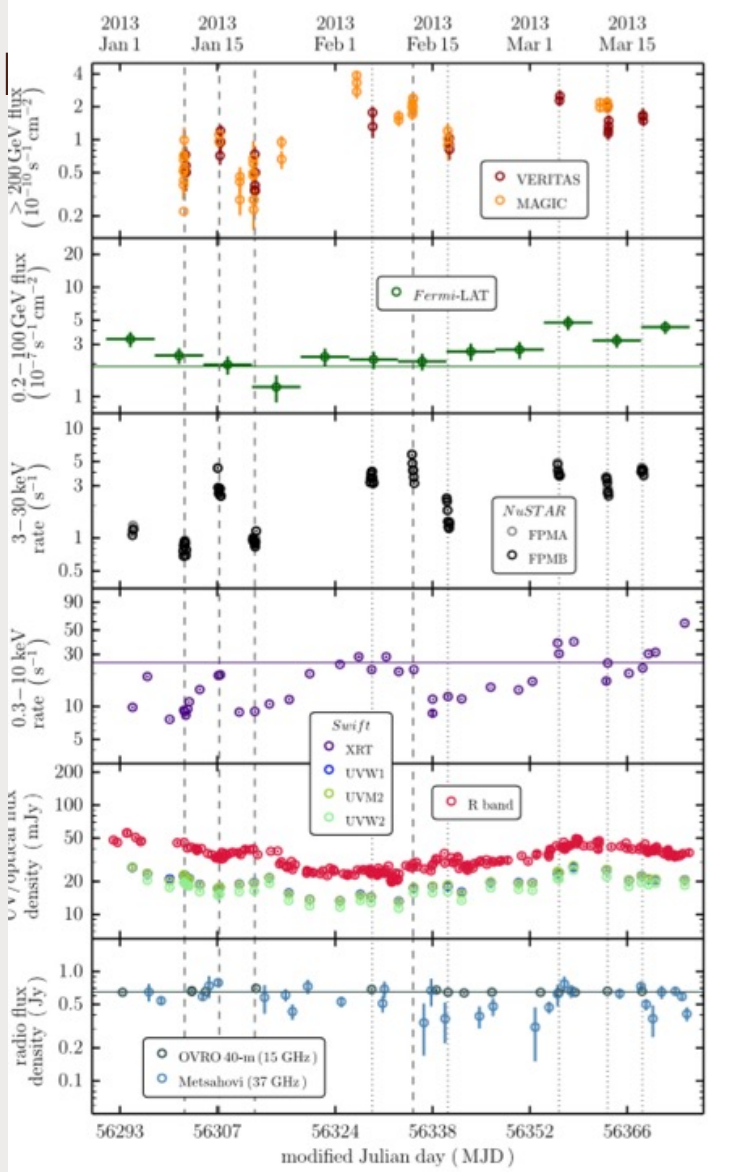
2/ Large projects: Multi-wavelength/multi-year

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





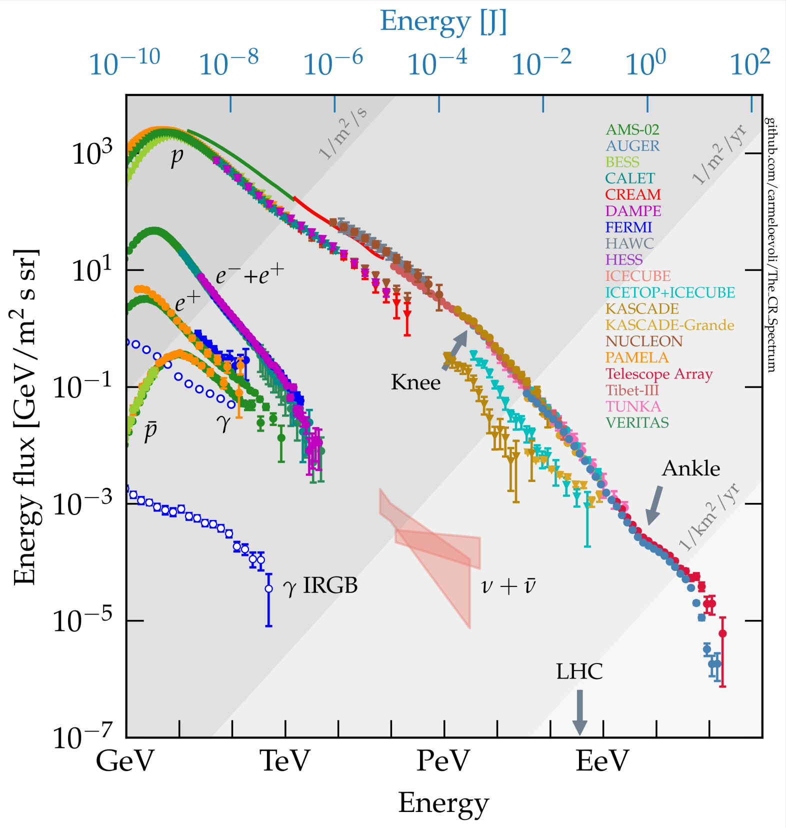


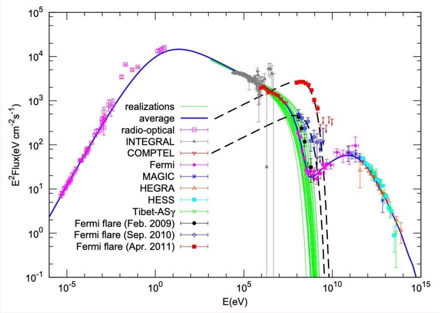


Astrophys.J. 819 (2016) 156

CONCLUSIONS
TAKE HOME MESSAGES

Take home messages

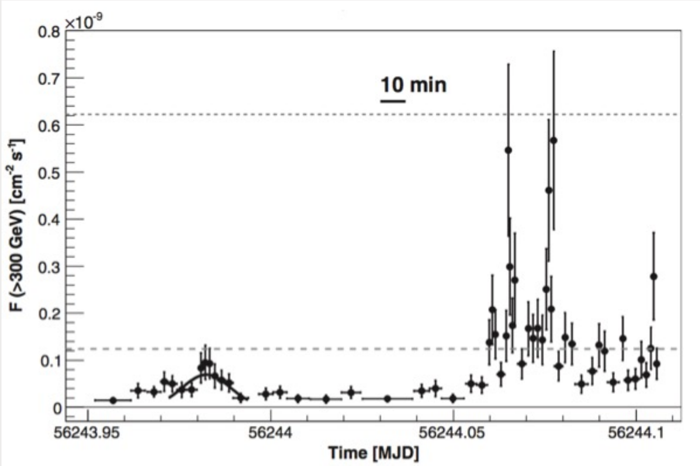


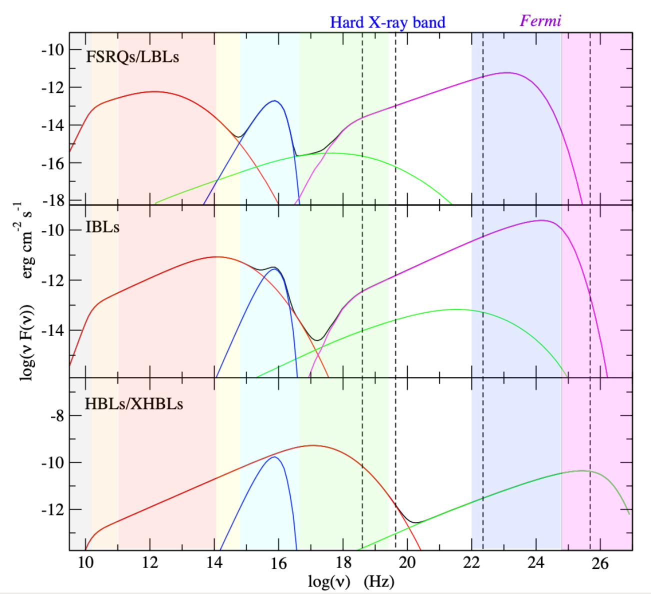


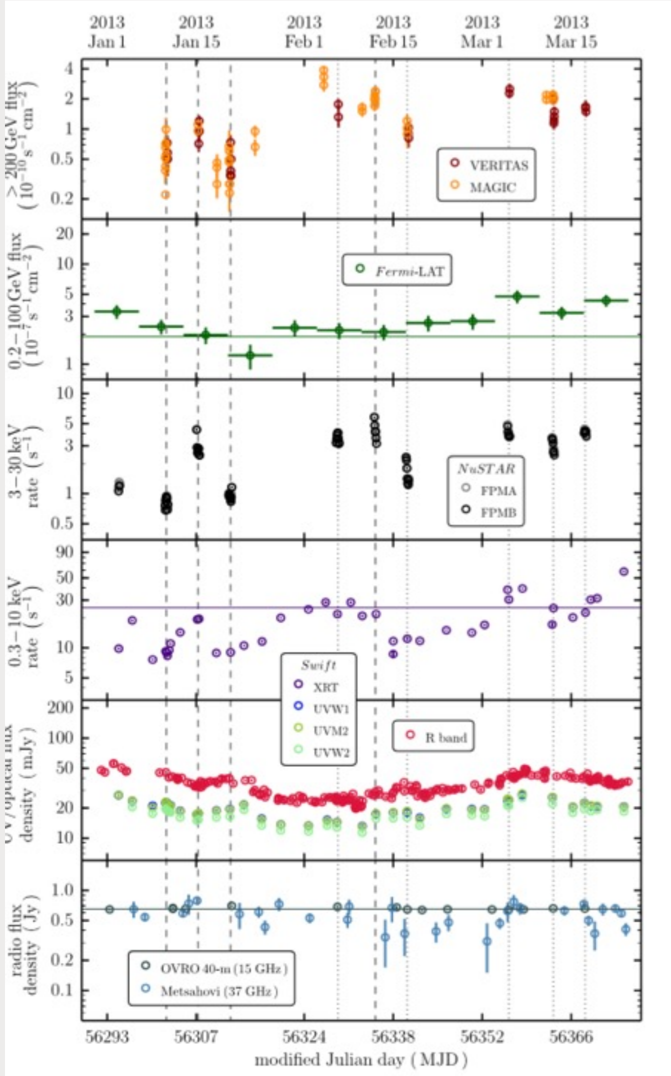
The amazing cosmic ray spectrum entails a world of physics phenomena

- 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

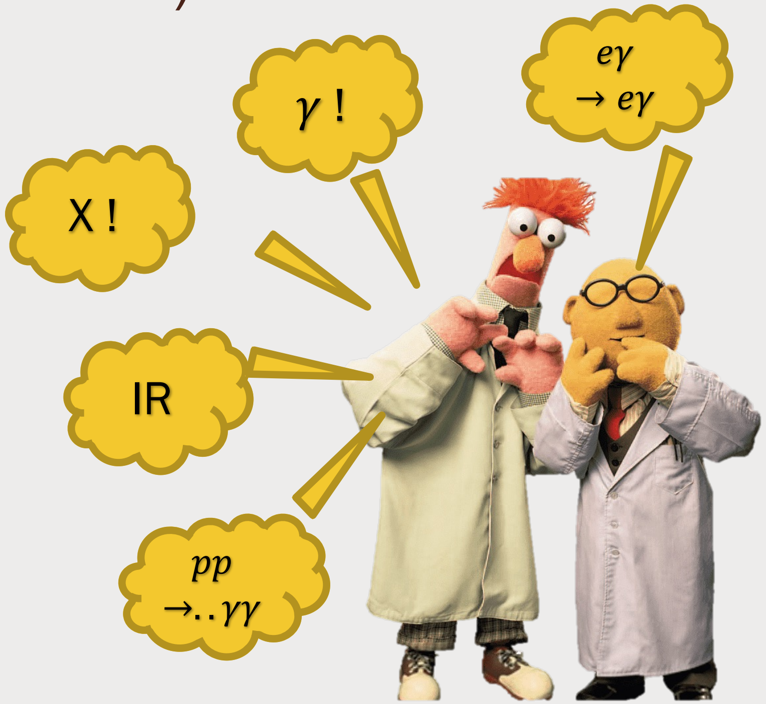
Gamma-ray physics/astrophysics/astroparticle







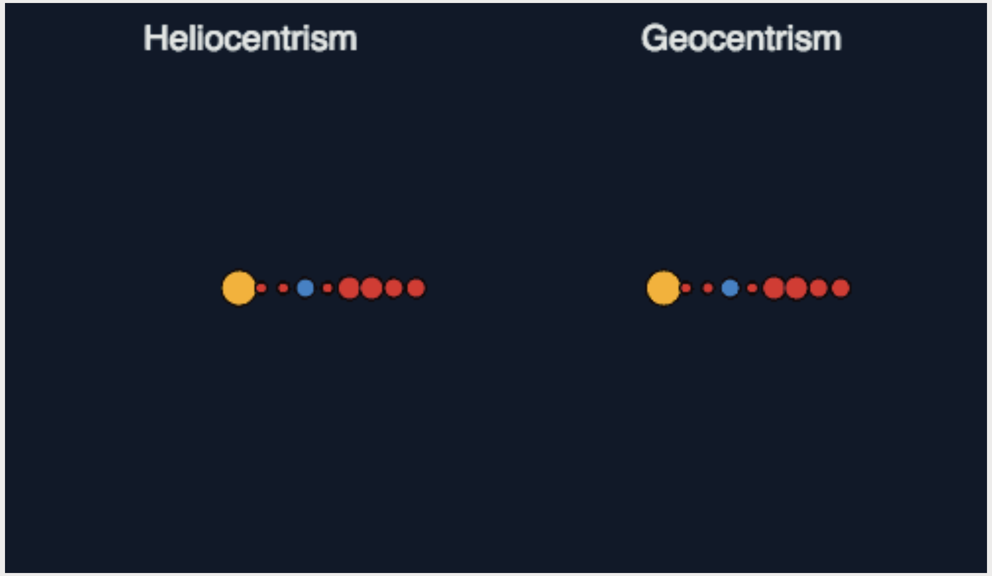
- It is a transient sky!
- A physical knowledge of the target require a strong astronomical knowledge (from radio to X)

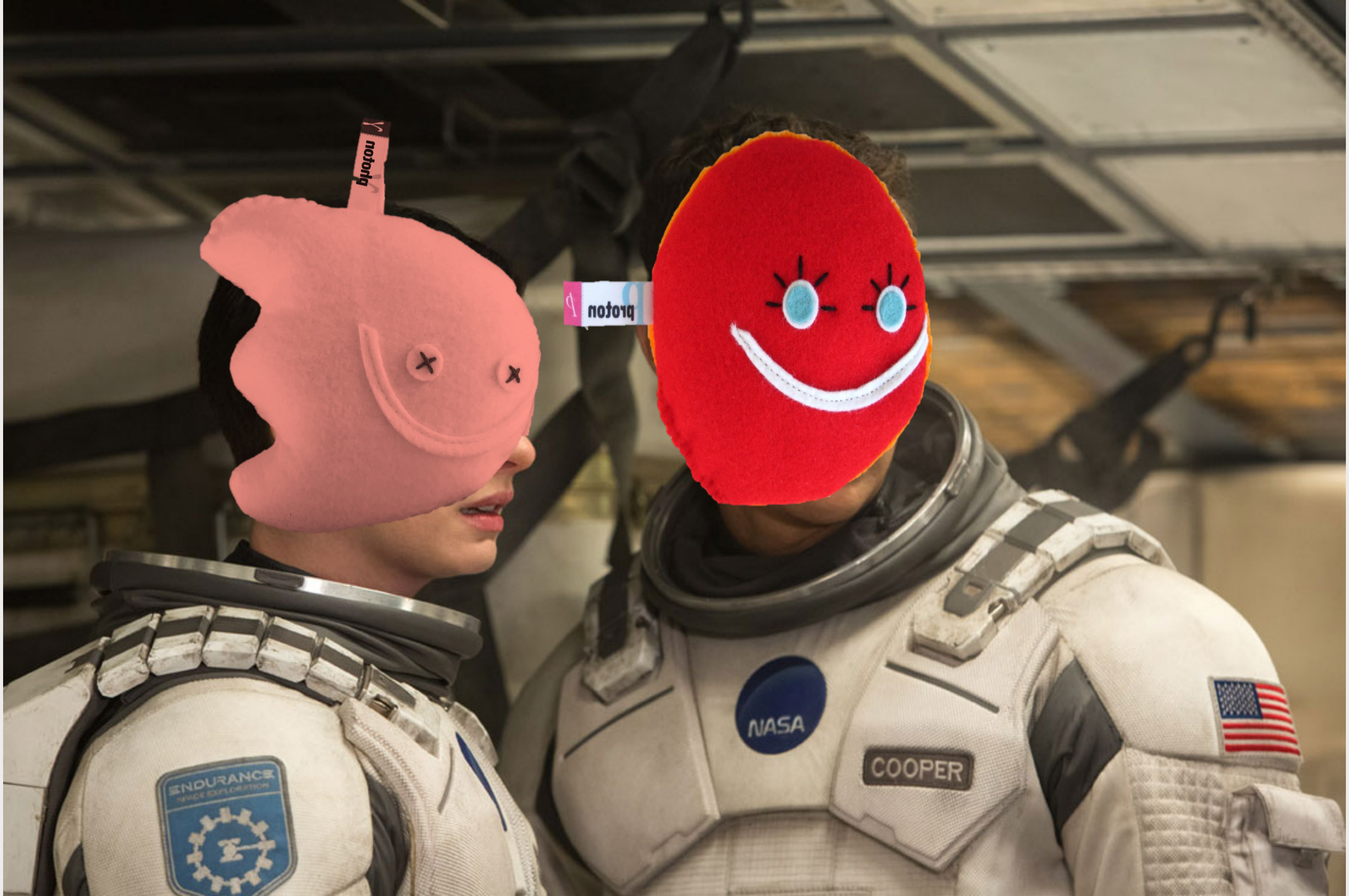


Gamma-ray revolutions

- 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?




NASA
COOPER
ENDURANCE
SPACE EXPLORATION

BACKUPS

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)

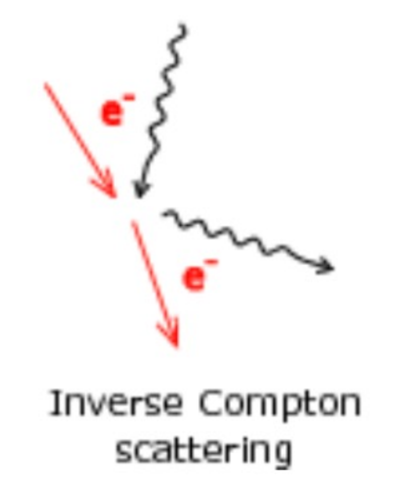
Synchrotron radiation

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

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

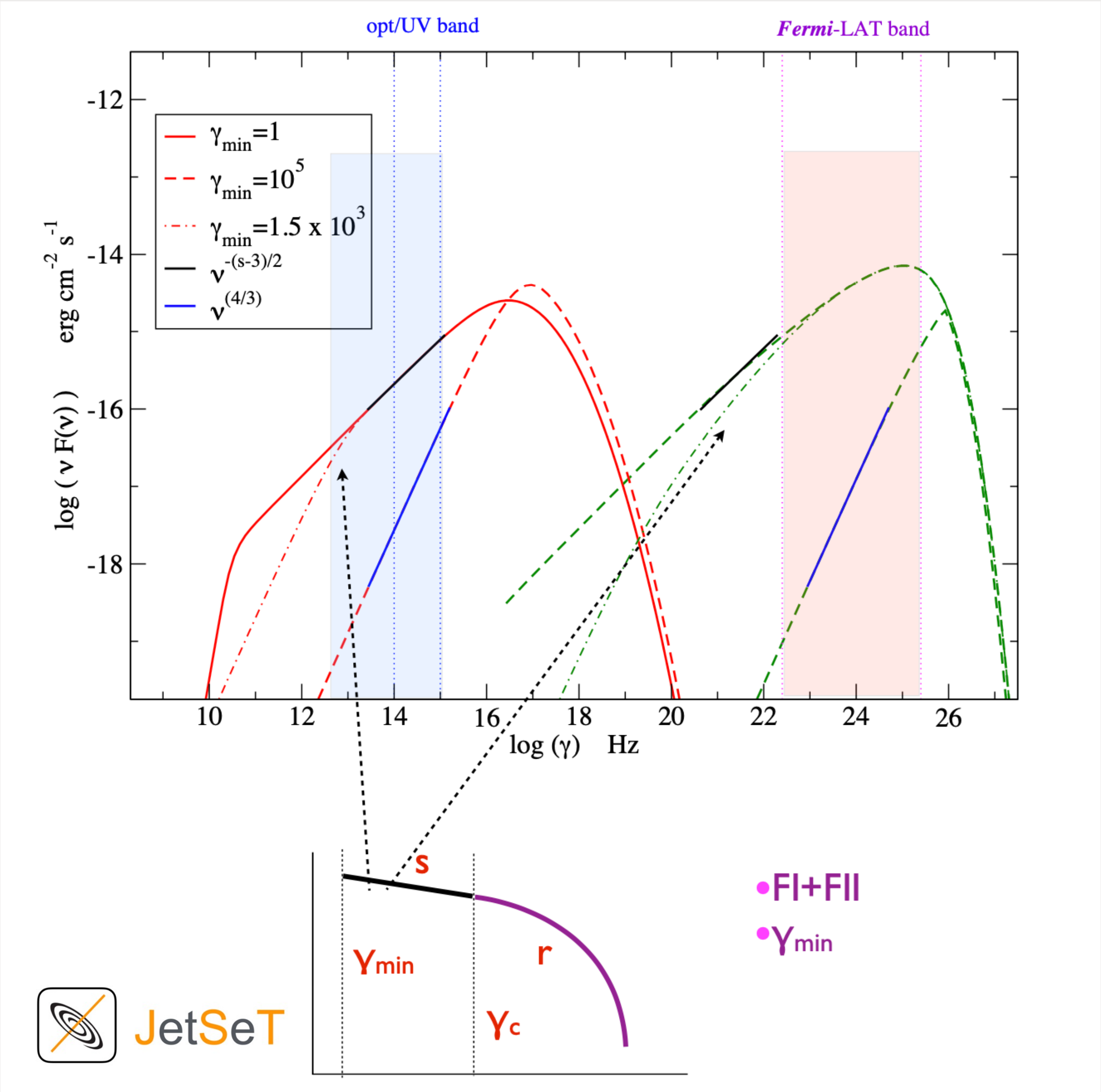
- Proton synchrotron only in very strong B

+ 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/

AGNpy

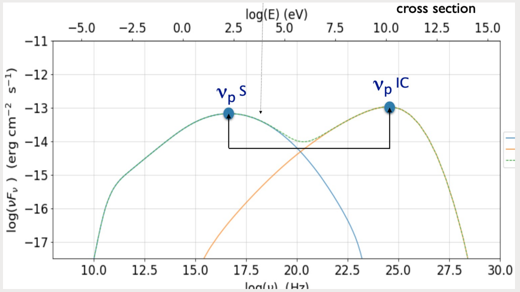
Cosimo Nigro

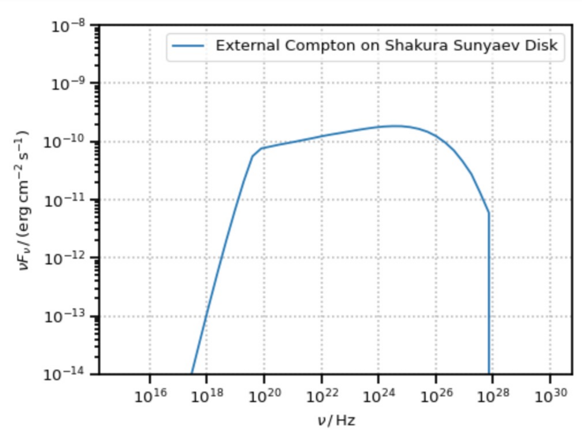
https://agnpy.readthedocs.io/

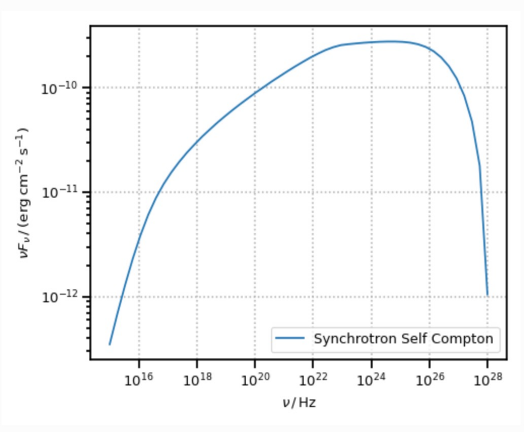
naima

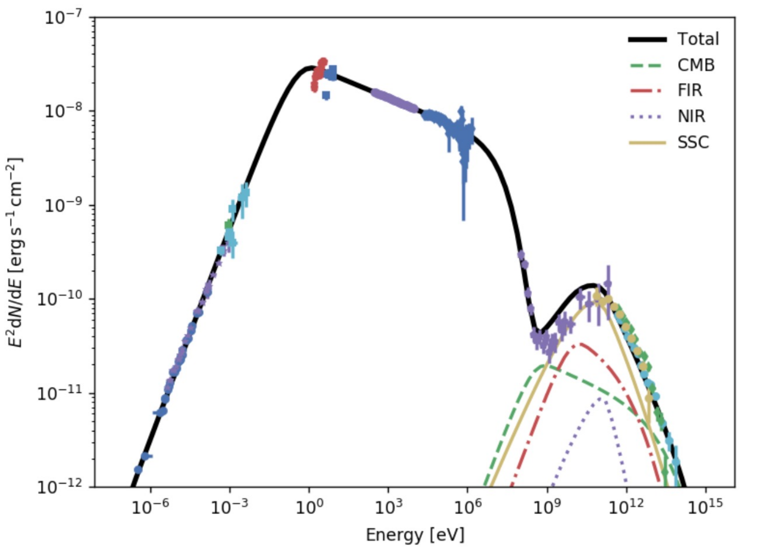
Python package for computation of non-thermal radiation from relativistic particle populations and MCMC fitting to observed spectra

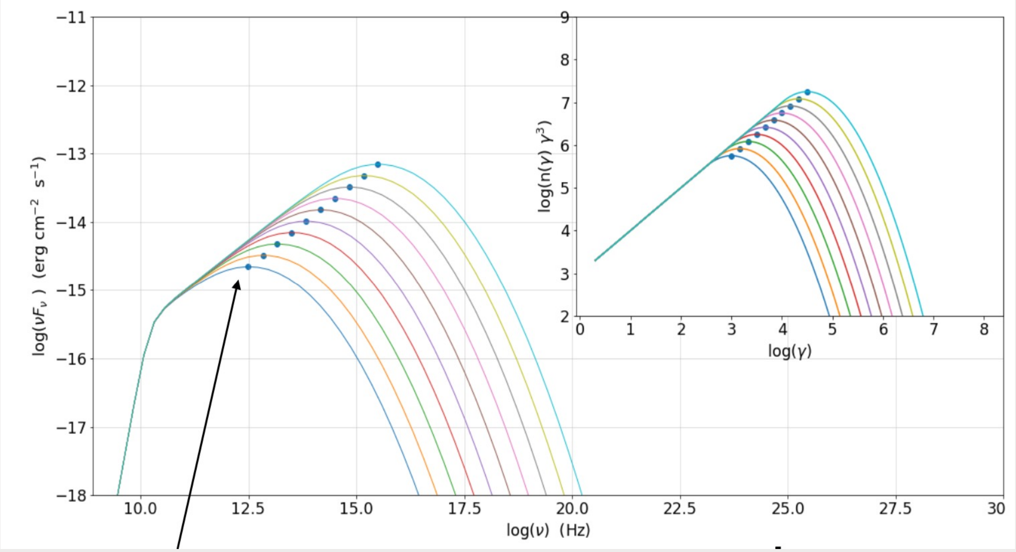
https://naima.readthedocs.io/



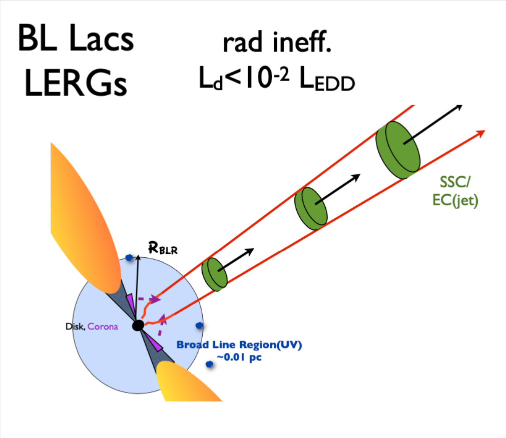


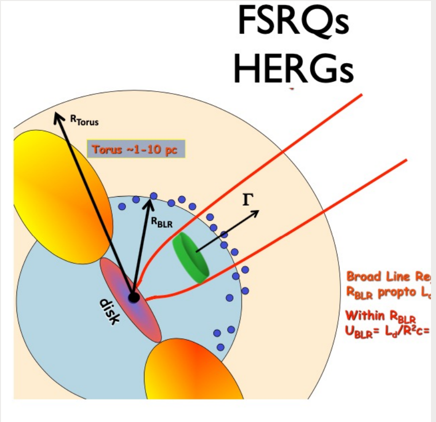




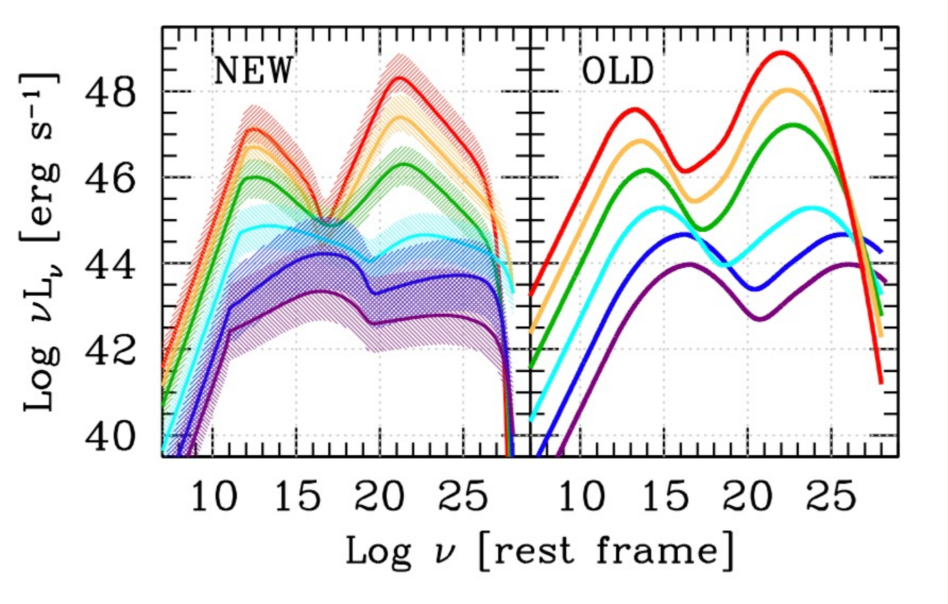


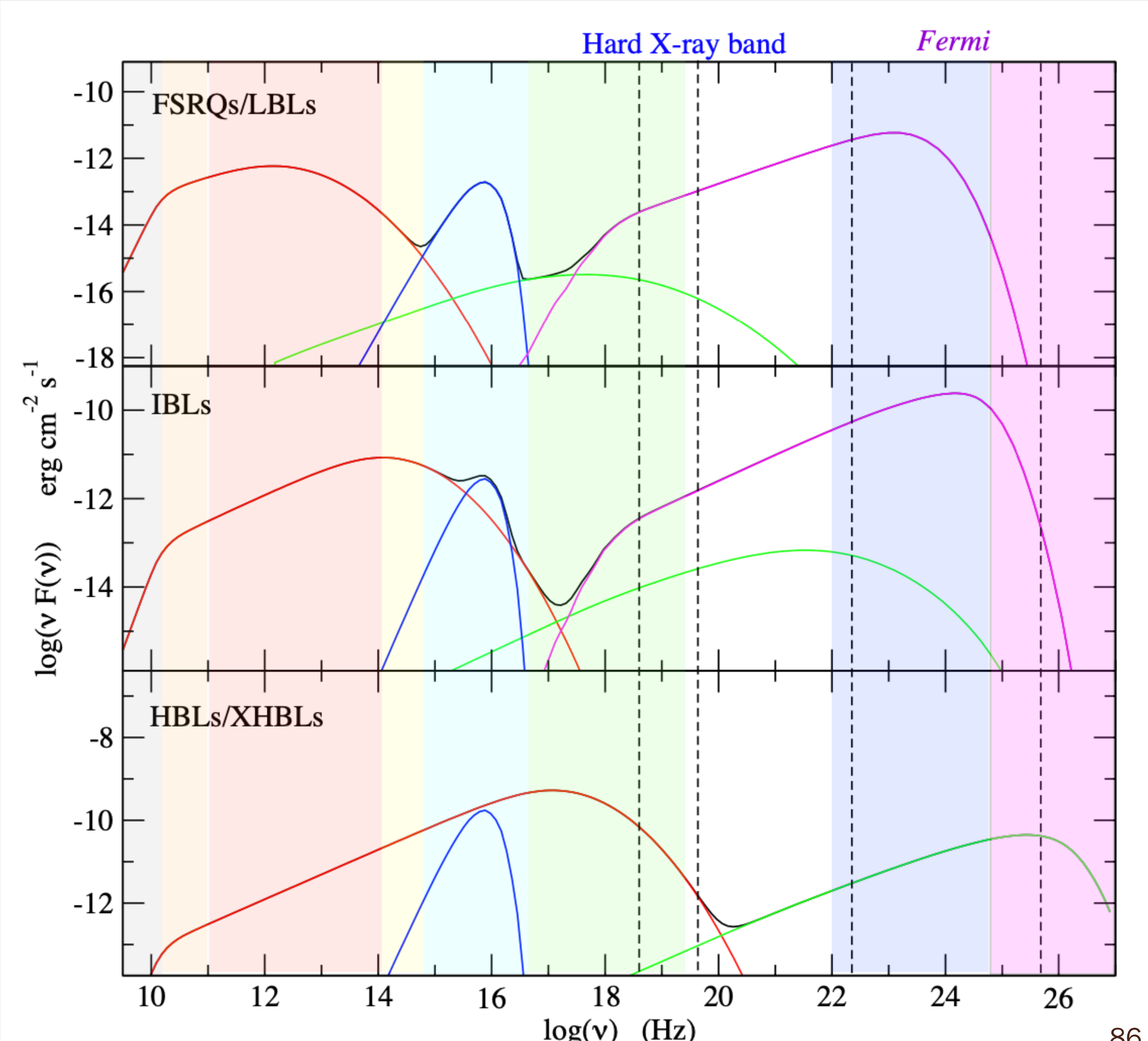
Not that clear after all





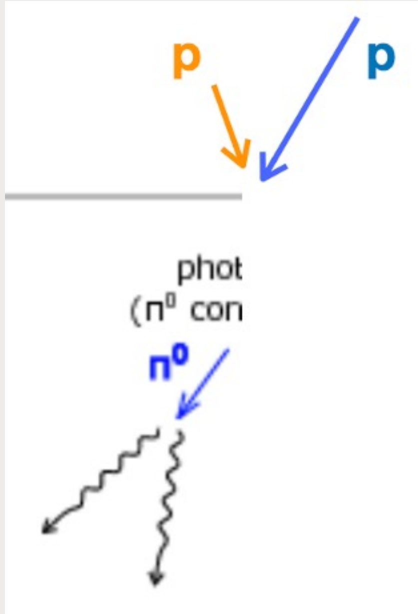
Evolution one into another





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 synchrothron