Galactic Cosmic Rays and the multimessenger connection

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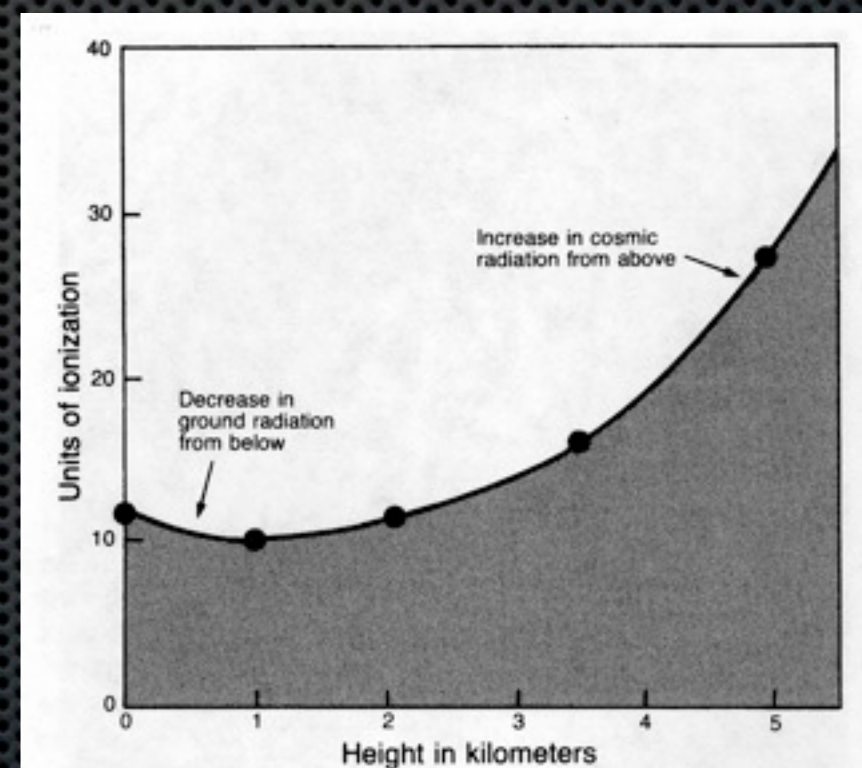
Ringberg Schloss 24.07.2012

An historical discovery

Victor Hess (nobel lecture, 1936)

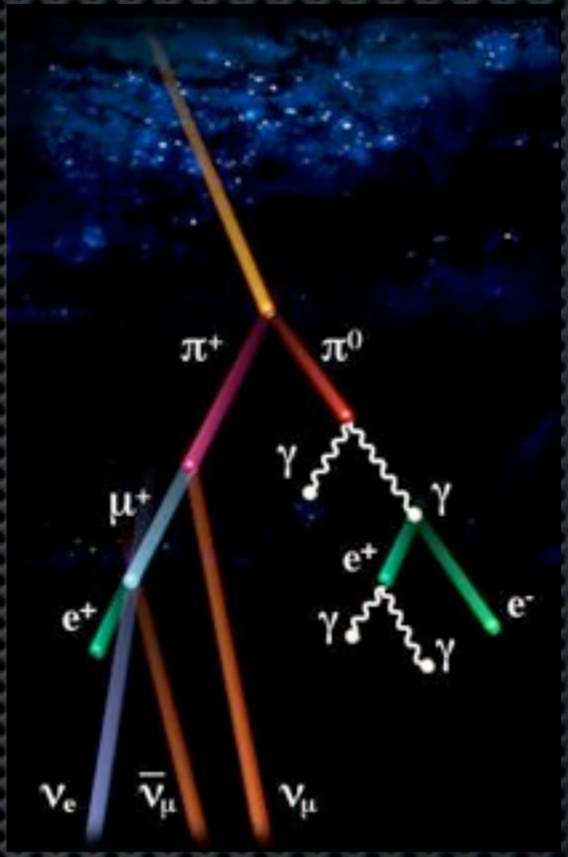
« [...]When, in 1912, I was able to demonstrate by means of a series of balloon ascents, that the ionization in a hermetically sealed vessel was reduced with increasing height from the earth (reduction in the effect of radioactive substances in the earth), but that it noticeably increased from 1km onwards, and at 5 km height reached several times the observed value at earth level, I concluded that this ionization might be attributed to the penetration of the earth's atmosphere from outer space by hitherto **unknown radiation of exceptionally high penetrating capacity**, which was still able to ionize the air at the earth's surface noticeably [...]. »

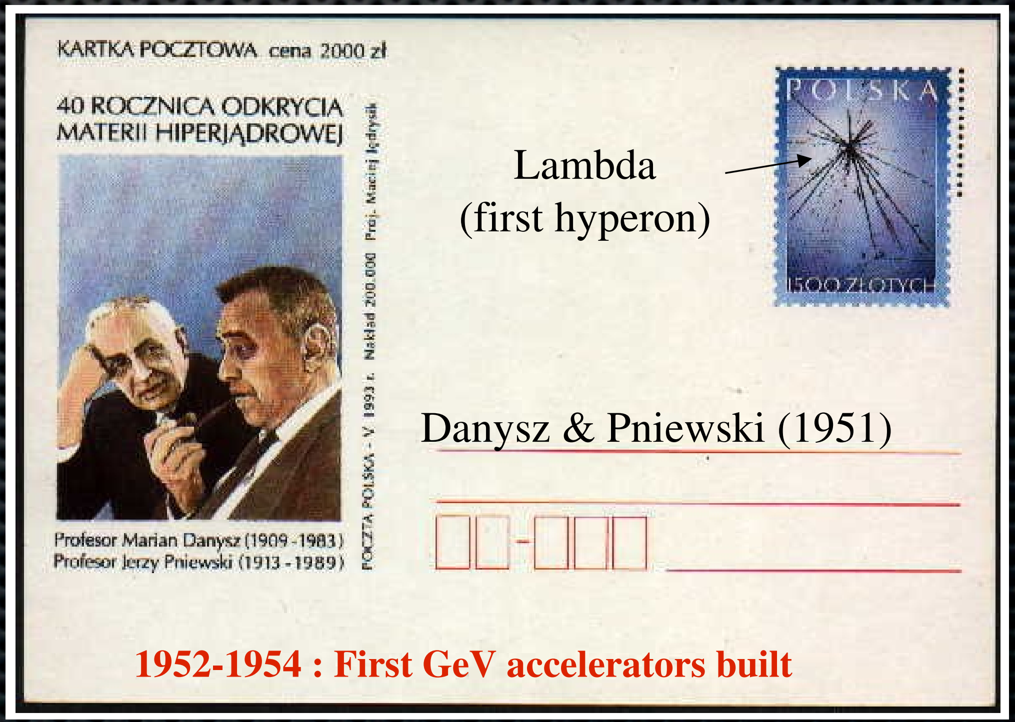


Readings on ionization chamber Victor Hess carried aloft in the Böhmen. Above four kilometers the ionization rose rapidly indicating "that rays of very great penetrating power are entering our atmosphere from above". These cosmic rays contain the only modern samples of matter from outside our solar system which can be investigated directly.

Discovery of new particles in CR showers:

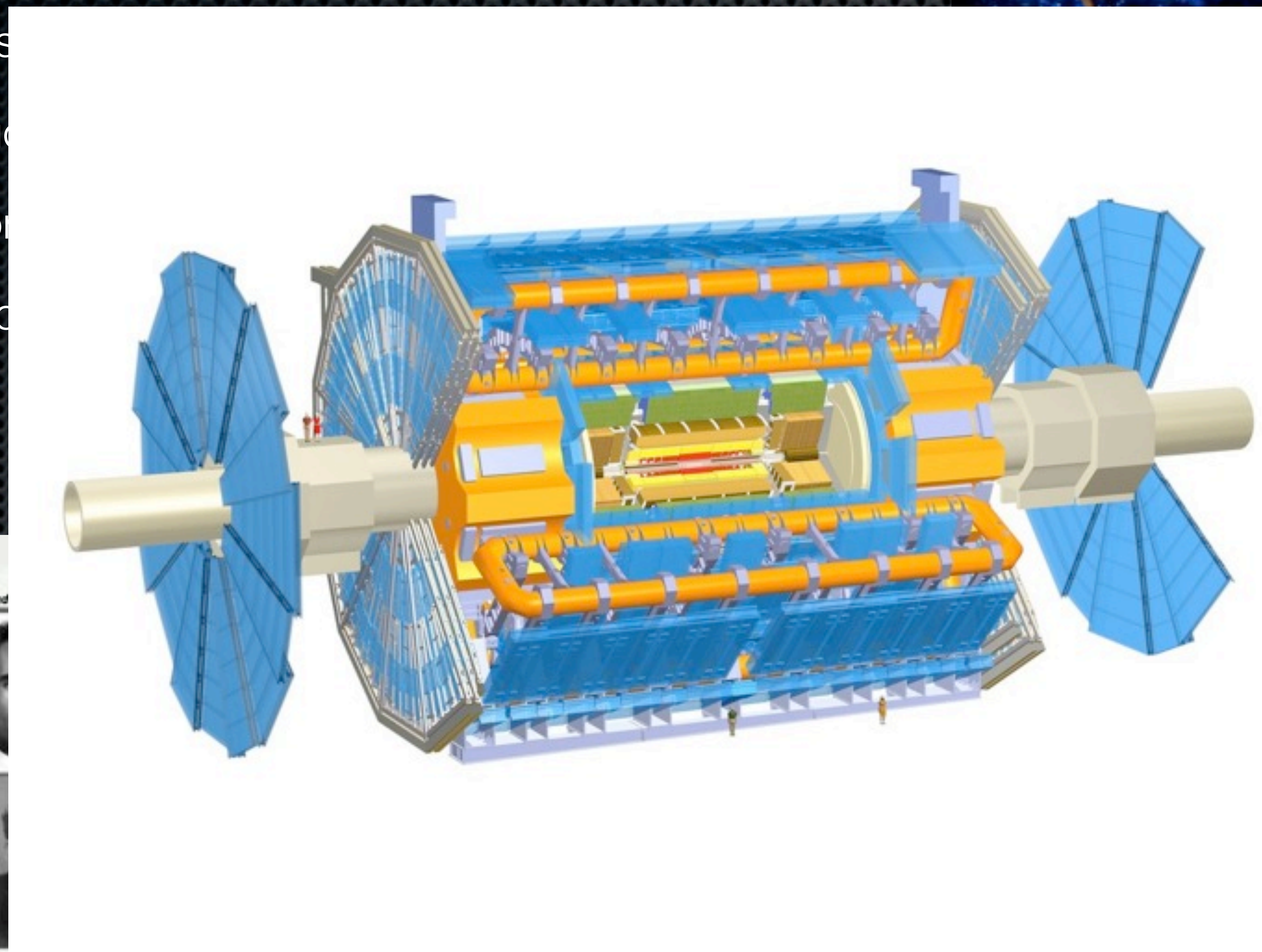
- Positron: Anderson (1932)
- Muon: Anderson & Neddermeyer (1936)
- Pion: Powell (1947)
- Kaon [strange particle]: Rochester & Butler (1947)

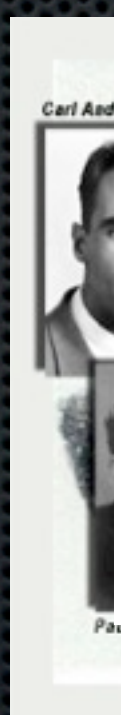




Discovery of new particles in CR showers:

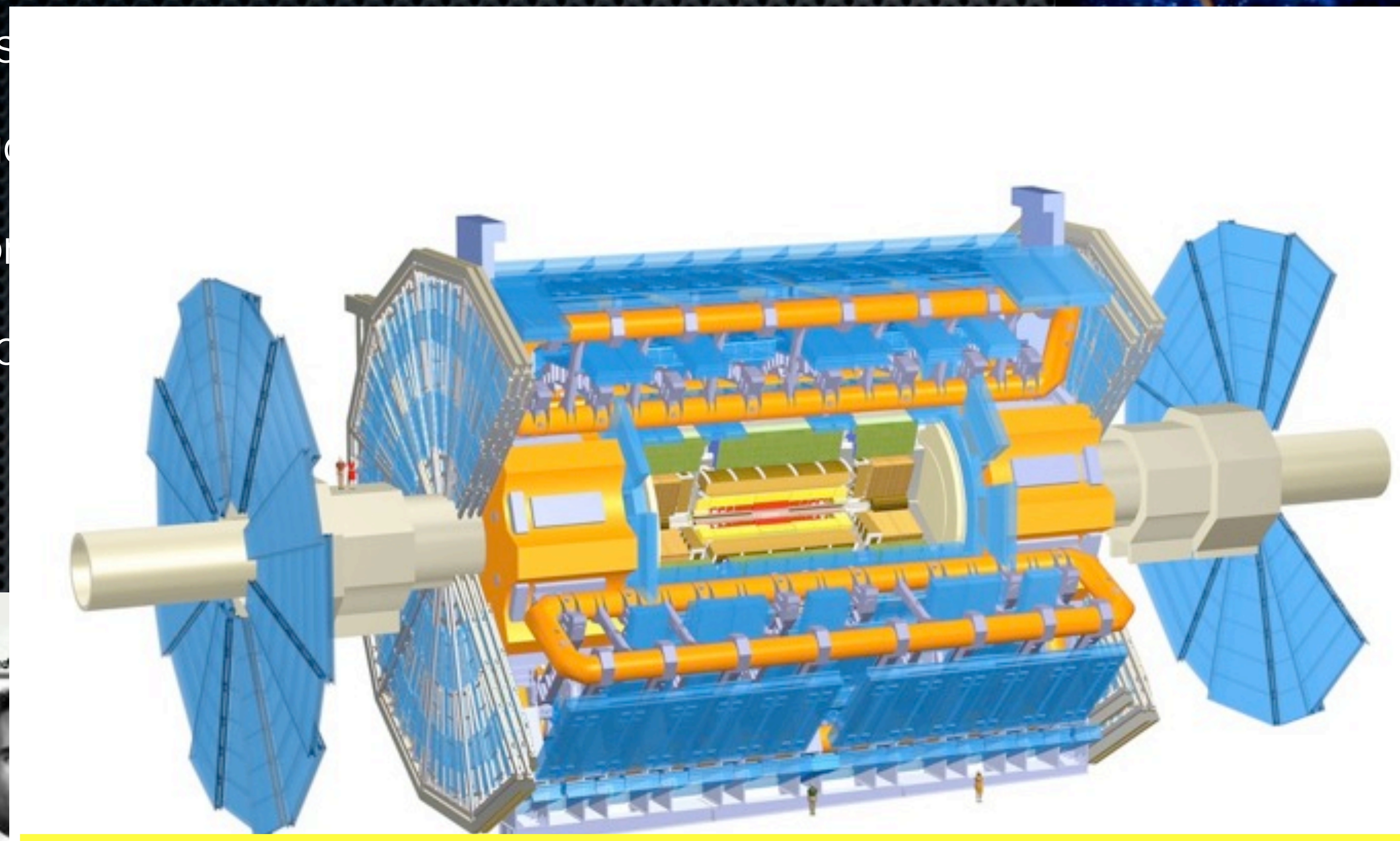
- Pos
- Mu
- Pio
- Ka



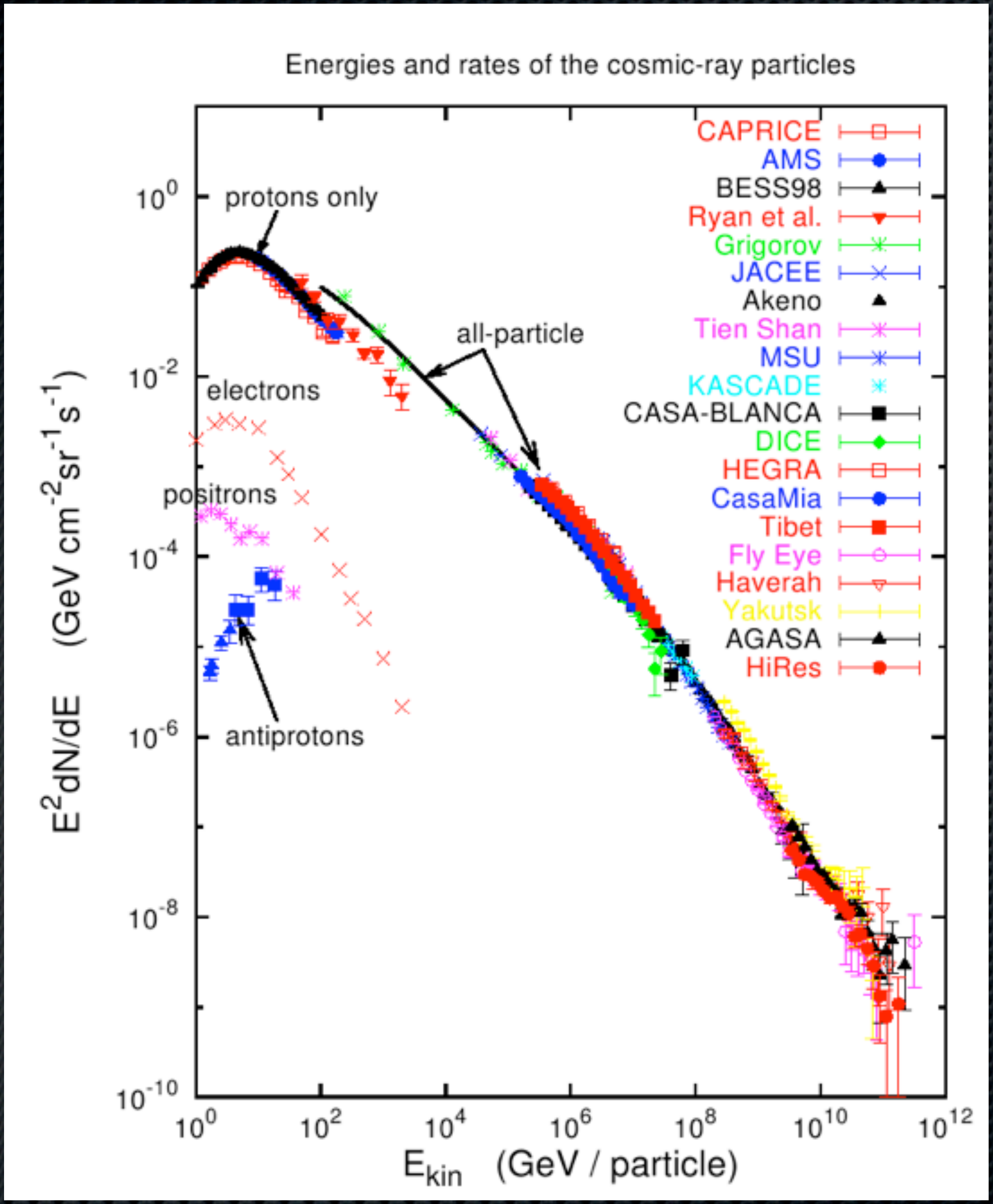


Discovery of new particles in CR showers:

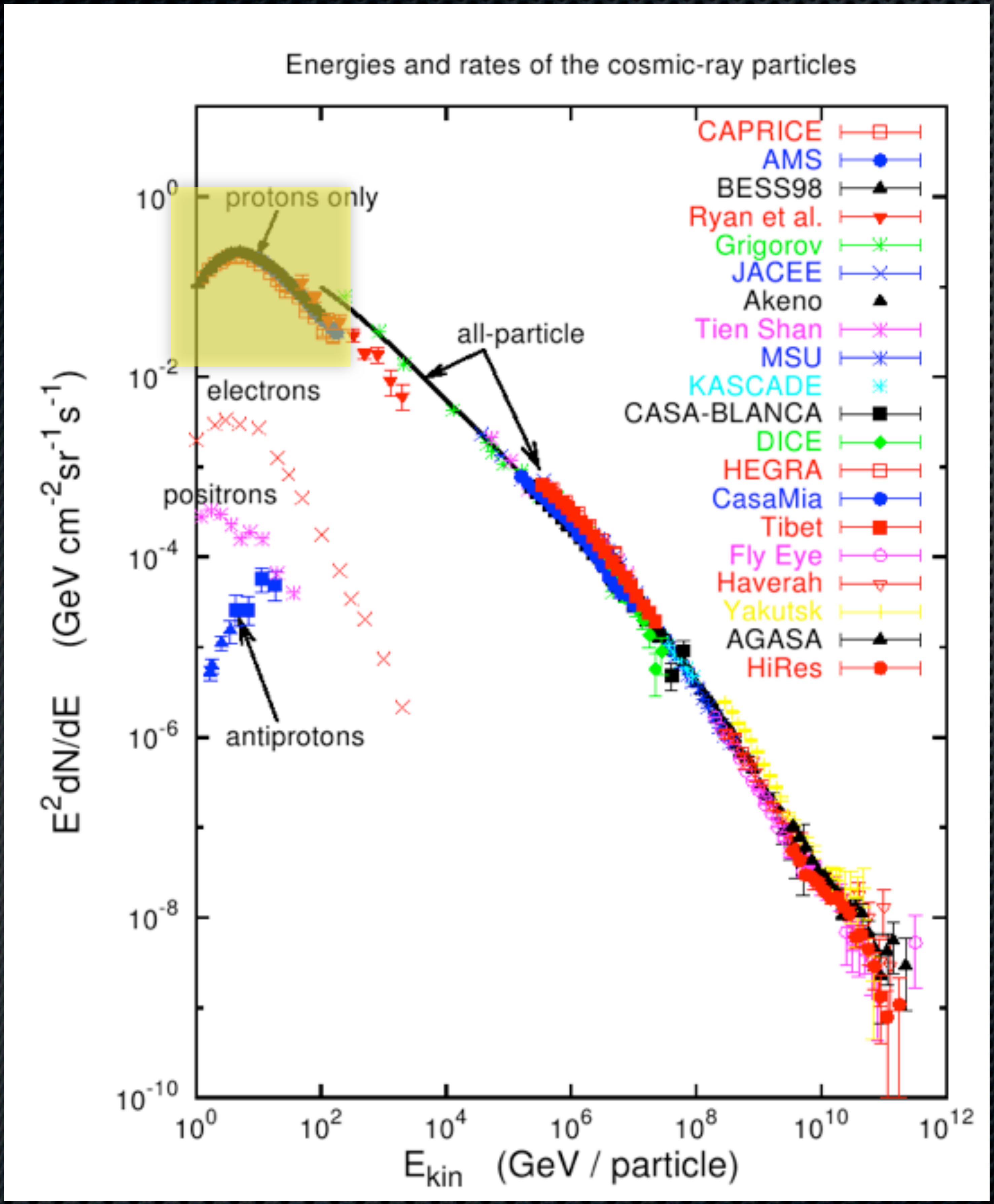
- Pos
- Muc
- Pion
- Kac



Notice: this is the 5th time that the ATLAS detector appears...


Energies and rates of the cosmic-ray particles
protons only
all-particle
electrons
positrons
antiprotons
CAPRICE
AMS
BESS98
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
Yakutsk
AGASA
HiRes
$E^2 dN/dE$ $(\mathrm{GeV\ cm^{-2} sr^{-1} s^{-1}})$
E_{kin} (GeV / particle)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}

$1/cm^2/s$



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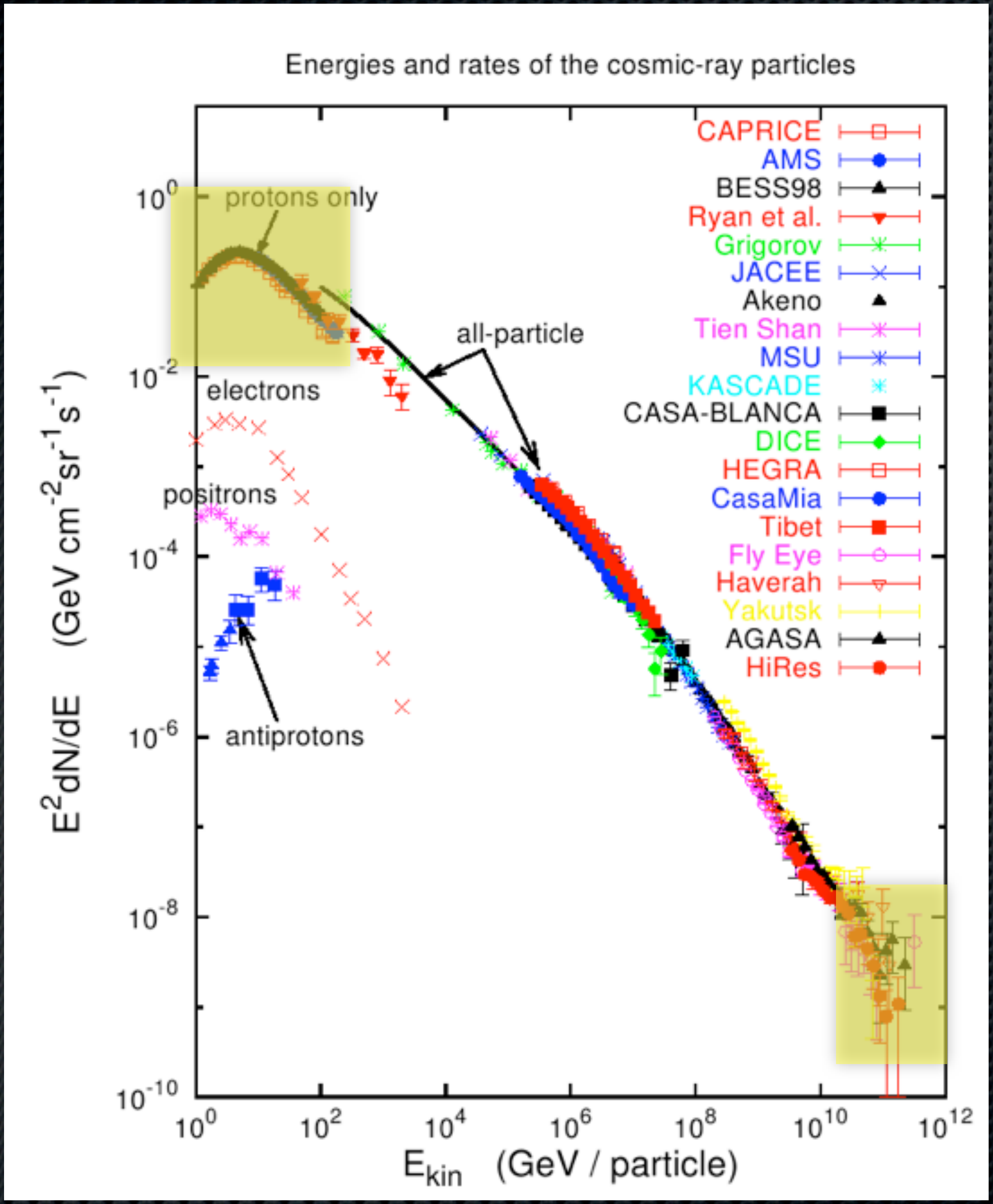
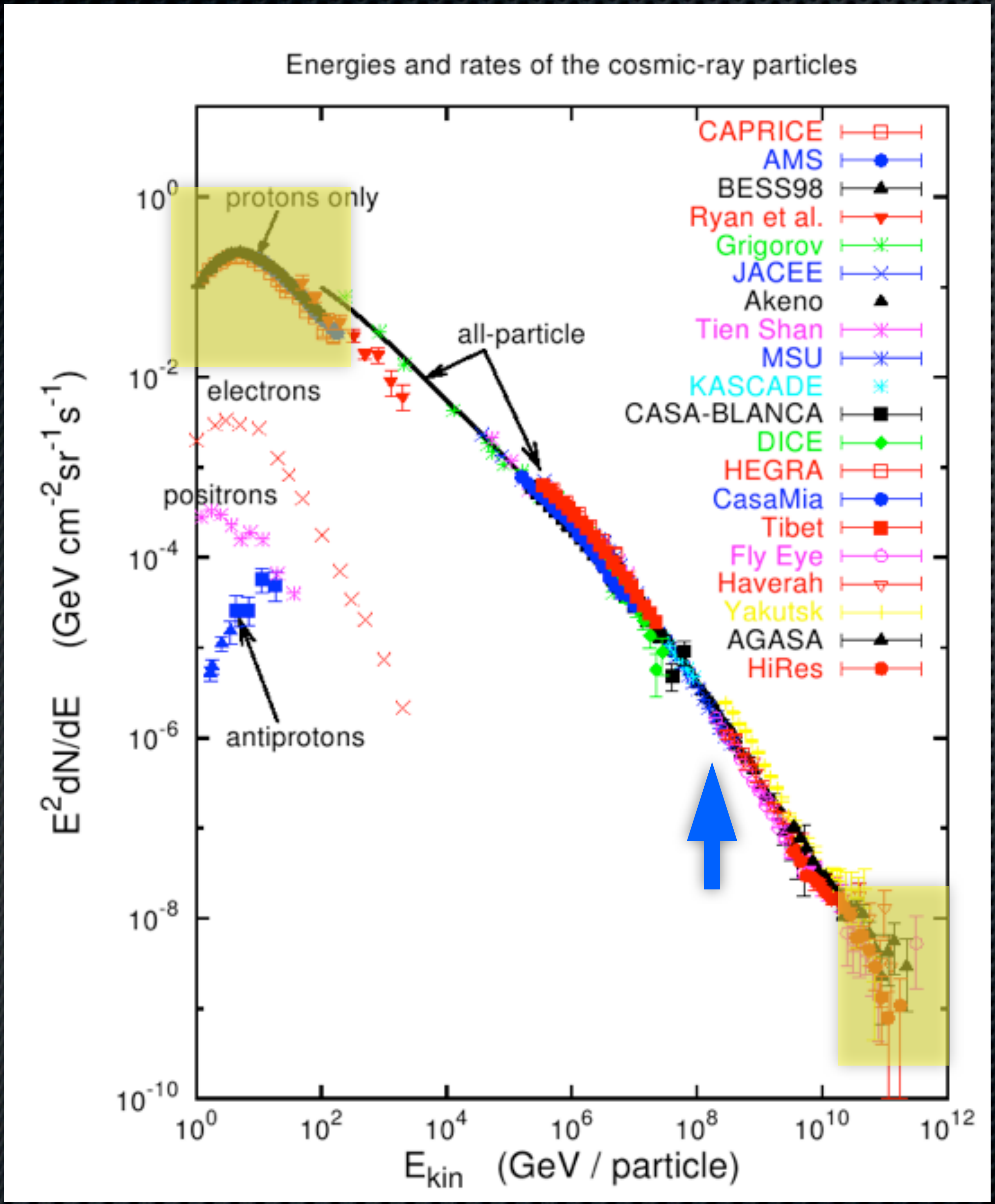
E²dN/dE (GeV cm⁻² sr⁻¹ s⁻¹)
E_kin (GeV / particle)

1/cm²/s



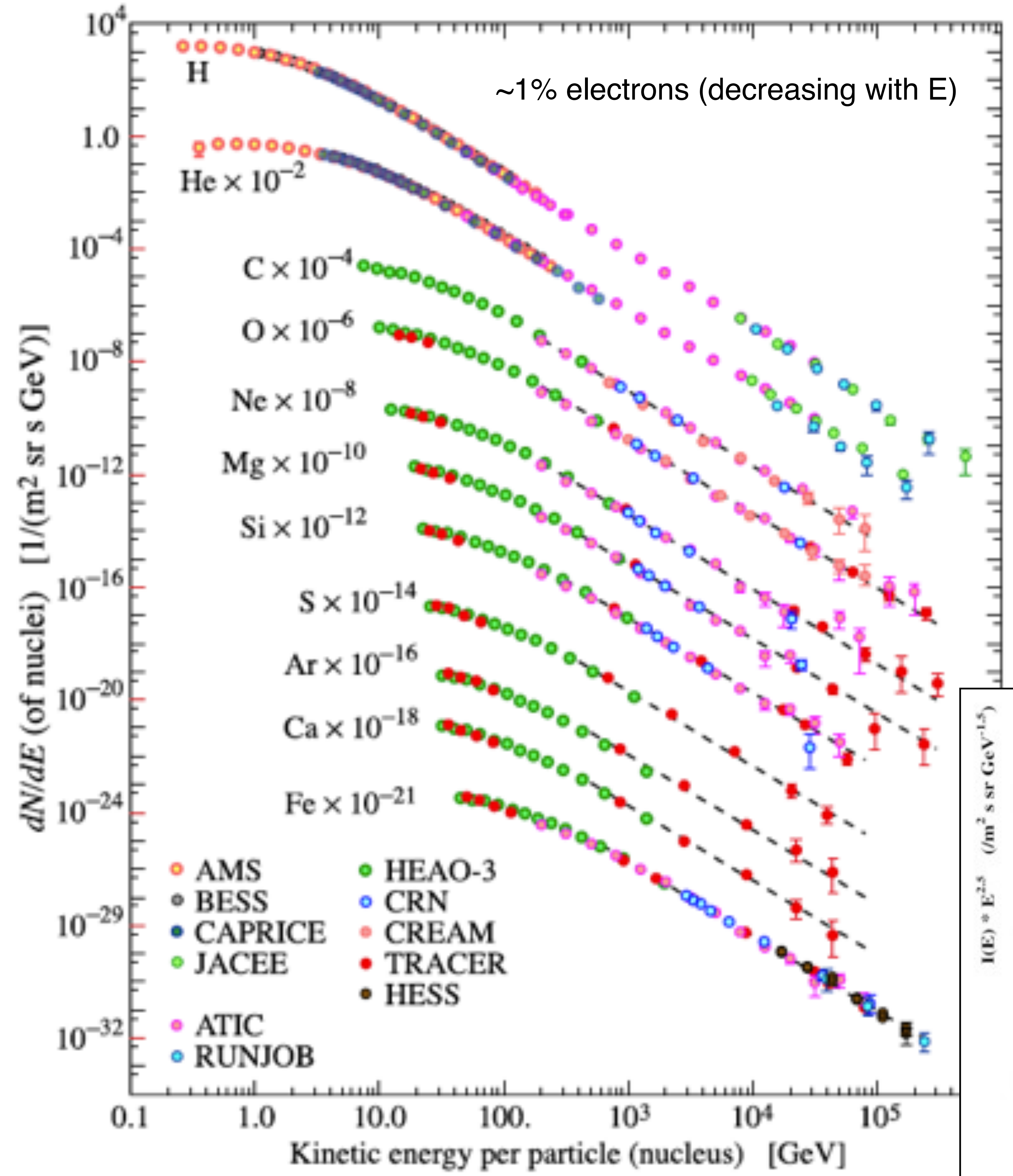
1/km²/century

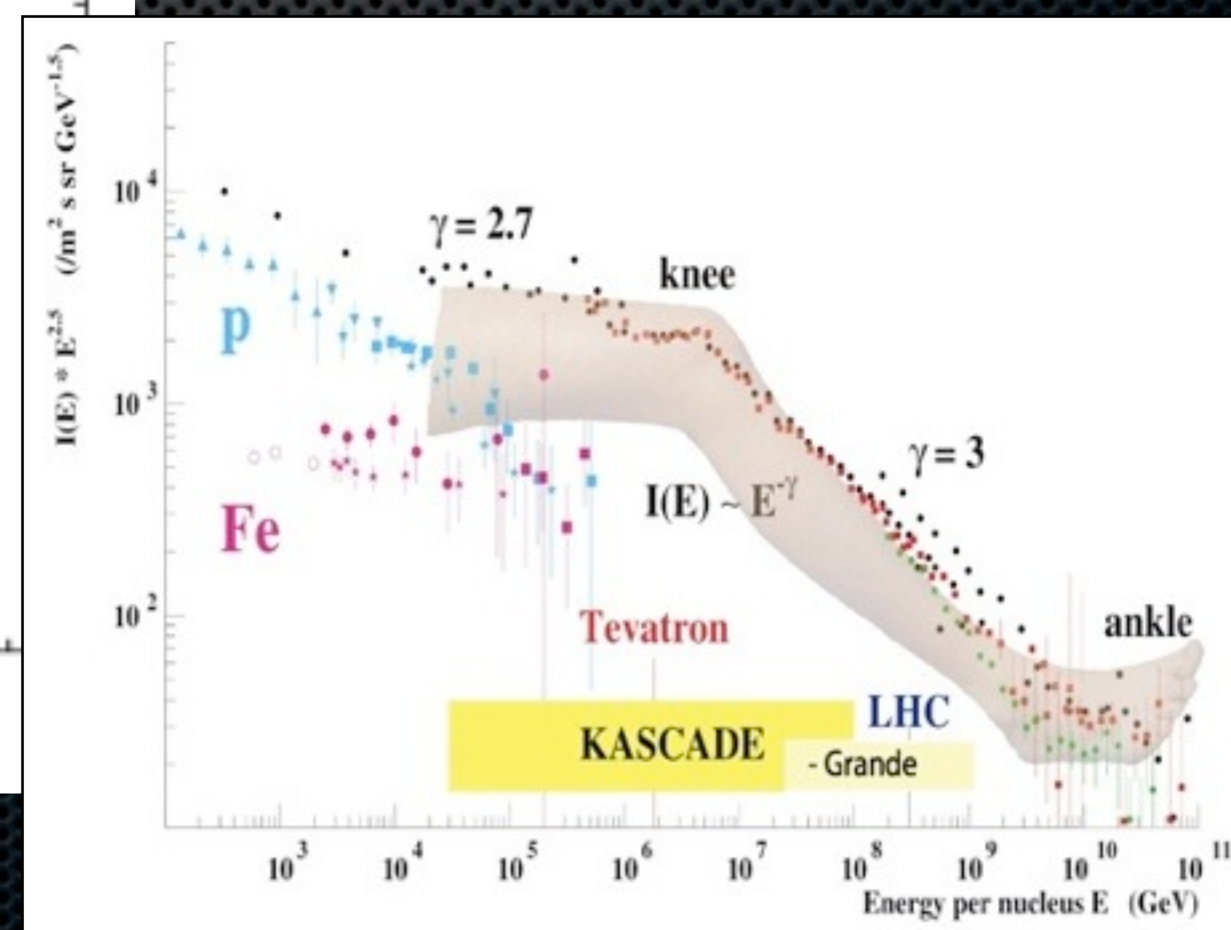
1/cm²/s



1/km²/century

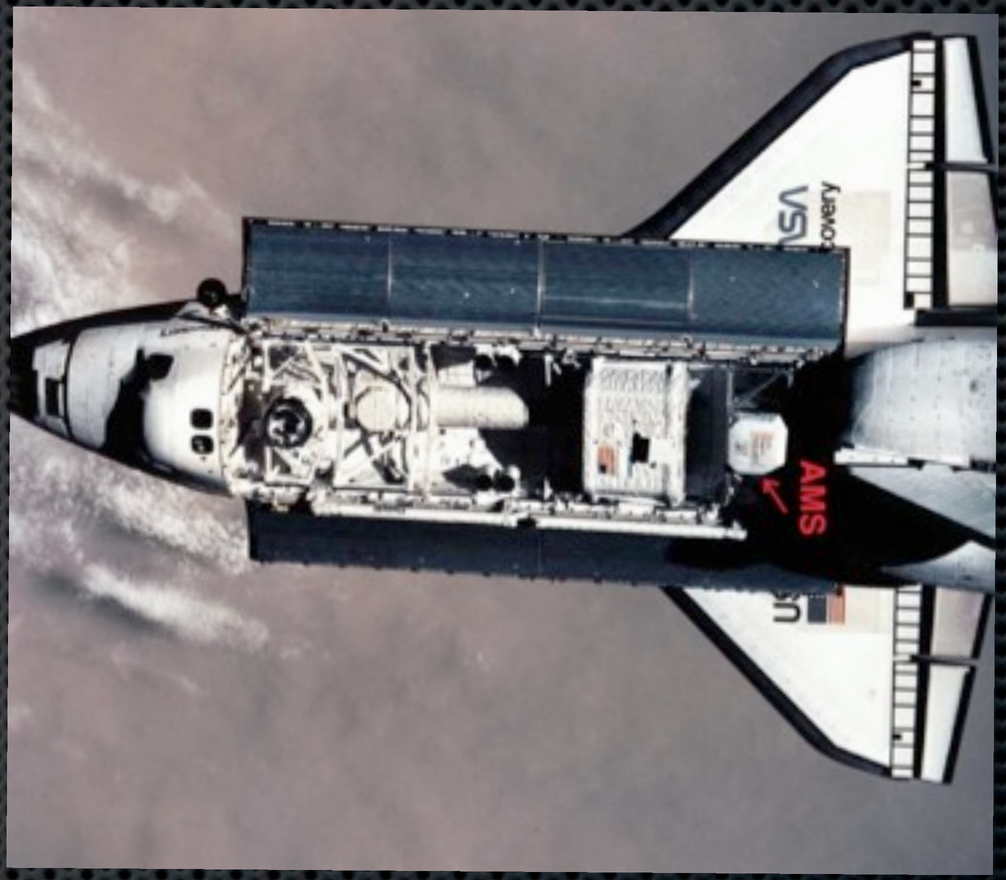
LHC


~1% electrons (decreasing with E)
H
He × 10^−2
C × 10^−4
O × 10^−6
Ne × 10^−8
Mg × 10^−10
Si × 10^−12
S × 10^−14
Ar × 10^−16
Ca × 10^−18
Fe × 10^−21
AMS
BESS
CAPRICE
JACEE
ATIC
RUNJOB
HEAO-3
CRN
CREAM
TRACER
HESS
dN/dE (of nuclei) [1/(m² sr s GeV)]
Kinetic energy per particle (nucleus) [GeV]


γ = 2.7
knee
p
Fe
I(E) ~ E^−γ
γ = 3
ankle
Tevatron
LHC
KASCADE
- Grande
I(E) * E^2.5 (/m² s sr GeV^−1.5)
Energy per nucleus E (GeV)

Experiments...

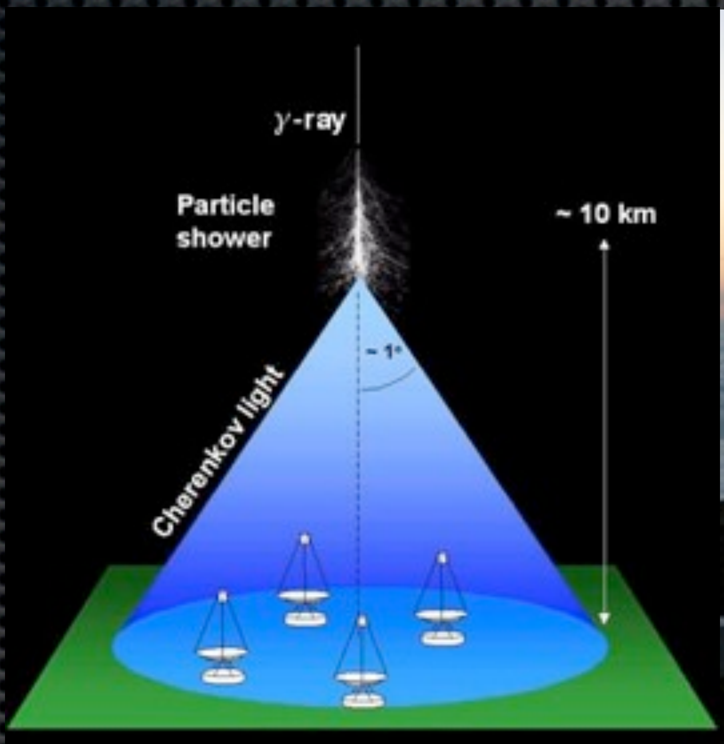
CREAM
ATIC
PAMELA



AMS-01
AMS-02 is coming!

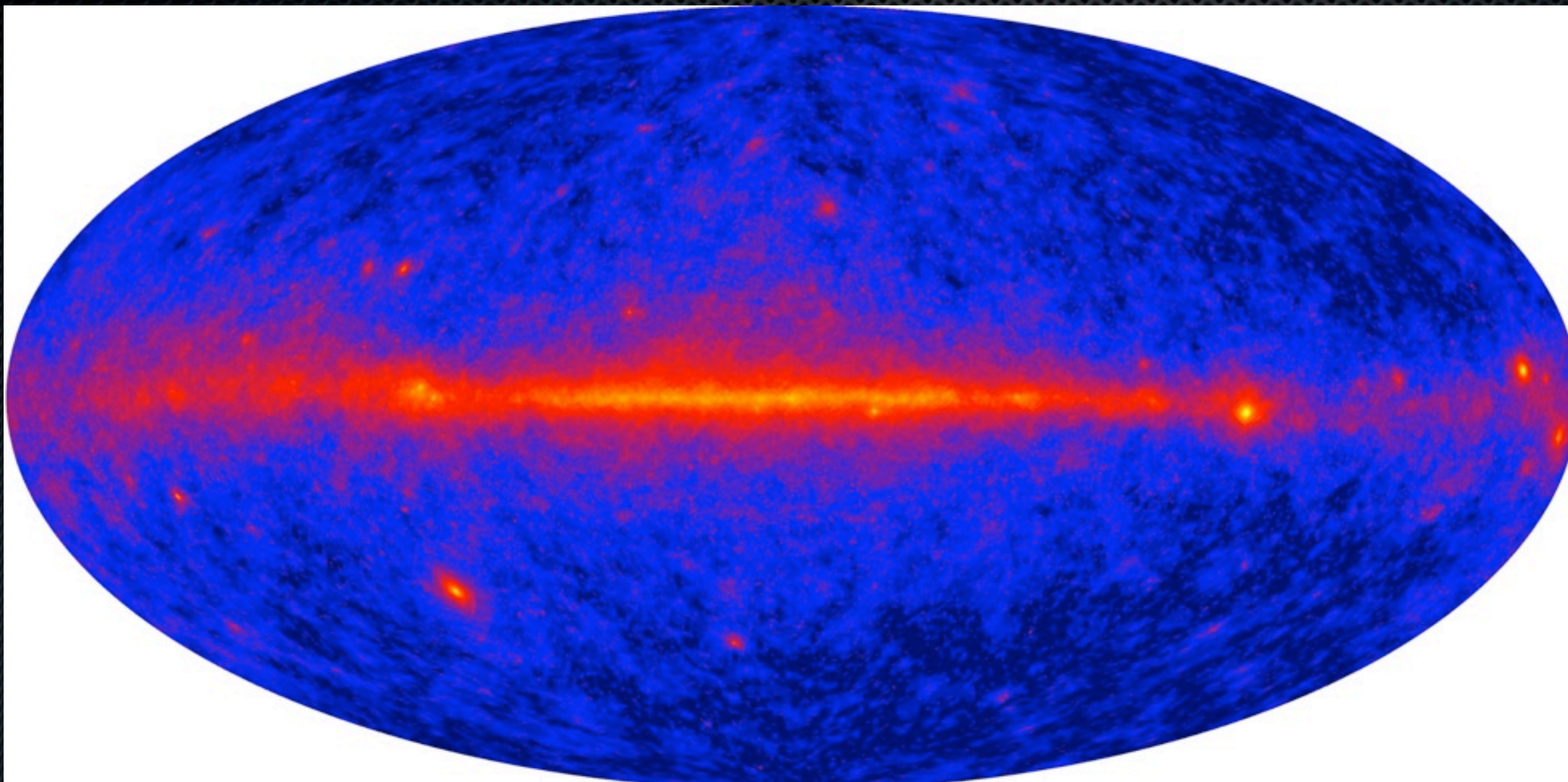
Experiments...

FERMI



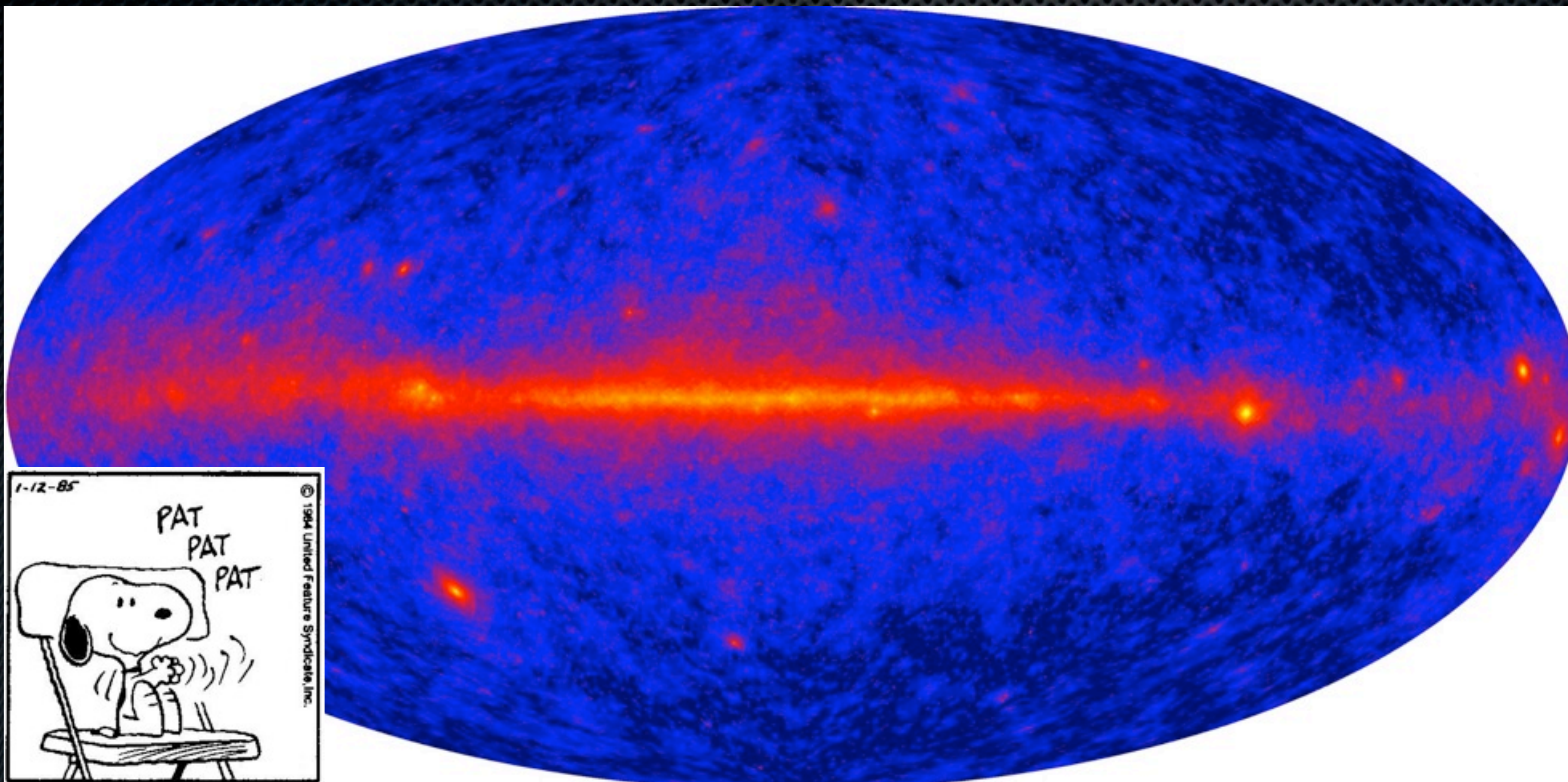
H.E.S.S.
CANGAROO
MAGIC

Experiments...



FERMI

Experiments...



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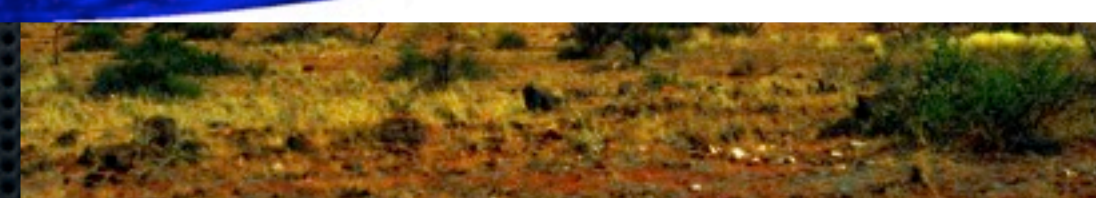

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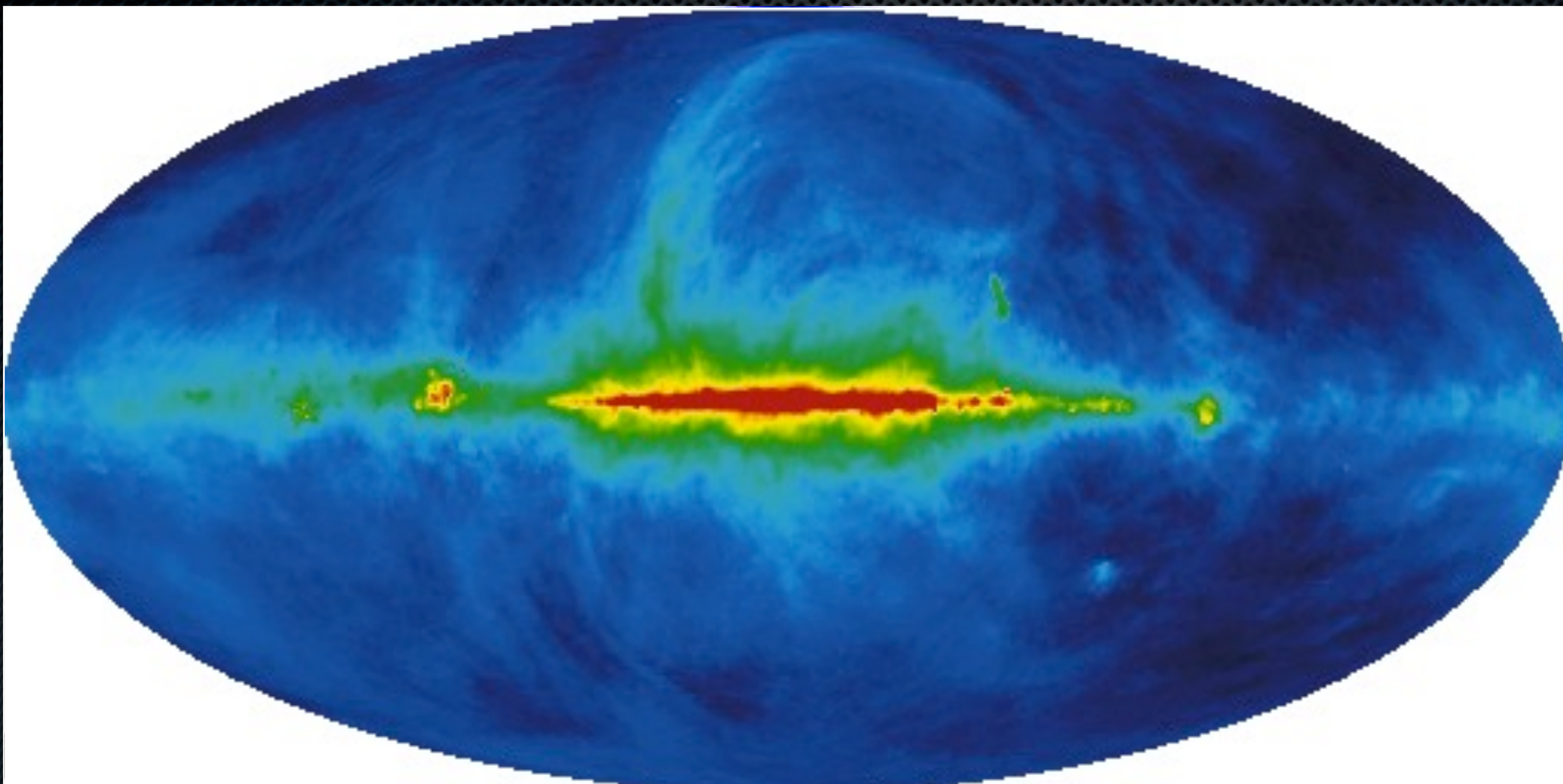

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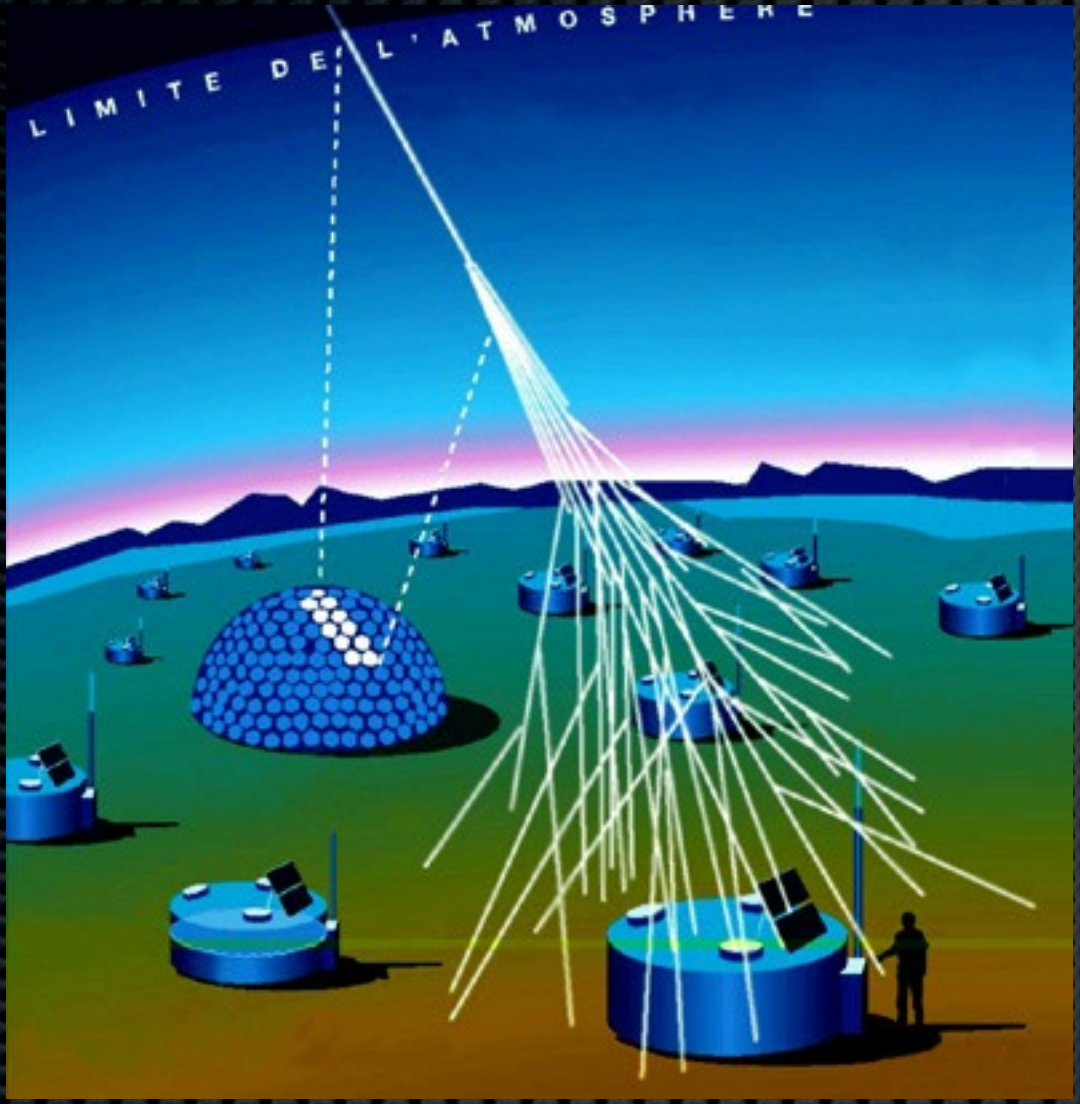
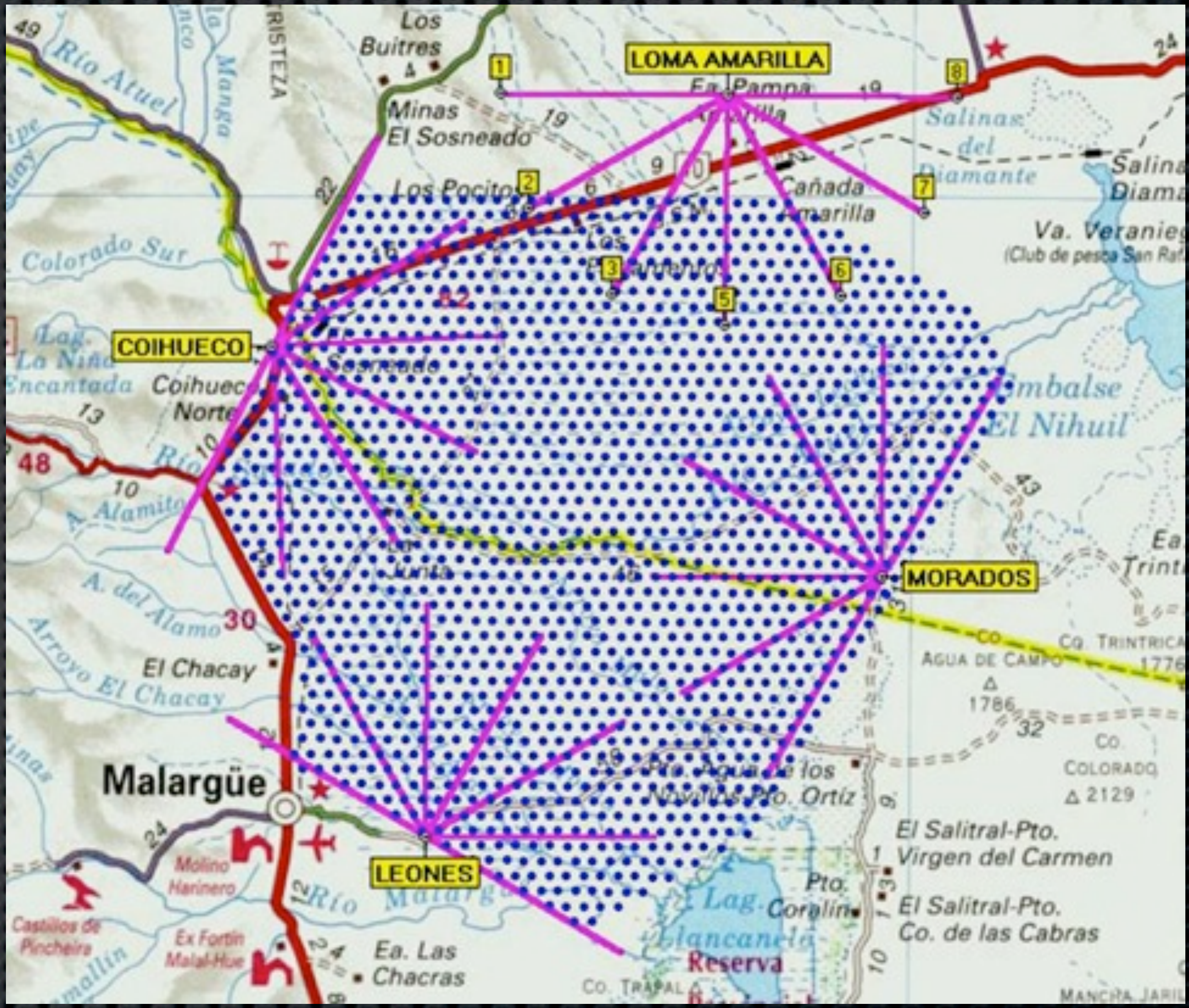
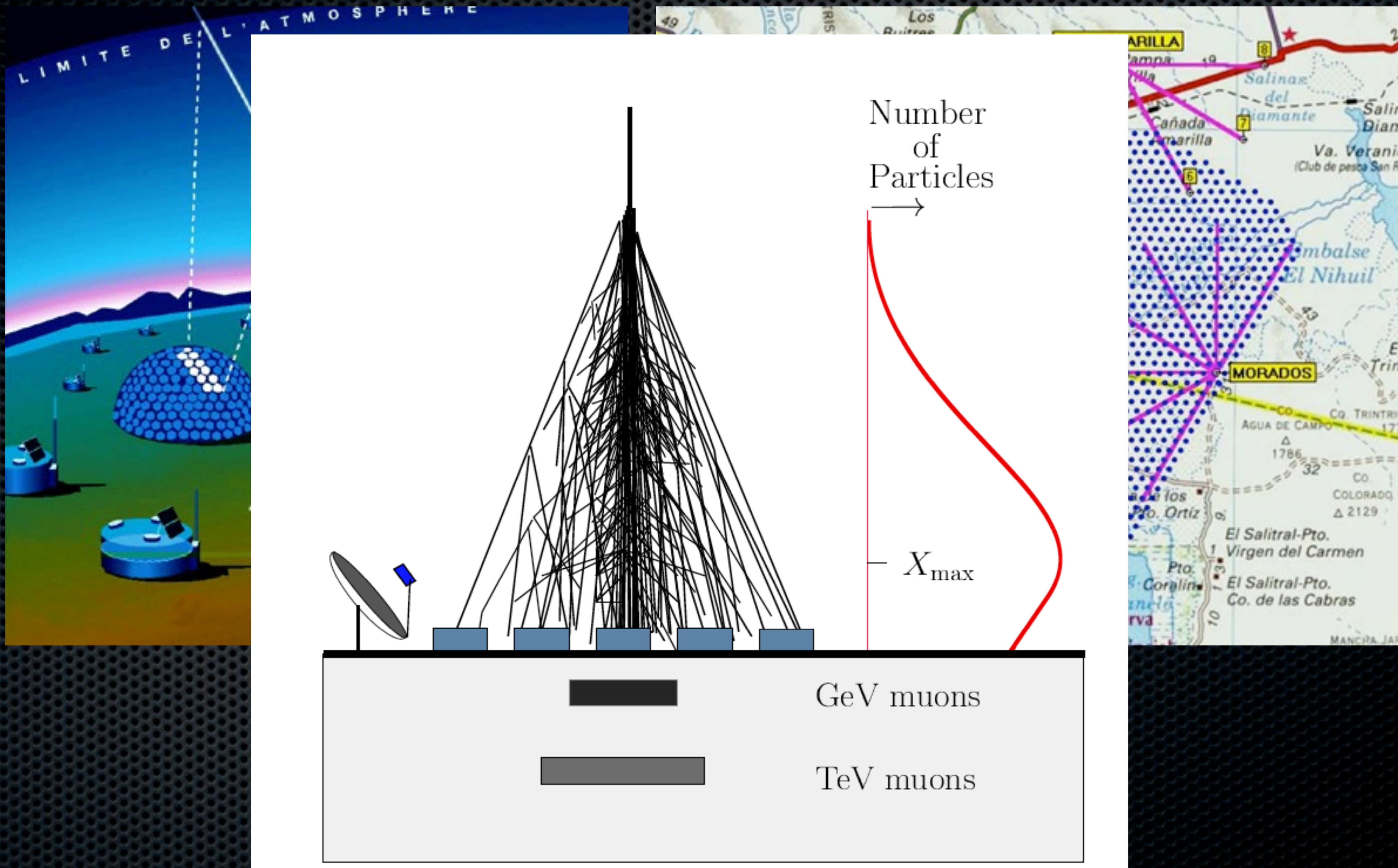




Pierre Auger Observatory

Experiments...

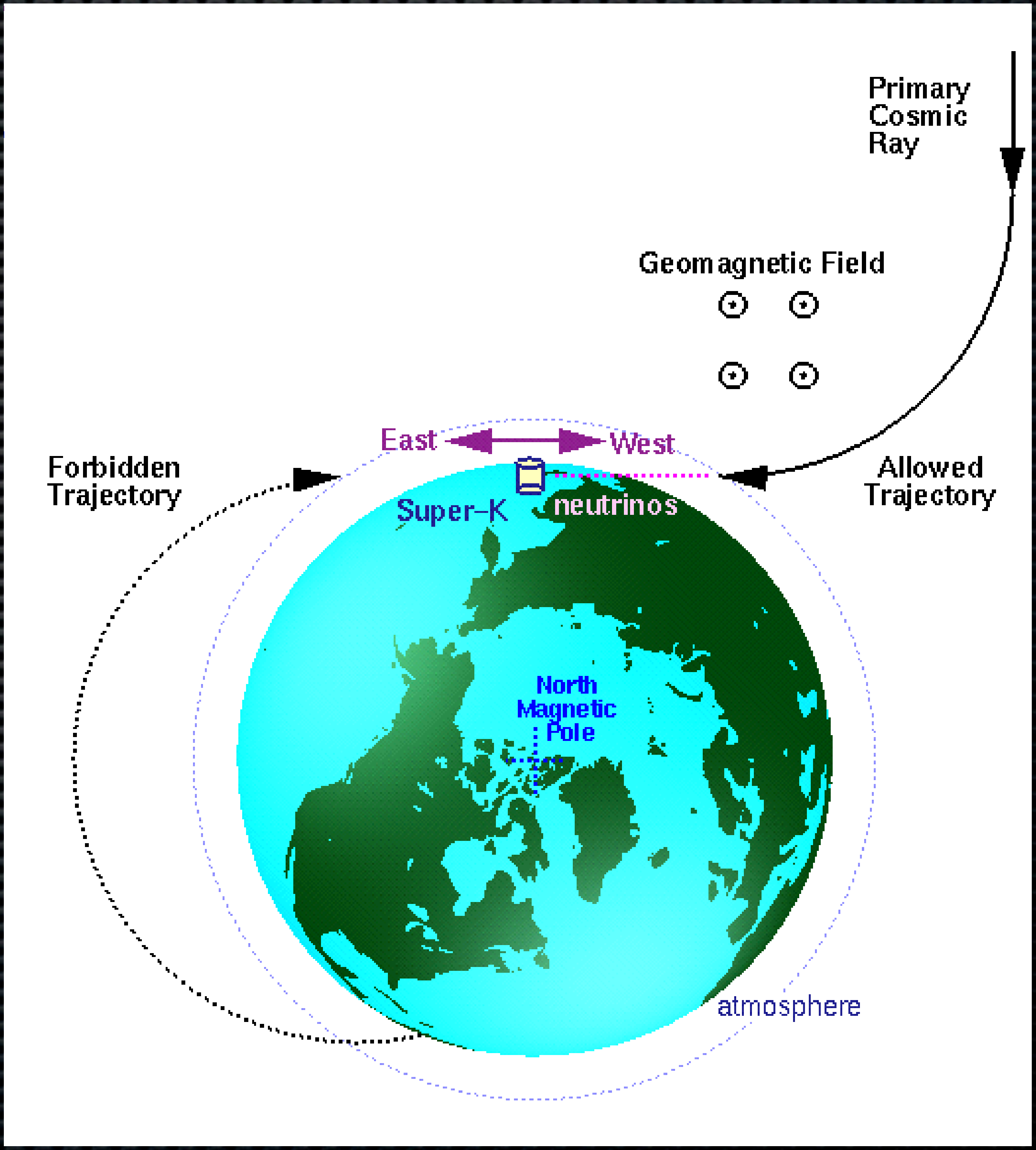


Cosmic Rays are charged...

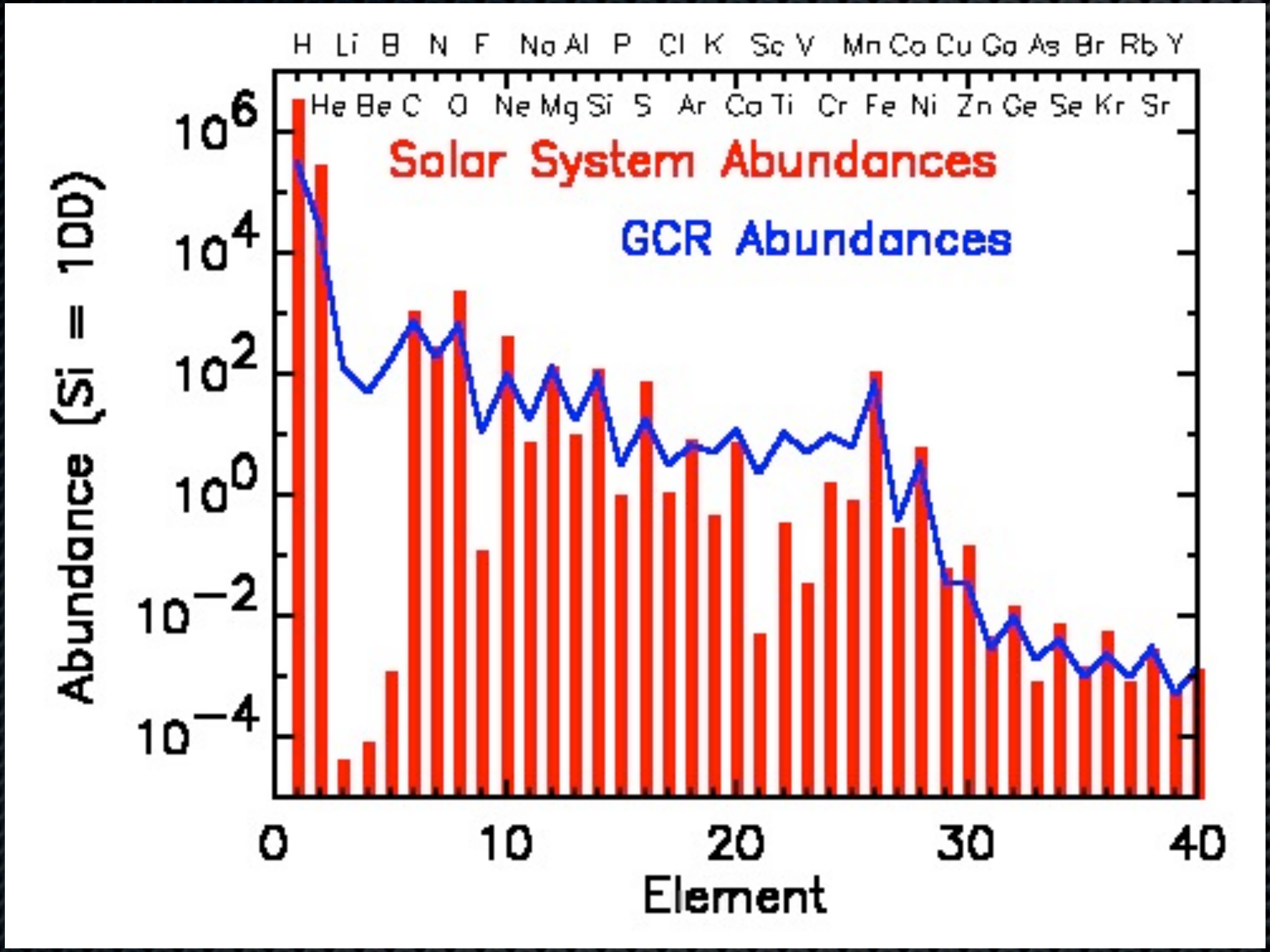
East-West asymmetry and latitude effect (flux grows with latitude)

Some trajectories are forbidden due to Lorentz force

Latitude effect discovered in 1929.
East-West asymmetry determined in 1934.
CRs are protons!



Secondary / Primary



- **Primary** species are present in sources (CNO, Fe). Produced by stellar nucleosynthesis. Acceleration in SN shocks ($\geq 10^4$ yr).
- **Secondary** species are absent of sources (LiBeB, SubFe).

Produced during propagation of primaries

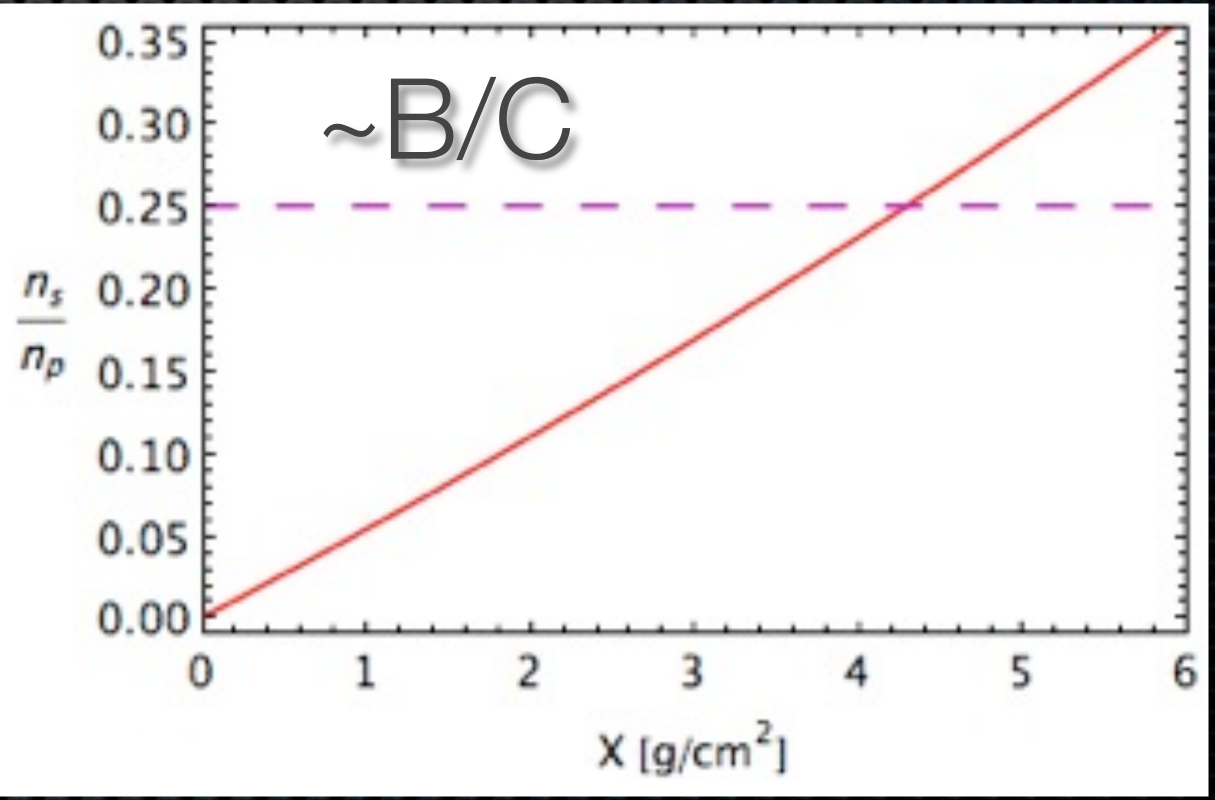
Secondary / Primary

Consider two species:
p, s, coupled through
spallation: **p --> s + ...**

$$\frac{dn_p}{dX} = -\frac{n_p}{\lambda_p}$$

$$\frac{dn_s}{dX} = -\frac{n_s}{\lambda_s} + p_{\rm sp}\frac{n_p}{\lambda_p}$$

X = grammage (traversed matter) [g/cm^2]
λ_i = interaction probs
p_{sp} = spallation prob



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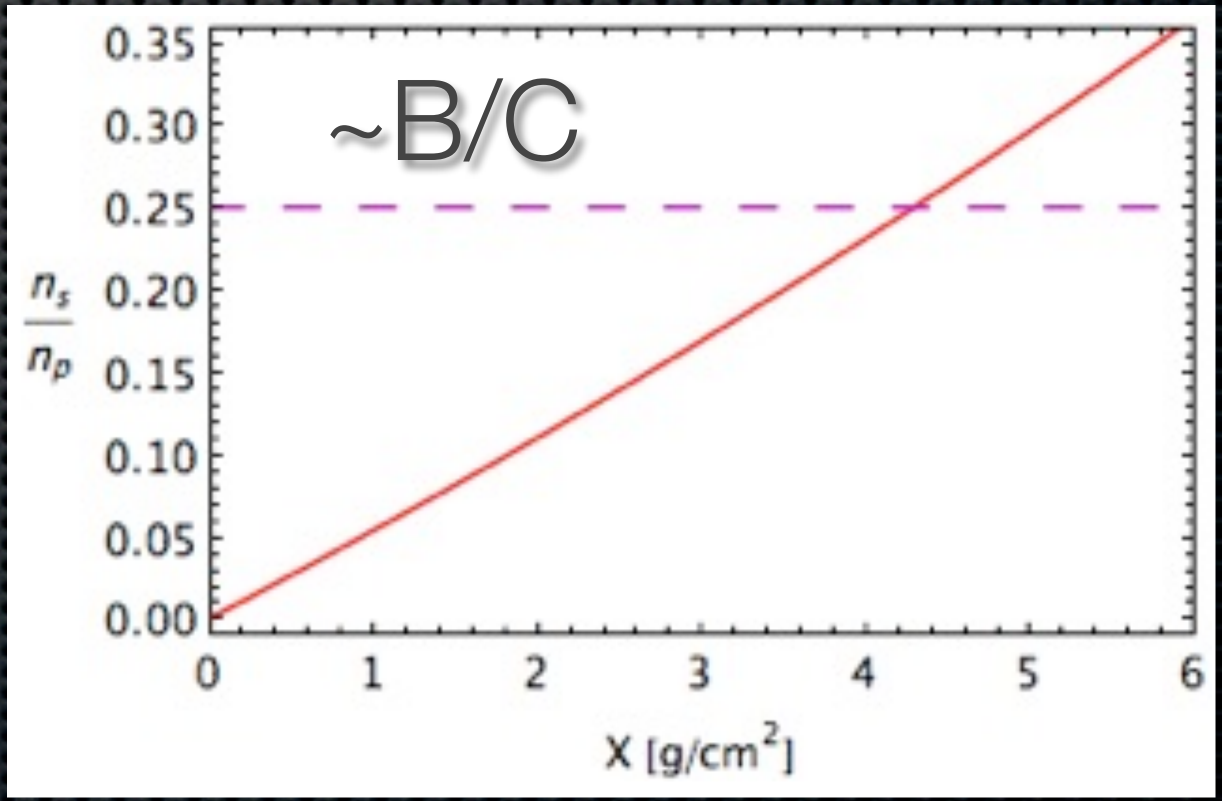

$$L = \frac{\rm grammage}{n_{ISM} m_p} \sim 10^4 {\rm kpc}$$

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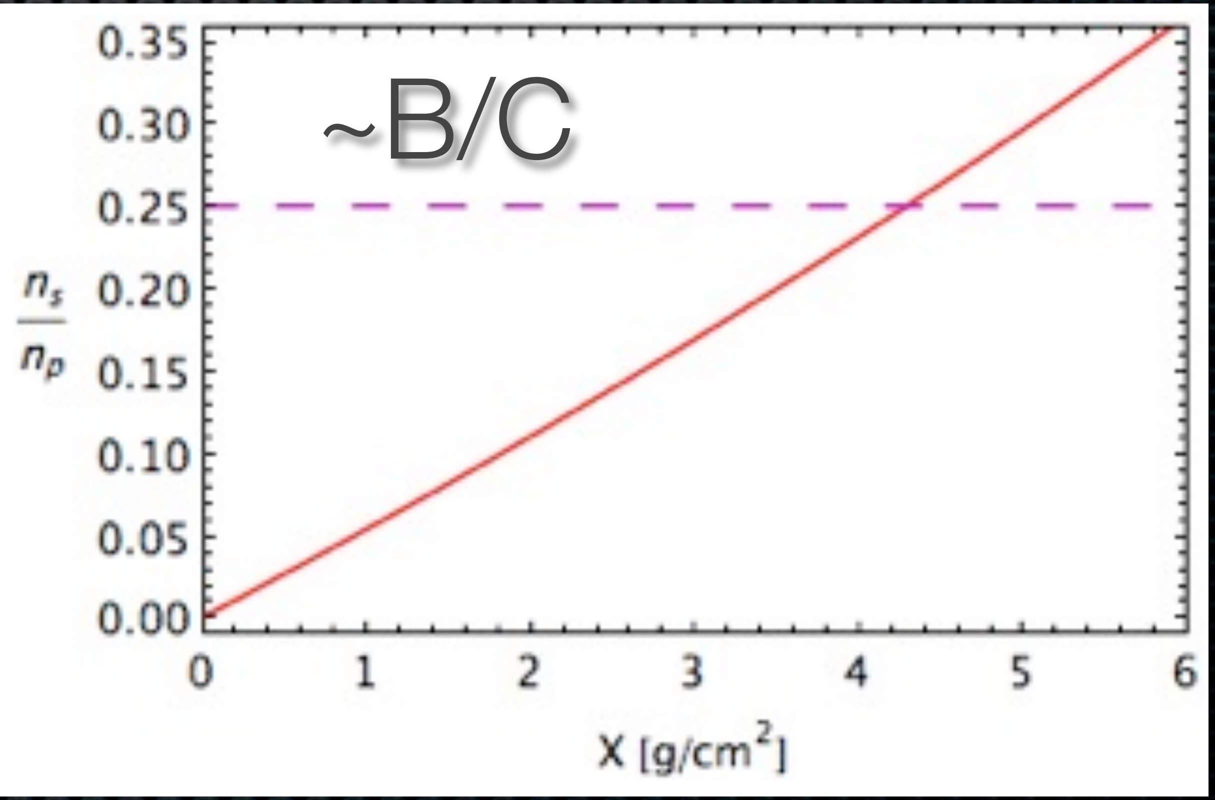

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>> Galaxy size!

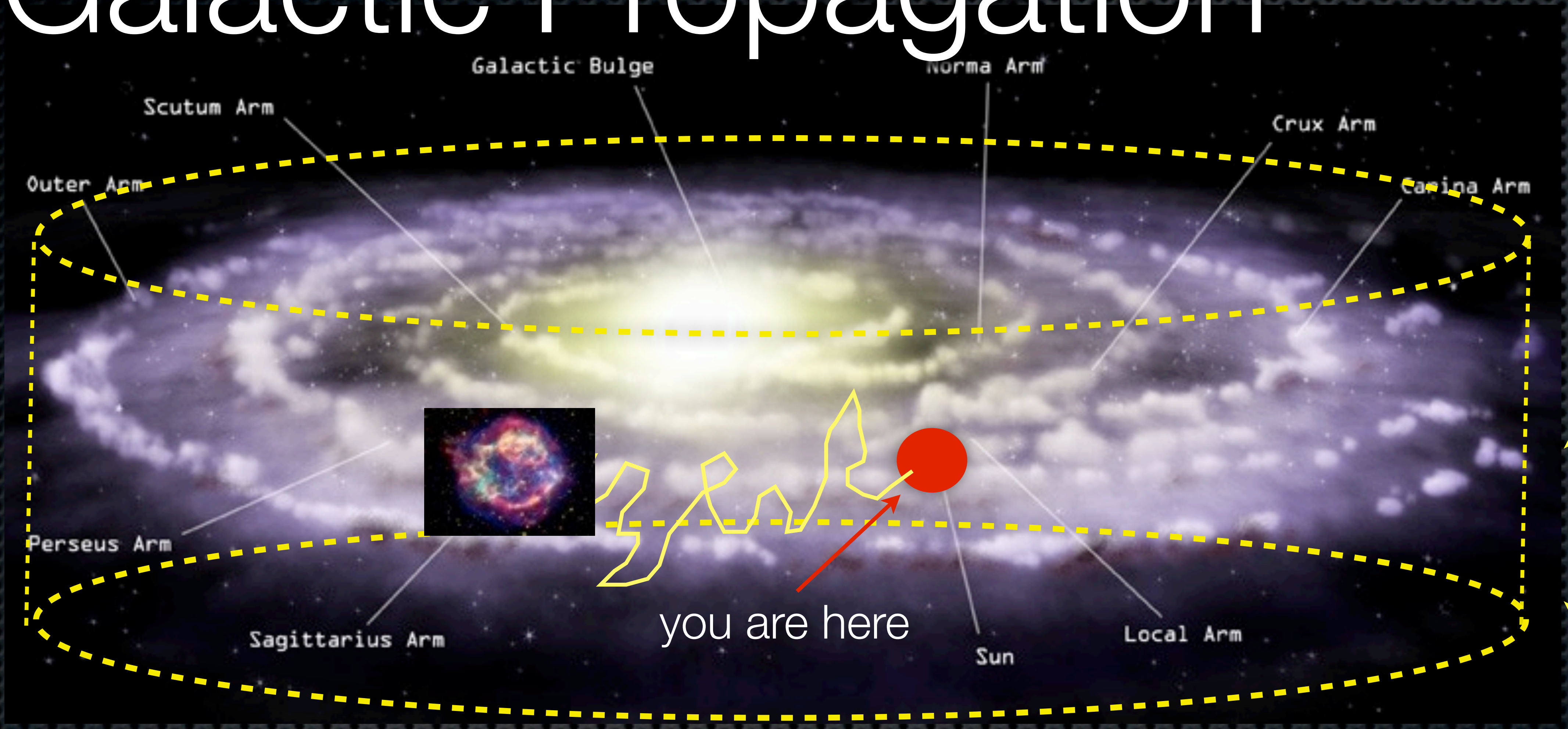
CR clocks

Year	Experiment	Energy range (MeV)	^{10}Be/Be	Age (Myr)
1977-1981	IMP7-IMP8	31-151	0.028±0.014	17
1980	ISEE-3	60-185	0.064±0.015	84
1977-1991	Voyager I II	35-92	0.043±0.015	27
1990-1996	Ulysses/HET Shuttle discovery	68-135	0.046±0.006	26
1997	CRIS/ACE	70-145		145

- Radioactive isotopes can be used as “CR clocks” to measure their residence time:
  if purely secondary
  if decay time ~ residence time

CR propagation is not ballistic!

Galactic Propagation

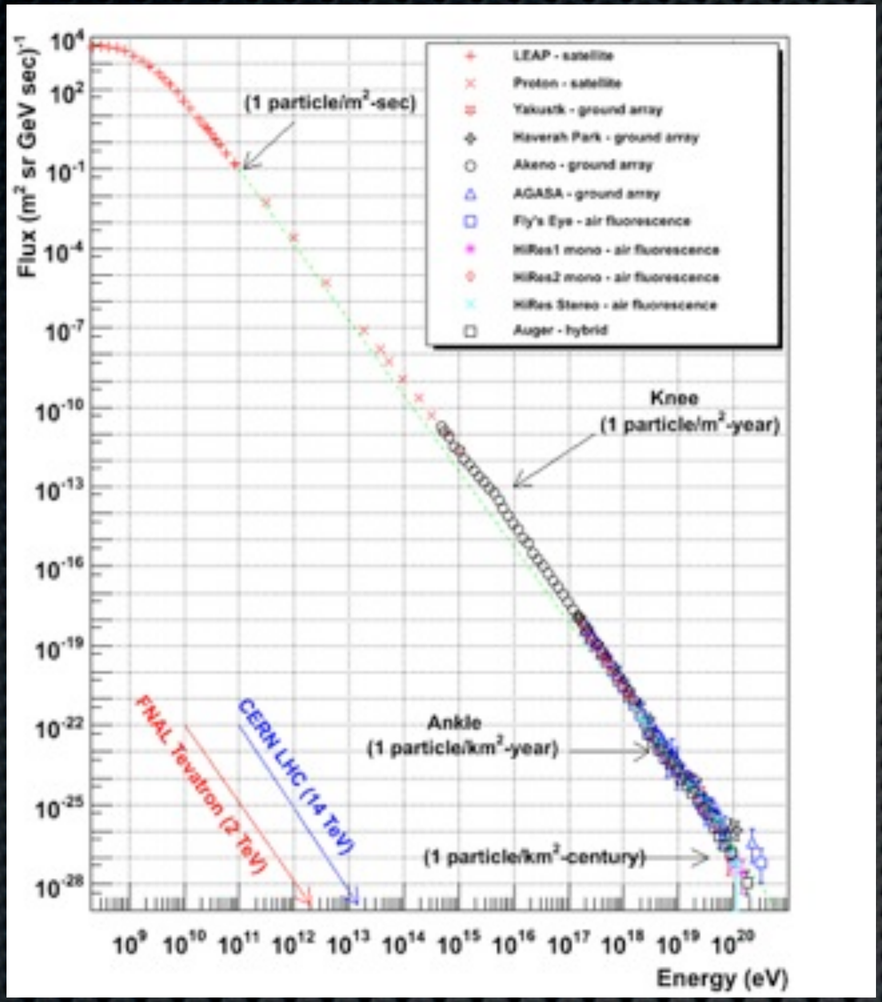


CRs propagate into the turbulent Galactic magnetic field!
The Larmor radius of a CR is

$$r_L(E) = \frac{E}{ZeB} \sim 1\,\mathrm{pc}\left(\frac{E}{10^{15}\mathrm{eV}}\right)\left(\frac{B}{1\mu G}\right)^{-1}$$

for a typical disk height ~100 pc ⇒ propagation is diffusive up to ~ **10^{16}-10^{17} eV**.

Supernovae as sources



$$\omega_{CR} = 0.5 \mathrm{eV cm^{-3}}$$

Supernovae as sources

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$$V_{\text{conf}} = \pi R^2 h = 2 \times 10^{67}\,\text{cm}^3$$

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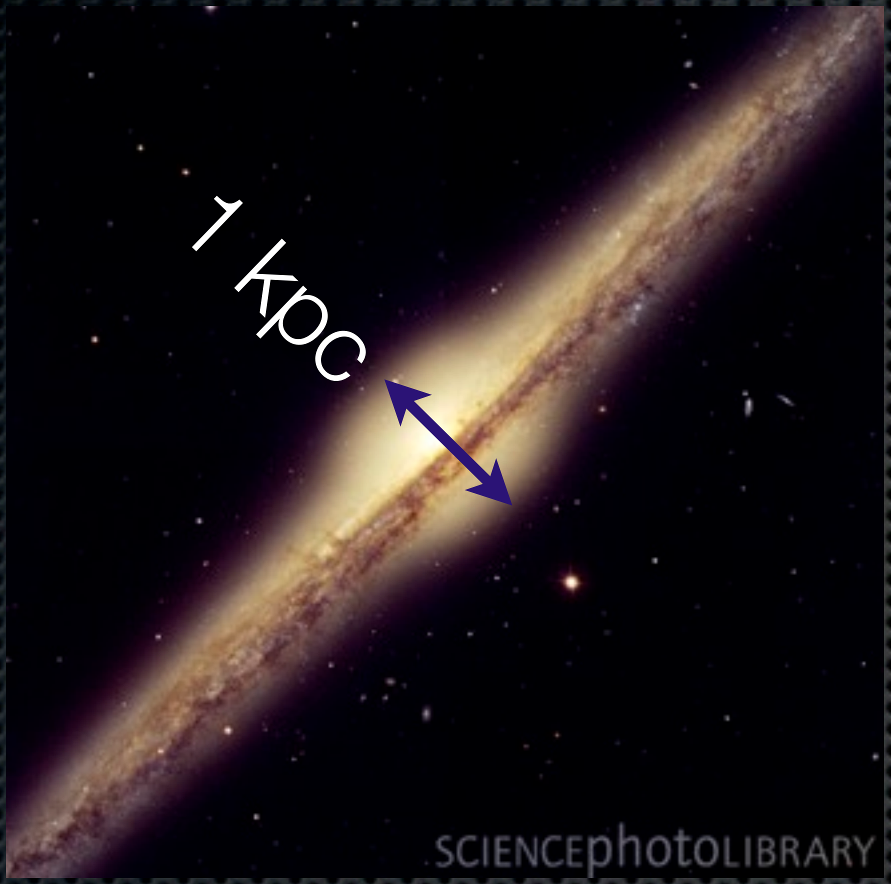

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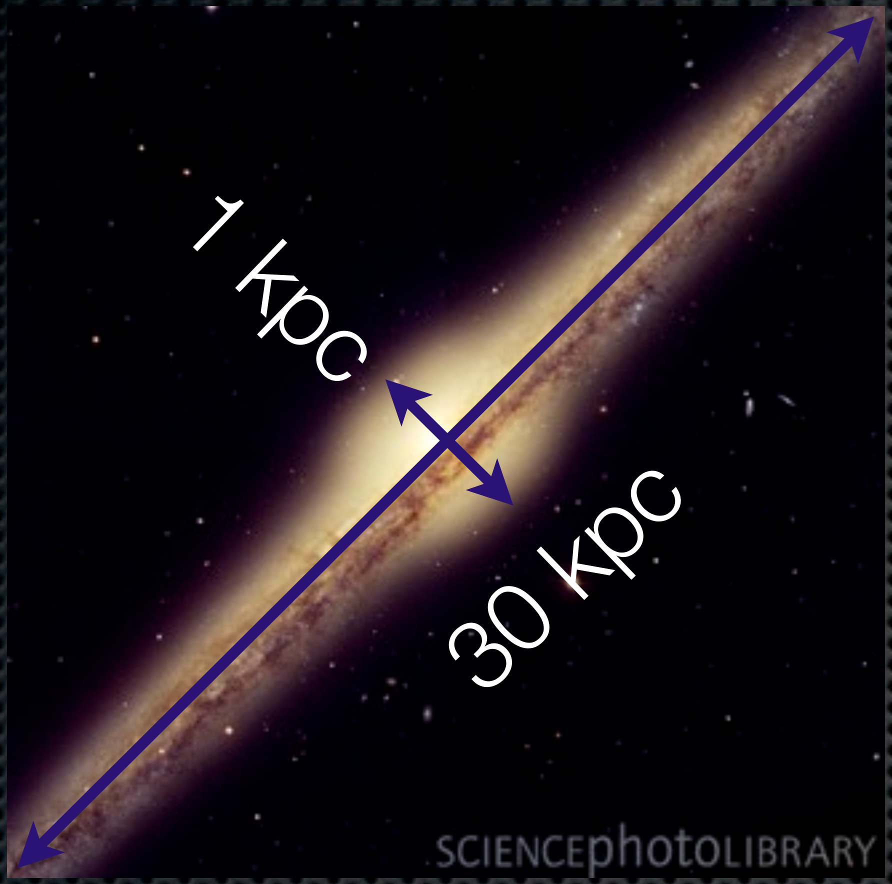

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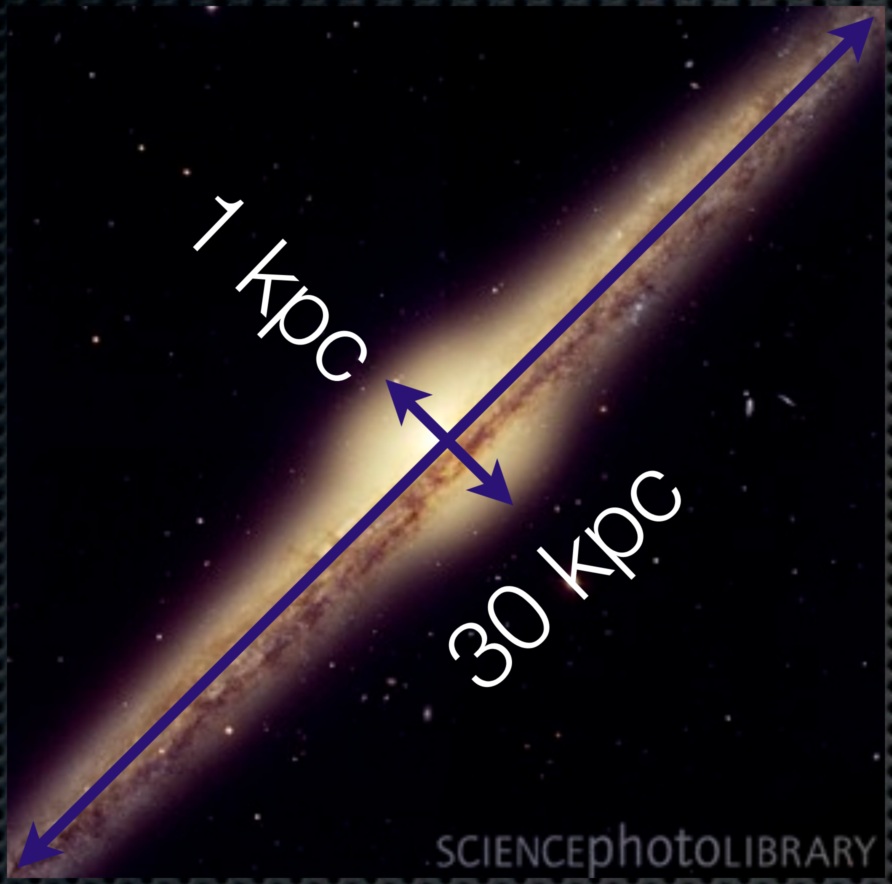

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$$W_{CR} = \omega_{CR} V_{\mathrm{conf}} \sim 2 \times 10^{55} \mathrm{erg}$$

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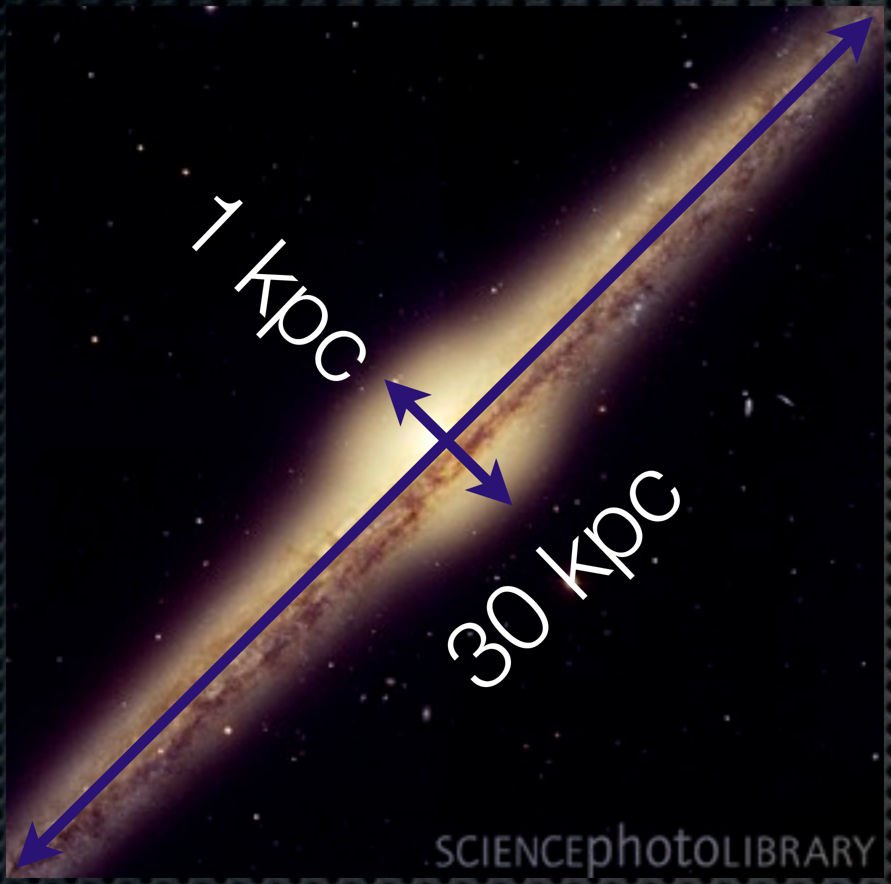

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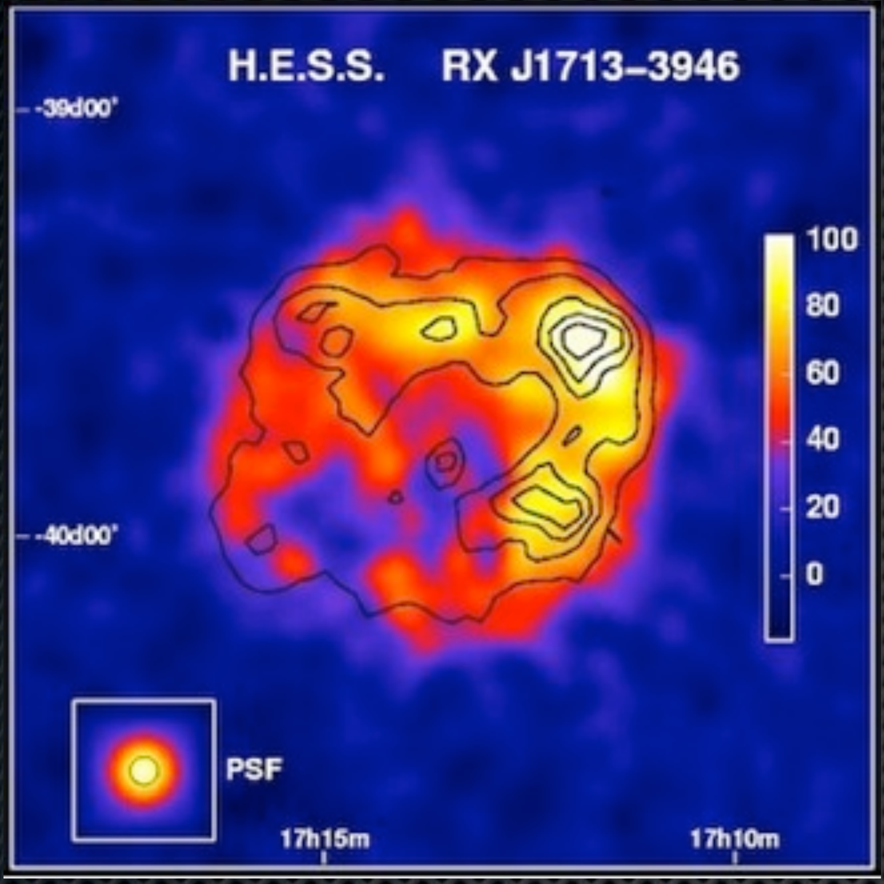

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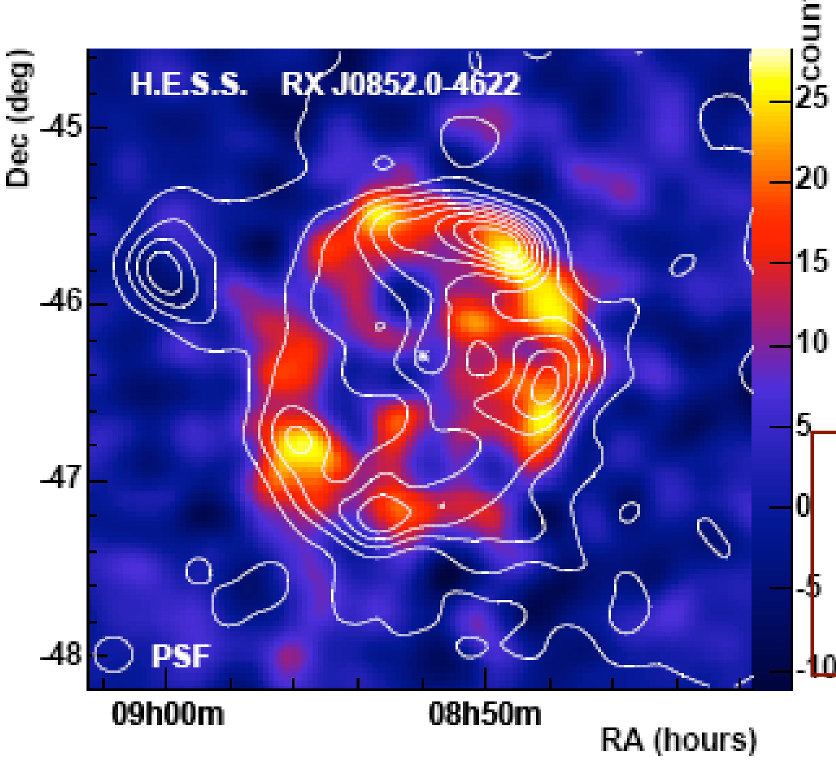
VS

$$L_{SN} \sim R_{SN} E_{\mathrm{kin}} \sim 3 \times 10^{41} \mathrm{erg\,s}^{-1}$$

Supernovae as sources

Predictions of supernova shock acceleration:

$\phi(E) \propto E^{-\alpha}$ with **α**≃2



SNR RX J0852.0-4622

← Observed in X-ray & γ-rays →

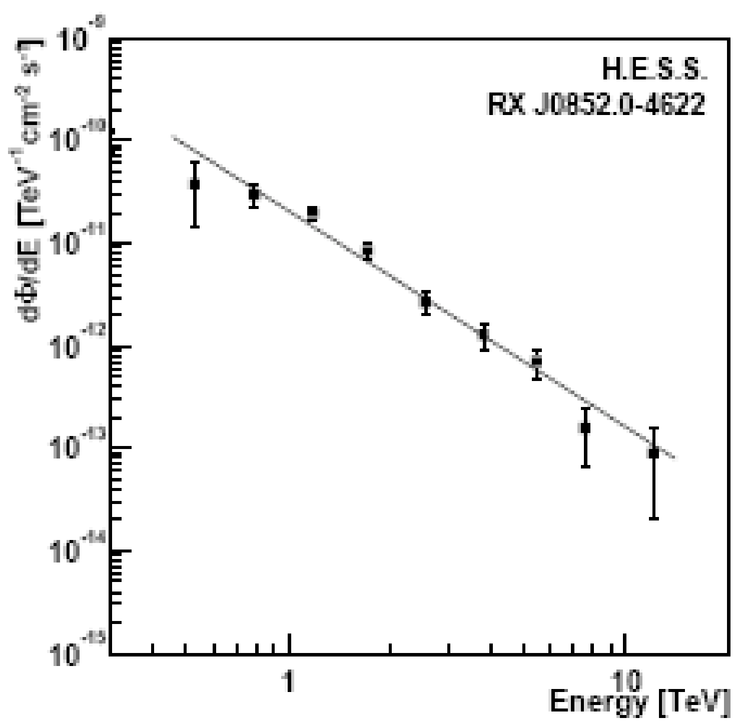
(Hess Coll. A&A 2005)

$\Phi(E) \propto E^{-\alpha}$ $\alpha = 2.1 \pm 0.1$ →

If all from hadronic sources

⇒ α IS acceleration spectrum

BUT: how much is IC?



Why to bother with HE CR?

- Energy density in equipartition with other galactic components.
- Wander over the galaxy: probe its environment.
- We still have to learn a lot: sources? components?
- Responsible for the diffuse gamma-ray emission in the Galaxy.
- Act as a background for exotic component searches.

CR Diffusion in the MW

The diffusion equation:

$$\frac{\partial N^i}{\partial t} - \nabla \cdot (D\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla \cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} =$$

$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Ginzburg & Syrovatsky, 1964

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Source term:

- assumed to trace the SNR in the Galaxy
- assumed the same power-law everywhere

Ginzburg & Syrovatsky, 1964

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Spallation cross-section:

- appearance of nucleus i due to spallation of nucleus j

Ginzburg & Syrovatsky, 1964

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Spallation cross-section:

- appearance of nucleus i due to spallation of nucleus j
- total inelastic cross-section: disappearance of nucleus i

Ginzburg & Syrovatsky, 1964

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Diffusion tensor:

- $D(E) = D_0(\rho/\rho_0)^{\delta}\exp(z/z_t)$

Ginzburg & Syrovatsky, 1964

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Energy losses:

- ionization, Coulomb, synchrotron
- adiabatic convection

Ginzburg & Syrovatsky, 1964

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Reacceleration:

- $D_{pp} \propto \frac{p^2 v_A^2}{D}$

Ginzburg & Syrovatsky, 1964

SOLVING THE DIFFUSION EQUATION

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- **leaky-box models**

  Back of the envelope approach with many useful predictions.

- **semi-analytic models**

  Assume simplified distributions for sources and gas, and try to solve the diffusion equation analytically

  (see Maurin, Salati, Donato et al.)

- **numerical models (GALPROP)**

  use more realistic distribution

  (Strong and Moskalenko, 1998 ... 2012)

SOLVING THE DIFFUSION EQUATION

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- **semi-analytic models**

  Assume simplified distributions for sources and gas, and try to solve the diffusion equation analytically

  (see Maurin, Salati, Donato et al.)

- **numerical models (GALPROP)**

  use more realistic distribution

  (Strong and Moskalenko, 1998 ... 2012)

- a new numerical model: **DRAGON** (Diffusion of cosmic RAys in the Galaxy modelizatiON). See Evoli et al. 2008.

CR diffusion in the MW

Neglect everything but diffusion (and take it constant...)

The solution can be obtained by convolution with the Green's function (heat diffusion kernel...)

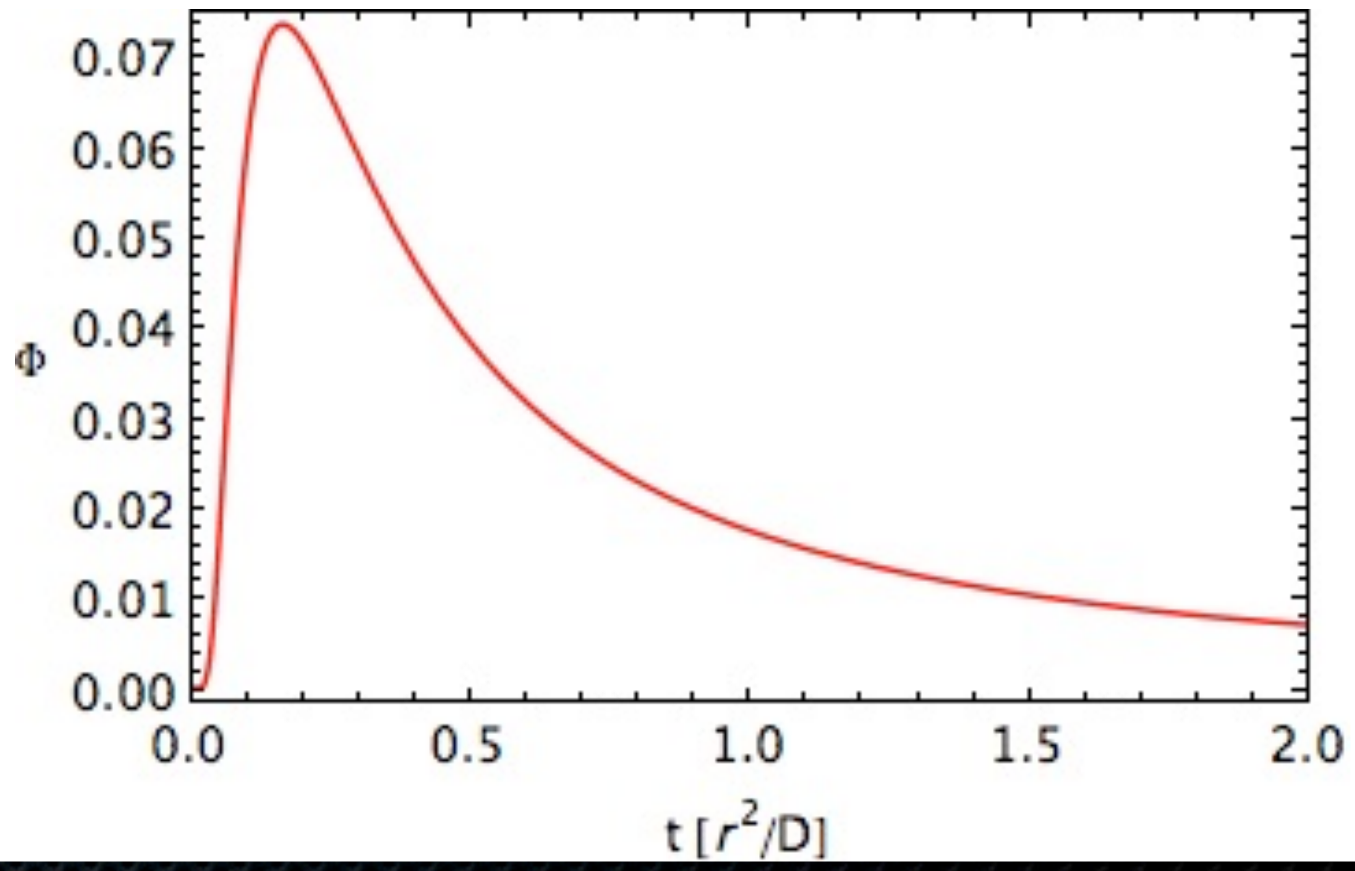
$$G(\mathbf{x}, t) = \frac{1}{(4\pi\, D\, t)^{3/2}} \exp\left(-\frac{\mathbf{x}^2}{4D\, t}\right)$$

For an impulsive event, localized in space and time

$$Q = \mathcal{N} \delta(r) \delta(t)$$

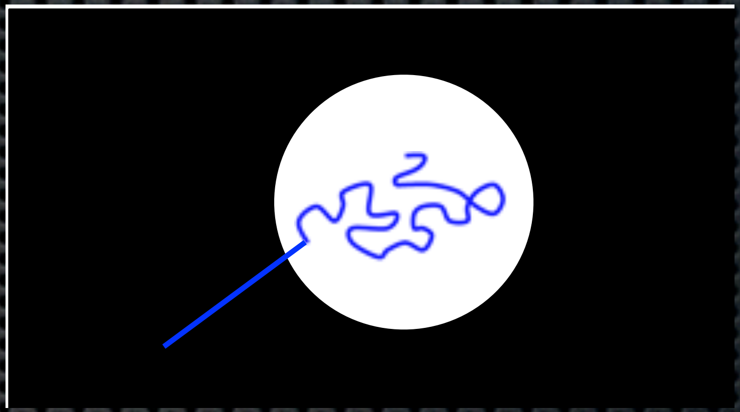
the solution writes

$$\Phi(\mathbf{x}, t) = \frac{\mathcal{N}}{(4\pi\, D\, t)^{3/2}} \exp\left(-\frac{\mathbf{x}^2}{4D\, t}\right)$$



CR diffusion in the MW

Consider an isotropic, homogeneous and stationary problem. In this case diffusion can be seen as a **leakage** process



$$\frac{\partial N}{\partial t} - D\nabla^2 N = Q \rightarrow \frac{\partial N}{\partial t} - \frac{N}{\tau_{\mathrm{diff}}(E)} = Q$$

Stationary solution

$$N = Q(E)\tau_{\mathrm{diff}}(E)$$

$$\tau_{\mathrm{diff}}(E) \propto D(E)^{-1} \propto E^{\delta}$$

Useful tools: secondary to primary ratios

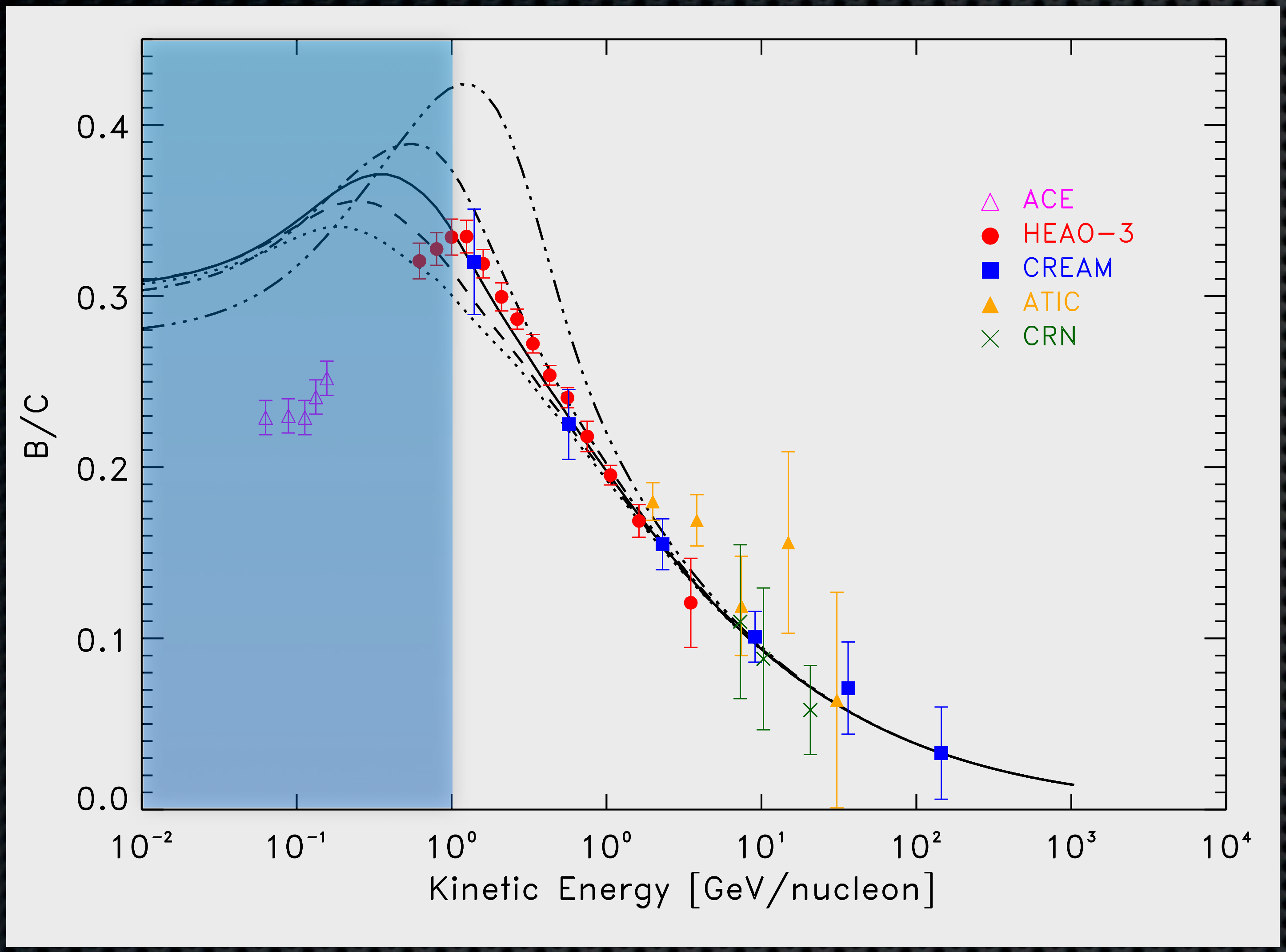
Spectral slopes of **Primary CRs** at high energy mainly depend on:
Injection spectrum ($E^{-\alpha}$)
Energy dependence of diffusion coefficient (E^{δ})

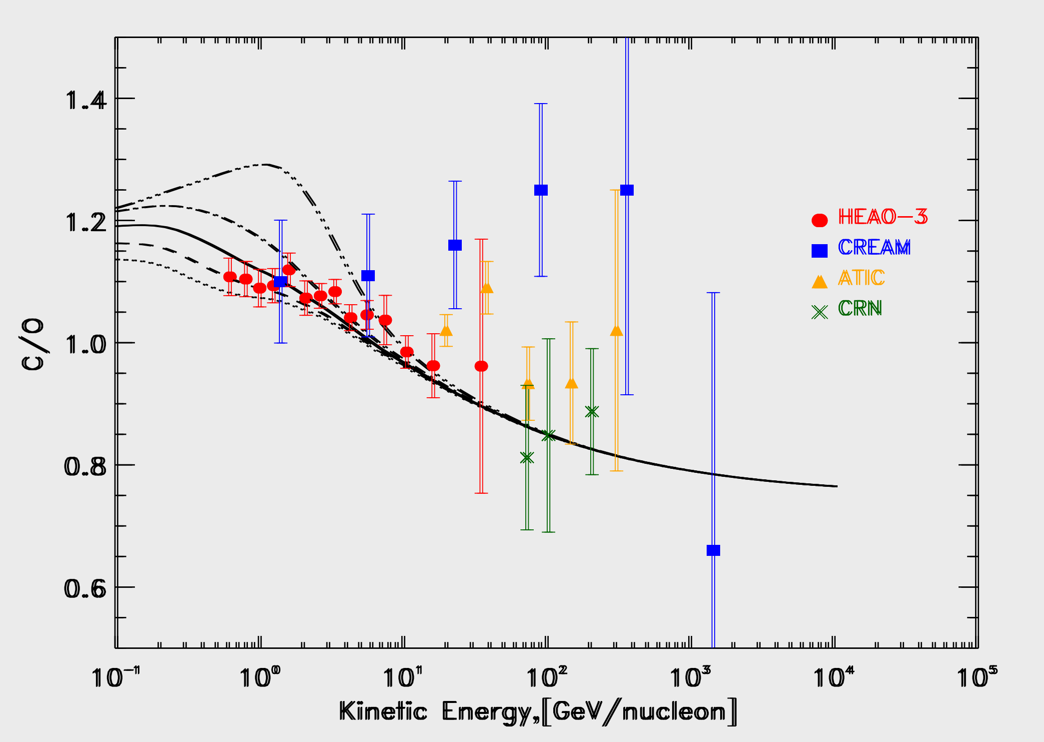
$$0 = Q(E) - \frac{N(E)}{\tau_{\rm esc}(E)} \rightarrow N(E) \propto Q(E)\tau_{\rm esc}^{-1}(E) \rightarrow N(E) \propto E^{-\alpha-\delta}$$

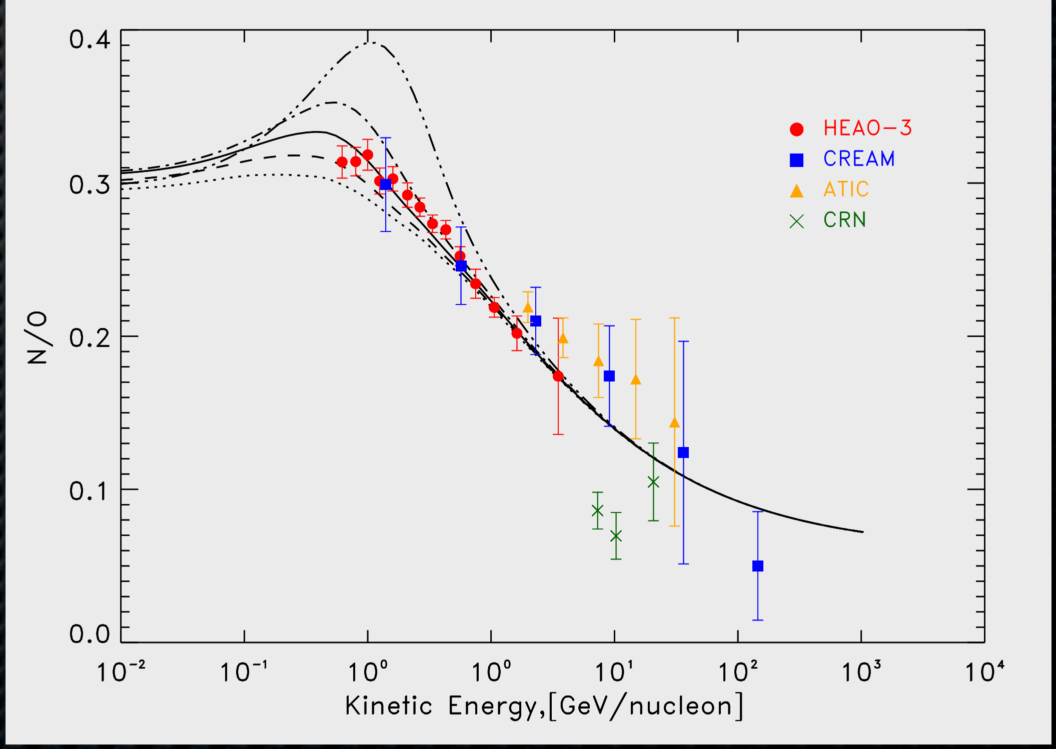
The slopes of ratios of **Secondary/Primary CRs** do not show this degeneracy: they only depend on energy dependence of diffusion coefficient.

$$\frac{N_{\rm sec}(E)}{\tau_{\rm esc}(E)} + \frac{N_{\rm sec}(E)}{\tau_{\rm int}(E)} = \frac{N_{\rm pri}(E)P_{\rm spall}(E)}{\tau_{\rm int}(E)} \rightarrow \frac{N_{\rm sec}}{N_{\rm pri}} \propto \frac{P_{\rm spall}(E)\tau_{\rm esc}(E)}{\tau_{\rm int}(E)} \rightarrow E^{-\delta}$$

Secondary/Primary







Dependence of secondary/primary ratios on the reacceleration level in the “best fit” case. Modulation potential fixed by requiring to reproduce the proton spectrum

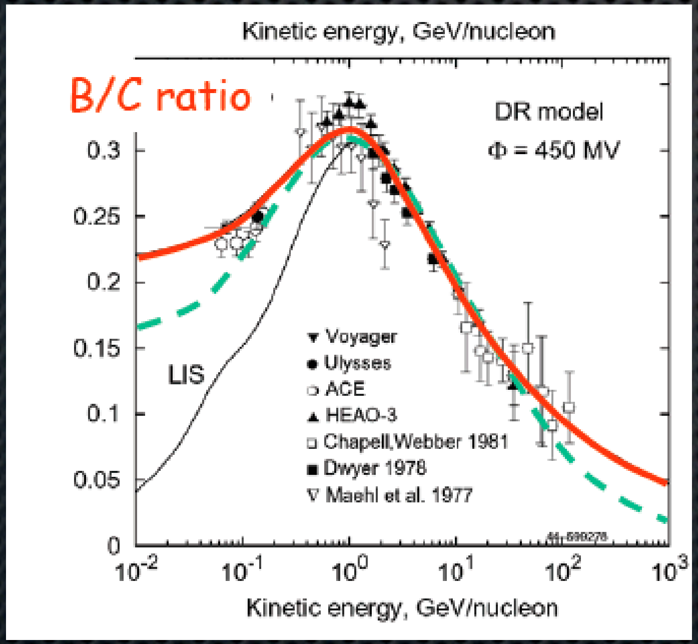
Secondary Antiprotons

CR proton/He spallation onto the Galactic gas is an avoidable antiproton source

$$p + p_{\rm gas} \rightarrow p + p + p + \bar{p}$$

kinematical threshold 7 GeV.

In principle, antiprotons data may then be used to constraint a primary component which may produced by astrophysical sources or by dark matter annihilation/decay.



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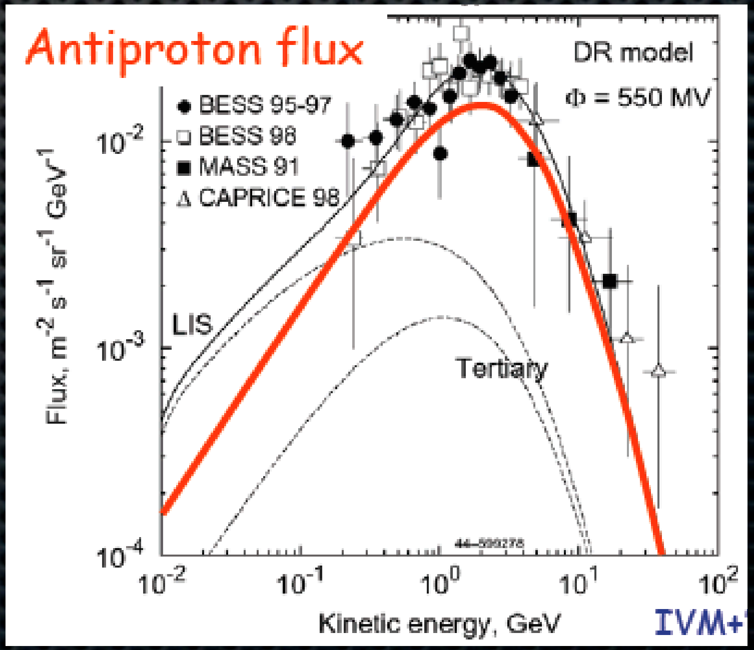
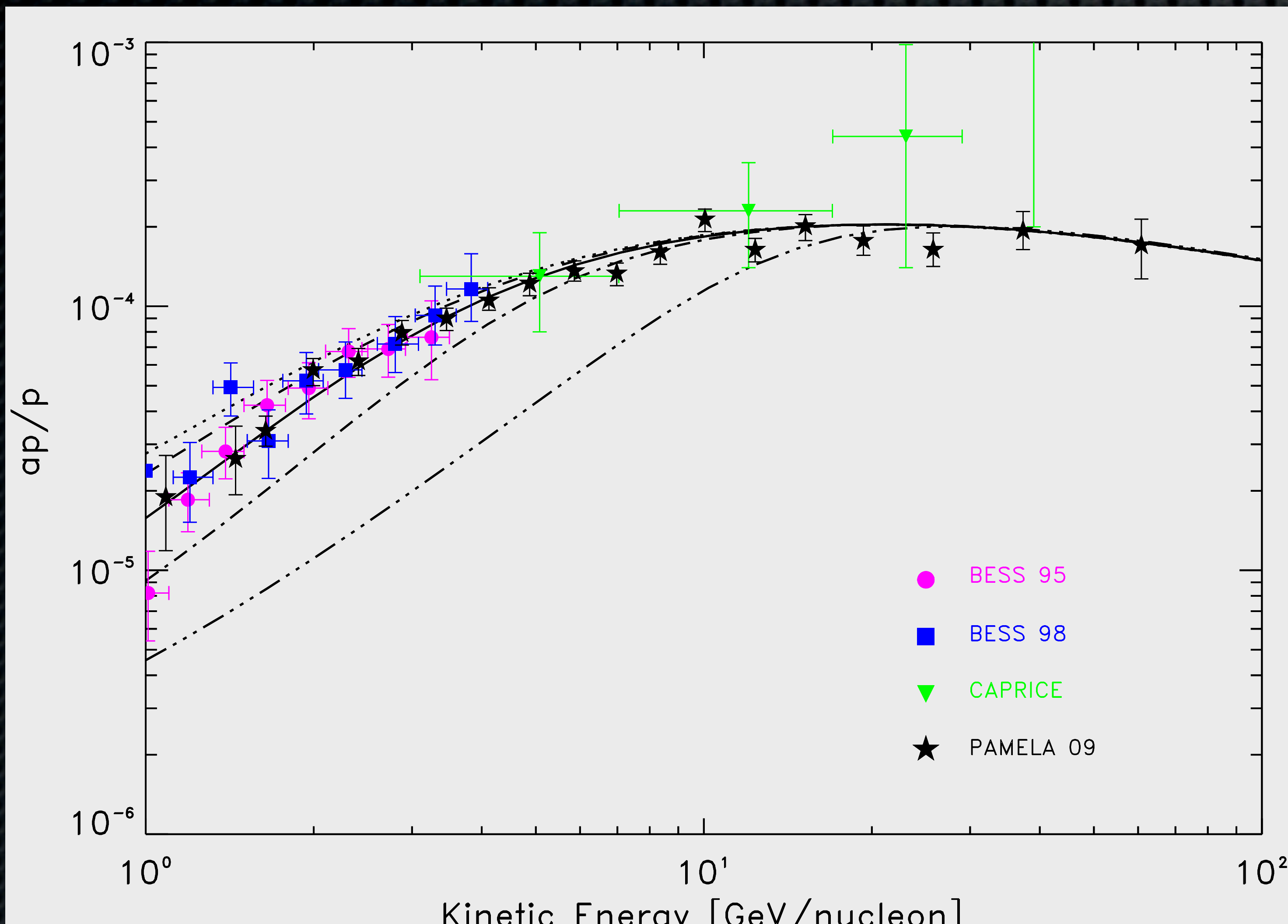
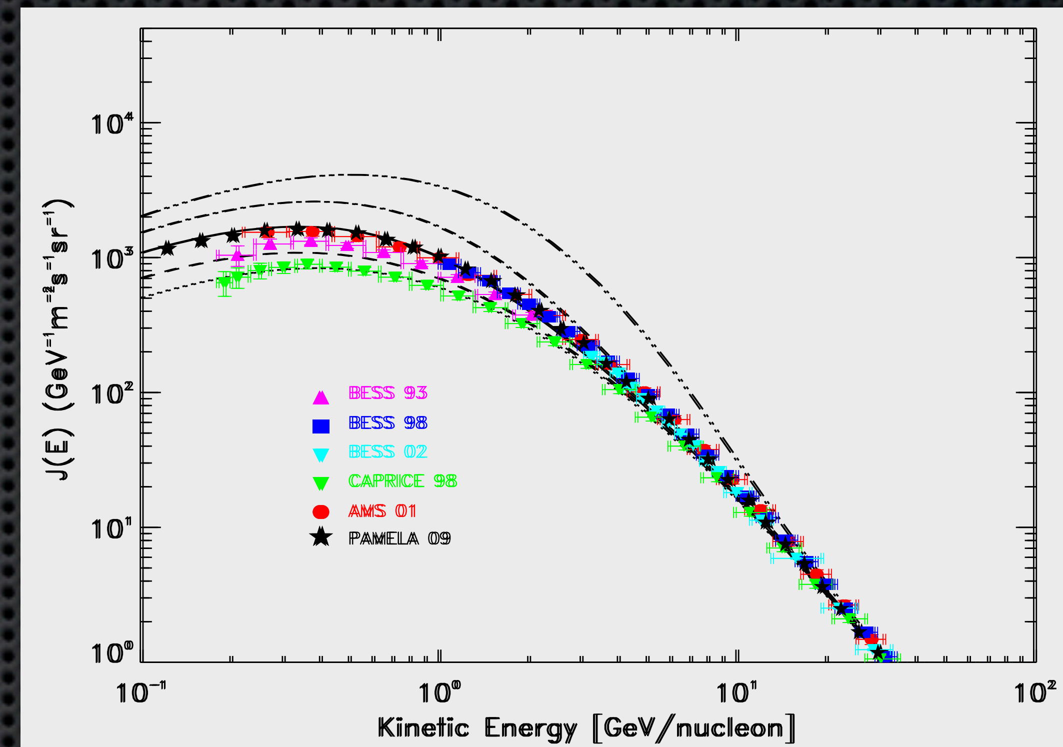
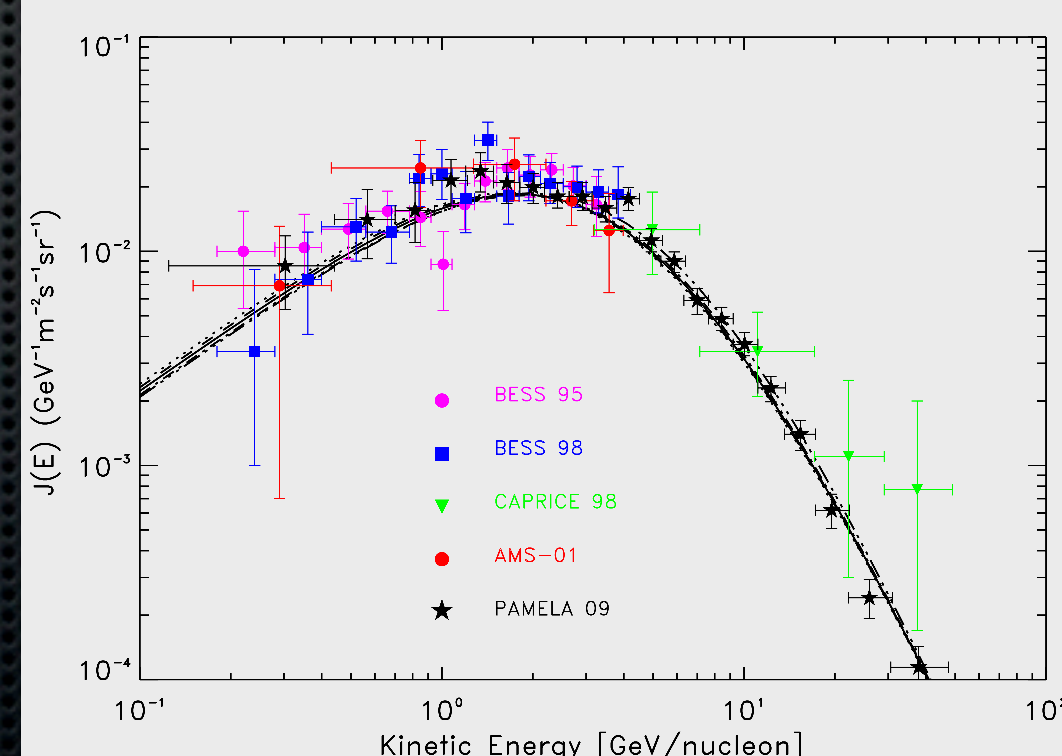


See GALPROP website

Antiproton/Protons







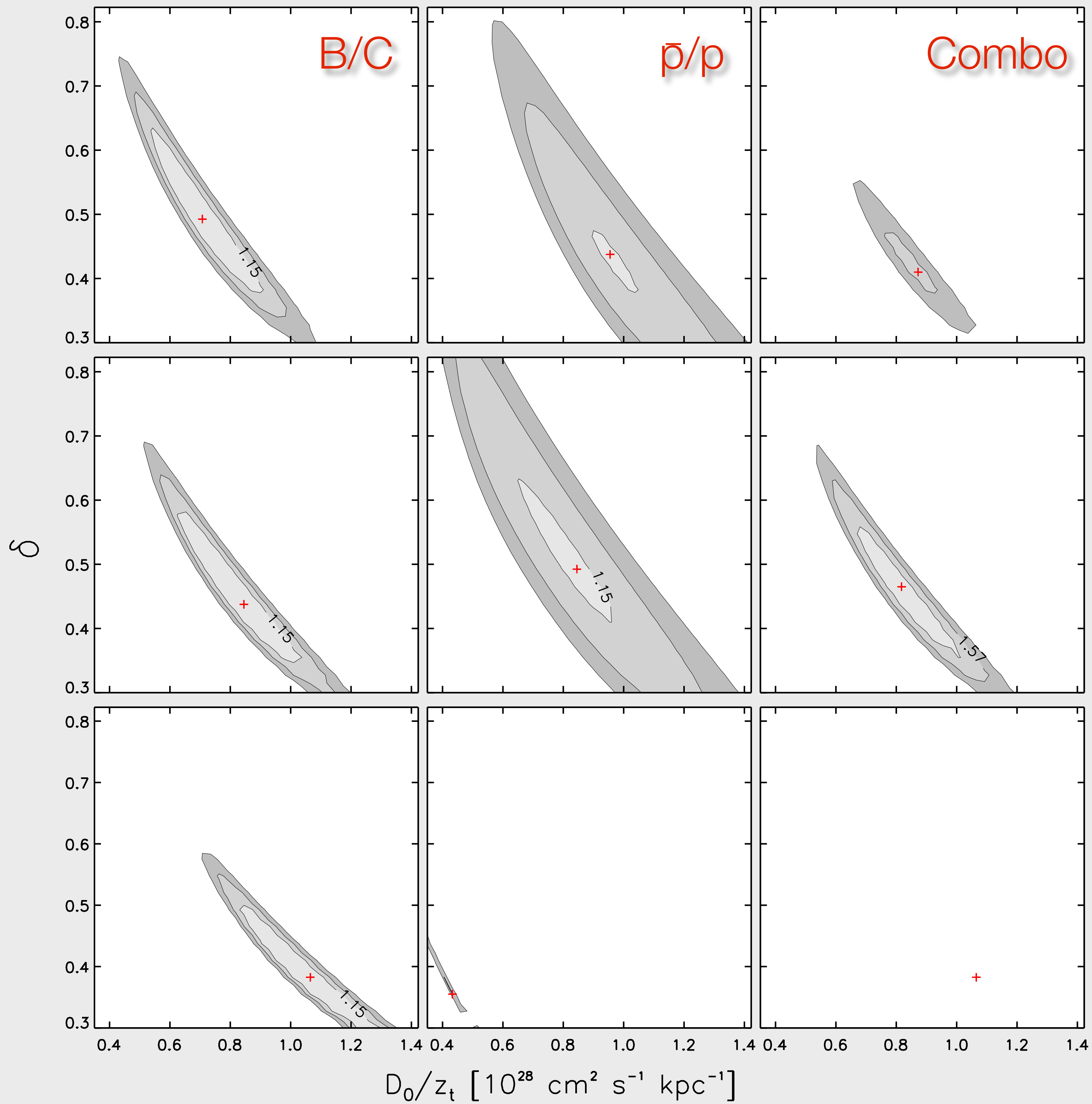
Large effects of reacceleration on the proton spectrum: can it constrain v_A?
Interesting feature: the antiproton flux is less affected by reacceleration.

Results - I

$v_A \sim 10$

$v_A \sim 20$

$v_A \sim 30$



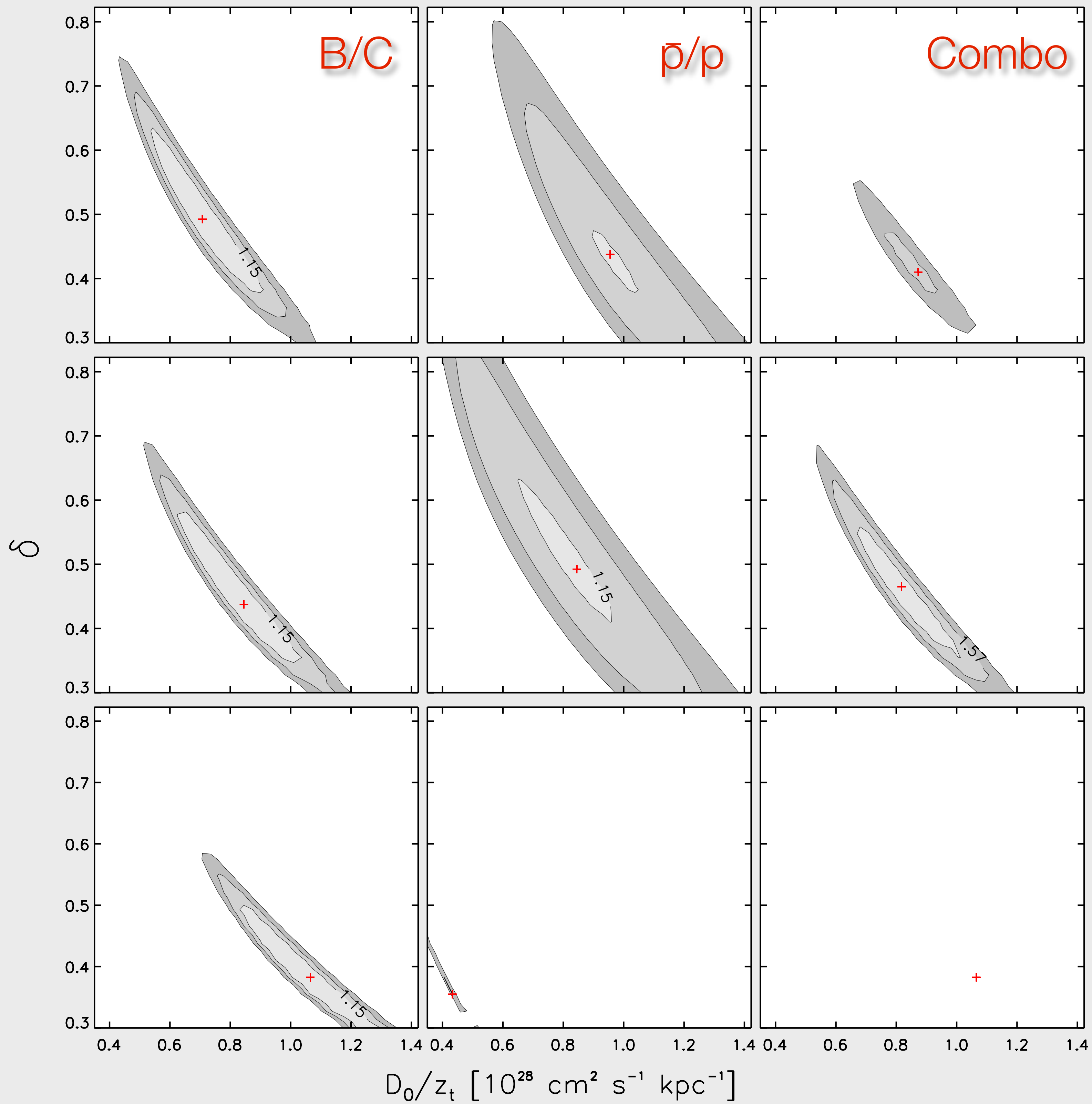
$E_{\min} = 5$ GeV/n

Results - I

$v_A \sim 10$

$v_A \sim 20$

$v_A \sim 30$



$E_{\min} = 5$ GeV/n

No spectrum breaks here!

Results - II

		B/C analysis			joint analysis		
v_A [km/s]	E_{min} [GeV/n]	δ	D_0/z_t	χ^2	δ	D_0/z_t	χ^2
0	1	0.57	0.60	0.38	0.47	0.74	3.25
	5	0.52	0.65	0.33	**0.41**	**0.85**	**2.04**
	10	0.46	0.76	0.19	0.44	0.82	1.57
10	1	0.52	0.68	0.32	0.49	0.71	1.47
	5	0.49	0.71	0.28	**0.41**	**0.85**	**1.69**
	10	0.44	0.82	0.20	0.44	0.82	0.12
15	1	0.46	0.76	0.33	0.47	0.76	0.94
	5	0.49	0.73	0.26	**0.44**	**0.82**	**0.12**
	10	0.44	0.84	0.18	0.41	0.98	0.16
20	1	0.41	0.90	0.47	0.47	0.79	2.28
	5	0.44	0.84	0.22	**0.44**	**0.84**	**0.85**
	10	0.44	0.87	0.20	0.44	0.85	0.98
30	1	0.33	1.20	0.40	0.33	1.20	5.84
	5	0.38	1.06	0.20	**0.36**	**1.09**	**2.47**
	10	0.41	0.98	0.16	0.38	1.04	1.61

What we learn from this analysis is:

@95% C.L.
$0.2 < \delta < 0.7$
$v_A < 30$ km/s

@best-fit:
$\delta = 0.45$
$v_A = 15$ km/s

CR positrons

In the standard scenario e^+ are not expected to be significantly produced in the SNRs (see however Blasi, PRL 2009)

they are mainly produced by spallation of primary nuclei, *e.g.*

$$p + p_{\rm gas} \rightarrow p + n + \pi^+ \rightarrow \cdots + \mu^+ \rightarrow \cdots + e^+$$

Secondary e^+ are produced with the same spectral shape of primary *p* (scaling regime)

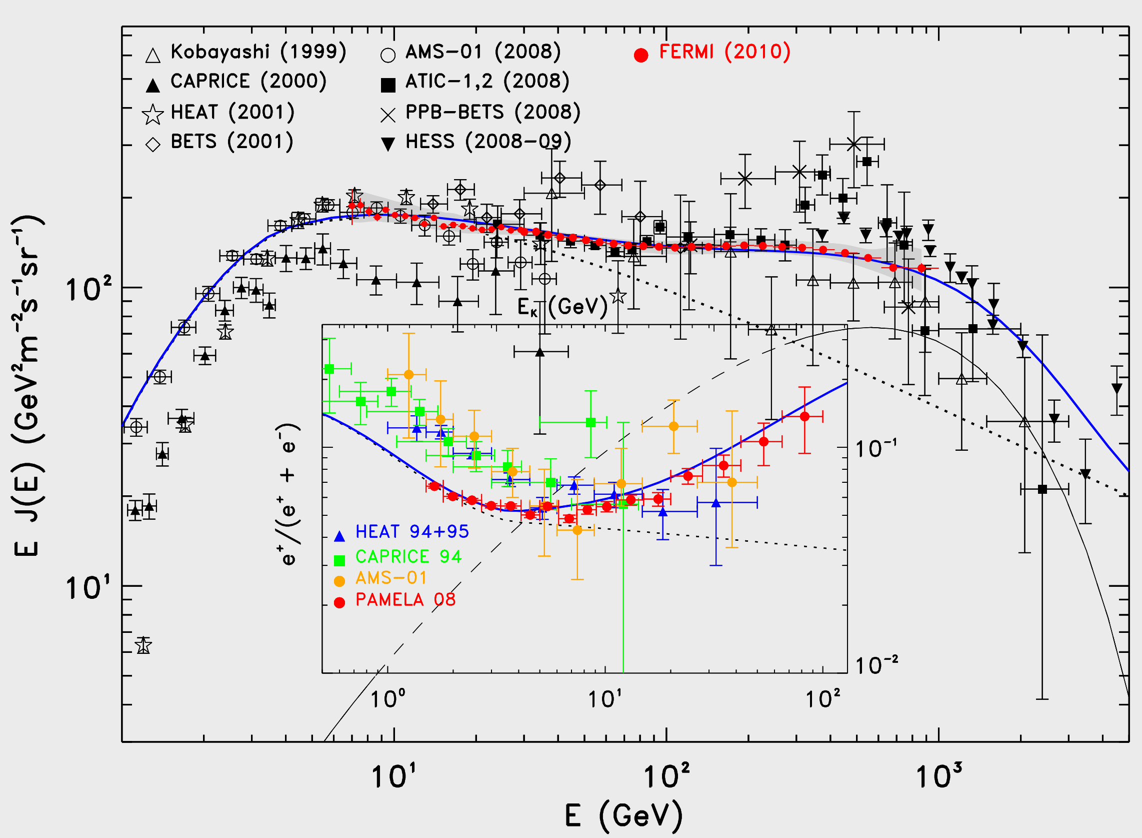
Then they propagate like the electrons:

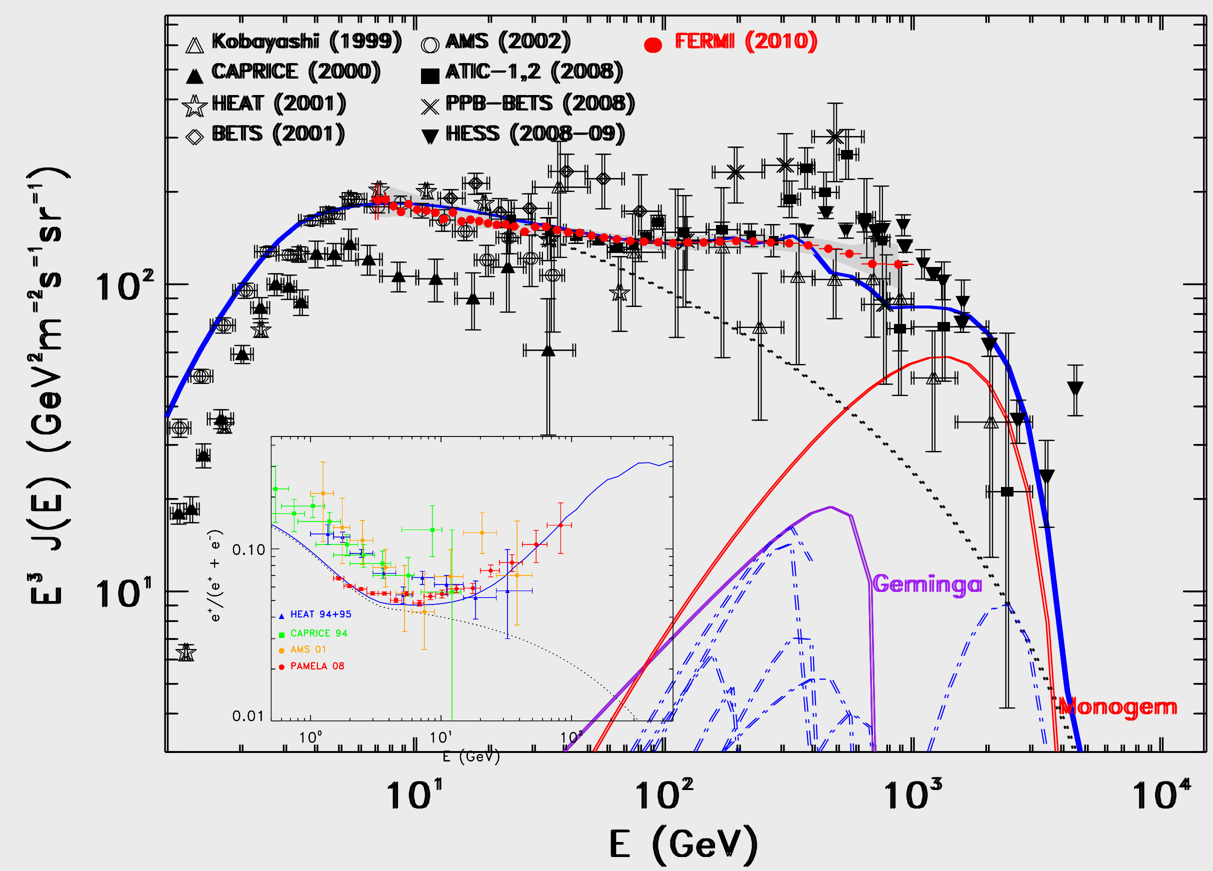
$$\frac{e^+}{e^- + e^+} \sim \frac{e^+}{e^-} \propto \frac{E^{-\gamma_p - \tau}}{E^{-\gamma_0 - \tau}} \propto E^{-\gamma_p + \gamma_0}$$ (for 1 < E < 100 GeV)

Since $\gamma_p > \gamma_0$ a decreasing ratio is expected

Two Galactic Components?

$\gamma_0 = 2.0/2.65$, $\delta = 0.46$





Toy model:

$$N_{extra} \propto E^{-1.5} \exp(E/1TeV)$$

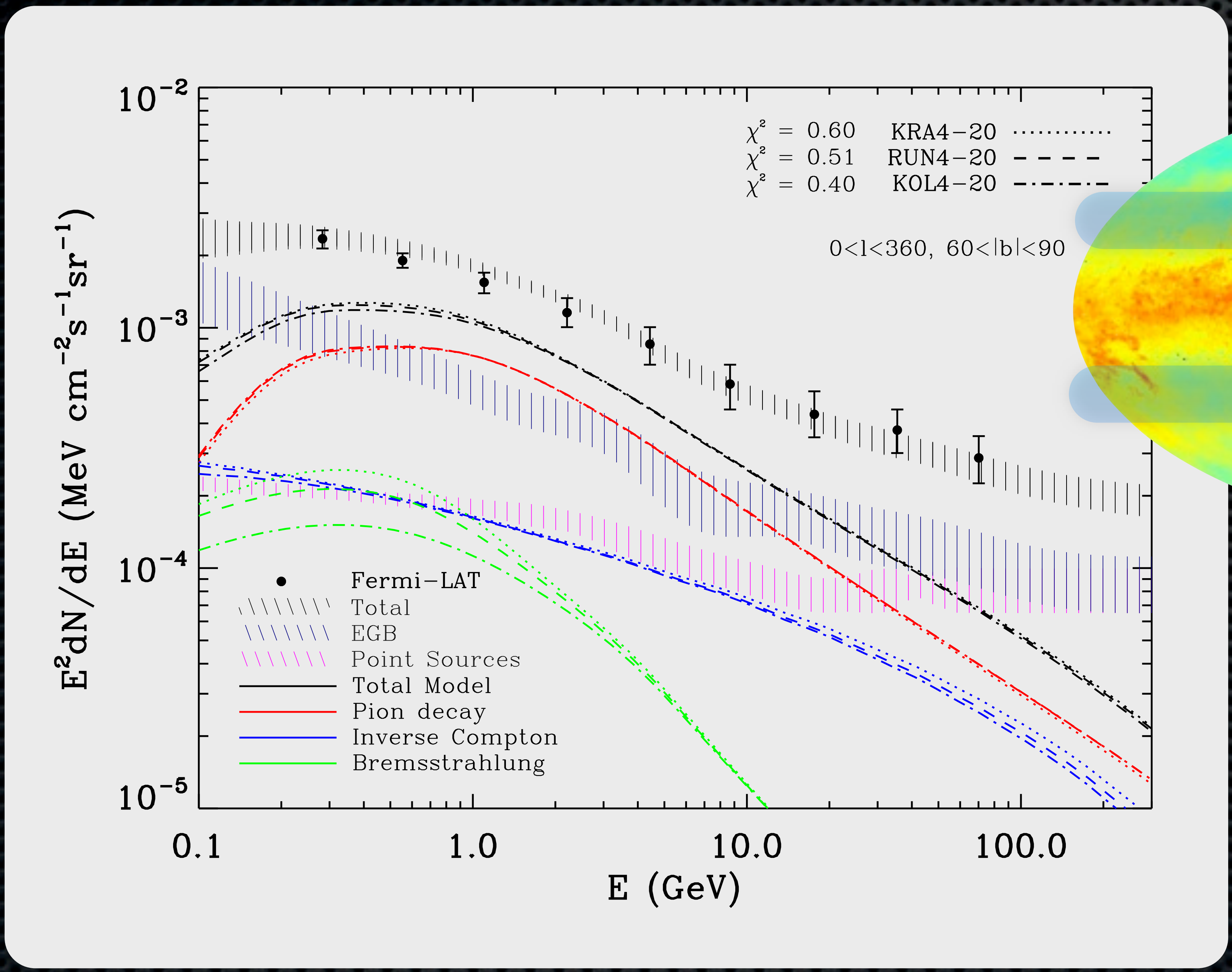
galactic component that follows the pulsar distribution

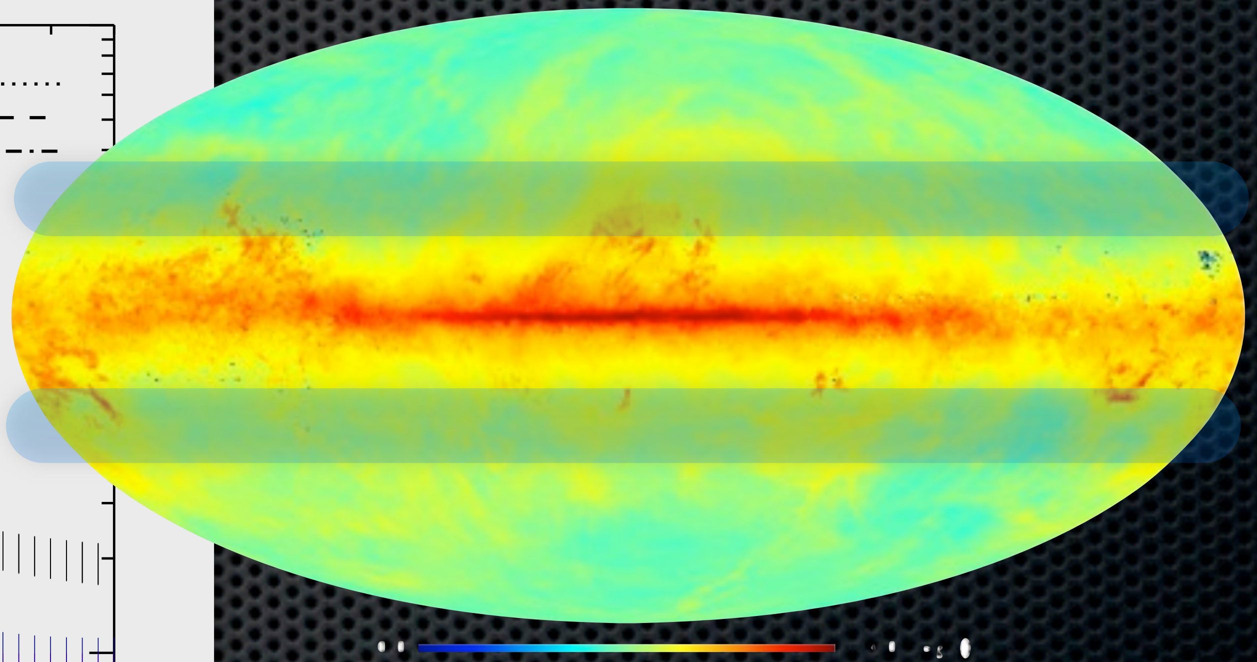
Point-sources model:

$$\gamma_e = 1.4\,,\, E_{cut} = 2TeV$$
$$t_0 = 75\,kyr\,,\, \eta_p = 0.35$$

contribution from nearby pulsars (<2kpc) taken from the ATFN catalogue

Further constraints from diffuse emissions?





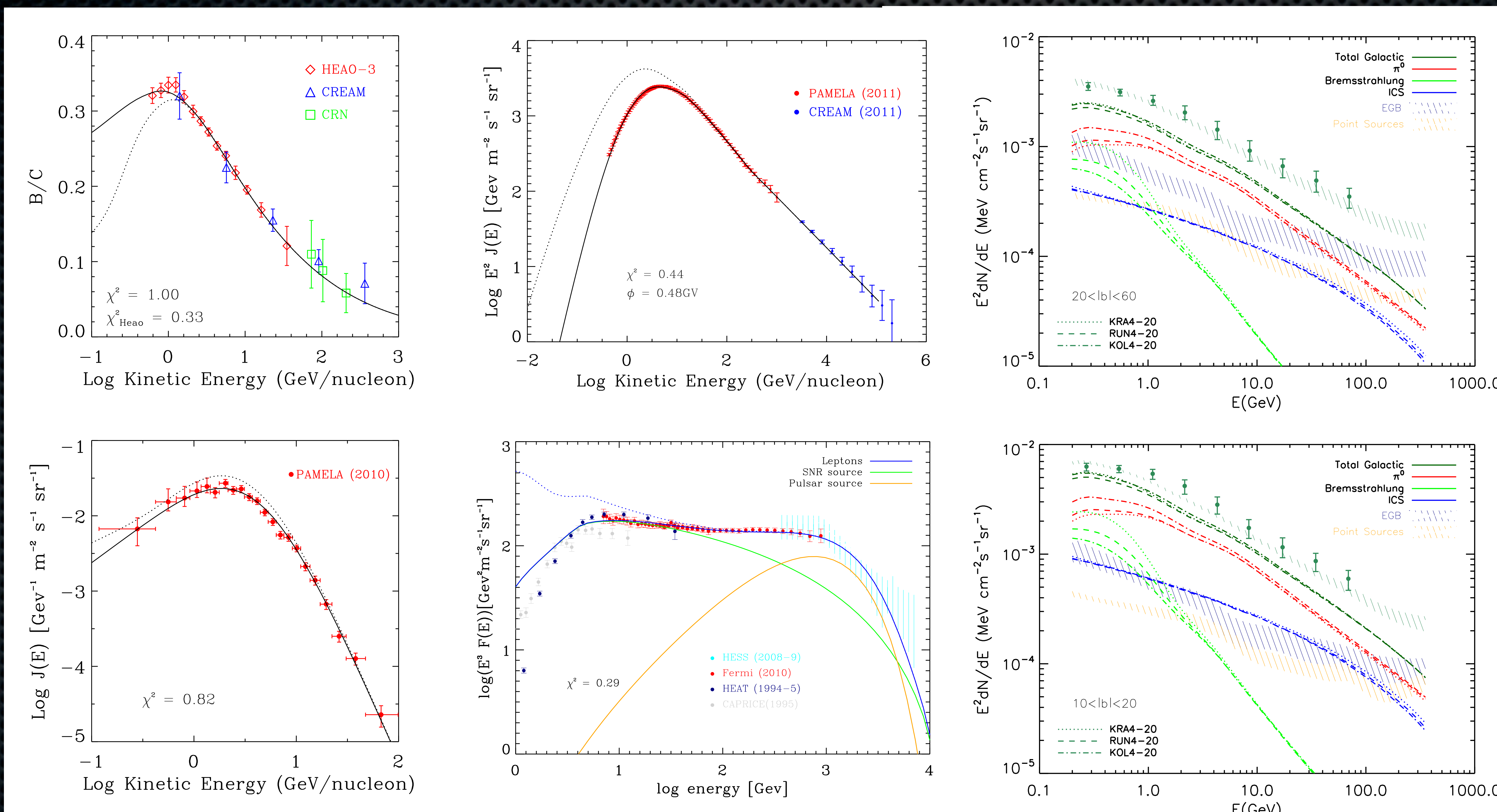
$$p\, p_{\rm ISM} \to \gamma\gamma$$

$$p\, \gamma_{ISRF} \to p\, \gamma$$

$$e^-\, N \to e^-\, N\, \gamma$$

I. Cholis, M. Tavakoli, C. Evoli, LM & P. Ullio, arXiv:1110.5922

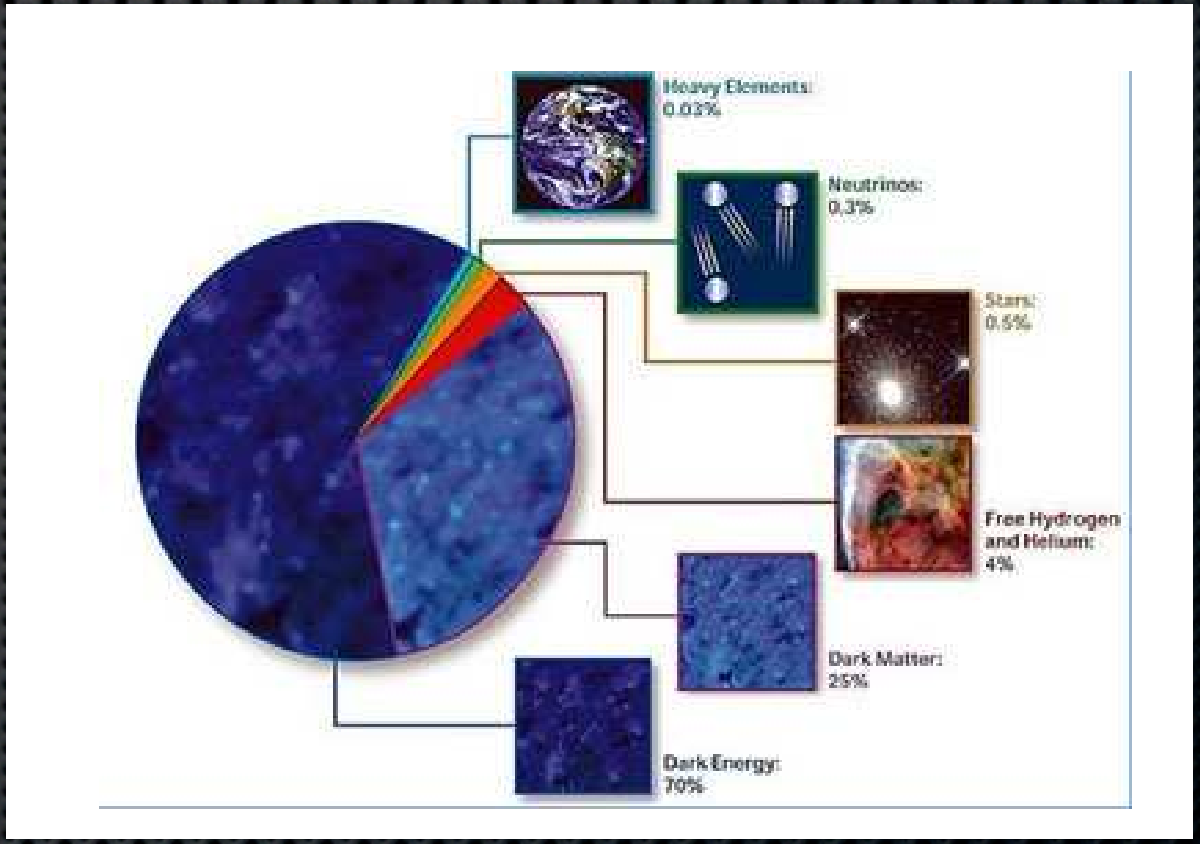
Recap



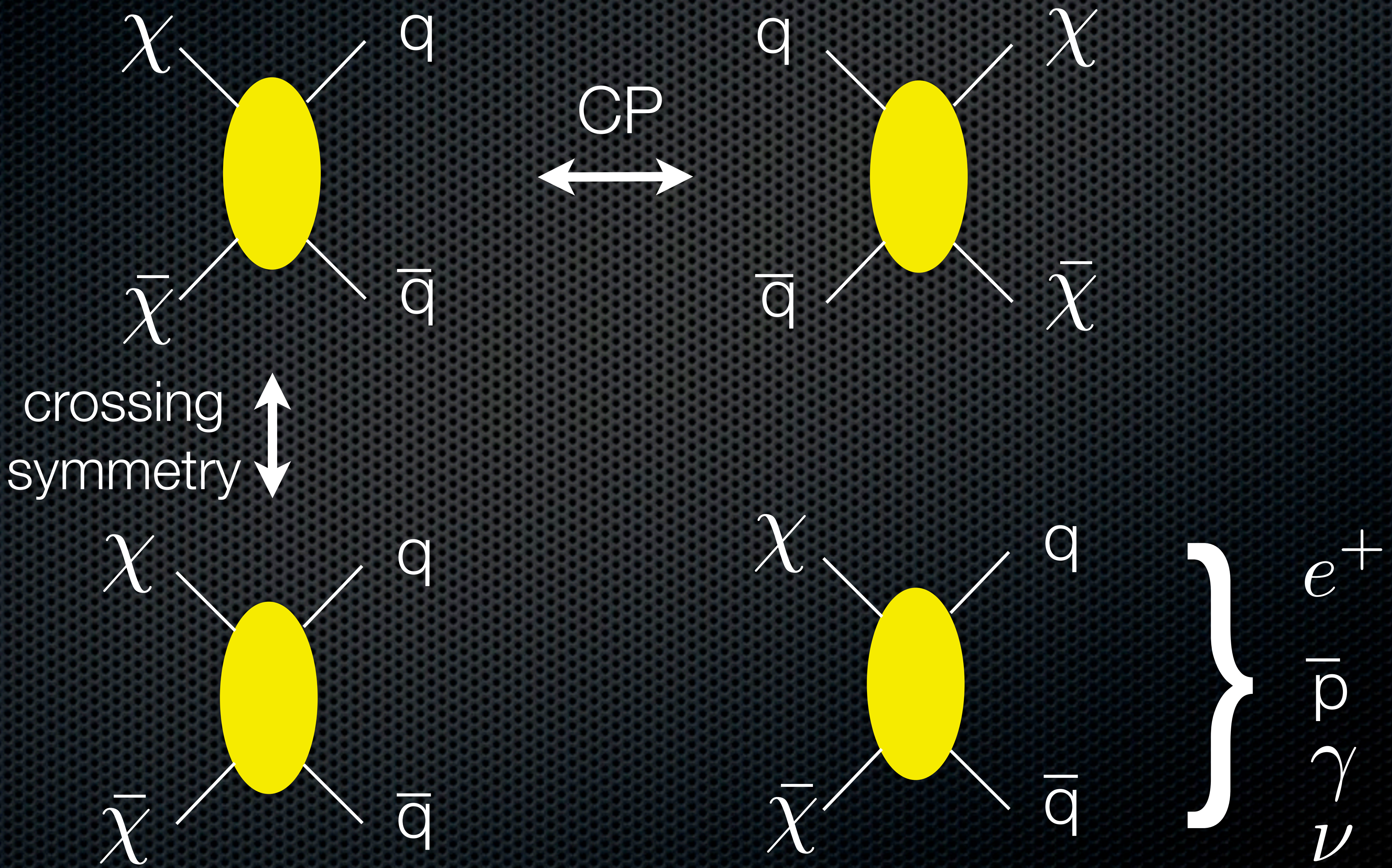
B/C
Log Kinetic Energy (GeV/nucleon)
HEAO−3
CREAM
CRN
χ² = 1.00
χ²Heao = 0.33
Log E² J(E) [Gev m⁻² s⁻¹ sr⁻¹]
PAMELA (2011)
CREAM (2011)
χ² = 0.44
ϕ = 0.48GV
E²dN/dE (MeV cm⁻²s⁻¹sr⁻¹)
E(GeV)
Total Galactic
π⁰
Bremsstrahlung
ICS
EGB
Point Sources
20<|b|<60
KRA4−20
RUN4−20
KOL4−20
Log J(E) [Gev⁻¹ m⁻² s⁻¹ sr⁻¹]
PAMELA (2010)
χ² = 0.82
log(E³ F(E))[Gev²m⁻²s⁻¹sr⁻¹]
log energy [Gev]
Leptons
SNR source
Pulsar source
HESS (2008−9)
Fermi (2010)
HEAT (1994−5)
CAPRICE(1995)
χ² = 0.29
10<|b|<20

The DM puzzle

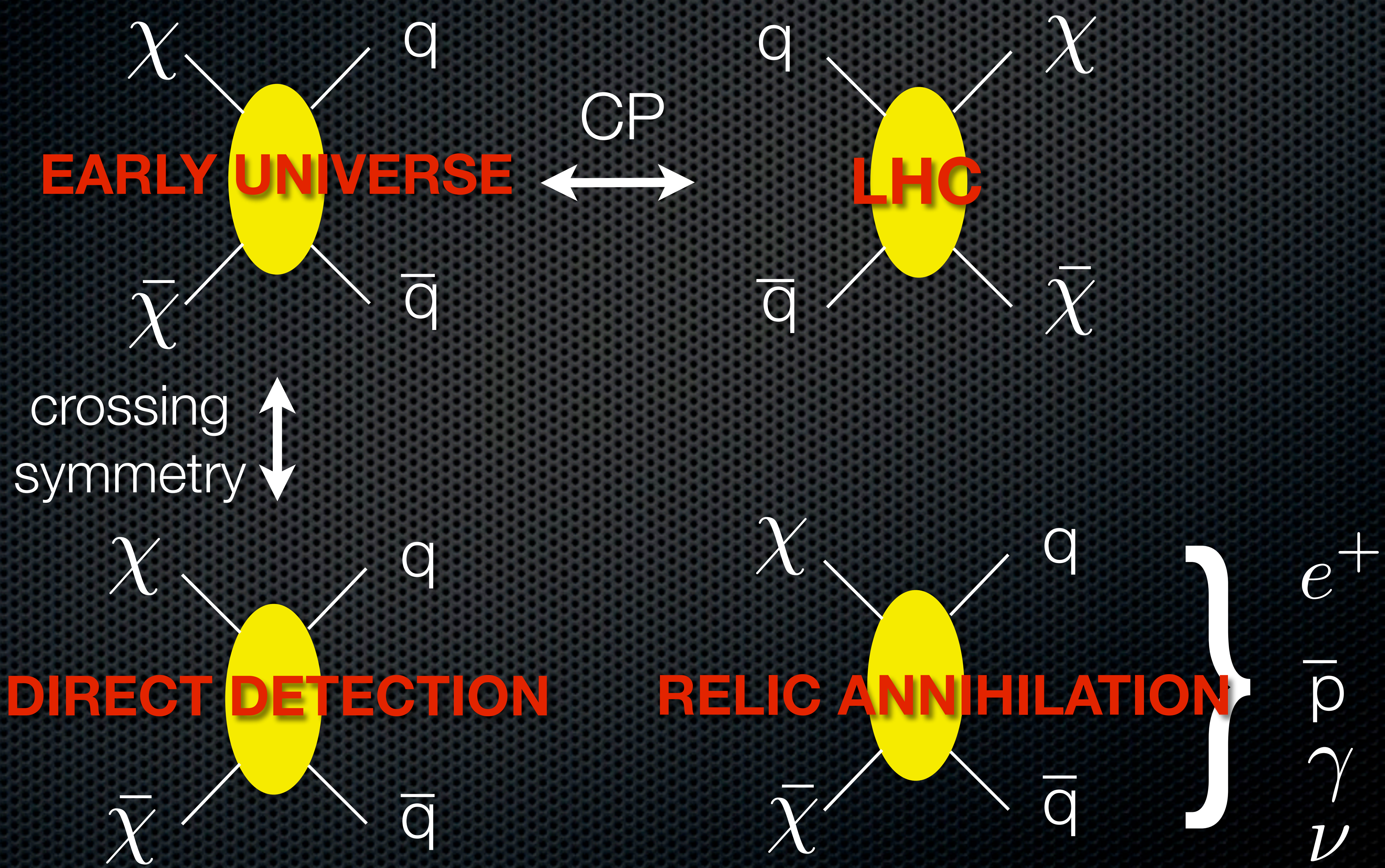
- Plenty of indirect (gravitational) evidence for **non-baryonic** cold (as opposed to hot) DM being the building block of all structures in the Universe.



The DM puzzle

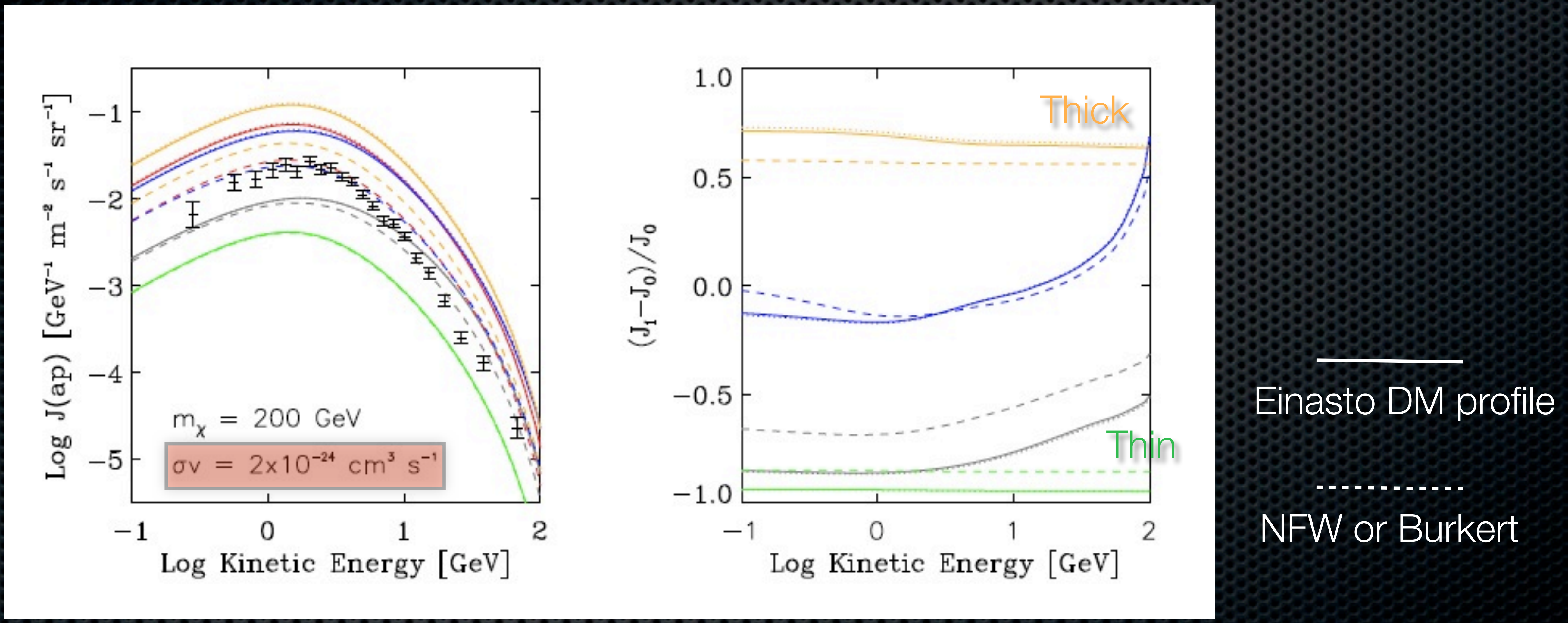


The DM puzzle



Uncertainties on the $\bar{p}$ flux from DM annihilation

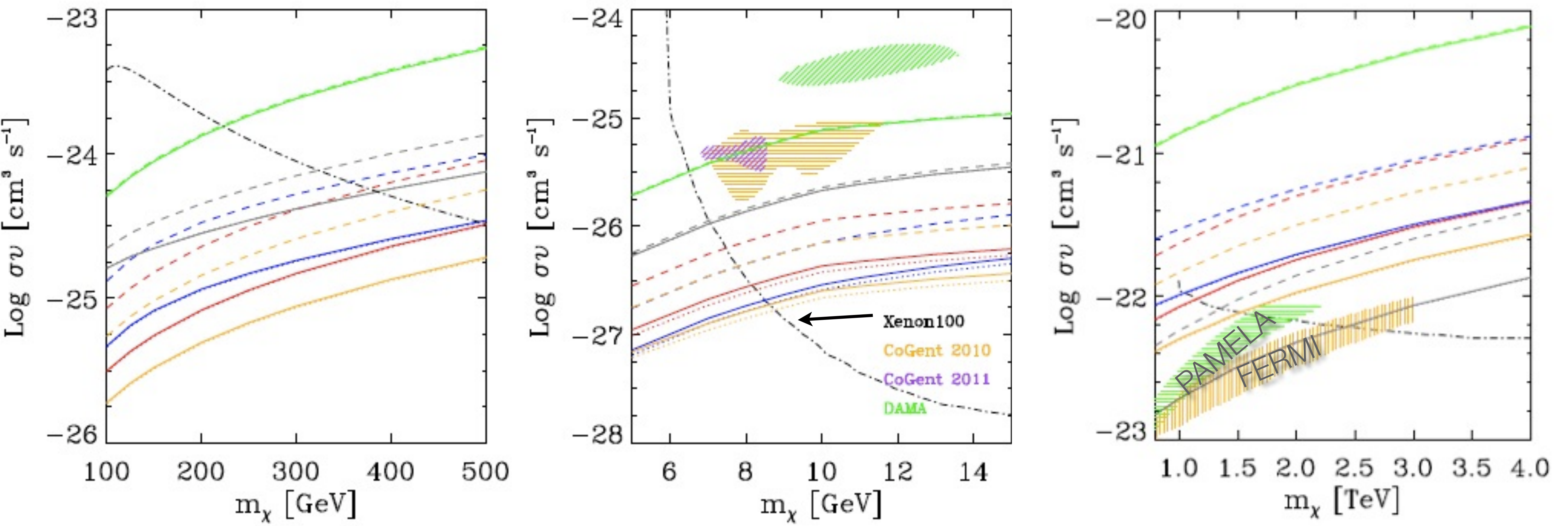
For a given DM model, the main uncertainties are those on the propagation parameters and the DM density profile



Very large scatter mainly due to the uncertainty on the propagation setup !

The dominant uncertainty source is that on the diffusive halo height

Constraints on DM models



$$\tilde{W}^0\tilde{W}^0 \to W^+W^-$$

$$\chi\chi \to \bar{b}b$$

$$\chi\chi \to \mu^+\mu^-$$

Wino model
(motivated by SUSY and PAMELA e^+ anomaly)

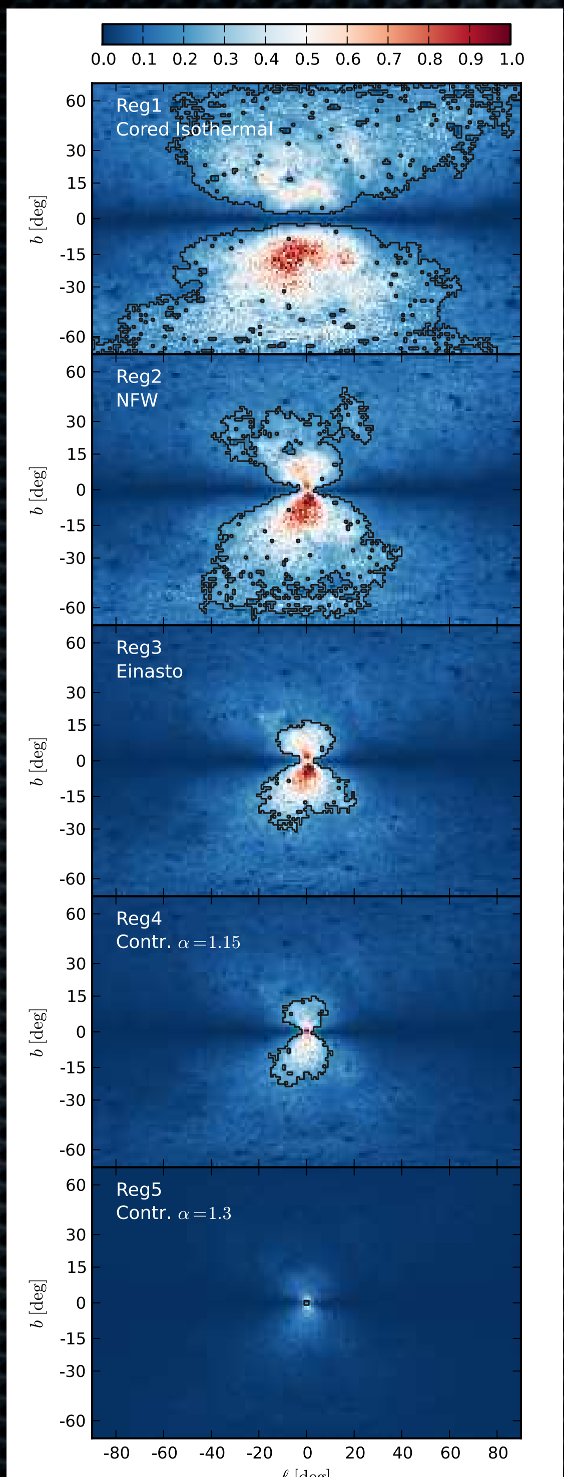
Light WIMPs
with sizable quark coupling (motivated by direct detection recent results)

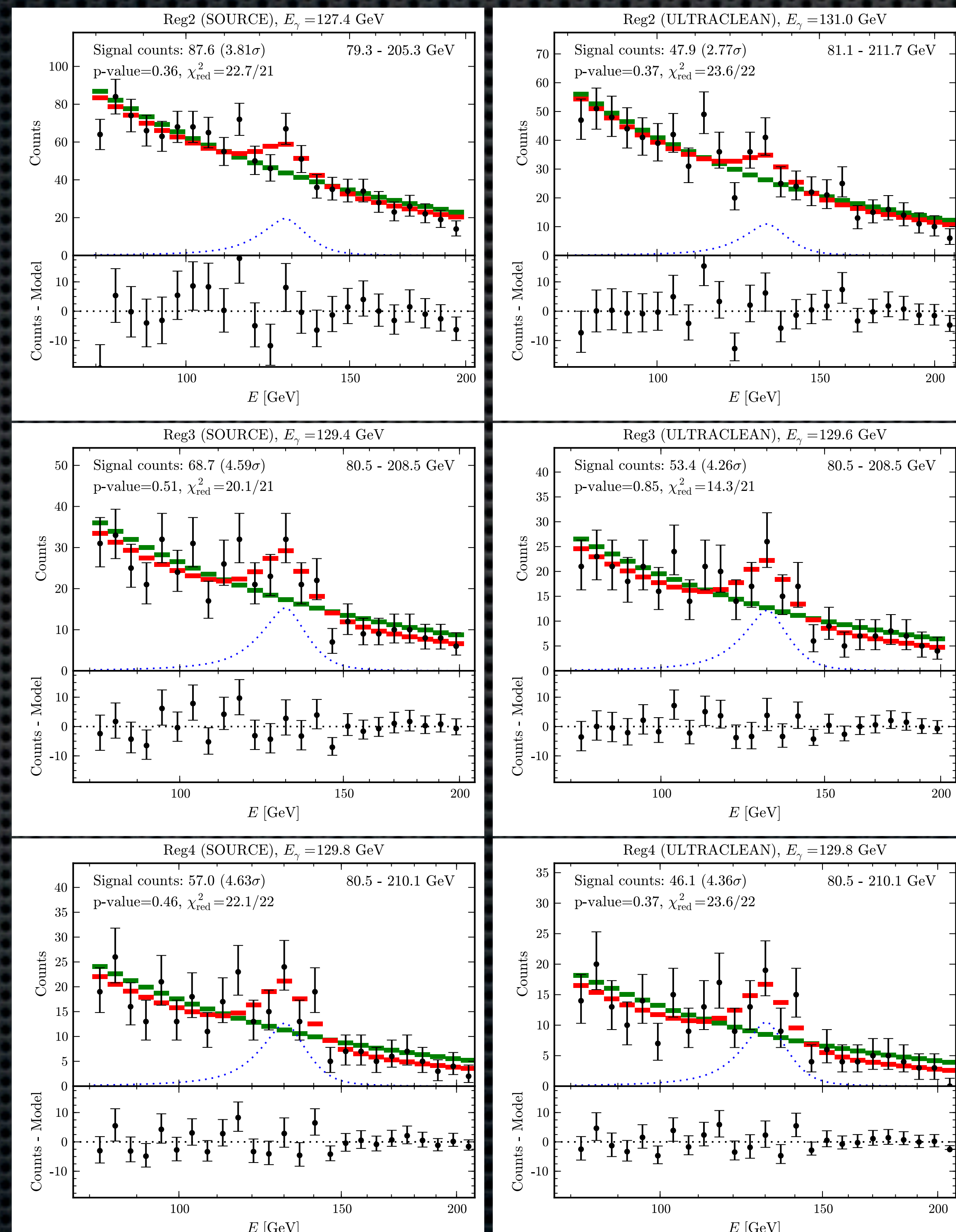
Heavy "leptophilic" WIMPs
(motivated by PAMELA, Fermi, HESS) + radiative corrections

C.Evoli, I. Cholis, D. Grasso, LM & P. Ullio, arXiv:1110.5922

C. Weniger, 2012

Gamma-rays: a tentative line from DM?





- Smart selection of target region (high S/N ratio)
- Hint for a line in the spectrum ~ towards the GC

Conclusions

- Exciting period for Cosmic Ray physics
- Lots of new data available now, more soon
- Present data already challenge standard description
- Need of a step forward to undestand plasma effecs in CR physics
- Interesting constraints on DM candidates. Even a tentative detection....