

Astrofisica delle Alte Energie

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Perugia, 27 aprile 2011
IFAE2011
Incontri di Fisica delle Alte Energie

1. Relativistic Particles in the Galaxy and the Universe

2. Gamma Astronomy
“Golden Age”

3. Search for Dark Matter
[“WIMP” paradigm]



MILKY WAY



LARGE MAGELLANIC CLOUD



SMALL MAGELLANIC CLOUD

“Bubble” of cosmic rays generated in the Milky Way and contained by the Galaxy magnetic field

Space extension and properties of this “CR bubble” remain very uncertain

$$\phi_j(E) = \frac{c}{4\pi} n_j(E)$$

Flux of Cosmic Rays

$$N_j(E) = \int d^3x n_j(E, \vec{x})$$

Cosmic Rays contained
In the Milky Way

$$N_j(E) = Q_j(E) \times T_j(E)$$

p , nuclei(Z, A)

\bar{p} , e^- , e^+

Injection
of cosmic rays

Containment
time

Different particles

Injection
of cosmic rays

Containment
time

$$N_j(E) = Q_j(E) \times T_j(E)$$

$$L_j = \int dE E Q_j(E)$$

LARGE Power
Requirement

$$\sim 5 \times 10^7 L_{\odot}$$

Spectral Shape
[Dynamics of acceleration process]

Source
Identification

Key problem!

Injection
of cosmic rays

Containment
time

$$N_j(E) = Q_j(E) \times T_j(E)$$

Competition of different times:

$$T_{\text{int}}^{p,A}(E) \propto [\sigma_j(E)]^{-1} \sim \text{slowly varying}$$

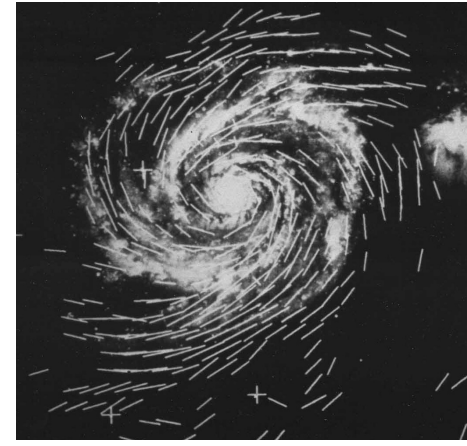
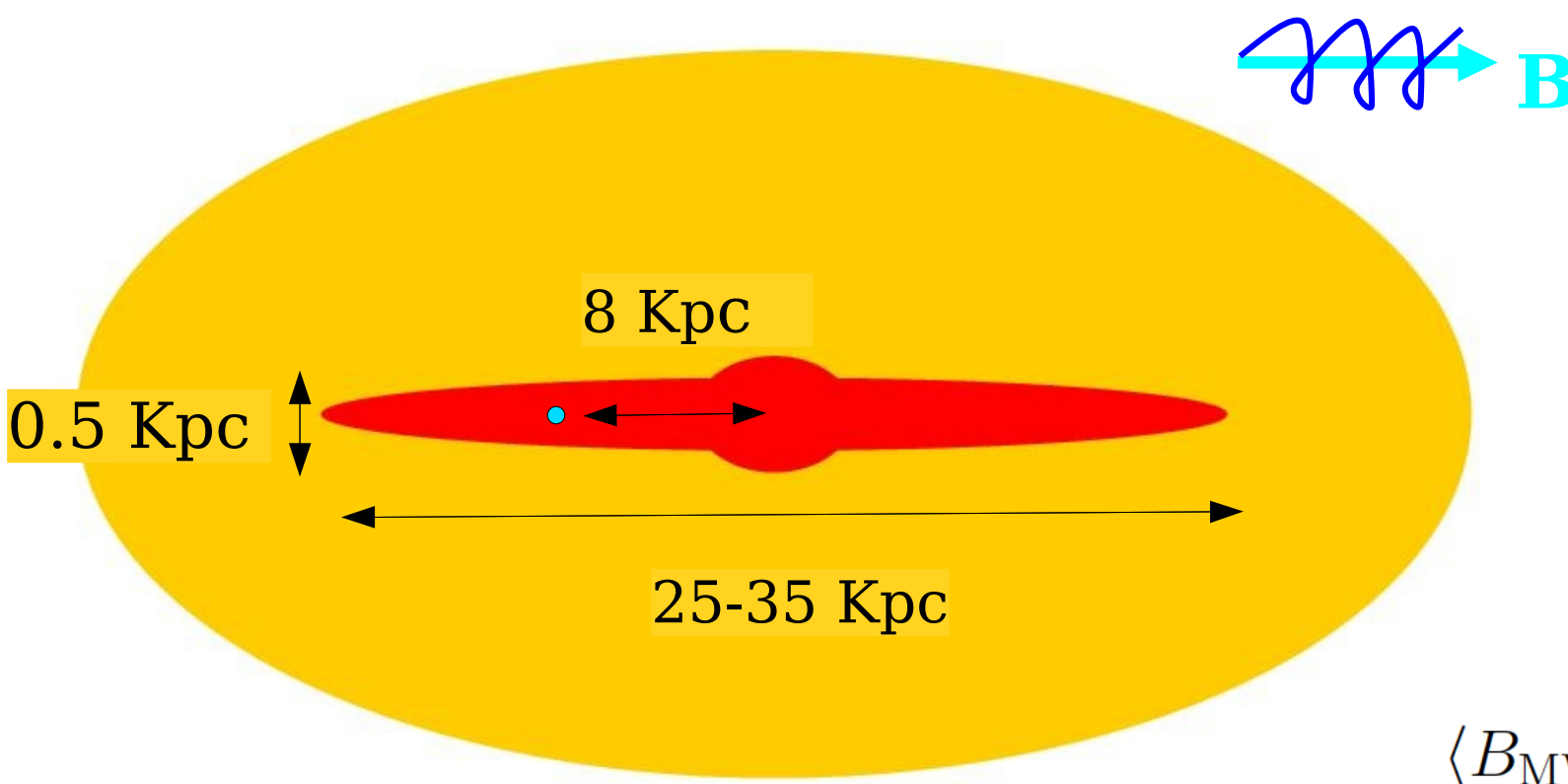
Interaction
(hadrons)

$$T_{\text{diffusion}} \left(\frac{pc}{Z} \right) \propto \left(\frac{pc}{Z} \right)^{-\delta}$$

Escape
from Galaxy Rrigidity

$$T_{\text{loss}}^{(e^\mp)}(E) \propto \frac{1}{E}$$

Energy losses
(electrons/positrons)
 m^{-4}



$$r_L = \frac{p_{\perp} c}{q B}$$

$$\langle B_{\text{MW}} \rangle \simeq 3 \mu\text{Gauss}$$

$$r_L = \frac{1.08 \text{ Kpc}}{Z} \left[\frac{E}{10^{18} \text{ eV}} \right] \left[\frac{\mu\text{Gauss}}{B} \right]$$

$$r_{\text{Larmor}}^p(100 \text{ GeV}) \simeq 3.6 \times 10^{-8} \text{ Kpc}$$

$$r_{\text{Larmor}}^p(10^{20} \text{ eV}) \simeq 36 \text{ Kpc}$$

$$r_{\text{Larmor}}^{\text{Fe}}(10^{20} \text{ eV}) \simeq 1.4 \text{ Kpc}$$

- Diffusion approximation
- Maximum energy for containment

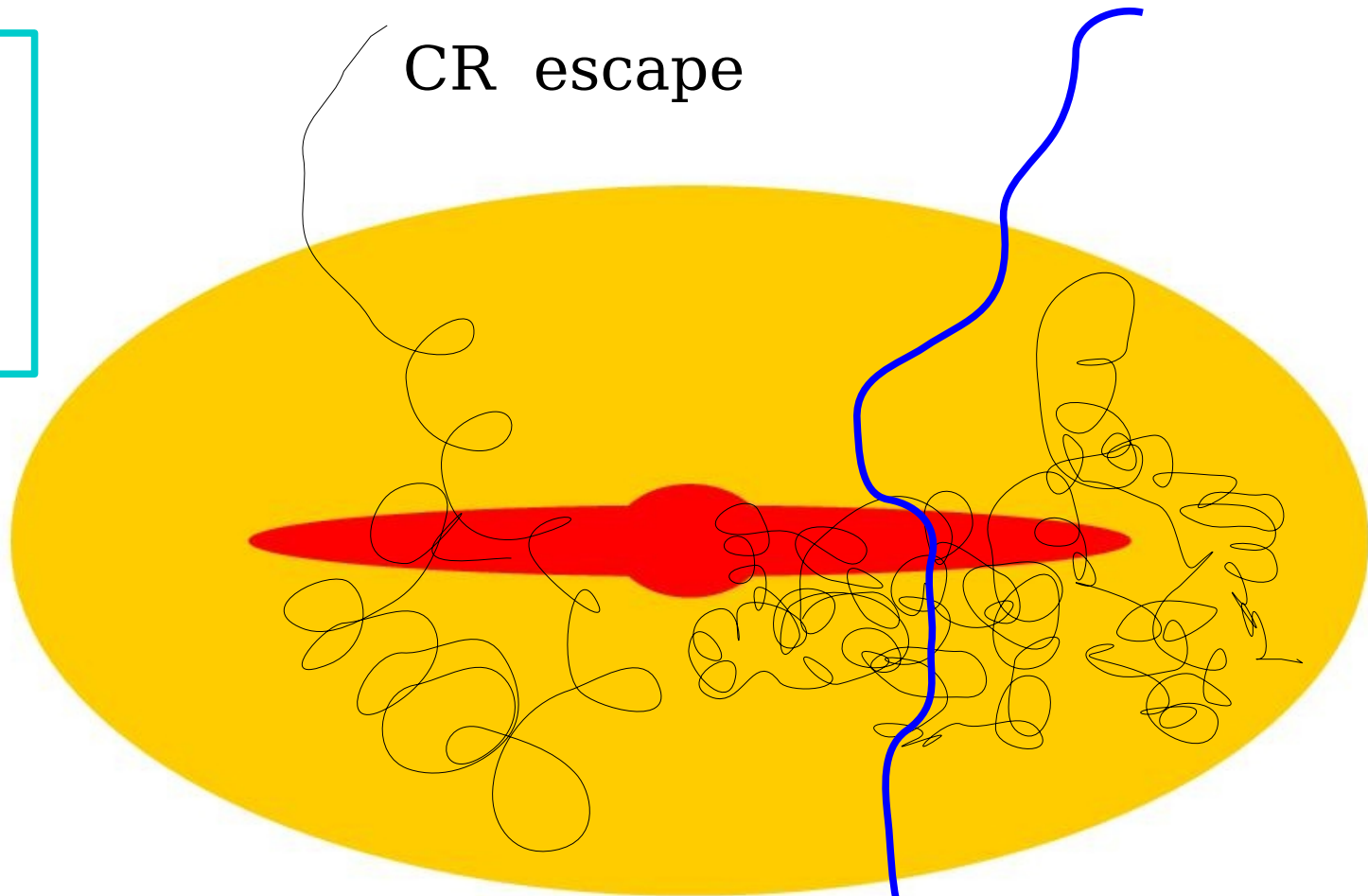
Observable CR populations:

$$n_j(E, \Omega, \vec{r})$$

Injection:

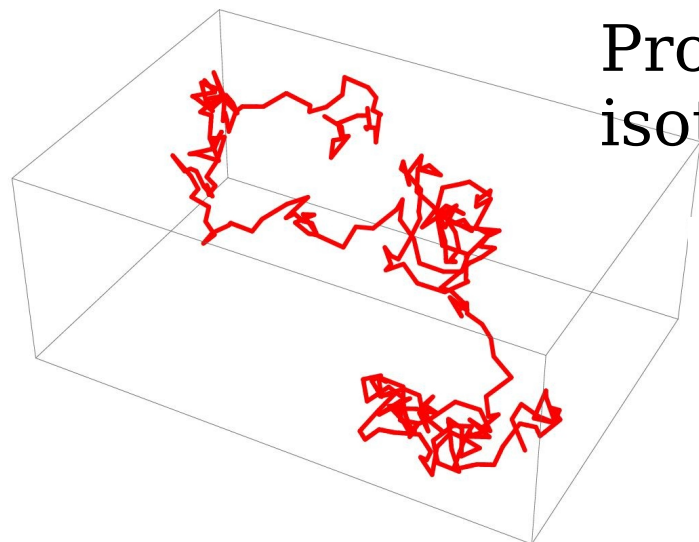
$$q_j(E, \vec{r}, t)$$

CR escape



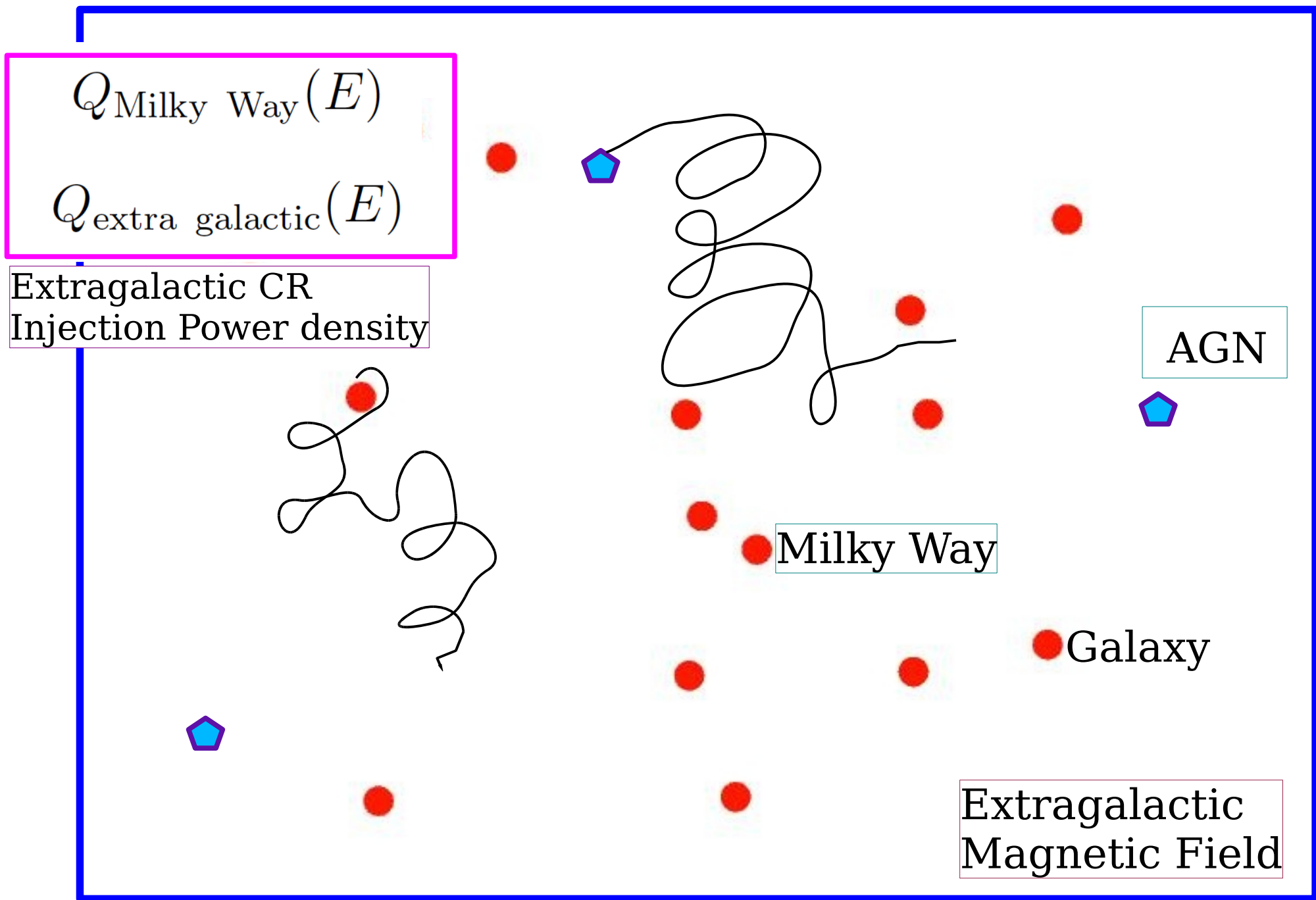
Propagation as isotropic diffusion

$$D(p/Z, \vec{r})$$

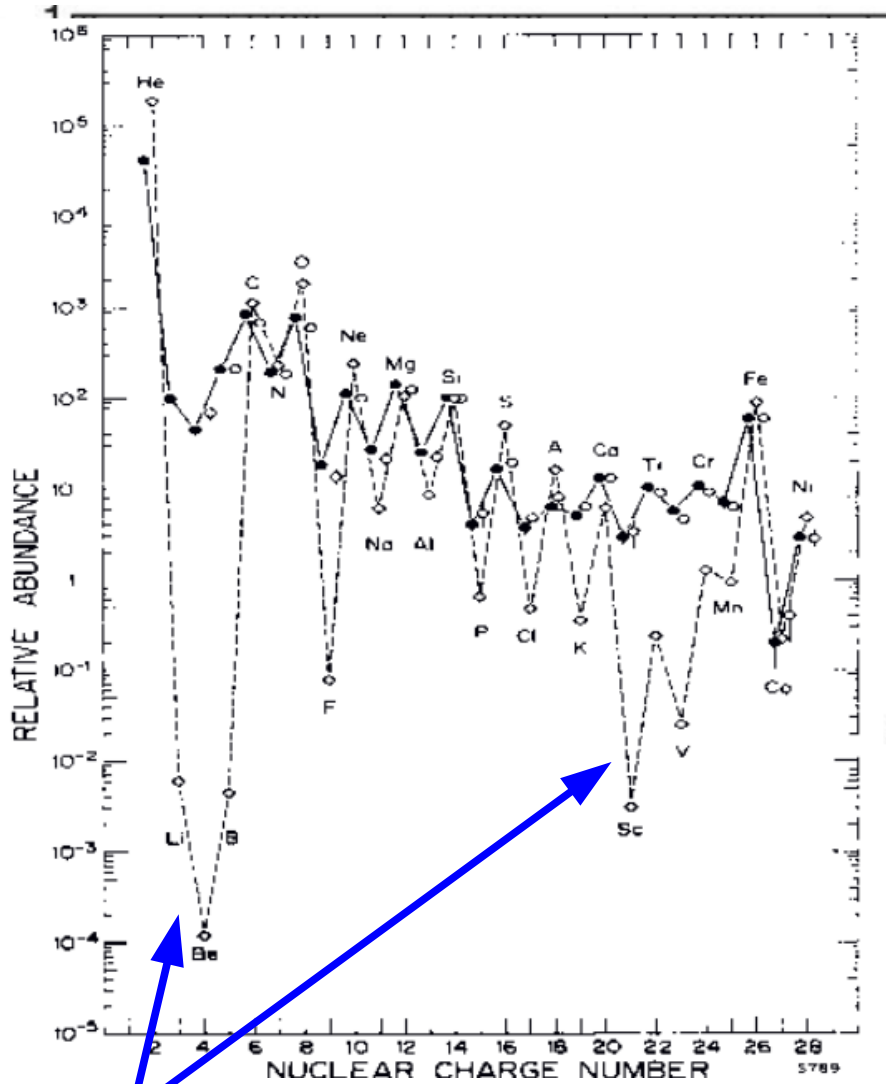


Extra galactic particle

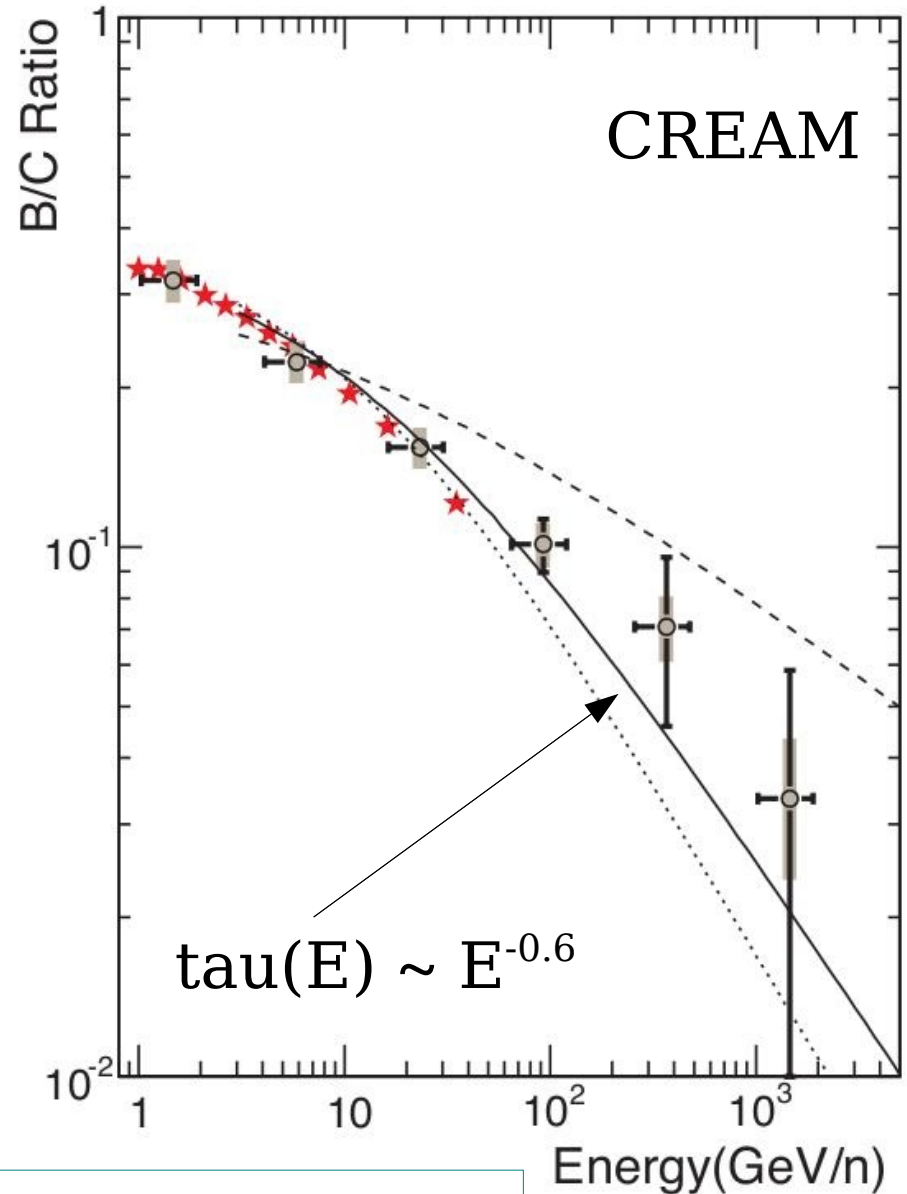
Piece of extragalactic space: Non MilkyWay-like sources



Cosmic Ray Composition



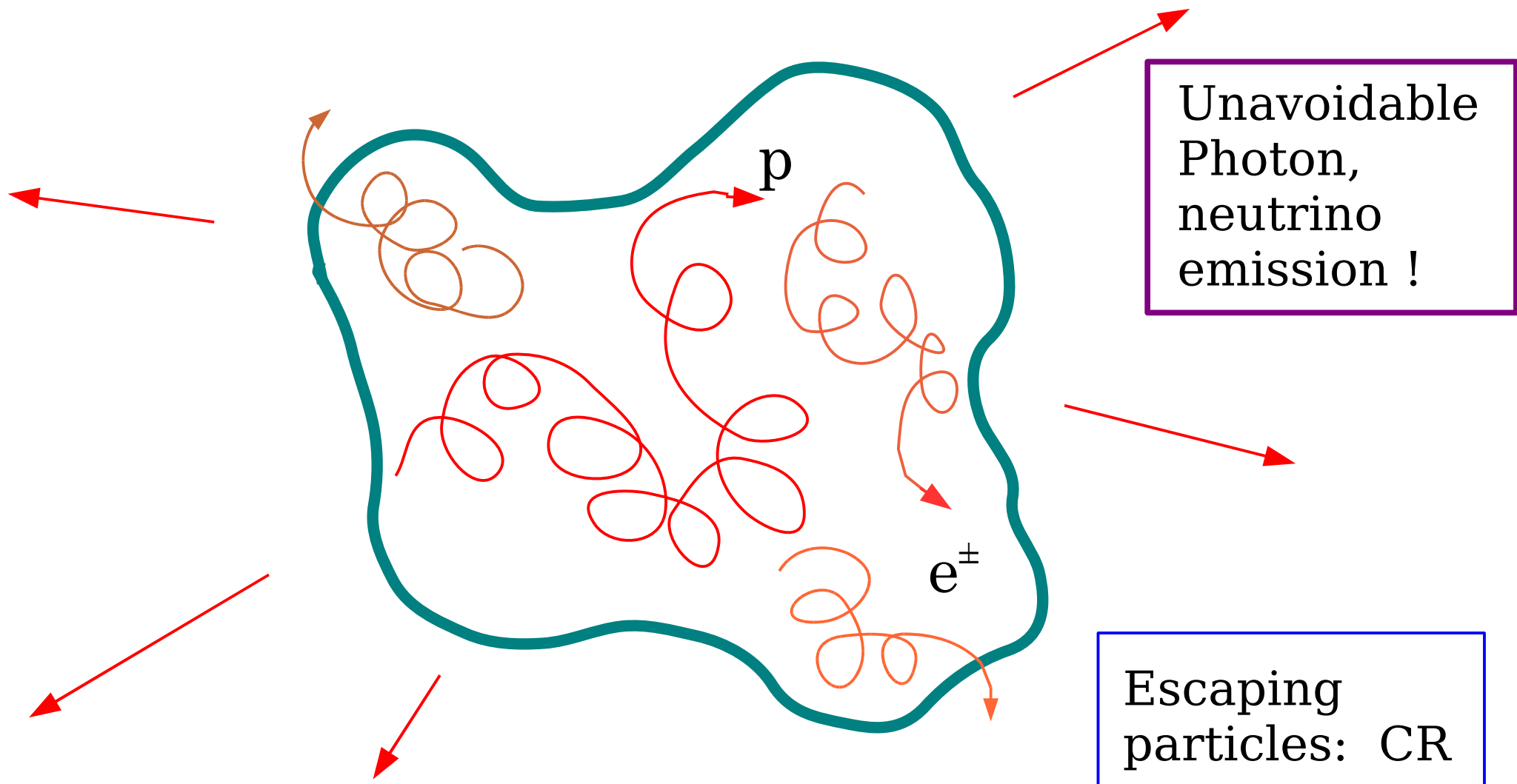
Overabundance of
•Li, Be, B
•Sub-iron elements



Atomic clocks [Be-10]

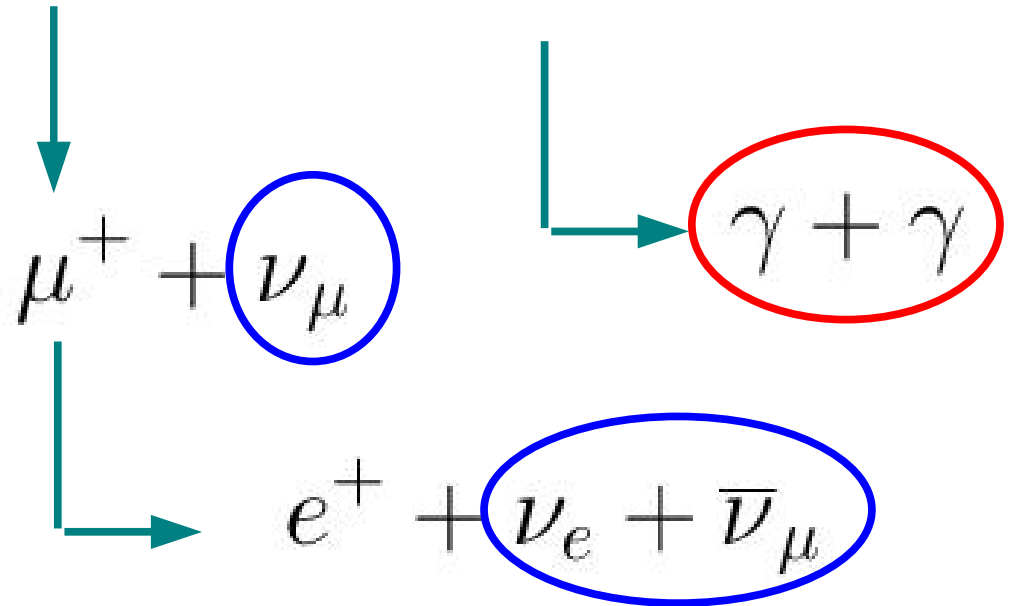
High Energy Astrophysical Source:

Object (or an “event”) that produces
(and for some time contains)
relativistic particles



$p + \text{target} \rightarrow \text{many particles}$

$$\rightarrow p(n) + \pi^+ + \pi^- + \pi^0$$



“Hadronic Emission”

$$e^\mp + B \rightarrow e^\mp + \gamma_{\text{synchrotron}}$$

“Leptonic Emission”

$$e^\mp + \gamma_{\text{soft}} \rightarrow e^\mp + \gamma_{\text{Inverse Compton}}$$

Multi-messenger Astrophysics

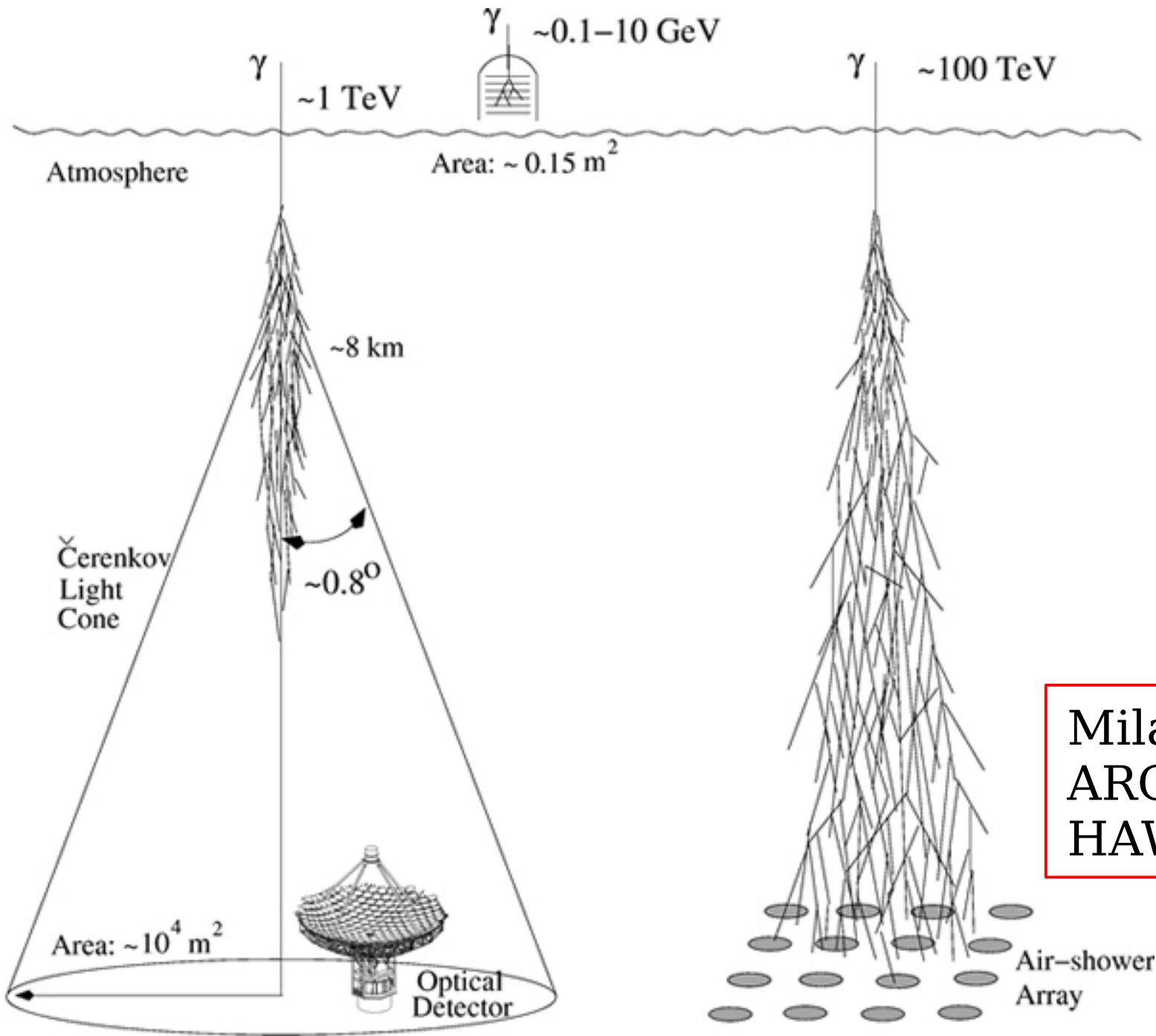
COSMIC RAY physics

GAMMA Astronomy

NEUTRINO Astronomy

Accelerators associated with
Acceleration of astronomical masses.
Emission of Gravitational Waves

Egret
Agile
Fermi



Hess
Magic
Veritas

CTA

Milagro
ARGO
HAWC

Launch of (GLAST) FERMI telescope

11th june 2008



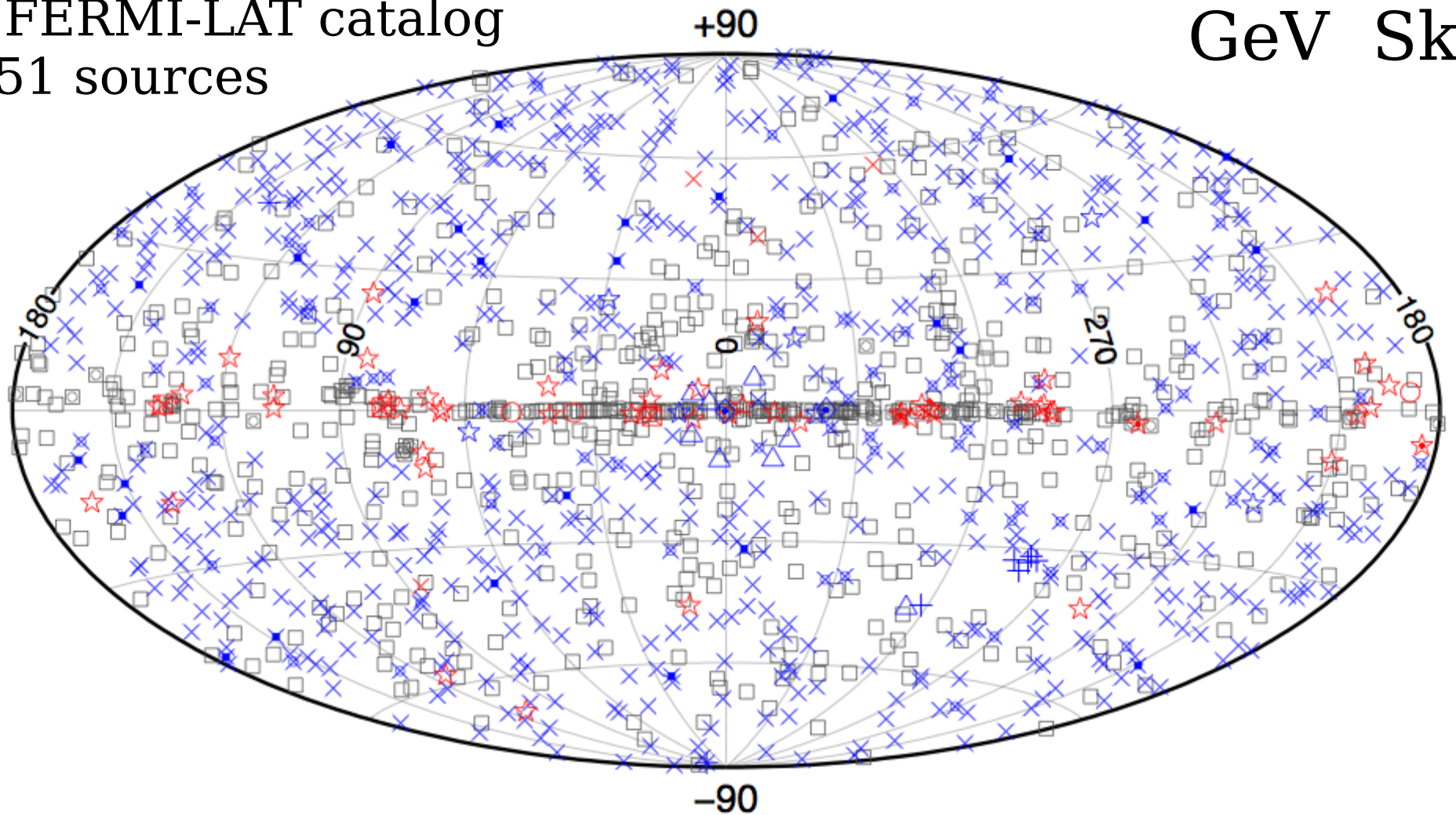
MAGIC 2 x 236 m²

2nd telescope : April 2009



1st FERMI-LAT catalog
1451 sources

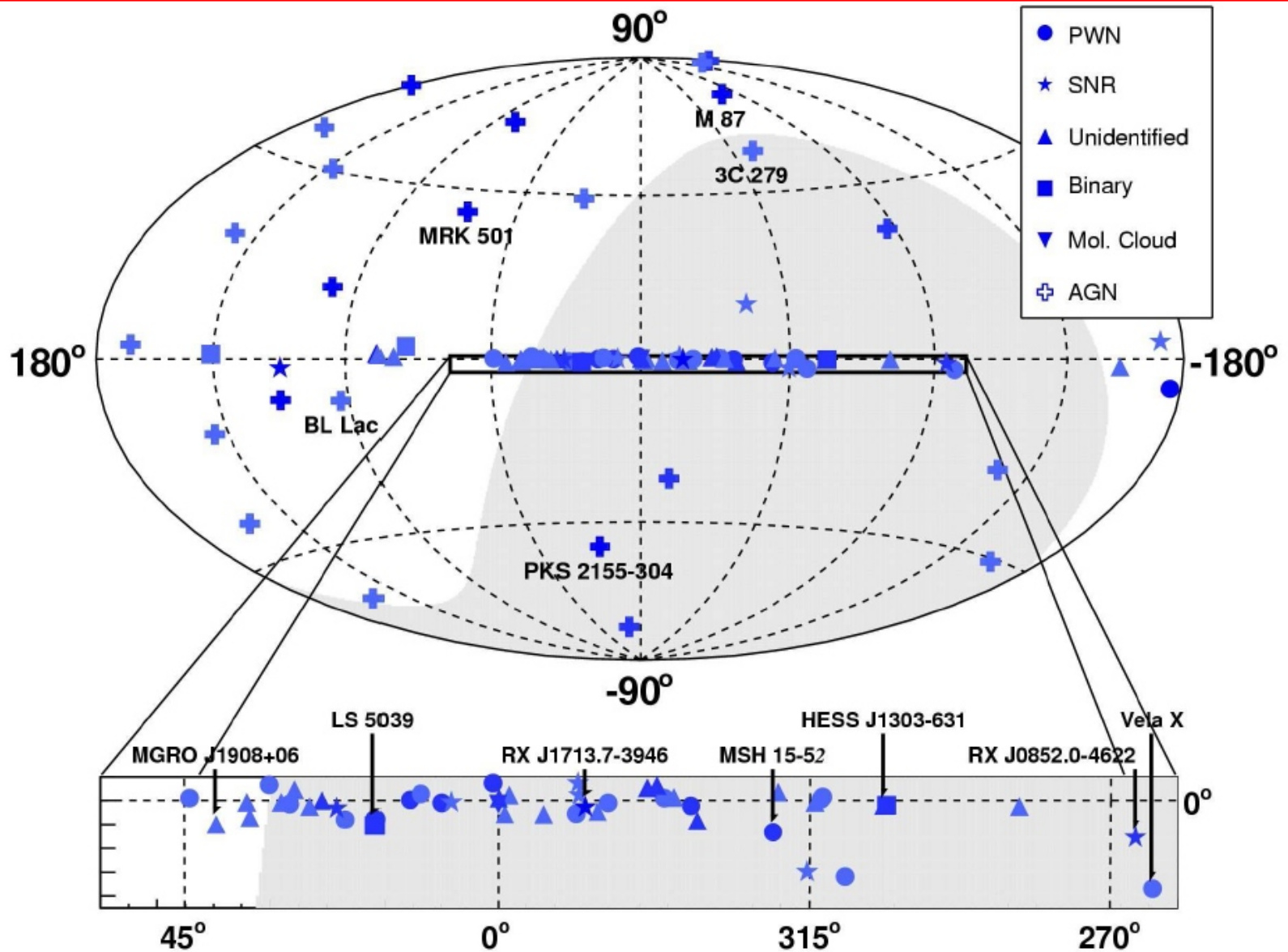
GeV Sky



□ No association	◻ Possible association with nearby SNR or PWN		
× AGN – blazar	* Starburst Gal	☆ Pulsar	★ Pulsar w/PWN
⊗ AGN – unknown	+ Galaxy	◊ PWN	△ Globular cluster
⊠ AGN – non blazar	○ SNR	⊠ XRB or MQO	

2nd catalog release
imminent.

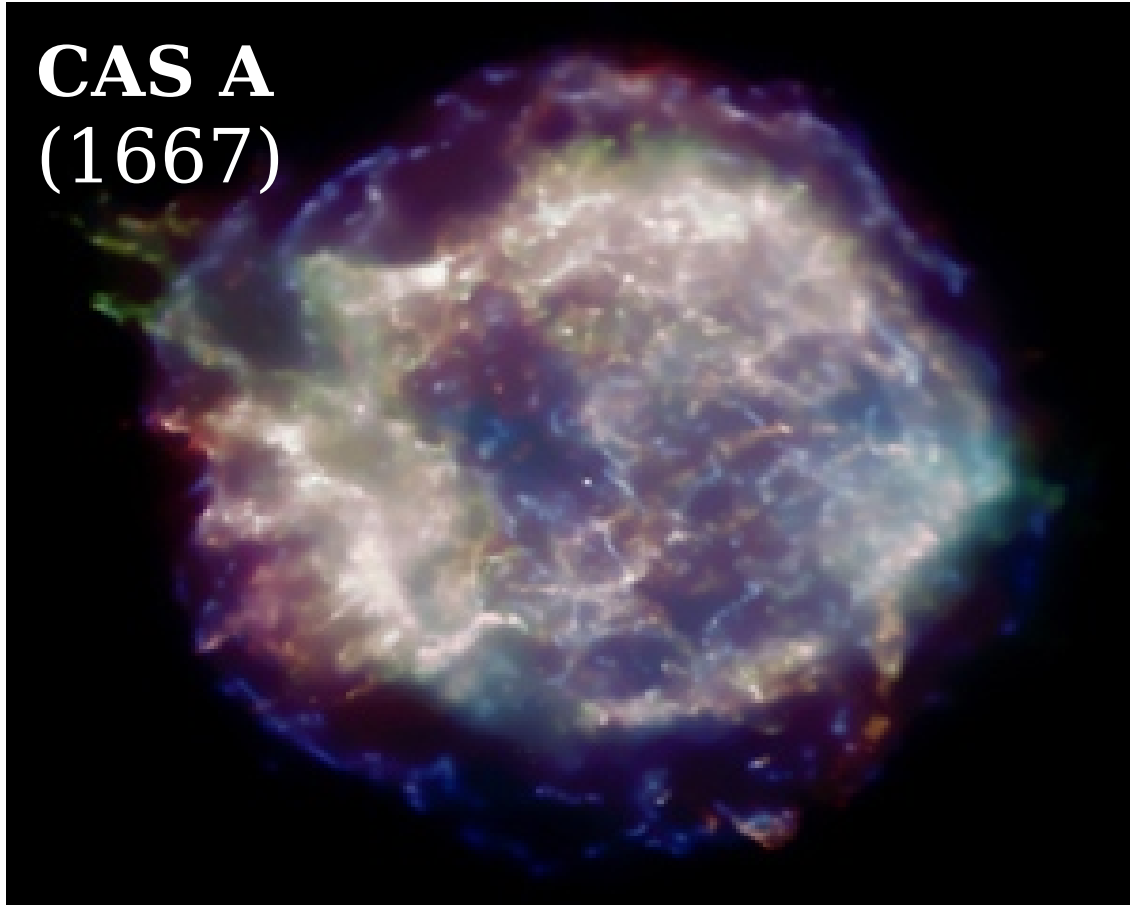
TeV SKY



The TeV sky is approaching 100 sources belonging to several different classes:

- PULSARS (PSR)
- Pulsar Wind Nebulae (PWN)
- Binary Systems
- SuperNova Remnant (SNR)
- Active Galactic Nuclei (AGN)
- Gamma Ray Bursts (GRB)

The SuperNova “Paradigm” for CR acceleration



Powering the galactic Cosmic Rays

$$L_{\text{cr}}(\text{Milky Way}) \simeq \frac{\rho_{\text{cr}} V_{\text{conf}}}{T_{\text{conf}}}$$
$$\simeq 2 \times 10^{41} \left(\frac{\text{erg}}{\text{s}} \right)$$

$$L_{\text{SN kinetic}}^{\text{Milky Way}} \simeq E_{\text{SN}}^{\text{Kinetic}} f_{\text{SN}}$$

$$L_{\text{SN kinetic}}^{\text{Milky Way}} \simeq \left[1.6 \times 10^{51} \text{ erg} \right] \left[\frac{3}{\text{century}} \right]$$

$M = 5 M_{\odot}$
 $v \simeq 5000 \text{ Km/s}$

$$L_{\text{SN kinetic}}^{\text{Milky Way}} \simeq 1.5 \times 10^{42} \frac{\text{erg}}{\text{s}}$$

Match for 15% efficiency

- ENERGETICS

- DYNAMICS [Diffusive Shock acceleration]

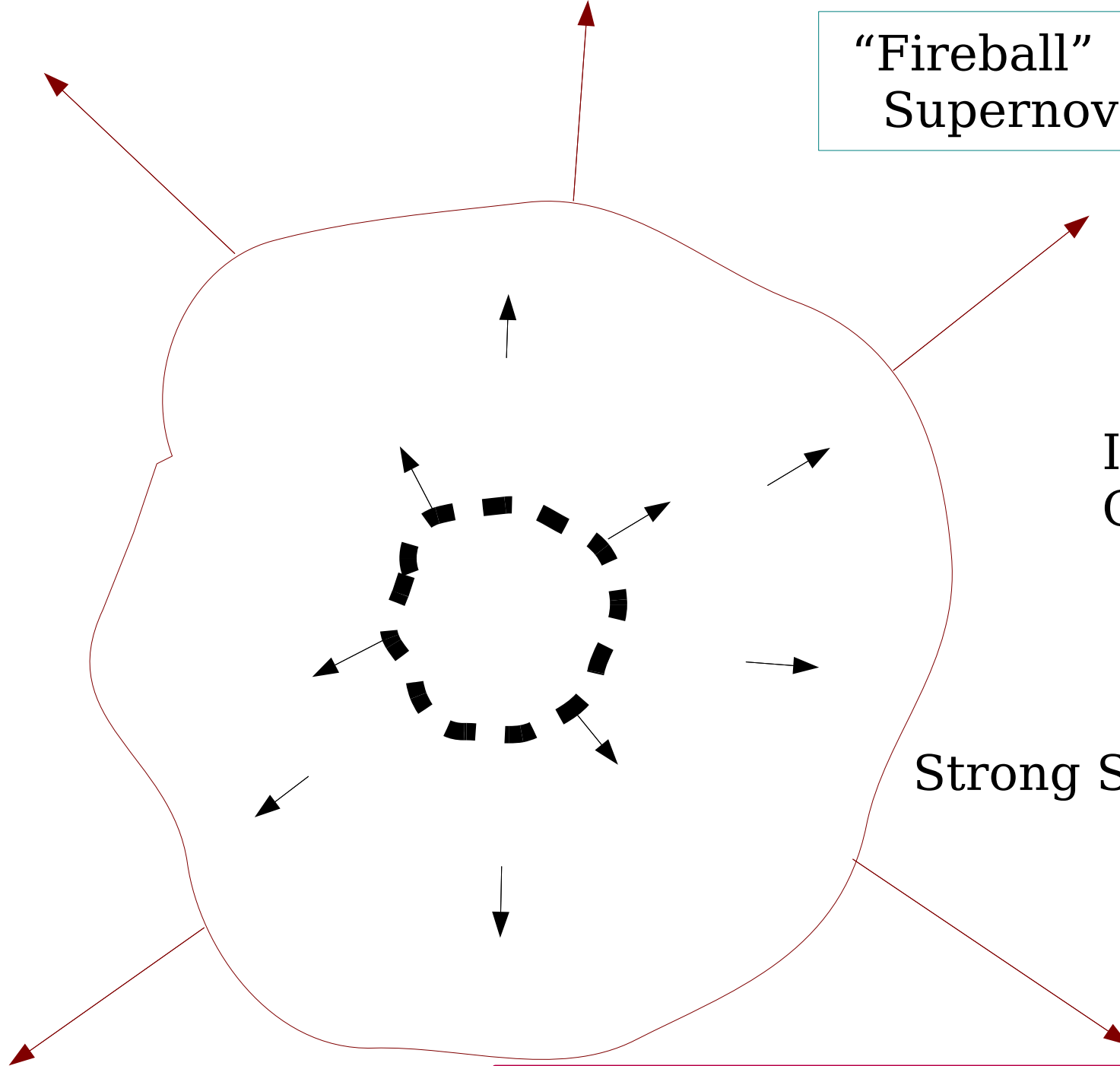
“Fireball” of an
Supernova explosion

Interstellar
Gas

Strong Shock

Fermi 1st order
acceleration

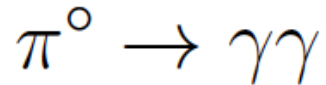
$$q(E) \propto E^{-(2+\epsilon)}$$



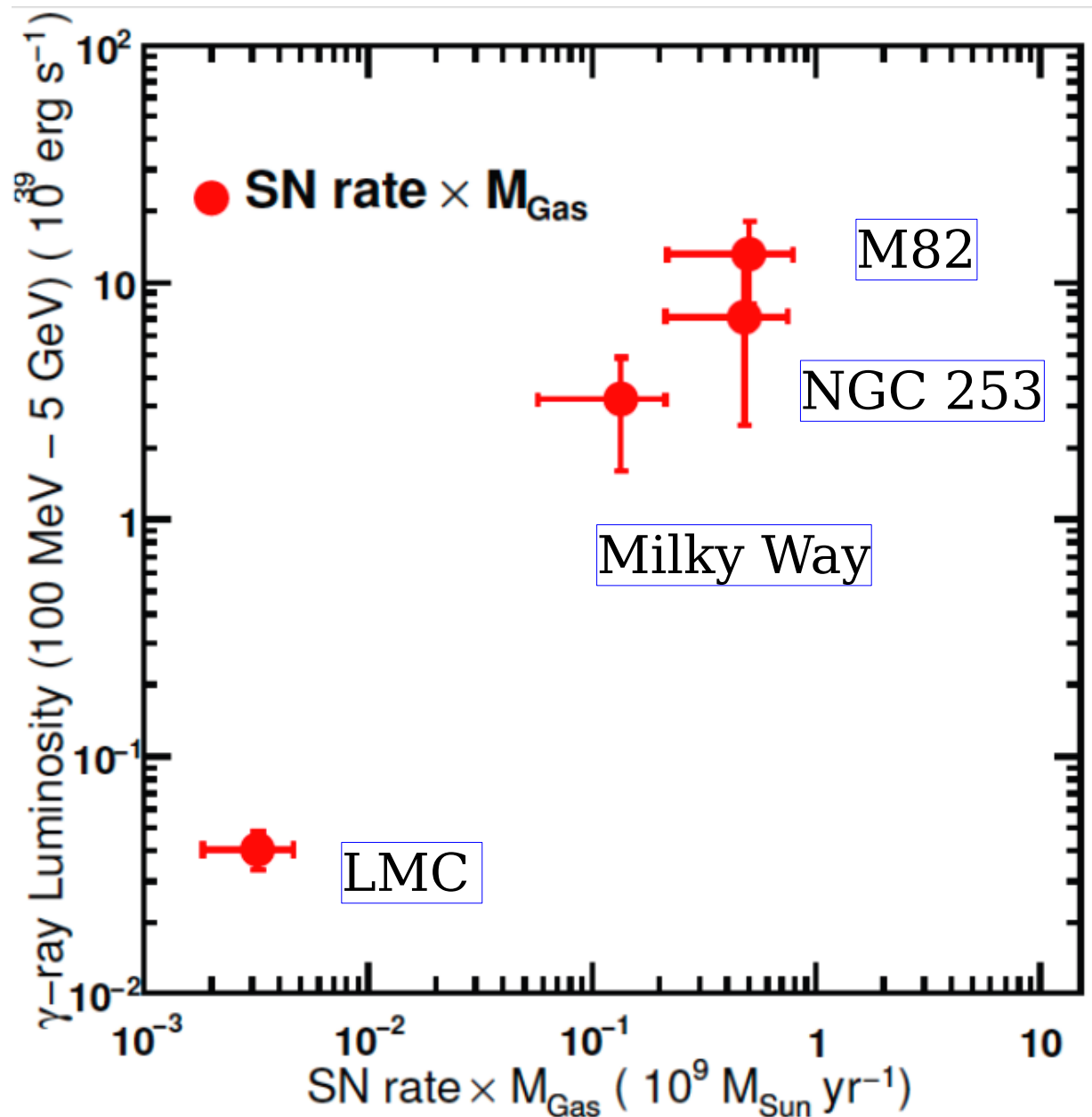
FERMI
Telescope:

Detection of
Starburst galaxies

Gamma Ray
Luminosities
(> 100 MeV)



Determination
of the Milky Way luminosity
[consistent with π° Decay



Cosmic Ray production
Correlated with
Star Birth/Death Rate

M81, M82



M82



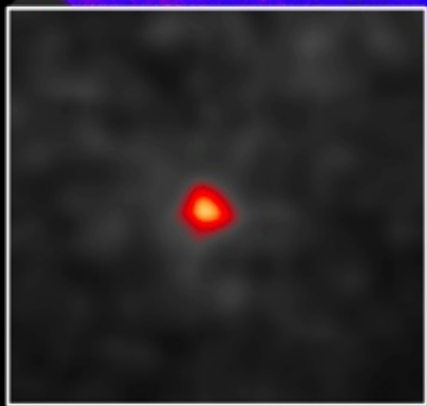
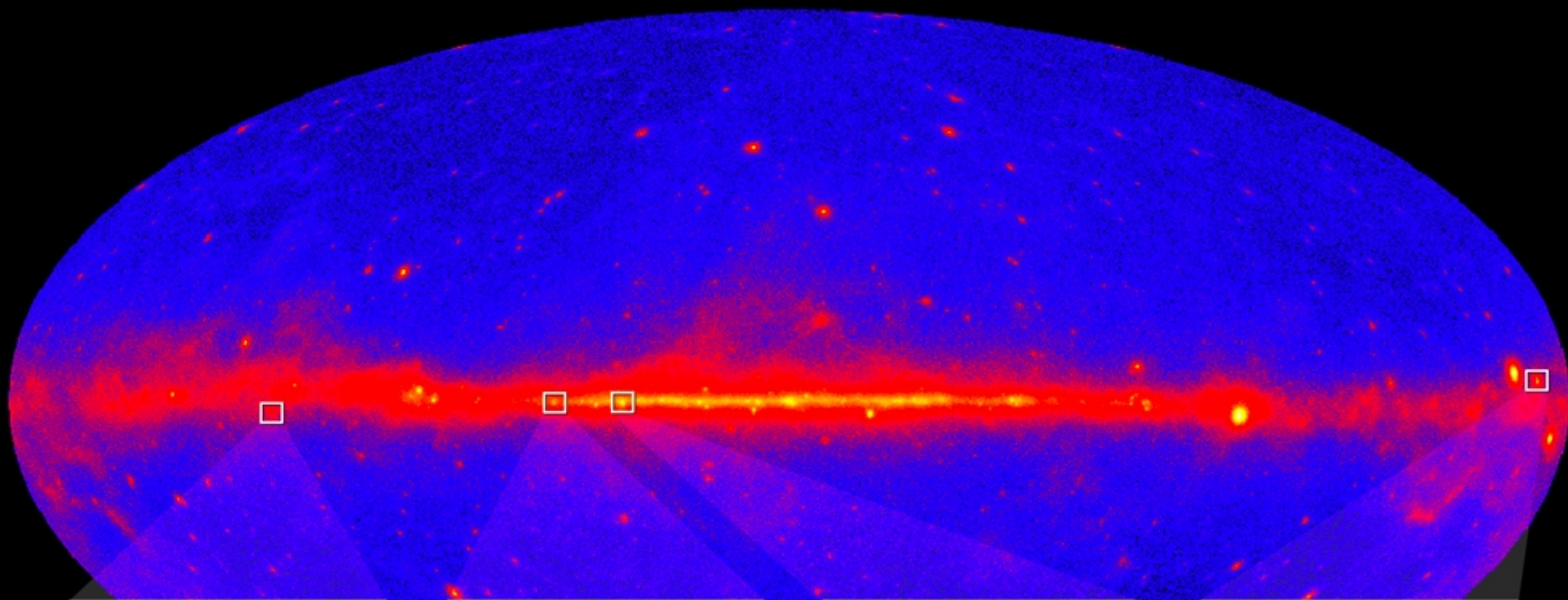
Very High SN rate
(density waves)

LMC

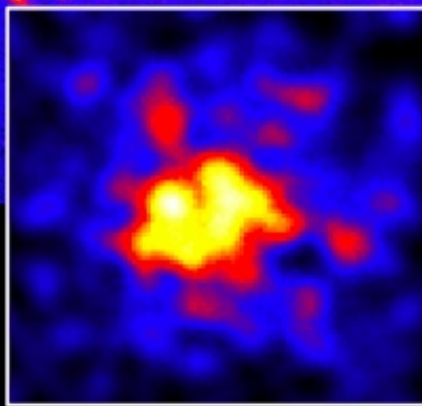
Dorado Region



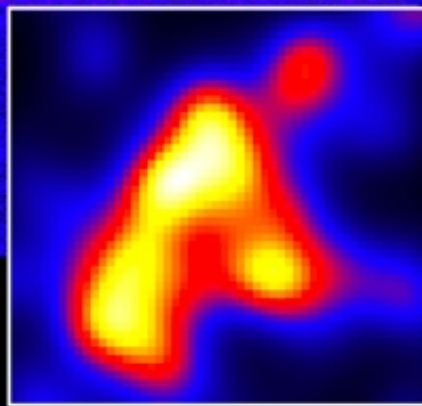
NASA's Fermi telescope resolves supernova remnants at GeV energies



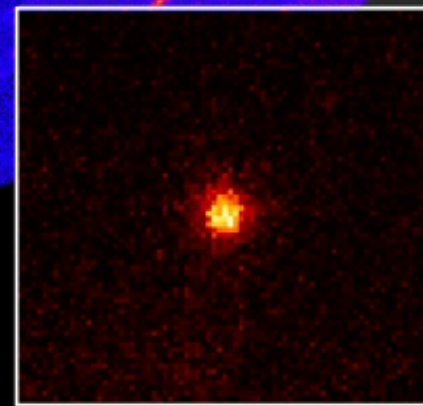
Cas A



W51C



W44

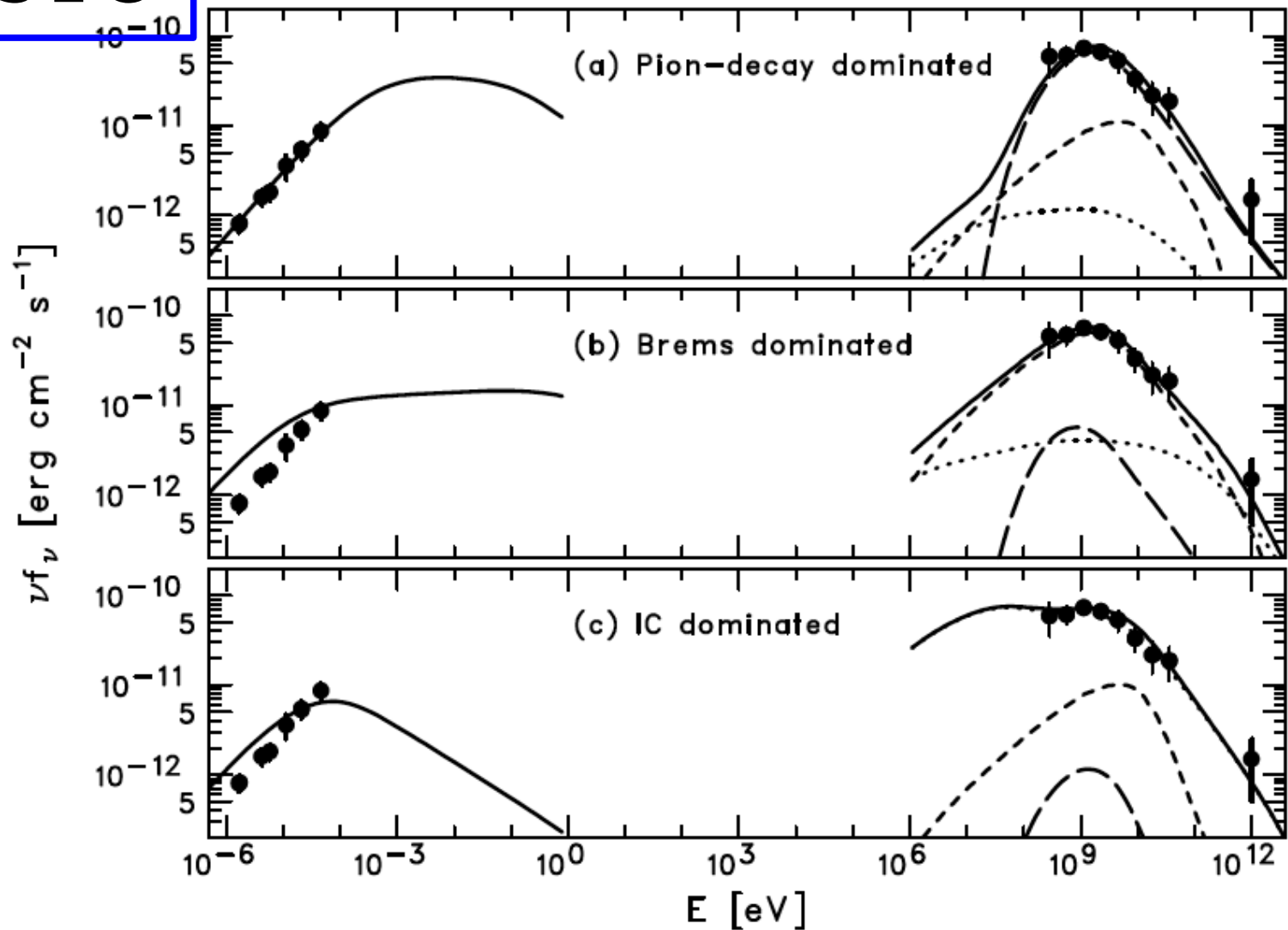


IC 443

W49B

SNR W51C

Alternative Interpretations



Model	Parameters					Energetics	
	a_e/a_p	Δs	p_{br} (GeV c^{-1})	B (μG)	\bar{n}_H (cm^{-3})	W_p (10^{50} erg)	W_e (10^{50} erg)
(a) π^0 -decay	0.02	1.4	15	40	10	5.2	0.13
(b) Bremsstrahlung	1.0	1.4	5	15	10	0.54	0.87
(c) Inverse Compton	1.0	2.3	20	2	0.1	8.4	11

Hadronic or
Leptonic origin ?

SuperNova 393A

RX J1713.7-3946

Observed in AD 393
By chinese court astromers
22-october, 19-november

(Re)-discovered in 1996
by the Roentgen Satellite

Foreground star

Neutron Star

之并斬其從弟緒司馬道子由是失勢禍亂成矣
太元十六年十一月癸巳月奄心前星占曰太子憂是
時太子常有篤疾
太元十七年九月丁丑歲星熒惑填星同在亢氏占曰
三星合是謂驚位絕行內外有兵喪與飢改立王公
太元十八年正月乙酉熒惑入月占曰憂在宮中非賊
乃盜也一曰有亂臣若有戮者二十一年九月帝暴崩
內殿兆庶宣言夫人張氏潛行大逆于時朝政闇緩不
加顯戮但默責而已又王國寶邪狡卒伏其辜
太元十八年二月有客星在尾中至九月乃滅占曰燕

Declination (J2000)

-39°30'

-40°0'

X-ray image

17^h16^m

14^m

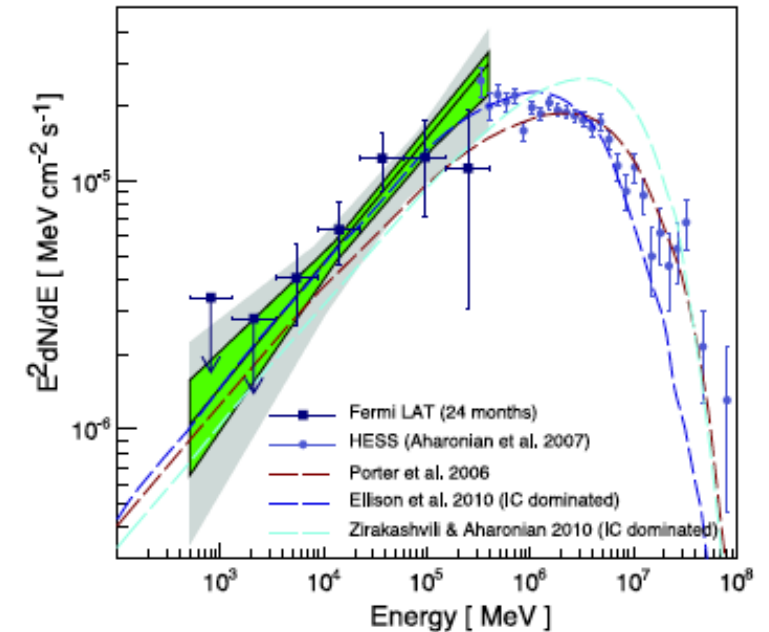
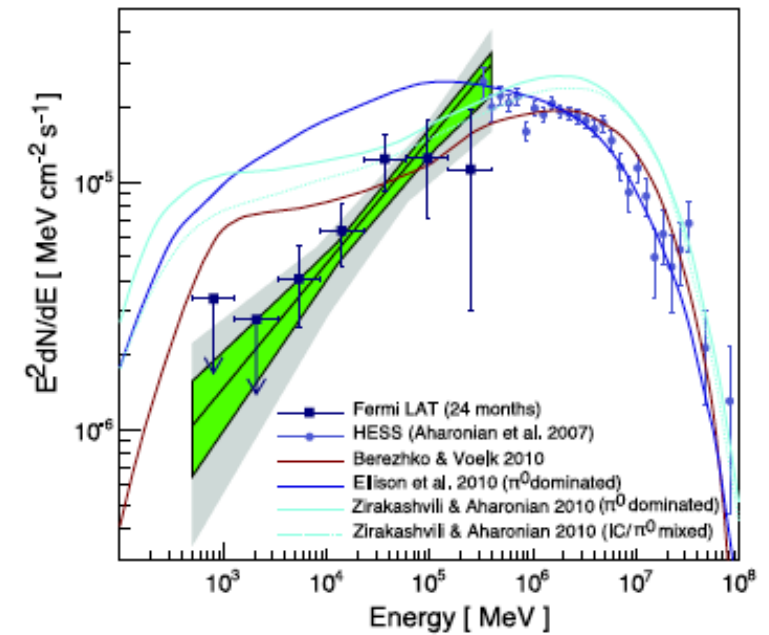
12^m

Detected in 2004 by HESS in TeV gamma rays

Observations of the young Supernova remnant RX J1713.7–3946
with the *Fermi* Large Area Telescope

astro-ph/1103.5727.
29th march 2011

Favors
leptonic interpretation.



Have we proved that SNR are
the source of the bulk of
the Galactic Cosmic Rays ?

Case is not closed...

A picture more complex than the “simplest scheme”
is probably emerging

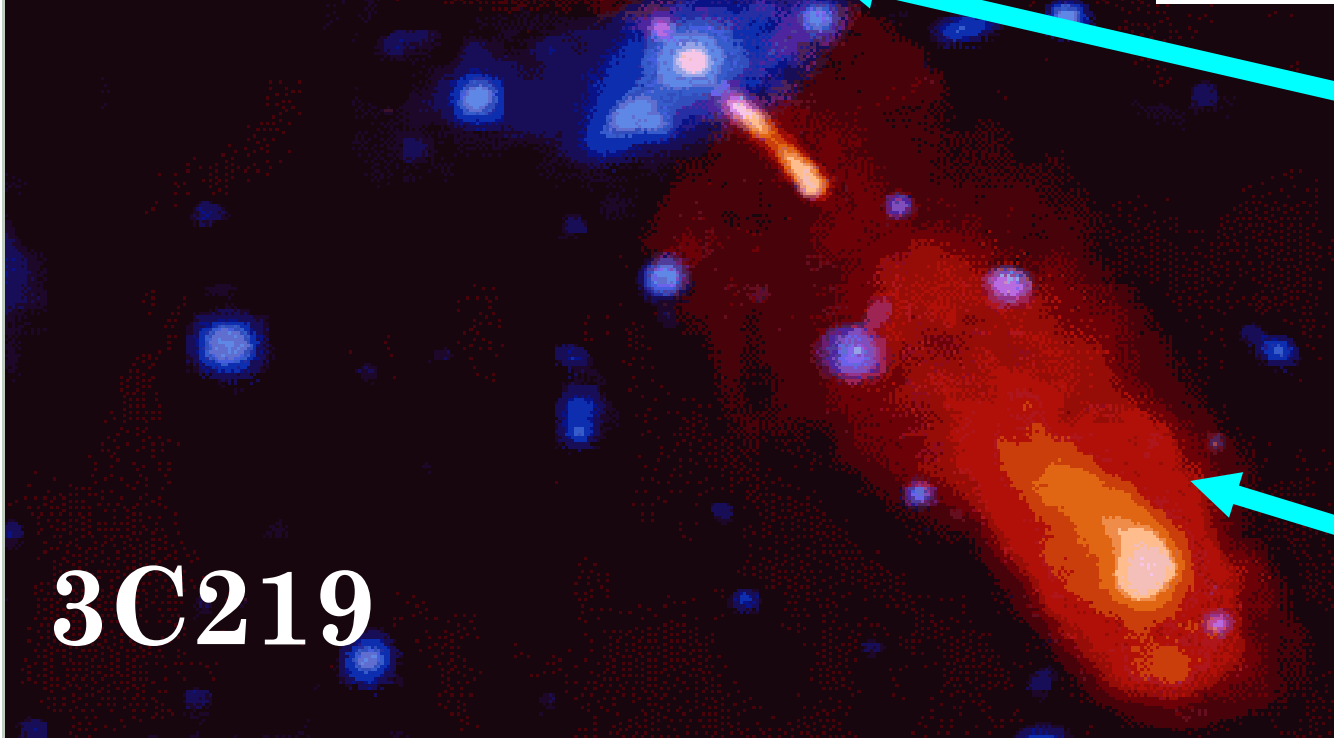
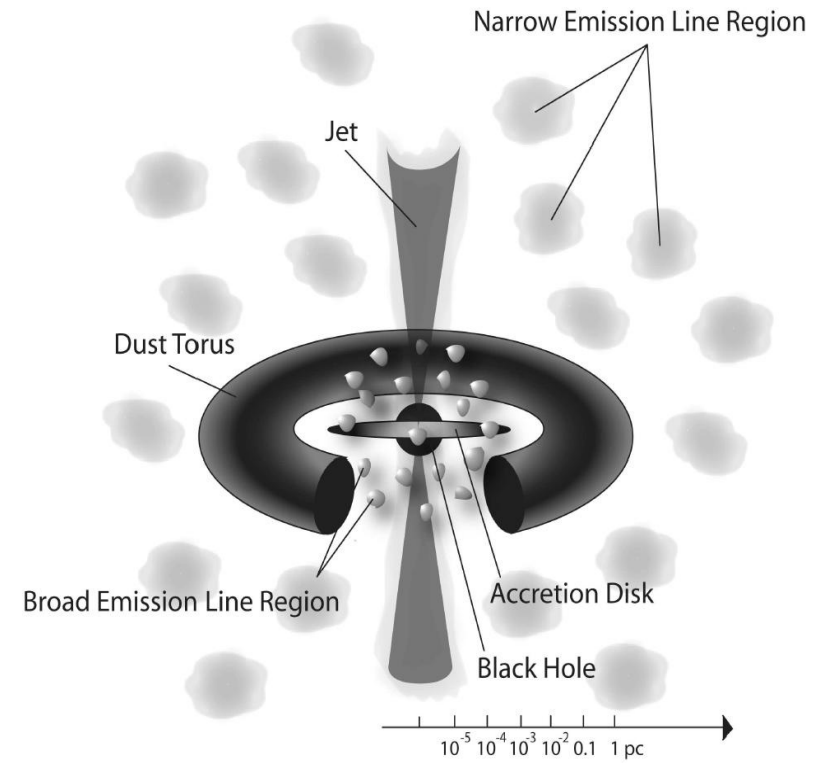
Ultra high Energy Cosmic Rays

Possible sources:

AGN (Active Galactic Nuclei)

GRB (Gamma Ray Bursts)

ACTIVE GALACTIC NUCLEI



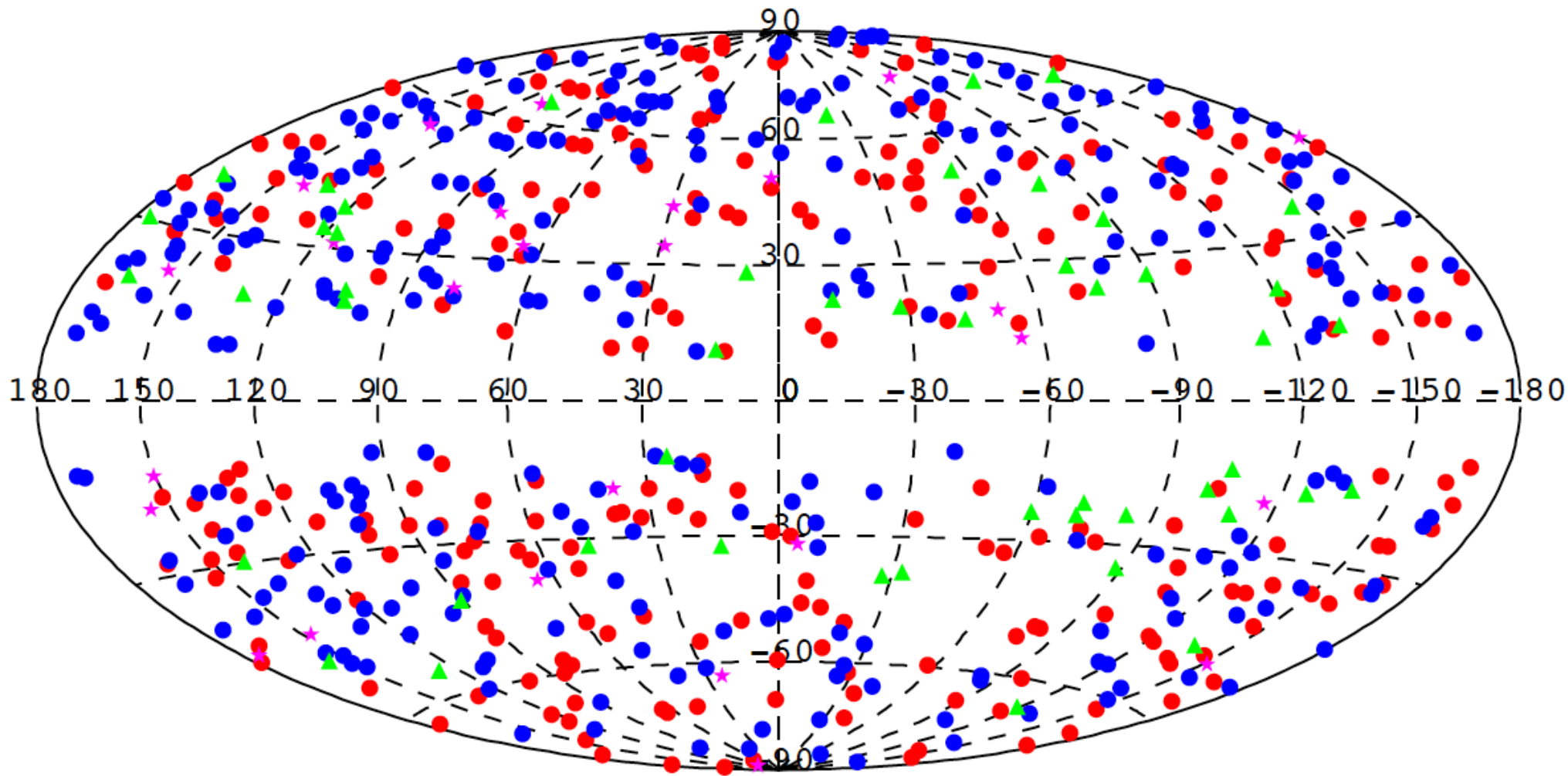
Optical

Radio

AGN observed by FERMI:

671 AGN's

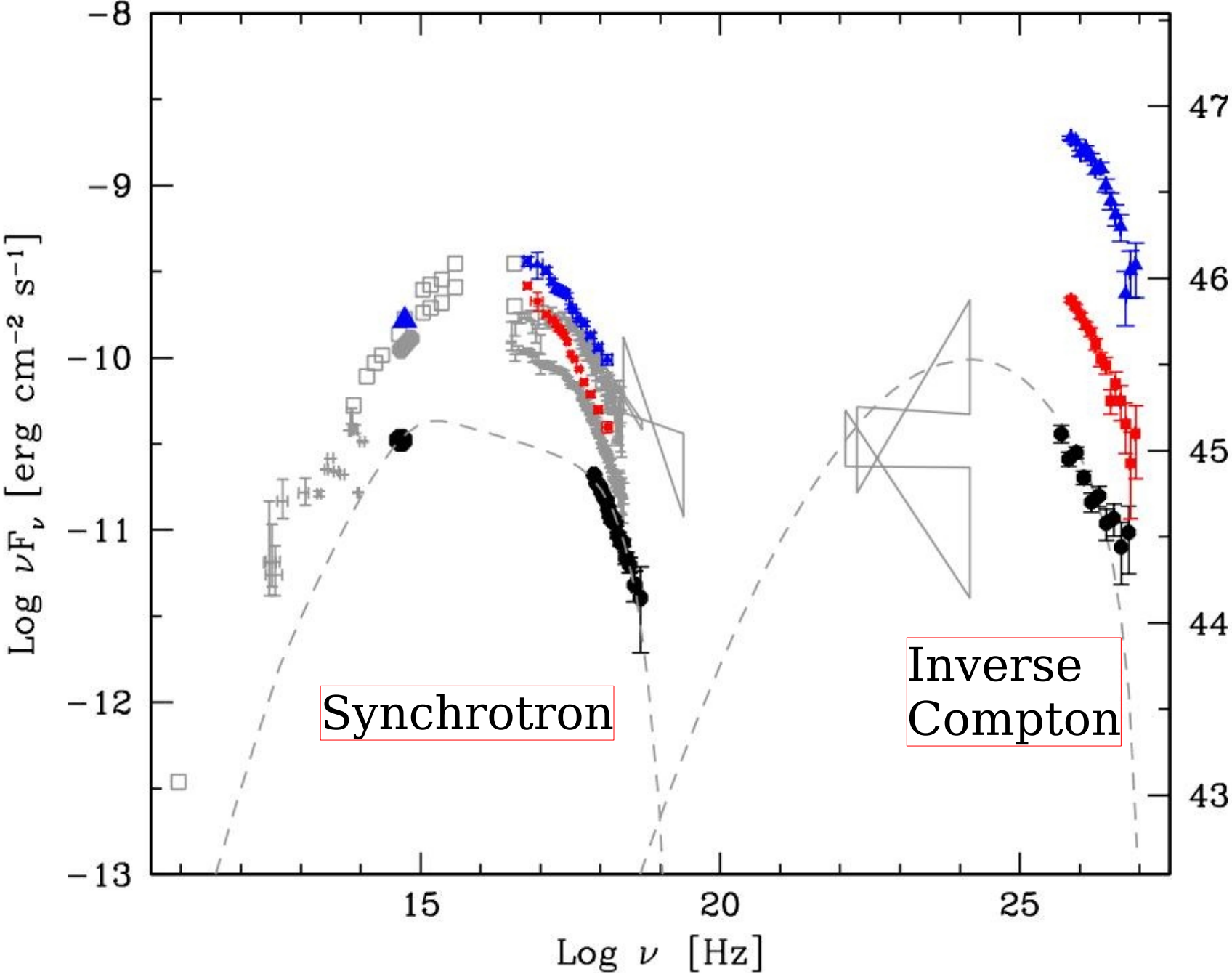
(1st AGN catalog)



Red: FSRQ
Blue: Blac
Magenta: Radio Galaxies

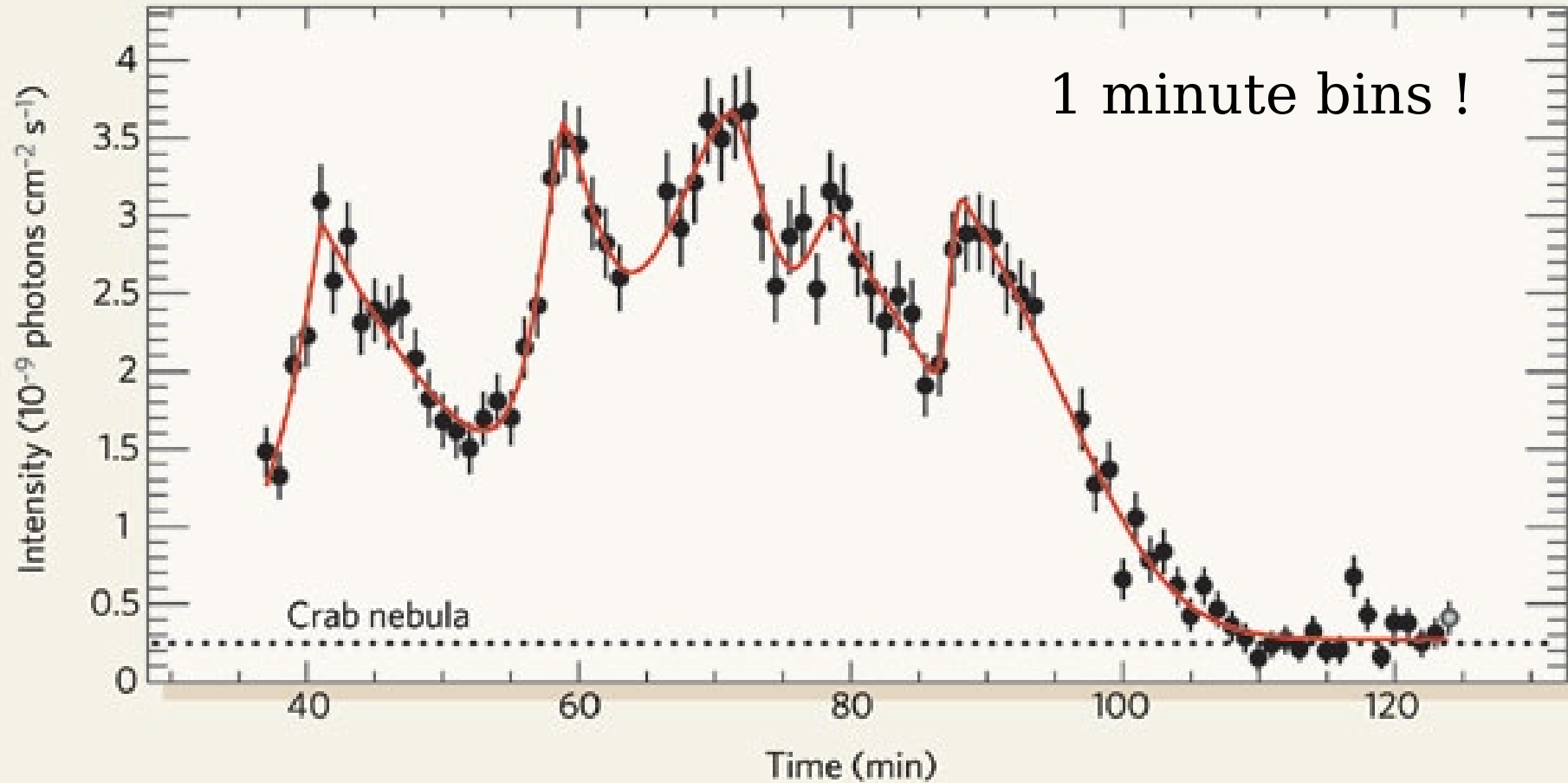
PKS 2155-304

Electron acceleration Rapid Time Variations

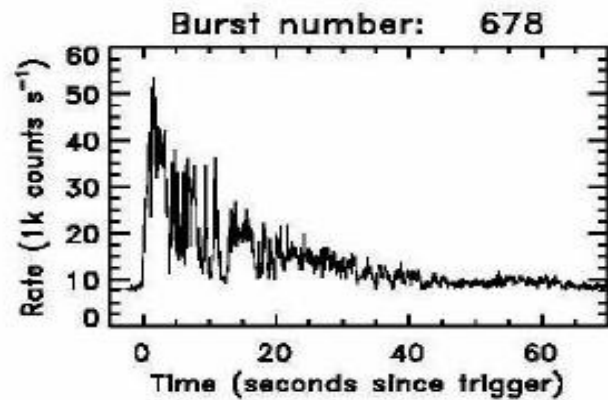
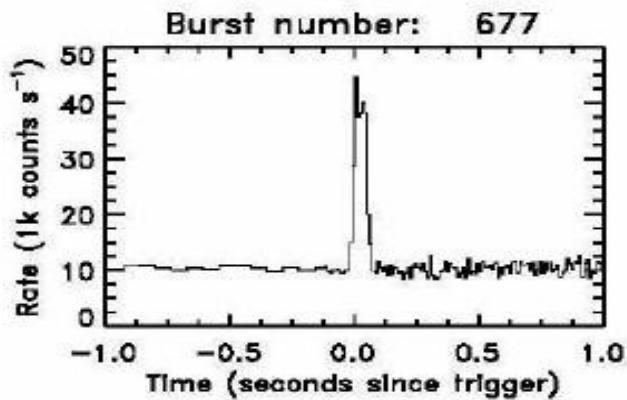
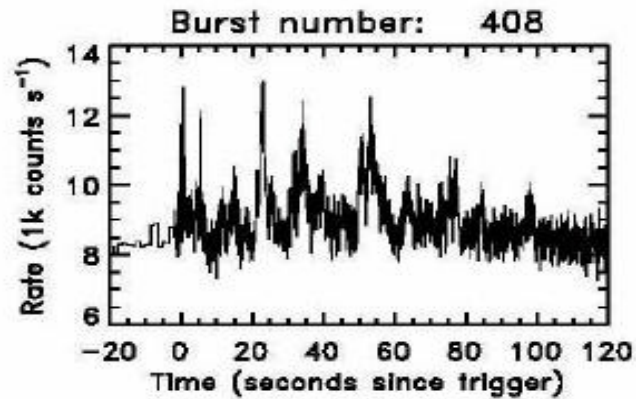
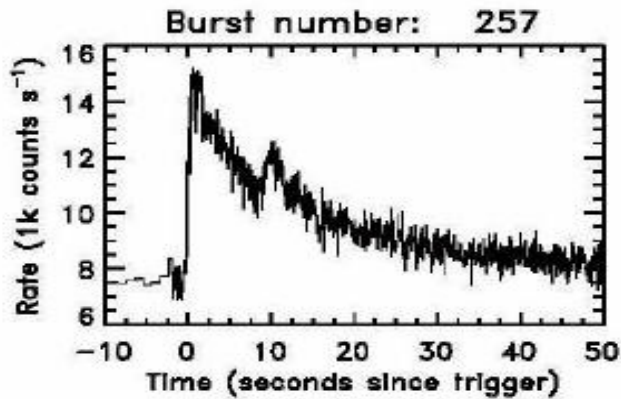
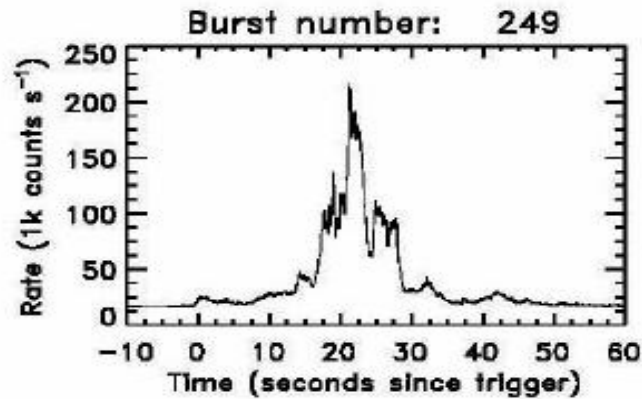
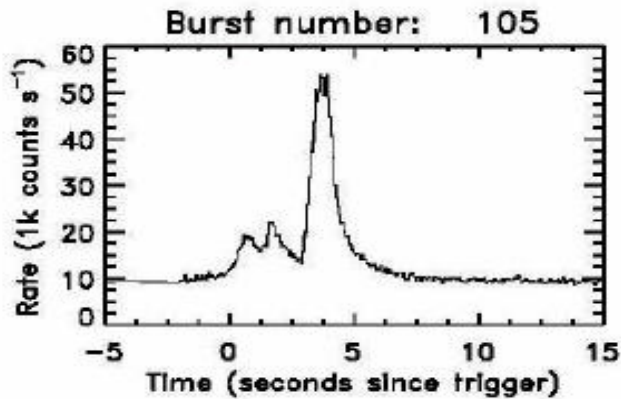


PKS 2155-304 (HESS measurements)

Very Rapid Time Variations !

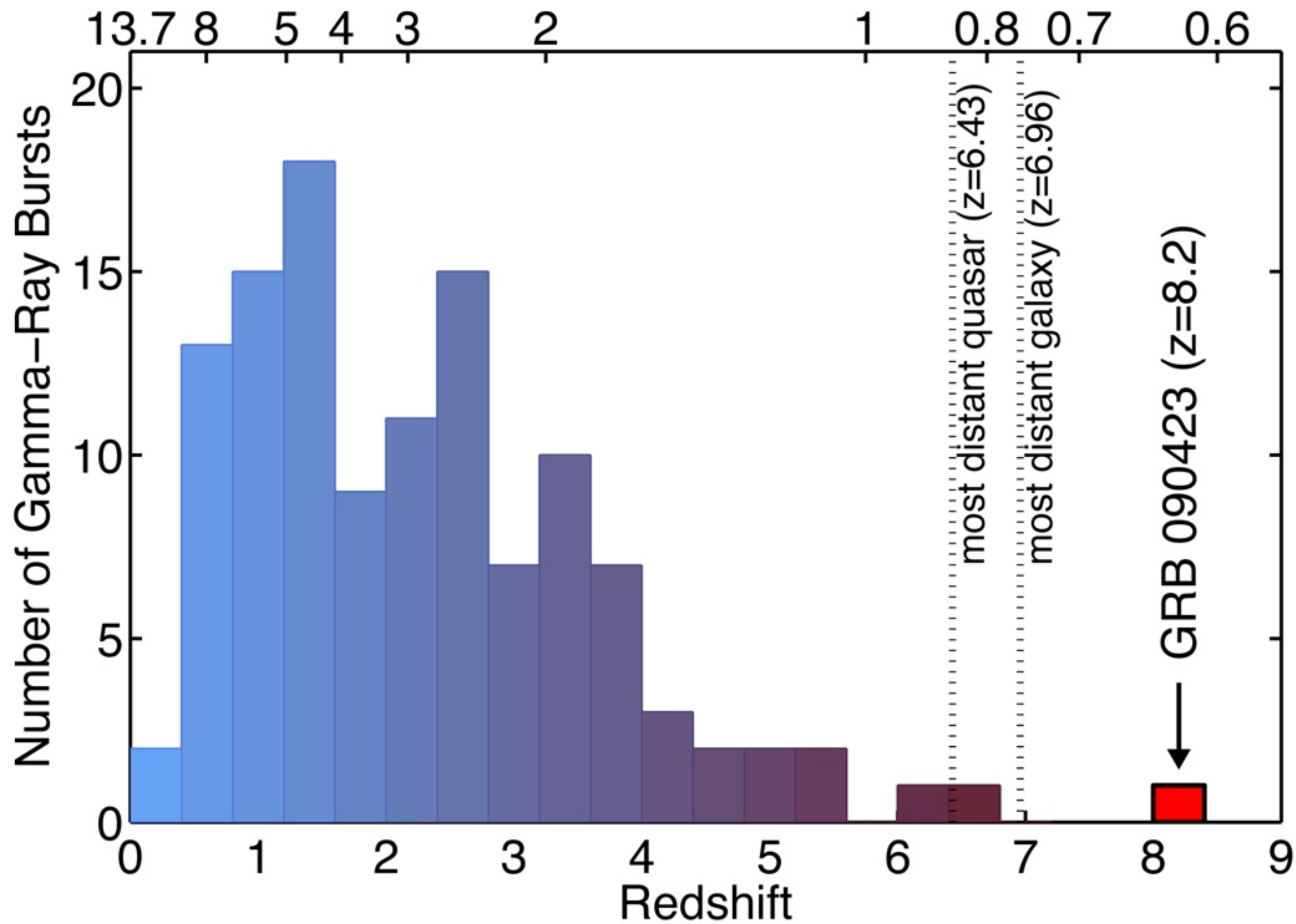


GAMMA RAY BURSTS (GRB's)

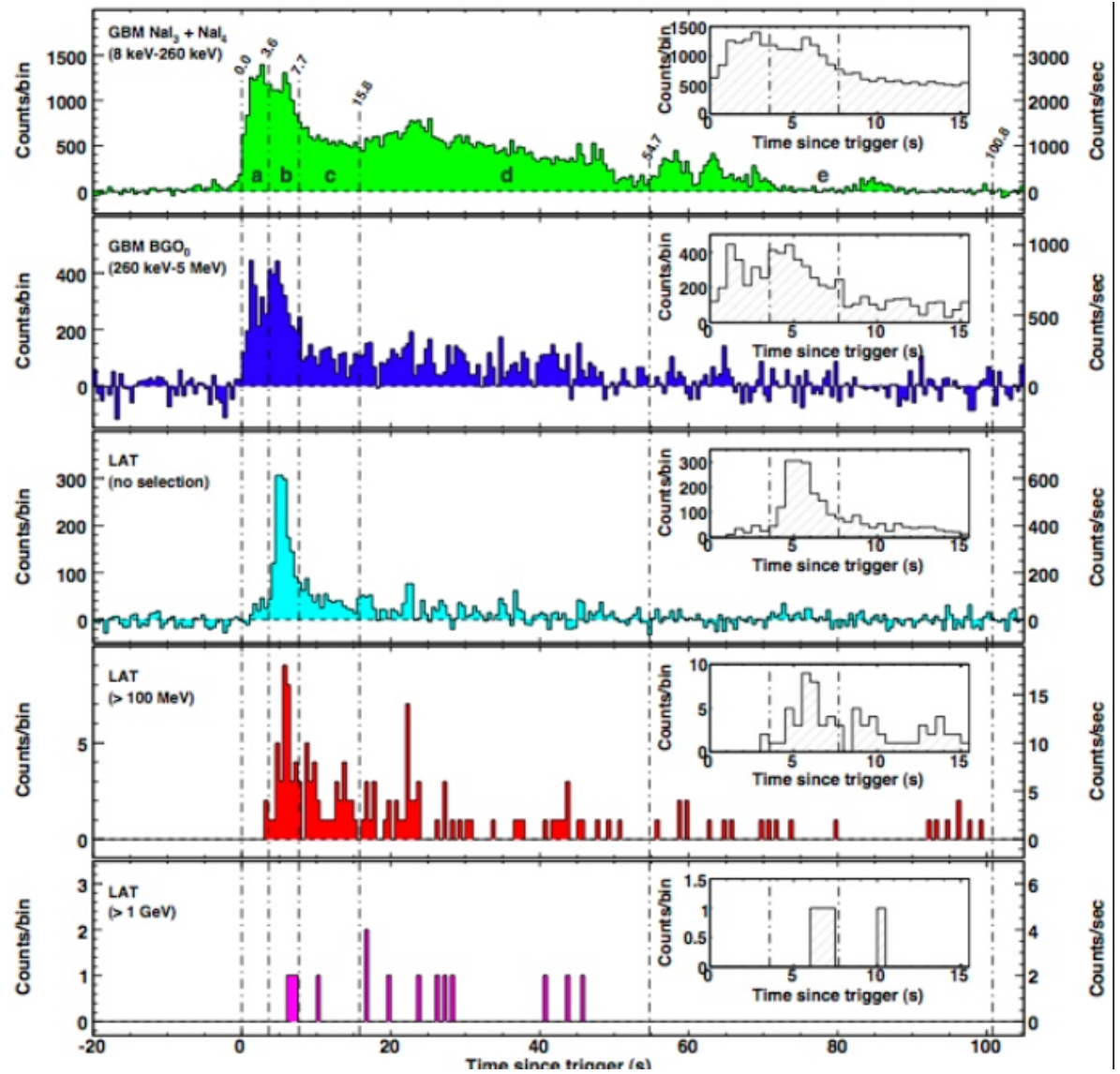


Proposed source
Of the CR

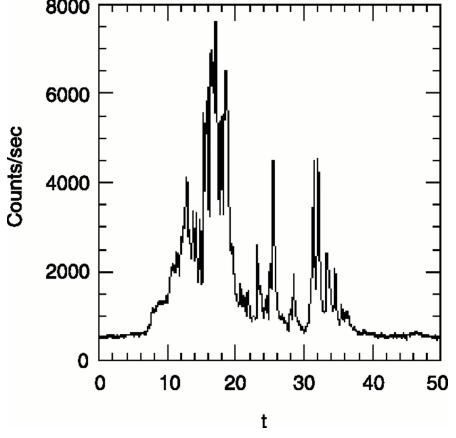
Age of the Universe (billions of years)



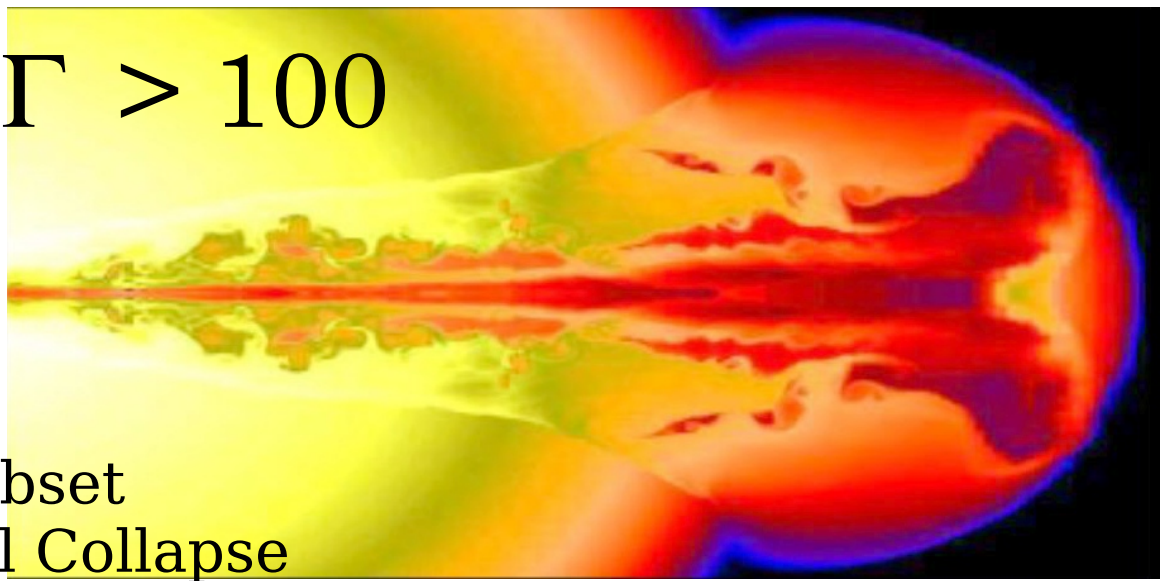
GRB 080916C
 $Z = 4.3$
(Fermi)



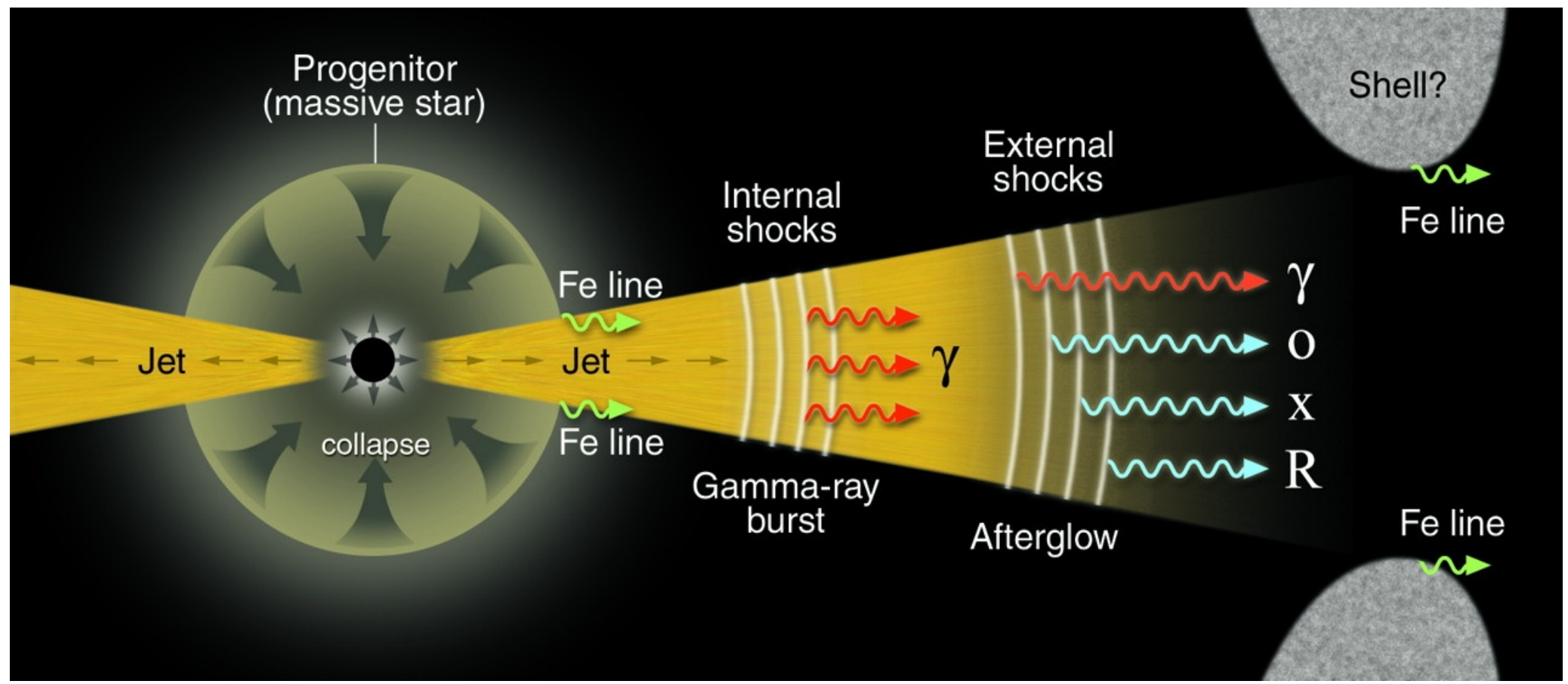
Most Powerful emission of energy
Ever recorded (assuming isotropy)



$\Gamma > 100$



GRB : associated with a subset of SN Stellar Gravitational Collapse



But:

A complete understanding of the mechanism behind GRB's remains elusive.

Their possible role as the source of UHECR (or even of ALL Cosmic Rays) remains only a speculation.

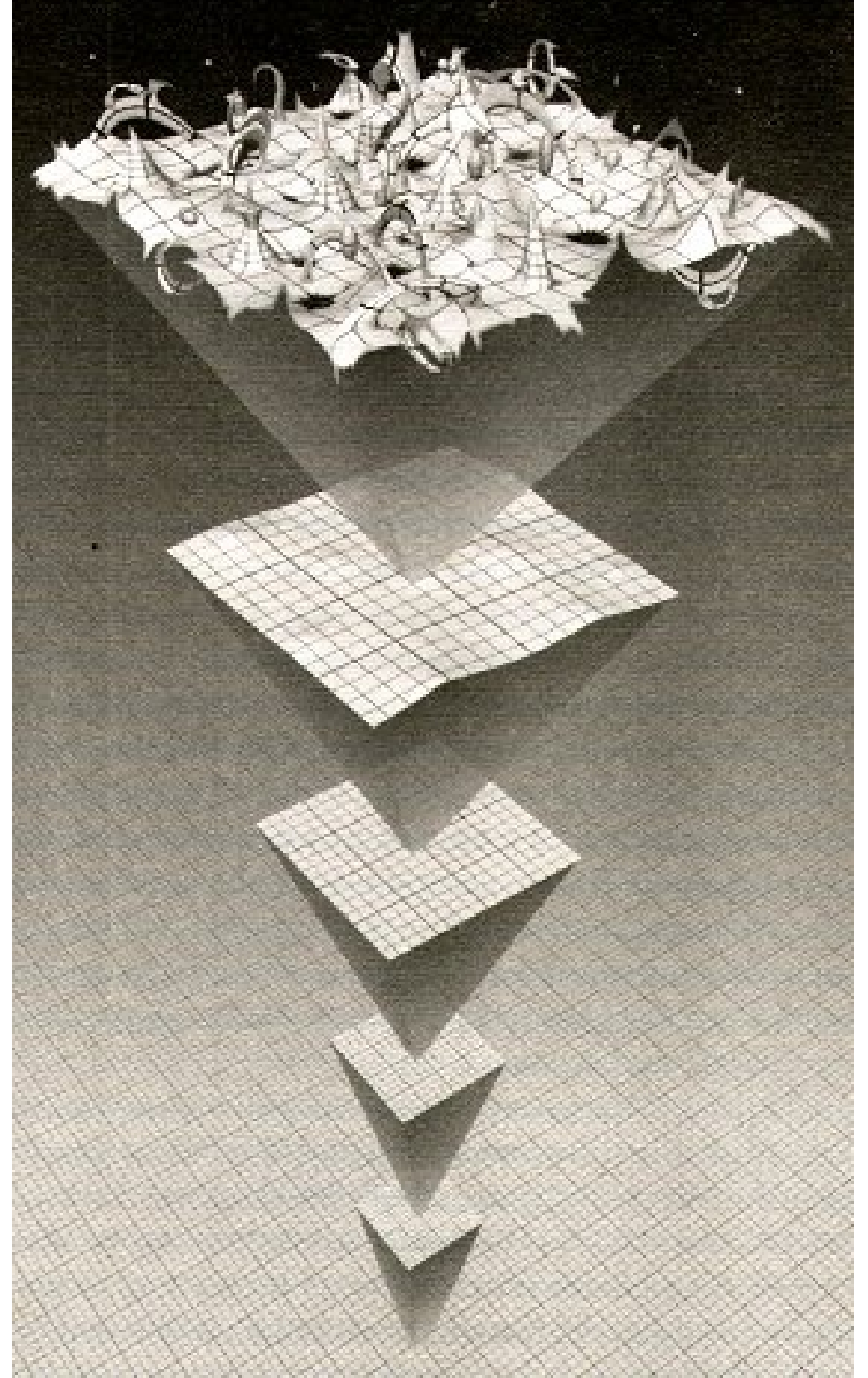
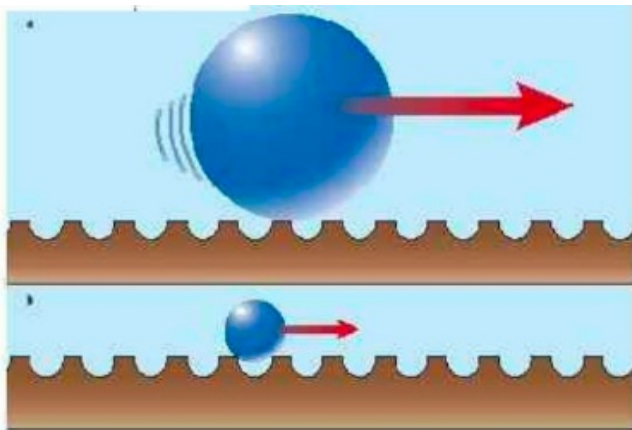
Short distance structure
of space time

$$c(E) = c \times \left(1 - \xi \frac{E}{M_{\text{Planck}}} + \dots \right)$$

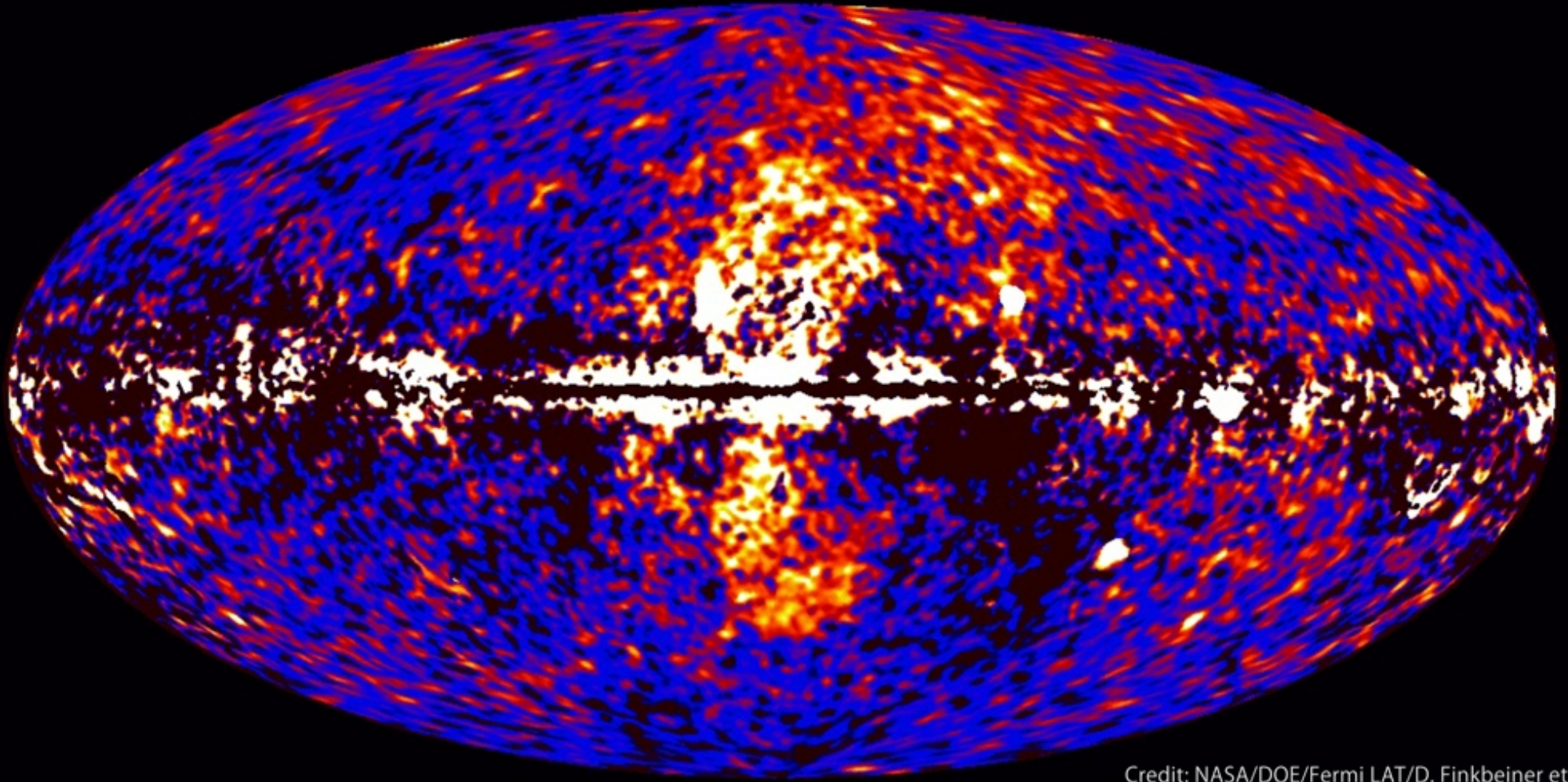
$$\Delta t \simeq \xi \frac{E}{M_{\text{Planck}}} \frac{L}{c}$$

$$\Delta t \simeq 0.06 E_{\text{GeV}} z$$

Delay of high energy photons



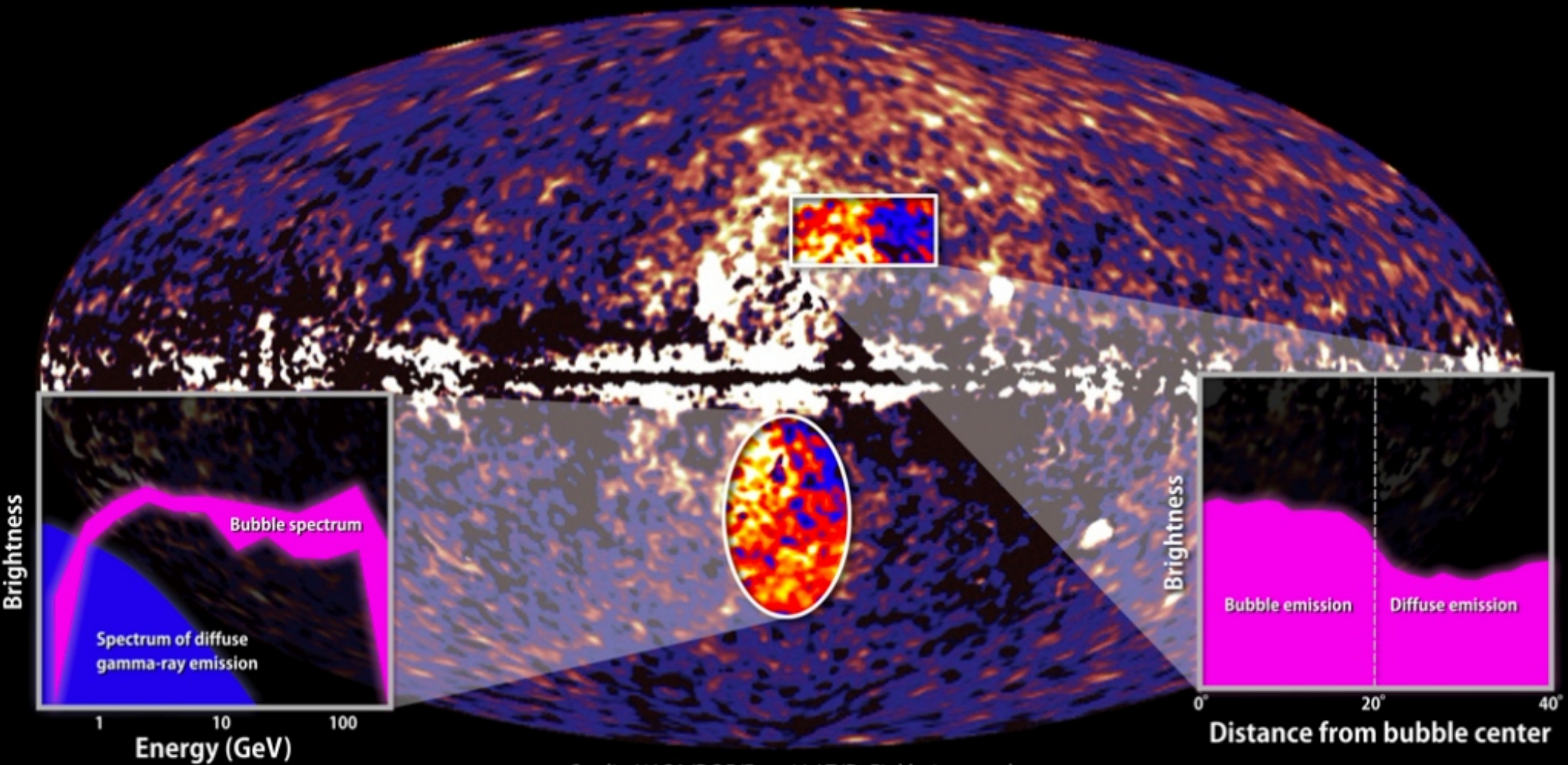
Scientific American news. Title:
**Hidden in Plain Sight: Researchers Find Galaxy-Scale
Bubbles Extending from the Milky Way**



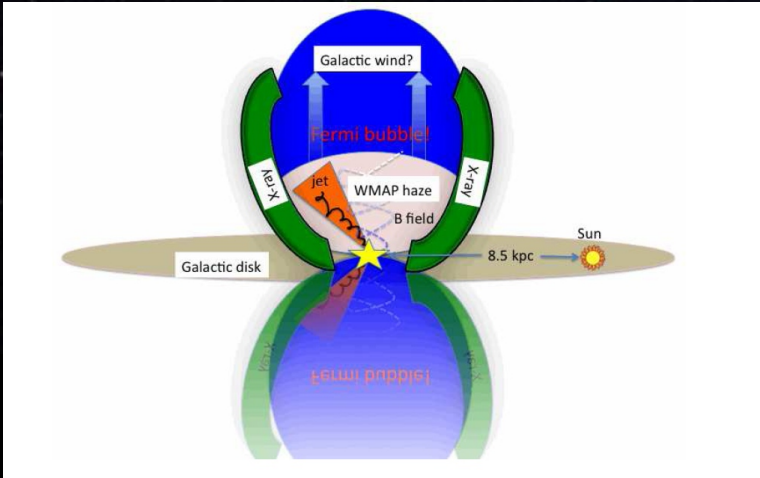
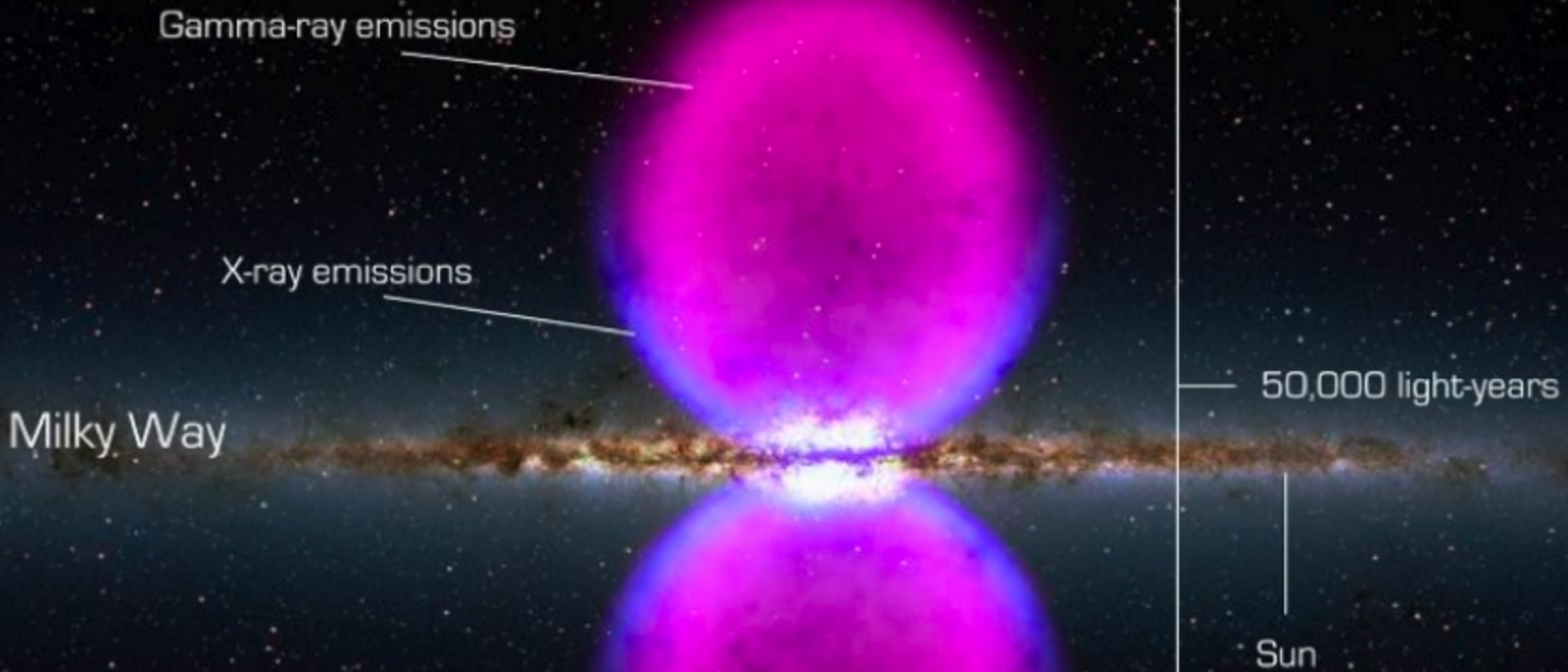
Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

M. Su, T. R. Slatyer, D. P. Finkbeiner,
“Giant Gamma-ray Bubbles from Fermi-LAT: AGN Activity or Bipolar Galactic Wind?,”
Astrophys. J. **724**, 1044-1082 (2010). [[arXiv:1005.5480](https://arxiv.org/abs/1005.5480) [astro-ph.HE]].

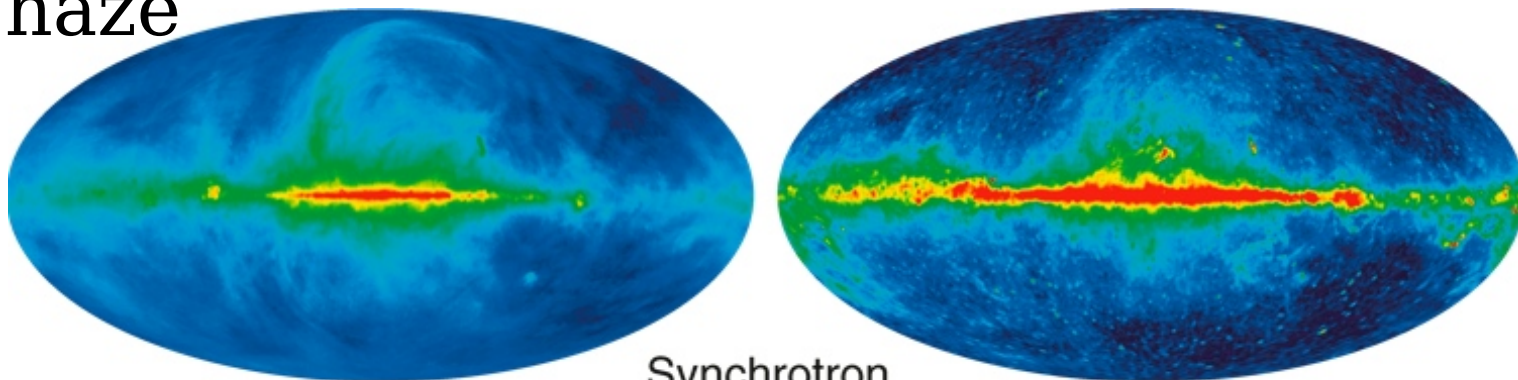
Bubbles show energetic spectrum and sharp edges



Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

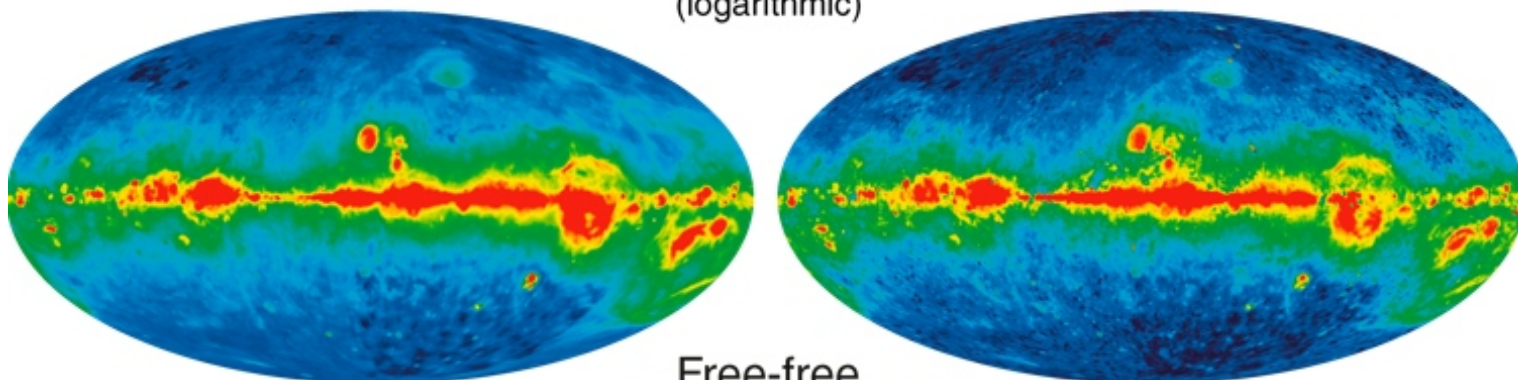


WMAP "haze"



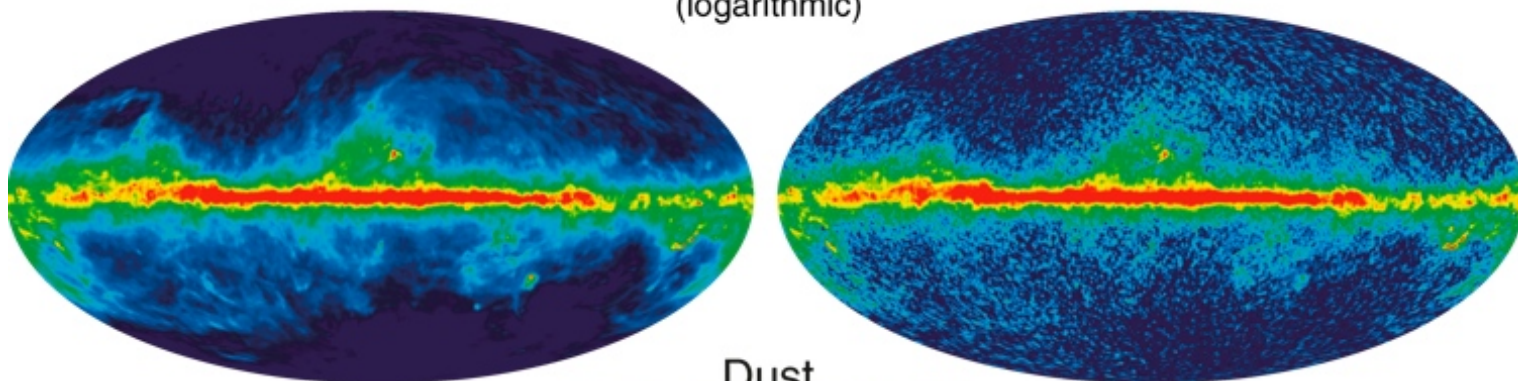
Synchrotron

30 $T_A(\mu\text{K})$ @ K-band 3000
(logarithmic)



Free-free

0.5 $T_A(\mu\text{K})$ @ K-band 1500
(logarithmic)

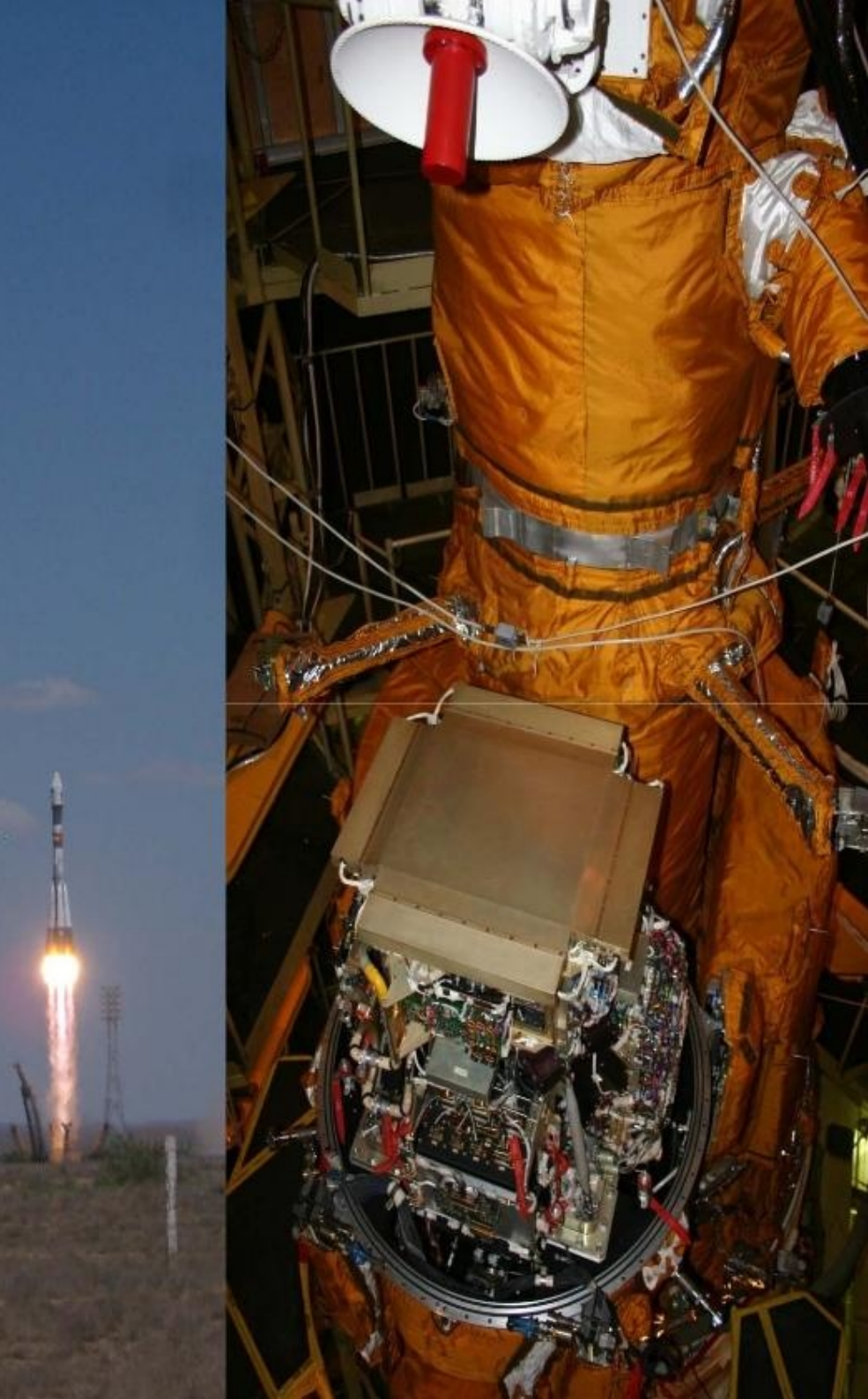


Dust

3 $T_A(\mu\text{K})$ @ W-band 300
(logarithmic)



The origin and implications
of the “Fermi Bubbles”
remain very open problems



PAMELA

detector

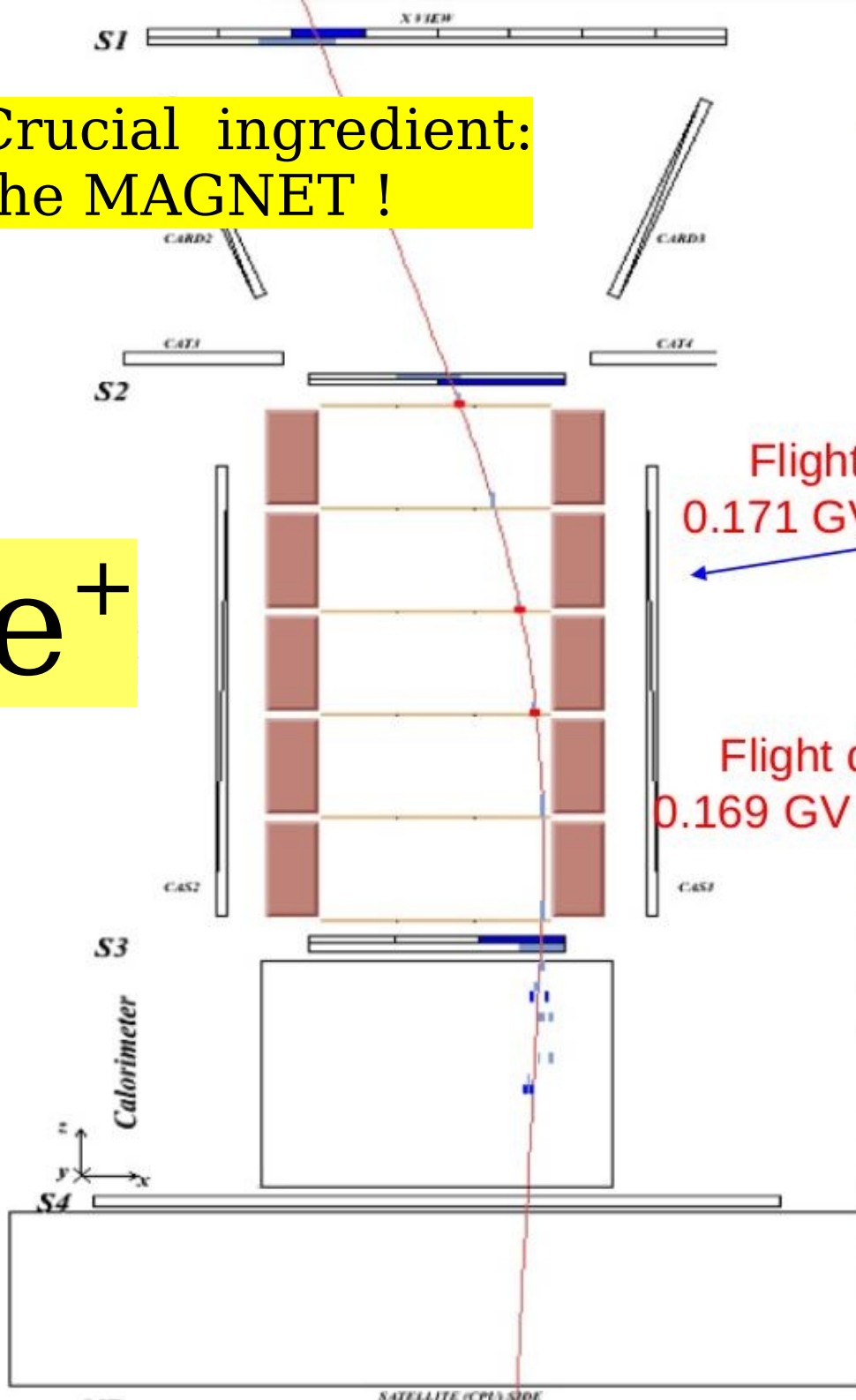
Launch

15th june 2006

The “positron excess”:
Evidence for DM ??
or astrophysical effect ?

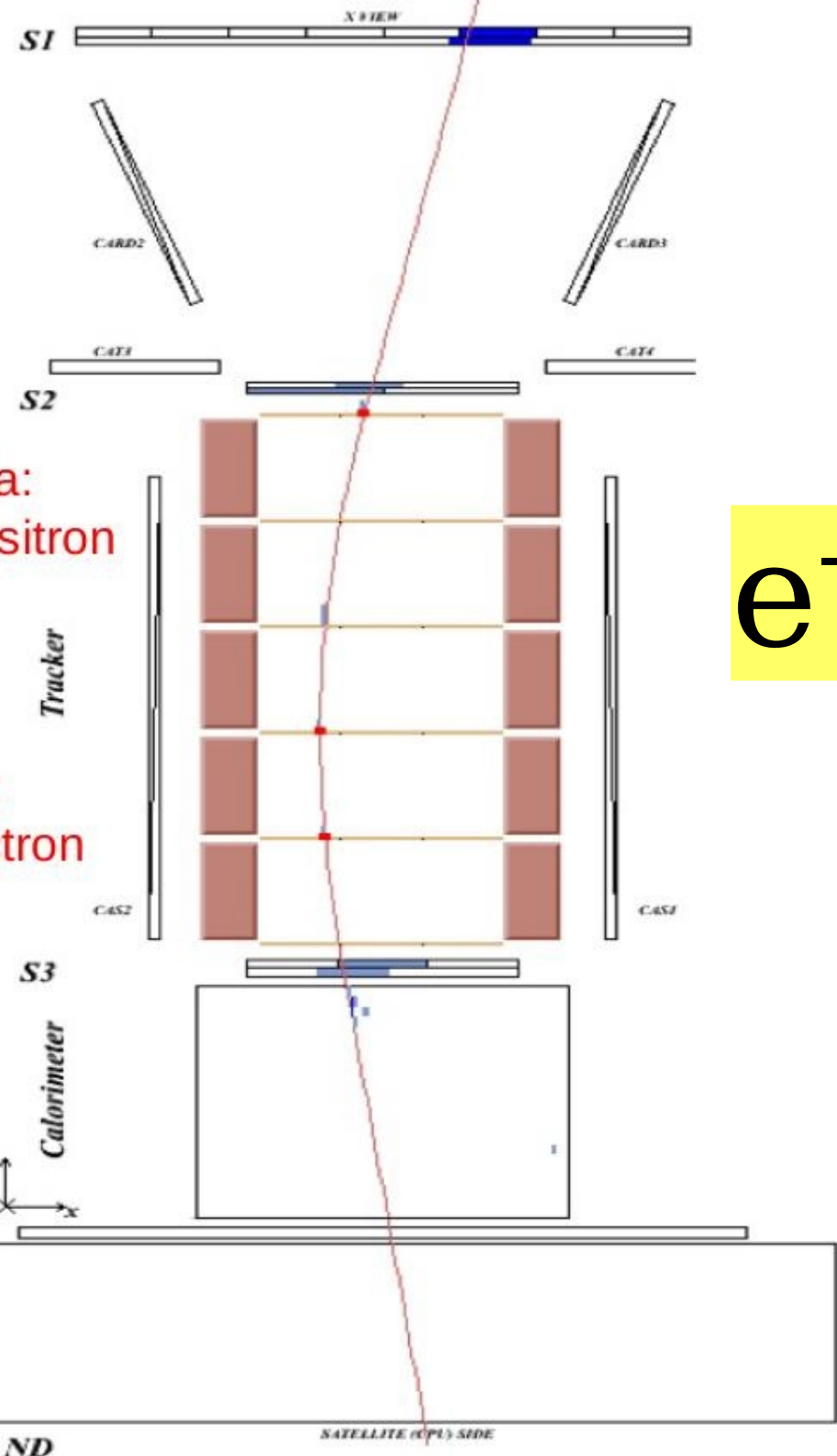
Crucial ingredient:
the MAGNET !

e^+



Flight data:
0.171 GV positron

Flight data:
0.169 GV electron



e^-

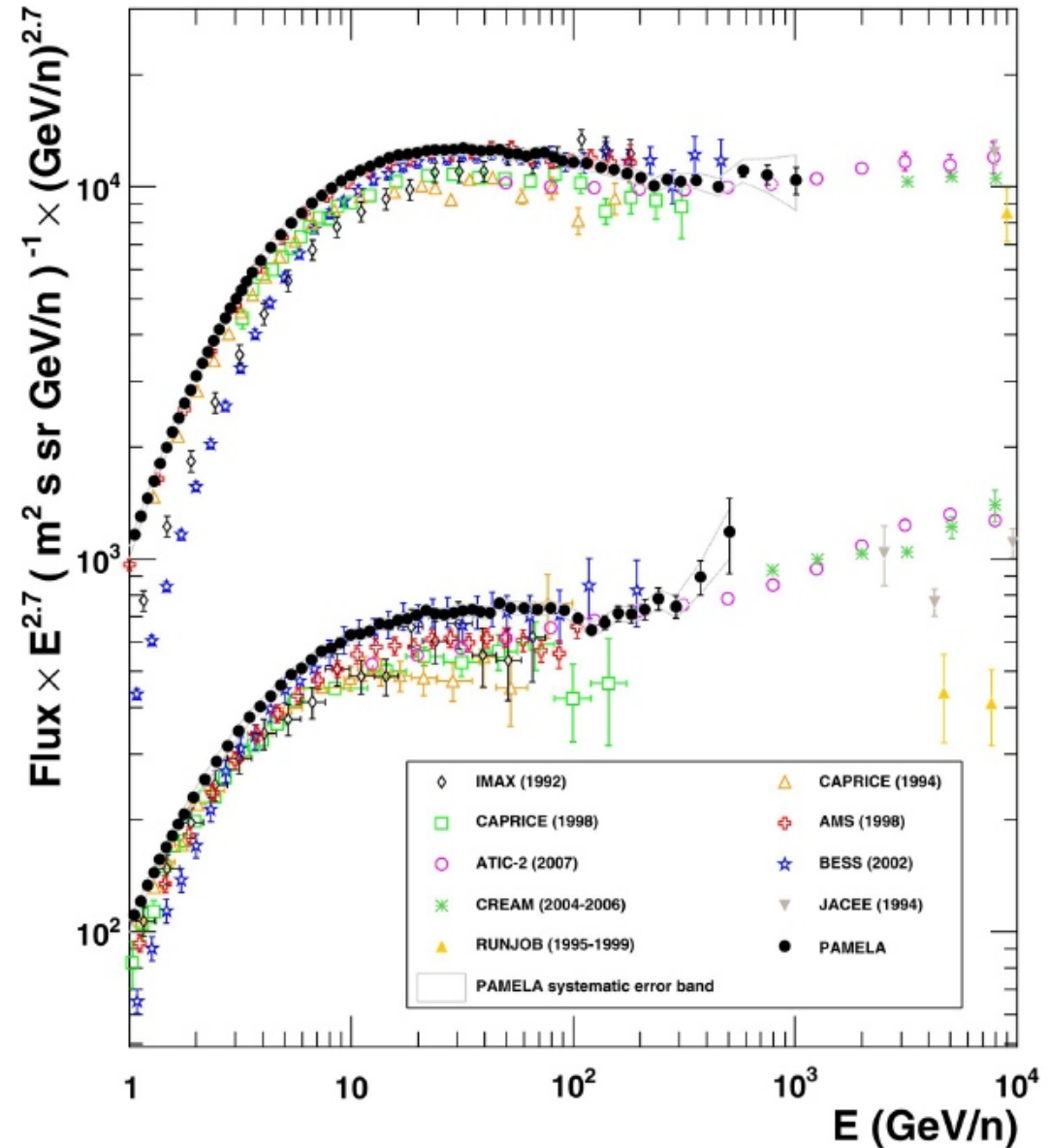
ND

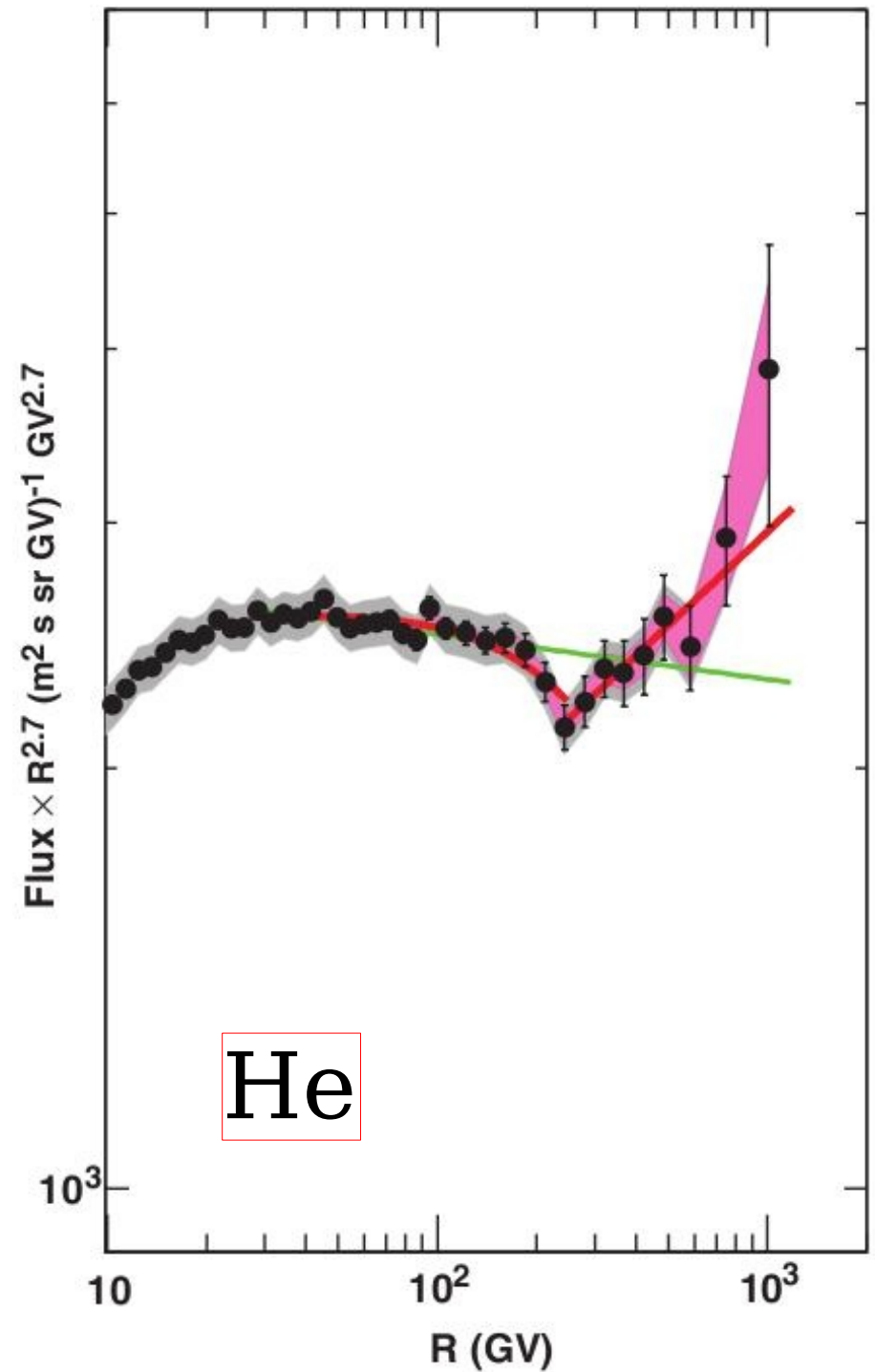
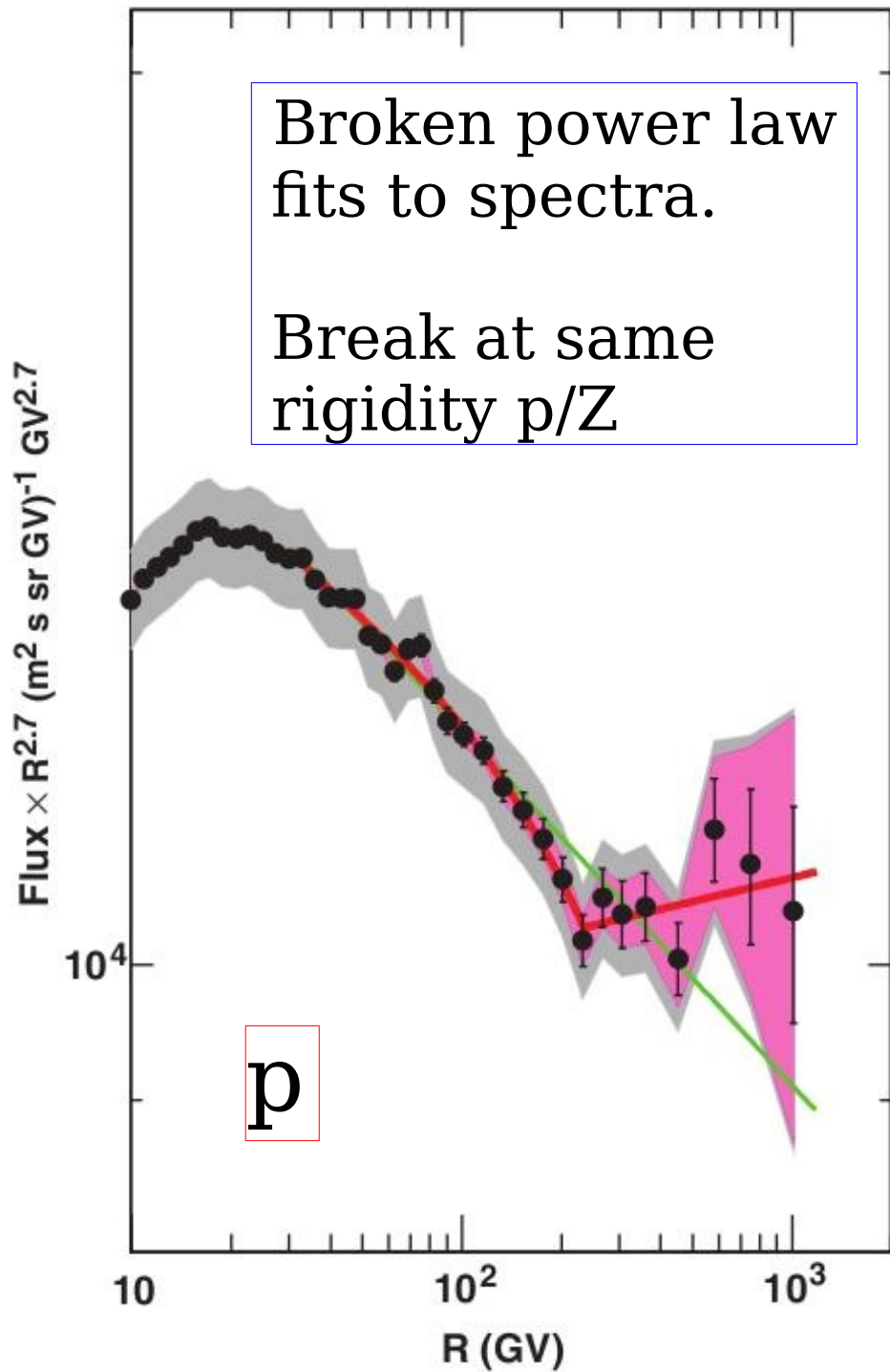
PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra

Proton/Helium
CR fluxes

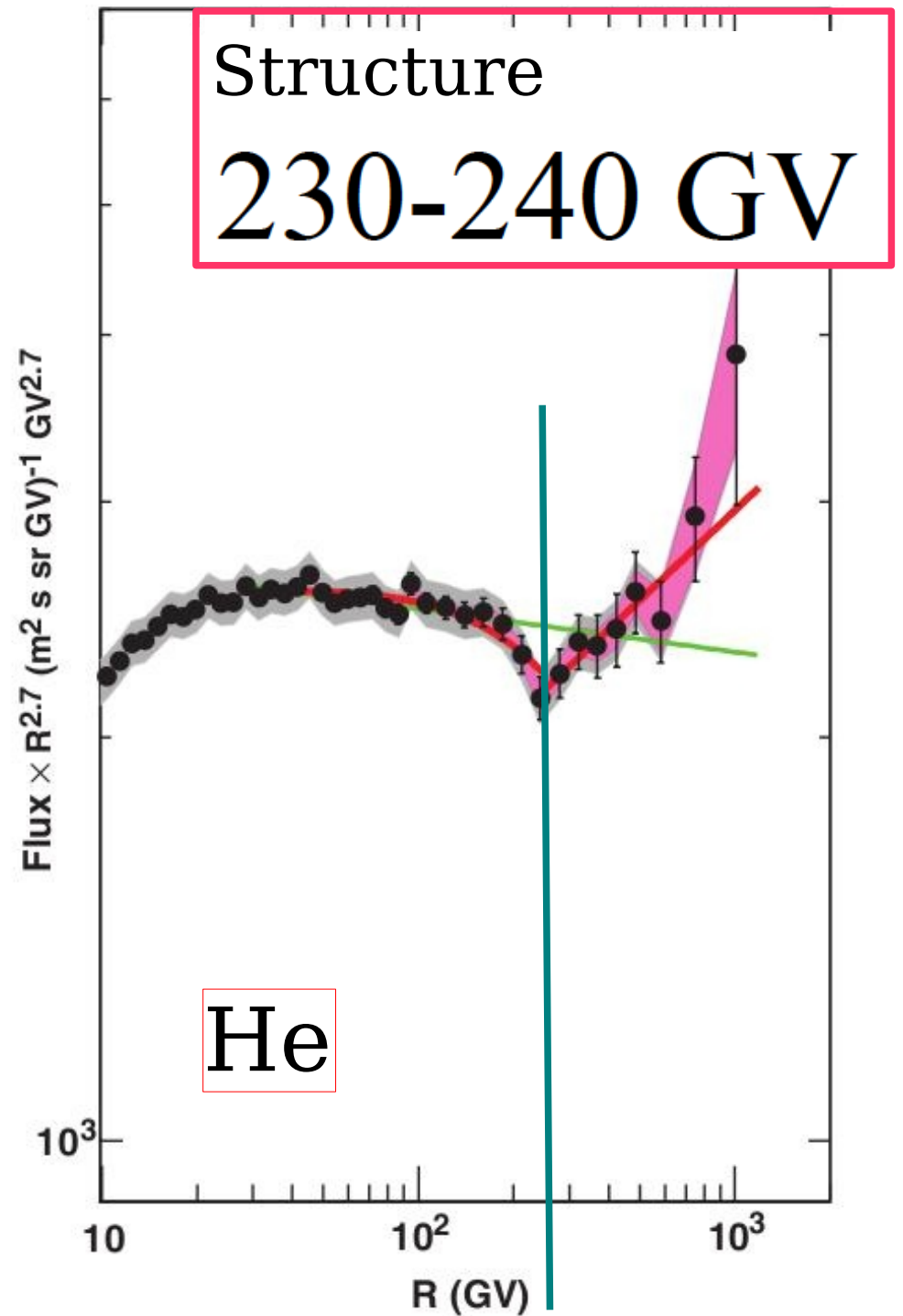
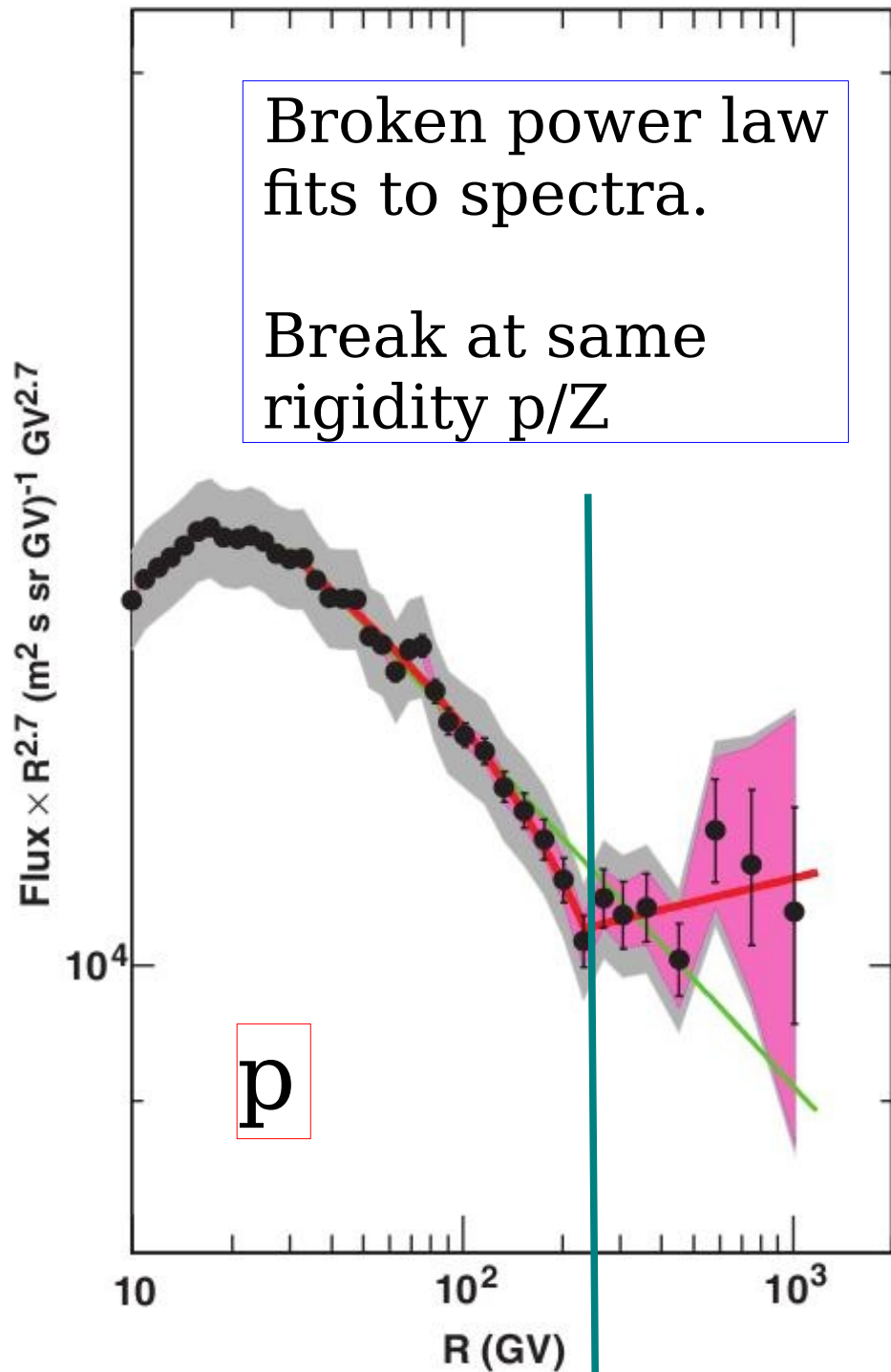
1 GV - 1.2 TV

Science vol. 332
(1st april 2011)

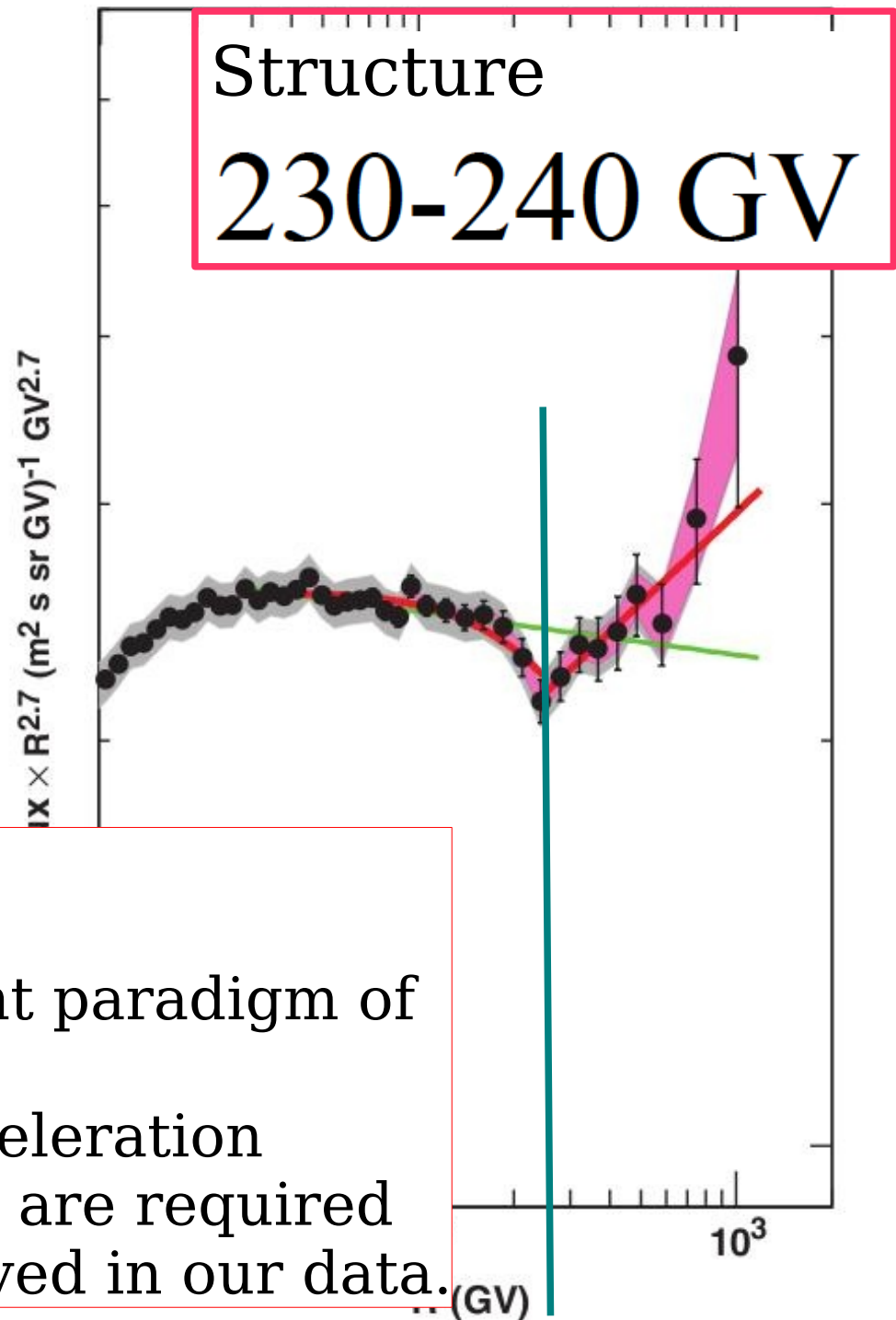
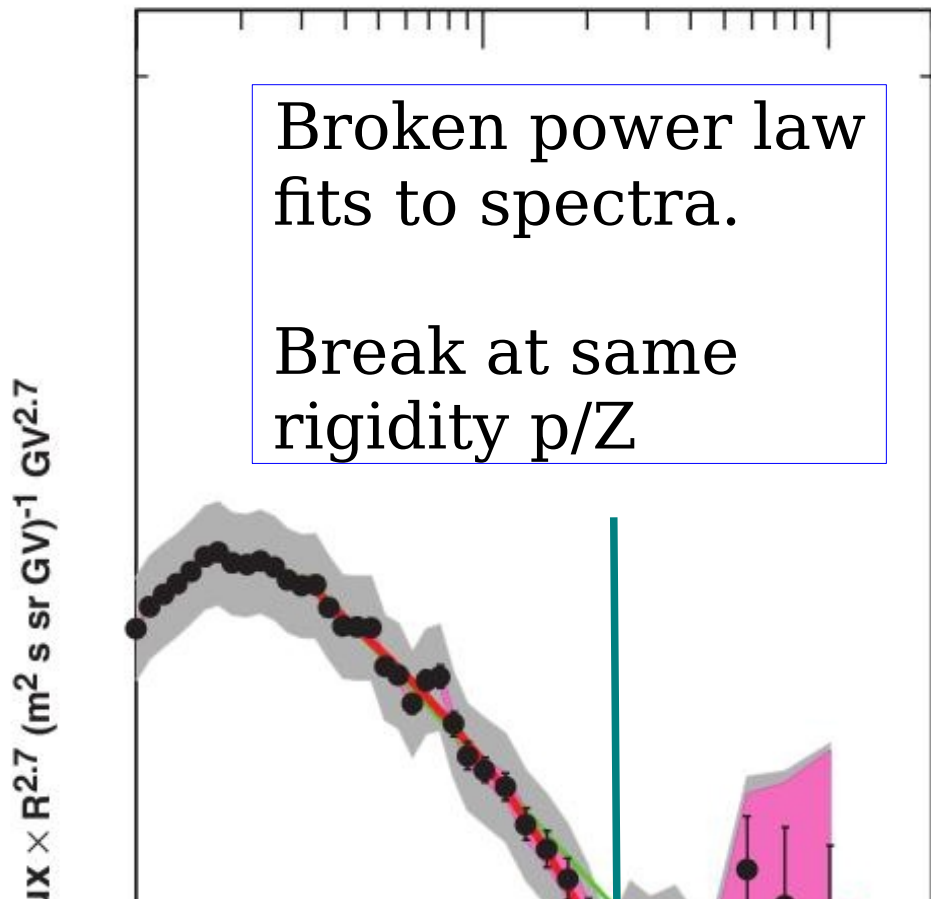




Surprising and important result.



Surprising and important result.



From the abstract of the paper:

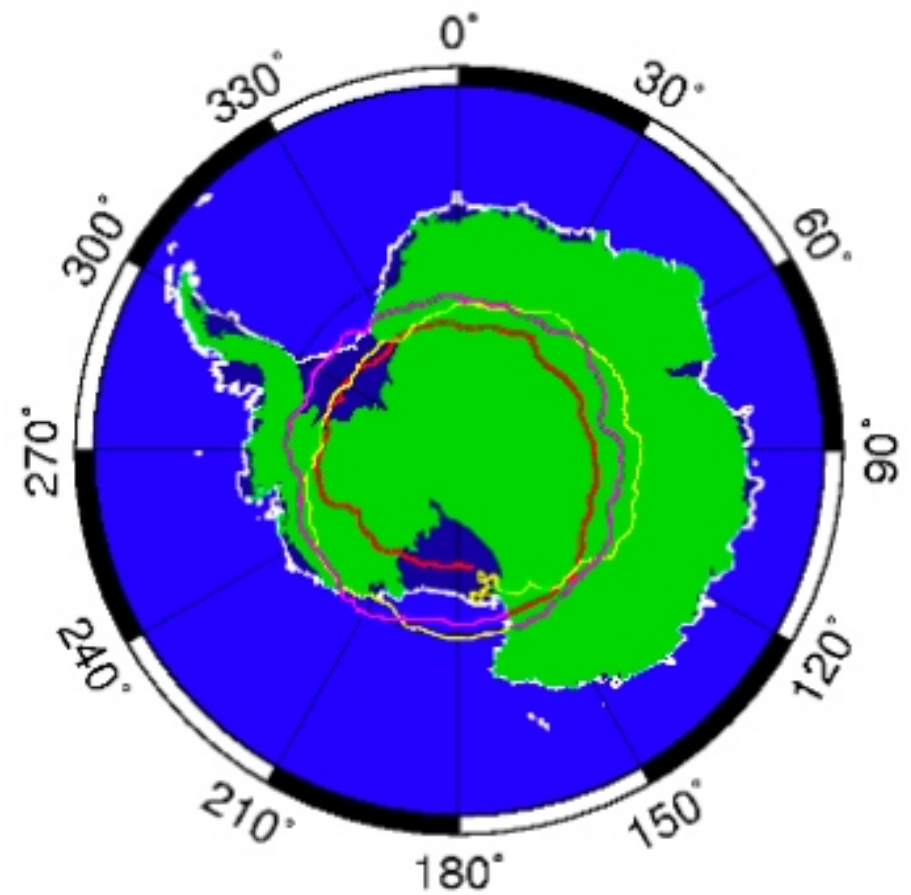
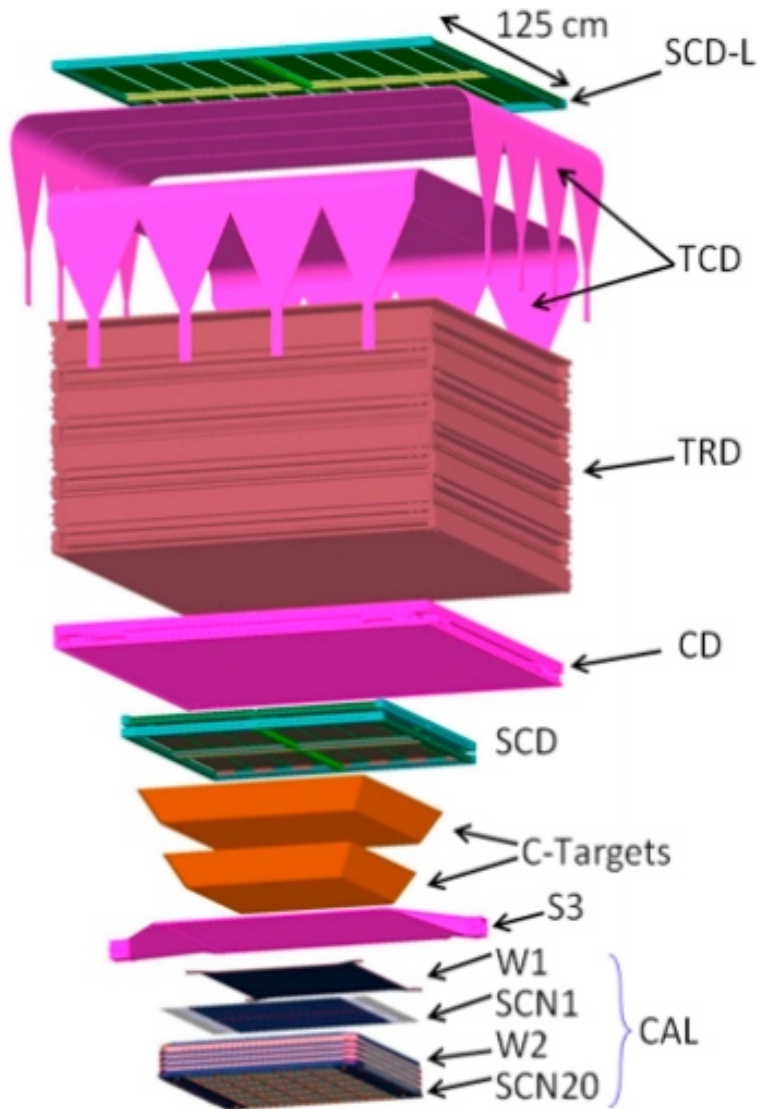
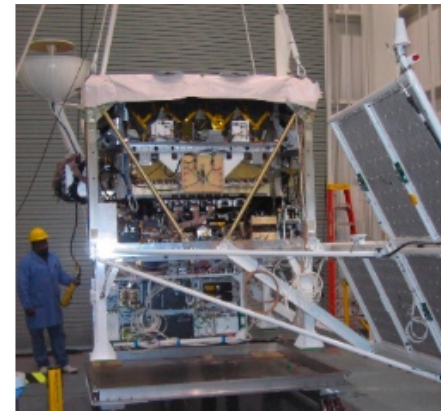
These data challenge the current paradigm of cosmic ray acceleration. [...]

More complex processes of acceleration and propagation of cosmic rays are required to explain the structures observed in our data.

Surprising and important result.

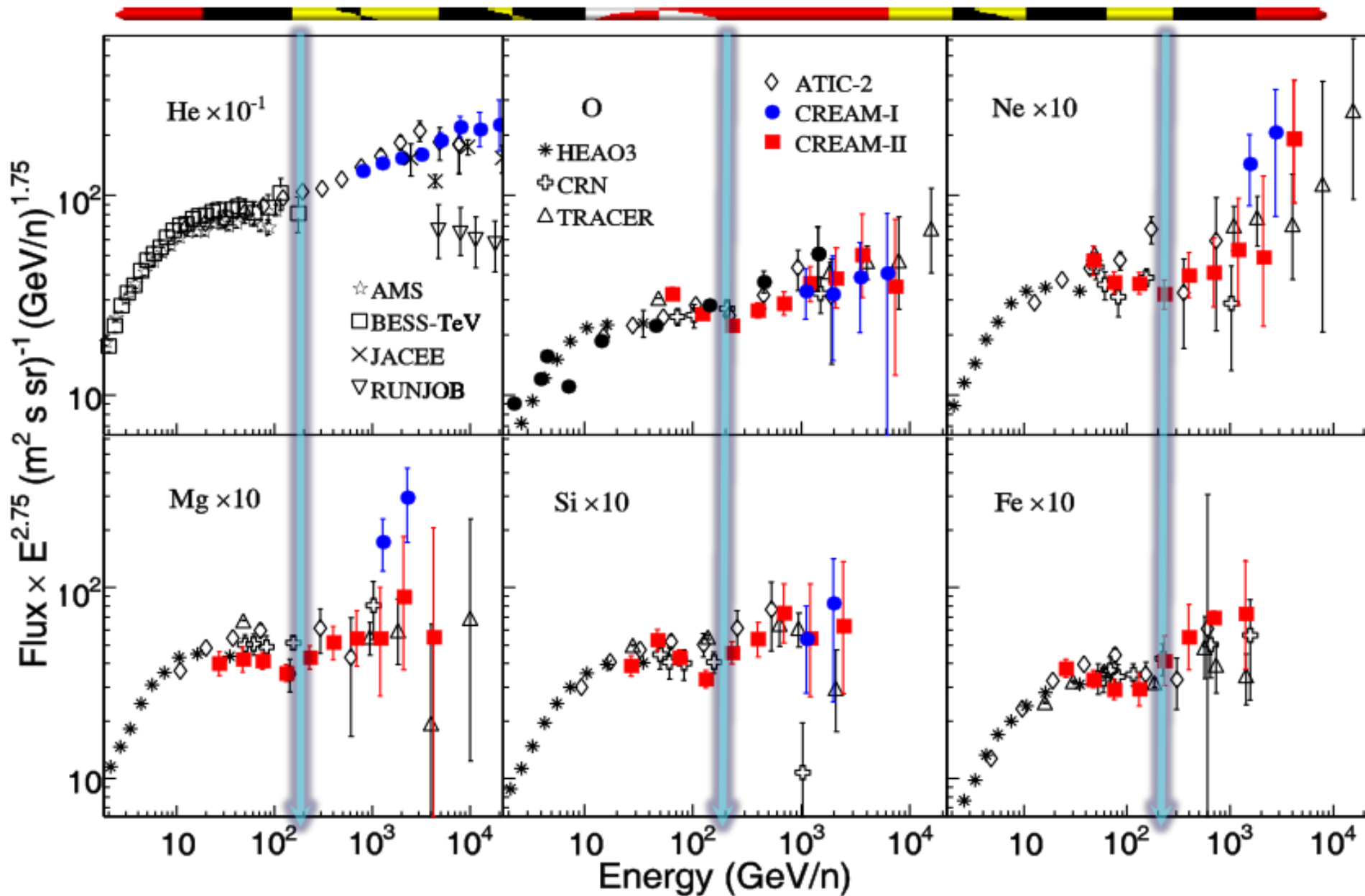
CREAM (calorimeter on balloon)

(5 flights in Antarctica. Total of 156 days)



Cream 5 trajectory
37 days 12/2009-01/2010

Discrepant hardening

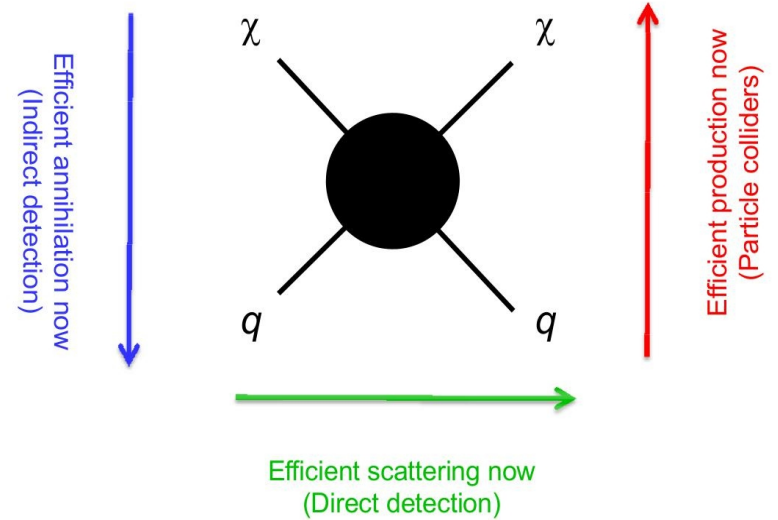


DARK

MATTER

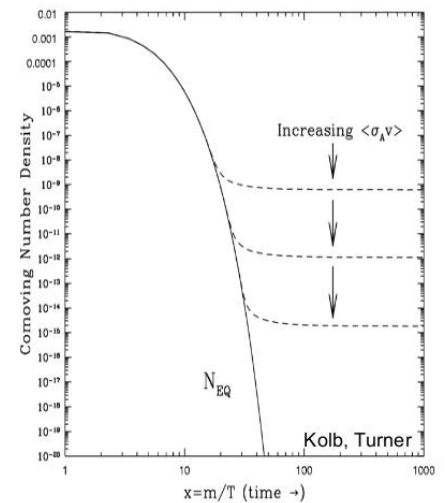
Three roads to the study of the “WIMP” hypothesis:

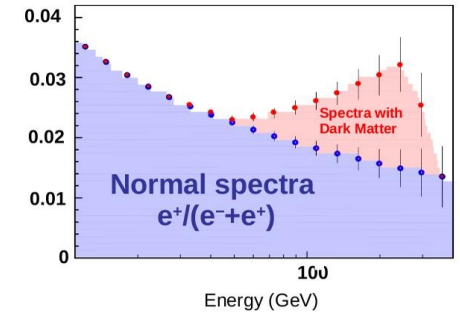
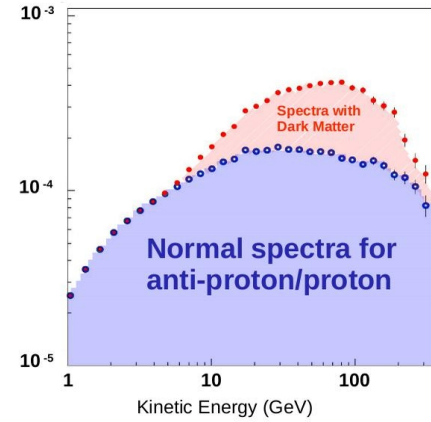
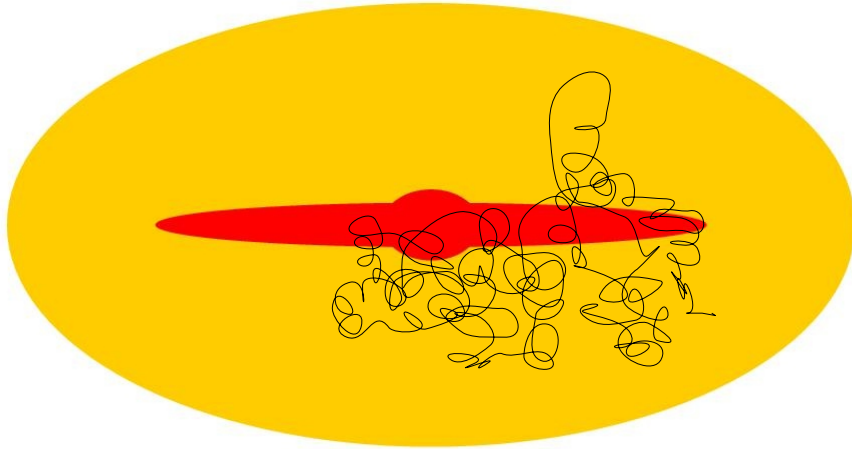
1. Direct Detection
2. Indirect Detection
[Observation of annihilation products
In our own Galaxy]
3. Discovery of a new stable particle
In an accelerator [LHC]



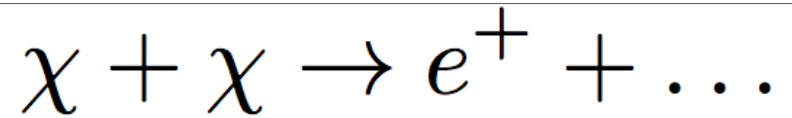
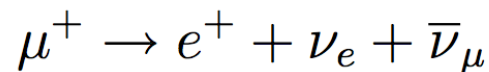
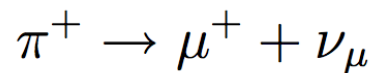
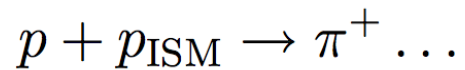
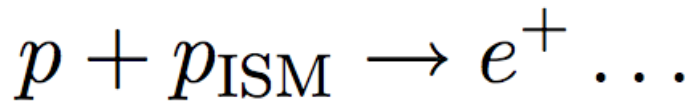
$$\Omega_j^0 \simeq 0.3 \left[\frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle} \right]$$

$$L(\vec{x}) = \frac{\rho(\vec{x})^2}{M_\chi^2} \langle \sigma v \rangle M_\chi$$





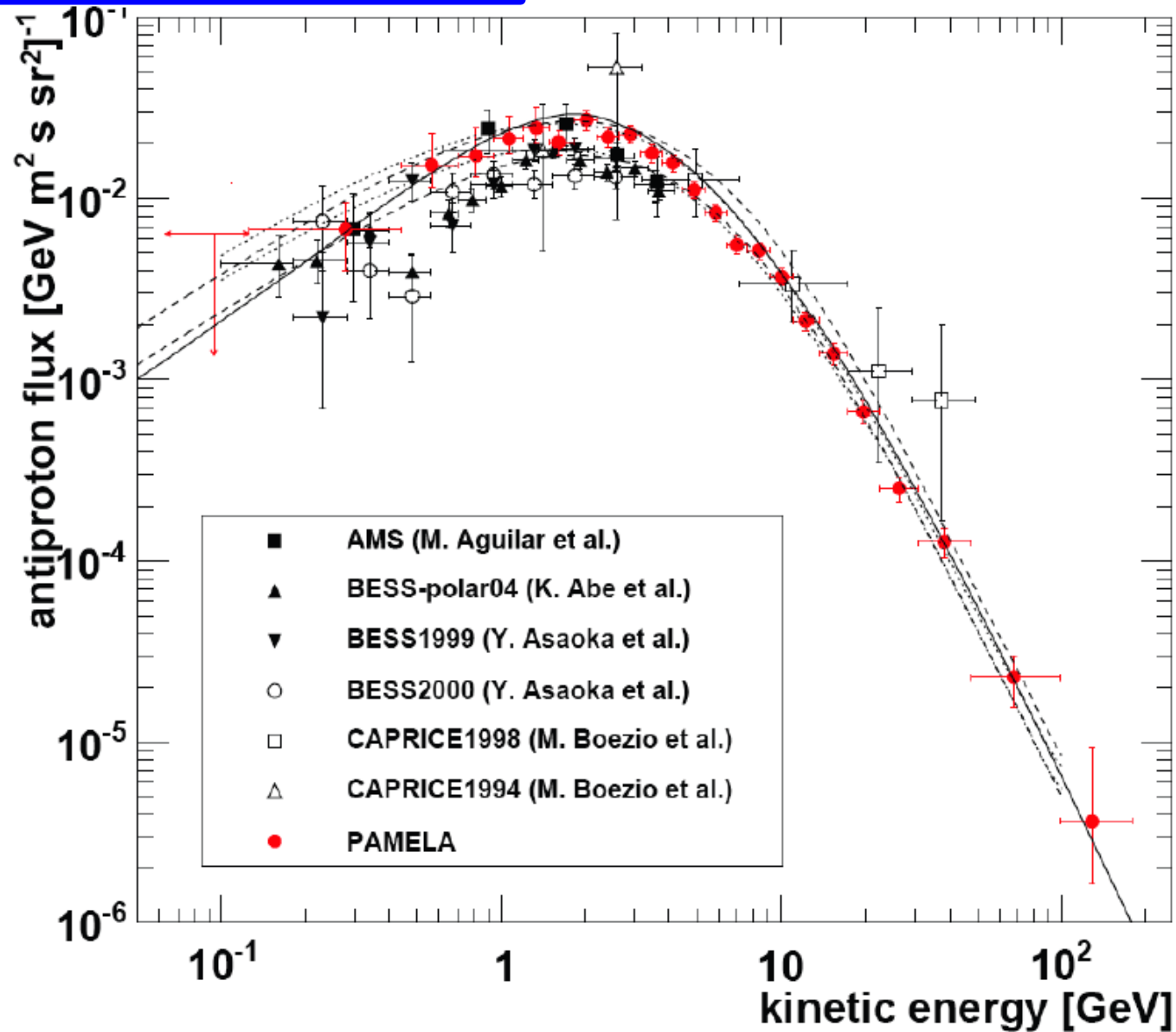
SOURCE(s) + Propagation → Observable Cosmic Rays



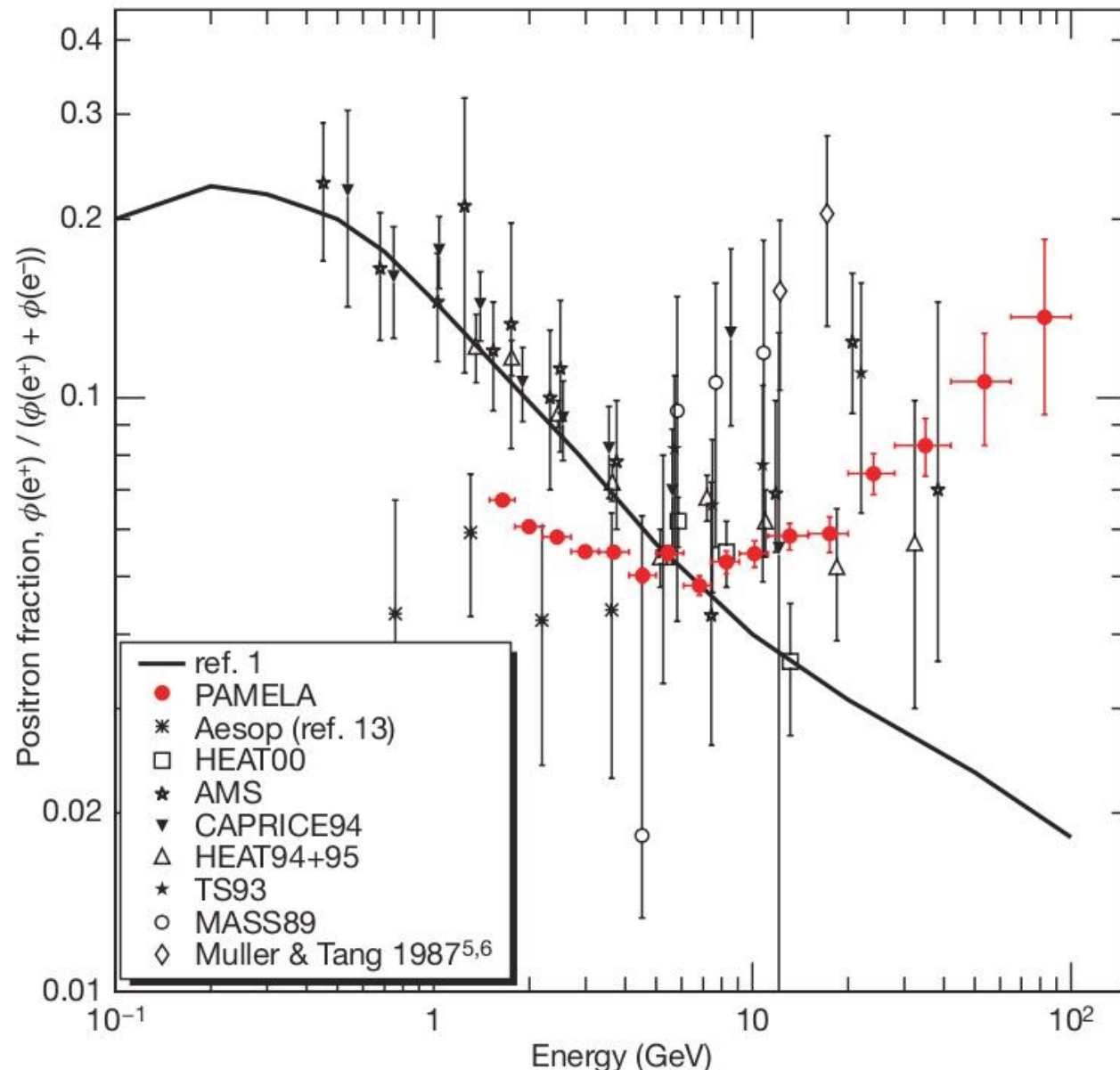
Possible
positron accelerators

PAMELA Antiproton result

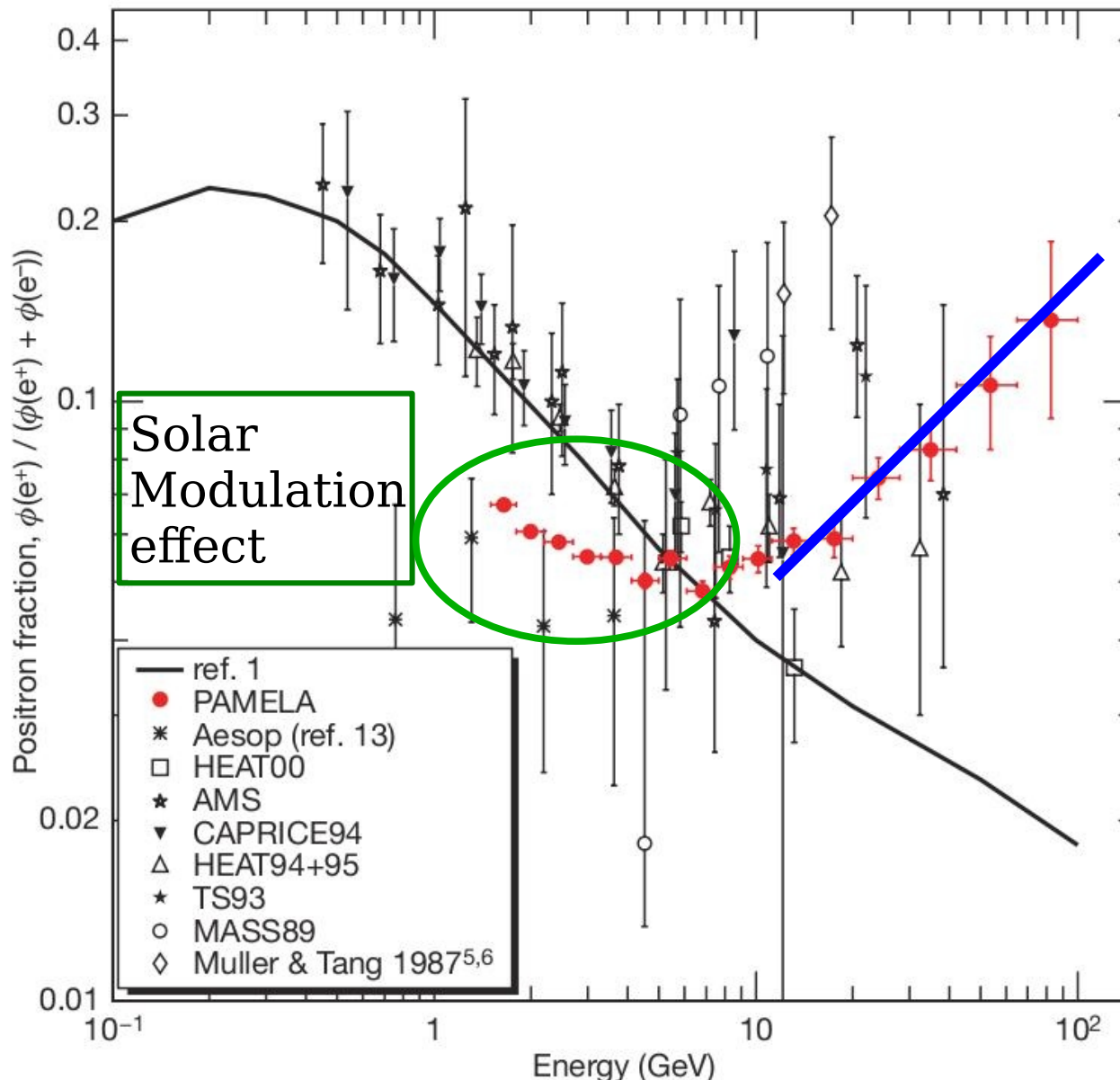
Agreement with
Standard production
Mechanism



An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV



An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

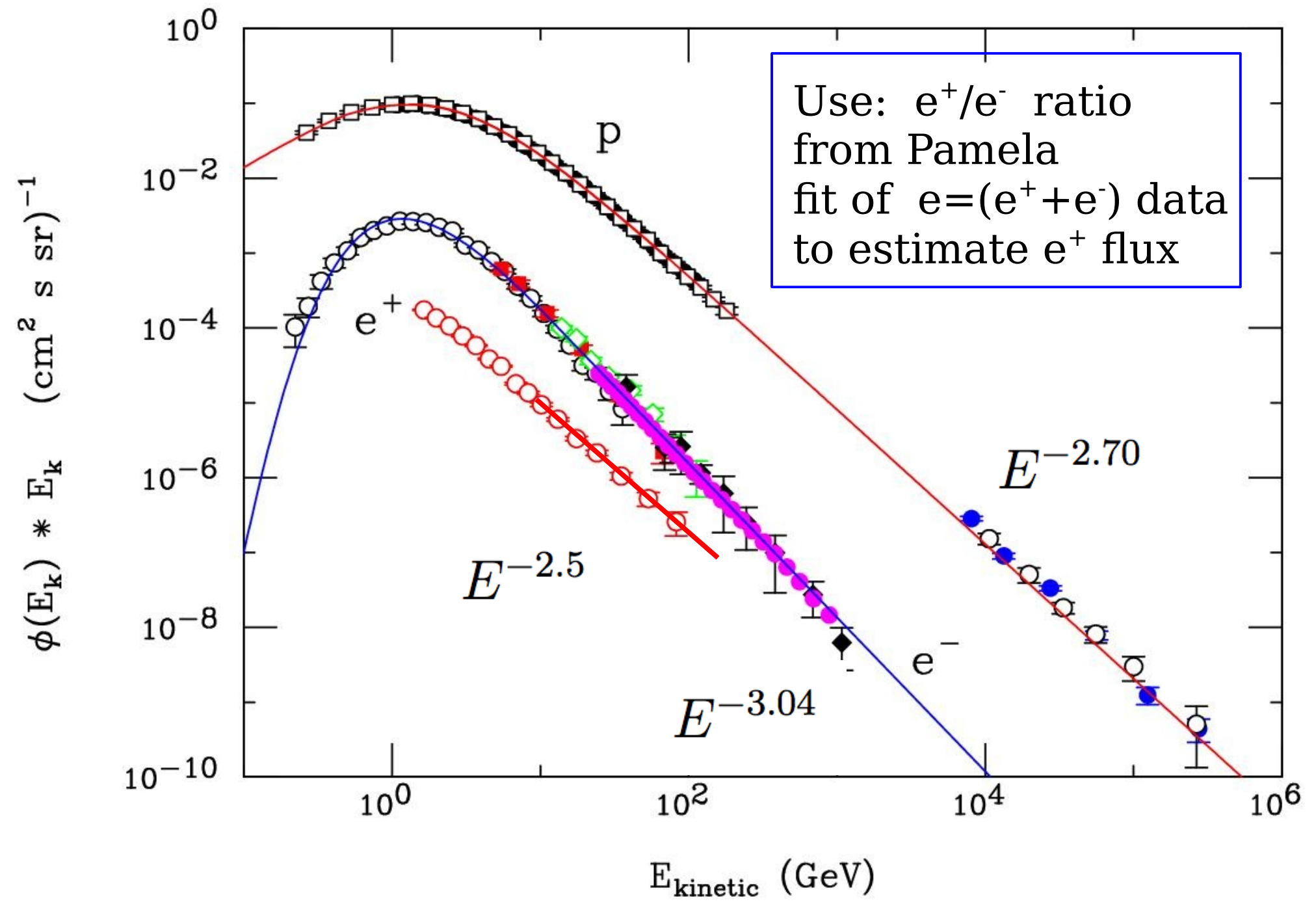


High energy:
ratio e^+/e^-
grow with E !!

$$\frac{\phi_{e^+}}{\phi_{e^-}} \propto E^{0.52}$$

Very unexpected
result !

Proton and electron + Positron energy spectra



Spectra approximately of form:

protons

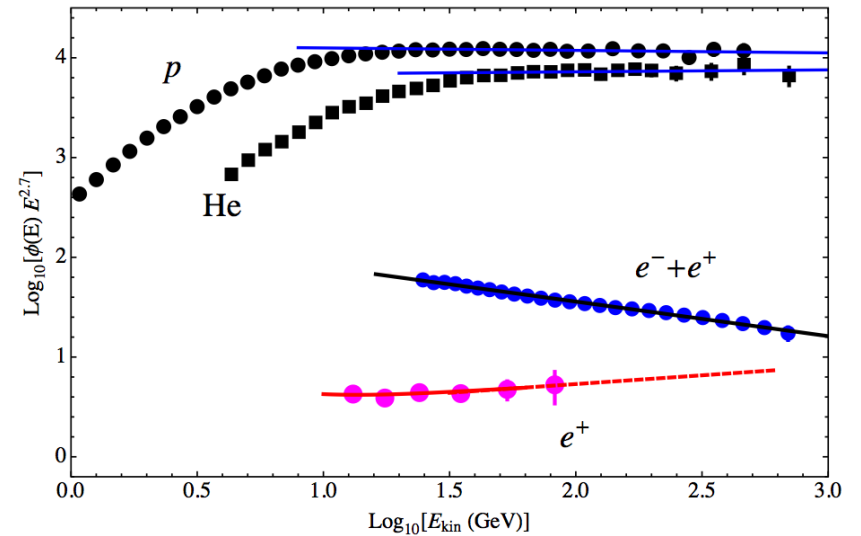
$$E^{-2.70}$$

electrons

$$E^{-3.04}$$

positrons

$$E^{-2.5}$$



$$E^{-3.1}$$

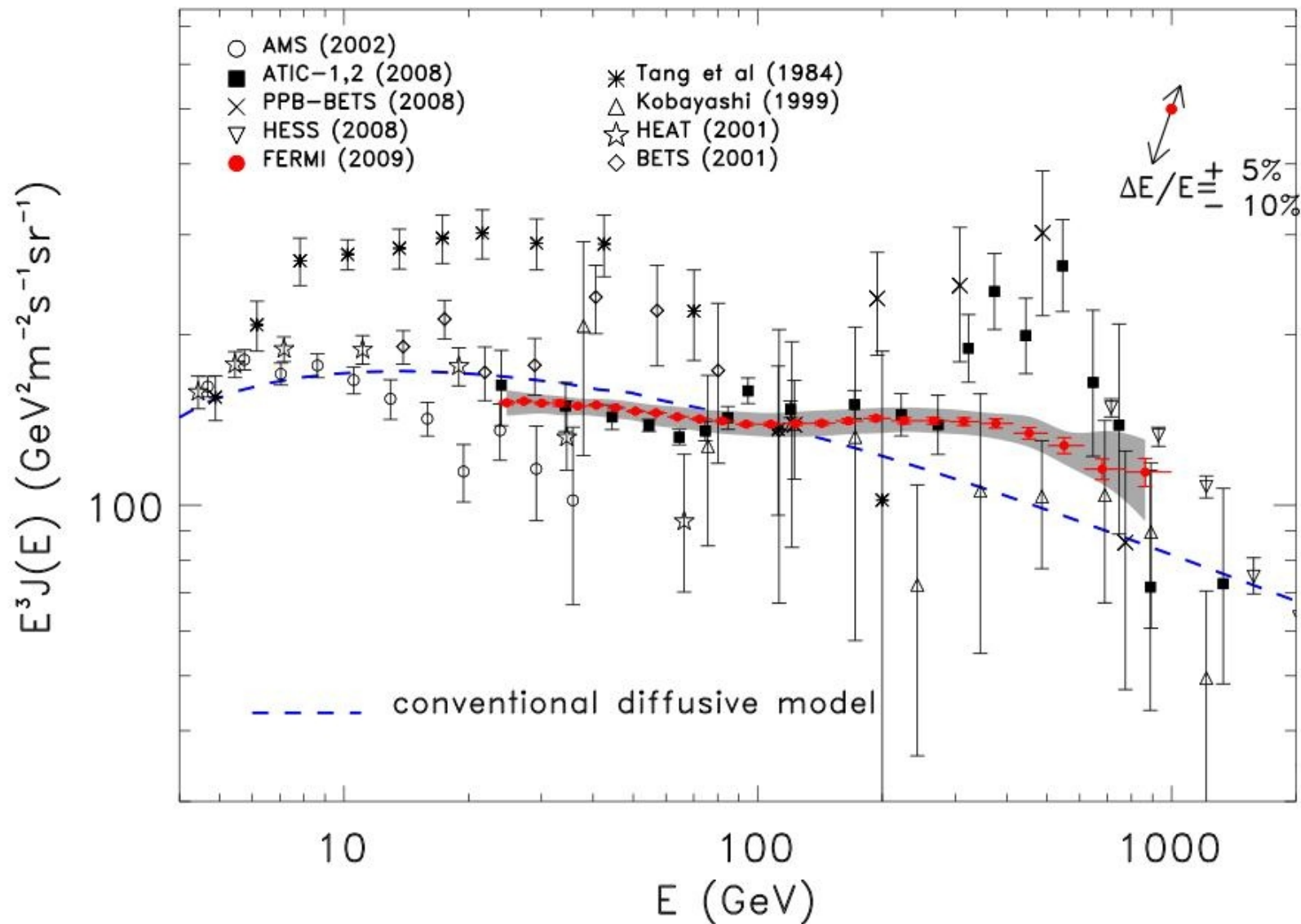
$$E^{-3.5}$$

Completely unexpected result

[Additional source of positrons
(or positrons + electrons)]

Rough expectation
For the positron slope
SOFTER than electrons

FERMI: electron + positron flux



“Room” for
Extra- component ! Dark Matter ??!

From : Cirelli

Results

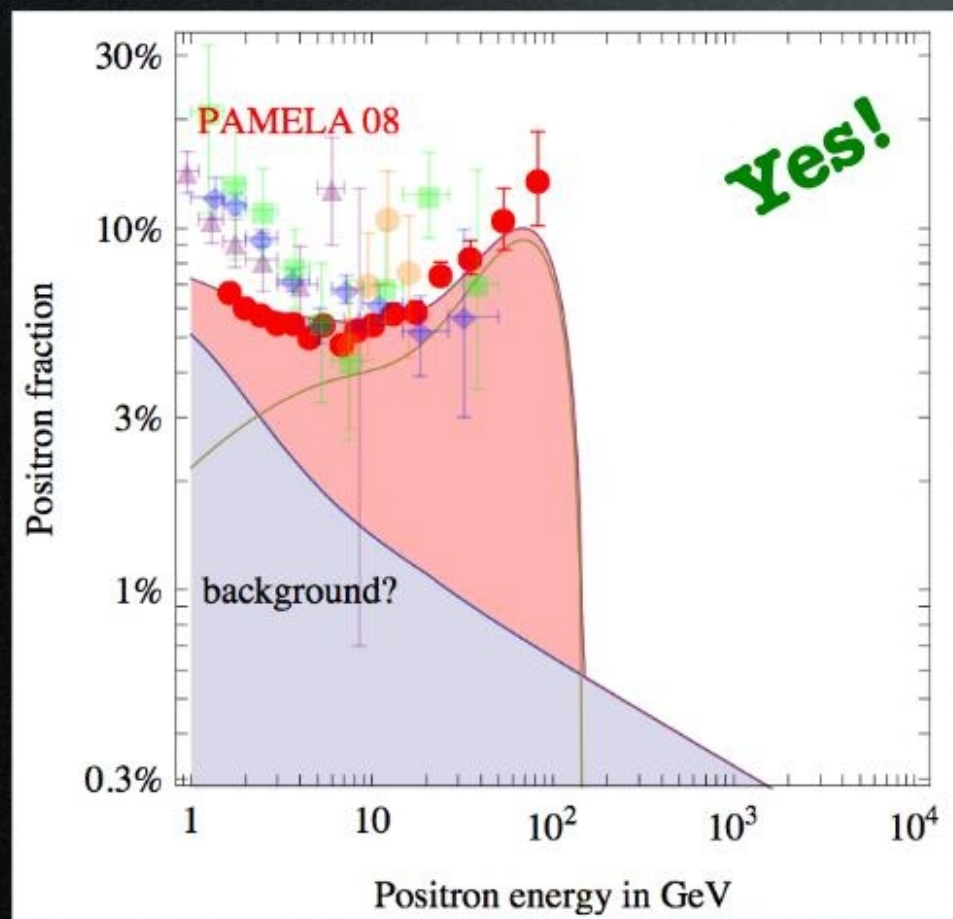
Which DM spectra can fit the data?

E.g. a DM with: -mass $M_{\text{DM}} = 150 \text{ GeV}$

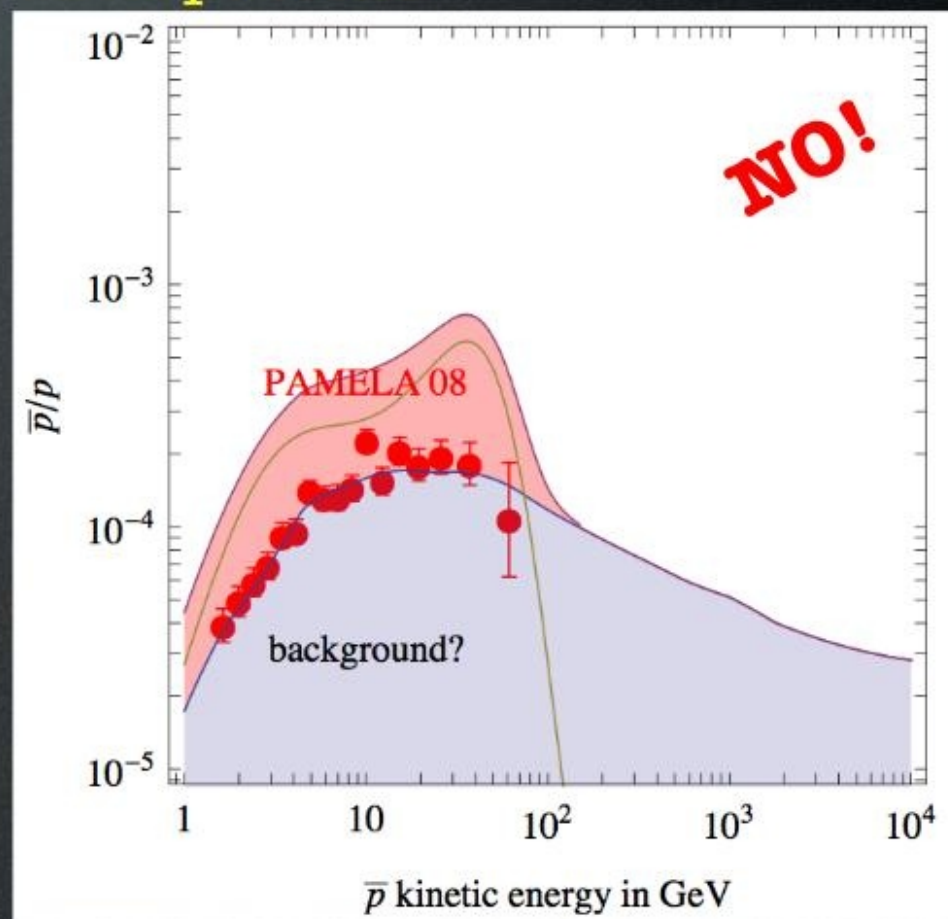
-annihilation $\text{DM DM} \rightarrow W^+W^-$

(a possible SuperSymmetric candidate: wino)

Positrons:



Anti-protons:



Dark Matter explanation of the
“Pamela positron excess” in terms of the
“WIMP” model is possible, but not in its
simplest, most natural version.

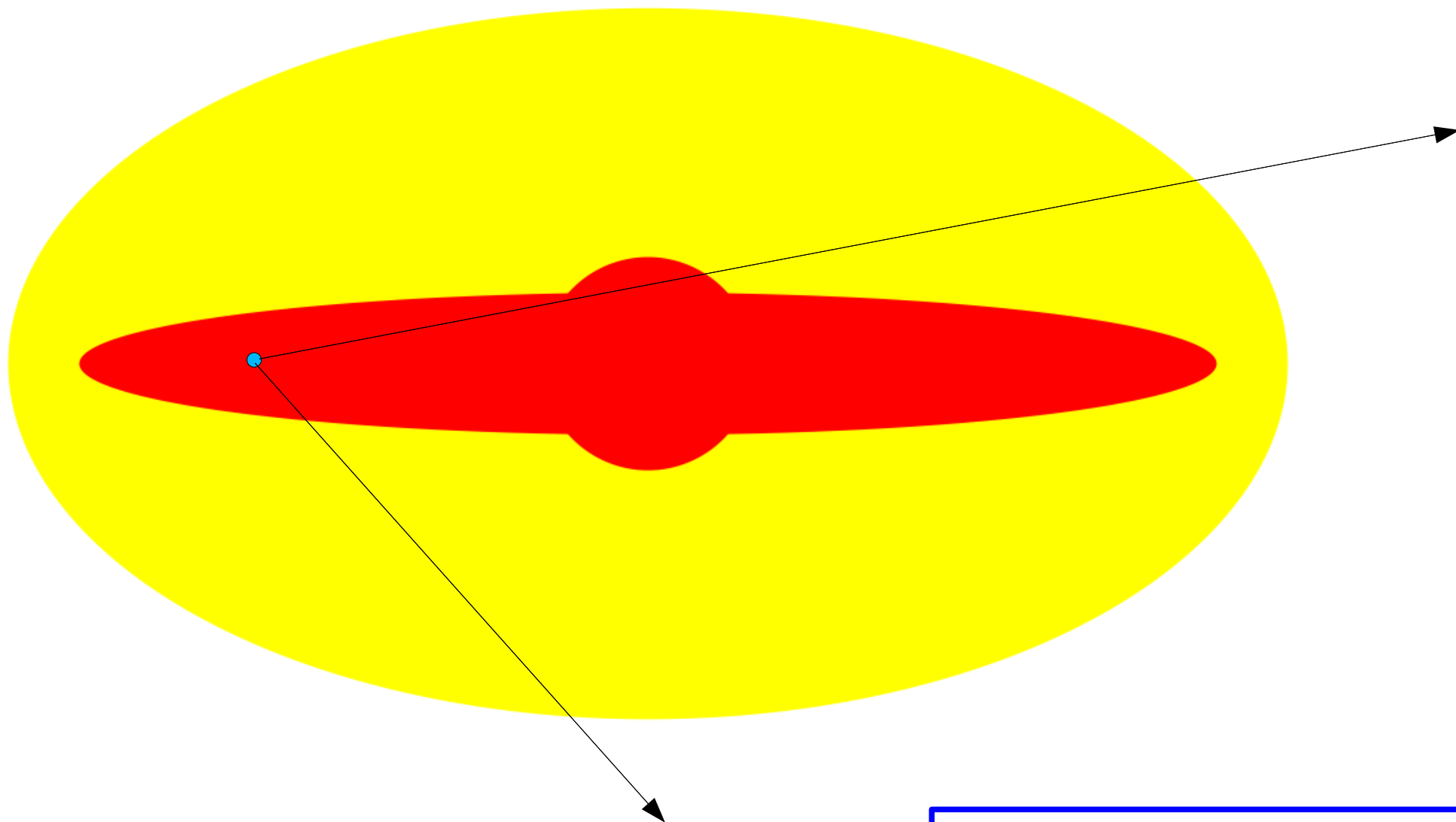
[1.] The DM annihilation does not produce antiprotons
“Leptophilic” Dark Matter [?]
(no convincing dynamical explanation)

[2.] Include a large “Boost factor”
to increase the rate of the DM annihilations.
Very “clumpy” dark matter.
(very lucky in being close to a big clump)
“winning the jackpot” [?]

Is this “adding epicycles” to the wrong theory ?

Astrophysical interpretations for the positron excess

Photon emission from DM annihilation



$$J(\Omega) = \frac{1}{R_{\odot}} \int dl \frac{\rho^2(l, \Omega)}{\rho_{\odot}^2}$$

No evidence
From Gamma Ray
measurements

PULSARS

Proposed as possible
Accelerators of $e^+ e^-$

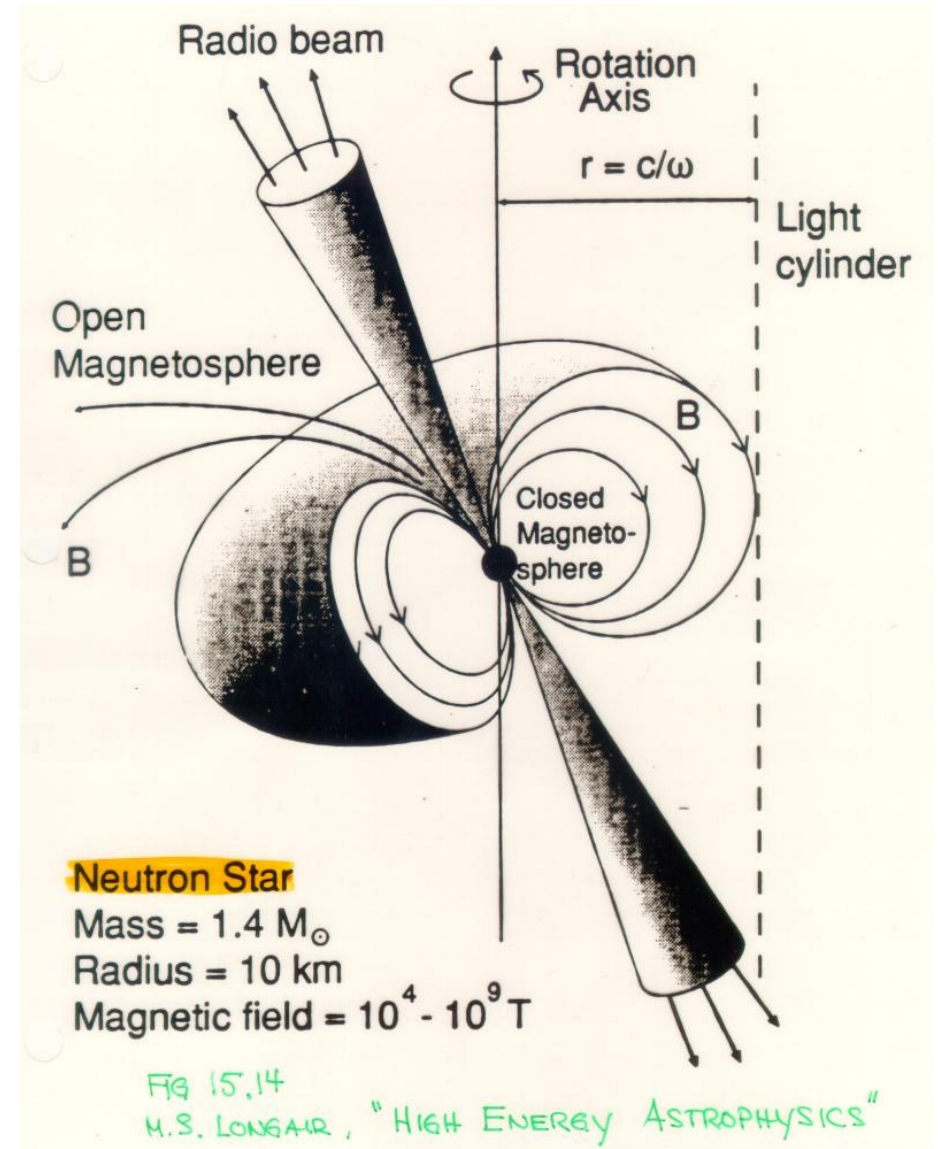


CRAB Nebula

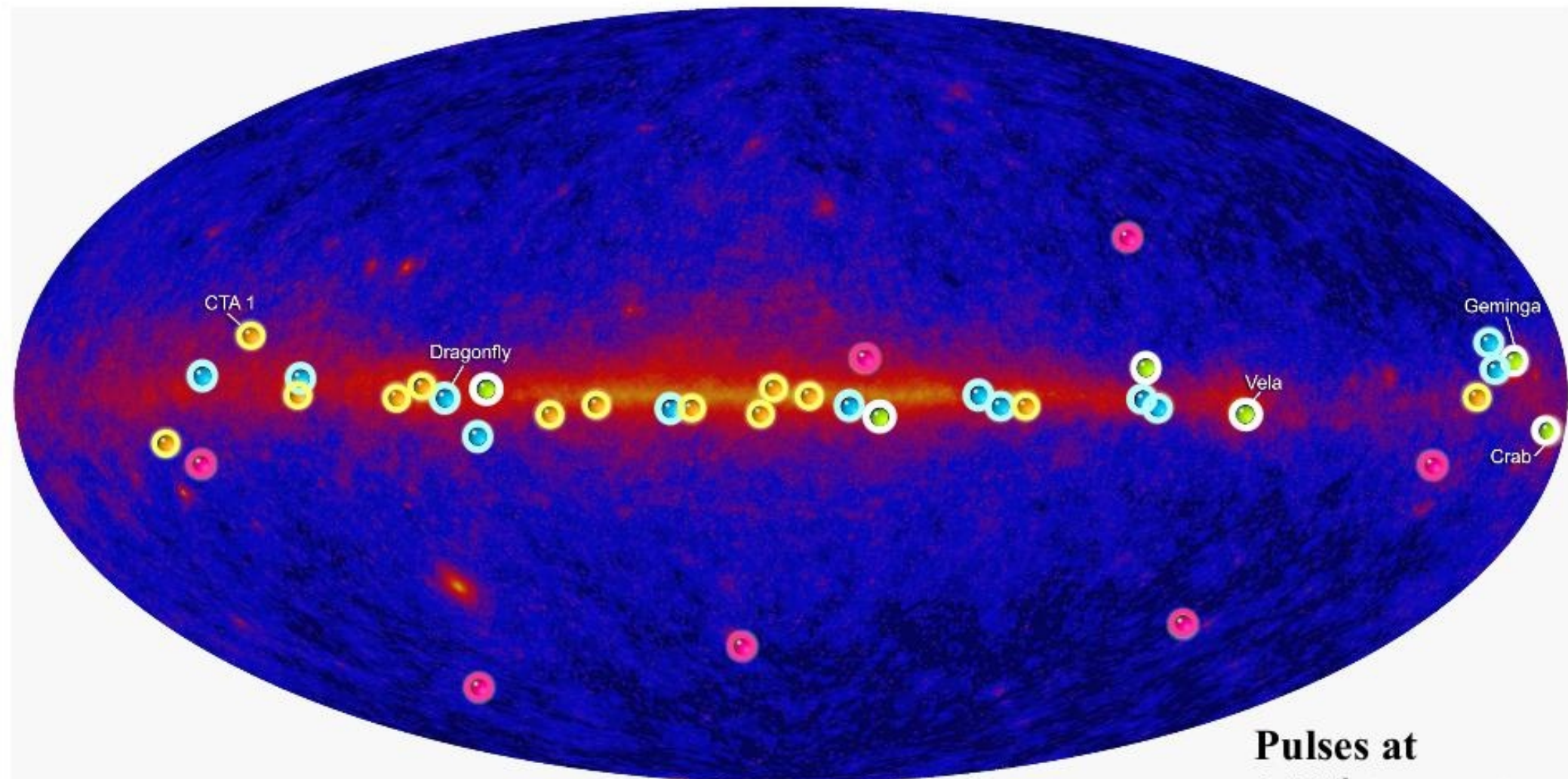
$$P_{\text{Crab}} = 0.0334 \text{ s}$$

$$\dot{P}_{\text{Crab}} = 4.2 \times 10^{-13} \text{ s}$$

$$(\Delta P_{\text{Crab}})_{\text{year}} = 13.2 \times 10^{-6} \text{ s}$$



Fermi Pulsar detection

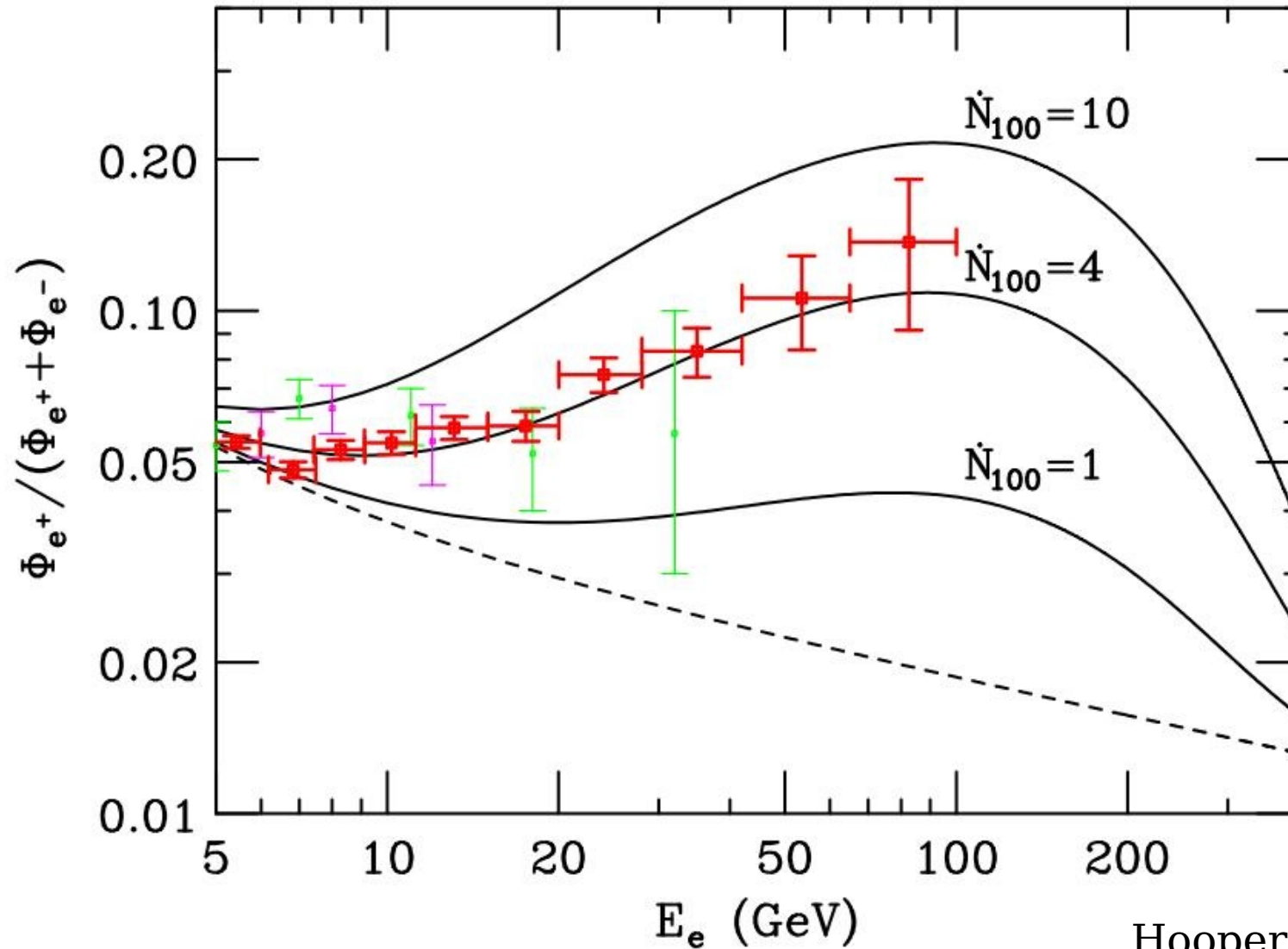


Fermi Pulsar Detections

- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Confirmed pulsars seen by Compton Observatory EGRET instrument

Explanation of the “PAMELA POSITRON EXCESS”

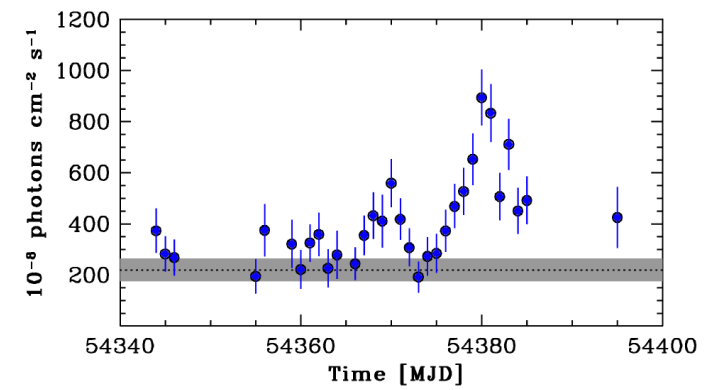
Contribution
from all Pulsars



Hooper, Blasi, Serpico 2008

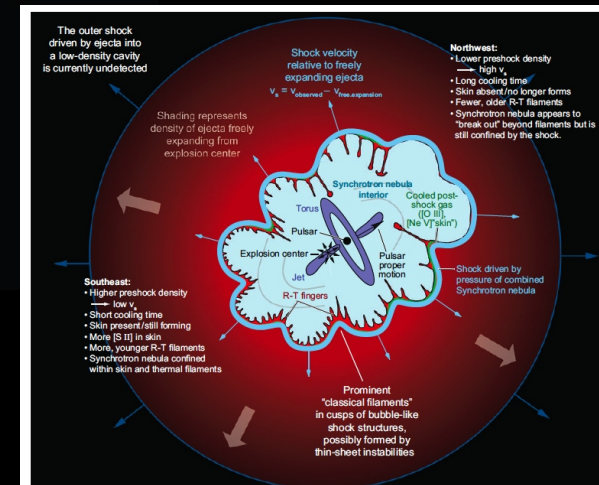
$$\frac{dN_e}{dE_e} \approx 8.6 \times 10^{38} \dot{N}_{100} (E_e/\text{GeV})^{-1.6} \exp(-E_e/80 \text{ GeV}) \text{ GeV}^{-1} \text{ s}^{-1}$$

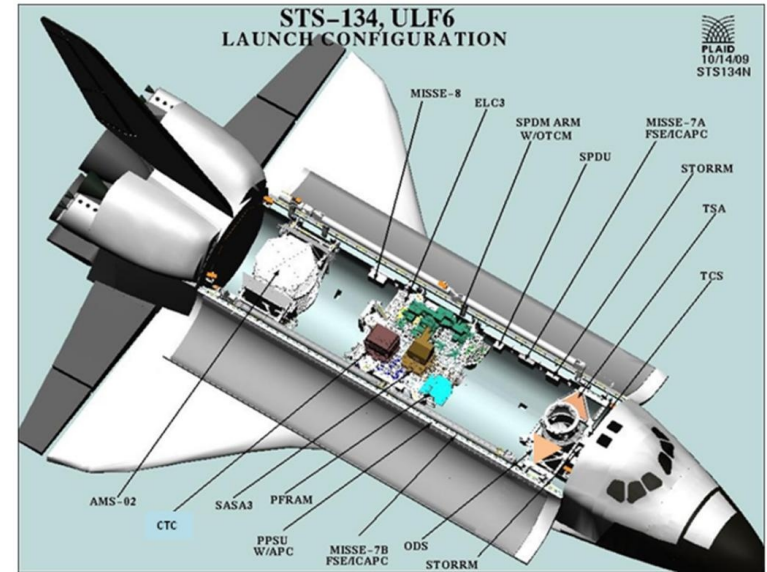
CRAB Nebula



Very strong flaring
(factor of 10!)
In the the past days

Discovery of flaring
at GeV energies
AGILE, FERMI

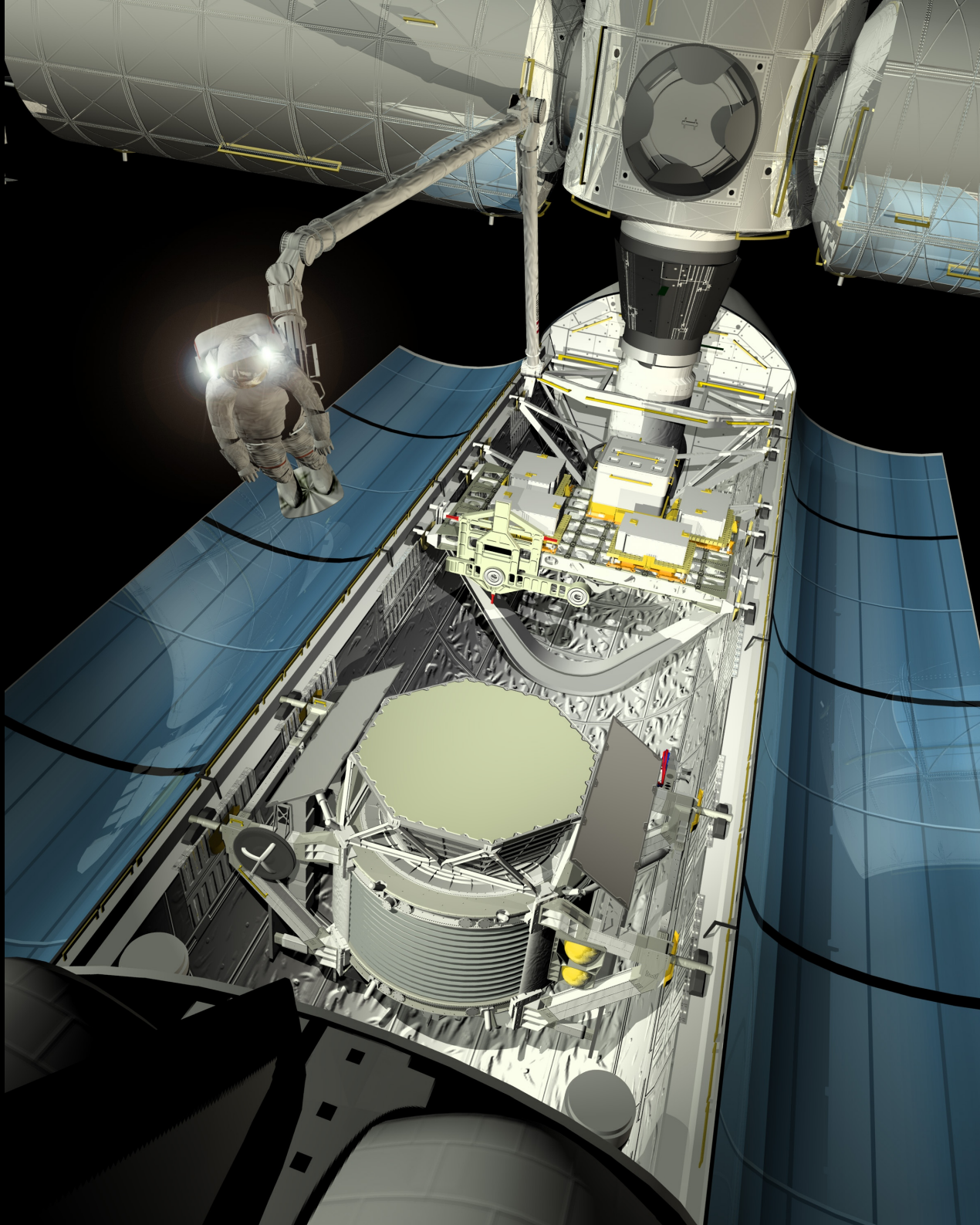




Greg Chamitof
(STS-134 mission specialist)

Neutral Buoyancy Lab. (NBL)
NASA Johnson Space Center

Discovery potential of AMS Mission



UHECR

1. Energy Spectrum

- Clear identification of a high energy suppression [the “END” (... well the “suppression”) of exotic/fundamental physics modeling for UHECR].
- Excellent agreement between experiments [“small” but important question about the energy scale].
- Physical interpretation strongly coupled to (2., 3.) (anisotropy + composition). [proton GZK ?]

UHECR

Crucial Problem:

Galactic
Extragalactic
Transition

1. Energy Spectrum

2. Anisotropy

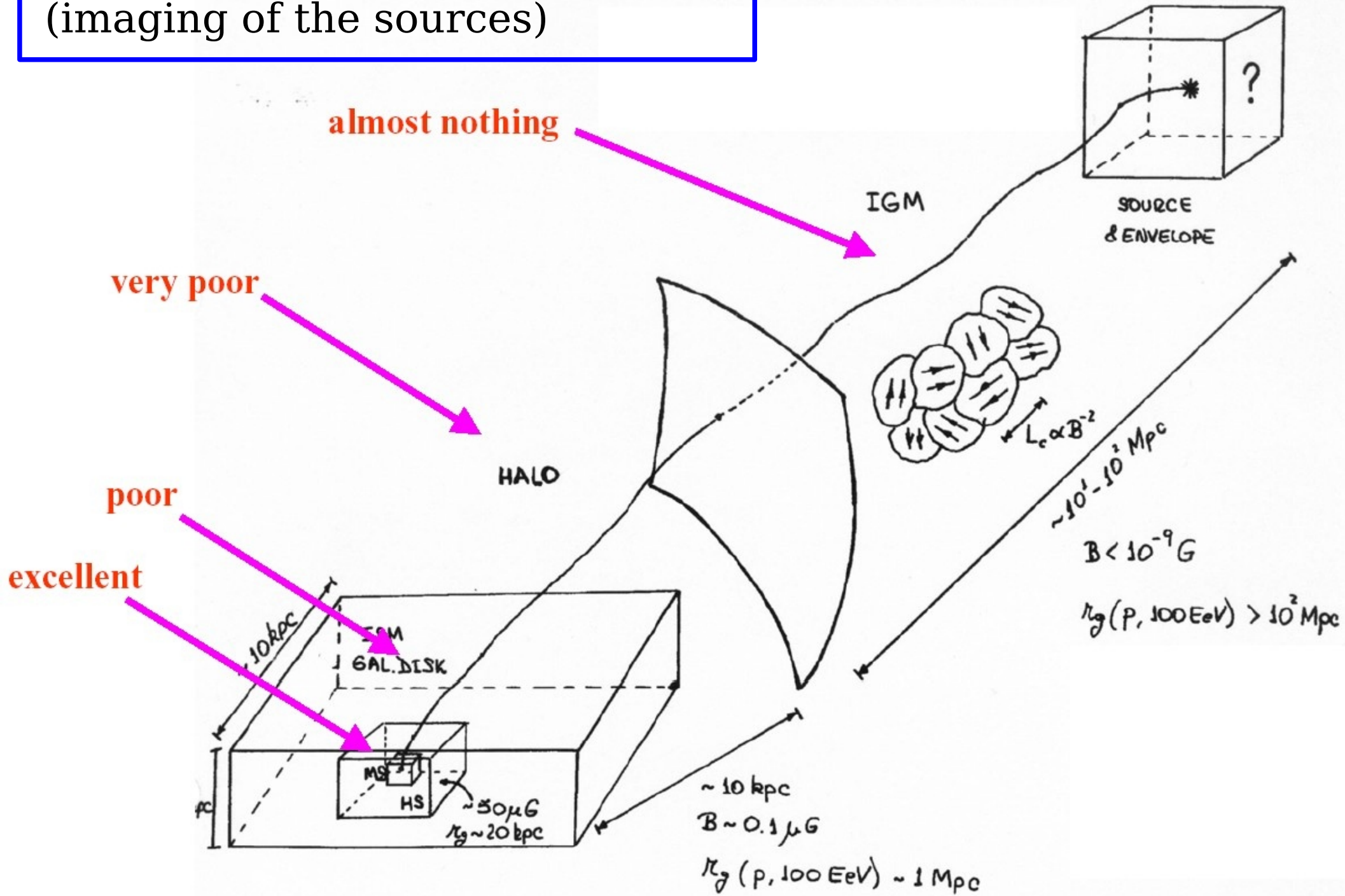
3. Composition

Significant
Experimental
Discrepancies

Auger/Hires

Confusing
situation.

COSMIC Ray ASTRONOMY [?!] (imaging of the sources)

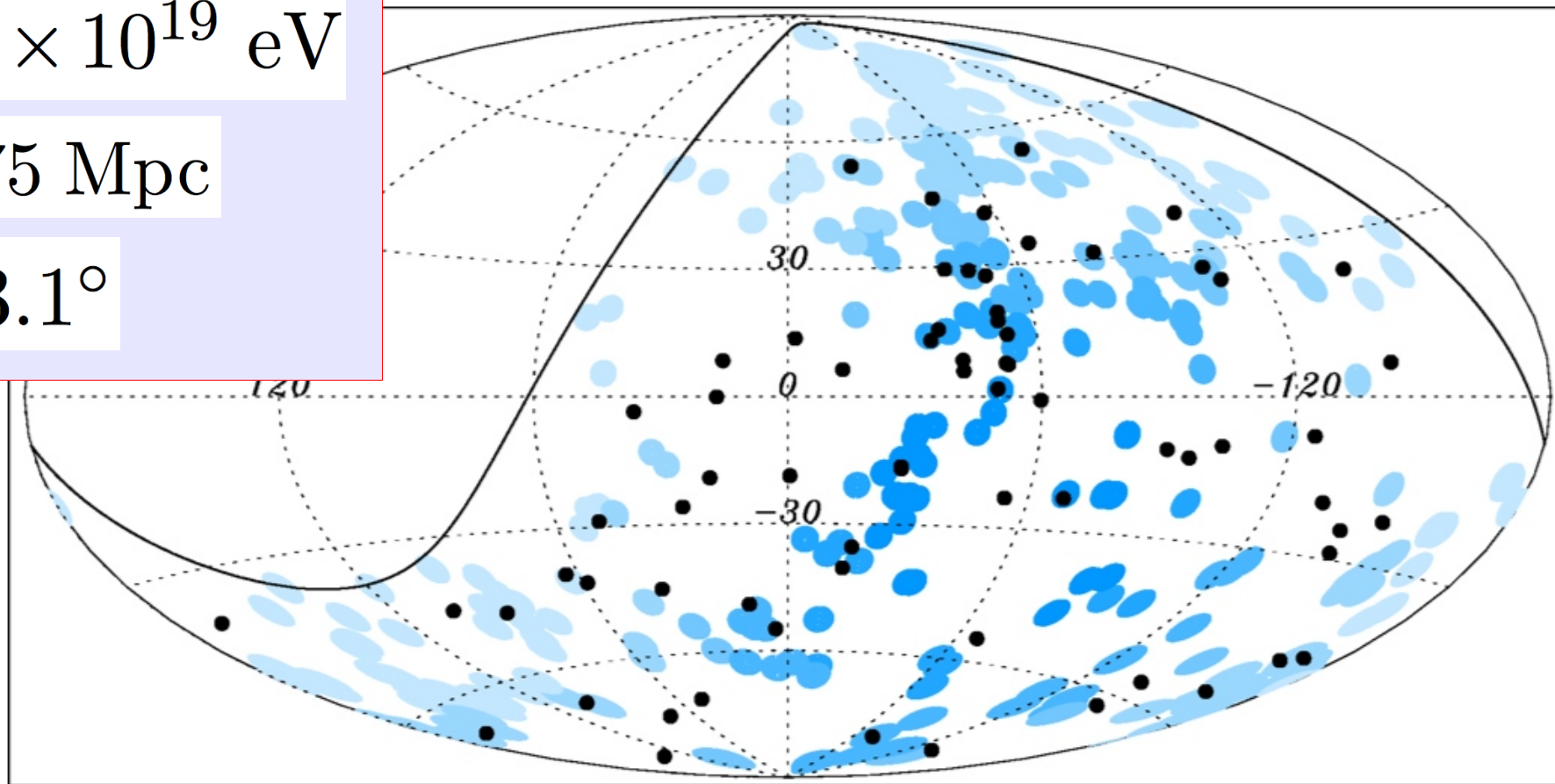


AUGER result on Correlations with the VCV AGN catalogue
November 2008. Update september 2010.

6×10^{19} eV

75 Mpc

3.1°



Significant dilution
[but not disappearance]
of the statistical significance

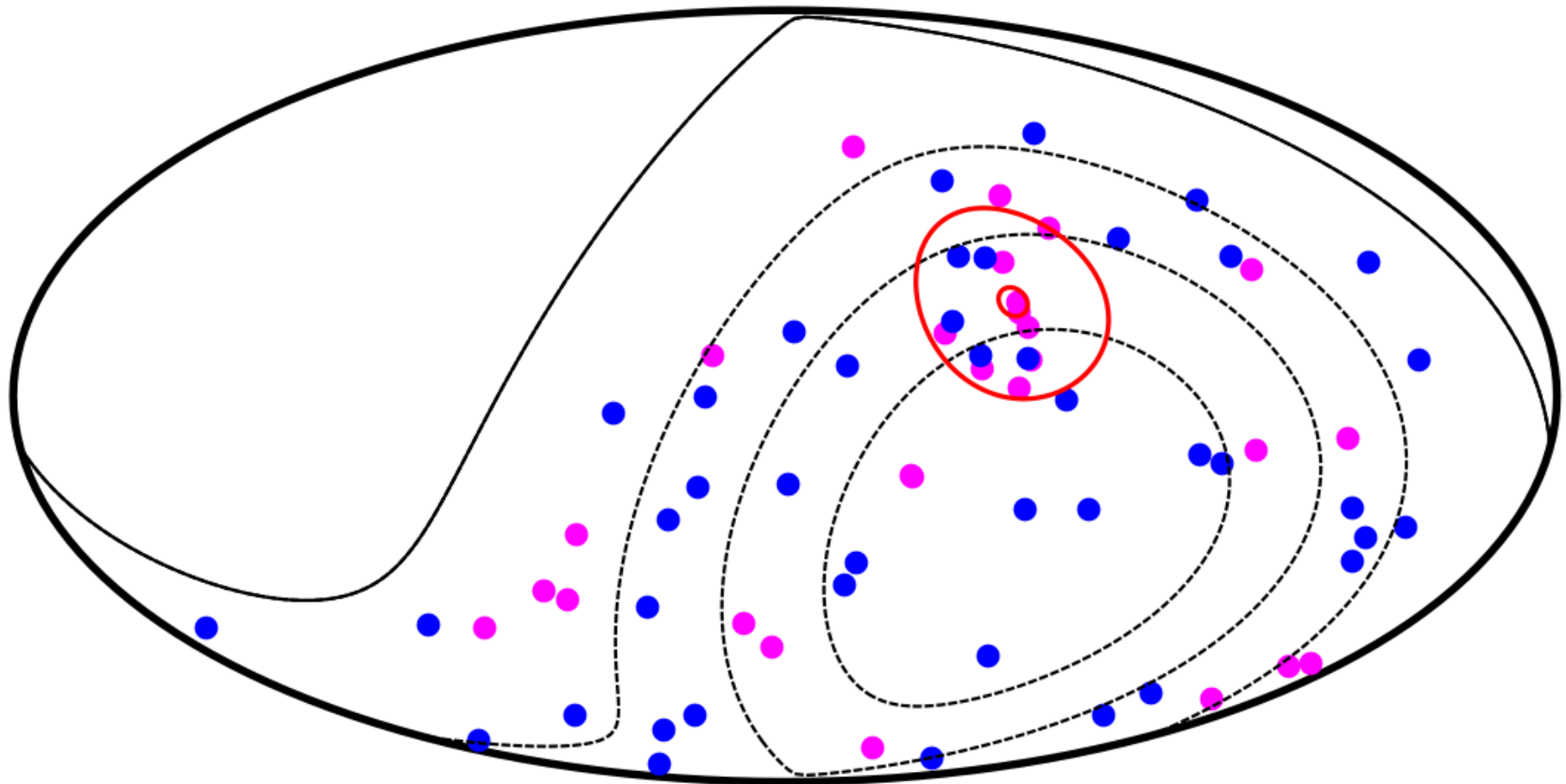
14 ev.	8 coincid.	(2.9)
13 ev.	9 coincid.	(2.7)
42 ev.	12 coincid.	(8.8)

Discussion on CEN A

The AGN closest to us.

3 events within 3 degrees
8 events within 18 degrees

+0 events within 3 degrees
+5 events within 18 degrees

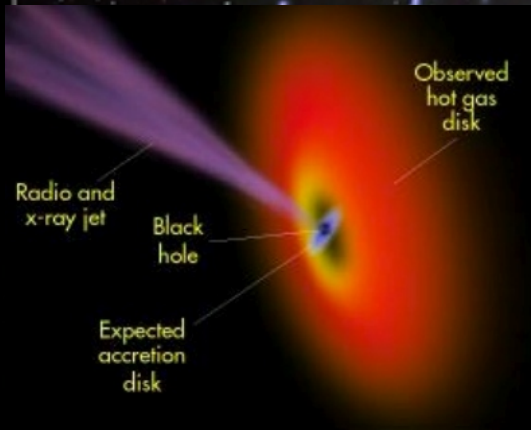
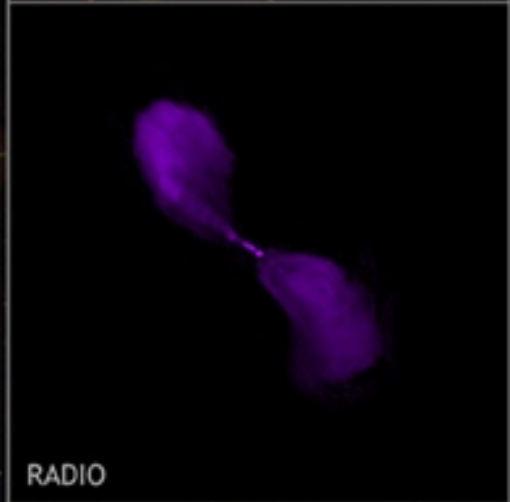
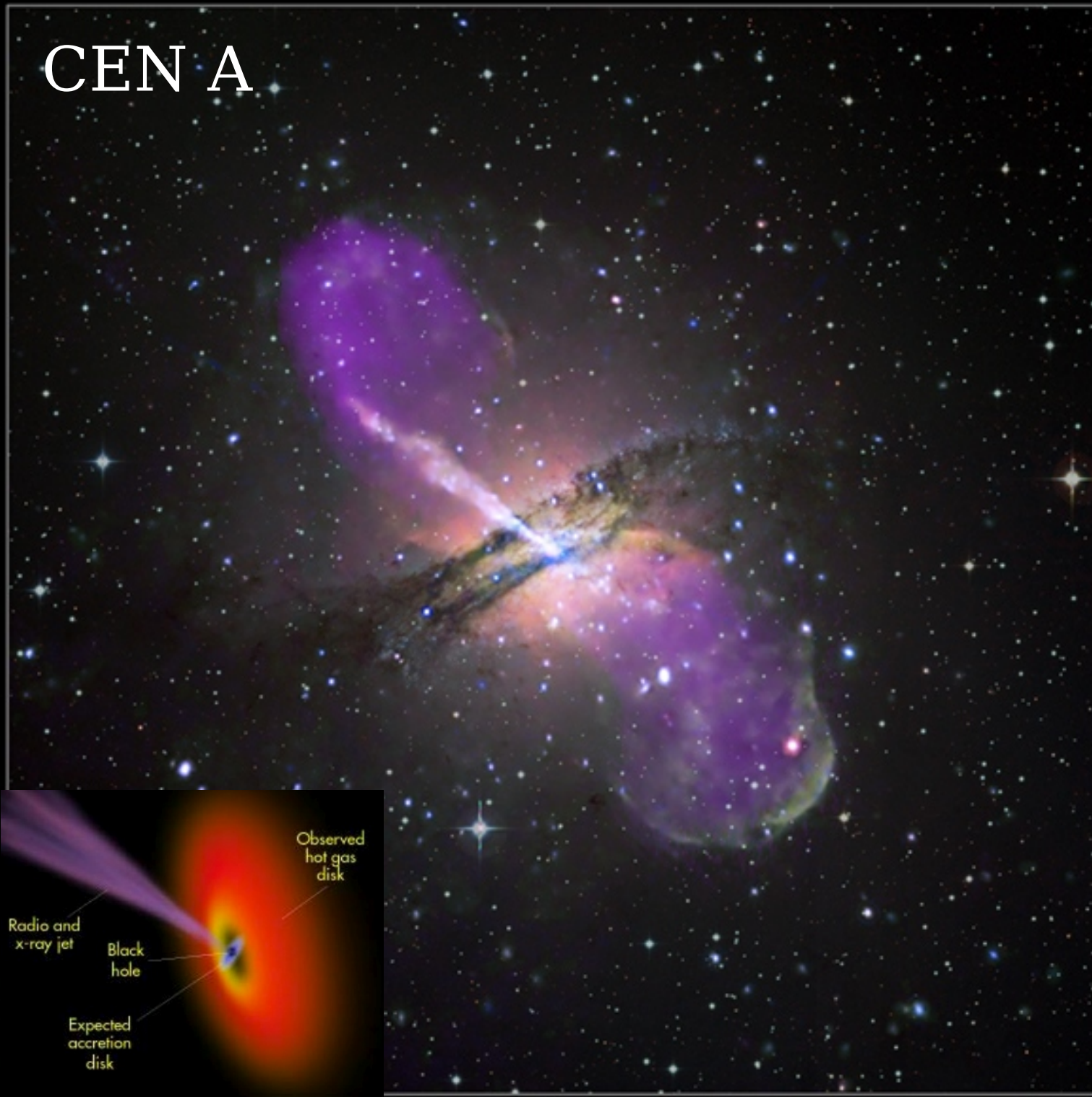


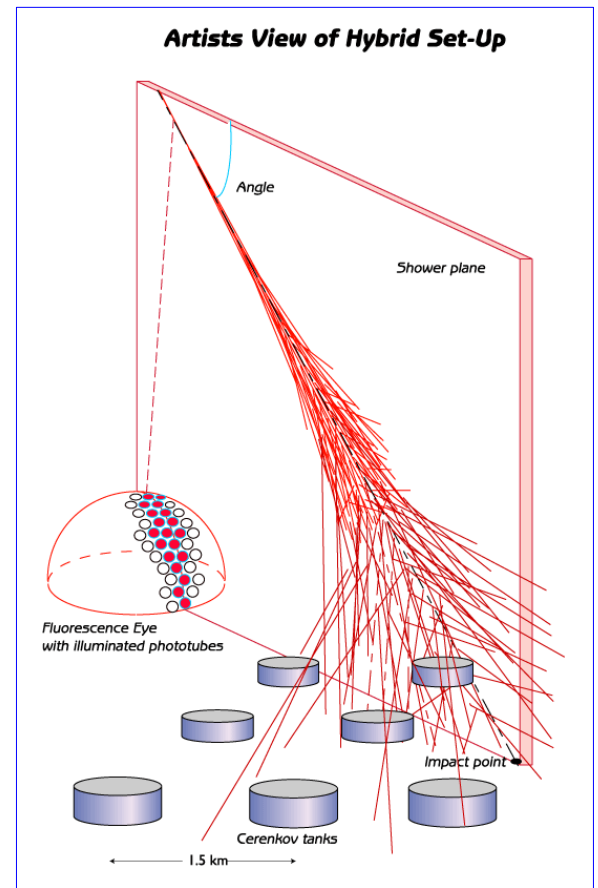
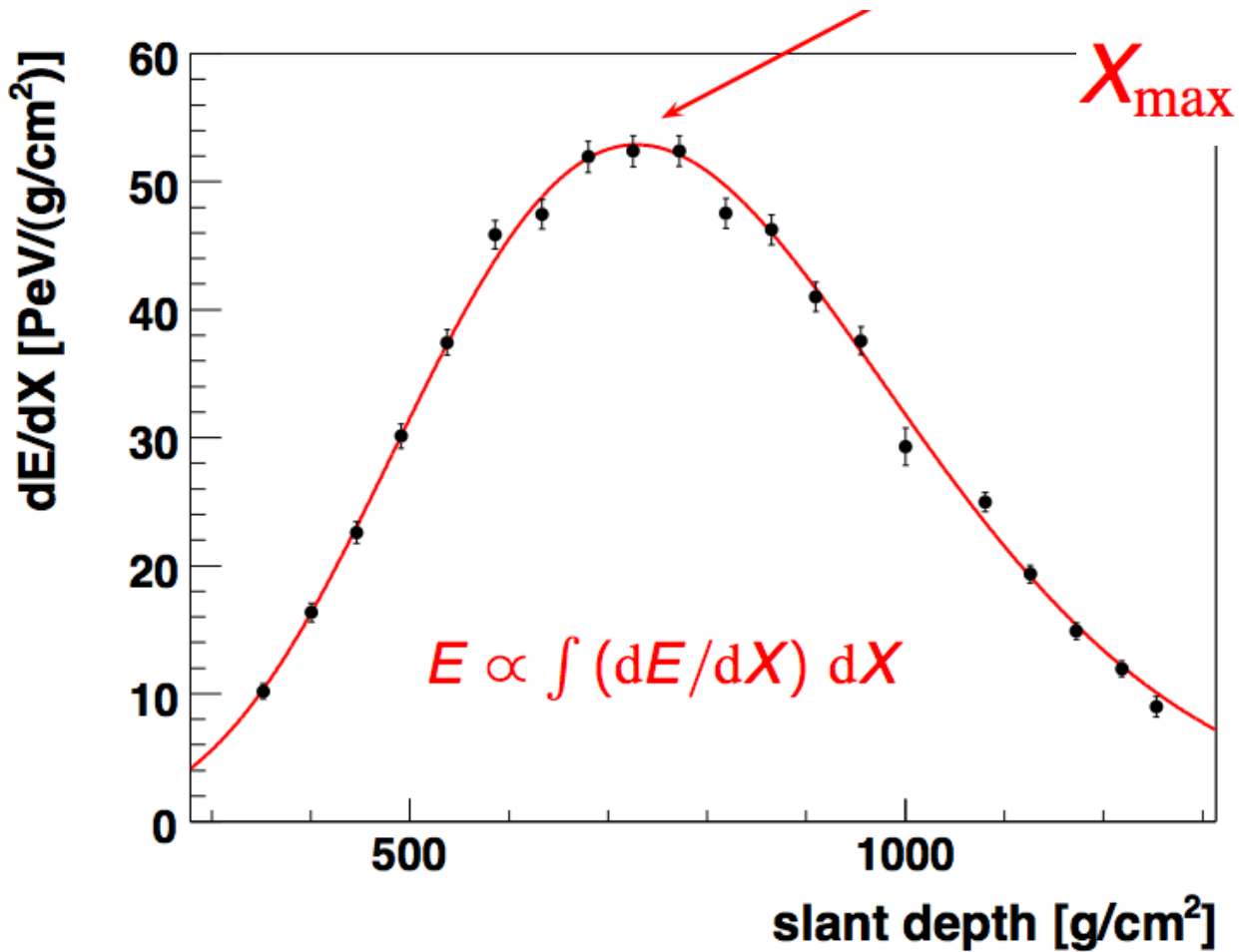
November 2008 (13 + 14 events)

Update september 2010 (+42 events)

3, 20 degrees circles

CEN A



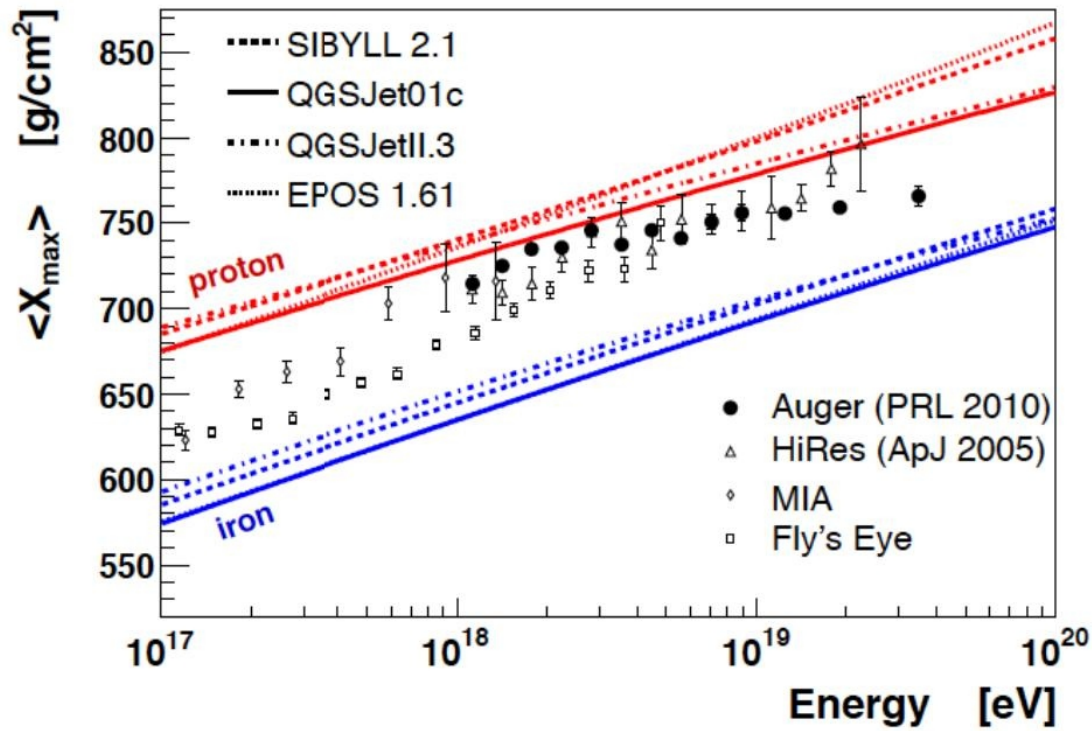


$$E_{\text{ionization}} = \int dX N_e(X) \left\langle -\frac{dE}{dX} \right\rangle$$

Area \propto Energy

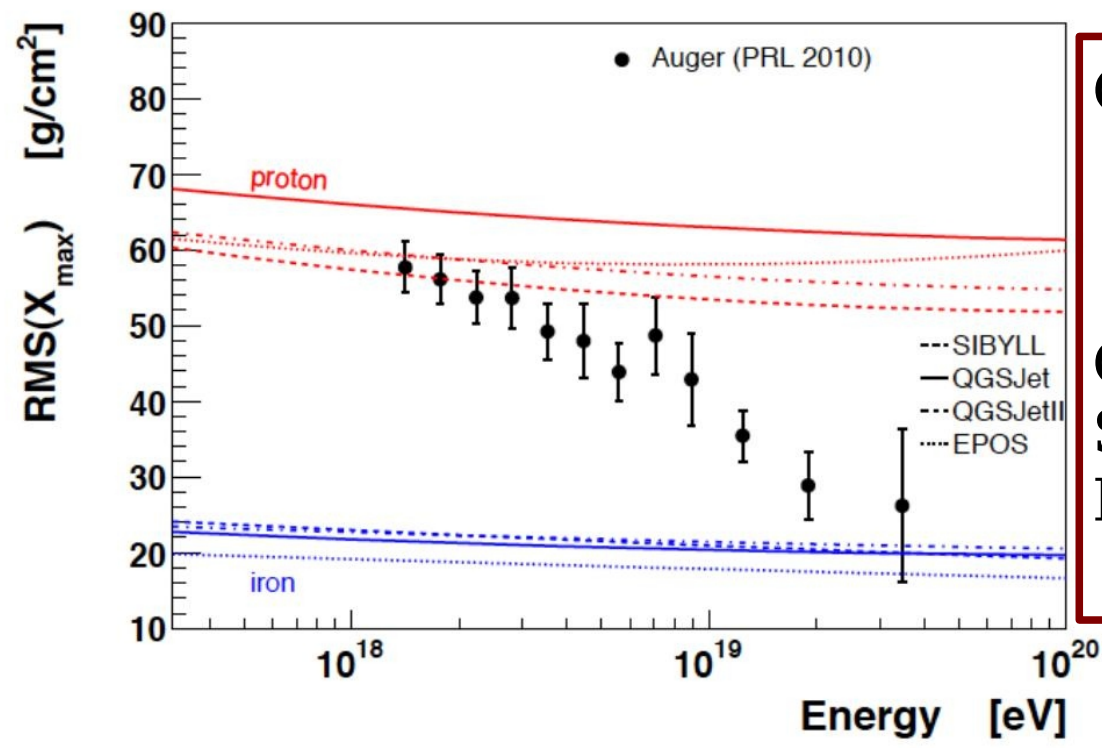
Shape depends on :

- Primary Identity
- Interaction Model



Mass Composition becoming heavy ? at very high energy ?

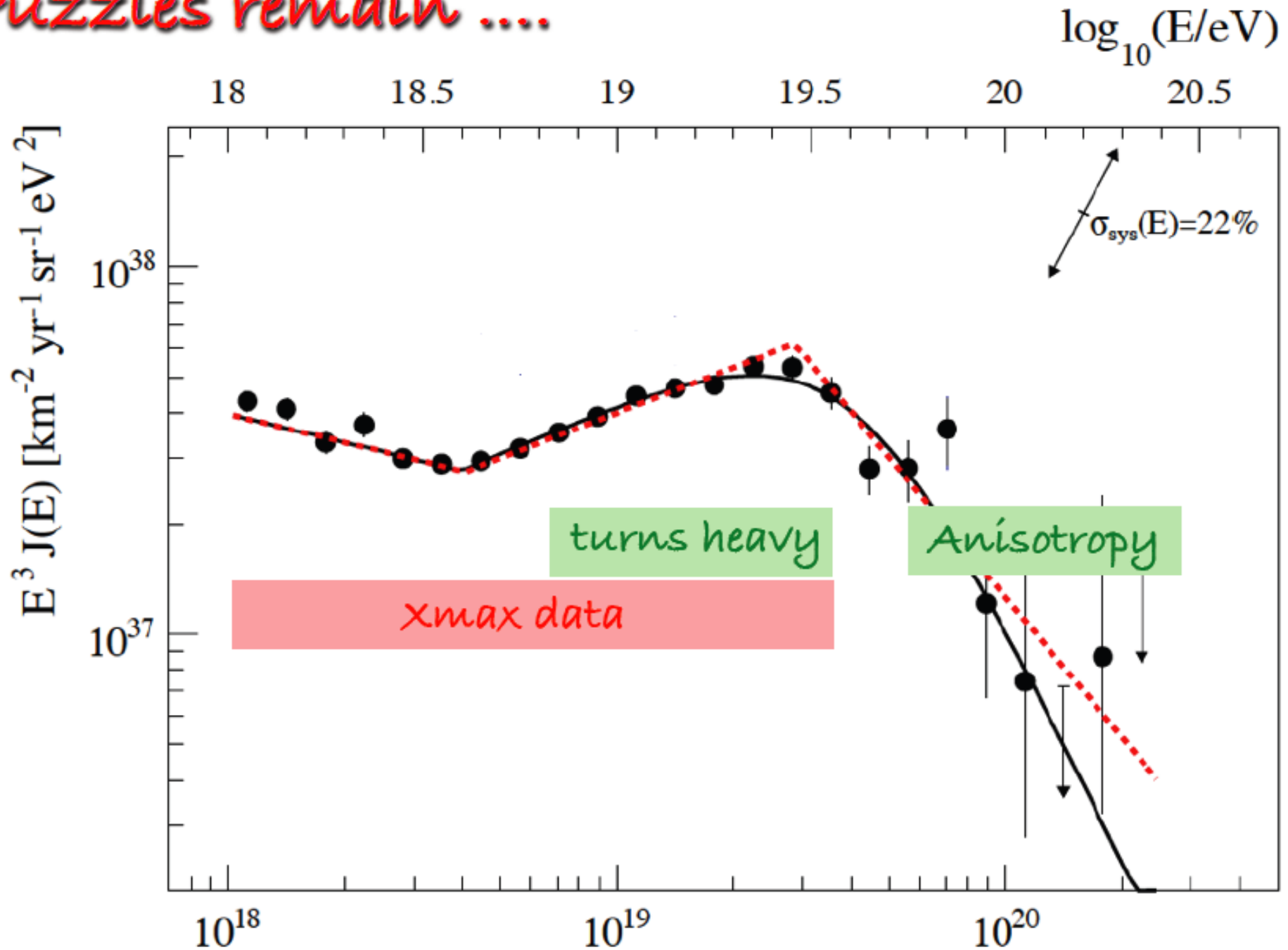
Significance would be very important ! Constraints on the structure and properties of the astrophysical sources.



Observational controversy NON confirmation of HiRes

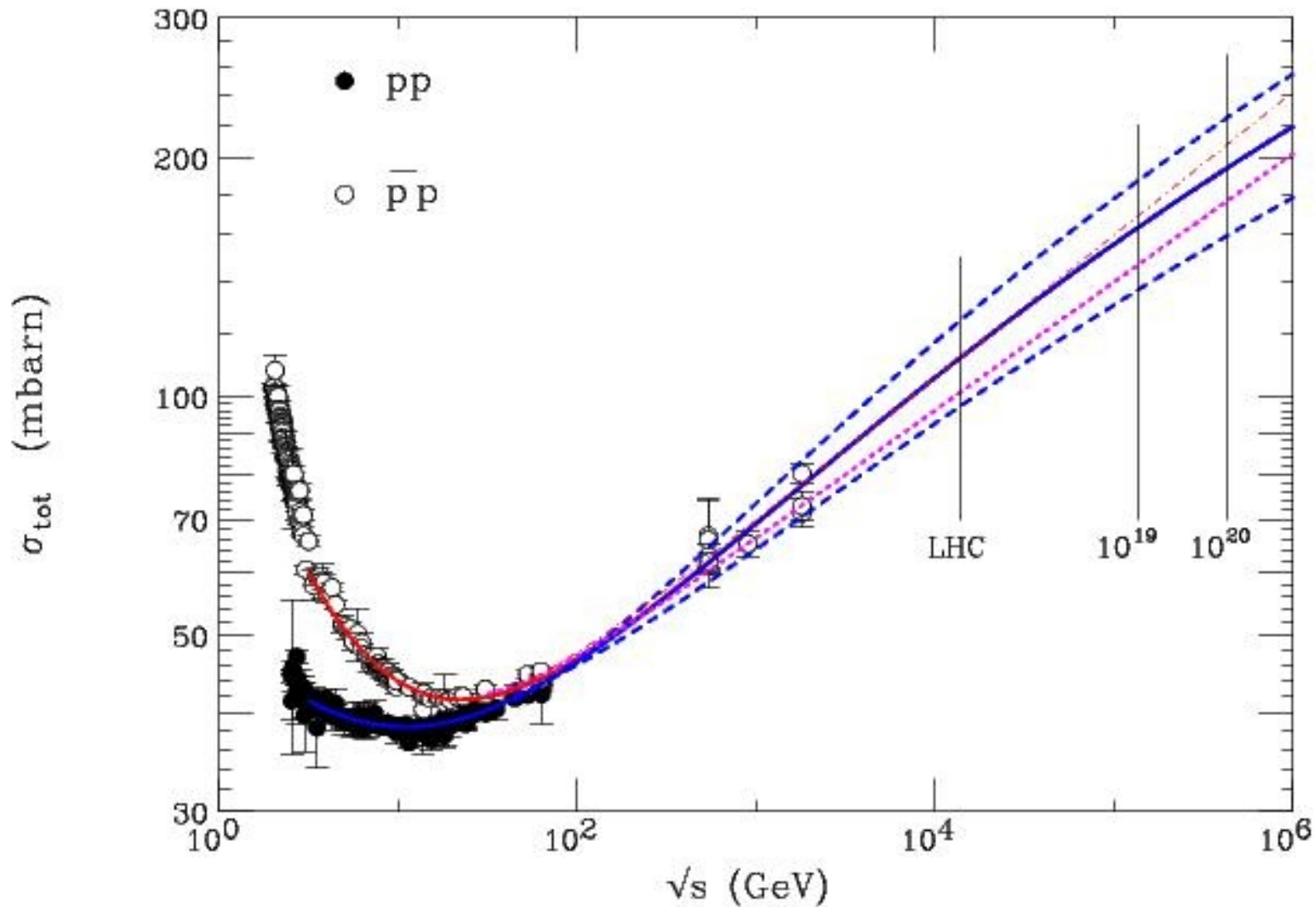
Correlation with sources Small deviation in magnetic Fields ($Z < 3$?)

Puzzles remain



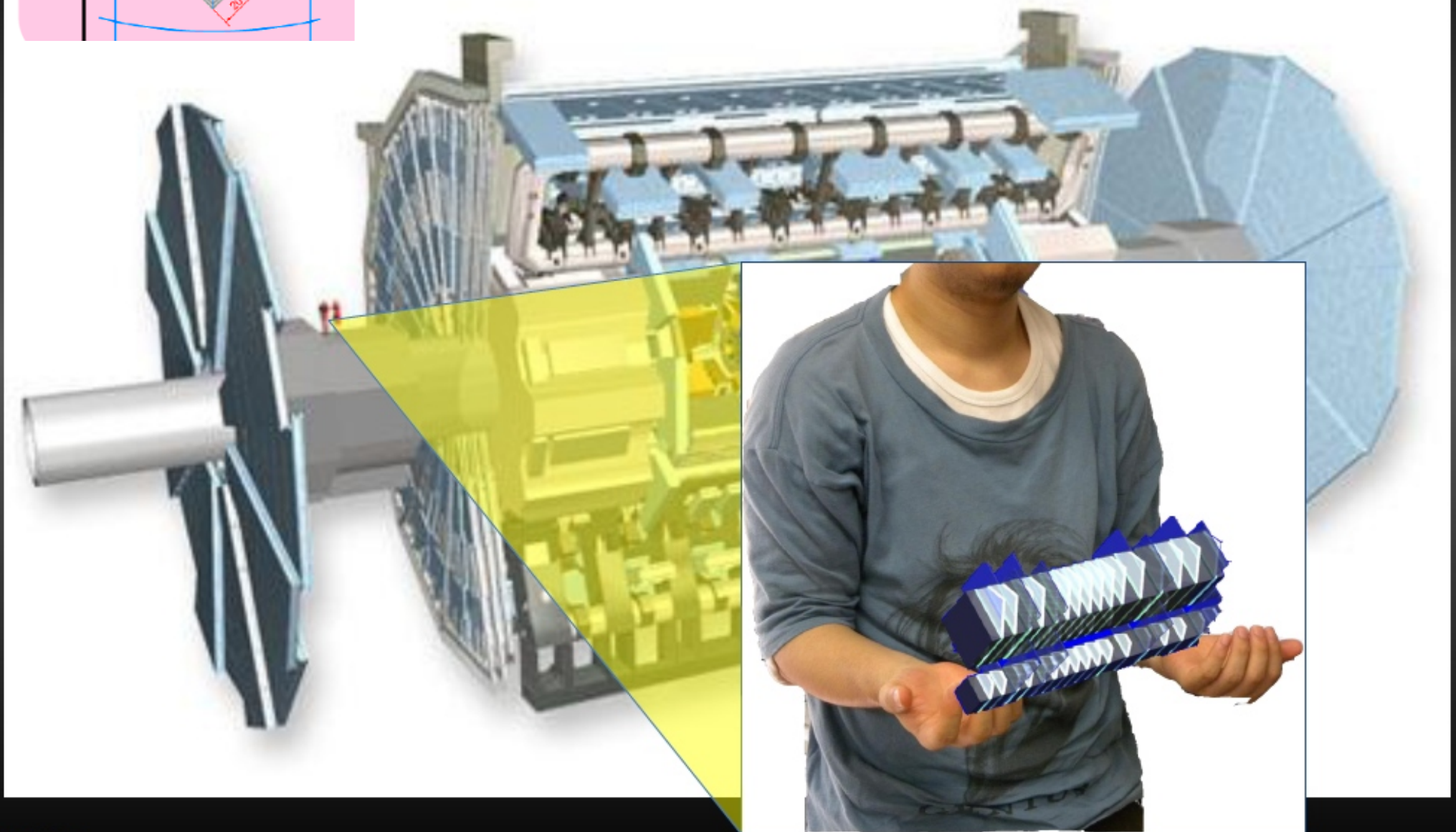
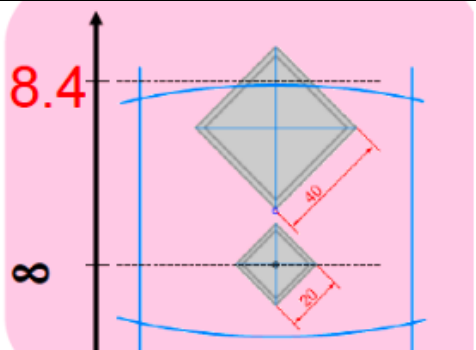
LHC and Ultra-High Energy Cosmic Rays

Total pp Cross Section



ATLAS & LHCf

140 m from interaction point



NEUTRINO ASTRONOMY

The idea to observe the Universe using Neutrinos is profoundly fascinating.

The insights about Nature that are possible using this:

“New Way” to look at the Sky
can be profound.

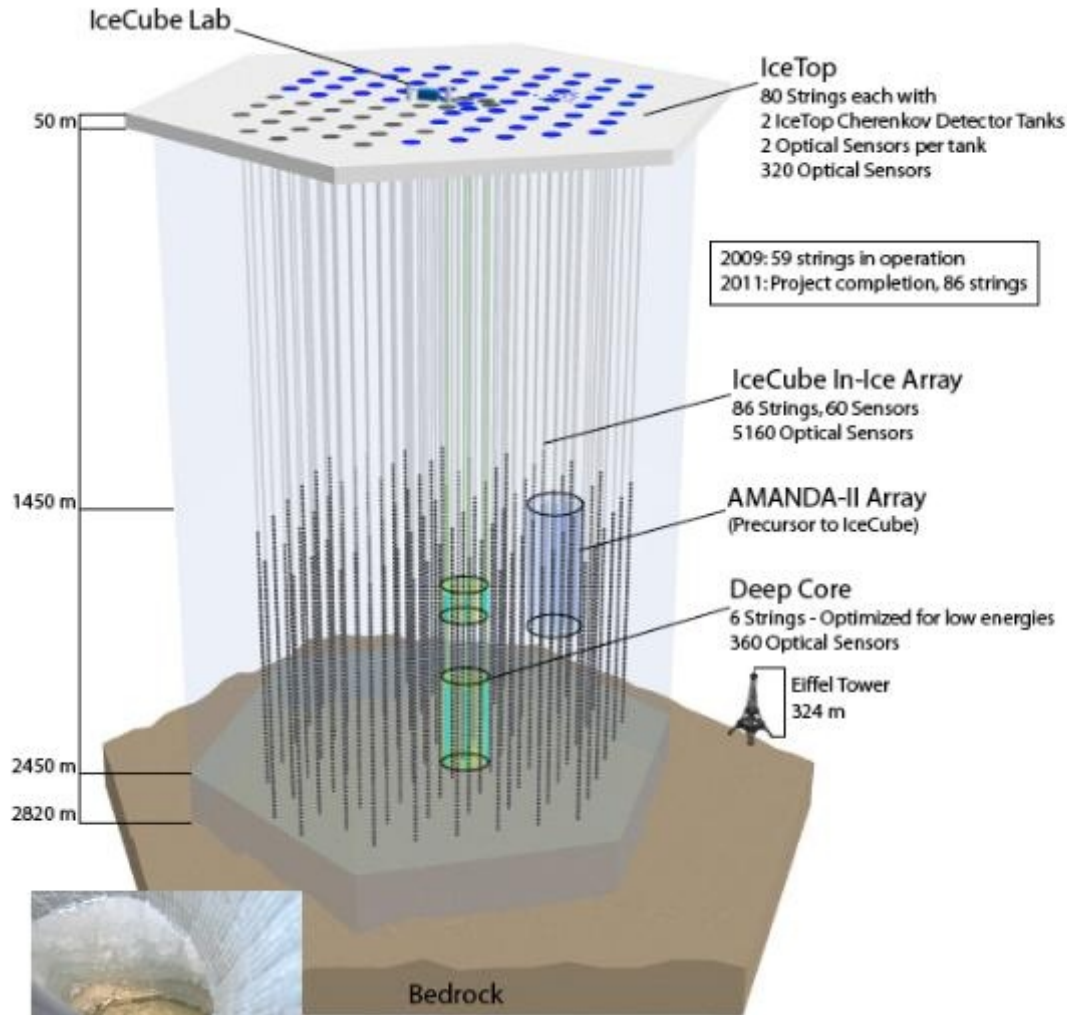
ICECUBE completed!

80 + 6 strings (125 m)

60 PMT / strings (17 m)

2400 PMT

+ surface array



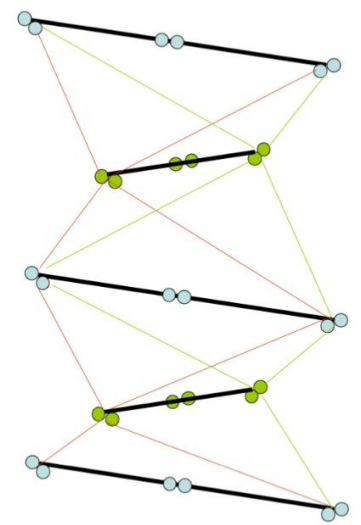
No SIGNAL
(yet)

Possible structure of a "KM3" detector in the Mediterranean Sea:

**Km3NET
Design Study**
Near completion

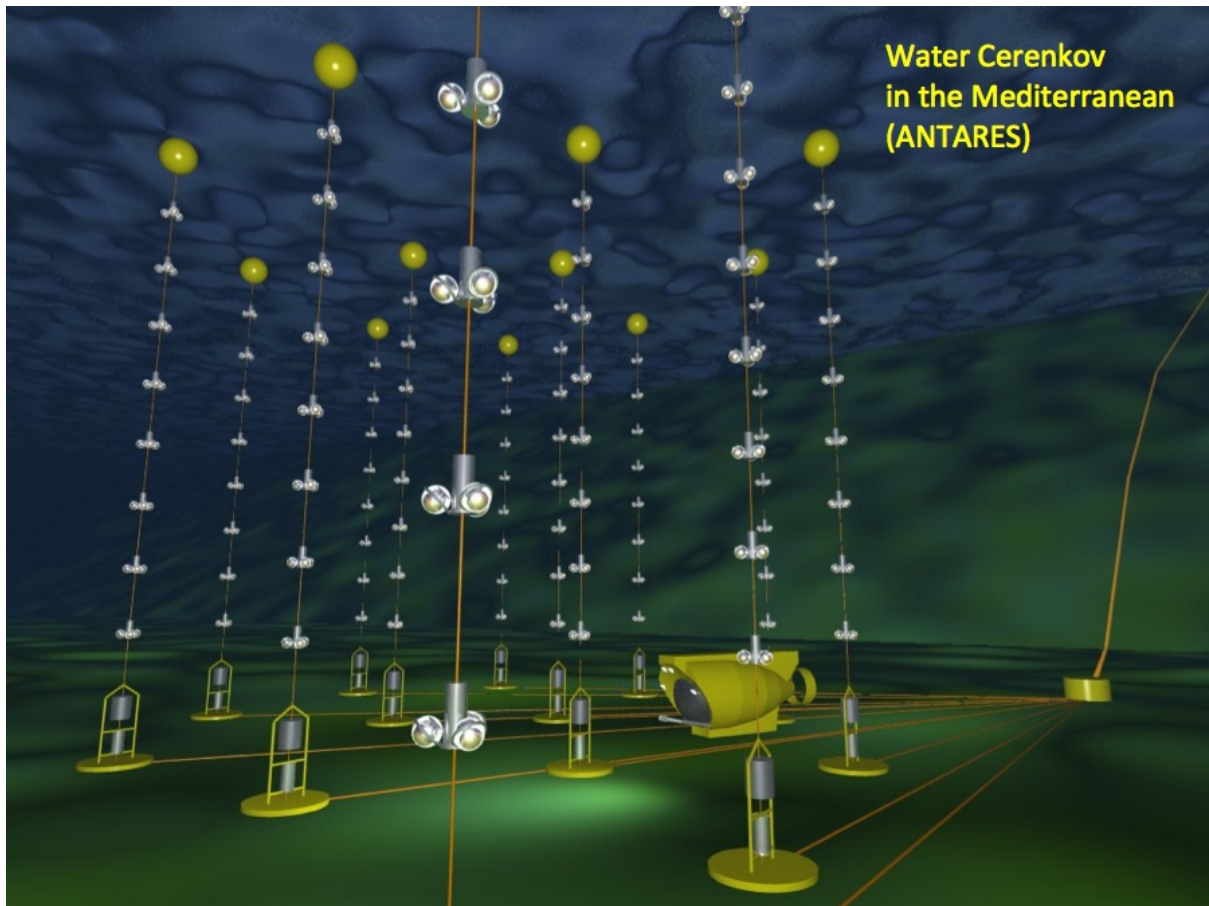
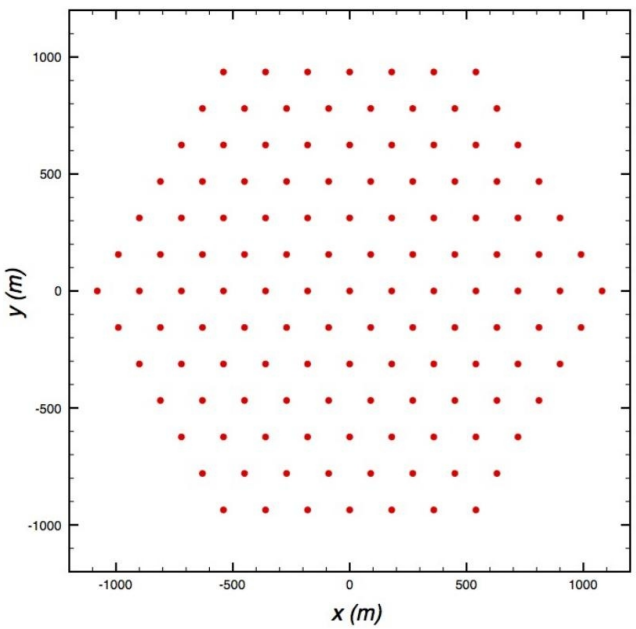
"tower"
[6 PMT's]

40 m



Detection Unit layout.

127 towers (180 m)



Final Remarks:

The efforts to understand the objects and the mechanisms that generate high energy relativistic particles in our Galaxy and in the universe form a vibrant field with continuous surprises and new discoveries.

This is beautiful Science, still very much controlled by the data, with theorists continuously surprised.

Multi-messenger astrophysics is essential, and [...sooner or later...] Neutrino Telescopes will play a key role.

Search for Dark Matter remain one of the most important problem for Science