Some physics and astrophysics of very high energy cosmic rays

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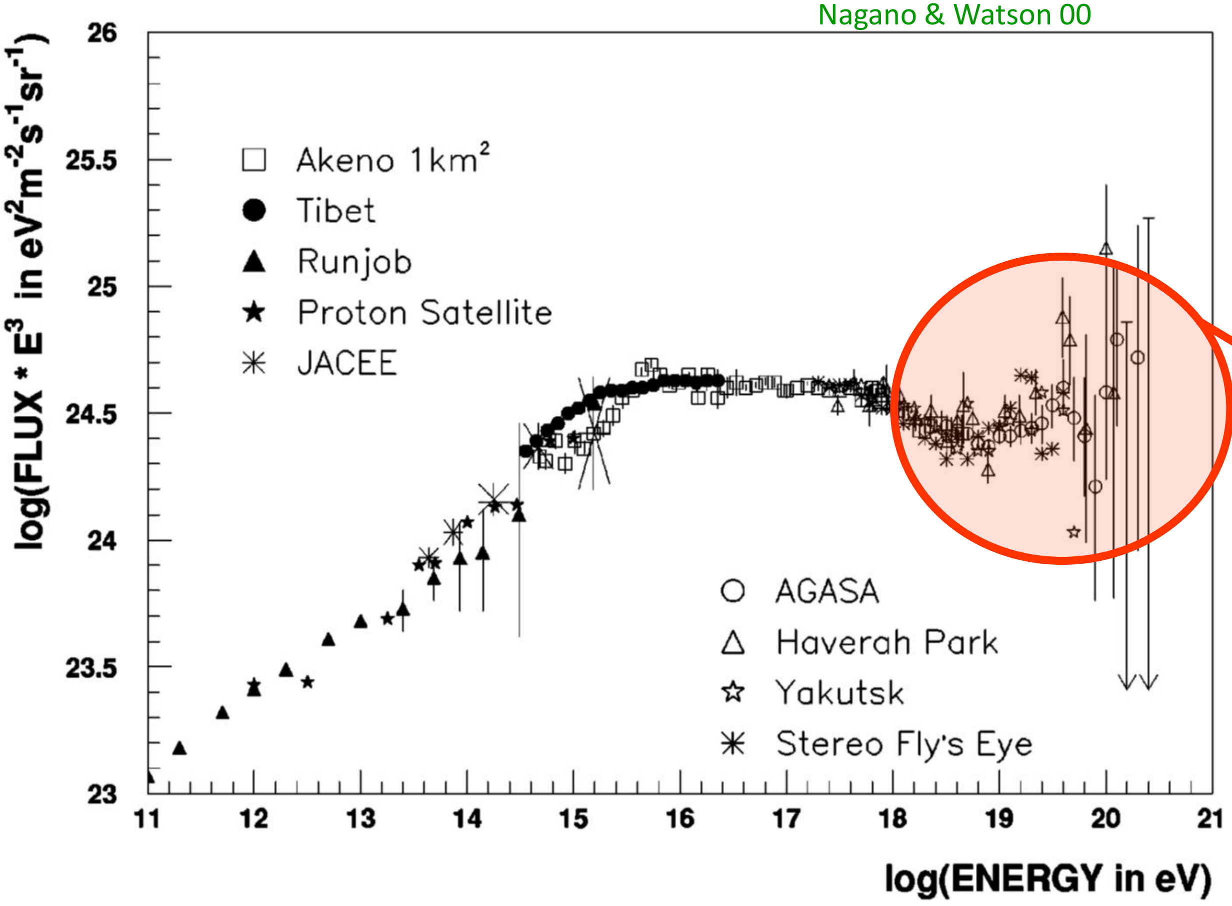
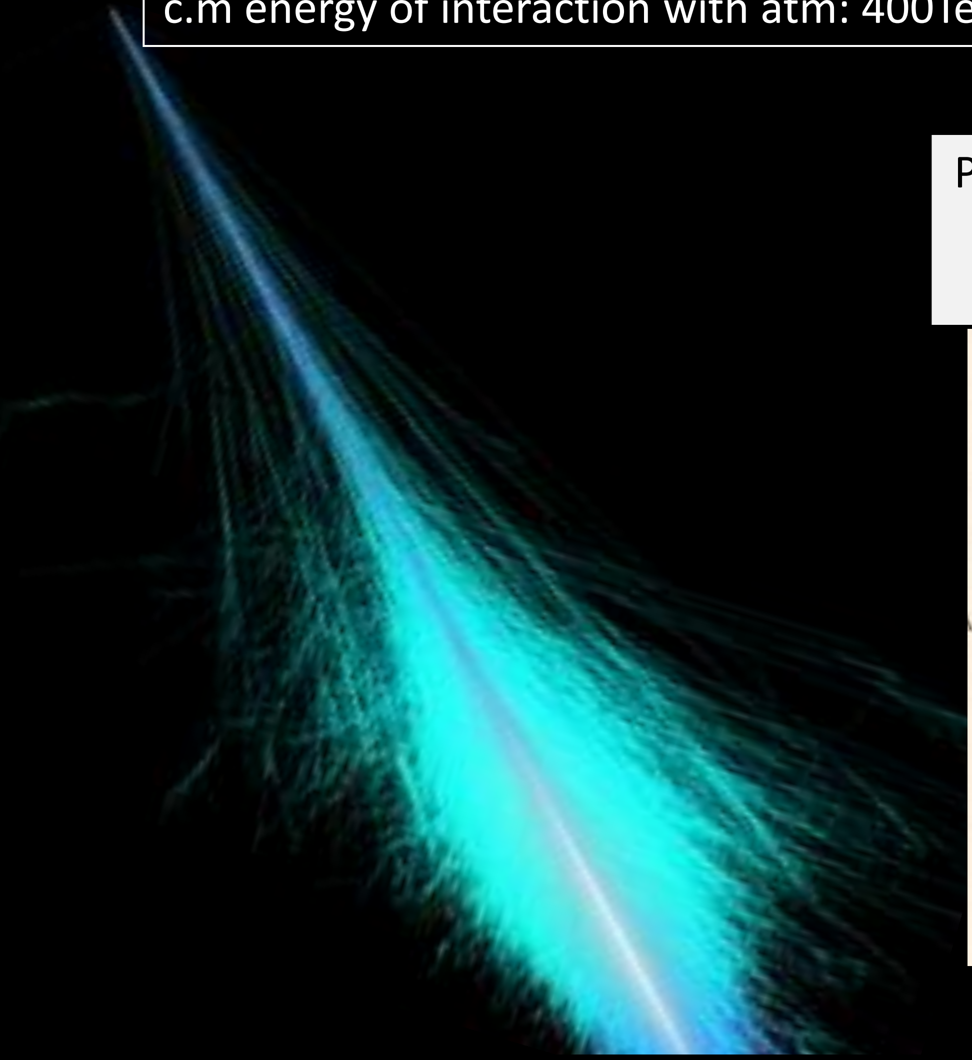
Nagano & Watson 00



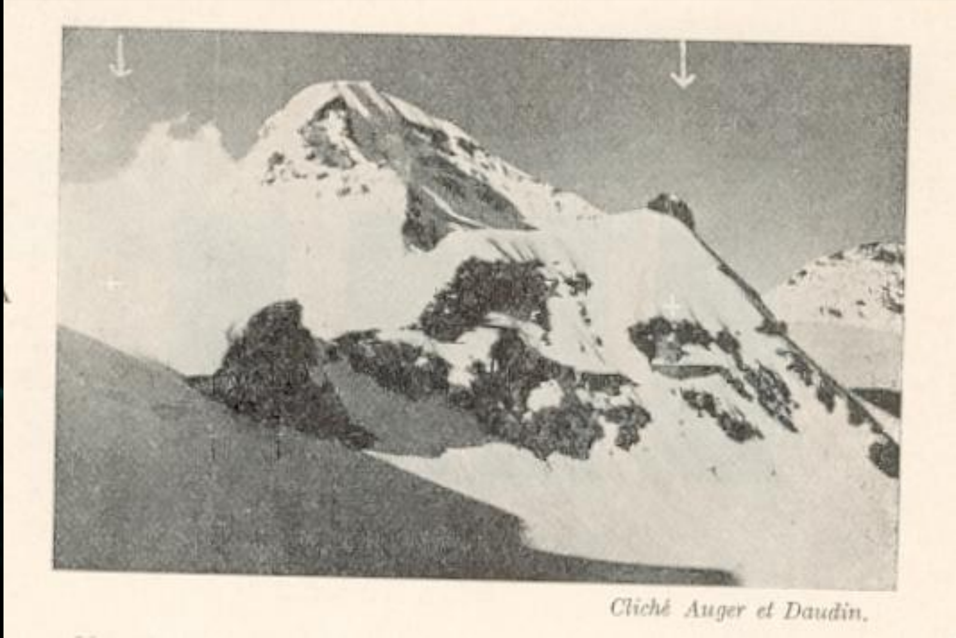
very small flux at UHE:
1/km^2/century at 10^{20}eV

Introduction - giant air showers

c.m energy of interaction with atm: 400TeV!



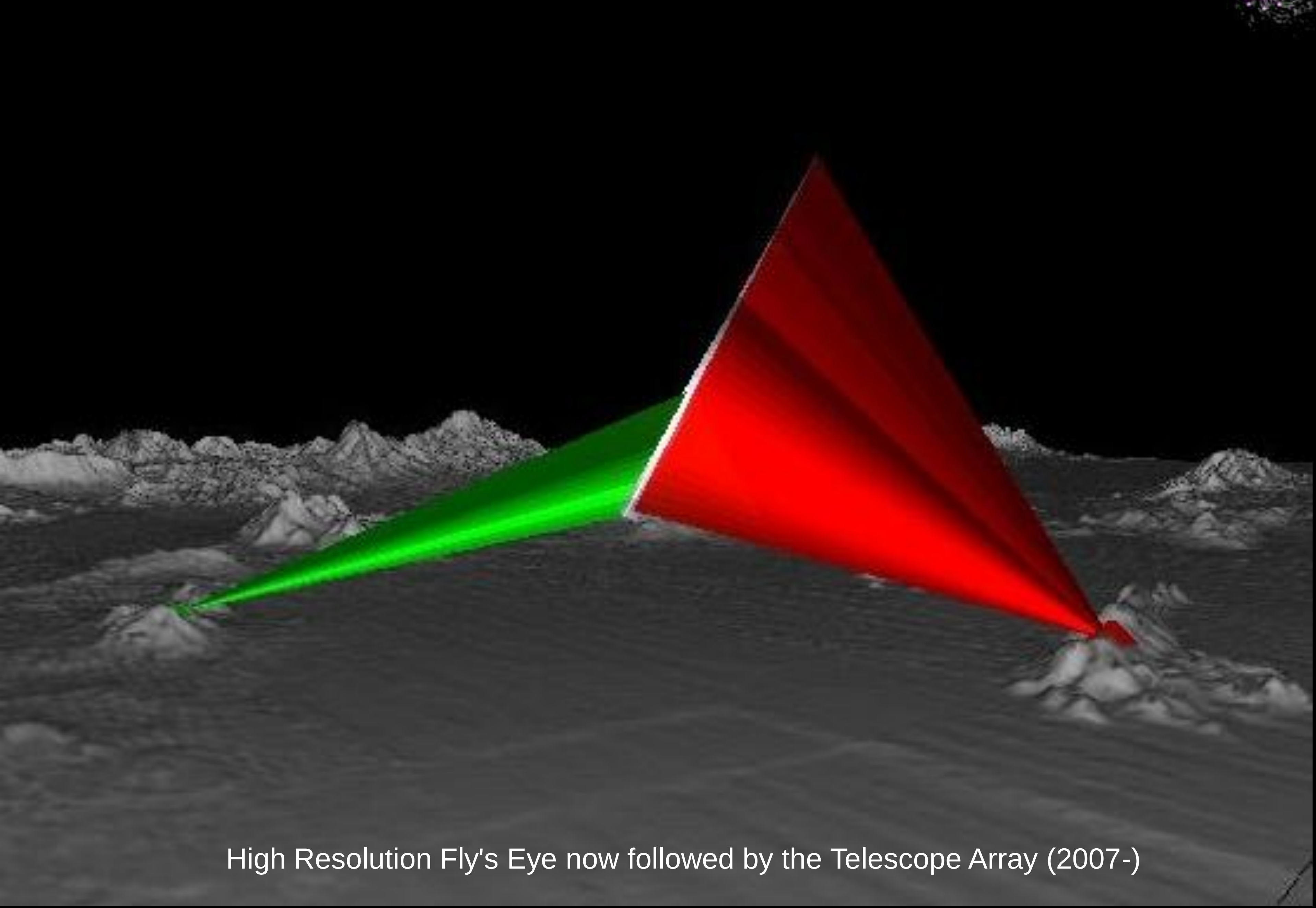
P. Auger (1938): timing coincidence experiments lead tothe detection of giant air showers with energy $\gtrsim 10^{15}$ eV…



Cliché Auger et Daudin.

at 10^{20}eV: several km^2 on the ground

Introduction - Fluorescence telescopes



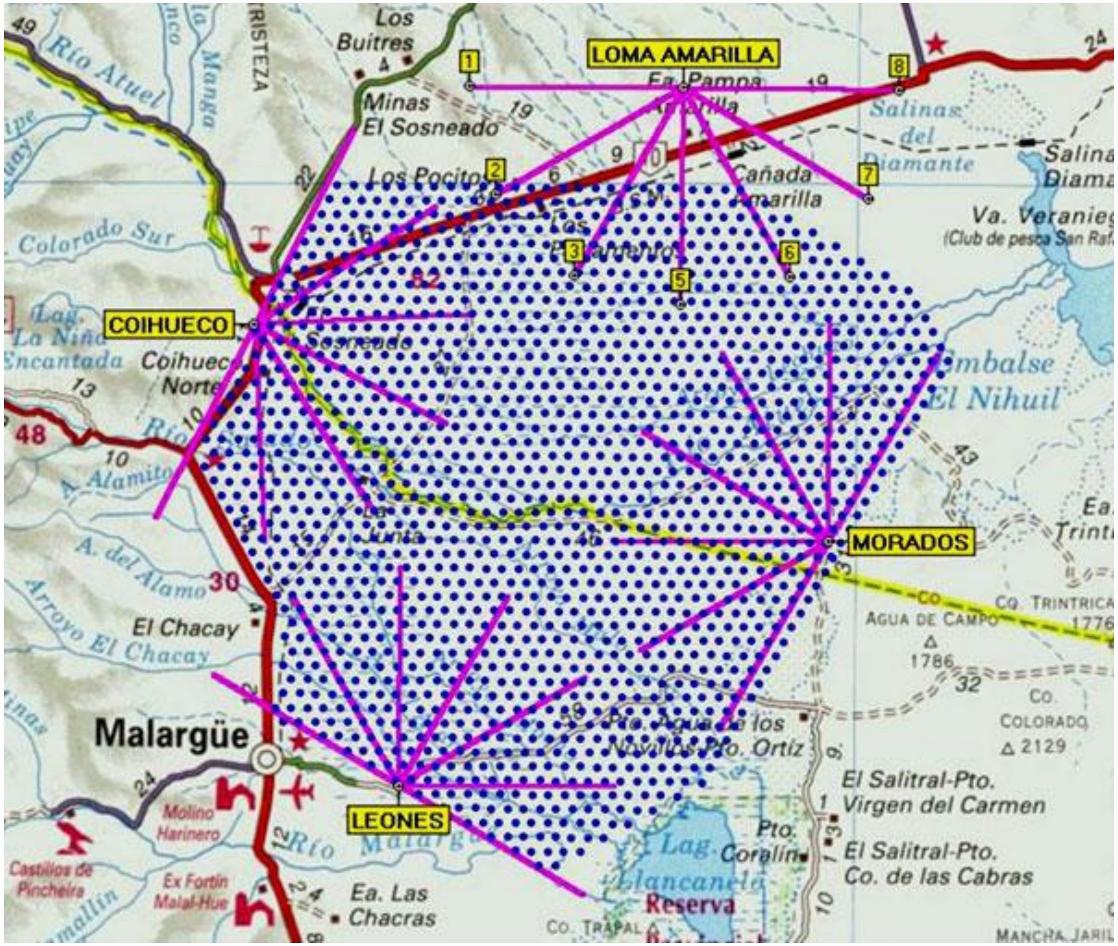
High Resolution Fly's Eye now followed by the Telescope Array (2007-)

Introduction - Pierre Auger Observatory (2005-)

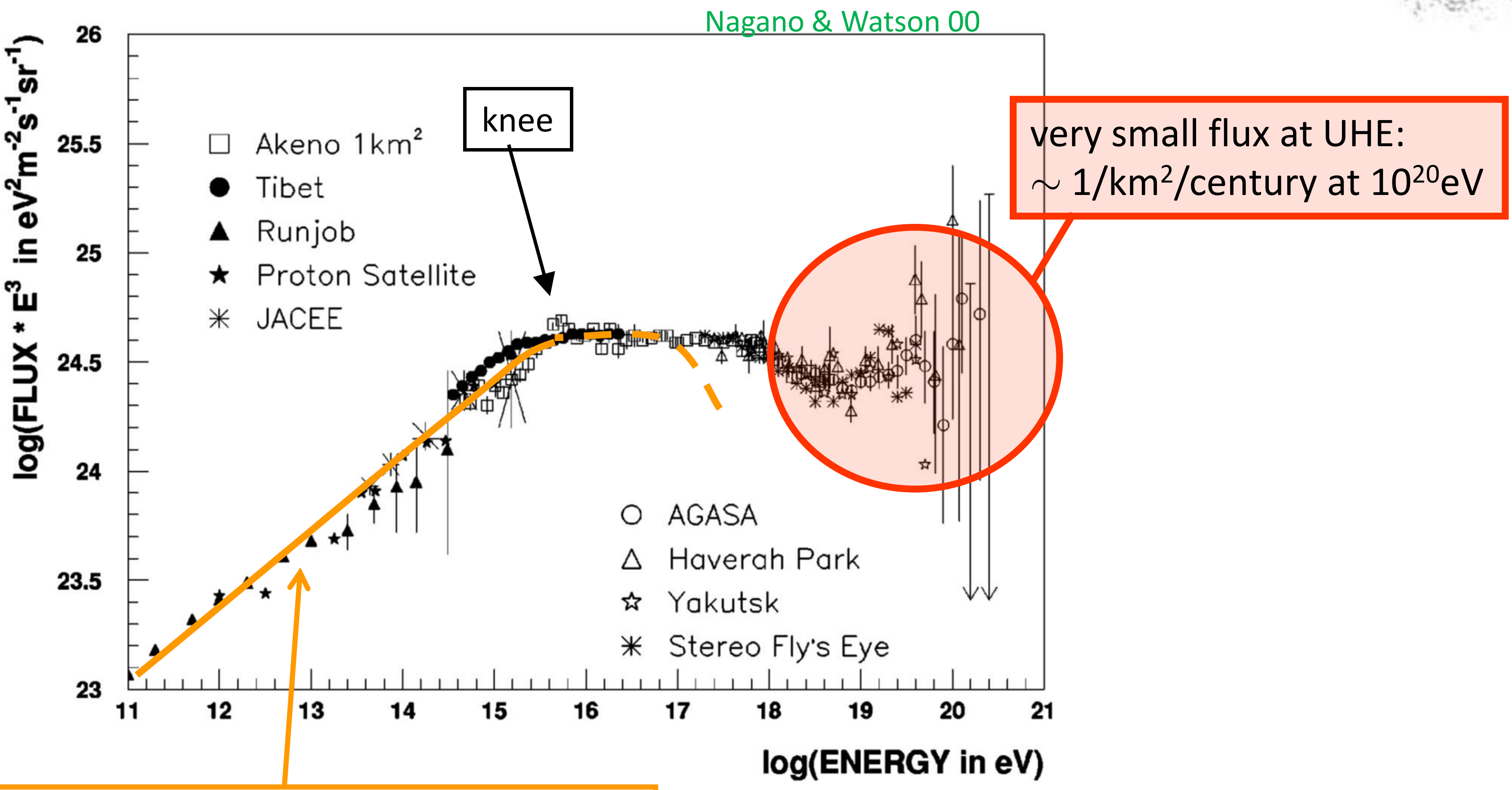
The Pierre Auger Observatory:

→ **the largest cosmic ray detector ever built : about 3000 km^2 !**

→ a combination of ground detectors and fluorescence detectors…



Introduction - all particle CR spectrum

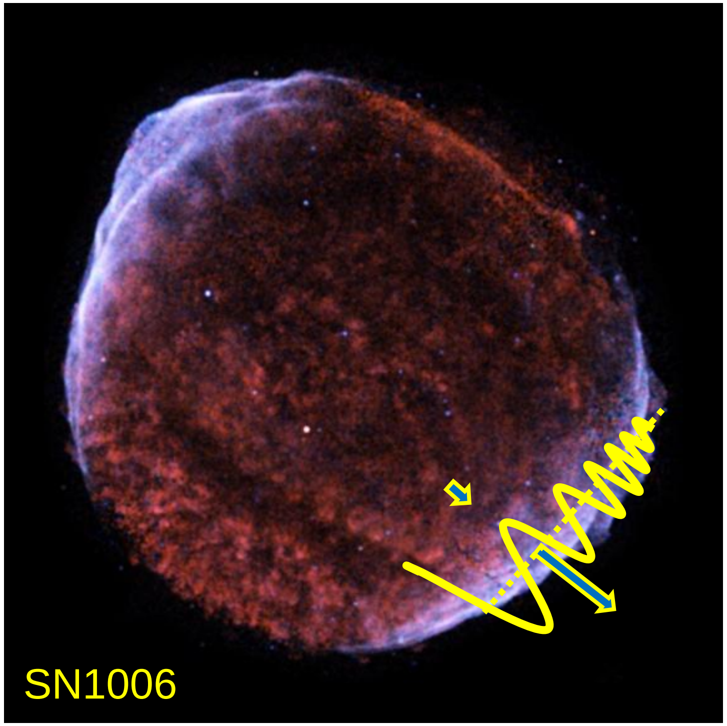


very small flux at UHE: $\sim$ 1/km^2/century at 10^{20}eV

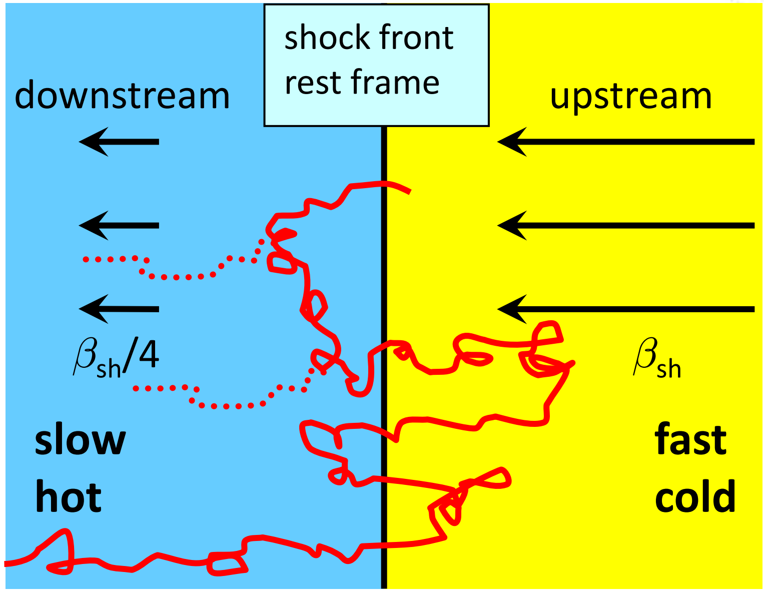
'low' energy cosmic rays likely originate in Galactic supernovae remnants …

Introduction - Galactic cosmic rays

Axford et al. 77, Krimskii 77, Bell 78, Blandford & Ostriker 78



model for the forward shock



particles experience systematic energy gain in each cycle u→d→u around the shock... accelerating agent: ***E*** *=* *-* $\boldsymbol{\beta}$ *x* ***B***

Energetics:

→ global CR luminosity: $\dot{N}_{\rm SN} \sim 10^{-2}\,{\rm yr}^{-1}$ and $E_{\rm CR/SN} \sim 10^{50}\,{\rm erg}$

→ confinement time: $\tau_{\rm conf} \sim 10^{7}\,{\rm yr} \quad ({\rm at} > 1{\rm GeV})$ (measured!)

→ confinement volume: $V_{\rm conf} \sim \pi\,(10\,{\rm kpc})^2 \times 1\,{\rm kpc} \sim 10^{67}\,{\rm cm}^3$

→ energy density: $\epsilon_{\rm CR} \sim \dfrac{E_{\rm CR/SN}\dot{N}_{\rm SN}\tau_{\rm conf}}{V_{\rm conf}} \sim 1\,{\rm eV/cm}^3$ **OK!**

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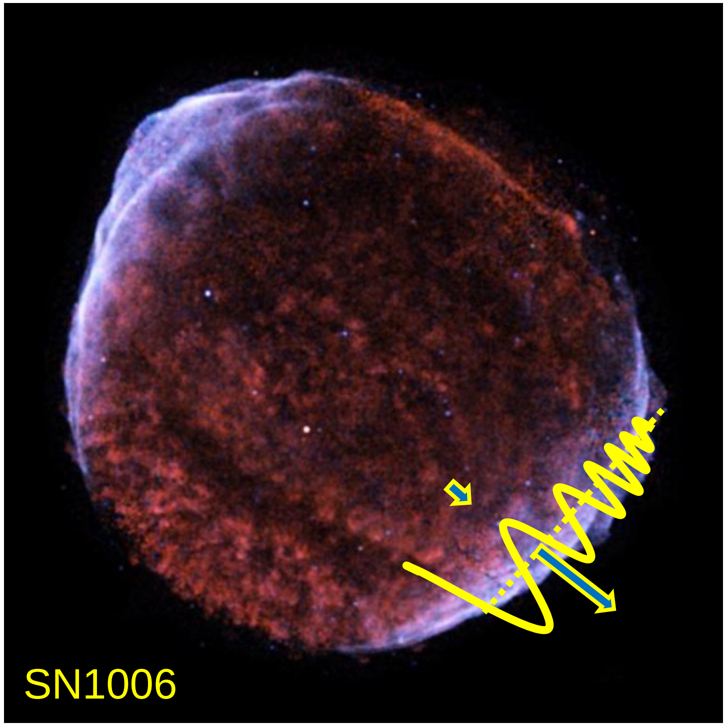

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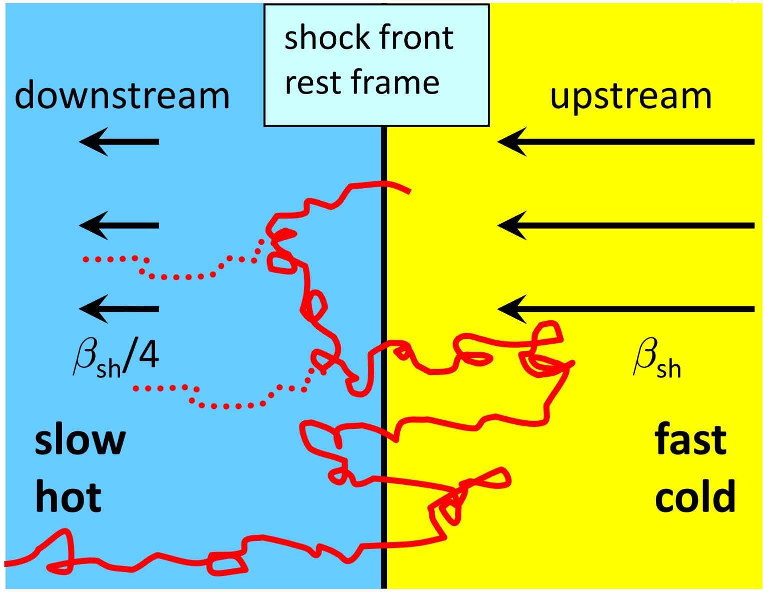


particles experience systematic energy gain in each cycle u → d → u around the shock… accelerating agent: ***E* = - *β* x *B***

Maximal energy:

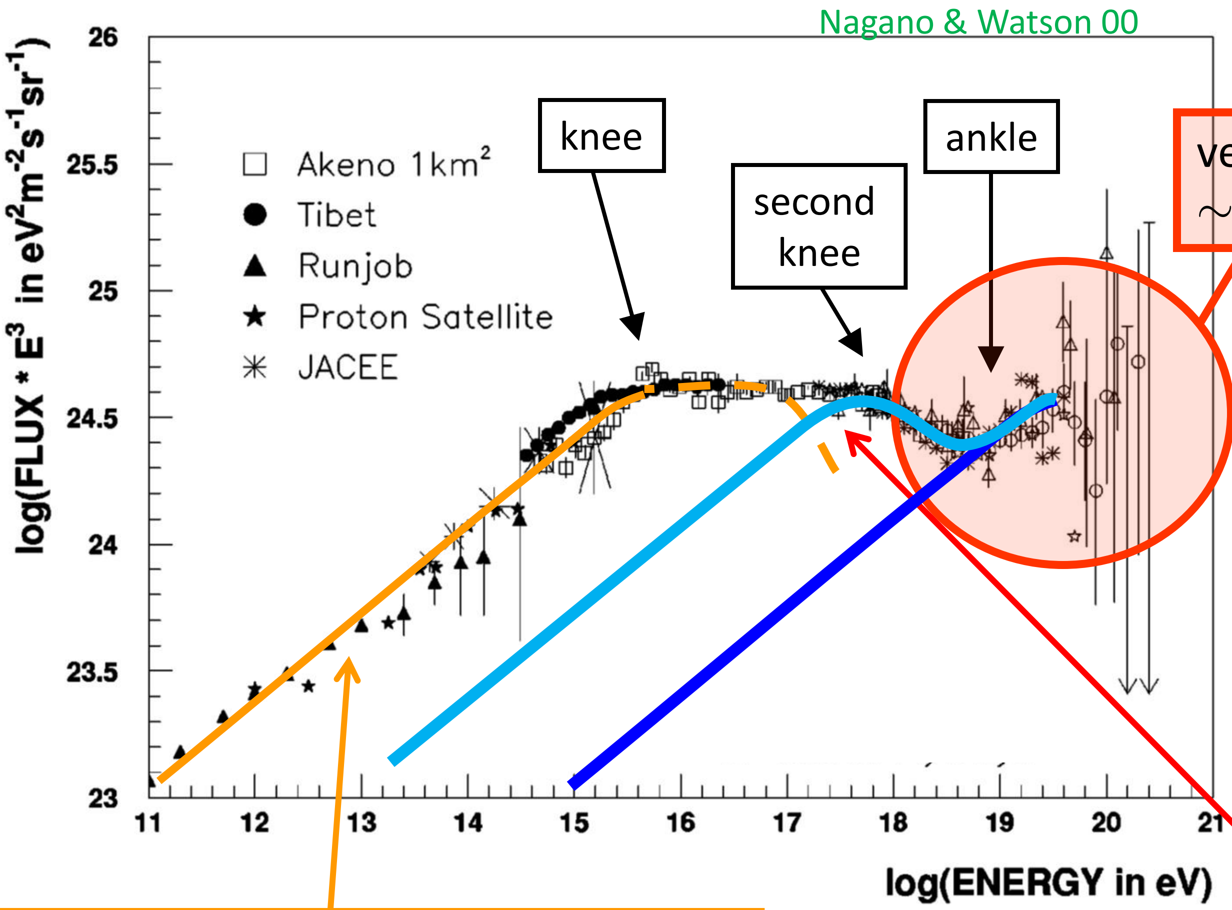
→ acceleration timescale: $t_{\rm acc} \equiv \dfrac{t_{\rm u} + t_{\rm d}}{\Delta E/E} \approx \dfrac{t_{\rm scatt}}{\beta_{\rm sh}^2}$

→ at the Bohm limit: $t_{\rm scatt} \sim t_{\rm L},\quad t_{\rm acc} \leq \dfrac{R}{\beta_{\rm sh}c} \Rightarrow E_{\rm max,p} \sim 10\,{\rm TeV}\dfrac{B}{1\mu{\rm G}}$

Lagage & Césarsky 83

→ most of the action today: how to amplify the field by ~10-100 to reach PeV … fine structure of the acceleration process… transport of the cosmic rays in the Galactic magnetic field vs observations (spectrum + anisotropies)

Introduction - all particle CR spectrum



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

‘low’ energy cosmic rays likely originate in Galactic supernovae remnants …

$\rightarrow$ energetics globally OK,
$\rightarrow$ spectrum globally OK,
$\rightarrow$ maximal energy $\sim$ OK?
$\rightarrow$ gamma-ray astronomy OK

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

Many questions ... a few hints...

- **What is the source of ultrahigh energy cosmic rays ?**

  → **leading contenders: gamma-ray bursts, powerful AGN, young pulsars?**

  → what is the fundamental acceleration process to ultrahigh energies?

- **Where does the cosmic ray spectrum stop?**

  → **HiRes, Auger and TA have detected a high energy cut-off at the expected location for the Greisen-Zatsepin-Kuzmin cut-off $\sim 5\ 10^{19}$ eV**

  [... fits well with all astrophysical models of UHECR origin,
  GZK cut-off , sources are distributed on cosmological scales...]

- **What are ultrahigh energy cosmic rays: protons, nuclei, photons, neutrinos?**

  → the giant air showers are typical of hadronic showers

  → **Yakutsk, HiRes TA see protons at UHE, Auger sees an increasing fraction of heavies...?**

  → light (small Z) vs heavy (large Z): large differences in terms of phenomenology!

- **Should we expect to see the source in the arrival directions of UHECR?**

  → what are the effects of the Galactic and extra-galactic magnetic fields?

  → no powerful source seen in the arrival directions of highest energy CR...?

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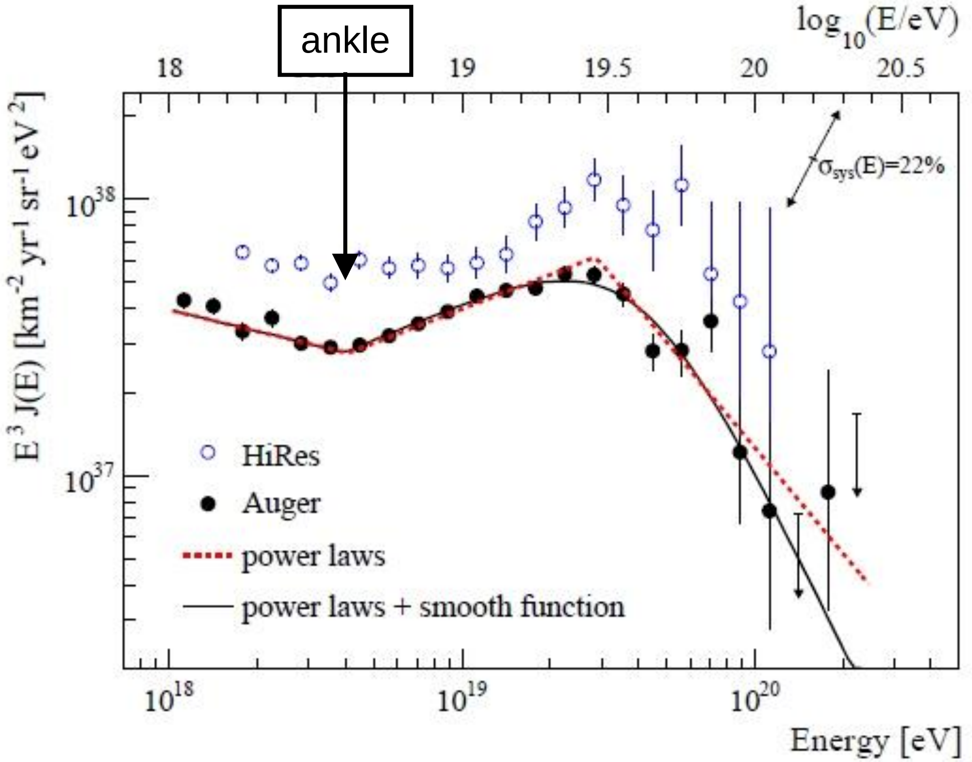


Auger 2010
HiRes 2010

Greizen-Zatsepin-Kuzmin cut-off: CMB becomes opaque to pion production through $p+\gamma_{cmb} \rightarrow \pi + p/n$ for $E \gtrsim 6\ 10^{19}$ eV

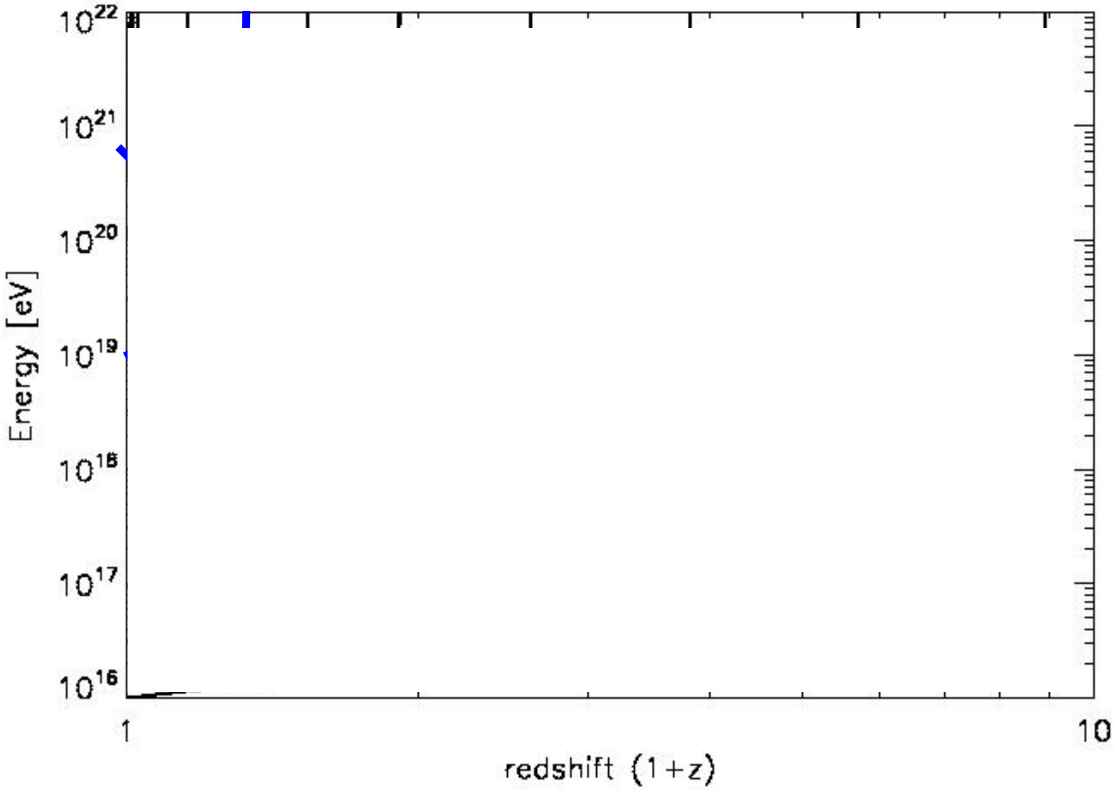
... detecting the GZK cut-off ⇔ UHECR are protons (or heavy nuclei) and sources are distributed on cosmological scales…

... **BUT** this cut-off might also represent the maximal energy at the source...

Greisen-Zatsepin-Kuzmin cut-off

Greisen 66, Zatsepin & Kuzmin 66

- GZK cut-off: the Universe becomes opaque to protons of energy > 6 10^{19} eV (in the cosmic rest frame) as a result of pion production on the CMB, with characteristic energy loss length 100 Mpc



- Consequence: **the source of: >10^{20} eV particles must lie within ∼100 Mpc**
  >4 10^{19} eV particles must lie within ∼1000 Mpc

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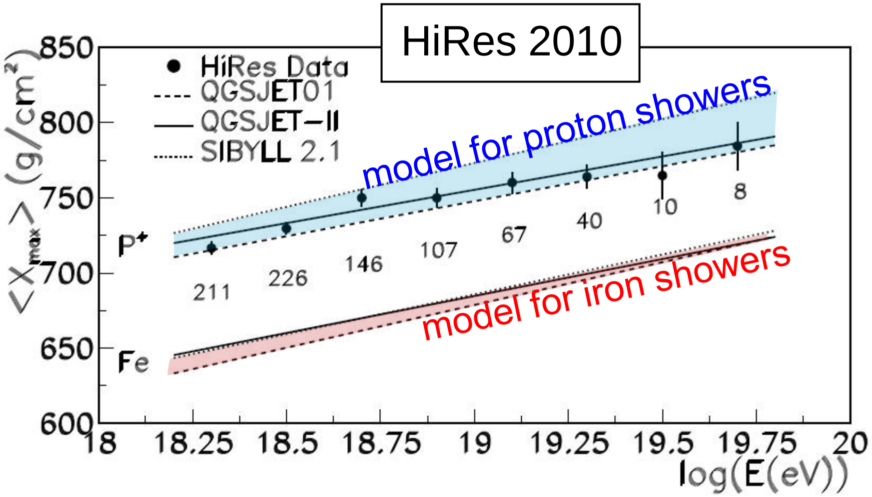
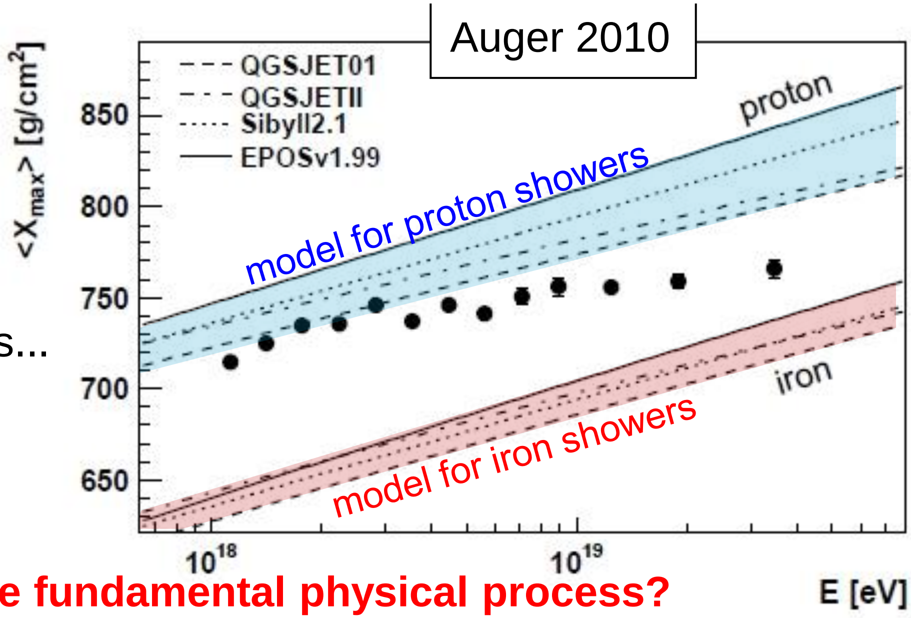
HiRes:

light composition above ankle



Auger:

composition becomes **heavier** above ankle...
also seen in shower fluctuations...
but various observables are inconsistent...



... discrepancy related to some fundamental physical process?
... a proton or iron composition bears a crucial impact on phenomenology...

→ any signal from arrival directions of UHECR ?

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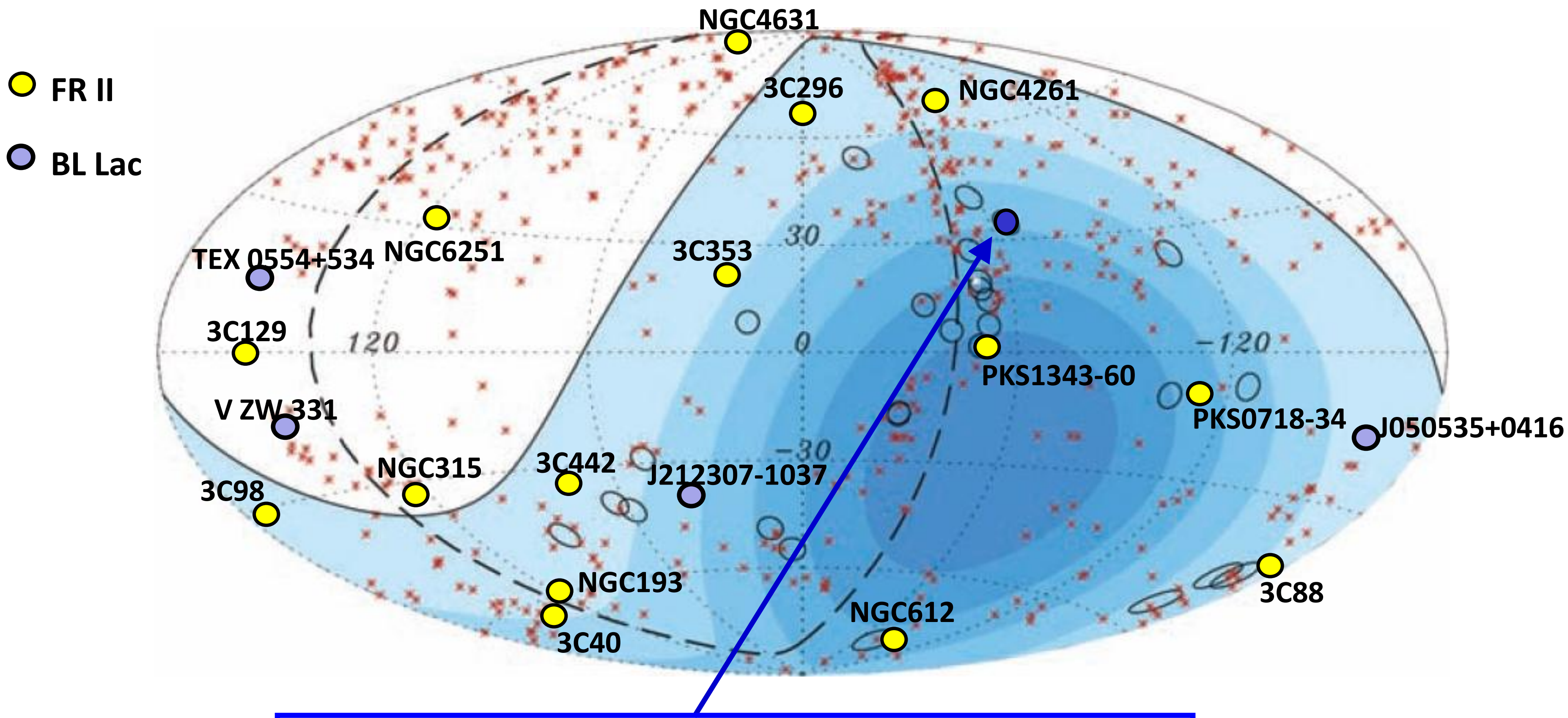
Arrival directions of Auger events

- Distribution on the sky of FR-II galaxies located within 130Mpc: (Massaglia 07)



highest energy PAO event : E = 1.48 ± 0.27 × 10^{20} eV

(not counting the systematic uncertainty on energy calibration: 22%)

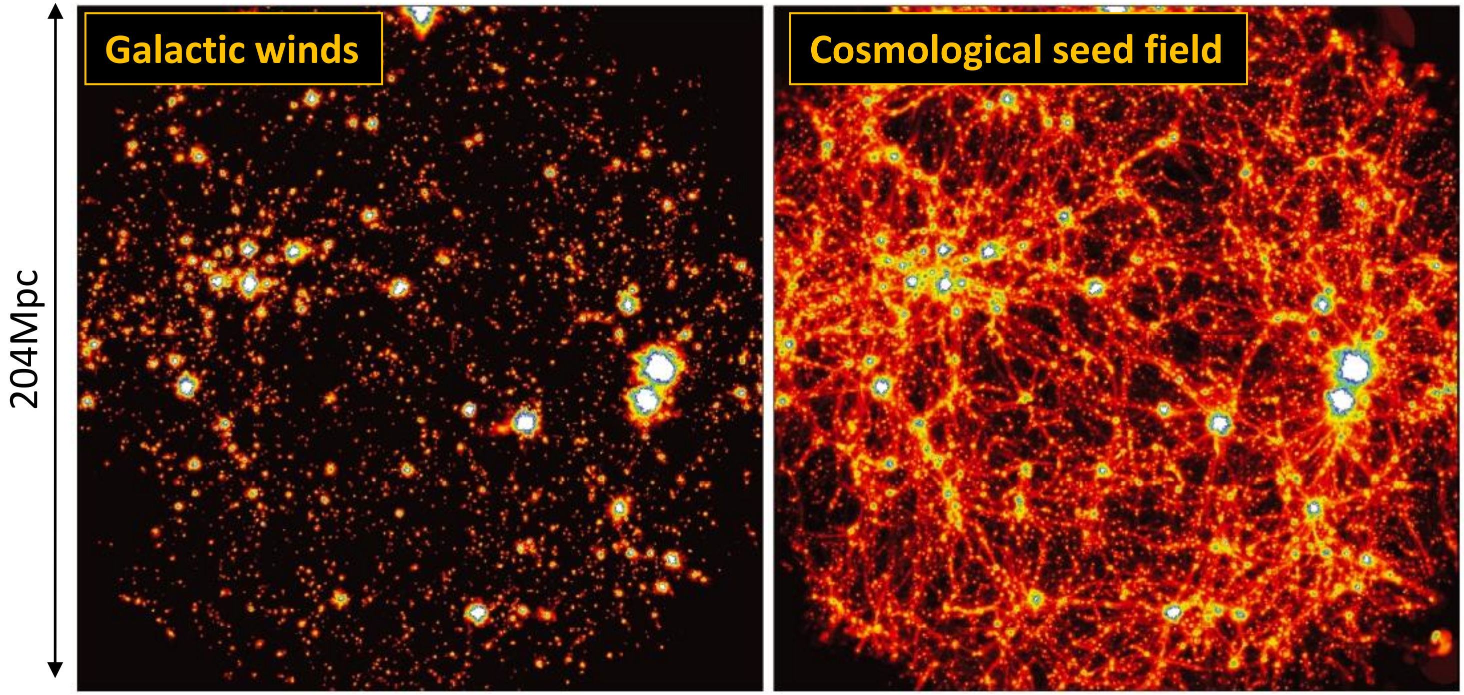
closest FRII: NGC4261, PKS1343-60, separation: 30°

closest blazar (with identified z): TEX0554+534, separation: 115°

Extra-galactic magnetic fields?

The origin of (extra-)Galactic magnetic fields is a long-standing problem… very little data on fields outside of galaxies, and many debated models: from inflation to recombination to structure formation…

… fields created at high redshifts are further processed and enhanced during the build-up of large scale structure (e.g. Miniati et al. 04, Dolag et al. 05)…



Donnert et al. 06

⇒ the magnetized IGM is expected to be highly inhomogeneous, patchy, with strength up to ~ 10^{-8} G in the filaments of large scale structure, much weaker in the voids...

Propagation – transport in extra-galactic magnetic fields

Ultra-high rigidities:

$$r_{\rm L} \simeq 100\,{\rm Mpc}\,Z^{-1}\left(\frac{E}{10^{20}{\rm eV}}\right)\left(\frac{B}{1\,{\rm nG}}\right)^{-1}$$

if B follows large scale structure:

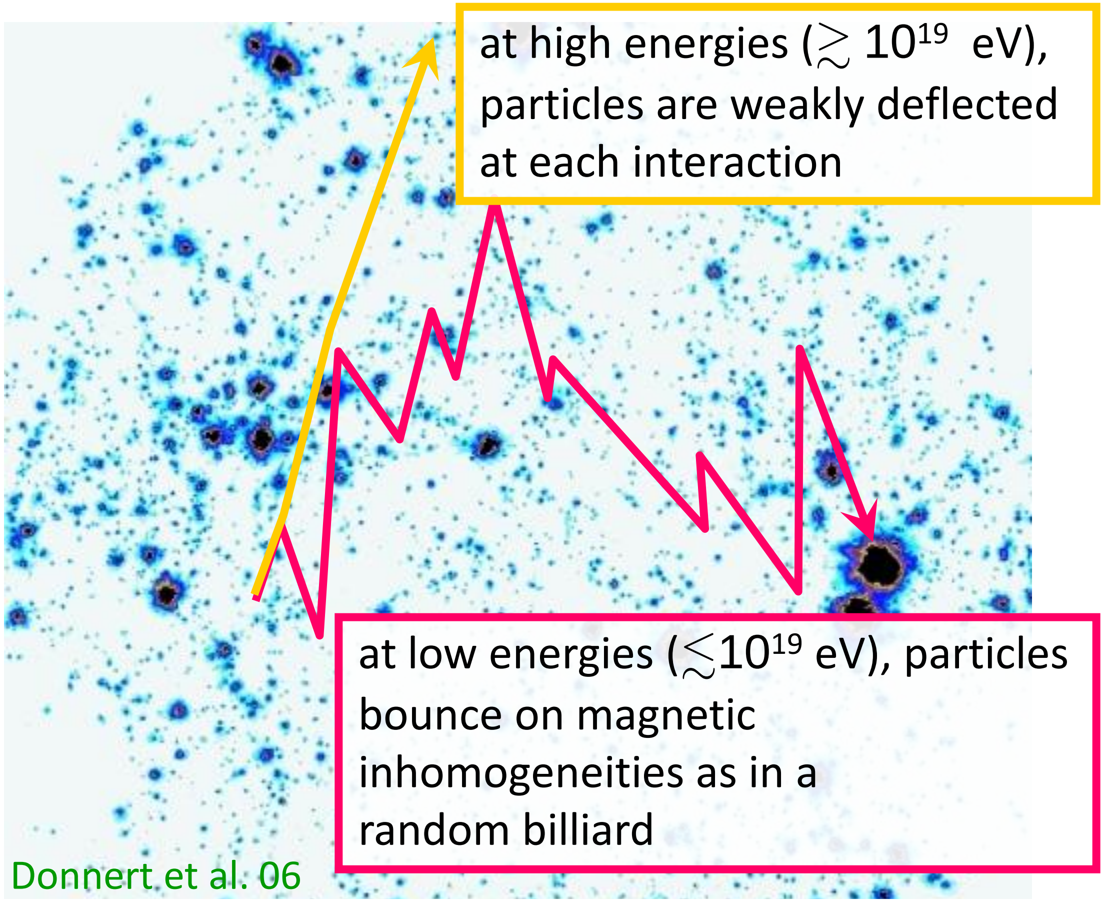
→ particles of different energies probe different structures…

→ at high energies, few interactions with small deflection:

$$\delta\theta_i^2 \simeq 1.7^\circ E_{20}^{-2} B_{-8}^2 \lambda_{0.1{\rm Mpc}} R_{1{\rm Mpc}}$$

per interaction, with typical mfp ~ 30Mpc (Kotera & ML 08)

⇒ a few deg total at Z 10^{20} eV over 100 Mpc…



at high energies ($\gtrsim 10^{19}$ eV), particles are weakly deflected at each interaction

at low energies ($\lesssim 10^{19}$ eV), particles bounce on magnetic inhomogeneities as in a random billiard

Donnert et al. 06

→ at low energies:

interesting diffusion process in the extra-galactic magnetic fields below ~ Z 10^{19} eV, with a possible magnetic horizon below ~ Z 10^{17}-10^{18} eV (ML 05, Aloisio et al. 05)

Expected angular deflection

Integrating over all sources at a given energy:

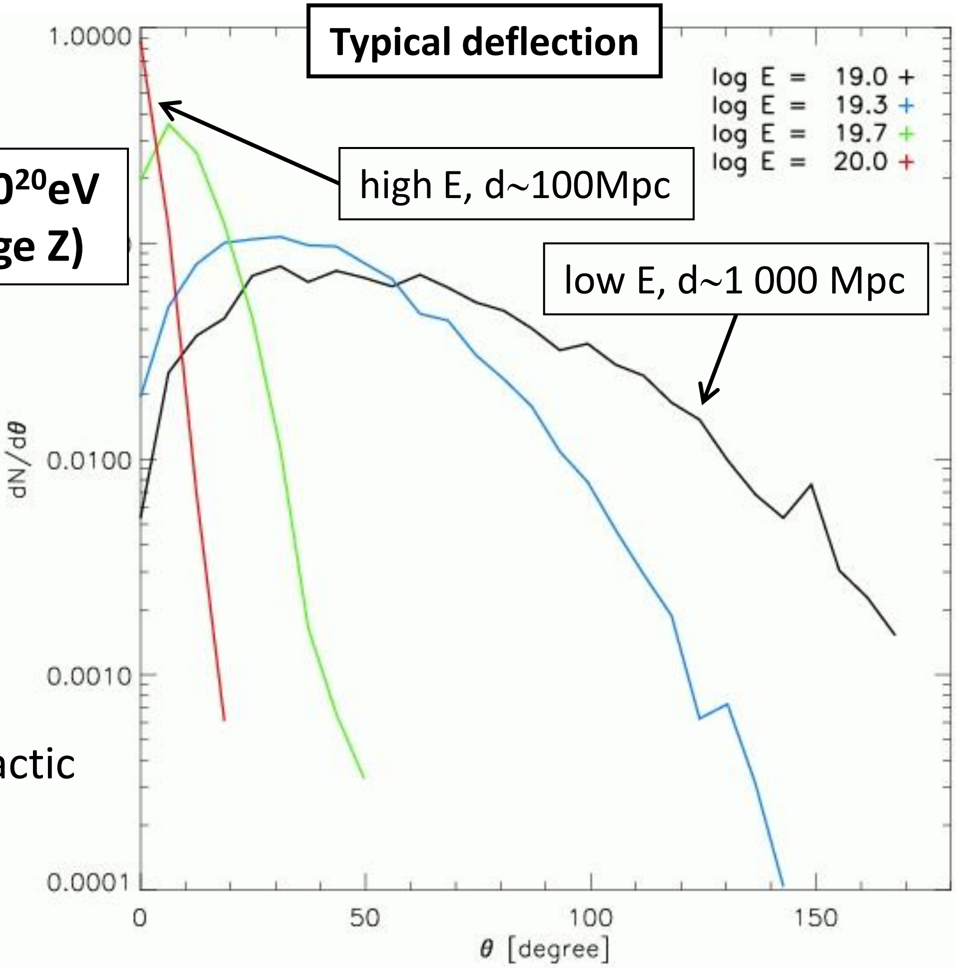
→ note that most of the flux comes from $l_{max}(E)$ (→ Olbers' paradox!)

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

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

⇒ near isotropy for E $\lesssim$ 3 10^{19}Z eV...
... small deflection above 5 10^{19}Z eV

→ deflection of similar magnitude in Galactic magnetic field…



Typical deflection

high E, d~100Mpc

low E, d~1 000 Mpc

so far:

→ current measurements indicate that UHECRs are extragalactic protons or nuclei…

→ whether one is dealing with protons or iron at UHE has drastic consequences for phenomenology...

p: few candidate sources, small angular deflection
Fe: more candidate sources, large angular deflection...

→ interpretation of anisotropies suggest that protons exist at UHE…

Many questions ... a few hints...

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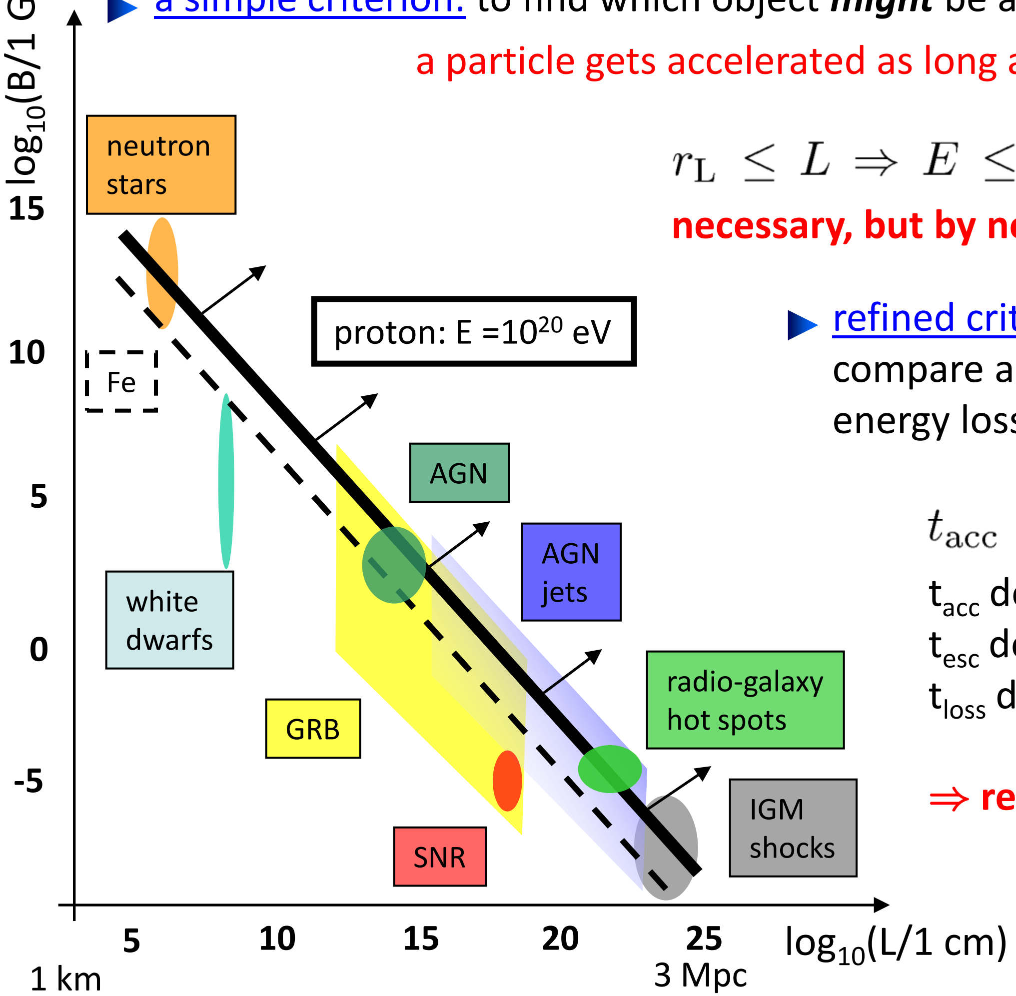
▶ What is the source of ultrahigh energy cosmic rays ?

▶ a simple criterion: to find which object *might* be a source of UHE cosmic rays:

a particle gets accelerated as long as it is confined in the source:



$$r_{\rm L}\ \leq\ L\ \Rightarrow\ E\ \leq\ 10^{20}\,{\rm eV}\,Z B_{\mu{\rm G}} L_{100\,{\rm kpc}}$$ Hillas 84

necessary, but by no means sufficient!

▶ refined criterion:

compare acceleration timescale with energy loss timescale and escape timescale

$$t_{\rm acc}\ \leq\ t_{\rm loss},\quad t_{\rm esc}$$

t_{acc} depends on acceleration mechanism...

t_{esc} depends on magnetic field...

t_{loss} depends on environment...

⇒ requires an object by object study...

Norman et al. 95

... magnetars, gamma-ray bursts and giant radio-galaxies are promising candidates...

→ any signal from arrival directions of UHECR ?

Acceleration... general schemes

Particle dynamics: $$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = q\left(\mathbf{E} + \mathbf{v}\times\mathbf{B}/c\right)$$

Motional electric field: $\mathbf{E} \simeq -\mathbf{v}_{\rm pl}\times\mathbf{B}/c$ (v_{pl} plasma velocity)

→ acceleration timescale $t_{acc} \geq r_L/v_{pl}$ (+ subtle effects when $v_{pl} \sim c$)

→ need to 'push' particle along E, across B (→ Lyutikov & Ouyed 07)

→ e.g.: + stochastic interactions with waves Fermi 49

slow in non-relativistic limit: $t_{acc} \propto t_{scatt} / \beta_A^2$! (e.g. O'Sullivan et al. 10)

\+ shock diffusive acceleration

slow at non-relativistic shocks: $t_{acc} \propto t_{scatt}/\beta_{sh}^2$

inefficient for UHE in ultra-relativistic limit ?

efficient at mildly relativistic shocks with $\beta_{sh}\gamma_{sh} \sim 1$?

\+ shear acceleration (requires scattering or force)

e.g. Rieger et al. 07, Lyutikov & Ouyed 07

\+ magnetized rotators (push through drift or inertia effects)

e.g. Bell 92, Arons 03, Rieger & Aharonian 09, Istomin & Sol 09

Some other possibilities:

→ e.g.: reconnection... e.g. de Gouveia dal Pino & Lazarian 05, Giannios 10, Hoshino 12..

ponderomotive force of coherent waves (wakefield)...

Chen & Tajima 02

Acceleration… shock acceleration

Particle dynamics: $\dfrac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = q\left(\mathbf{E} + \mathbf{v}\times\mathbf{B}/c\right)$

Motional electric field: $\mathbf{E} \simeq -\mathbf{v}_{\rm pl}\times\mathbf{B}/c$ ($v_{\rm pl}$ plasma velocity)

→ acceleration timescale $t_{\rm acc} \geq r_{\rm L}/v_{\rm pl}$ (+ subtle effects when $v_{\rm pl} \sim c$)

⇒ **relativistic flows to reach UHE…**

Energy output of a source:

→ to match the flux above 10^{19} eV, $\dot\epsilon \approx 0.5\times 10^{44}\,\mathrm{erg/Mpc^3/yr}$ (e.g. Katz et al. 10)

→ per source, assuming it is steady: $L_{\rm UHECR} \approx 10^{41}\,\mathrm{erg/s}\;\, n_{-5}^{-1} \quad (n\,\mathrm{in\,Mpc^{-3}})$

→ per transient source: $E_{\rm UHECR} \approx 10^{50}\,\mathrm{erg}\;\,\dot n_{-6} \qquad (\dot n\,\mathrm{in\,Mpc^{-3}yr^{-1}})$

⇒ shock dissipation as an ideal mechanism to channel a sizable fraction of the source luminosity above 10^{19} eV…

(note that if $>10^{19}$eV are heavy nuclei, UHE baryon luminosity bound increases by >> 1…)

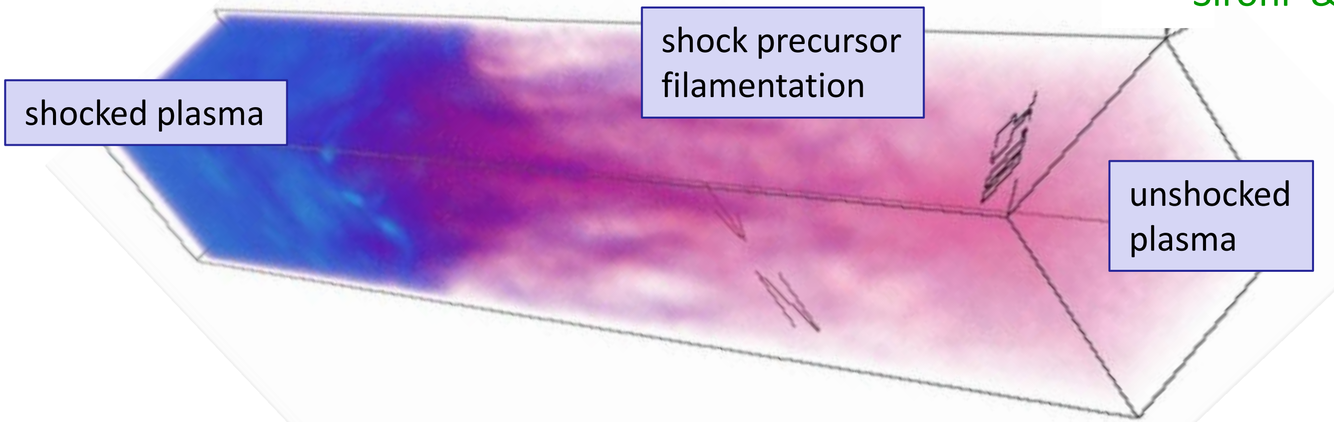
Acceleration at relativistic collisionless shock waves...

→ the shock wave moves about as fast as the accelerated particle!

e.g. Achterberg et al. 01

→ Fermi acceleration appears to work in unmagnetized ultra-relativistic shocks... how does this work for realistic astrophysical shocks of various magnetization and for mildly relativistic shocks?

Spitkovsky 08, Martins et al. 09, Sironi & Spitkovsky 09, 11, 13



→ performance (controlled by the acceleration timescale):

Pelletier, M.L., Marcowith 09; M.L.& Pelletier 11

$t_{acc} \sim \min(r_{L,0}/\gamma_b c\, ,\, r_L^2 / l_{\delta B}\, \gamma_b^2 c)$ with $r_{L,0}$ measured in background field

⇒ no Bohm scaling in self-generated turbulence...

⇒ max proton energy ~ 10^{17}eV for $\gamma \sim 300$...

⇒ optimal accelerating machines:

mildly relativistic shocks (e.g. internal shocks with $\gamma \sim 3$) ?

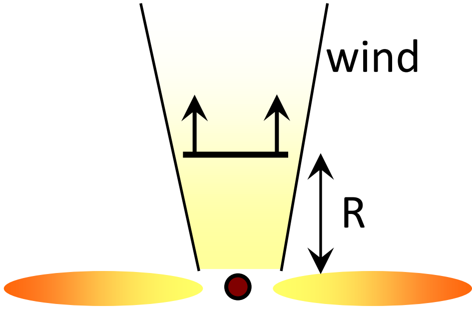
Acceleration – a luminosity bound

(Lovelace 76, Norman et al. 95, Waxman 05, Aharonian et al. 02, Lyutikov & Ouyed 05, M.L. & Waxman 09)

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

    A >> 1, A ~ 1 at most:

    - for non-relativistic Fermi I, A ~ g/β_{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

Seyfert galaxies: $L_{bol} \sim 10^{43}$-10^{45} ergs/s

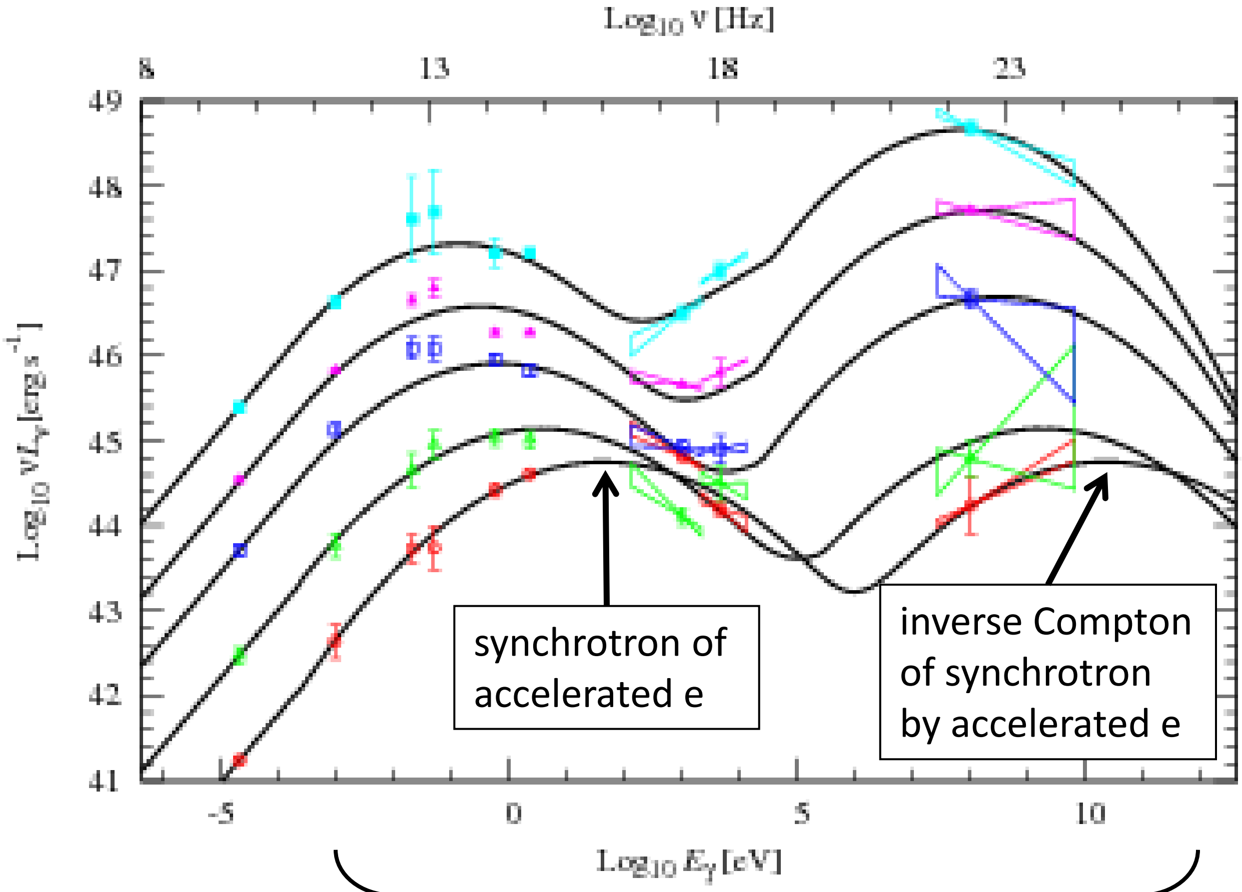
high luminosity AGN: $L_{bol} \sim 10^{46}$-10^{48} ergs/s

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

⇒ only most powerful AGN jets, GRBs or magnetars for UHE protons...

Acceleration in giant radio-galaxies?

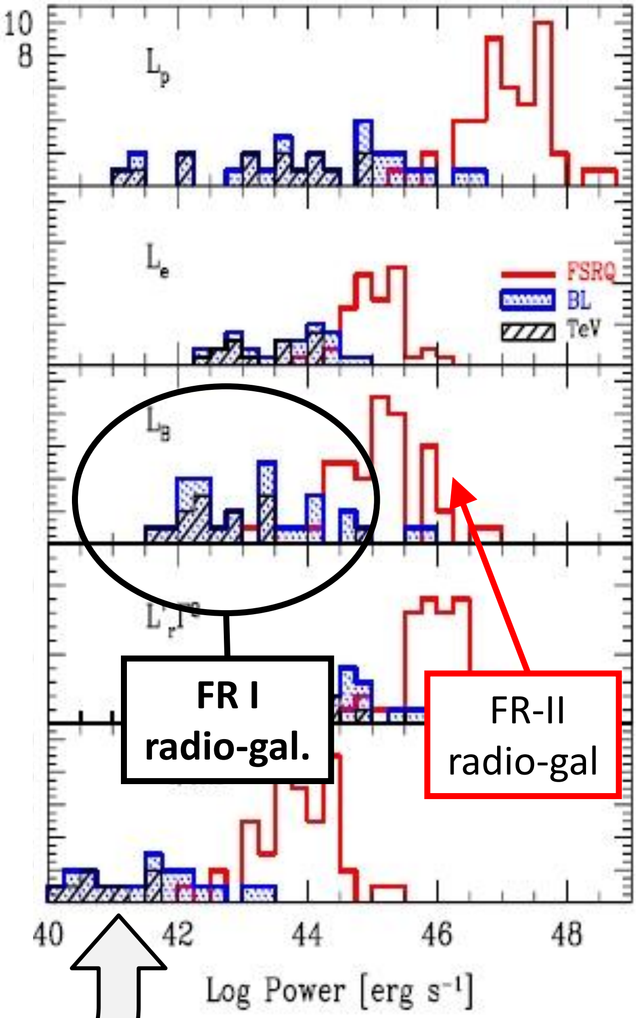
Modelling of the spectral energy distribution of blazars:



synchrotron of accelerated e

inverse Compton of synchrotron by accelerated e

Celotti & Ghisellini 08



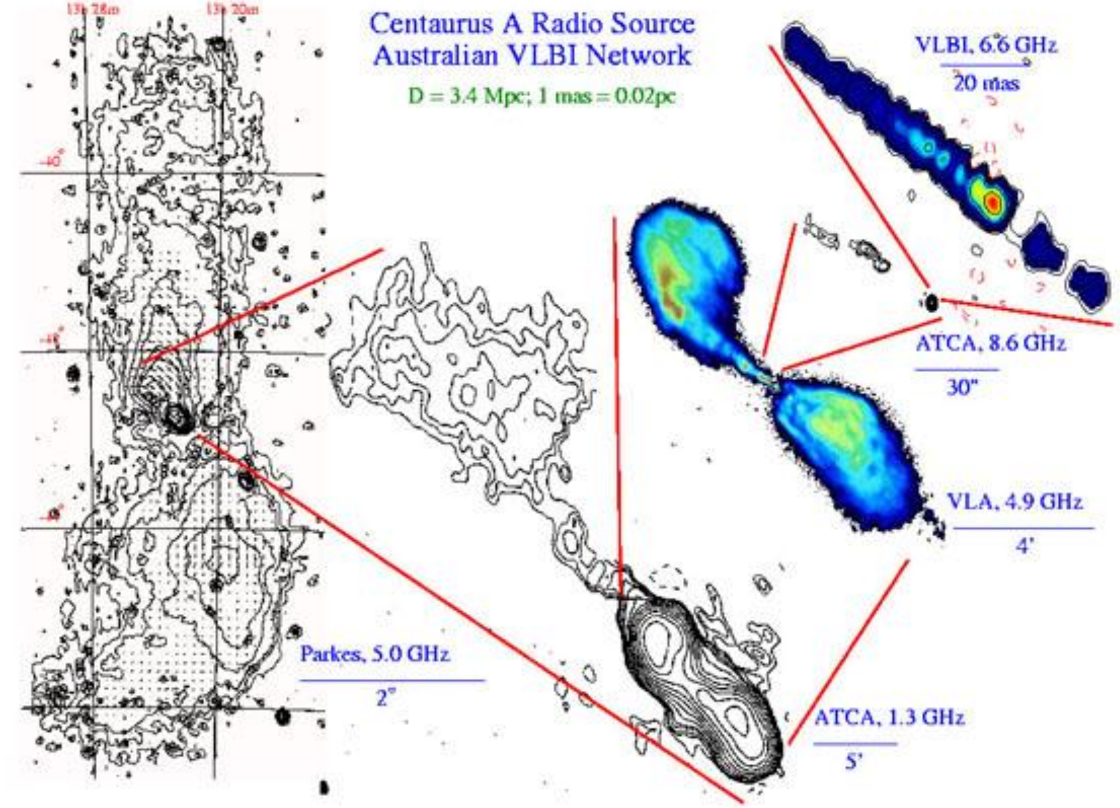
FR I radio-gal.

FR-II radio-gal

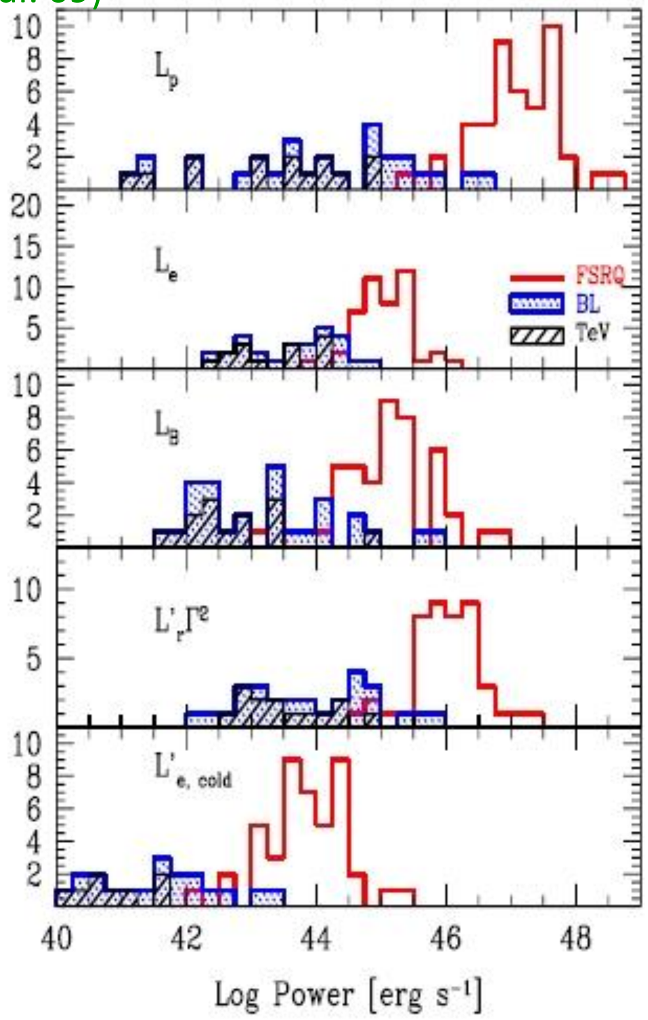
Self-Synchro-Compton model leads to magnetic luminosity +…

Centaurus - a close FR I radio-galaxy

- Centaurus A: (Romero et al. 96, Farrar & Piran 00, Gorbunov et al. 08, Dermer et al. 08, Hardcastle et al. 09, O'Sullivan et al. 09)



Celotti & Ghisellini 08

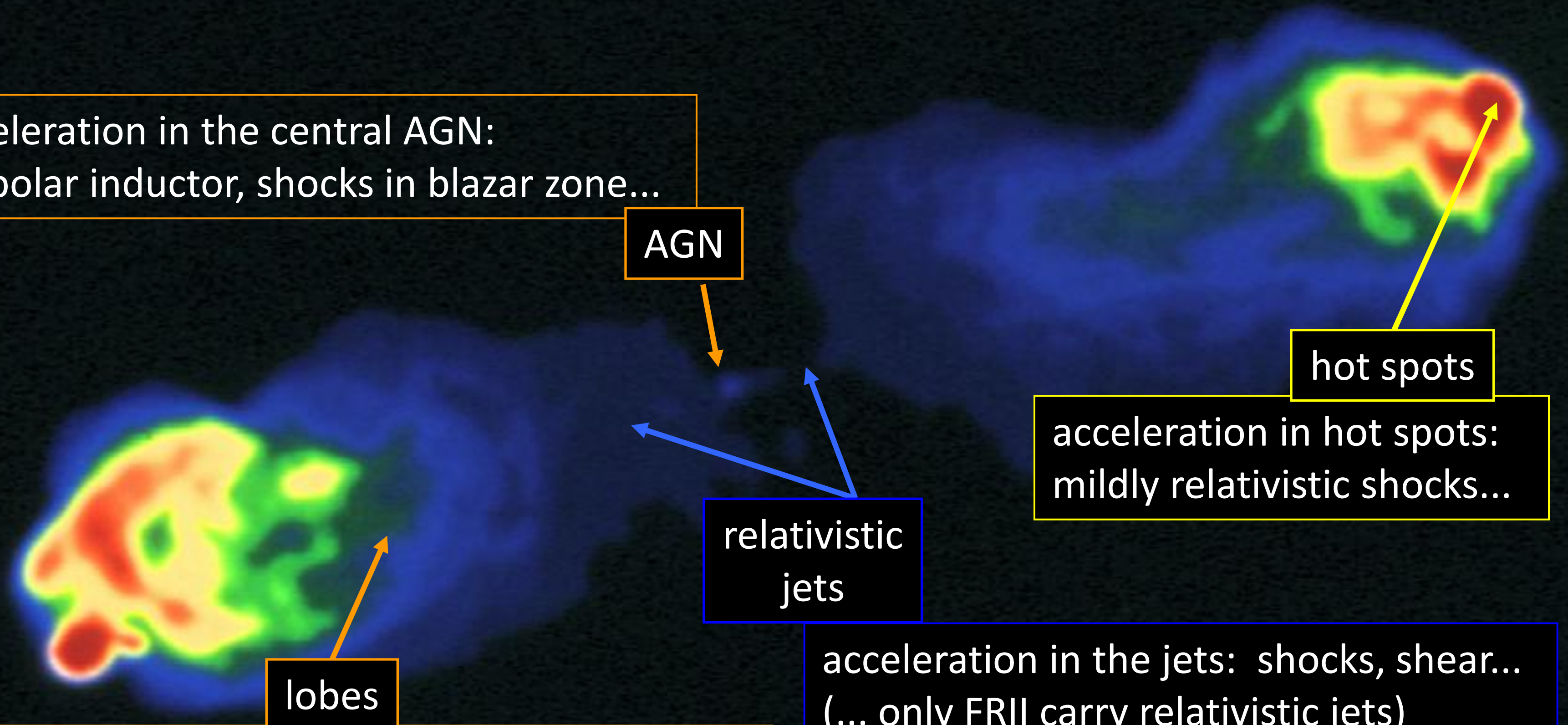


jet kinetic luminosity: $L_{\rm jet} \simeq 2 \times 10^{43}\,{\rm erg/s}$

⇒ **too small to account for 10^{20} eV protons …** $E_{\max} \sim Z \times 10^{18}\,{\rm eV}$ in jet/lobe

Acceleration – FR II radio-galaxies

Faranoff-Riley II radio-galaxy Cygnus A



acceleration in the central AGN:
unipolar inductor, shocks in blazar zone...

AGN

hot spots

acceleration in hot spots:
mildly relativistic shocks...

relativistic jets

acceleration in the jets: shocks, shear...
(... only FRII carry relativistic jets)

lobes

acceleration in the lobes:
no strong shock... stochastic Fermi acceleration

→ too few such sources in the GZK volume to account for the bulk of UHECRs...
unless they are heavy nuclei (← large magnetic deflection)...

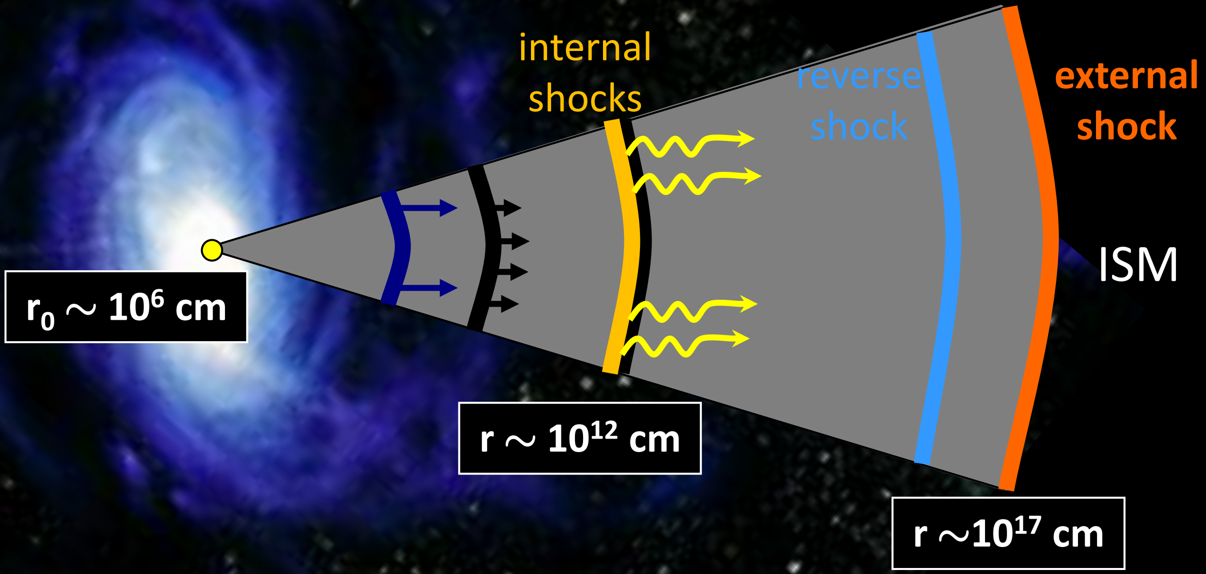
e.g. Ptuskin et al. 13, Aloisio et al. 11

Gamma-ray bursts

… gamma-ray bursts: burst (<1 sec → 1000sec) of gamma radiation, with erratic time behavior in the MeV range, followed by a slowly decaying afterglow

… at the origin: collapse of massive stars (long?), coalescence of compact objects (short)?

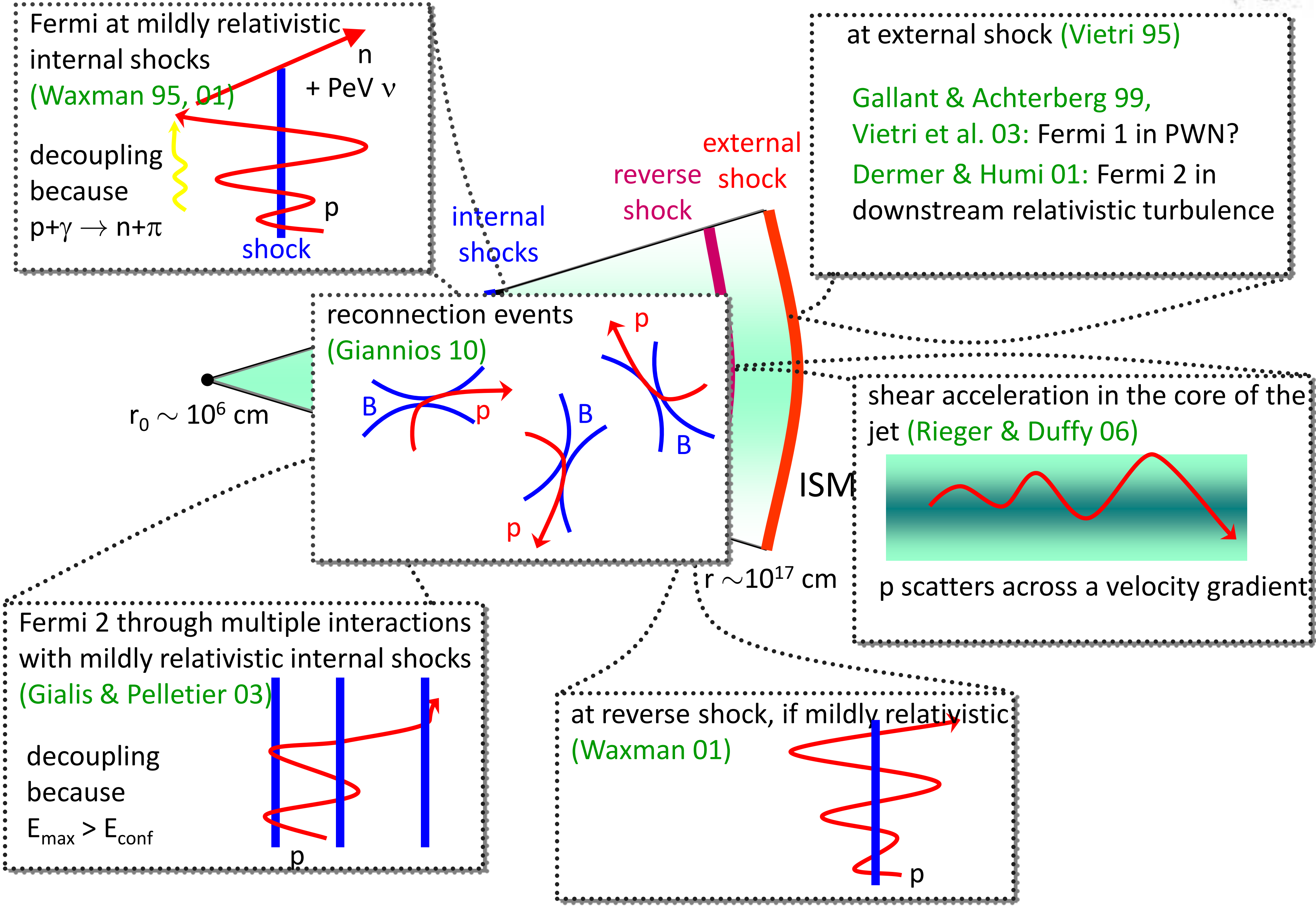
… canonical description: narrow jet accelerated to large Lorentz factor $\Gamma \sim$ 100-1000



… prompt MeV radiation: dissipation of jet bulk kinetic (magnetic?) energy

… afterglow: dissipation of jet energy through a strong collisionless relativistic shock with the surrounding medium
shock heating of swept up electrons and shock acceleration

Acceleration to UHE in gamma-ray bursts fireballs



Fermi at mildly relativistic internal shocks (Waxman 95, 01)

decoupling because $p+\gamma \rightarrow n+\pi$

at external shock (Vietri 95)

Gallant & Achterberg 99,
Vietri et al. 03: Fermi 1 in PWN?
Dermer & Humi 01: Fermi 2 in downstream relativistic turbulence

$r_0 \sim 10^6$ cm

$r \sim 10^{17}$ cm

reconnection events (Giannios 10)

shear acceleration in the core of the jet (Rieger & Duffy 06)

p scatters across a velocity gradient

Fermi 2 through multiple interactions with mildly relativistic internal shocks (Gialis & Pelletier 03)

decoupling because $E_{max} > E_{conf}$

at reverse shock, if mildly relativistic (Waxman 01)

Acceleration to UHE in gamma-ray bursts fireballs

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

→ internal energy density: $u' = \epsilon_e^{-1}\frac{L_\gamma}{4\pi r^2\Gamma^2 c}$ (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: $t_{\rm acc} < \frac{r}{\Gamma c} \Rightarrow E_{\rm obs,20} \lesssim 7\times\epsilon_{B,-1}^{1/2}\epsilon_{e,-1}^{-1/2}\Gamma_{2.5}L_{\gamma,52}^{1/2}\mathcal{A}^{-1}$

→ 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 OK if internal shocks at radii > 10^{12}cm… as expected from observations

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

$\Rightarrow \frac{r/(\Gamma c)}{t_{\rm pi}} \sim \frac{L_{\gamma,52}}{\Gamma_{2.5}^4\Delta t_{-2}}$ suggests that protons can escape the flow, avoid adiabatic losses, through conversion to n in γ-π reactions, leading to a neutrino signal with $E_\nu \sim E_{\rm UHECR}$

Acceleration to UHE in gamma-ray bursts fireballs

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▶ **Notes:**

→ 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...

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

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

flux of UHECR above 10^{19} eV requires an energy input rate: ~ **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., $E_{\rm UHECR/GRB}$ / $E_{\gamma/\rm GRB}$ ~ 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)

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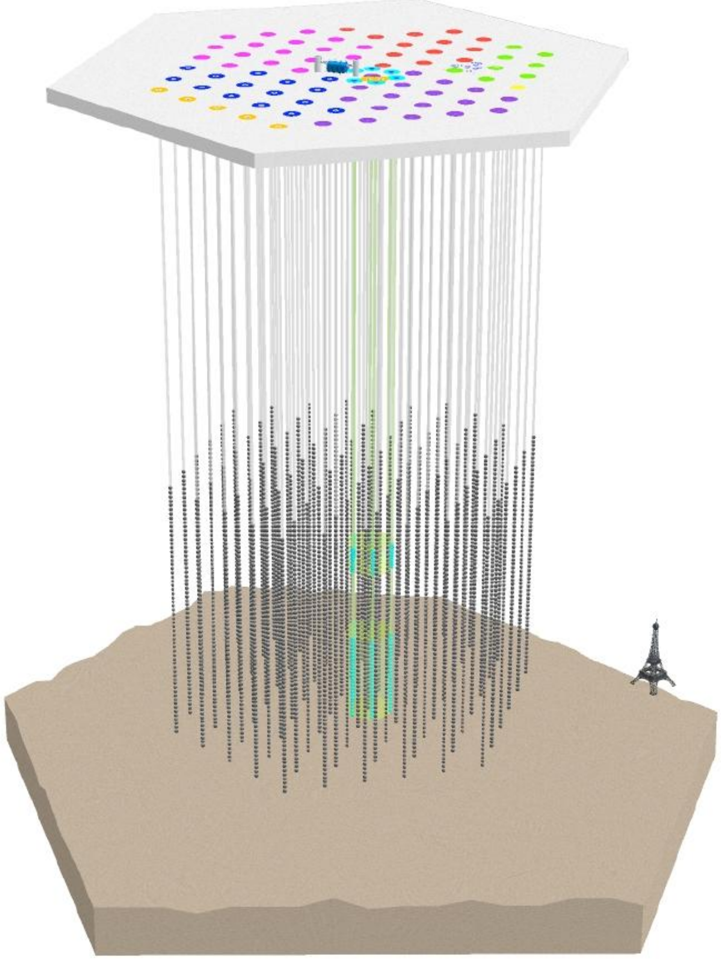
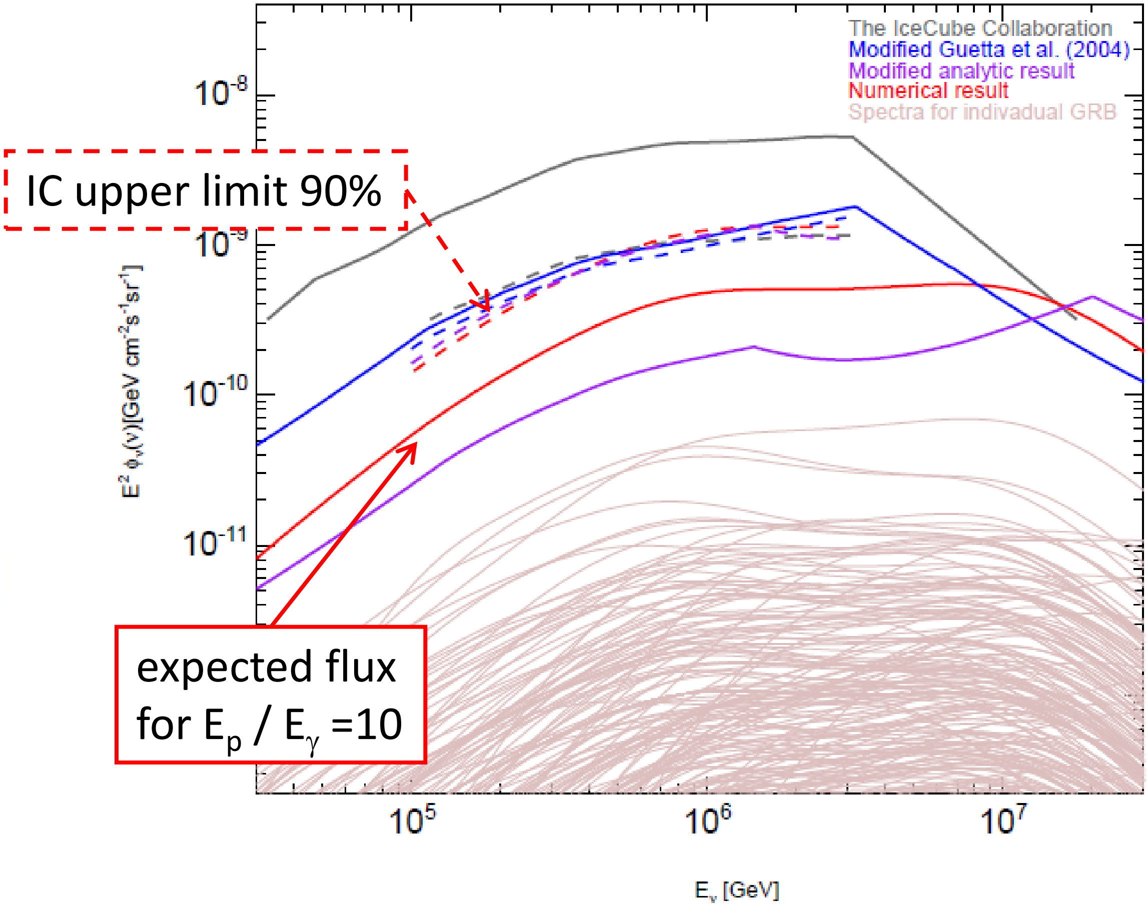
Current Ice Cube limits...

km^3 neutrino detector at the South Pole



→ **IceCube is now probing the WB bound!**

Ice Cube 11, He et al. 12



IC upper limit 90%

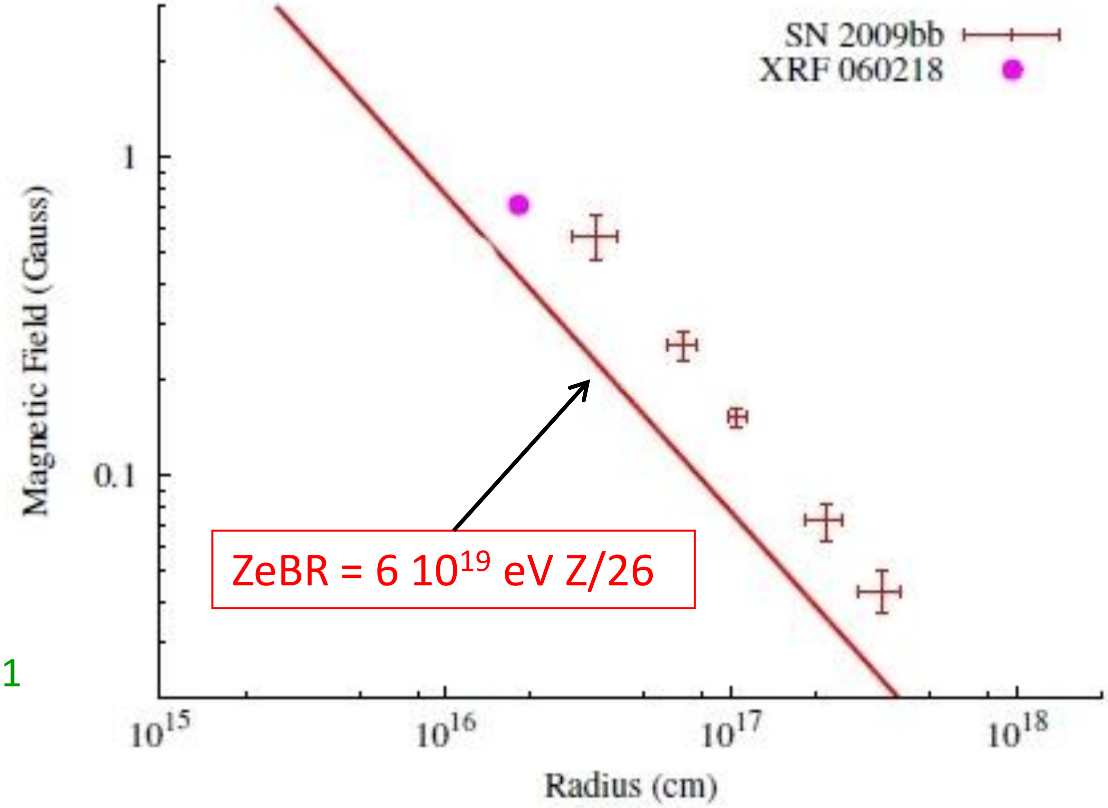
expected flux for E_p / E_γ =10

Acceleration to UHE in low luminosity GRBs

→ low luminosity GRBs, also associated to X-ray flashes, are interpreted as trans-relativistic supernovae with ejecta velocity $\gamma\beta \sim 1$ … the missing link to standard supernovae? possible sources of UHE nuclei (Wang et al. 08,Chakaborty et al. 11, Liu & Wang 12, Budnik et al. 08)

energy budget OK: $\dot{n}_{\rm LLGRB} \sim 10^{-7} - 10^{-6}\,{\rm Mpc}^{-3}\,{\rm yr}^{-1}, \quad E \sim 10^{50}\,{\rm erg}$

maximal energy: $E_{\rm max} \sim Z \times 10^{18} - 10^{19}\,{\rm eV}$ $\Rightarrow$ **heavy nuclei at UHE**



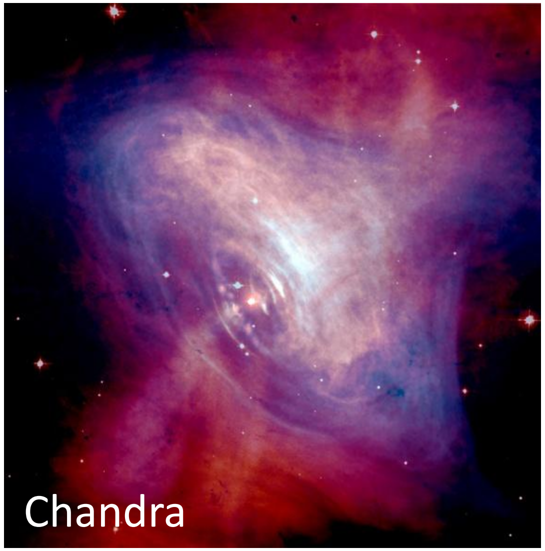
ZeBR = 6 10^{19} eV Z/26

Chakraborty et al. 11

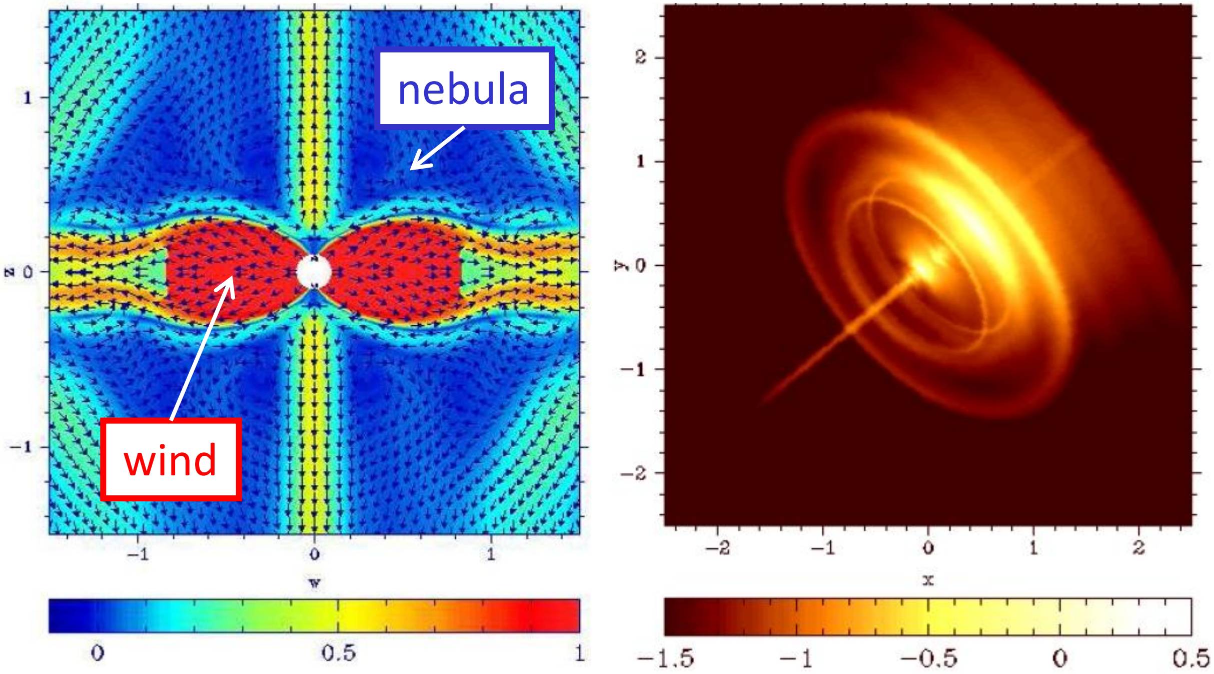
Acceleration in pulsar winds

$\rightarrow$ Crab output $\sim 10^{38}$ erg/s far too low to account for UHECR flux with Crab-like sources

$\rightarrow$ Crab nebula cannot confine nuclei with $E/Z > 3\ 10^{17}$ eV... (for $B \sim 300\ \mu$G)



Model of synchrotron Crab nebula (Komissarov & Lyubarsky 03)



$\rightarrow$ acceleration must take place in fast-spinning (high L) young pulsars, in the wind zone to avoid losses...

.... through which mechanism? see e.g. Venkatesan et al. 97, Arons 03, Fang et al. 12
… at the termination shock? Shock driven reconnection? Crab: $\Gamma \sim 10^3$-10^6, $\sigma \sim 10^{-3}$ …

acceleration… to sum up:

→ **acceleration of protons to 10^{20} eV requires extraordinary conditions: fast spinning neutron stars, gamma-ray bursts, FRII radio-galaxies...**

→ magnetic luminosity: $L_B \gtrsim 10^{45} Z^{-2} E_{20}$ erg/s...

→ much larger pool of candidates for acceleration of high Z nuclei...

→ AGN/radio-galaxies can possibly accelerate high Z nuclei to UHE… unlikely sources of UHE protons…

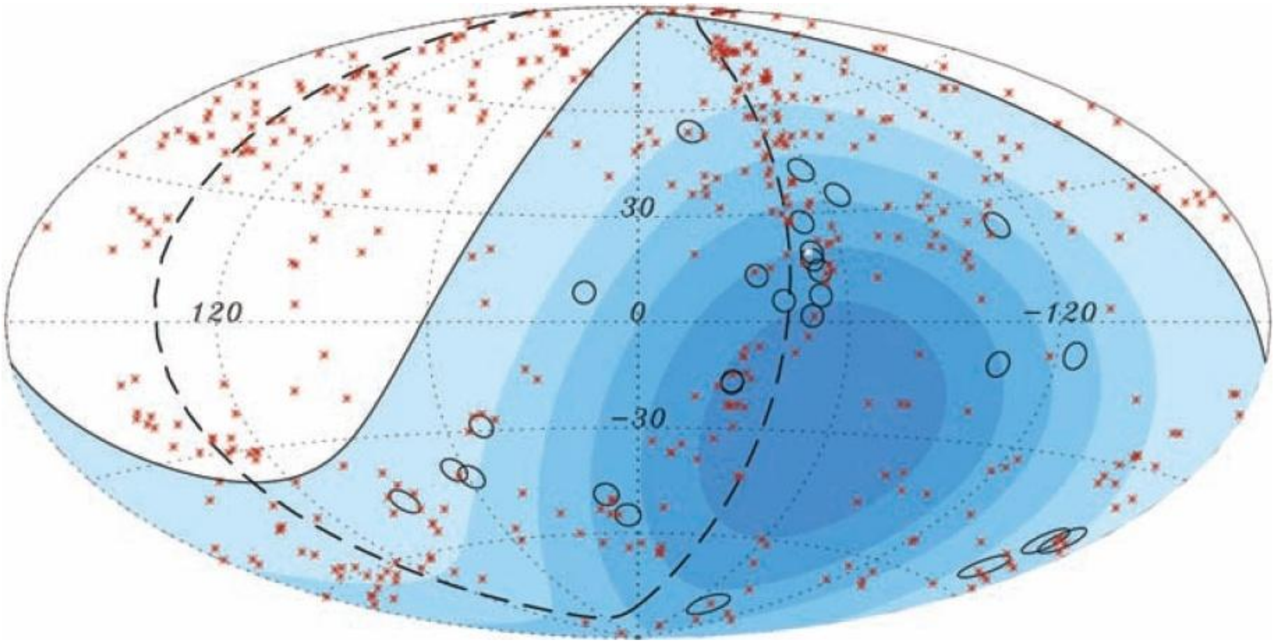
→ GRBs are potential sources of UHE protons, but energy budget is difficult to satisfy…

→ weak GRBs (aka low luminosity or trans-relativistic SNe) are potential sources of UHE nuclei…

→ young pulsars appear promising, but which acceleration mechanism?

Do we expect to detect γ rays, neutrinos?

▶ What is the source of ultrahigh energy cosmic rays ?



short answer:

no counterpart in optical/IR photons ⇔ no counterpart in gamma-rays,
neutrinos, gravitational waves...

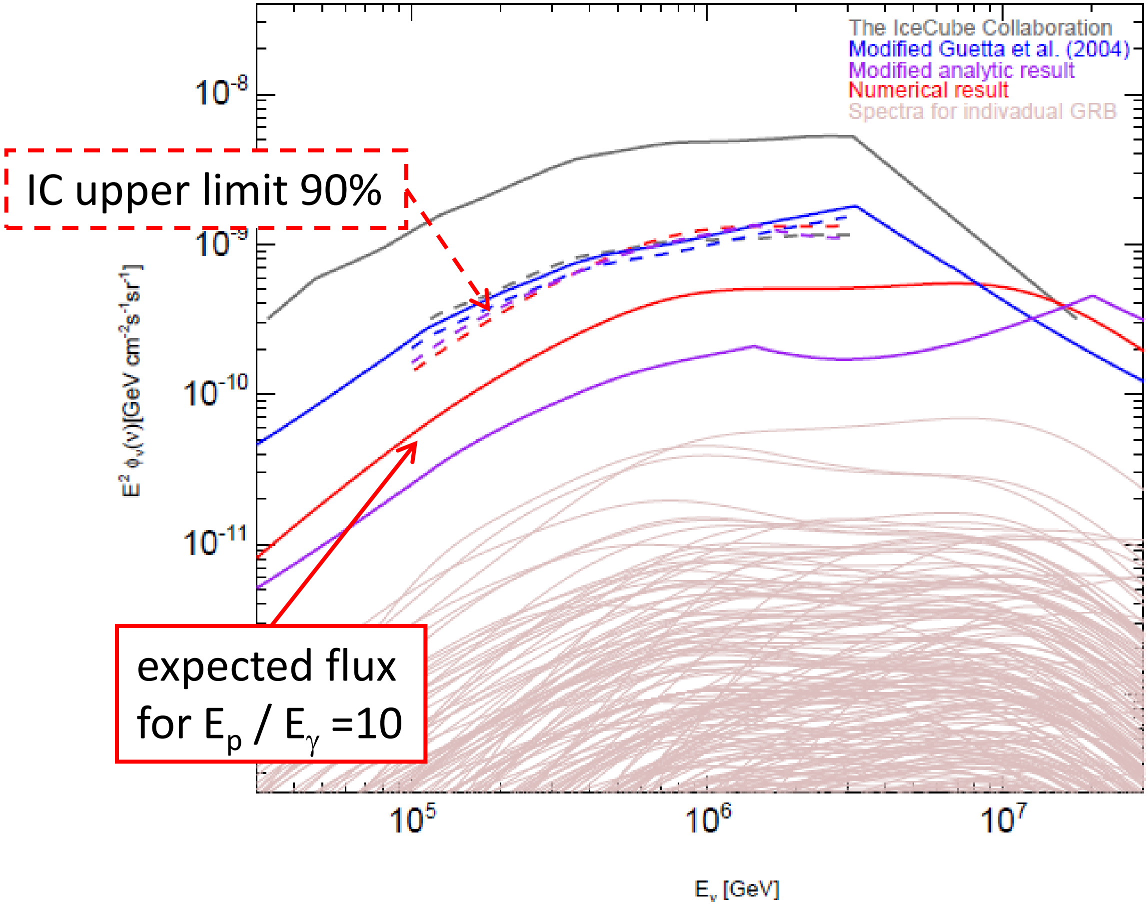
e.g.: → for gamma-ray burst sources, time delay ~ 10^4-10^5 yrs at 10^{20} eV
→ for high Z nuclei, large angular deflection...

Do we expect to detect γ rays, neutrinos?

▶ What is the source of ultrahigh energy cosmic rays ?

... but diffuse backgrounds are expected: $N+\gamma \rightarrow N' + \pi$, $\pi^{\pm} \rightarrow \nu$ +... in gamma-ray burst

Ice Cube 11, He et al. 12



IC upper limit 90%

expected flux for E_p / E_γ =10

Ice Cube 12: possible detection of 2 astrophysical neutrinos at PeV energies… uncorrelated with gamma-ray bursts…

High energy gamma-rays

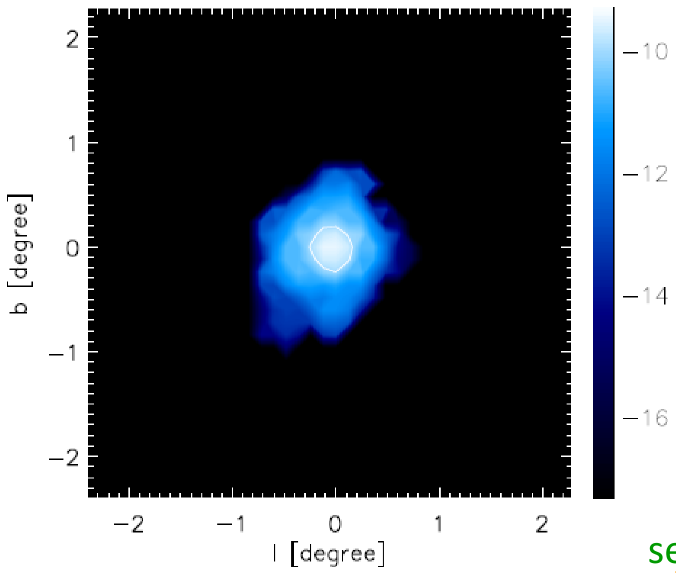
- What is the source of ultrahigh energy cosmic rays ?

... but diffuse backgrounds are expected: N+$\gamma \rightarrow$ e.m. cascade down to GeV-TeV from steady sources such as FRII radio-galaxies

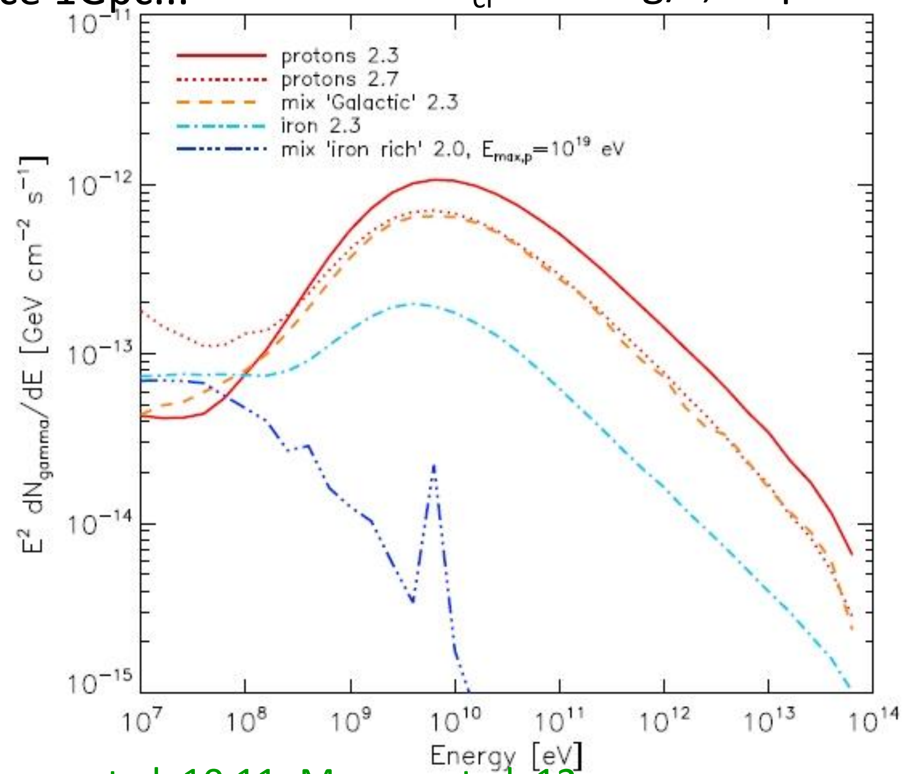
Aharonian 02, Gabici & Aharonian 05, Kotera et al.11:
synchrotron emission from UHE electrons (p+$\gamma \rightarrow$ p + e^++e^-)

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

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



L_{cr}=10^{44}erg/s, 1Gpc



see also Essey et al. 10,11, Murase et al. 12

→ any signal from arrival directions of UHECR ?

Summary

- **Acceleration to ultra-high energies:**

  → $L_B \gtrsim 10^{45} Z^{-2}$ ... erg/s to accelerate up to 10^{20}eV
  → a true challenge for 10^{20}eV protons!

- **Issue of chemical composition:**

  → most pressing issue: pinning down the chemical composition at GZK energies
  → current anisotropies, if real, suggest that there are protons at UHE!
  ⇒ possible gamma + neutrino secondary signatures...

"best case"

IF light composition at UHE + distribution of arrival directions according to LSS:

→ **most likely sources are bursting objects camouflaged in ordinary galaxies: gamma-ray bursts, magnetars...**

→ do not expect counterparts from these directions due to time delay $\gtrsim 10^4$ yrs between arrival of cosmic rays and photons/neutrinos/...

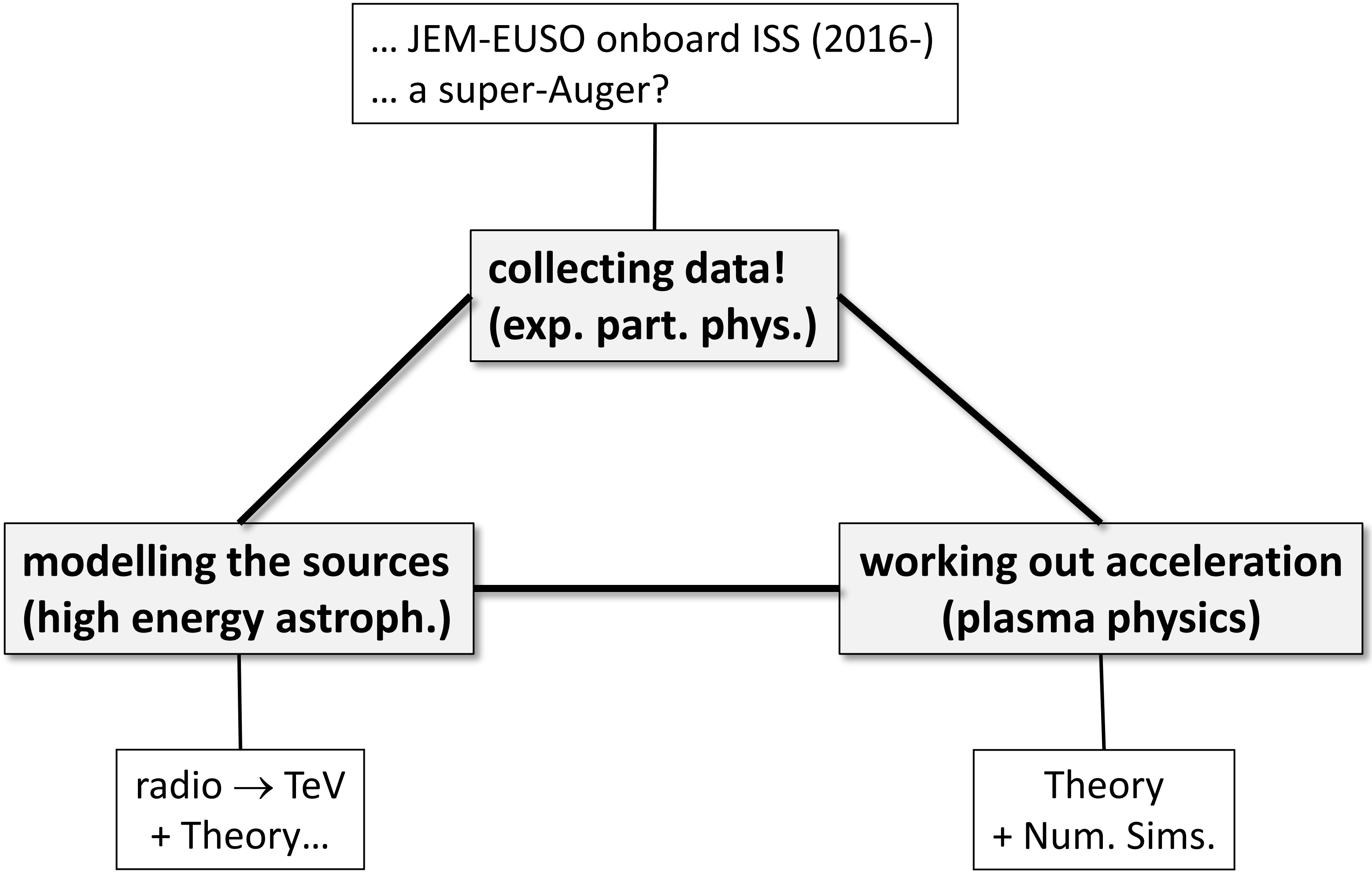
→ but diffuse backgrounds...

IF heavy composition at UHE: pessimistic scenario...

→ expect substantial to large angular deflection: no source identification...?
→ larger pool of source candidates... **best candidates: radio-galaxies, LL GRBs...**
→ production of secondary neutrinos/photons suppressed down to below detection?

"worst case"

A wish-list to go forward…



… JEM-EUSO onboard ISS (2016-)
… a super-Auger?

collecting data!
(exp. part. phys.)

modelling the sources
(high energy astroph.)

working out acceleration
(plasma physics)

radio → TeV
+ Theory…

Theory
+ Num. Sims.