A quest for sources of ultrahigh energy cosmic rays

1984

Ann. Rev. Astron. 1984 ... 44

THE ORIGIN OF ULTRA-HIGH-ENERGY COSMIC RAYS

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Where do cosmic rays originate?

Are they all extragalactic? Burbidge (18, 19) has pointed out the possibilities of such schemes. At low energies we really only have weak gamma-ray evidence against an extragalactic origin (83), and an earlier conclusion that cosmic-ray protons were less numerous in the outer parts of the Galaxy has now been overturned by observations from COS-B (74). There is, however, a consistent galactic picture, and near 10^{18} eV the 10–20% N/S asymmetries just alluded to speak against a very distant origin.

2010

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Astrophysics of Ultrahigh Energy Cosmic Rays

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Key Words cosmic rays, neutrinos, ultrahigh energy, cosmic accelerators, magnetic fields, particle astrophysics

The origin of ultrahigh energy cosmic rays is still unknown.

Abstract The origin of ultrahigh energy cosmic rays is still unknown. Recent evidence shows that they come from extragalactic regions, but the actual sources are still a mystery. After a brief introduction to the current state of the observations, the astrophysics of propagation at

Why is it so difficult?

in a way we don't know!

Astrophysical issues:

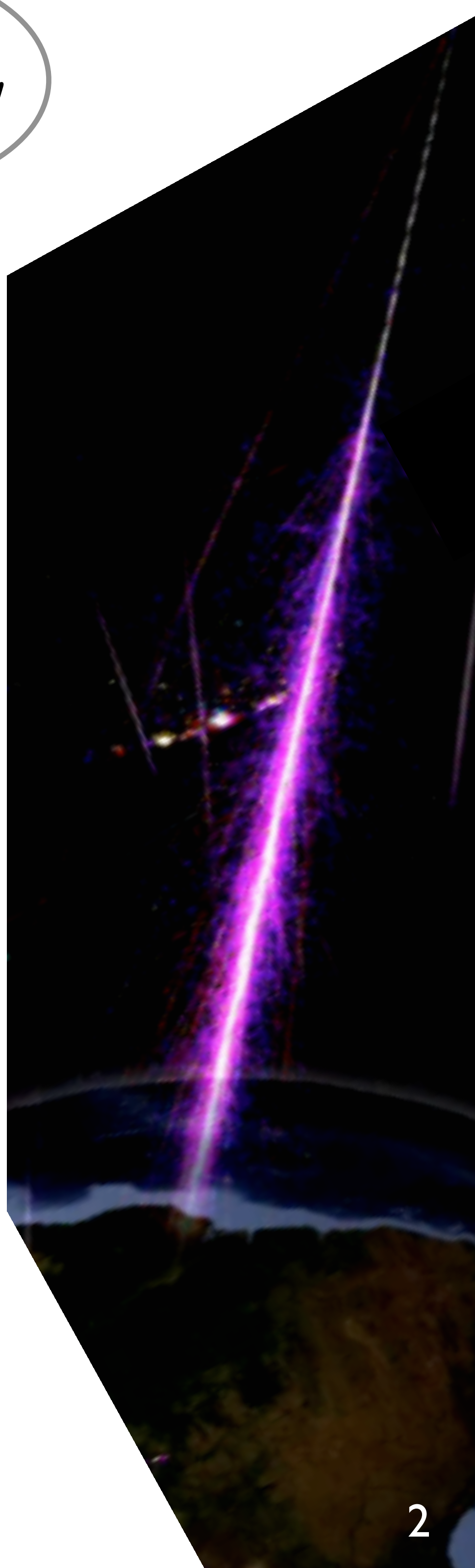
- UHECRs are charged particles *and* the Universe is magnetized
- Physics of powerful astrophysical objects is not known in detail

Particle Physics issues:

ultrahigh energies that cannot be reproduced on Earth:
shower development (hadronic interactions) still speculative

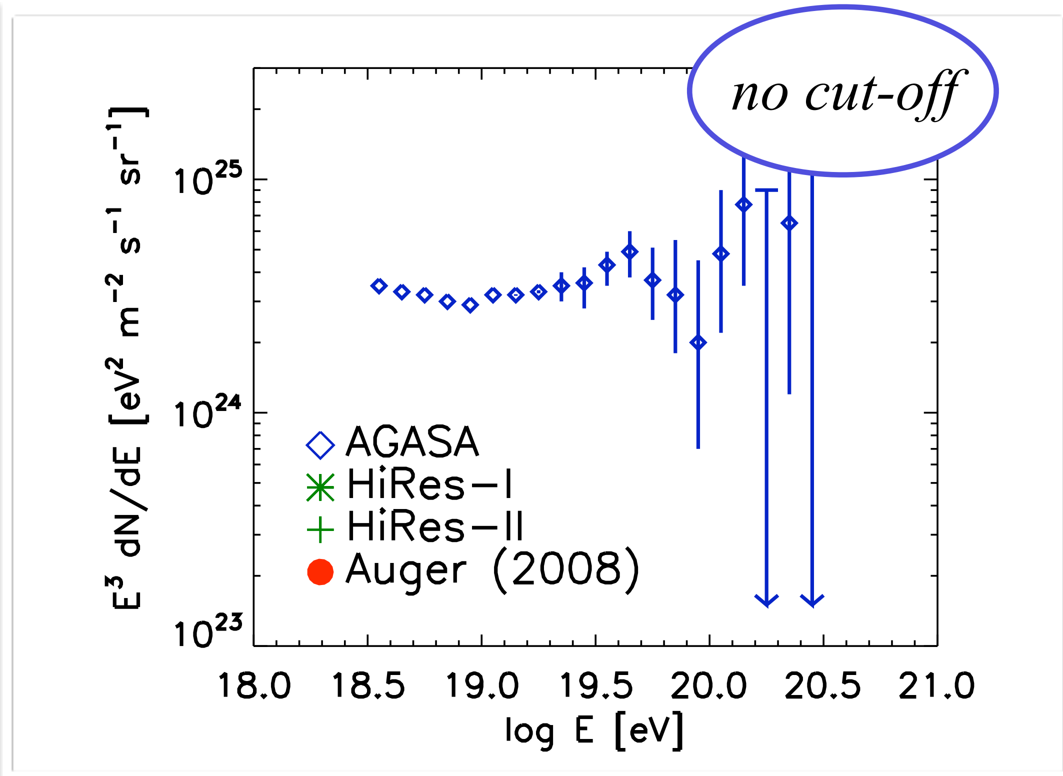
What observational information do we have?

- energetics
- arrival directions in sky
- chemical composition
- secondary messengers (gamma-rays, neutrinos, gravitational waves)

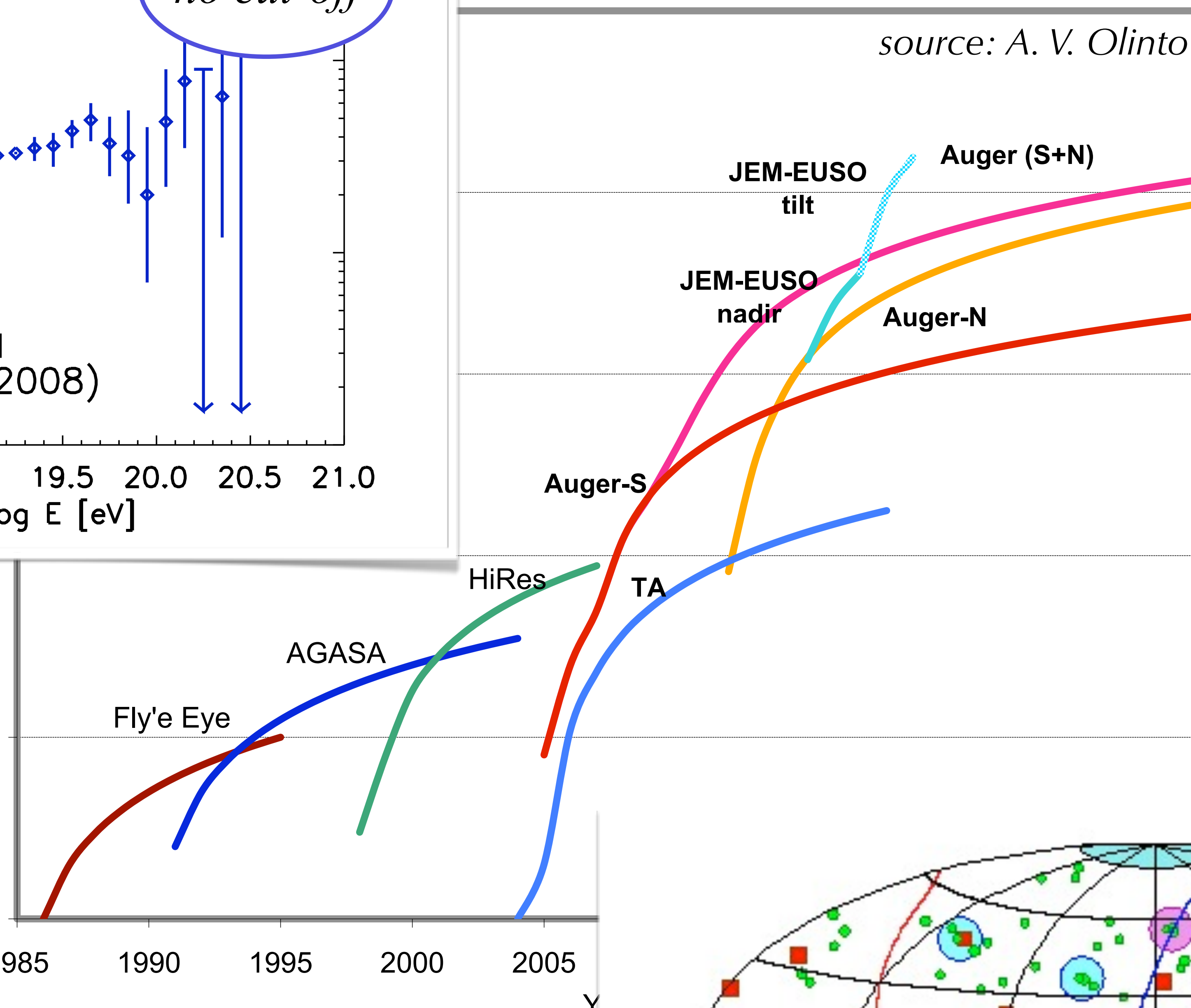


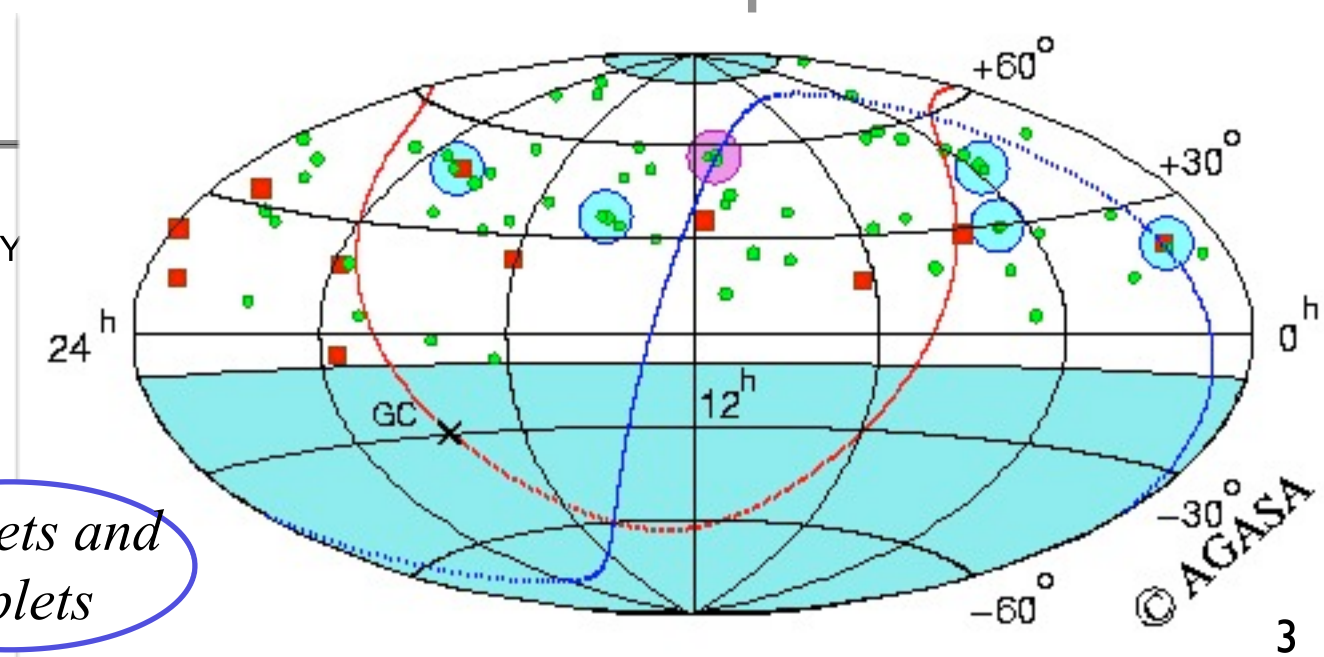
Since 1984 in UHECRs: the AGASA era

57 events
$E > 4\text{x}10^{19}$ eV



no cut-off

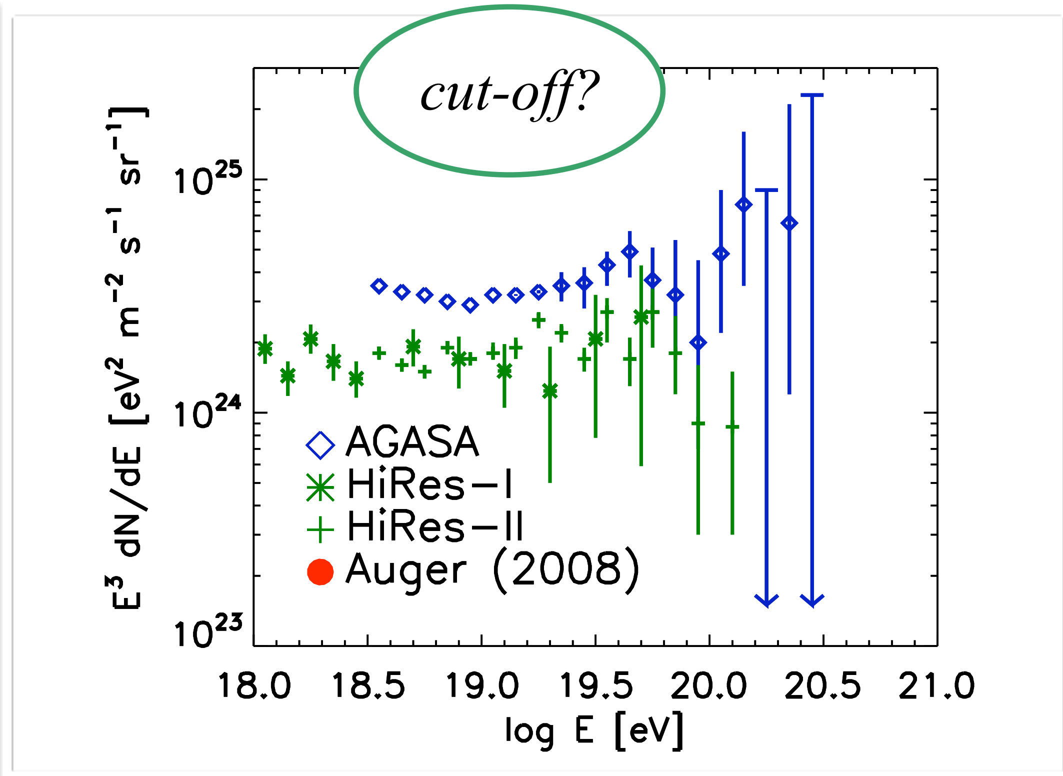


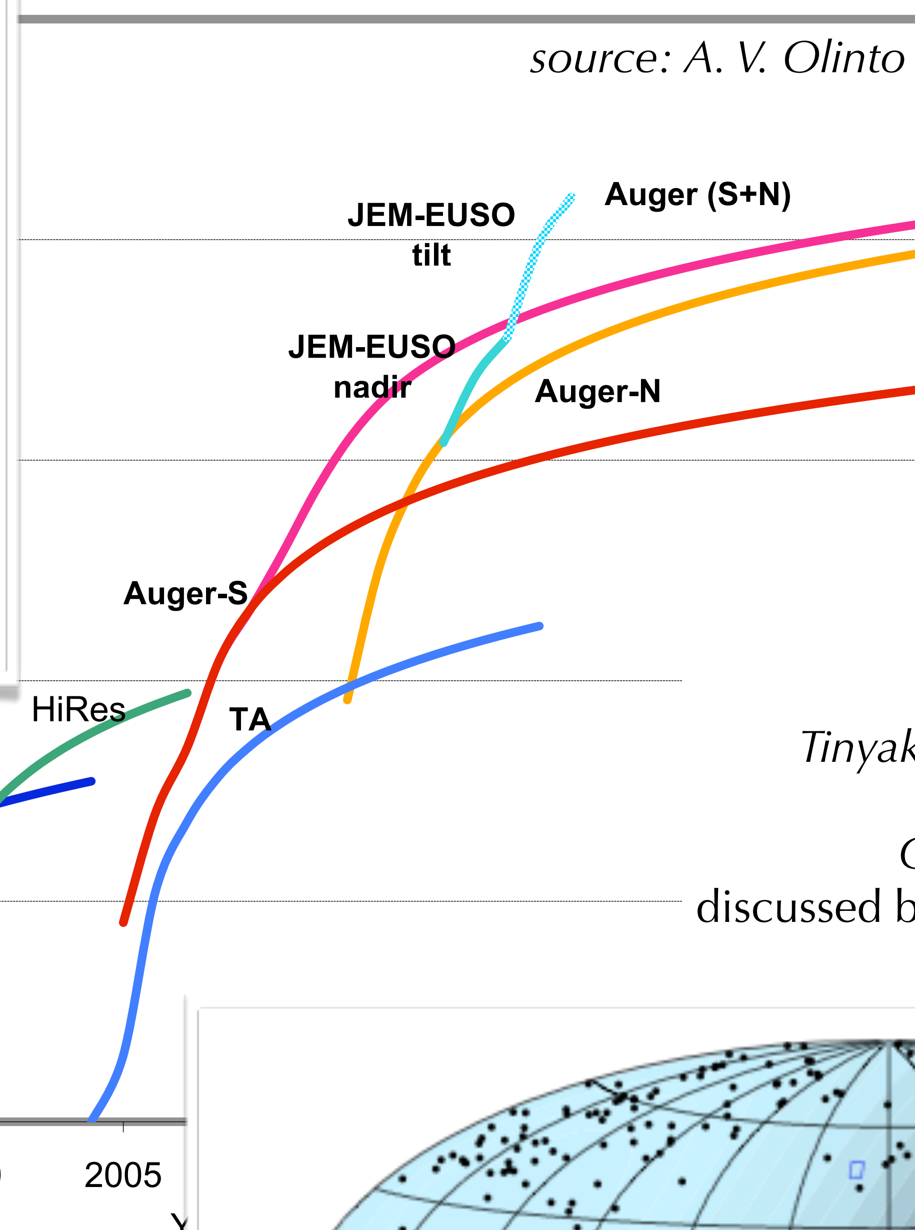


doublets and triplets

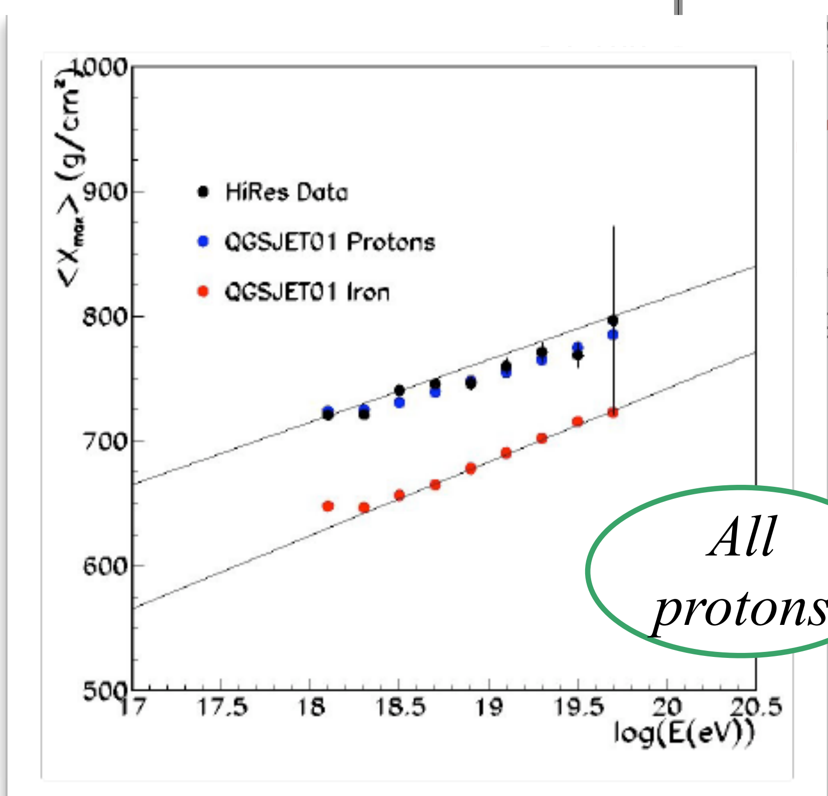
Since 1984 in UHECRs: HiRes era

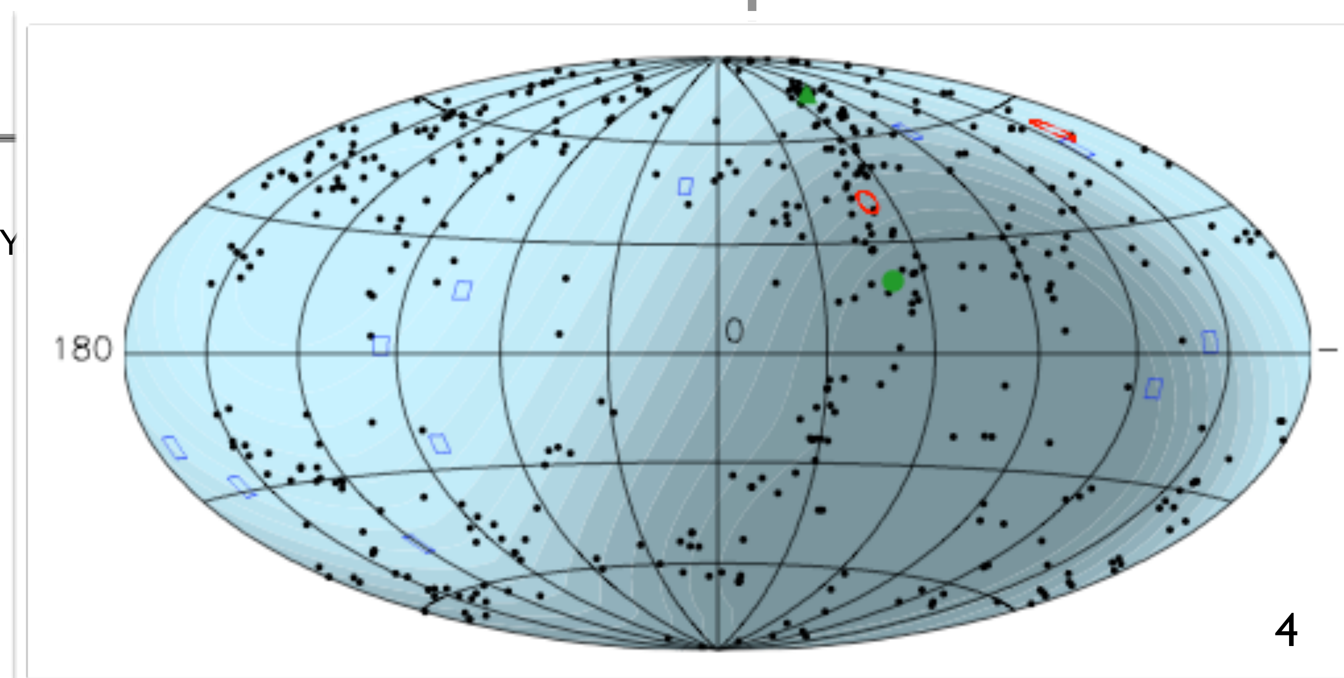
27 events
$E > 4\text{x}10^{19}$ eV





correlation with BL Lac?
Tinyakov & Tkachev (2001,2002)
Gorbunov (2002)
Gorbunov & Troitsky (2005)
discussed by *Evans et al. (2002, 2004)*

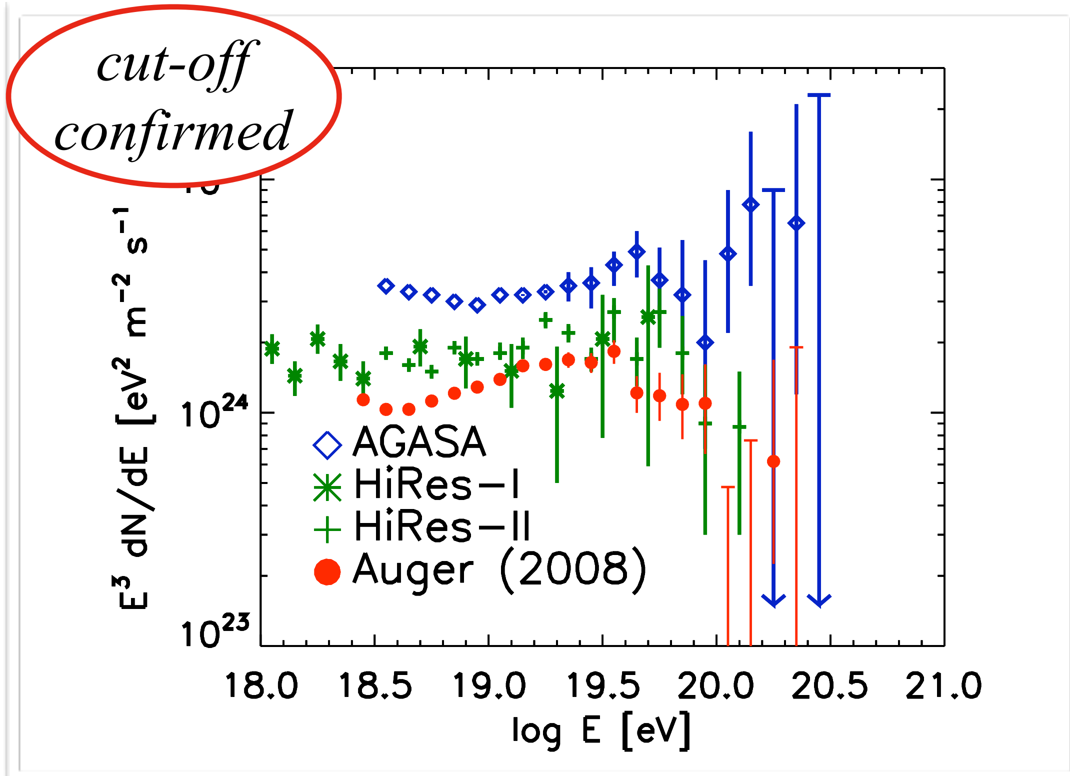


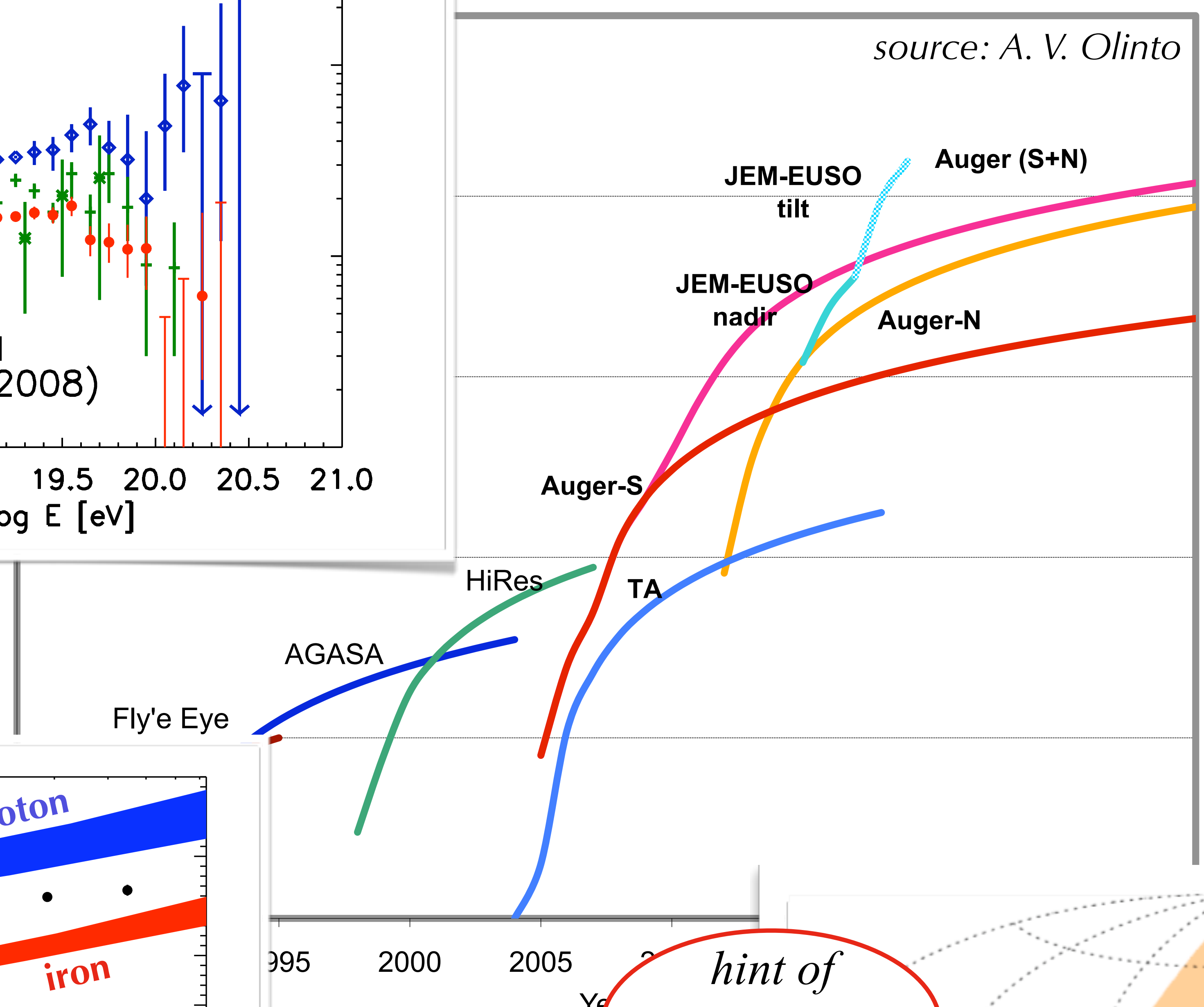


Since 1984 in UHECRs: Auger era

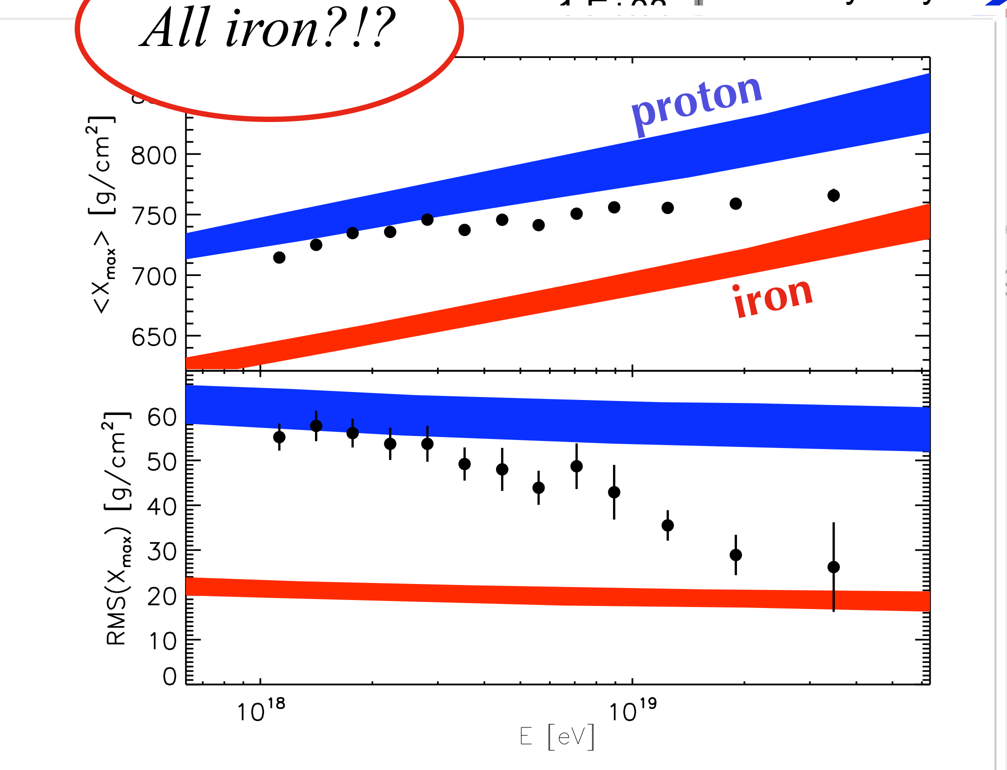
69 events
E > 5.5x10^{19} eV

cut-off confirmed

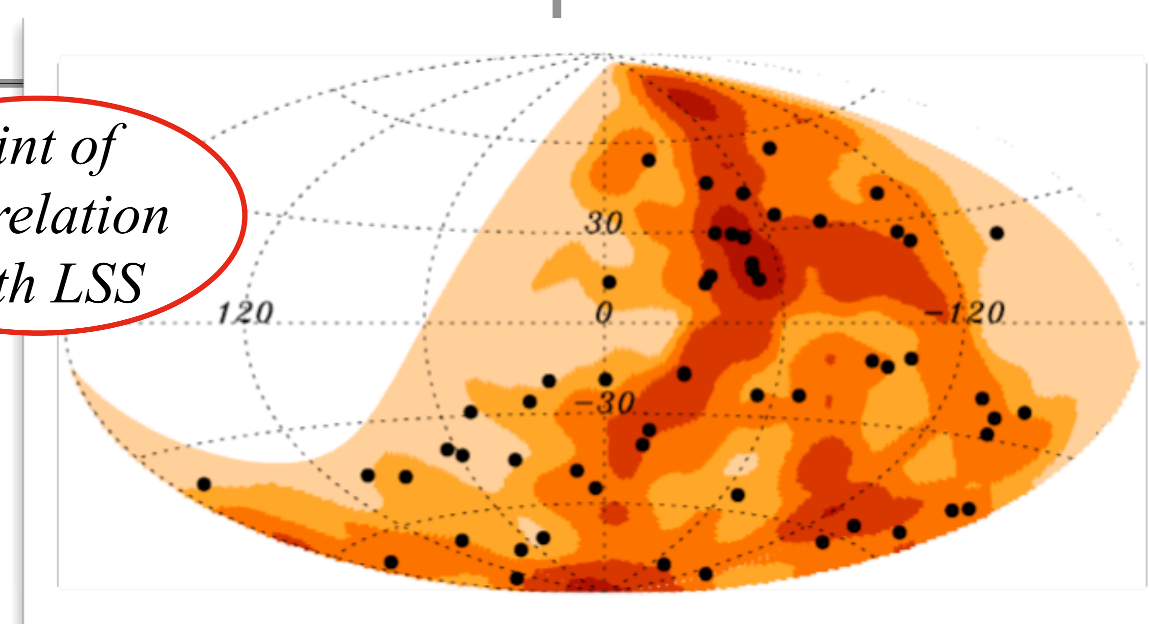




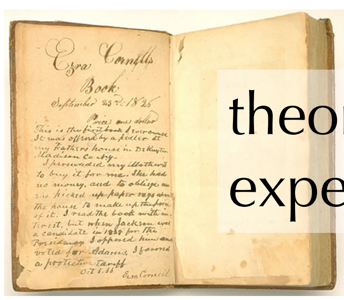
All iron?!?



hint of correlation with LSS



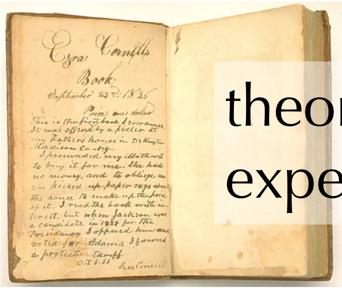
density map of 2MRS
Auger Coll. (2010)



theoretical
expectations

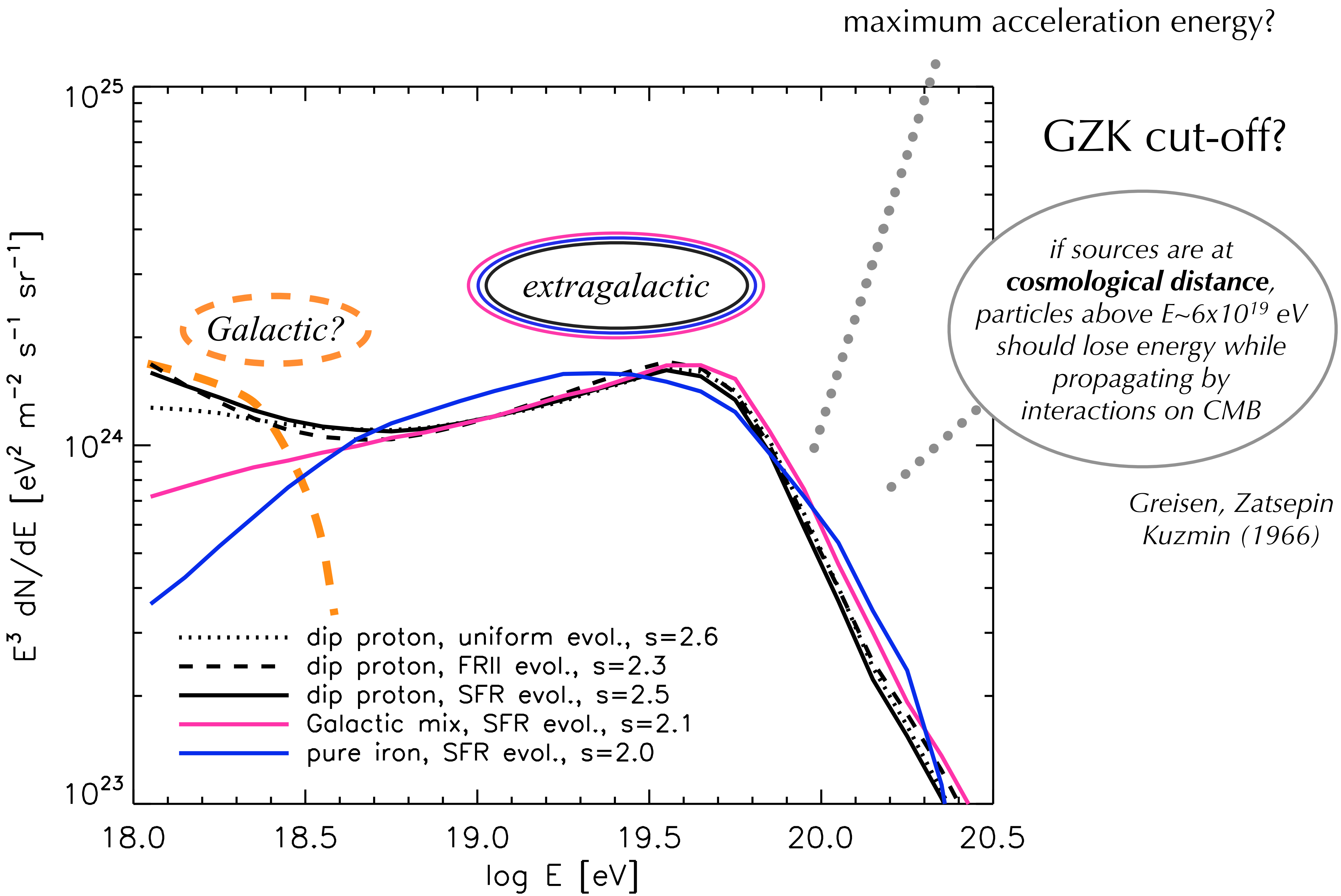
what Auger
data tell us

how to
go further



theoretical
expectations

Energy spectrum



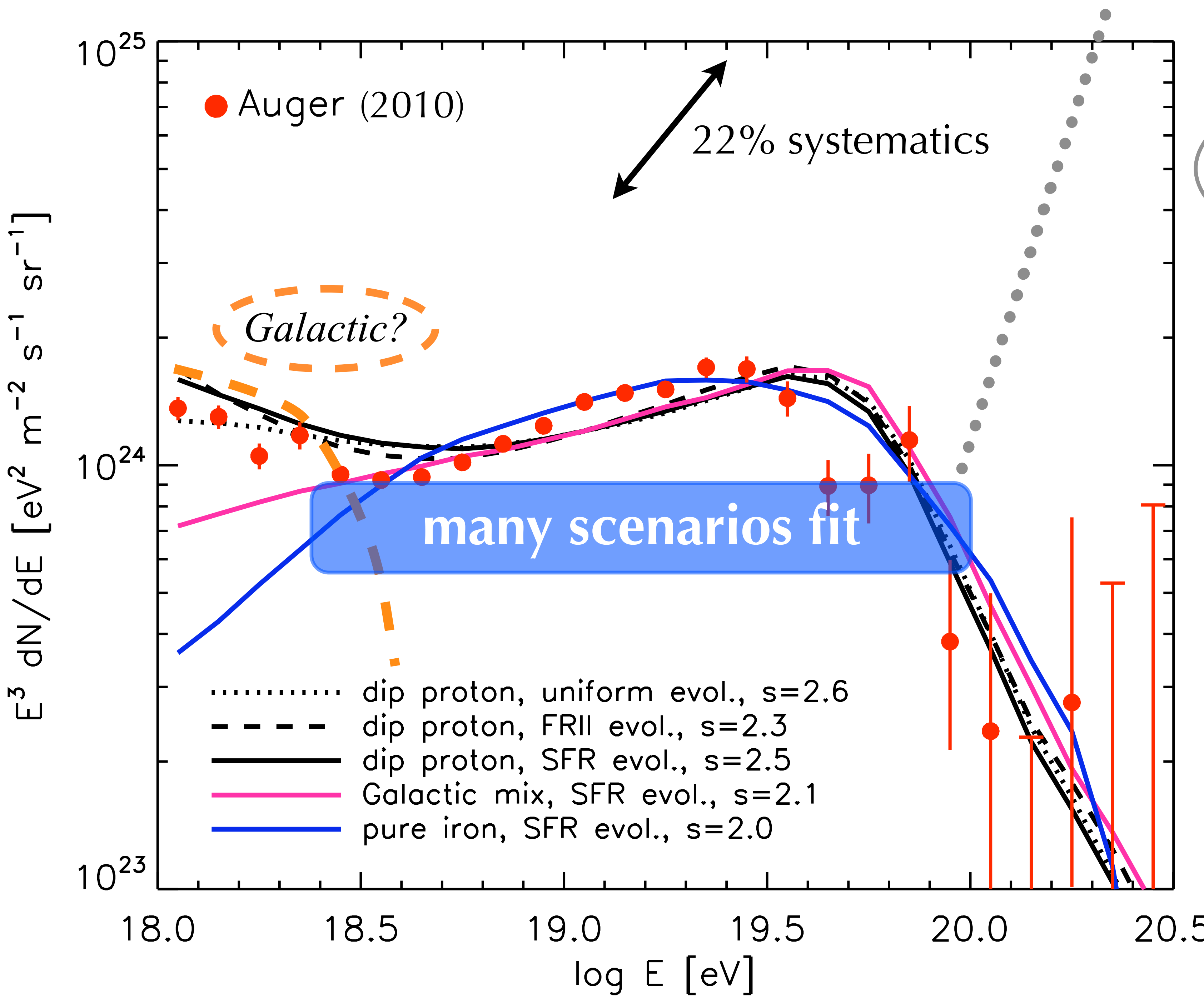
what Auger
data tell us

Energy spectrum

maximum acceleration energy?

or GZK cut-off?

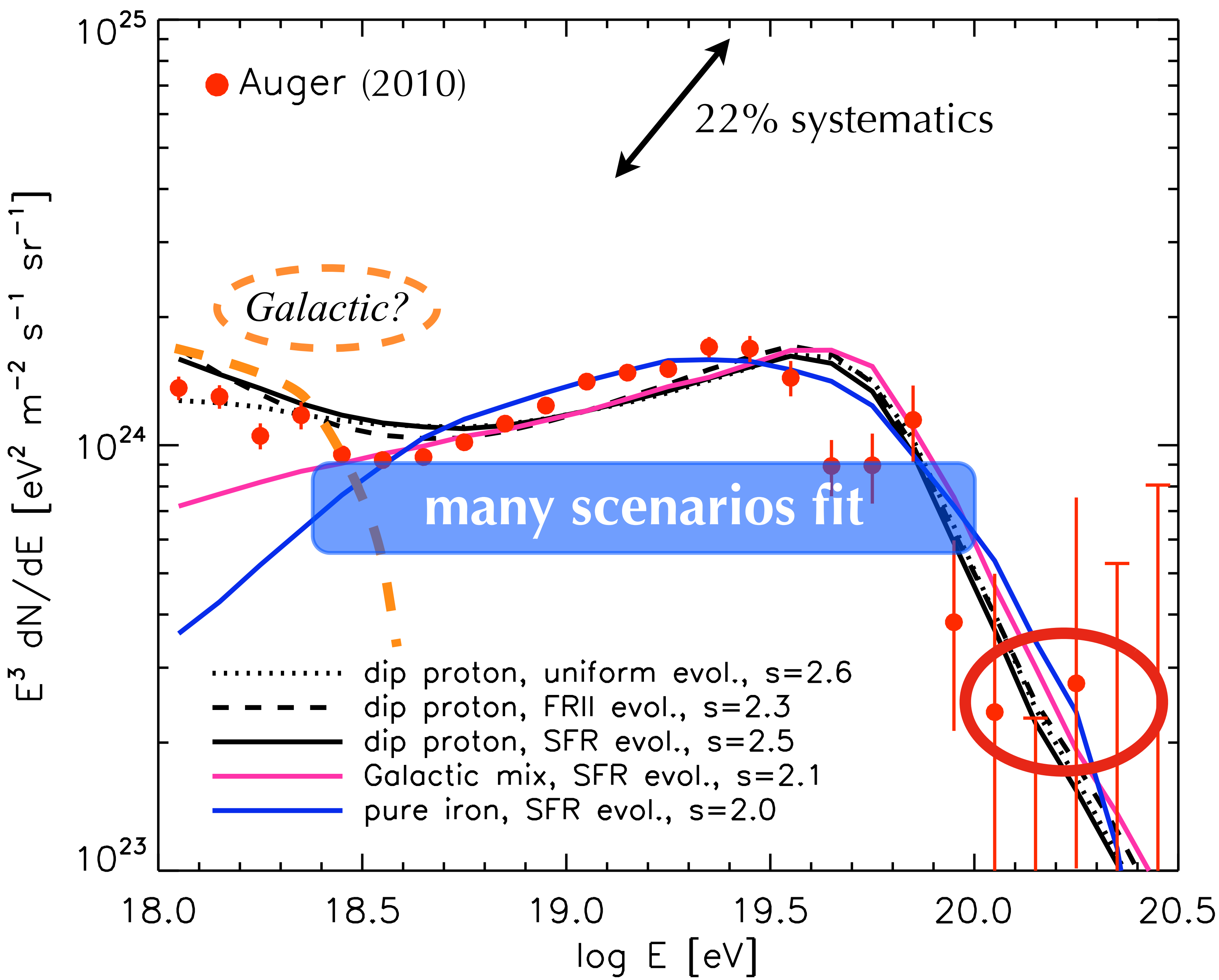
sources should be located at cosmological distance within ~ few 100 Mpc.



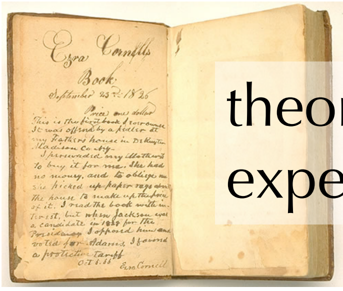
how to
go further

Energy spectrum

with better systematics + statistics, constrain shape?

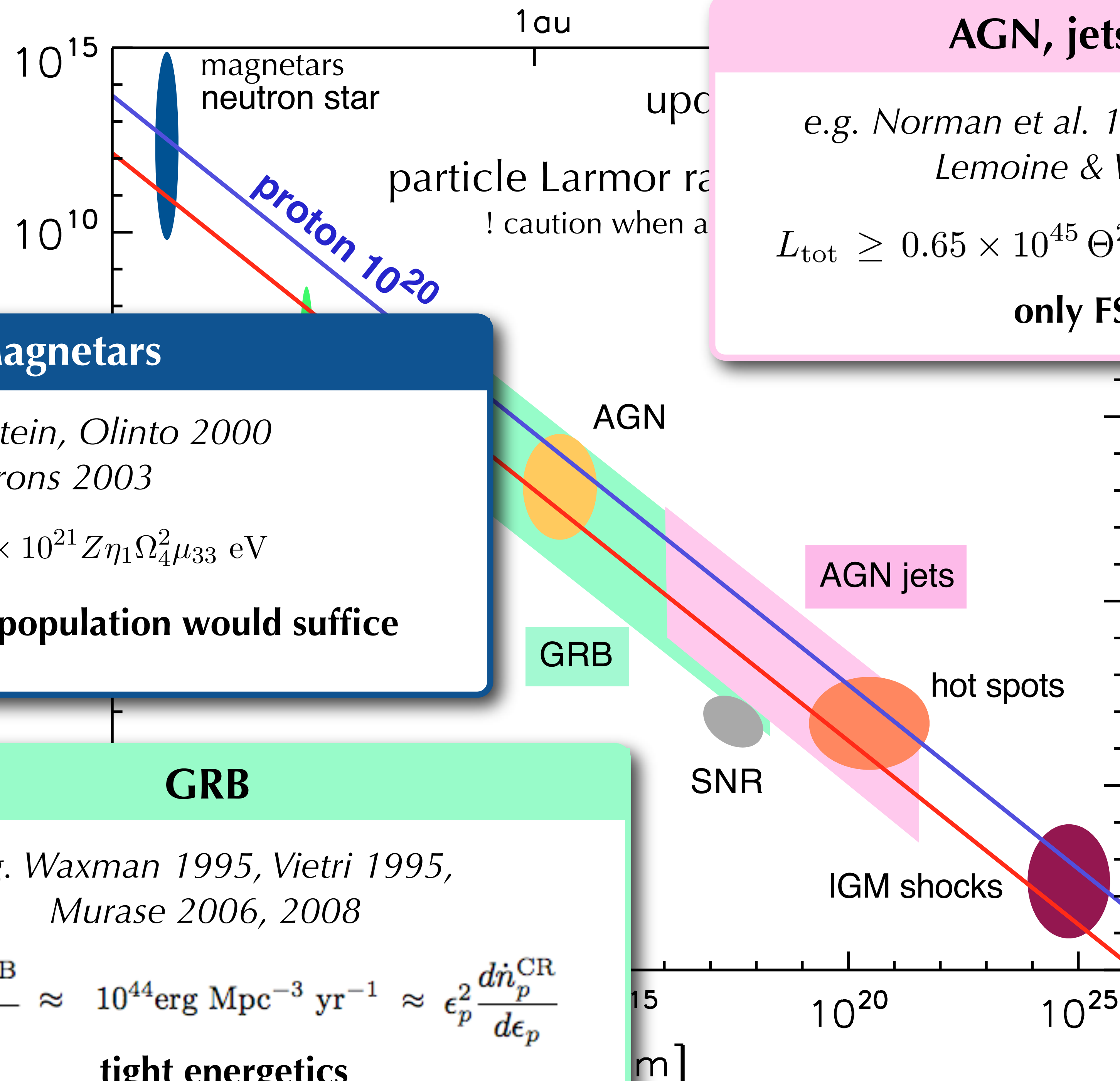


particles with
$E > 10^{20}$ eV



theoretical expectations

Which *cosmological local* source?
simple energetics



AGN, jets, hot spots

e.g. Norman et al. 1995, Henri et al. 1999
Lemoine & Waxman 2009

$$L_{\rm tot} \geq 0.65 \times 10^{45}\,\Theta^2\Gamma^2\mathcal{A}^2\beta^3c^2Z^{-2}E_{20}^2\ {\rm erg/s}$$

only FSRQ/FRII

continuous emission

Magnetars

Blasi, Epstein, Olinto 2000
Arons 2003

$$E = 3\times10^{21}Z\eta_1\Omega_4^2\mu_{33}\ {\rm eV}$$

5% of magnetar population would suffice

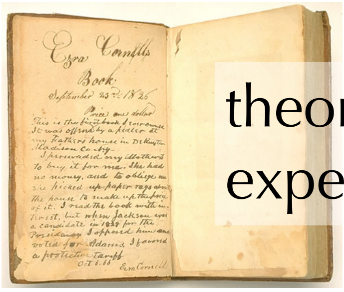
transient sources

GRB

e.g. Waxman 1995, Vietri 1995,
Murase 2006, 2008

$$\epsilon_e^2\frac{d\dot{n}_e^{\rm GRB}}{d\epsilon_e} \approx 10^{44}{\rm erg\ Mpc^{-3}\ yr^{-1}} \approx \epsilon_p^2\frac{d\dot{n}_p^{\rm CR}}{d\epsilon_p}$$

tight energetics



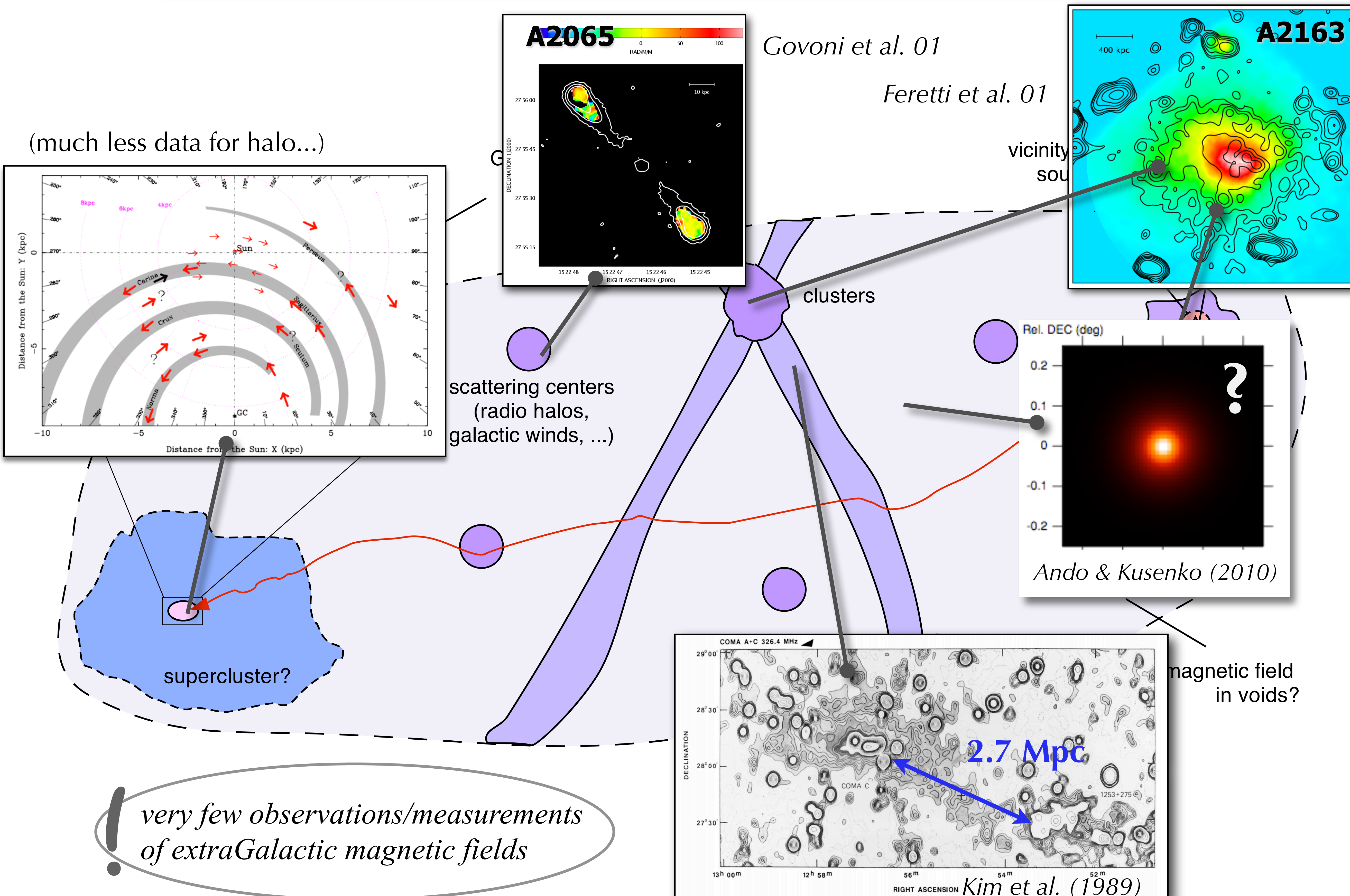
theoretical
expectations

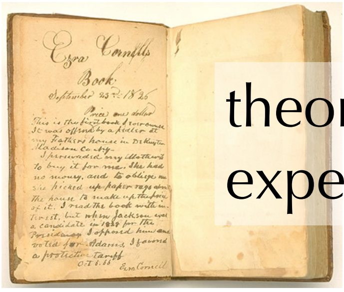
Expected distribution of UHECRs in the sky

related to magnetic fields

deflections: spatial + temporal decorrelation

Propagation of UHECRs in the magnetized Universe





theoretical expectations

Expected distribution of UHECRs in the sky

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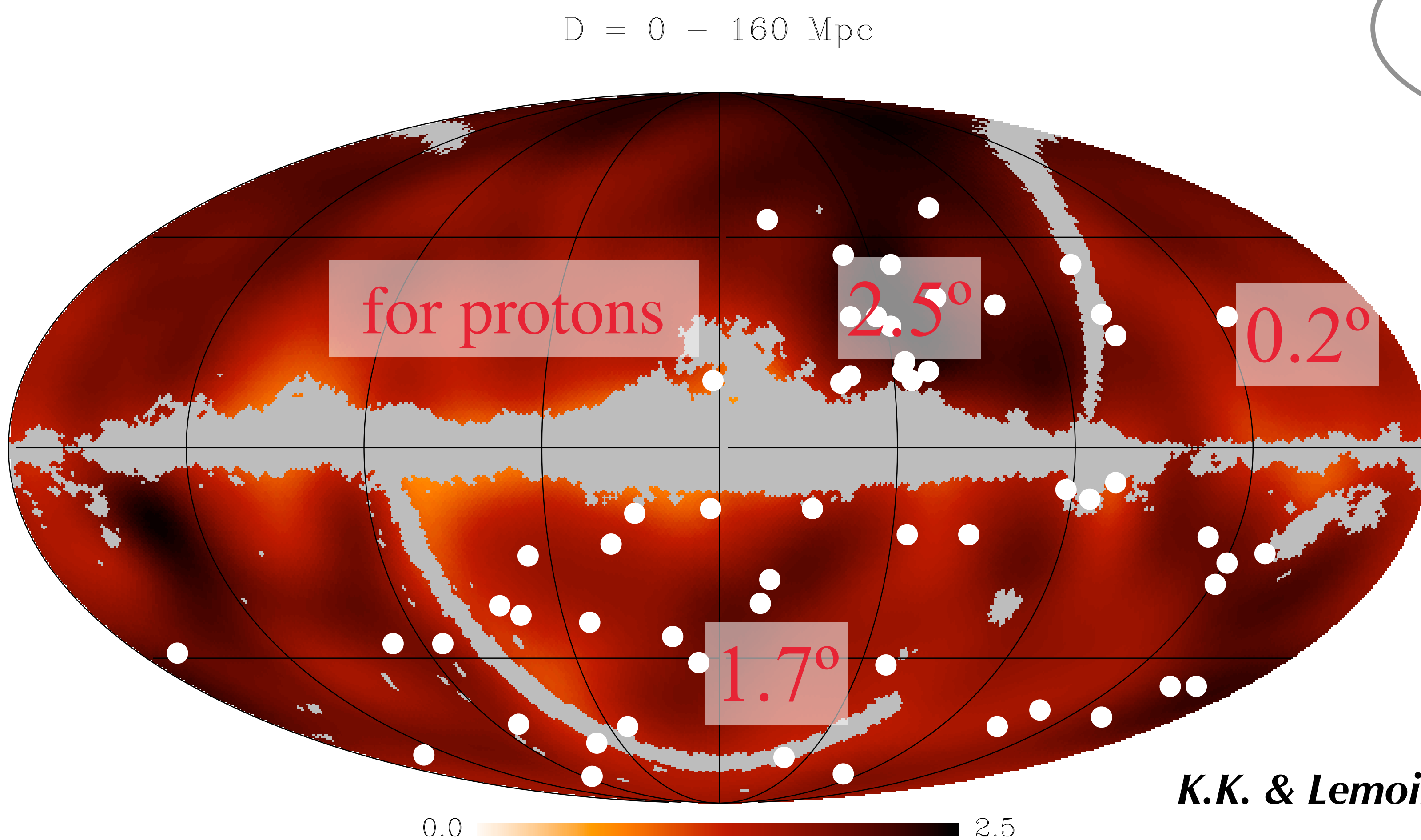


K.K. & Lemoine 08b

● positions of cosmic rays E > 6×10^{19} eV observed by Auger (2010)
map obtained using the PSCz catalog

Continuously emitting sources

FRII in arrival direction of highest energy events *unless*

- strong extragalactic magnetic field
- UHECR = heavy nuclei

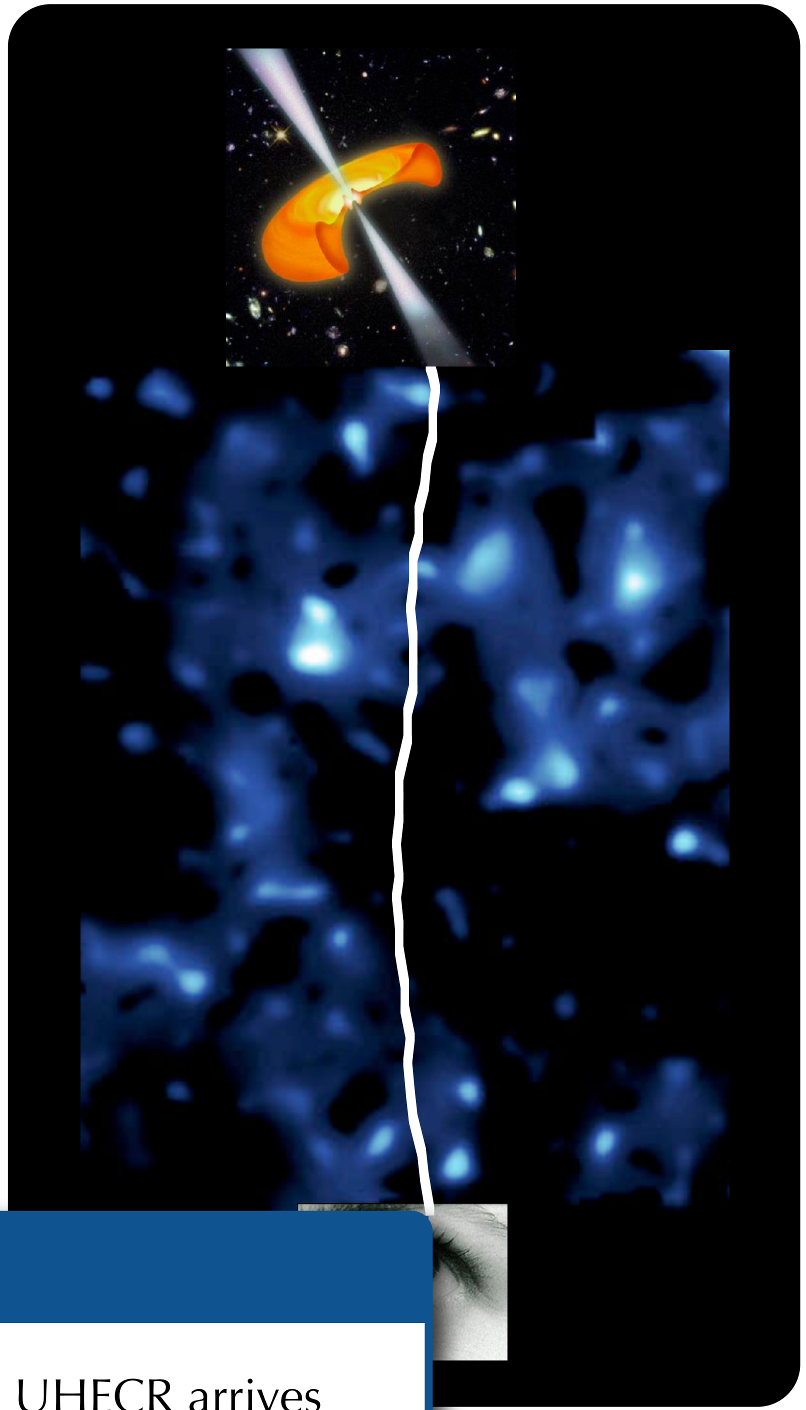
Temporal decorrelation for transient sources

bursting sources

the Universe is magnetized

time delay when charged particle propagates through it δt

source is absent in arrival direction (already extinguished)



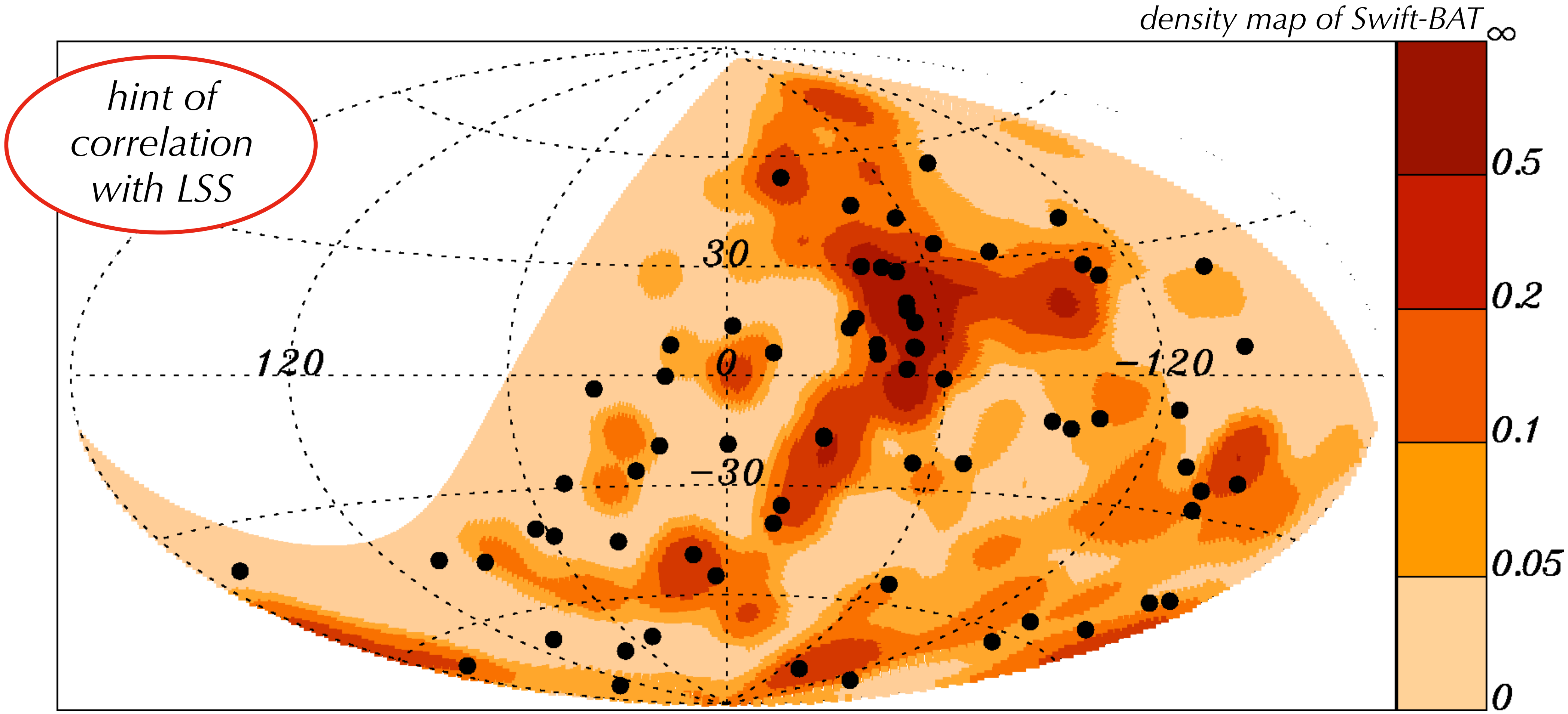
Transient sources

1) source already extinguished when UHECR arrives
correlation with LSS with no visible counterpart

2) no correlation with
secondary neutrinos, photons, grav. waves

what Auger
data tell us

Auger arrival directions



No powerful source associated to UHECRs OR

Continuously emitting source?

- particularly strong extragalactic magnetic field
- UHECR = heavy nuclei

Transient source?

>165 events (>4 years with Auger South) to reach a 5σ significance

Will better statistics help?

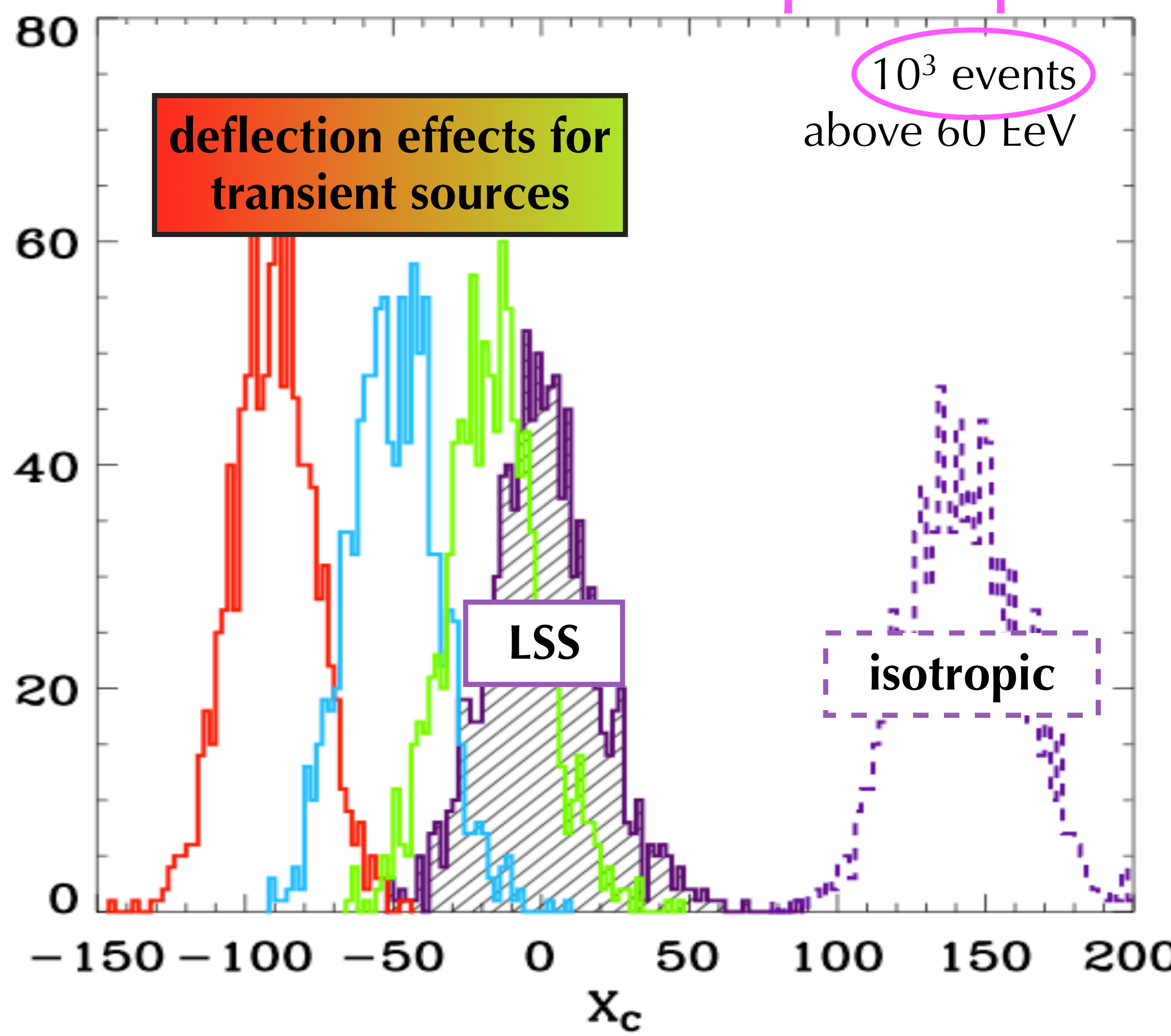
how to
go further

Separate source populations with anisotropy

time delay effects (deflections in magnetic fields)
-> distribution of UHECRs for **transient sources** different from LSS

YES

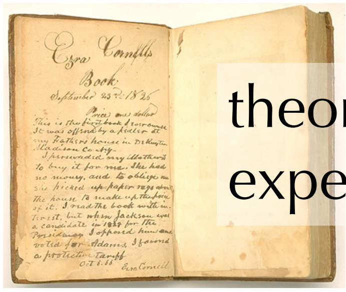
separation possible for



Kalli, Lemoine, K.K., submitted to A&A

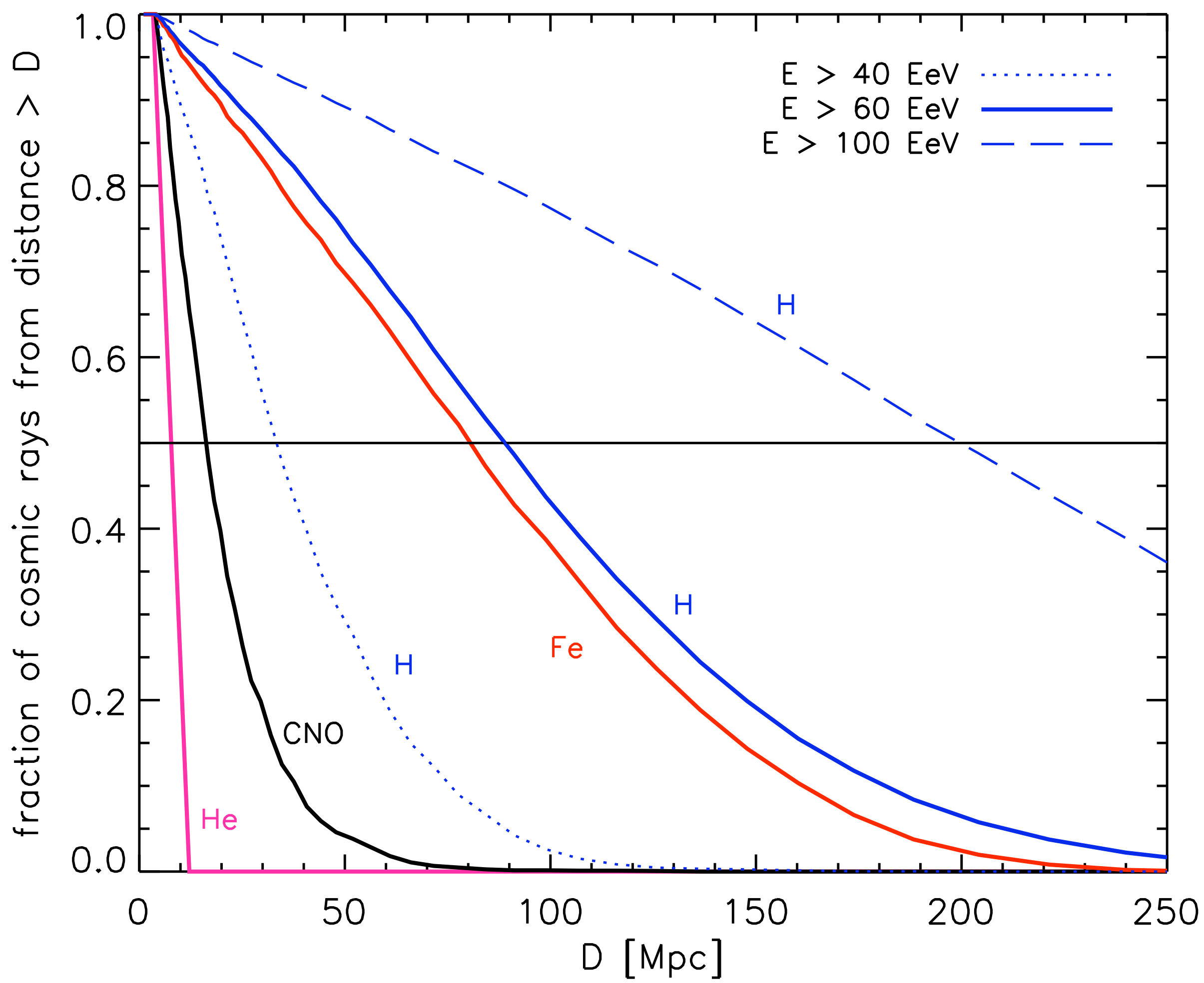
measurement of correlation btw observed and predicted event distributions

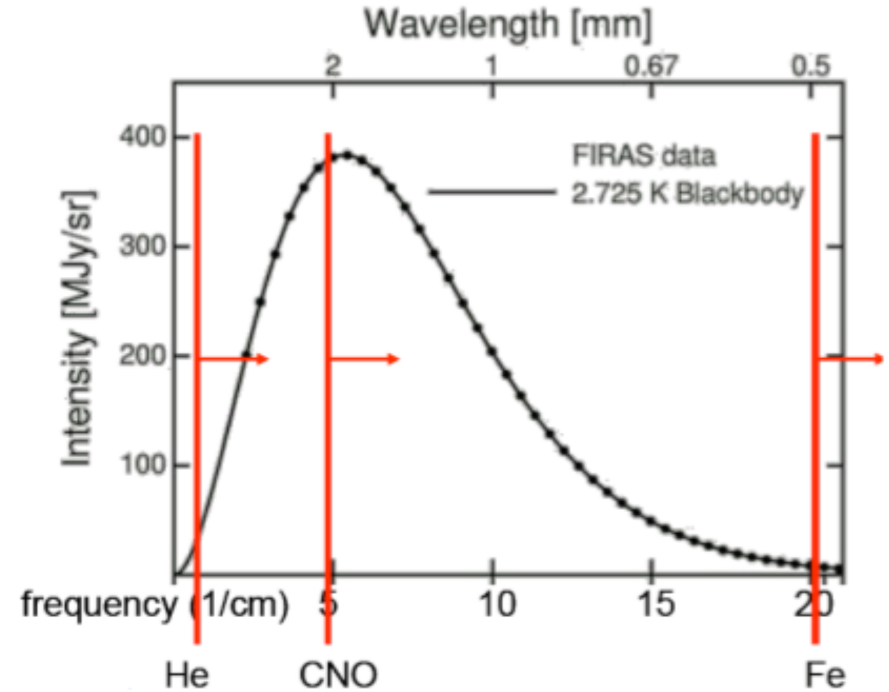
$$X_C = \sum_{i=1}^{N_{tot}} \frac{(N_i^T - \langle N_{i,\rm LSS}\rangle)(\langle N_{i,\rm iso}\rangle - \langle N_{i,\rm LSS}\rangle)}{\langle N_{i,\rm LSS}\rangle}$$



theoretical expectations

Chemical composition





what about metal rich supernova envelopes...?

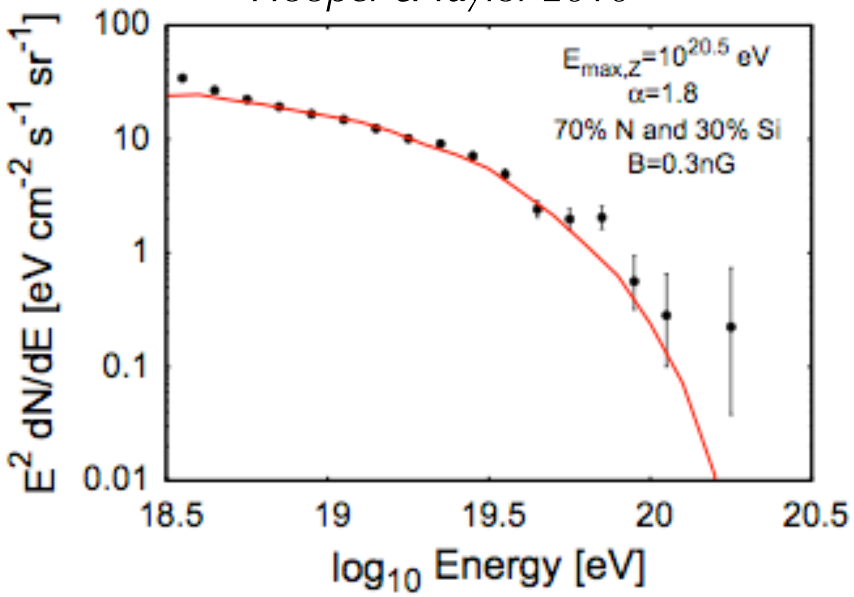
for sources at $D > 50$ Mpc, above $E > 6 \times 10^{19}$ eV, propagated composition can only be **proton or iron-like**

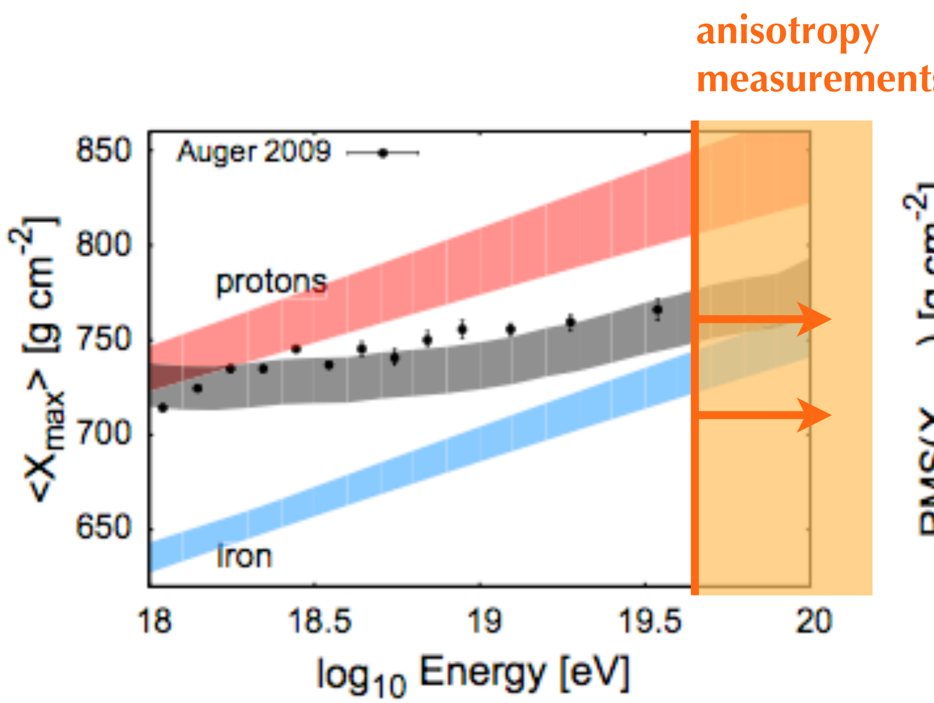
at the sources: iron not favored due to low abundance? escape difficult due to photo-disintegration in source?

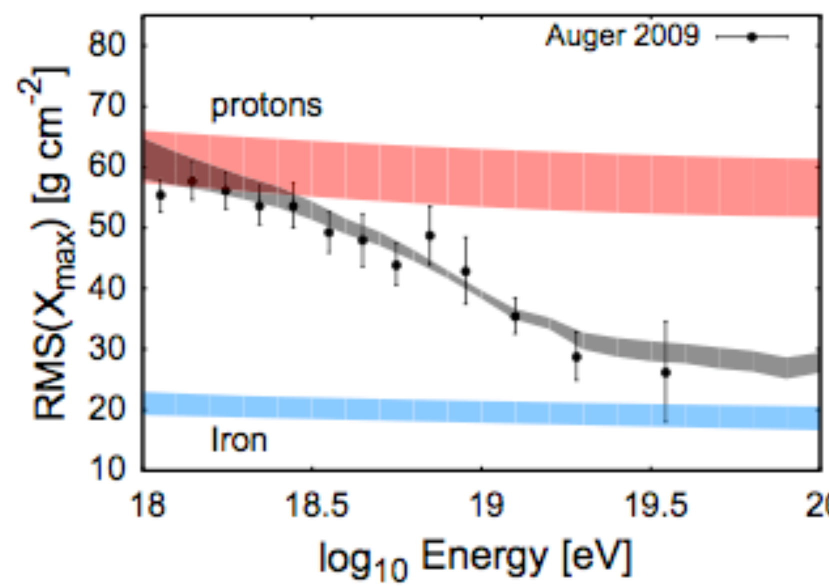
see e.g., Dermer 2007, Allard & Protheroe 2009, but has never been studied in detail and in particular source cases

Puzzling composition measurements?

Hooper & Taylor 2010



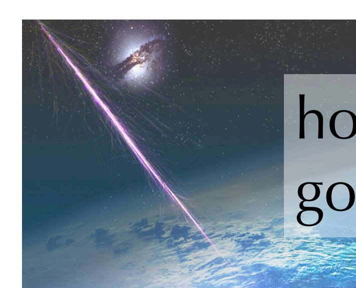




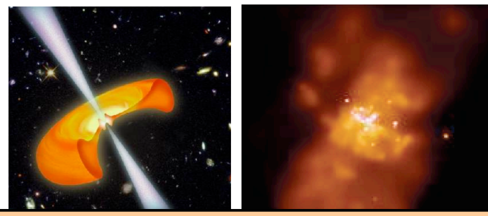
- Unusual choices necessary in attempts to fit the observed composition indicators + E spectrum
  e.g. hard injection spectrum (s~1.6) with primaries dominated by nitrogen or silicon (Hooper & Taylor 2010)

- Playing around with the cross-section or mixing compositions
  can change <X_{max}> but not fit RMS(X_{max}) very well

- Currently, uncertainties on interaction characteristics have comparable magnitude as mass composition differences.
  LHC has potential to drastically improve composition interpretation.



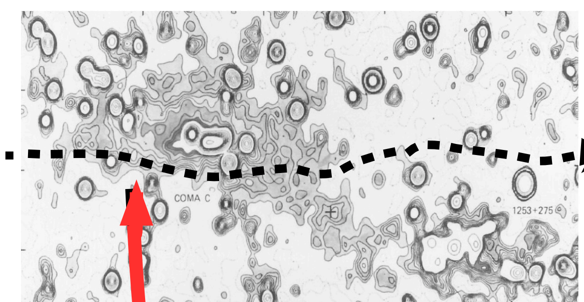
Why do we care about multi-messengers?

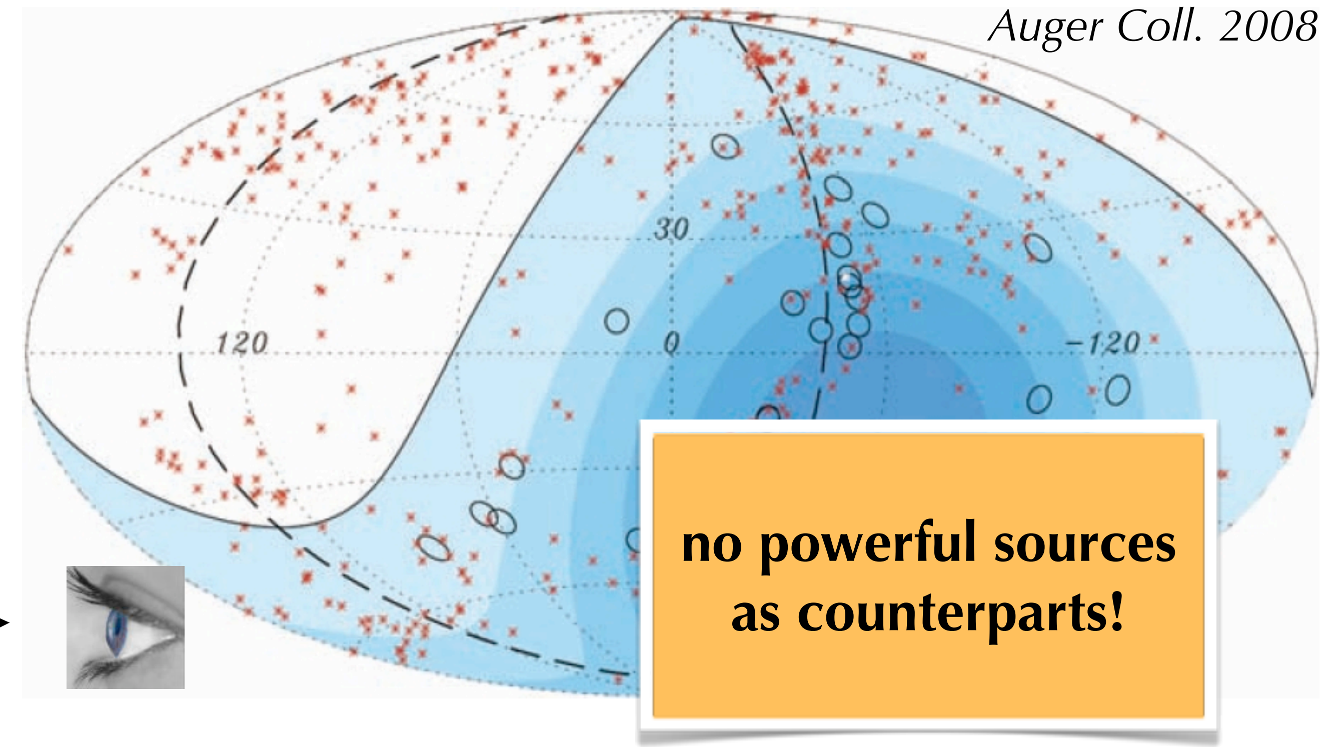


astrophysical sources

acceleration (ex. in shocks)

ultrahigh energy cosmic rays





interactions on baryonic and photonic (CMB/IR) backgrounds

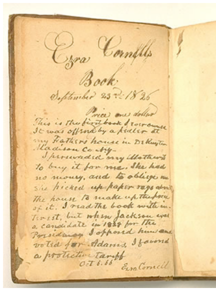
extragalactic magnetic fields?

deflection : spatial decorrelation
time delay : temporal decorrelation if transient source

neutrinos

γ rays

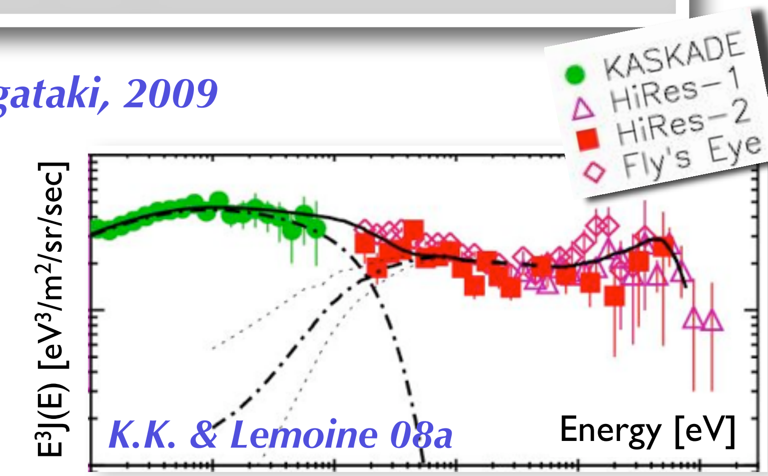
observable?
what information?



theoretical expectations

A complete interaction and propagation code

K.K., D. Allard, K. Murase, J. Aoi, Y. Dubois, T. Pierog, S. Nagataki, 2009



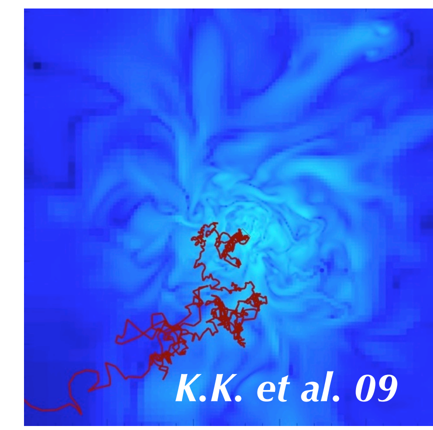
interpretation of Galactic/extraGalactic transition with magnetic horizon effect

1) Propagation in magnetic fields: *Kotera & Lemoine 2008a*

- Mapping of magnetic field from $B=f(\rho)$, ρ DM density grid
- Cellular method (semi-analytical: faster than classical traj. integration)

2) Calculation of energy losses and production of secondary ν, γ:

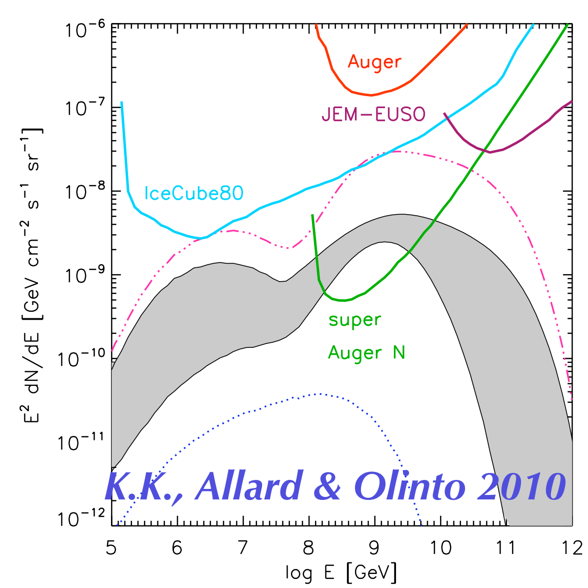
- marriage and improvement of existing codes:
- photo-hadronic processes *SOPHIA*
- photo-disintegration processes for nuclei *Allard et al. 06*
- hadronic processes *CONEX, EPOS* (hadronic interaction codes for air showers)
- post-treatment of gamma-ray cascades



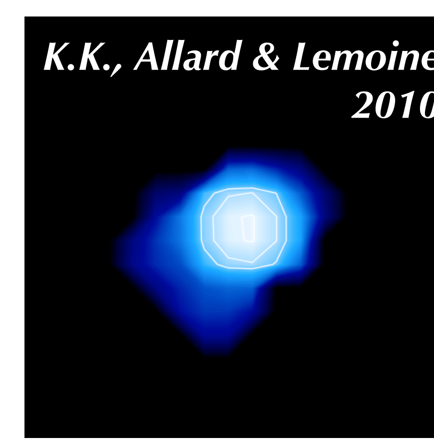
propagation of nuclei in clusters of galaxies: resulting composition and secondary emissions

can be used for...

- emission of neutrons from Galactic sources
- interaction of CR with molecular clouds
- acceleration in specific sources/physical environments: resulting spectra and secondary emissions
- ...



cosmogenic neutrino flux calculation

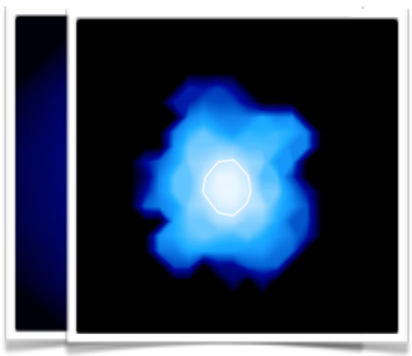


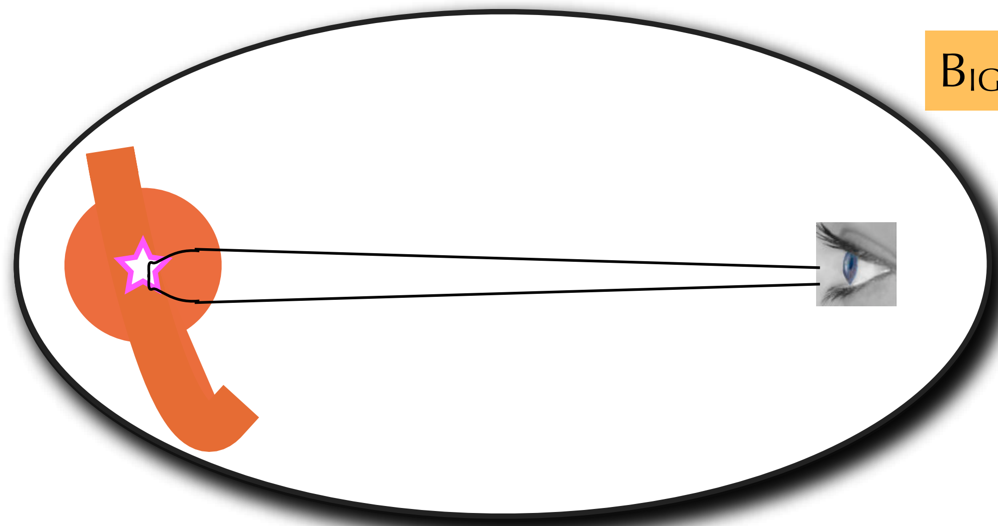
gamma ray signatures from sources in magnetic environments

Fate of gamma rays after their production by UHECRs

CR (10^{20} eV) + γ_{bg} ⟶ e^{+-}, γ_{UHE}

$B_{IGM} > 3 \times 10^{-11}$G





Cascade in IGM

interactions with radio/CMB photons

$\gamma\gamma_{bg} \rightarrow e^+e^- \longrightarrow e\,\gamma_{bg} \rightarrow e\,\gamma \longrightarrow \dots \quad \gamma_{\text{TeV-GeV}}$

pair production — **B deflections** — **Inverse Compton** — **no more interactions**

Synchrotron nearby source

if source environment sufficiently magnetized

$e^{+-} \longrightarrow \gamma_{GeV}$

B, synchrotron — **no more interactions**

γ ray halo of limited extension around source

homogeneous B: flux completely diluted if $B_{IGM} > 3 \times 10^{-11}$G

Protheroe 86, Protheroe & Stanev 93, Aharonian et al. 94

inhomogeneous B: flux dilution according to fraction of Universe where $B_{IGM} > 3 \times 10^{-11}$G

K.K. et al. 2010

$$E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \approx f_{1d}(< B_\theta)\,\chi_e \frac{L_{cr}}{8\pi d^2}\left(\frac{E_\gamma}{E_{\gamma,\max}}\right)^{1/2}$$

homogeneous magnetized sphere around source

Gabici & Aharonian 06

filaments, inhomogeneous B, mixed composition
flux ultimately depends only on
injected energy at the source

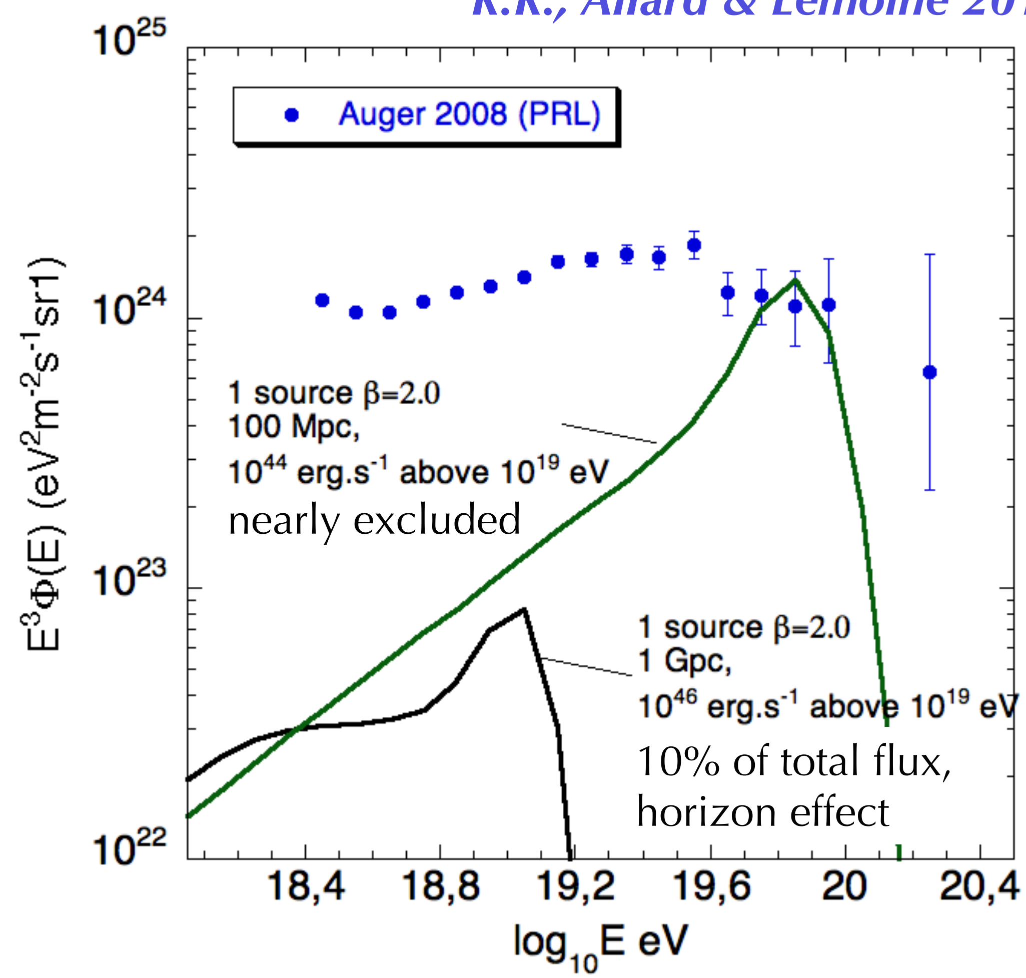
K.K. et al. 2010

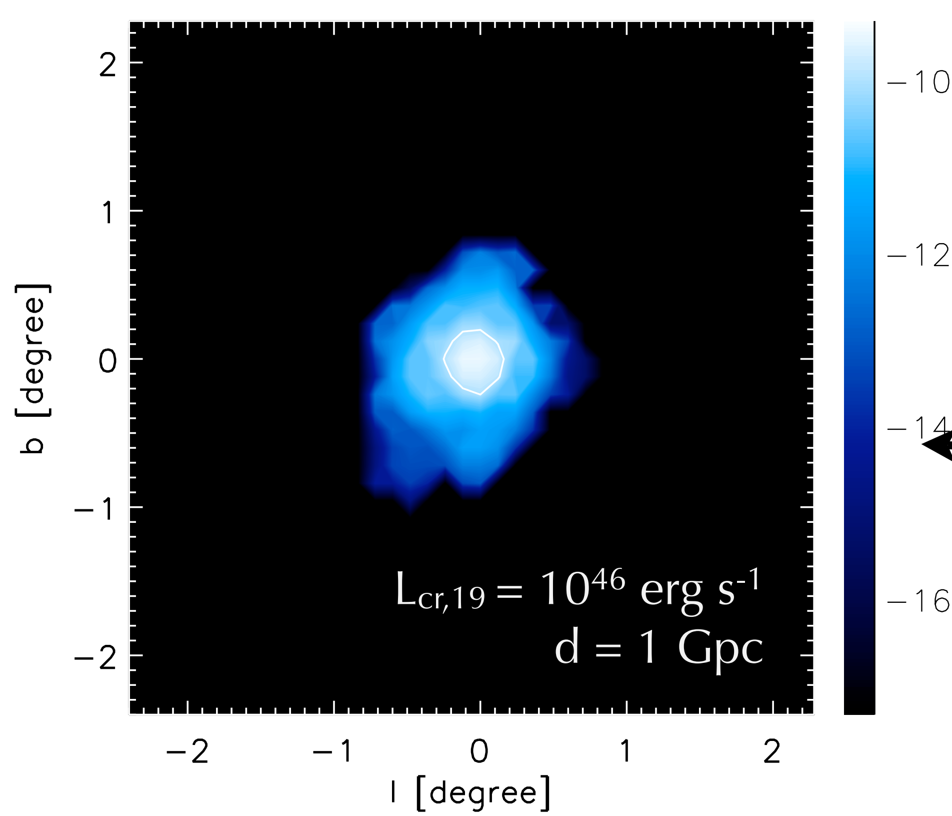
What source can produce detectable gamma-ray signatures?

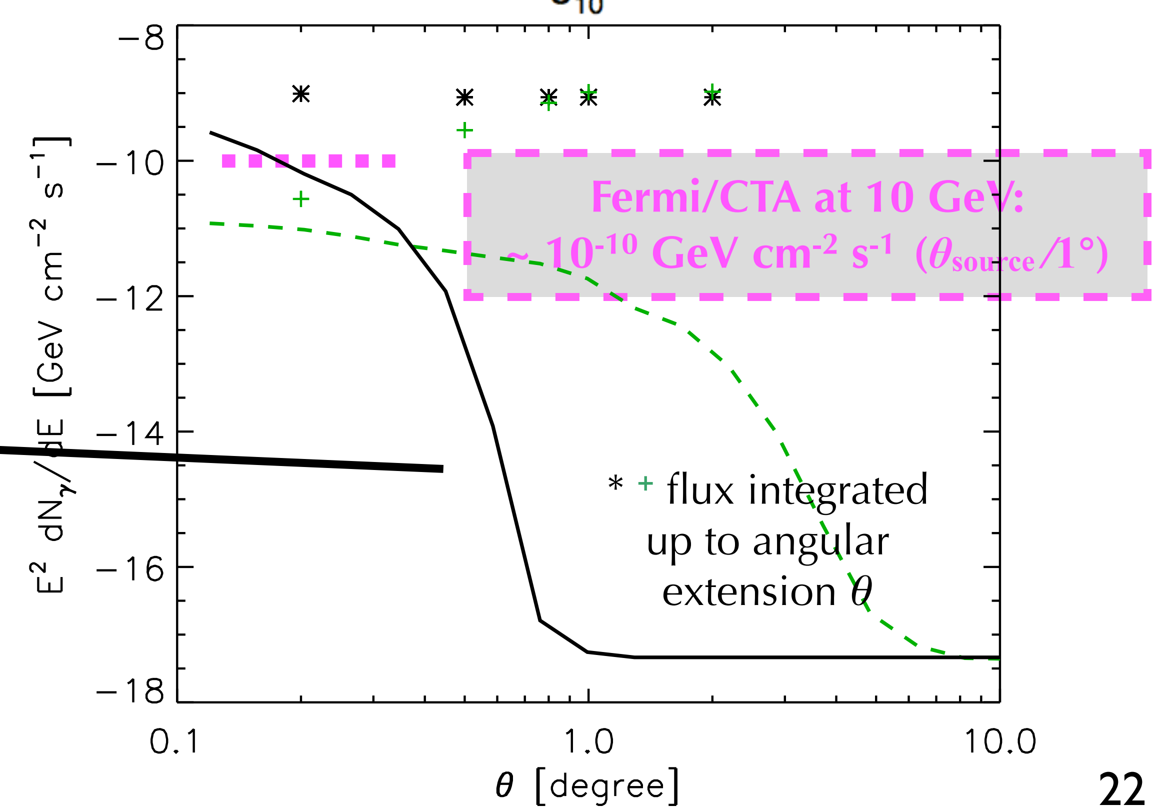
gamma ray signature detectable only if:

- particularly powerful source (rare) $L_{19} \sim 10^{45-46}$ erg/s
- close-by source? (magnetized lobes of Cen A? - not observable ***K.K., Allard & Lemoine 10***)
- transient sources not observable (***Gabici & Aharonian 06***)

K.K., Allard & Lemoine 2010

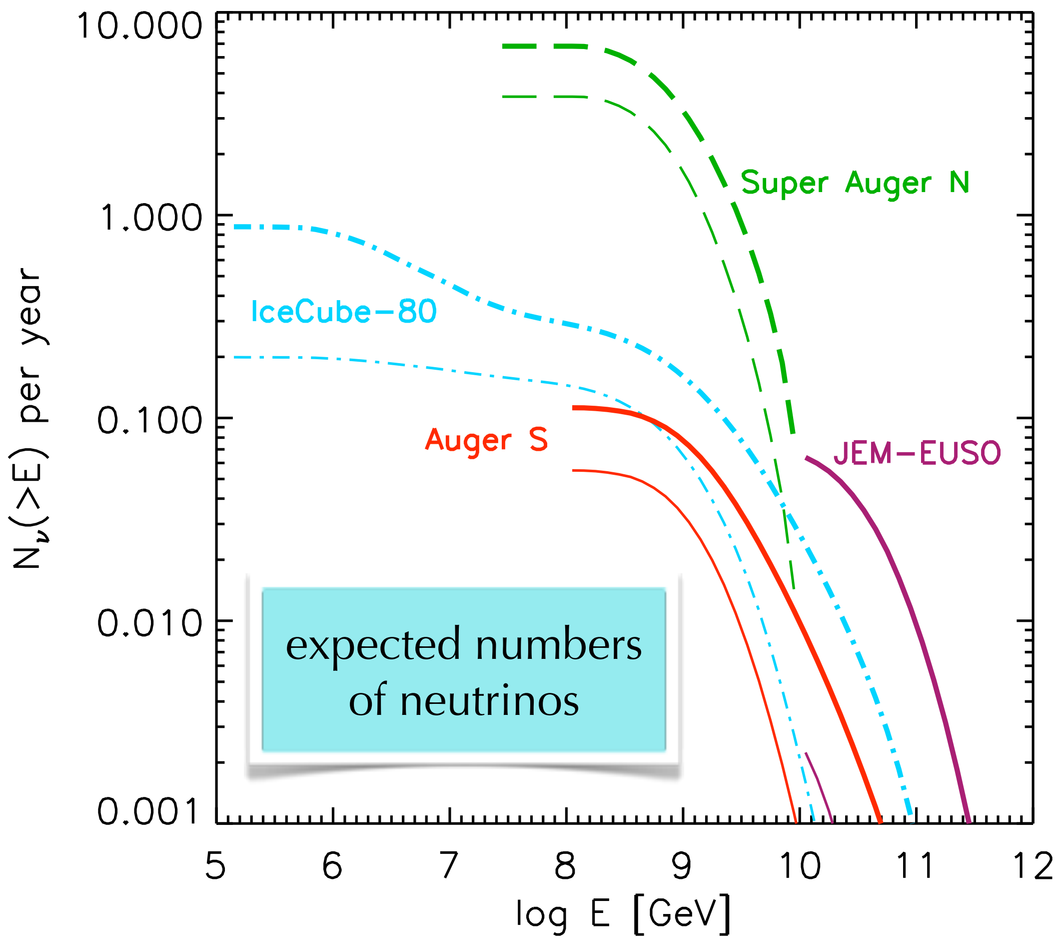






Cosmogenic neutrinos: parameter space and detectability from PeV to ZeV

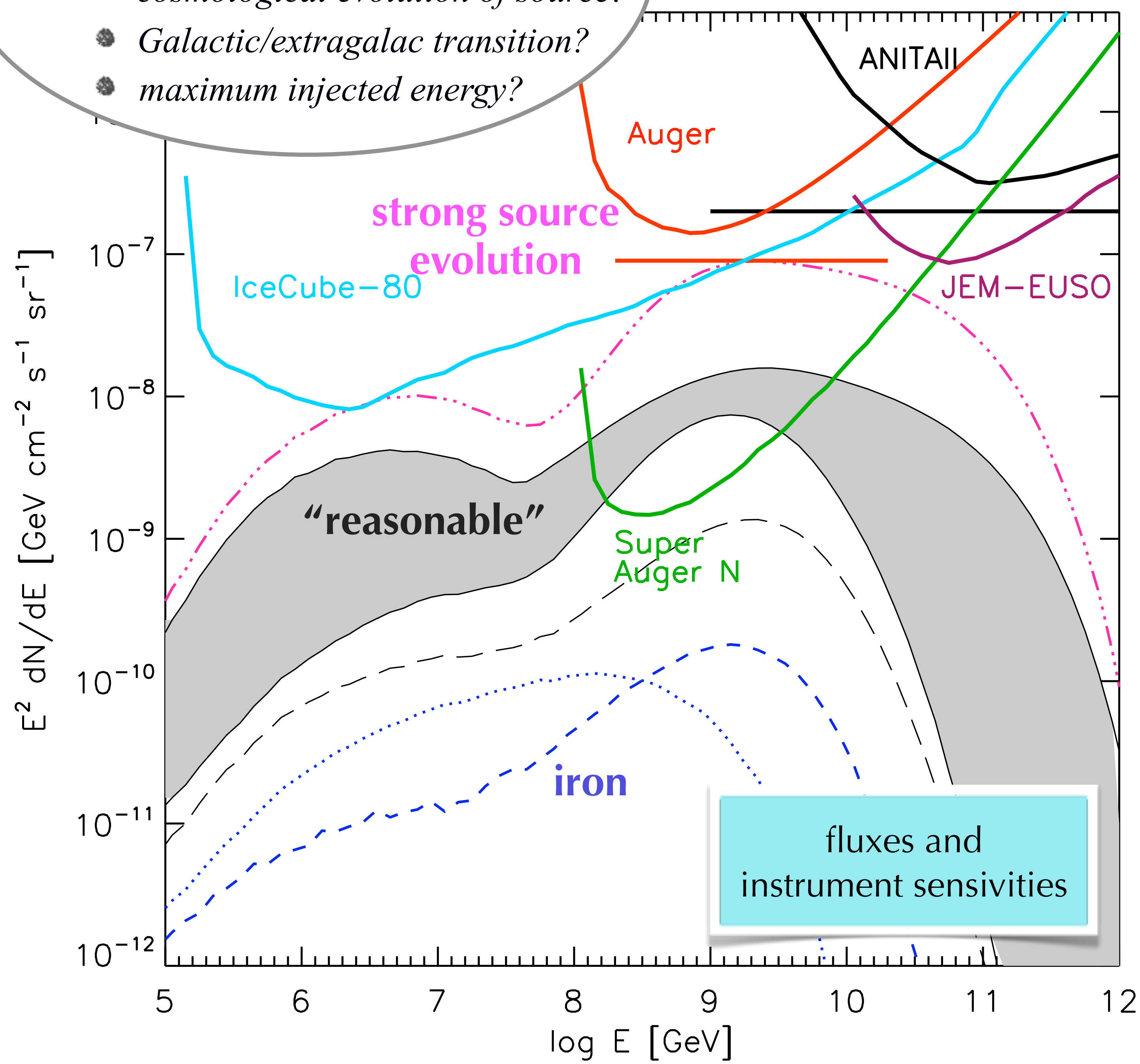
K.K., Allard & Olinto, 2010



UHECR source(s)?

some associated issues:

- *injected chemical composition?*
- *cosmological evolution of source?*
- *Galactic/extragalac transition?*
- *maximum injected energy?*



in terms of neutrino detection:
in “reasonable” param. range, EeV region is safe

in terms of getting info on sources:
once EeV region has been observed, PeV region can help discriminate composition and Galactic/extraGal. transition models

sad cases for neutrino detection:
iron and/or no source evolution

A quest for sources of UHECRs

Continuously emitting sources

FRII in arrival direction of highest energy events *unless*
...ong extragalactic magnetic field
...lei

*one could discriminate these two by **anisotropy** signatures*

Transient sources

1) source already extinguished when UHECR arrives
correlation with LSS with no visible counterpart

2) **distortion of arrival direction maps according to LSS**

3) **no counterpart in neutrinos, photons, grav. waves**
will be observed in arrival directions of UHECRs

4) **magnetars and GRBs have same anisotropy signature**

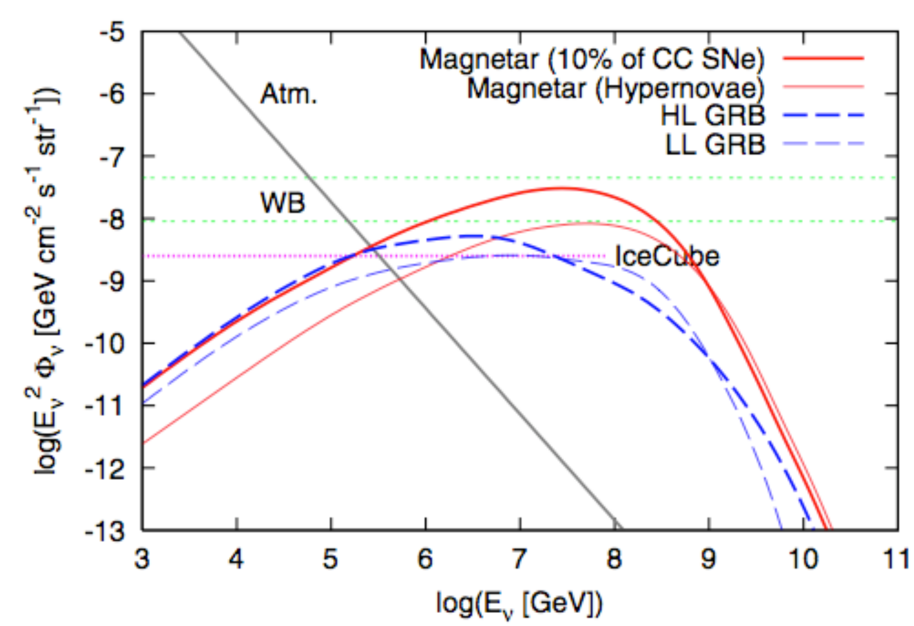
secondary gamma-rays wouldn't be of much help...
in both cases: not observable

cosmogenic neutrinos wouldn't be of much help...
same source evolution

UHE neutrinos at the source?

Waxman & Bahcall 1997, Murase et al. 2006, 2008
secondary neutrinos from hadronic interactions of UHECRs accelerated in shocks inside GRBs

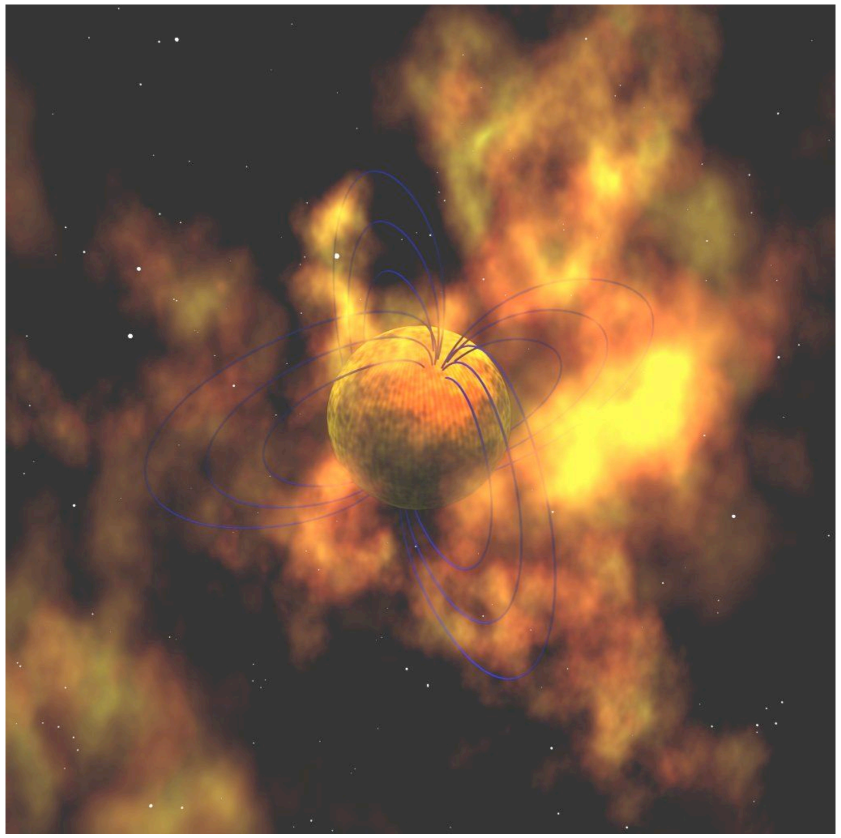
Murase et al. 2009
secondary neutrinos from hadronic interactions in wind ejecta of newly born magnetar (proton case)



caution: dependency on Physics inside source
and in source environment + composition of UHECR

gravitational waves?

Magnetars and UHECRs



Duncan & Thompson 1992

Magnetar characteristics (theoretical predictions):
- isolated neutron star
- fast rotation at birth ($P_i \sim 1$ ms)
- strong surface dipole fields ($B_* \sim 10^{15\text{-}16}$ G)

Plausible explanation for observed
Anomalous X-ray Pulsars (AXP)
and Soft Gamma Repeaters (SGR)

e.g. Koveliotou 1998, 1999, Baring & Harding 2002

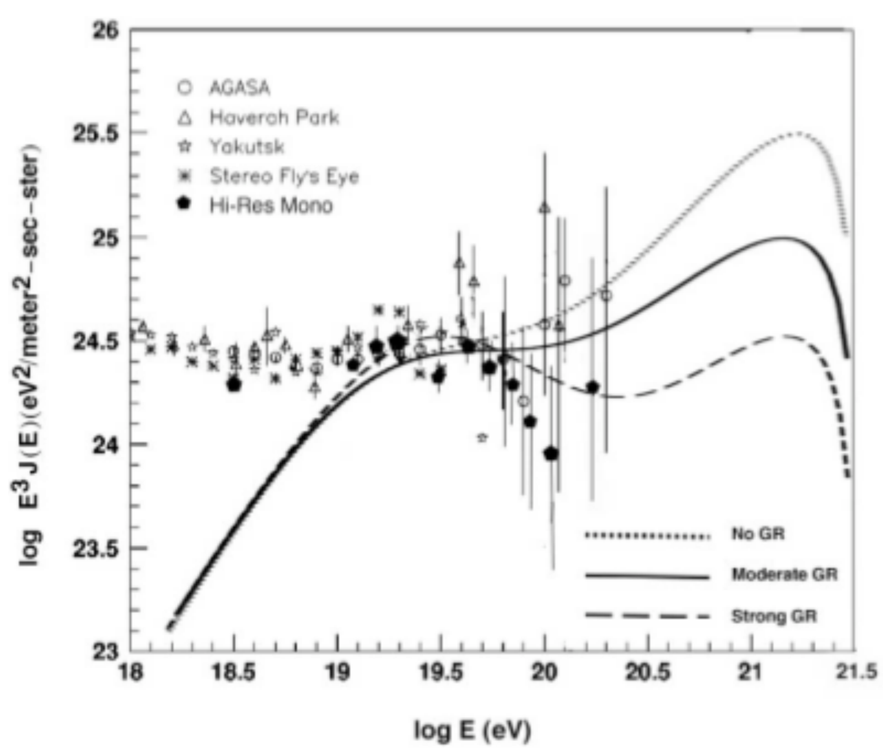
Magnetars as progenitors of UHECRs:
idea introduced during the "AGASA era"

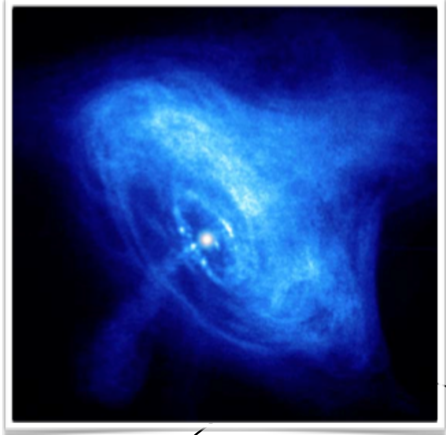
Blasi, Epstein, Olinto 2000

Galactic magnetars + iron particles
aim: isotropic distribution in sky

Arons 2003

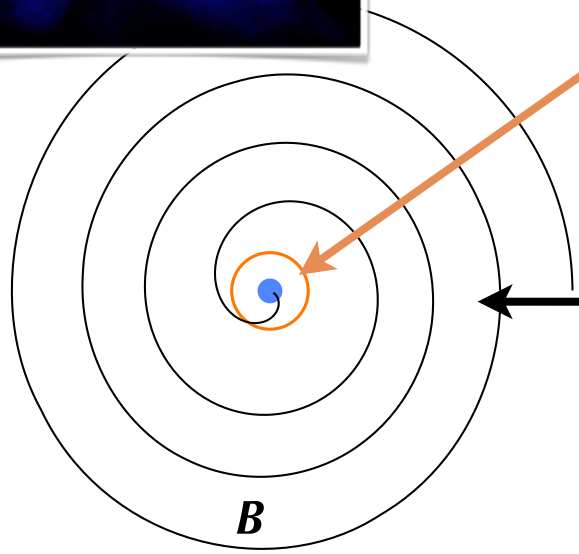
extragalactic, faint GZK cut-off due to hard spectral index





Acceleration mechanism in magnetars

Blasi et al. 2000
Arons 2003



light cylinder

$$r < R_{\rm L} \equiv \frac{c}{\Omega}$$

$$B(r) = \frac{1}{2} B(R_*) \left(\frac{R_*}{r}\right)^3$$

relativistic wind

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

induced electric field: $\mathbf{E} = \frac{\mathbf{v}}{c} \times \mathbf{B}$

leads to voltage drop:

$$\Phi \sim rE = rB = R_{\rm L} B(R_{\rm L}) = \frac{\Omega^2 B_* R_*^3}{2c^2}$$

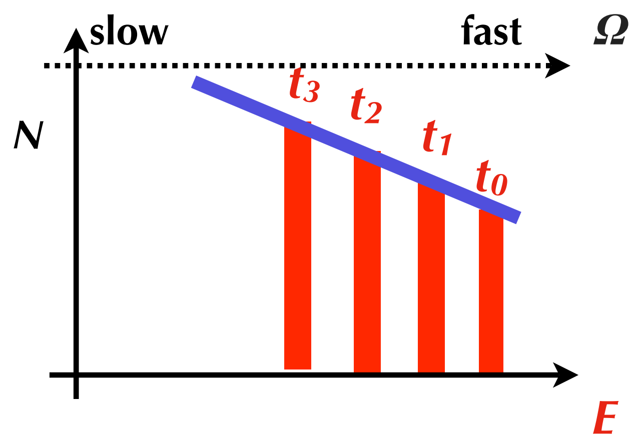
$$\sim 3 \times 10^{22}\ {\rm V}\ \frac{B_*}{2 \times 10^{15}\ {\rm G}} \left(\frac{R_*}{10\,{\rm km}}\right)^3 \left(\frac{\Omega}{10^4\ s^{-1}}\right)^2$$

particles accelerated to energy:

$$E(\Omega) = q\eta\Phi = q\eta \frac{\Omega^2 B_* R_*^3}{2c^2}$$

$$\sim 3 \times 10^{21}\ {\rm eV}\ Z\eta_1 \frac{B_*}{2 \times 10^{15}\ {\rm G}} \left(\frac{R_*}{10\,{\rm km}}\right)^3 \left(\frac{\Omega}{10^4\ s^{-1}}\right)^2$$

10%: fraction of voltage experienced by particles



particle injection rate:

$$\dot{N}_{\rm i} = \frac{A_{\rm PC}\,\rho_{\rm GJ}\,c}{Ze} = \frac{\Omega^2 B_* R_*^3}{2|q|c}$$

surface of polar cap **Goldreich-Julian density**

energy spectrum for one magnetar:

$$\frac{{\rm d}N_{\rm i}}{{\rm d}E} = \dot{N}_{\rm i} \left(-\frac{{\rm d}t}{{\rm d}\Omega}\right) \frac{{\rm d}\Omega}{{\rm d}E}$$

$$\frac{{\rm d}N_{\rm i}}{{\rm d}E} = \frac{9}{2} \frac{c^2 I}{ZeB_* R_*^3 E} \left(1 + \frac{E}{E_{\rm g}}\right)^{-1}$$

hard injection spectrum: -1 slope

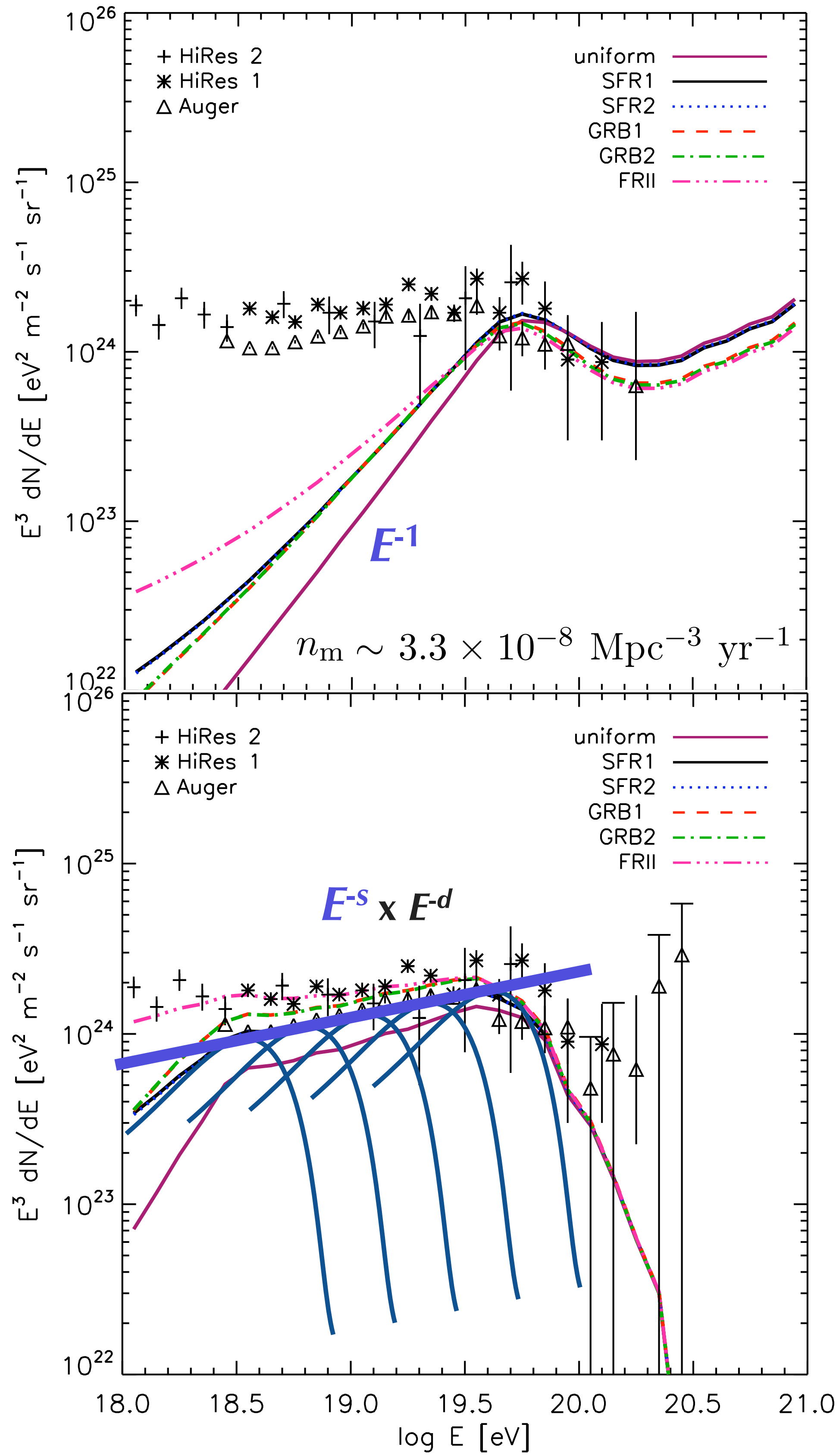
spin-down rate:

$$-\frac{{\rm d}\Omega}{{\rm d}t} = \frac{\dot{E}_{\rm EM} + \dot{E}_{\rm grav}}{I\Omega} = \frac{1}{9} \frac{B_*^2 R_*^6 \Omega^3}{Ic^3} \left[1 + \left(\frac{\Omega}{\Omega_{\rm g}}\right)^2\right]$$

angular velocity at which e.m. losses = grav. losses

Possible way to reconcile the magnetar spectrum with observed data

K.K. in prep.



distribution of magnetar rates according to starting voltage

$$\frac{dn_m}{d\Phi_i} = \frac{n_m}{\Phi_{i,max}} \frac{s-1}{(\Phi_{i,max}/\Phi_{i,min})^{s-1} - 1} \left(\frac{\Phi_i}{\Phi_{i,max}}\right)^{-s}$$

$$\Phi_{i,min} \le \Phi \le \Phi_{i,max}$$

$$\Phi_i = \frac{E_i}{q\eta}$$

equivalent to distribution in max acceleration energy:

$$\frac{dn_m}{dE_i} = \frac{dn_m}{d\Phi_i}\frac{d\Phi_i}{dE_i} = n_m \chi \left(\frac{E_i}{E_{i,max}}\right)^{-s}$$

corrected energy spectrum: **s = 2.2**

$$J(E) = \int_{E_{i,min}}^{E_{i,max}} \frac{\partial J(E, E_i)}{\partial E_i} dE_i$$

magnetar rate necessary at z=0:

$$n_m = \epsilon_m n_g \nu_m / f \sim 10^{-6} \text{ Mpc}^{-3} \text{ yr}^{-1}$$

~ hypernovae rate

Gravitational waves to distinguish GRBs from magnetars?

Gravitational waves?

GRBs: shocks produce only faint GW

e.g. Piran 2004

magnetars:
dipolar magnetic field B_*,
principal inertial momentum I,
initial rotation velocity Ω_i

→ UHECR acceleration
specific spectrum + E_{max}

Blasi, Epstein, Olinto 2000
Arons 2003

↓ GW signal
specific spectrum + span in frequency

Regimbau & de Freitas Pacheco 2006
Dall'Osso & Stella 2007
Regimbau & Mandic 2008

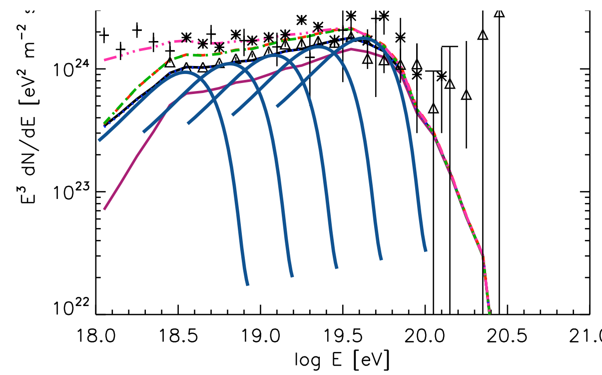
observation of specific spectrum of GW
= evidence of adequate magnetar parameters for acceleration of UHECR?

Implications for the gravitational stochastic background

K.K. in prep.

distribution of initial voltages:

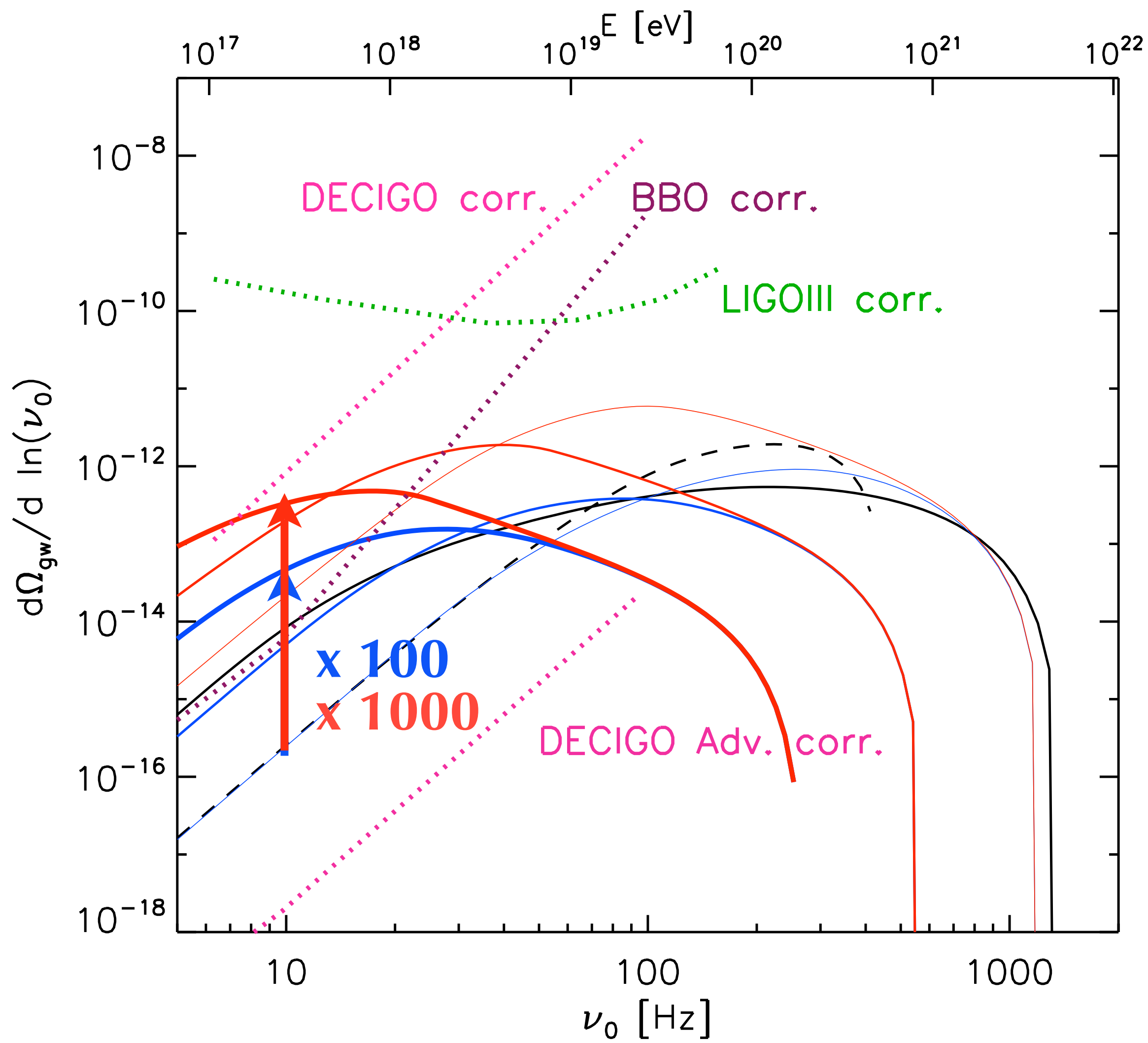
$$\Phi_\mathrm{i} = f(\nu_\mathrm{i}, B_*)$$



$$E_\mathrm{i} = q\eta \frac{\pi^2 \alpha R_*^3}{2c^2} \nu_\mathrm{i}^3$$

generation of B by $\alpha\omega$-dynamo: $B_* = \alpha \nu_\mathrm{i}\,, \quad \alpha \in [10^{13}, 10^{16}]\ \mathrm{G\ Hz}^{-1}$ *Thompson & Duncan 1992*

lead to distribution of initial frequencies: $$\frac{\mathrm{d}n_\mathrm{m}}{\mathrm{d}\nu_\mathrm{i}} = n_\mathrm{m}\chi \frac{3q\eta\pi^2}{c^2} \frac{\alpha R_*^3}{2} \nu_\mathrm{i}^2 \left(\frac{\nu_\mathrm{i}}{\nu_\mathrm{i,max}}\right)^{-3s}$$



$\beta = 100$ $\beta = 1000$

increasing thickness: $\alpha = 10^{13,14,15}\ \mathrm{G\ Hz}^{-1}$

$E_\mathrm{i,min} = 3 \times 10^{18}\ \mathrm{eV},\ E_\mathrm{i,max} = 10^{21.5}\ \mathrm{eV}$

how to
go further

What will be needed

Astrophysics:

- better understanding of most powerful sources: escape issues
- measurements of intergalactic magnetic fields

multi-wavelength studies from radio to gamma-rays

measurement of gamma-ray halos? (e.g. Neronov & Semikoz 09)

Particle Physics:

http://www-ik.fzk.de/~needs/
shower development, parameters for hadronic interactions

UHECR data:

- more statistics for anisotropy signatures (transient/steady sources)
- more statistics for shape of energy spectrum at highest E
- more statistics for chemical composition at highest E

Auger North
JEM-EUSO

Other messengers:

- cosmogenic neutrinos (produced during propagation)
- gamma-rays (GeV to UHE)
- gravitational waves

could be observed for reasonable source scenarios if composition is dominated by protons

a way to probe magnetars as UHECR accelerators?

Summary: recipe to identify UHECR sources

Astrophysical sources with **sufficient energetics**:
FRII/FSRQ   GRB   magnetars

How do we discriminate them?

By increasing the statistics and looking at **anisotropy signatures**:
if anisotropy persists and no visible counterpart, source is probably transient

If the source is transient, how do we tell apart GRBs from magnetars?

By looking at **diffuse secondary emissions**:
UHE neutrino spectrum   ***Murase et al. 2009***

observation of specific spectrum of GW
= evidence of adequate magnetar parameters for acceleration of UHECR?

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Astrophysics of Ultrahigh Energy Cosmic Rays

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Key Words cosmic rays, neutrinos, ultrahigh energy, cosmic accelerators, magnetic fields, particle astrophysics

The origin of ultrahigh energy cosmic rays is still unknown.

...ws that they come from extragalactic regions, but the actual sources are still a mystery. After a brief introduction to the current state of the observations, the astrophysics of propagation at

2030

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Astronomy of Ultrahigh energy cosmic rays

Key Words cosmic rays, neutrinos, ultrahigh energy, cosmic accelerators, magnetic fields, particle astrophysics