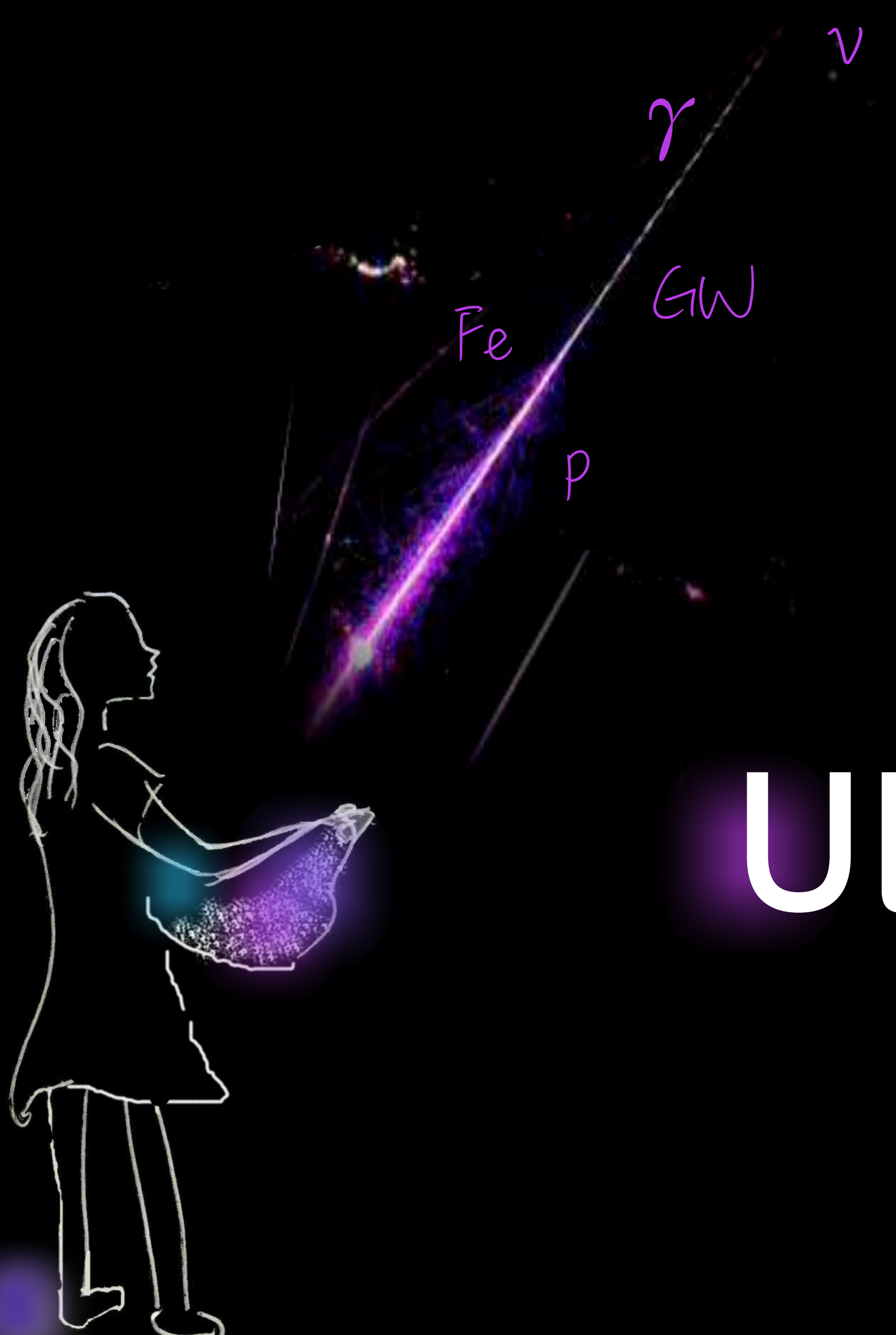
Kumiko Kotera - Institut d'Astrophysique de Paris

PLASMA Physics School - 17/05/2019

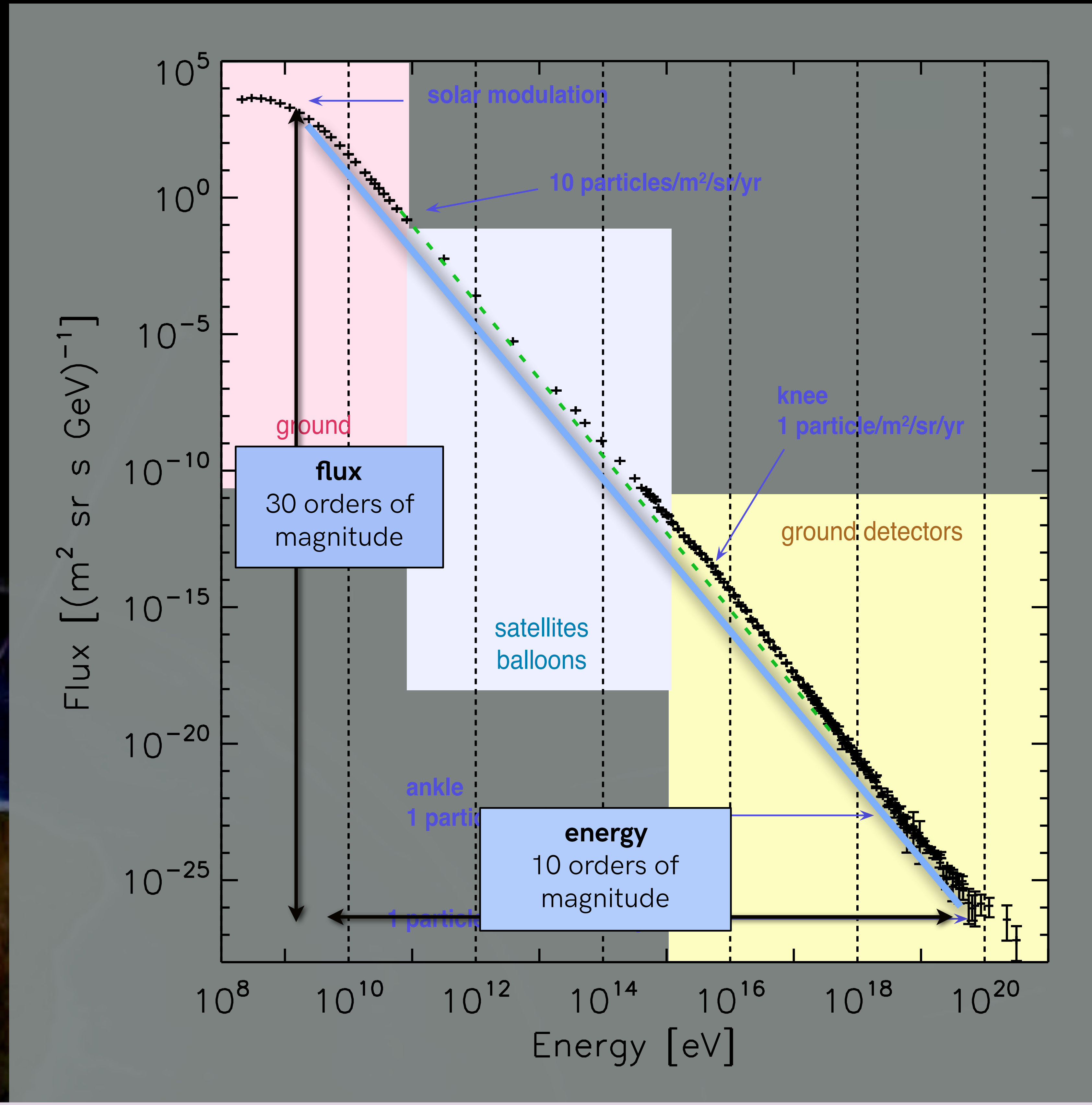


Ultra-high-energy Cosmic Rays

e.g., see *KK & Olinto 2011*
with elements on acceleration inspired from talks by
P. Blasi, M. Lemoine, E. Parizot

1 kg of cosmic rays per year on Earth (~10^{27})

Why do we care about cosmic rays at the PLASMA school?



Non-thermal particles are ubiquitous in the Universe

magnetized plasmas <—> non-thermal particles (acceleration)

A macroscopic energy (10^{20} eV ~ 10 Joules)

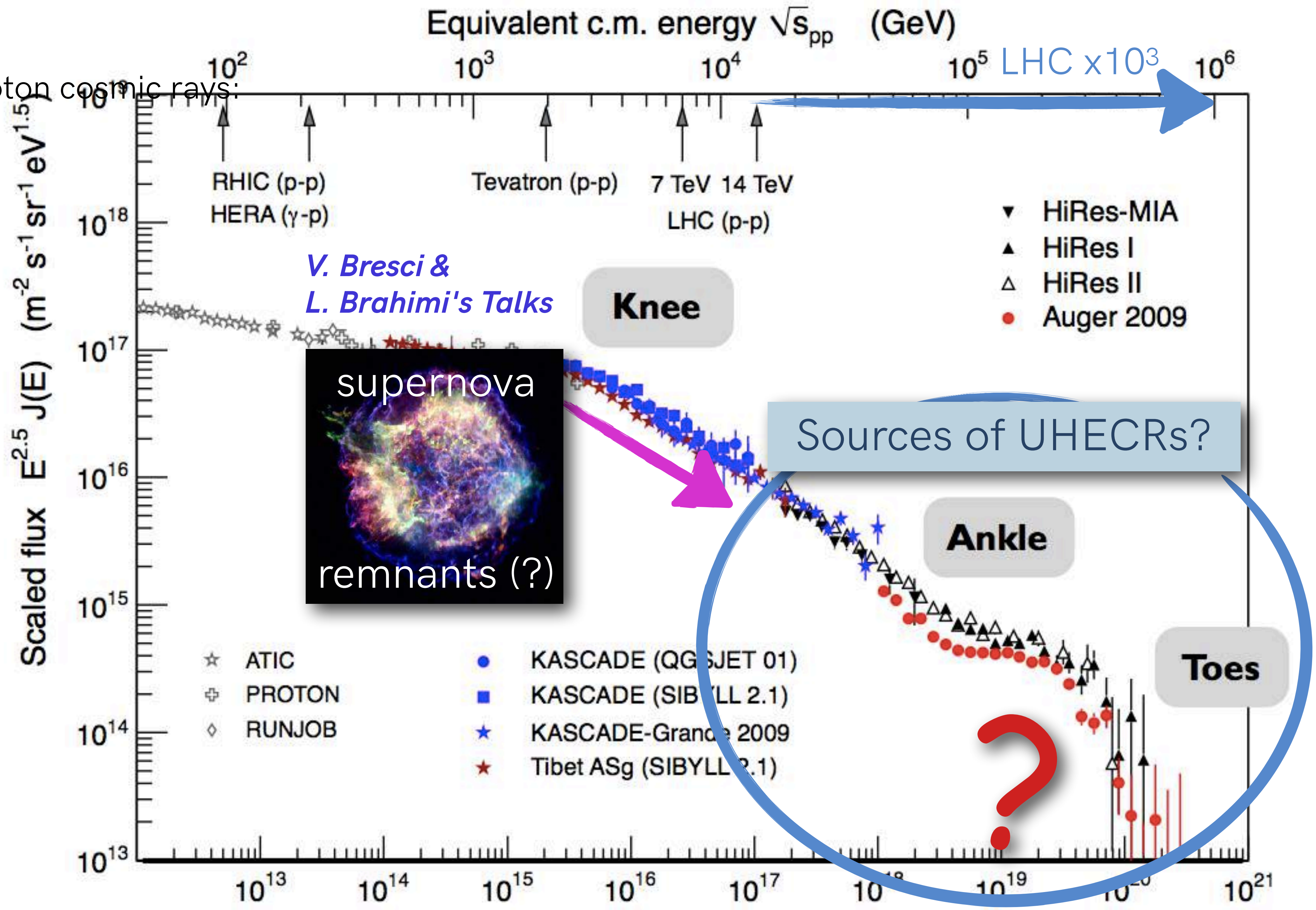
energy of a tennis ball
hit by Roger

in a subatomic particle!

at the LHC,
particles are accelerated at 10^7 times lesser energies...

The mystery of UHECRs

for proton cosmic rays:

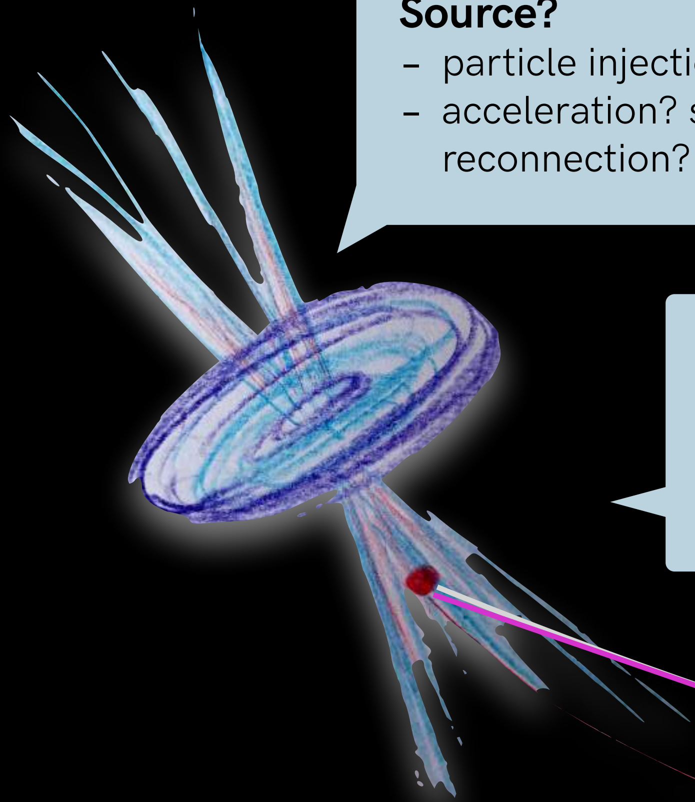


source: R. Engel

difficulties:

- charged particles in a magnetized universe
- low particle flux (few per km^2 per century)
- beyond energy range experimentally probed by LHC
- powerful astrophysical sources not well understood

A UHECR journey



Source?
- particle injection?
- acceleration? shocks? reconnection?...

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Outflow
- structure?
- B?
- size?

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Cosmic backgrounds
interactions on CMB, UV/opt/IR photons

cosmogenic neutrino and gamma-ray production

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Intergalactic magnetic fields
magnetic deflection
temporal & angular spread/shift

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p Fe

γ ν

γ ν

Backgrounds
- radiative? baryonic?
- evolution, density?
- magnetic field: deflections?

associated neutrino and gamma-ray production

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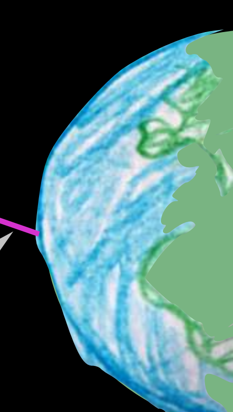
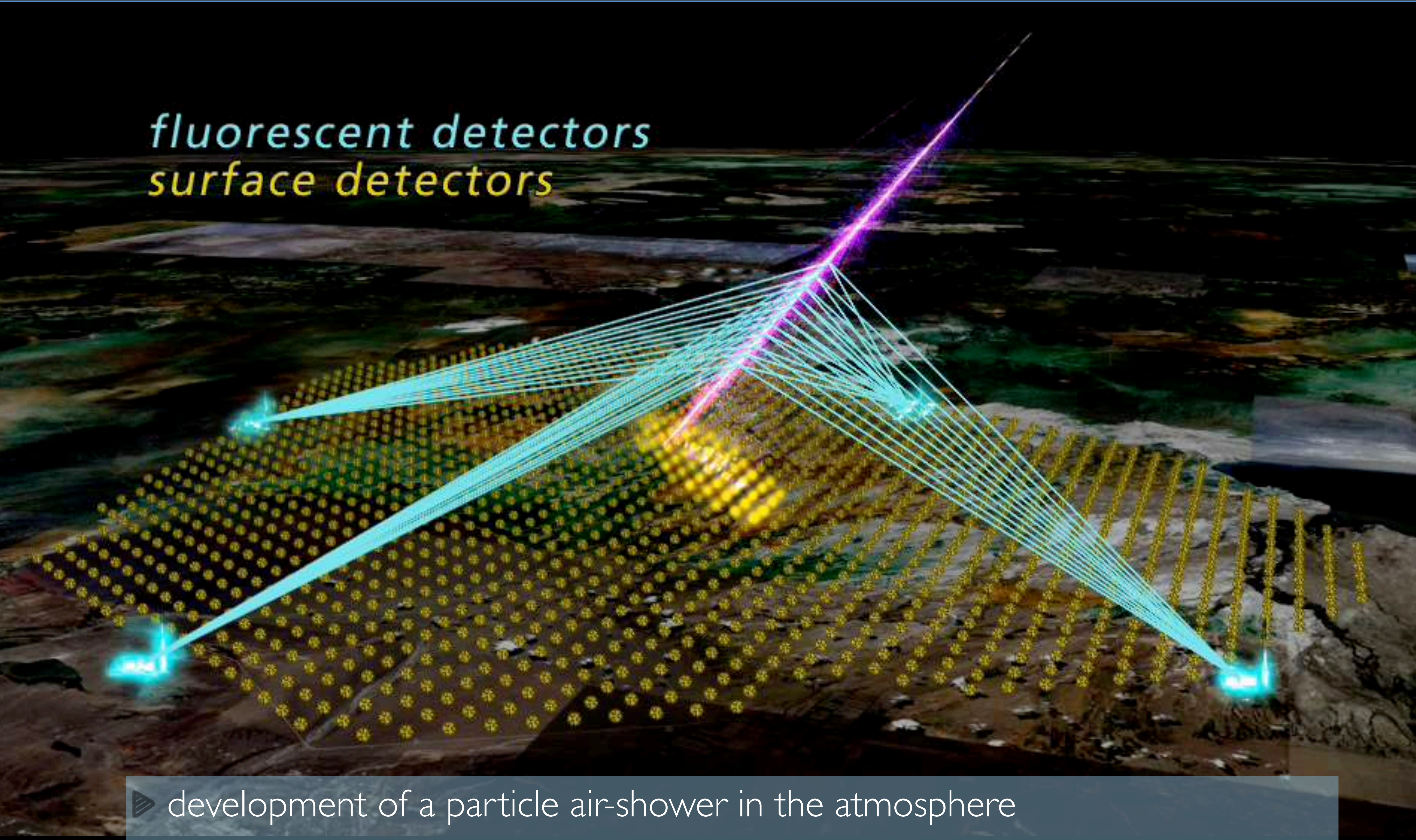
Observables

UHECR	*neutrinos*	*multi-wavelength photons*	*GW*
– mass	– flavors	– spectral features	– spectrum
– spectrum	– spectrum	– time variabilities	– arrival directions
– anisotropy	– anisotropy	– angular spread	– time
	– time variabilities	– source distribution	



How do we detect ultrahigh energy (UHE) particles?



- development of a particle air-shower in the atmosphere
- detection of secondary particles at ground
- detection of fluorescence light emitted during development of air-shower

The Pierre Auger Observatory

Auger Observatory

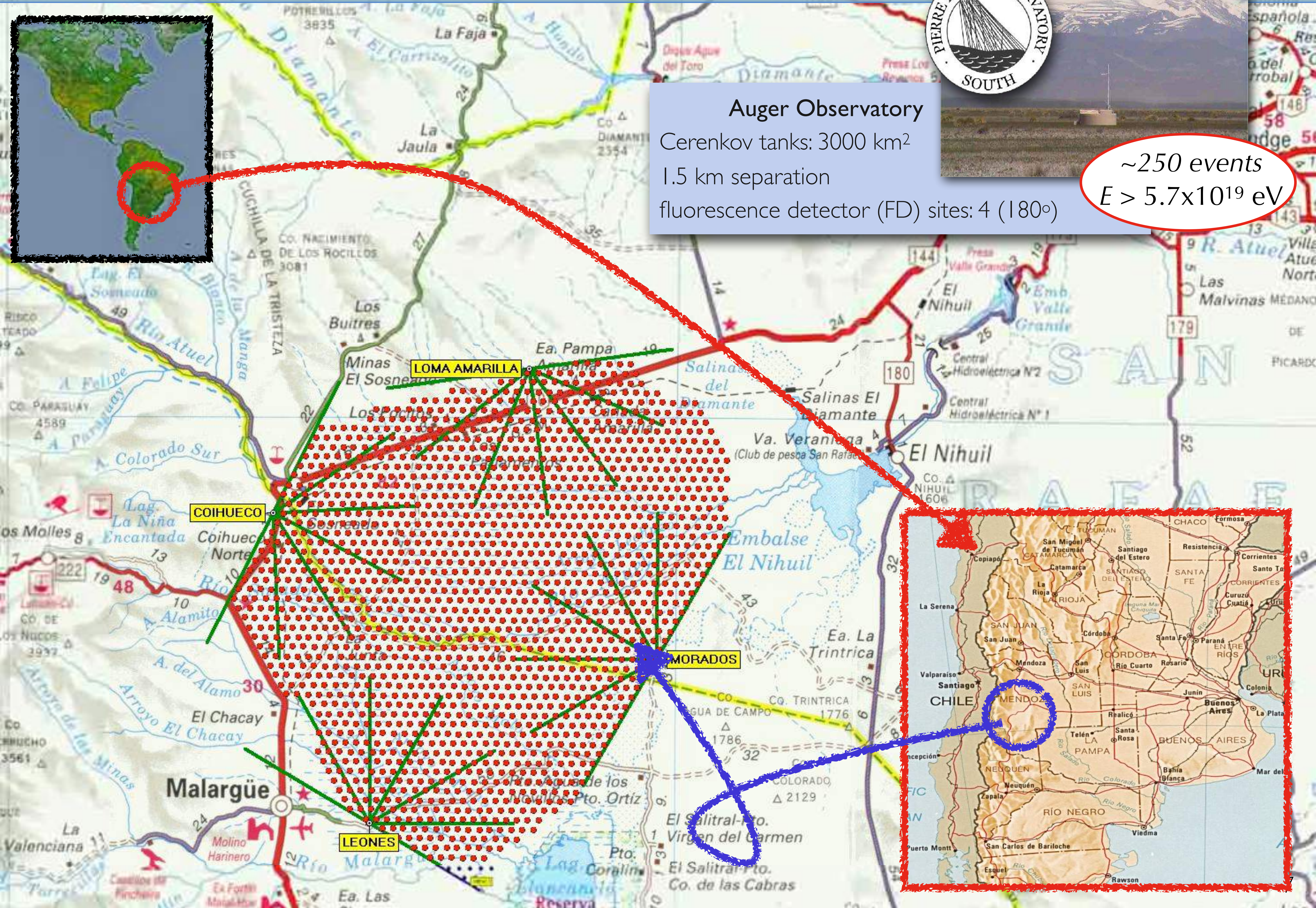
Cerenkov tanks: 3000 km^2

1.5 km separation

fluorescence detector (FD) sites: 4 (180^o)

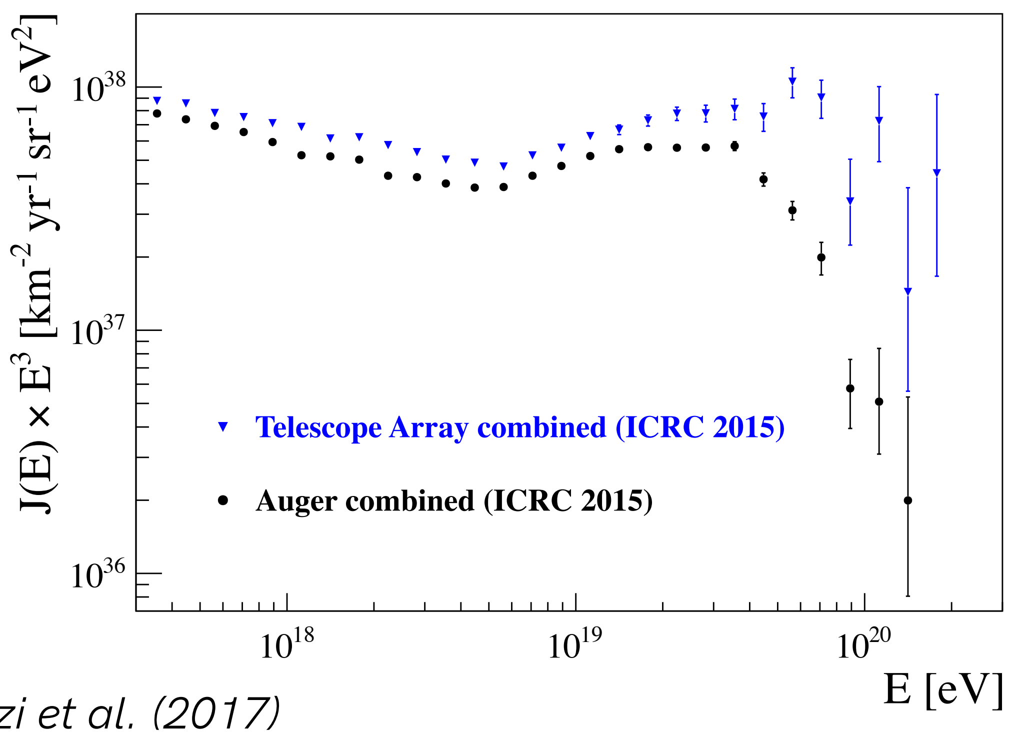
~250 *events*

$E > 5.7\text{x}10^{19}$ eV



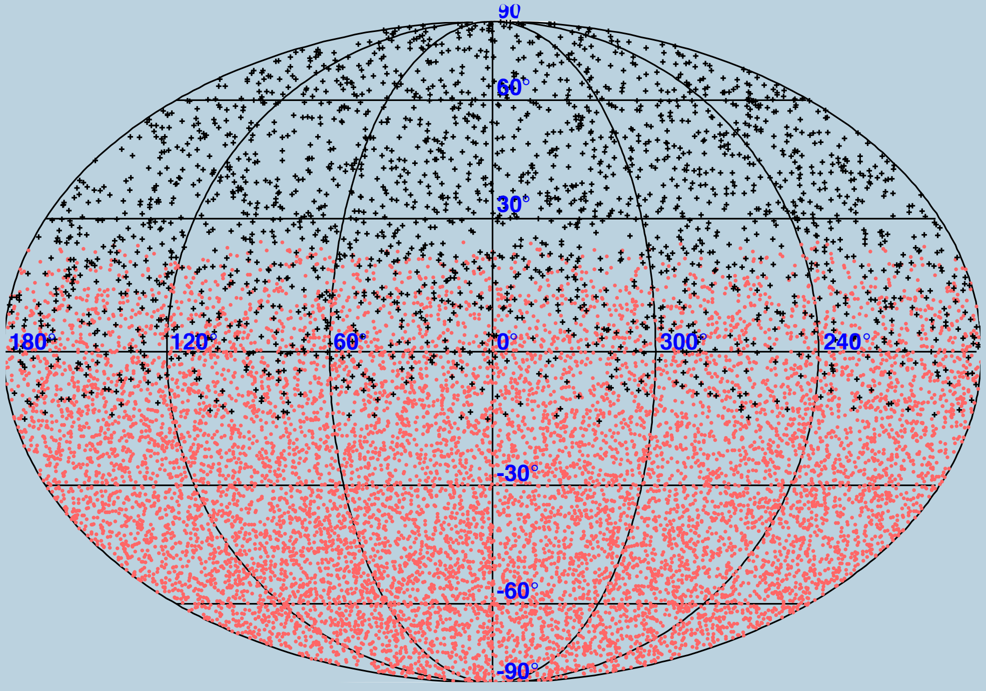
Learning from UHECR data

Energy spectrum

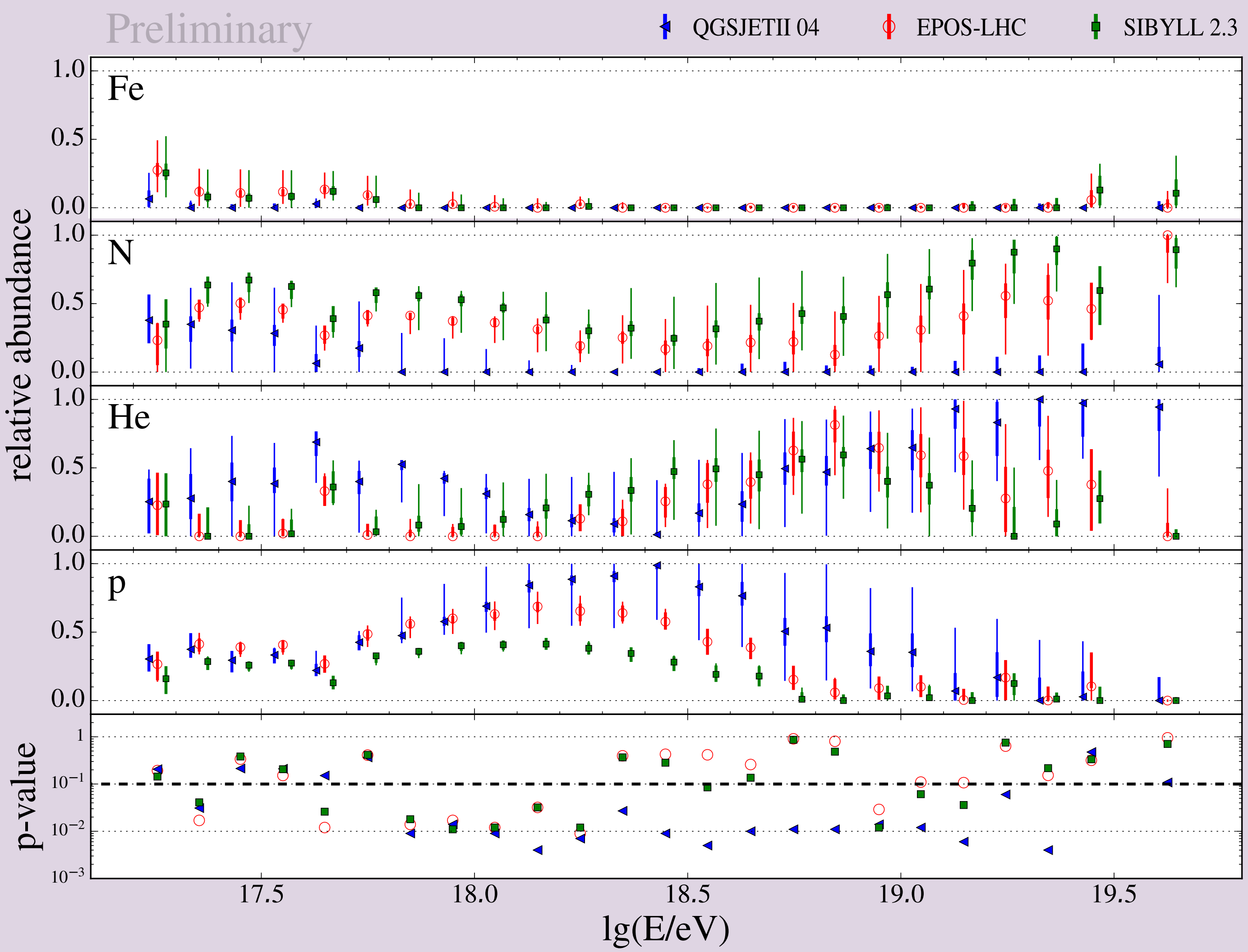


Verzi et al. (2017)

Arrival directions



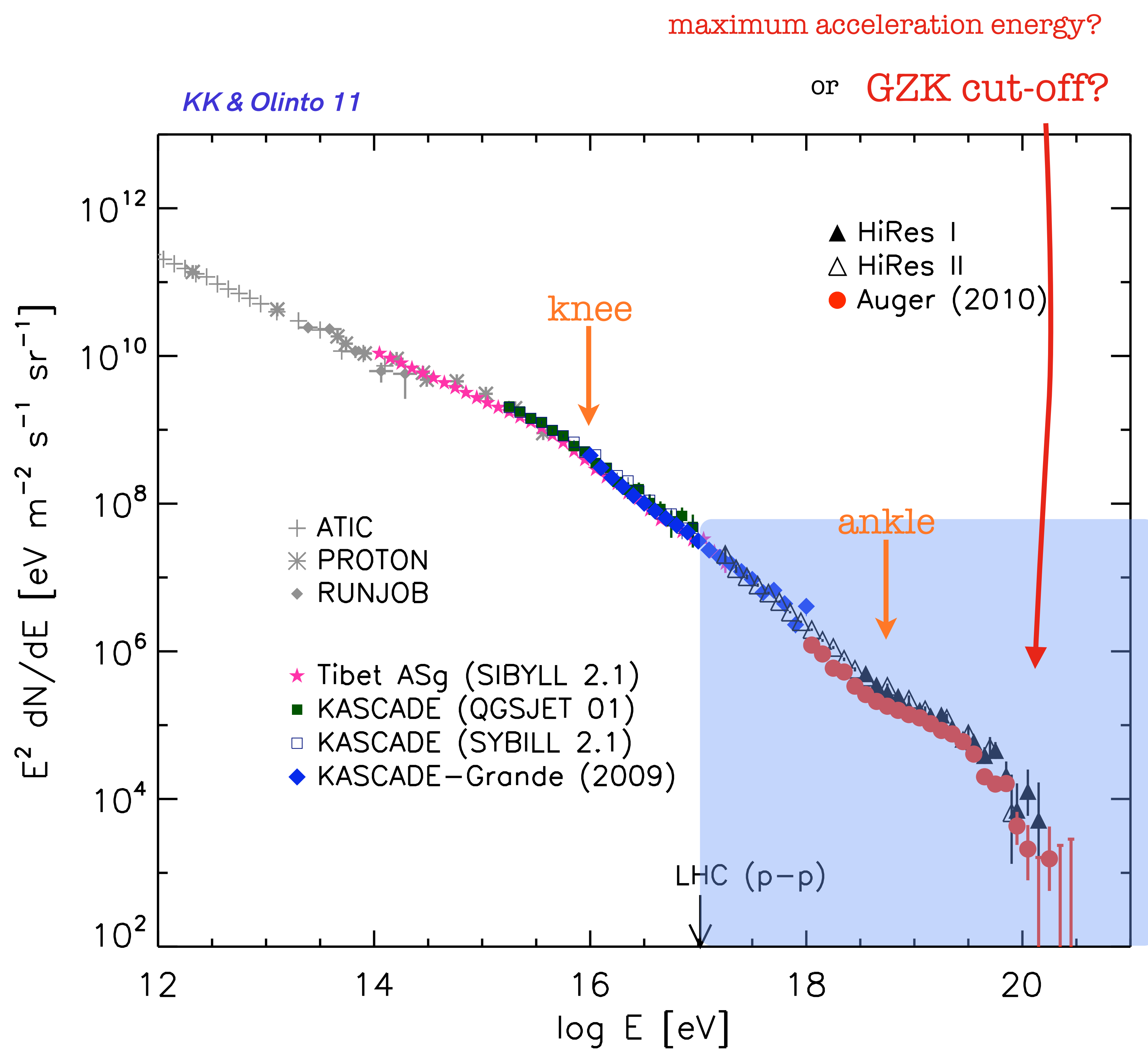
E>10^{19} eV
Auger & TA combined analysis
Aab et al. (2014)



Auger Coll. ICRC 2017

Mass composition

Learning from the energy spectrum

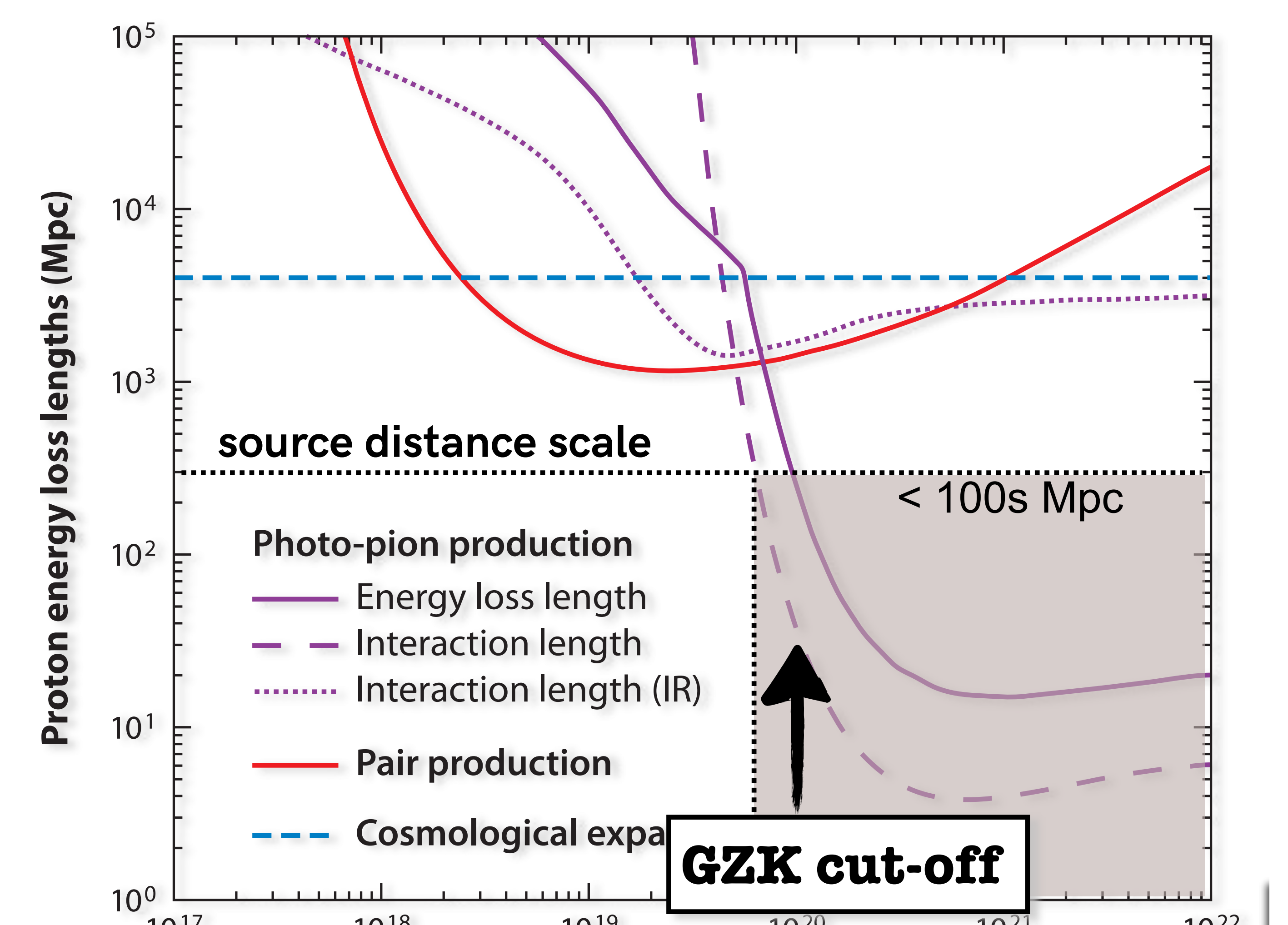


Energy losses of UHECRs and the GZK horizon

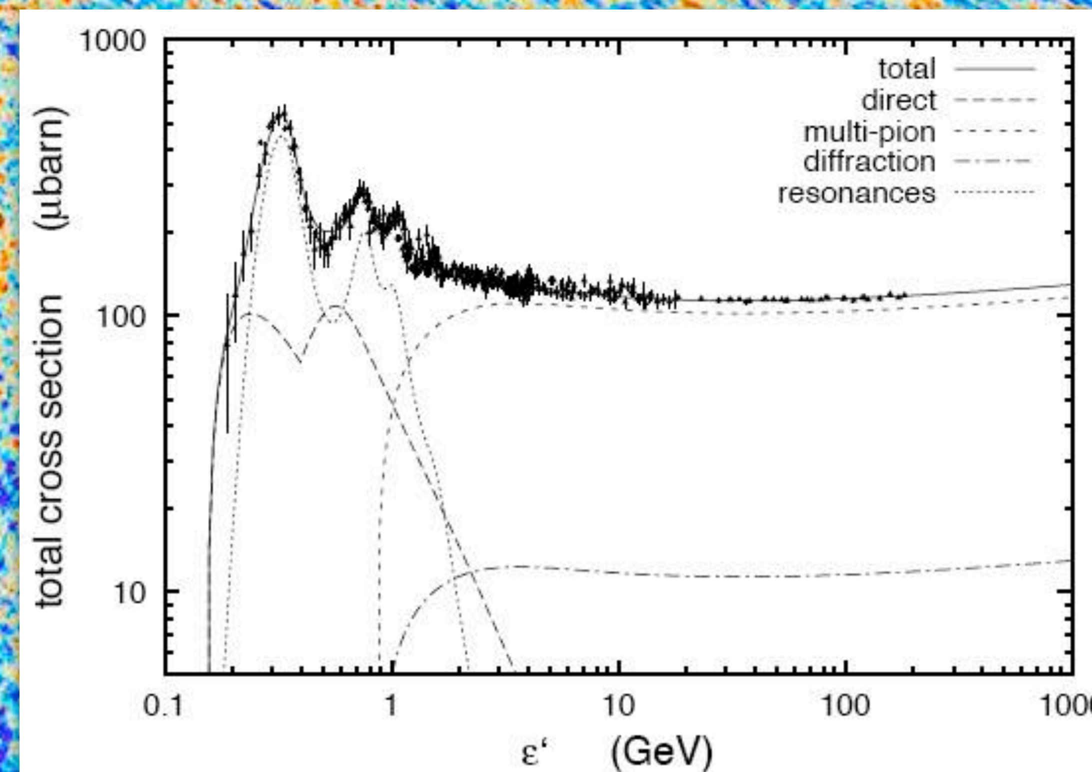
for proton cosmic rays: backgrounds: CMB IR/optical/UV photons

pion photoproduction $p + \gamma \longrightarrow N + n\pi$ $E_p \gtrsim \frac{m_\pi (m_\pi + 2m_p)\, c^4}{2\epsilon} \sim$ 6 x10^{19} eV

pair photoproduction $p + \gamma \longrightarrow p + e^+ + e^-$ $E_p \gtrsim \frac{m_e m_p}{\epsilon} \sim$ 10^{19} eV



Greisen 1966, Zatsepin & Kuzmin 1966



photon energy in proton rest frame

extragalactic sources within ~200 Mpc

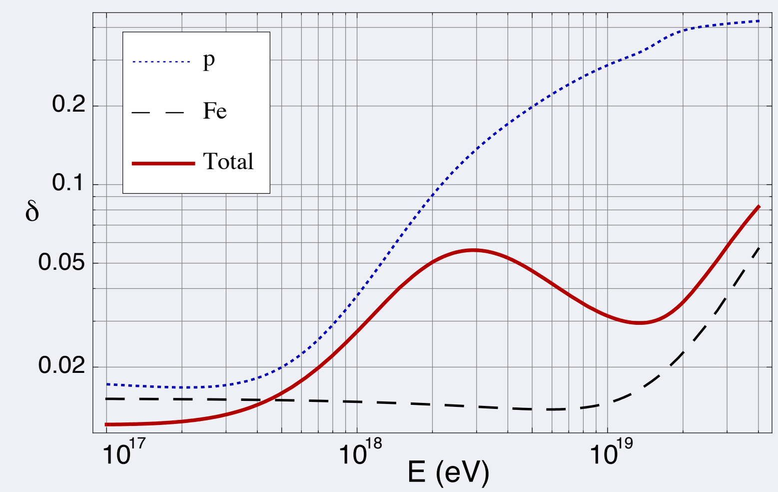
Learning from large scale anisotropies

Galactic or extragalactic?

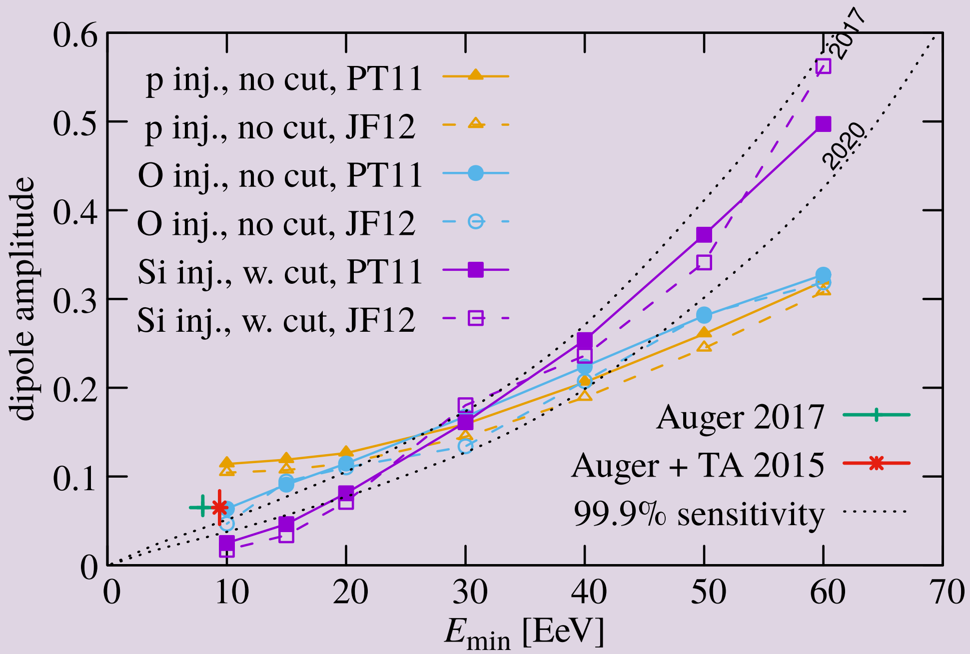
UHECR source(s) in our Galaxy imply high level of dipole amplitude

esp. for light mass composition @ 8 EeV

e.g., Calvez et al. 2010
Giacinti et al. 2011
Eichler et al. 2016



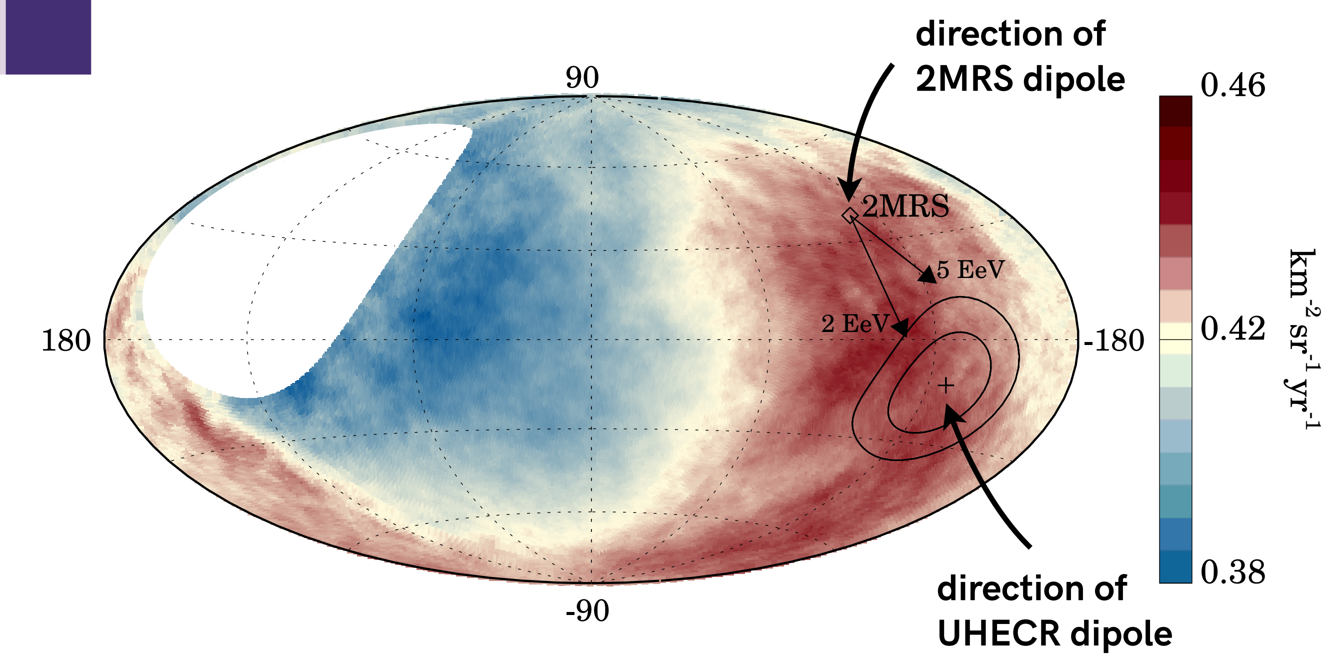
di Matteo & Tinyakov 2018



also Globus & Piran 2018 —> dipole from LSS 5% @[4-8] EeV

dipole expected from LSS

Auger Coll. Science 2017
Ahlers (2018) 1805.08220v1

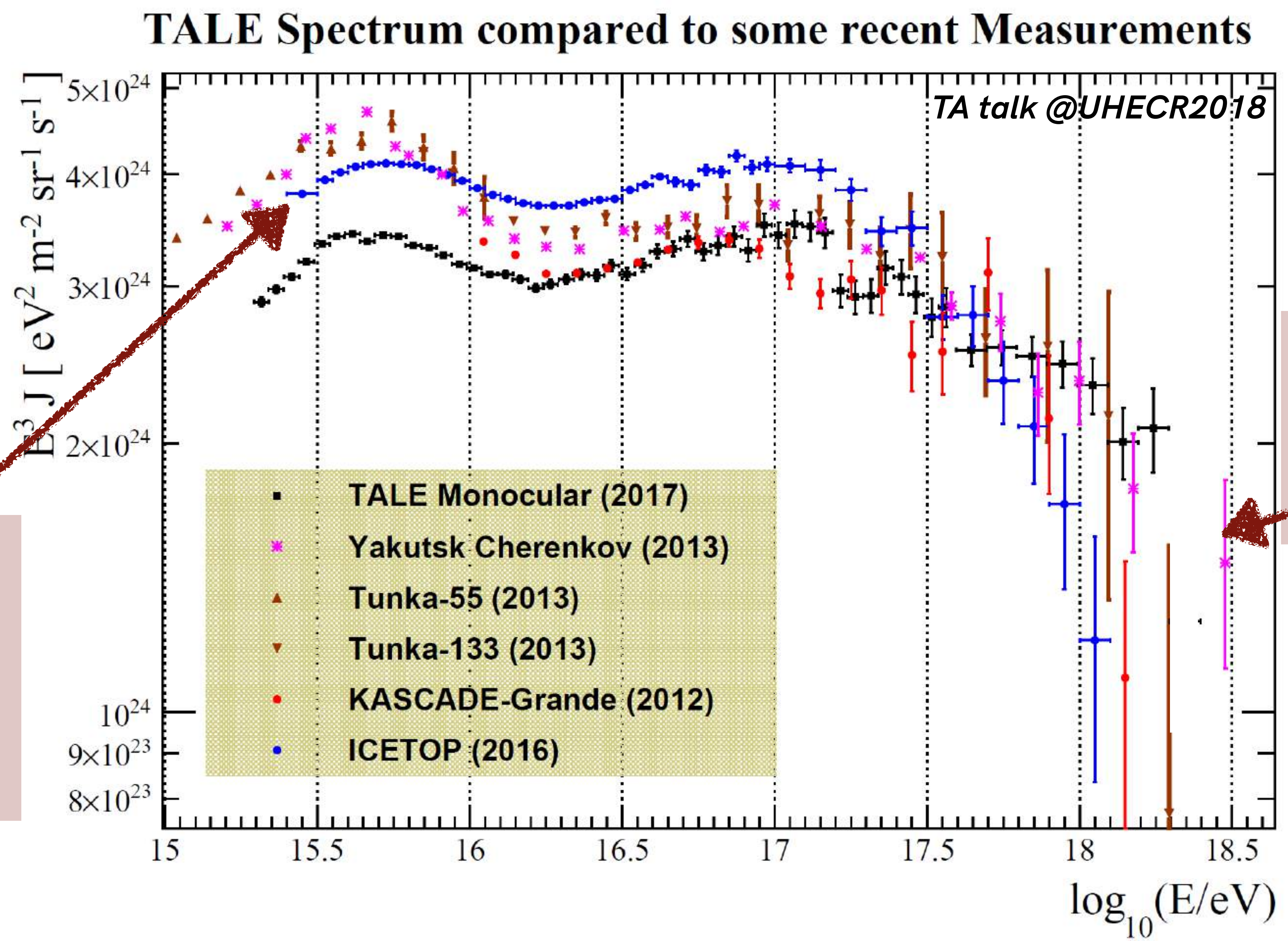


Auger confirms that UHECRs are of extragalactic origin

5.2 sigma dipole of 6.5% observed at E>8 EeV

dipole direction, amplitude
and light composition at EeV energies
in tension with source inside Galaxy

Galactic to extragalactic transition region



knee
Galactic
SNR
origin

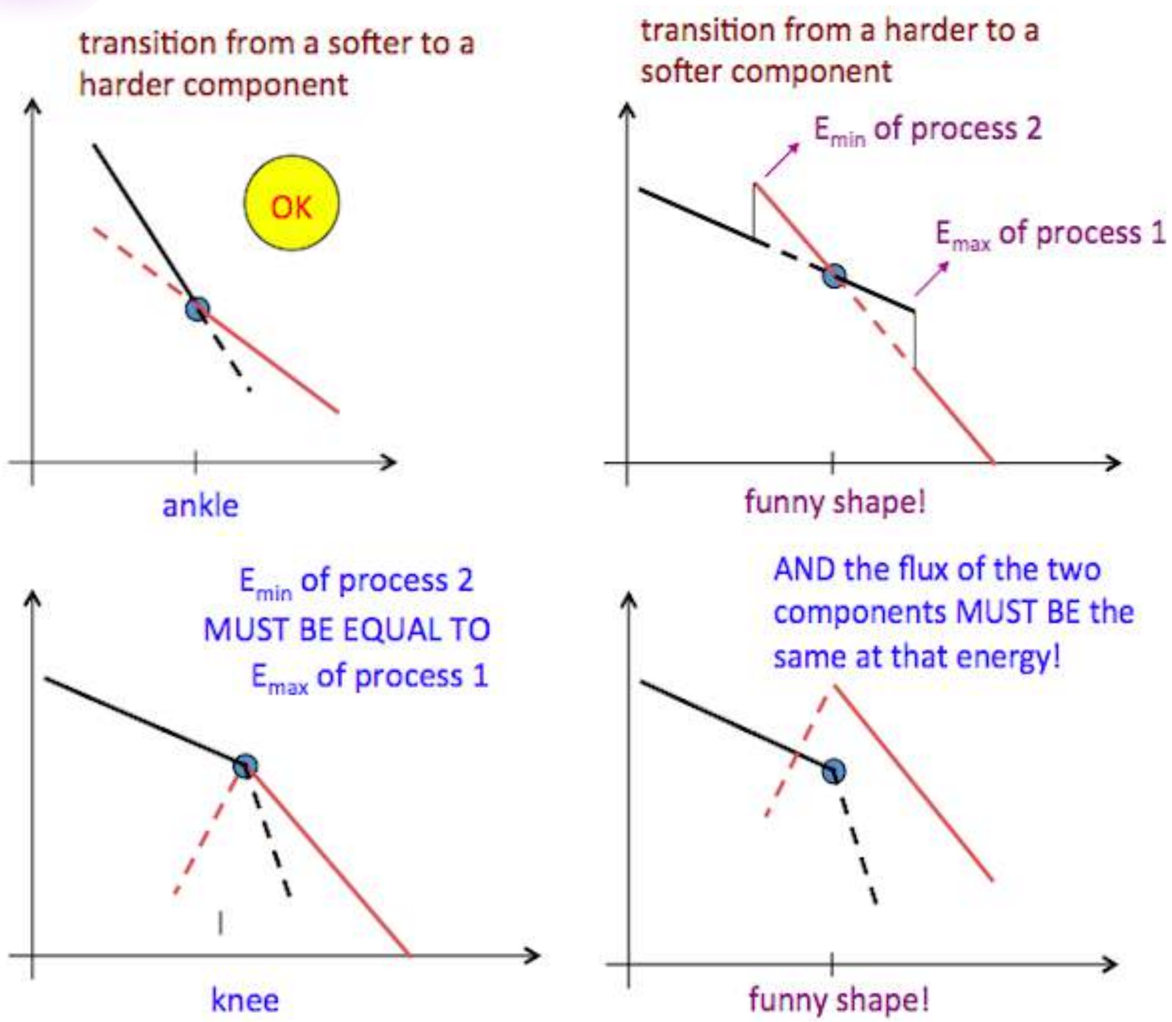
> 8 EeV
extragalactic
origin

dipole measurement
Auger Coll. 2018

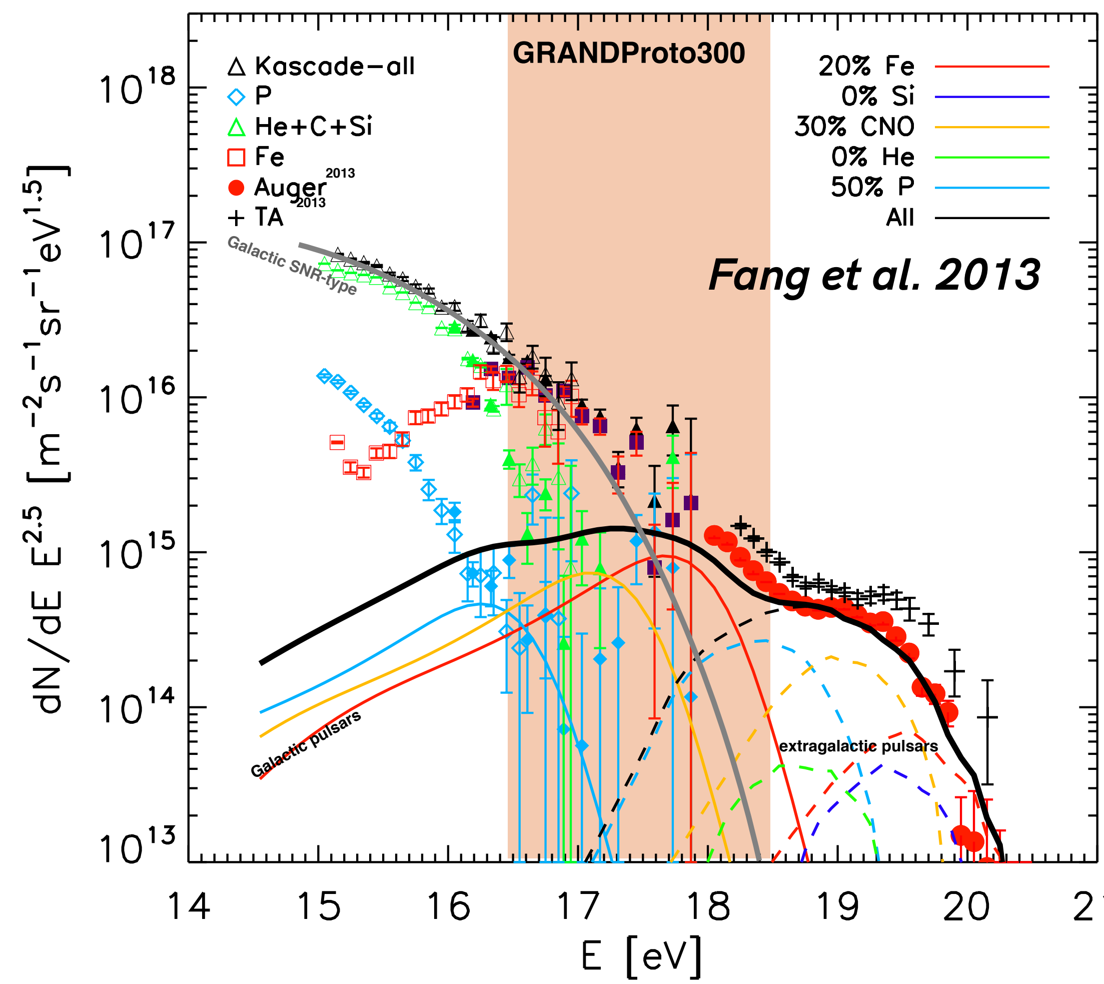
virtues of this transition region

- relatively important particle flux (few 100 cm^{-2} sr^{-1} s^{-1} GeV^2)
  —> accumulate reasonable statistics with mid-sized detectors
- overlaps with energy range experimentally probed by LHC

Galactic to extragalactic transition region



Parizot 2014



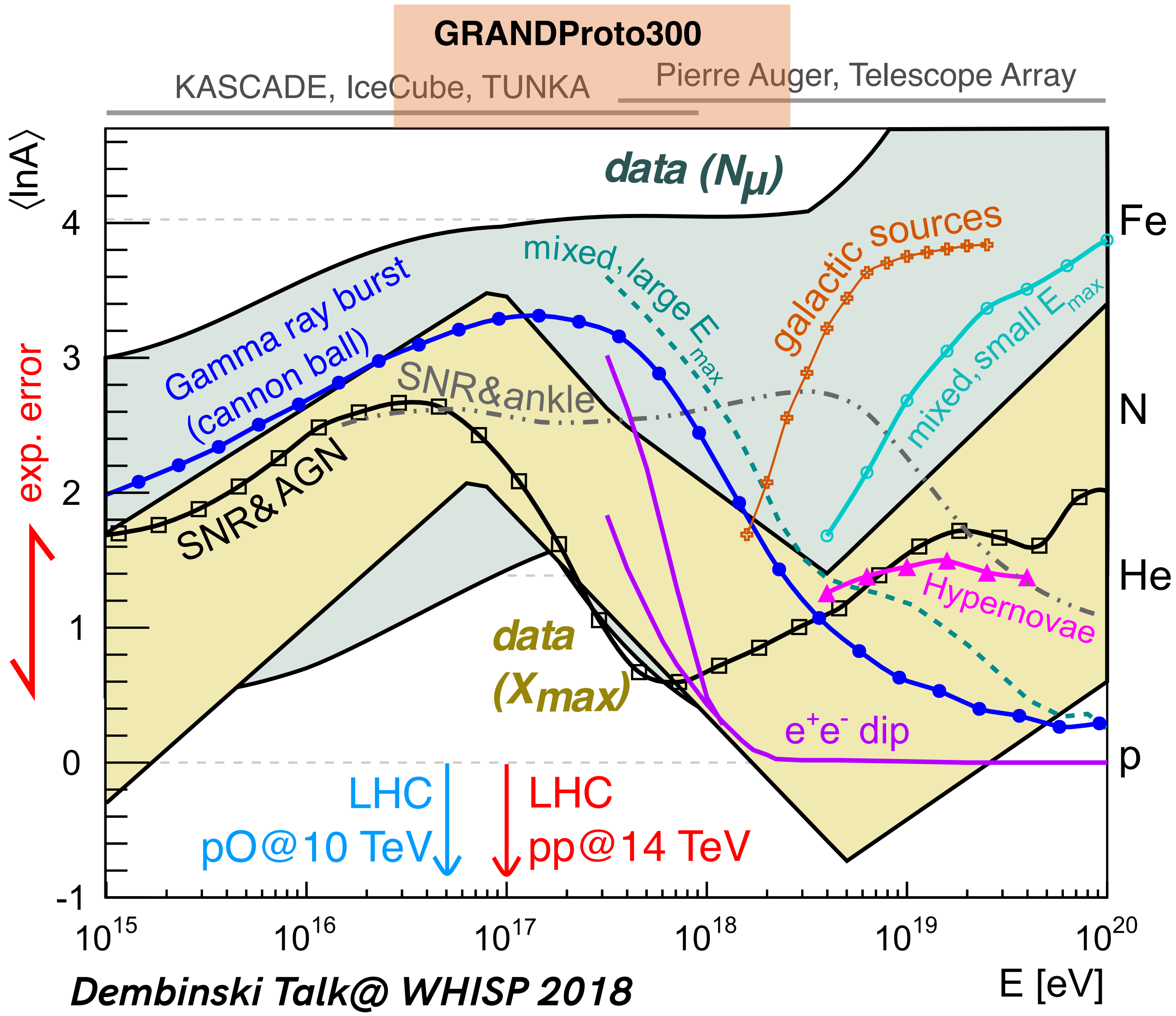
status

- bumpy spectrum
- emerging and vanishing mass elements?
- most theory models fit because of systematic uncertainties
- experimental gap around 10^{17}eV
- need for more statistics + accuracy

associated puzzles

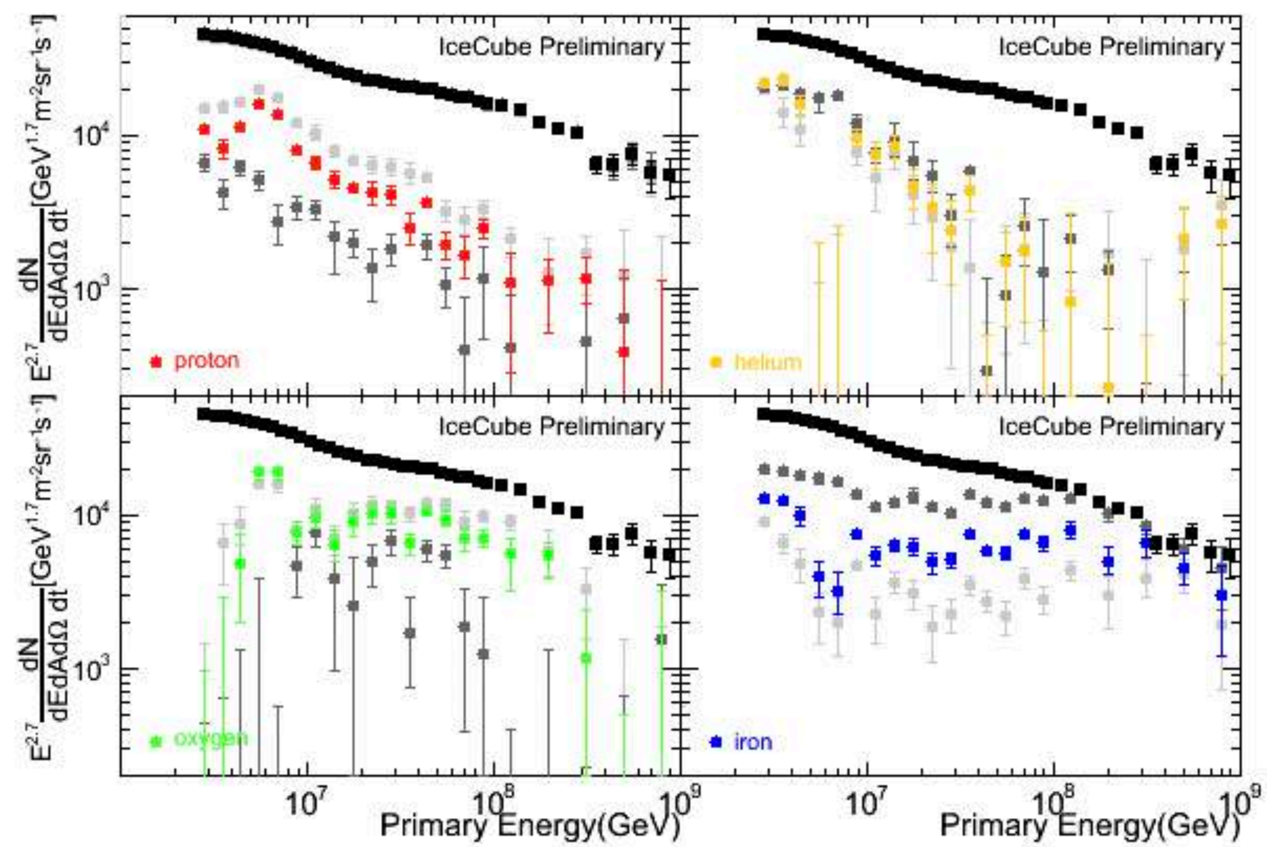
- **maximum acceleration energy in the Galaxy?**
- **1-2-3…? source components?**
- **injection/population of extreme UHE component**

Learning from mass composition?



Dembinski Talk@ WHISP 2018
from Kampert & Unger (2012)

zoom on transition region



IceCube ICRC 2015

light—>heavy —> light —> intermediate ??

- not precise enough for constraints on models
- muon data —> large uncertainties

Selection of UHECR candidate sources

to accelerate, first confine in source: $r'_{\mathrm{L}} \leq R'$

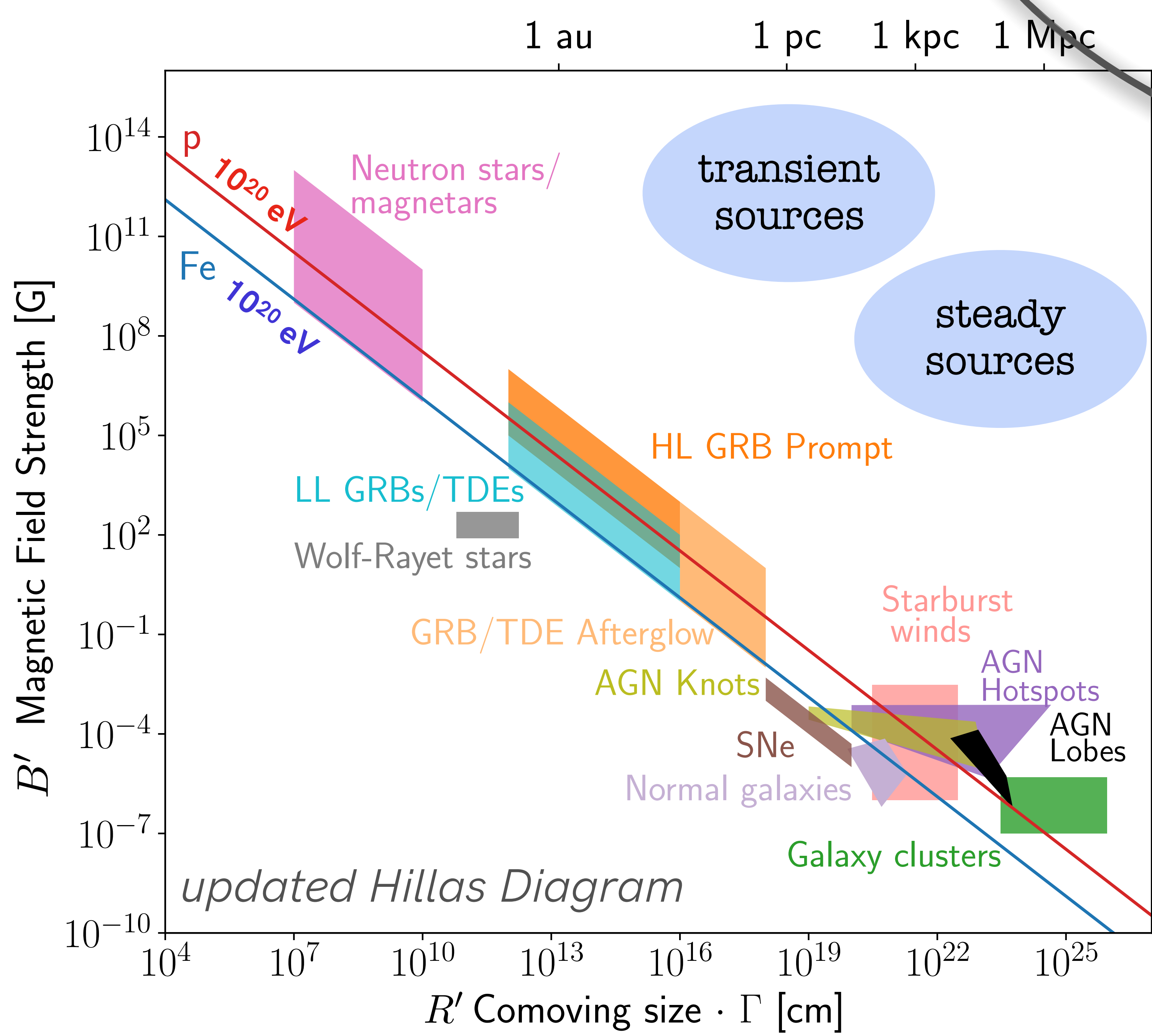
comoving size of source

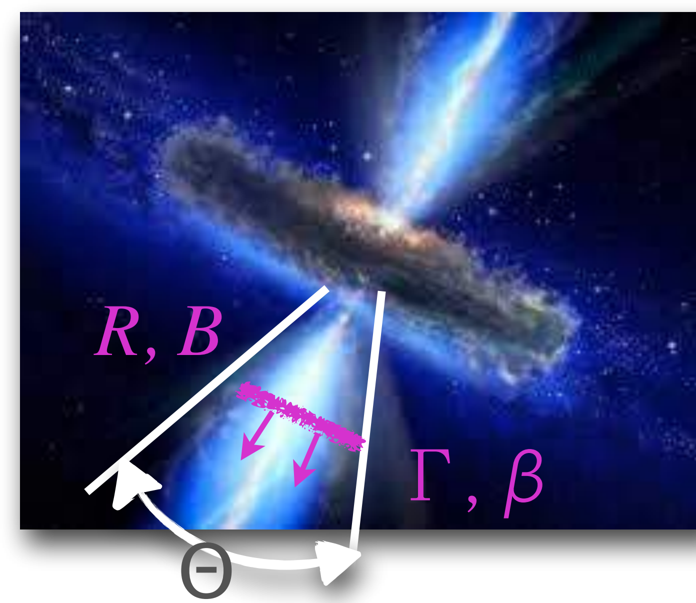
$$E \leq E_{\max} \sim 10^{15}\ \mathrm{eV} \times Z \left(\frac{B'}{1\ \mu\mathrm{G}}\right)\left(\frac{R'}{1\ \mathrm{pc}}\right)\Gamma$$

primed quantities: in comoving frame

$$r'_{\mathrm{L}} = 1.08\ \mathrm{Mpc}\, Z^{-1}\left(\frac{E'}{10^{18}\ \mathrm{eV}}\right)\left(\frac{B'}{1\ \mathrm{nG}}\right)^{-1}$$

particle charge | particle energy | source mag. field





Hillas (1984), KK & Olinto (2011)
***Guépin (PhD 2019)**, adapted from Alves Batista (2019)*

Condition for acceleration at sources

luminosity budget

steady sources

$>10^{45}$ erg/s

FRII: 10^{46-48} erg/s

FRI: $<10^{45}$ erg/s

transient sources

High luminosity GRB: 10^{51-52} erg/s

Low luminosity GRB: 10^{50-51} erg/s

pulsars: 10^{45-47} erg/s

magnetars: 10^{45-47} erg/s

condition for acceleration

$$t_{\rm acc} \lesssim t_{\rm dyn}$$

$$t_{\rm acc} = \mathcal{A}\, t_{\rm L}$$

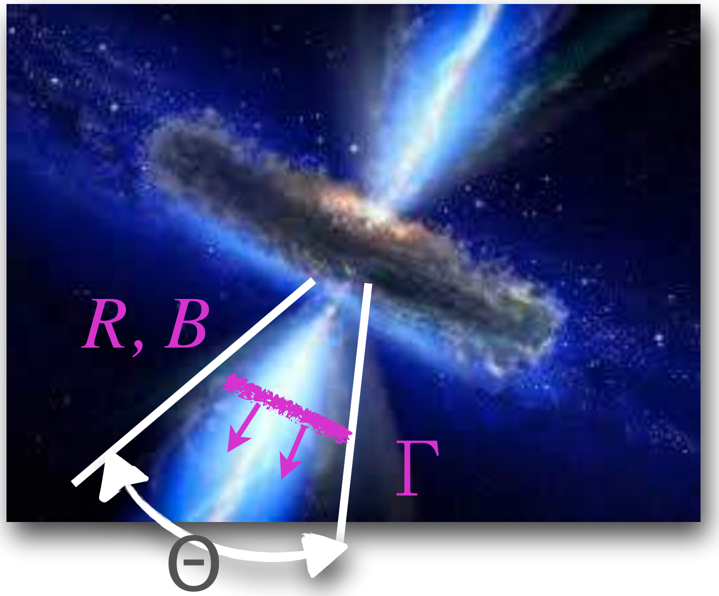
depends on acc. mechanism and environment

Larmor time

$\mathcal{A} \gg 1$

$\mathcal{A} \sim 1$ at best

$$t_{\rm dyn} \sim R/\beta\Gamma c$$



outflow magnetic luminosity

$$L_B \equiv 2\pi R^2\Theta^2\frac{B^2}{8\pi}\Gamma^2\beta c > 10^{45}\ Z^{-2} E_{20}^2\ \text{erg s}^{-1}$$

lower bound of the bolometric luminosity of source

Lemoine & Waxman 2009

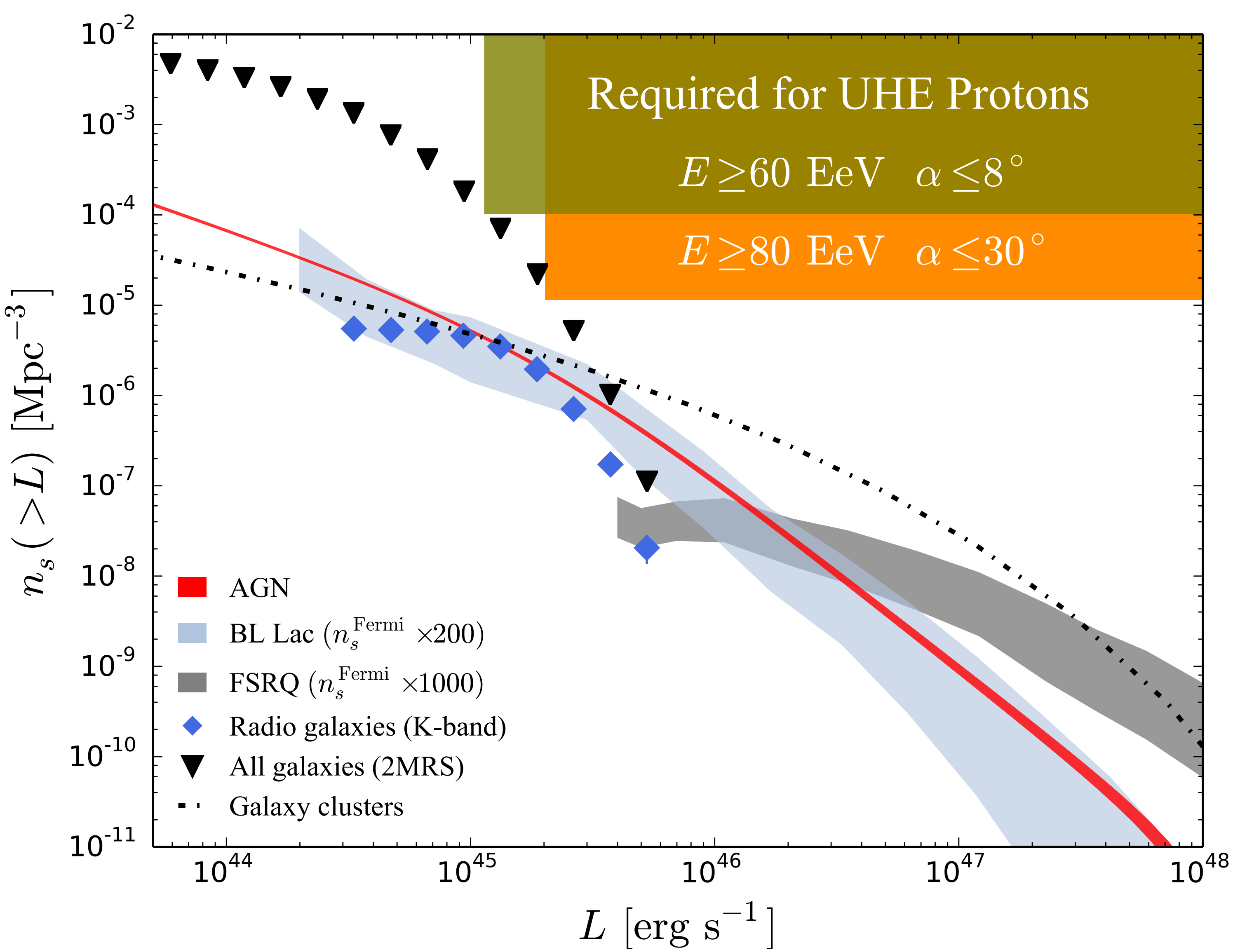
Condition for acceleration at sources

+ UHECR anisotropy

source bolometric luminosity $> 10^{45}\, Z^{-2} E_{20}^{2}$ erg s^{-1} *Lemoine & Waxman 2009*

level of clustering in the sky in Auger data
➢ apparent number density of sources @ given energy and angular deflection α *Abreu et al. 2013*

UHECRs cannot be dominantly protons from steady sources



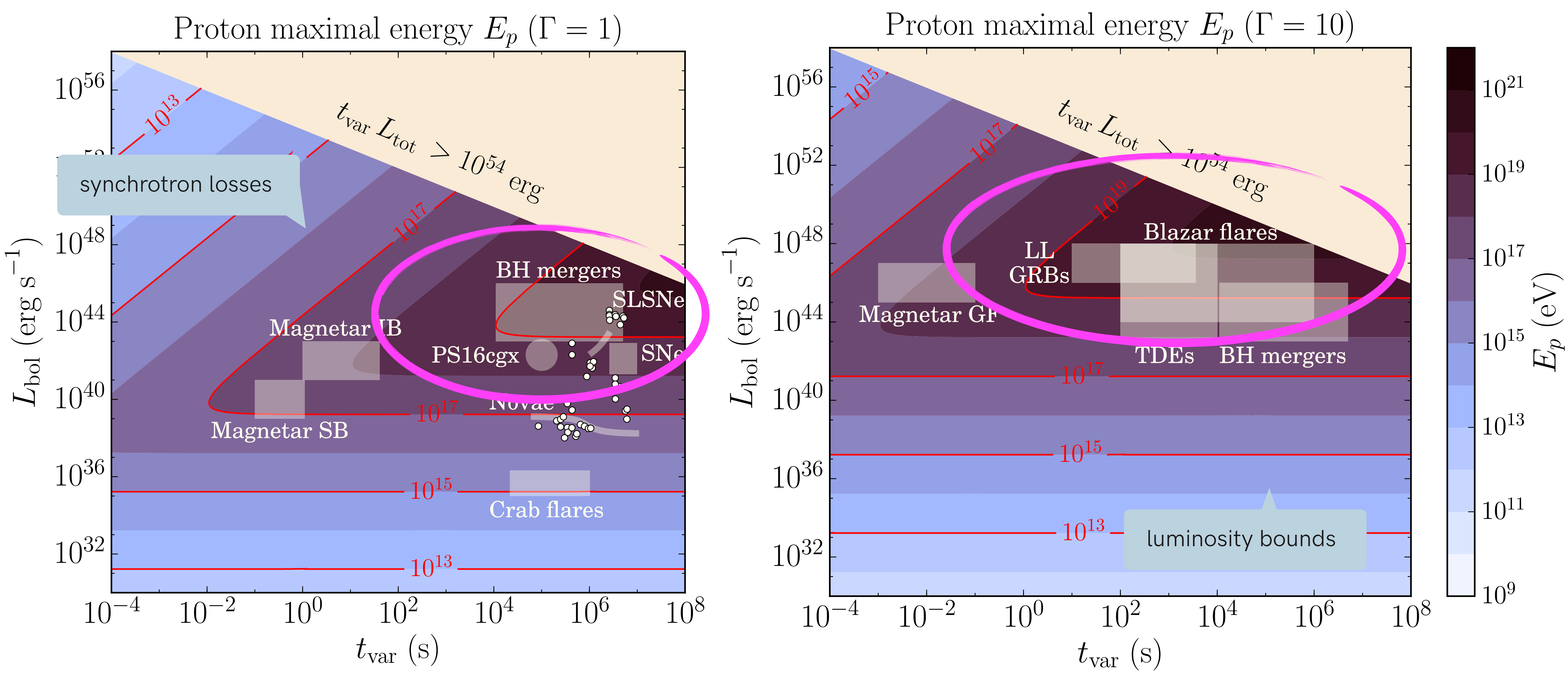
Fang & KK, 2016

possibilities for heavy/intermediate composition from steady sources e.g.,
BH jets: *Fang & Murase 2016*
radio galaxies: *Eichmann et al. 2018*

Condition for acceleration at sources for transients

source bolometric luminosity $> 10^{45}\, Z^{-2} E_{20}^2$ erg s^{-1} *Lemoine & Waxman 2009*

many transient sources could make it *Guépin & KK 2016*



"Hillas plot for transients"

Condition for acceleration at sources

energy losses

e.g., Guépin & KK (2017), Guépin et al. (2018) and many refs. therein

in reality $t_{\rm acc} \lesssim t_{\rm esc}, t_{\rm age}, t_{\rm loss}$

depends on B strength and structure

photo-hadronic interactions $t_{\rm pi}$
synchrotron radiation in B $t_{\rm syn}$
inverse Compton ...

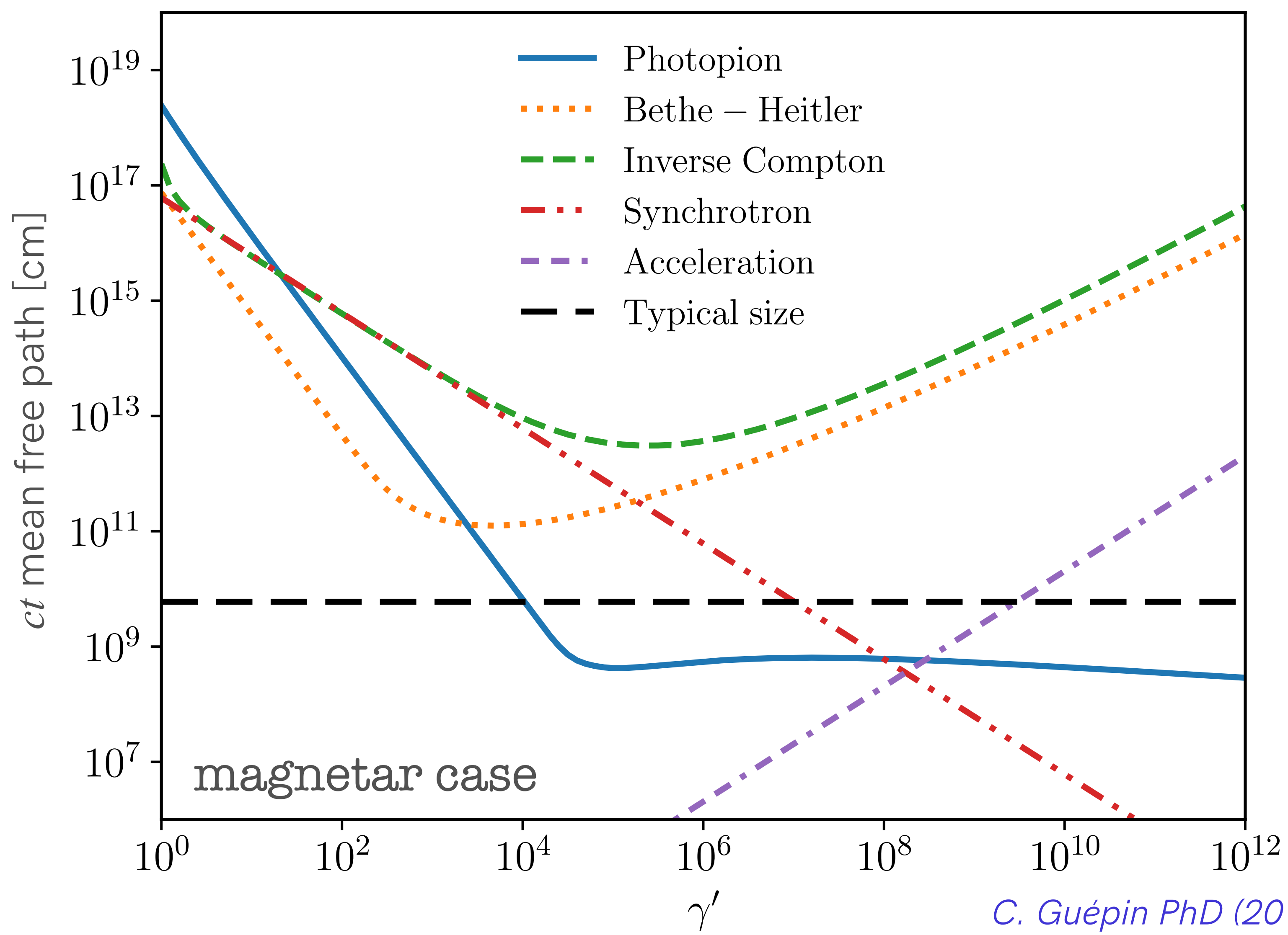
$t_{\rm acc} = \mathcal{A}\, t_{\rm L}$

depends on acc. mechanism and environment

Larmor time

$\mathcal{A} \gg 1$
$\mathcal{A} \sim 1$ at best

e.g., Norman et al. 1995, Waxman 1995, Lyutikov & Ouyed 2005, Waxman 2005 Lemoine & Waxman 2009



C. Guépin PhD (2019)

Cosmic-ray acceleration?

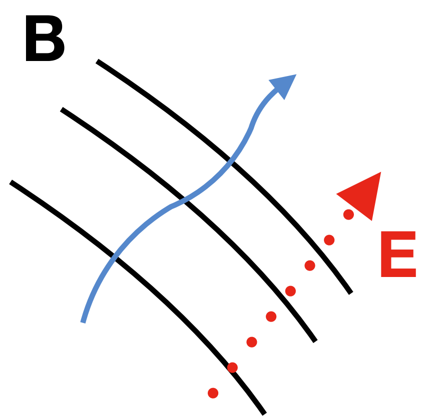
e.g., Bykov et al. 2012 review

Lorentz force $$\frac{d\mathbf{p}}{dt} = q\left(\mathbf{E} + \frac{\mathbf{v}\times\mathbf{B}}{c}\right)$$

Electric fields needed for acceleration (**B** alone do not make work on particles)

Electric field in plasma in motion (**v**) $$\mathbf{E} \sim -\frac{\mathbf{v}\times\mathbf{B}}{c}$$

Typical acceleration timescale $$t_{\rm acc} \gtrsim t_{\rm L}$$



acceleration if particle successfully crosses **B** lines, motion along **E**

"Bulk" acceleration

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

large-scale **E**
(special conditions required to achieve this because of high conductivity of plasmas)

Stochastic acceleration

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

small-scale **E**
(random magnetic fluctuations, frequent in astrophysical obj.)

examples

- unipolar inductors
- reconnection
- wakefield acceleration

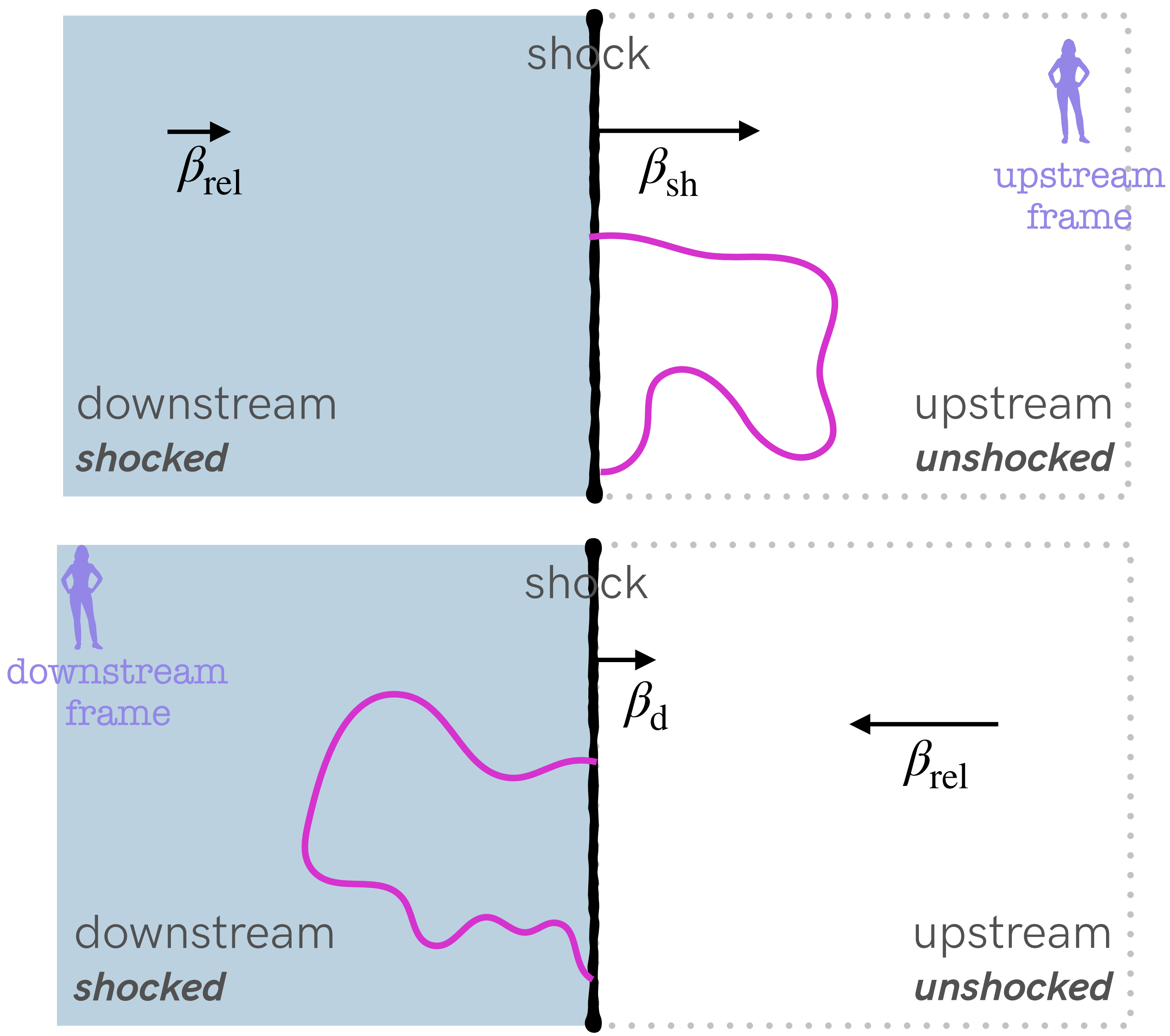
- Fermi mechanisms
- diffusive Shock Acceleration
- shear acceleration

Stochastic acceleration

- random magnetic fluctuations —> resonant scattering of particles
- particle distribution ~isotropized in reference frame of the wave

see A. Spitkovsky's talk

example: 1st order Fermi acceleration



- in each frame, particle diffuses but energy does NOT change
- particle experiences head-on collisions

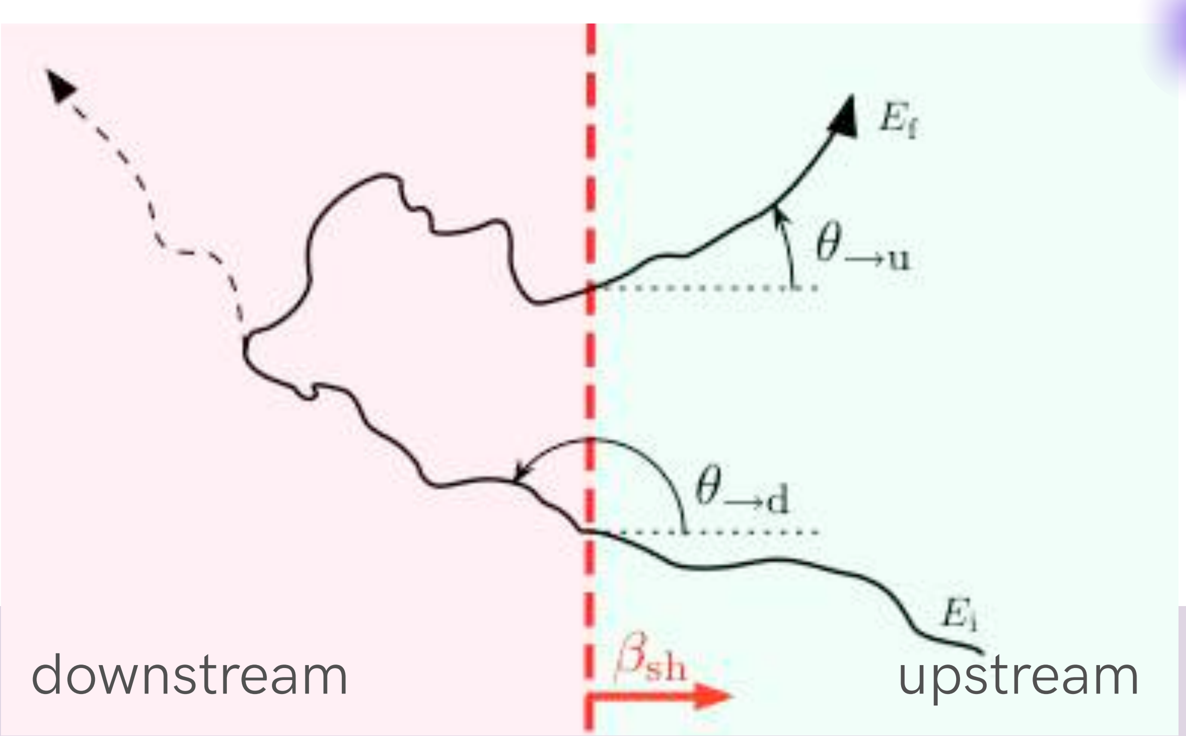
relative velocity and Lorentz factors

$$\beta_{\rm rel} = \frac{\beta_{\rm u} - \beta_{\rm d}}{1 - \beta_{\rm u}\beta_{\rm d}}, \quad \Gamma_{\rm rel}$$

ultra-relativistic shock $\quad \beta_{\rm d} \to \frac{1}{3} \qquad \Gamma_{\rm rel} \to \frac{\Gamma_{\rm sh}}{2}$

1st order Fermi acceleration

e.g., Gallant (2002)



- 2 Lorentz transforms
- energy gain for one cycle (u-d-u):

$$\frac{E_f}{E_i} = \Gamma_{rel}^2 (1 - \beta_{rel} \mu_{\to d})(1 + \beta_{rel} \mu_{\to u})$$

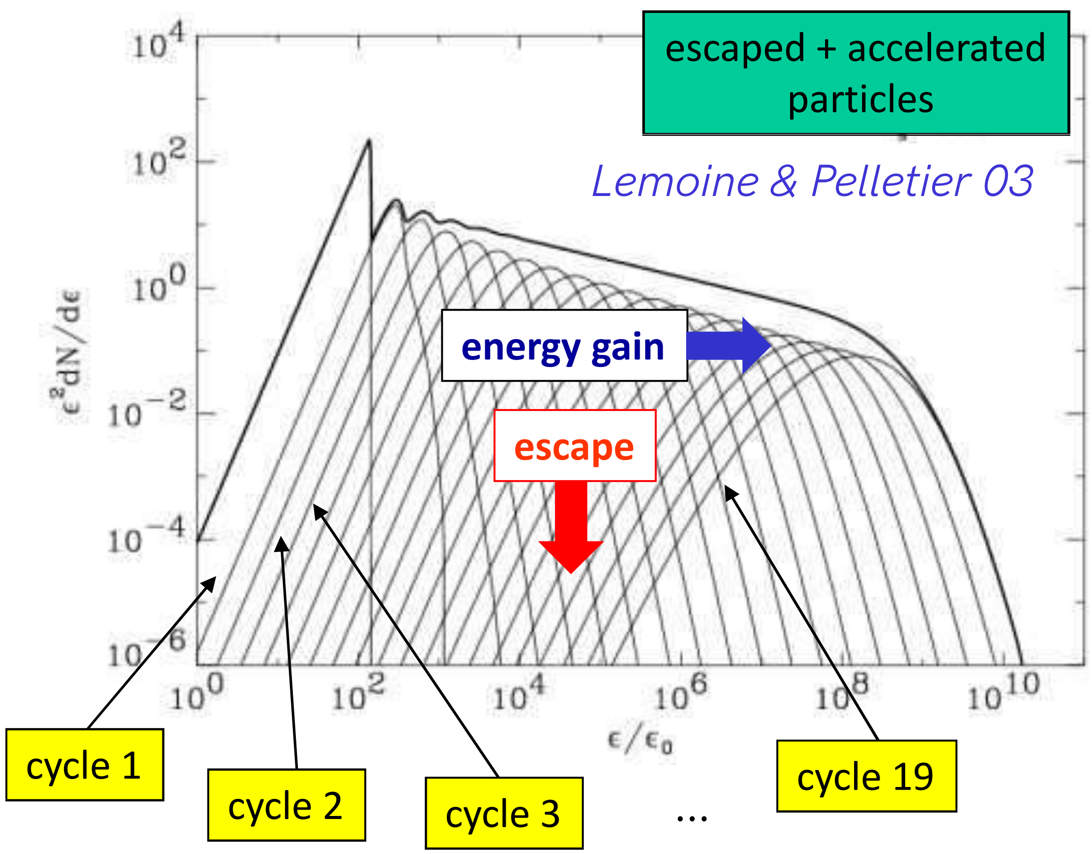
crossing up—>down   crossing down—>up

- average over the angles to calculate total energy gain
- non-relativistic shock (particle distribution isotropic):

$$\frac{\Delta E}{E} = -\int_0^1 d\mu 2\mu \int_{-1}^0 d\mu' 2\mu' \left[\gamma^2(1+\beta\mu)(1-\beta\mu') - 1\right] \approx \frac{4}{3}\beta$$

- relativistic shocks: high gain in principle… but…

e.g., Gallant (2002), Lemoine & Pelletier (2003)



from M. Lemoine (Dublin 2011)

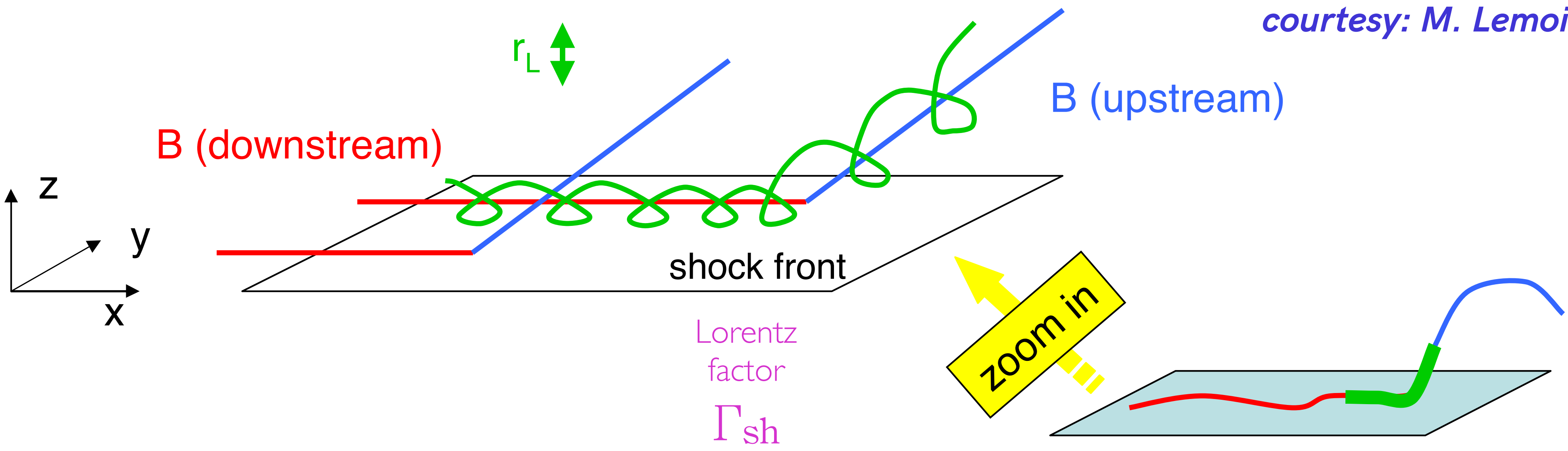
Cosmic-ray acceleration at relativistic shocks

Lemoine et al. 06
Pelletier et al. 09

Successful Fermi acceleration: particle has to return to the shock

Problem **for ultra-relativistic shocks**:
particle entangled in (perp.) B lines downstream and **advected** away from shock

courtesy: M. Lemoine



Condition for particle to escape from this advection:

micro-turbulence: (downstream)

$$\frac{\delta B}{\langle B \rangle} \gg \frac{r_L}{l_{coh}}$$

Larmor radius in total magnetic field

$$r_L = 1.08\ \mathrm{Mpc}\ Z^{-1} \left(\frac{E}{10^{18}\ \mathrm{eV}}\right) \left(\frac{B}{1\ \mathrm{nG}}\right)^{-1} \beta_\perp$$

l_{coh} coherence length of small-scale field

bounds on particle Larmor radius (downstream)

Pelletier et al. 09

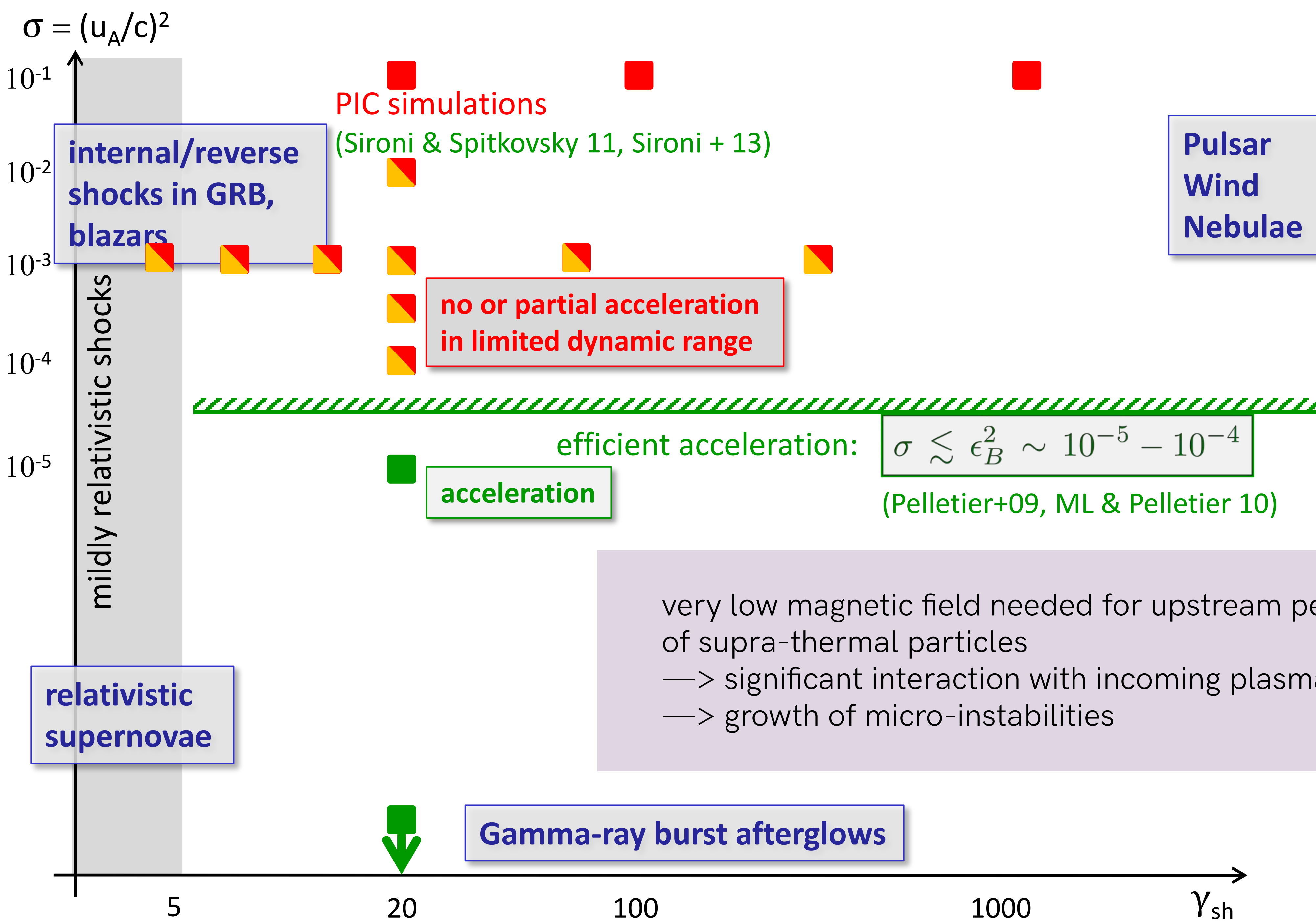
$$l_{coh} \ll r_L \ll \frac{\delta B}{B}\, l_{coh}$$

efficient micro-turbulence generation needed

Cosmic-ray acceleration at relativistic shocks

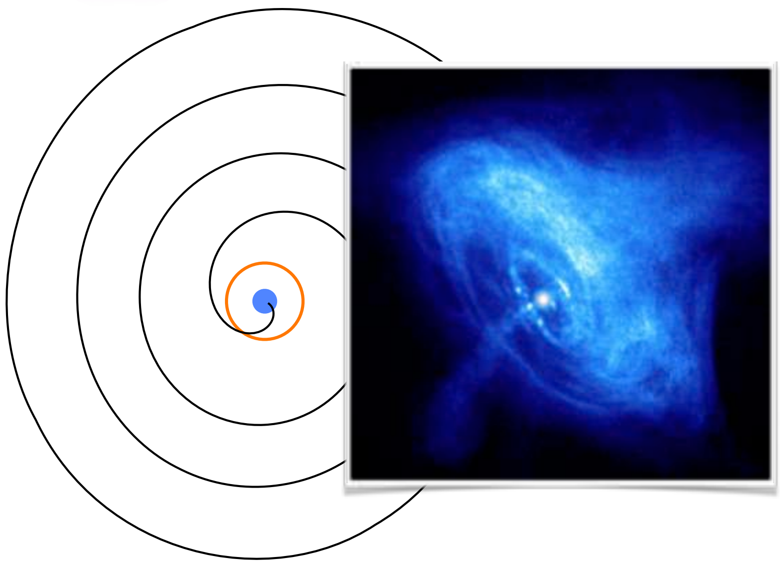
from M. Lemoine (APC 2016)

- Lorentz factor of the shock $\gamma_{sh} \equiv \left(1-\beta_{sh}^2\right)^{-1/2}$
- upstream magnetization $\sigma \equiv \dfrac{B_{|sh}^2}{4\pi\gamma_{sh}^2 nmc^2}$

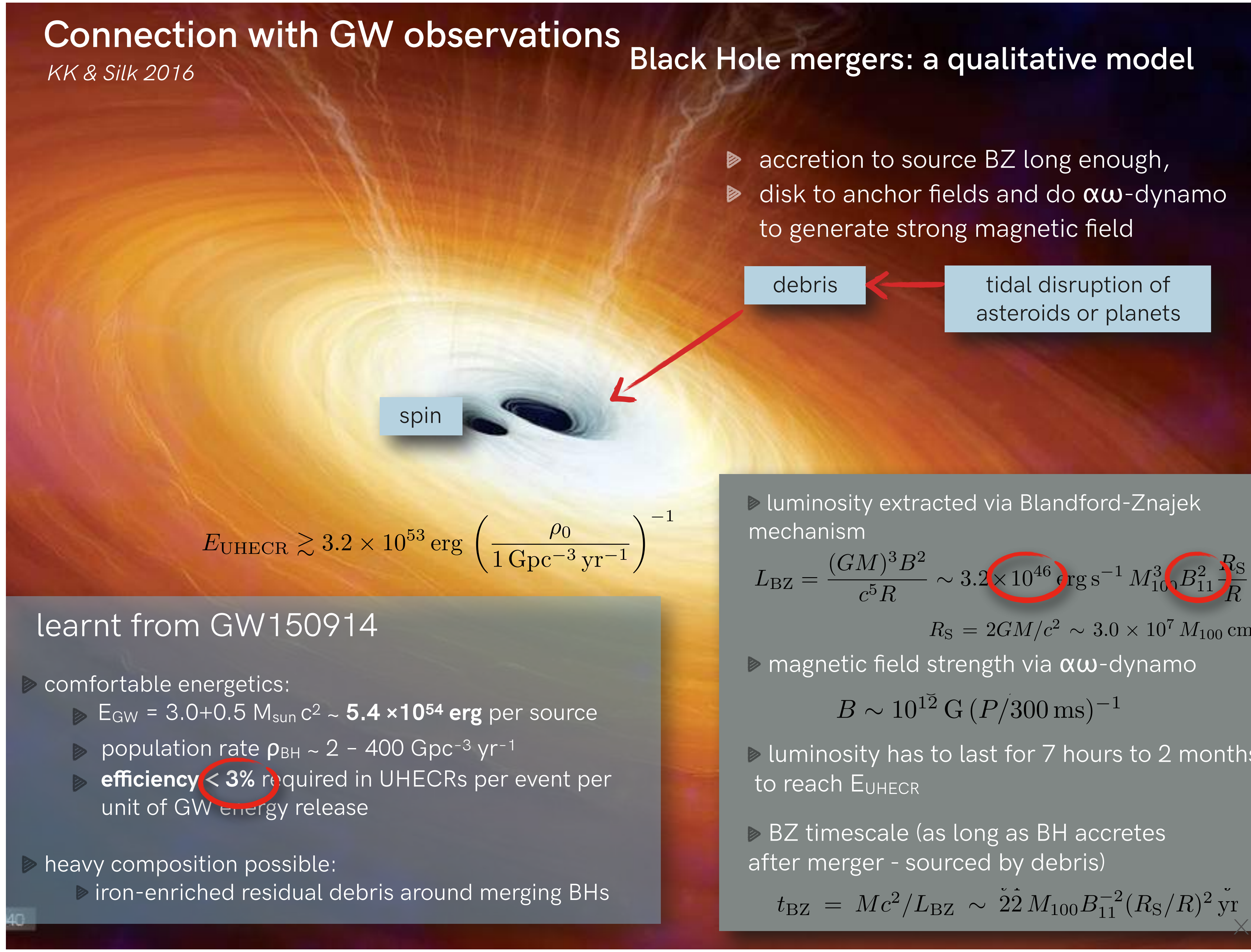


very low magnetic field needed for upstream penetration of supra-thermal particles
—> significant interaction with incoming plasma
—> growth of micro-instabilities

"Bulk" acceleration $\langle \mathbf{E} \rangle \neq 0$



B. Crinquand's Talk
E. Zweibel's Talk
J. Mehlhalff's Talk



- Unipolar inductors: (pulsars, rotating BHs)
rotating magnetic fields —> electric potential established (gaps) where **E.B** = 0 violated

- Reconnection: (magnetospheres of pulsars, rotating BHs…)
local merging of magnetic fields —> local electric field E~LB (L=size of reconnection region)

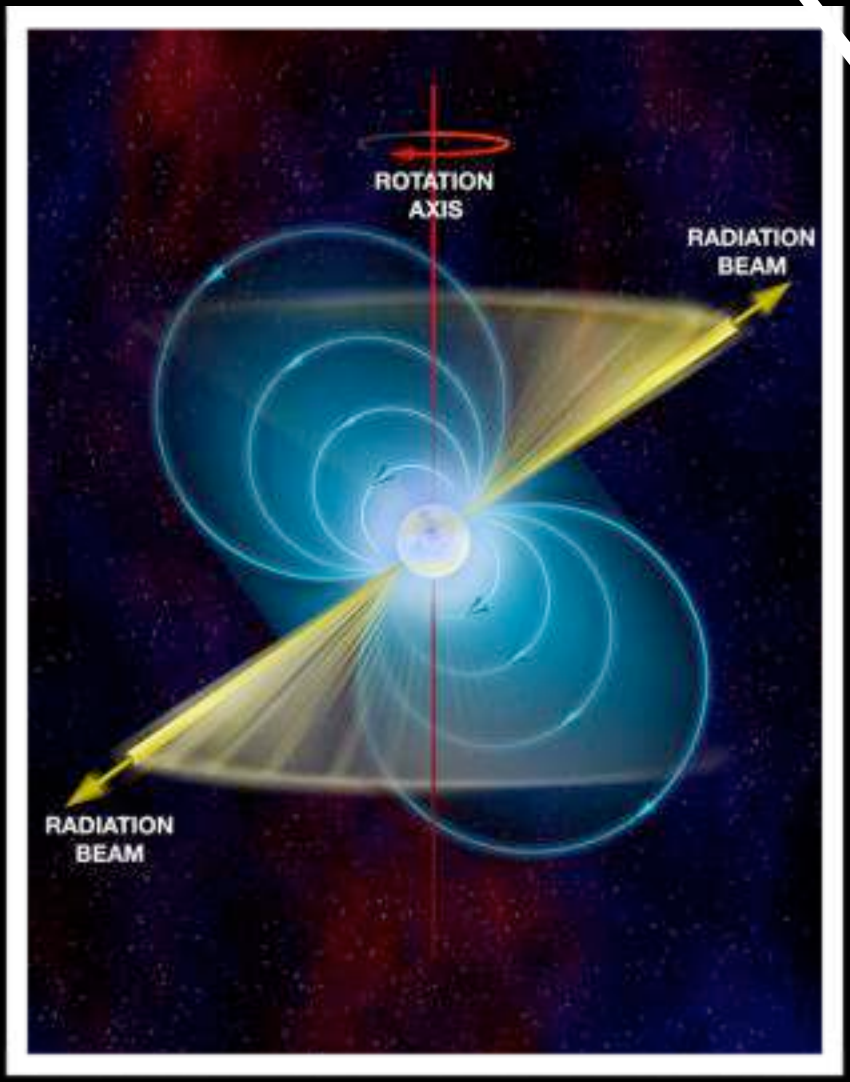
Pulsar characteristics

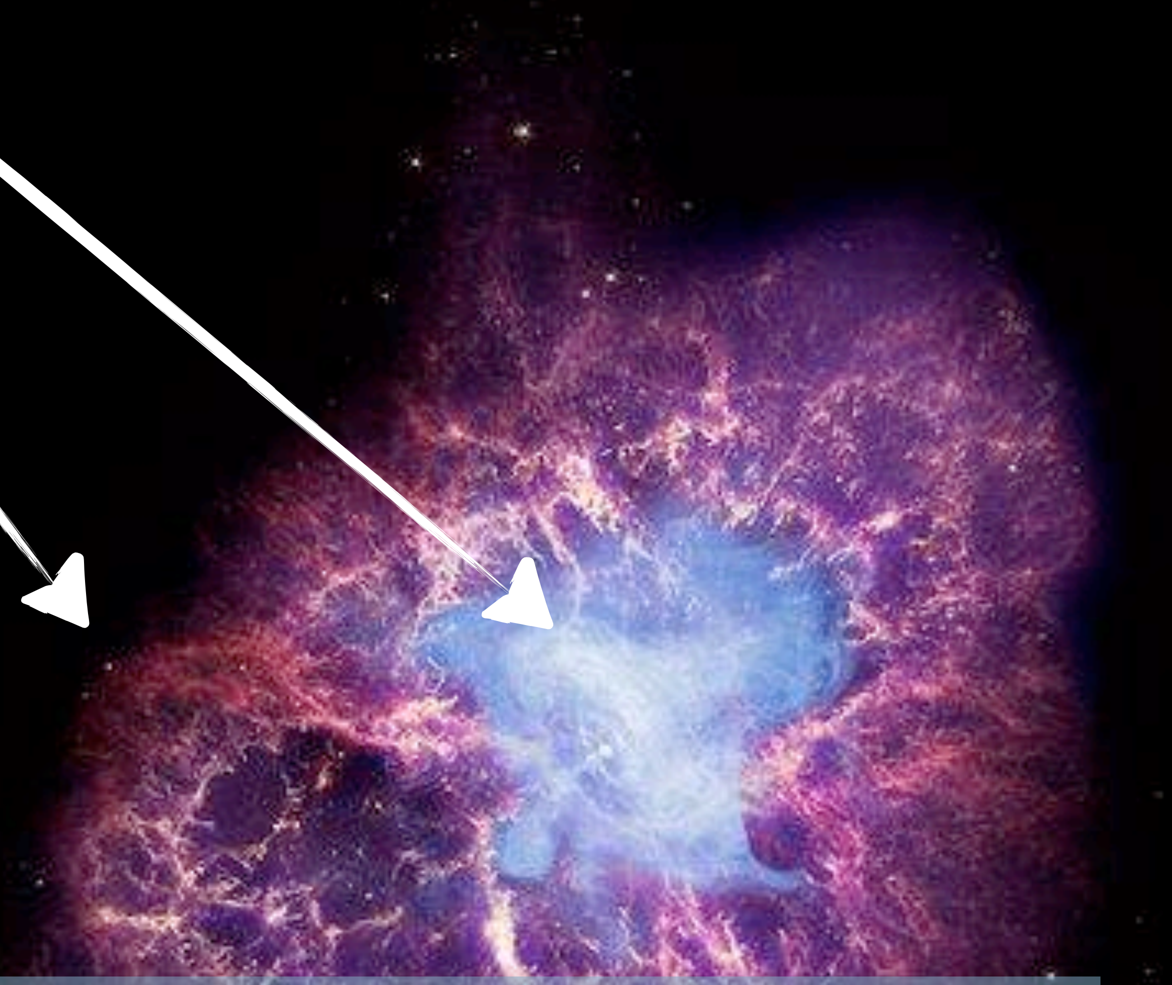
see B. Cerutti's talk
F. Cruz's talk

end of life of massive stars

collapse of core --> neutron star or black hole

explosion --> supernova





- neutron star
- fast rotation, period P
- strong magnetic field B
- spins down by electromagnetic losses

Acceleration of UHECRs in newly-born pulsars

Blasi et al. 00, Arons 03, Lemoine, KK, Pétri 2016

acceleration

particle maximum Lorentz factor:

$$\gamma_{\rm M} \simeq \frac{L_{\rm p}}{\dot{N} m c^2}$$

pulsar luminosity

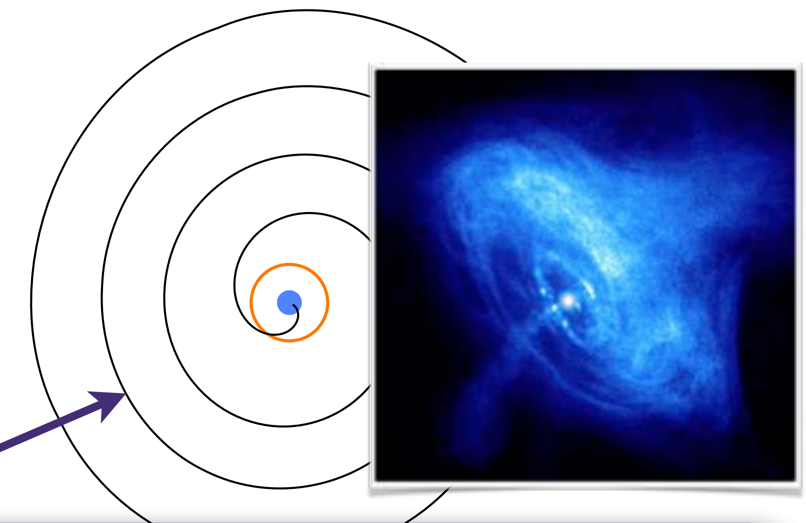
Goldreich-Julian charge density

maximum energy: *Lemoine, KK, Pétri 2016*

$$E_0 \sim 1.5\times 10^{20}\,{\rm eV}\,A_{56}\,\eta\,\kappa_4^{-1}\,P_{{\rm i},-3}^{-2}\,B_{13}\,R_{\star,6}^3$$

fraction of luminosity into particle kinetic energy

pair multiplicity



relativistic wind

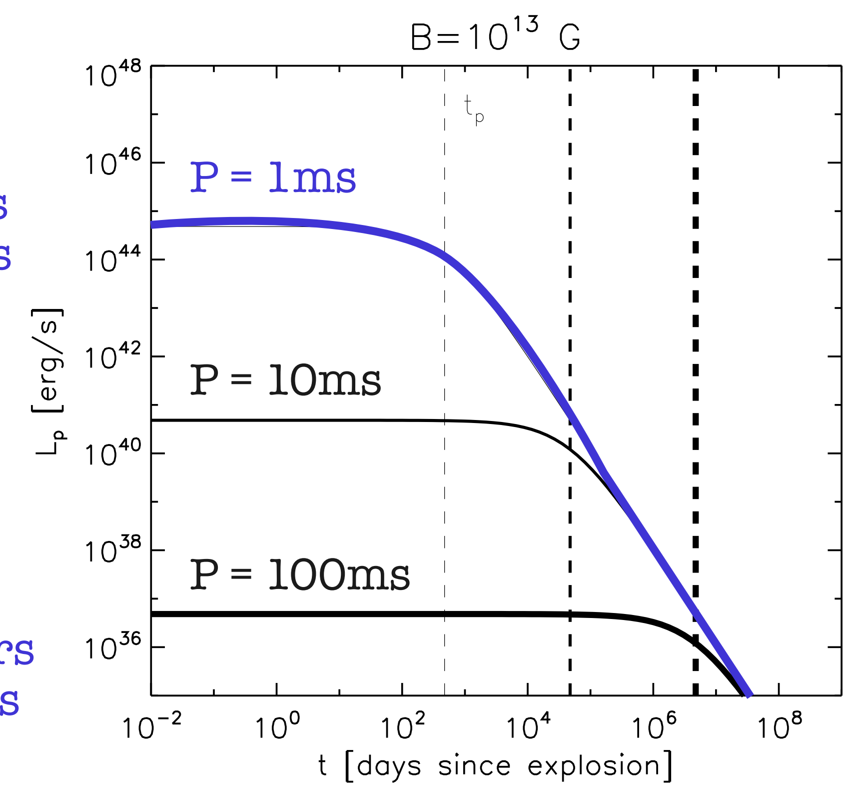
$$B \propto \frac{1}{r}$$

total energy $\quad E_{\rm p} = \dfrac{I\Omega_{\rm i}^2}{2} \sim 1.9\times 10^{52}\,{\rm erg}\,I_{45} P_{{\rm i},-3}^{2}$

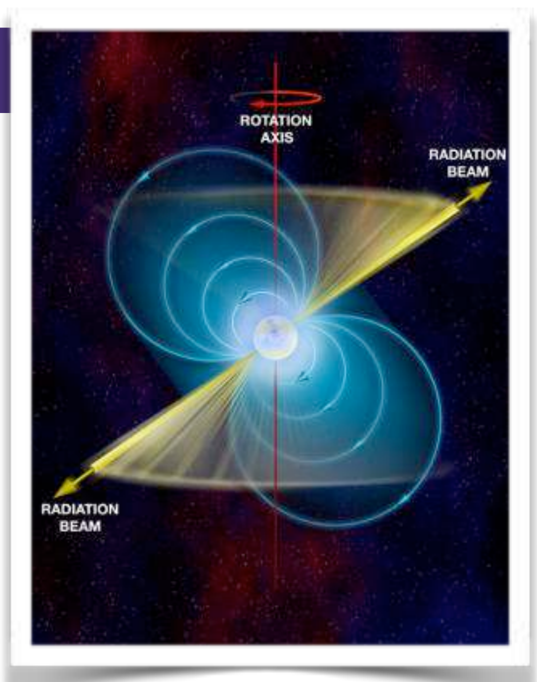
pulsar luminosity $\quad L_{\rm p}(t) = \dfrac{E_{\rm p}}{t_{\rm p}}\dfrac{1}{(1+t/t_{\rm p})^2}$

$L_{\rm p} \sim 10^{45}$ erg/s for ms pulsars

$t_{\rm p} \sim$ a few years for ms pulsars



Goldreich-Julian charge density



induced electric field:

$$\mathbf{E} = -\frac{\mathbf{v}}{c}\times\mathbf{B} = -\frac{1}{c}(\mathbf{\Omega}\times\mathbf{r})\times\mathbf{B}$$

everywhere where the plasma is in corotation

implies the presence of a charge density:

$$\rho = \frac{1}{4\pi}\nabla\cdot\mathbf{E} \approx -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi c} \equiv \rho_{GJ}$$

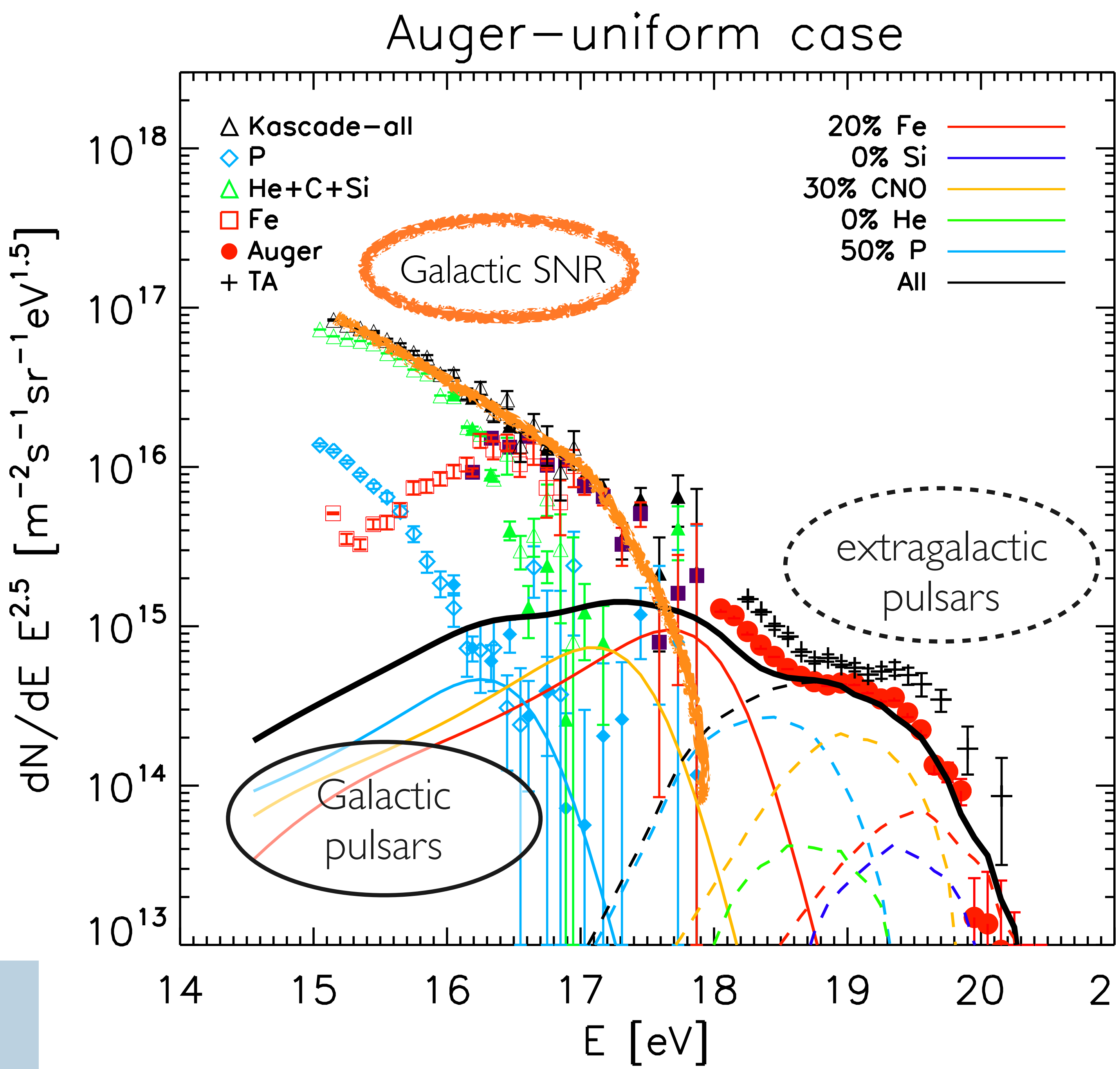
Goldreich & Julian (1969)

UHECR and pulsars

Blasi et al. 00, Arons 03, Fang et al. 2012, 2013, 2015, 2016, KK et al. 2015

a model with good initial conditions

- energetics ($E_{rot} > 10^{52}$ erg for the fastest)
- number density ($n_{pulsars} \sim 10^{-4}$ Mpc^{-3} yr^{-1})
- natural spot to produce heavy nuclei



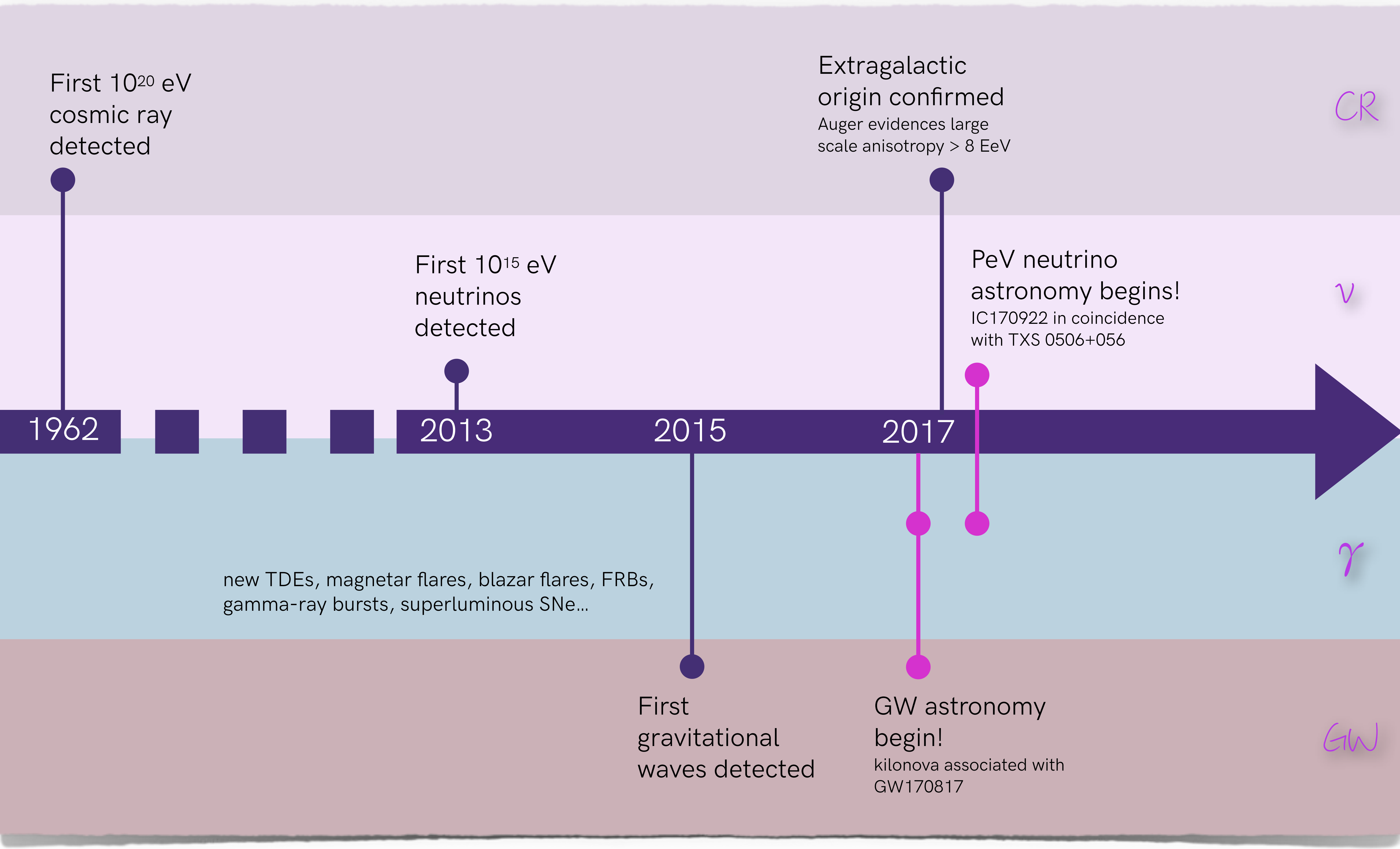
a model that works!

- fits composition at UHE
- fits spectrum at UHE
- bridges gap between SNR - extragalactic sources

a testable model!

- unavoidable neutrino flux observable with IceCube in the next decade

Exciting times!



And we still don't know the origin of UHECRs

Current multi-messenger data: useful to understand UHECRs?

$$p + \gamma \rightarrow n + \pi^+$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$p + \gamma \rightarrow p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

Cosmic backgrounds
interactions on CMB, UV/opt/IR photons

cosmogenic neutrino and gamma-ray production

Backgrounds
- radiative? baryonic?
- evolution, density?
- magnetic field: deflections?

associated neutrino and gamma-ray production

γ ν

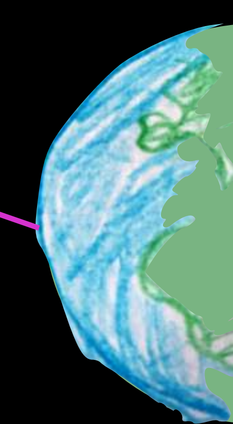
Secondaries take up 5-10% of parent cosmic-ray energy

$E_\nu \sim 5\%\ E_{CR}/A$ $\quad$ $E_\gamma \sim 10\%\ E_{CR}/A$

$E_{CR} > 10^{18}$ eV

$E_\nu > 10^{16}$ eV

γ ν

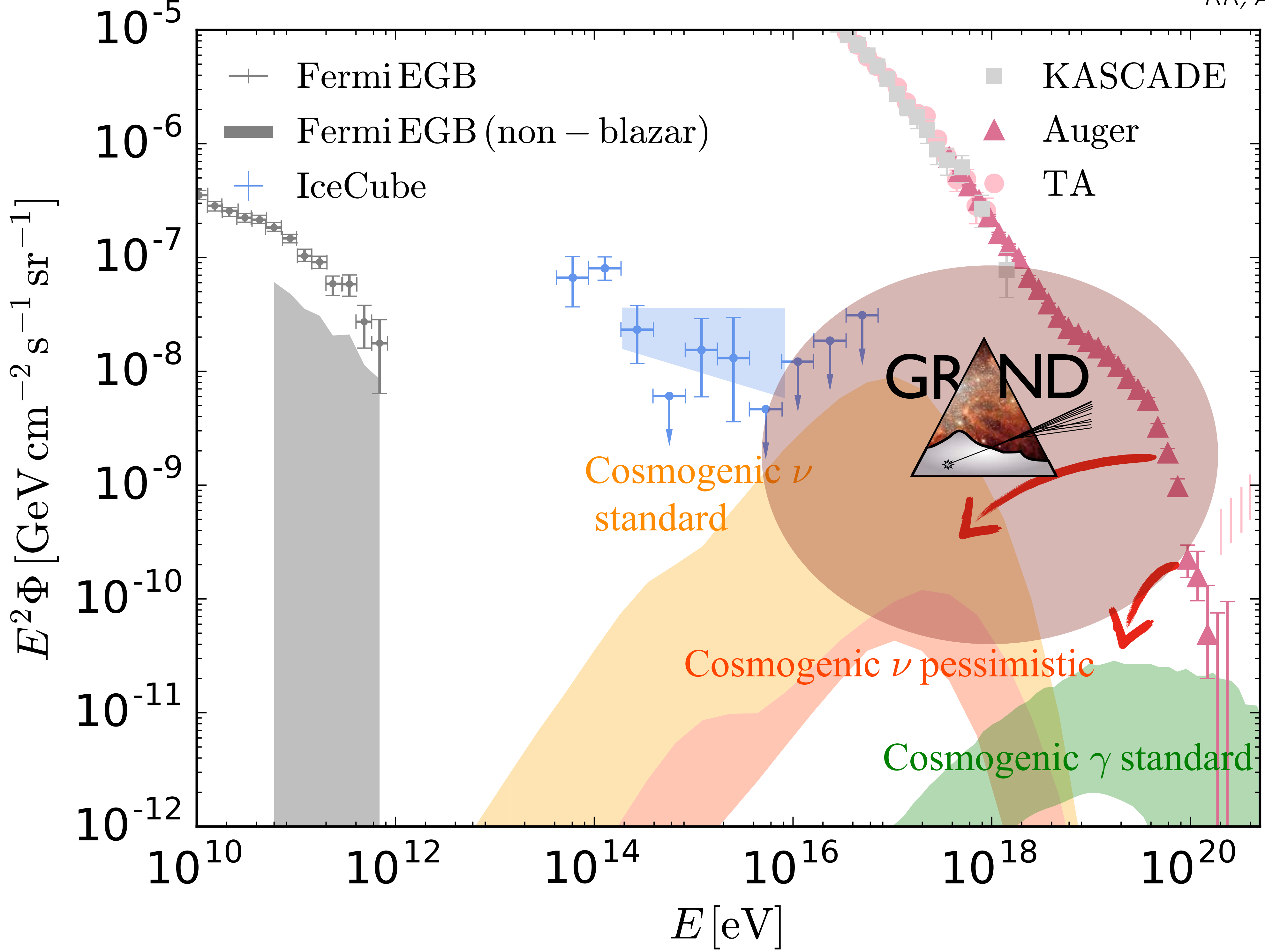


IceCube neutrinos do not directly probe UHECRs

Actually, none of the current multi-messenger data (except UHECR data) can directly probe UHECRs ... but they help :-)

The guaranteed cosmogenic neutrinos

Alves Batista, de Almeida, Lago, KK, 2018
GRAND Science & Design, 2018
KK, Allard, Olinto 2010



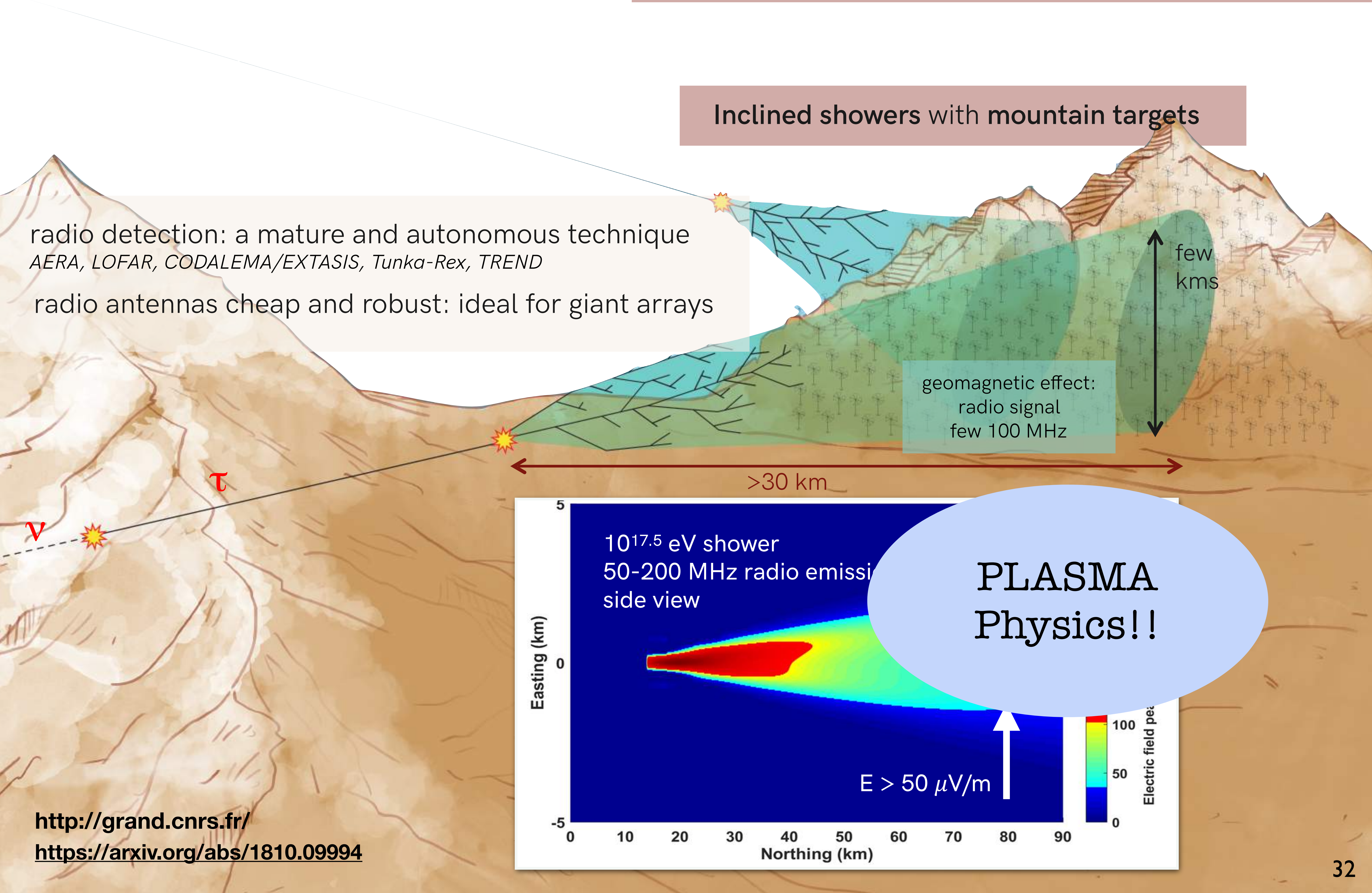
The GRAND Concept

200,000 radio antennas over 200,000 km²
~20 hotspots of 10k antennas
in favorable locations in China & around the world

Inclined showers with **mountain targets**

radio detection: a mature and autonomous technique
AERA, LOFAR, CODALEMA/EXTASIS, Tunka-Rex, TREND

radio antennas cheap and robust: ideal for giant arrays



http://grand.cnrs.fr/
https://arxiv.org/abs/1810.09994

Learn plasma Physics and help us hunt for the origin of UHECRs!