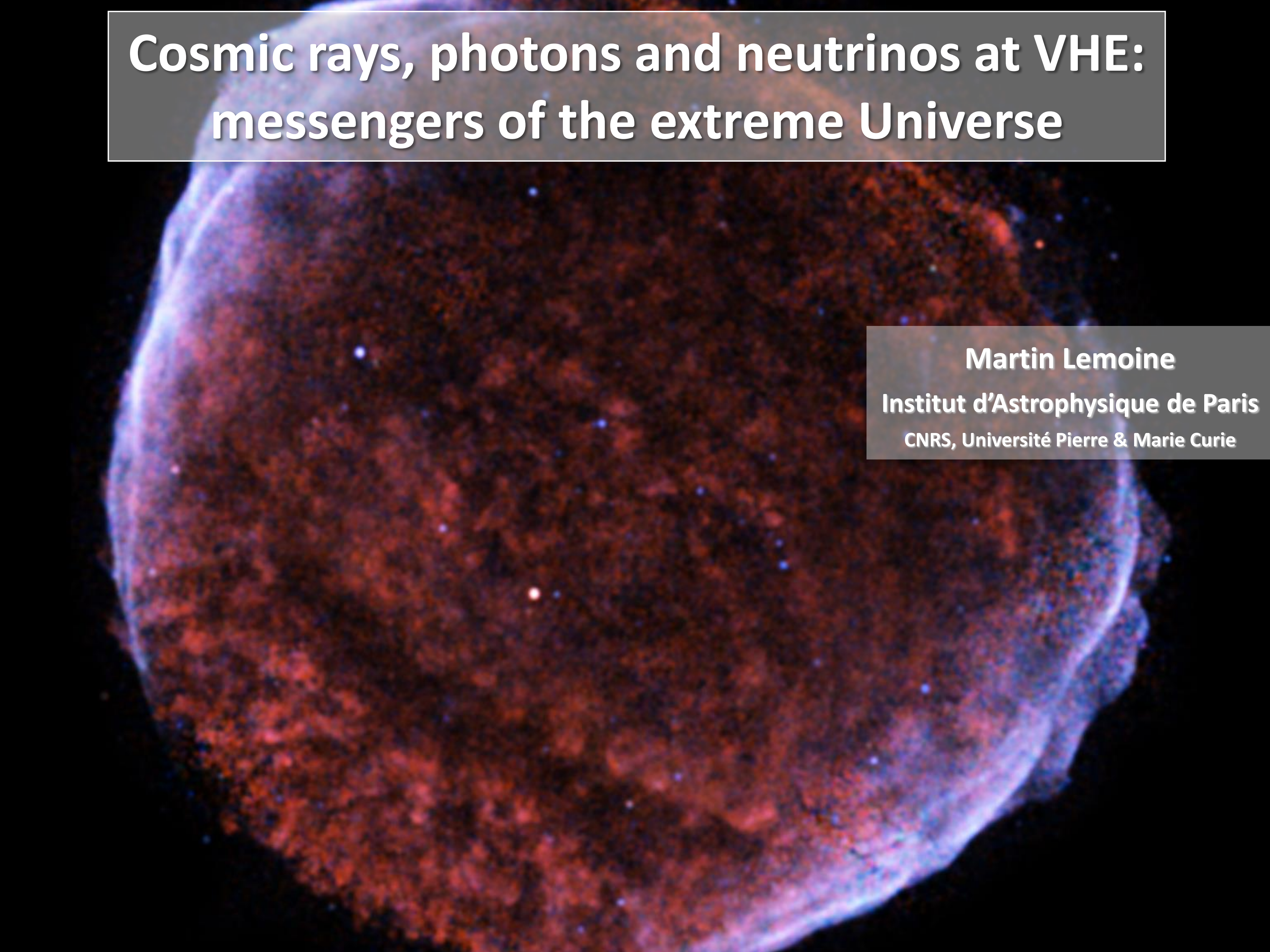
Cosmic rays, photons and neutrinos at VHE: messengers of the extreme Universe



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Outline

1. <u>Overview: the CR-γ-ν connection and motivations</u>

   a. Introduction: detection and experimental facilities…
   b. The CR-γ-ν connection
   c. Motivations: extreme astrophysics, fundamental physics, dark matter physics etc.

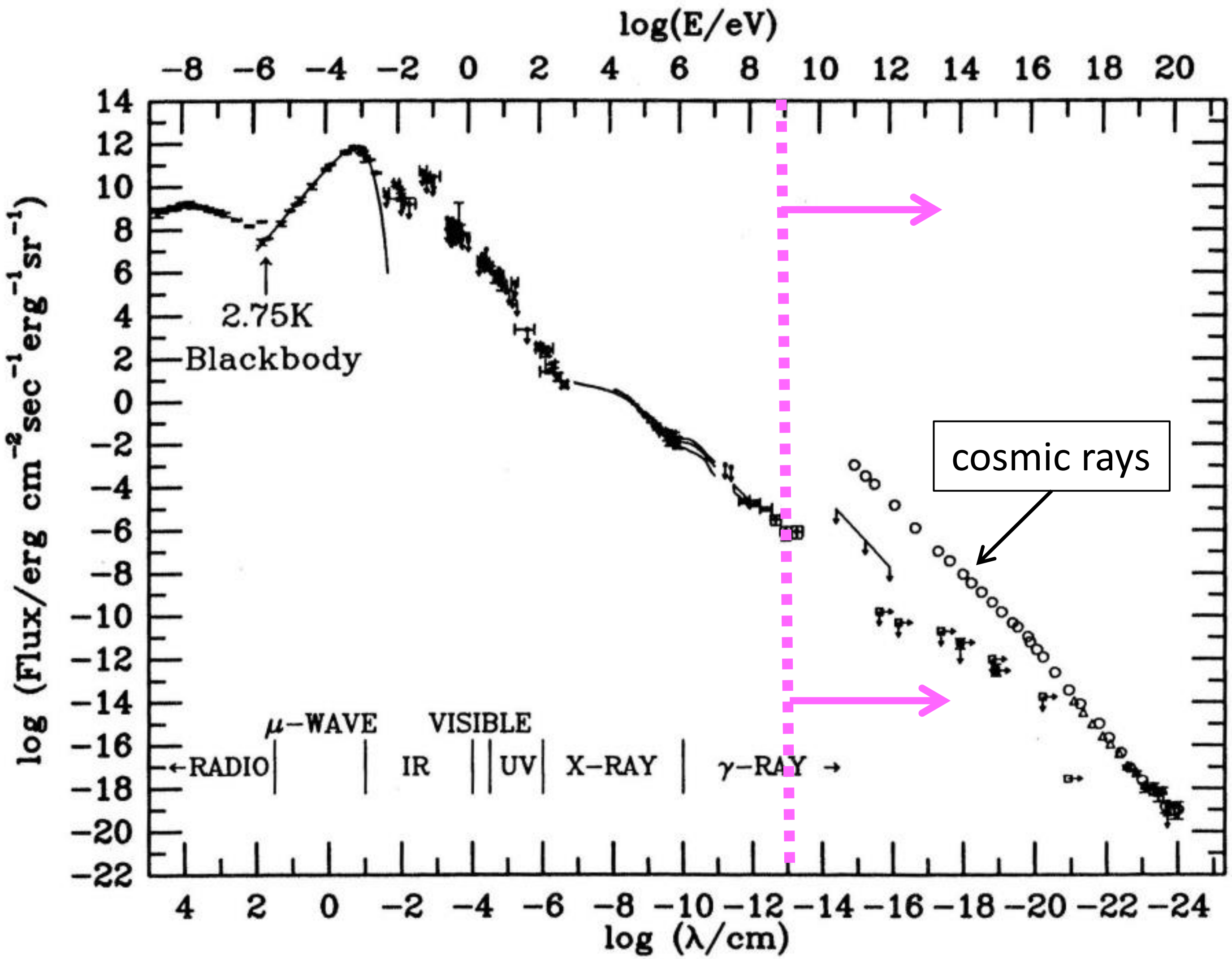
2. <u>Beyond PeV: the extreme energy frontier</u>

   a. The ultra-high energy cosmic ray enigma
   b. A prototype source: gamma-ray burst
   c. Connection with neutrinos and photons

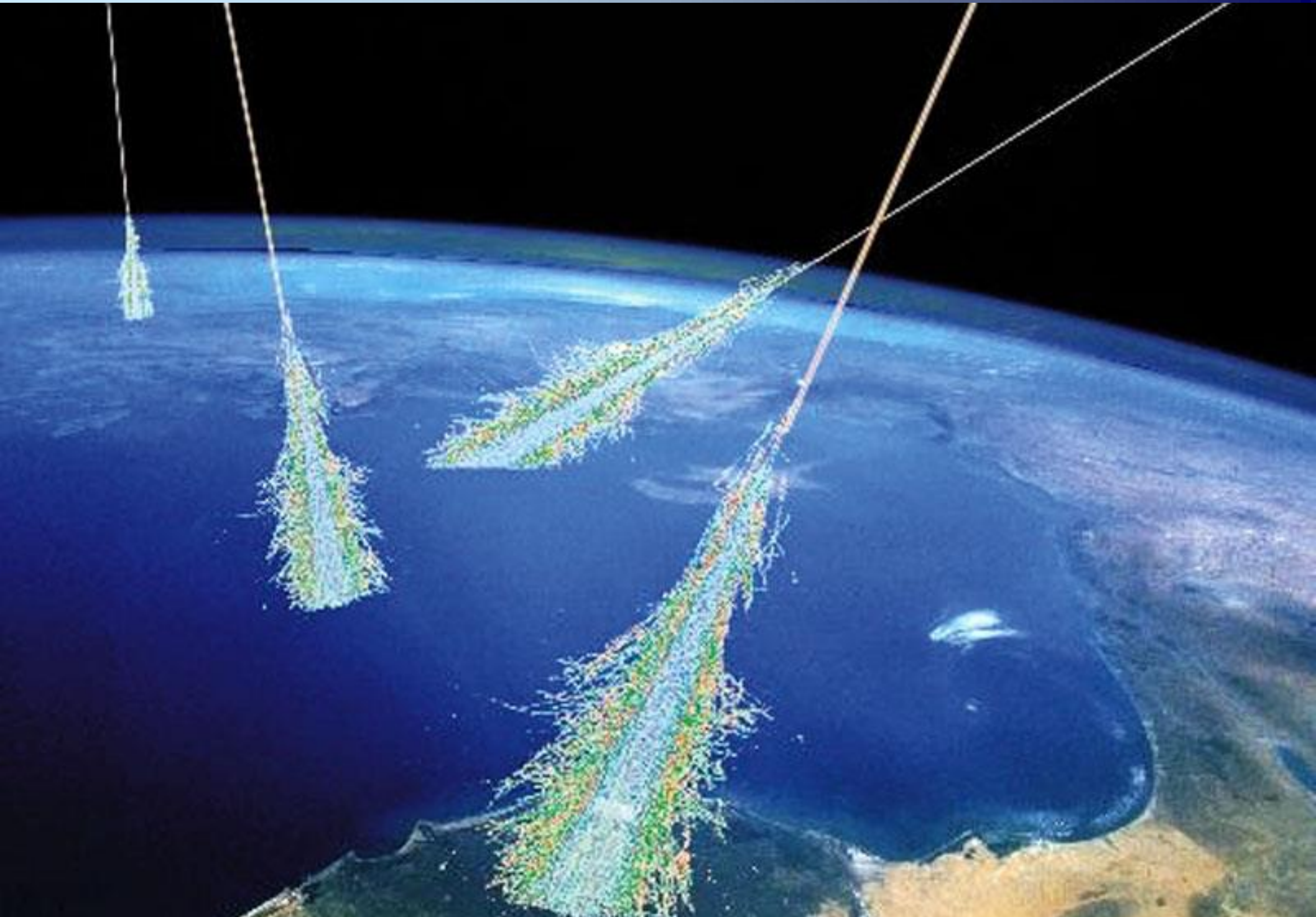
3. <u>Astroparticle physics in the GeV – PeV range</u>

   a. Supernovae as cosmic ray sources
   b. Connection to the origin of Ice Cube neutrinos
   c. Transport of cosmic rays and the anti-matter 'anomalies'

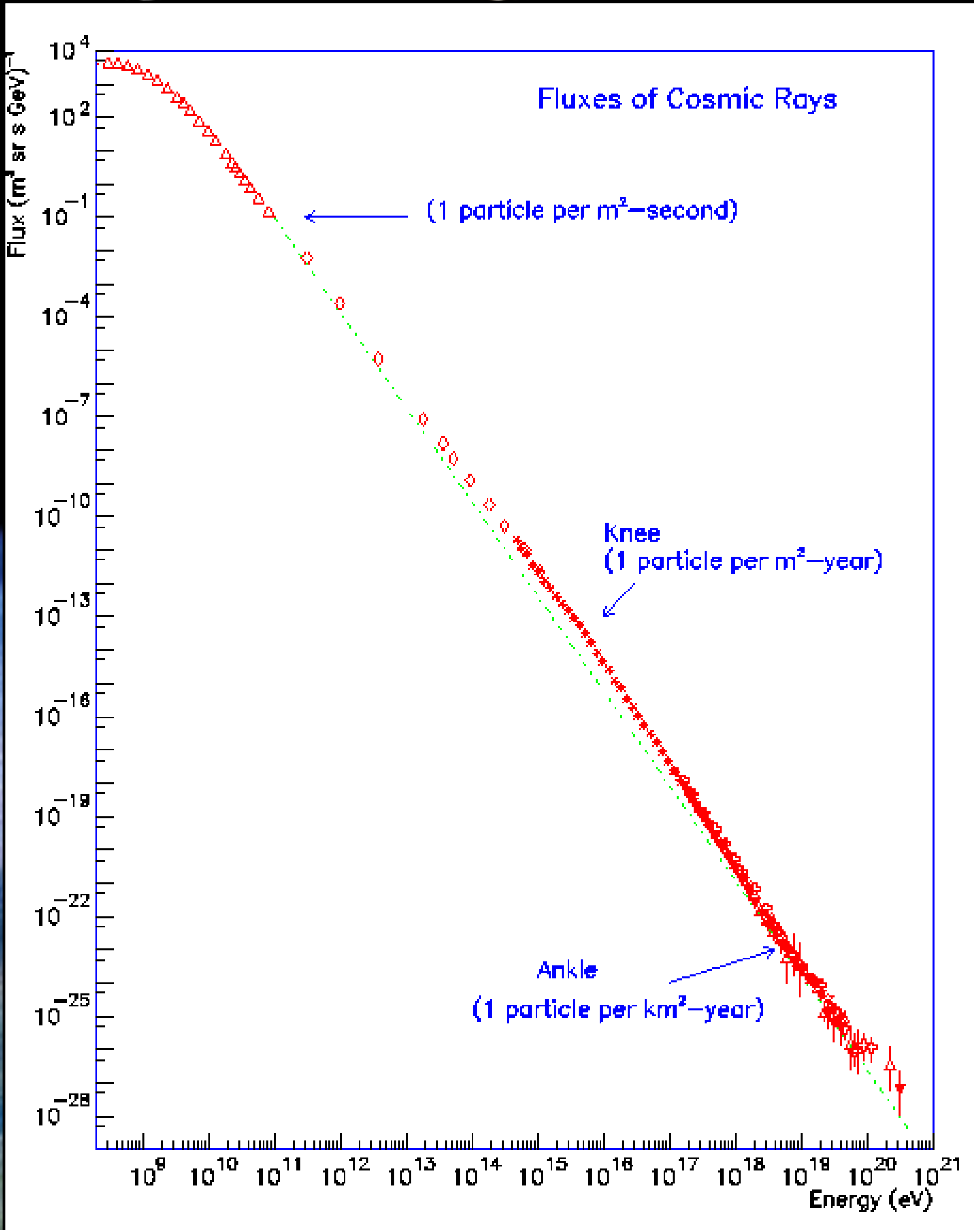
1.a Introduction: photon diffuse backgrounds



1.a Introduction: air showers



1.a Introduction: cosmic ray spectrum



Cosmic ray showers:

- spans ~12 orders of magnitude in energy

  ~10^4 particles/m^2/s at 1 GeV…
  ~1 particle/km^2/century at 10^{11}GeV…

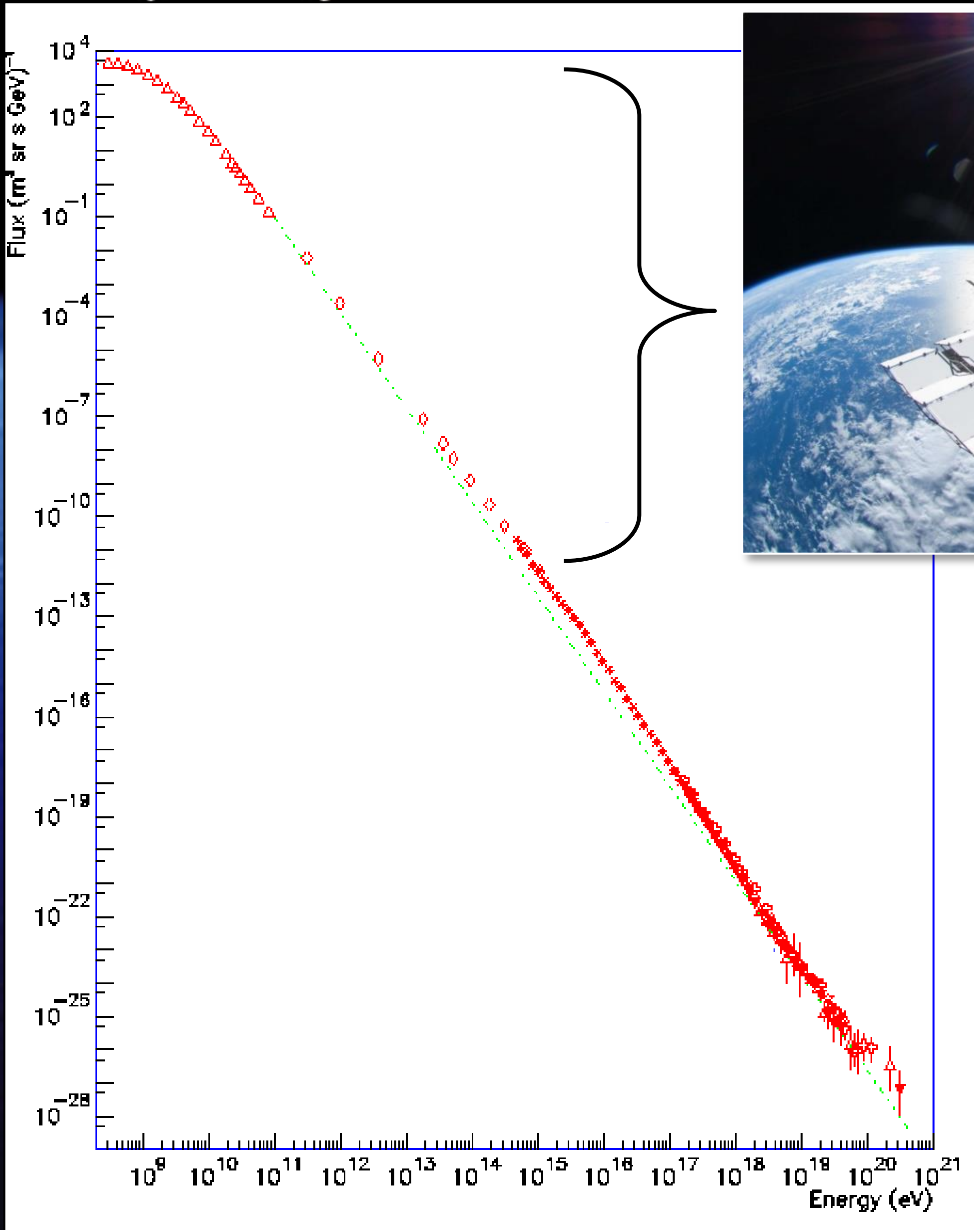
- approximate power-law

$$\frac{\mathrm{d}N}{\mathrm{d}p} \propto p^{-2.7}$$

- no astronomy below 10^{11} GeV due to intervening magnetic fields (non-trivial transport!)

- a window on the non-thermal Universe

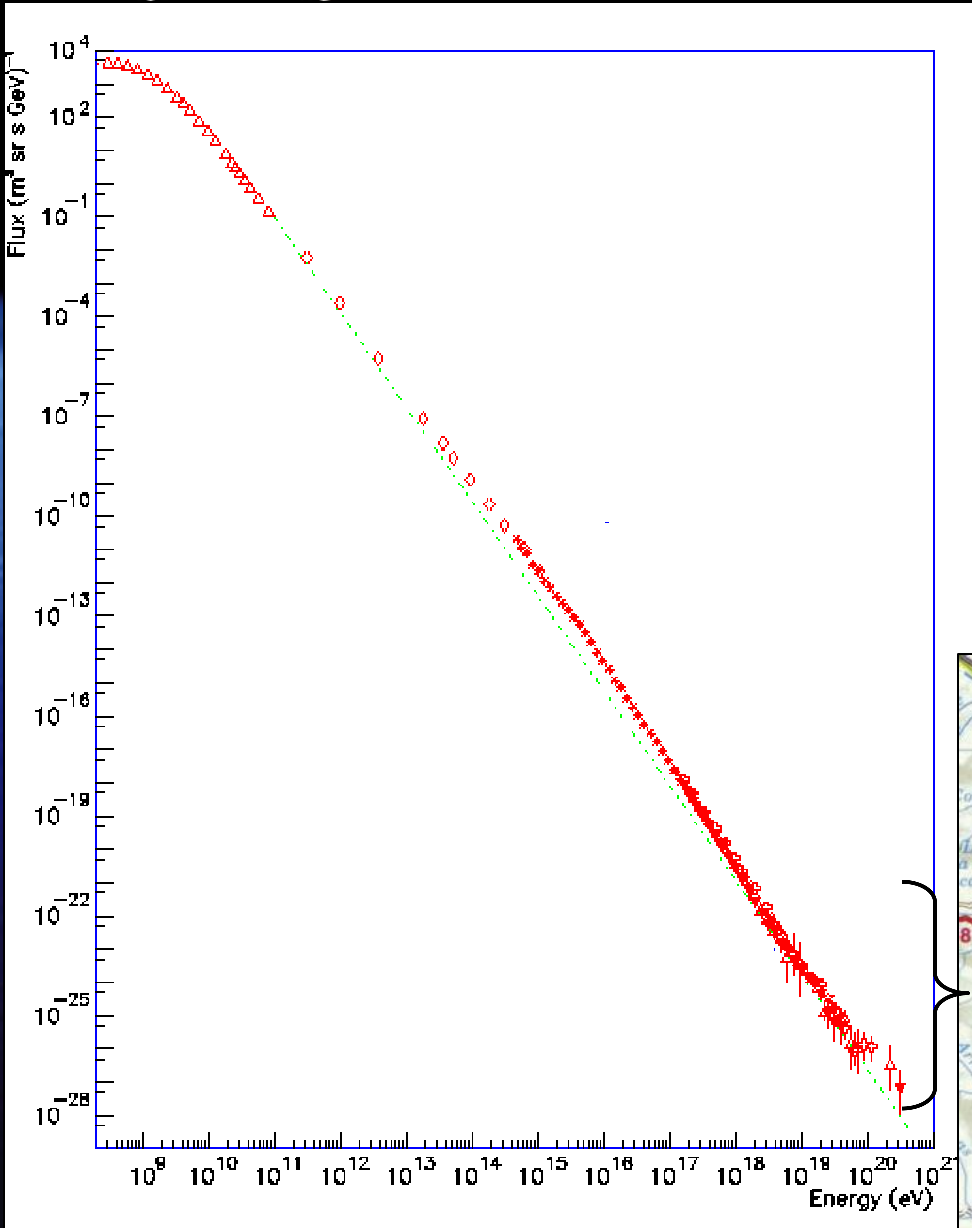
1.a Introduction: GeV – PeV cosmic rays



GeV – PeV cosmic rays:

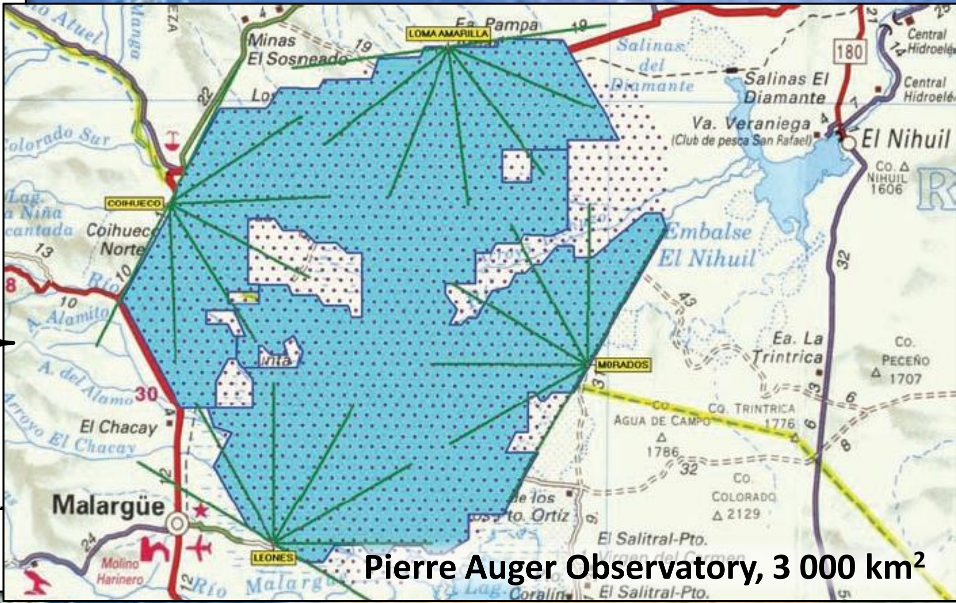
- mostly H, He; chemical composition roughly similar to the Sun
- likely origin: acceleration in sub-relativistic collisionless shock waves of supernovae remnants
- flux is matched if each supernova injects 10^{50} ergs (0.1% of energy budget) in cosmic rays

1.a Introduction: >EeV cosmic rays



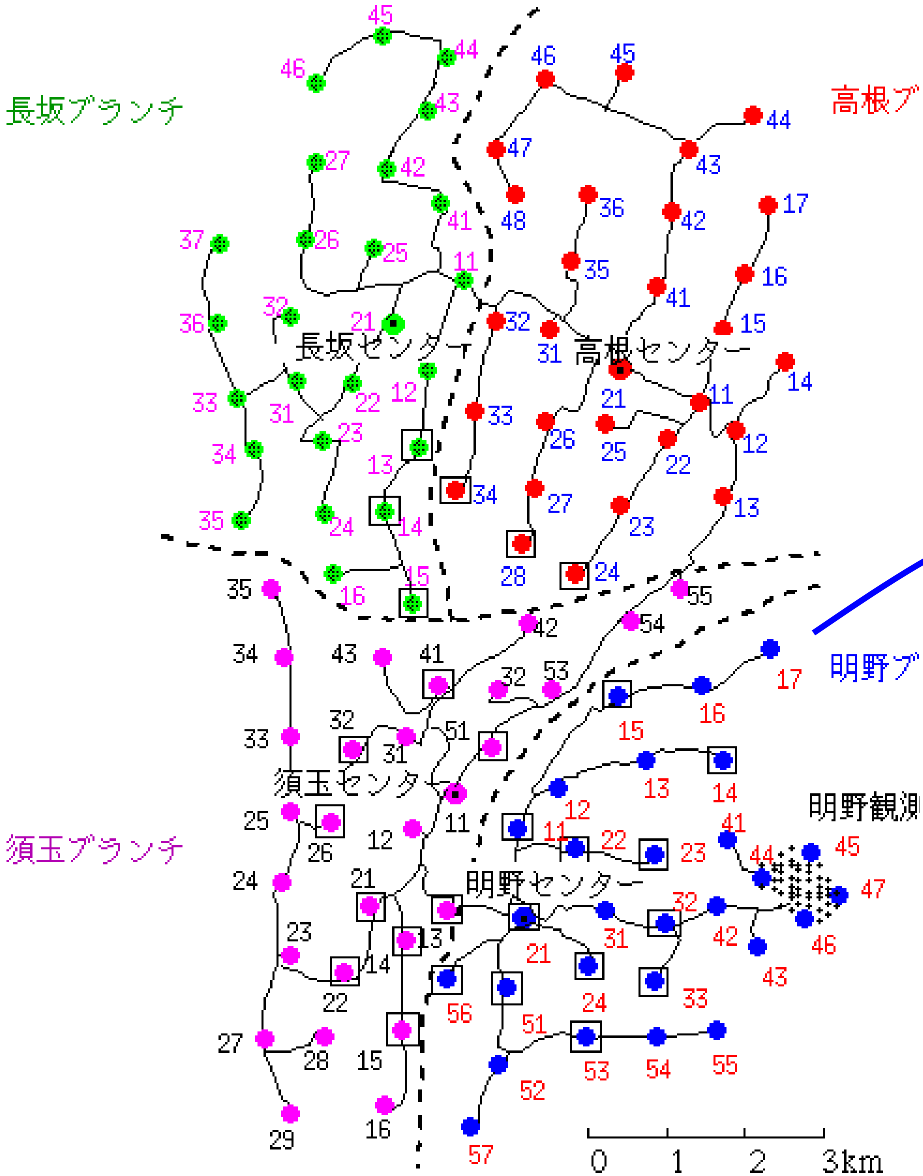
>EeV cosmic rays:

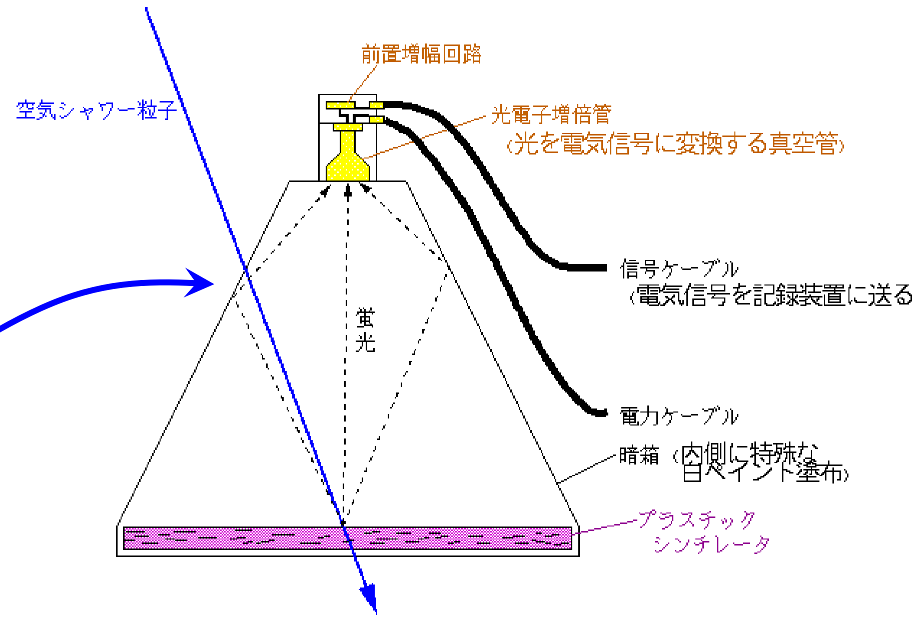
- ill-known chemical composition
- ***unknown origin***
- origin likely involves the most powerful objects in the Universe: gamma-ray bursts, giant radio-galaxies, ...
- energies well above LHC



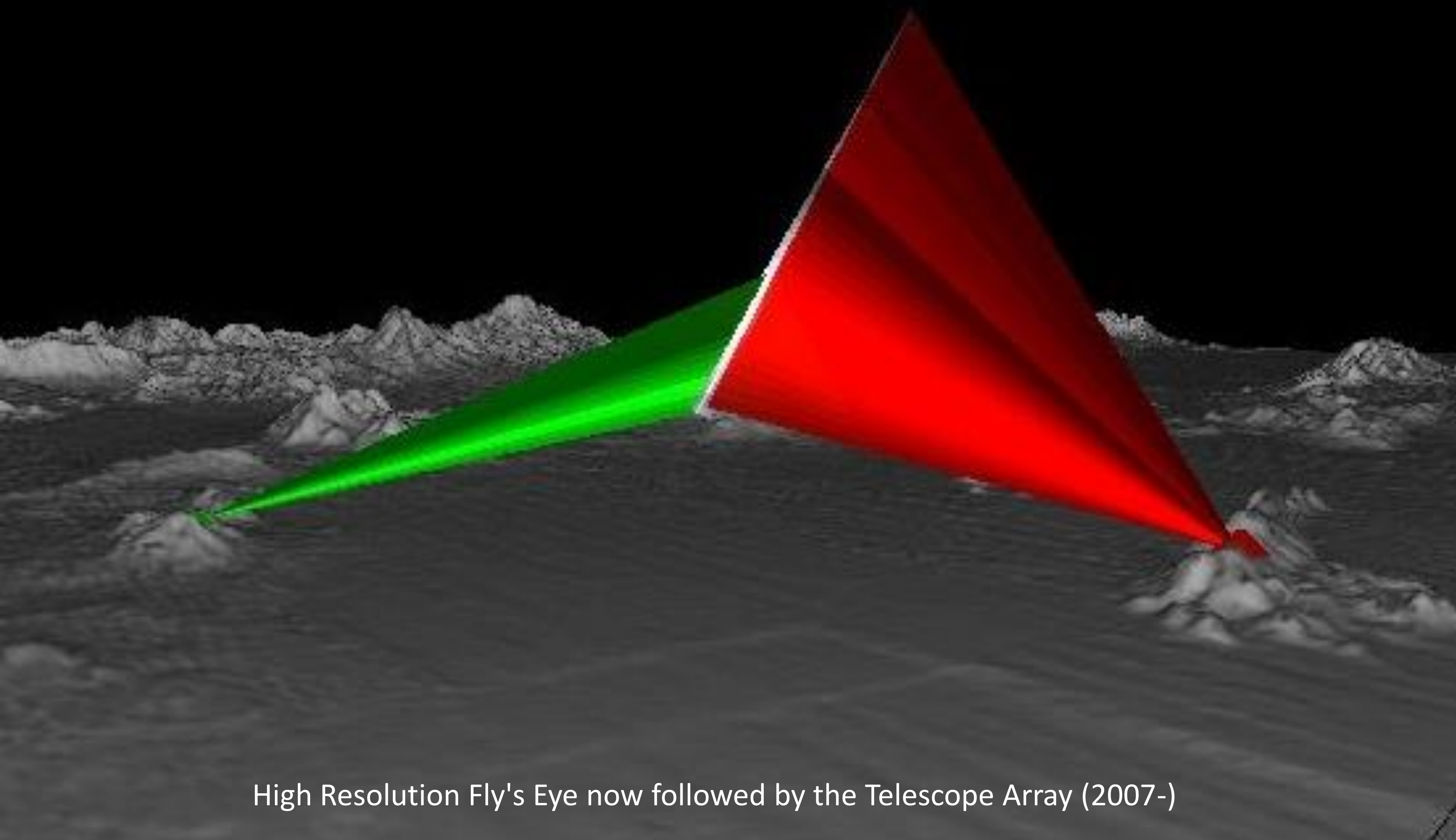
Pierre Auger Observatory, 3 000 km²

1.a Introduction: Akeno Giant Air Shower Array (AGASA)





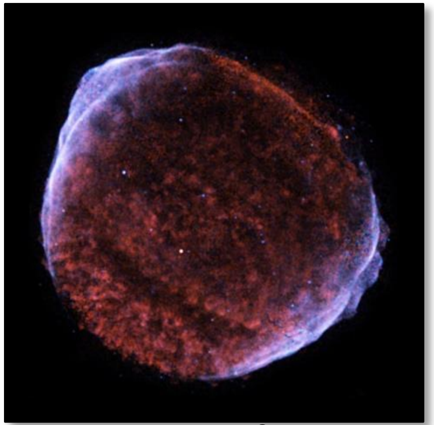
1.a Introduction: fluorescence observations



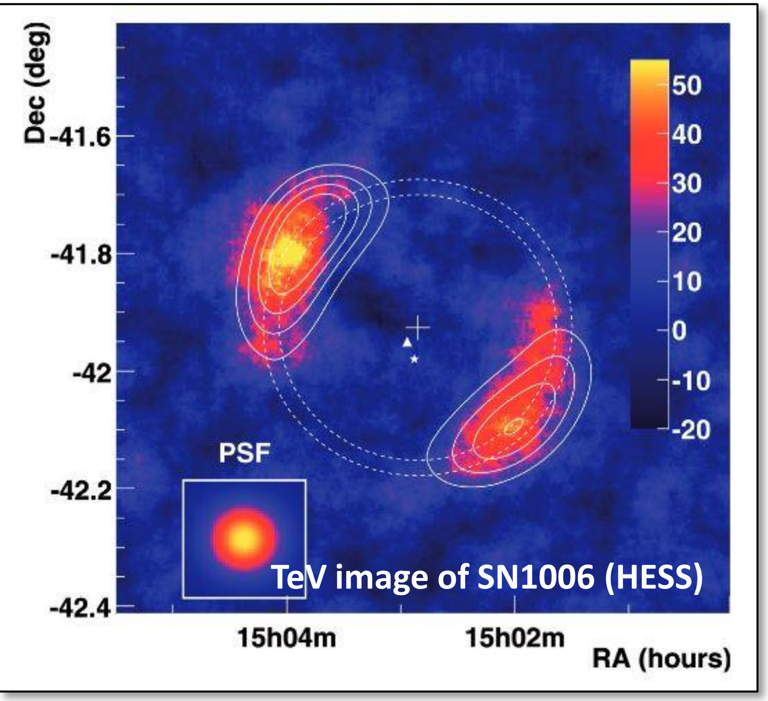
High Resolution Fly's Eye now followed by the Telescope Array (2007-)

1.a Introduction: HESS II Cerenkov gamma-ray telescope

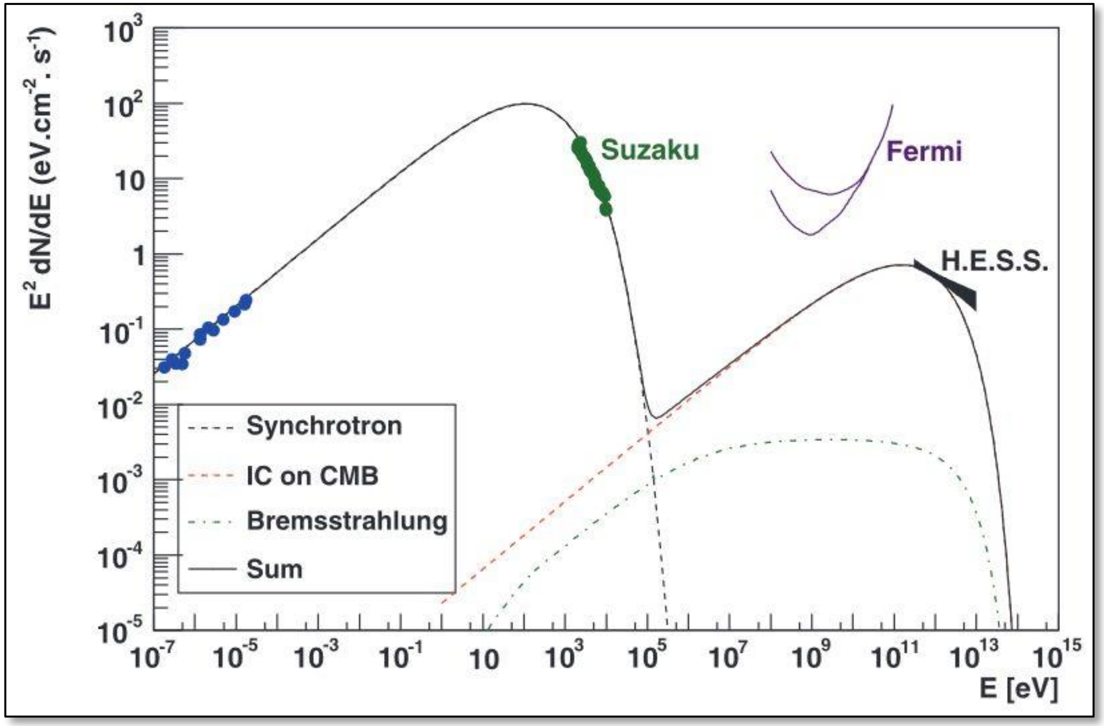
1.a Introduction: gamma-ray observations of supernovae



X-ray image of SN1006 (Chandra)

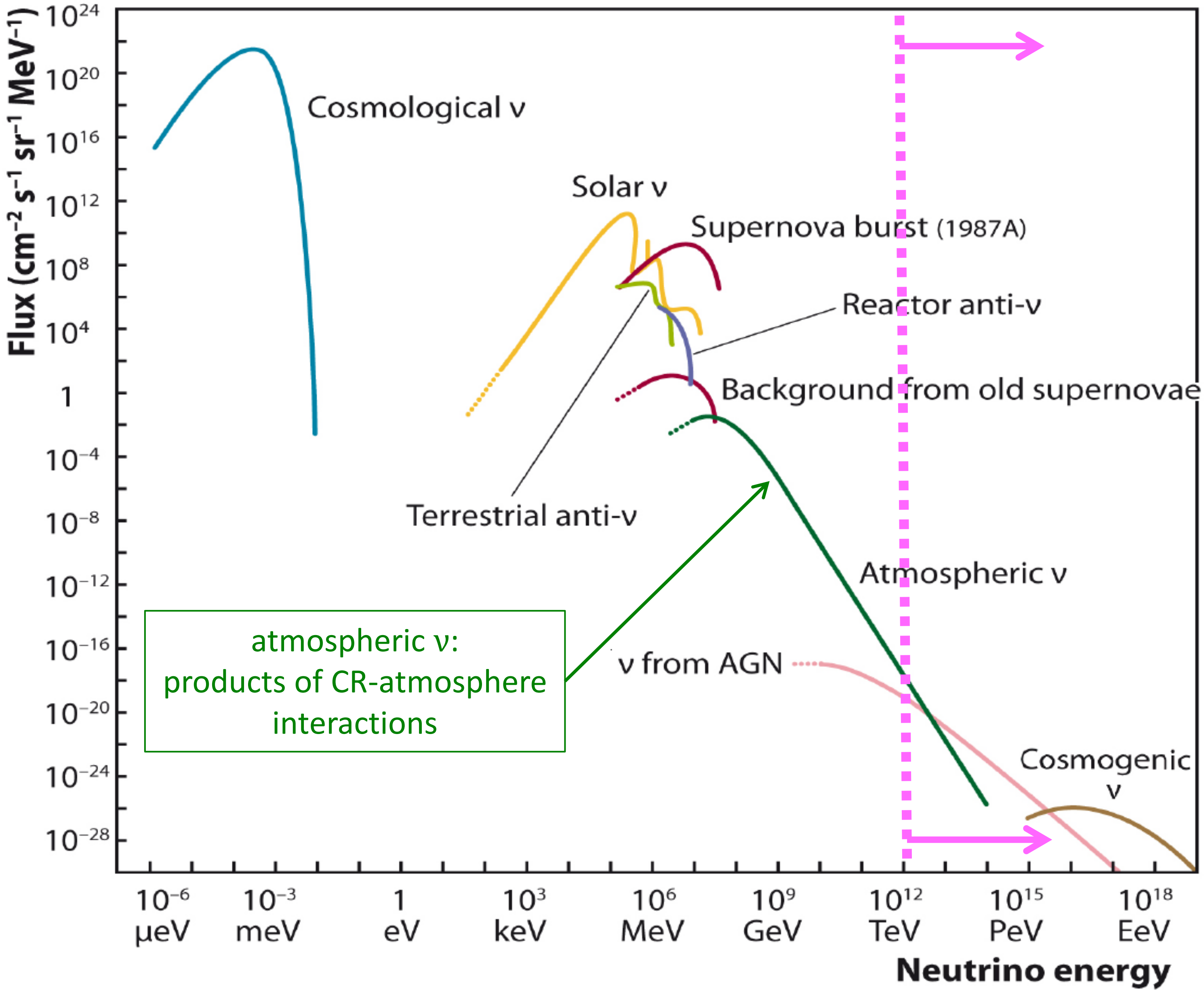


TeV image of SN1006 (HESS)

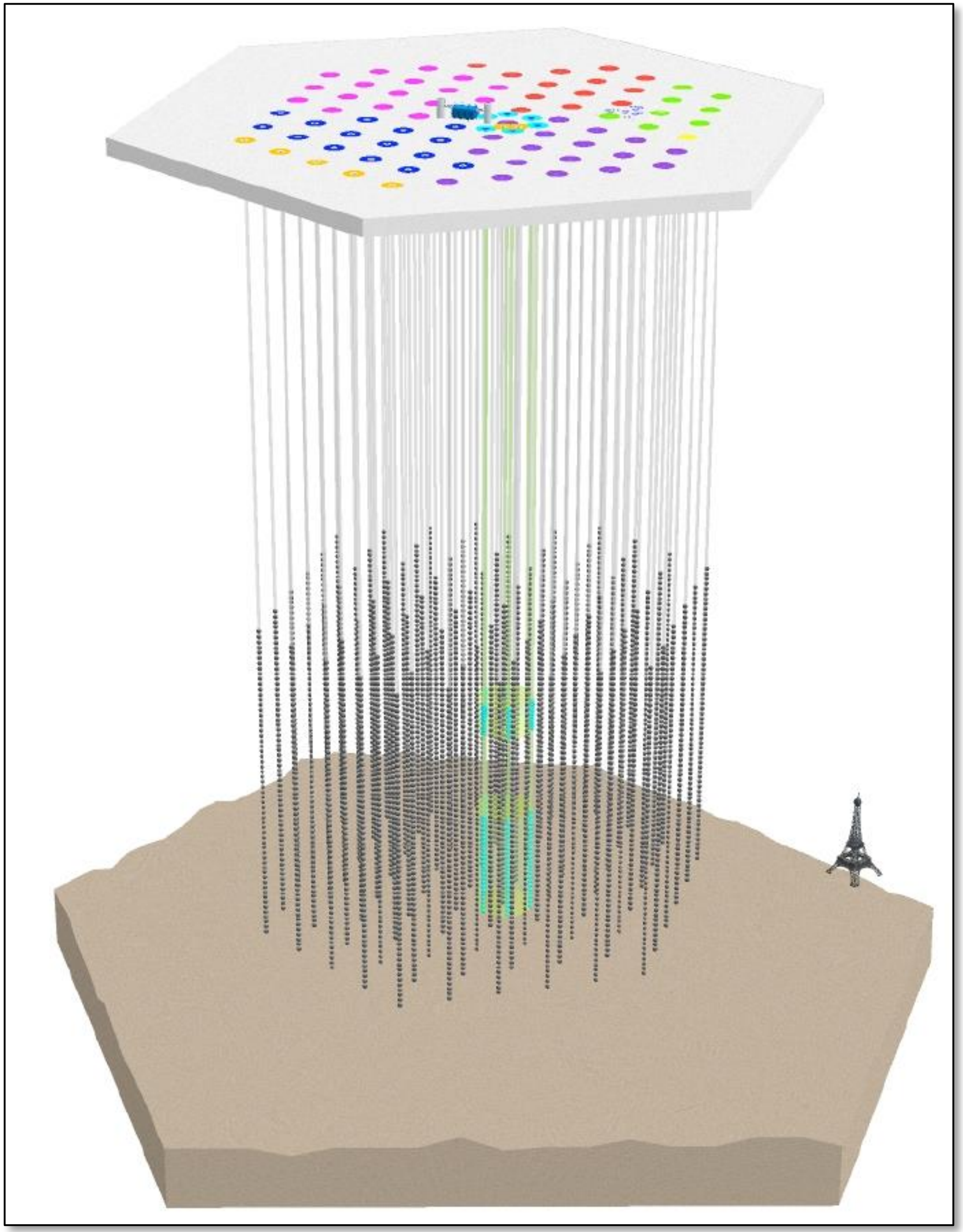


gamma-ray telescopes have demonstrated that particles (e, nuclei) are accelerated to > TeV energies in supernovae remnants…

1.a Introduction: neutrino diffuse backgrounds



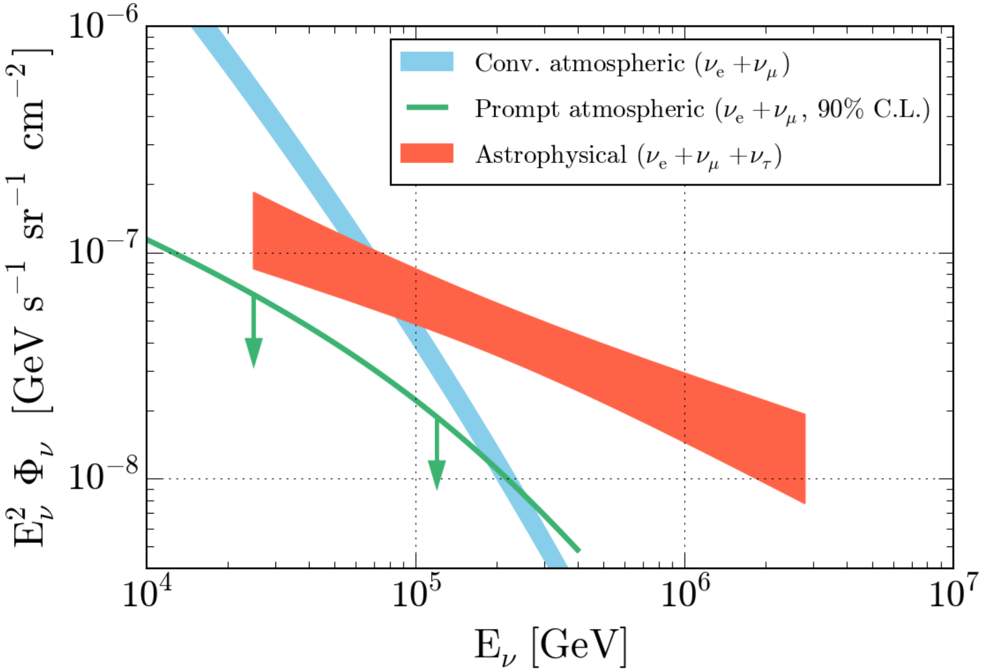
1.a Introduction: the Ice Cube neutrino detector



The Ice Cube experiment:

- located at the South Pole
- effective volume 1km^3
- about 5000 photomultipliers between 1500m and 2500m deep

1.a Introduction: the Ice Cube neutrinos

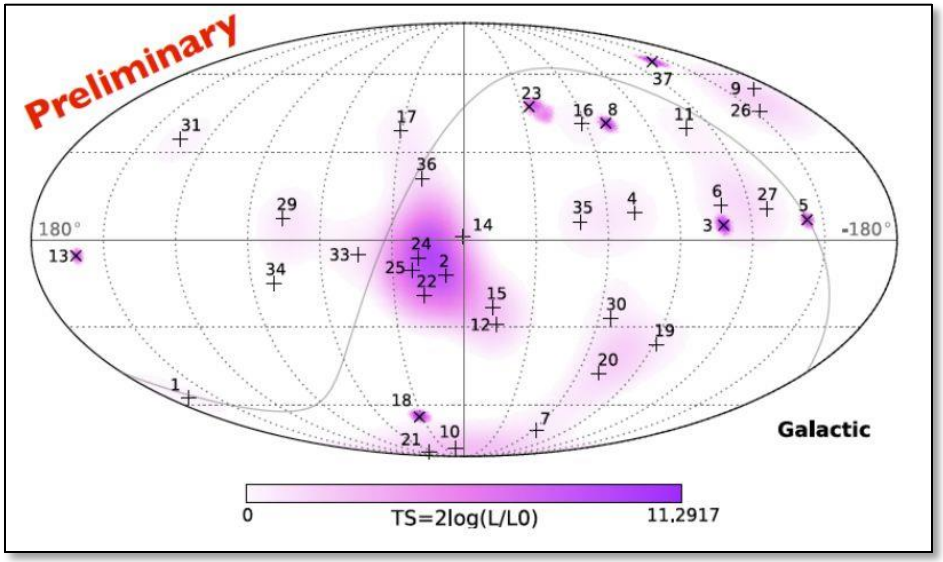


Ice Cube has reported in 2013 the first detection of « astrophysical » neutrinos…

… a few dozens of events at ~PeV energies

… consistent with isotropic arrival directions…

and with flavor ratio 1:1:1 expected from oscillations…



1.b CR-ν-γ connection: energy loss processes

High energy electrons (and e+): $\gamma_e \equiv E_e/(m_e c^2)$

synchrotron radiation, with typical frequency:

$$\nu_{\rm syn} \sim 70\,{\rm Mhz}\,E_{\rm GeV}^2 B_{\mu{\rm G}}$$

inverse Compton on seed photon: $e+\gamma \to e+\gamma$

$$E_\gamma' \simeq 2\gamma_e^2 E_\gamma \sim 10\,{\rm keV}\,E_{\rm GeV}^2 E_{\gamma,{\rm CMB}}$$

large loss rates imply that most radiation is of leptonic origin (in general!)

High energy protons:

p-p interaction: $p+p \to p+\,(p\,{\rm or}\,n)\,+\,\pi+\ldots$

p-γ interaction: $p+\gamma \to (p\,{\rm or}\,n)\,+\,\pi+\ldots$

with threshold: $E_p E_\gamma \gtrsim m_\pi^2 c^4$

hence neutrino production:

$$\begin{aligned}\pi^+ &\to \mu^+ + \nu_\mu \\ \mu^+ &\to e^+ + \nu_e + \overline{\nu}_\mu\end{aligned}$$

and gamma production: $\pi^0 \to \gamma+\gamma$

(+pair production p+γ→p+e+e with small inelasticity, possibly synchrotron radiation in strong magnetic fields, etc.)

astrophysical ν: unambiguous signature of hadron acceleration

1.b CR-ν-γ connection: energy output

Concomittant production of neutrinos and photons in hadronic interactions imply a relationship between cosmic ray, neutrinos and photons spectra:

→ assume a source of cosmic ray (protons) with spectrum $\mathrm{d}N_p \propto E_p^{-s_p}\,\mathrm{d}E_p$

→ write f_π the fraction of proton energy lost to pion production (either in source or during transport)
pp or pγ produce neutral and charged pions with approximate ratio 1:1

→ energy carried by individual photons/neutrinos:

$$\begin{aligned} \langle E_\gamma \rangle &\sim 0.5\,E_\pi \sim 0.1 E_p \\ \langle E_\nu \rangle &\sim 0.25\,E_\pi \sim 0.05 E_p \end{aligned}$$

→ corresponding energy spectra:

$$\begin{aligned} E_\gamma^2 \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} &\simeq f_{\pi\to\gamma}\, E_p^2 \frac{\mathrm{d}N_p}{\mathrm{d}E_p} \\ E_\nu^2 \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} &\simeq f_{\pi\to\nu}\, E_p^2 \frac{\mathrm{d}N_p}{\mathrm{d}E_p} \end{aligned}$$

with $f_{\pi\to\gamma} \sim 0.5 f_\pi \sim f_{\pi\to\nu}$

⇒ gamma-rays and neutrinos offer complementary probes of the inner engines of cosmic rays …

1.b CR-ν-γ connection: the Waxman-Bahcall limit

The correspondence between neutrino and cosmic ray spectra can be used to set a limit on the diffuse neutrino flux from the observed CR spectra at UHE:

→ assuming a power-law with index s_p = 2.0 in the range 10^{19}-10^{20} eV, one infers from the observed cosmic-ray flux dI_p/dE_p an emissivity

$$\frac{\mathrm{d}I_p}{\mathrm{d}E_p} \sim \frac{c}{4\pi}\tau_p \frac{\mathrm{d}\dot{n}_p}{\mathrm{d}E_p} \Rightarrow E_p^2 \frac{\mathrm{d}\dot{n}_{\mathrm{CR}}}{\mathrm{d}E_p} \sim 10^{44}\,\mathrm{erg/Mpc^3/yr}$$

τ_p lifetime of cosmic-rays (→ lecture 2)

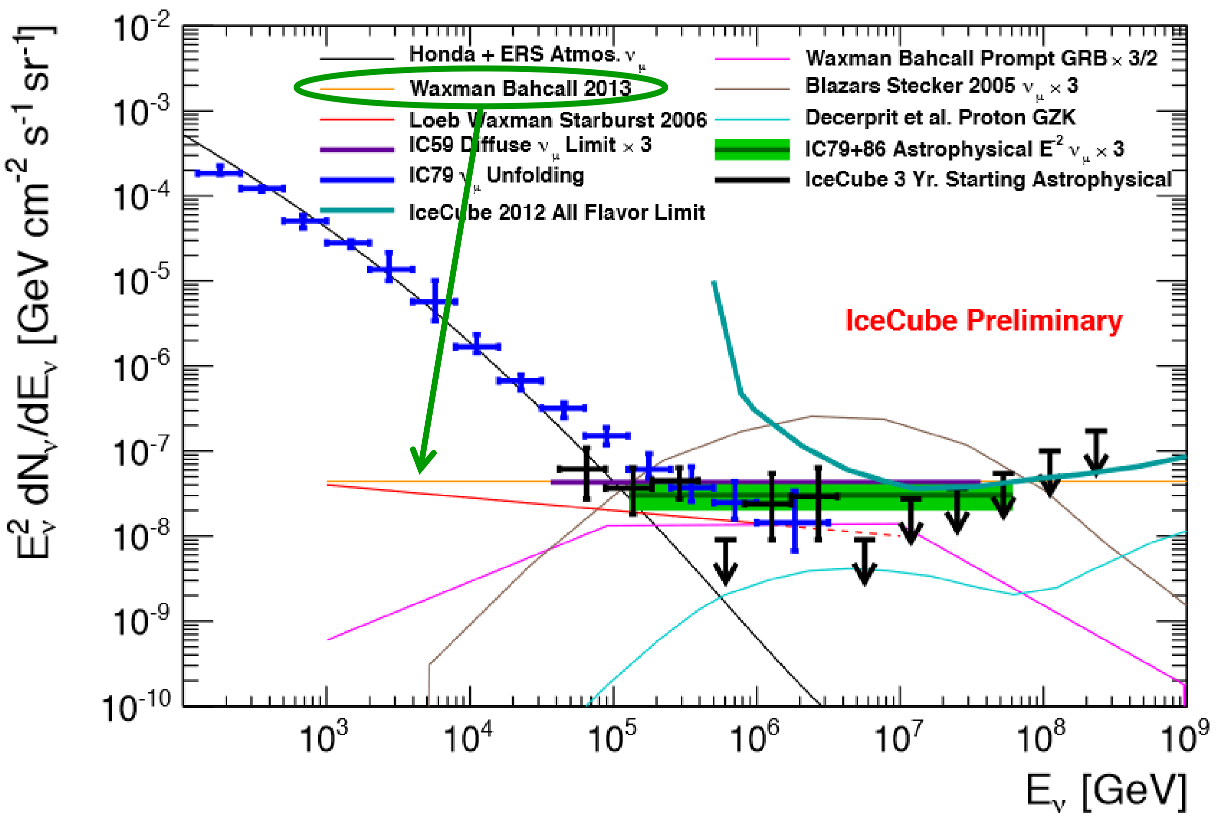
→ extrapolating this flux to lower energies, in the PeV range, one infers a neutrino limit flux of

$$E_\nu^2 \frac{\mathrm{d}I_\nu}{\mathrm{d}E_\nu} \simeq \frac{c}{4\pi} f_z \frac{f_\pi}{4} t_{\mathrm{H}} E_p^2 \frac{\mathrm{d}\dot{n}_p}{\mathrm{d}E_p} \sim 2\times 10^{-8}\,\mathrm{GeV/cm^2/s/sr}$$

t_H: Hubble time, accounts for the fact that neutrinos up to z~1 are observed,
f_z~1: accounts for cosmological redshift effects

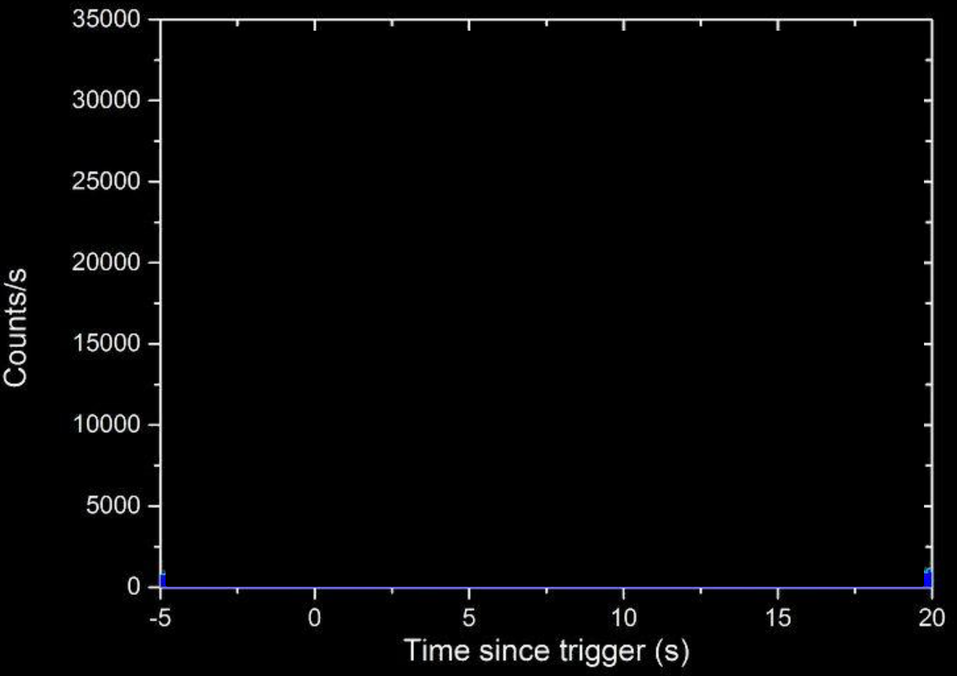
1.b CR-ν-γ connection: the WB limit vs Ice Cube

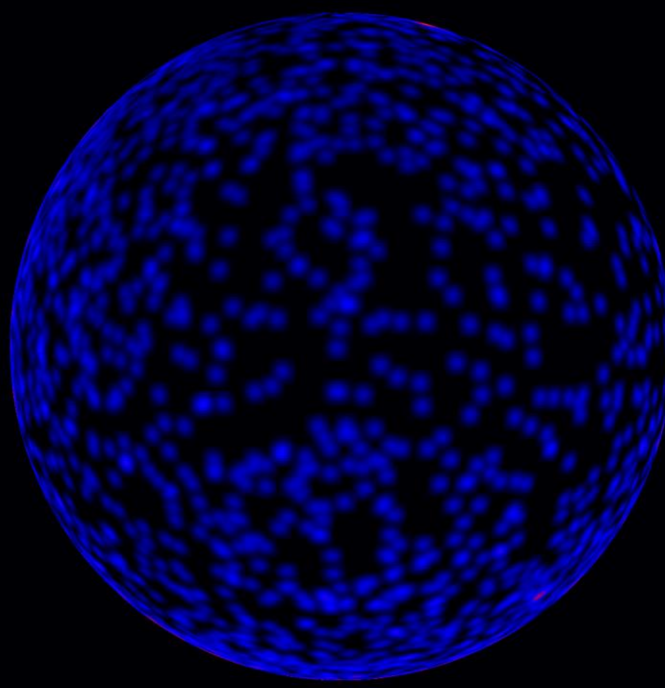
The Waxman-Bahcall bound sets the standard for the detection of high energy neutrinos, predicting O(few) events per yr in a km^3 cube neutrino detector such as Ice Cube at PeV energies…



… the observed flux at Ice Cube matches nicely the WB bound: a connection to high energy cosmic ray physics?

1.c Motivations: gamma-ray bursts





Sky map above 100MeV on April 27 2013 (Fermi)

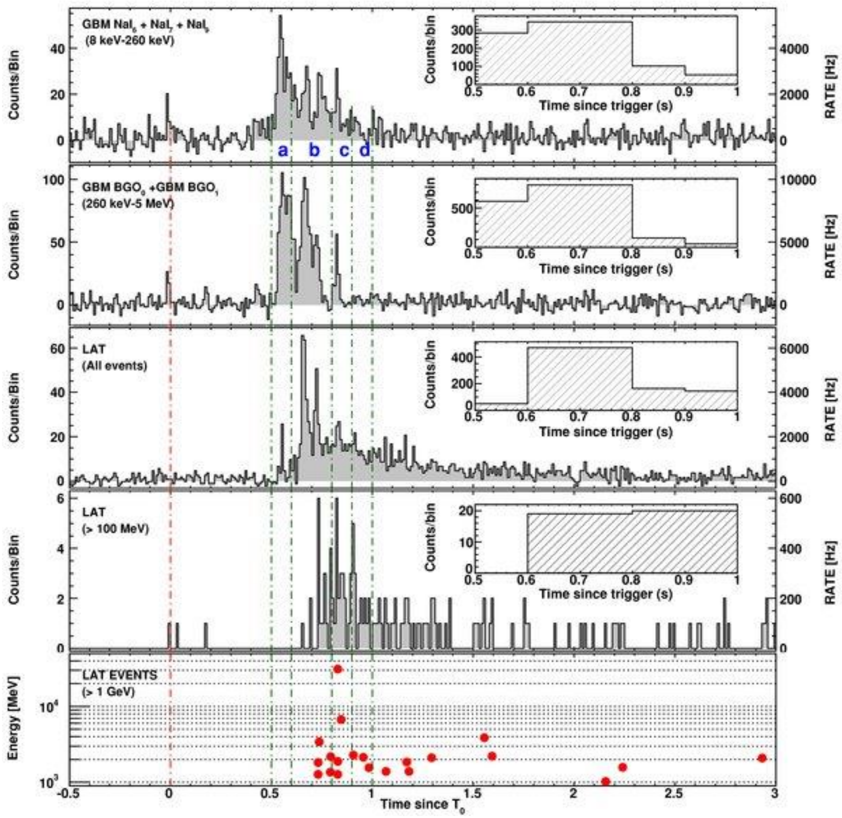
Gamma-ray bursts:

- a burst of <1 to >100sec at MeV energies (and higher), non-repeating, with erratic behavior
- cosmological origin: likely associated with rare ($\sim 1/\mathrm{Gpc}^3/\mathrm{yr}$) events at redshift z ~ 1 and above, originating from the collapse of massive stars of coalescence of compact objects

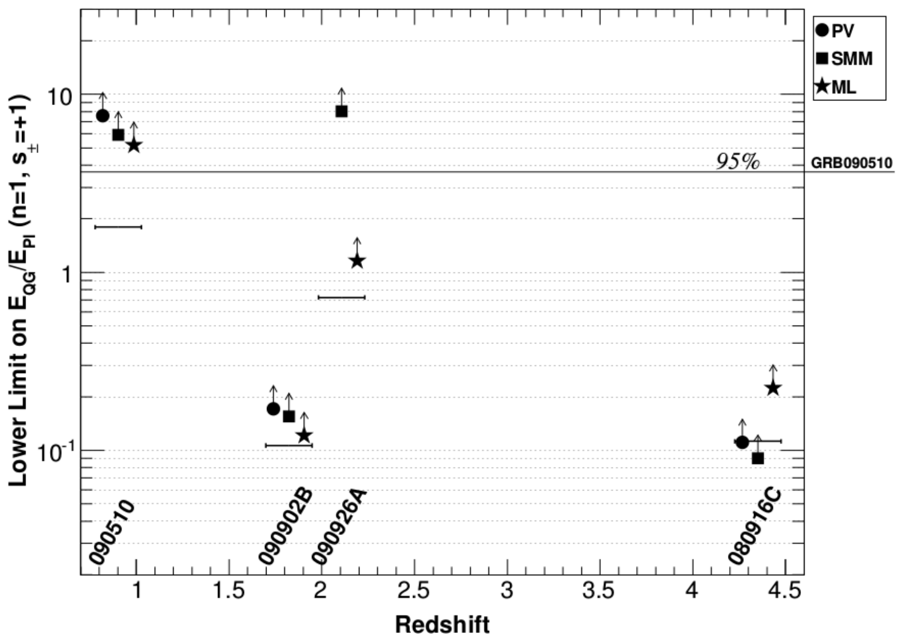
1.c Motivations: Lorentz invariance violation probes

The large distance of gamma-ray bursts and the small time dispersion of photons arrival times are used to place constraints on modified photon dispersion relations at high energy:

e.g. $$E^2 = p^2c^2\left[1+\sum_{n=1} s_{n,\pm}\left(\frac{E}{E_{\mathrm{QG}}}\right)^{2n}\right]$$



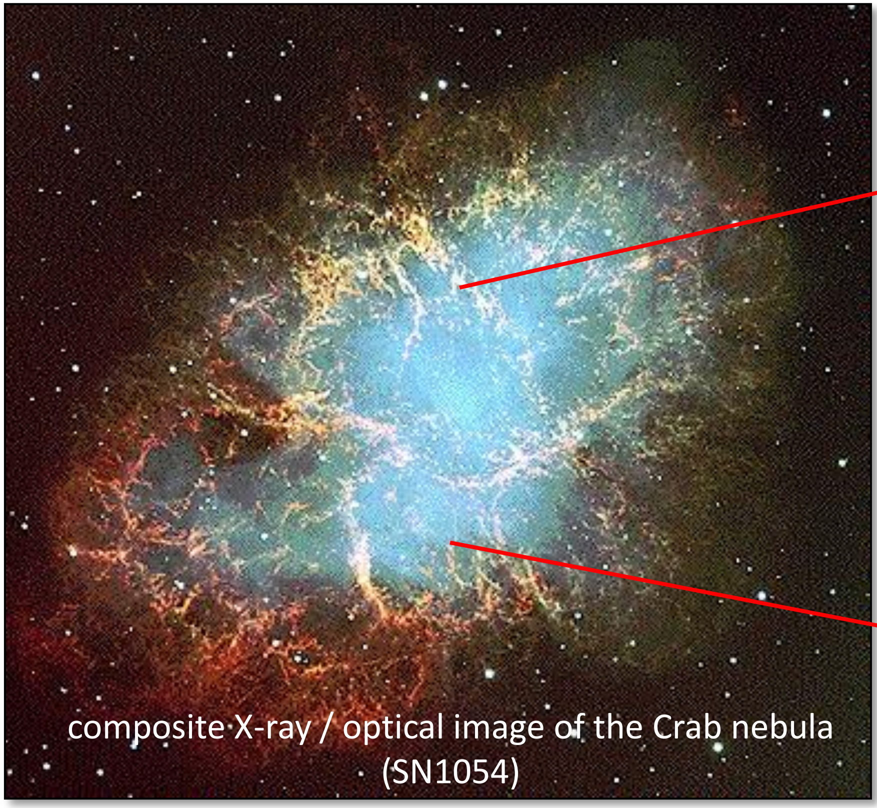
Fermi Coll. 10

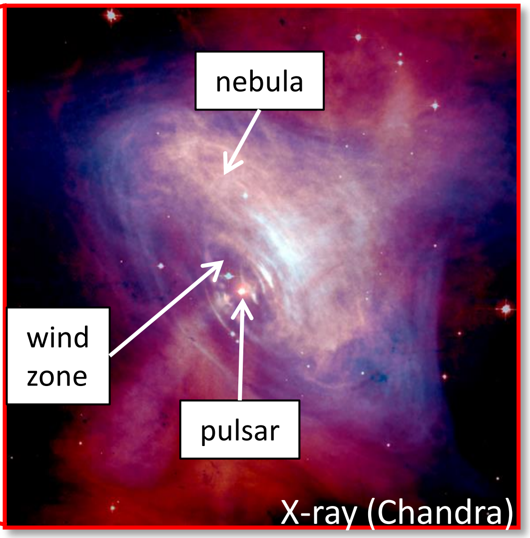


Vasileiou+ 13

1.c Motivations: extreme astrophysics, pulsars

Some supernovae remnants harbor a pulsar, surrounded by a pulsar wind nebula…


composite X-ray / optical image of the Crab nebula (SN1054)



… origin of the nebular radiation: electrons with energies up to a PeV!
acceleration at a relativistic collisionless shock wave moving with Lorentz factor 10^6?

… origin of the radio to GeV emission of the pulsar, including pulses and flares?

1.c Motivations: the unexpected flaring of the Crab

AGILE and Fermi have detected flares at GeV energies from the Crab nebula….

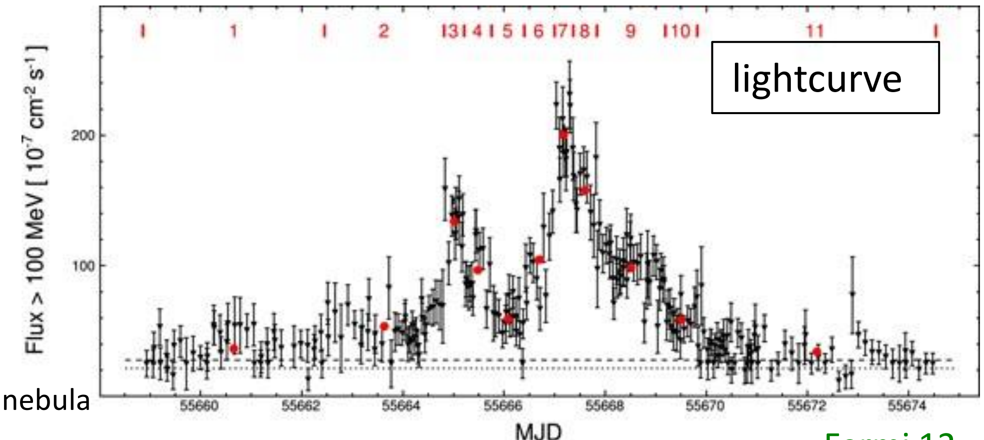
→ flux increase x10 in ~few hrs

→ causality scale: $c\,t \sim 10^{-4}$ pc $\ll R_{nebula}$

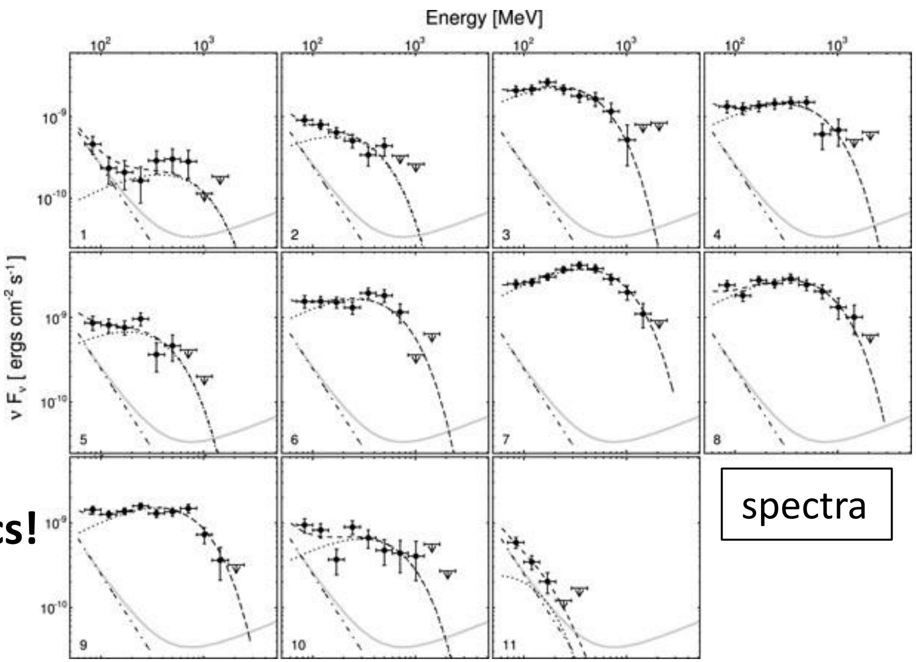
→ hard spectrum $dN_\gamma/dE_\gamma \propto E^{-s_\gamma}$, with $s_\gamma \sim 1.3$

→ no morphological change in any wavebands…

a new puzzle for high energy astrophysics!



Fermi 12

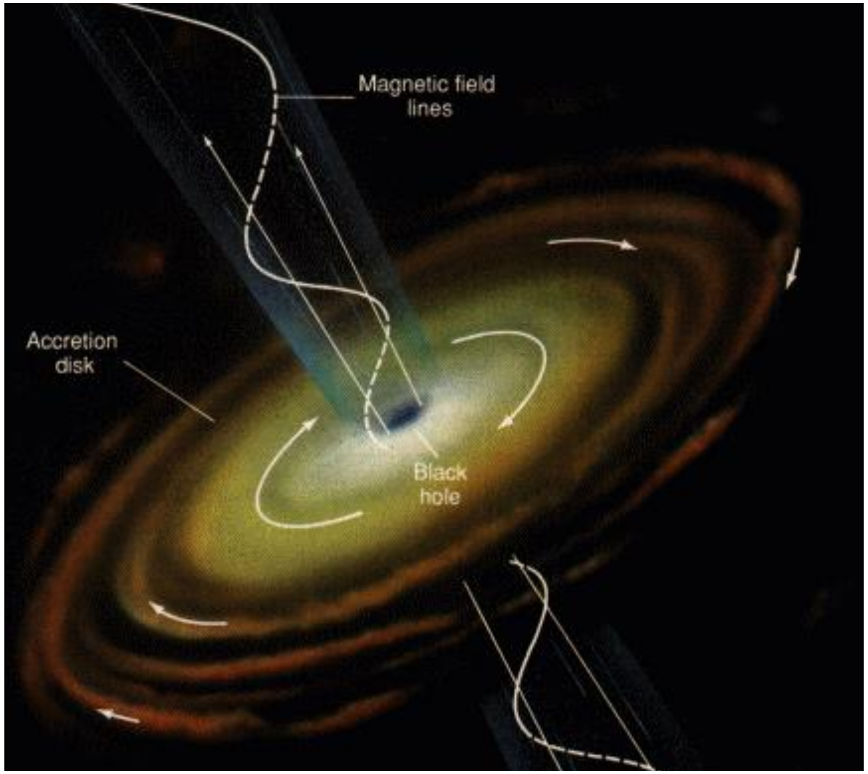


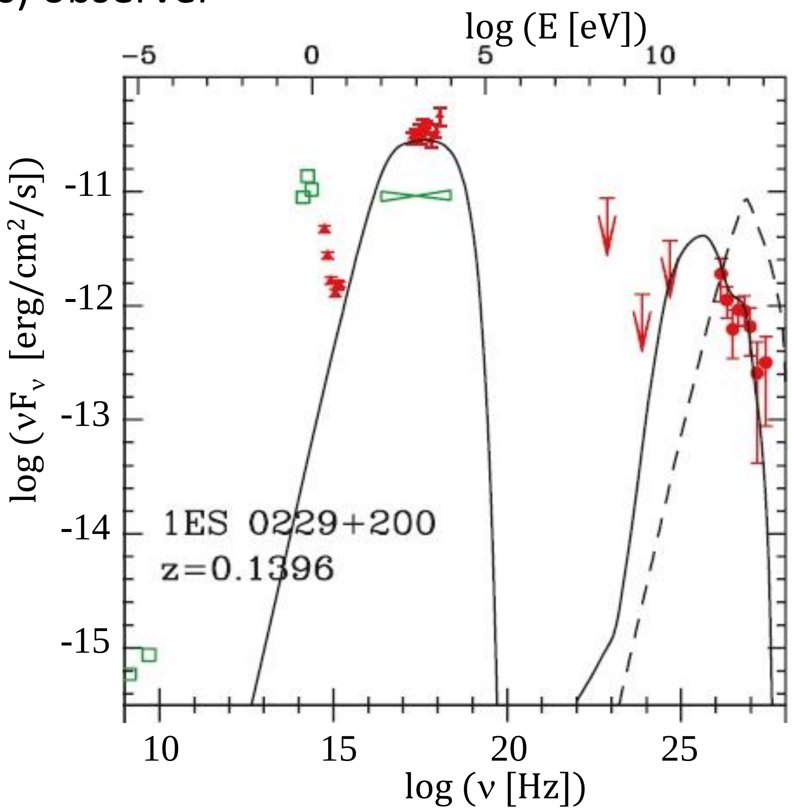
1.c Motivations: extreme astrophysics, blazars

Blazar:

radiation emitted by ultra-relativistic particles, accelerated in a jet launched from a super-massive black hole…

high energy radiation beamed towards the (on-axis) observer



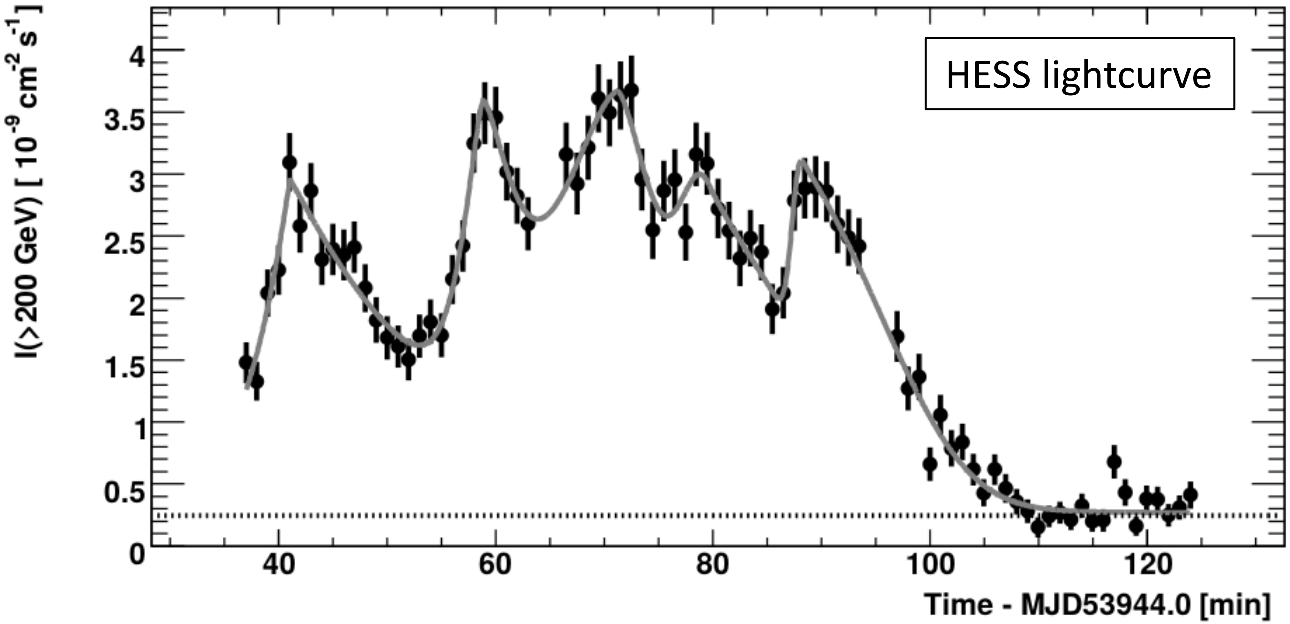


Main questions:

- How are jets launched and accelerated?
- How are particles accelerated in the jets, where, and what are the main radiation processes? Do blazar contribute to ultra-high energy cosmic rays?
- What causes the extreme time variability observed?

1.c Motivations: the extreme variability of blazars

Some blazars, e.g. PKS2155-304, are observed at very high energies with variability down to a few minutes!



however, $\frac{R_{\rm s}}{c} \simeq 3\,{\rm hrs}\frac{M_{\rm bh}}{10^9\,M_\odot}$ implies a compact emitting region

and relativistic bulk motion (which enhances the variability by the Lorentz factor)

1.c Motivations: the origin of magnetic fields

Recent observations of blazars have placed interesting lower limits on the strength of an all-pervading magnetic field…

… an interesting connection to the long-standing problem of the origin of cosmic magnetic (Hoyle 58)

… some scenarios of magnetogenesis:

inflation	phase transition	reionization	gal. formation	pollution
non-conformal coupling (Turner & Widrow 88; Ratra 92; Garretson et al. 92, Lemoine & Lemoine 95; Gasperini et al. 95; Calzetta et al. 98; Davis et al. 01, Caprini & Durrer 00, Martin & Yokoyama 08…)	charge sep. (Hogan 83, Vachaspati 91, Quashnock et al. 89, Enqvist & Olesen 93, Cheng & Olinto 94, Baym et al. 96, Sigl et al. 97, Boyanovski 01)	inhomogeneity/ anisotropy (Subramanian et al. 94, Gnedin et al. 00, Langer et al 03, 05) first stars (Gruzinov 01, Bell & Miniati 11)	Biermann battery (Pudritz & Silk 89, Kulrsud et al. 97, Davies & Widrow 00) large scale shocks (Shickeiser & Shukla 03, Medvedev et al. 04, Lazar et al. 09, Ryu et al. 08)	stellar pollution (Syrovatskii 70, Bisnovatyi-Kogan et al. 73, Rees 87) AGN (Hoyle 69; Rees 87, 94; Daly & Loeb 90; Chakrabarti et al 94)

log(t)

$z \sim 10^{20}$	$z \sim 10^{12}$ - 10^{15}	$z \sim$ 6-10	$z \sim$ a few	$z \sim$ a few

log(1+z)

$E \sim 10^9$ GeV $E \sim 10^3$ GeV $T \sim 3$ K

1.c Motivations: electromagnetic cascades

The limits on an all-pervading magnetic field rests on the development of electromagnetic cascades following the absorption of VHE photons by diffuse backgrounds (infra-red for TeV photons)

→ Pair production: $\gamma + \gamma_b \rightarrow e^+ + e^-$

$$\lambda_\gamma \simeq 80\,\mathrm{Mpc}\,(E_{\gamma,0}/10\,\mathrm{TeV})^{-1}$$

(interaction/cooling length)

electron energy: $E_e \simeq E_\gamma/2$

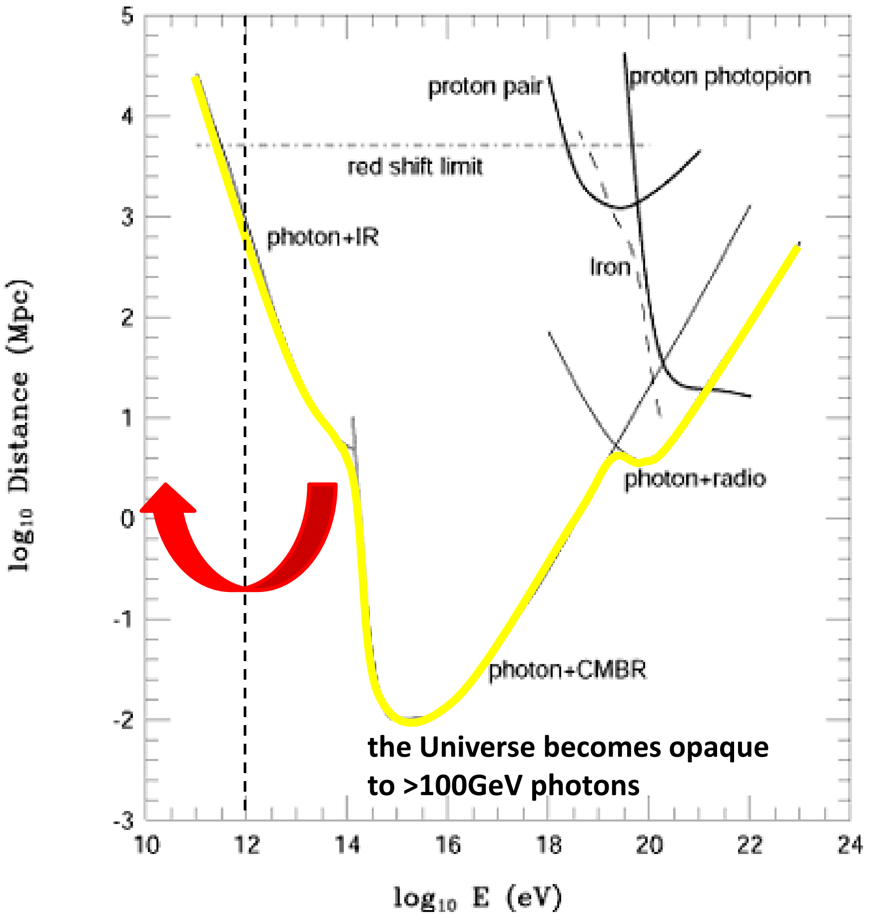
→ Inverse Compton: $e + \gamma_b \rightarrow e + \gamma$

e cooling length through inverse Compton on the cosmic microwave background:

$$\lambda_e \simeq 0.07\,\mathrm{Mpc}\,(E_e/5\,\mathrm{TeV})^{-1}$$

energy of upscattered photons:

$$\begin{aligned} E_\gamma &\simeq \frac{4}{3} k_B T_{\rm cmb} \left(E_e/m_e c^2\right)^2 \\ &\simeq 80\,\mathrm{GeV}\,(E_{\gamma,0}/10\,\mathrm{TeV})^2 \end{aligned}$$

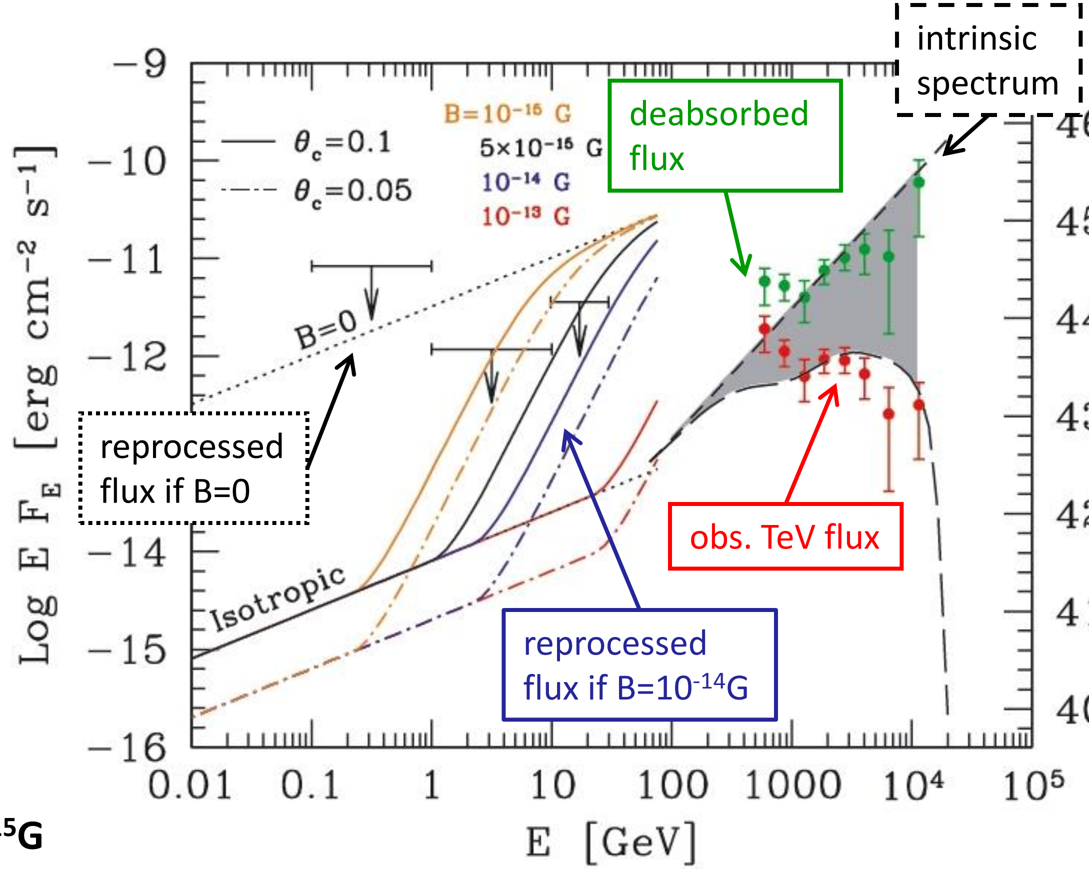


⇒ overall: all >TeV energy of far away sources is redeposited in the 1-100 GeV range through an electromagnetic cascade...

deflection of e^+e^- in intervening magnetic fields also leads to angular deflection (halos) and time delay (echos) of impulsive point-like energy injection (Aharonian et al. 94)

1.c Motivations: magnetic field signatures in blazars

The energy of photons emitted at >TeV energies should be seen in the multi-GeV range...
… upper limits on multi-GeV flux allows to put a lower limit on intergalactic B



→ reprocessed component is deflected by $\delta\theta$, spread over halo of extension Θ :

if $\delta\theta$ exceeds the beaming angle of the source θ_c, or if Θ exceeds the PSF extension, reprocessed flux is depleted...

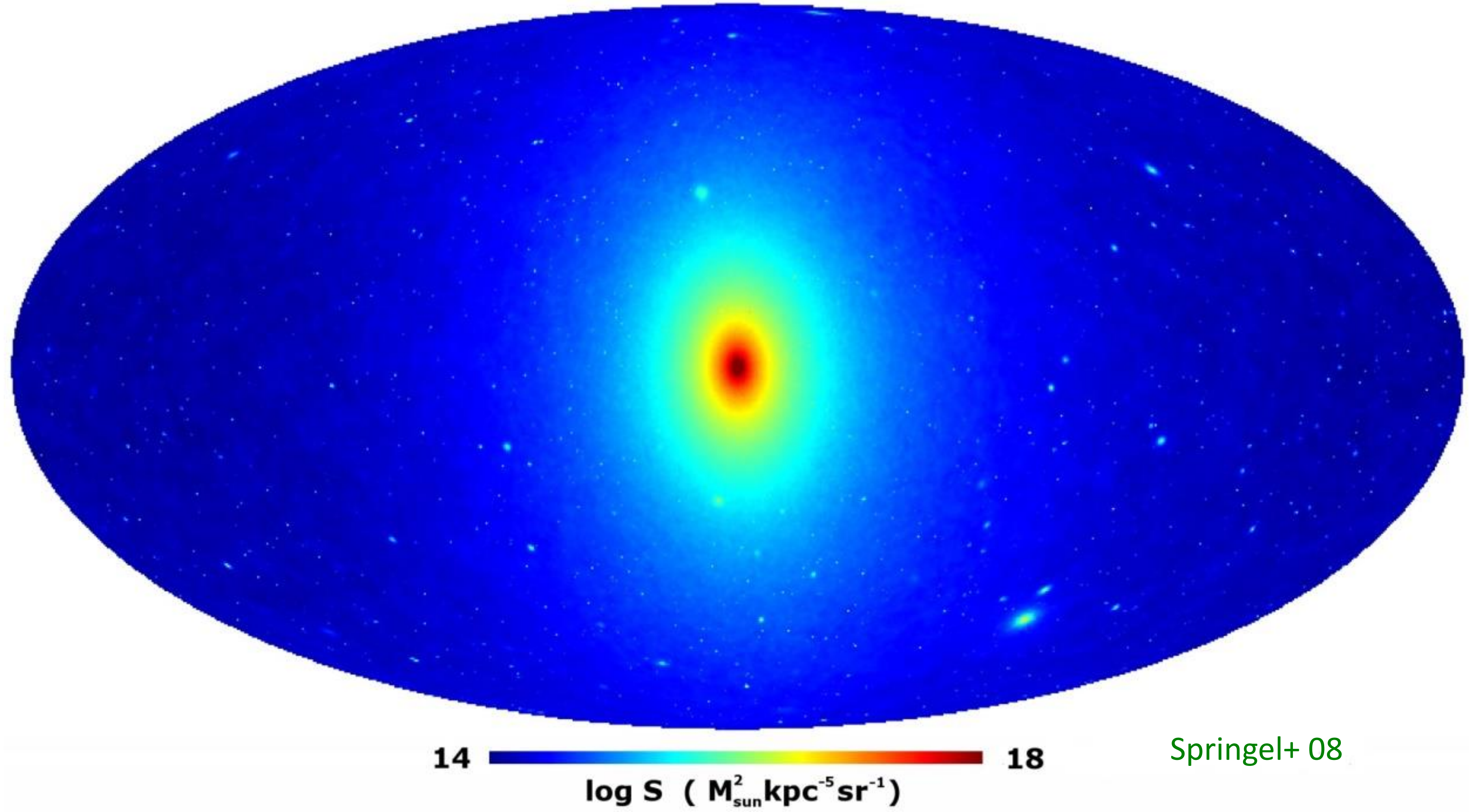
⇒ **assuming homogeneous B, B > 10^{-15}G**

Neronov & Vovk (10), Tavecchio et al. (10)

Note: constraint assumes steady source, if limited activity timescale T_s, $\delta t < T_s$ implies a weaker limit B > 10^{-17}G... (Dermer et al. 11, Taylor et al. 11)

1.c Motivations: dark matter in the Galactic center?

Sky map at very high energies with annihilating dark matter (w/o astrophysical foregrounds)



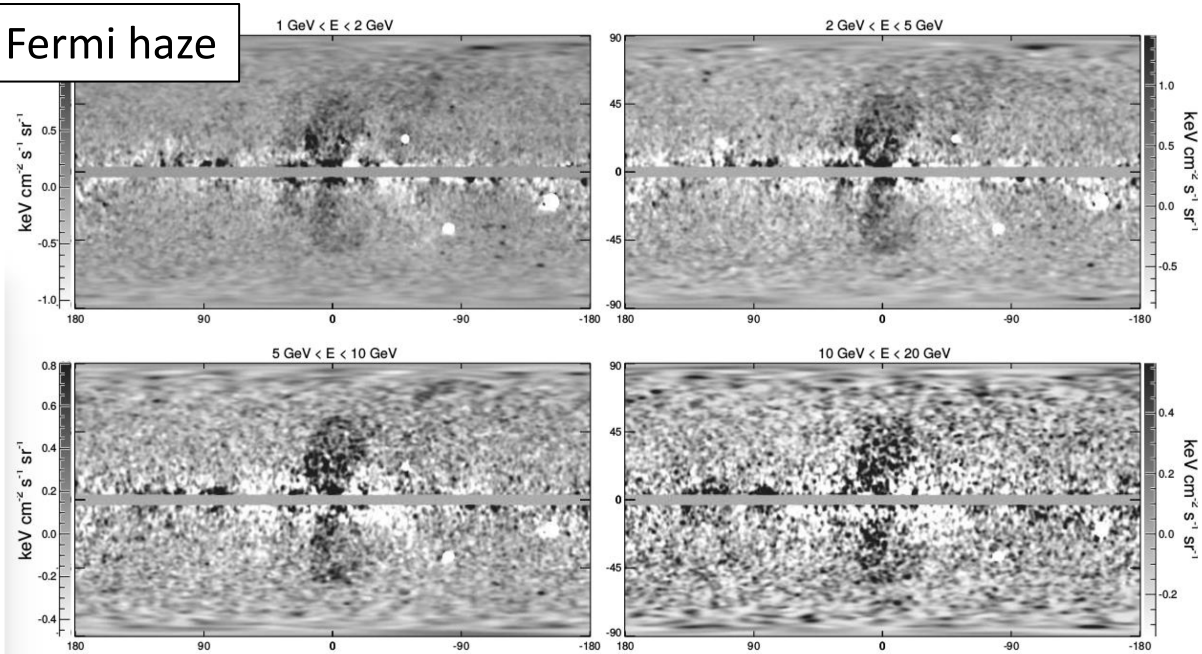
Springel+ 08

High energy photons, neutrinos and cosmic rays can be used to search for indirect signatures of dark matter annihilation, e.g. for photons:

$$\frac{\mathrm{d}I_\gamma}{\mathrm{d}E_\gamma} = \frac{\langle \sigma_{\chi\chi} v \rangle}{8\pi m_\chi^2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \int_{\mathrm{l.o.s}} \mathrm{d}s \, \rho_\chi^2$$

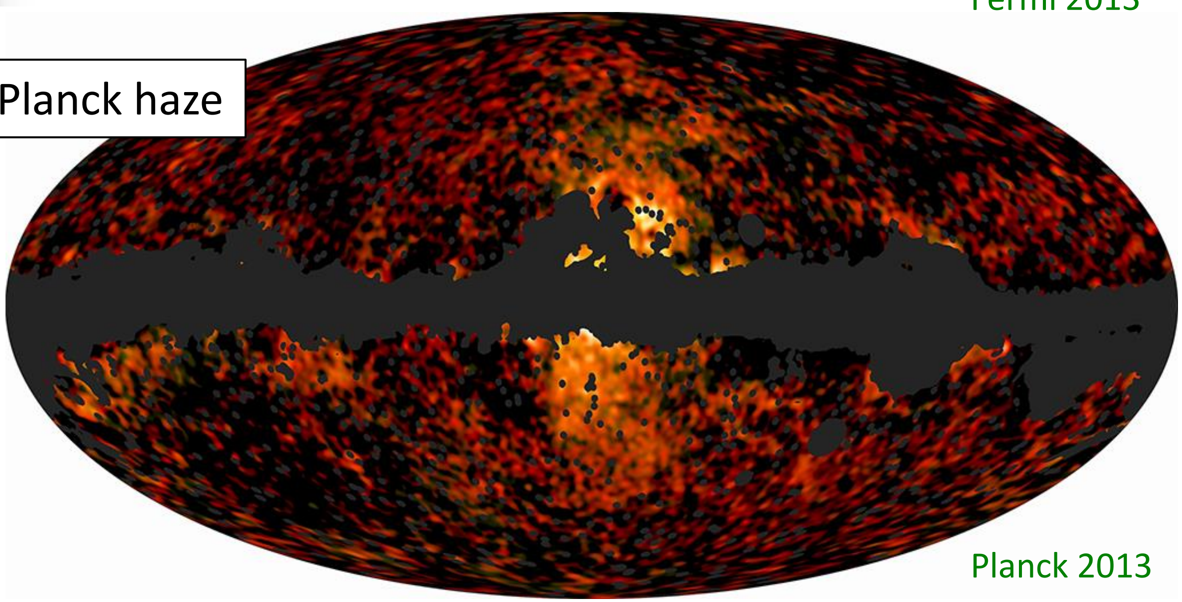
1.c Motivations: dark matter in the Galactic center?

Fermi haze



Fermi 2013

Planck haze

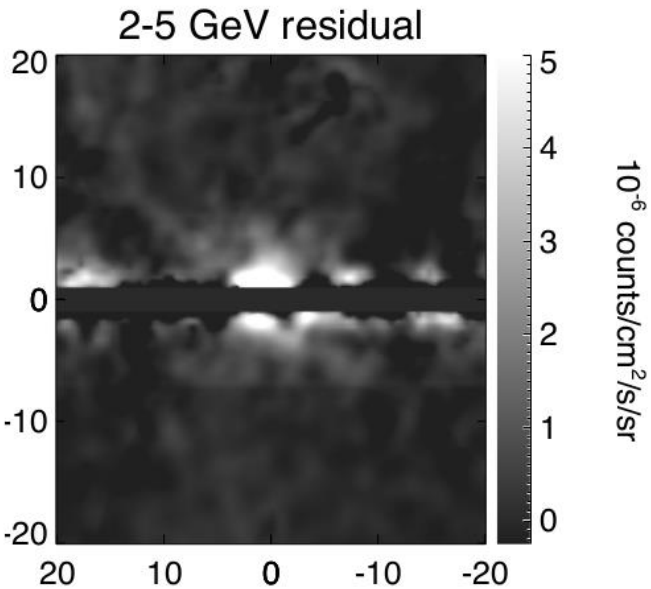


Planck 2013

likely origin:

- Planck: synchrotron emission of accelerated electrons
- Fermi: inverse Compton on CMB of electrons…

1.c Motivations: dark matter in the Galactic center?



recently, a GeV excess has been detected in the Galactic center, with an (interesting) spherical morphology extending over 10deg… Hooper+ 08

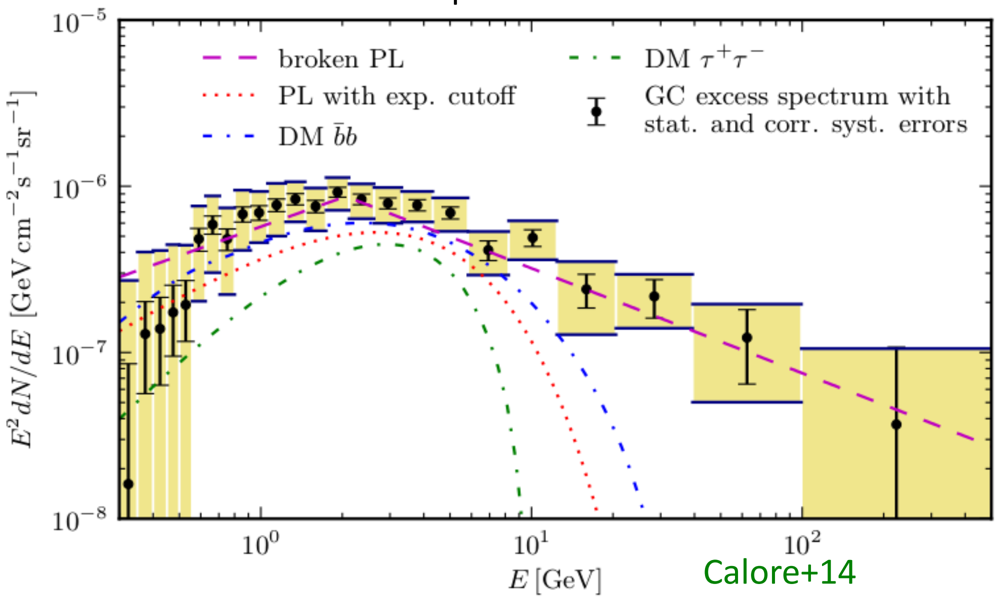
… interestingly, the level of emission is compatible with standard halo models of dark matter, and with the canonical annihilation rate $3\text{x}10^{-26}$ cm^3/s…

$$\Omega_\chi \sim \frac{10^{-26}\,\mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\chi\chi} v \rangle}$$

… however, extraction of astrophysical foregrounds in the Galactic center is complex!

1.c Motivations: dark matter in the Galactic center?

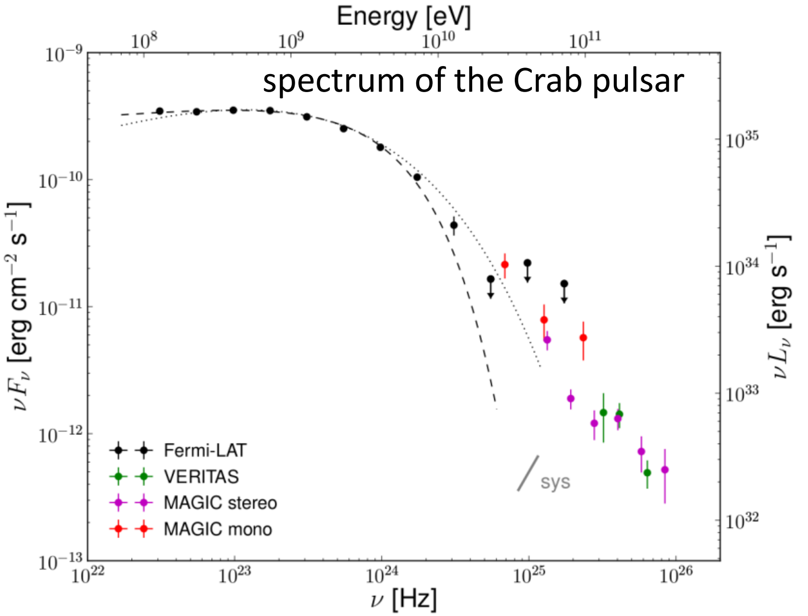
reconstructed spectrum of the GeV excess



Calore+14

Dark matter annihilation nicely matches the flux and the morphology, but fails to account for the power-law behavior…

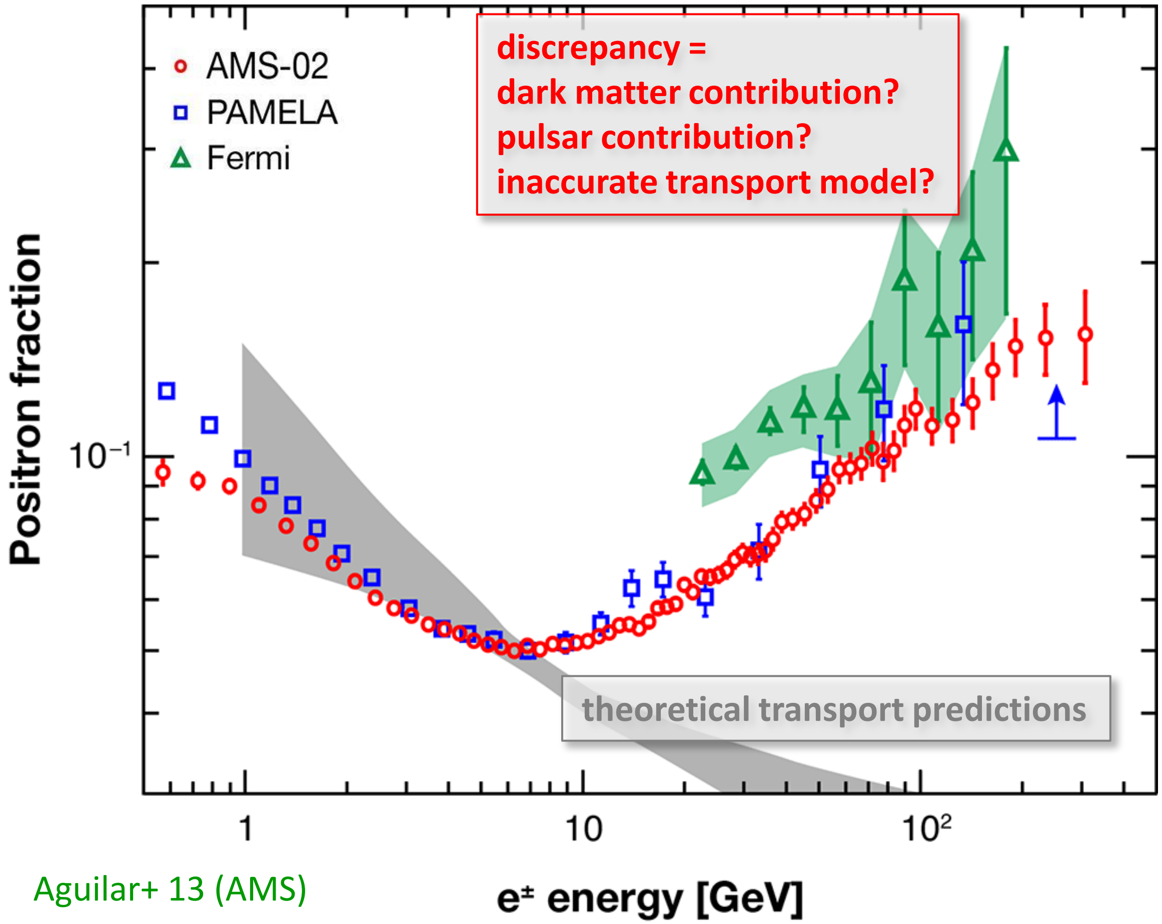
the reconstructed spectrum of the GeV excess nicely matches that of millisecond pulsars, which abound in the Galactic center… however, the morphology of the signal remains debated…



⇒ no conclusive evidence for dark matter…

1.c Motivations: dark matter signatures in cosmic rays?

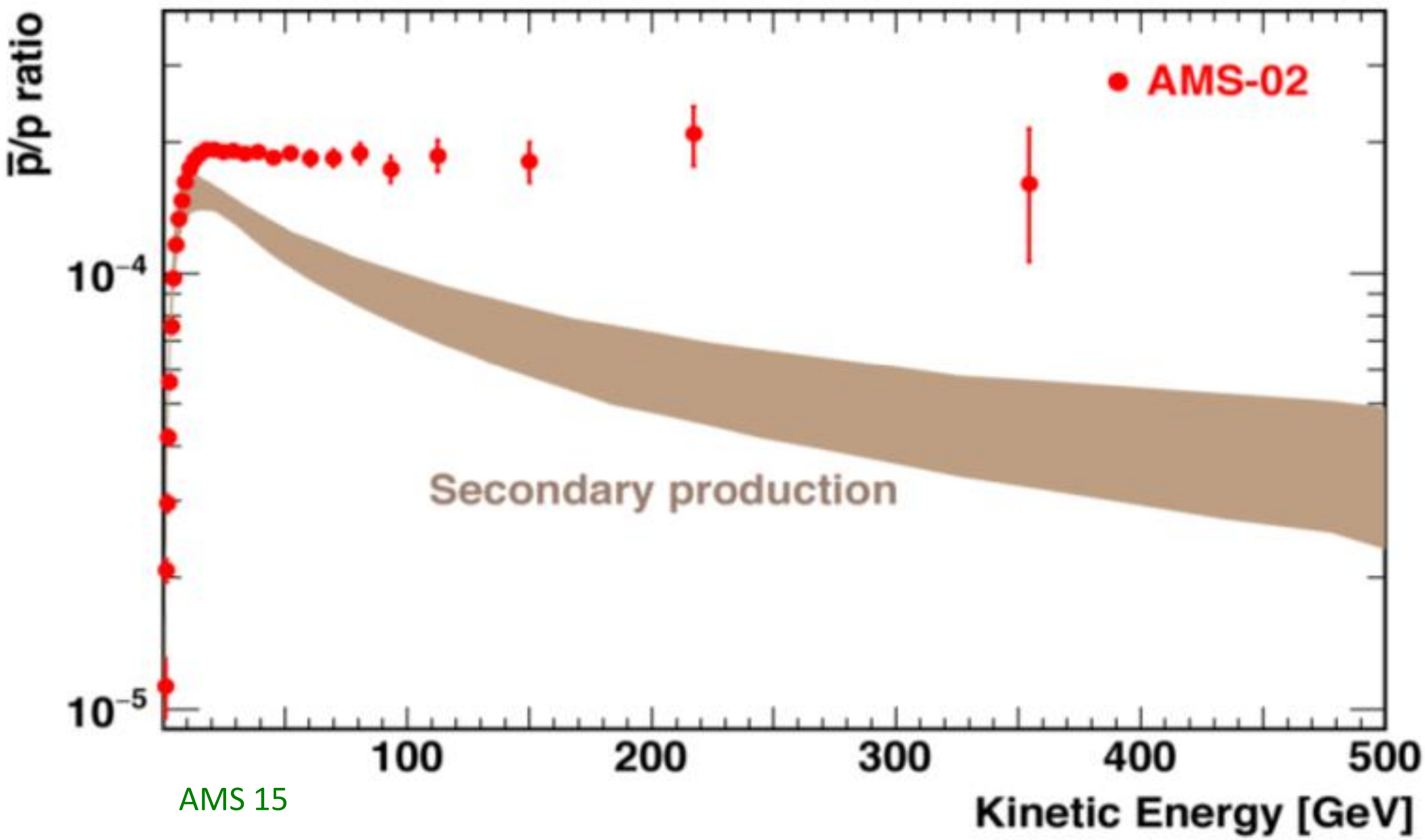
Recent data of cosmic-ray anti-matter has been claimed to present an excess, which might constitute an indirect signature of dark matter annihilation…



Aguilar+ 13 (AMS)

1.c Motivations: dark matter signatures in cosmic rays?

In the anti-proton sector of cosmic rays, the most recent AMS data has also been claimed to be in excess of standard expectations: needs for an exotic source?



AMS 15

Summary

1. Overview: the CR-γ-ν connection and motivations

   a. Introduction: detection and experimental facilities…

   … Cosmic rays are seen from GeV to 10^{20} eV, photons up to 100TeV and now neutrinos with PeV energies: a new window on the extreme Universe

   b. The CR-γ-ν connection

   … Charged leptons generically produce high energy photons through inverse Compton (or synchrotron etc.) interactions
   … Charged hadrons produce photons and neutrinos in similar proportions through hadronic pp or pgamma interactions: opens a connection between photons, neutrinos and cosmic rays which can be used to probe the inner engines of cosmic ray sources
   … application: the Waxman-Bahcall bound connects PeV neutrinos to UHECRs

   c. Motivations: extreme astrophysics, fundamental physics, dark matter physics etc.

   … VHE photons, neutrinos and cosmic rays are useful probes of extreme astrophysics (highly relativistic outflows, compact objects, powerful sources etc.), of fundamental physics (e.g. Lorentz invariance violation), and of dark matter annihilation

Outline

1. Overview: the CR-γ-ν connection and motivations

    a. Introduction: detection and experimental facilities…
    b. The CR-γ-ν connection
    c. Motivations: extreme astrophysics, fundamental physics, dark matter physics etc.

2. Beyond PeV: the extreme energy frontier

    a. The ultra-high energy cosmic ray enigma
    b. A prototype source: gamma-ray burst
    c. Connection with neutrinos and photons

3. Astroparticle physics in the GeV – PeV range

    a. Supernovae as cosmic ray sources
    b. Connection to the origin of Ice Cube neutrinos
    c. Transport of cosmic rays and the anti-matter ‘anomalies’

2.a UHECR: the enigma of extreme energies

World record (1993, Fly's Eye) : **E $\sim 3 \pm 0.6\ 10^{20}$ eV**

→ center of mass interaction energy (with atmosphere):

$$\sqrt{s} = \sqrt{2m_p c^2 (E + m_p c^2)} \simeq 800\,\mathrm{TeV}$$

… requires extrapolation of known hadronic physics!

→ energy: $E \simeq 48\,\mathrm{J}$ … macroscopic!

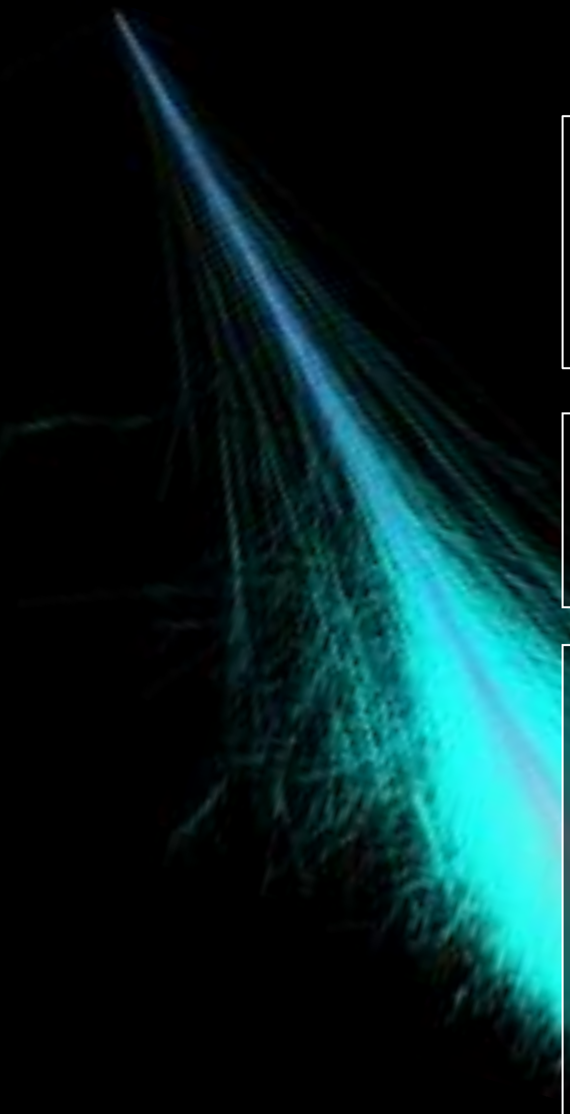
→ velocity:

$$\gamma = \frac{E}{m_p c^2} \simeq 3 \times 10^{11} \Rightarrow v = c\,(1-\epsilon)\ ,\ \epsilon \simeq 5\ 10^{-24}$$

Two main questions:

→ how (+ where) to accelerate particles to such extreme energies?

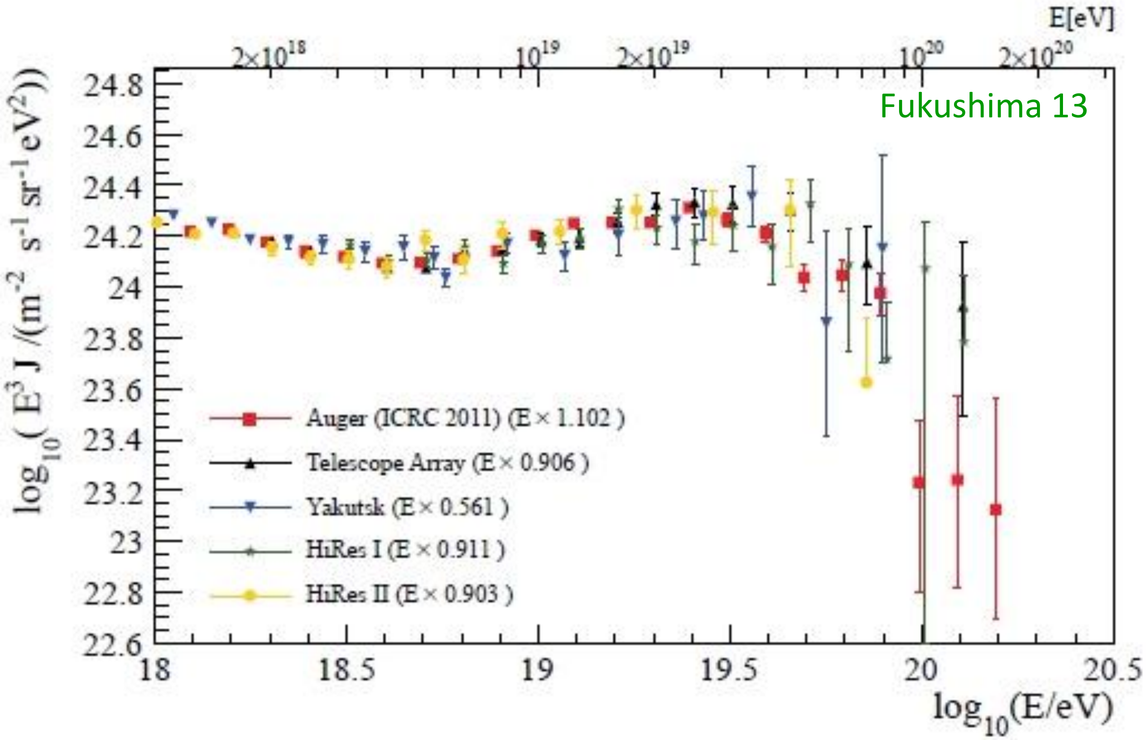
→ why do not we see (could we?) counterparts to arrival directions of the highest energy events?



10^{20}eV giant air shower:
a few km^2 on the ground!

2.a UHECR: the energy spectrum, with a cut-off

Diffuse spectrum of cosmic rays (xE^3) at the highest energies:



Greizen-Zatsepin-Kuzmin cut-off: the Universe becomes opaque to cosmic rays with E > 6 10^{19} eV because of pion production on the cosmic microwave background:

$$p + \gamma_{cmb} \rightarrow \pi + p/n$$

$\Rightarrow$ 10^{20} eV protons (or Fe nuclei) come from within ~ 100 Mpc…

… 10^{19} eV protons (Fe) come from within ~ 1 000 Mpc!

note: the observed cut-off may correspond to the maximal energy at the source...

2.a UHECR: cosmological spectrum

For a continuous distribution of sources, the spectrum can be calculated as follows:

$$\frac{\mathrm{d}n_{\mathrm{cr}}}{\mathrm{d}E} = \int_0^{t_0} \mathrm{d}t\, \frac{\mathrm{d}\dot{N}}{\mathrm{d}E_g}\, \frac{\mathrm{d}E_g}{\mathrm{d}E}\, n_{\mathrm{s}}$$

comoving density of CRs / E interval (=density today)

\# of CRs injected / E_g / time

comoving density of sources (= density today)

with: $E_g = E_g(t; E, t_0)$ injection energy at t such that E_g=E at t=t_0: accounts for energy losses

$$\frac{\mathrm{d}\dot{N}}{\mathrm{d}E_g} \sim \frac{L_{\mathrm{cr}}}{E_{\mathrm{min}}} \left(\frac{E}{E_{\mathrm{min}}}\right)^{-\gamma}$$

E_{min}: minimum E at source
γ ($\geq$2): injection index
L_{cr}: CR luminosity (ergs/s)

$$\frac{\mathrm{d}I_{\mathrm{cr}}}{\mathrm{d}E} = \frac{c}{4\pi} \frac{\mathrm{d}n_{\mathrm{cr}}}{\mathrm{d}E}$$

observed differential flux

Note:
- L_{cr} may depend on t
- n_s generally depends on t, e.g. / SFR (star formation rate)
  … higher by a few at z > 3-4…

2.a UHECR: Greisen – Zatsepin – Kuz'min cut-off

Greisen 66, Zatsepin & Kuzmin 66

→ threshold energy: p(γ,π)N reaction is permitted when

$$E'_\gamma \geq m_\pi c^2 \left(1 + \frac{m_\pi}{2m_p}\right)$$ in nucleus rest frame

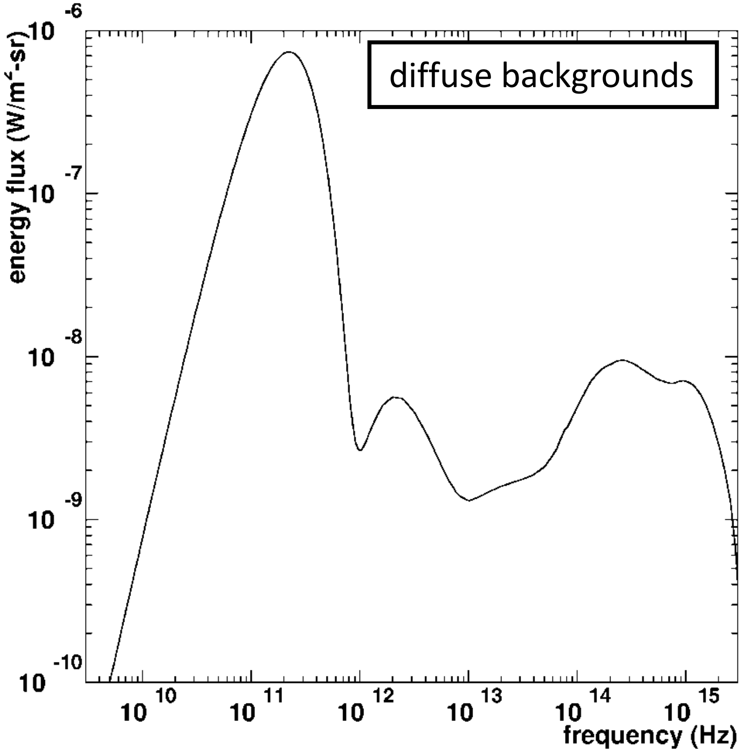
or, in the cosmic rest frame (frame where CMB is isotropic):

$$E_p \geq \frac{m_\pi \left(m_\pi + 2m_p\right) c^4}{2E_\gamma \left(1 - \cos\theta\right)} \sim 6 \times 10^{19}\,\mathrm{eV}$$ after folding over photon distr.

→ energy loss: $$\epsilon_{p\gamma} \equiv \frac{\Delta E_p}{E_p} \sim \frac{m_\pi}{m_p} \sim 0.15$$

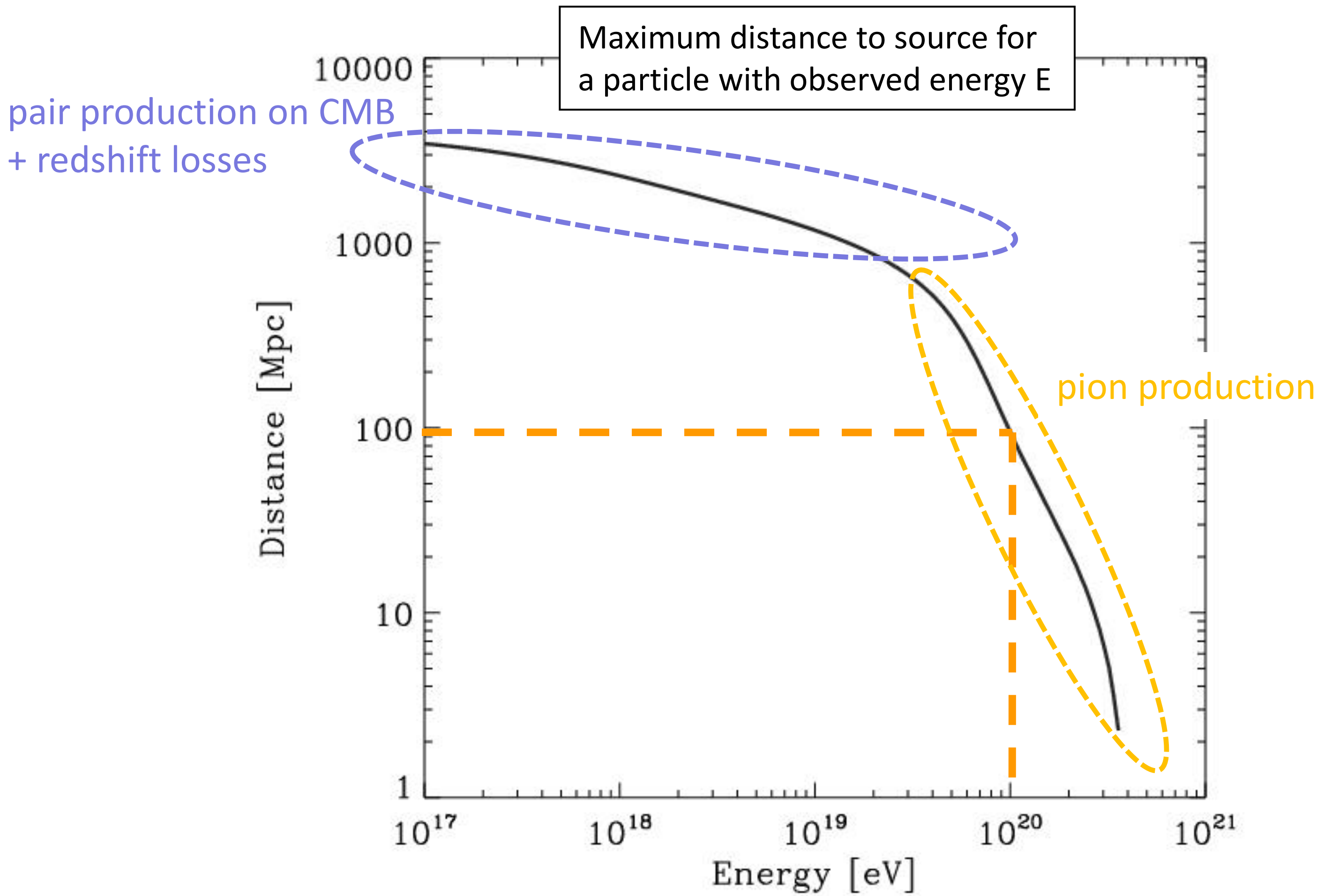
→ interaction length: $$\lambda_{p\gamma} \equiv \frac{1}{\langle n_\gamma \sigma_{p\gamma} \rangle} \sim 8\,\mathrm{Mpc}$$

→ energy loss distance: $$l_{\mathrm{loss}} \equiv \frac{\lambda_{p\gamma}}{\epsilon_{p\gamma}} \sim 50\,\mathrm{Mpc}$$



⇒ ***the Universe is opaque to protons with energy > 6 x 10^{19} eV !***

2.a UHECR: Maximum distance scale



<u>Consequence 1:</u> **> 10^{20} eV particles must lie within 100 Mpc**
> 4 10^{19} eV particles must lie within 1000 Mpc

<u>Consequence 2:</u> above 10^{19} eV, the cosmic ray lifetime decreases rapidly with energy…
recall: $$\frac{\mathrm{d}I_p}{\mathrm{d}E_p} \sim \frac{c}{4\pi}\tau_p \frac{\mathrm{d}\dot{n}_p}{\mathrm{d}E_p} \Rightarrow E_p^2 \frac{\mathrm{d}\dot{n}_{\rm CR}}{\mathrm{d}E_p} \sim 10^{44}\,\mathrm{erg/Mpc^3/yr}$$

2.a UHECR: main principles of acceleration

<u>Kinematics:</u>

→ Lorentz force: $$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = q\left(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}\right)$$

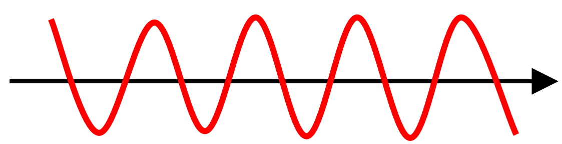
→ in astrophysical plasmas: **E** = 0 (generic) in the rest frame of the plasma…
(consequence of very large conductivity of plasmas)

→ in the lab reference frame, in which the plasmas moves with velocity $\mathbf{v_p}$:

$$\boldsymbol{E}_\perp = -\boldsymbol{v}_\mathbf{p} \times \boldsymbol{B}$$

<u>Consequence 1:</u> acceleration generically takes place in motional electric fields

<u>Consequence 2:</u> transport across B is necessary, which requires an external force



B uniform ⟺ particle confined in a cylinder of radius r_L

<u>Consequence 3:</u> typical acceleration timescale $t_{\rm acc} \simeq \left|\frac{1}{p}\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t}\right|^{-1} \simeq \frac{c}{v_{\rm p}} t_{\rm L}$

… in astrophysical sources, acceleration competes against losses and escape: reaching VHE requires a fast moving plasma!

2.a UHECR: main principles of acceleration

Kinematics:

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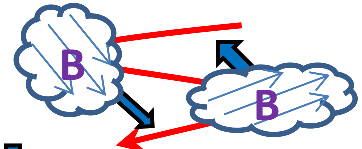
(consequence of very large conductivity of plasmas)

→ in the lab reference frame, in which the plasmas moves with velocity $\mathbf{v}_\mathbf{p}$:

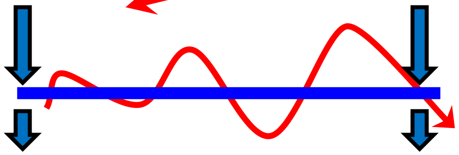
$$\boldsymbol{E}_\perp = -\boldsymbol{v}_\mathbf{p} \times \boldsymbol{B}$$

Examples:

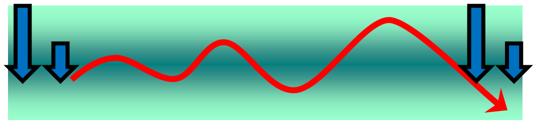
- turbulent Fermi acceleration



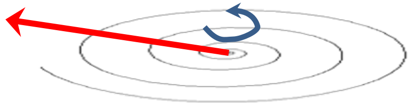
- Fermi acceleration at shock waves



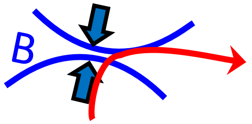
- acceleration in sheared velocity fields



- magnetized rotators



- reconnection



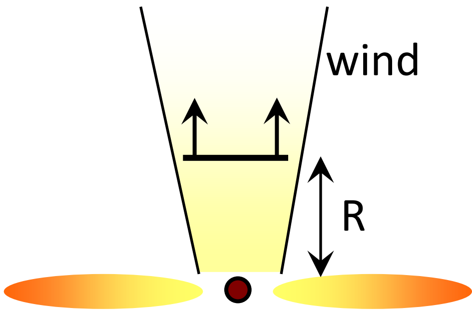
2.a UHECR: acceleration to UHE

The typical acceleration timescale can be used to constrain the source of ultra-high energy cosmic rays, e.g. consider acceleration in an outflow moving towards the observer, with

- acceleration timescale (comoving frame): $t_{\rm acc} = \mathcal{A}\, t_{\rm L}$

  A >> 1, A ~ 1 at most:

  - for non-relativistic Fermi I, $A \sim g/\beta_{sh}^2$ with $g > 1$



- time available for acceleration (comoving frame): $t_{\rm dyn} \approx \dfrac{R}{\beta\Gamma c}$
- maximal energy: $t_{\rm acc} \leq t_{\rm dyn} \Rightarrow E_{\rm obs} \leq \mathcal{A}^{-1} ZeBR/\beta$
- 'magnetic luminosity' of the source: $L_B = 2\pi R^2 \Theta^2 \dfrac{B^2}{8\pi}\Gamma^2\beta c$
- lower bound on total luminosity: $L_{\rm tot} \geq 0.65 \times 10^{45}\, \Theta^2\Gamma^2\mathcal{A}^2\beta^3 Z^{-2} E_{20}^2 \,{\rm erg/s}$

10^{45} ergs/s is robust: for $\beta \rightarrow 0$, $\mathcal{A}^2\beta^3 \geq 1/\beta \geq 1$

for $\Theta\Gamma \rightarrow 0$, $L_{\rm tot} \geq 1.2 \times 10^{45}\, \mathcal{A}\beta \dfrac{\kappa}{r_{\rm L} c} Z^{-2} E_{20}^2 \,{\rm erg/s}$

Lower limit on luminosity of the source: $L_{\rm tot} > 10^{45}\, Z^{-2}\, {\rm erg/s}$

low luminosity AGN: $L_{bol} < 10^{45}$ ergs/s

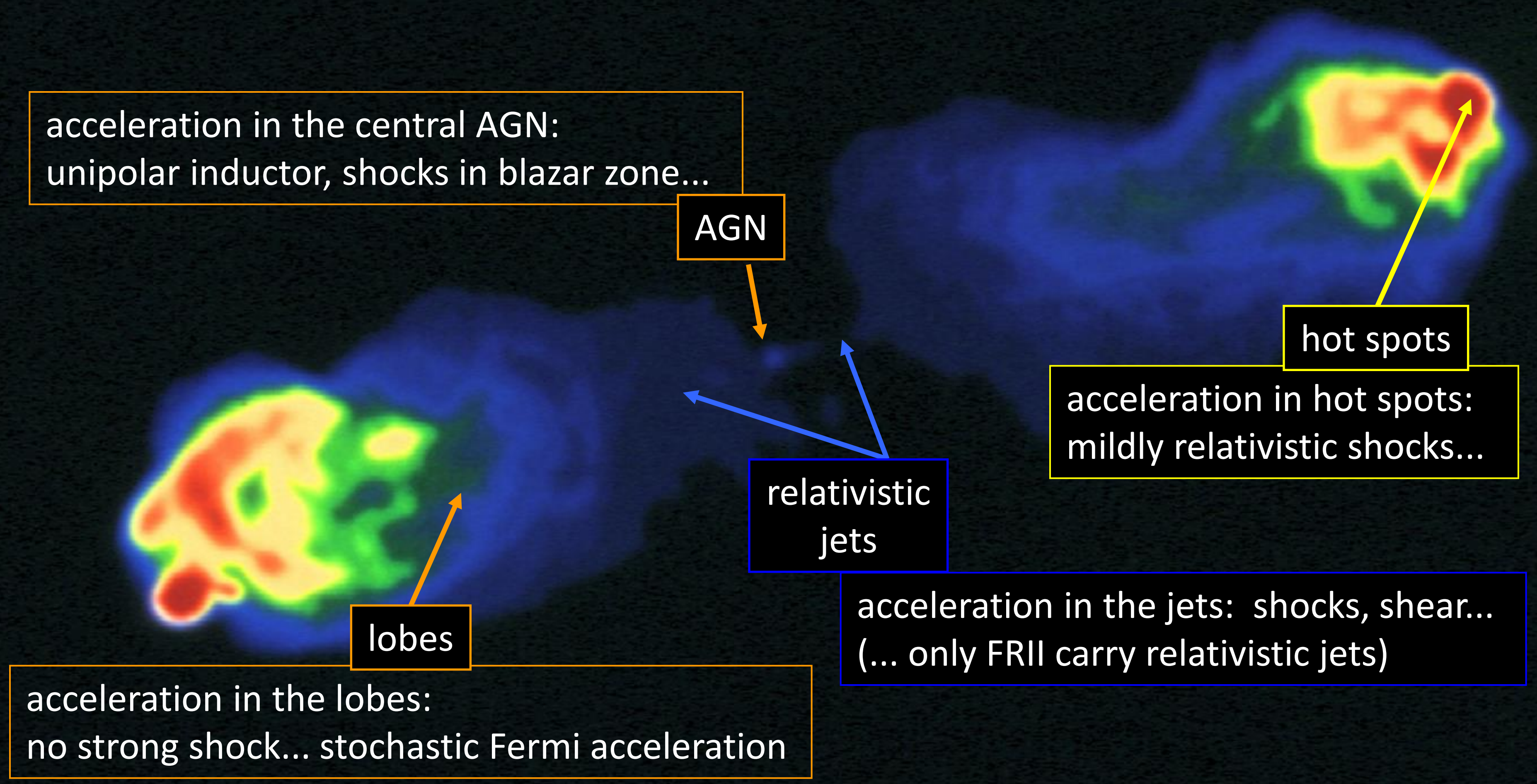
high luminosity AGN: $L_{bol} \sim 10^{46}$-10^{48} ergs/s

gamma-ray bursts: $L_{bol} \sim 10^{52}$ ergs/s

$\Rightarrow$ only most powerful AGN jets, gamma-ray bursts or very energetic pulsars for UHE protons...

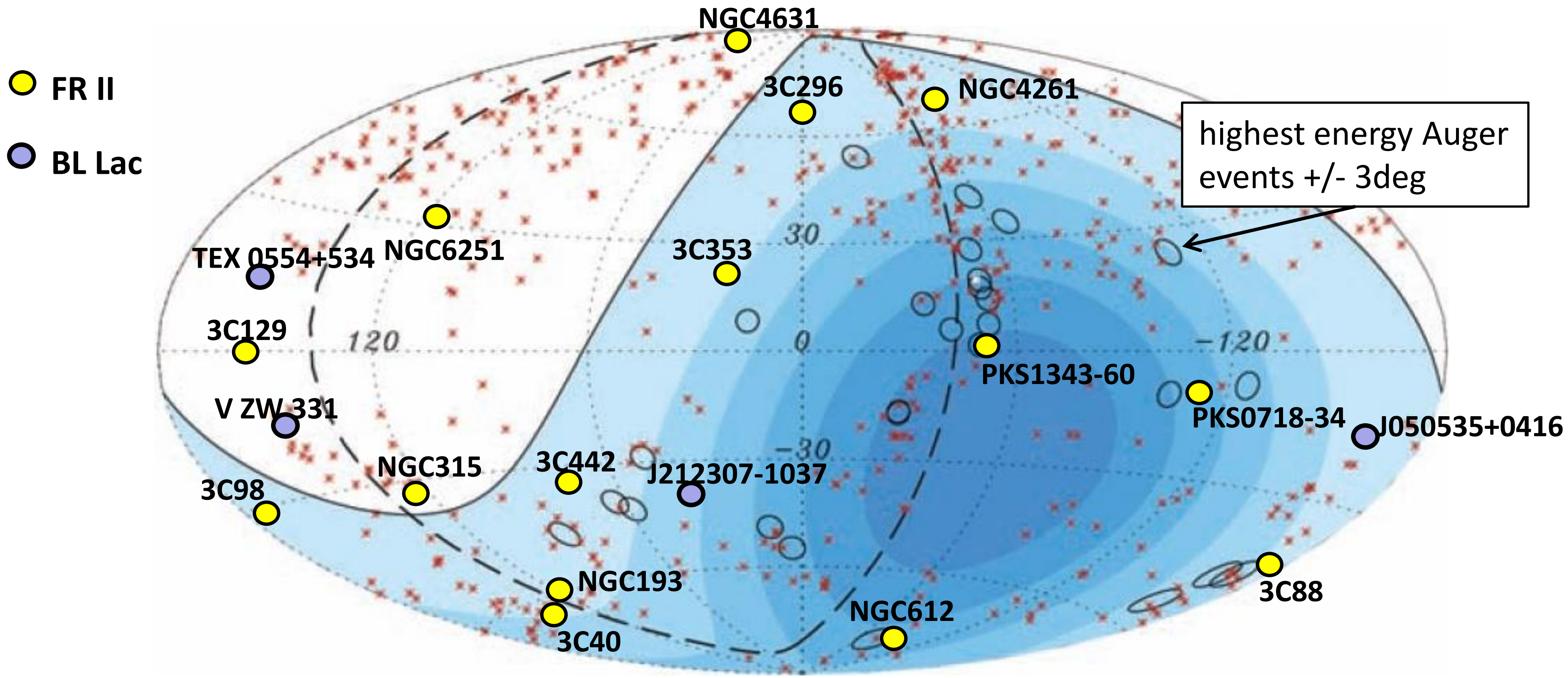
2.a UHECR: acceleration in giant radio-galaxies

Faranoff-Riley II radio-galaxy Cygnus A



2.a UHECR: arrival directions of Auger events

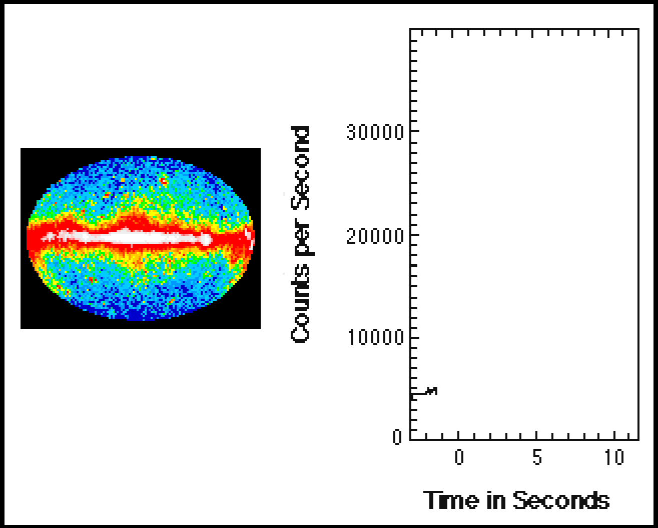
Distribution on the sky of FR-II galaxies located within 130Mpc:



... arrival directions do not point to most powerful giant-radio galaxies...

... interpretation: UHECRs are accelerated in sources which camouflage in galaxies (e.g. gamma-ray bursts), or angular deflection from the source is significant, because UHECRs are heavy nuclei?

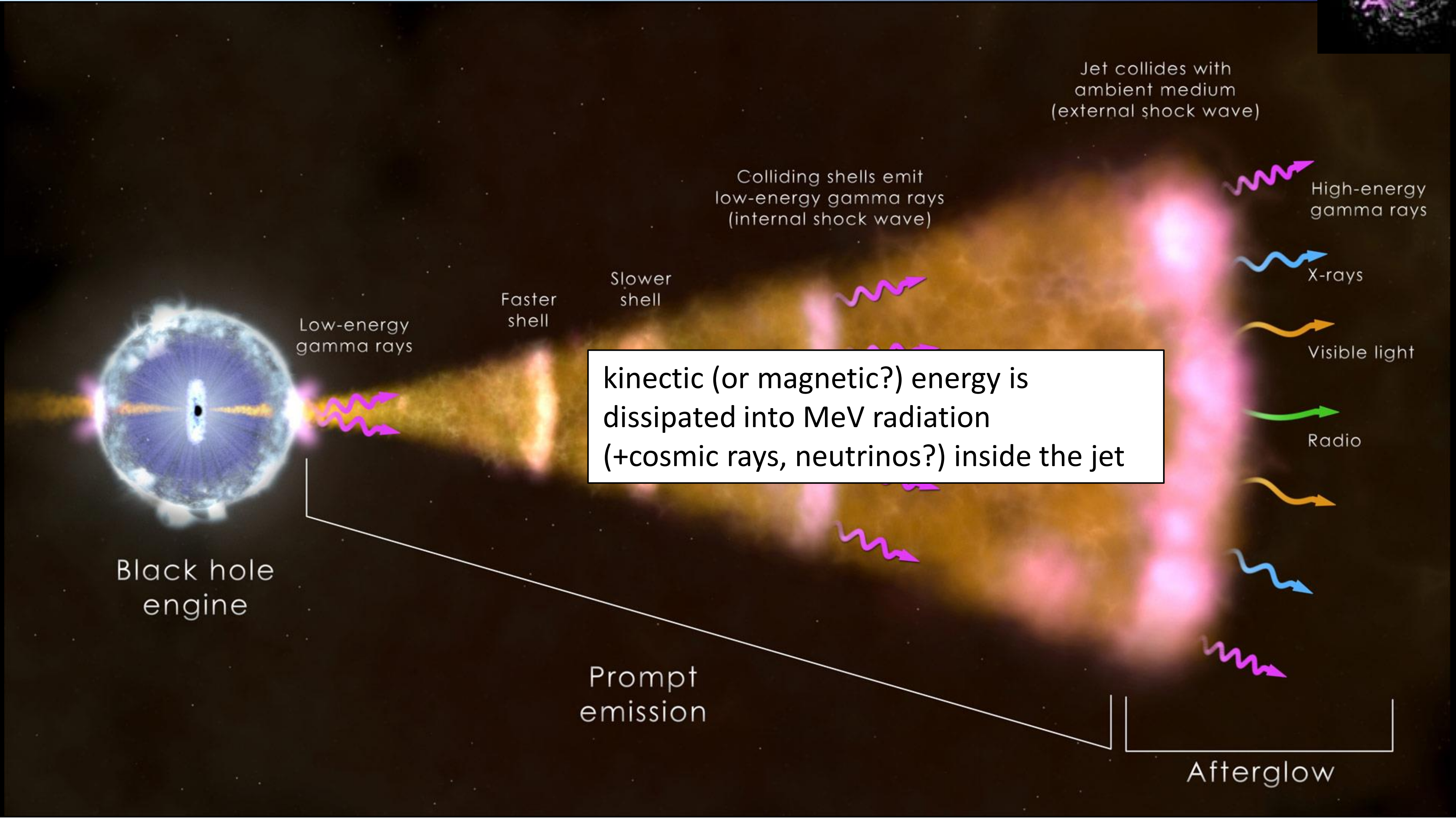
2.b A prototype model: gamma-ray bursts



Gamma-ray bursts: (in short)

- impulsive event, from <1sec to >1000sec
- compact (<10^{17} cm), ultra-relativistic ($\Gamma > 100$)
- tremendous energy release: about $0.01 M_{sun}\ c^2$
- associated with the collapse of giant stars or with the coalescence of neutron stars
- typical distance: radius of observable Universe

2.b A prototype model: gamma-ray bursts



kinectic (or magnetic?) energy is dissipated into MeV radiation (+cosmic rays, neutrinos?) inside the jet

Gamma-ray burst:

- output energy: $E \sim 10^{46}\,\mathrm{J}\,\frac{\Delta\Omega}{4\pi} \sim 0.1 M_\odot c^2 \frac{\Delta\Omega}{4\pi}$
- rate: $\dot{n} \sim 10^{-9}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$ in principle enough to match the flux of UHECRs!

2.b A prototype model: gamma-ray bursts

Fermi acceleration in mildly relativistic internal shocks: Waxman 95,01; Rachen & Meszaros 96

→ internal energy density: $u' = \epsilon_e^{-1} \dfrac{L_\gamma}{4\pi r^2 \Gamma^2 c}$ (assumes fast conversion of fraction $\varepsilon_e \sim 0.1$ of u into gamma-rays)

→ magnetic field: $B' = \sqrt{8\pi\epsilon_B u'}$ **($\varepsilon_B \sim 0.1$ assumes build-up of B through instabilities… to match obs. flux)**

→ acceleration timescale: $t_{\rm acc} \approx \mathcal{A}\, t_{\rm L}$ **(assumes ~ Bohm scaling in mildly relativistic shocks)**

→ age constraint: $t_{\rm acc} < \dfrac{r}{\Gamma c} \Rightarrow E_{\rm obs,20} \lesssim 7 \times \epsilon_{B,-1}^{1/2}\epsilon_{e,-1}^{-1/2}\Gamma_{2.5}L_{\gamma,52}^{1/2}\mathcal{A}^{-1}$

→ synchrotron losses: $t_{\rm acc} < t_{\rm syn}(E) \Rightarrow E_{\rm obs,20} \lesssim r_{12}^{1/3}\Gamma_{2.5}^{2/3}\mathcal{A}^{-2/3}$

(when combined with former bound)

⇒ acceleration to ~ 10^{20} eV if dissipation takes place at radii > 10^{12}cm… as expected from observations

→ photo-pion production: $t_{\gamma\pi}^{-1} = \dfrac{c}{2\gamma_p^2}\displaystyle\int_{\epsilon_{\rm th}}^{+\infty} {\rm d}\epsilon\, \sigma_{\gamma\pi}\epsilon\xi_{\gamma\pi} \int_{\epsilon/2\gamma_p}^{+\infty} {\rm d}\epsilon_\gamma\, \epsilon_\gamma^{-2}\dfrac{{\rm d}n_\gamma}{{\rm d}\epsilon_\gamma}$

$$\Rightarrow \frac{r/(\Gamma c)}{t_{\rm pi}} \sim \frac{L_{\gamma,52}}{\Gamma_{2.5}^4\Delta t_{-2}}$$

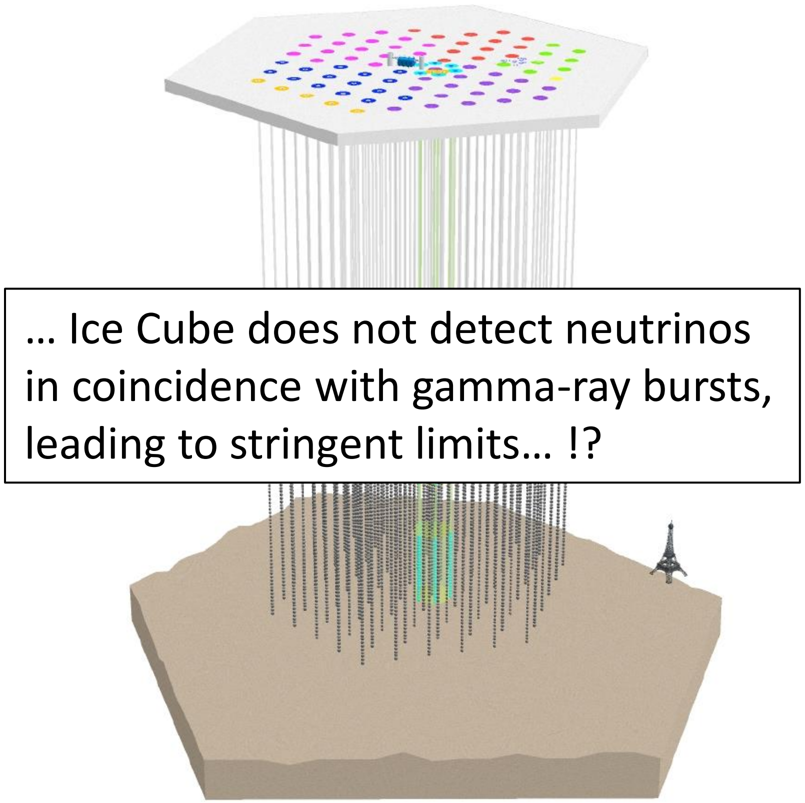
suggests that protons can escape the flow, avoid adiabatic losses, through conversion to n in γ-π reactions, leading to a neutrino signal with $E_\nu \sim E_{\rm UHECR}$

2.b A prototype model: connection to neutrinos!

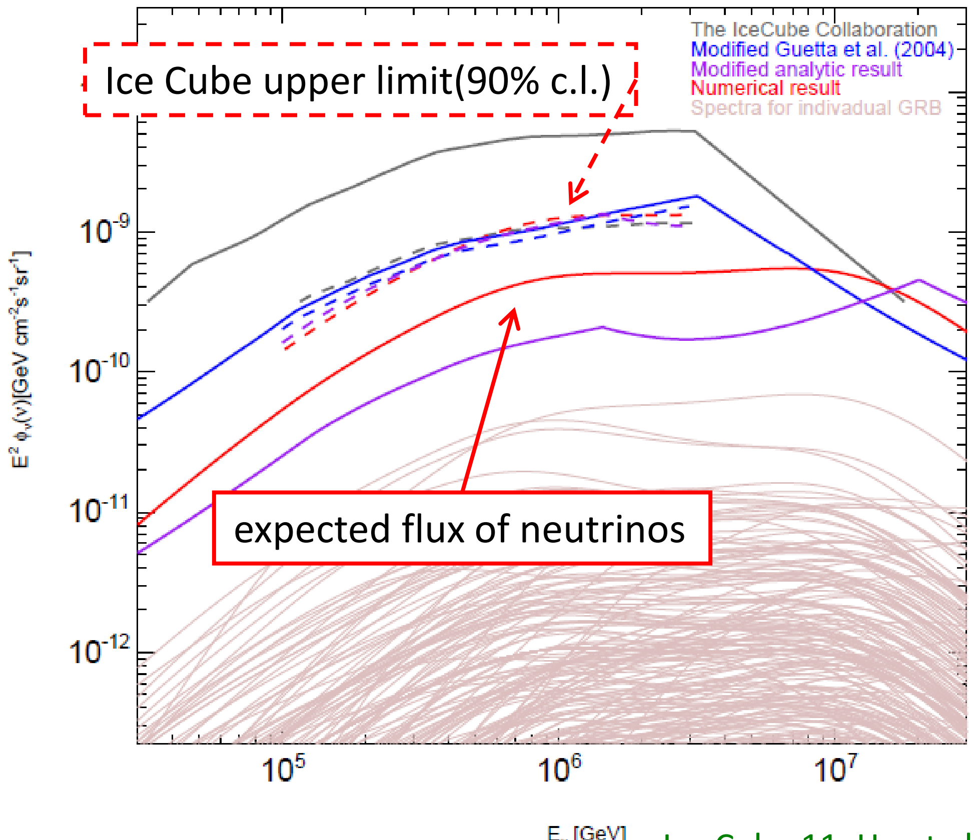
Neutrino production:

→ the energy lost in pion production through photo-hadronic interactions is close to unity for the Waxman 95 model

→ predicts a neutrino flux at energies >PeV, close to the Waxman-Bahcall limit:

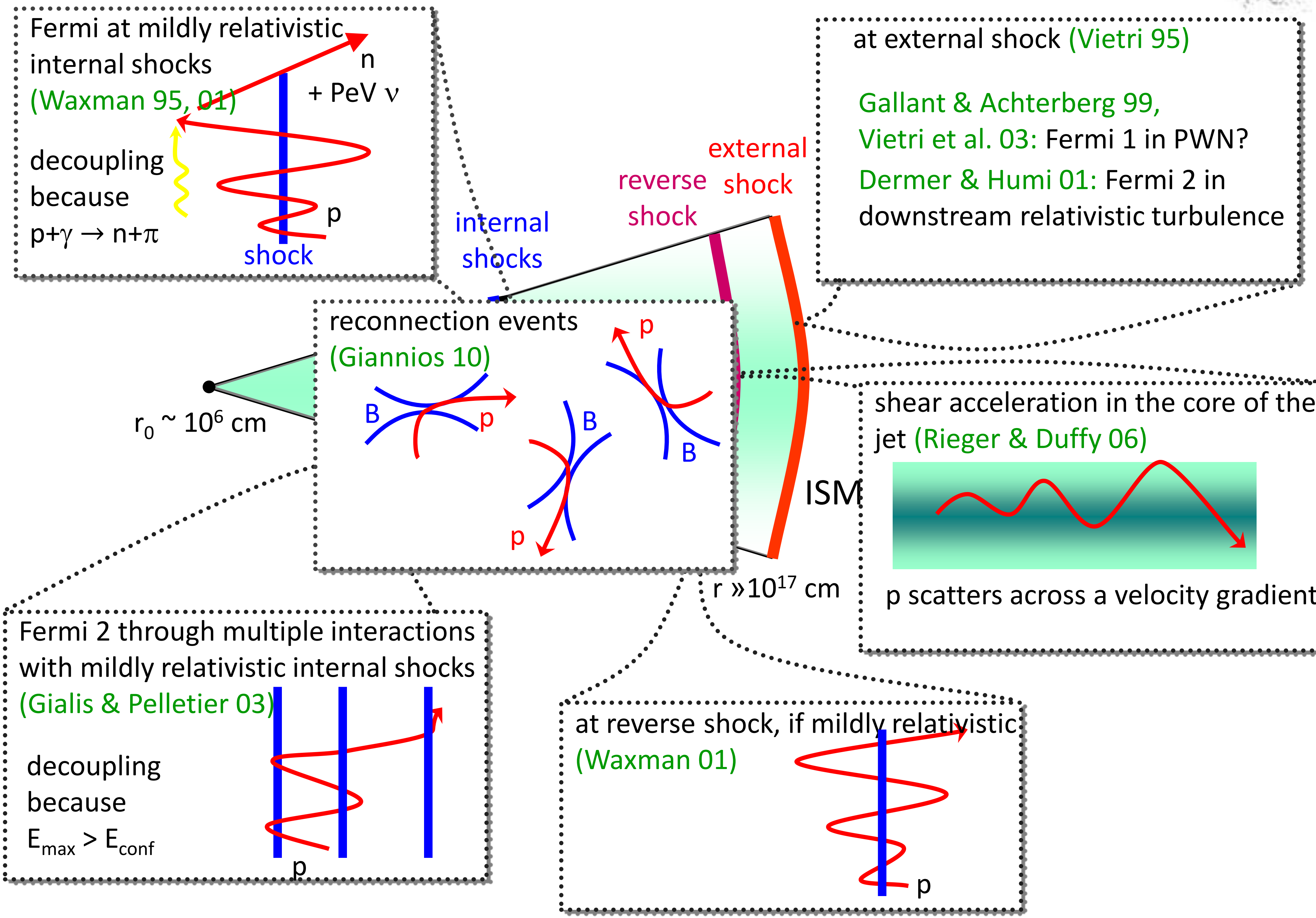


Ice Cube



Ice Cube 11, He et al. 12

2.b A prototype model: acceleration scenarios



2.b A prototype model: gamma-ray bursts

Summary:

→ acceleration in internal shocks may lead to a neutrino signal at the Waxman-Bahcall limit, now probed by Ice Cube... detection of PeV neutrinos would imply acceleration of p to >10^{17} eV... absence of detection would not rule out acceleration to UHE... as other acceleration scenarios can be envisaged...

→ radiative signatures of proton acceleration to ultra-high energies? (Asano et al. 09, 10, Razzaque et al. 10)

→ a 'difficulty' for GRB model is production rate:

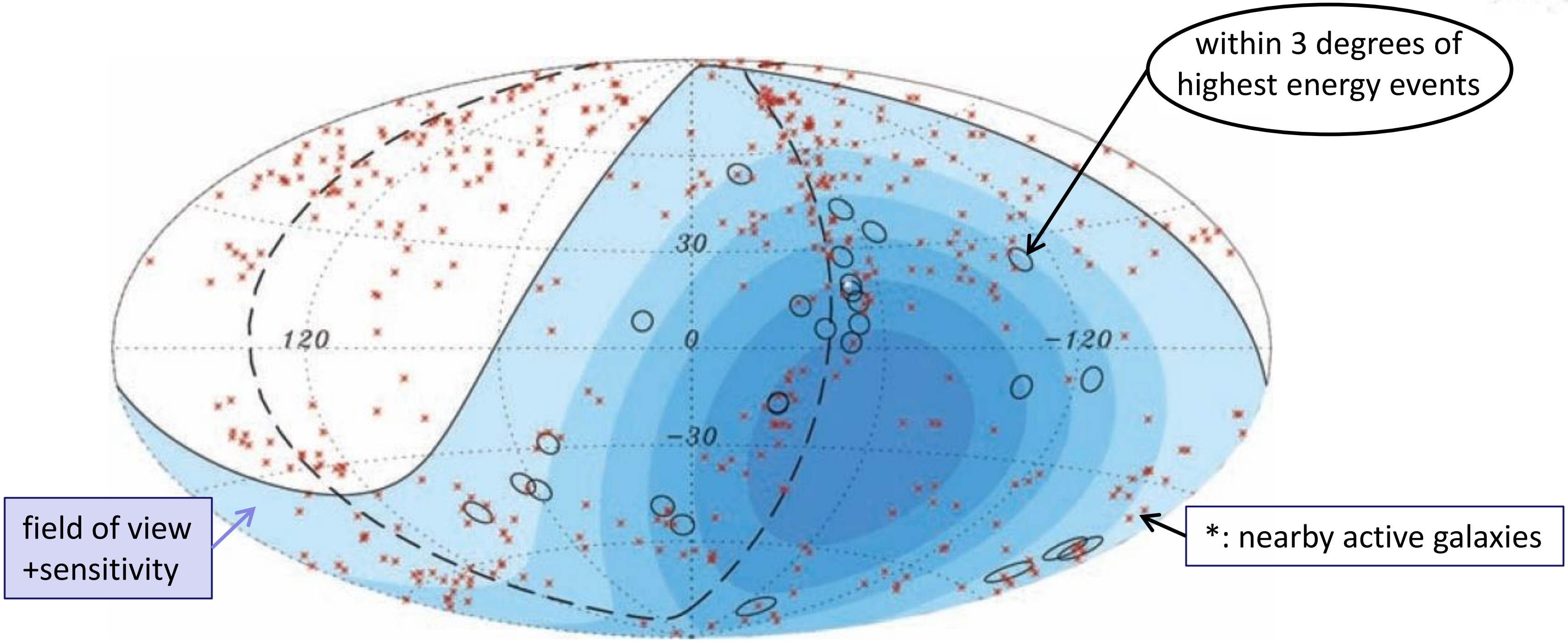
flux of UHECR above 10^{19} eV requires an energy input rate: $\sim 10^{44}$ erg/Mpc^3/yr

with a GRB rate $\dot{n}_{\rm GRB}$ this requires: $E_{\rm UHECR/GRB} \approx 10^{53}\,{\rm erg}\left(\frac{\dot{n}_{\rm GRB}}{1\,{\rm Gpc}^{-3}{\rm yr}^{-1}}\right)^{-1}$

i.e., $E_{\rm UHECR/GRB} / E_{\gamma/\rm GRB} \sim 10$ - ...? (Eichler & Pohl 11, Waxman 11)

→ do not expect association of UHECRs with observed GRBs! Time delay imparted by extra-galactic magnetic fields: $\delta t \sim 10^4$-10^5 yr ... (Waxman & Miralda-Escude 96)

2.c ν and γ from UHECRs: possible anisotropies



Pierre Auger Collaboration, Science 2007

… Anisotropies are seen, but at 95% confidence level only…

… interpretation: a mixture of light and heavy nuclei? intergalactic magnetic fields?

… no obvious counterpart in photons…

2.c ν and γ from UHECRs: expected angular deflection

The expected angular deflection increases rapidly with decreasing energy, because of decreasing magnetic rigidity and increasing source distance scale…

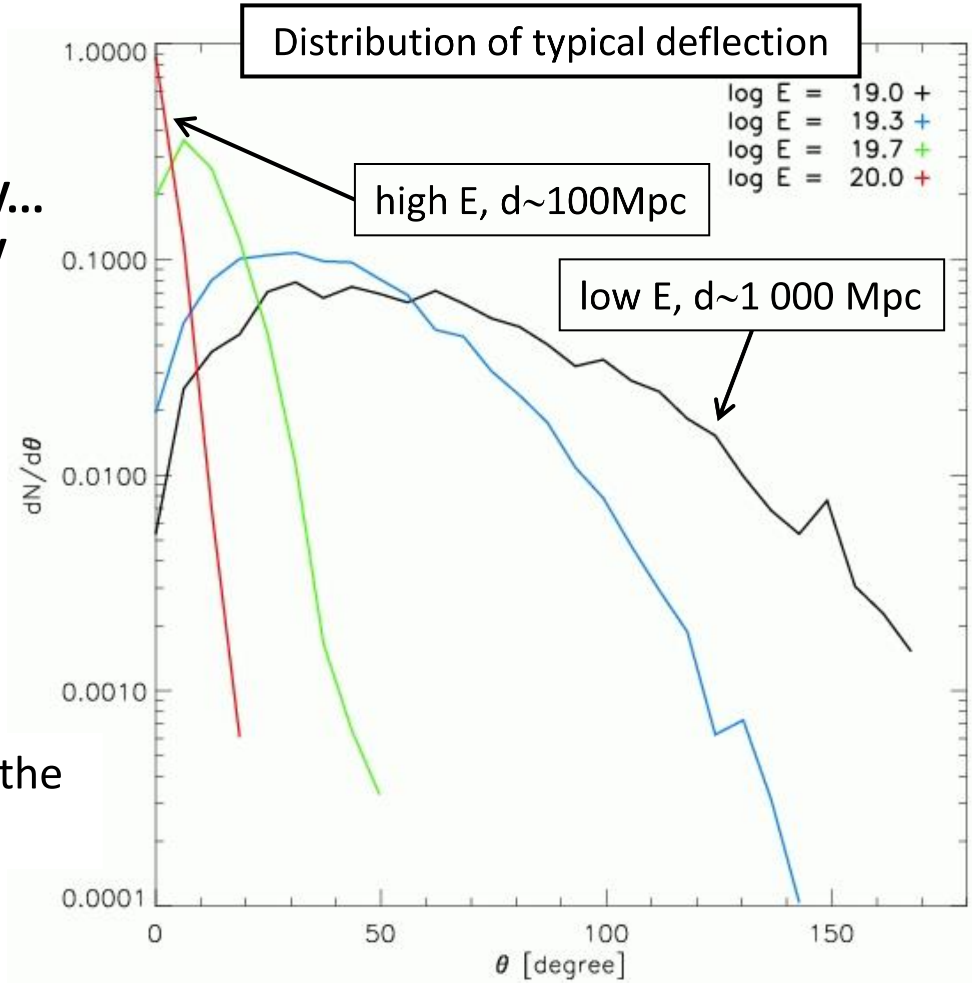
→ note that most of the flux comes from $l_{max}(E)$

$$F(<l) = \int_{r\leq l} \mathrm{d}^3 r\, n_{\mathrm{source}} \frac{\dot{N}_{\mathrm{UHECR}}}{4\pi r^2} = n_{\mathrm{source}} \dot{N}_{\mathrm{UHECR}}\, l$$

implies: near isotropy for E < 3 10^{19}Z eV...
... and small deflection above 5 10^{19}Z eV

… a few degrees for protons at 10^{20}eV (… Z times more for heavy nuclei of charge Z)

⇒ expect and search for anisotropies at the highest energies… if protons!



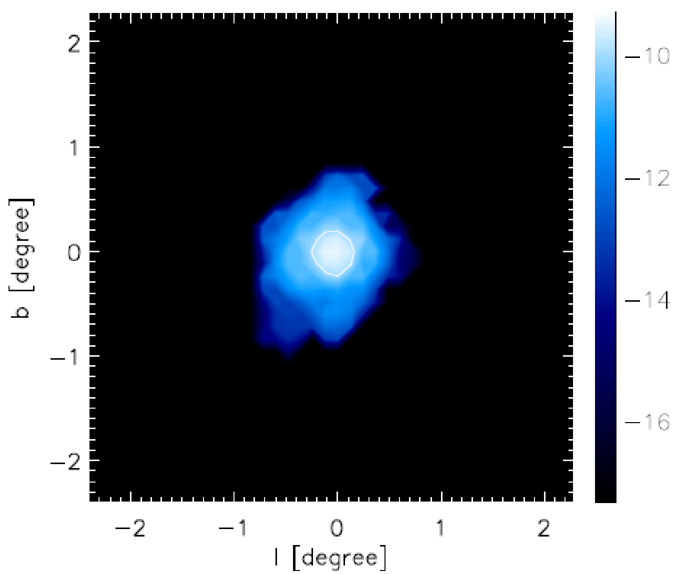
2.c ν and γ from UHECRs: High energy gamma-rays

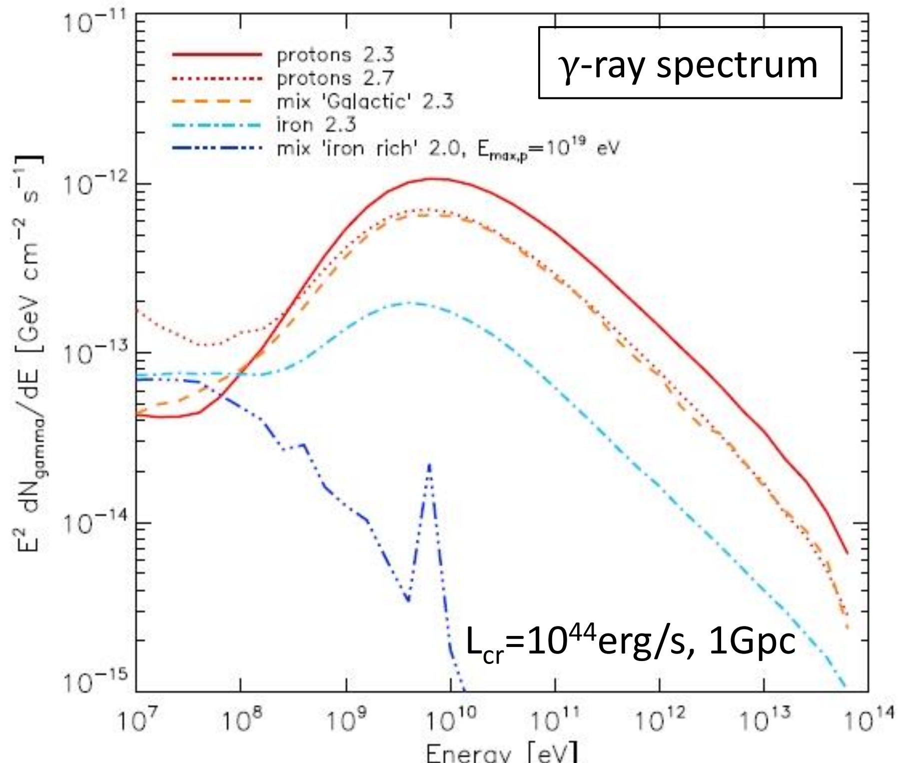
In optimistic cases, counterparts in very high energy gamma-rays could be seen through the electromagnetic cascades seeded in the environment of the source by UHECRs, e.g.

$$p + \gamma_{\rm CMB} \rightarrow p + e^- + e^+$$
$$e + \gamma_{\rm CMB} \rightarrow \text{e.m. cascade}$$

→ detection with upcoming instruments requires a huge CR luminosity above 10^{19}eV: $L_{cr} \sim 10^{46}$ erg/s for a distance 1Gpc...

note: halo ⇔ smoking gun
signature of p acceleration to $>10^{19}$eV





Aharonian 02, Gabici & Aharonian 05, Kotera et al.11, Essey et al. 10,11

2.c ν and γ from UHECRs: GZK neutrinos spectra

Secondary neutrinos are expected at UHE as a consequence of pion production on the CMB:

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}E_\nu} = \frac{c}{4\pi}\int_0^{t_0}\mathrm{d}t\int_{E_{\rm GZK}}\mathrm{d}E_{\rm cr}\,\underbrace{\frac{\mathrm{d}\dot{N}_{\rm cr}}{\mathrm{d}E_{\rm cr}}\,n_{\rm s}}\,\frac{\mathrm{d}N_\nu}{\mathrm{d}N_{\rm cr}\mathrm{d}E_{\nu,z}}\,\frac{\mathrm{d}E_{\nu,z}}{\mathrm{d}E_\nu}$$

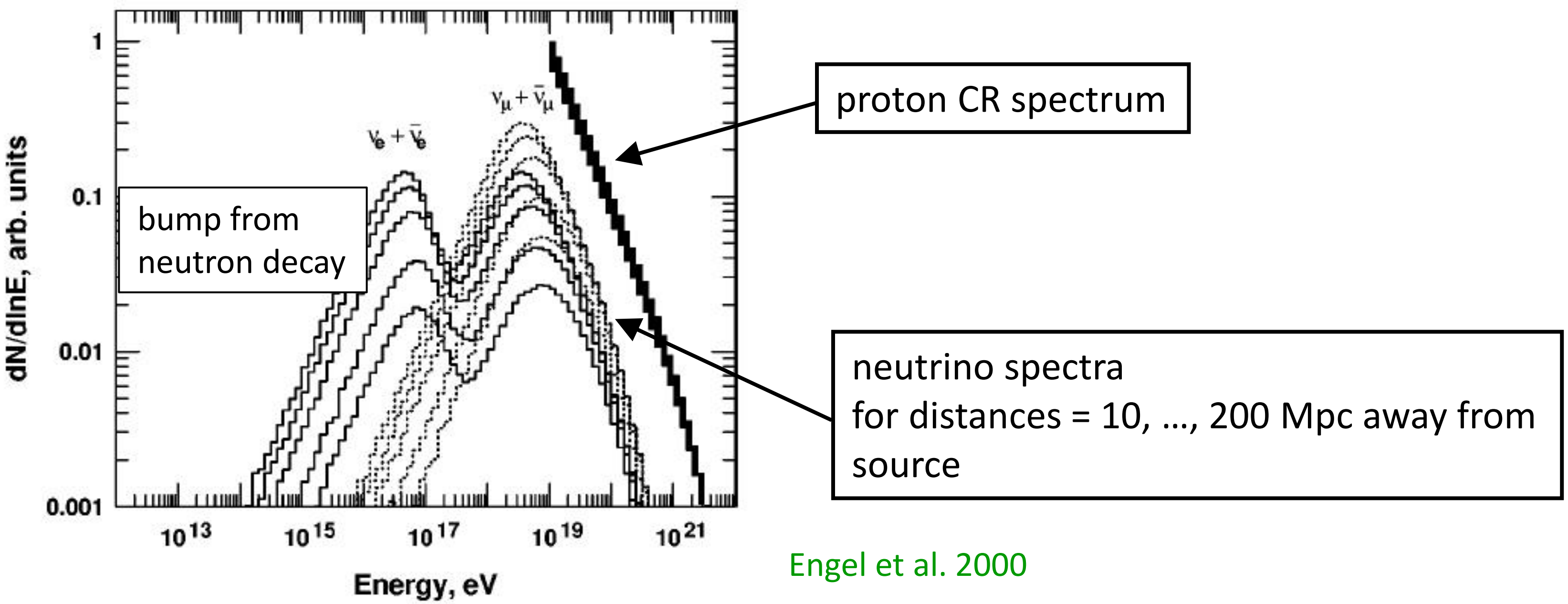
ν diff. flux

# of CRs injected per unit time and unit comoving volume

# of ν produced per unit CR per unit energy $E_{\nu,z}$

ν redshift loss

(nearly all GZK neutrinos are produced in immediate vicinity of source)

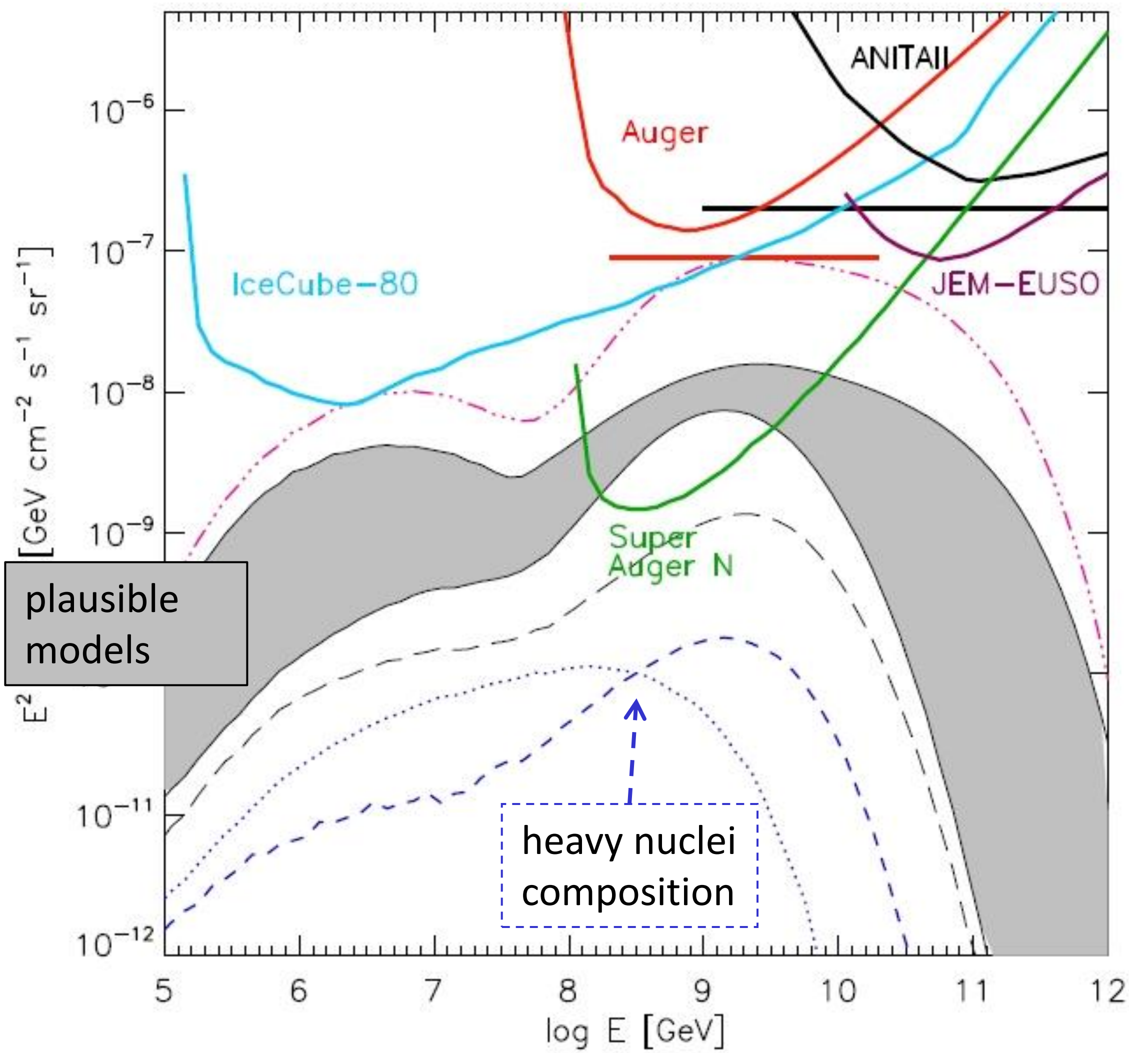


Engel et al. 2000

2.c ν and γ from UHECRs: GZK neutrino predictions

... The diffuse GZK neutrino (and photon) backgrounds are within reach of next generation experiments

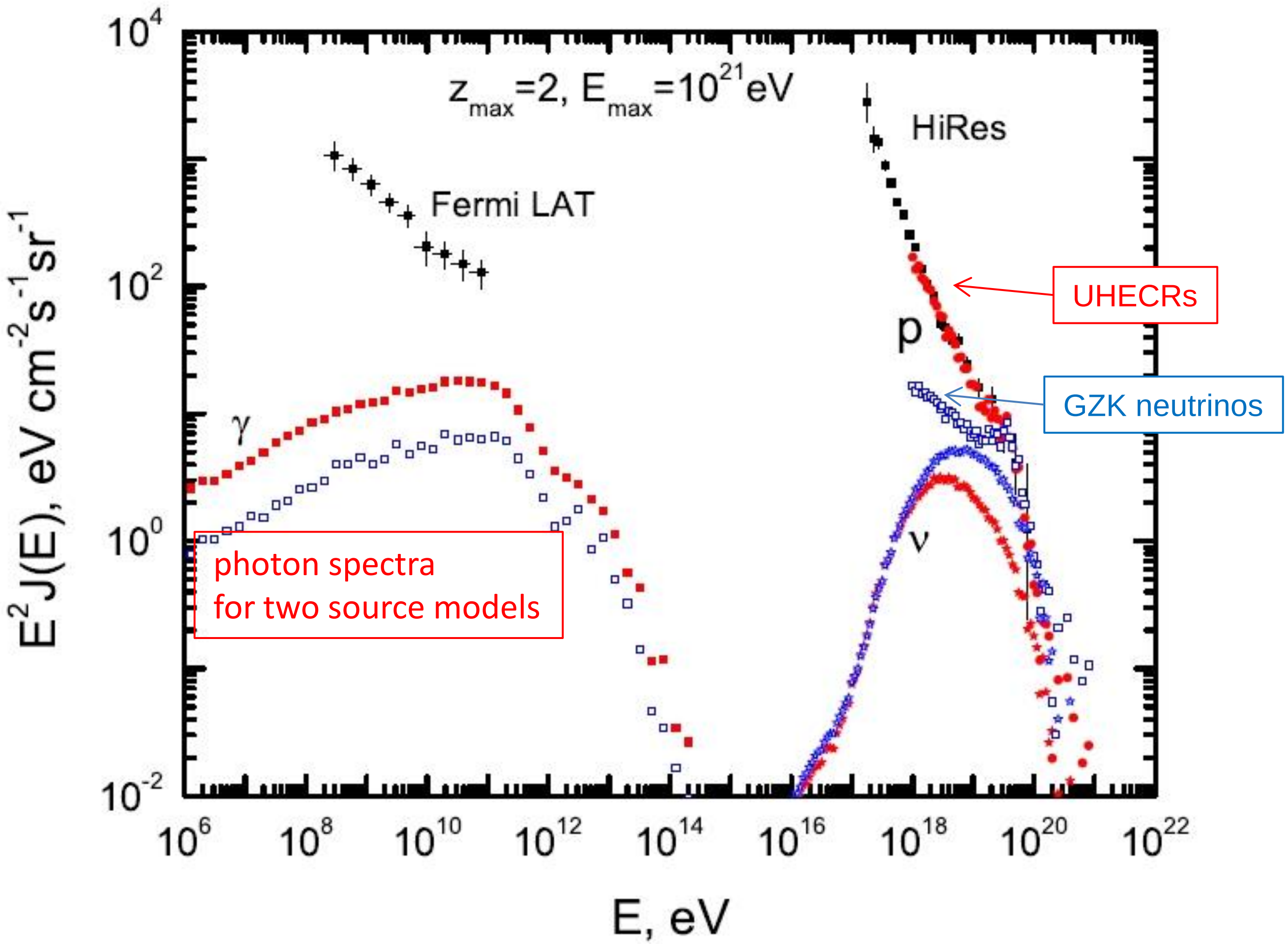
GZK neutrinos



Kotera et al. 11

2.c ν and γ from UHECRs: gamma-ray cascades

... electromagnetic cascades injected at ultra-high energies are reprocessed down to <TeV due to the opacity of the diffuse backgrounds to photon pair production



Berezinsky et al. 10

Summary

2. Beyond PeV: the extreme energy frontier

a. The ultra-high energy cosmic ray enigma

…Two essential questions: how to accelerate particles to extreme energies? Why are such powerful sources not seen in the arrival directions of the highest energy cosmic rays?

…Acceleration requires extreme conditions: relativistic outflows etc., corresponding to a source luminosity in excess of 10^{45} erg/sec… (for protons, less for charged nuclei)

a. A prototype source: gamma-ray burst

…gamma-ray bursts seemingly present the requisite conditions for accelerating particles to the observed energies and possibly enough energy in CR for matching the flux

…the 'standard' model implies a neutrino luminosity at a PeV at the Waxman-Bahcall limit, which is not seen by Ice Cube… a more definite answer within a few years…

…non detection would require another acceleration scenario or another source…

b. Connection with neutrinos and photons

…direct counterparts are not generally expected because cosmic rays are slowed down and deflected by magnetic fields… another connection to the distribution of magnetic fields on large scales…

…in some optimistic cases, gamma-ray counterparts could be seen at <TeV energies

…diffuse photon and neutrino backgrounds are expected from GZK interactions, with possible detection in the next decade…

Outline

1. <u>Overview: the CR-γ-ν connection and motivations</u>

   a. Introduction: detection and experimental facilities…
   b. The CR-γ-ν connection
   c. Motivations: extreme astrophysics, fundamental physics, dark matter physics etc.

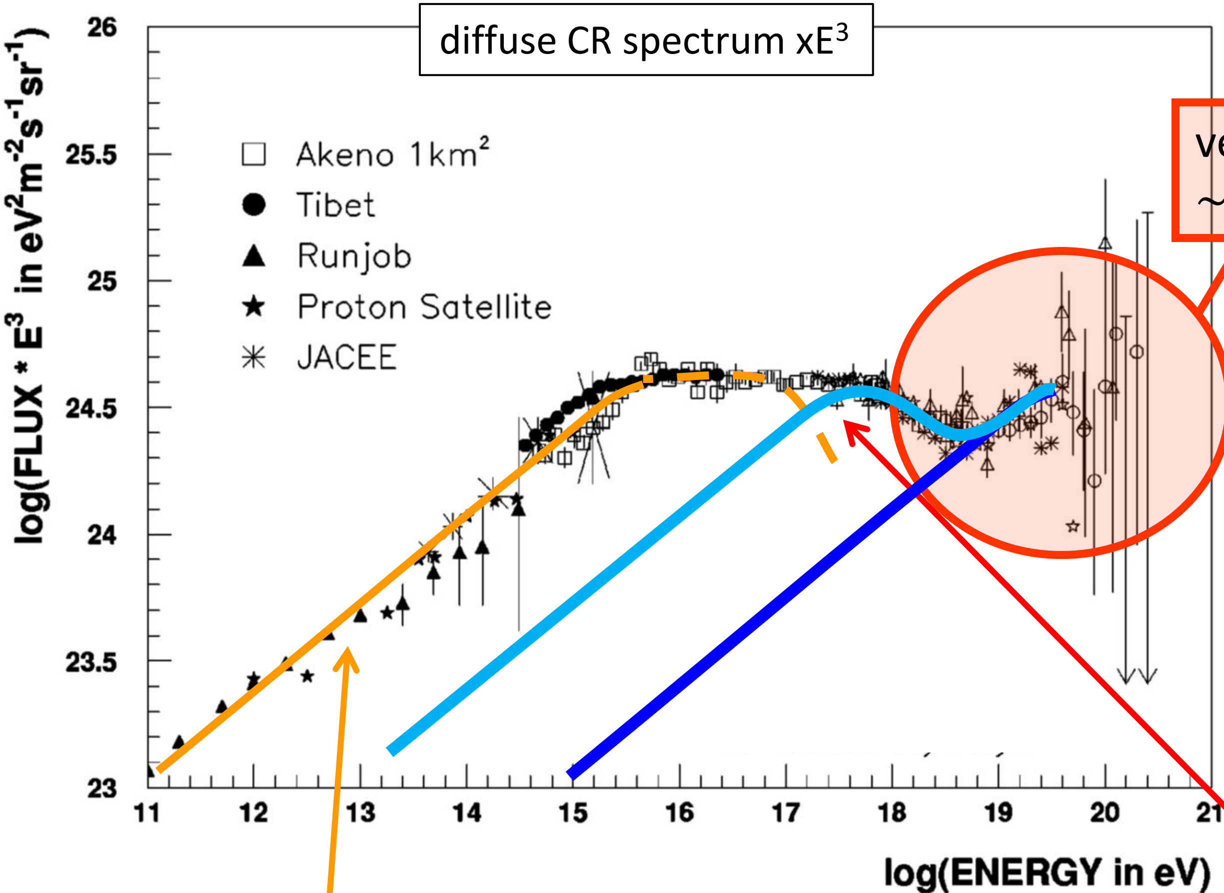
2. <u>Beyond PeV: the extreme energy frontier</u>

   a. The ultra-high energy cosmic ray enigma
   b. A prototype source: gamma-ray burst
   c. Connection with neutrinos and photons

3. <u>Astroparticle physics in the GeV – PeV range</u>

   a. Supernovae as cosmic ray sources
   b. Connection to the origin of Ice Cube neutrinos
   c. Transport of cosmic rays and the anti-matter ‘anomalies’

3.a CR sources: diffuse spectrum at all energies



very small flux at UHE:
~ 1/km^2/century at 10^{20}eV

Nagano & Watson 00

'low' energy cosmic rays likely originate in Galactic supernovae remnants …

→ energetics globally OK,
→ spectrum globally OK,
→ maximal energy ~ OK?
→ gamma-ray astronomy OK?

at 'high' energy... ???
where does 'high' energy starts?
where do the cosmic rays come from?
how many different components ?

3.a CR sources: supernovae remnants

Supernovae remnants are efficient particle accelerators at young age, with $R \sim 1$ pc, $v_{sh} \sim 0.01 - 0.1\, c$

<u>Energetics:</u> if each supernova (Galactic rate $r_{SN} \sim 2$ / 100yr) injects 10% of its shock kinetic energy ($E_{SN} \sim 10^{51}$ ergs) in cosmic rays, one recovers the observed low energy cosmic ray flux, accounting for the Galactic volume ($V \sim 10^{67}$ cm^3) and escape timescale ($\tau_{esc} \sim 10^7$ yrs):

$$u_{\rm cr} \sim \frac{r_{\rm SN}\tau_{\rm esc}\, 0.1 E_{\rm SN}}{V} \sim 1\,{\rm eV\,cm^{-3}}$$

<u>Spectrum:</u>

- in the test particle approximation, predicted spectral index s=2.0 (an oversimplification!)
… roughly consistent with observed spectral index 2.7 once transport effects are included…?

<u>Maximal energy:</u>

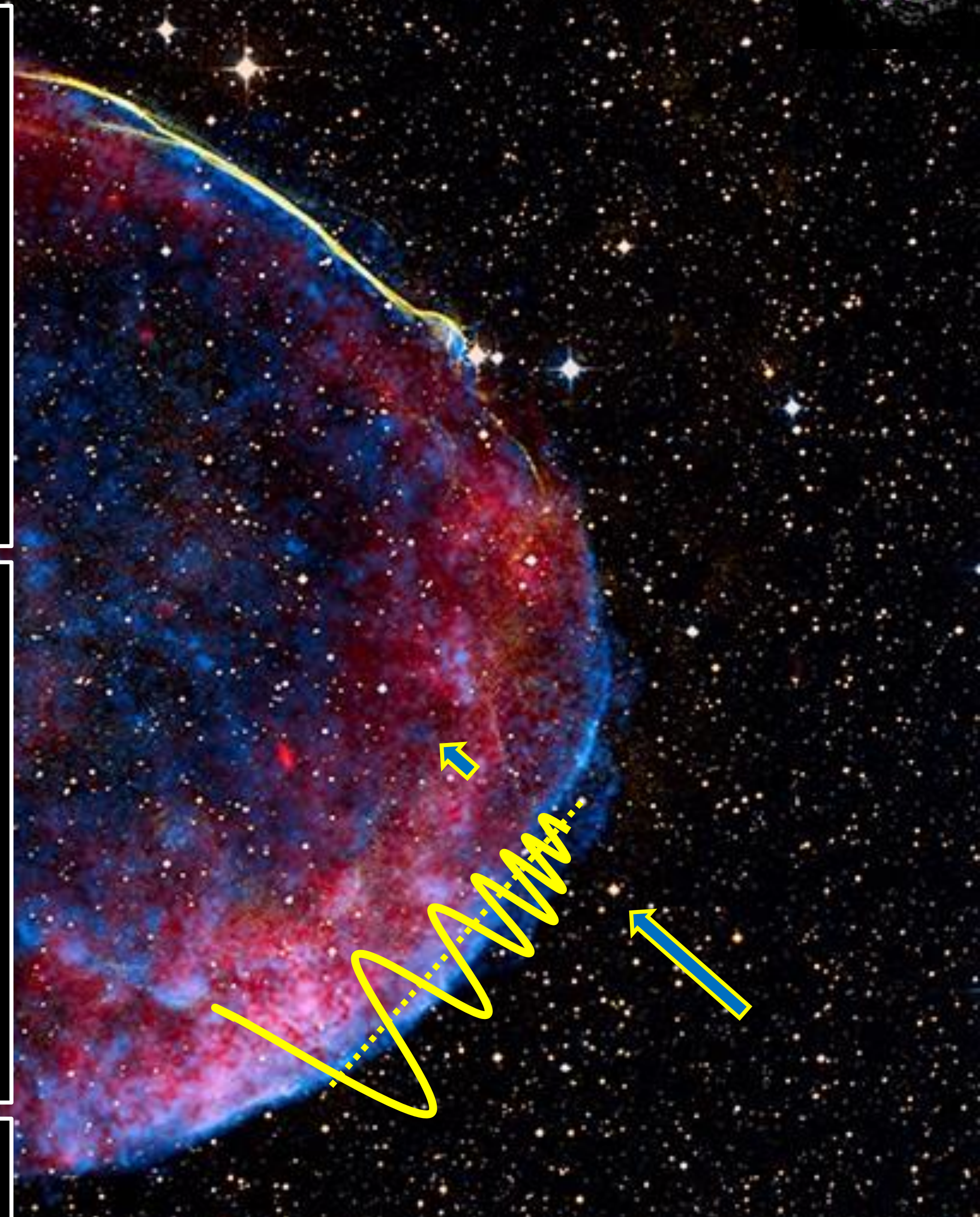
- comparing the age of the remnant and the acceleration timescale, one finds
$E_{max} \sim$ 10 TeV Z (B/3 μG) (assuming Bohm scaling $t_{scatt} \sim t_L$)
- understanding the cosmic ray spectrum requires to accelerate protons at least up to 2000 TeV !
- likely solution: magnetic field in the shock vicinity is amplified by the back-reaction of cosmic rays on the turbulence… a non-trivial problem in plasma physics!

3.a CR sources: acceleration in supernovae remnants

reference frame: interstellar medium at rest

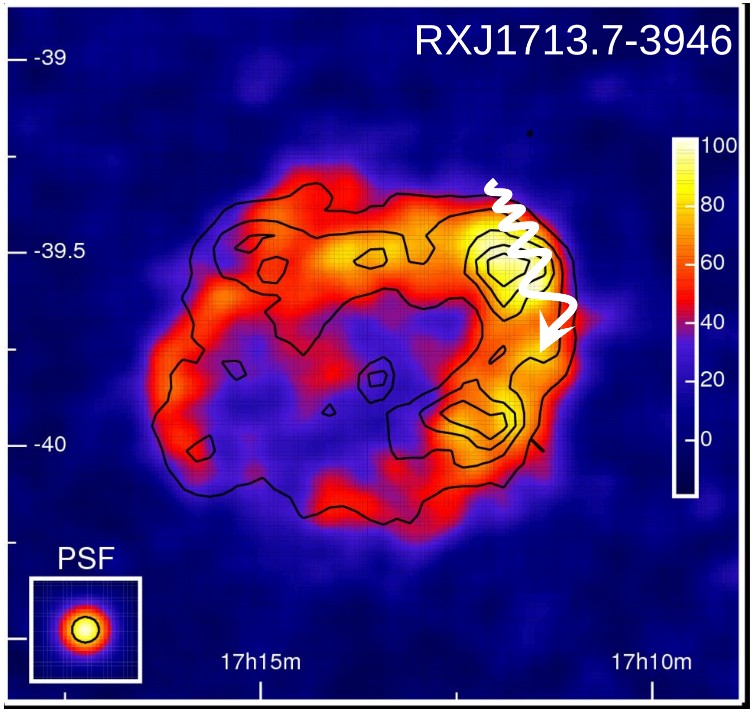
reference frame: shocked plasmas at rest

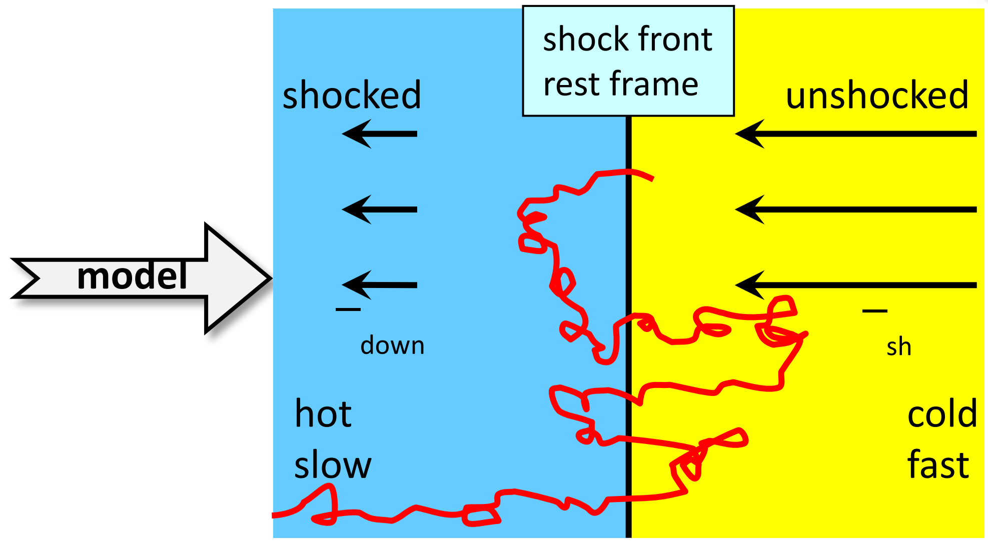
as long as particle bounces back and forth, it experiences acceleration because of the converging flows (as in tennis table!)



Bell 78, Krimsky et al. 77, Blandford & Ostriker 78

3.a CR sources: test particle Fermi acceleration





particles get accelerated as they bounce back and forth across the shock wave… acceleration stops when particles exit the system towards the shocked plasma…

→ generates a power-law with spectral index s: balance between energy gain and escape

$dN/dE \propto E^{-s}$, with $s = 1 + \ln(1-P_{esc})/\ln(1+g) = 2.0$ in strong shocks

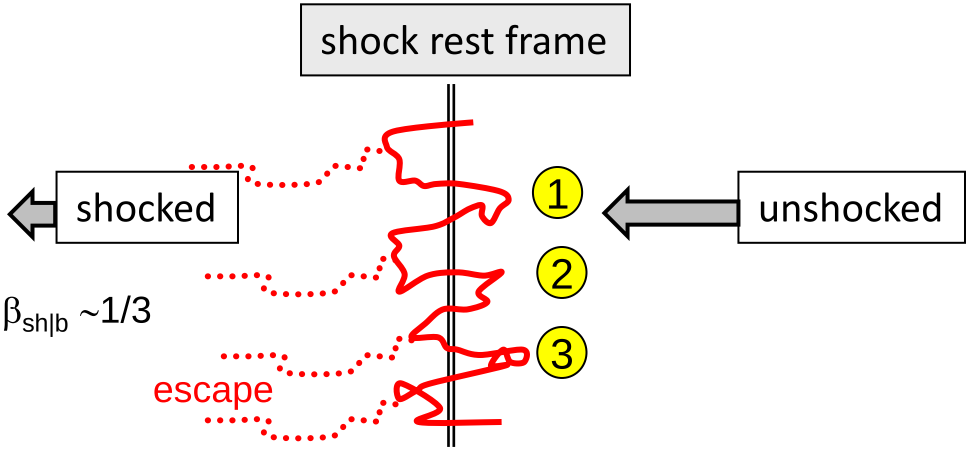
→ maximal energy: balance between acceleration timescale and loss/escape timescales

age limit: $E_{max} \sim 10$ TeV $Z\, B_{-6}\, \beta_{sh,-1.5}\, R_{3pc}$ (generally applies to ions)

synchrotron limit: $E_{max} \sim 600$ TeV $B_{-6}^{-1/2}\, \beta_{sh,-1.5}$ (for electrons)

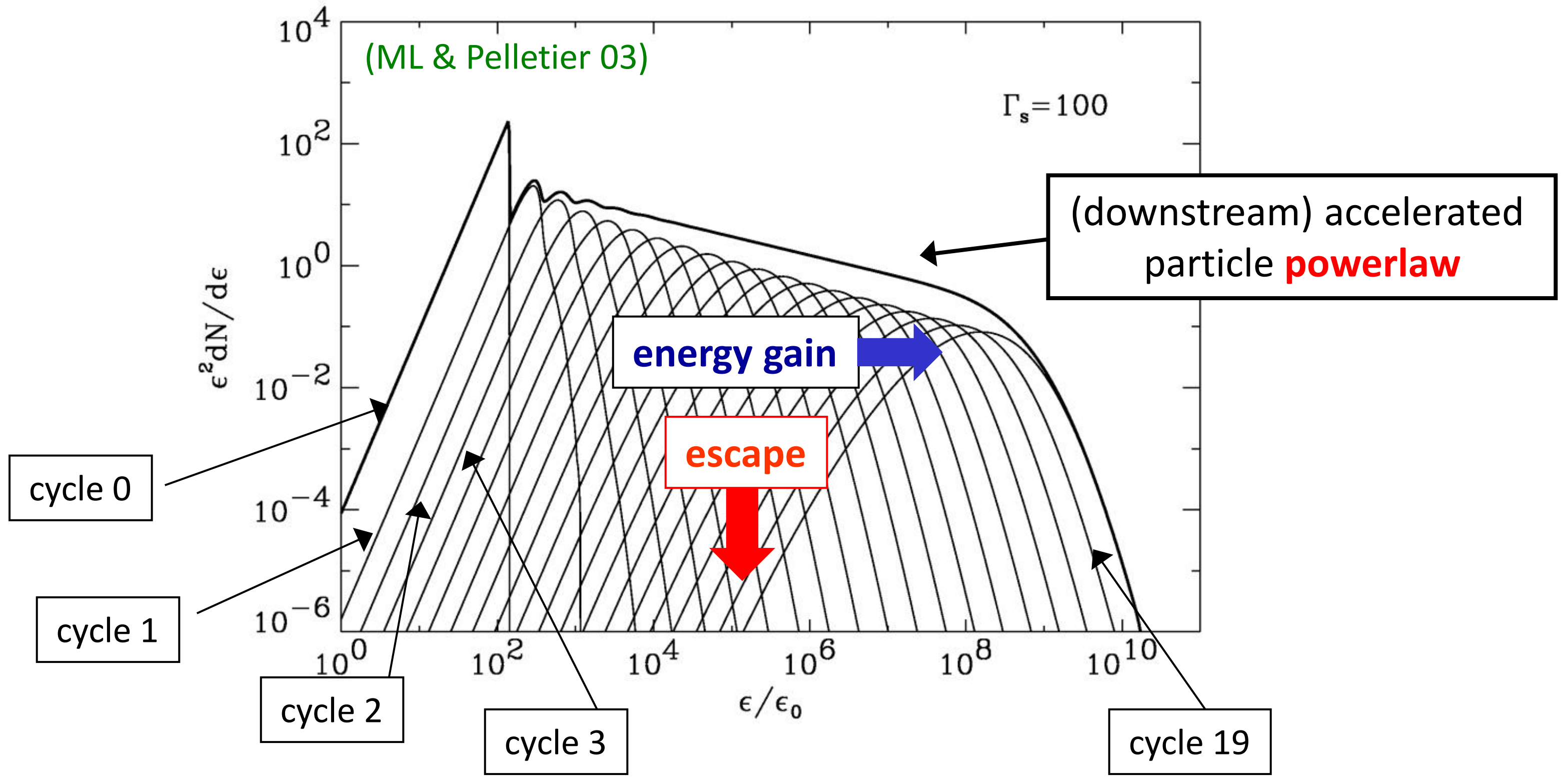
e.g. Bell 78, Axford et al. 77, Krimsky 77, Blandford & Ostriker 78, Drury 83, Blandford & Eichler 87

3.a CR sources: test particle Fermi acceleration



competition between escape and acceleration leads to powerlaw $dN/dE \propto E^{-s}$,

with $s = 1 + \ln(1+P_{esc})/\ln(1+g) = 2.0$
in non-relativistic strong shocks (Bell 78)



3.a CR sources: diffusive shock acceleration

<u>Microscopic derivation of diffusive shock acceleration:</u>

$\rightarrow$ energy gain per Fermi cycle: dowstream to upstream then back to downstream

$$p^{(1)}_{\rm down} = \gamma^2_{\rm up/down}\left(1+\cos\theta_{\rm up}\beta_{\rm up/down}/\beta\right)\left(1-\cos\theta_{\rm down}\beta_{\rm up/down}/\beta\right)p^{(0)}_{\rm down}$$

note: a double Lorentz transform from downstream rest frame to upstream rest frame, where random (elastic) pitch angle deflection takes place, then back to downstream…
<u>**this is a trick:**</u> it avoids solving for the trajectory of the particles in the motional electric fields…
of course, acceleration is provided by the motional electric fields…

$\rightarrow$ flux average:

$$\begin{aligned}\left\langle p^{(1)}_{\rm up}/p^{(0)}_{\rm up}\right\rangle &= 2\int_0^1 {\rm d}\cos\theta_{\rm up}\ \cos\theta_{\rm up}\ 2\int_{-1}^0 {\rm d}\cos\theta_{\rm down}\ \cos\theta_{\rm down}\ p^{(1)}_{\rm up}/p^{(0)}_{\rm up}\\ &\simeq \frac{4}{3}\frac{\beta_{\rm up/down}}{\beta} \simeq \frac{4}{3}\frac{u_1-u_2}{v}\qquad (u_1-u_2\ll c)\end{aligned}$$

<u>References:</u>

A. R. Bell, Month. Not. Roy. Astron. Soc., **182**, 147 (1978)

A. R. Bell, Month. Not. Roy. Astron. Soc., **182**, 443 (1978)

3.a CR sources: diffusive shock acceleration

$\rightarrow$ escape probability: (escape occurs downstream by advection)

$$P_{\rm esc} = \frac{\text{flux} \rightarrow +\infty}{\text{flux through shock}} = \frac{n u_2}{2\int_0^1 {\rm d}\cos\theta_{\rm up}\cos\theta_{\rm up} n v} = \frac{4u_2}{v}$$

$\rightarrow$ spectrum of accelerated particles: $N(>p) = \int_p^{+\infty} {\rm d}p' 4\pi p'^2 f_2(p')$

$N(>p_n) \propto$ probability of going through n Fermi cycles leading to momentum p_n

$\rightarrow$ after n Fermi cycles, $\langle p^{(n)}\rangle = p^{(0)} \prod_{i=1}^{n} \left(1 + \frac{4}{3}\frac{u_2 - u_1}{v_i}\right)$

i.e. $\ln\left(\langle p^{(n)}\rangle / p^{(0)}\right) \simeq \sum_{i=1}^{n} \frac{4}{3}\frac{u_1 - u_2}{v_i}$

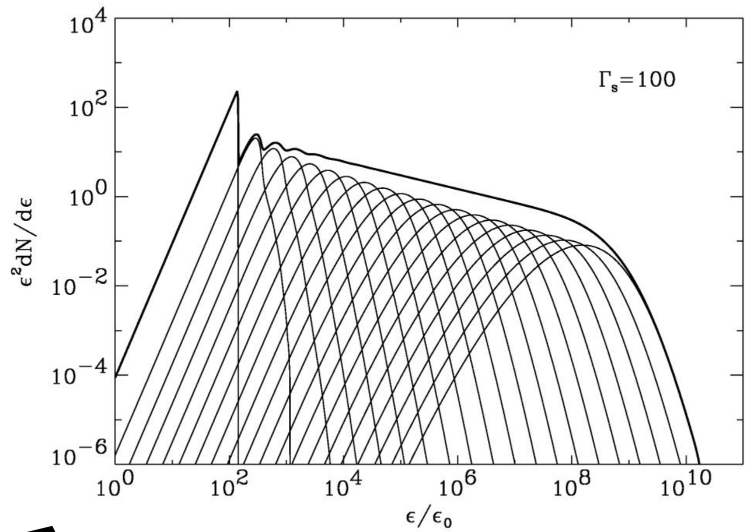
$\rightarrow$ probability of reaching n-cycles: $P_n = \prod_{i=1}^{n} \left(1 - P_{{\rm esc},i}\right)$

i.e. $\ln P_n \simeq \frac{-3u_2}{(u_2 - u_1)} \ln\left(\langle p^{(n)}\rangle / p^{(0)}\right)$

leads to: $\boxed{N(>p) \propto p^{-3/(r-1)} \Leftrightarrow {\rm d}N/{\rm d}p \propto p^{-(r+2)/(r-1)}}$ $\qquad r \equiv \frac{u_2}{u_1}$

3.a CR sources: main questions beyond test particle

The above test particle approximation fails to explain the origin of cosmic rays with energy up to a PeV… Modern developments focus on the back-reaction of particles on the turbulence and how particles are accelerated in the self-amplified field…



injection

crucial issue for e, w/o heating:

$r_{L,e} << r_{L,p} \sim \Delta_{shock}$

source of heating?

non-linear acceleration

$P_{cr} >> P_{up} \Rightarrow$ CR modify jump conditions in the precursor...

CR may also amplify B_{up} through streaming instabilities...

accelerated CR

shock structure

instabilities

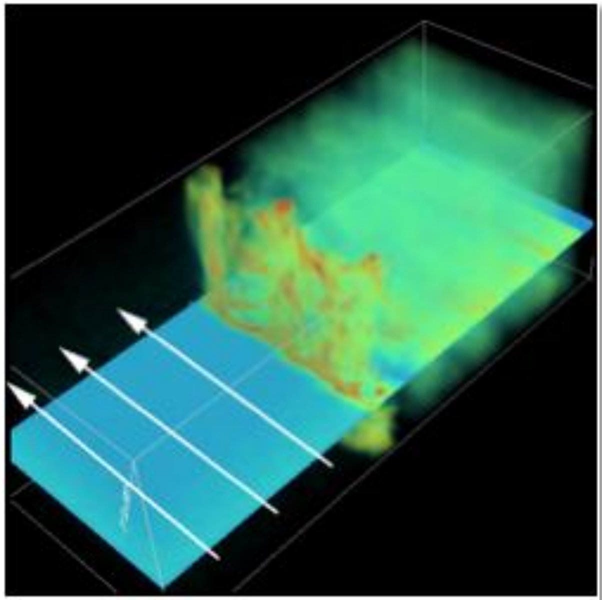
maximal energy and escape

how is escape realized?

maximal energy?

resulting spectrum integrated over SN evolution?

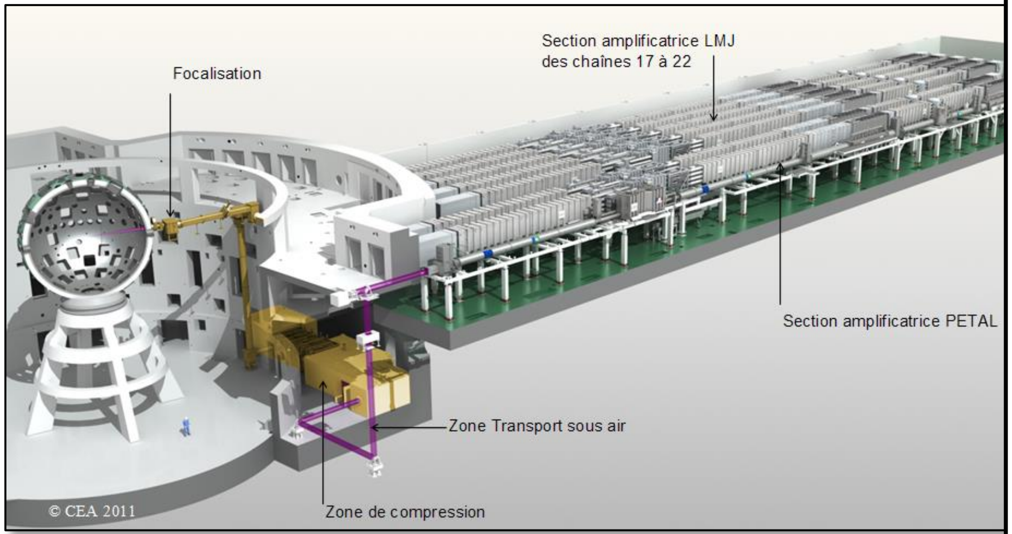
3.a CR sources: connection to laboratory astrophysics



particle-in-cell simulation of a collisionless shock wave (Spitkovsky 05)

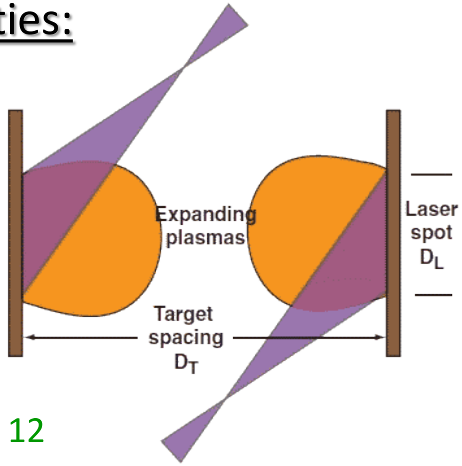
Collisionless shock wave:

- mean free path to Coulomb collisions ≫ thickness of the shock
- structure of the shock: a famous problem in plasma physics!
- effective coupling between particles: electromagnetic collective modes of the plasma…



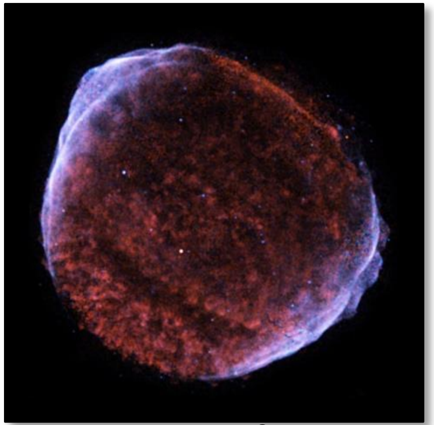
laser Mégajoule (LMJ - CEA)

laboratory astrophysics in high energy density facilities:

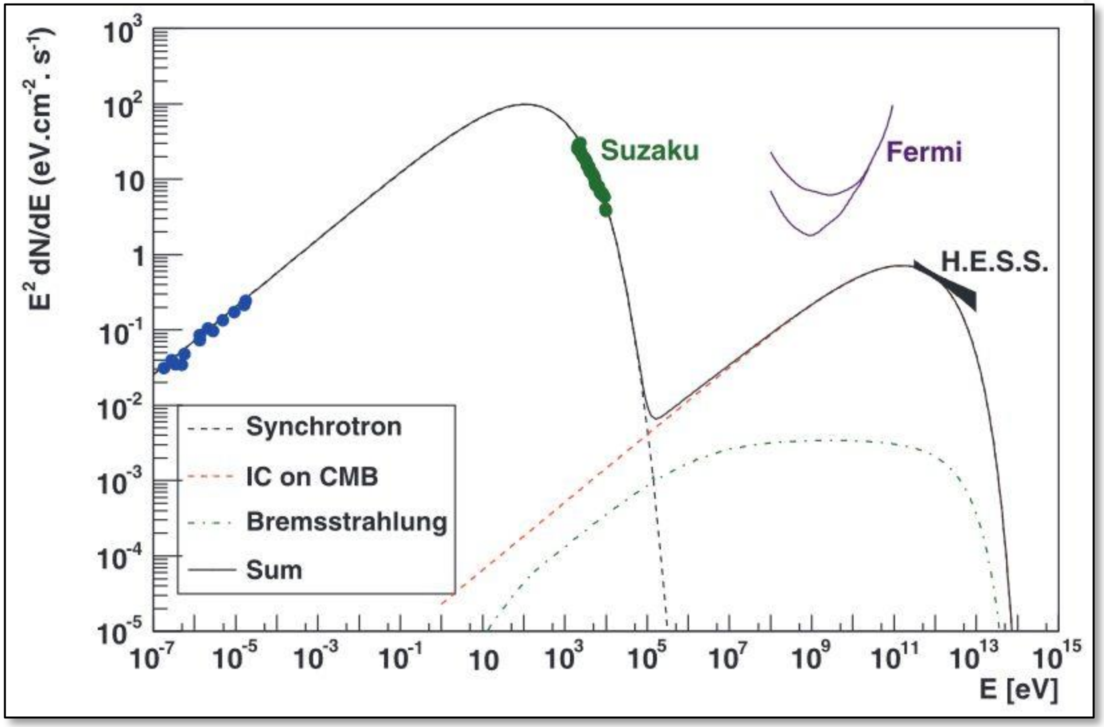


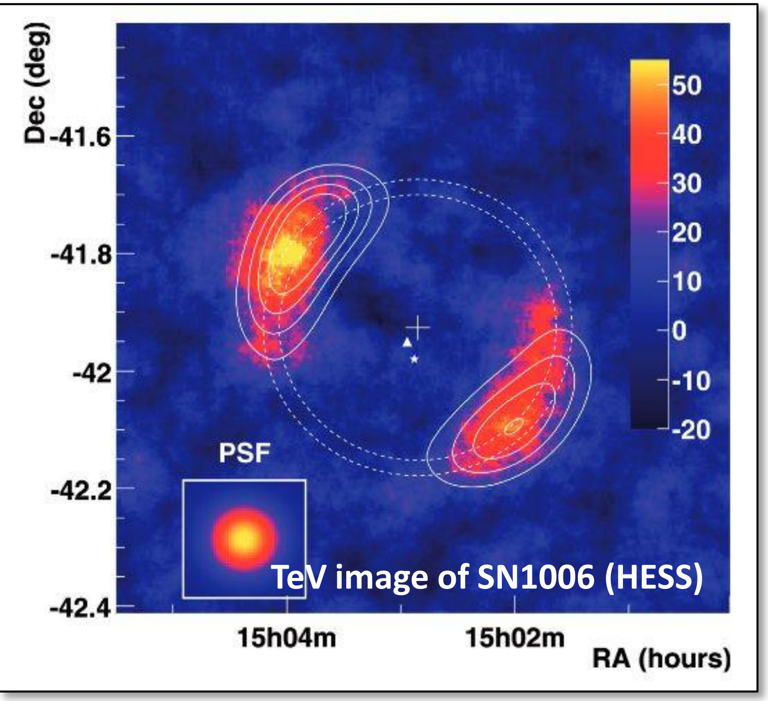
Gregori & Drake 12

3.a CR sources: searching for the source



X-ray image of SN1006 (Chandra)



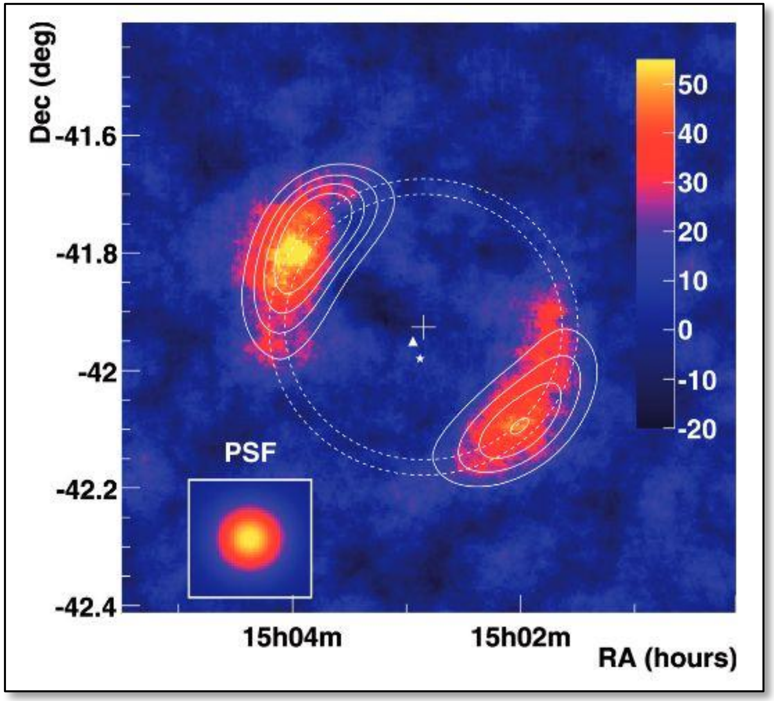


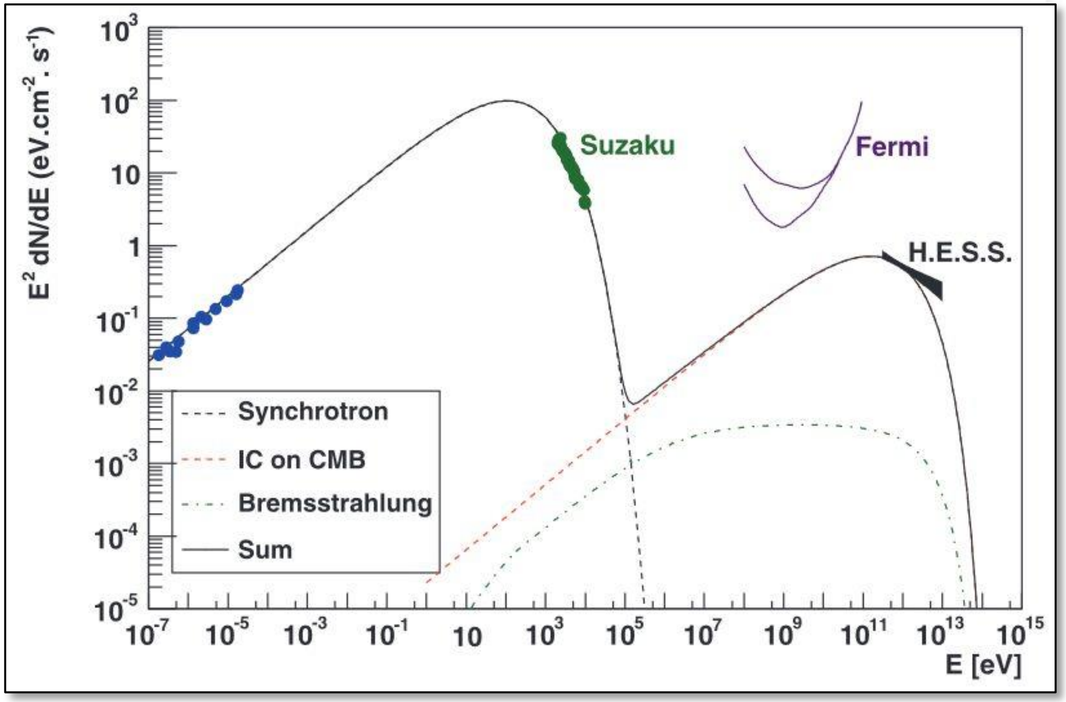
TeV image of SN1006 (HESS)

gamma-ray telescopes have demonstrated that particles (e, nuclei) are accelerated to > TeV energies in supernovae remnants…

however, the brightest TeV emitters so far rather indicate that the photons are emitted by accelerated electrons… where is the hadronic contribution?

3.a CR sources: searching for the source





<u>hadronic signature of the emission:</u>

- pion production cross-section ~ independent of energy above threshold (~m_p), hence $$\frac{\mathrm{d}I_\gamma}{\mathrm{d}E_\gamma} \propto \frac{\mathrm{d}N_p}{\mathrm{d}E_p} \propto E_\gamma^{-s_p} \quad (E_\gamma \gg 0.1\,\mathrm{GeV})$$ with $s_p \sim 2.0\text{-}2.4$

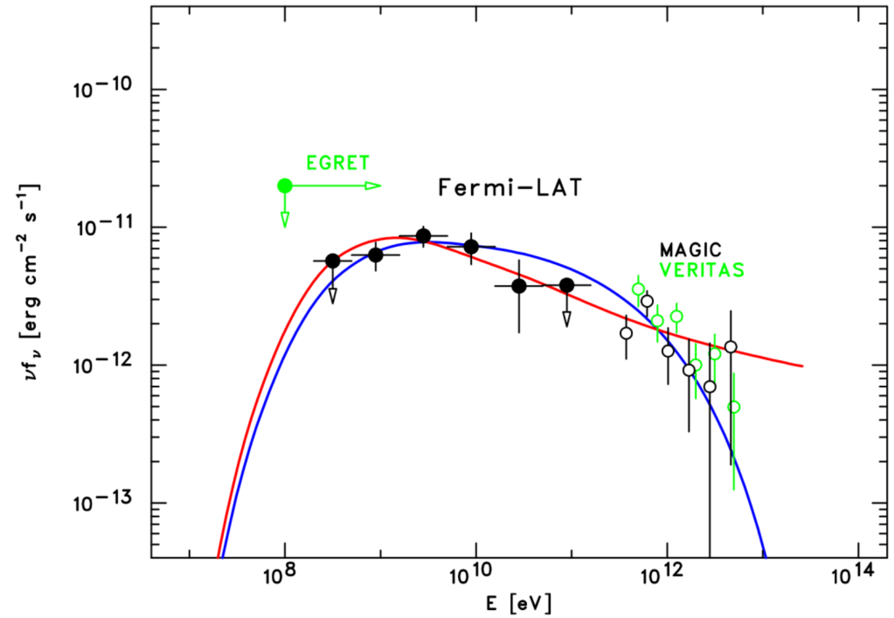
in apparent conflict with the data (Fermi data at GeV energies is essential here!)

3.a CR sources: searching for the source

So far, two convincing cases of hadronic signature in shell-type supernovae:

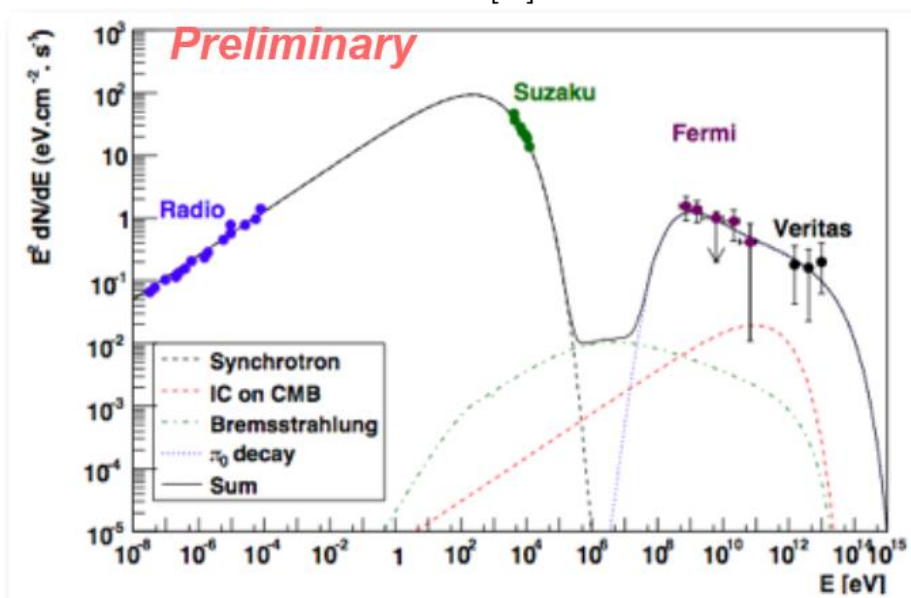
Cassiopae-A (SN1680):

emission compatible with ~1% of kinetic energy going into hadrons, for B ~ 120 μG (amplification!)



Tycho (SN1572):

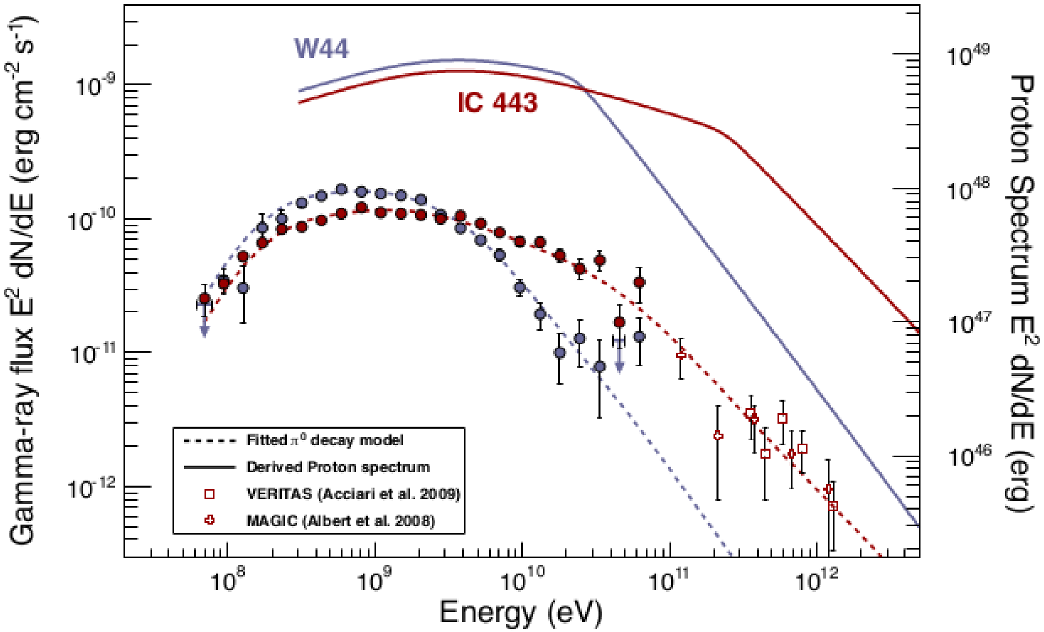
emission compatible with ~10% of kinetic energy going into hadrons, for B ~ 200 μG (amplification!), so E_p possibly as large as 500TeV!



3.a CR sources: evidence for hadronic acceleration

Most robust evidence so far for hadronic production: pion production bump in W44 and IC443

$$p + p \to \pi^0 + \ldots, \quad \pi^0 \to \gamma + \gamma$$

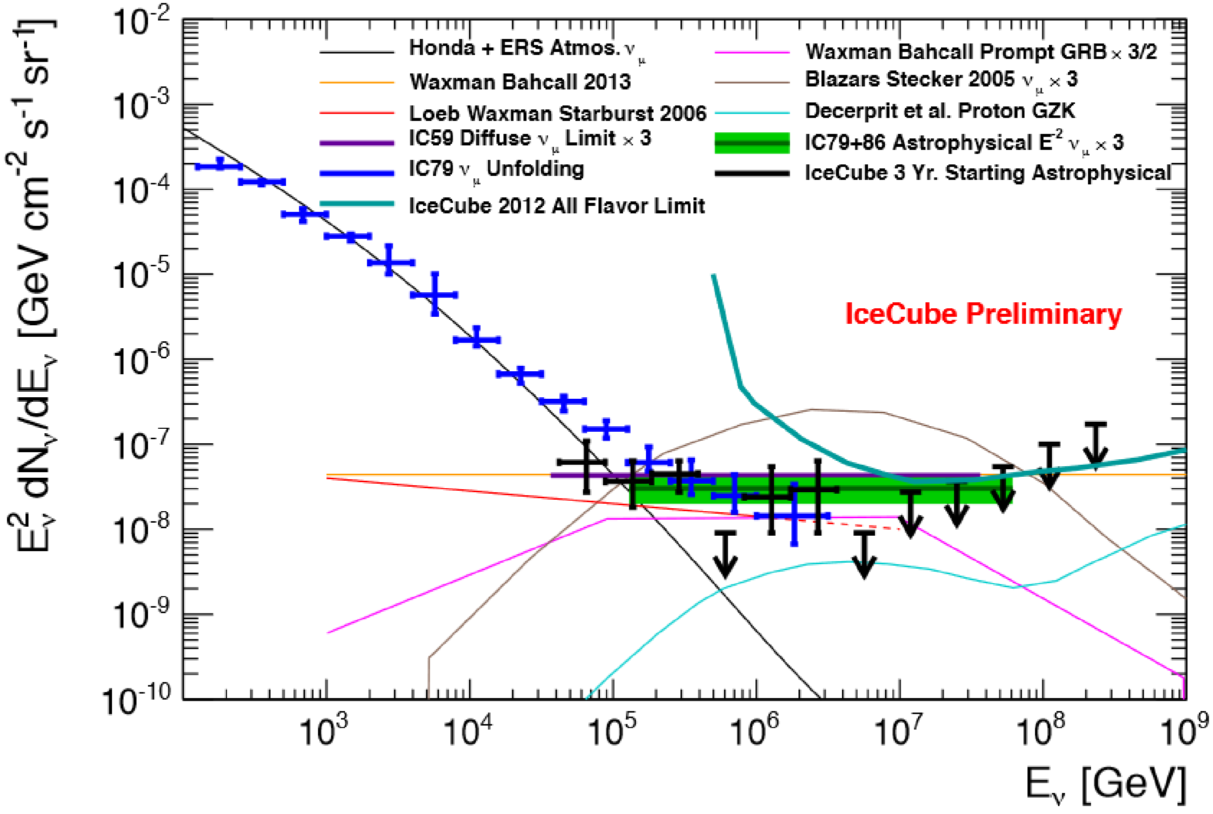


<u>Finding a PeVatron:</u>

… difficult, because galactic supernovae are rare (2-3 /century), invisible in optical because of absorption, and acceleration to PeV should take place during the first thousand years… a prime objective for future Cerenkov arrays!

3.b Ice Cube ν: a connection to CR physics?

The Waxman-Bahcall bound sets the standard for the detection of high energy neutrinos, predicting O(10) events per yr in a km3 cube neutrino detector such as Ice Cube at PeV energies…



… the observed flux at Ice Cube matches nicely the WB bound: a connection to high energy cosmic ray physics?

3.b Ice Cube ν: cosmic ray production in starbursts?

→ In starburst galaxies, the high density of the interstellar medium leads to a short pion interaction timescale:

$$t_\pi = \frac{1}{n_p \langle \sigma_{pp} c \rangle} \sim 2 \times 10^5 \, \mathrm{yr}$$

→ whereas the diffusive/convective escape timescale is $t_{esc} \sim 10^6$ yrs at 1 GeV, implying that most of CR energy is lost to pion production…

→ Fermi observations of starburst galaxies find $L_\gamma \sim 10^{40}$ erg/s for an estimated $L_{cr} \sim 10^{41}$ erg/s, i.e. a conversion factor of 10%

→ gamma spectrum must trace the injection spectrum of cosmic rays if t_π sets the life-time, and Fermi observations indicate dN/dE $\propto E^{-2.2}$, OK with cosmic-ray phenomenology…

→ if gamma-rays are indeed mostly hadronic, then:

→ starburst galaxies provide a substantial contribution to the diffuse gamma-ray background

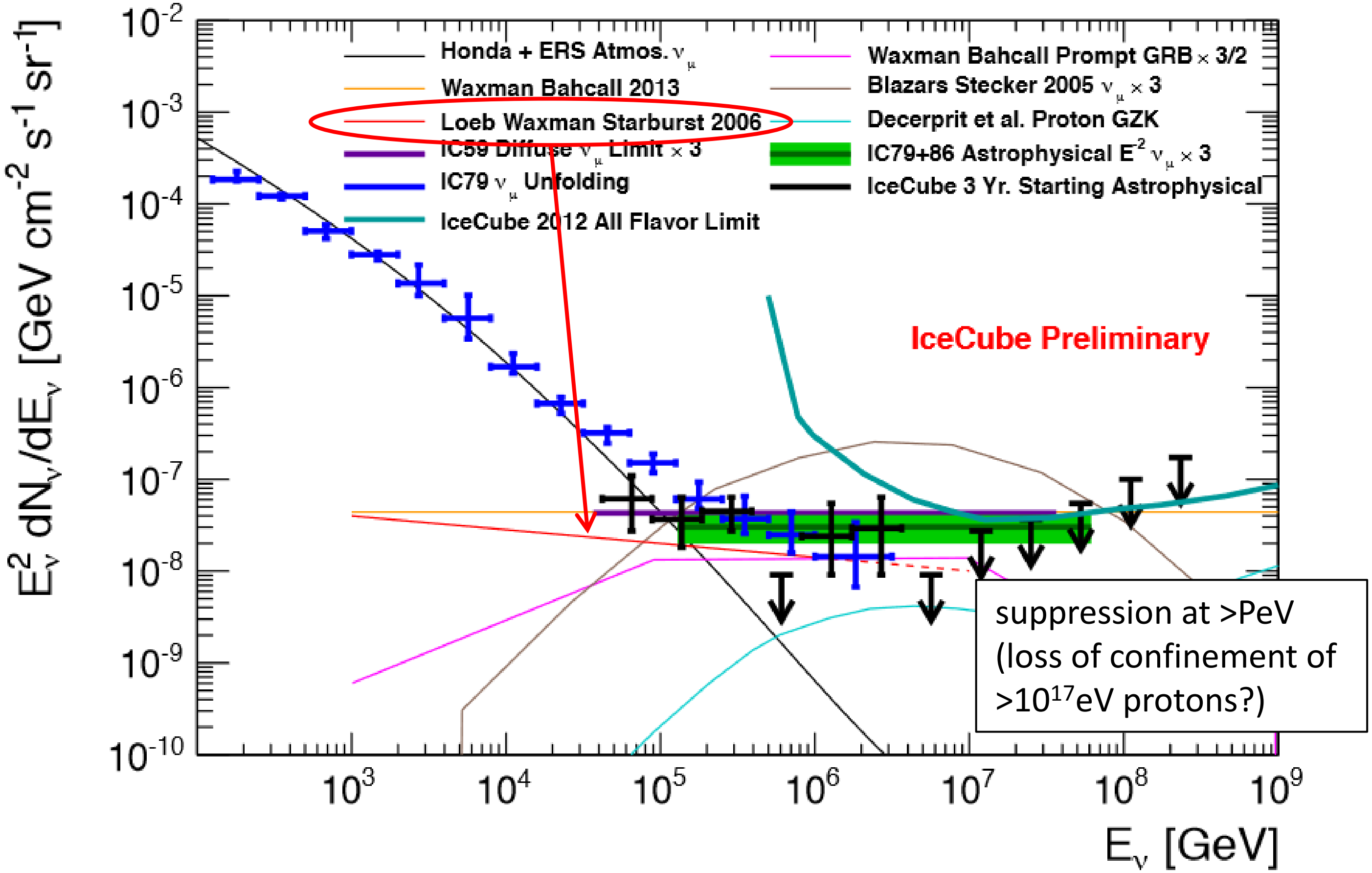
→ starburst galaxies output a neutrino flux

$$E_\nu \phi_\nu \sim 2 \times 10^{-8} \left(E_\nu / 100 \, \mathrm{TeV}\right)^{-2.2} \, \mathrm{GeV \, cm^{-2} \, s^{-1} \, sr^{-1}}$$

very close to the Ice Cube measurements…

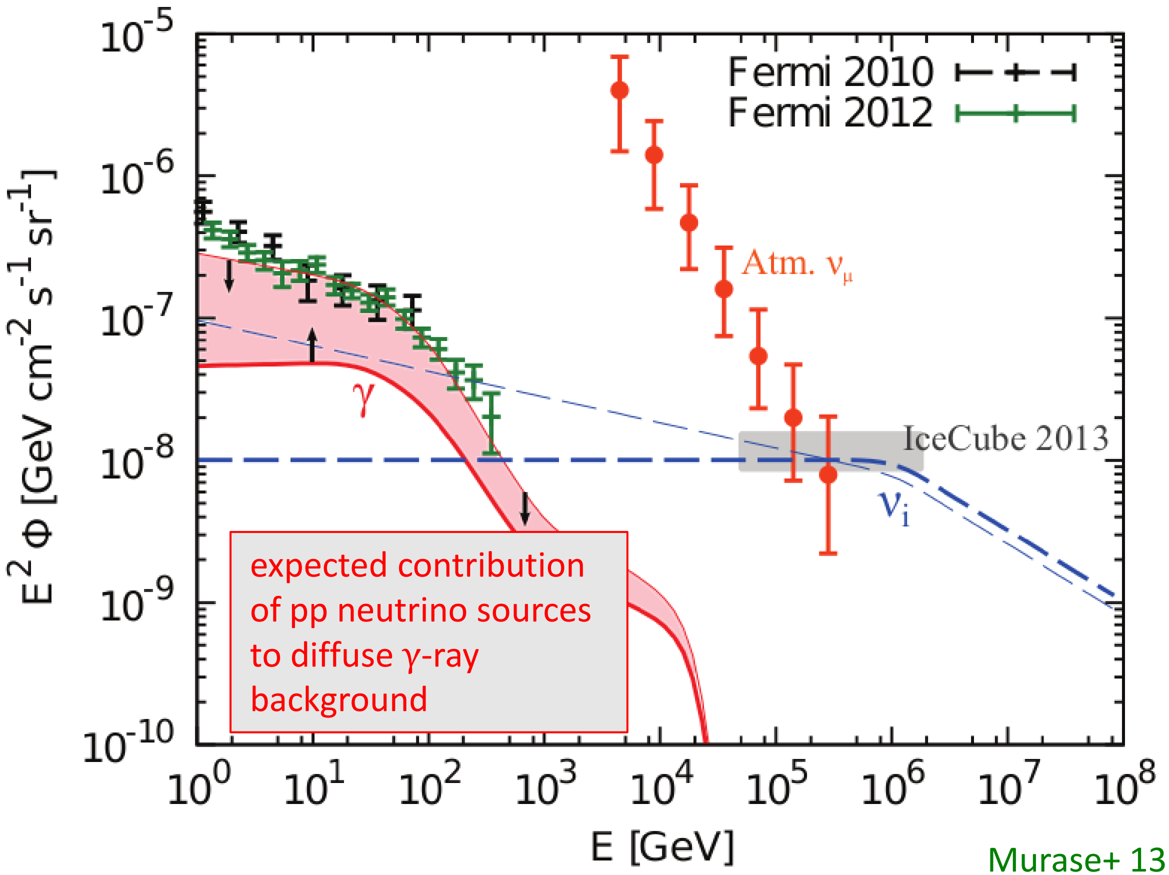
→ however, maximum energy of neutrinos imply acceleration and confinement up to 10^{17}eV?

3.b Ice Cube ν: origin in starburst galaxies?



… the observed flux at Ice Cube matches the prediction of the starburst model, but the maximal observed neutrino energy exceeds the prediction…?

3.b Ice Cube ν: connection to the gamma-ray background



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… a significant part of the diffuse gamma-ray background observed by Fermi must result from pion production in starburst galaxies, if these galaxies explain the signal observed by Ice cube… with already some tension…

3.c CR transport: general considerations

Transport of cosmic rays in galactic magnetic fields:

turbulent acceleration

$$\partial_t f_i + \boldsymbol{v}_{\mathbf{co}} \cdot \nabla_{\boldsymbol{r}} f_i \quad - \quad \frac{1}{3} \nabla_{\boldsymbol{r}} \cdot \boldsymbol{v}_{\mathbf{co}}\, p \partial_p f_i \;=\; \partial_{x^i} D_{ij} \partial_{x^j} f_i + \frac{1}{p^2} \partial_p D_{pp} \partial_p f_i$$

$$+ Q_i(\boldsymbol{r}, t, p) \;-\; \partial_p \left(\dot{p} f_i\right) \;-\; \frac{f_i}{\tau_i} \;+\; \sum_{j \to i} \frac{f_j}{\tau_{j \to i}}$$

source term:
acceleration by SNe

$$Q(\boldsymbol{r}, t, p) \sim \sum_i \delta(t - t_i) \delta\left(\boldsymbol{r} - \boldsymbol{r_i}\right) \frac{\mathrm{d}N}{\mathrm{d}p}$$

systematic energy losses
(e.g. ionization, synchrotron…)

net loss through radioactive decay
or inelastic collisions with interstellar gas

net gain through radioactive decay
or inelastic collisions from heavier nuclei

References:

V. S. Berezinsky, S. V. Bulanov, V. A. Dogiel, V. L Ginzburg, V. S. Ptsukin,
« Astrophysics of cosmic rays » (1990, North-Holland)

3.c CR transport: a generic simplified model

A simple model: particles are injected in sources, propagate in interstellar medium, then escape the galaxy after some (momentum dependent) time $\tau_{\rm esc}$

$\rightarrow$ assume stationary + homogeneous source distribution: $\dot{N}_{SN}\tau_{\rm esc} \gg 1$

$\rightarrow$ consider stable species, neglect collisions and decays

$\rightarrow$ average distribution: $$\frac{{\rm d}n}{{\rm d}p} \simeq \frac{\mathcal{N}}{p_0}\left(\frac{p}{p_0}\right)^{-s} \dot{n}_{\rm s}\ \tau_{\rm esc}$$

$\rightarrow$ connection to diffusion model: neglect all terms but diffusion and source, integrate over a finite volume… escaping flux balances injection,

$$\tau_{\rm esc} \sim \frac{H^2}{D}$$

H scale height for escape
D diffusion coefficient

$\rightarrow$ momentum dependence: $\tau_{\rm esc} \propto p^{-\alpha} \Rightarrow {\rm d}N/{\rm d}p \propto p^{-s-\alpha}$

theory - acceleration: $s \simeq 2$
measurements: $s+\alpha \simeq 2.7$

$\boxed{\Rightarrow \text{ suggests } \alpha \simeq 0.7}$

3.c CR transport: a generic simplified model

<u>A simple model</u>: particles are injected in sources, propagate in interstellar medium, then escape the galaxy after some (momentum dependent) time $\tau_{\rm esc}$

$\rightarrow$ momentum dependence: $\tau_{\rm esc} \propto p^{-\alpha} \;\Rightarrow\; {\rm d}N/{\rm d}p \,\propto\, p^{-s-\alpha}$

theory - acceleration: $s \simeq 2$
measurements: $s + \alpha \simeq 2.7$

$\Rightarrow$ suggests $\alpha \simeq 0.7$

$\rightarrow$ note: isotropic diffusion in Kolmogorov turbulence leads to $D \propto p^{0.3}$... which does not match the inferred scaling for $\tau_{\rm esc}$...

... solutions: diffusion in interstellar space is ill-understood...
or does acceleration lead to a slope $s \sim 2.3 - 2.4$?

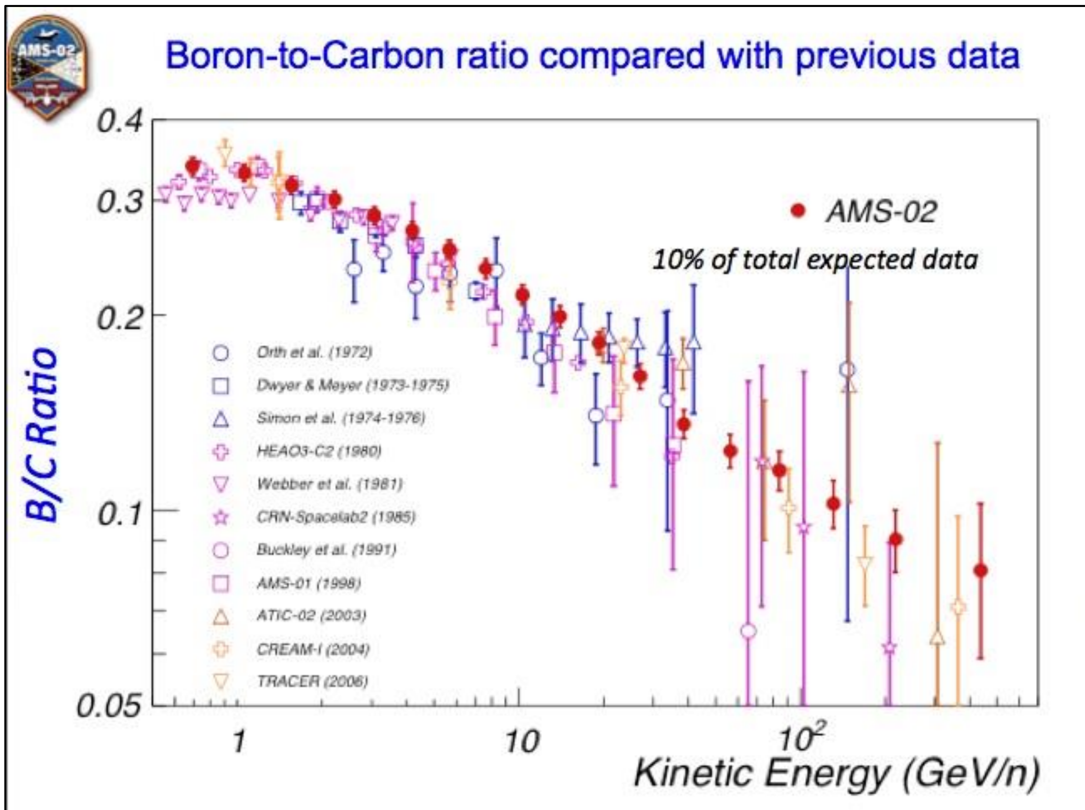
$\rightarrow$ check of the model: secondary species are not injected in acceleration sites but produced through inelastic collisions of primary species, e.g. Li, Be, B from interactions of cosmic ray C, N, O nuclei with interstellar p and He

3.c CR transport: model validation

→ injection rate of secondaries: $$Q_{\rm 2nd} \simeq \frac{{\rm d}N_{\rm prim.}}{{\rm d}p}\sigma_{\rm prim.\to 2nd}n_{\rm gas}c$$

→ average secondary spectrum: $$\frac{{\rm d}N_{\rm 2nd}}{{\rm d}p} \simeq Q_{\rm 2nd}\tau_{\rm esc}$$

→ test: $$\frac{{\rm d}N_{\rm 2nd}/{\rm d}p}{{\rm d}N_{\rm prim.}/{\rm d}p} \simeq \sigma_{\rm prim.\to 2nd}n_{\rm gas}c\tau_{\rm esc} \propto p^{-\alpha}$$



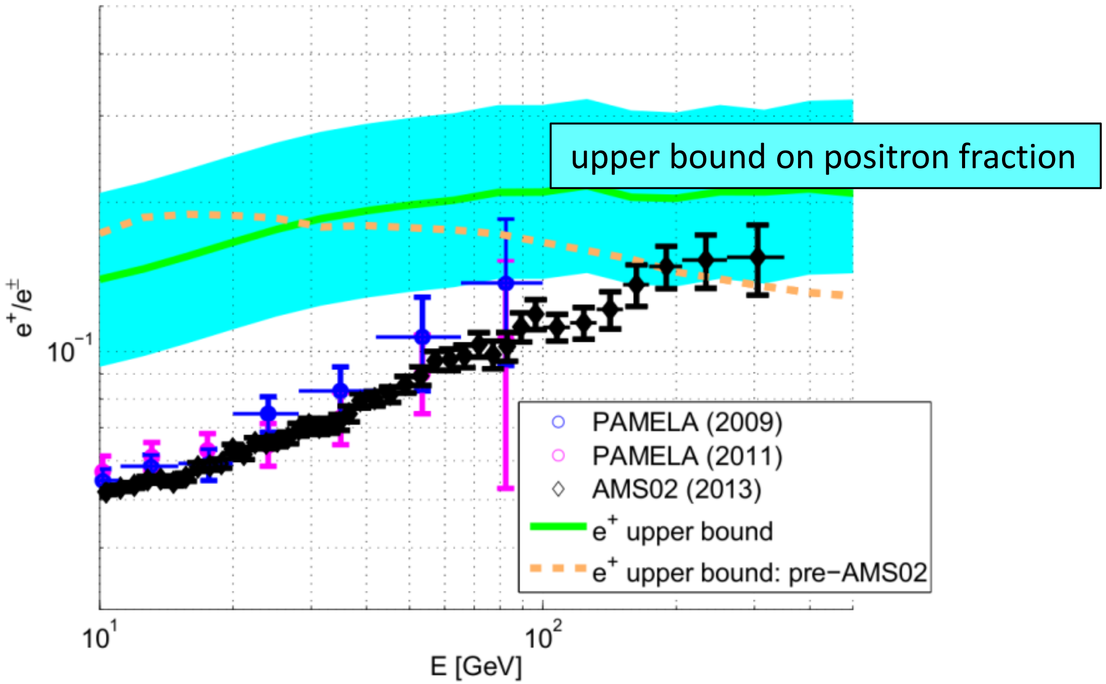
observed dependence:

$$ {\rm d}N_{\rm B}/{\rm d}N_{\rm C} \propto p^{-0.6}$$

indeed confirms simple model…

3.c CR transport: connection to anti-matter anomalies…

Simplified transport model neglects energy losses and decays/spallation of the secondary species… however it can be used to set an upper bound on the e+ secondary spectrum, the actual spectrum being suppressed by a factor f_{loss} characterizing energy losses (e.g. inverse Compton)



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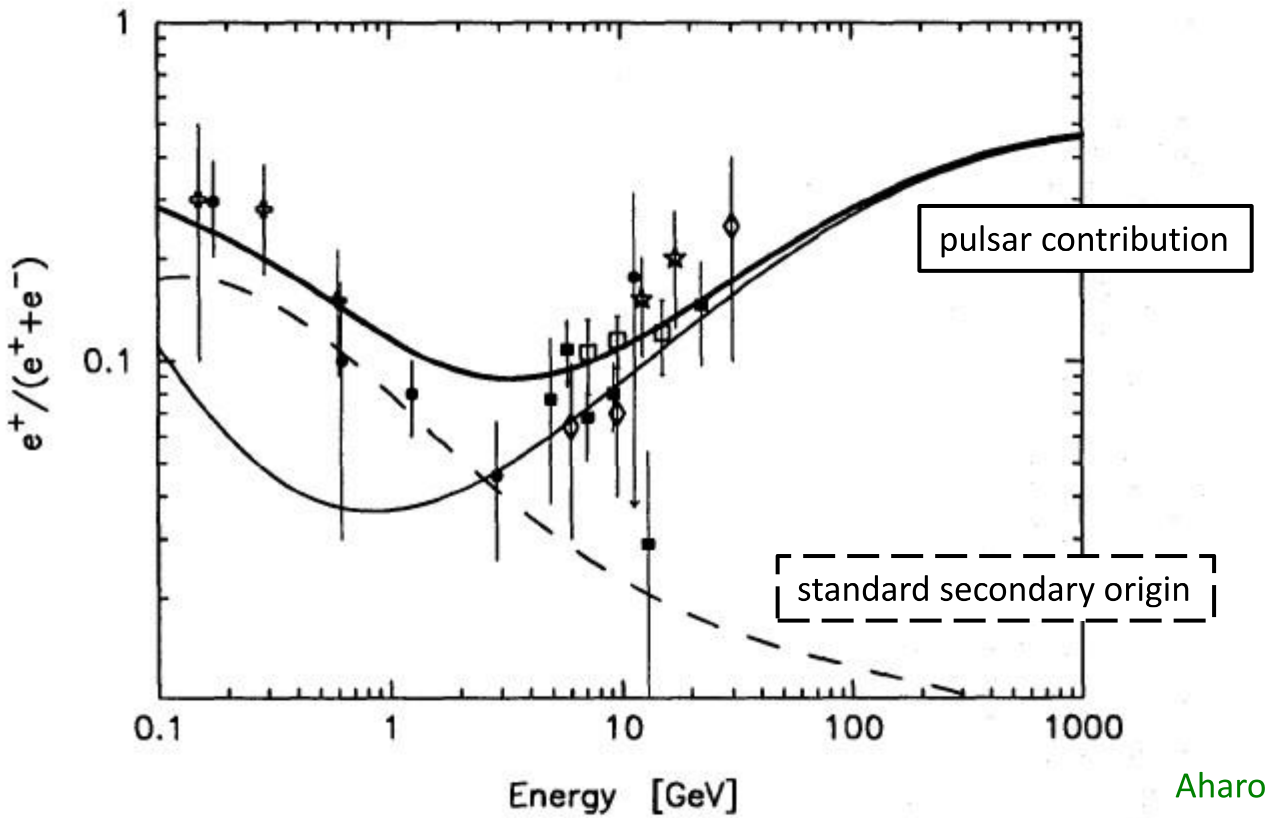
This analysis thus suggests that the excess exists with respect to transport models pre-AMS, not in itself, i.e. positrons could be pure secondary (no DM origin!) provided f_{loss} has the right dependence on energy

3.c CR transport: possible pulsar positron contribution

in the case of positrons, it had been predicted that nearby recent pulsars (e.g. Geminga) could possibly provide a primary source of positrons, leading an increasing positron fraction at high energies (pulsar wind: $e^+ \sim e^-$)… as observed!



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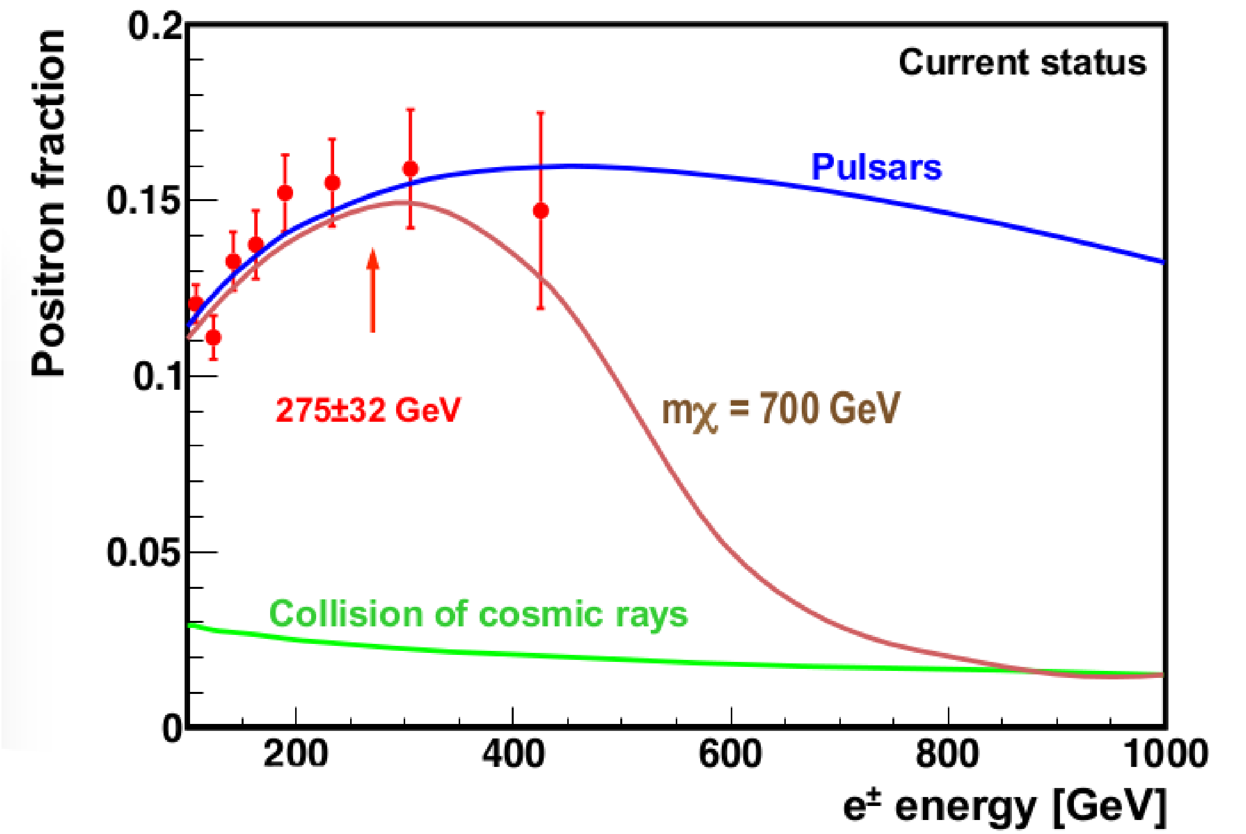
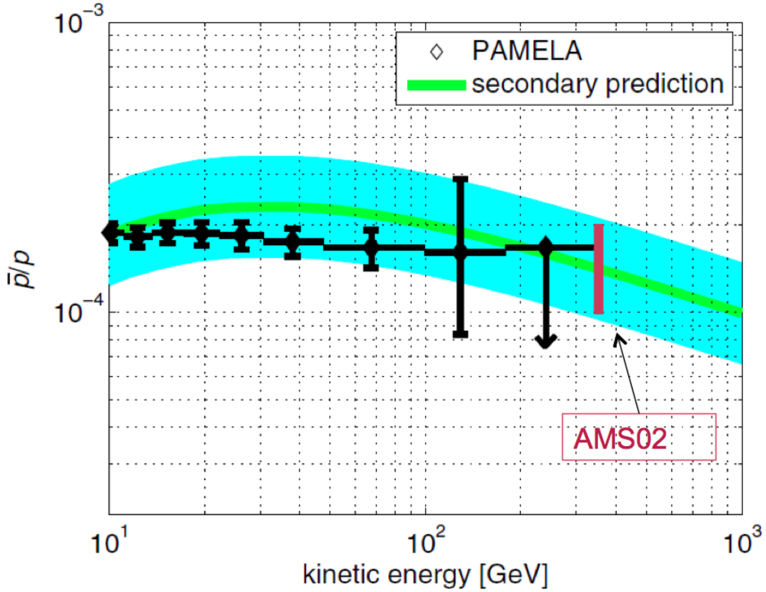
3.c CR transport: current status



AMS 15

current data cannot distinguish between a pulsar contribution, a contribution of leptophilic dark matter and a pure secondary origin….

3.c CR transport: anti-proton data



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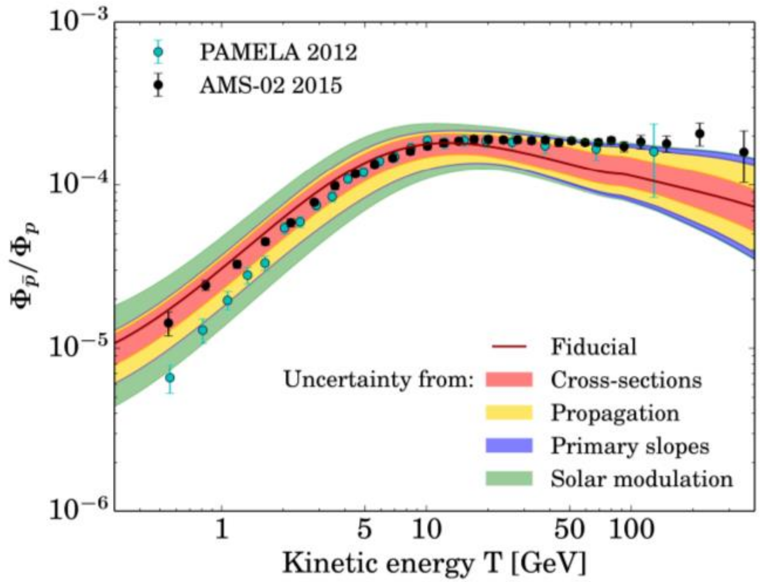

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… the latest anti-proton data is also consistent with a pure secondary origin…

Summary

3. Astroparticle physics in the GeV – PeV range

a. Supernovae as cosmic ray sources

… Supernovae remnants appear as the best candidate for the source of cosmic rays below 10^{17}eV: energy output in principle sufficient…

… crucial questions: can supernovae accelerate particles to Z x a few PeV?

… a major question for theorists and a prime objective for future observatories: find a PeVatron

… current data indicate that the bulk of the VHE emission in some SNR is dominated by leptons, while in others by hadrons…

b. Connection to the origin of Ice Cube neutrinos

… starbursts galaxies behave as calorimeters for protons energies below a few PeV: all the energy going into hadrons is transferred to gamma-rays and neutrinos through pion production…

… a direct connection to the supernova origin of cosmic rays, which nicely explains the origin of Ice Cube neutrinos…

… or a subset thereof? in particular, where is the expected turn-over at <PeV energies?

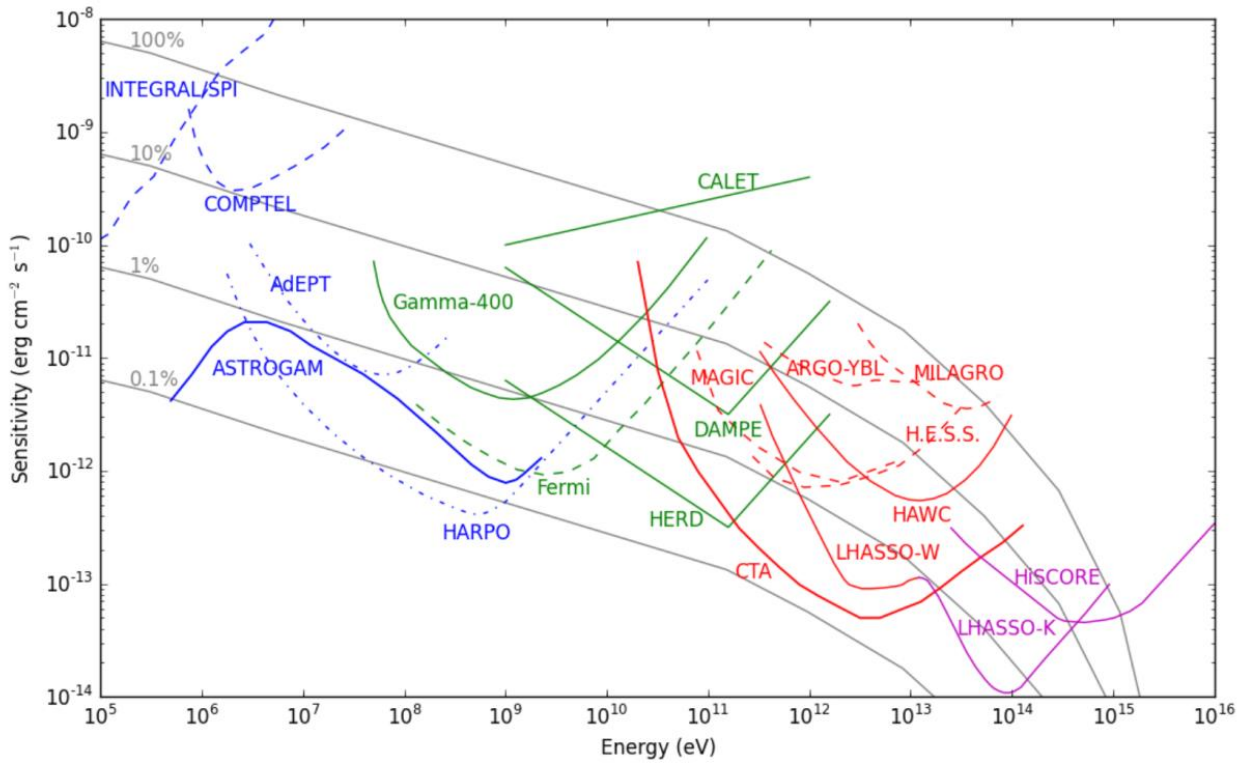
c. Transport of cosmic rays and the anti-matter 'anomalies'

… transport of cosmic rays in the Galaxy involves many ill-known processes (diffusion, advection, re-acceleration etc.)…

… so far, positron and anti-proton spectra are consistent with a secondary origin, with possibly a nearby pulsar contribution to the positron spectra: no need for exotic dark matter!

Some experimental perspectives

Photons:



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Neutrinos: a 10x Ice Cube is being projected, also KM3NET (~a few times Ice Cube) in the North

UHECR: situation not clear, developments projected at Auger, Telescope Array, possible deployment of the giant EUSO on the space station, with a clear need for better statistics and accurate chemical composition measurement…