Ultrahigh energy cosmic rays and pulsars

Kumiko Kotera

Institut d'Astrophysique de Paris

LPNHE - 16/01/14

Ultrahigh energy cosmic rays sources?
and pulsars

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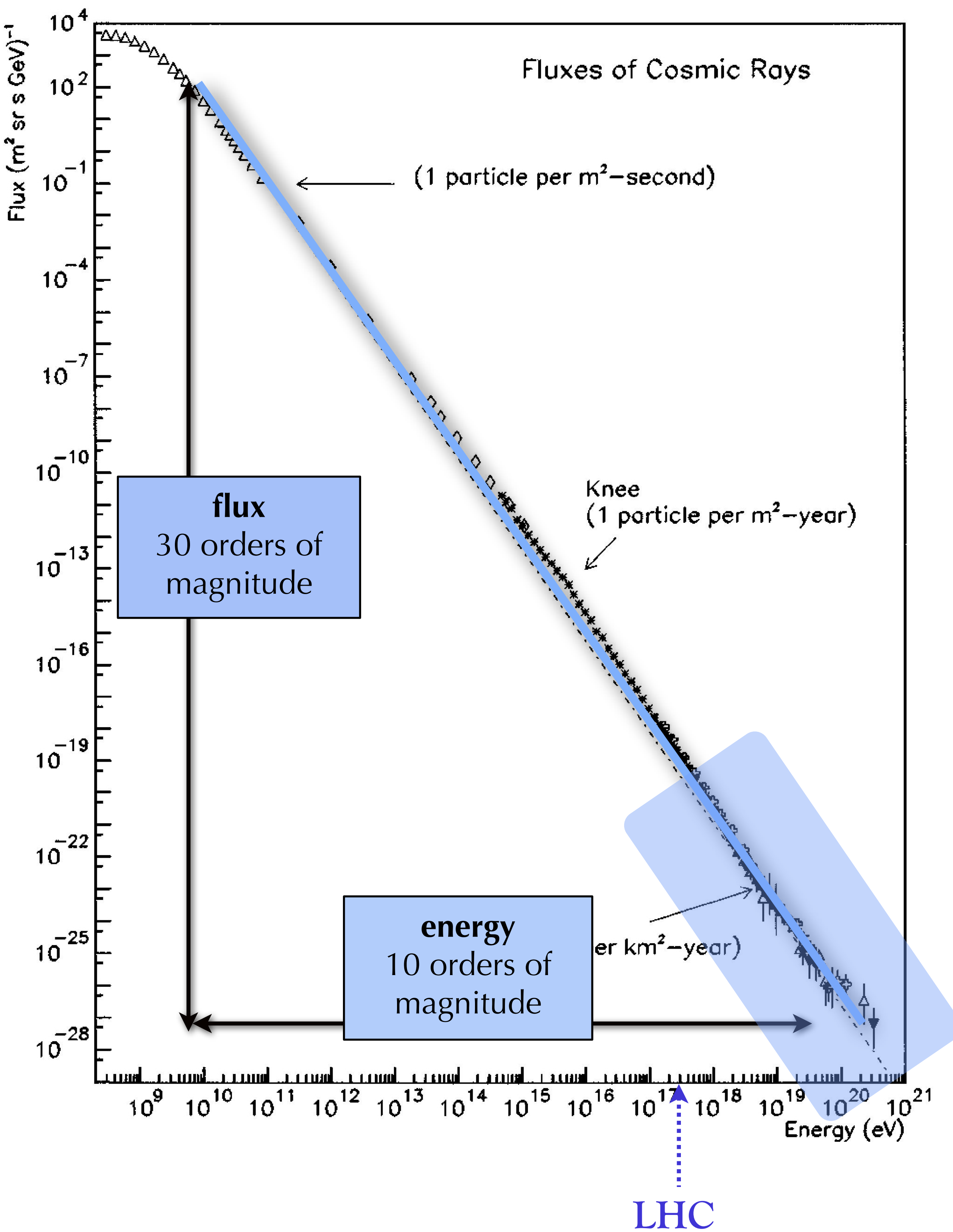
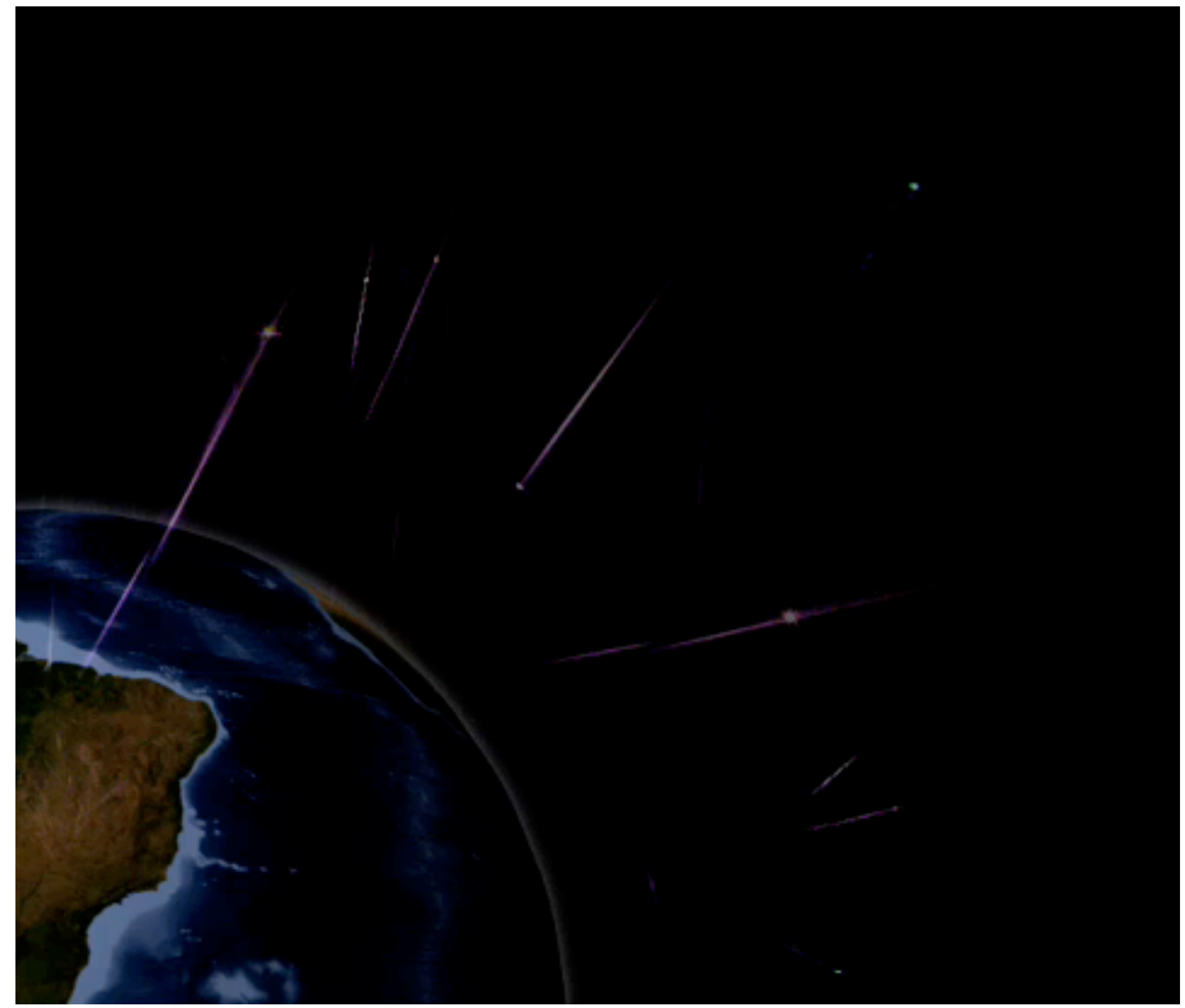
The puzzle of ultrahigh energy cosmic rays





- Energies that cannot be reproduced on Earth!
- Universe thru different eyes
- What source(s)? Physical mechanisms?

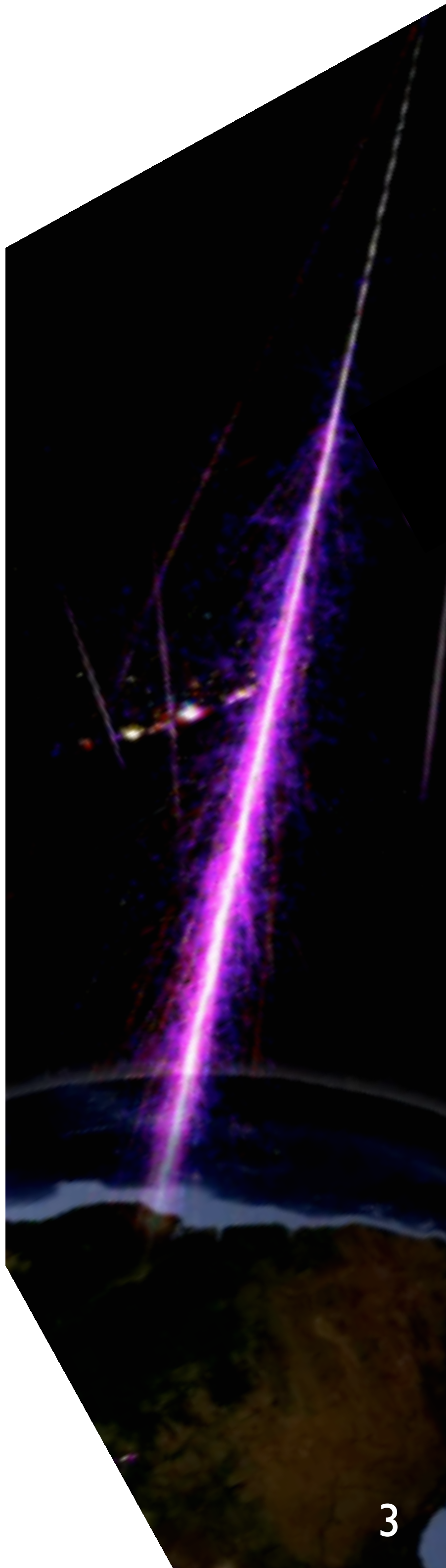
Why is it so difficult?

Astrophysical issues:

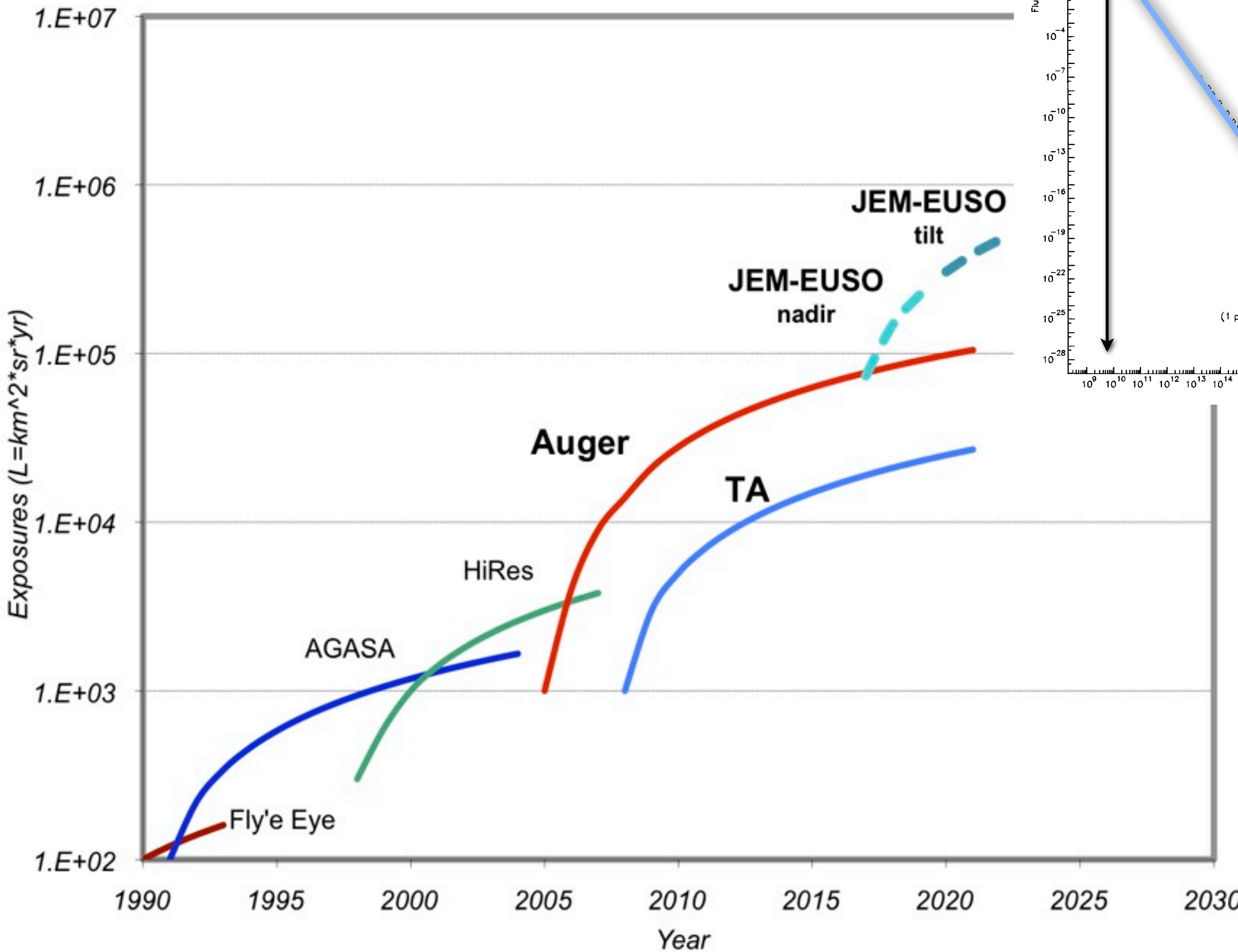
- UHECRs are charged particles *and* the Universe is magnetized
- Physics of powerful astrophysical objects is not known in detail

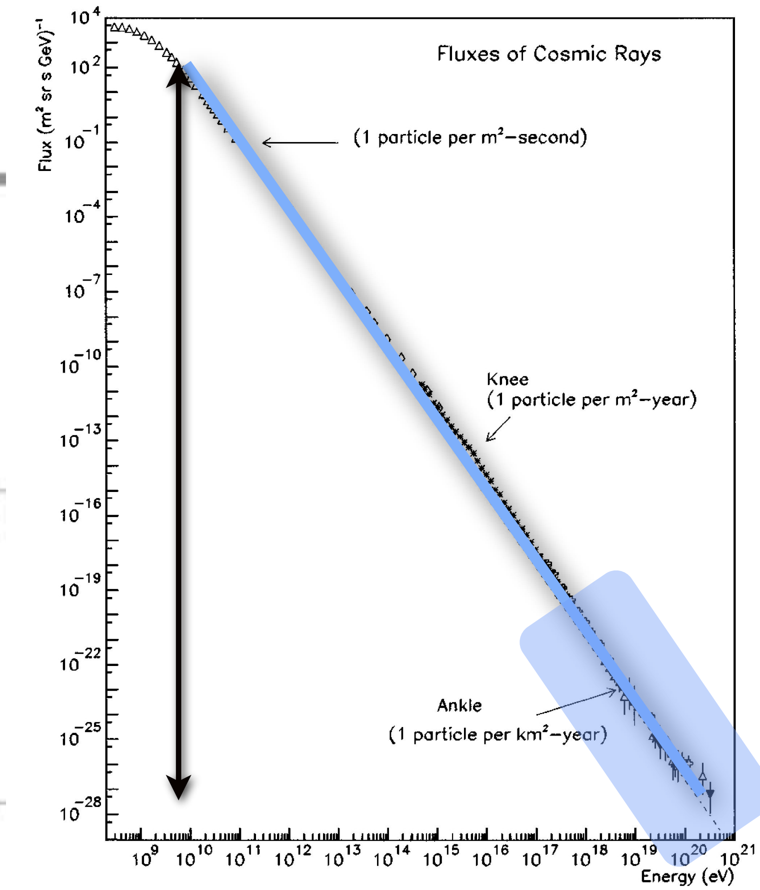
Particle Physics issues:

ultrahigh energies that cannot be reproduced on Earth ($E \sim 2 \times 10^{20}$ eV)
shower development (hadronic interactions) still unknown



Since 1990 in ultrahigh energy cosmic rays





K.K. & Olinto 11

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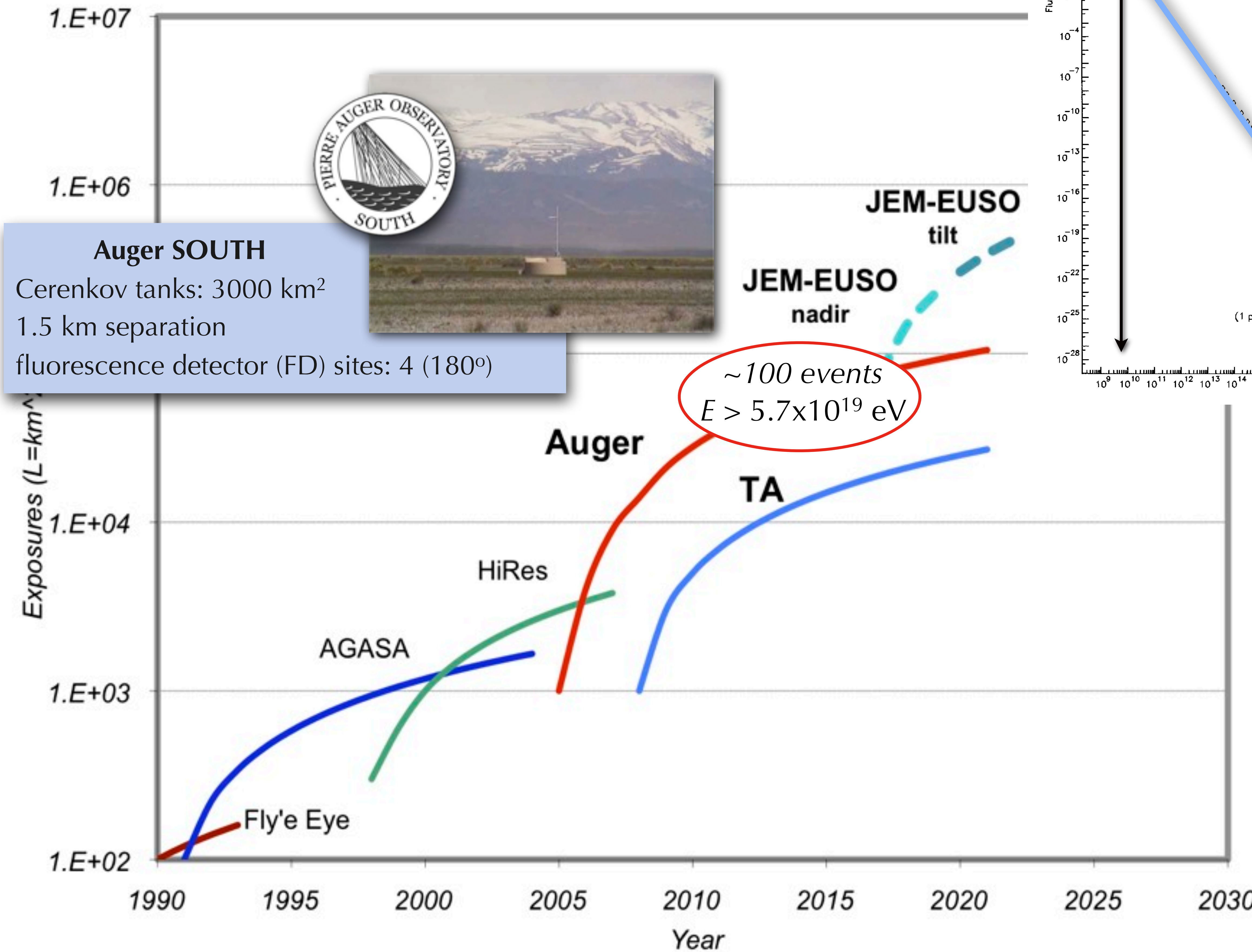
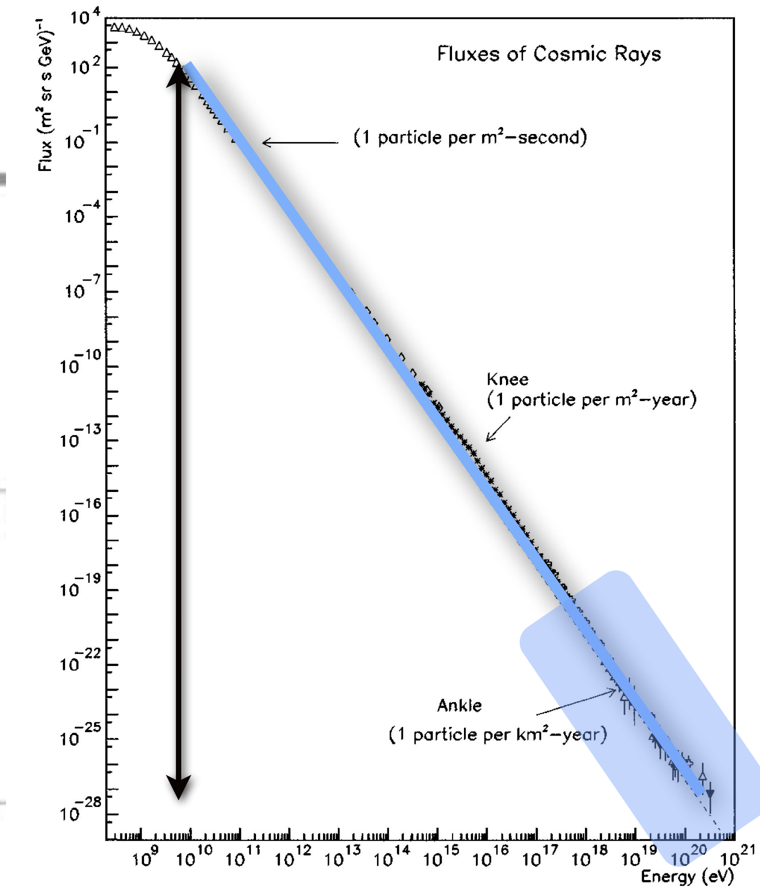


Auger SOUTH
Cerenkov tanks: 3000 km^2
1.5 km separation
fluorescence detector (FD) sites: 4 (180^o)



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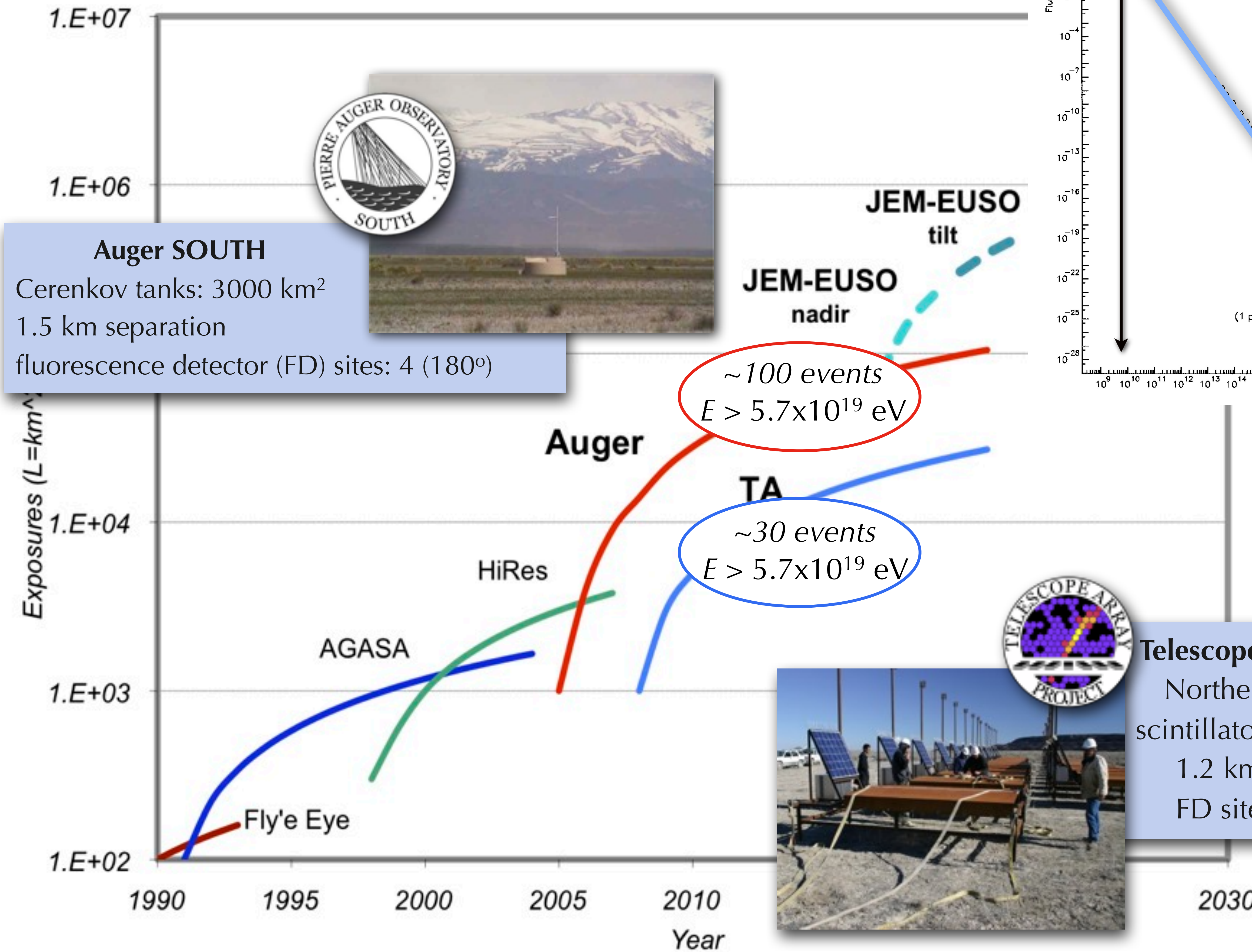
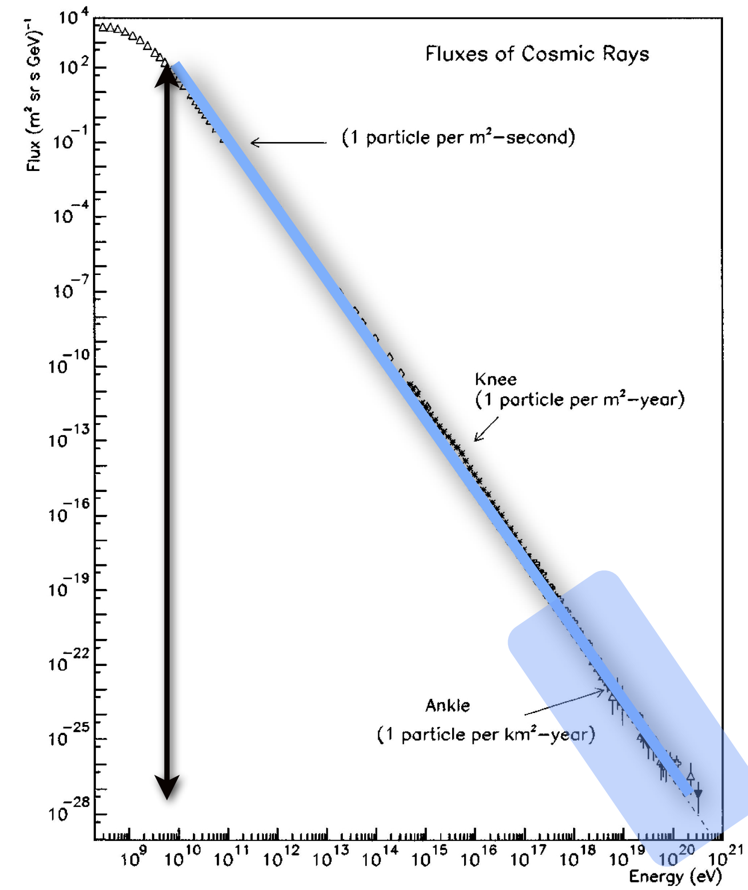


Auger SOUTH
Cerenkov tanks: 3000 km²
1.5 km separation
fluorescence detector (FD) sites: 4 (180°)

~100 events
E > 5.7x10¹⁹ eV

~30 events
E > 5.7x10¹⁹ eV

Telescope Array (TA)
Northern hemisph.
scintillators: 762 km²
1.2 km separation
FD sites - 3 (180°)



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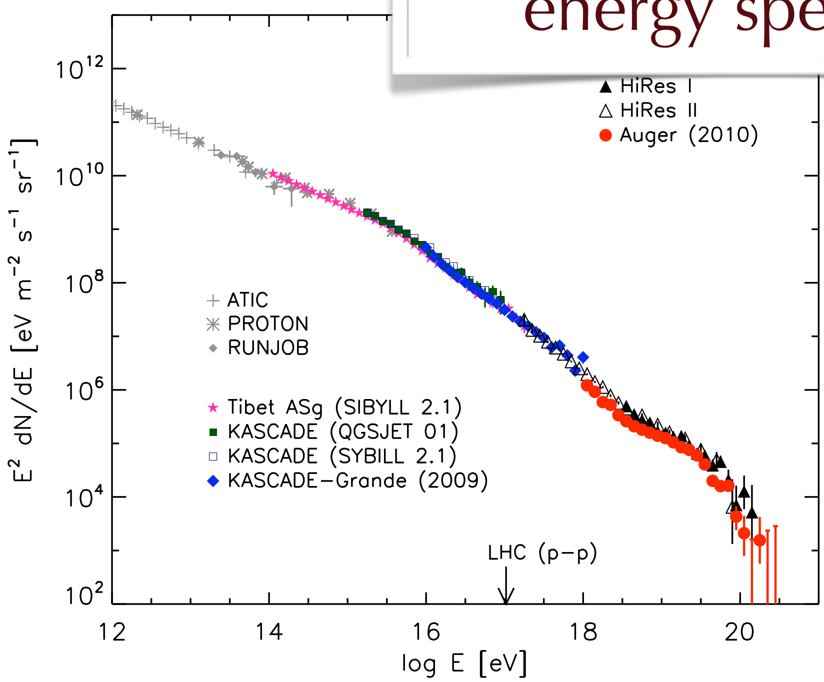
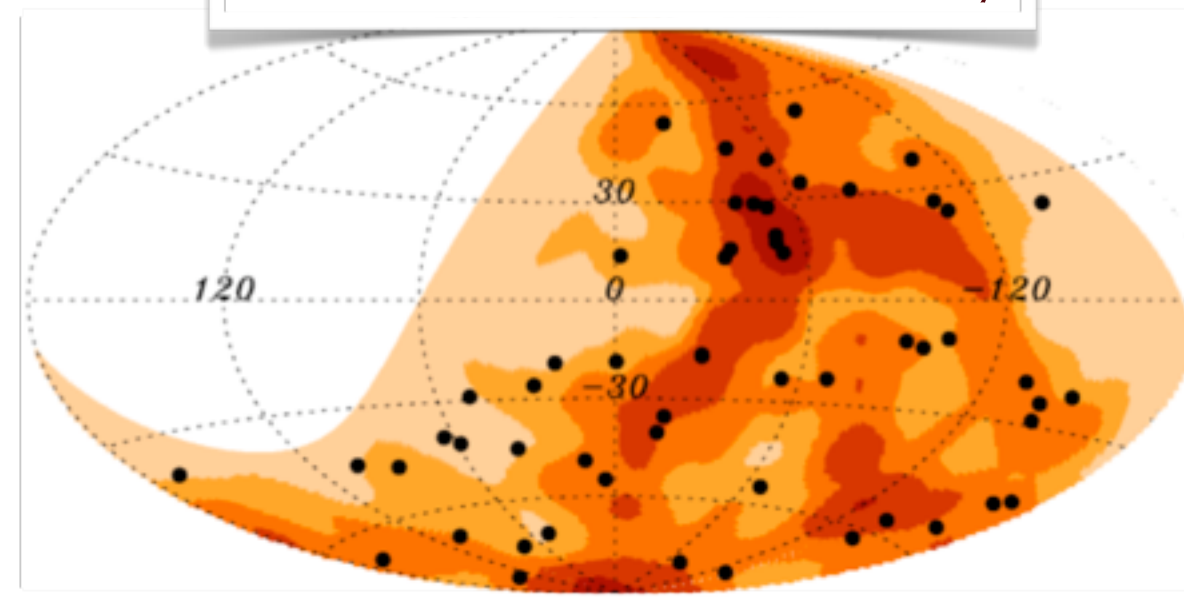
What observational information do we have?

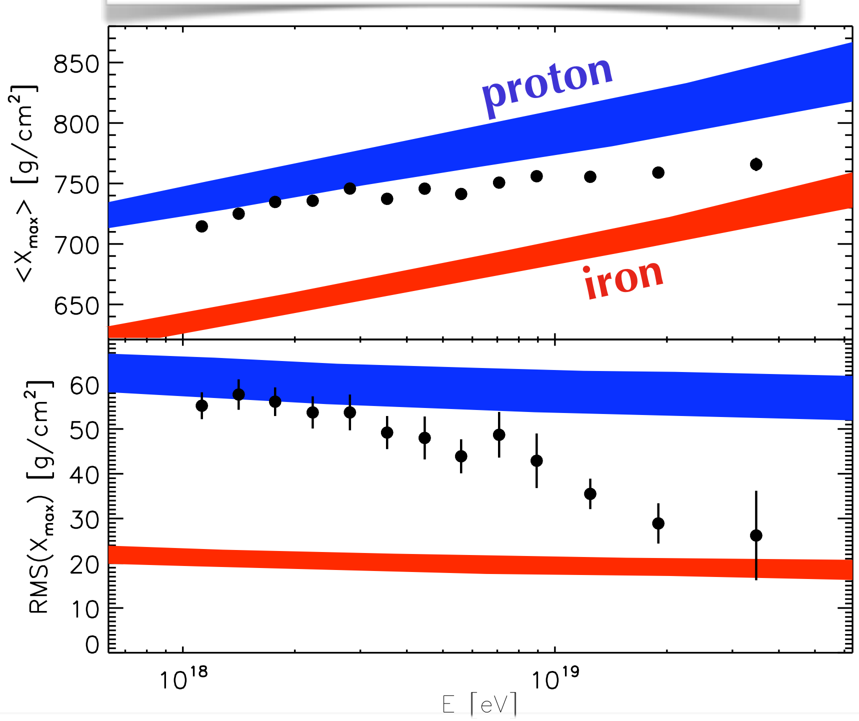
energy spectrum



arrival directions in the sky



chemical composition



other messengers:
secondary gamma-rays,
neutrinos

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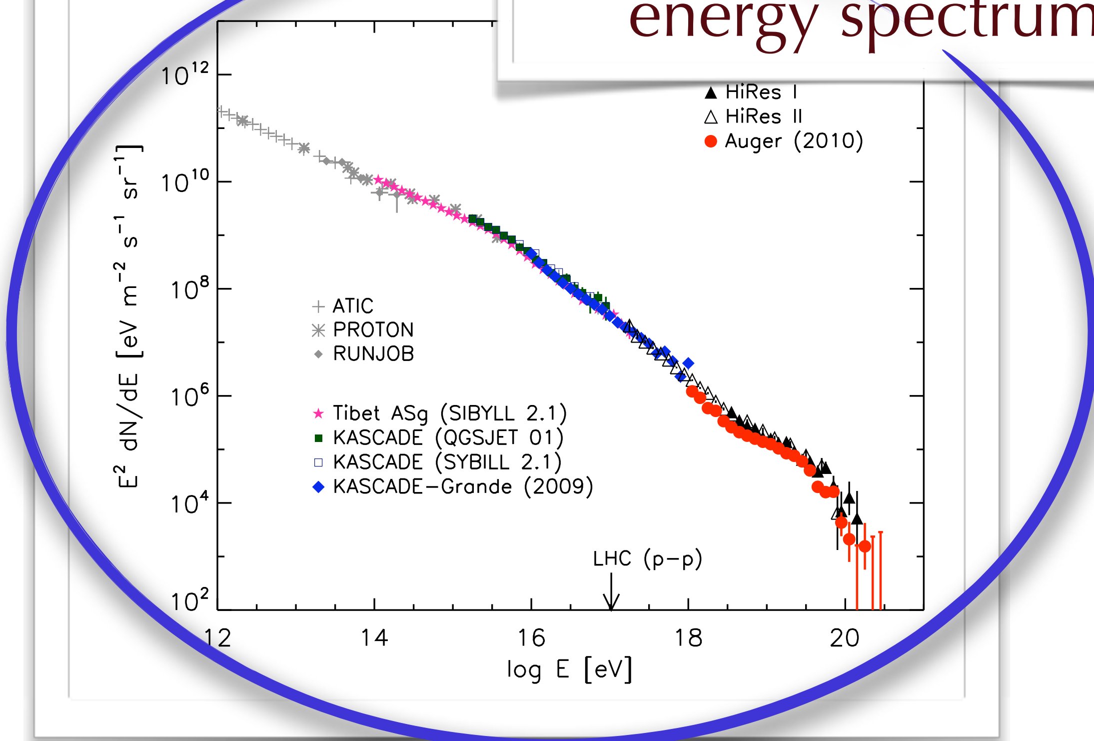

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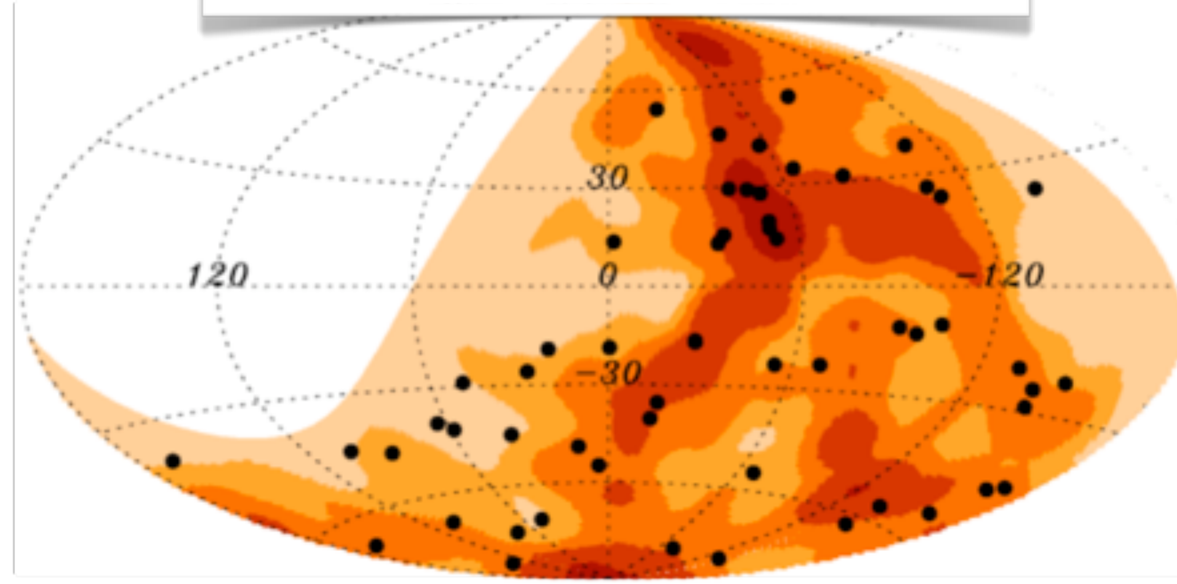

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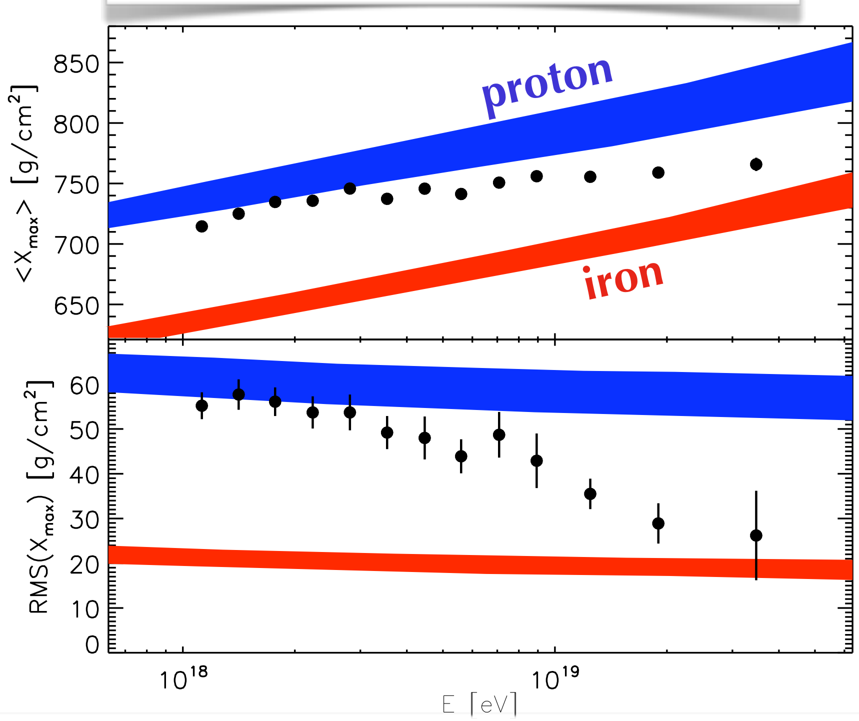

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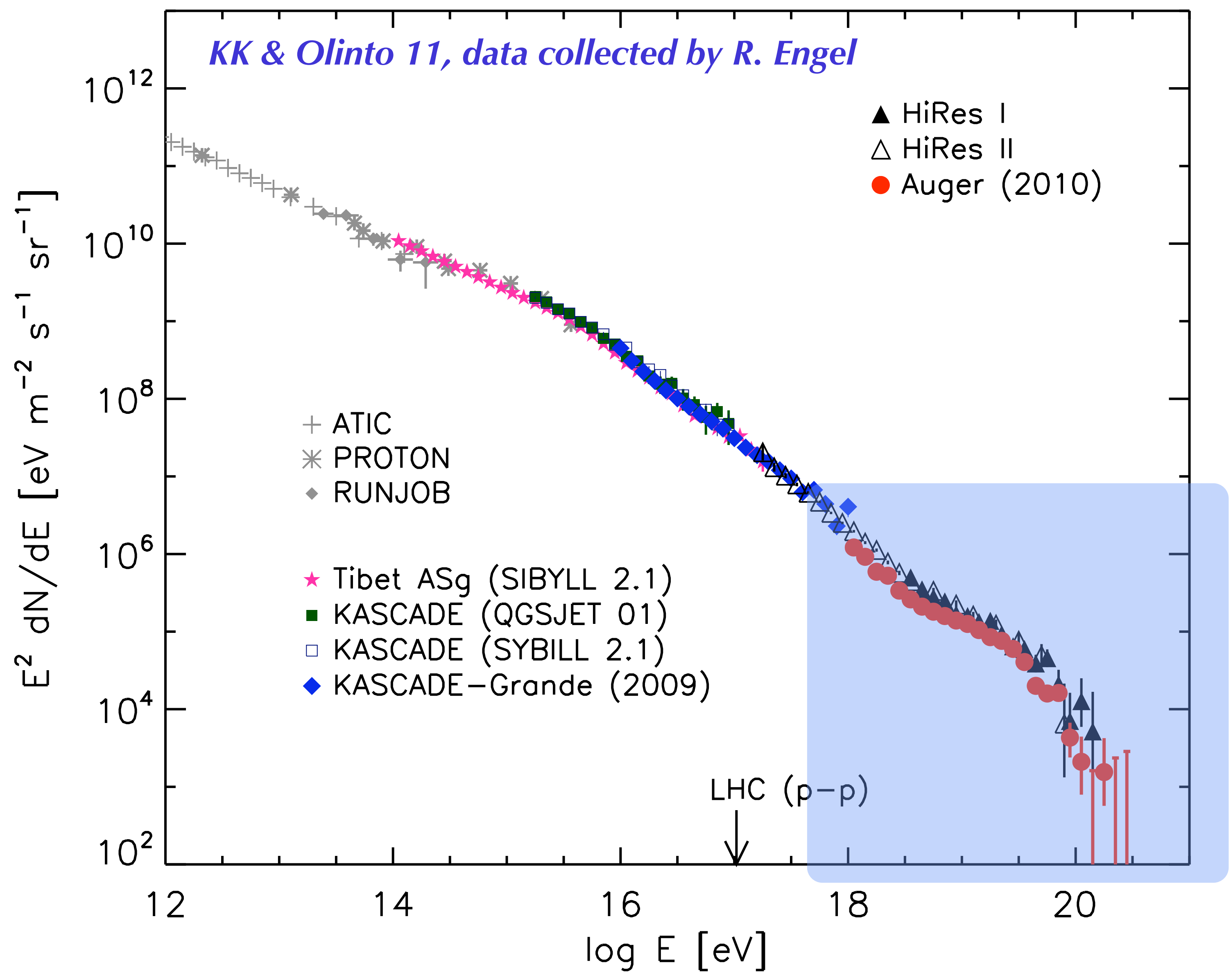

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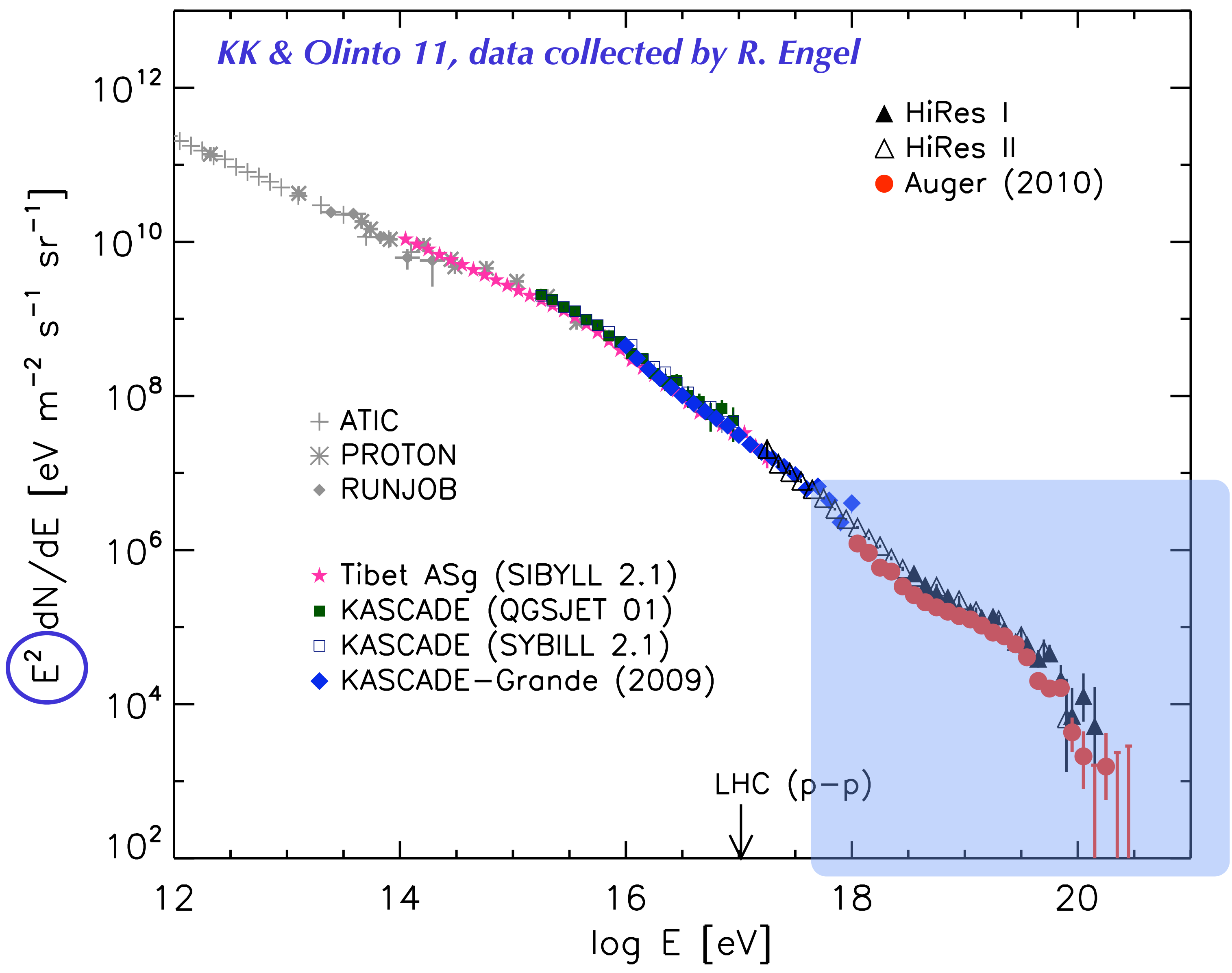

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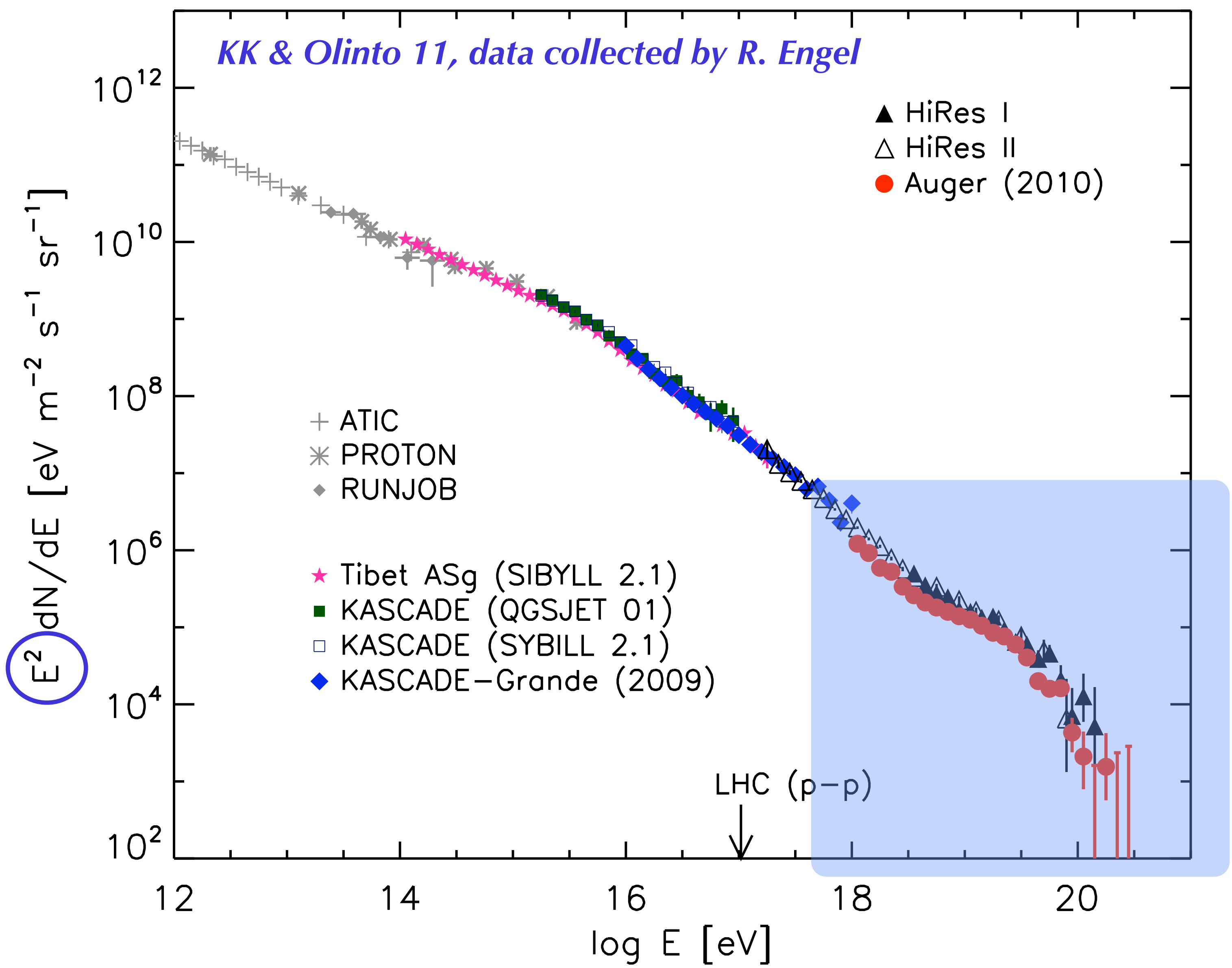

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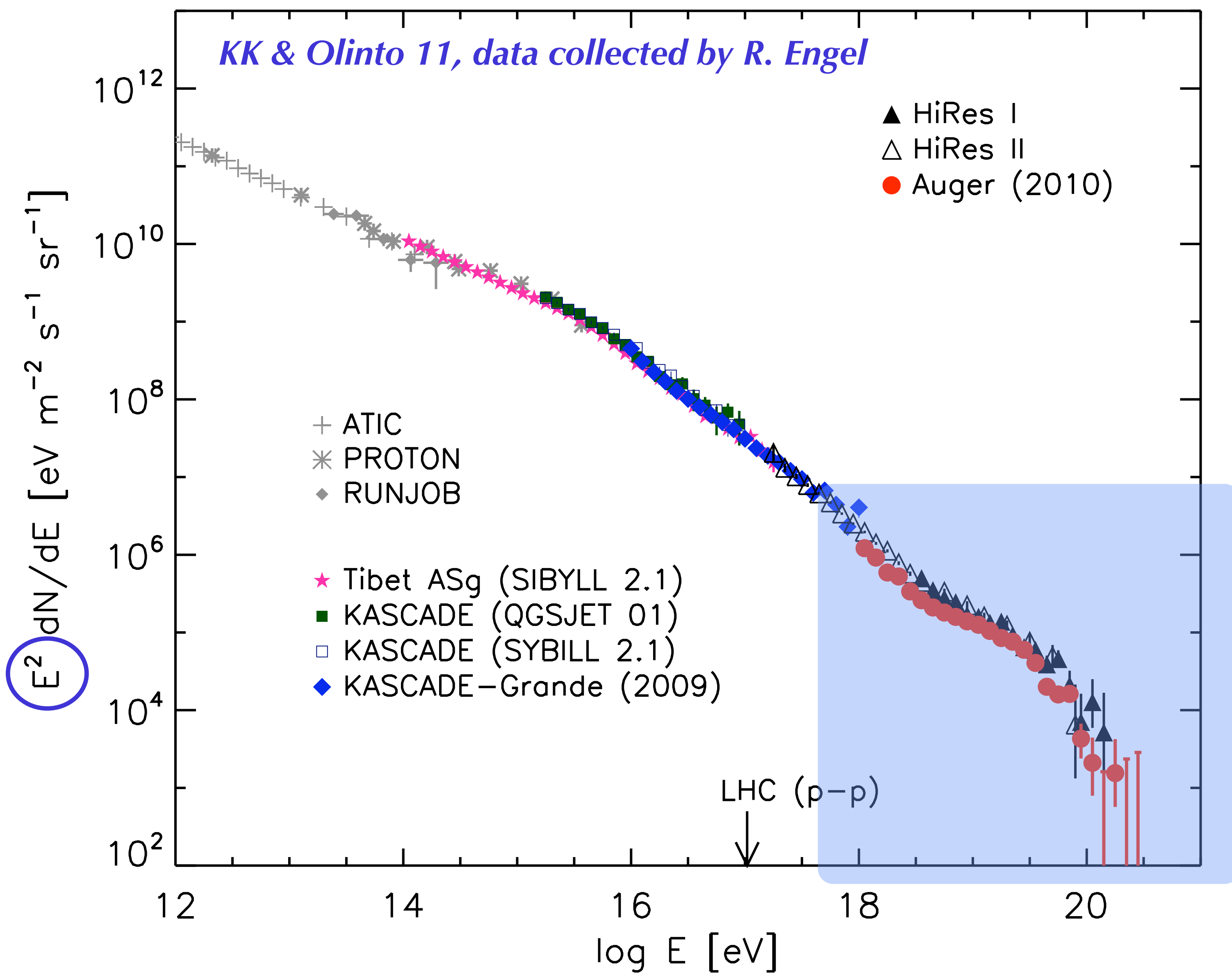

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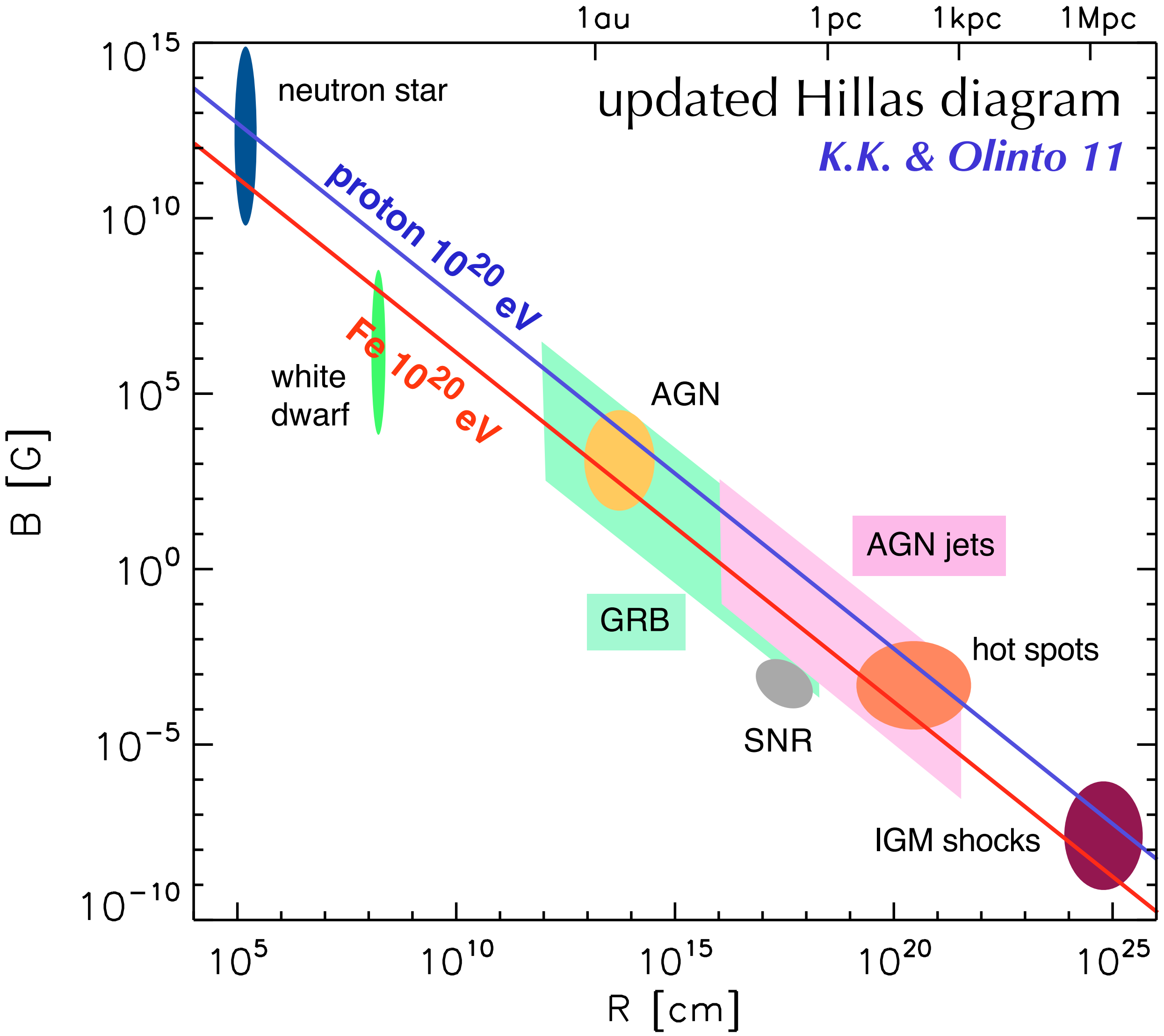
$E_{UHECR} > 10^{20}$ eV: first selection of sources



confinement of particle in source:
particle Larmor radius < size of source

$$r_{\rm L} \leq L$$

$$r_{\rm L} = 1.08 \text{ Mpc}\, Z^{-1} \left(\frac{E}{10^{18} \text{ eV}}\right) \left(\frac{B}{1 \text{ nG}}\right)^{-1}$$

! caution when applied to relativistic outflows

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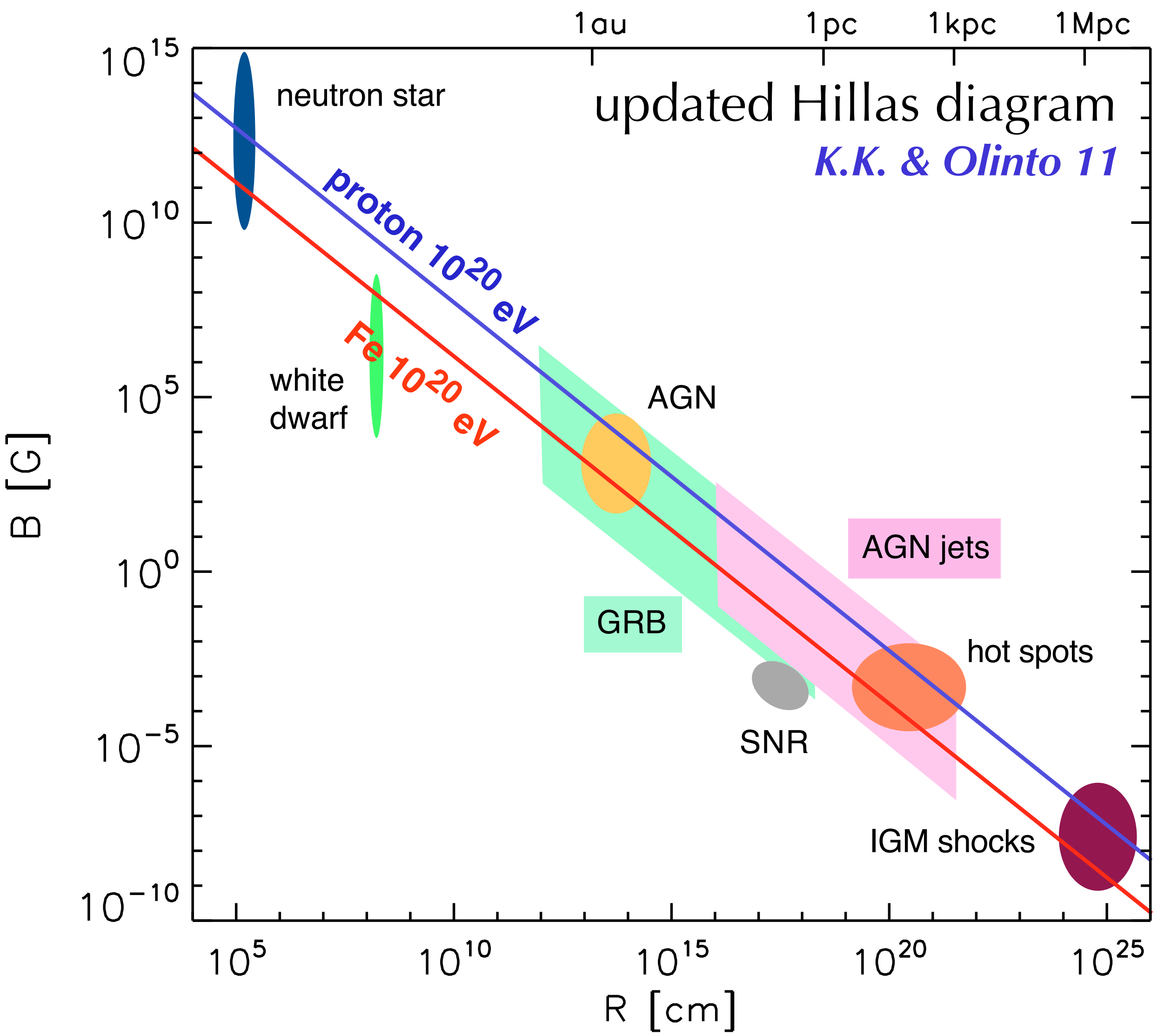

black holes/jets/hot spots acceleration limited by radiation losses
e.g. Norman et al. 1995, Rachen & Biermann 1995, Henri et al. 1999, Lemoine & Waxman 2009

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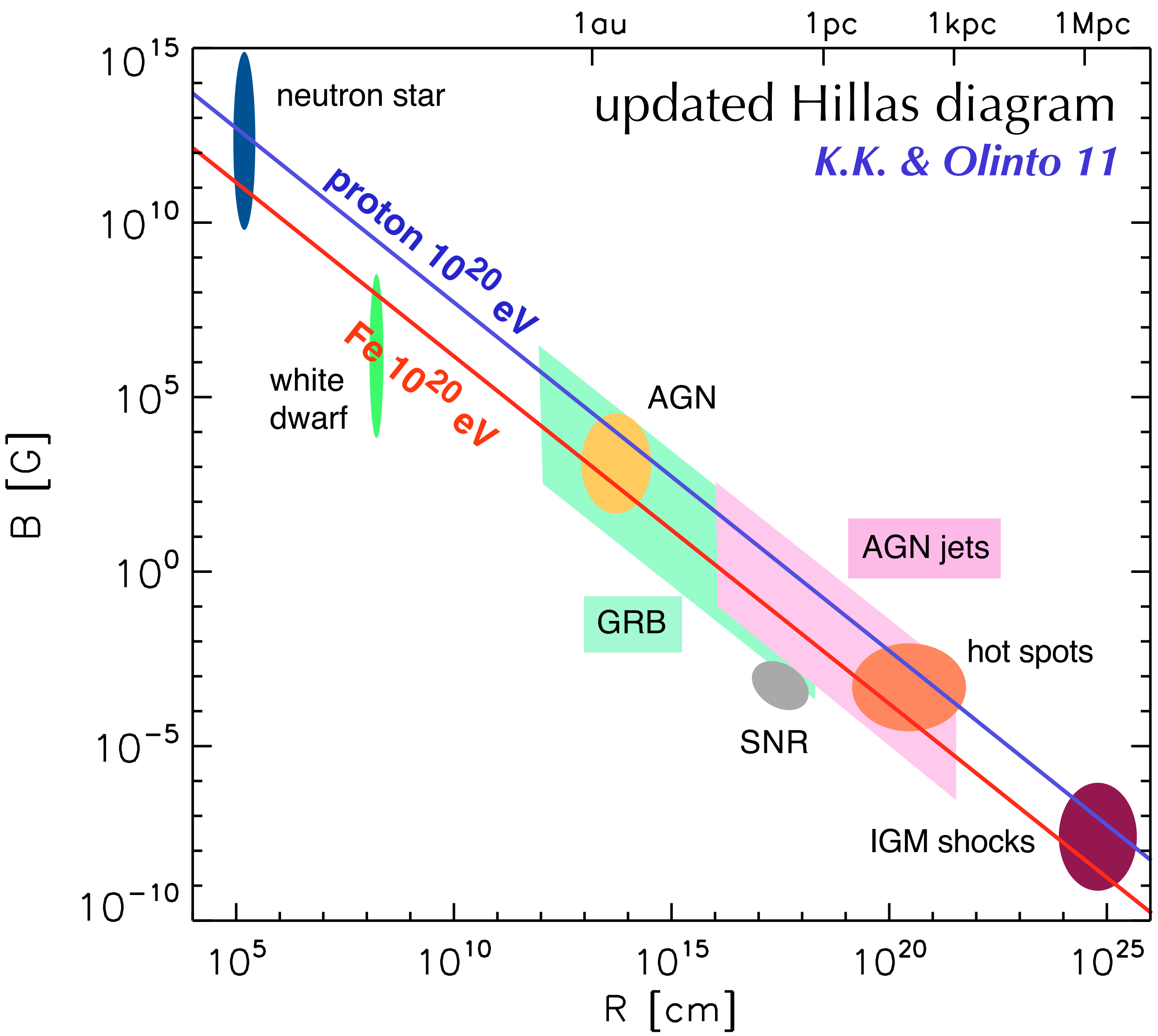

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R ~ 1-10 Mpc, $B_{downstr}$ ~ 1 μG
--> E ~ 10^{20} eV ?
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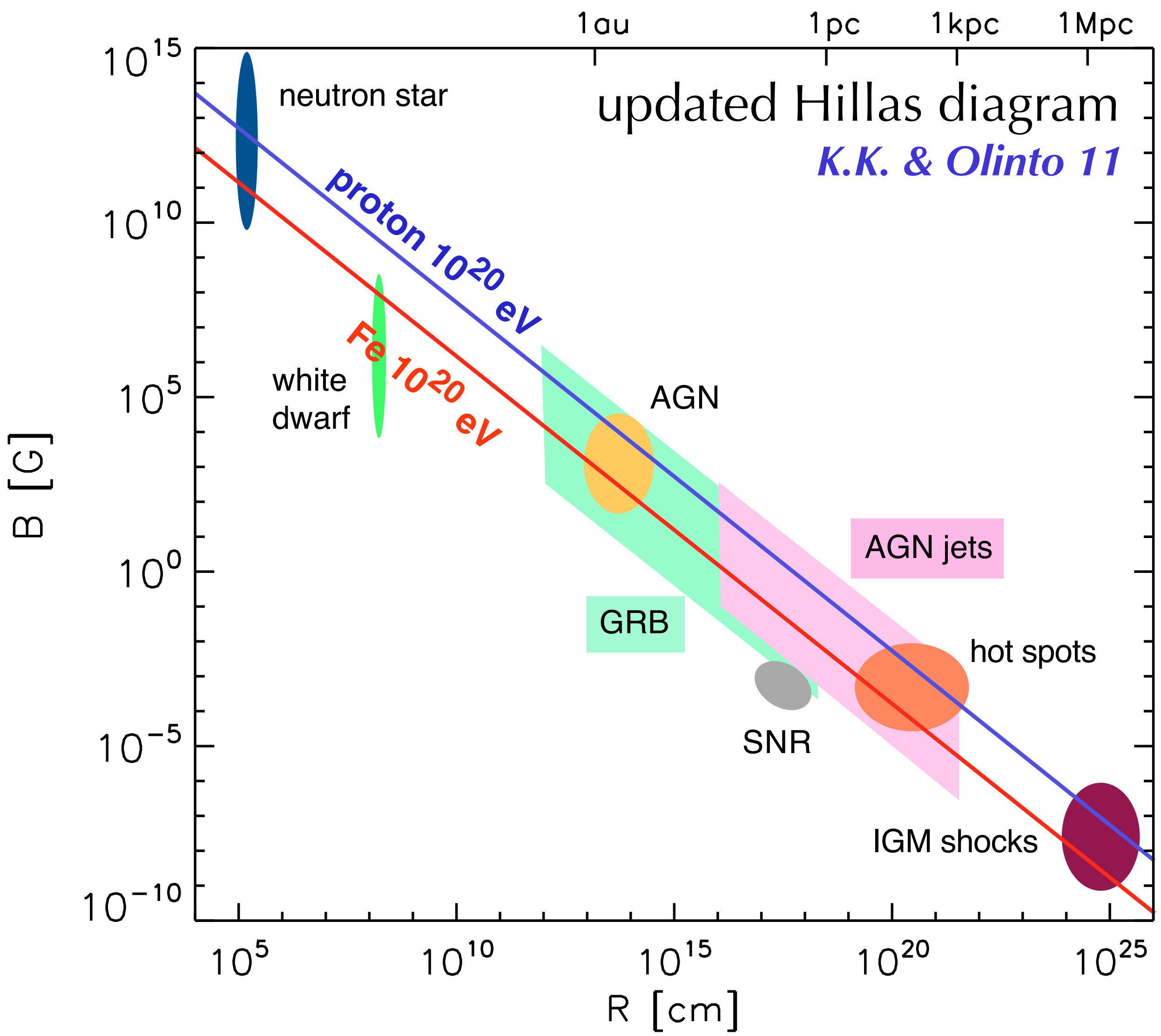

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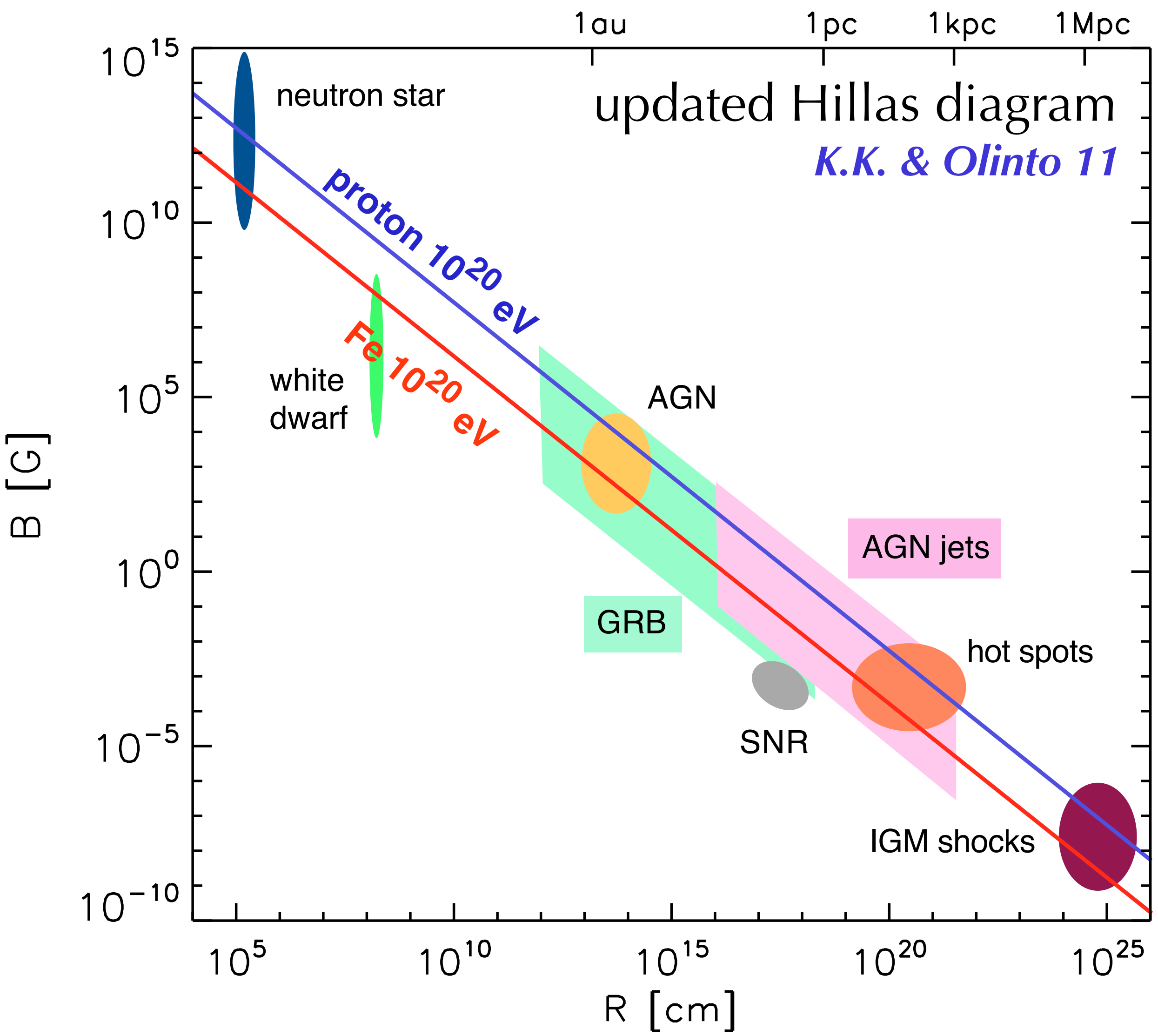

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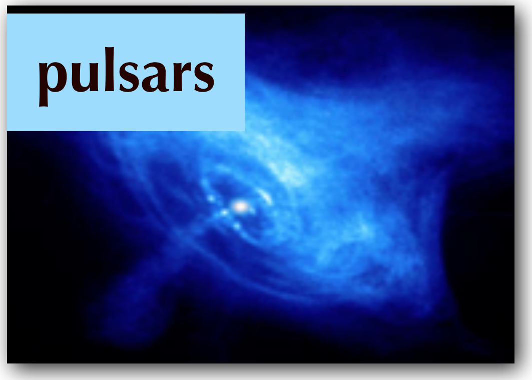

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Fang, K.K., Olinto 2012

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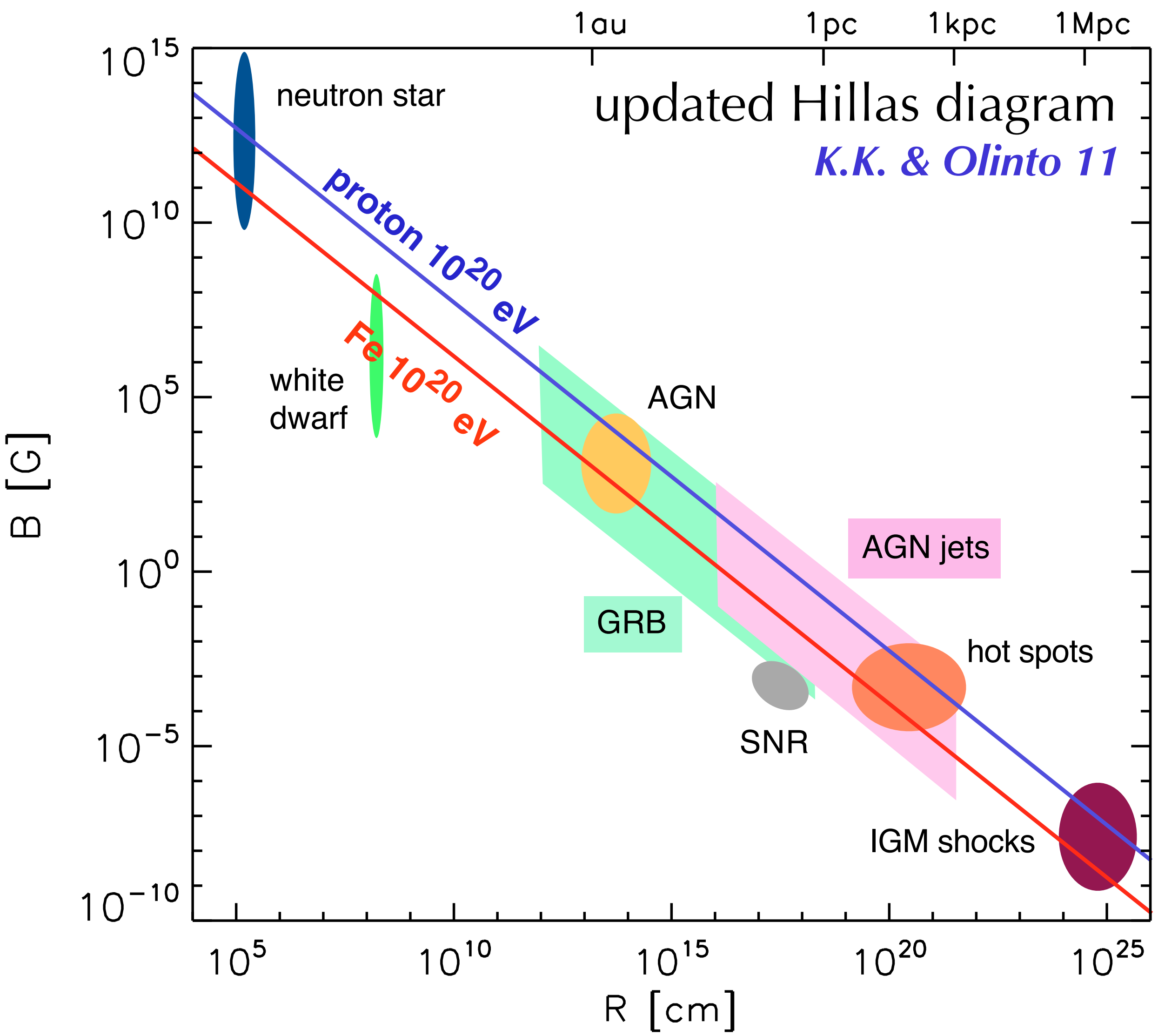

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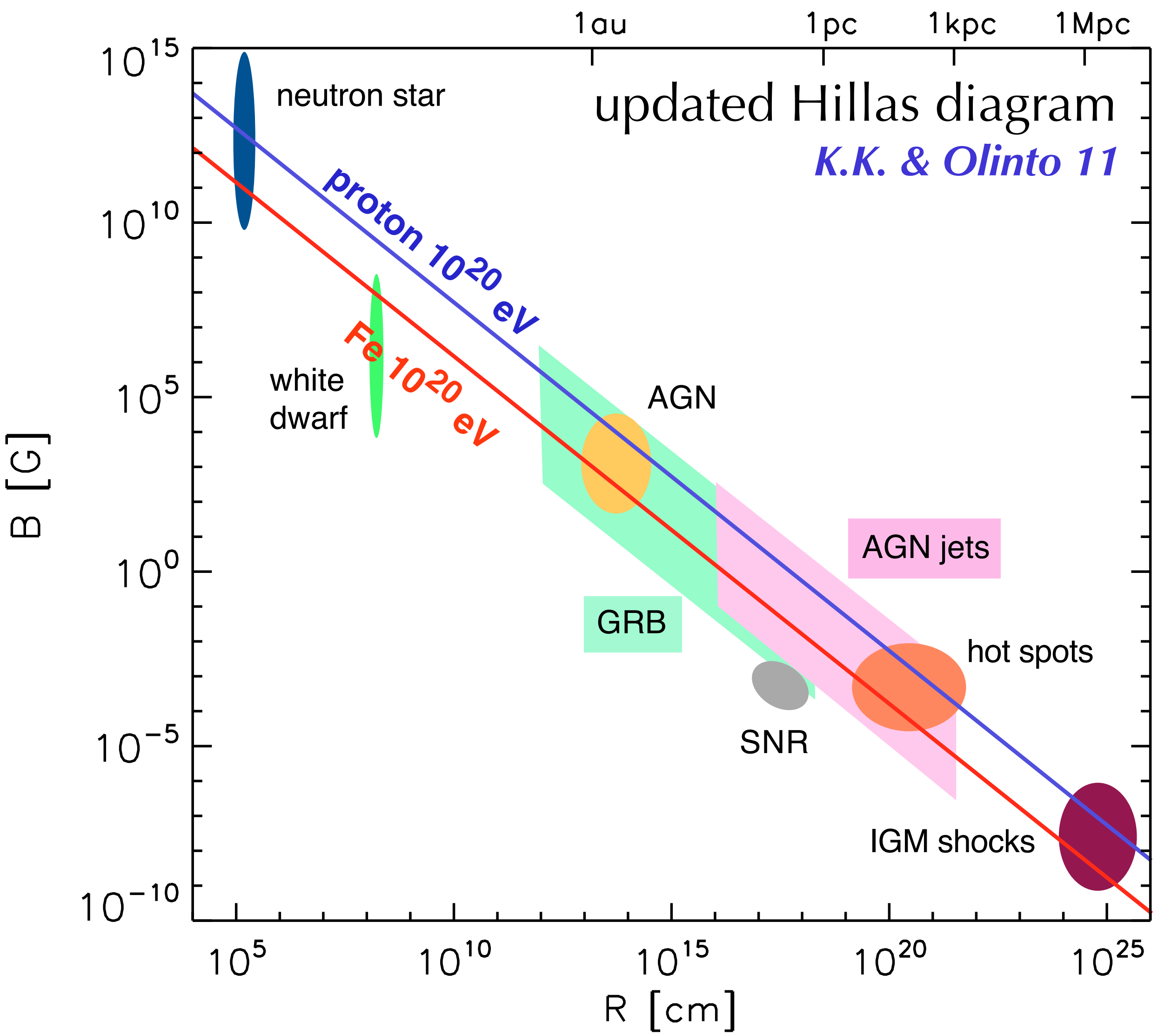

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transient sources

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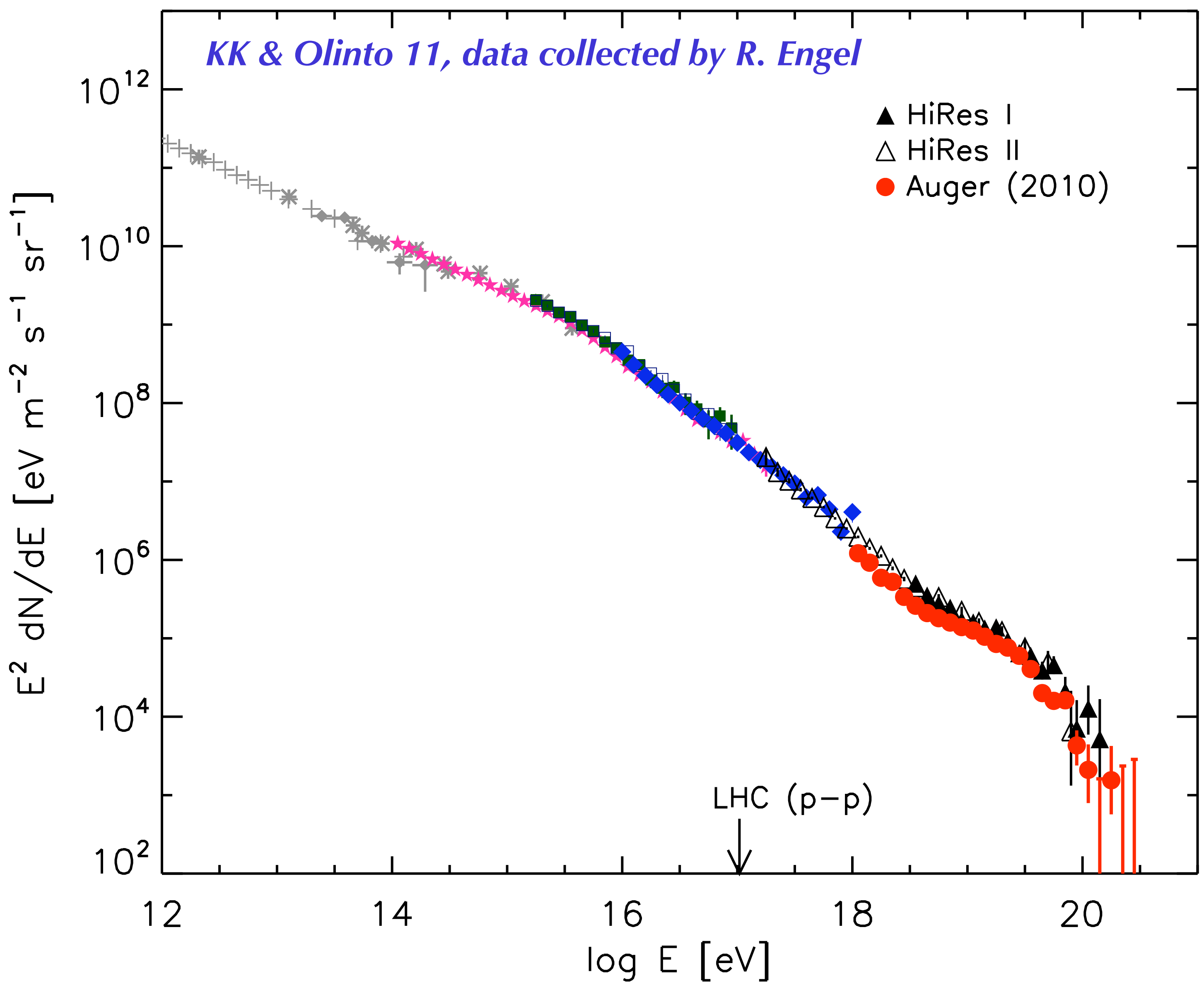
Fang, K.K., Olinto 2012

Crucial information from the energy spectrum



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Hillas criterion *Hillas 84*

necessary magnetic luminosity ($L_B \equiv \varepsilon_B L_{\rm outflow}$):

$L_B > 10^{45.5}$ erg/s Γ^2 β^{-1} *Lemoine & Waxman 09*

for particles with E > E_{GZK} (~6x10^{19}eV)

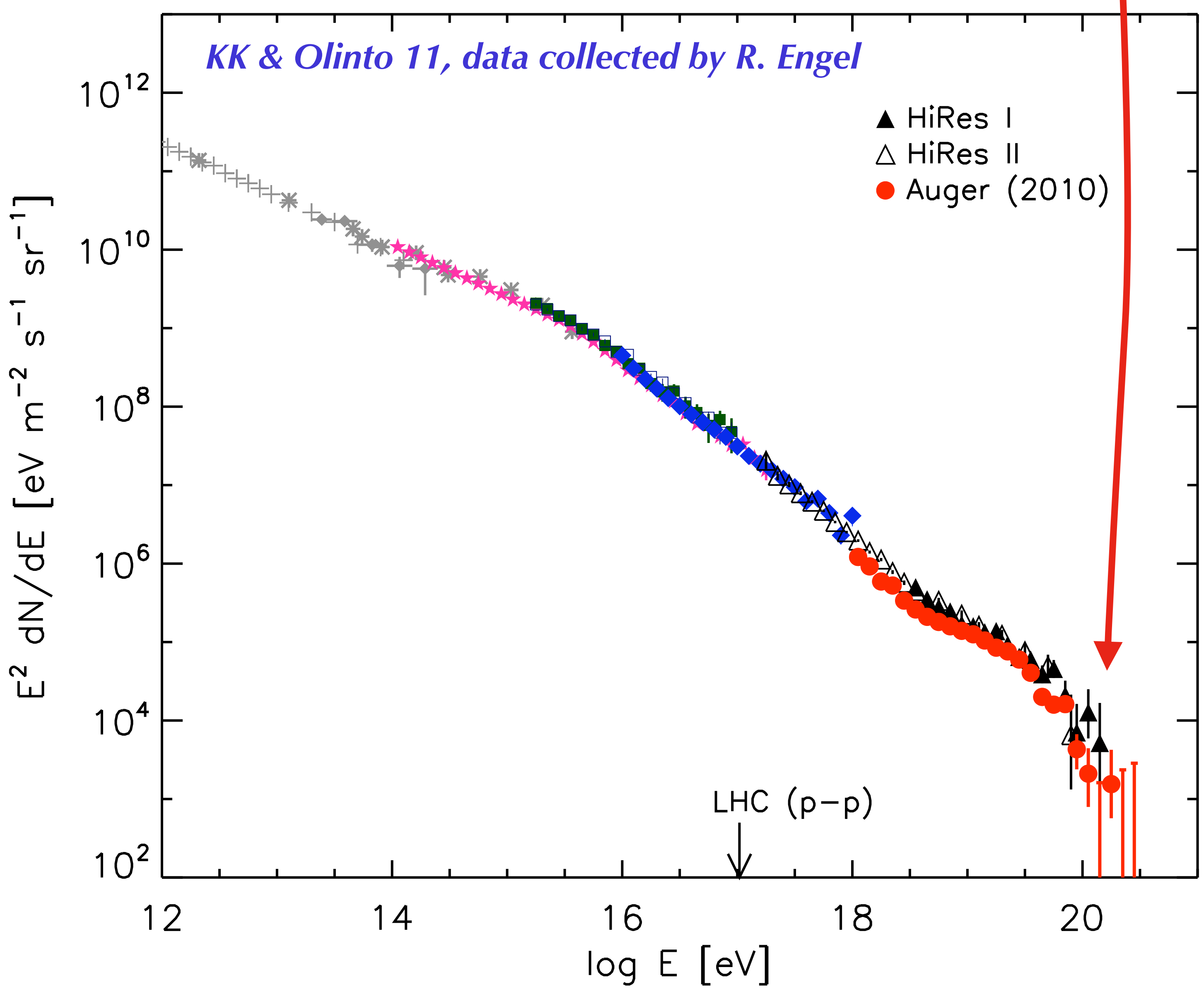
sources within ~ few 100 Mpc

Greisen 1966, Zatsepin & Kuzmin 1966

Crucial information from the energy spectrum

maximum acceleration energy?

or GZK cut-off?



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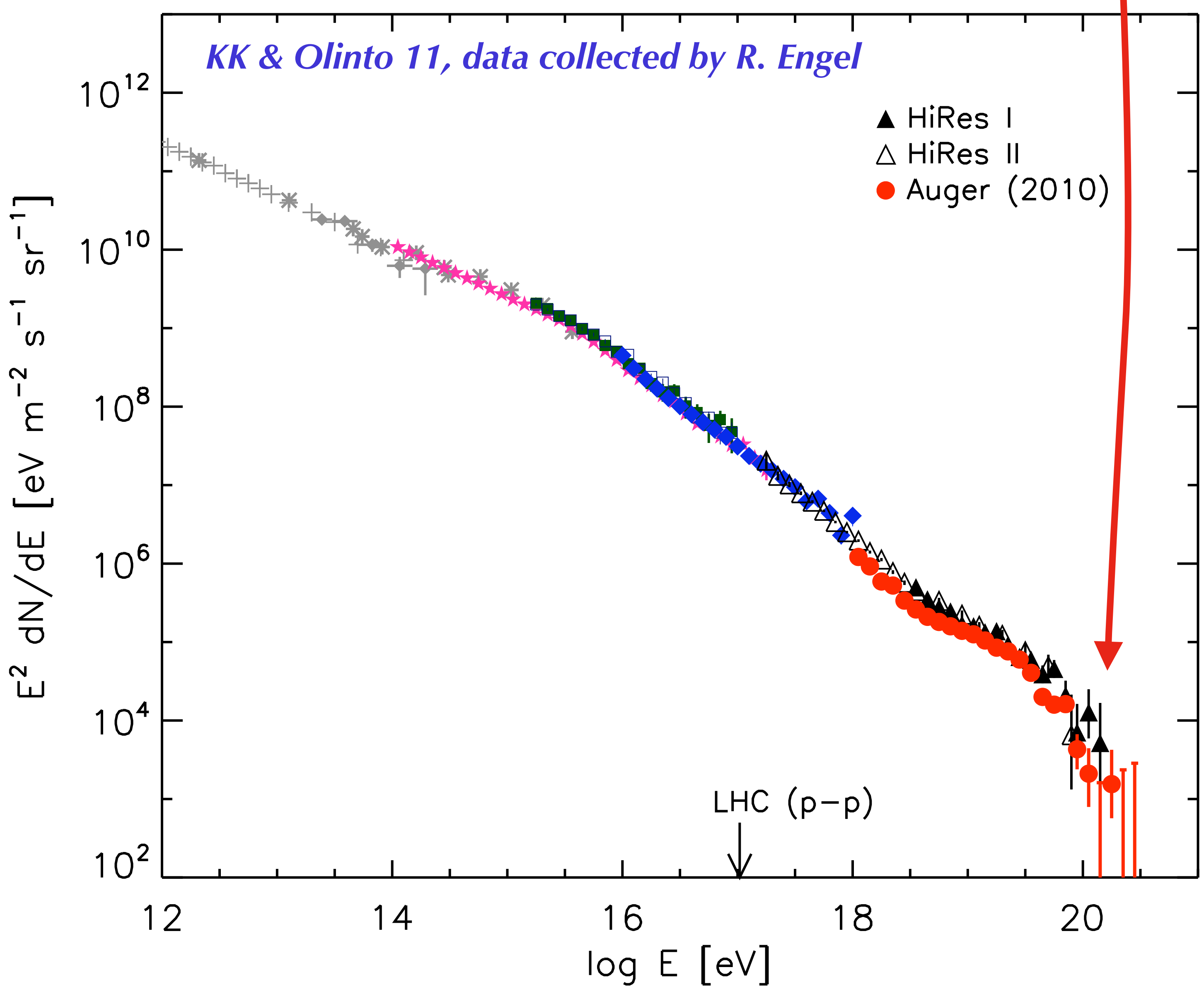

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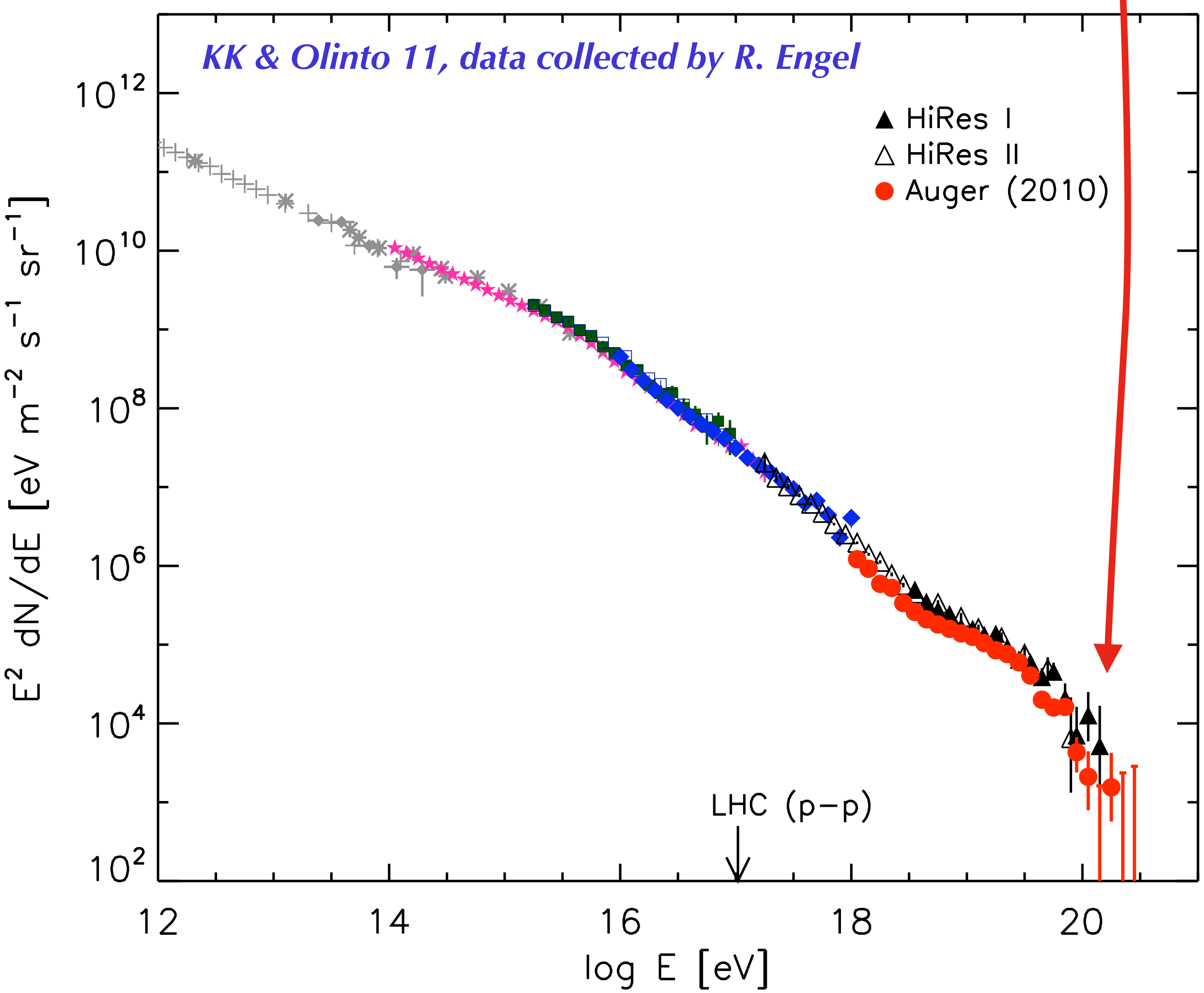

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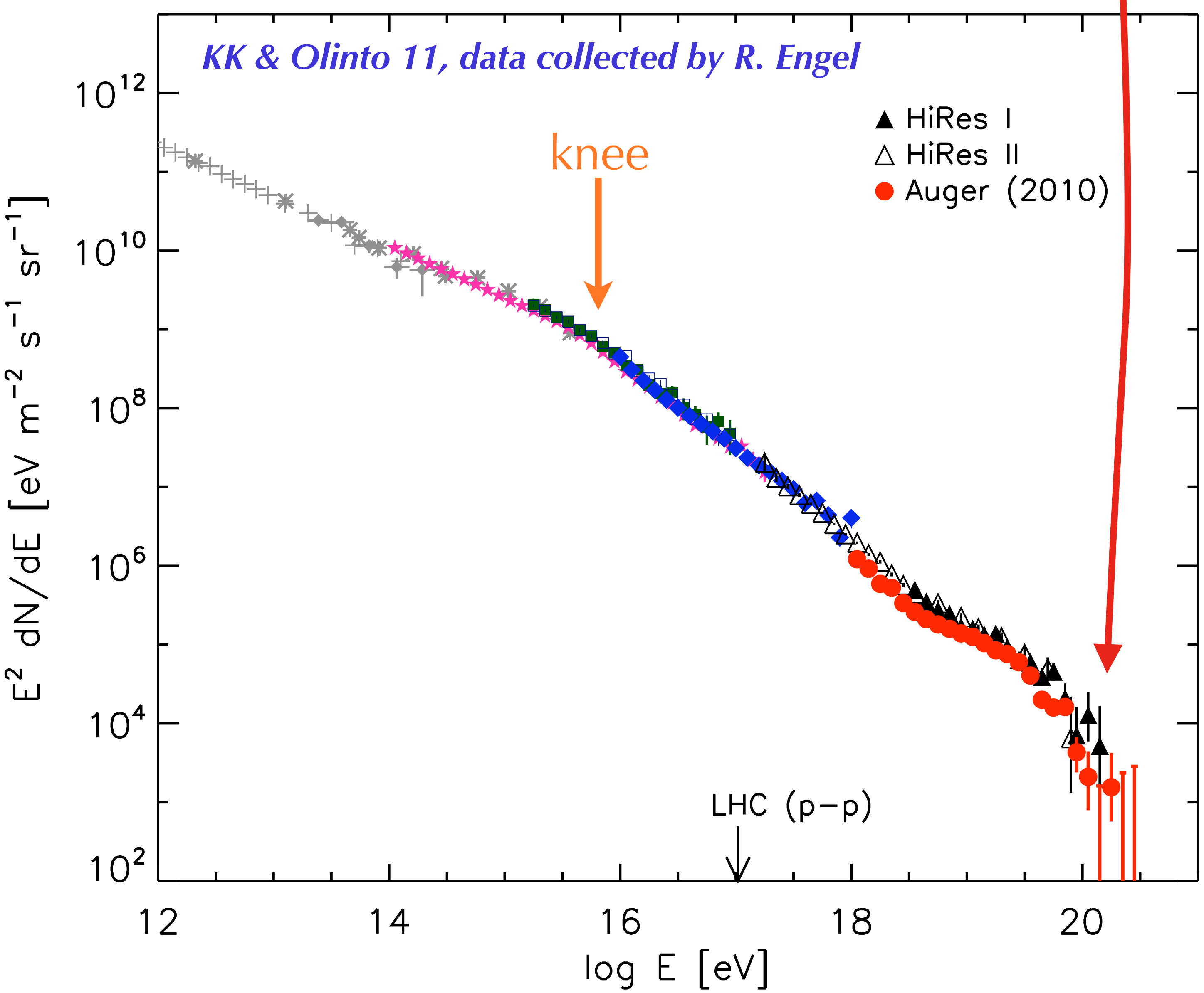

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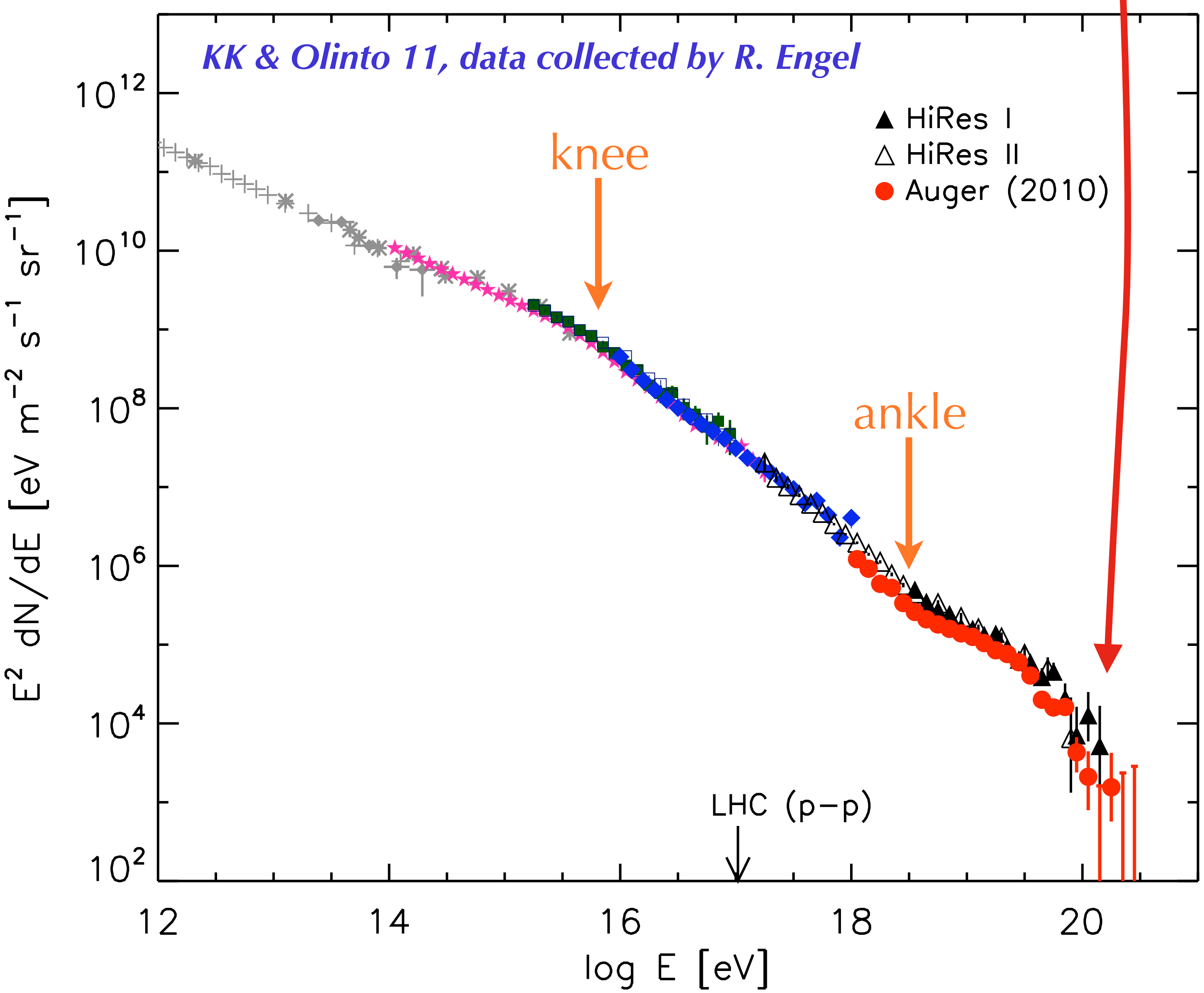

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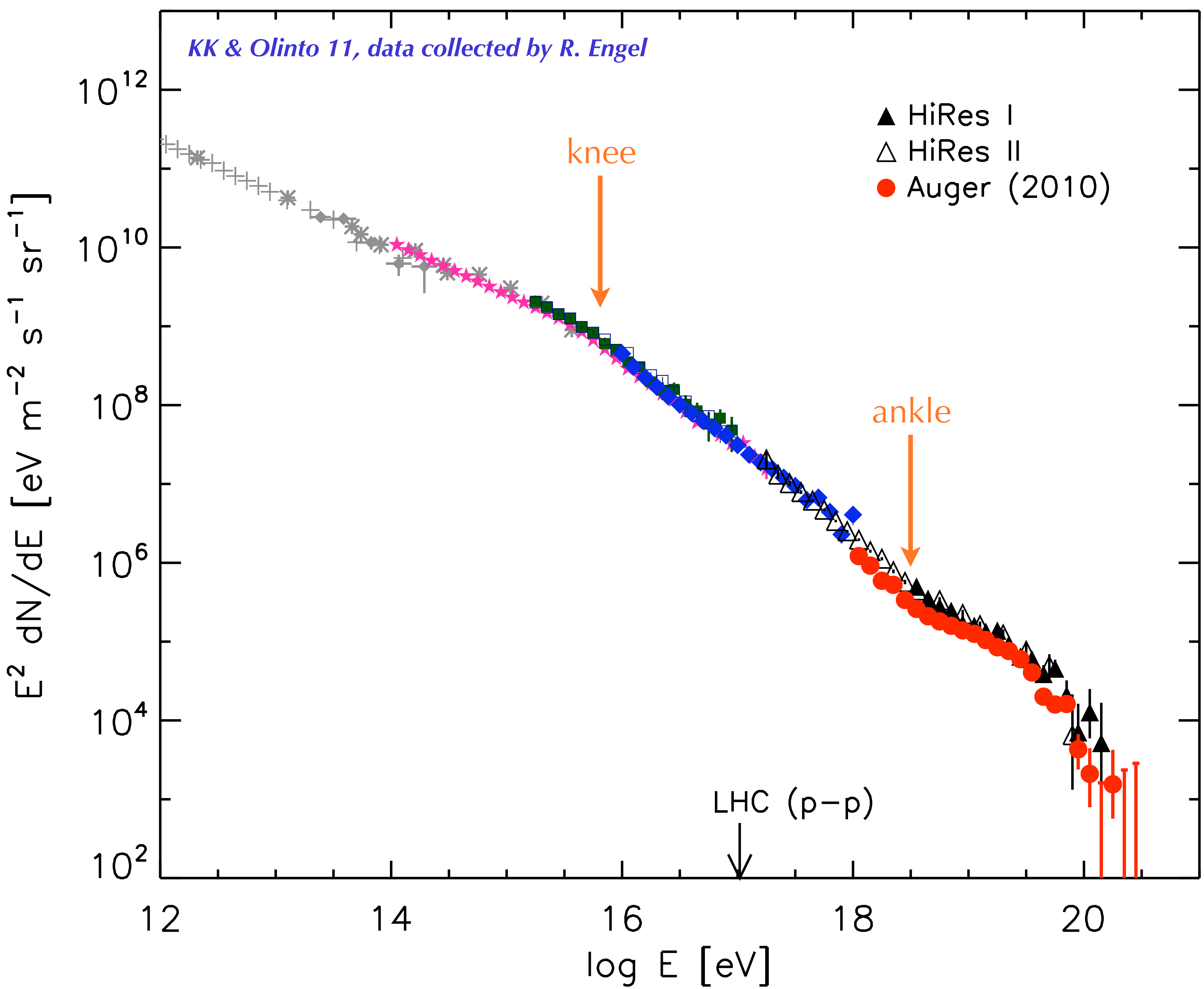

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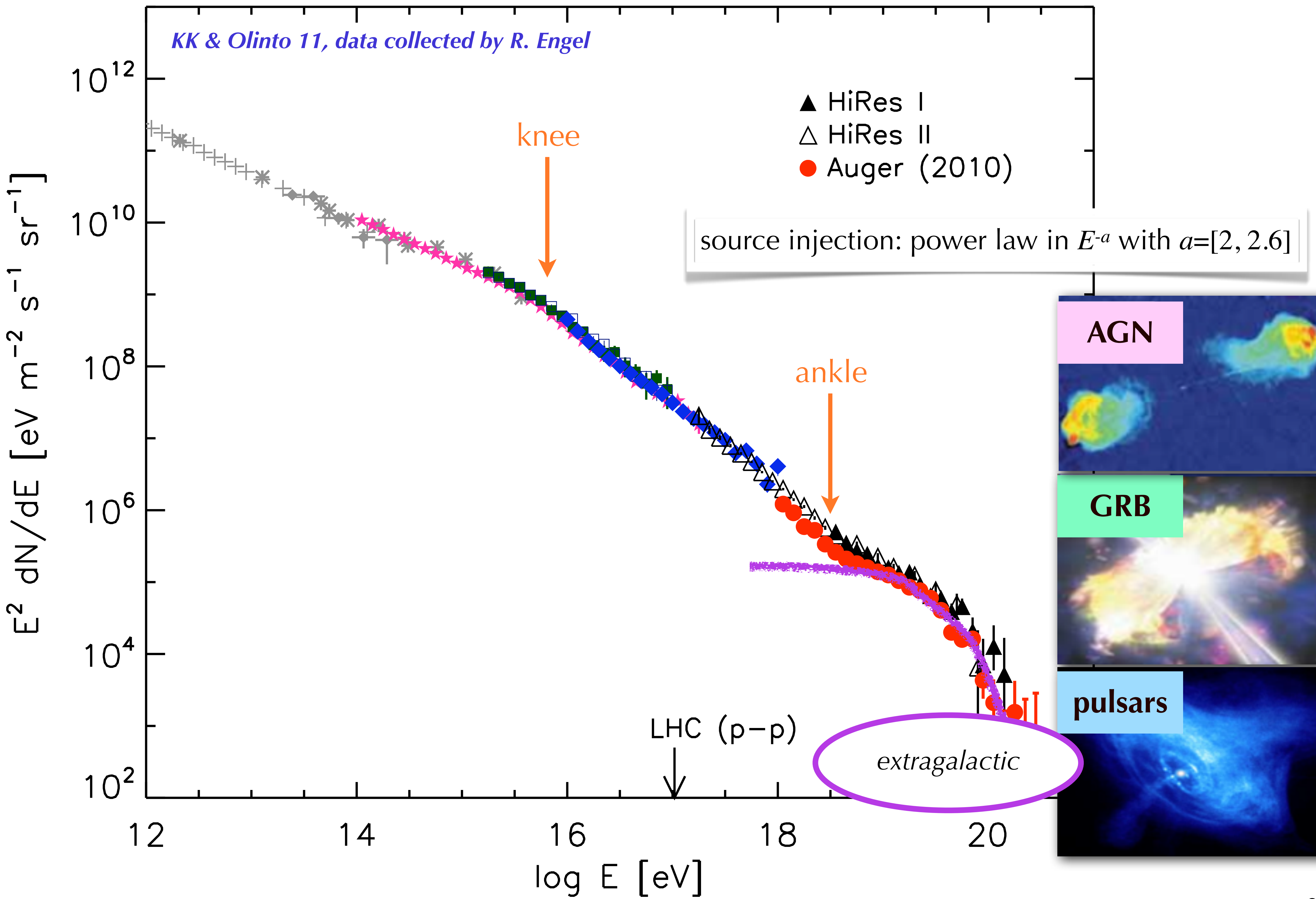

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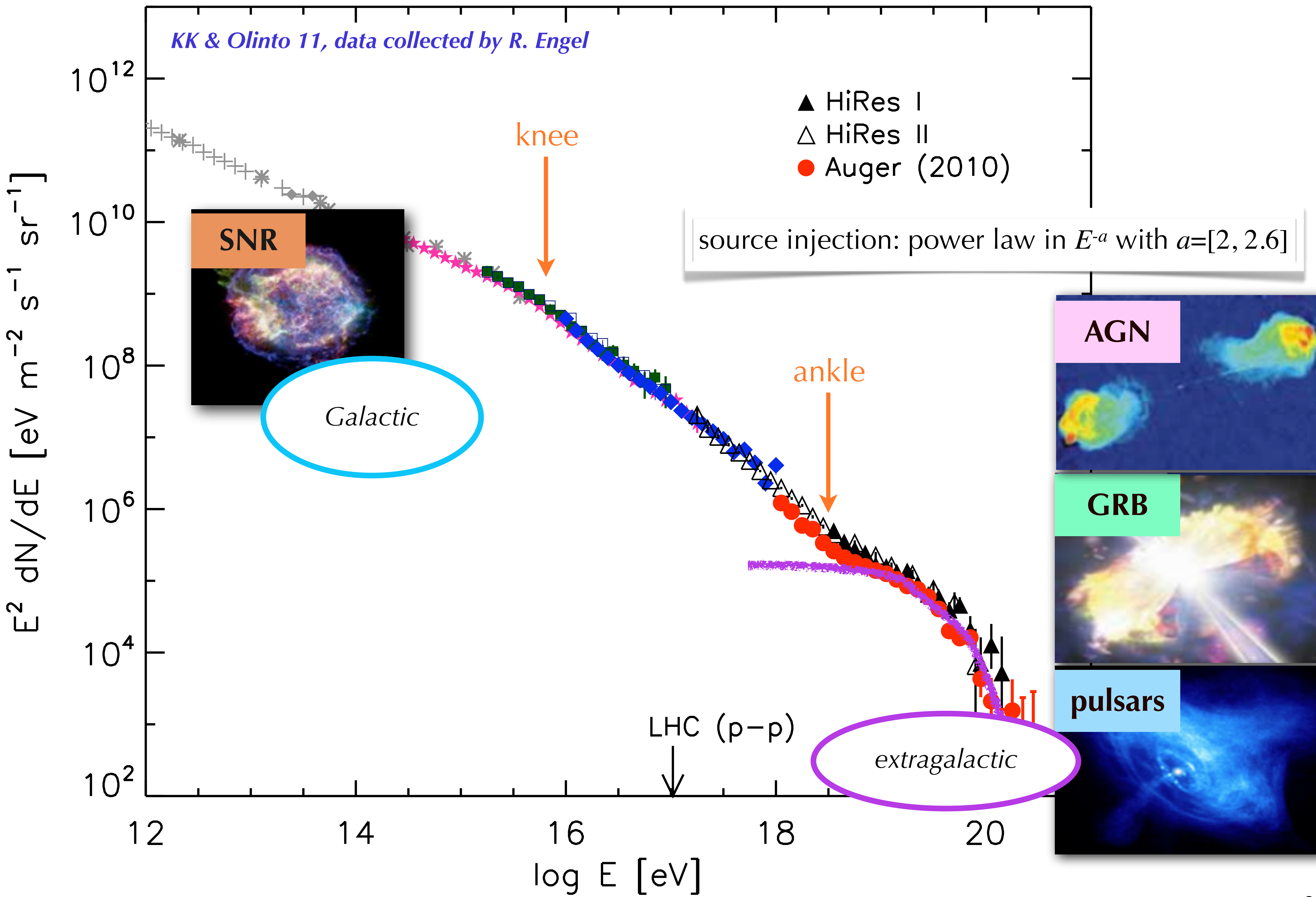

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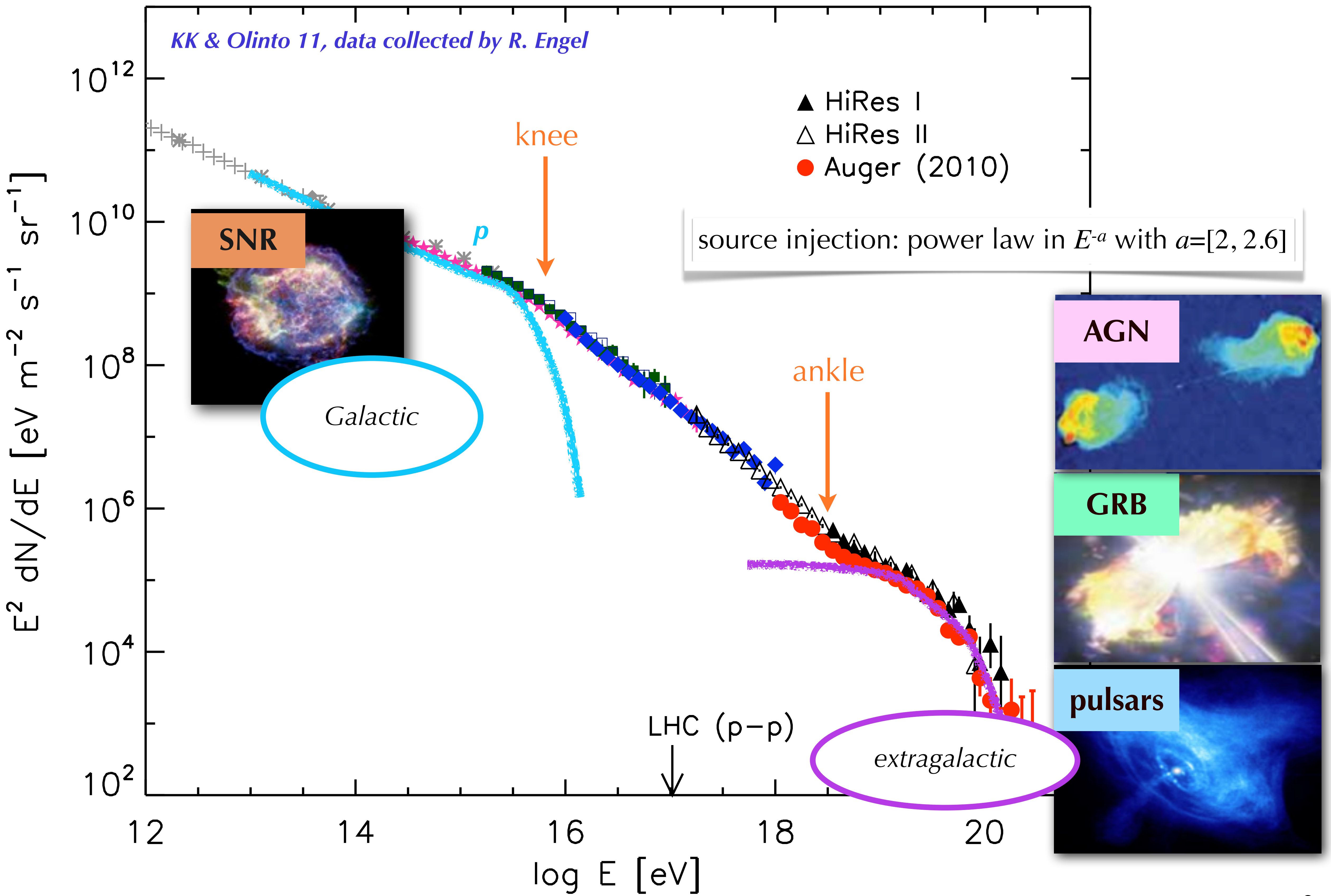

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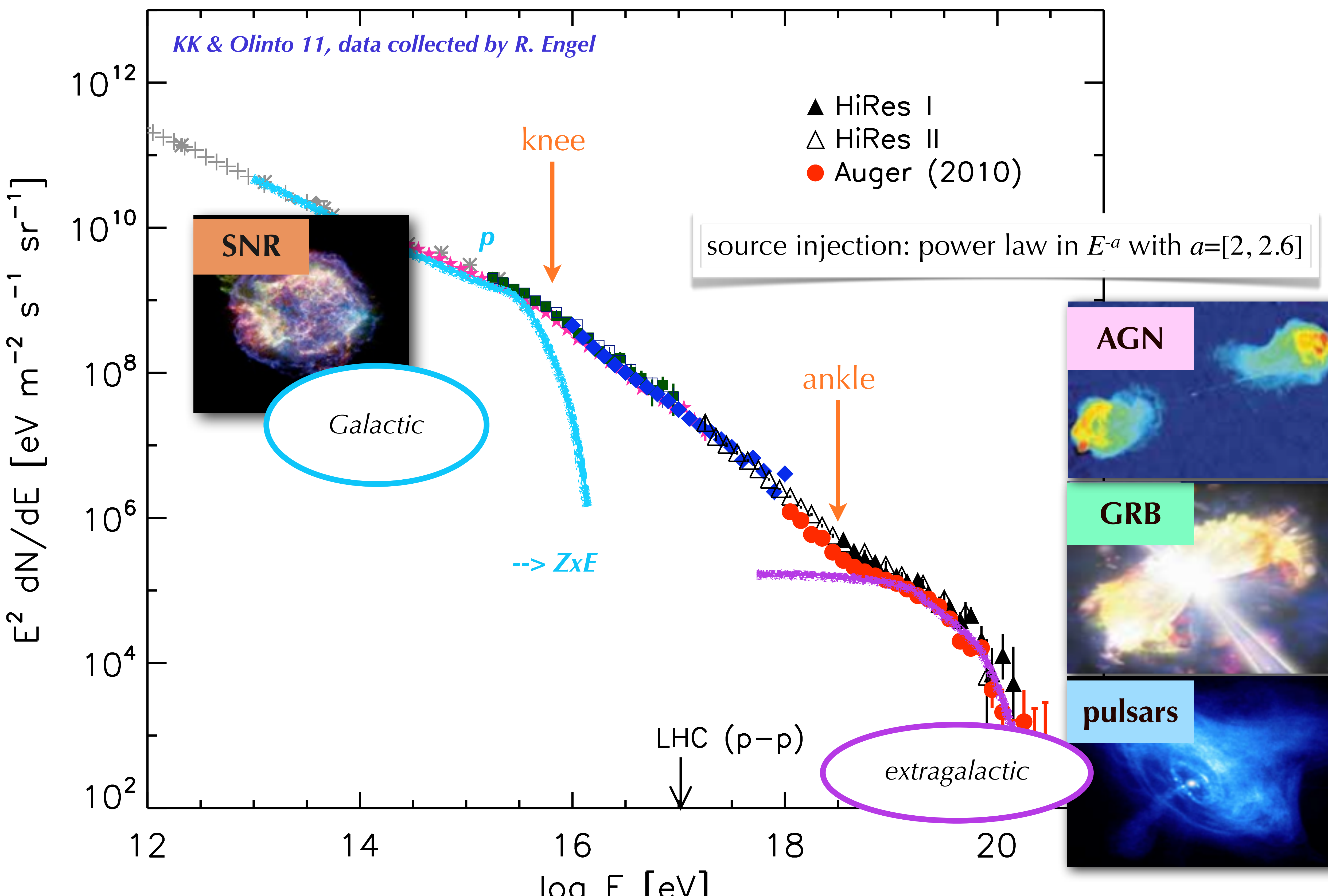

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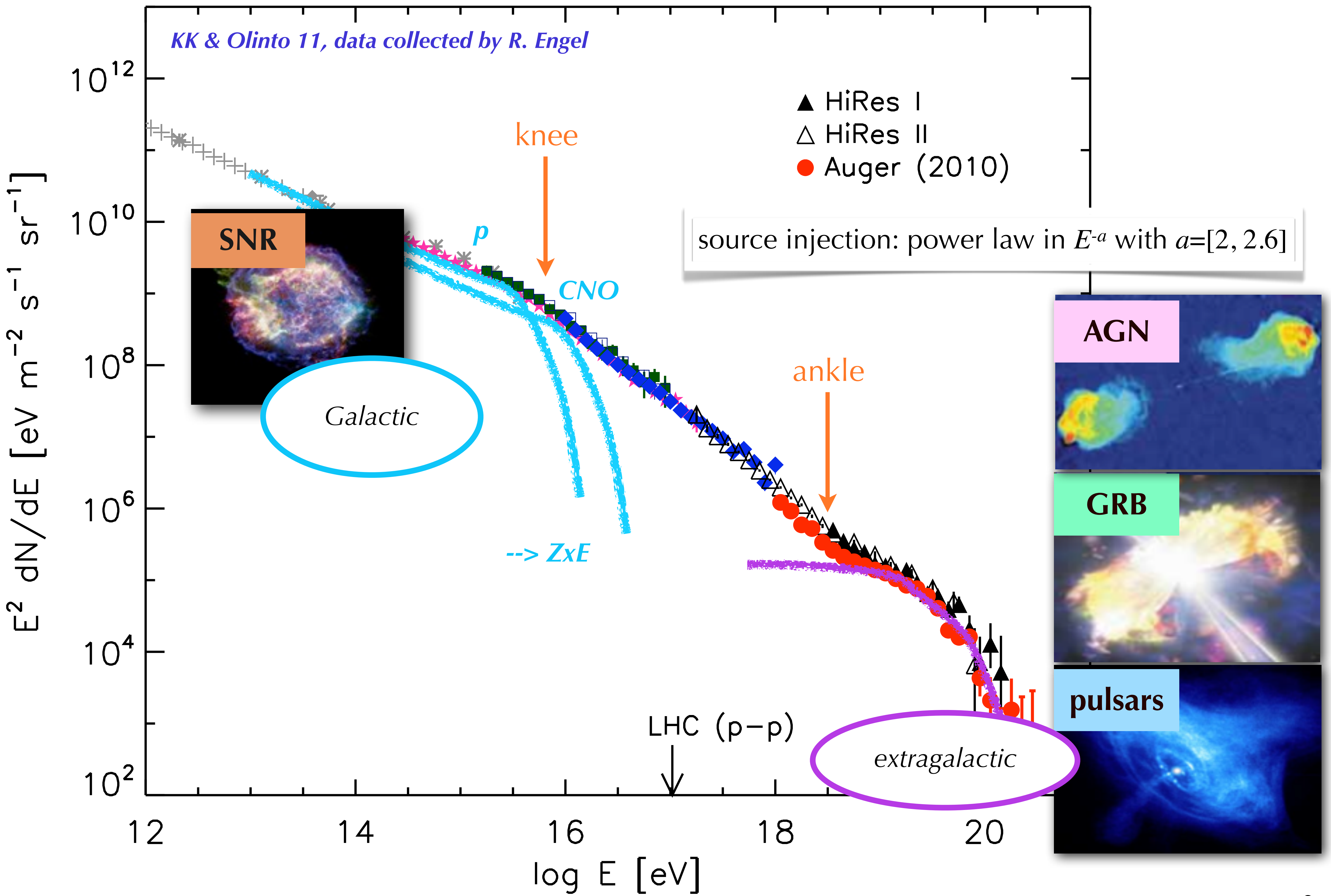

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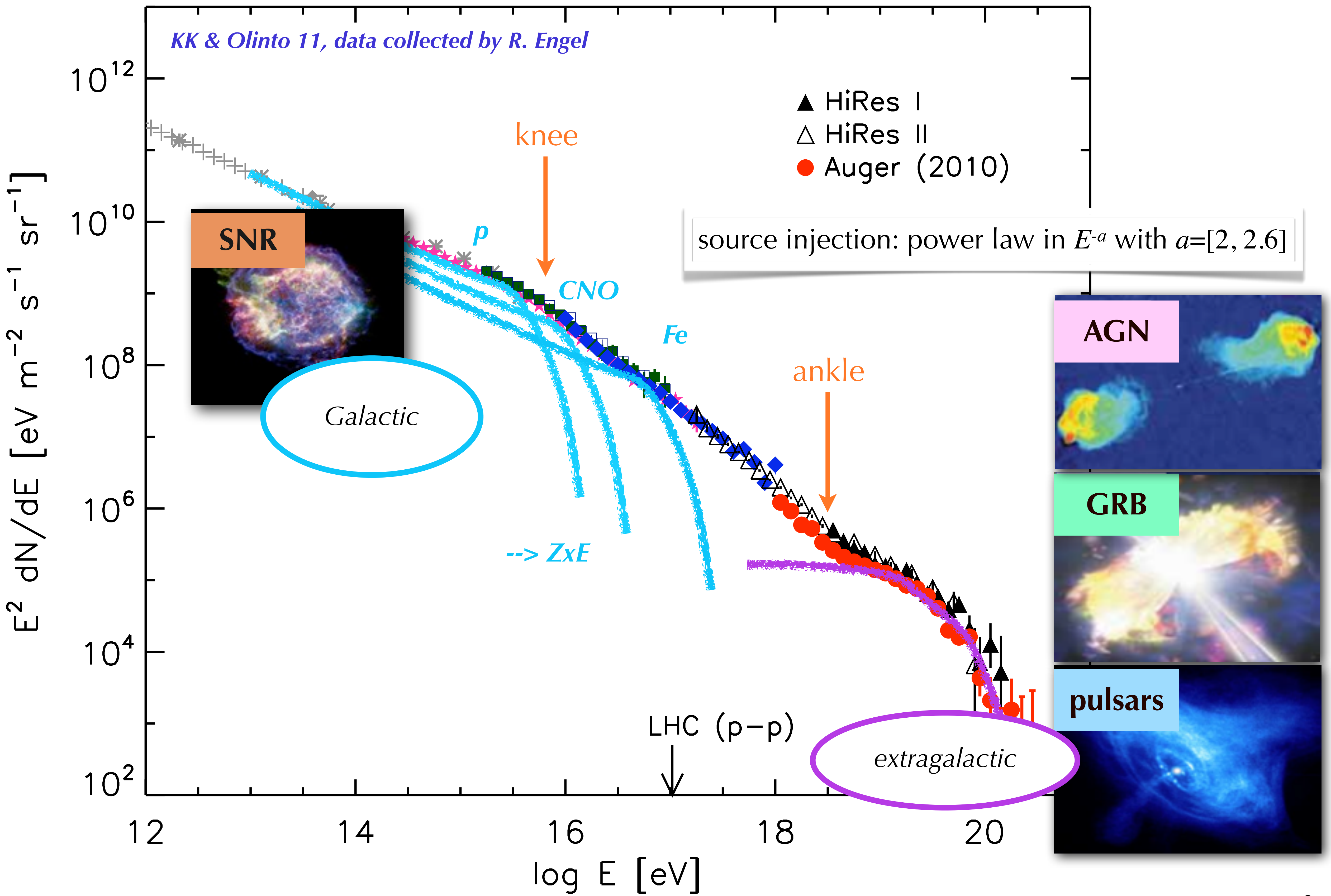

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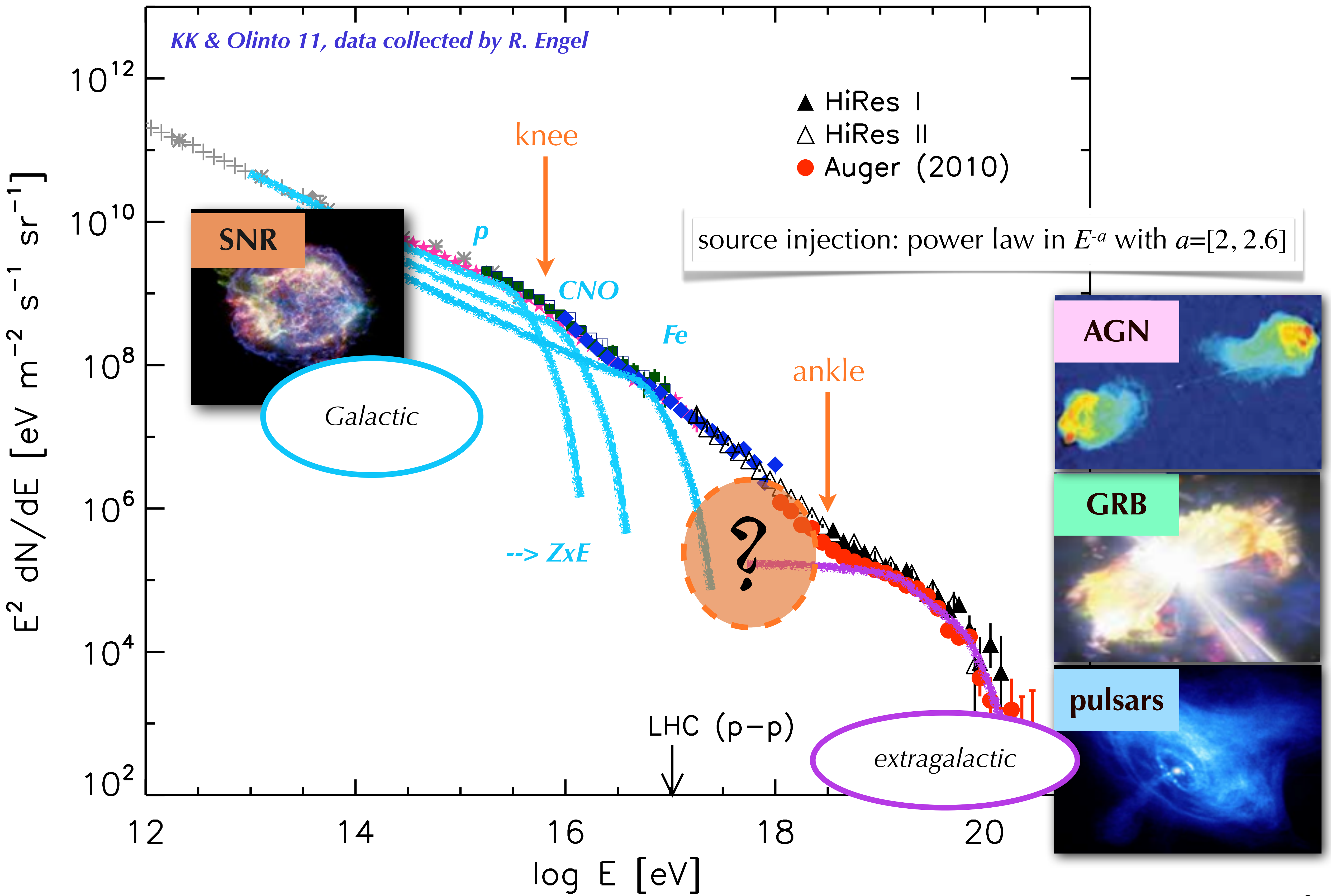

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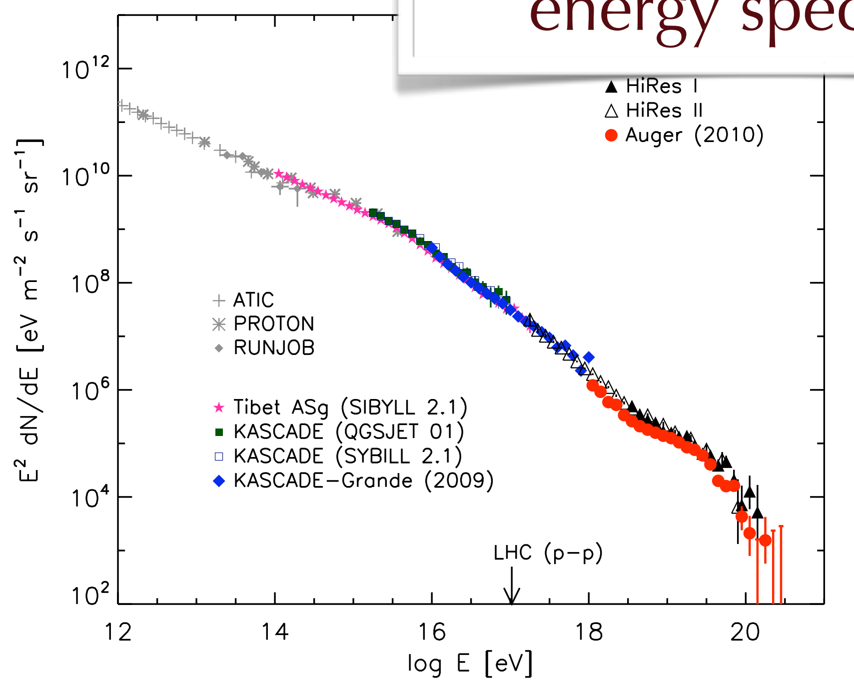
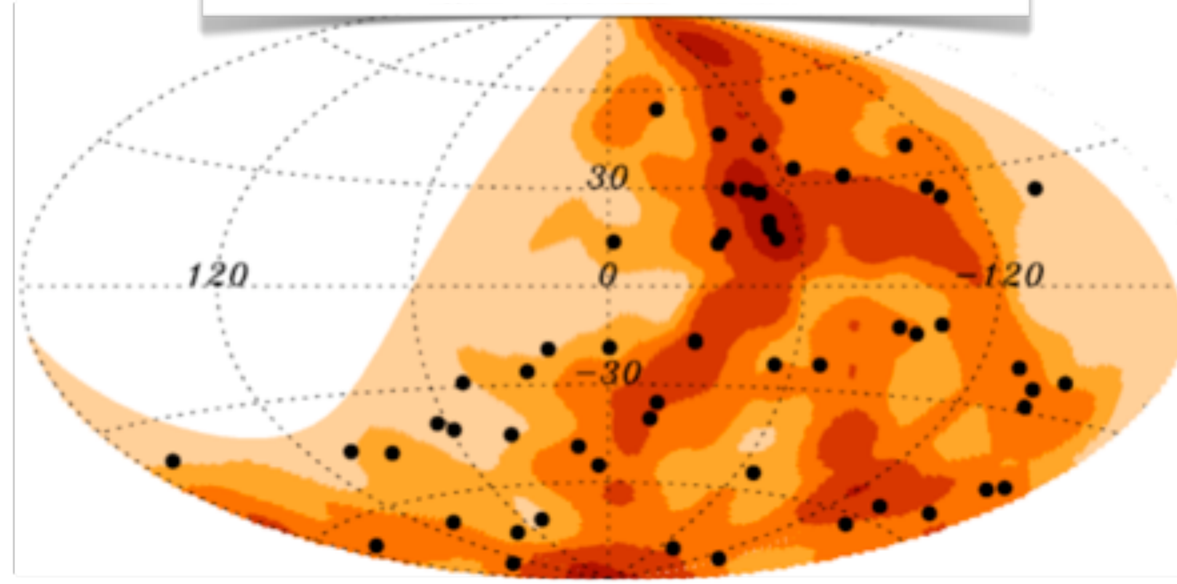
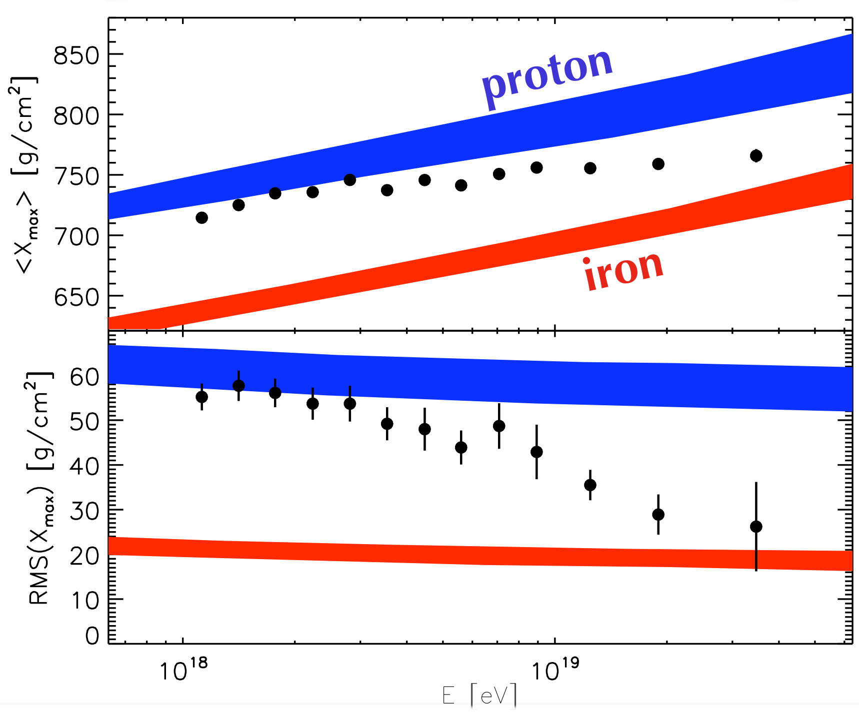


arrival directions in the sky



chemical composition



other messengers:
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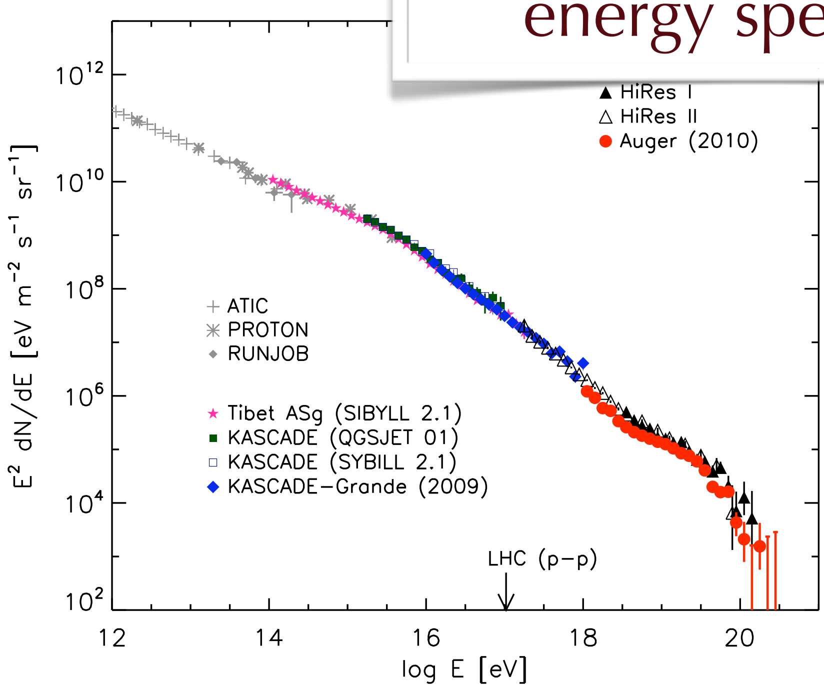

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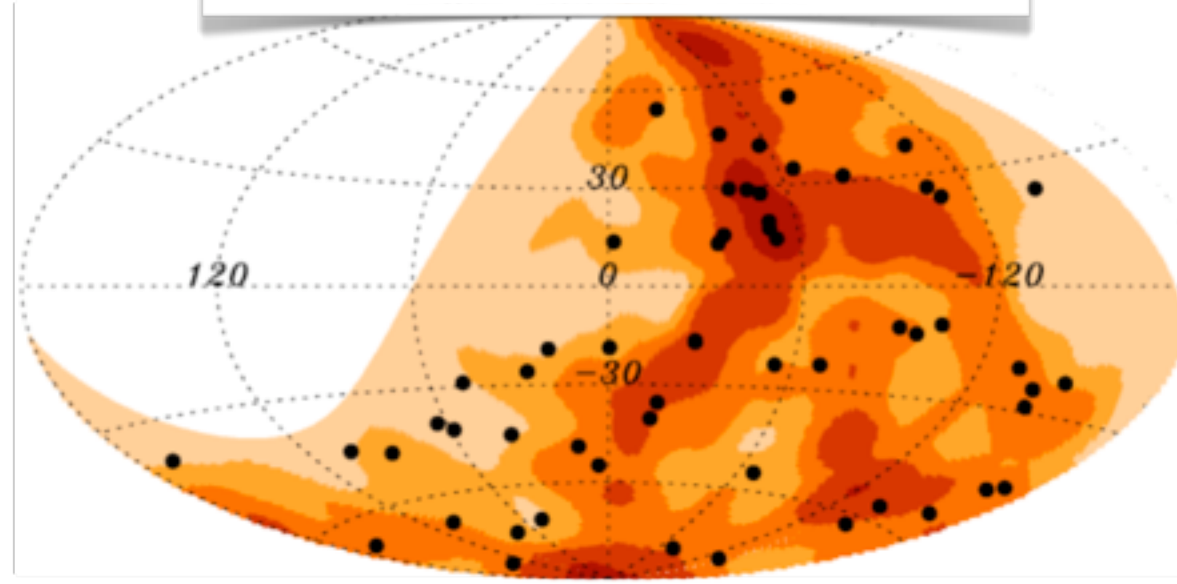

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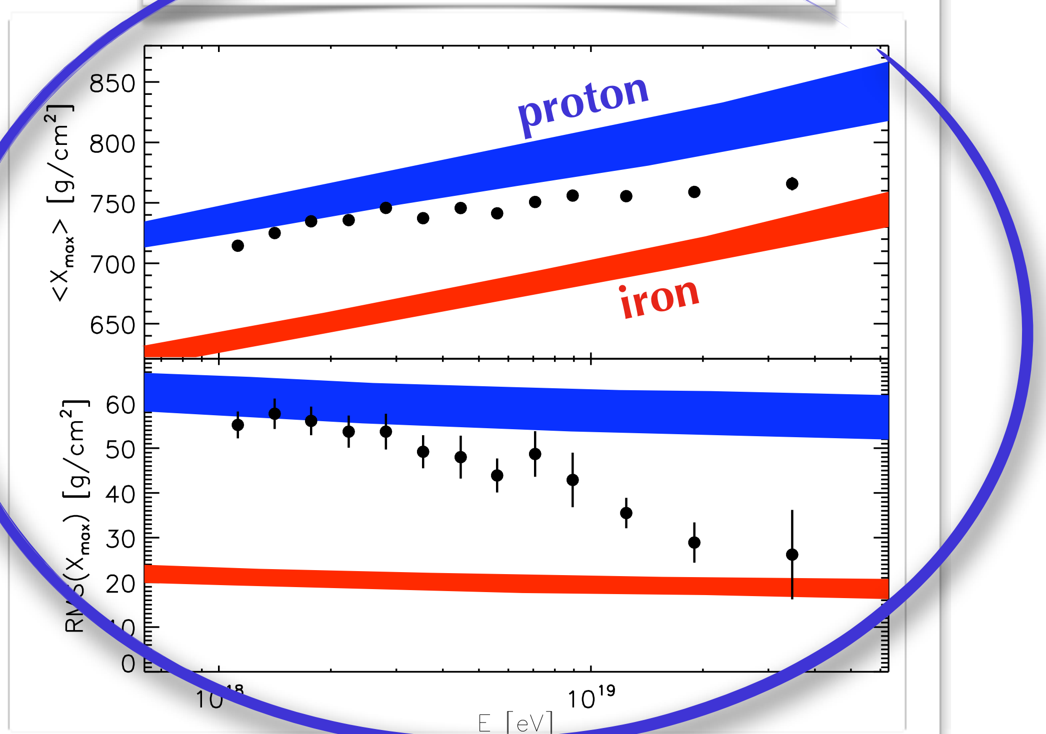

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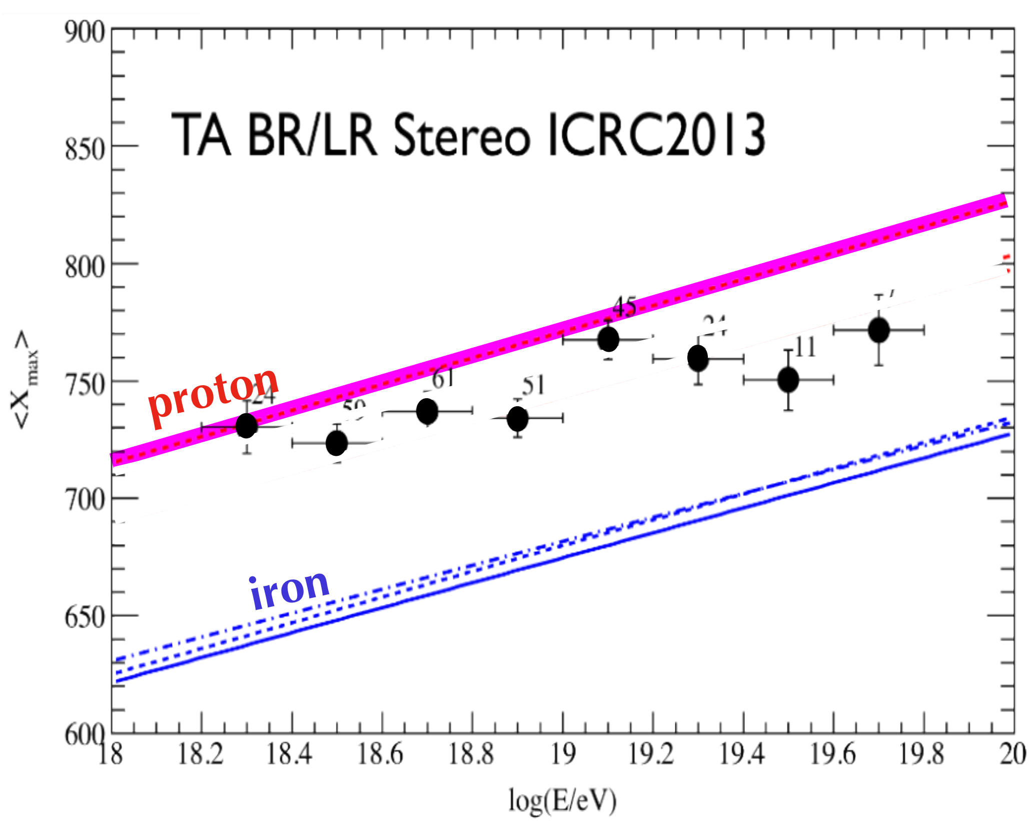
Puzzling composition measurements at UHE

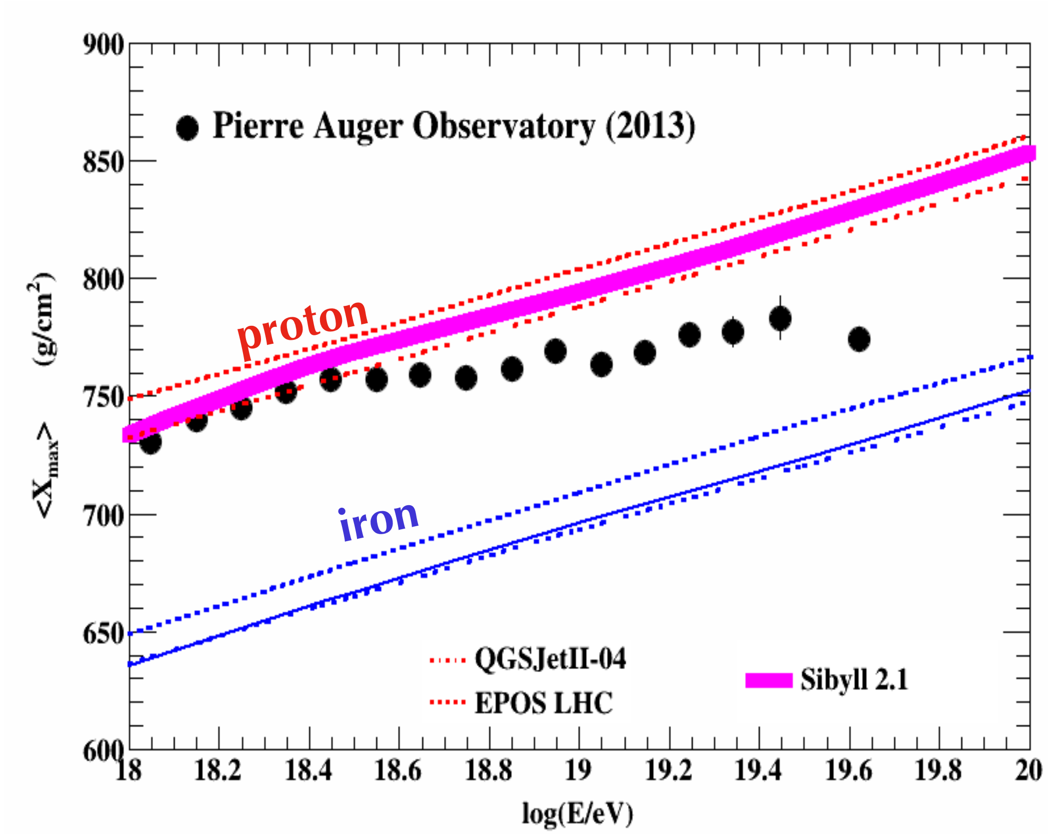
T. Pierog (KIT), MACROS workshop, IAP Nov. 2013

Air Showers | Post-LHC Models | PAO vs TA Composition

PAO vs TA after LHC

- **Composition with TA and PAO are similar**
  - ➡ light composition below the Ankle
  - ➡ change toward heavier composition above the Ankle





heavy transition around 10^{19} eV

T. Pierog (KIT), MACROS workshop, IAP Nov. 2013

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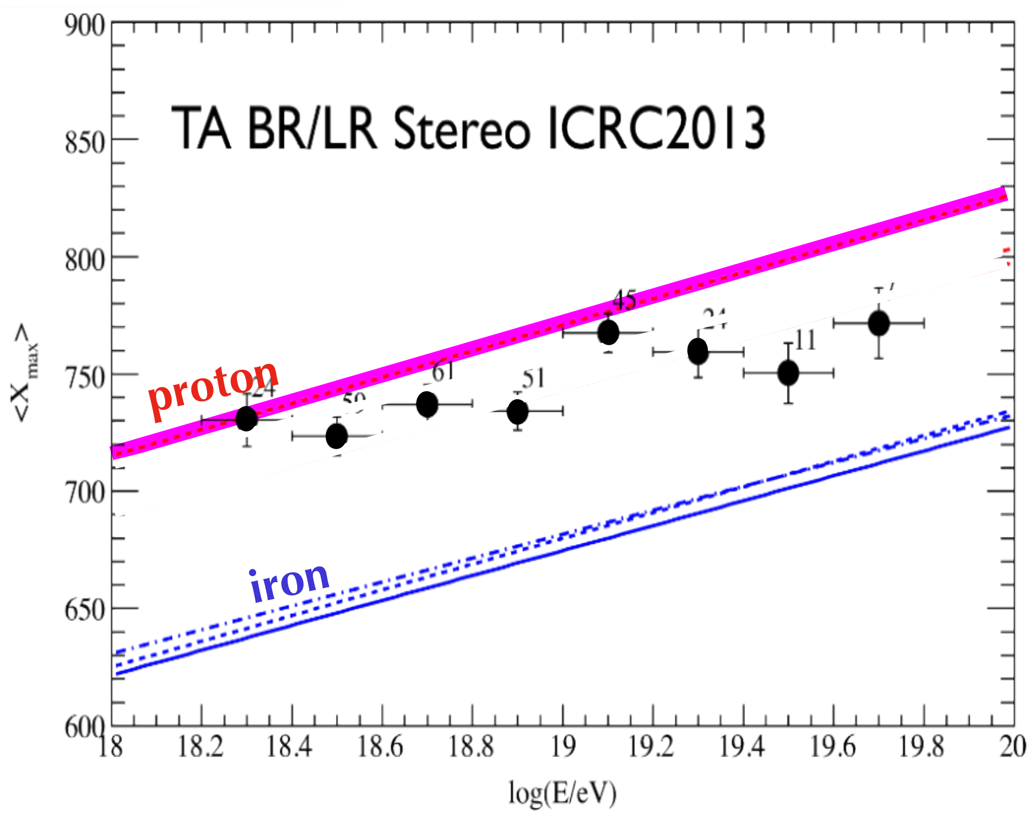
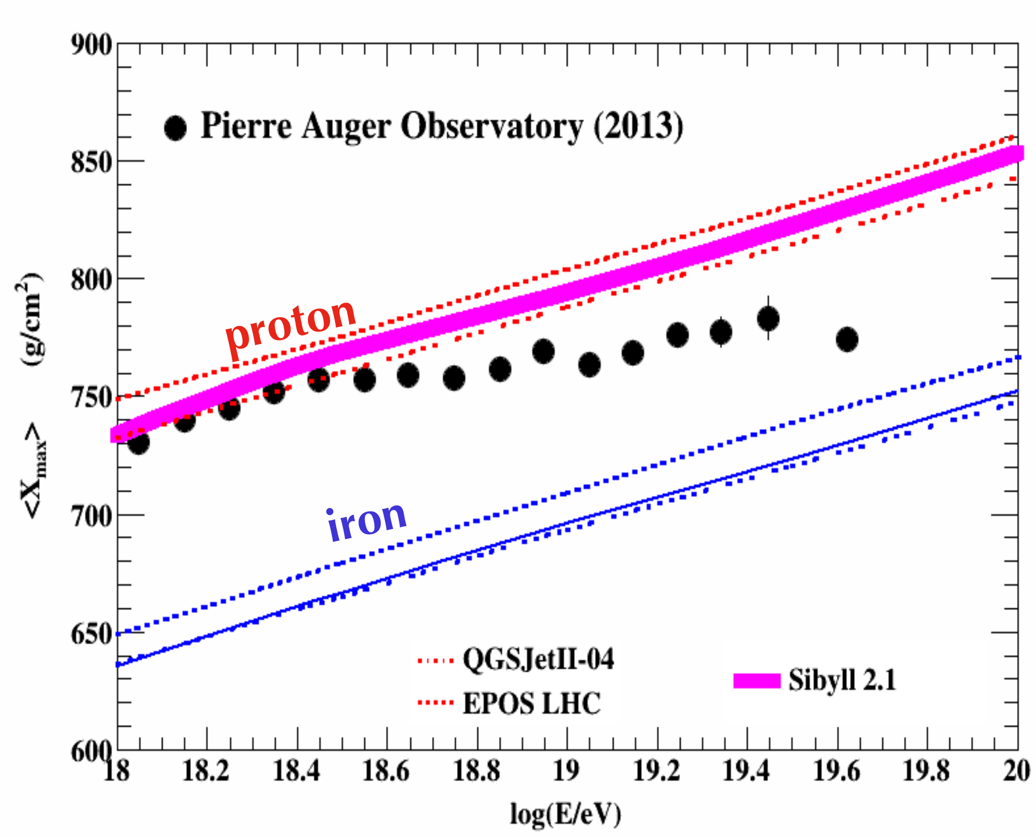
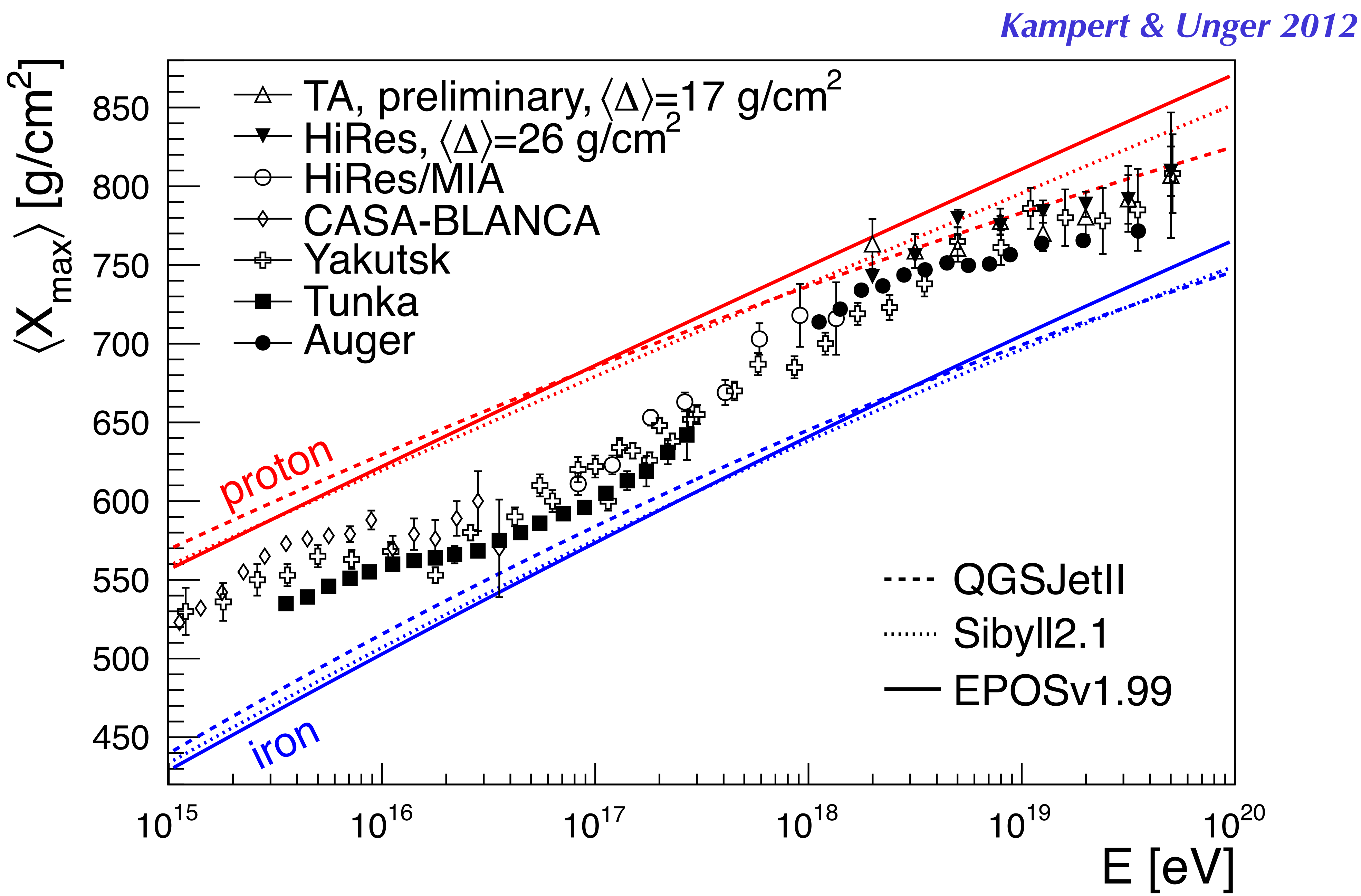




Clearer composition measurements at $10^{15\text{-}19}$ eV



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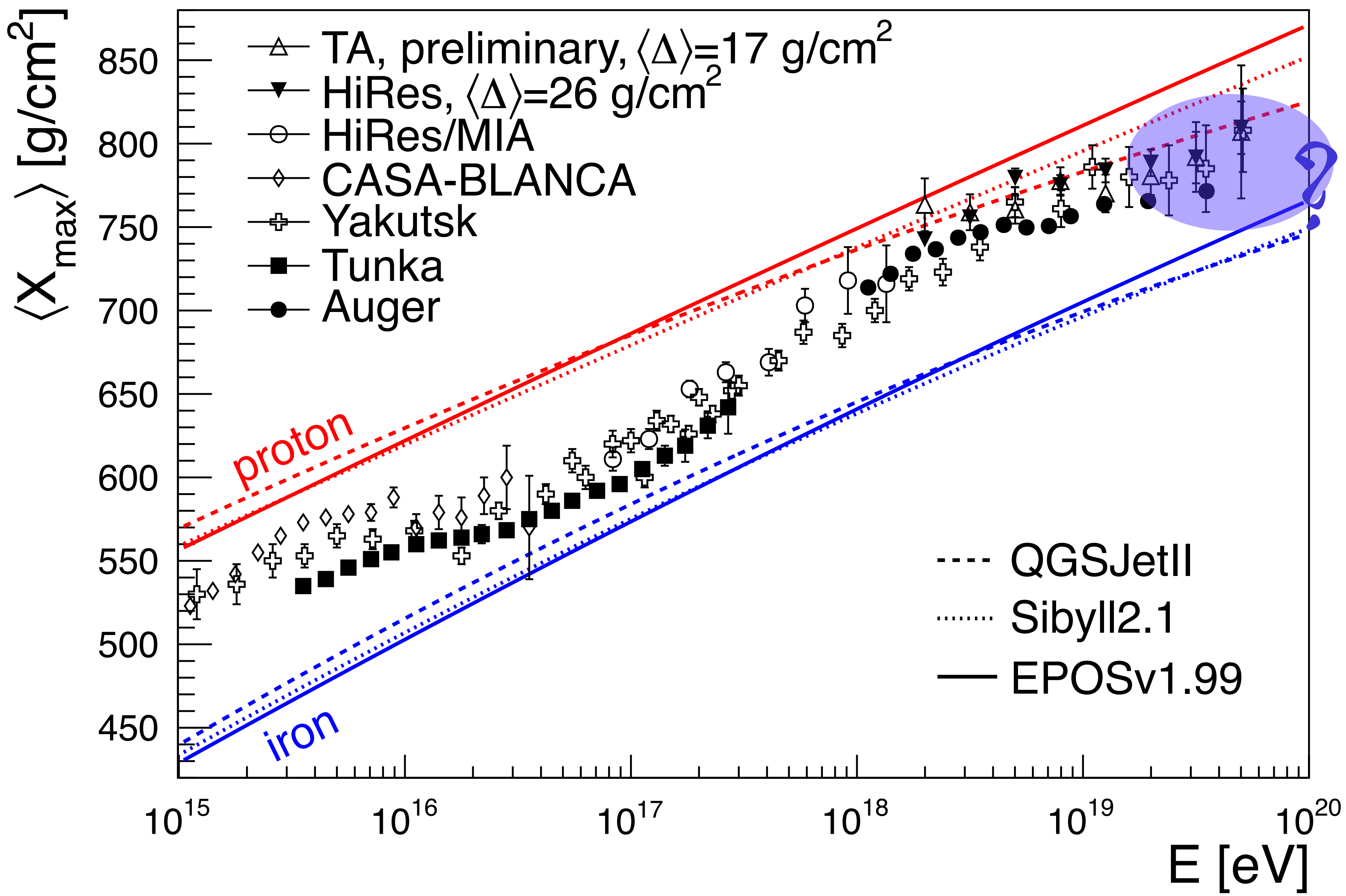
Kampert & Unger 2012



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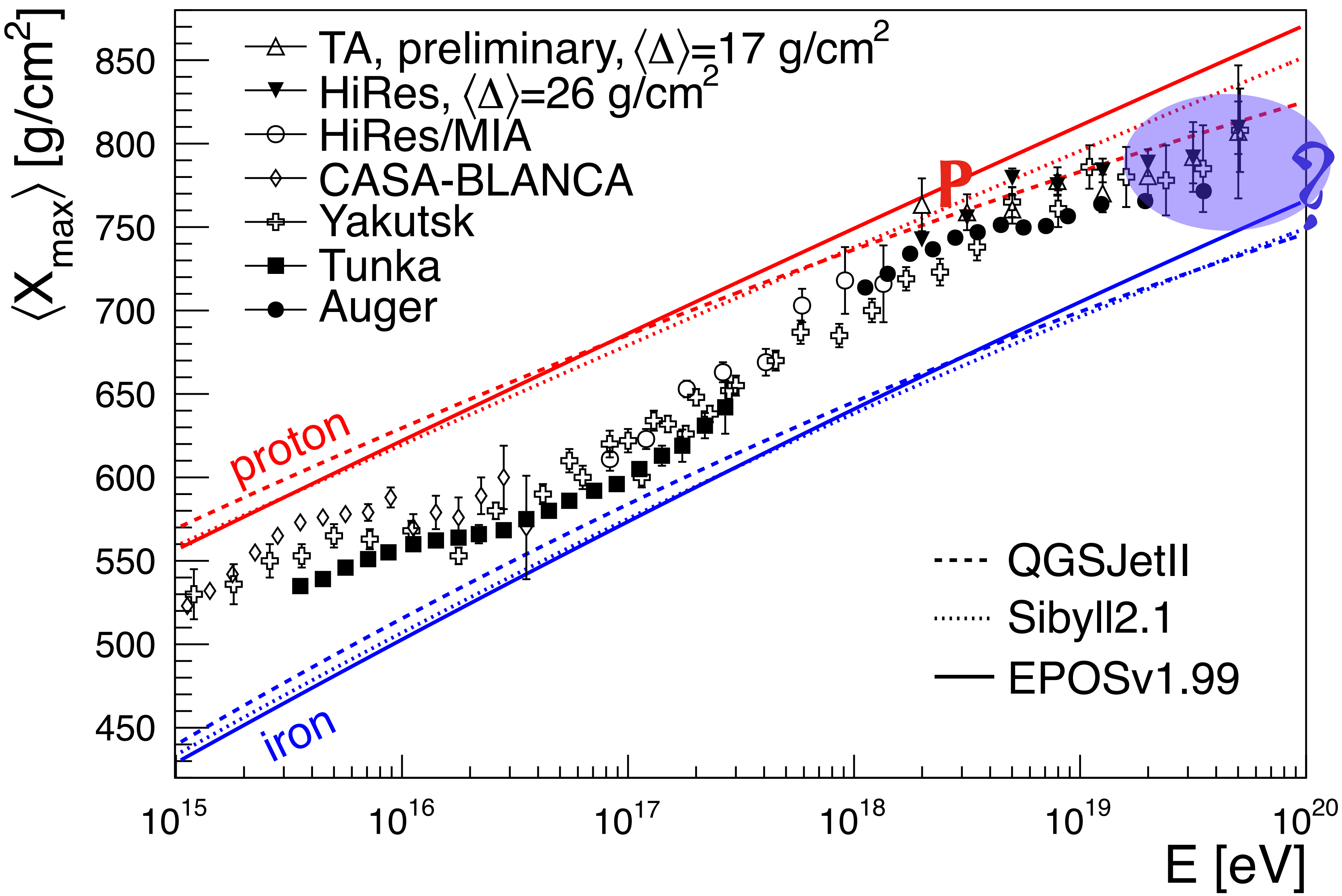

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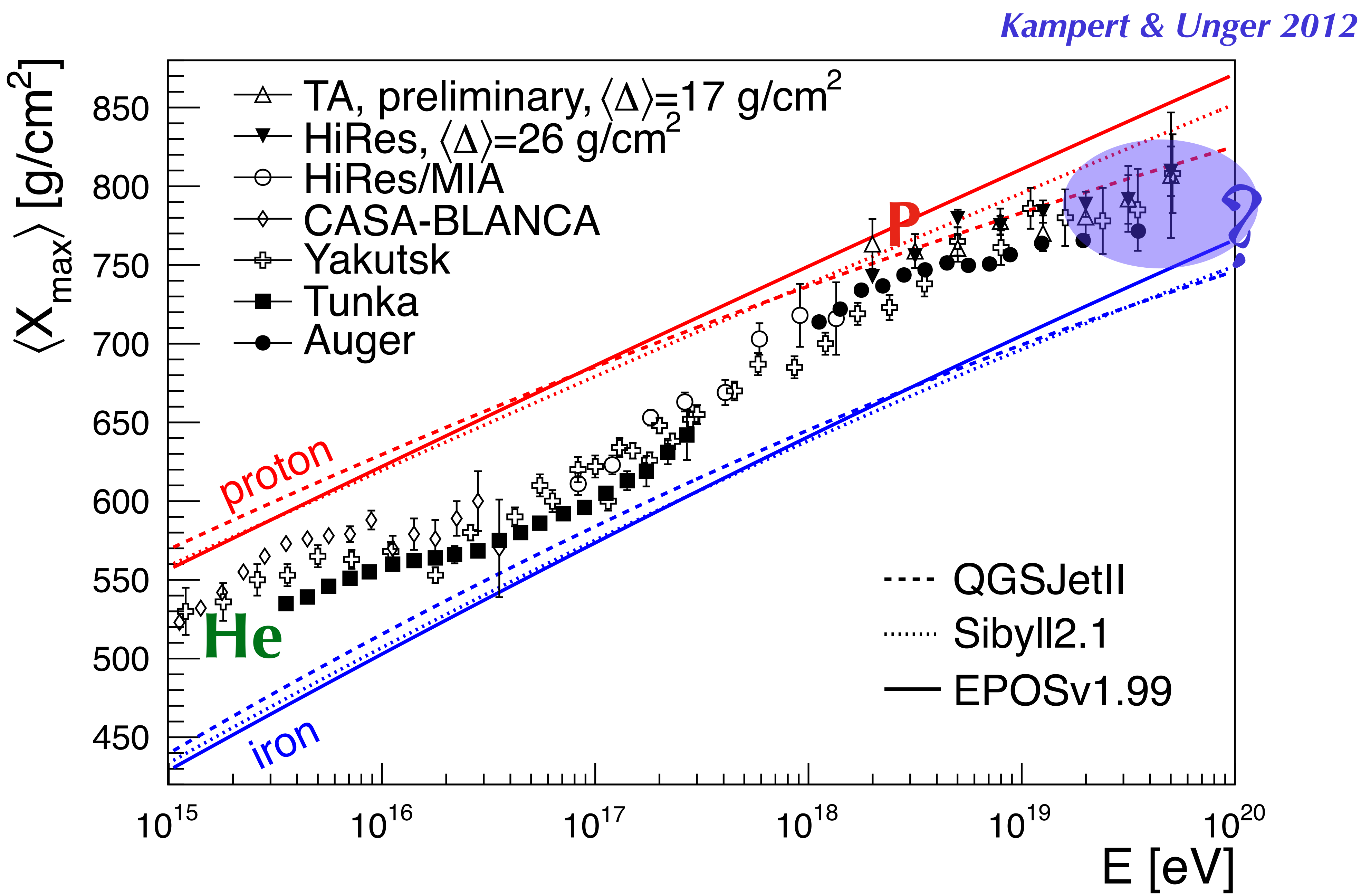

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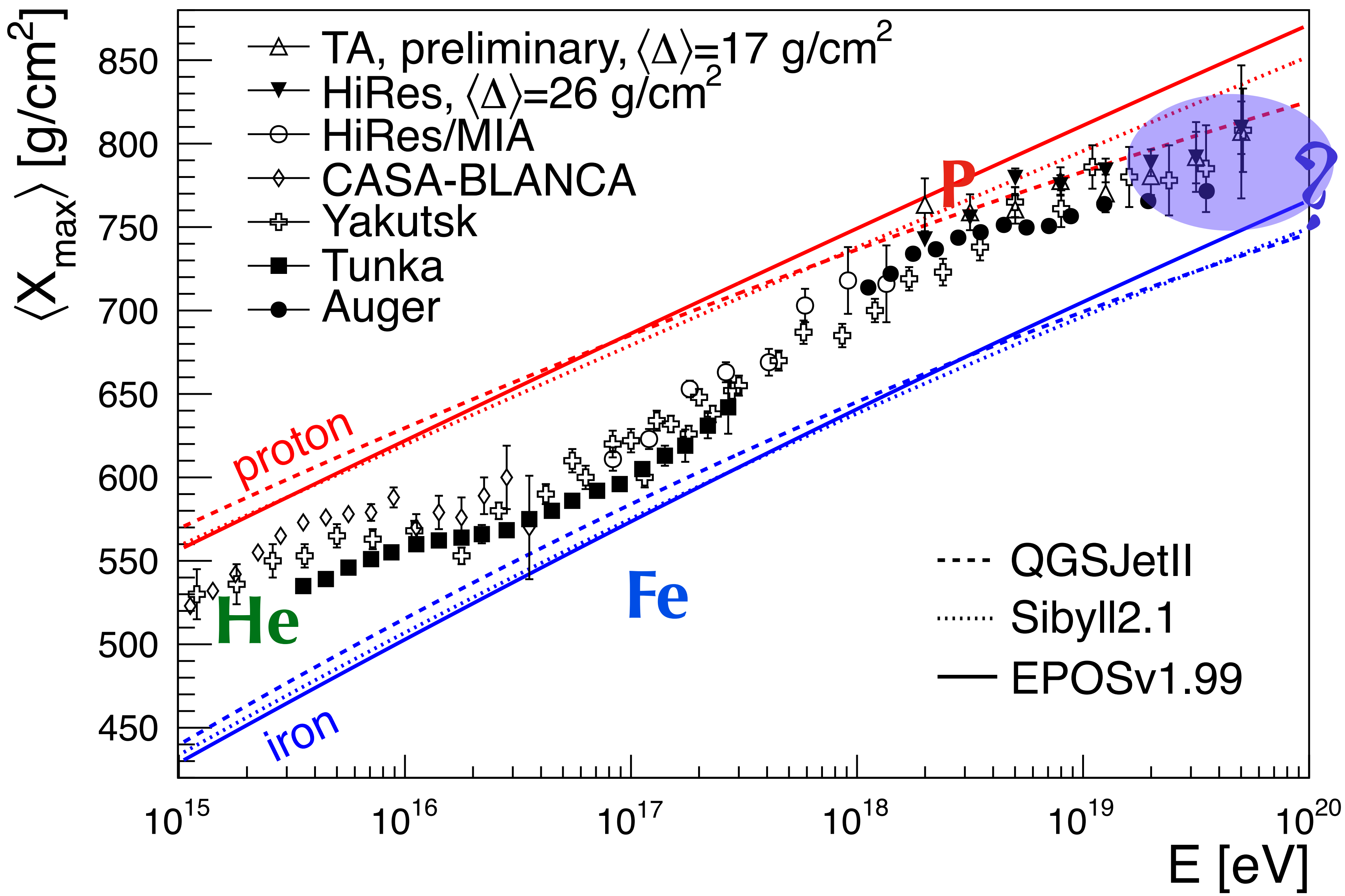

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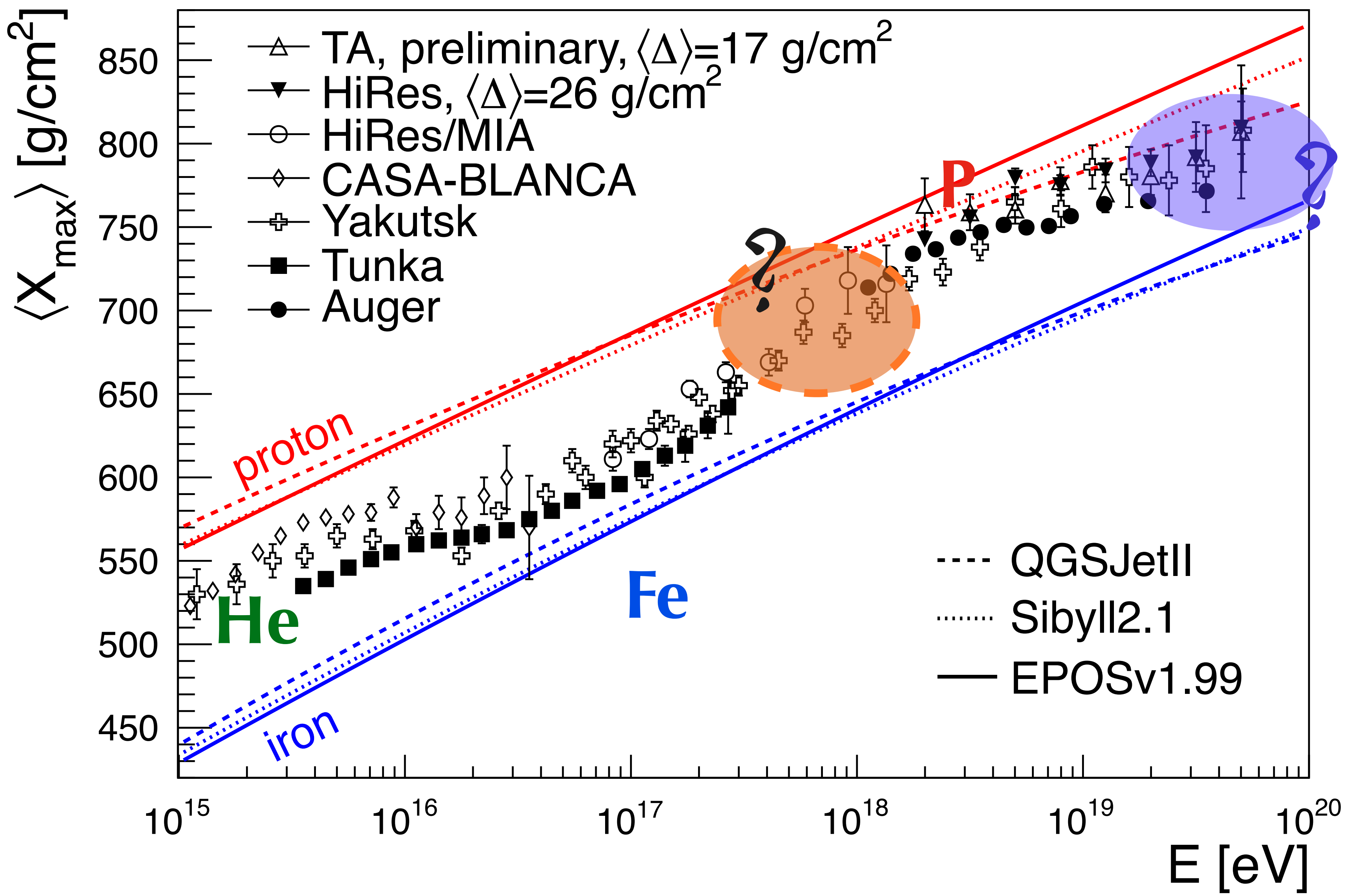

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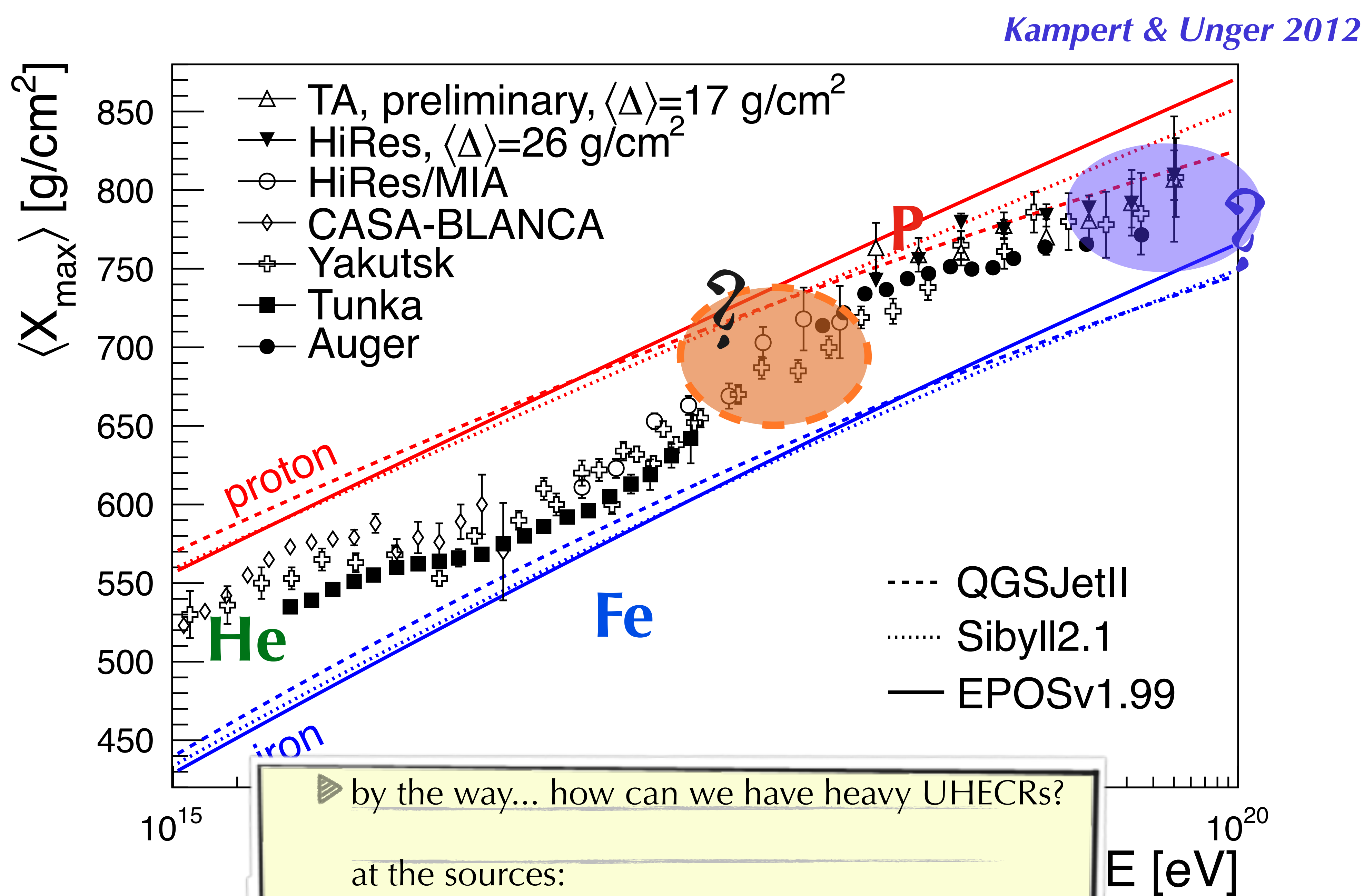

- by the way... how can we have heavy UHECRs?

  at the sources:
- heavy nuclei if **metal-rich** or **nucleosynthesis**
- escape difficult due to **photo-disintegration** in source?

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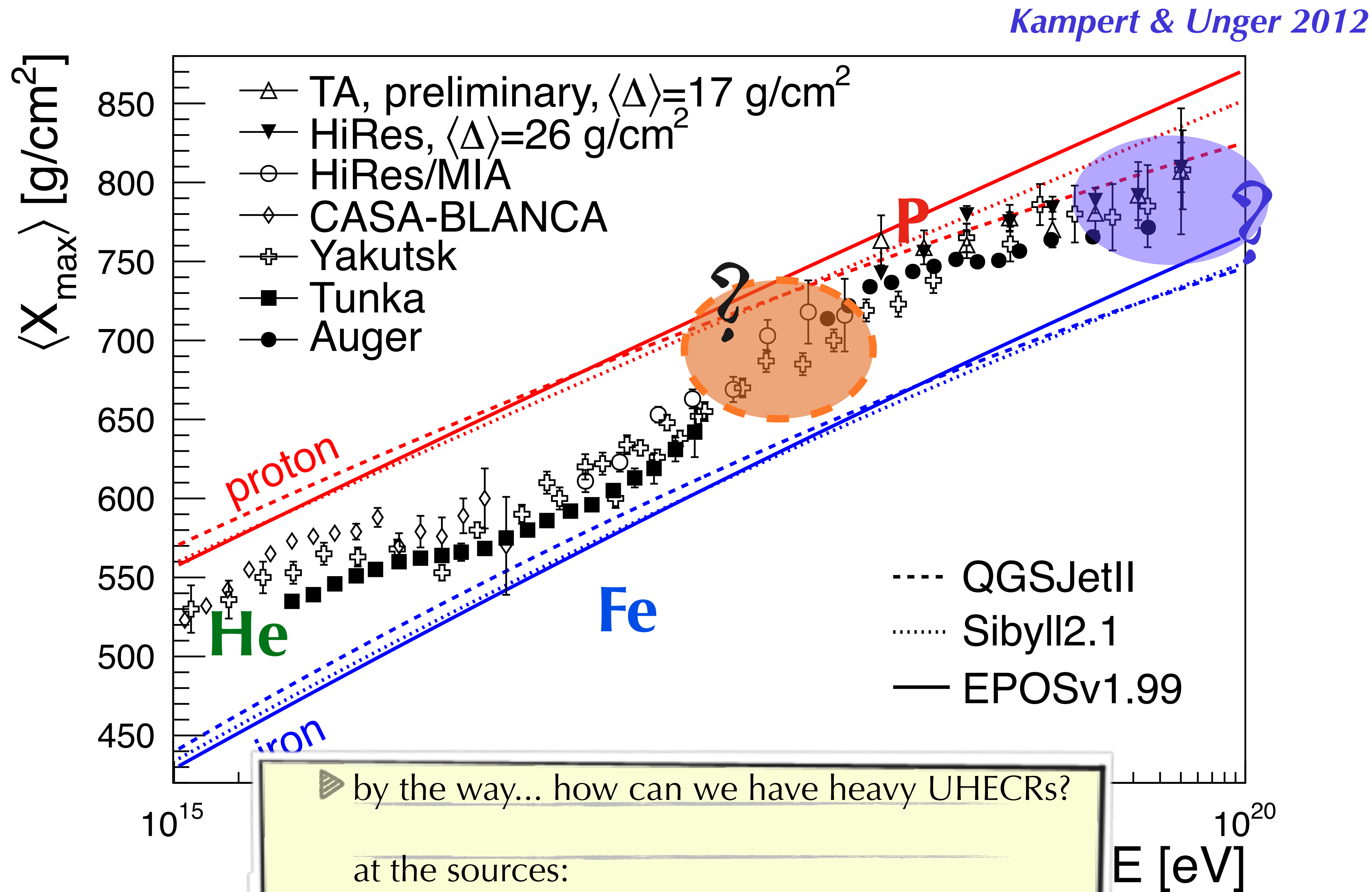

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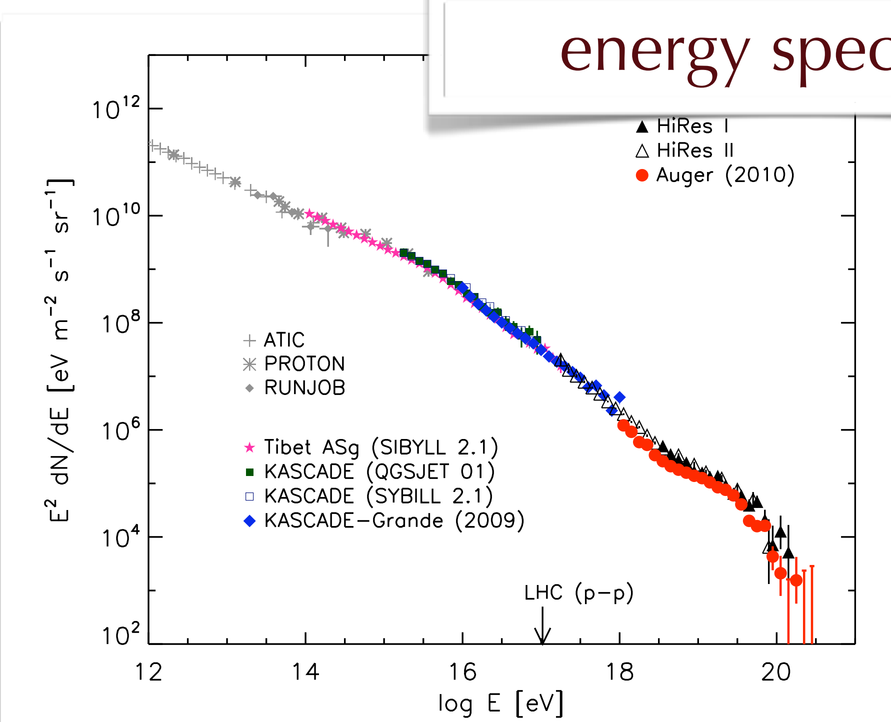
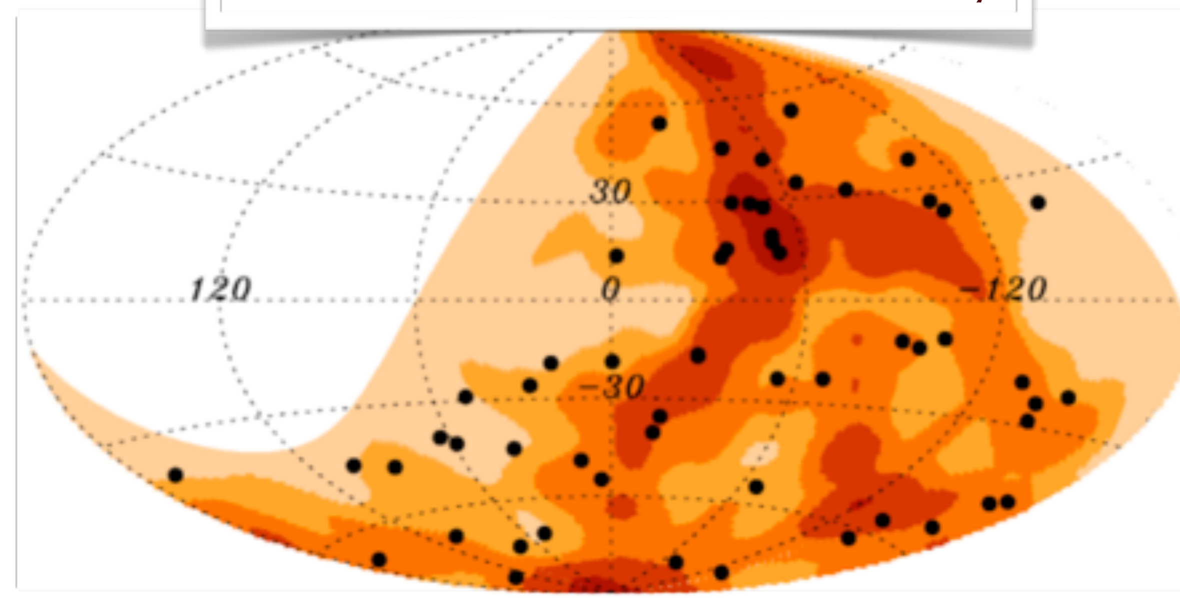


arrival directions in the sky



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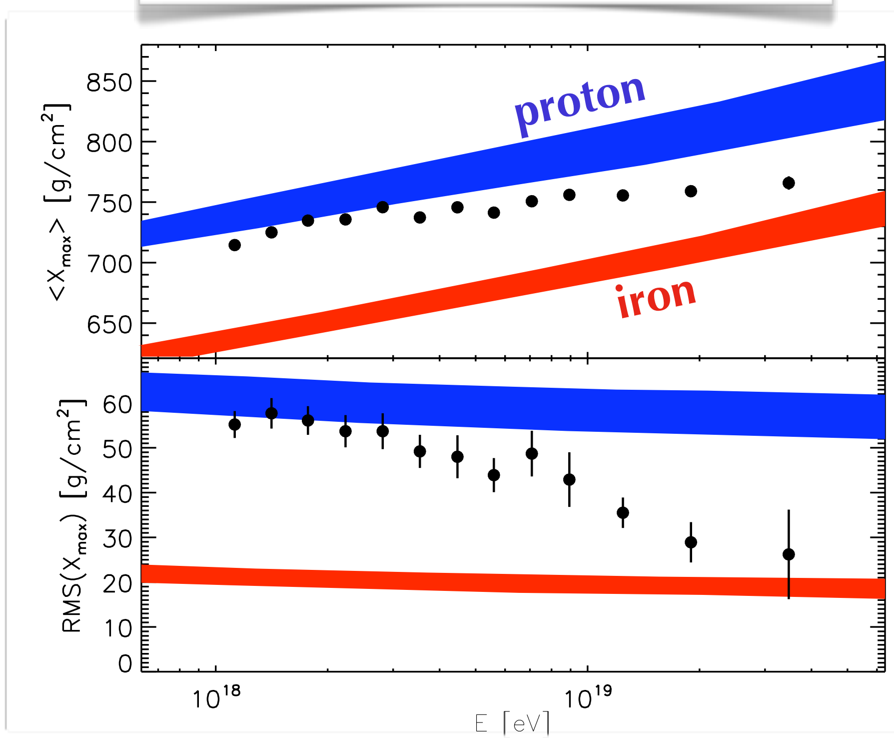

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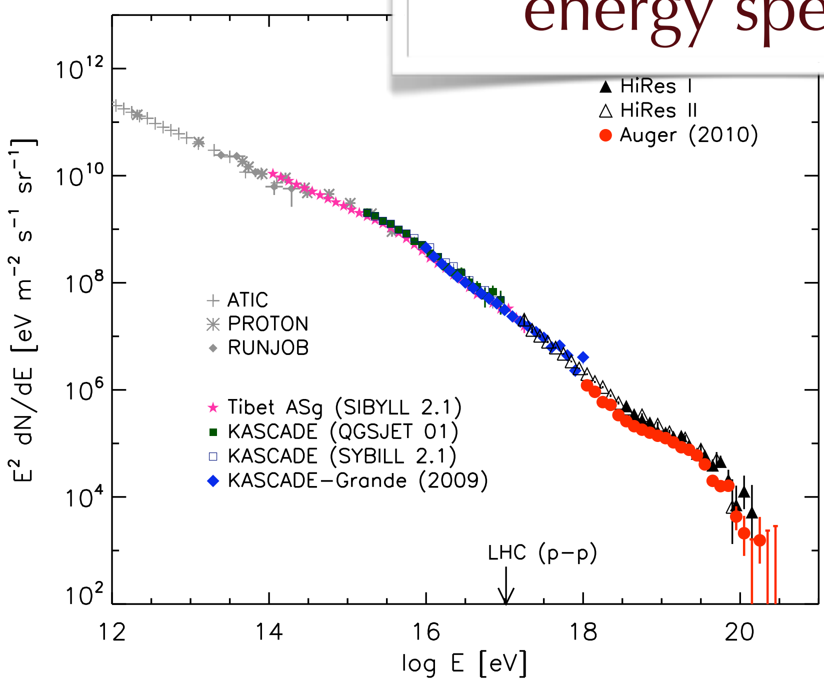

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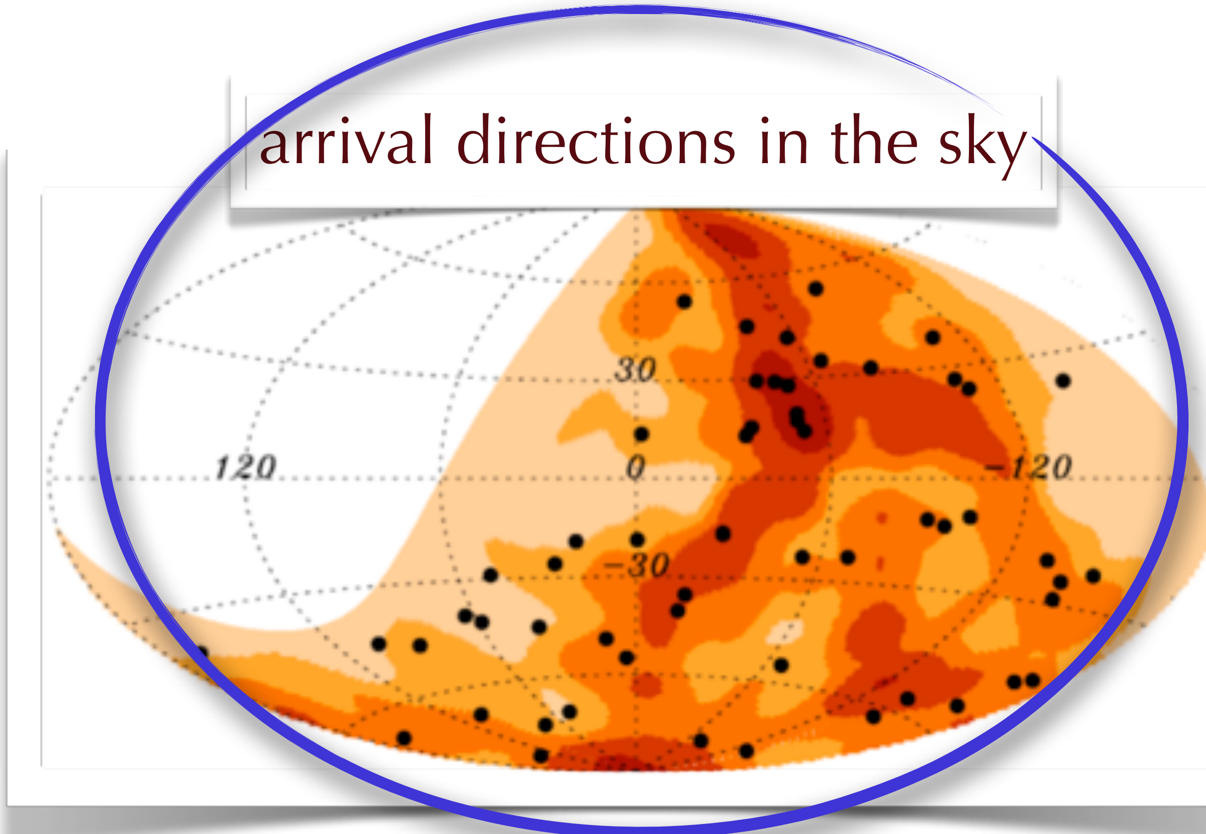

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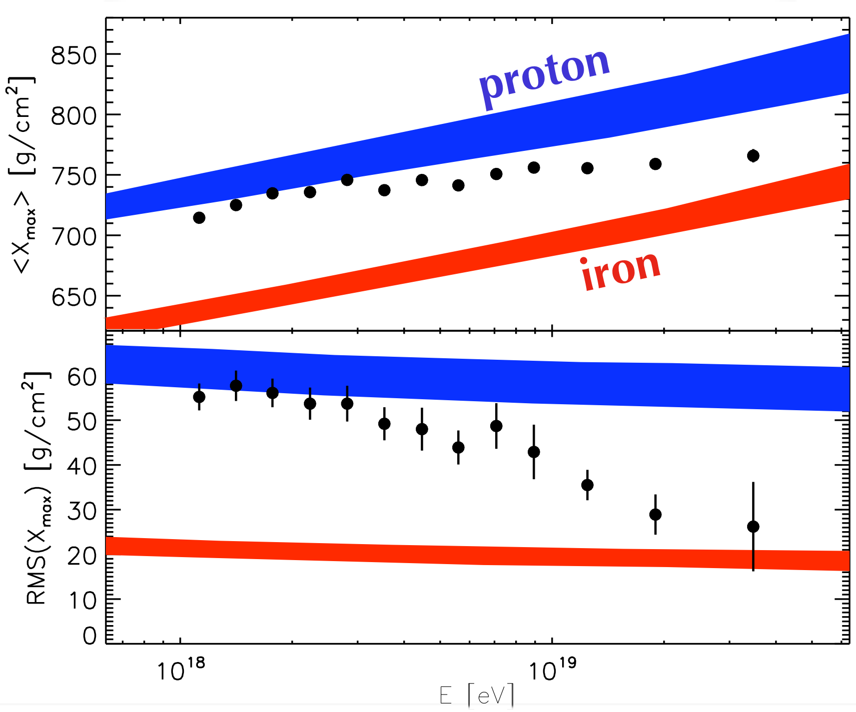

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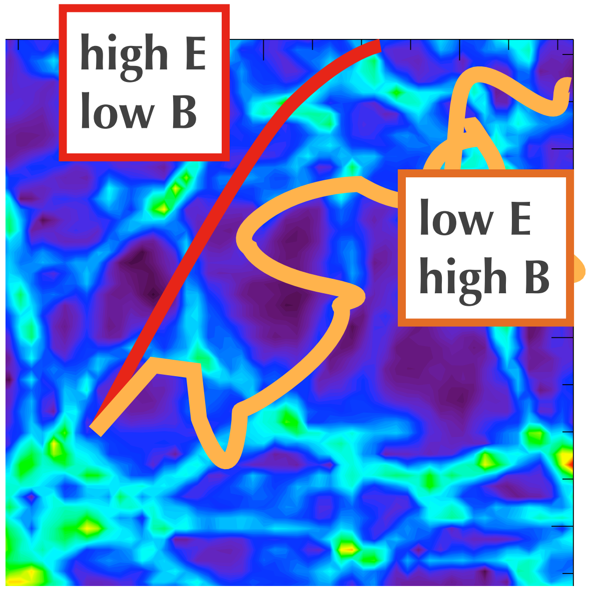
Arrival directions in the sky & magnetic fields



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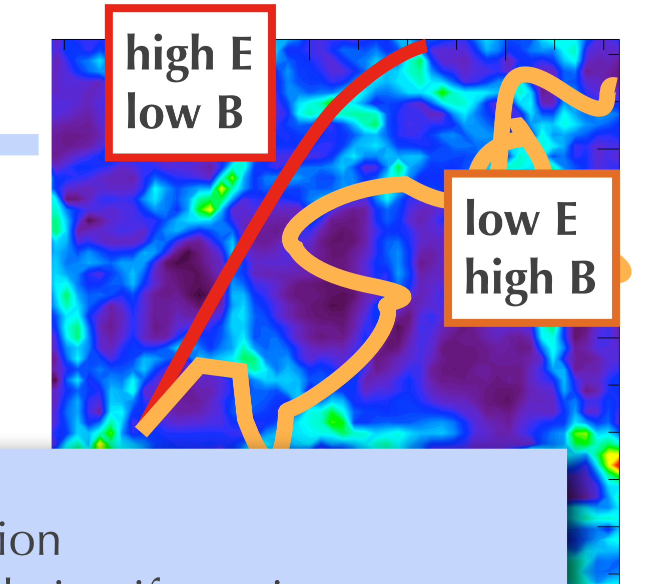
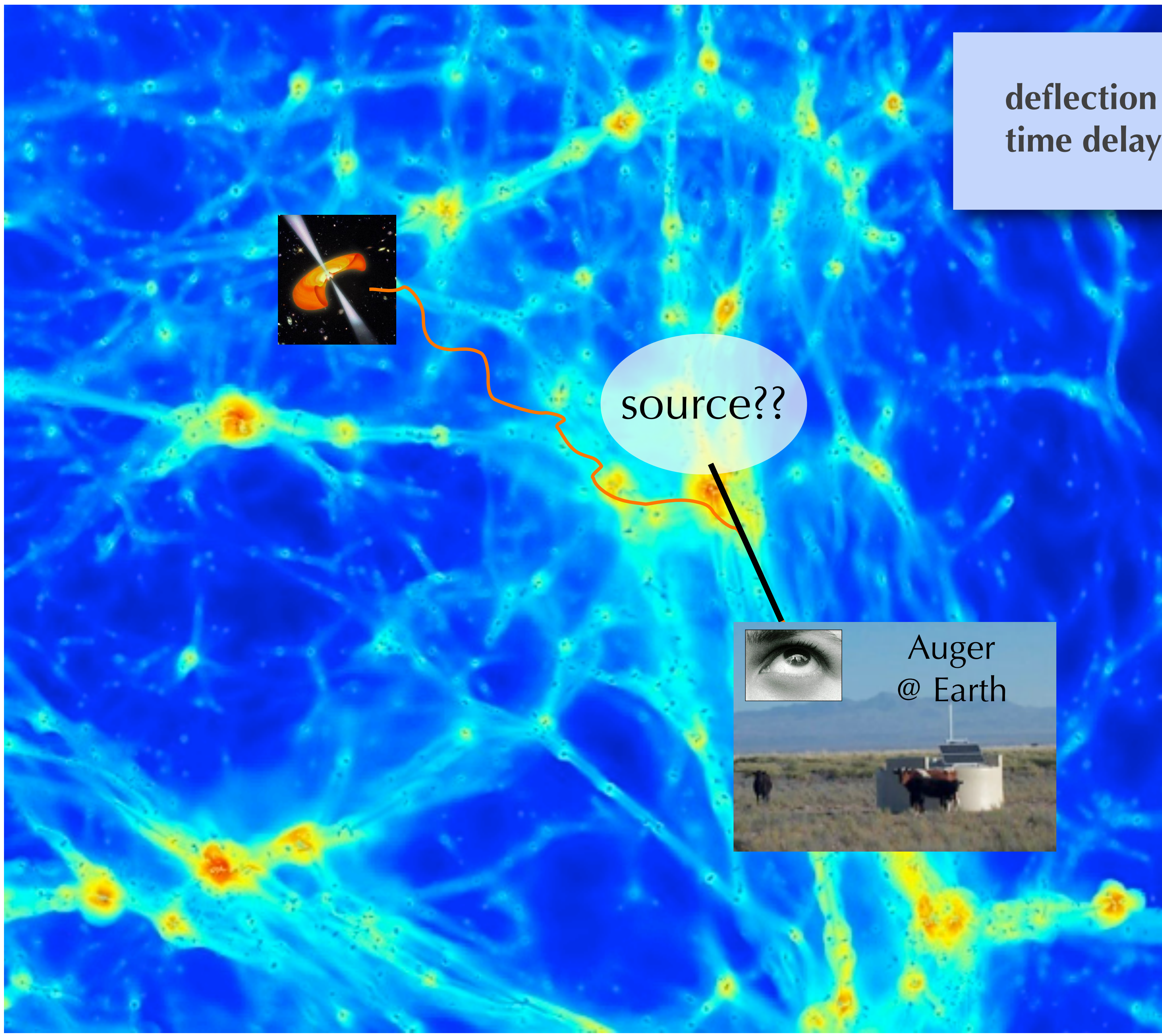


deflection : spatial decorrelation
time delay : temporal decorrelation if transient source



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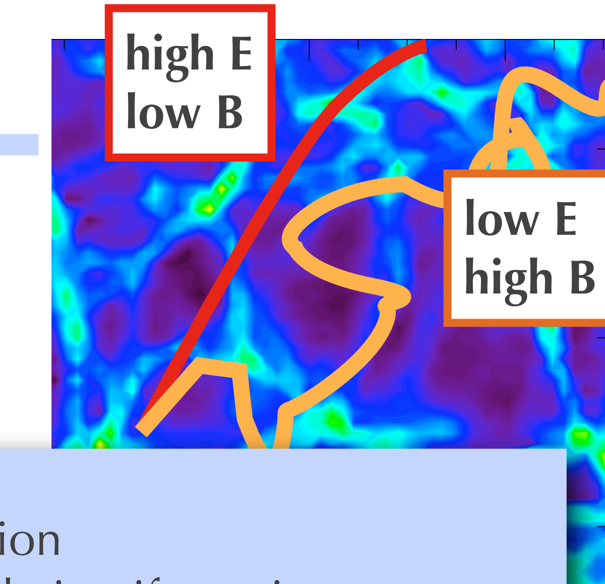

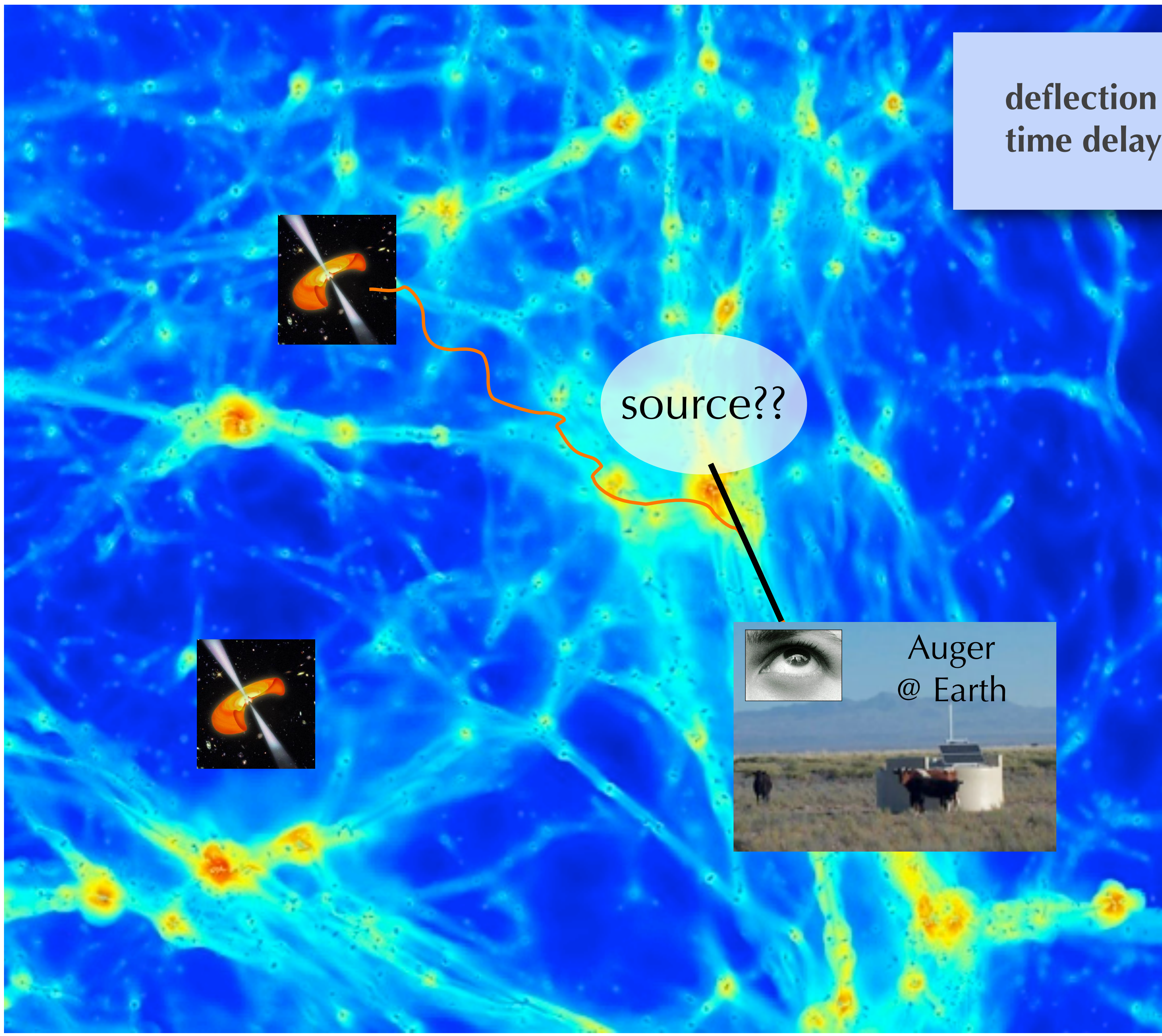

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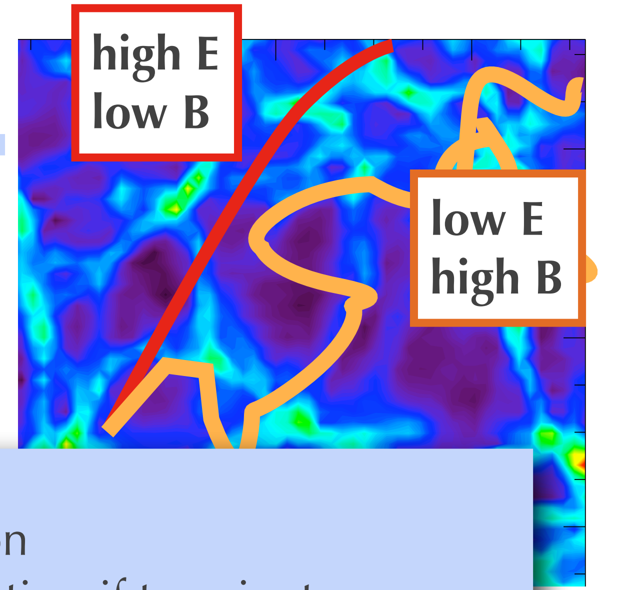

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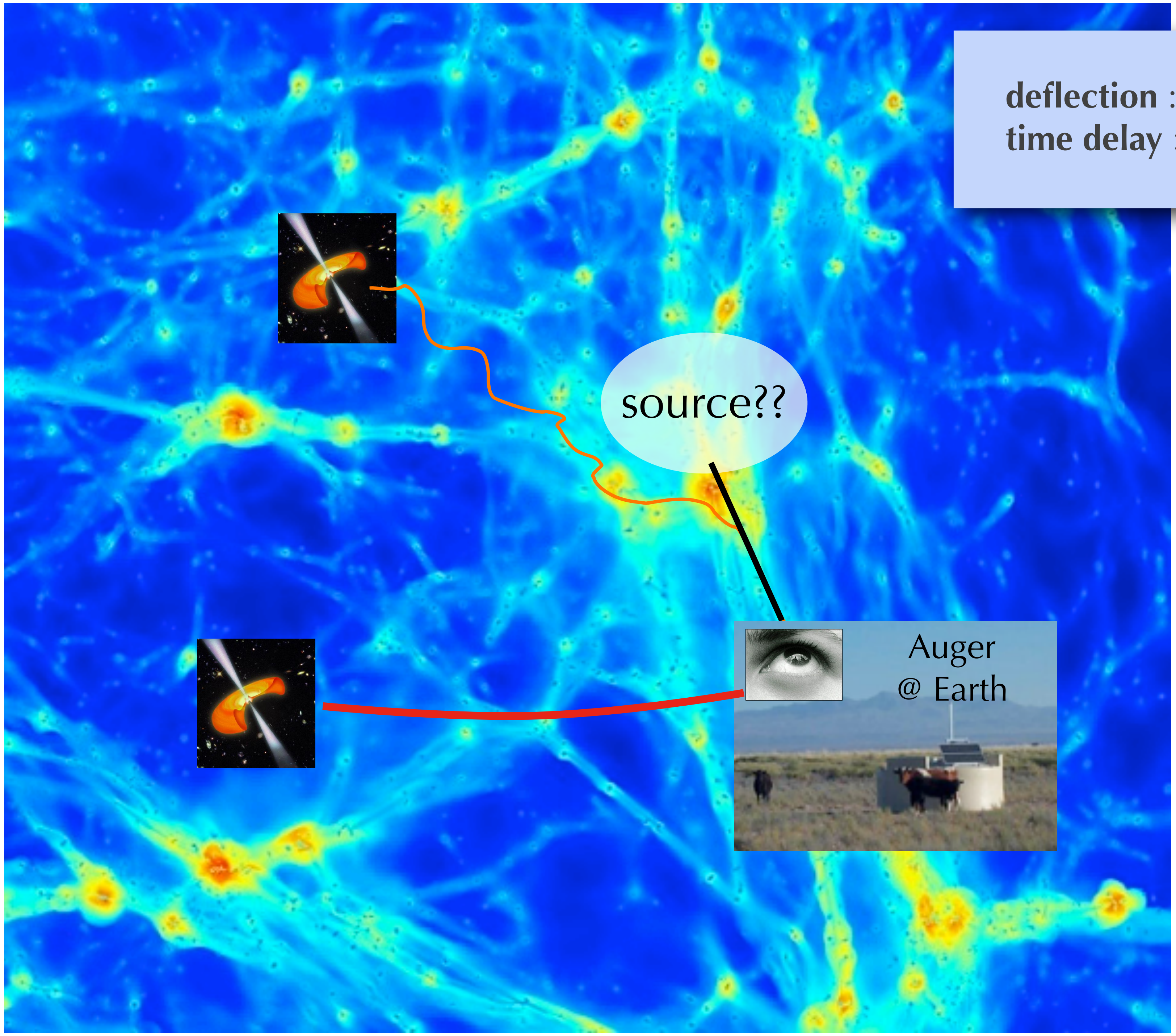

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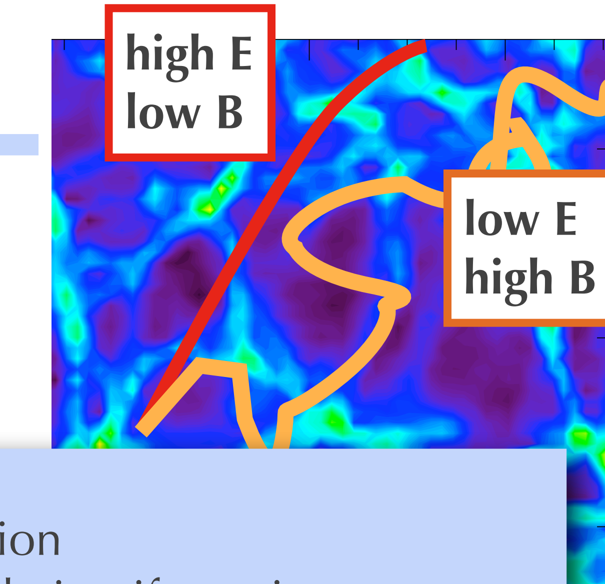

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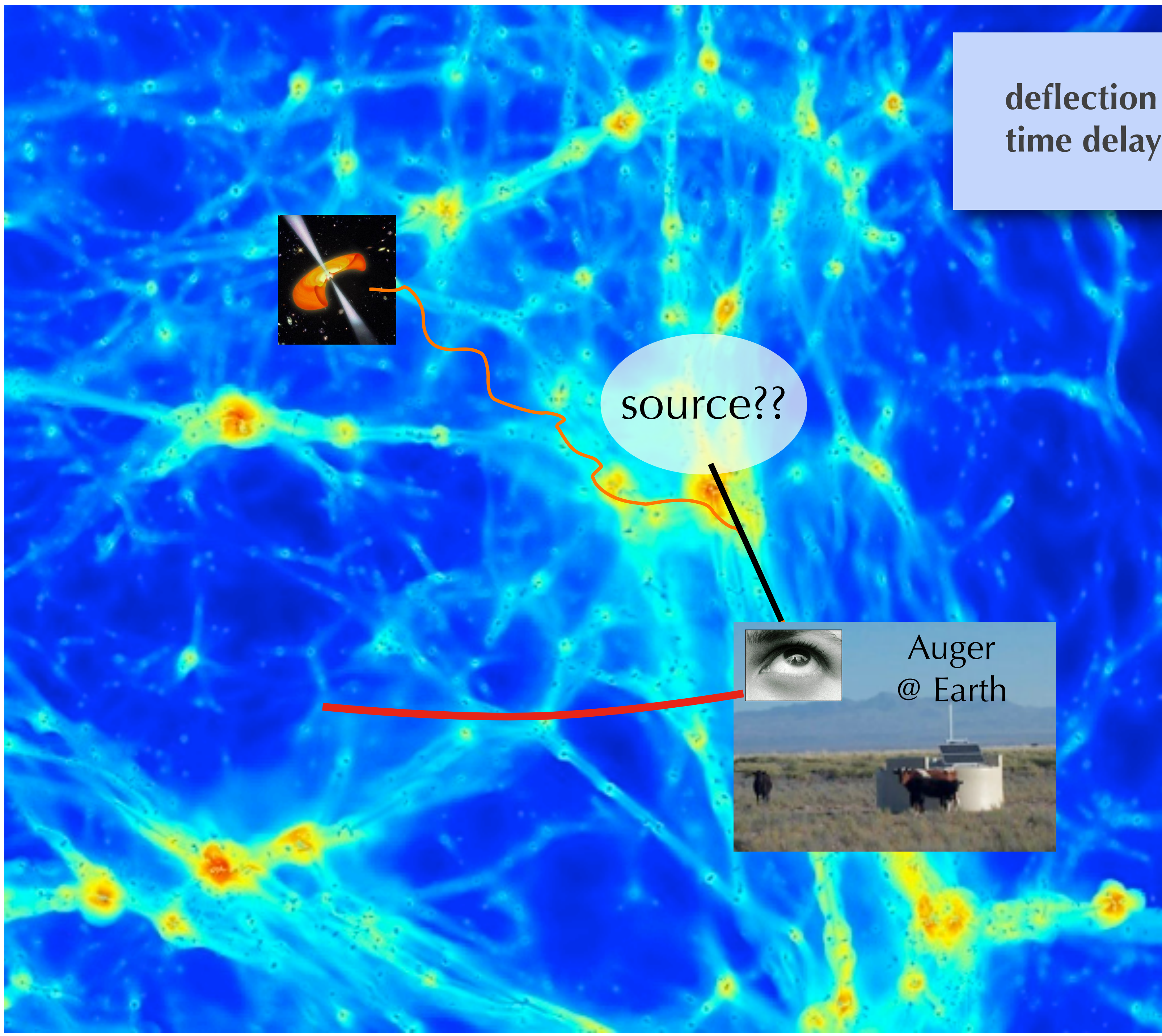

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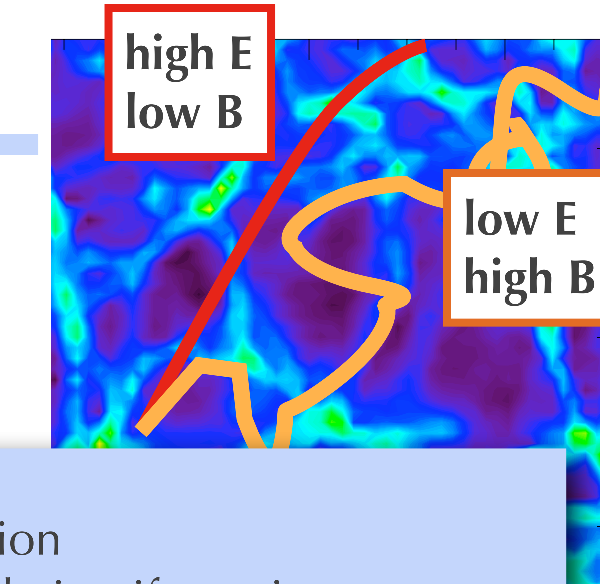

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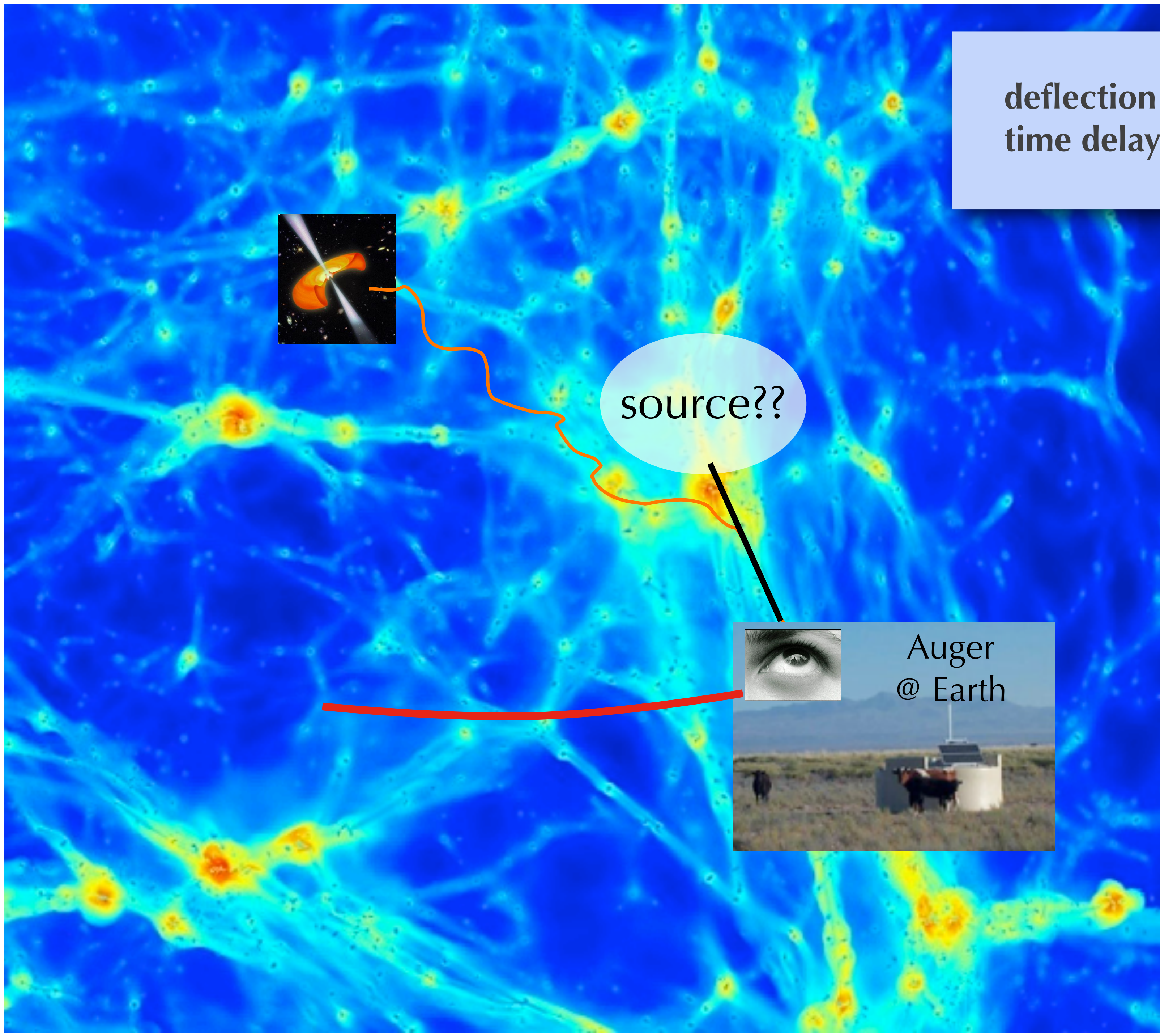

Extragalactic magnetic fields?

poorly known (no observation)
upper limits: B $l_{coh}^{1/2}$ < 1-10 nG Mpc$^{1/2}$
simulations --> complex and contradictory

Beck 08, Vallée 04, Dolag et al. 05, Sigl et al. 05, Ryu et al. 98, Donnert et al. 09...

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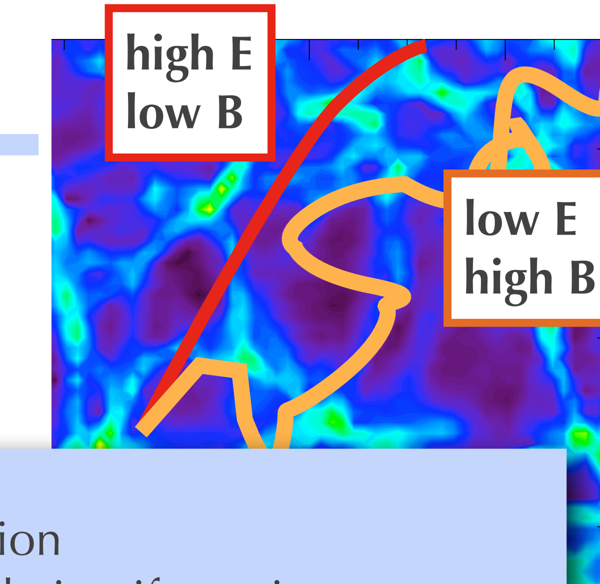

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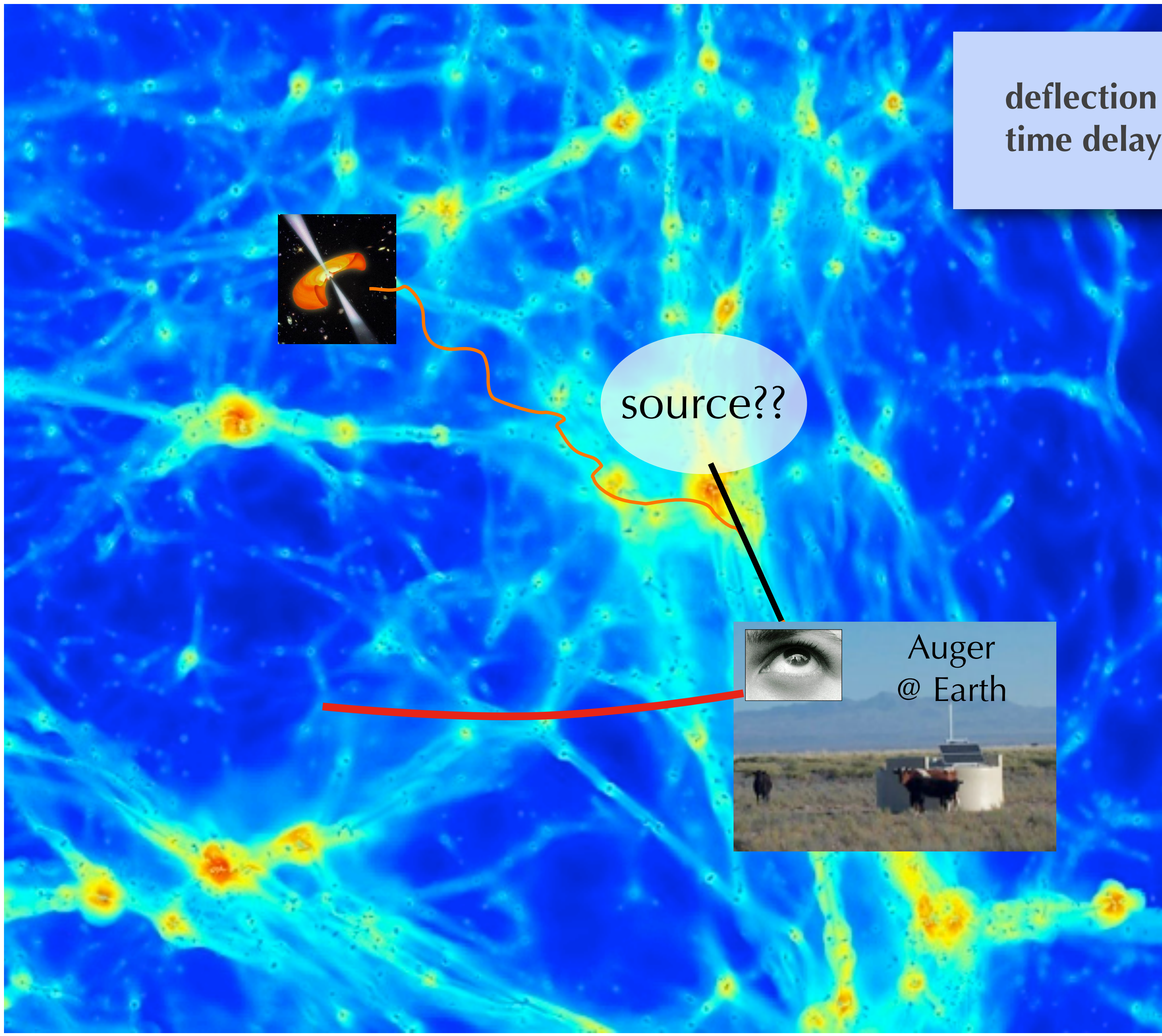

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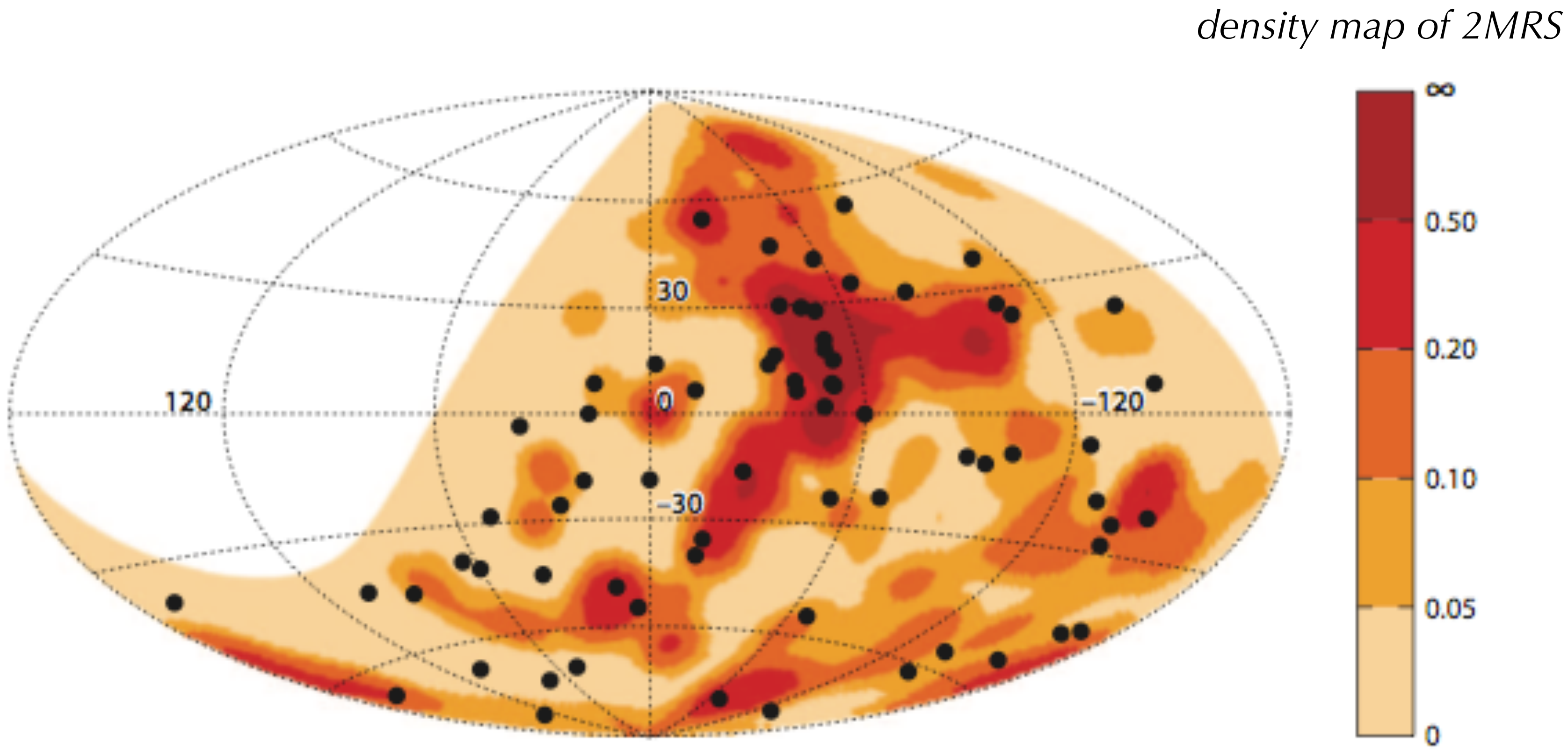
Propagation of UHECR in extragalactic magnetic fields?

complicated because B not known
standard B lead to low proton deflections

e.g., Dolag et al. 05, Sigl et al. 05, Ryu et al. 98, Takami & Sato 08, KK & Lemoine 08a, KK & Lemoine 08b

+ Galactic magnetic fields...

Arrival directions in the sky seen by Auger



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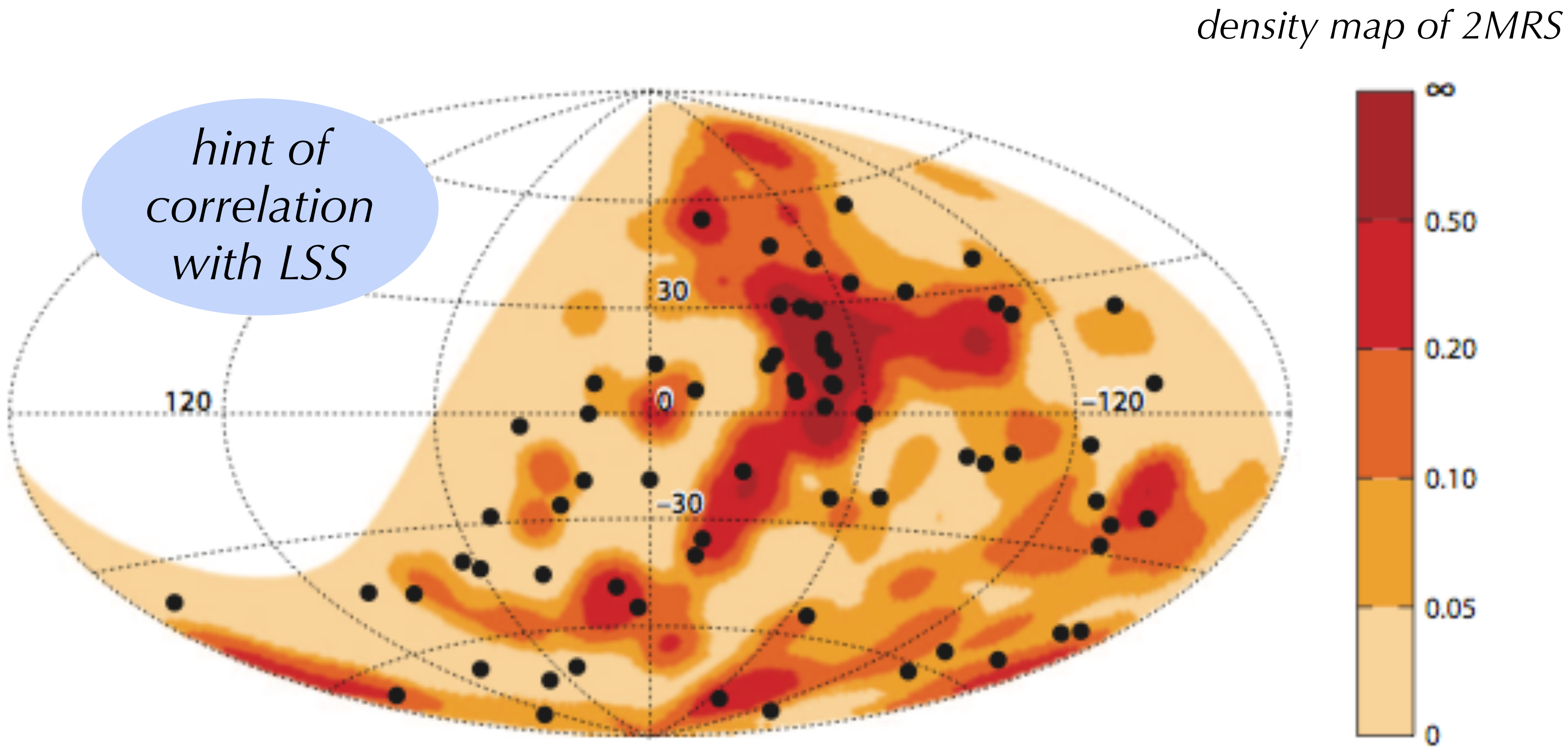

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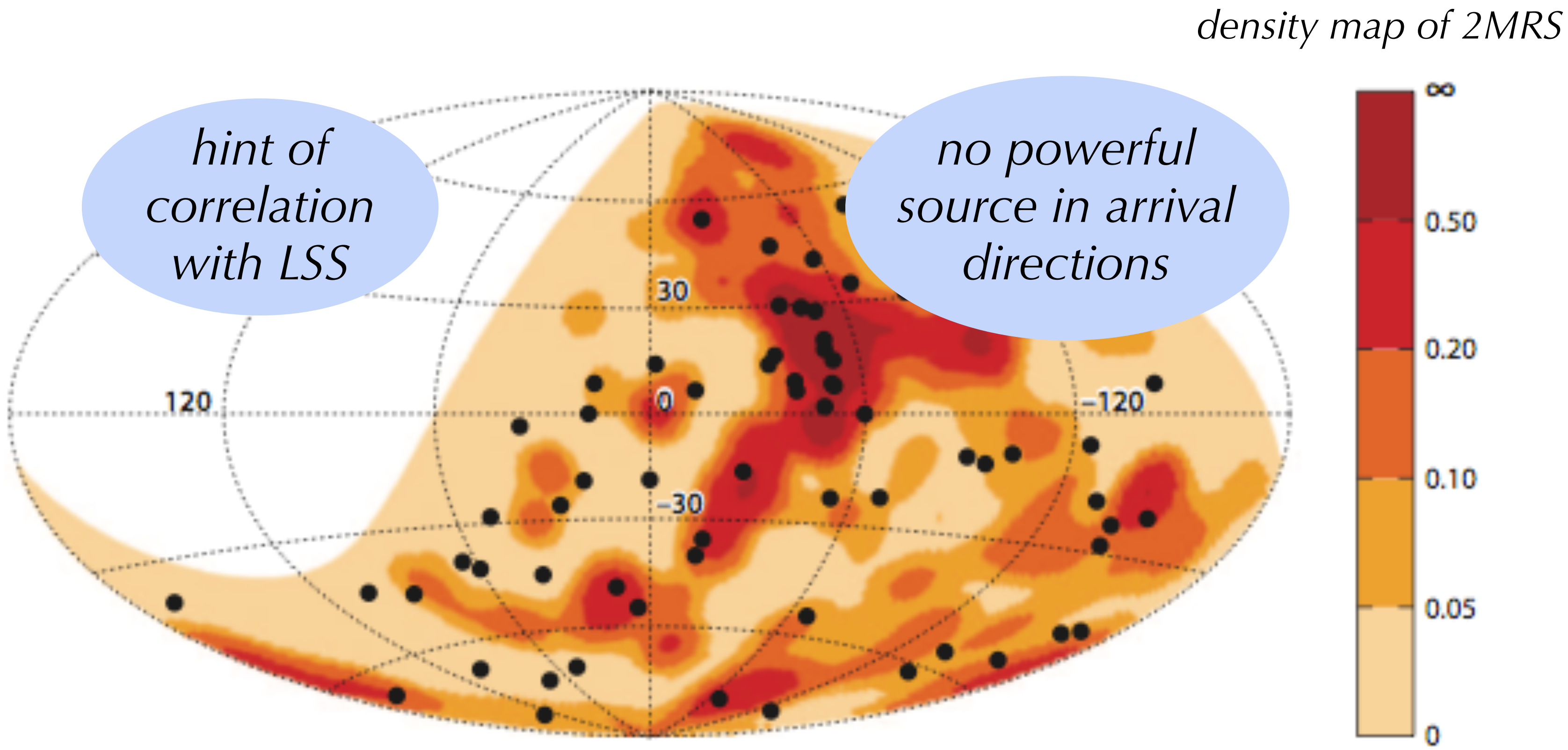
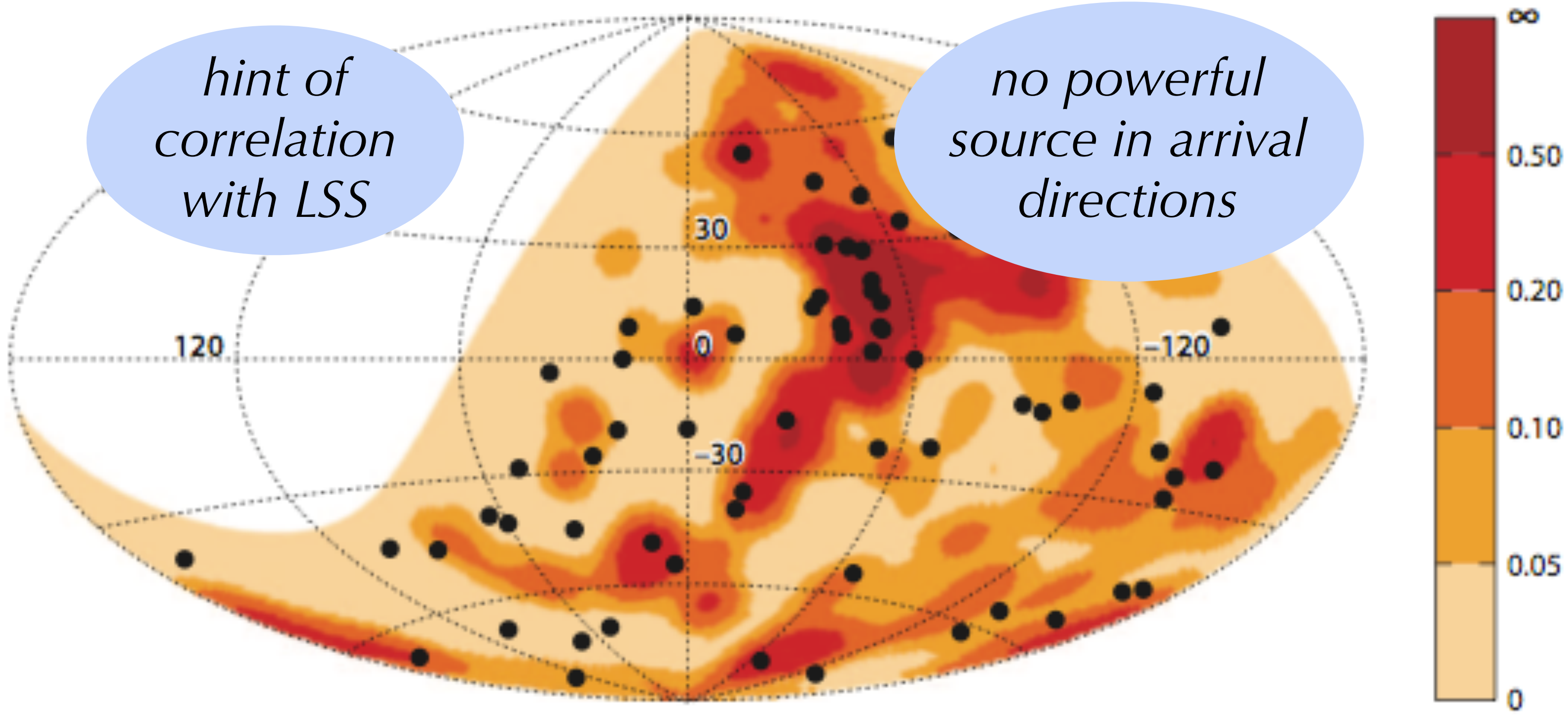


Arrival directions in the sky seen by Auger

density map of 2MRS



hint of correlation with LSS

no powerful source in arrival directions

steady sources?

- particularly strong extragalactic magnetic field
- UHECR = heavy nuclei

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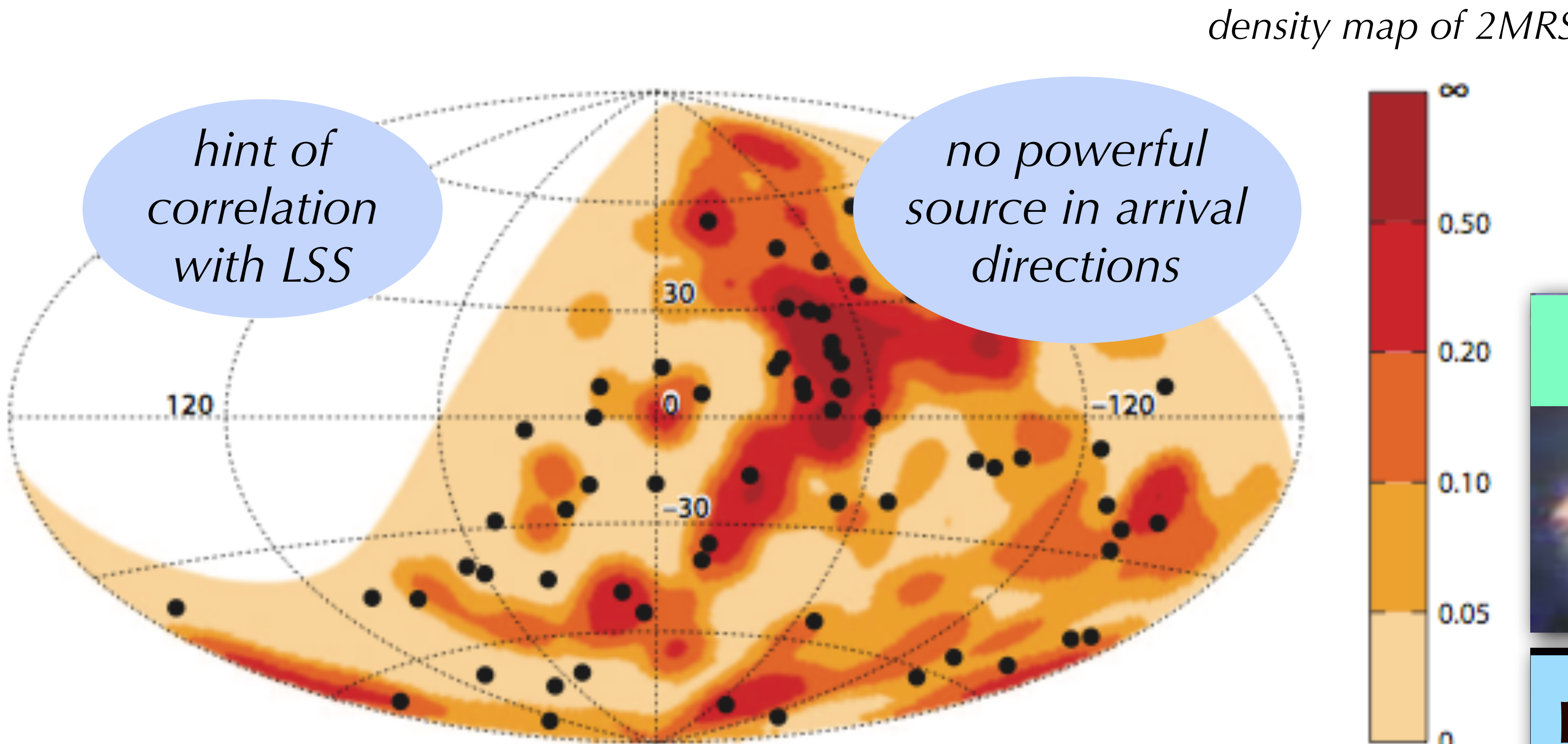

steady sources? **OR** **transient source?**

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

no correlation with
secondary neutrinos, photons, grav. waves

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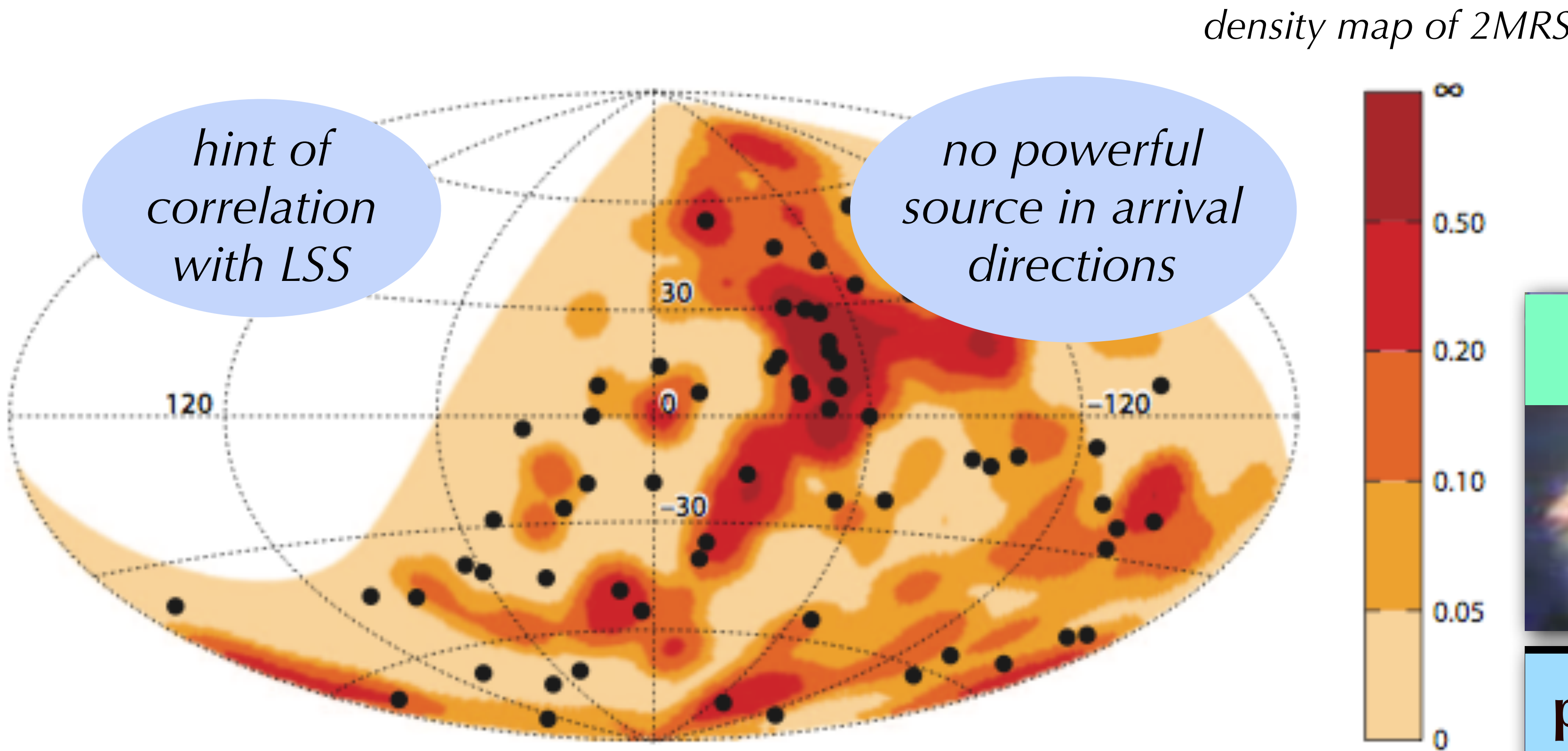

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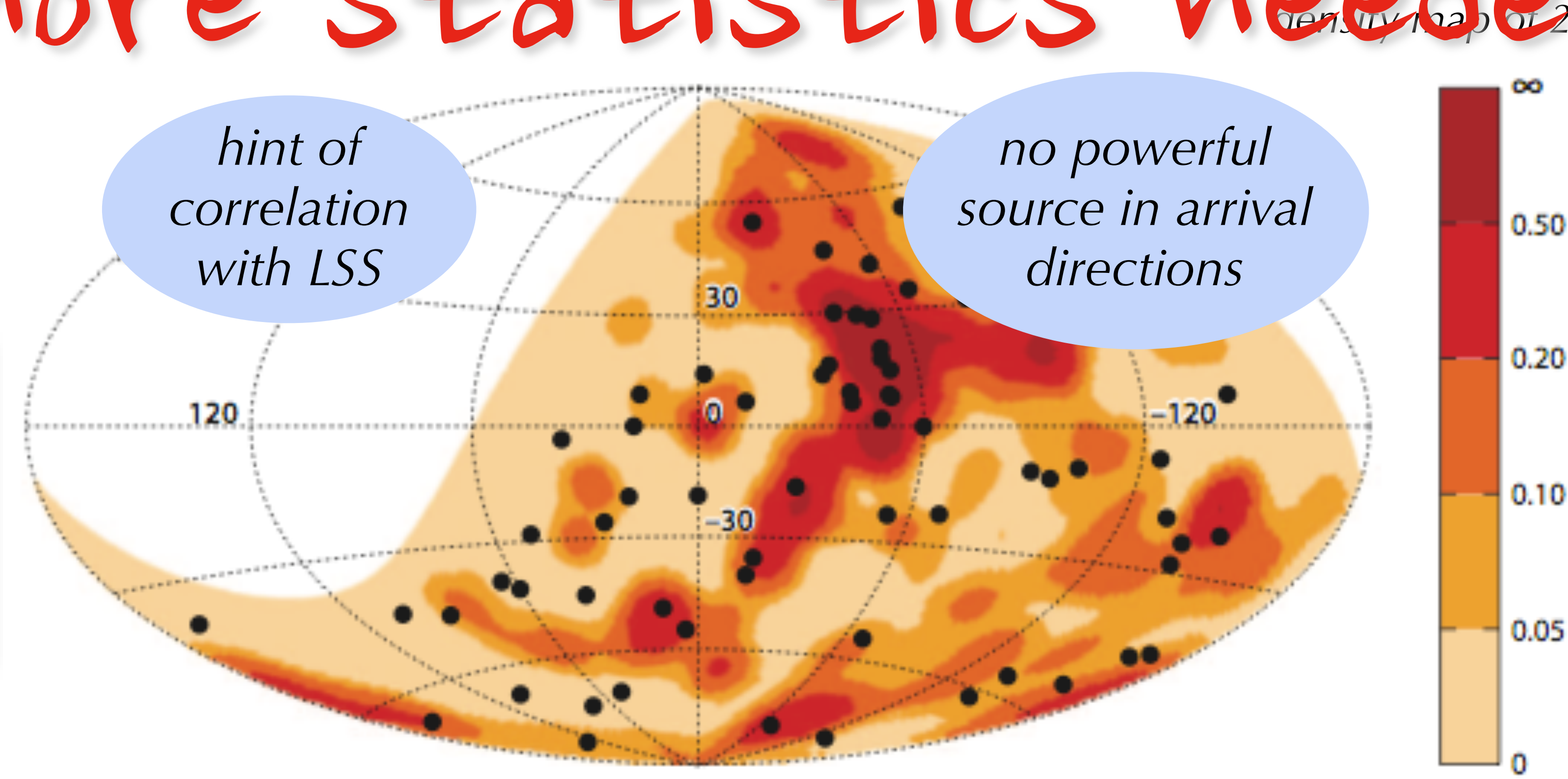
to make a distinction...

more statistics needed!



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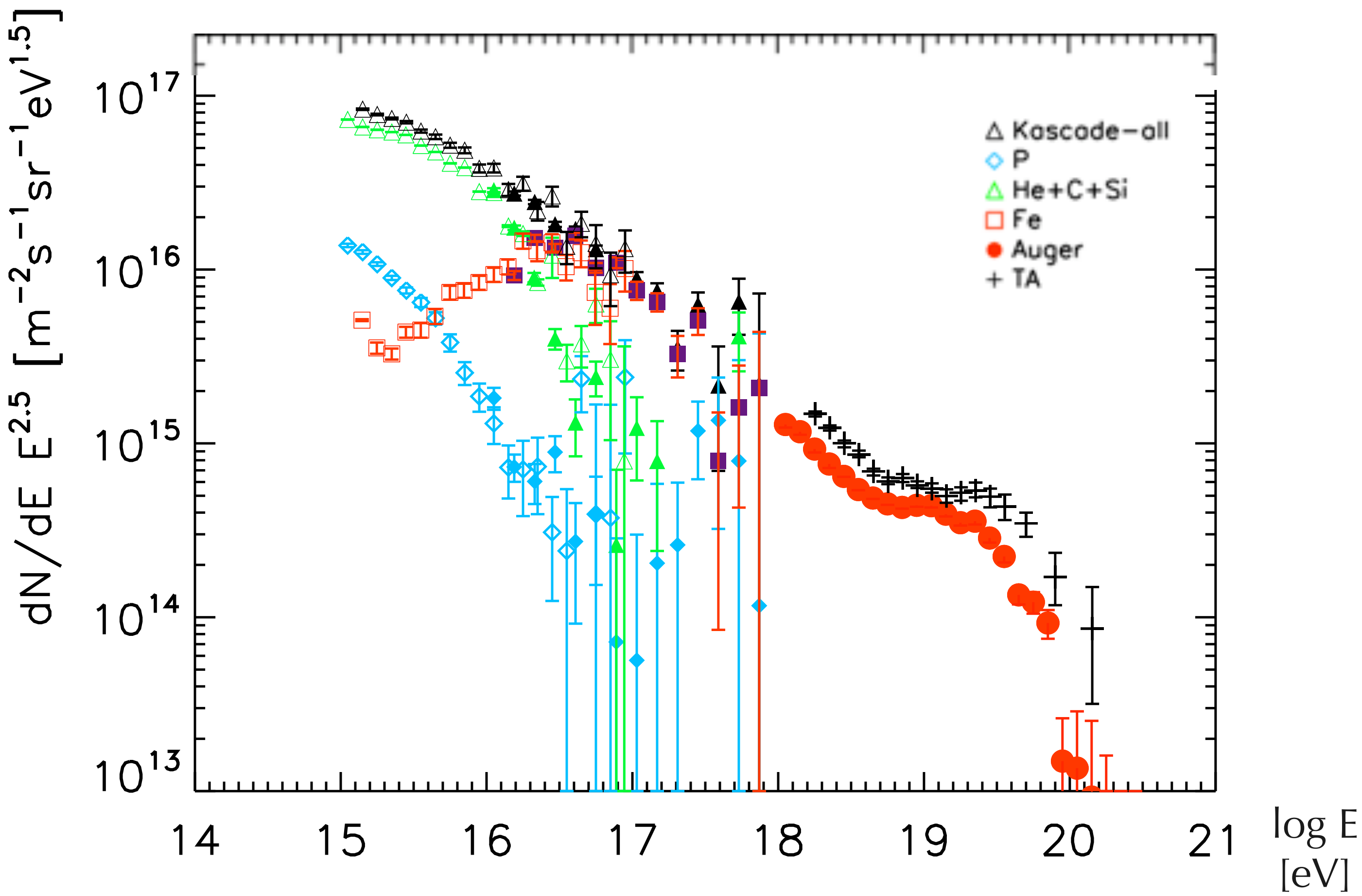
Spectrum, composition, anisotropies: tensions

spectrum



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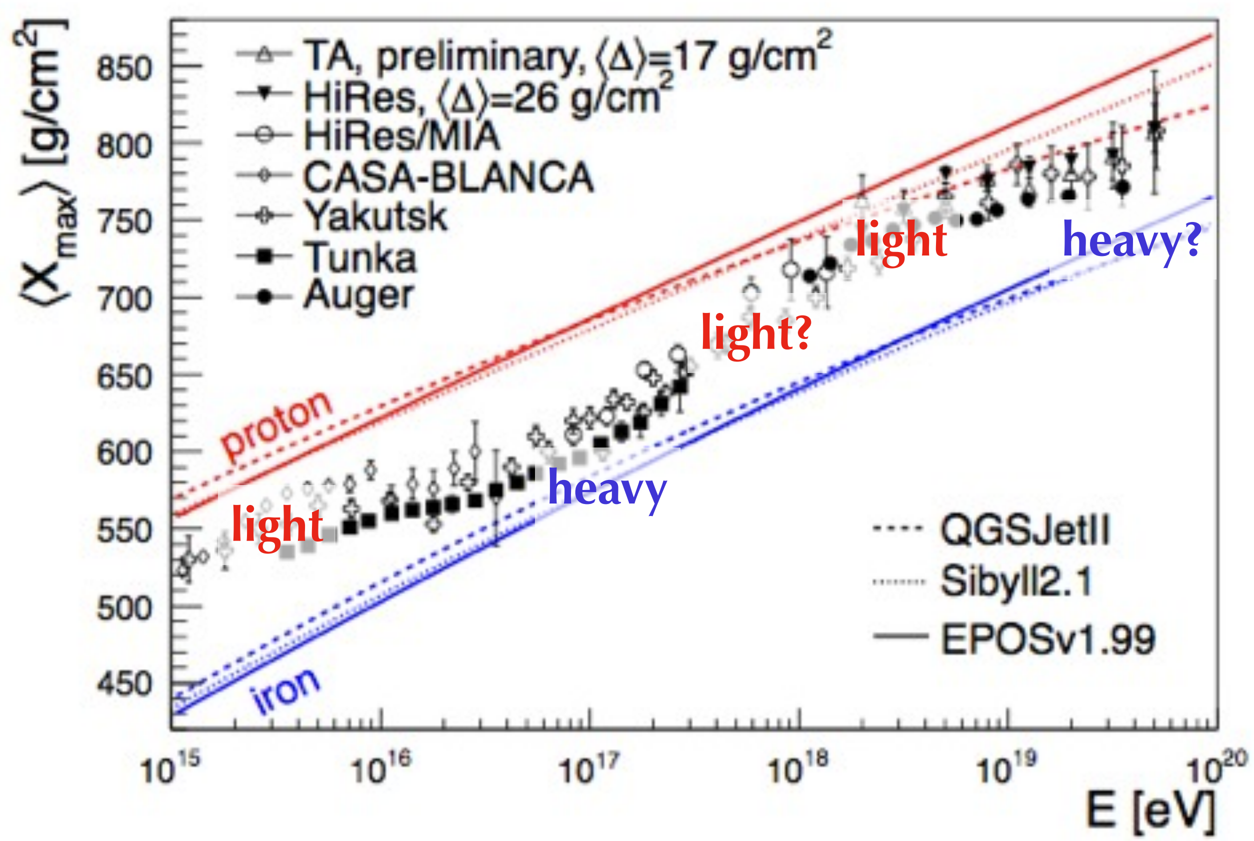

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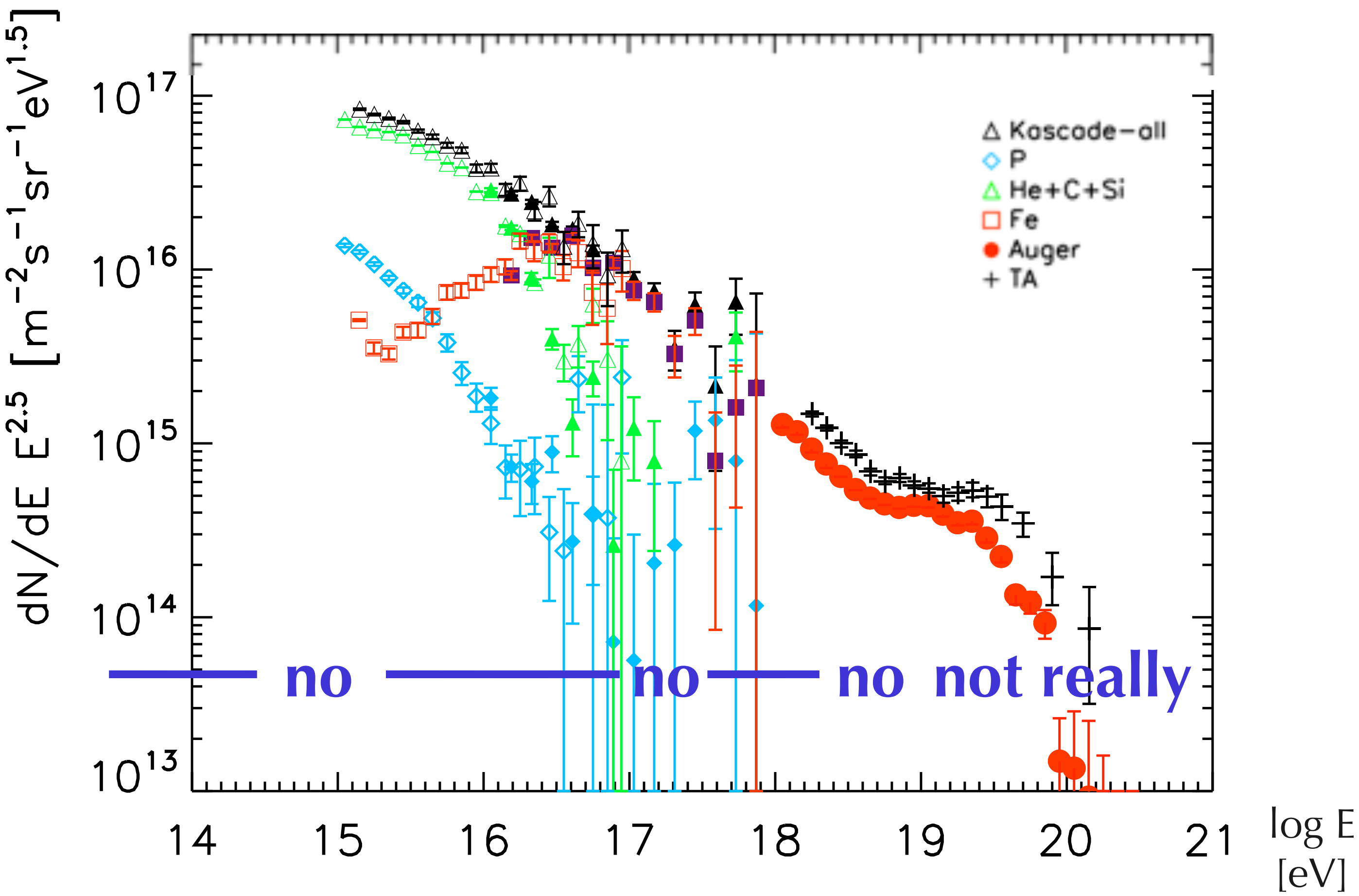
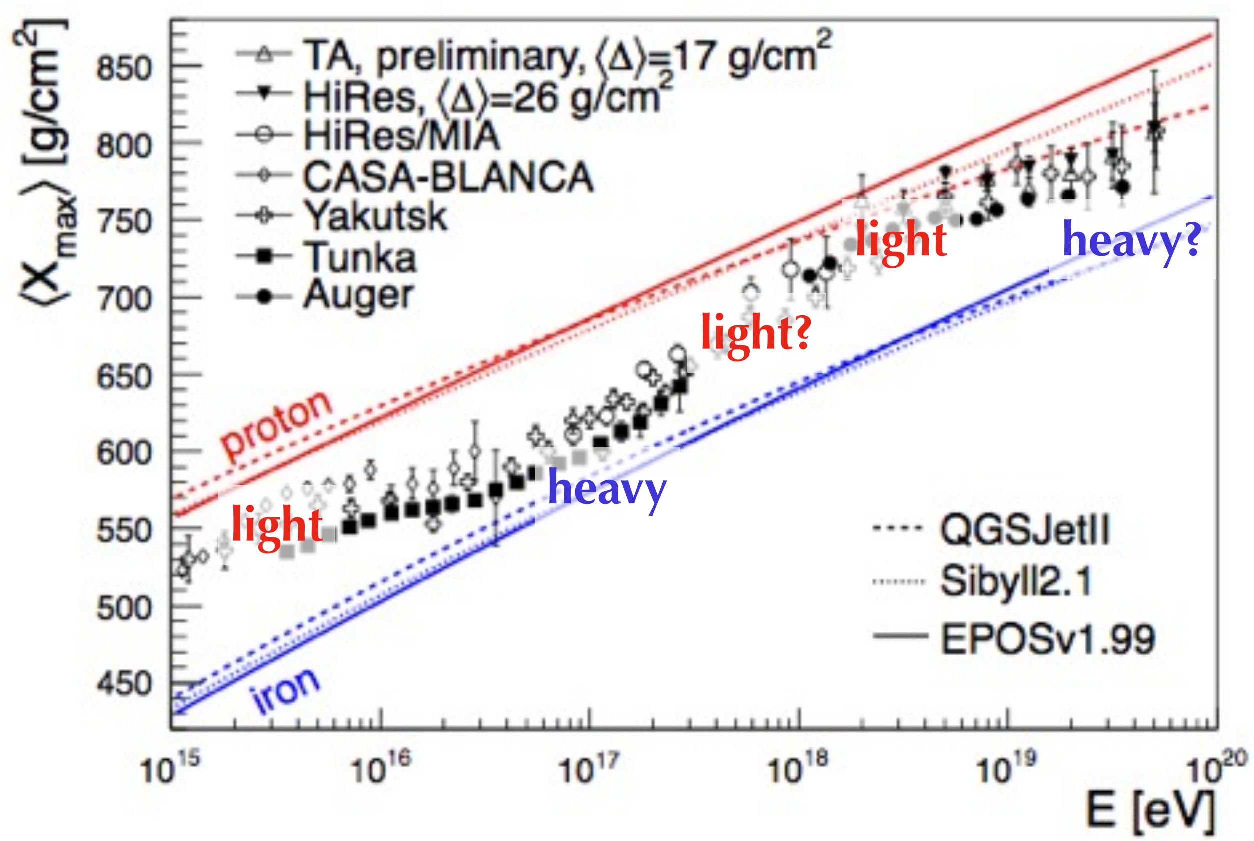


anisotropy
Tibet Coll. (2005)
EAS-TOP (2003)
Akeno (1986)
Auger Coll. (2010,2012a,b)

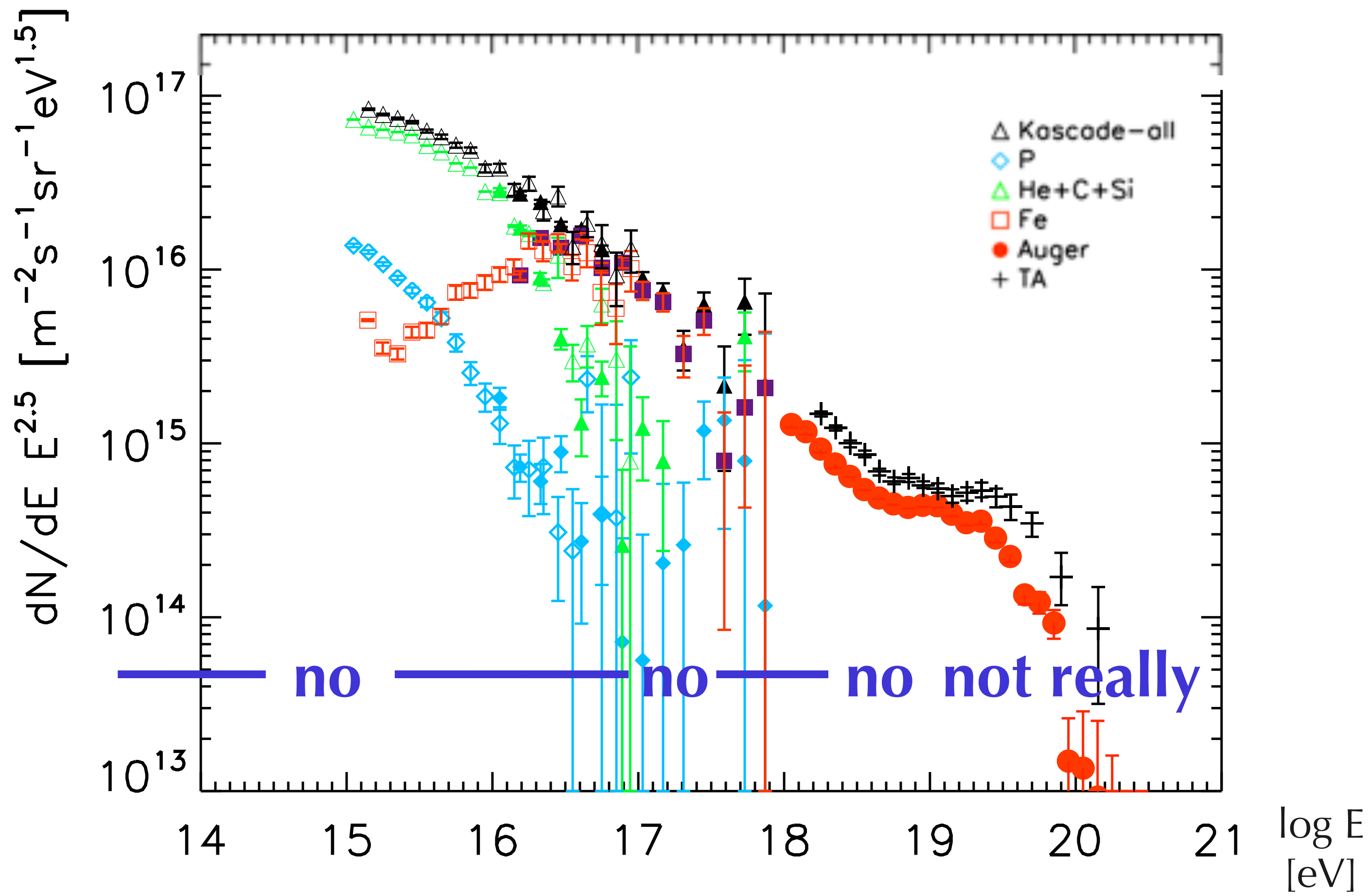


composition

Spectrum, composition, anisotropies: tensions

origin

spectrum



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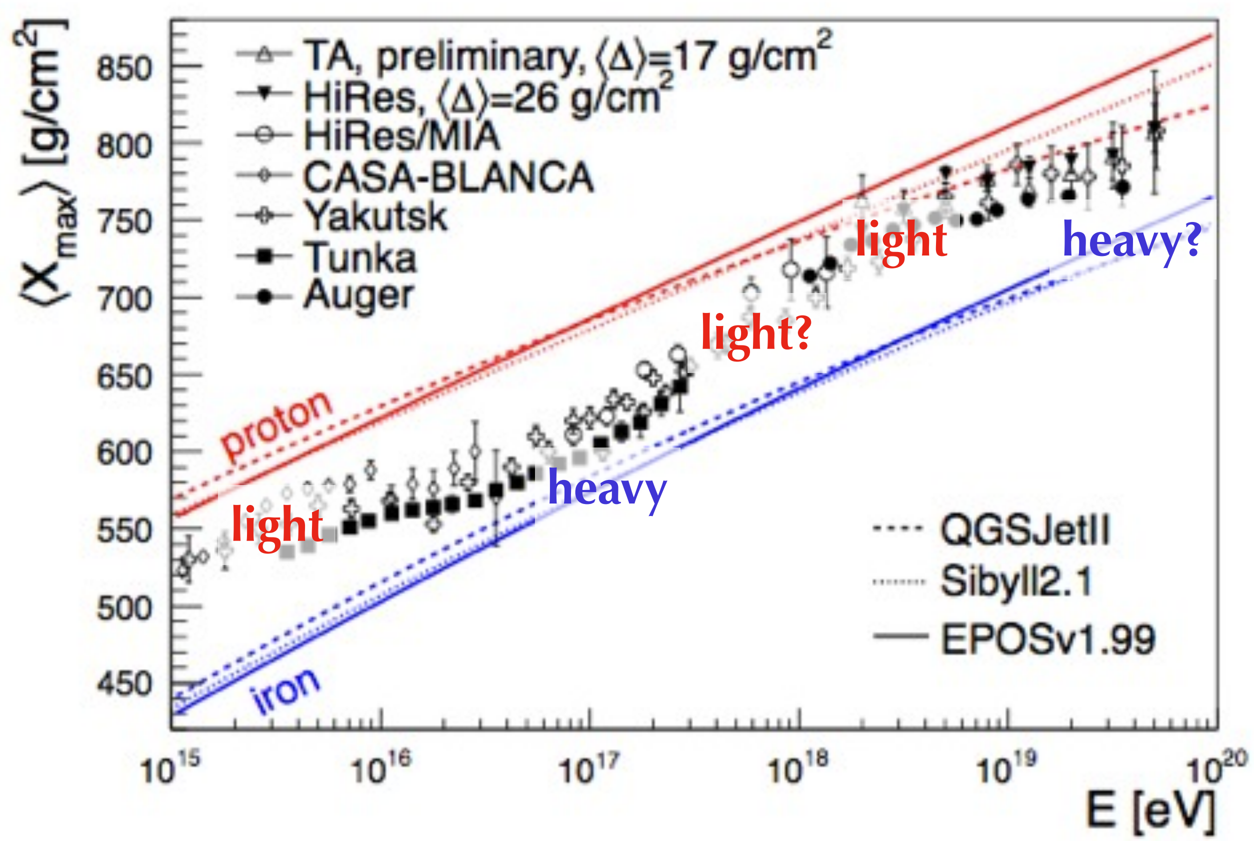

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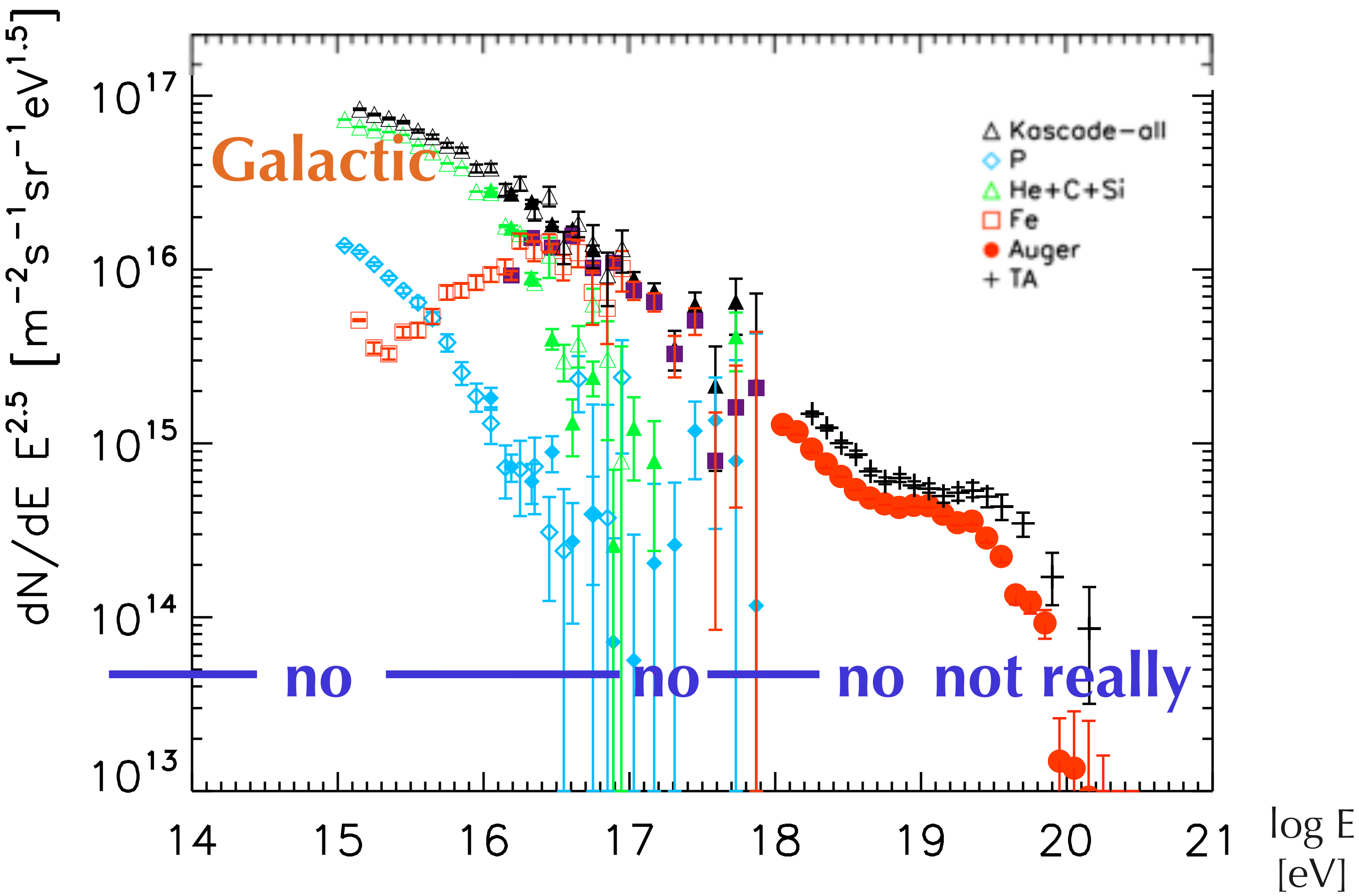

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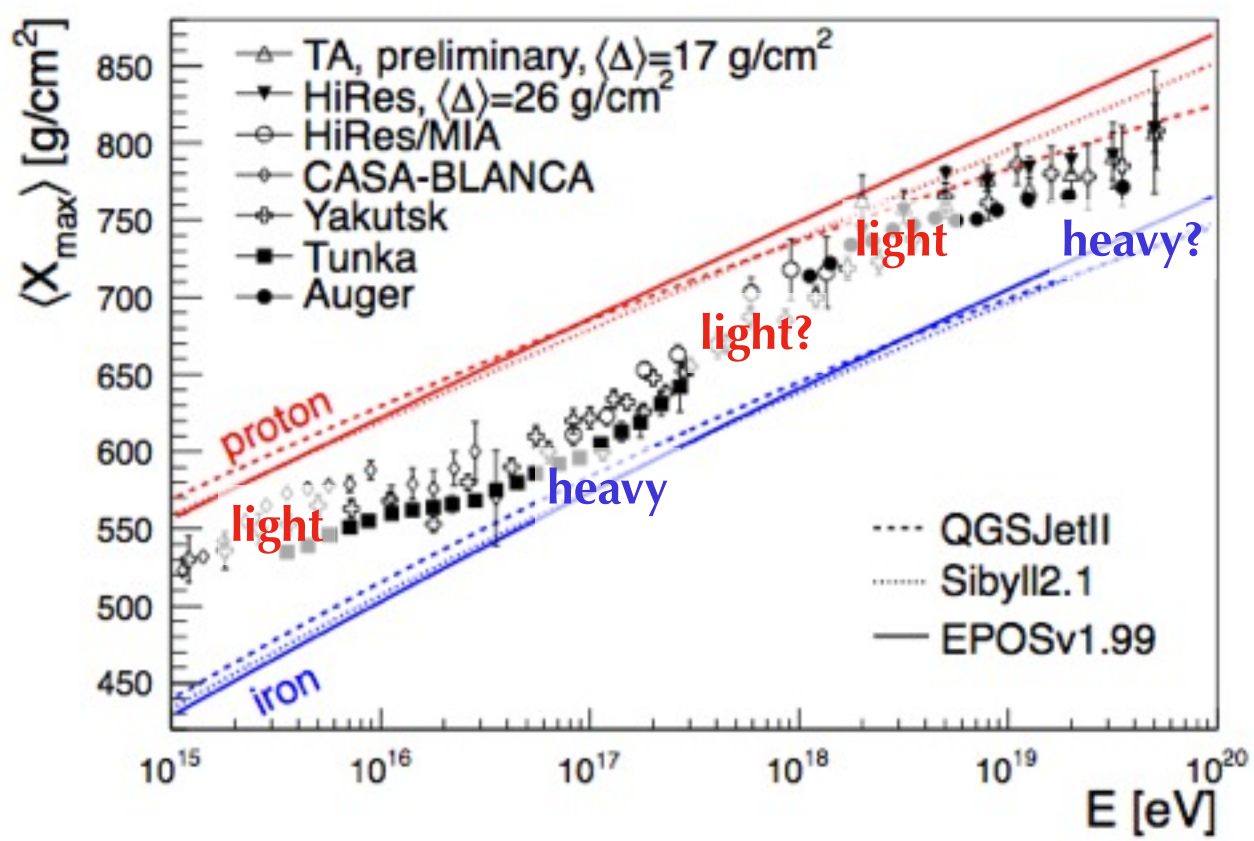

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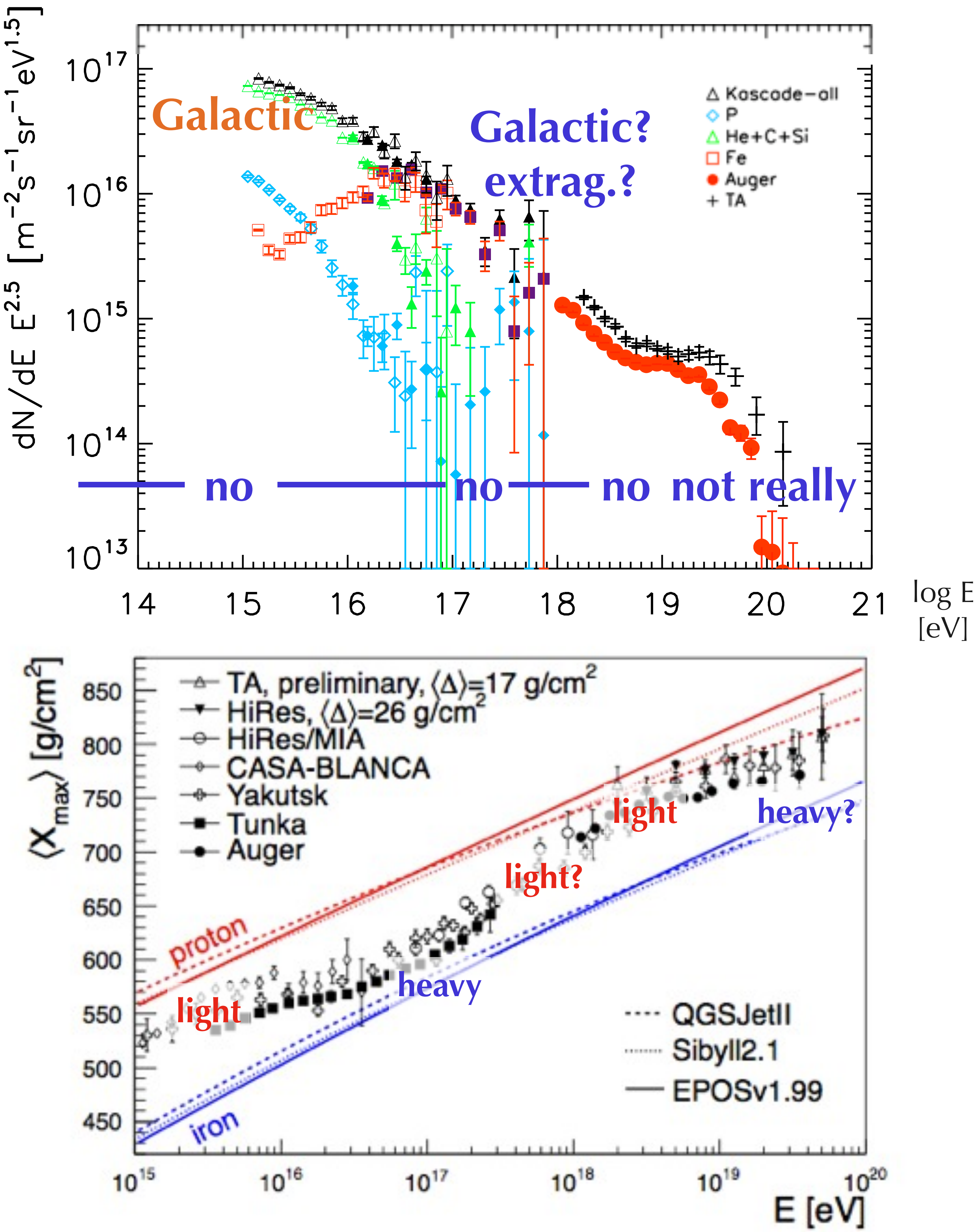

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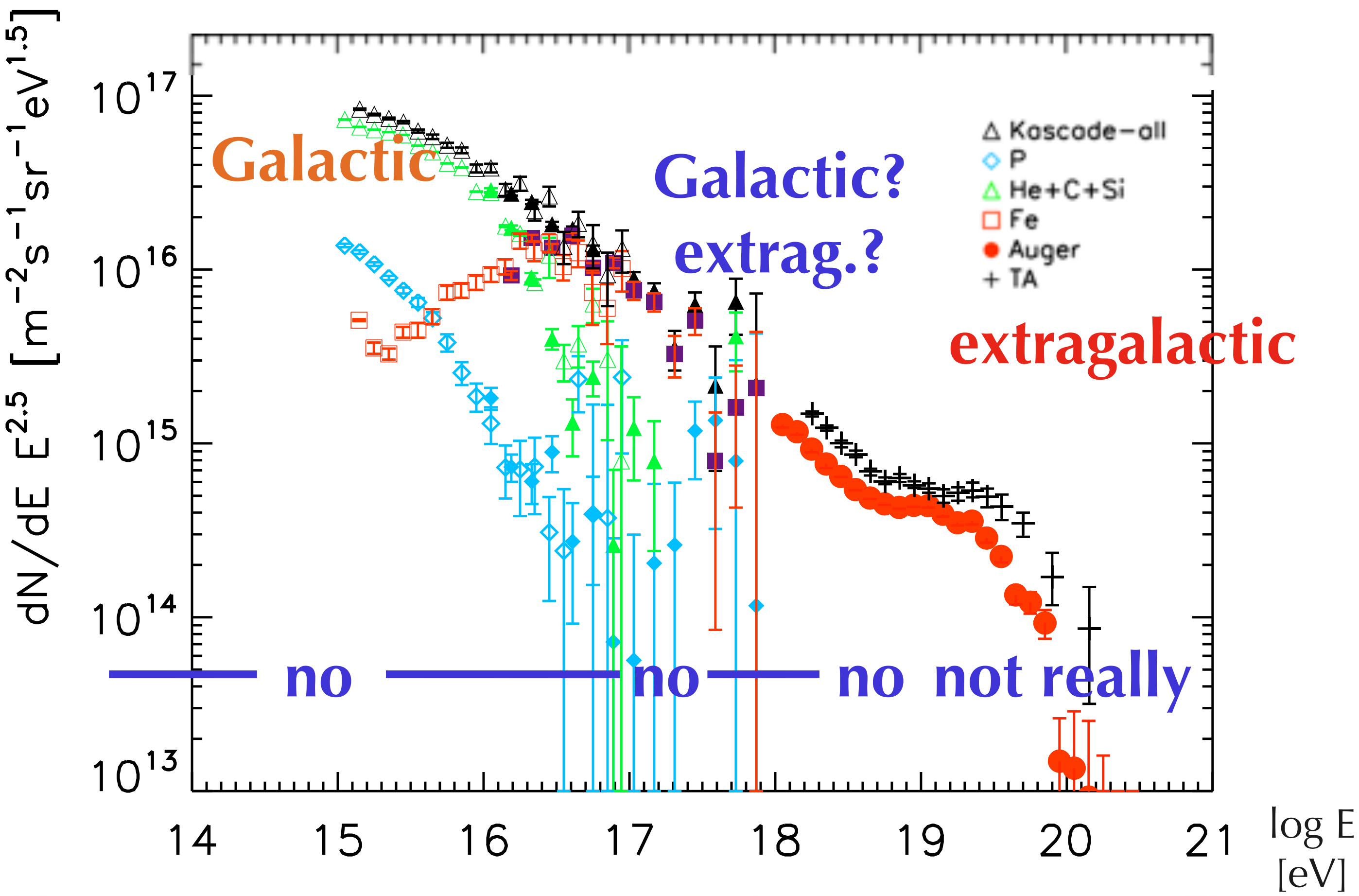

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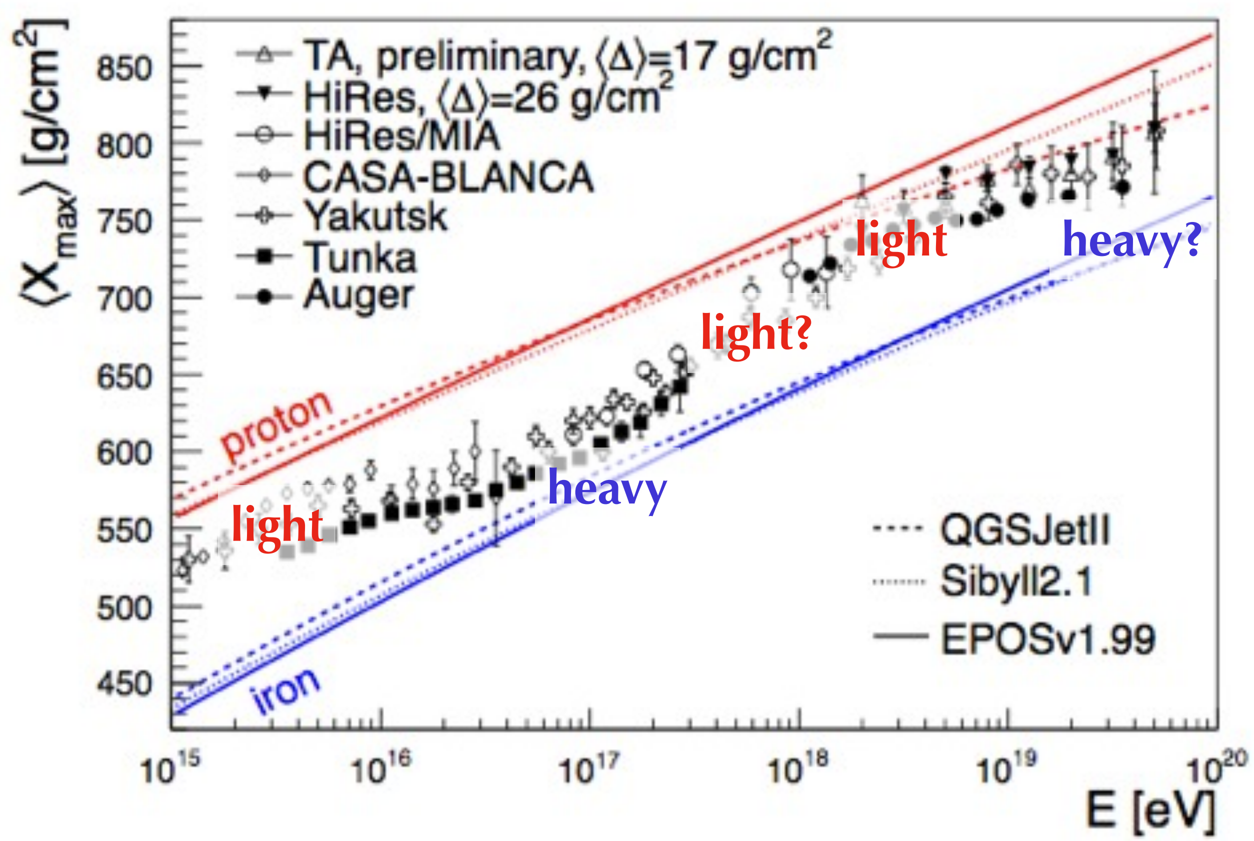

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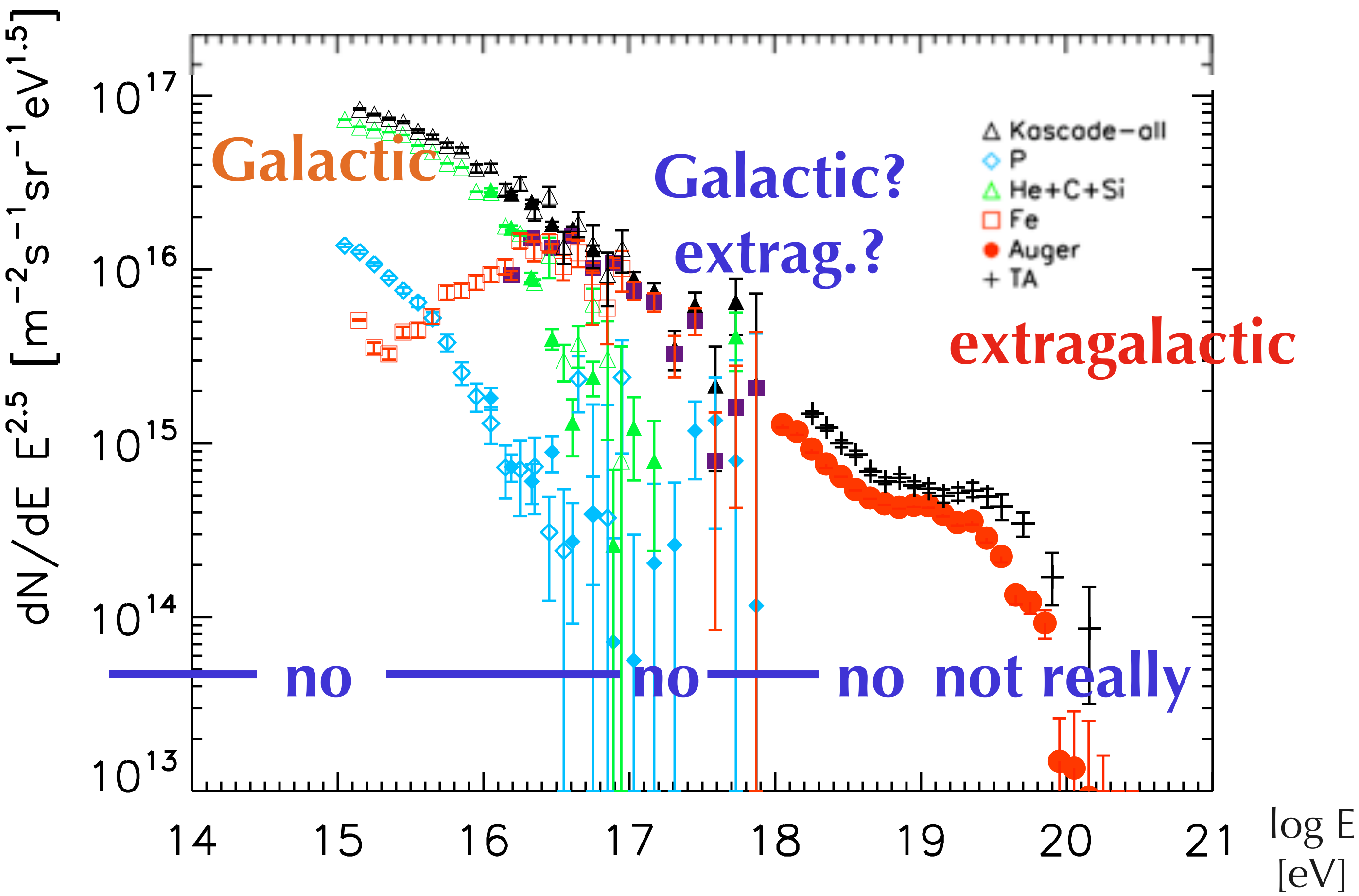
Spectrum, composition, anisotropies: tensions

UHE

origin

spectrum



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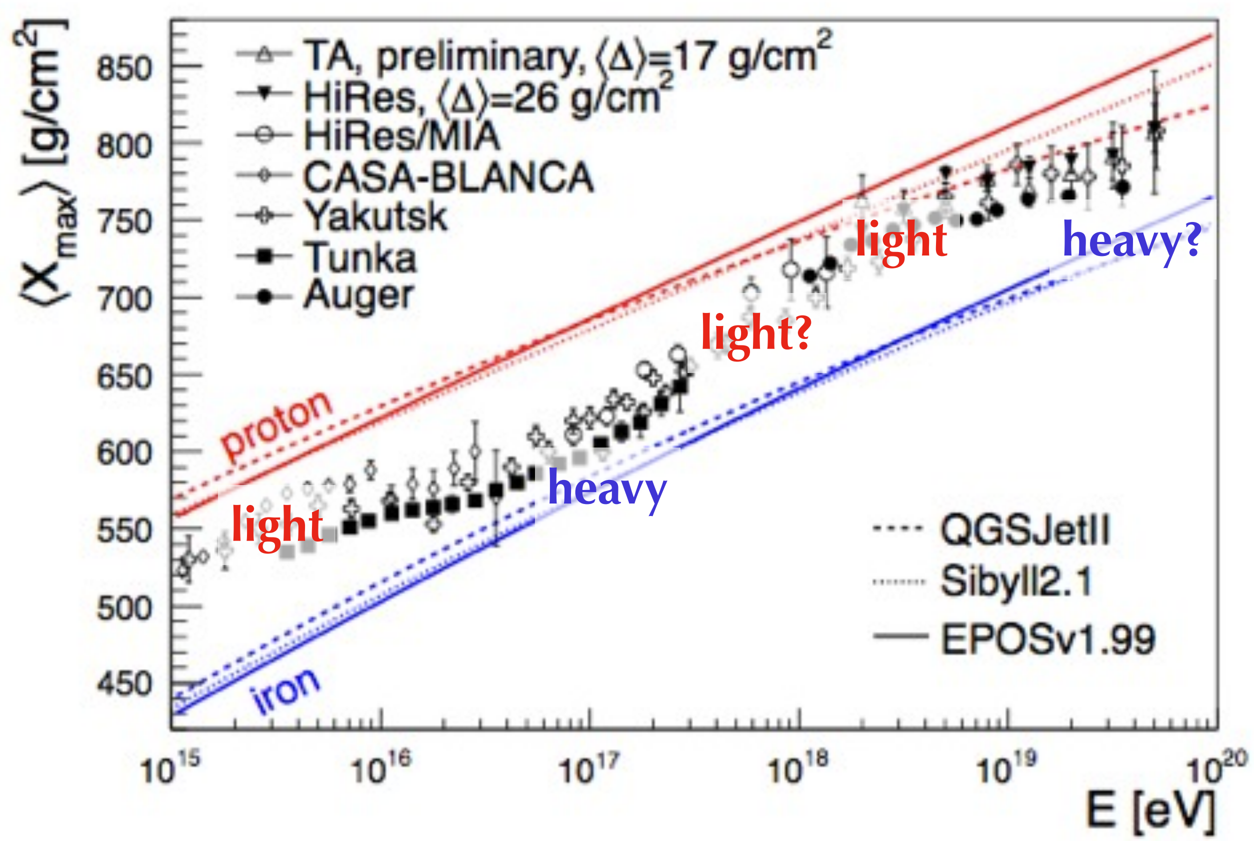

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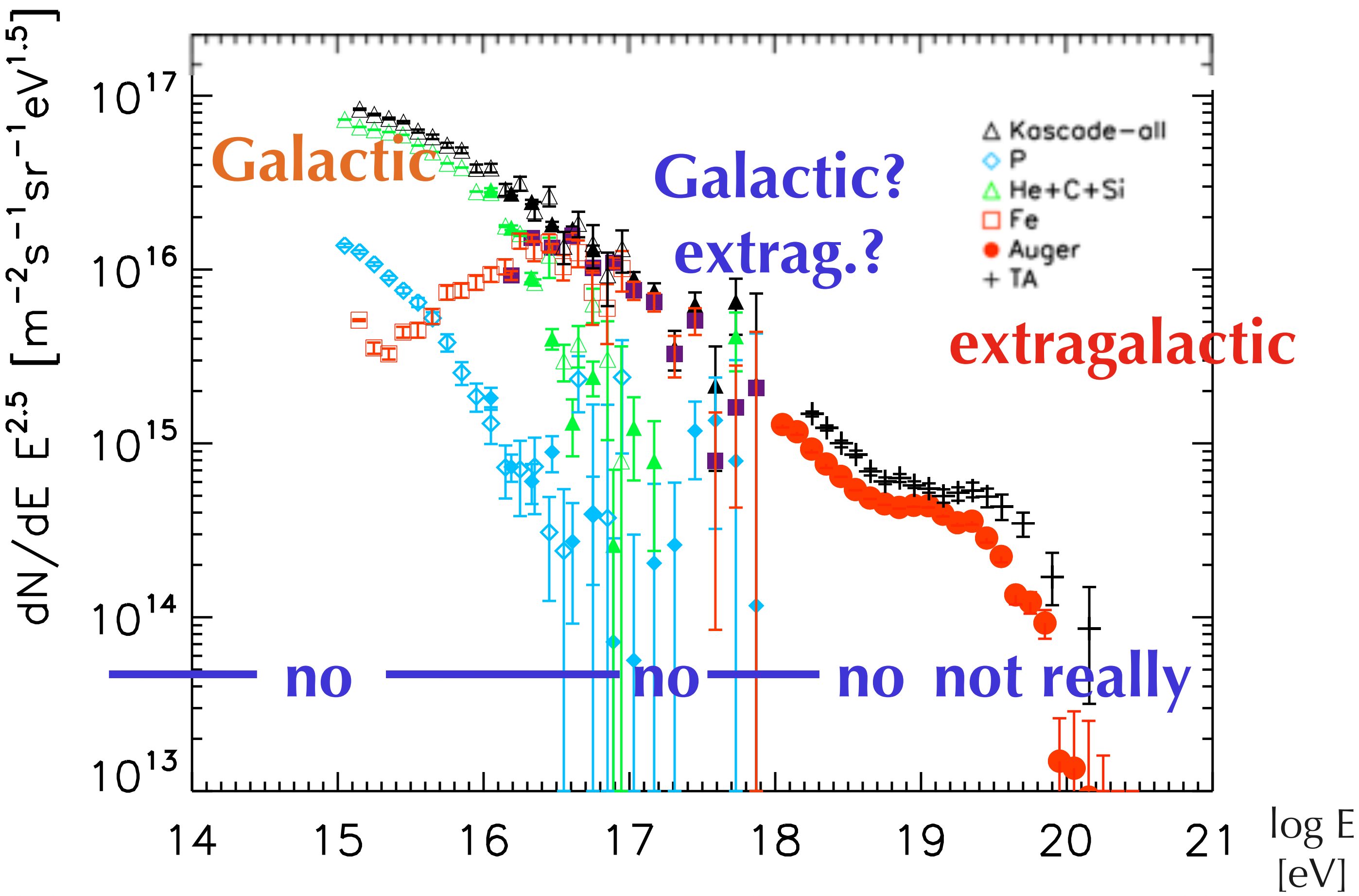

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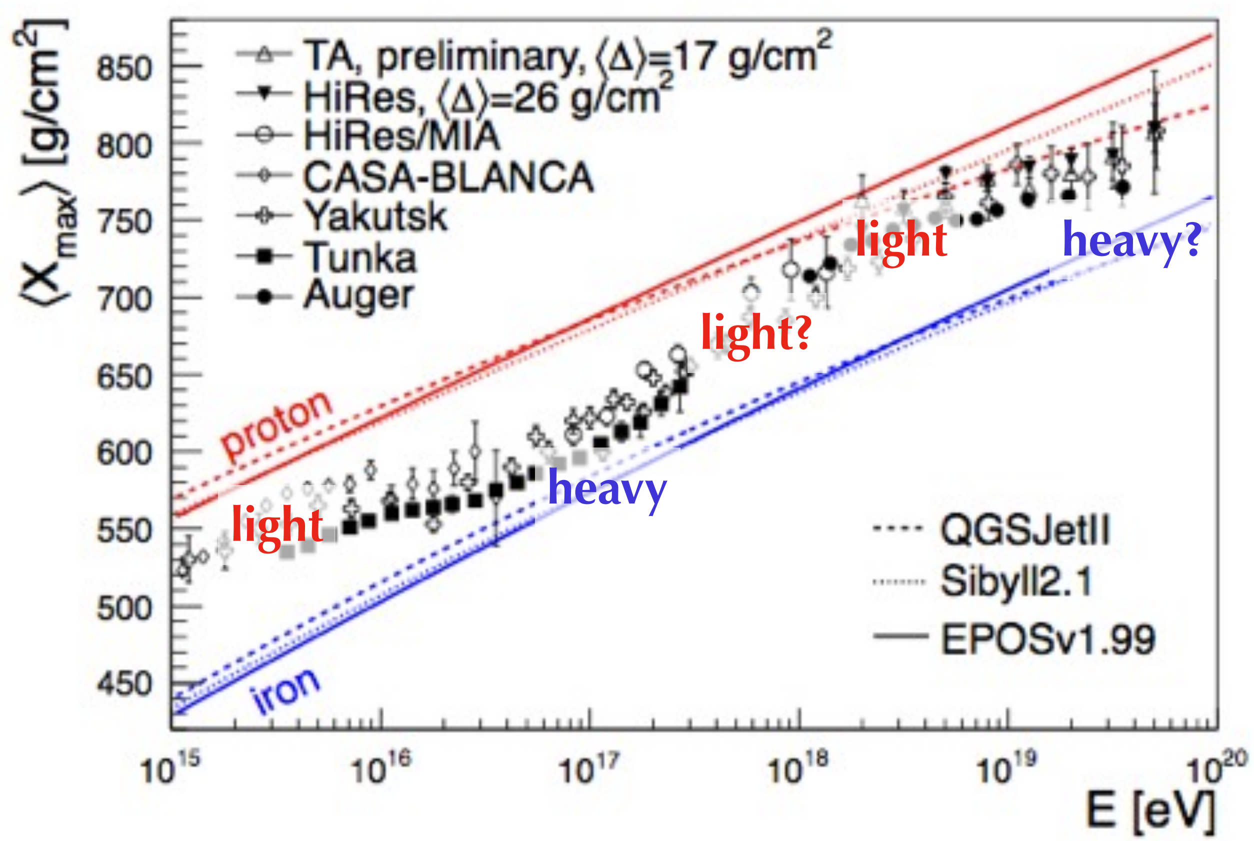
extragalactic protons

---> anisotropy?

---> auger results?

composition



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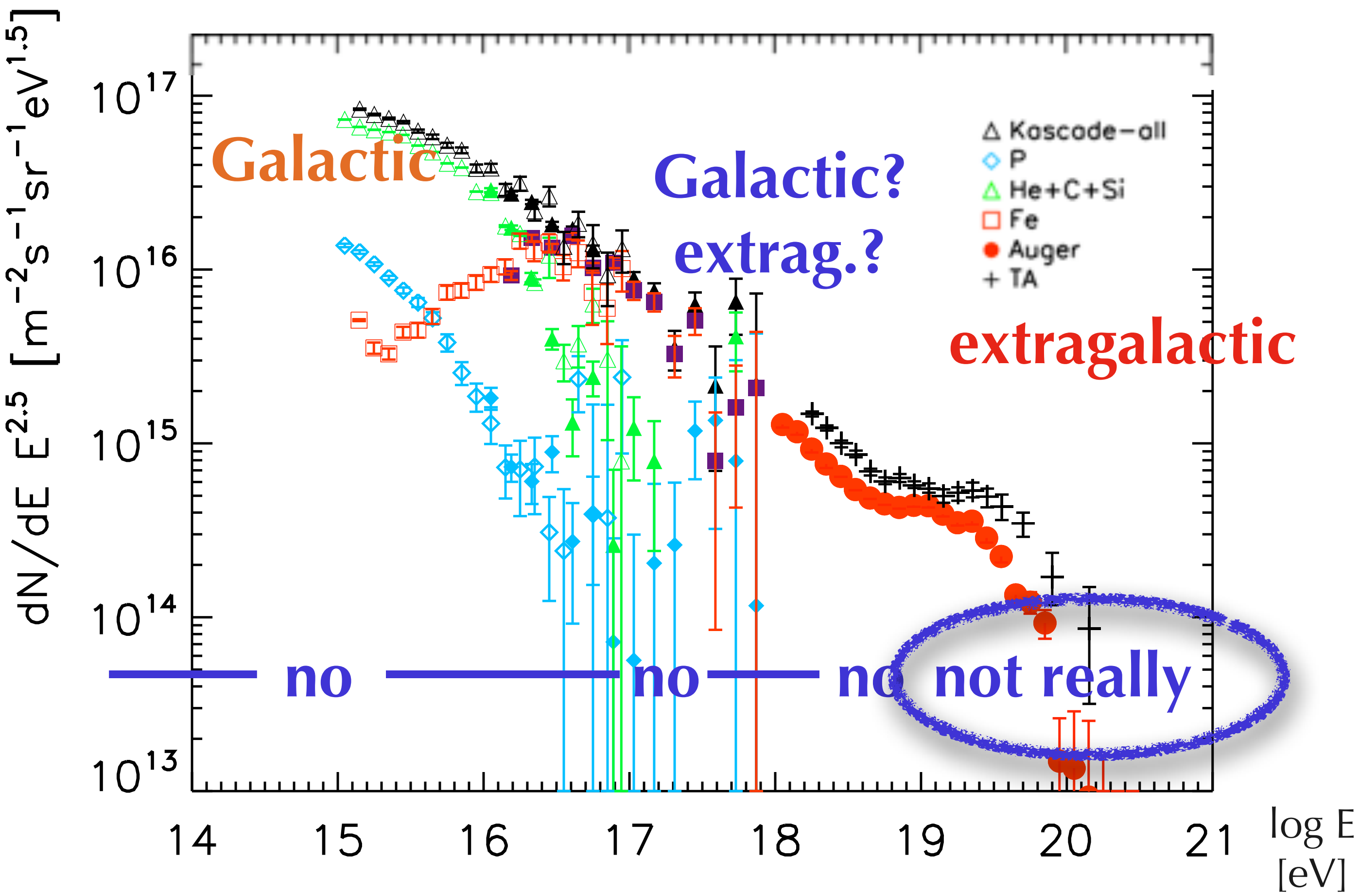

anisotropy
Tibet Coll. (2005)
EAS-TOP (2003)
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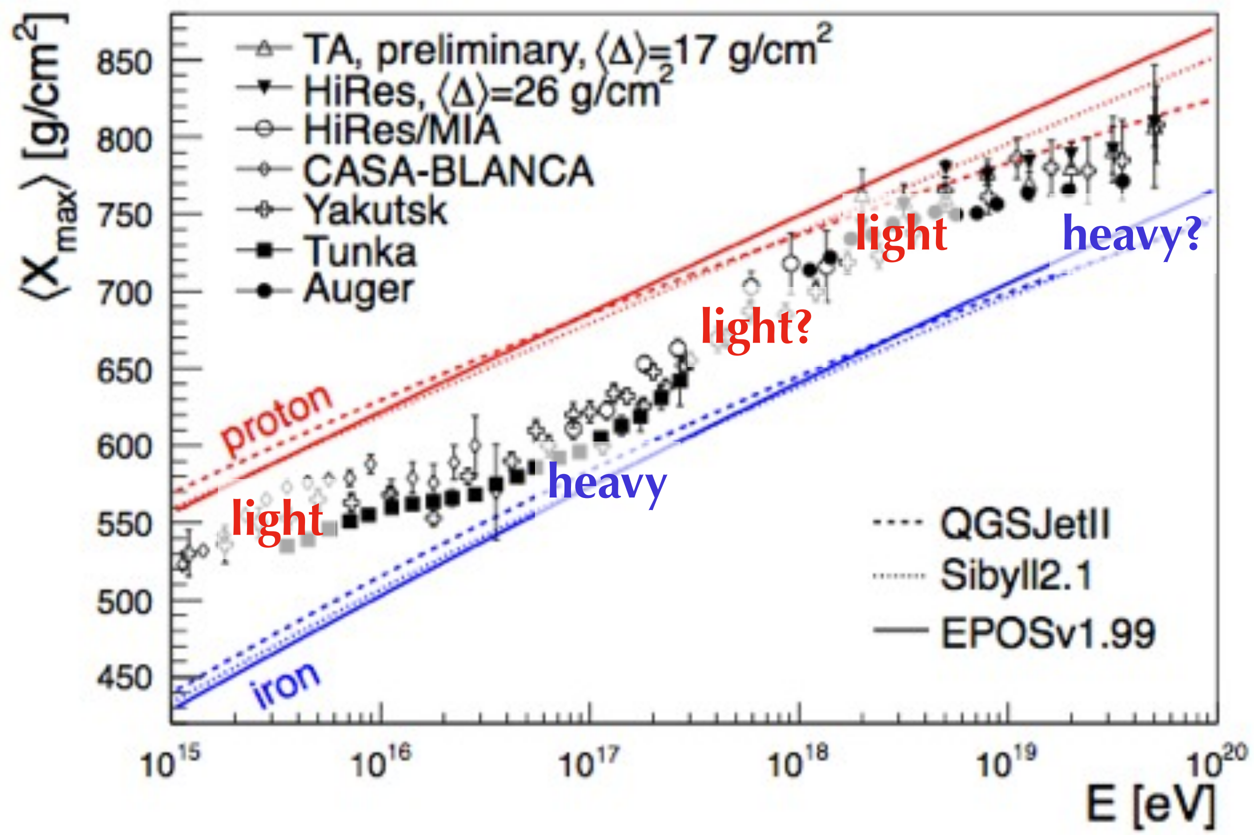


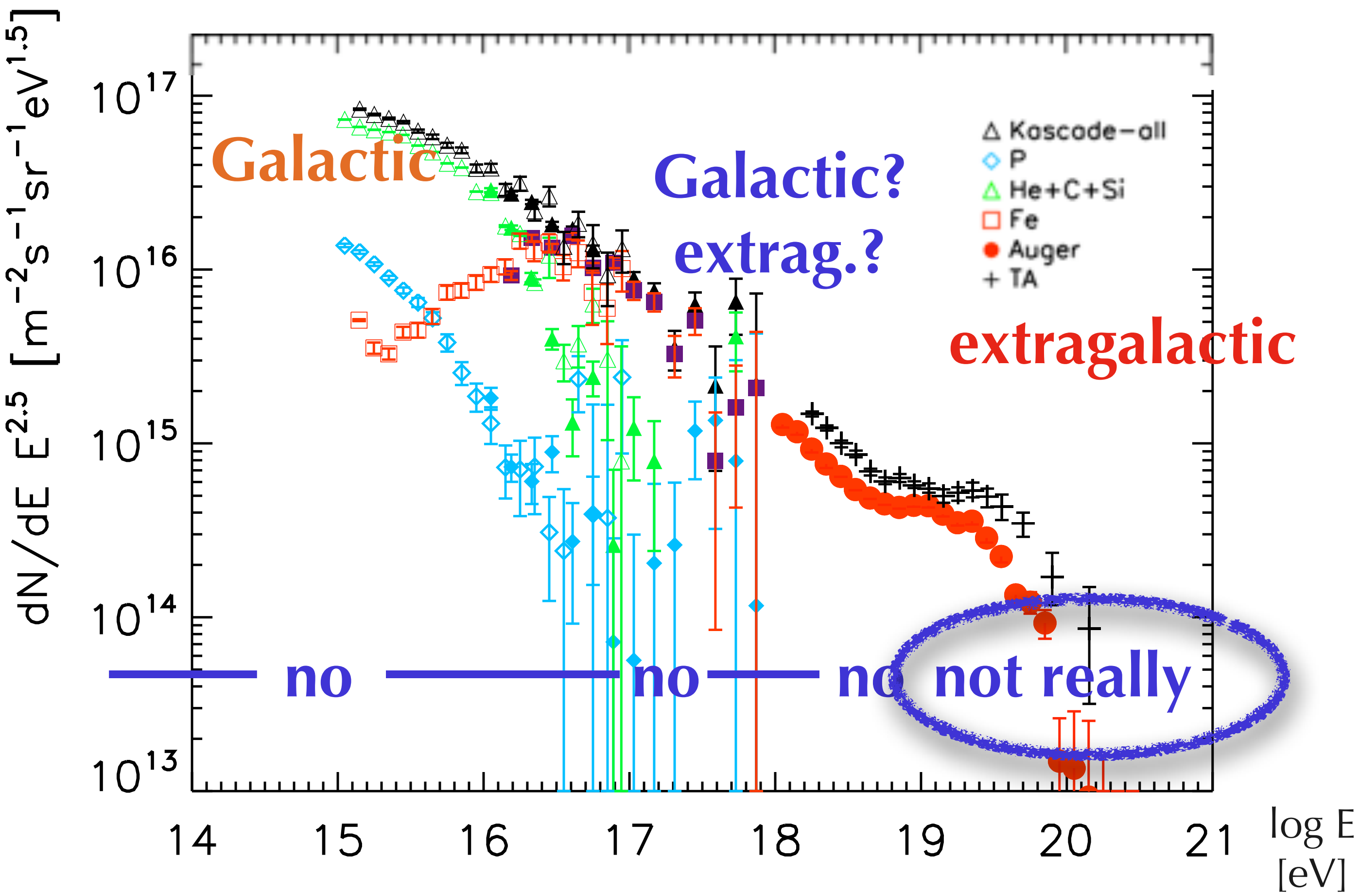
composition

Spectrum, composition, anisotropies: tensions

UHE

origin

spectrum



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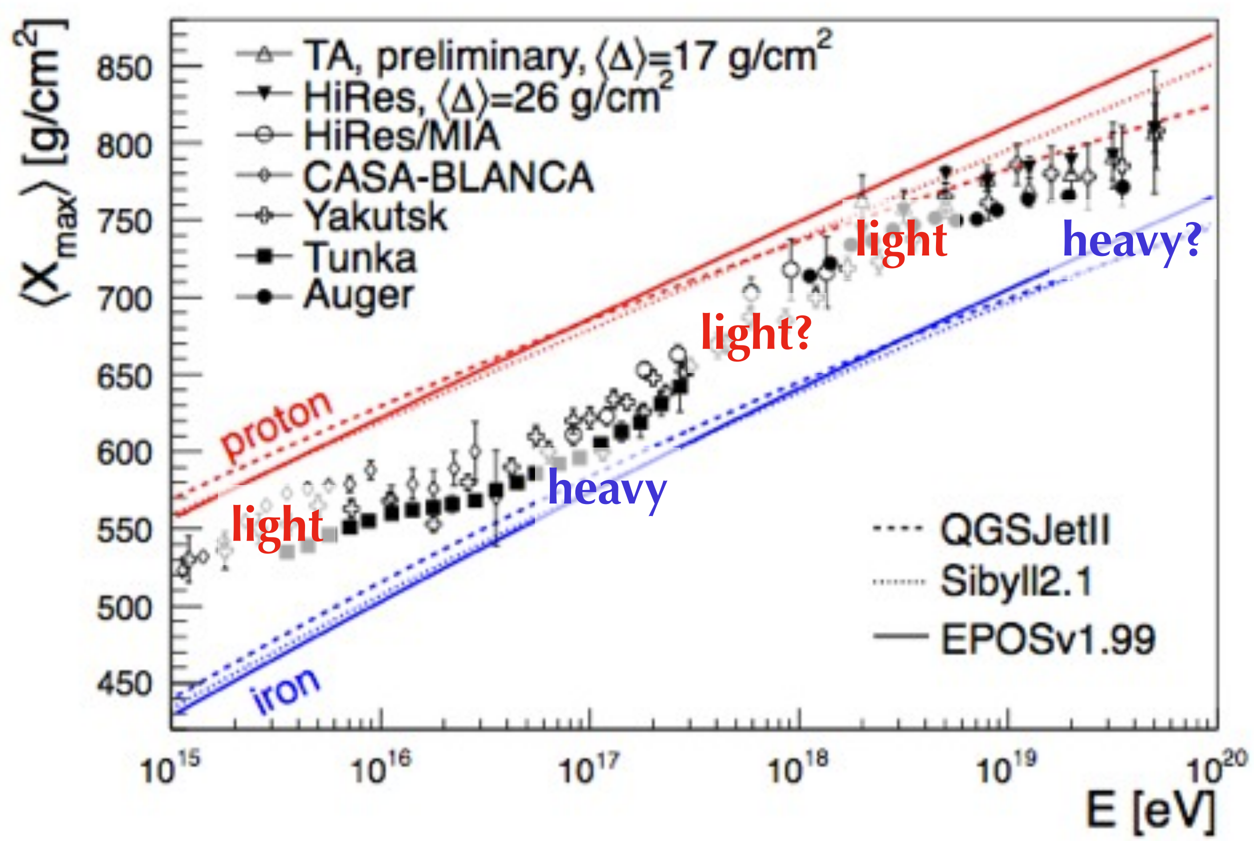

composition

extragalactic protons
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Spectrum, composition, anisotropies: tensions

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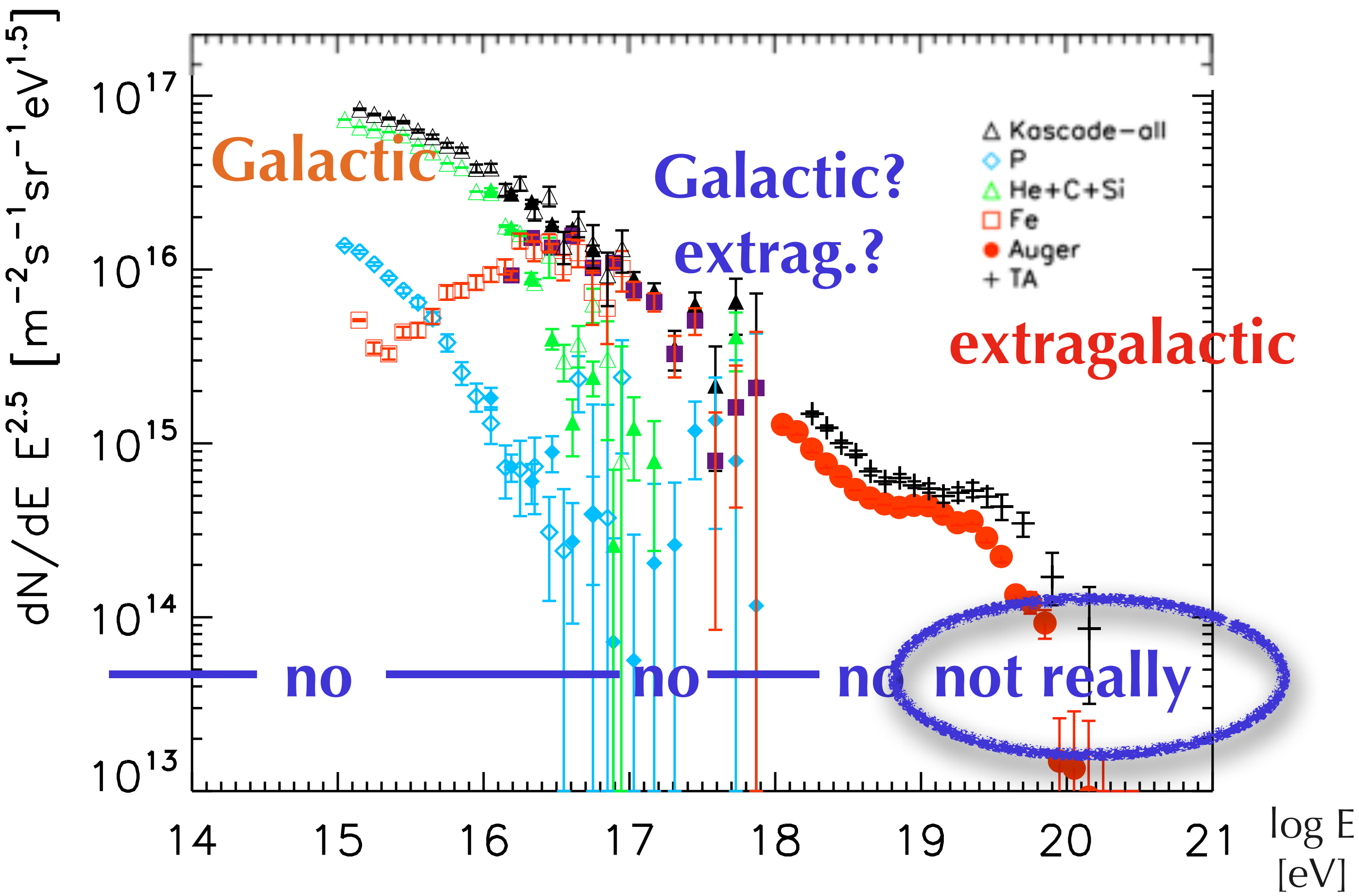

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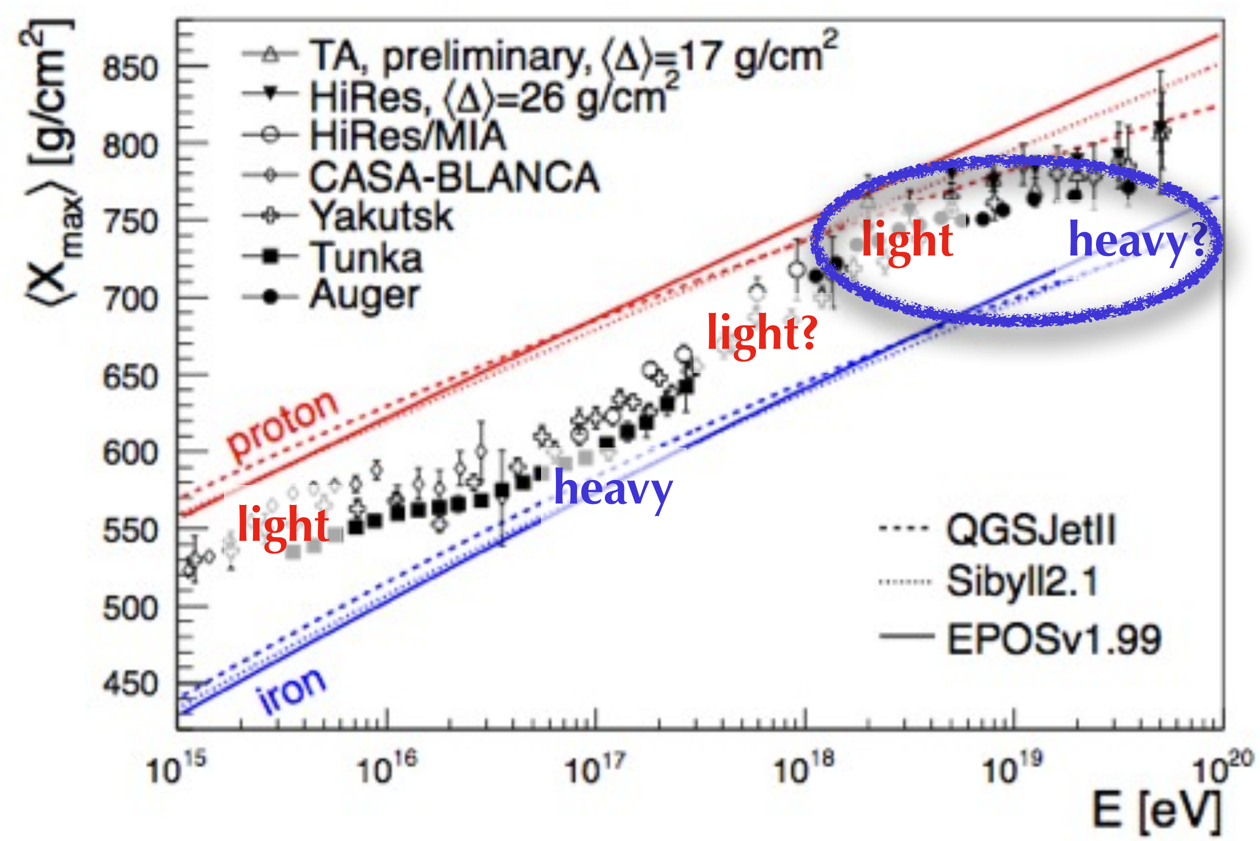

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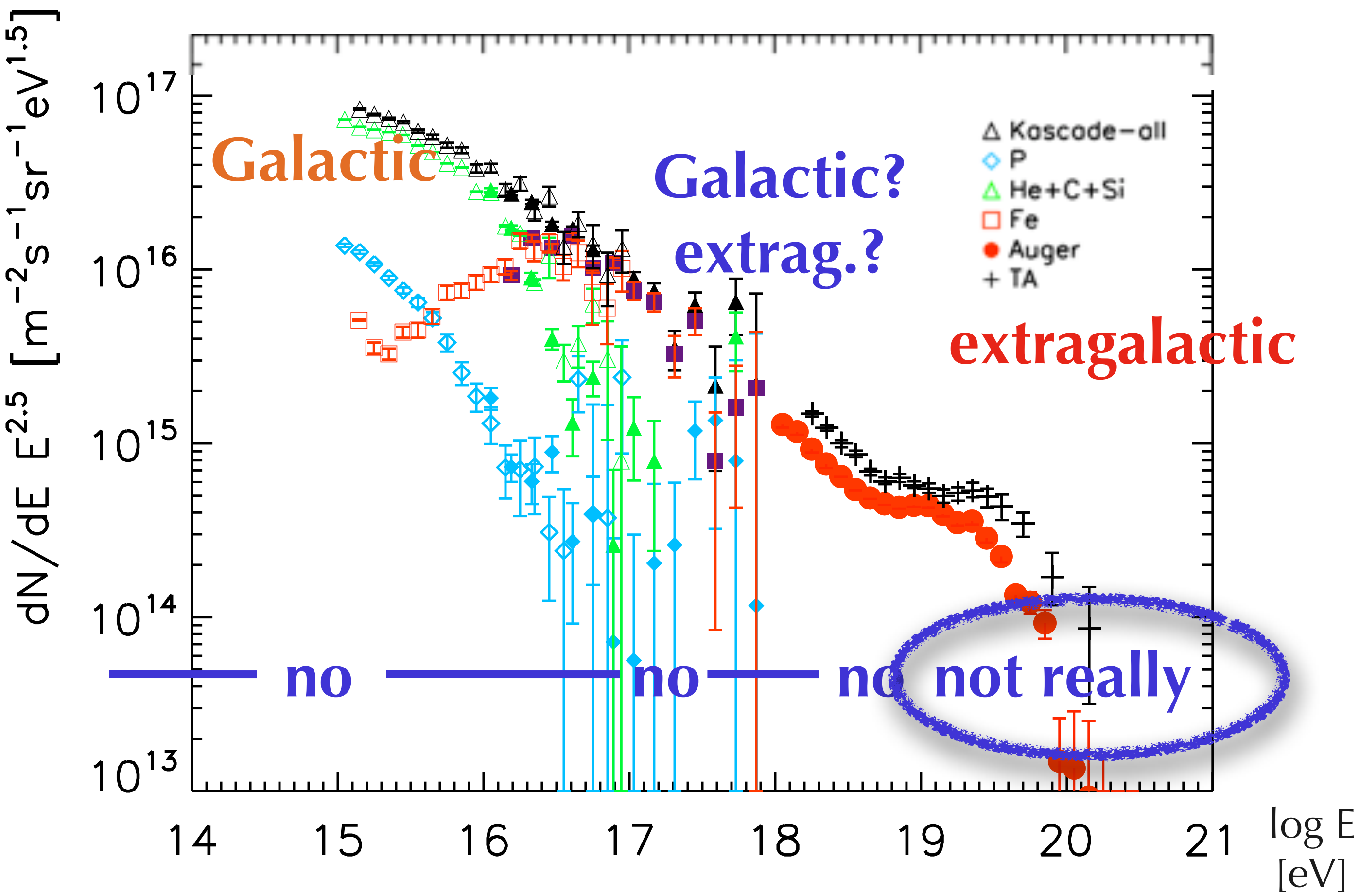

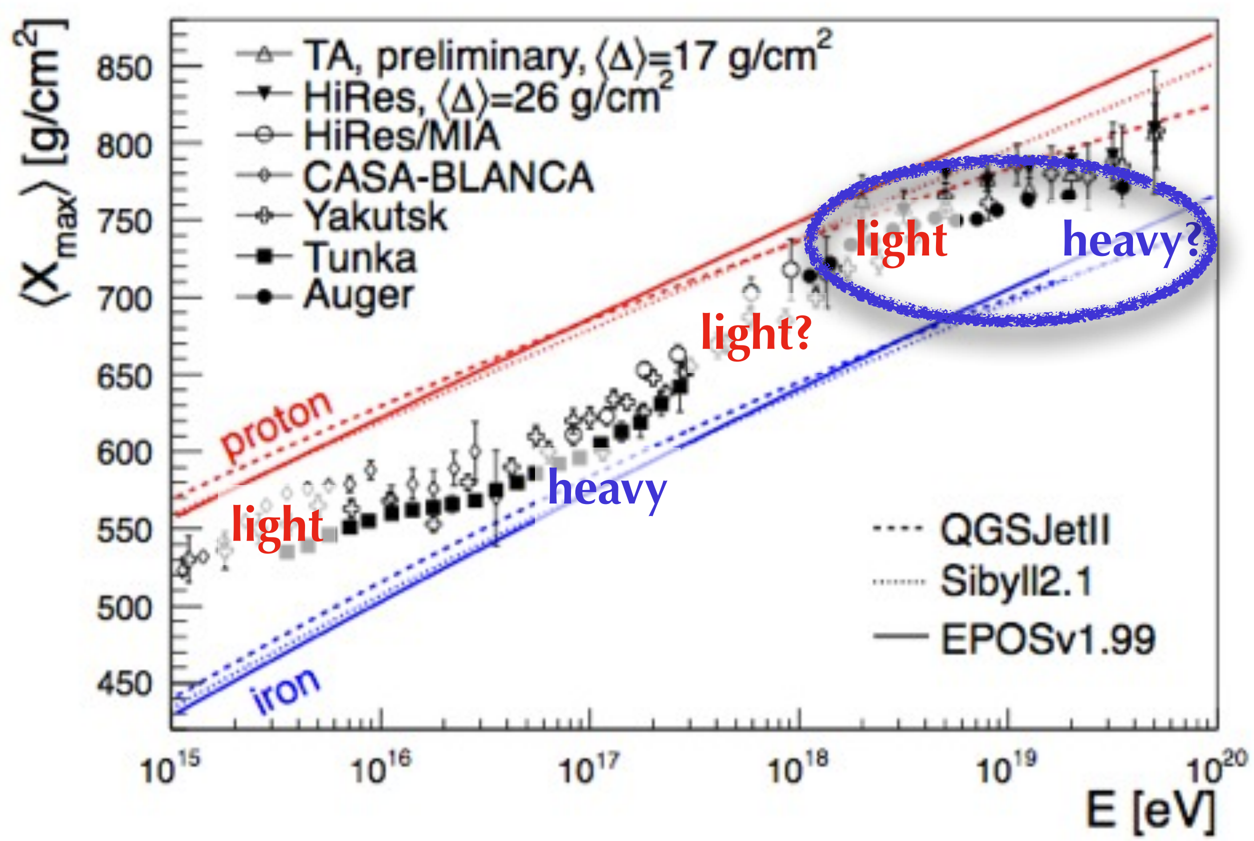

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Spectrum, composition, anisotropies: tensions

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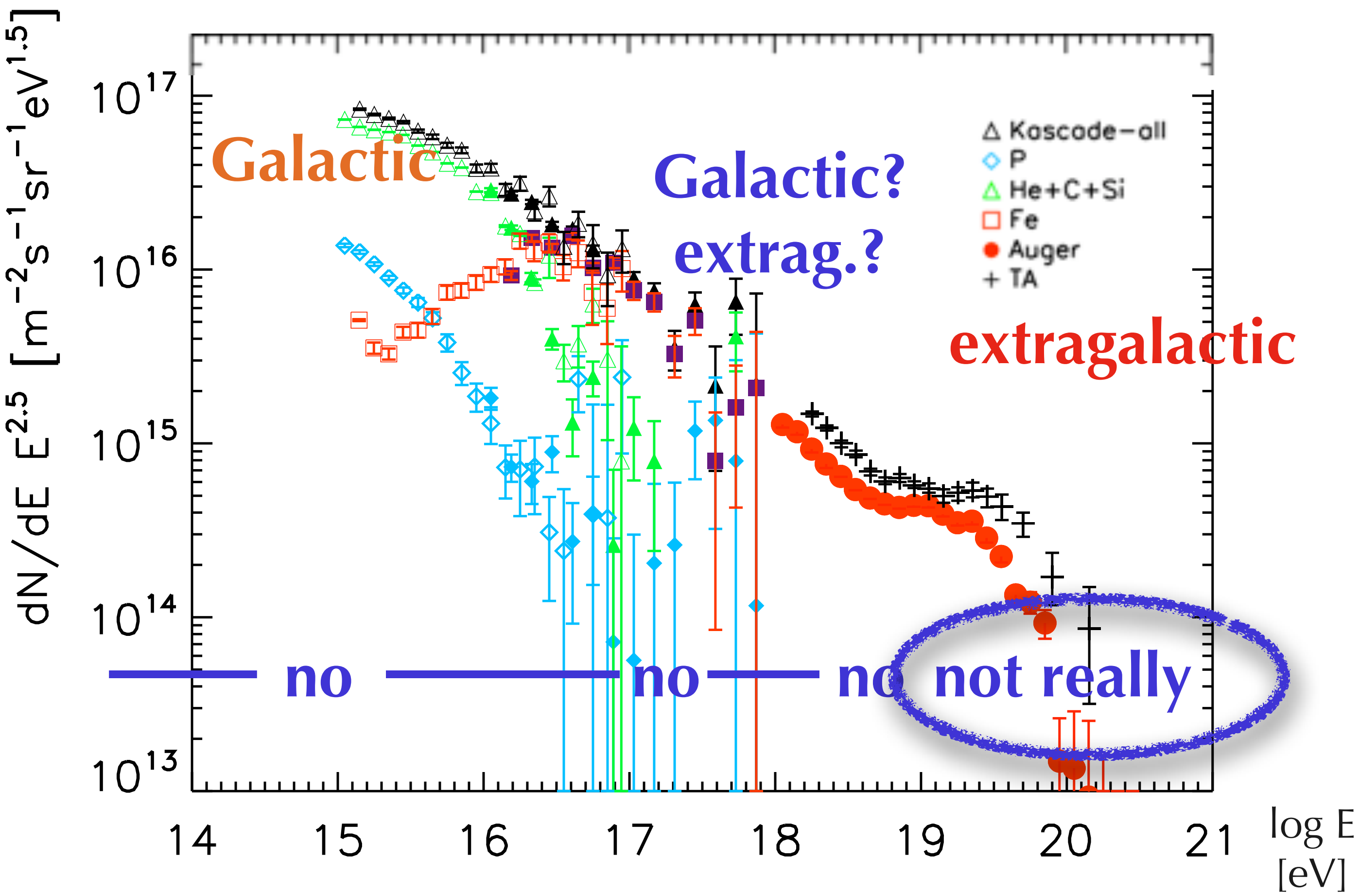

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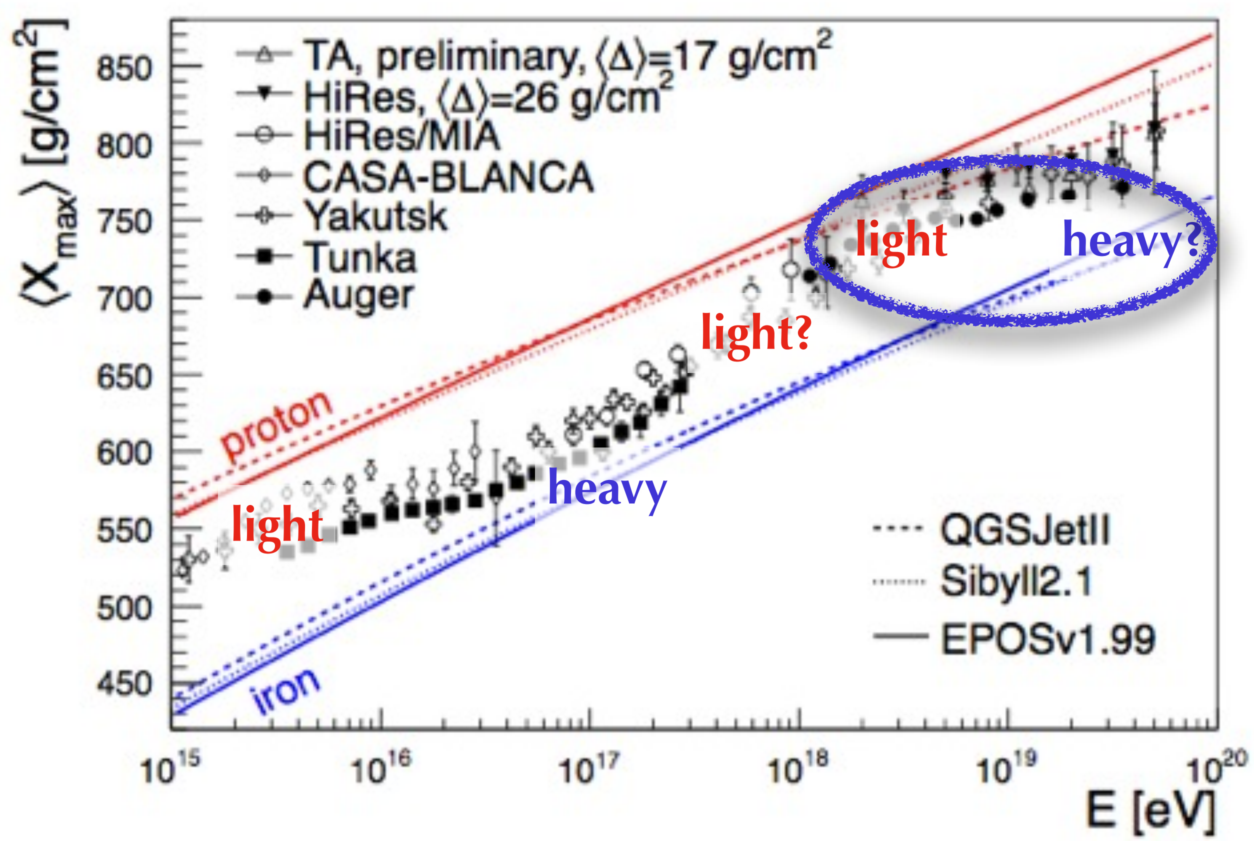

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Galactic protons
---> anisotropy?
---> in which source?

Spectrum, composition, anisotropies: tensions

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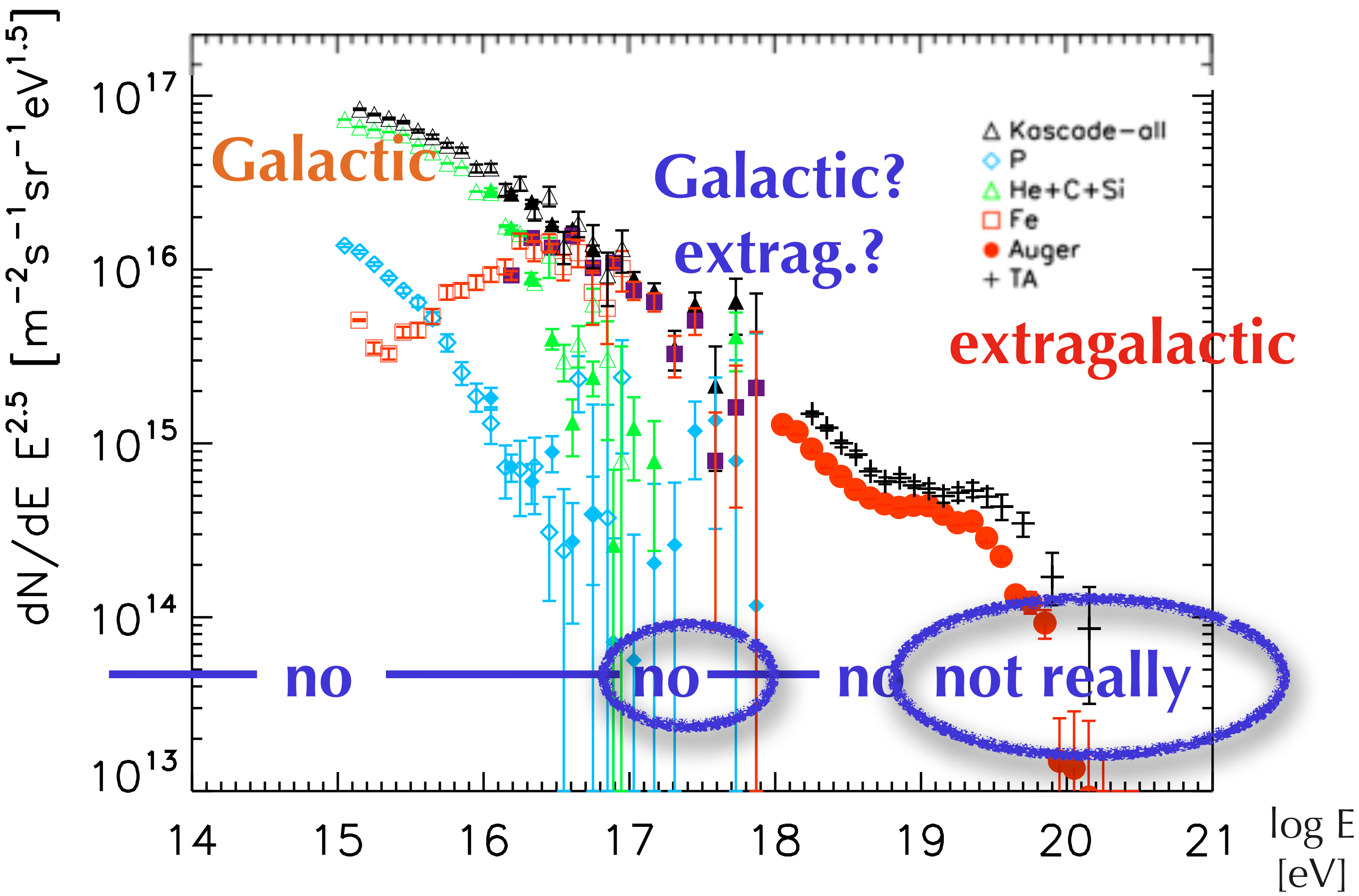

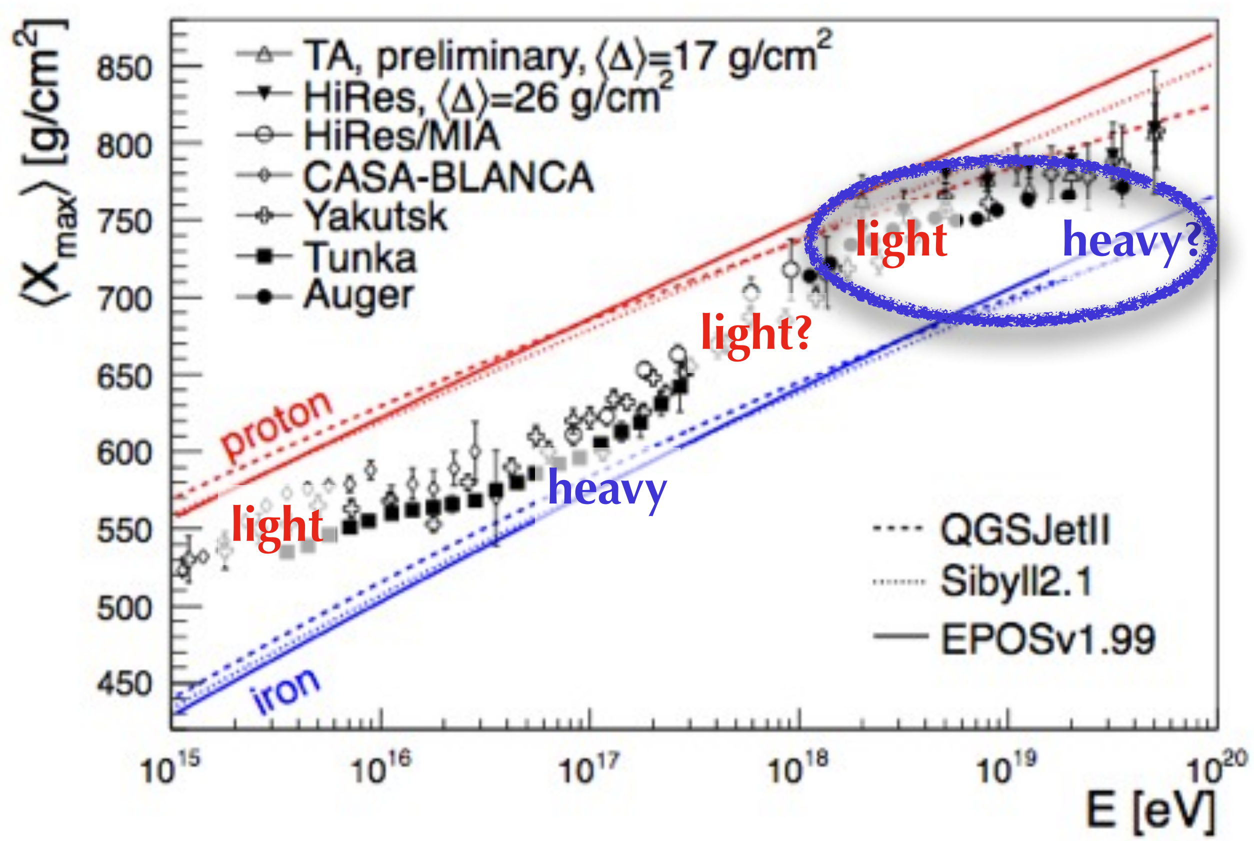

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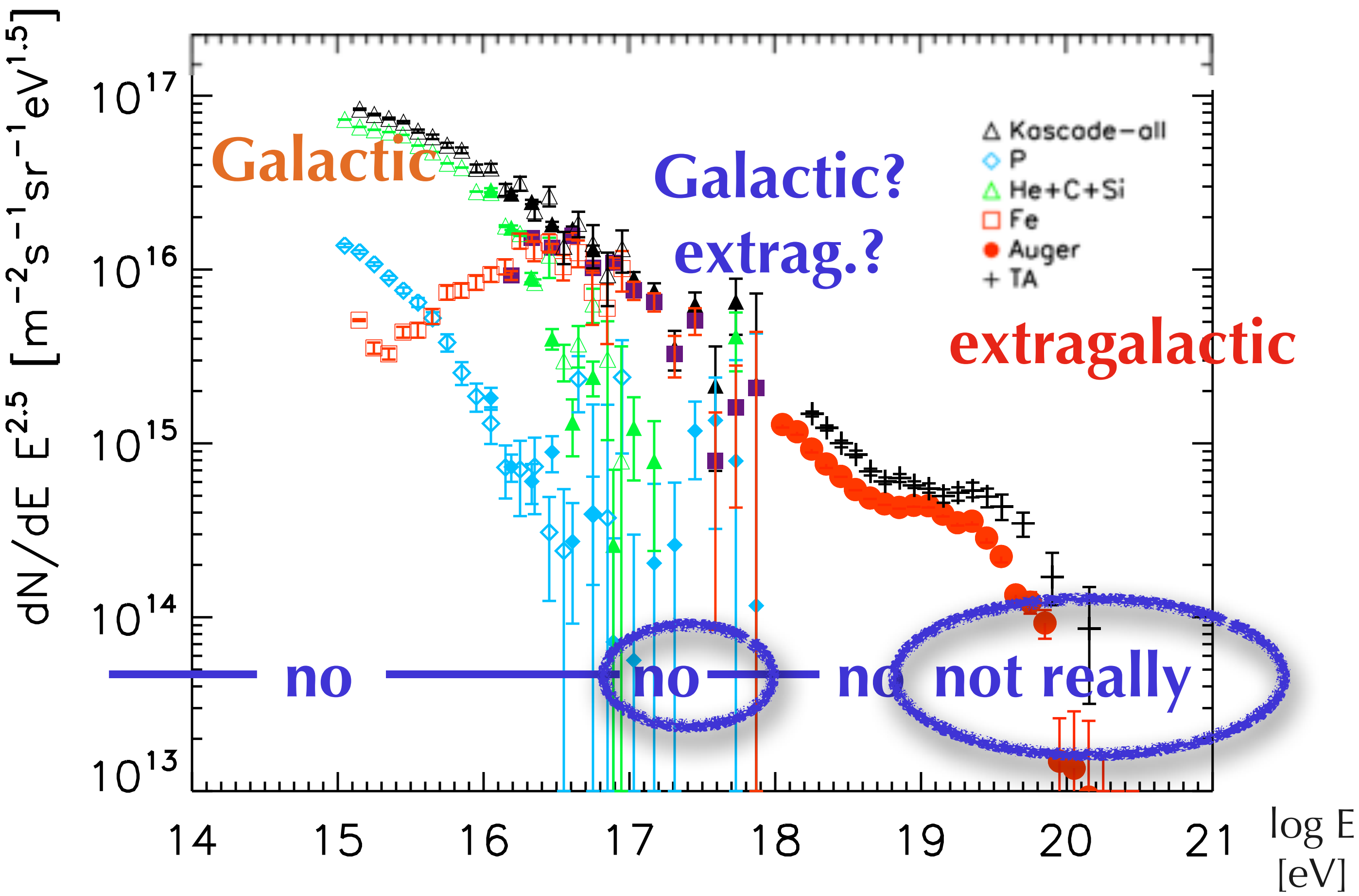

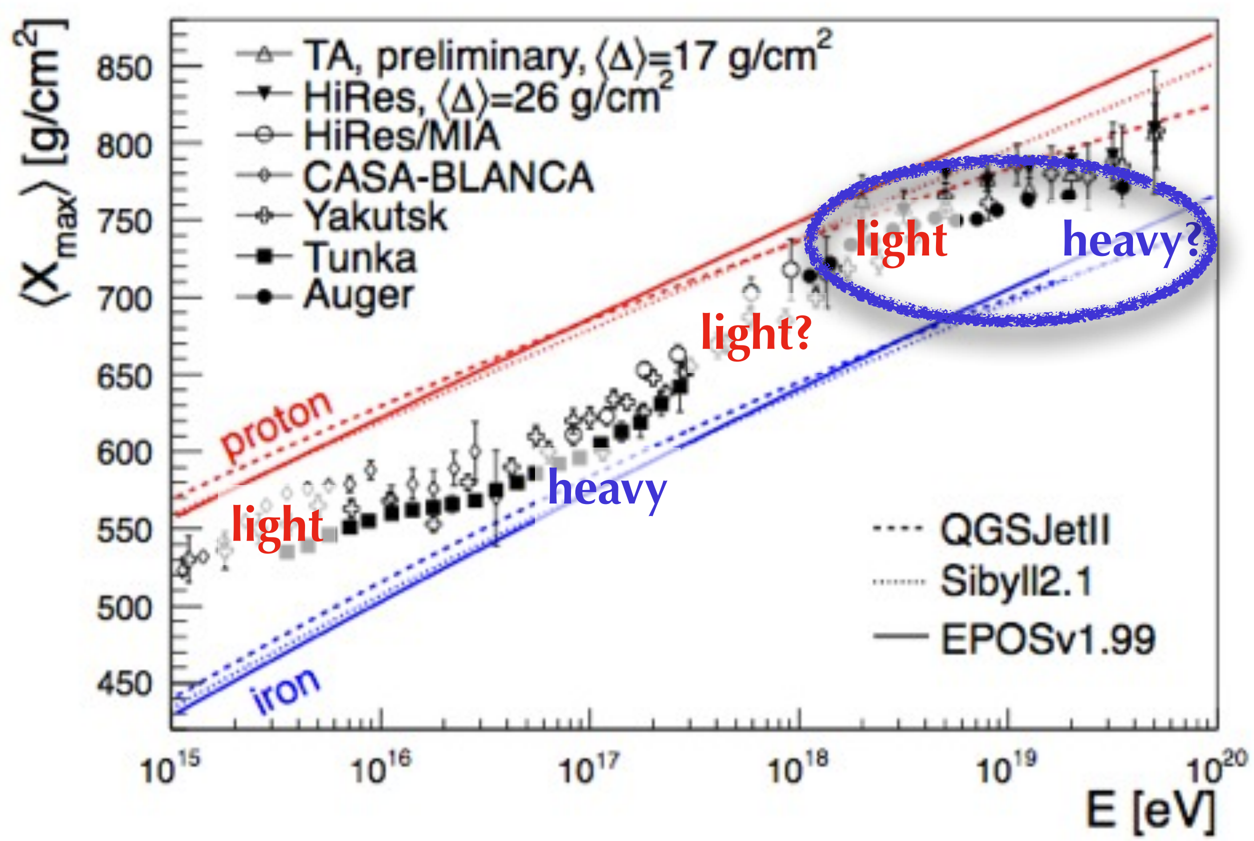

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Spectrum, composition, anisotropies: tensions

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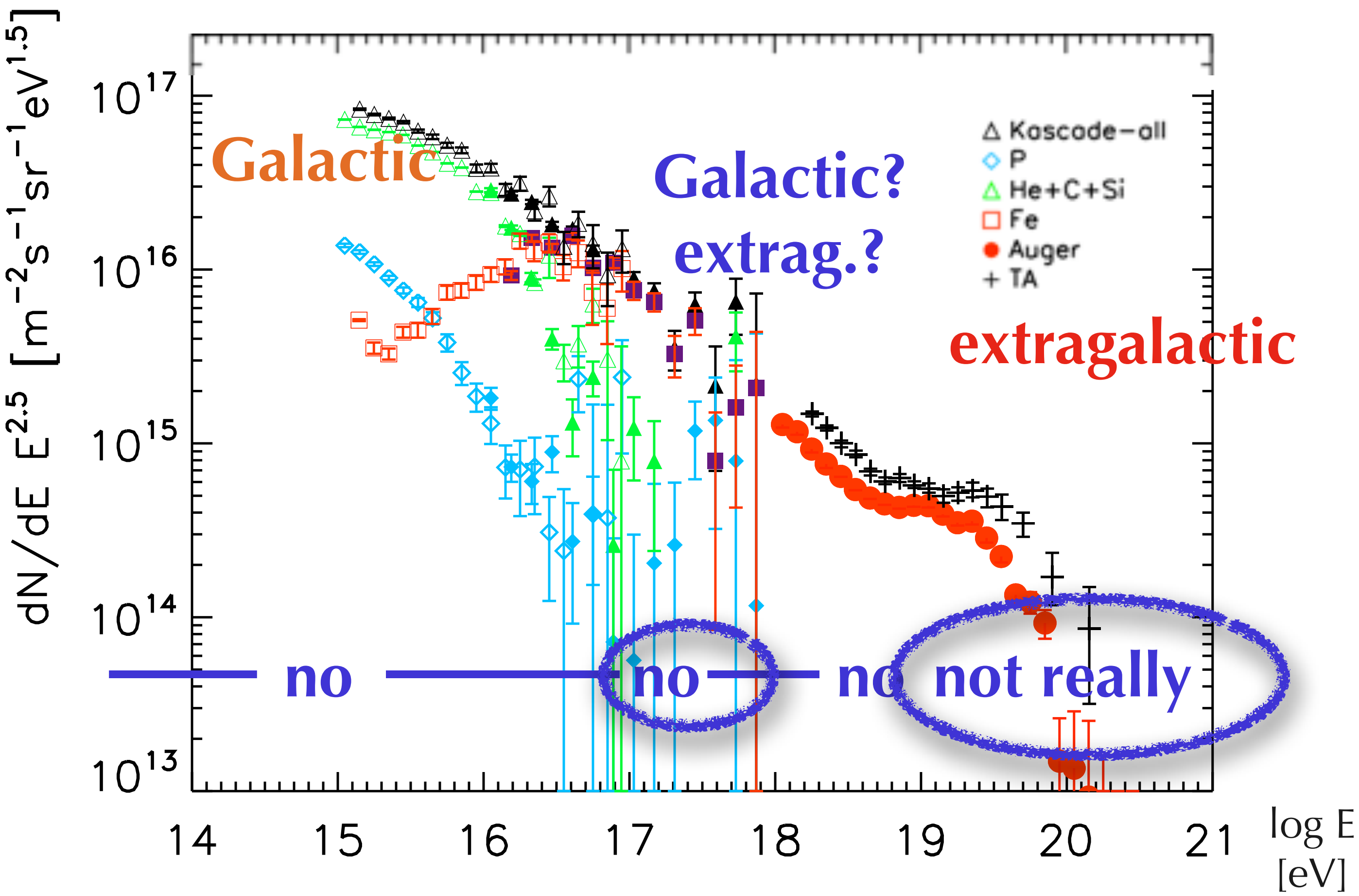

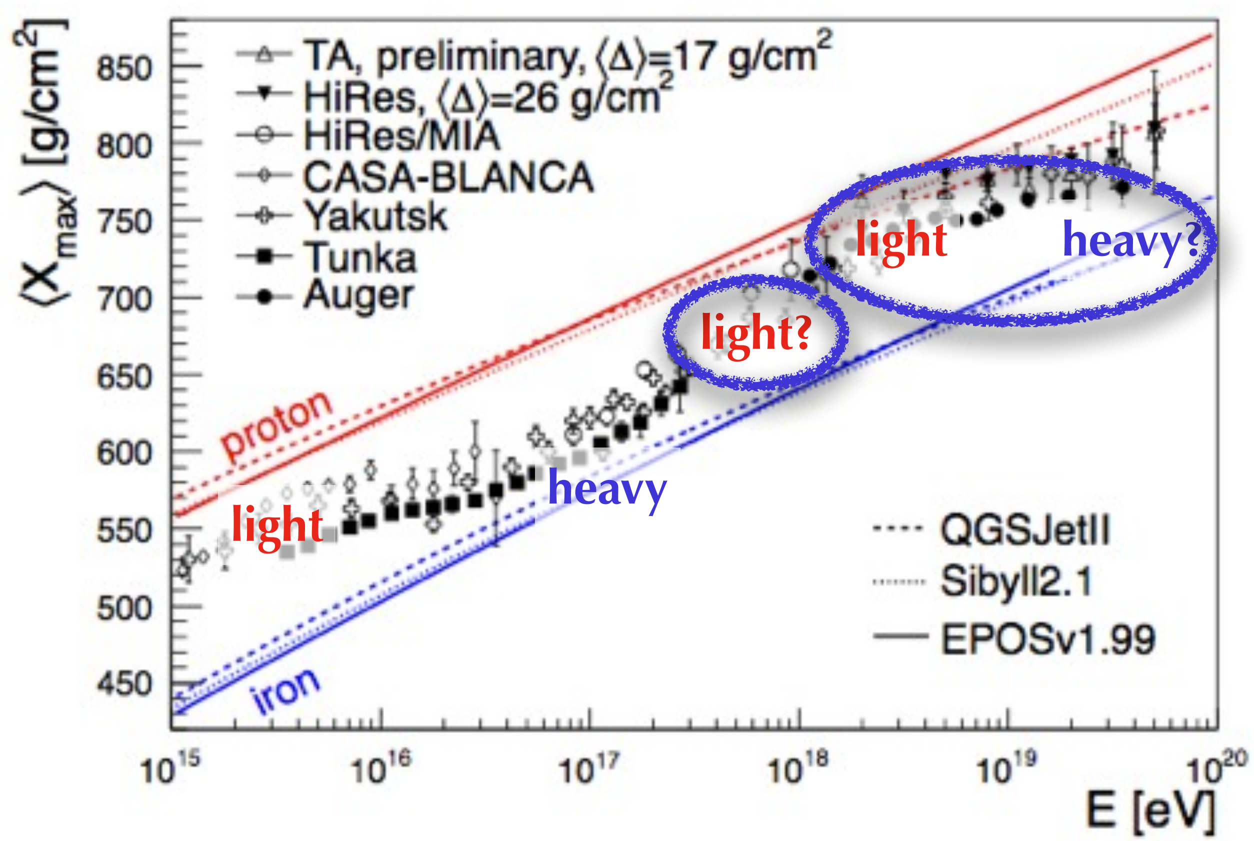

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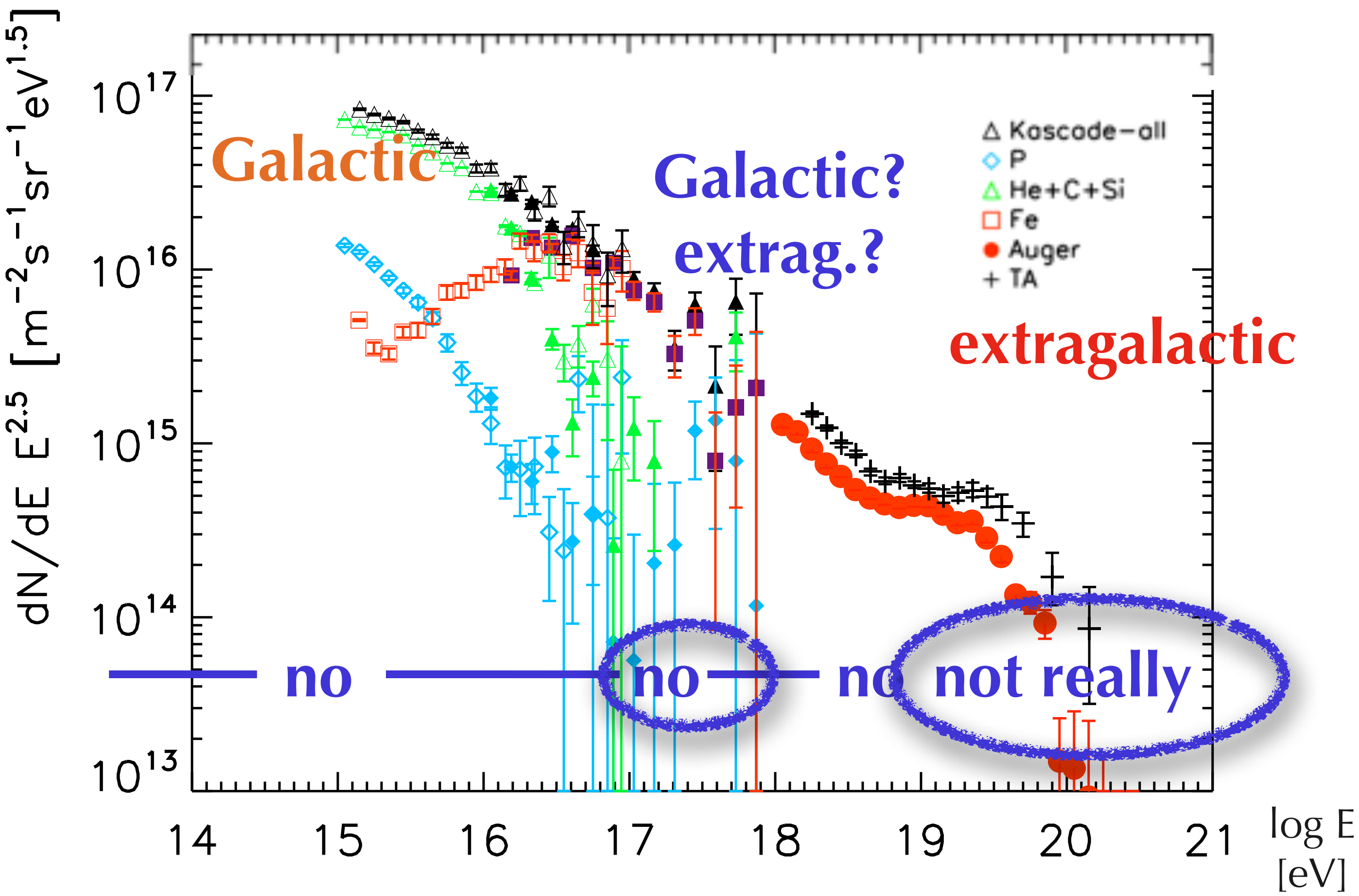

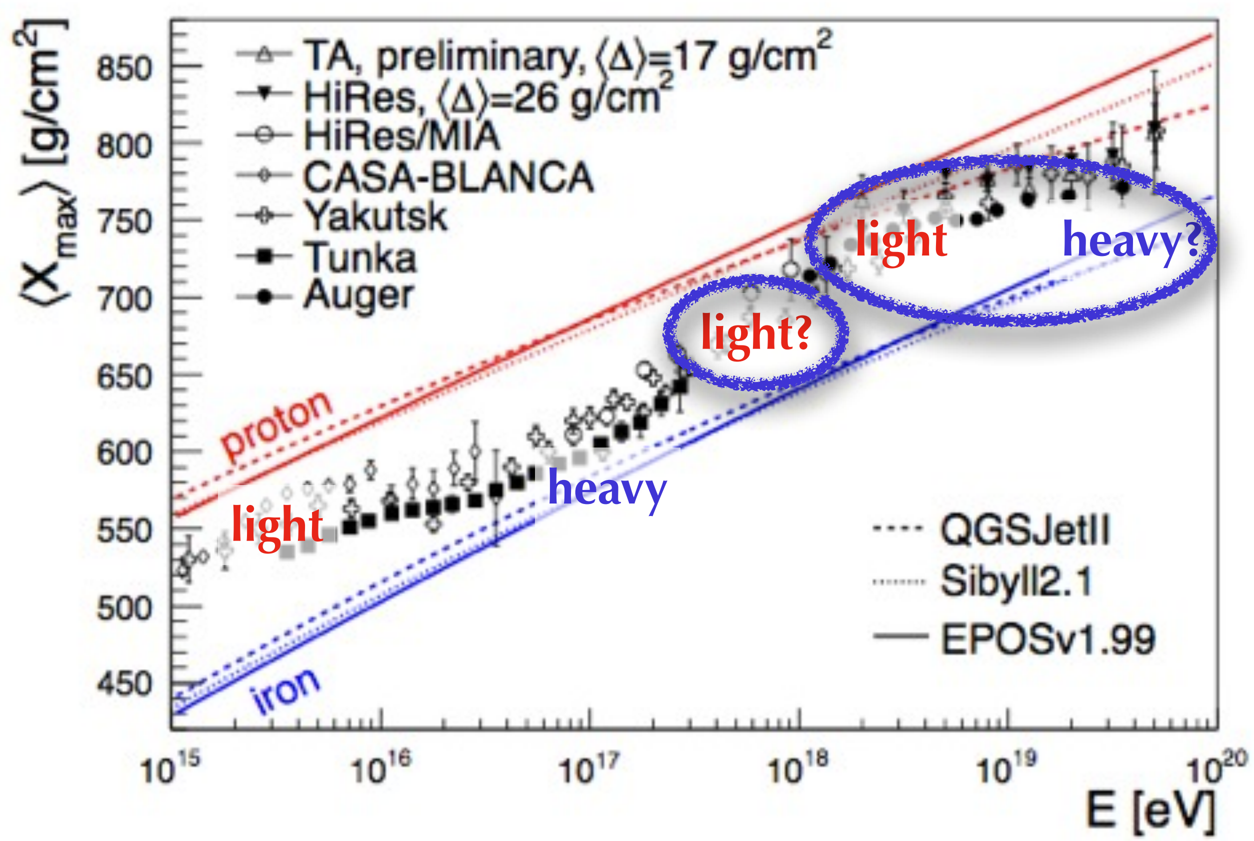

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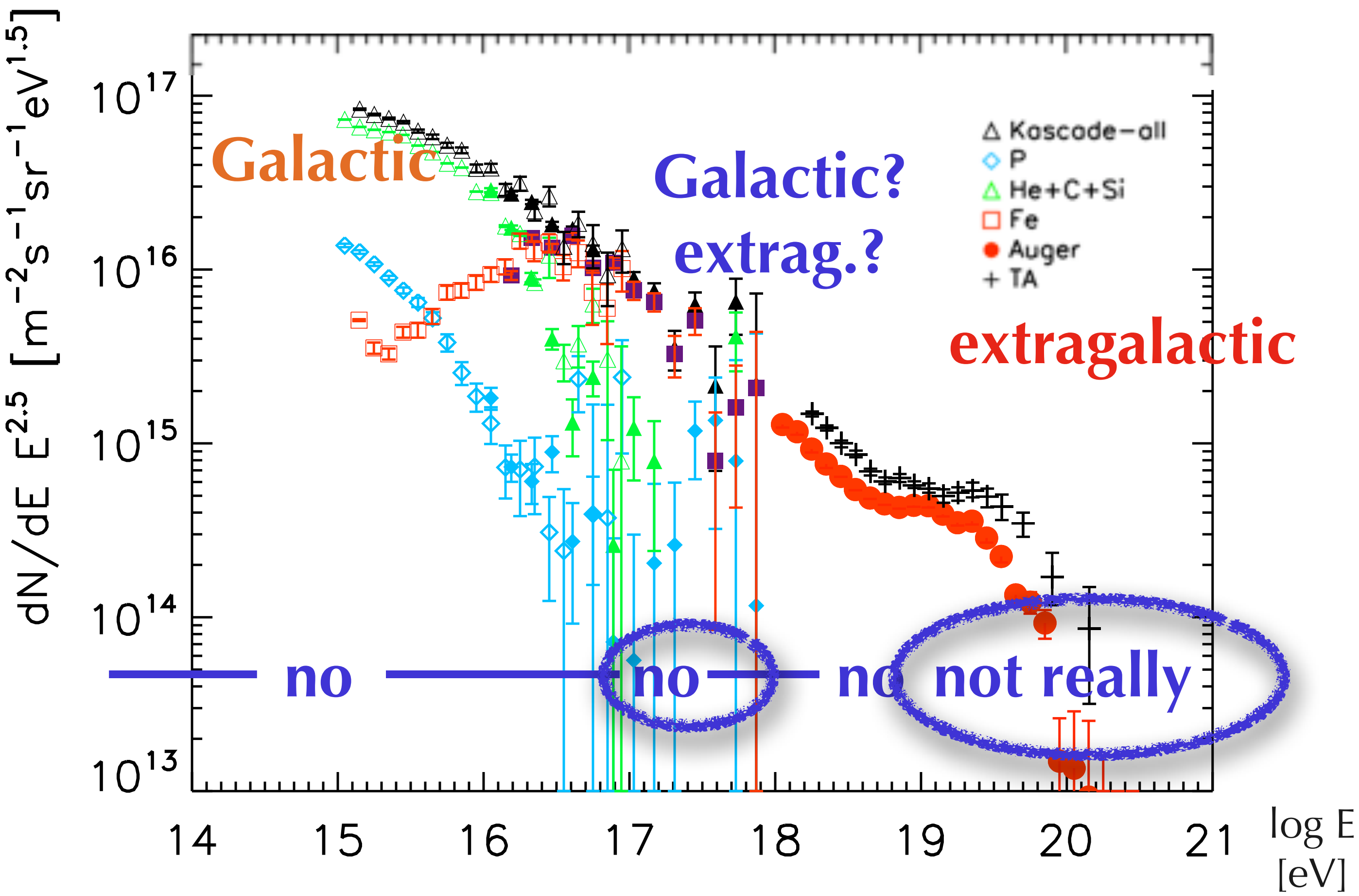

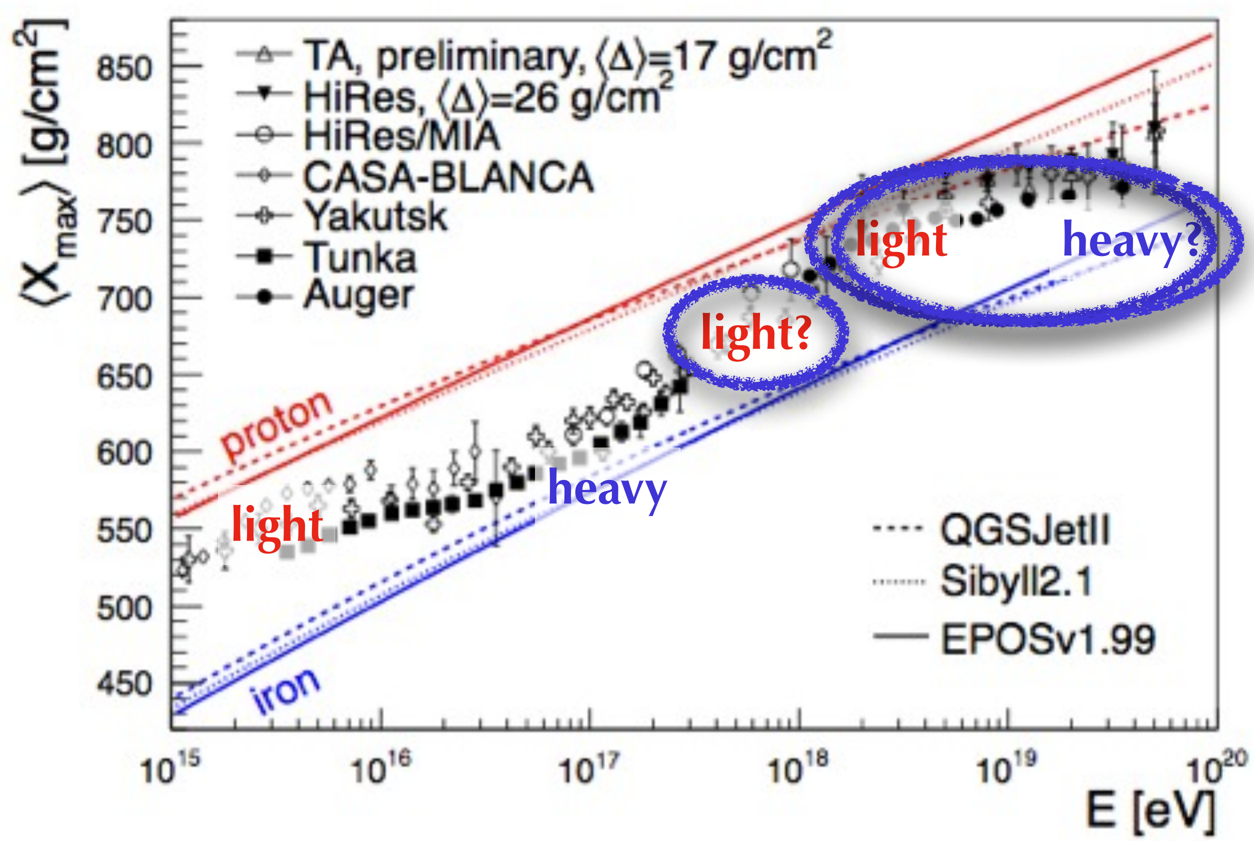

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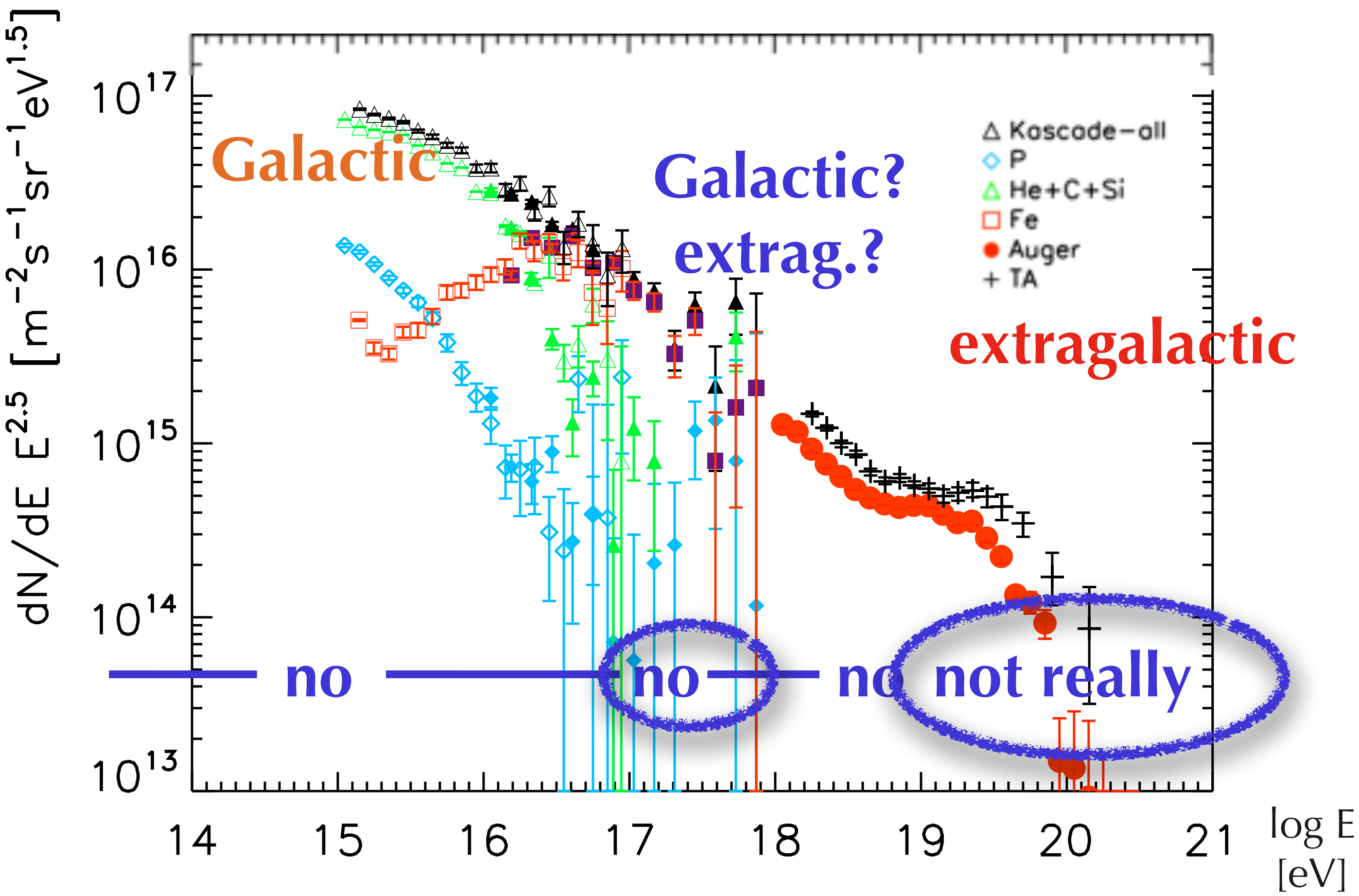

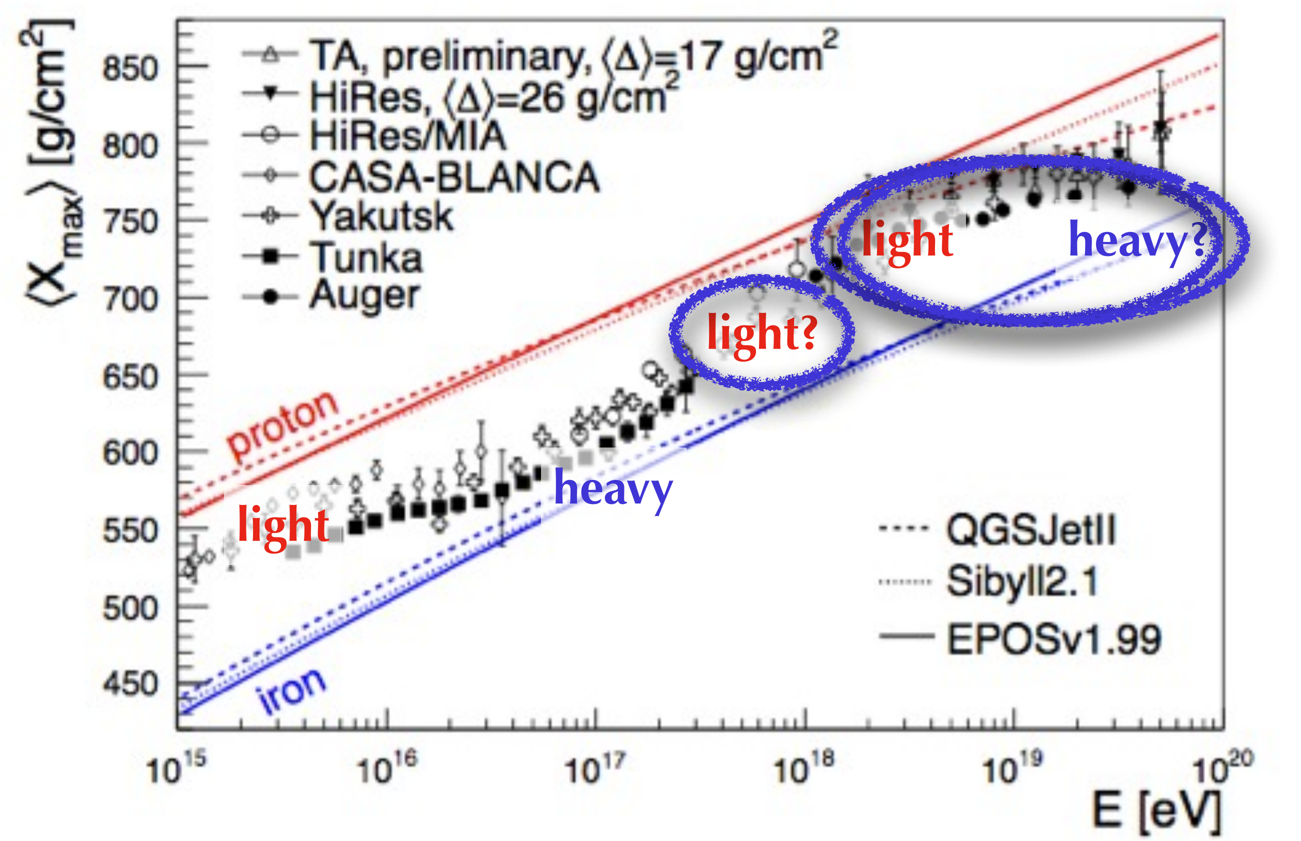

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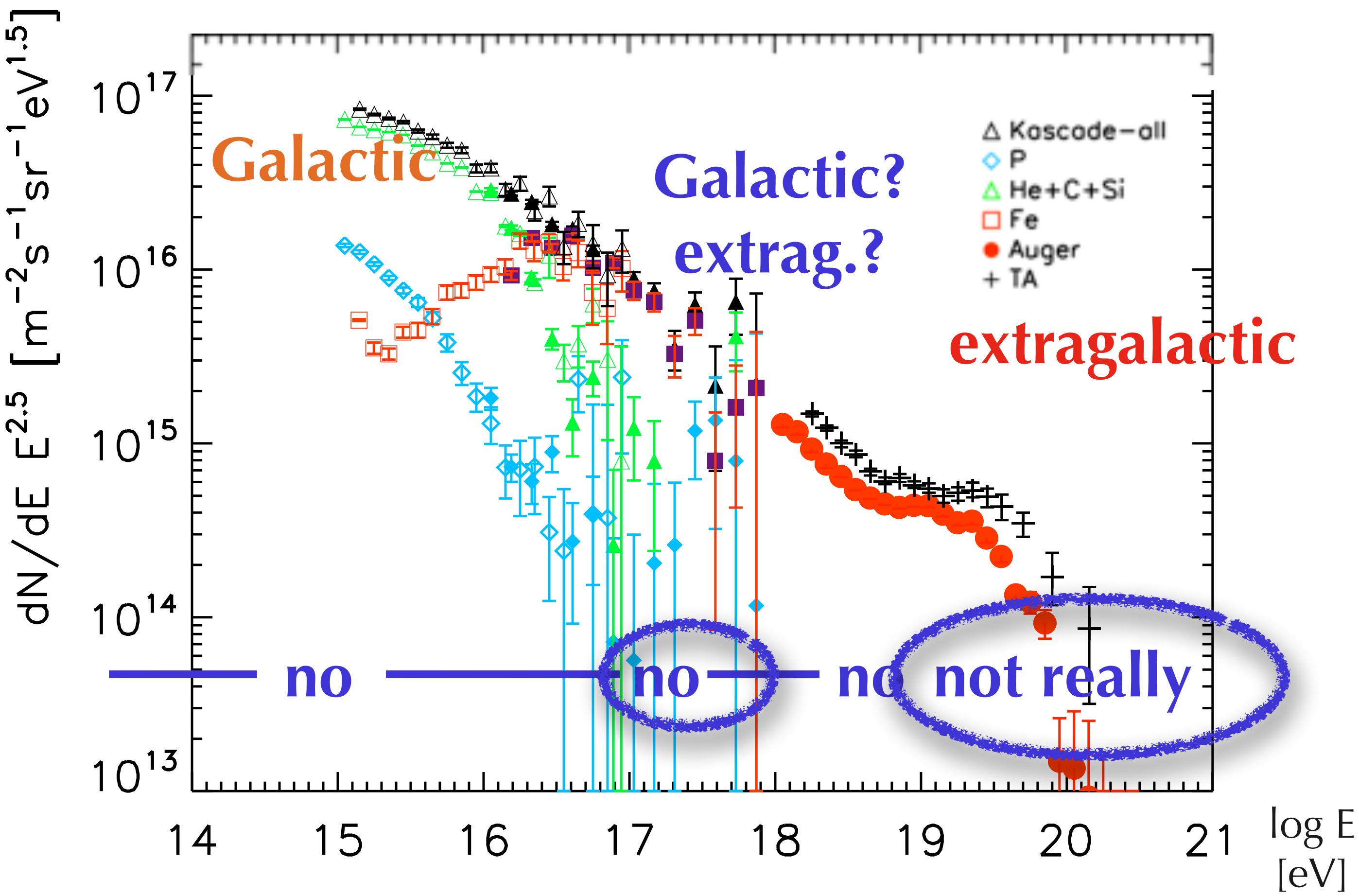

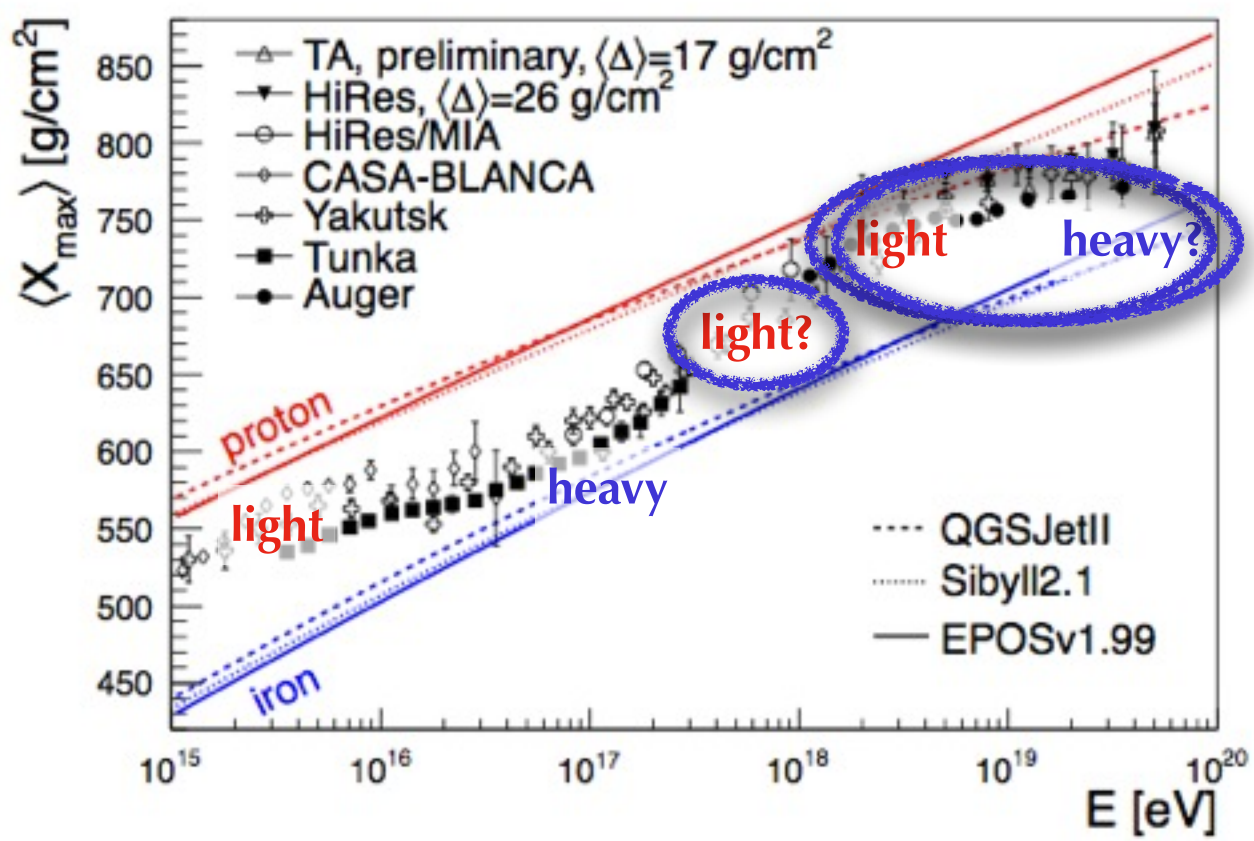

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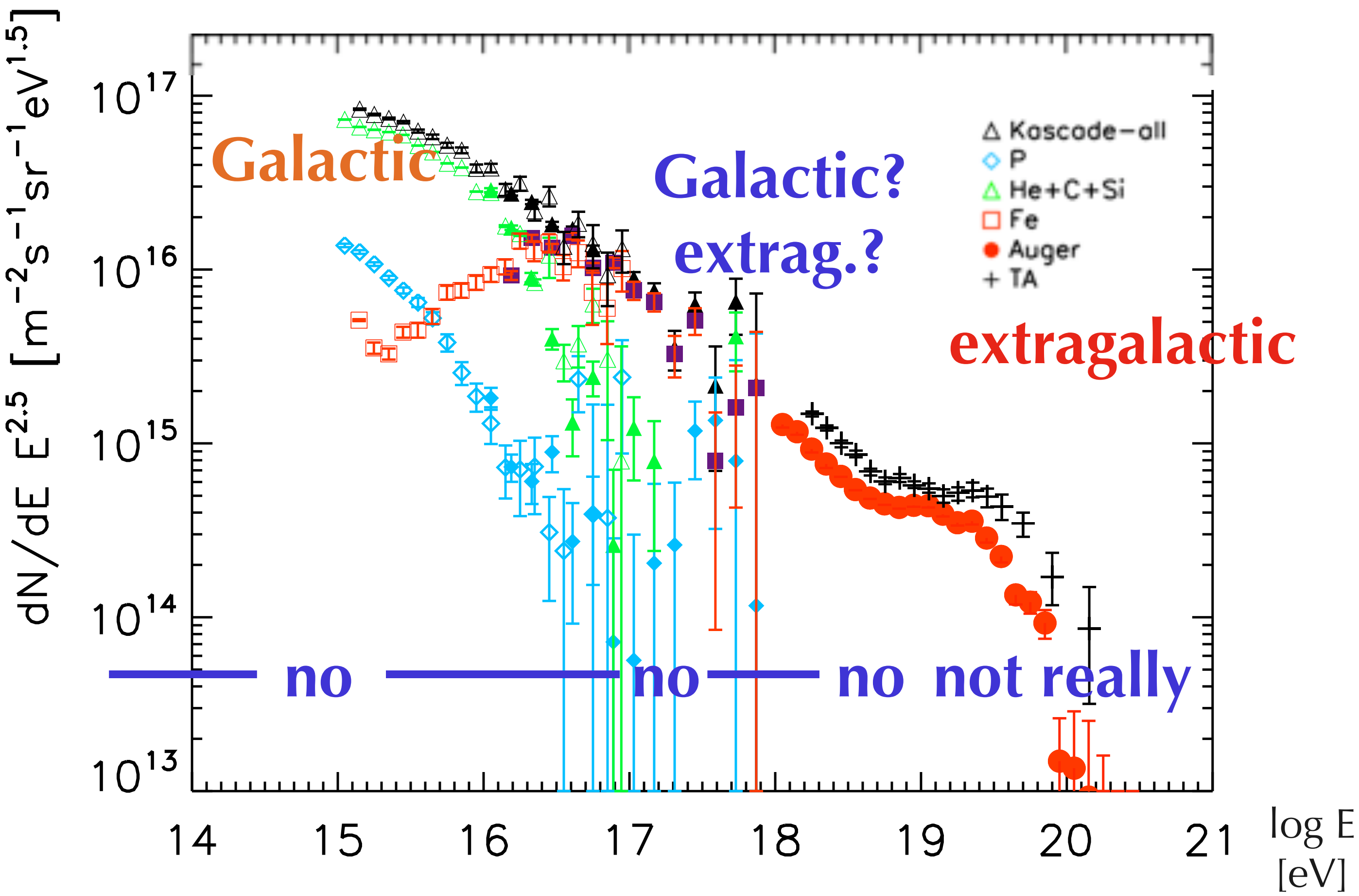

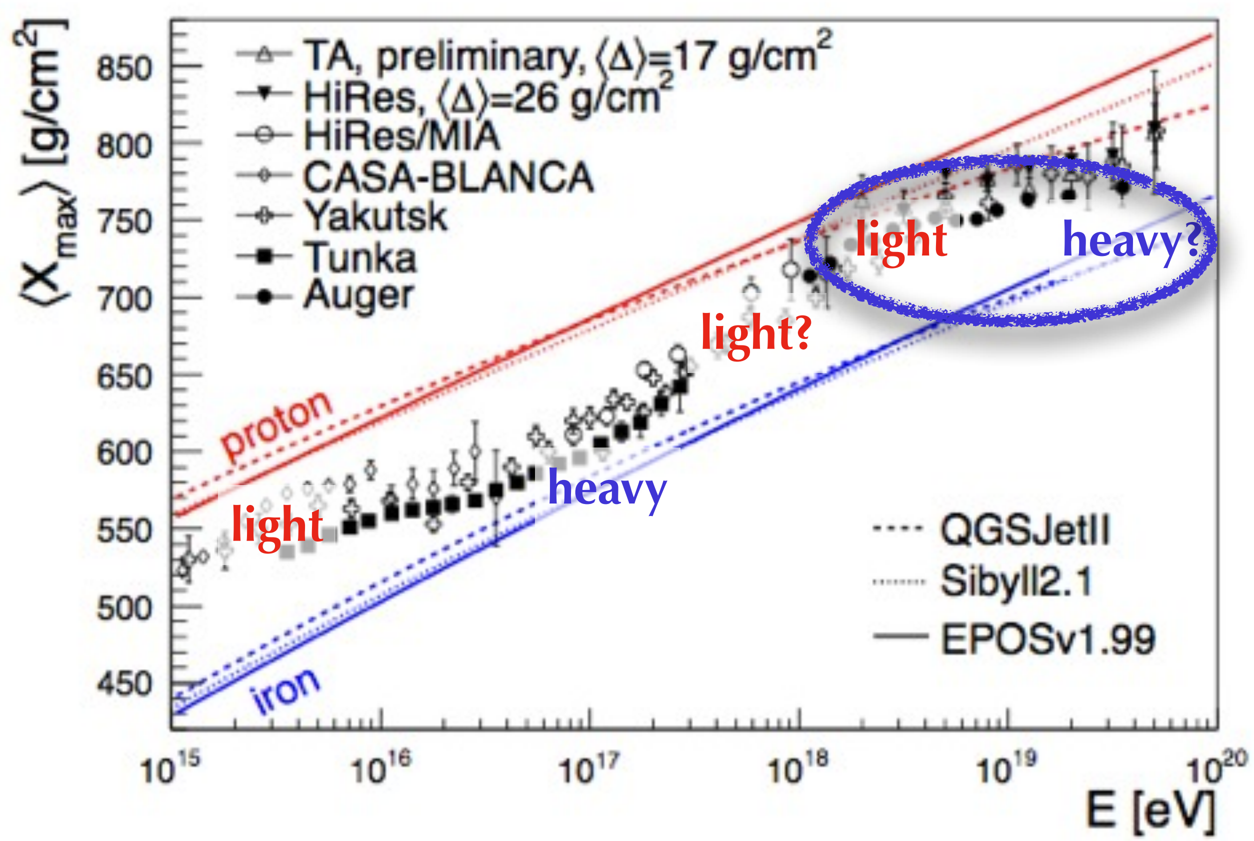

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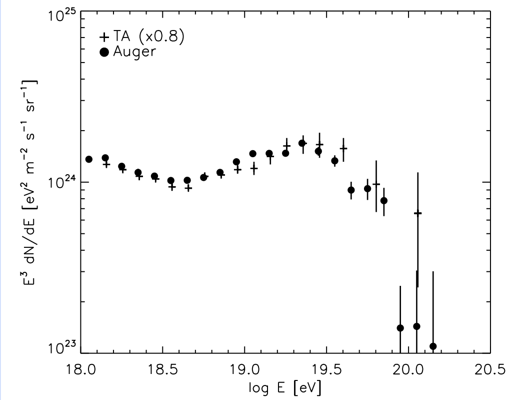
Confronting candidates to observables

Hillas diagram
(confinement in source)

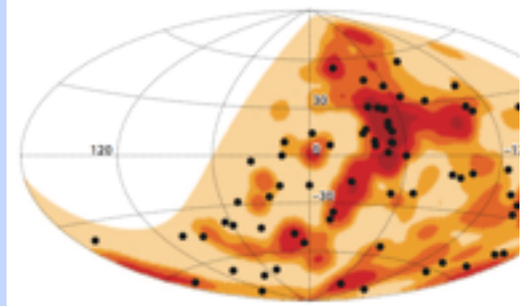
acceleration E>10^{20} eV
energy budget

$\mathcal{E}_{\rm UHECR}\dot{n}$
~ 0.5×10^{44} erg Mpc^{-3} yr^{-1}

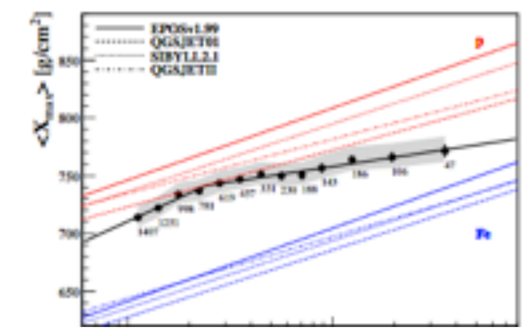
shape of spectrum



arrival directions



composition
heavy nuclei possible?



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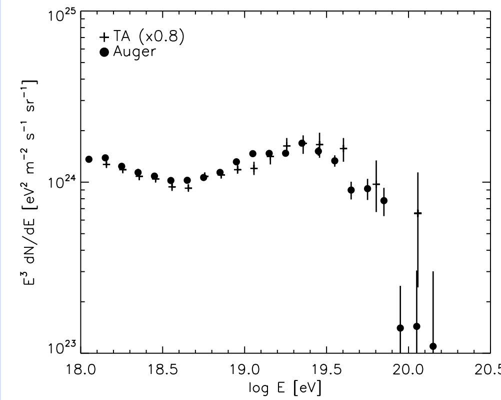

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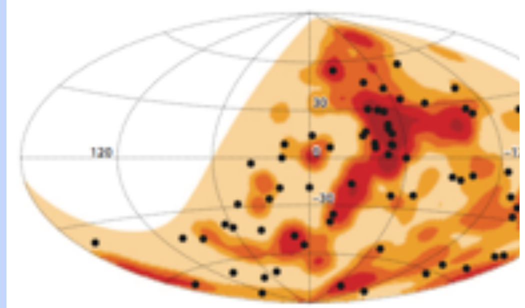

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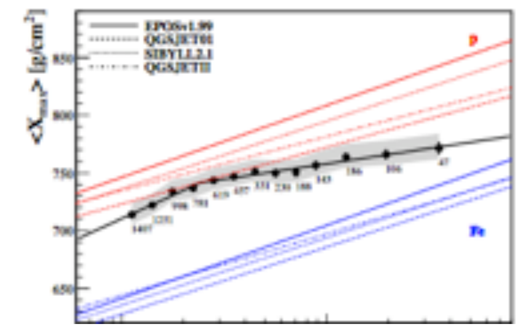

AGN

FRII: OK ✓?
FRI: energetics tight for protons

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

GRB

accelation ok, ✓?
but tight energy budget
because rare source

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

pulsars

Confronting candidates to observables

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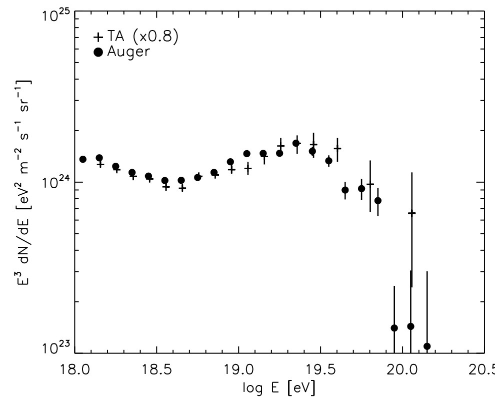

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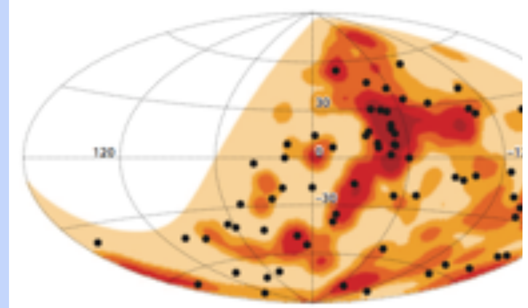

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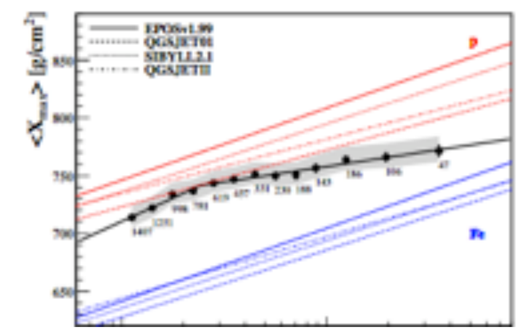

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e.g., unipolar induction
Blasi et al. 2000, Arons 2003 ✓

Confronting candidates to observables

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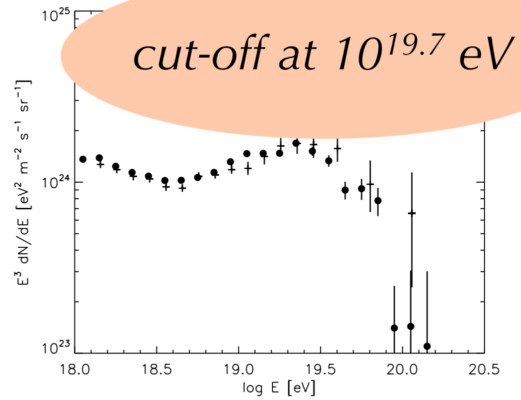
shape of spectrum

cut-off at $10^{19.7}$ eV



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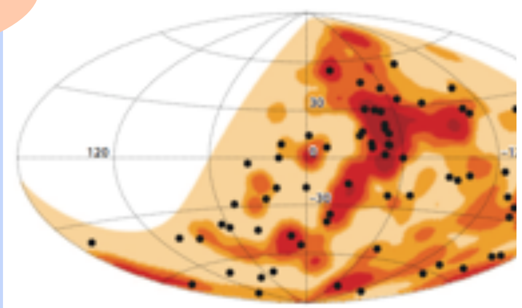

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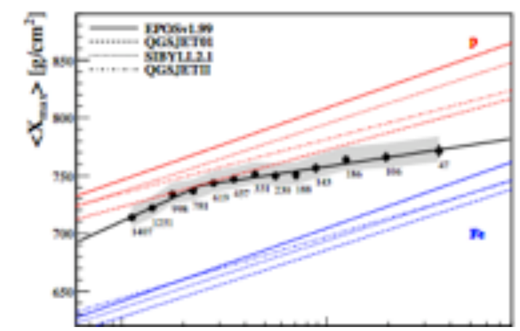

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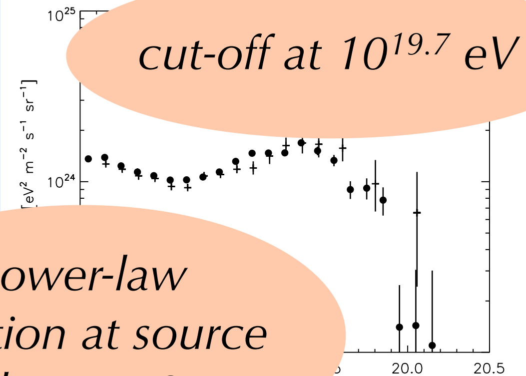
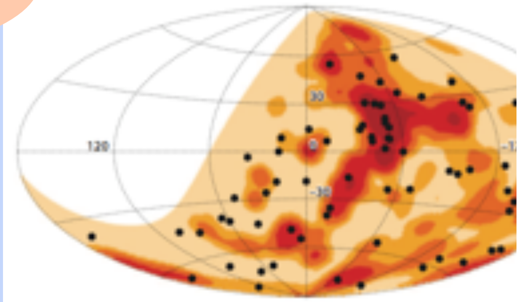
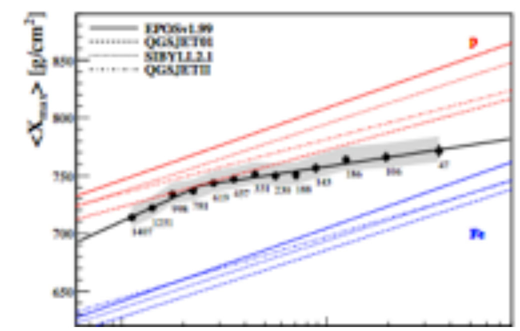
Confronting candidates to observables

Hillas diagram (confinement in source)	acceleration E>10^{20} eV energy budget	shape of spectrum	arrival directions	composition heavy nuclei possible?
	$\mathcal{E}_{\rm UHECR}\dot{n}$ ~ 0.5×10^{44} erg Mpc^{-3} yr^{-1}	 *cut-off at $10^{19.7}$ eV* — *power-law injection at source slope ~ -2*		
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Confronting candidates to observables

Hillas diagram (confinement in source)	**acceleration E>10^{20} eV energy budget**	**shape of spectrum**	**arrival directions**	**composition** heavy nuclei possible?

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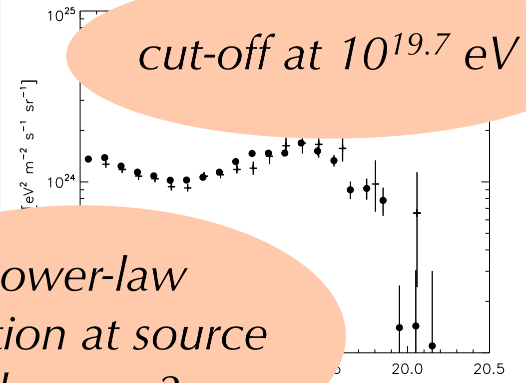

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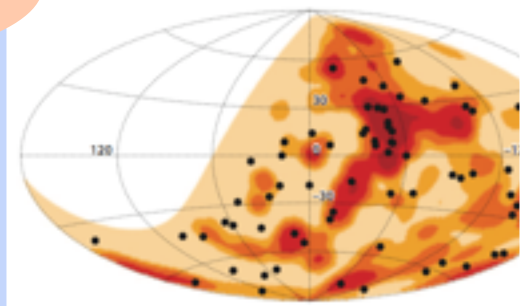

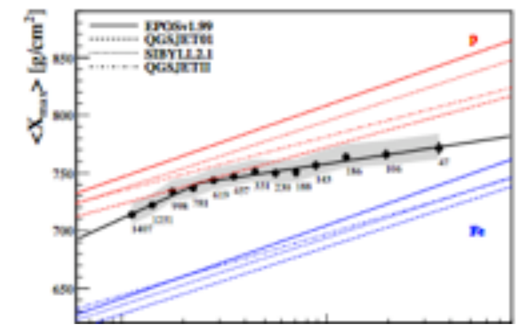

AGN

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Confronting candidates to observables

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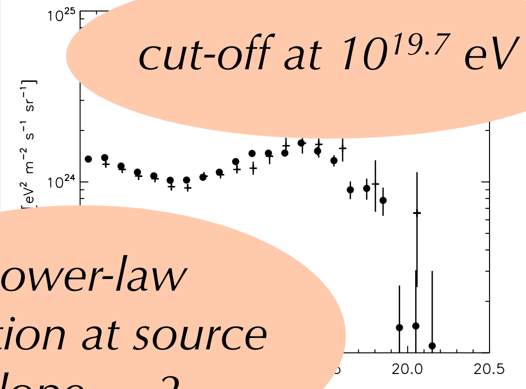

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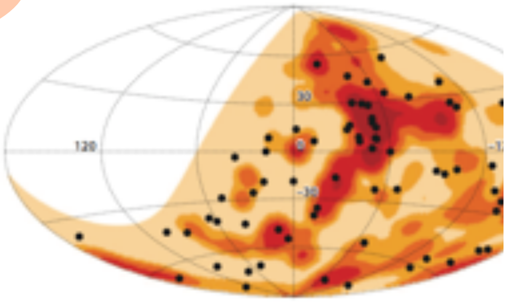

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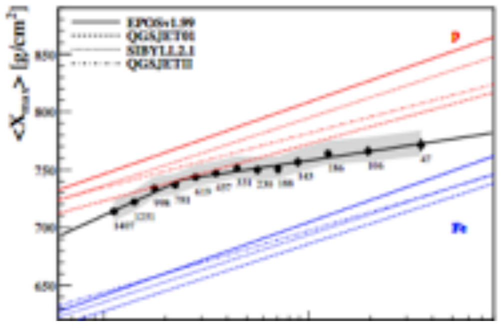

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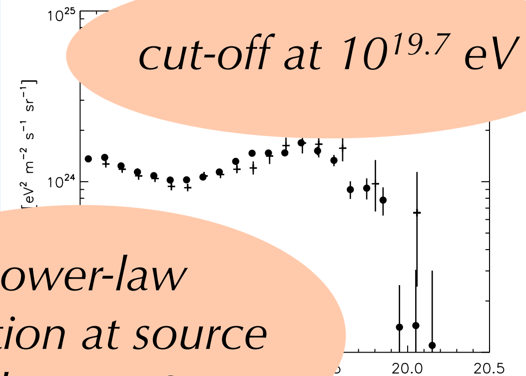

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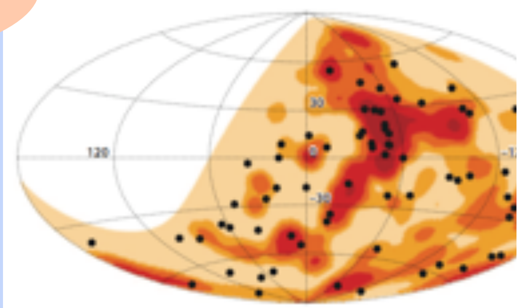

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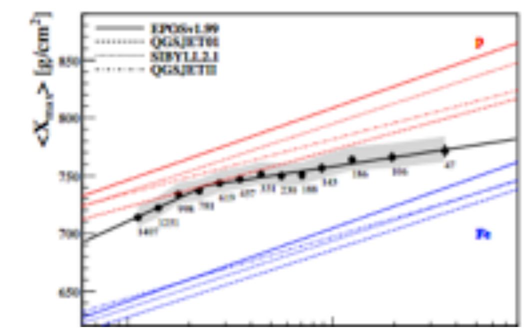

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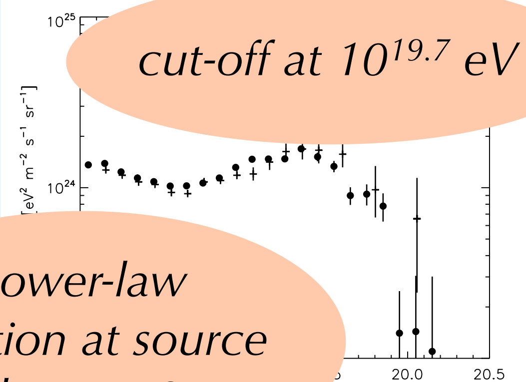

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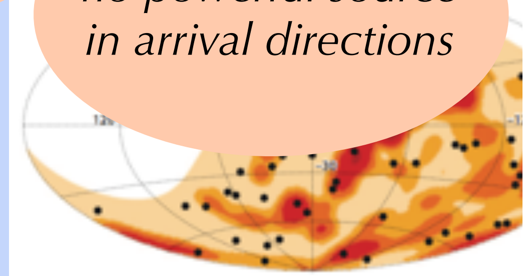

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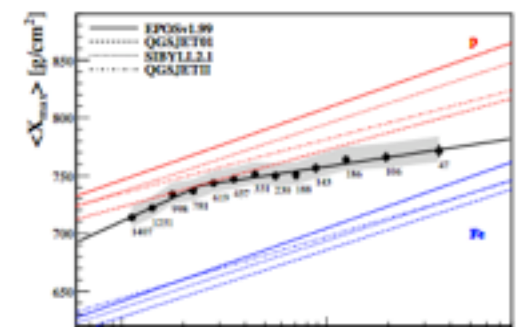

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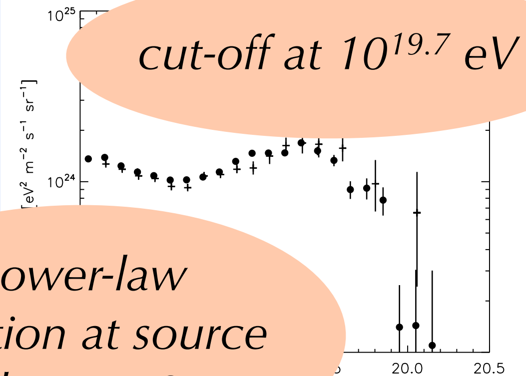
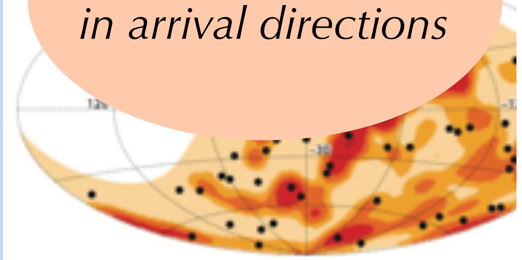
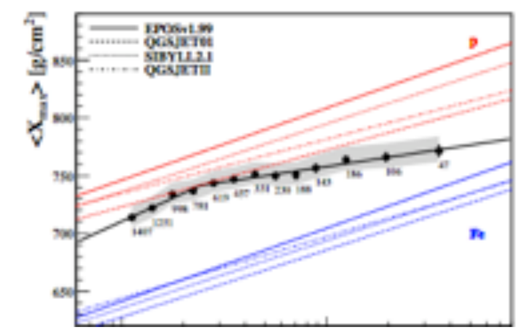
	$\mathcal{E}_{\rm UHECR}\dot{n}$ ~ 0.5×10^{44} erg Mpc^{-3} yr^{-1}	 *cut-off at $10^{19.7}$ eV* *power-law injection at source slope ~ -2*	 *no powerful source in arrival directions*	
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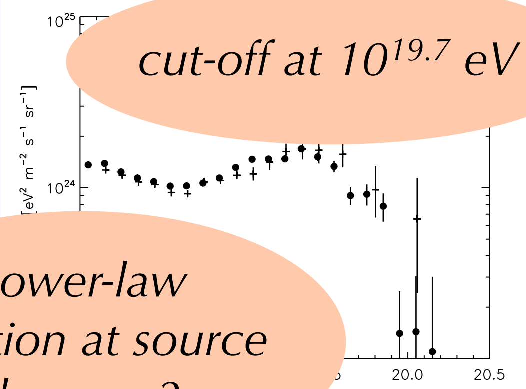

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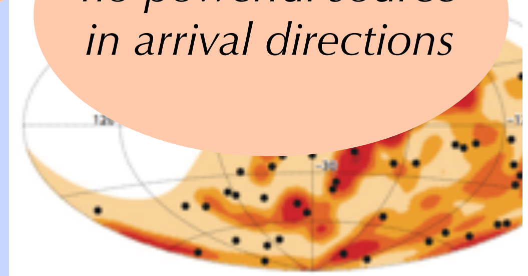

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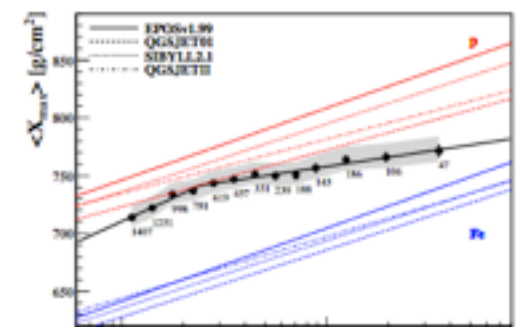

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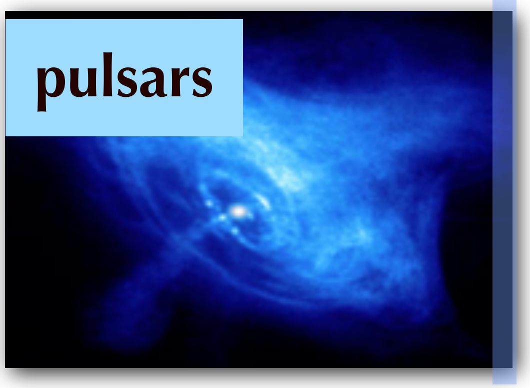

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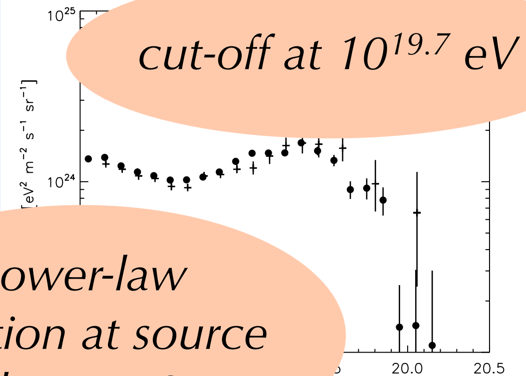
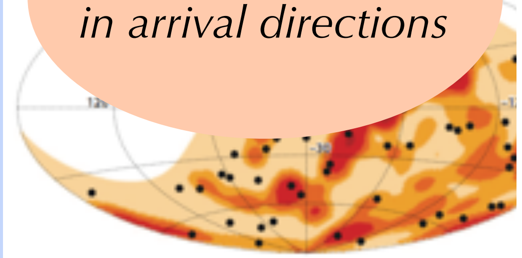
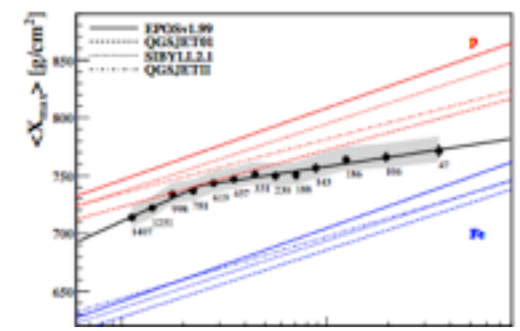
	$\mathcal{E}_{\rm UHECR}\dot{n}$ ~ 0.5×10^{44} erg Mpc^{-3} yr^{-1}	 *cut-off at $10^{19.7}$ eV* *power-law injection at source slope ~ -2*	 *no powerful source in arrival directions*	
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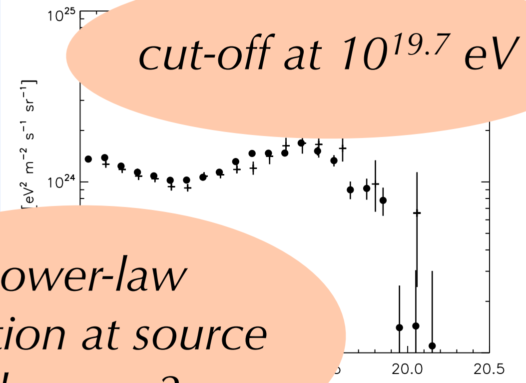
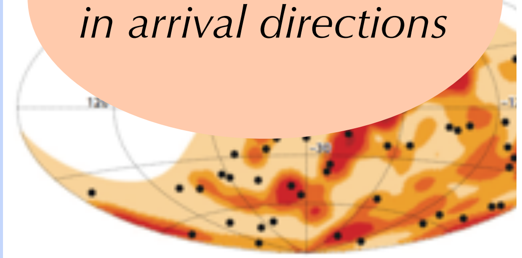
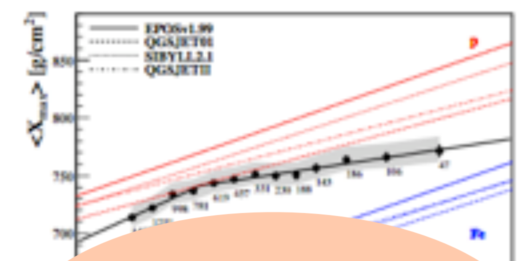
	$\mathcal{E}_{\rm UHECR}\dot{n}$ ~ 0.5×10^{44} erg Mpc^{-3} yr^{-1}	 cut-off at $10^{19.7}$ eV; power-law injection at source slope ~ -2	 no powerful source in arrival directions	 ?? light --> heavy transition ~10^{19} eV
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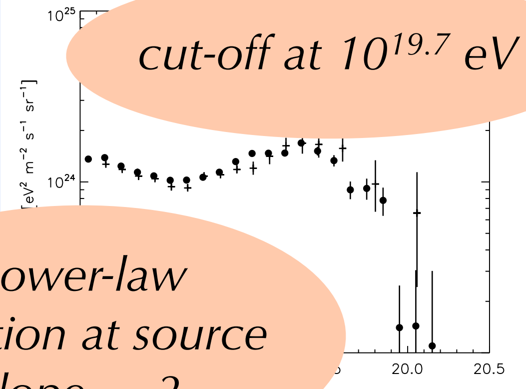
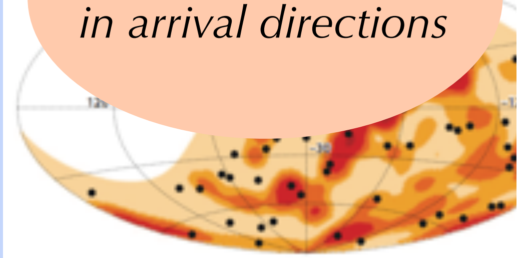
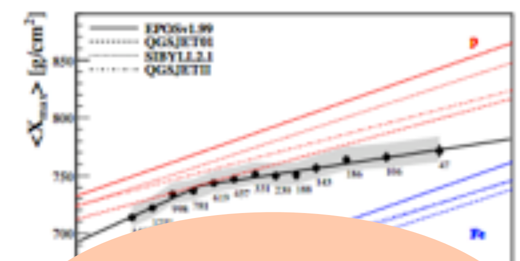
	$\mathcal{E}_{\rm UHECR}\dot{n}$ ~ 0.5×10^{44} erg Mpc^{-3} yr^{-1}	 *cut-off at $10^{19.7}$ eV* *power-law injection at source slope ~ -2*	 *no powerful source in arrival directions*	 *?? light --> heavy transition ~10^{19} eV*
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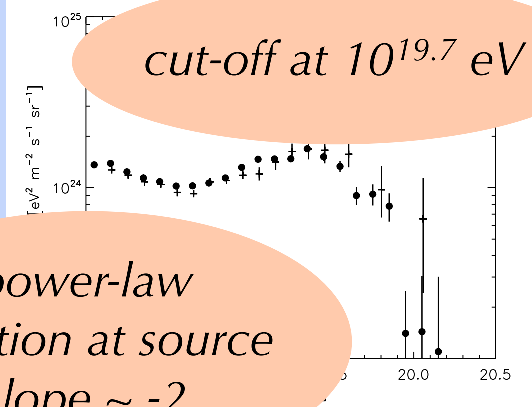
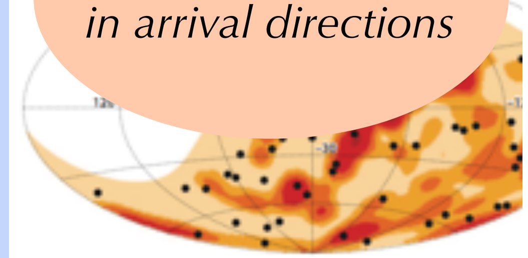
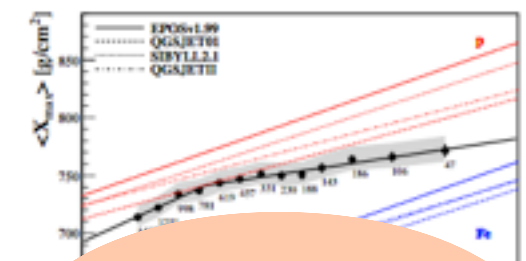
	$\mathcal{E}_{UHECR}\dot{n}$ ~ 0.5×10^{44} erg Mpc^{-3} yr^{-1}	 *cut-off at $10^{19.7}$ eV* *power-law injection at source slope ~ -2*	 *no powerful source in arrival directions*	 *?? light --> heavy transition ~10^{19} eV*
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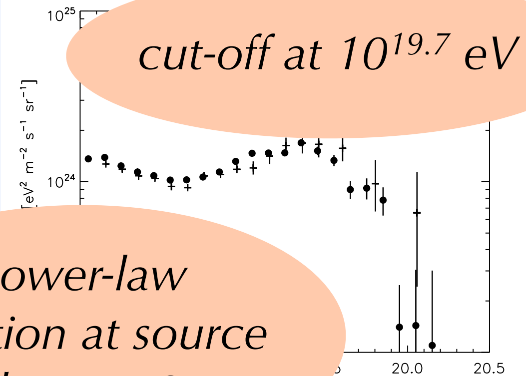
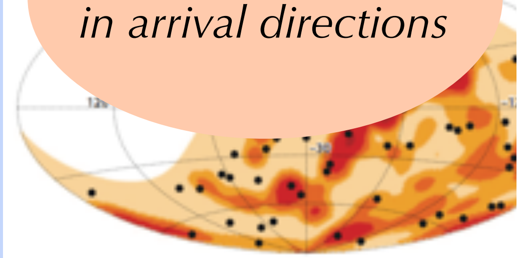
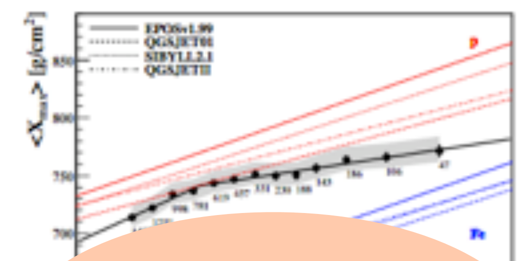
	$\mathcal{E}_{\rm UHECR}\dot{n}$ ~ 0.5×10^{44} erg Mpc^{-3} yr^{-1}	 cut-off at $10^{19.7}$ eV; power-law injection at source slope ~ -2	 no powerful source in arrival directions	 ?? light --> heavy transition ~10^{19} eV
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Pulsar properties

e.g., Shapiro & Teukolsky 83

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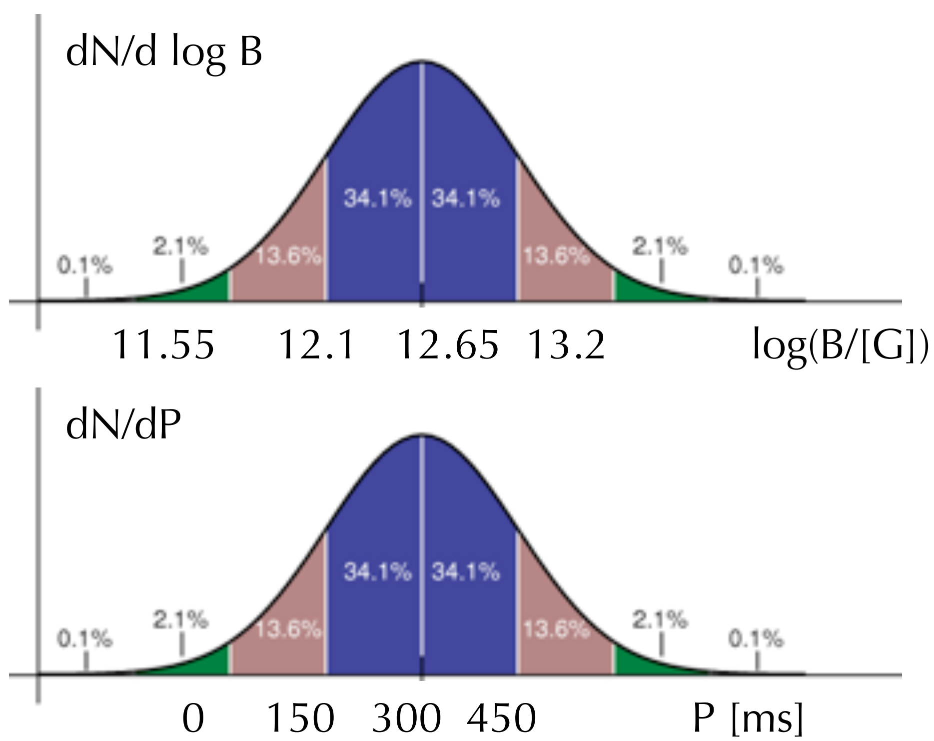

Faucher-Giguère & Kaspi (2006)
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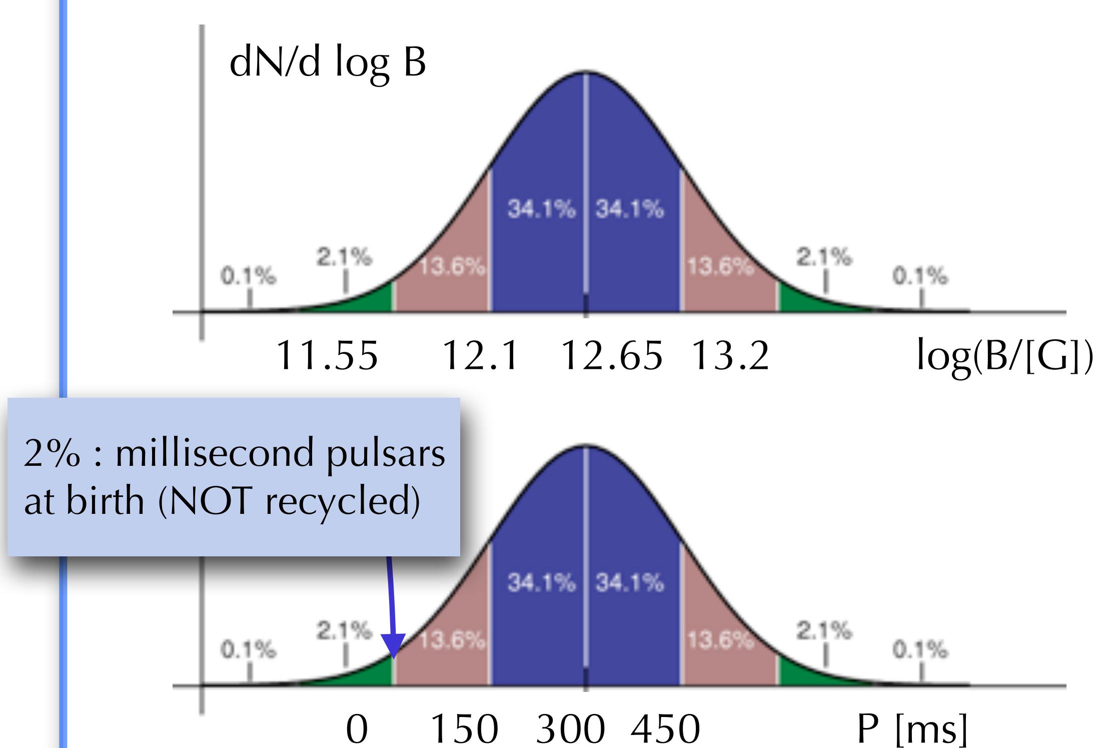

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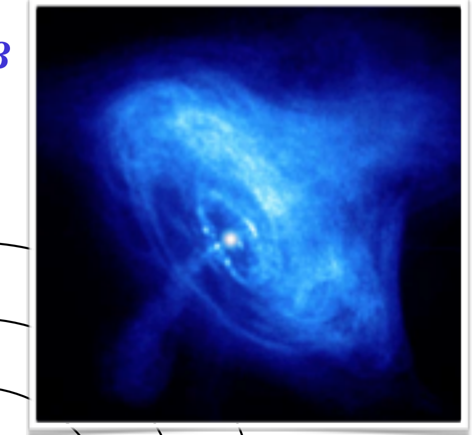

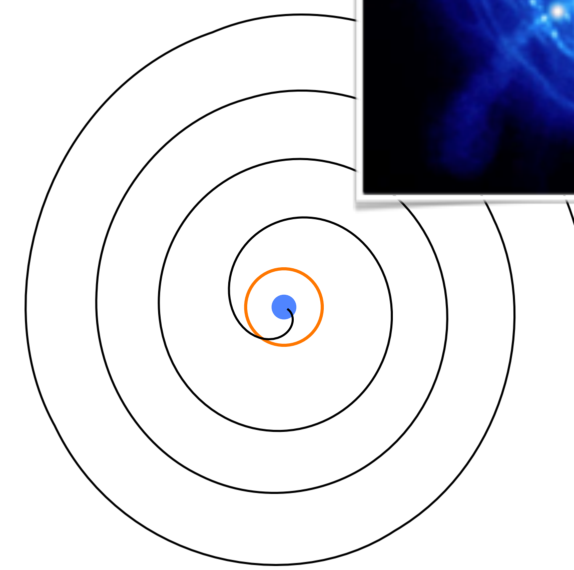

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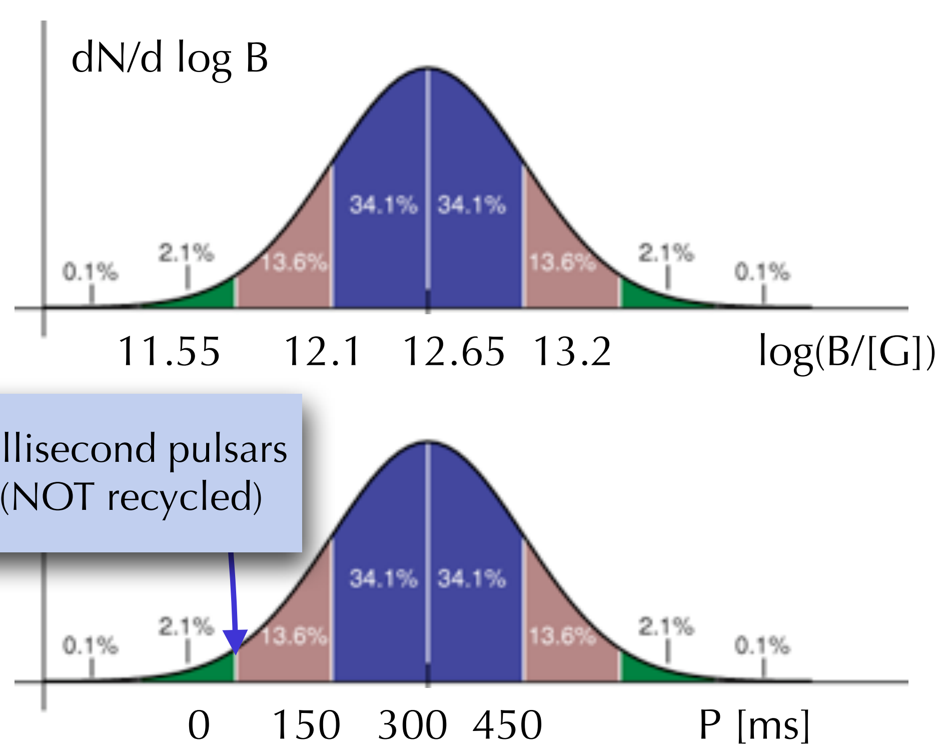

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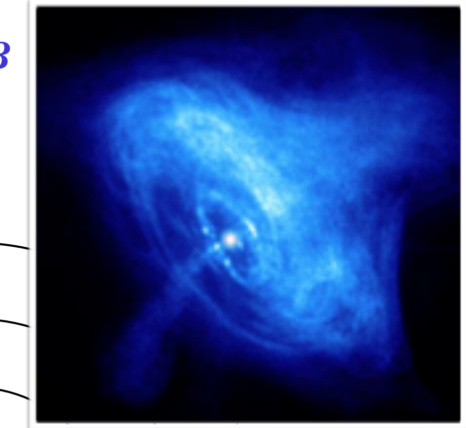
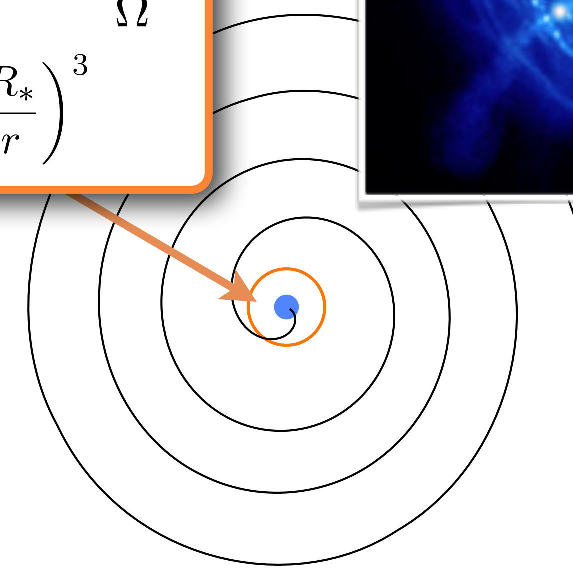


light cylinder

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

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



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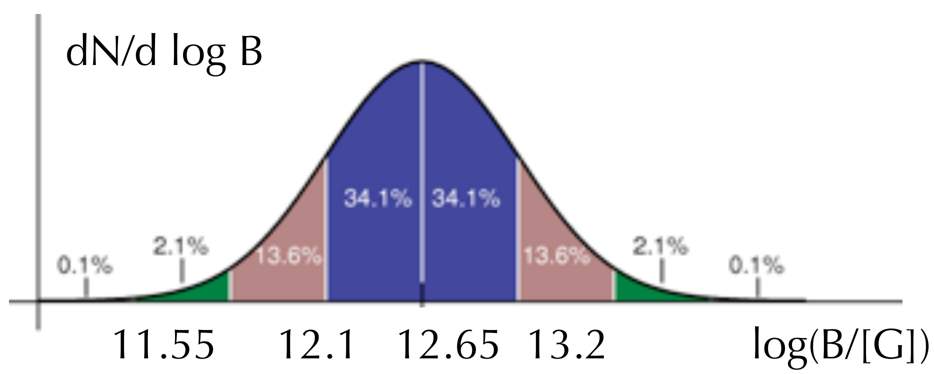

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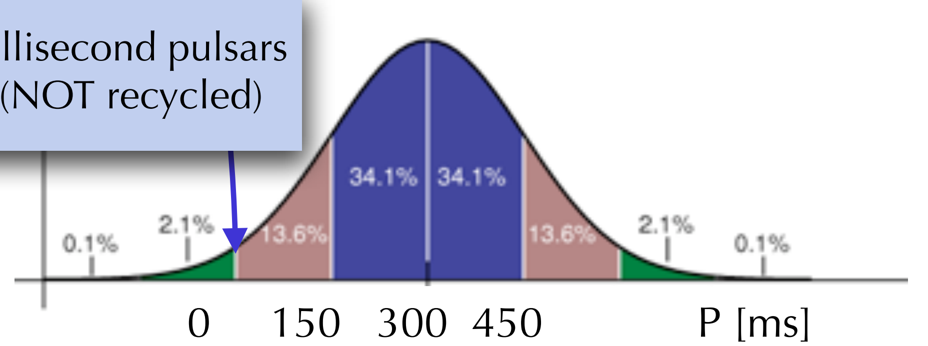

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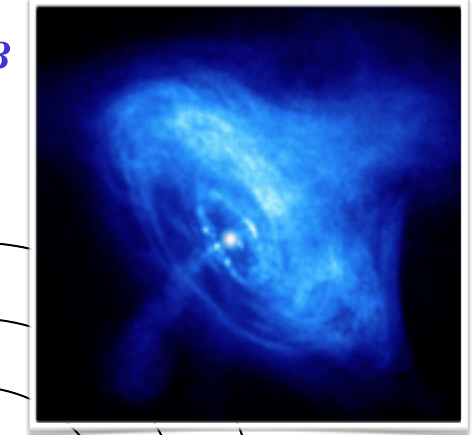

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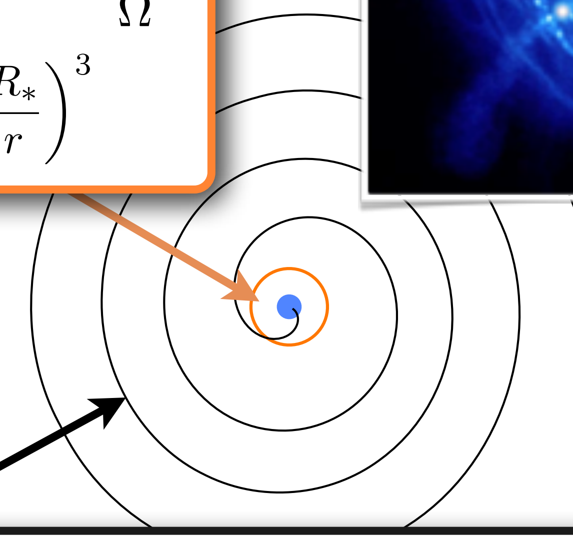

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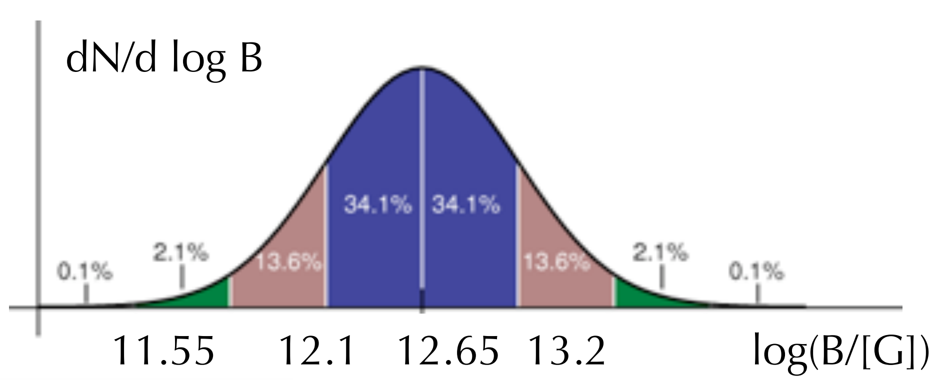

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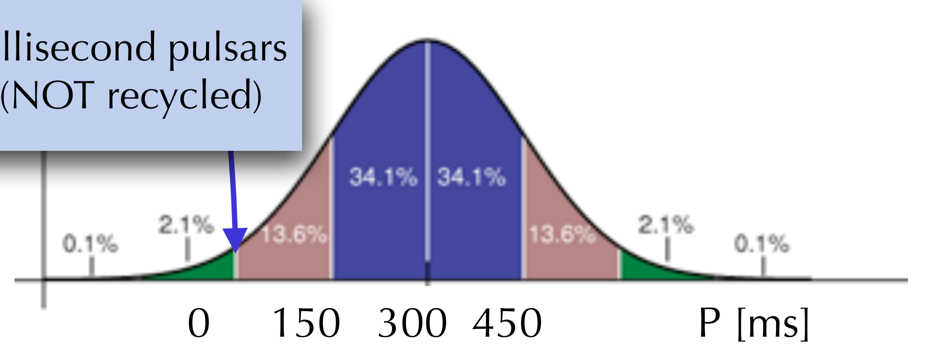

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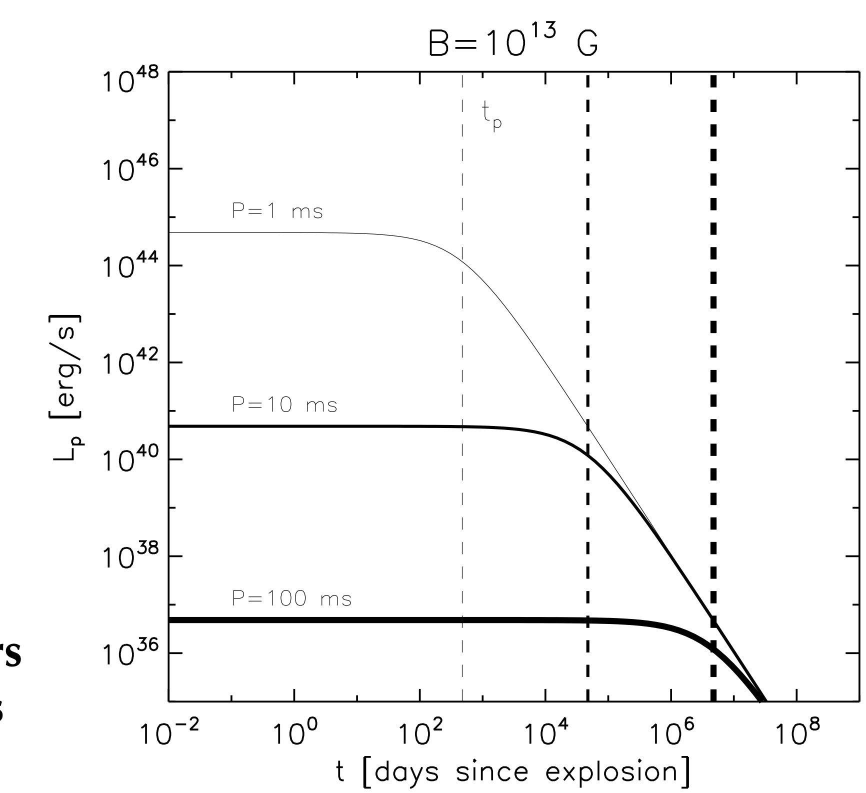
relativistic wind

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

total energy $$E_p = \frac{I\Omega_i^2}{2} \sim 1.9 \times 10^{52}\,\mathrm{erg}\, I_{45} P_{i,-3}^2$$

pulsar luminosity $$L_p(t) = \frac{E_p}{t_p} \frac{1}{(1+t/t_p)^2}$$



t_p~ a few years for ms pulsars

Acceleration of UHECR in newly-born ms pulsars

Blasi et al. 00,
Arons 03,
Fang, KK, Olinto 2012

unipolar induction in the pulsar wind

or reconnection+Fermi acceleration, ***Lemoine, KK, Petri, in prep.***

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$$\mathbf{E} = -\mathbf{\Omega} \times \mathbf{B}$$

particles accelerated to energy:

$$E(\Omega) \sim 8.6 \times 10^{20}\, Z_{26} \eta_1 \Omega_4^2 \mu_{31}\ \mathrm{eV}$$

10%: fraction of voltage experienced by particles

magnetic moment 10^{31} cgs (B~10^{13} G)

rotation velocity 10^4 s^{-1}

pulsar spins down

energy spectrum for one pulsar:

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

spin-down rate:

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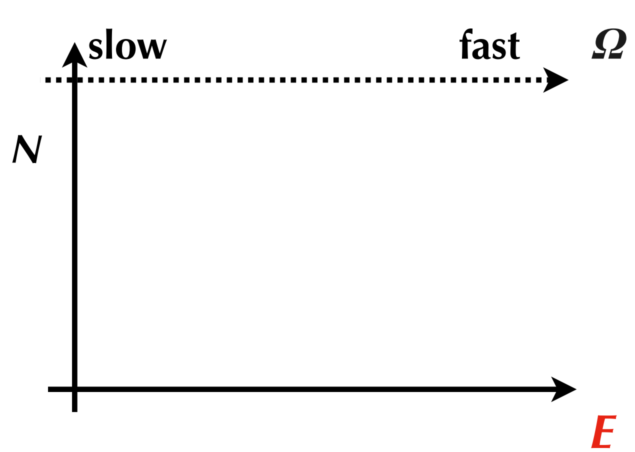

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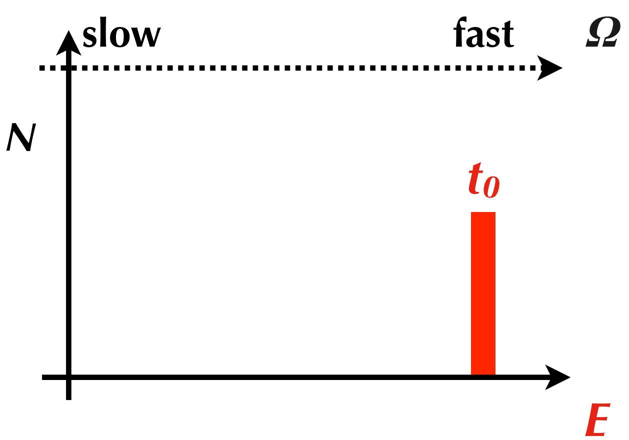

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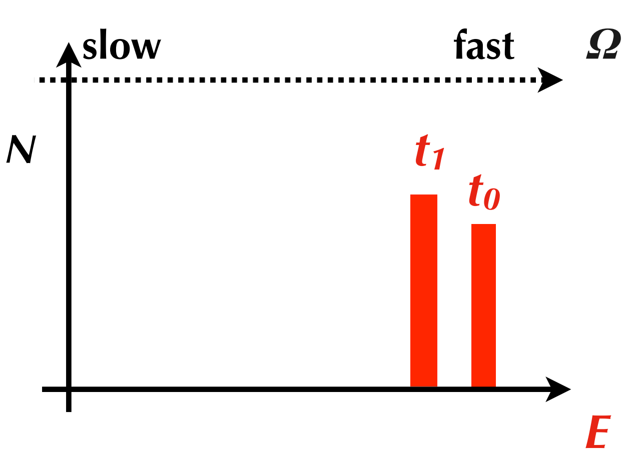

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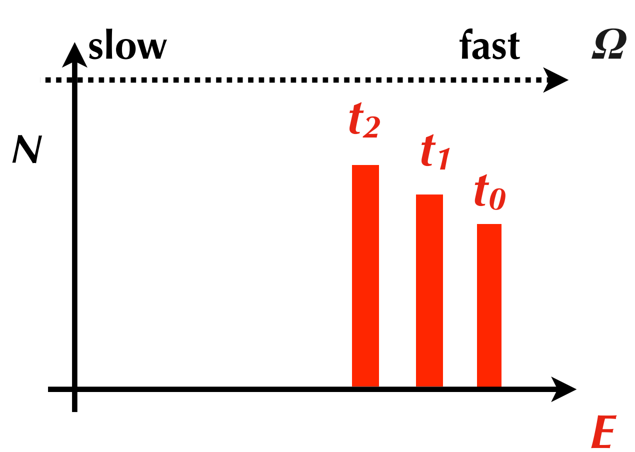

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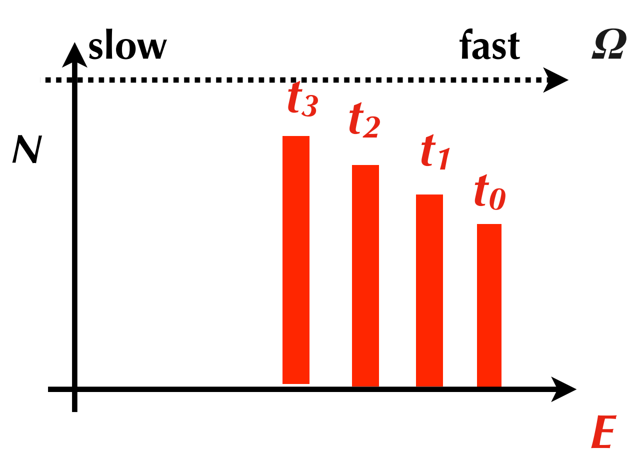

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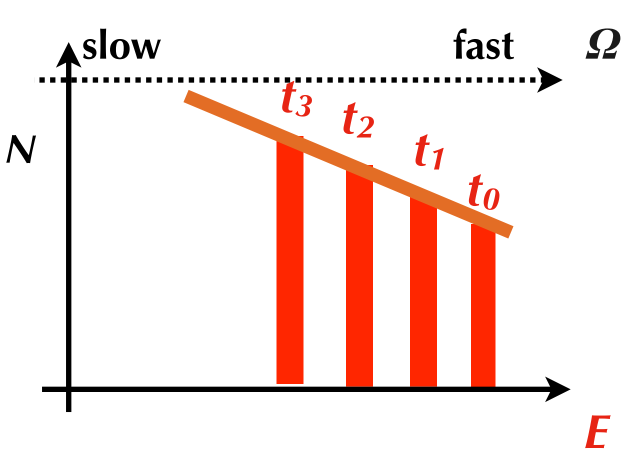

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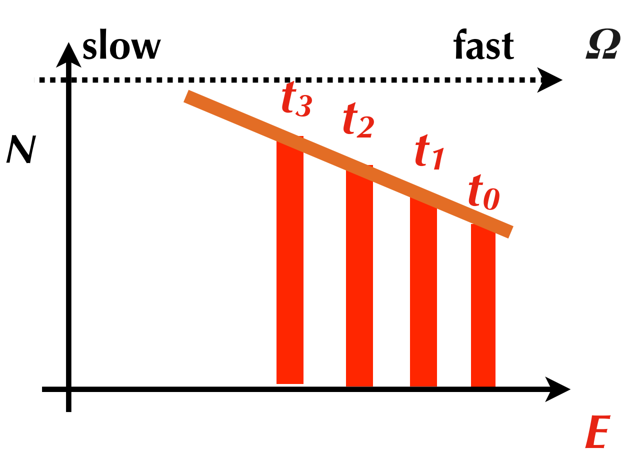
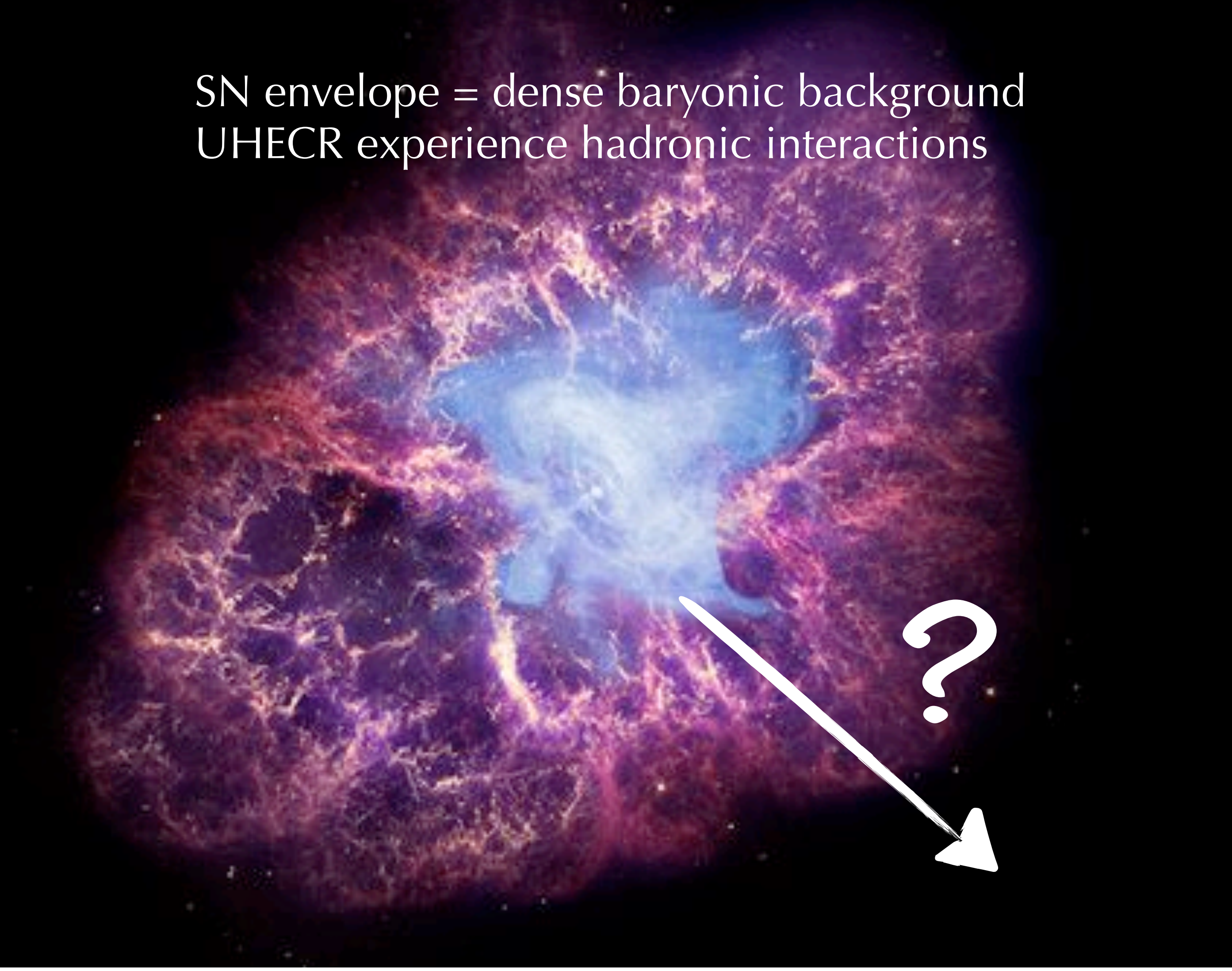


$$\frac{\mathrm{d}N_\mathrm{i}}{\mathrm{d}E} = \frac{9}{2}\frac{c^2 I}{ZeB_* R_*^3 E}\left(1 + \frac{E}{E_\mathrm{g}}\right)^{-1}$$

hard injection spectrum: -1 slope

UHECR escape

Fang, KK, Olinto 2012



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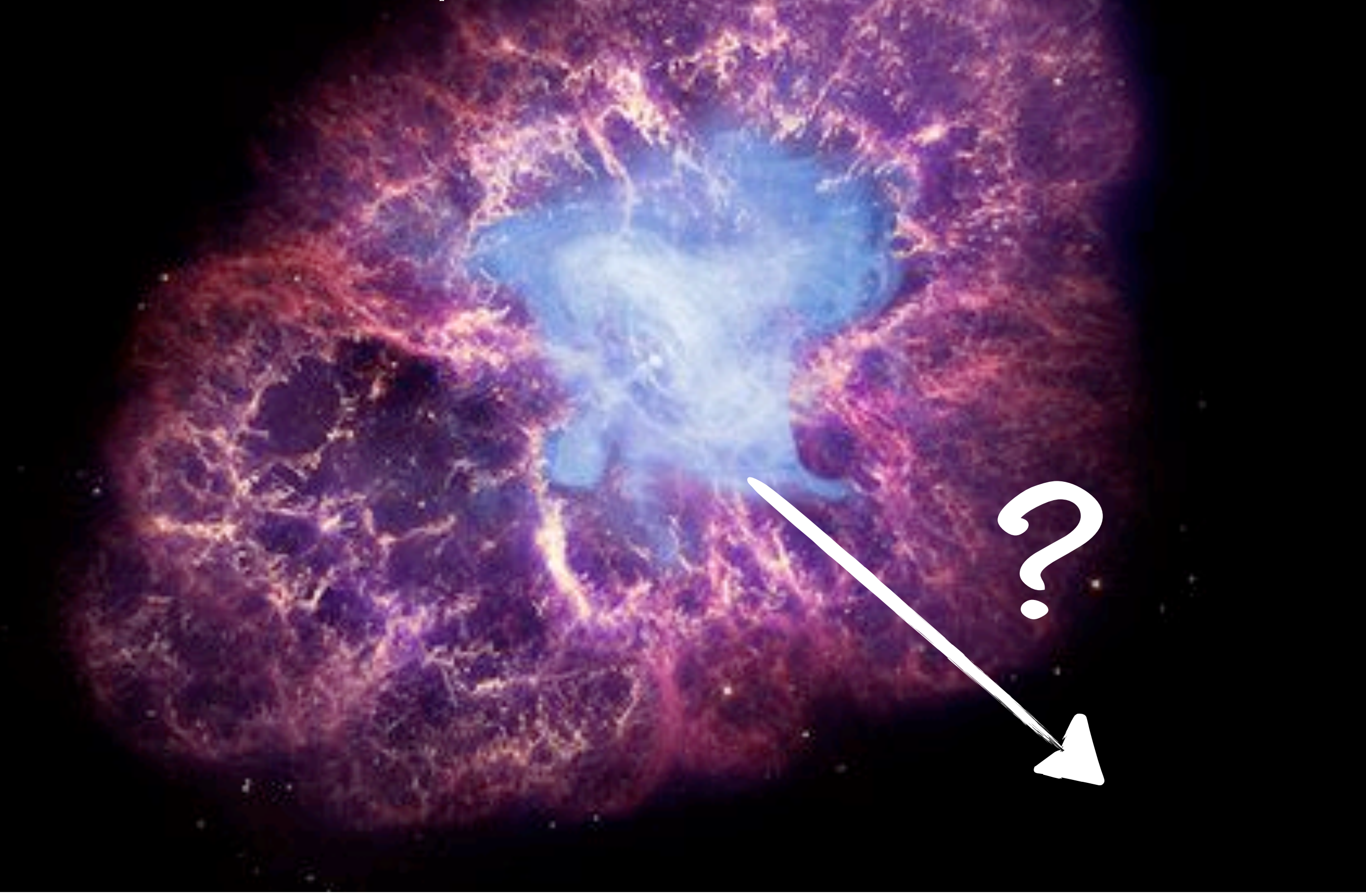
Ke Fang

SN envelope = dense baryonic background
UHECR experience hadronic interactions



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pulsar
magnetic moment μ,
rotation velocity Ω,
particle acceleration rate η

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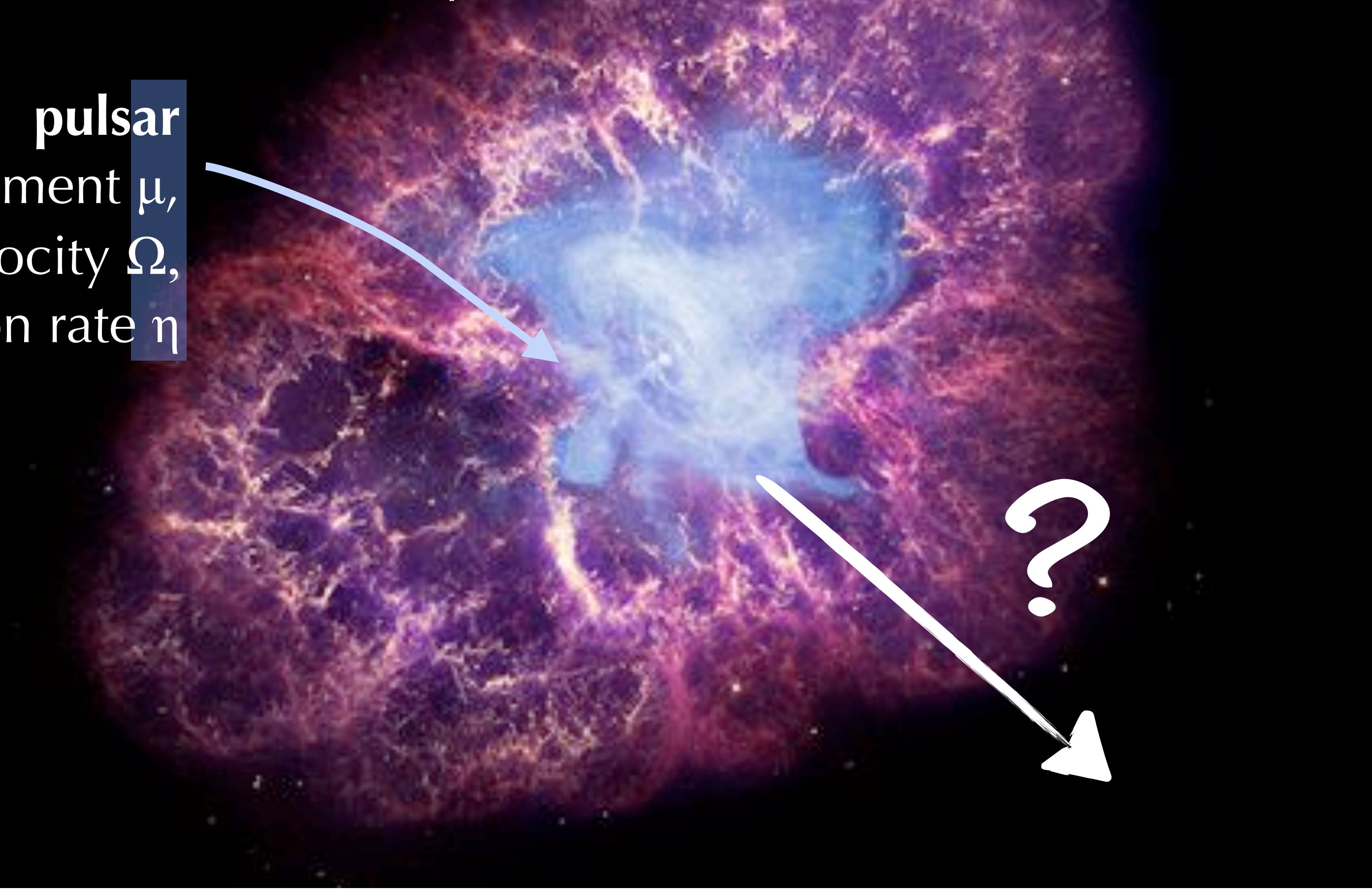

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ejecta energy E_{ej},
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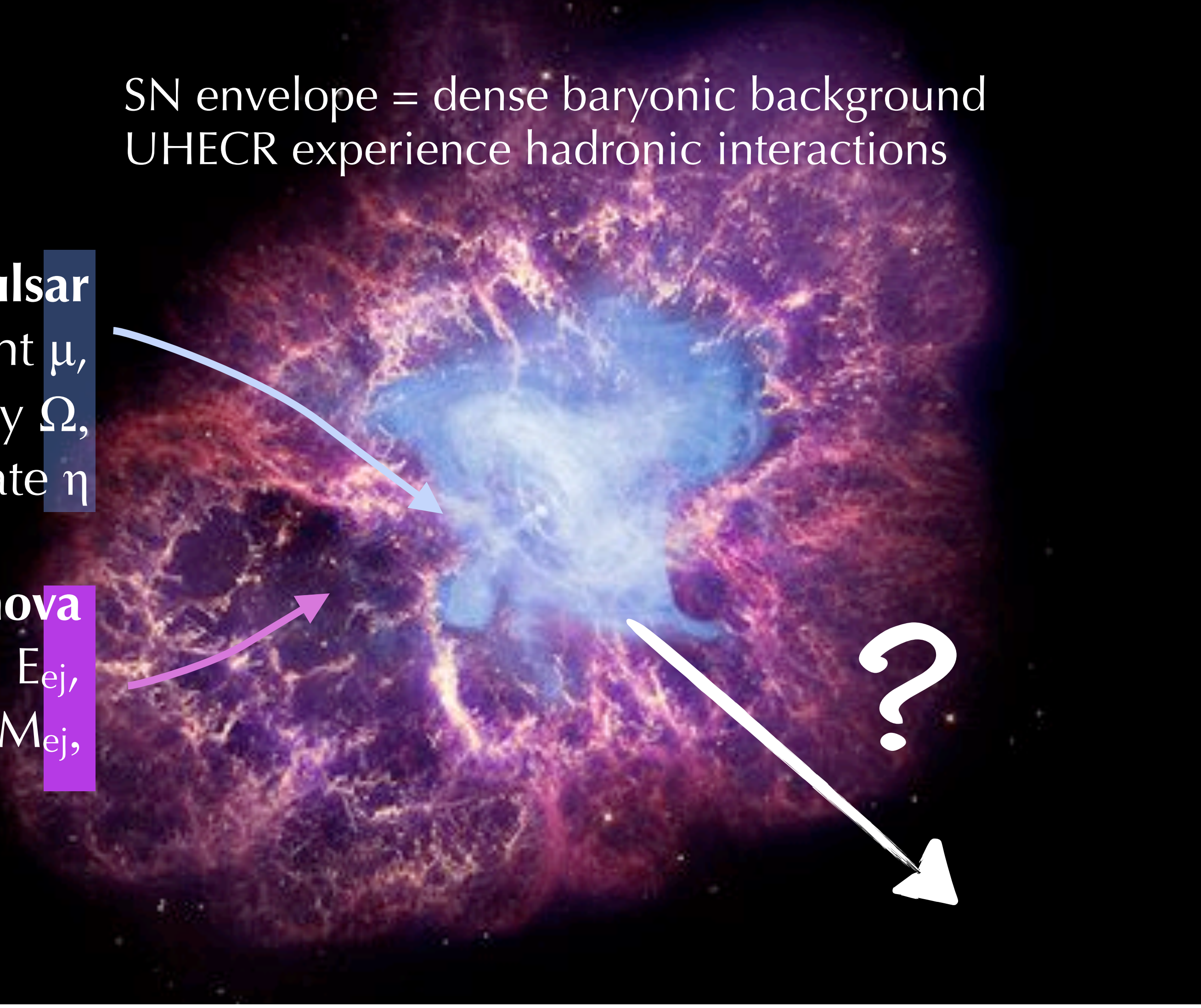

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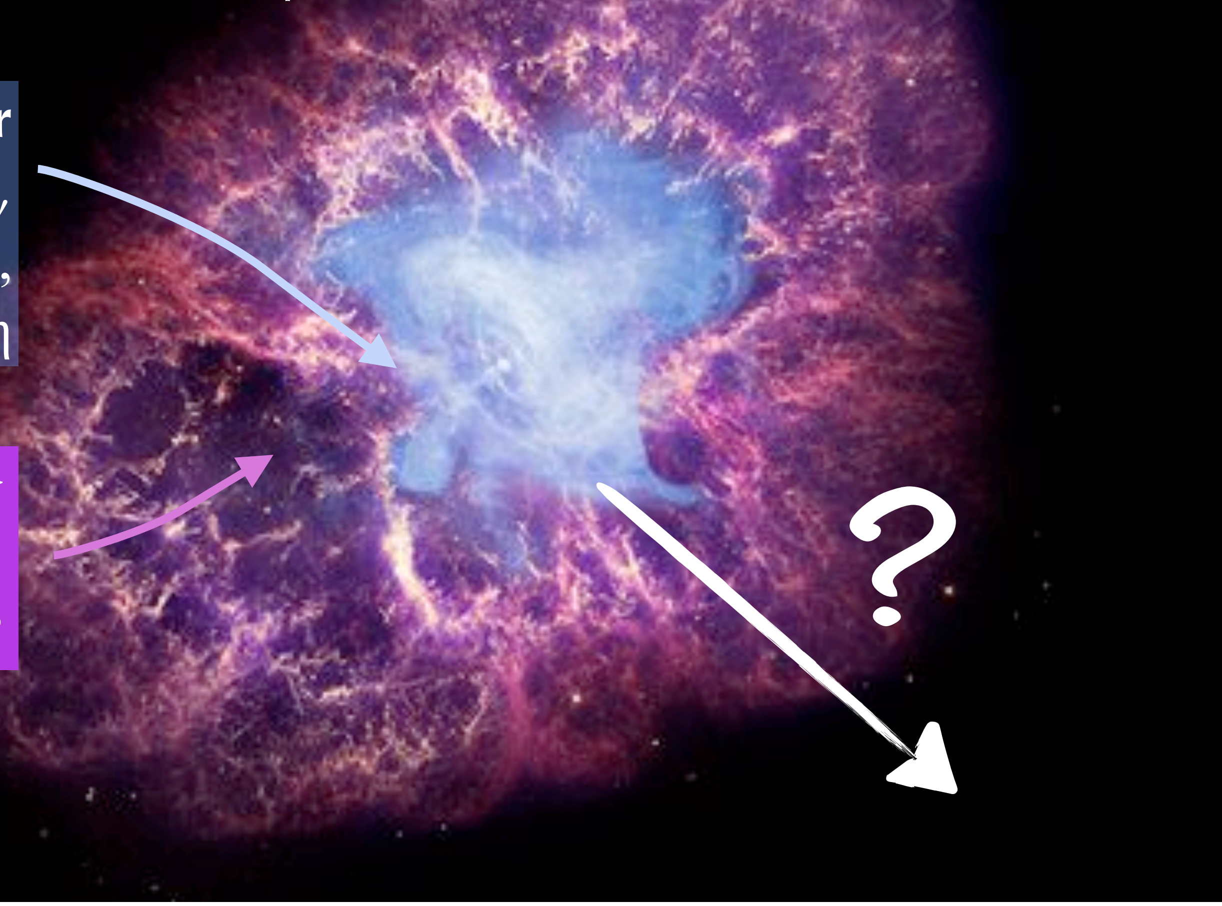
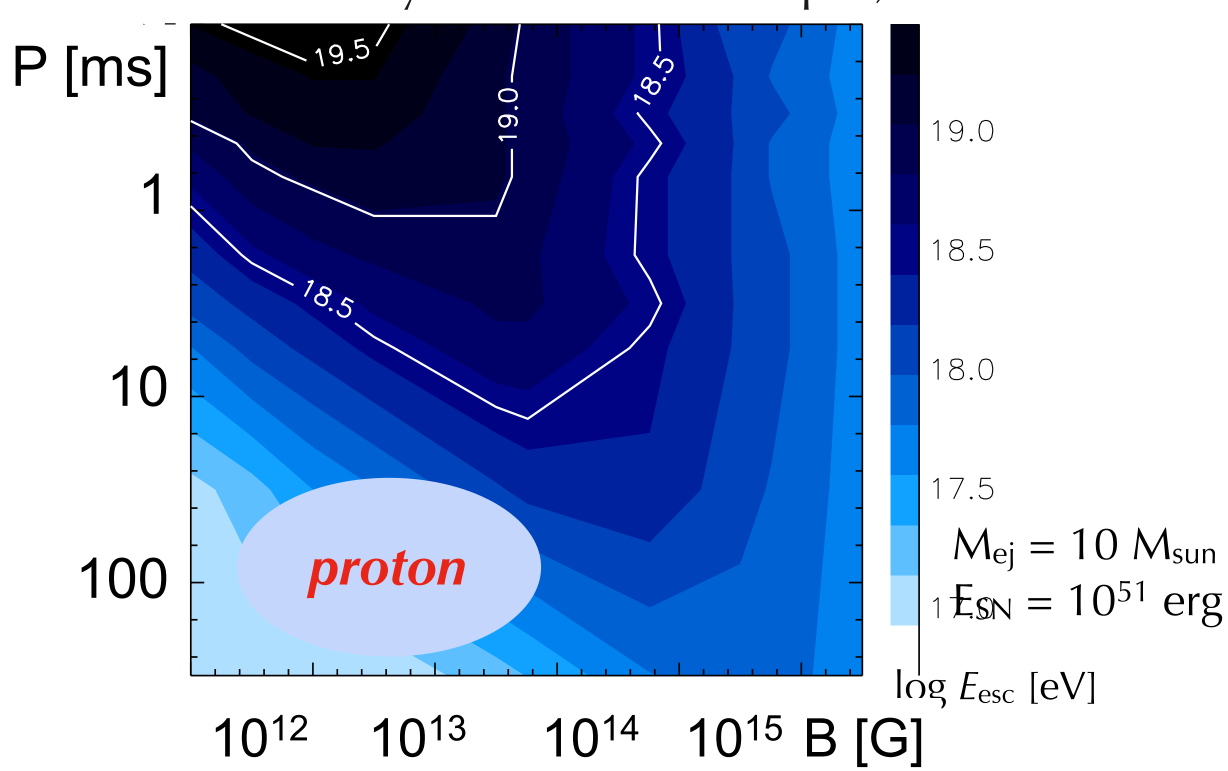
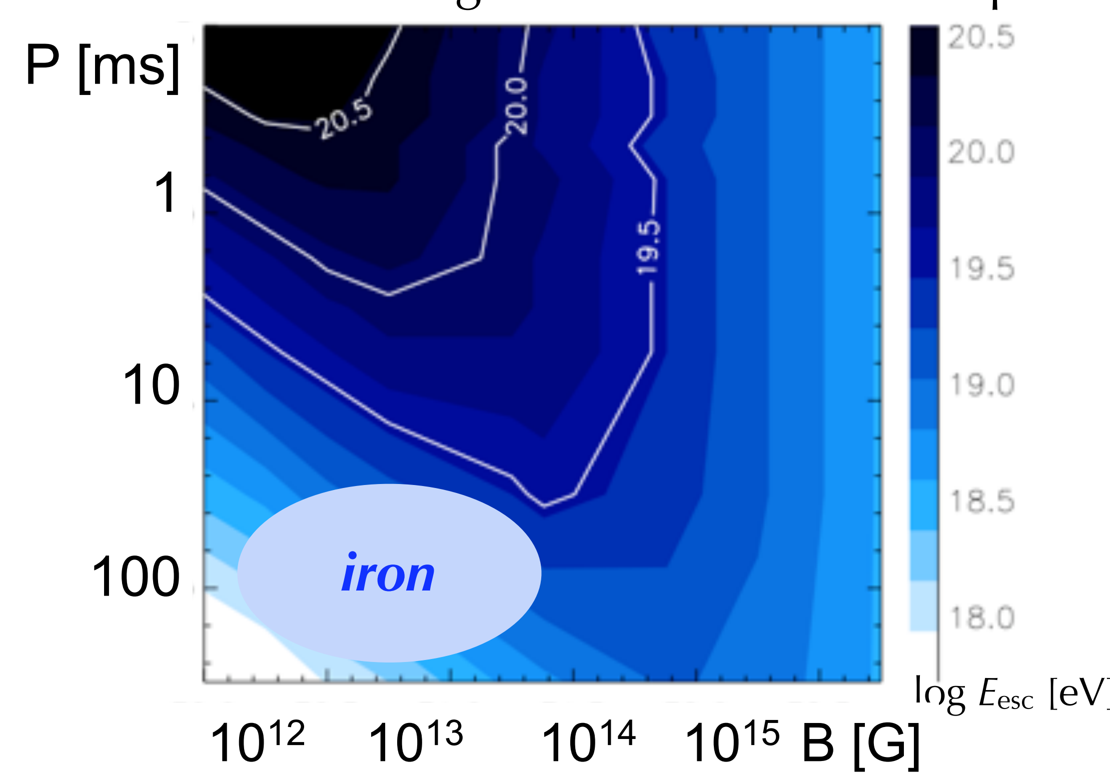


tight for protons
(would work for very dilute SN envelopes)



OK for iron:
accelerated to Z x higher E when SN envelope dilute



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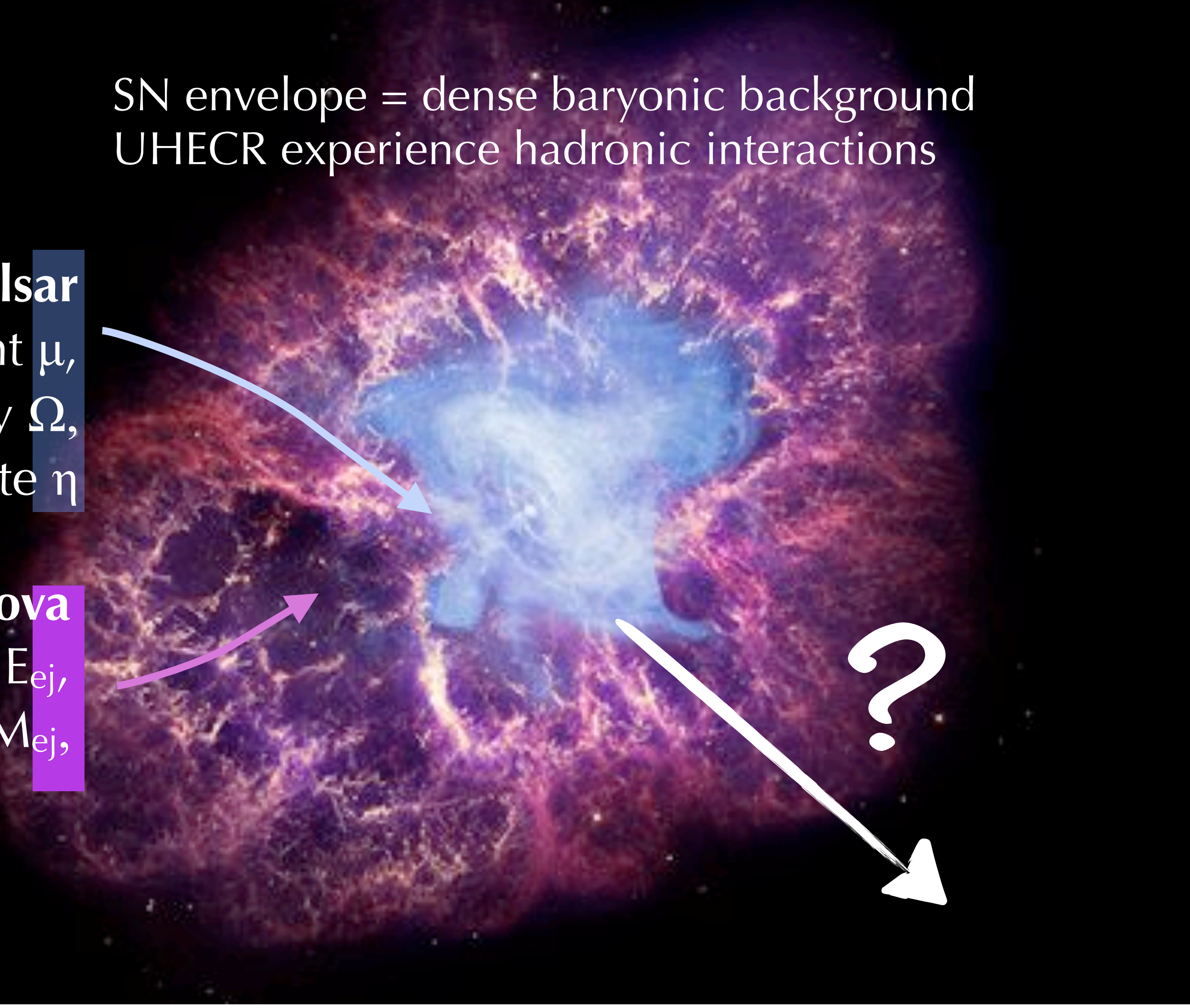

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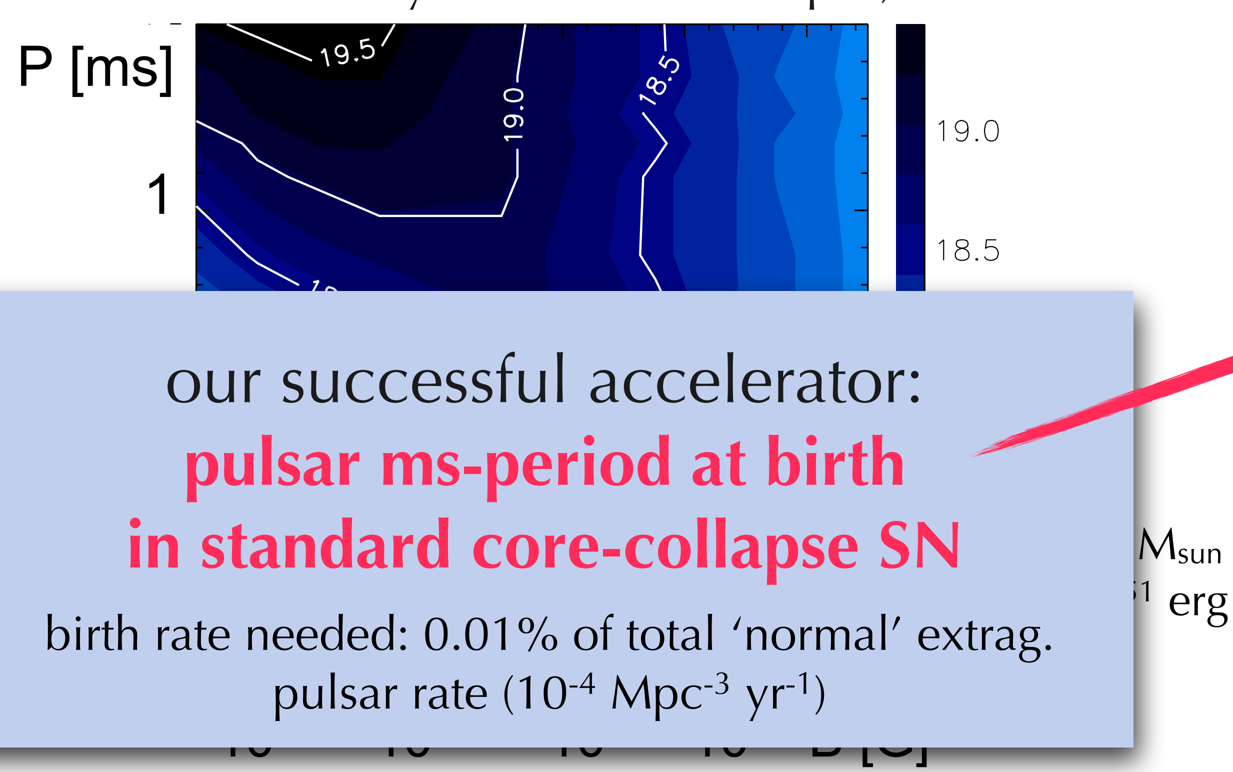

our successful accelerator:
pulsar ms-period at birth
in standard core-collapse SN
birth rate needed: 0.01% of total 'normal' extrag. pulsar rate (10^{-4} Mpc^{-3} yr^{-1})

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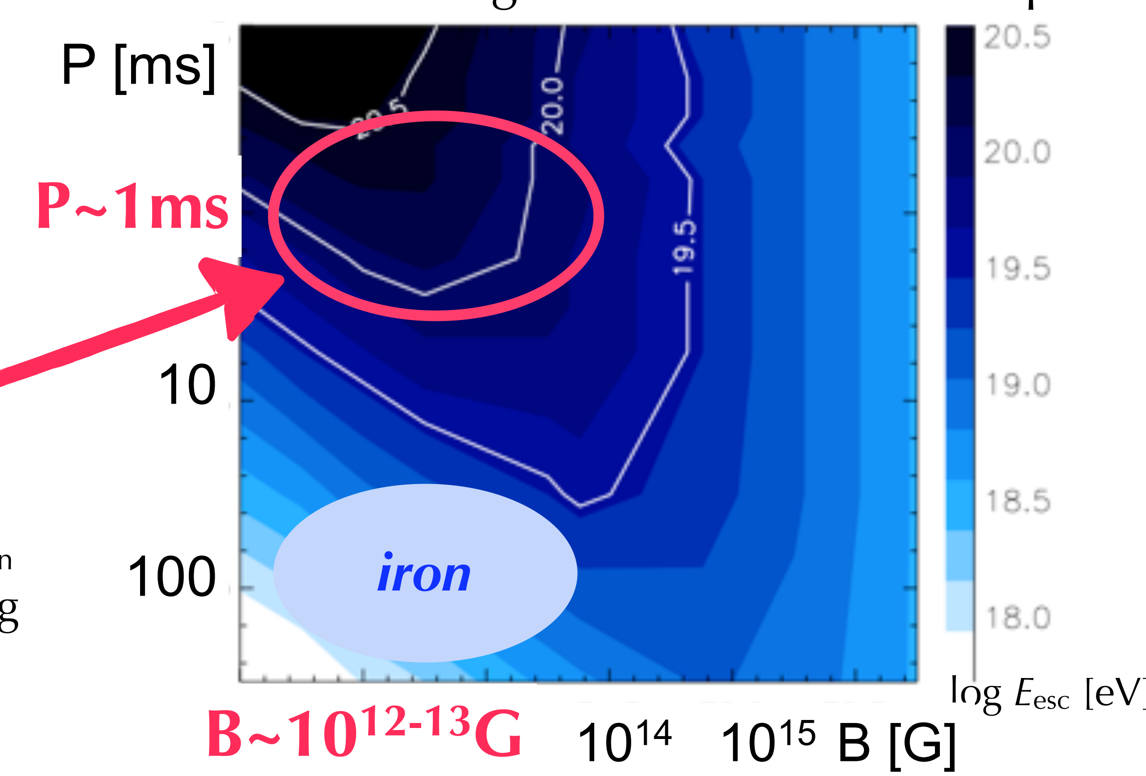
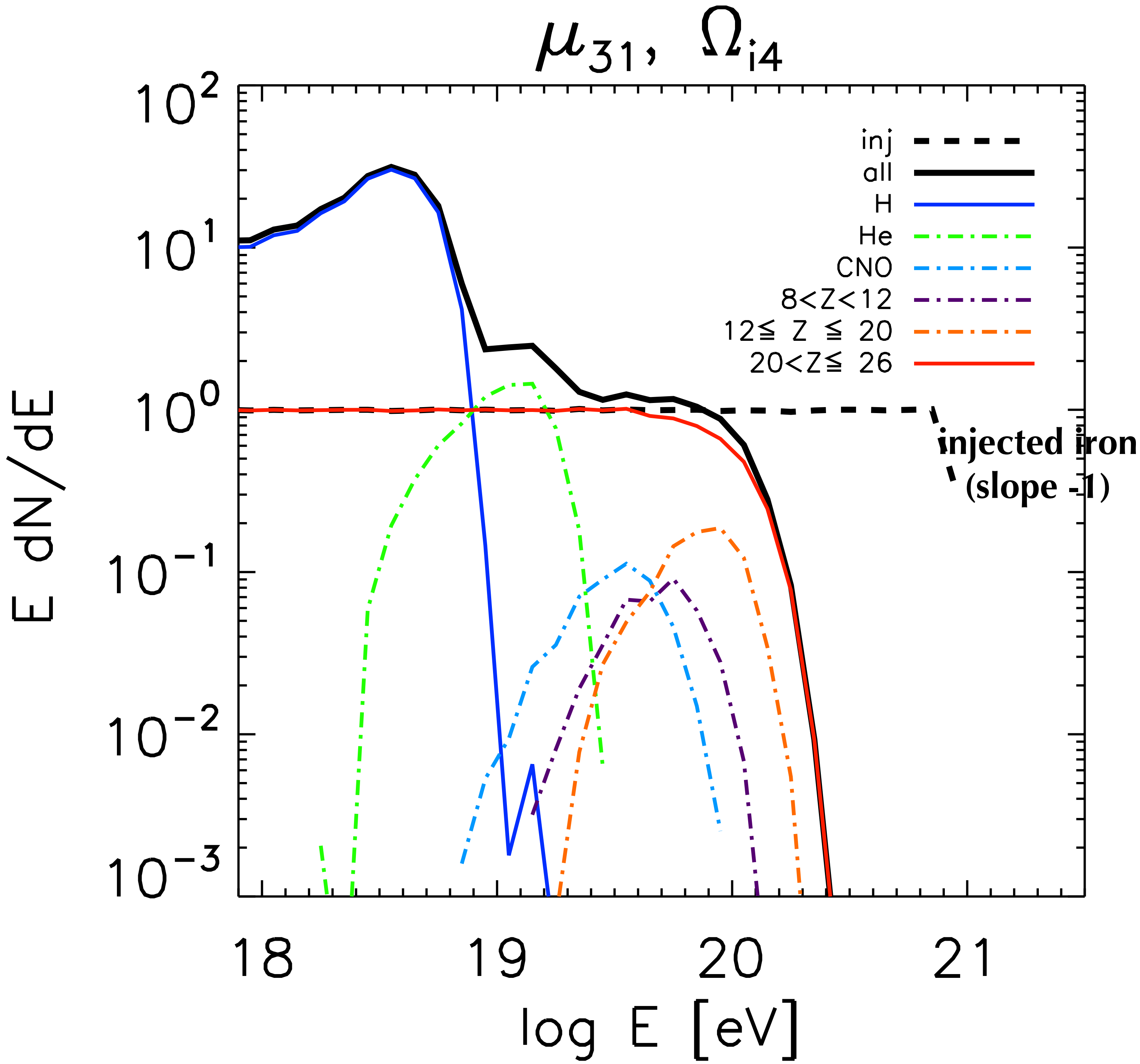


Collateral good news: spectrum, composition!

Fang, KK, Olinto 2012



escaped spectrum

pure iron injection

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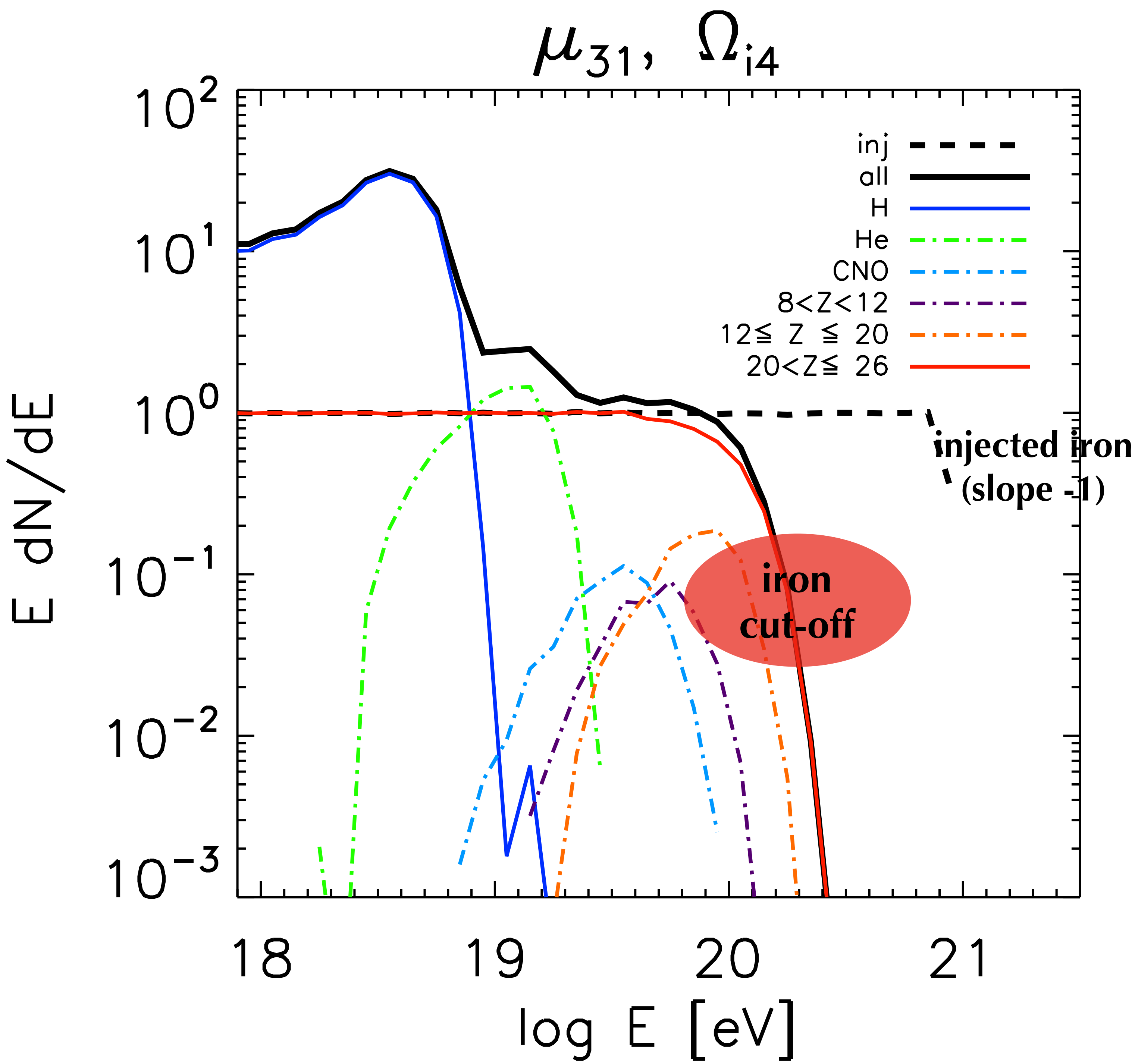

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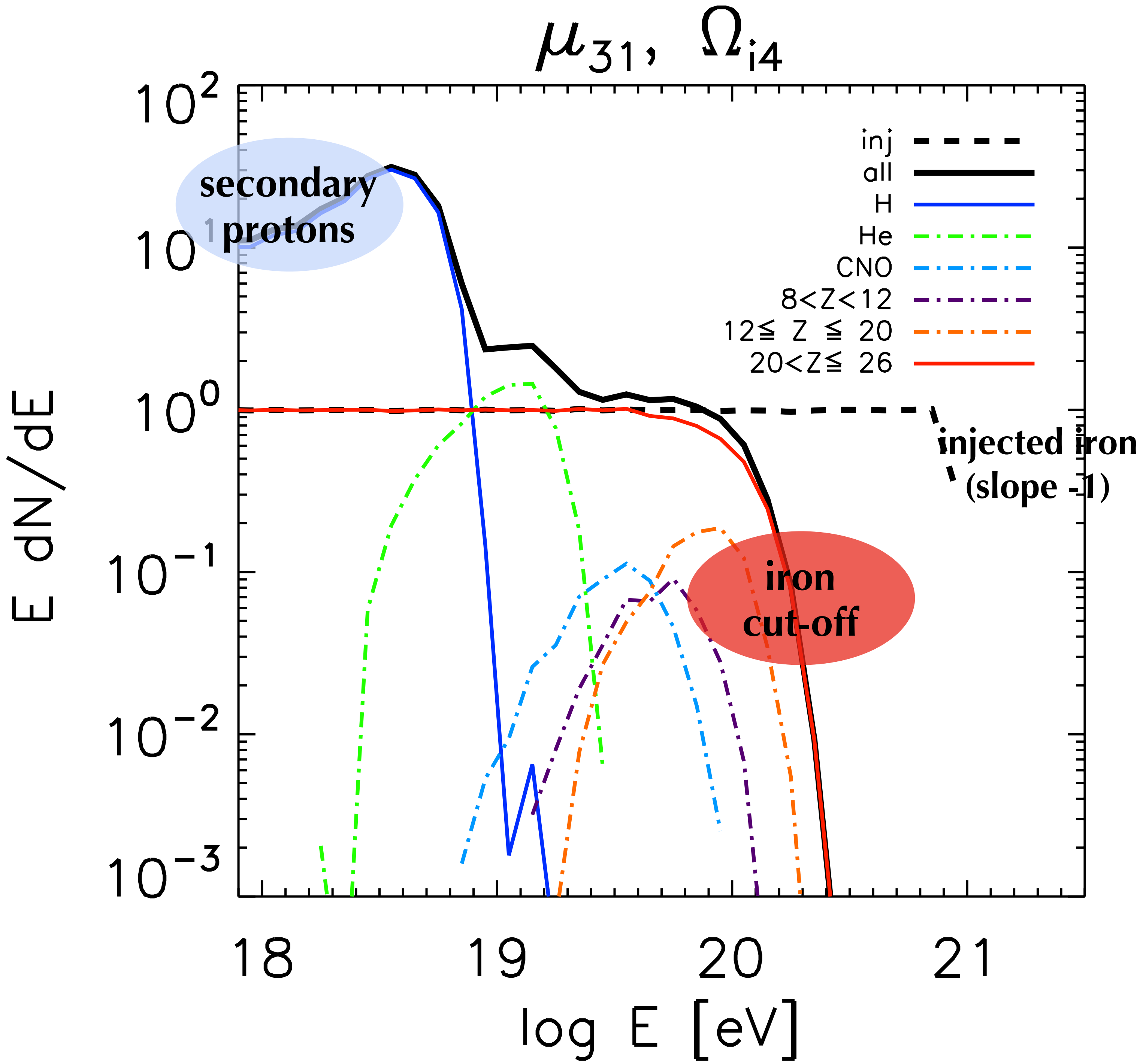

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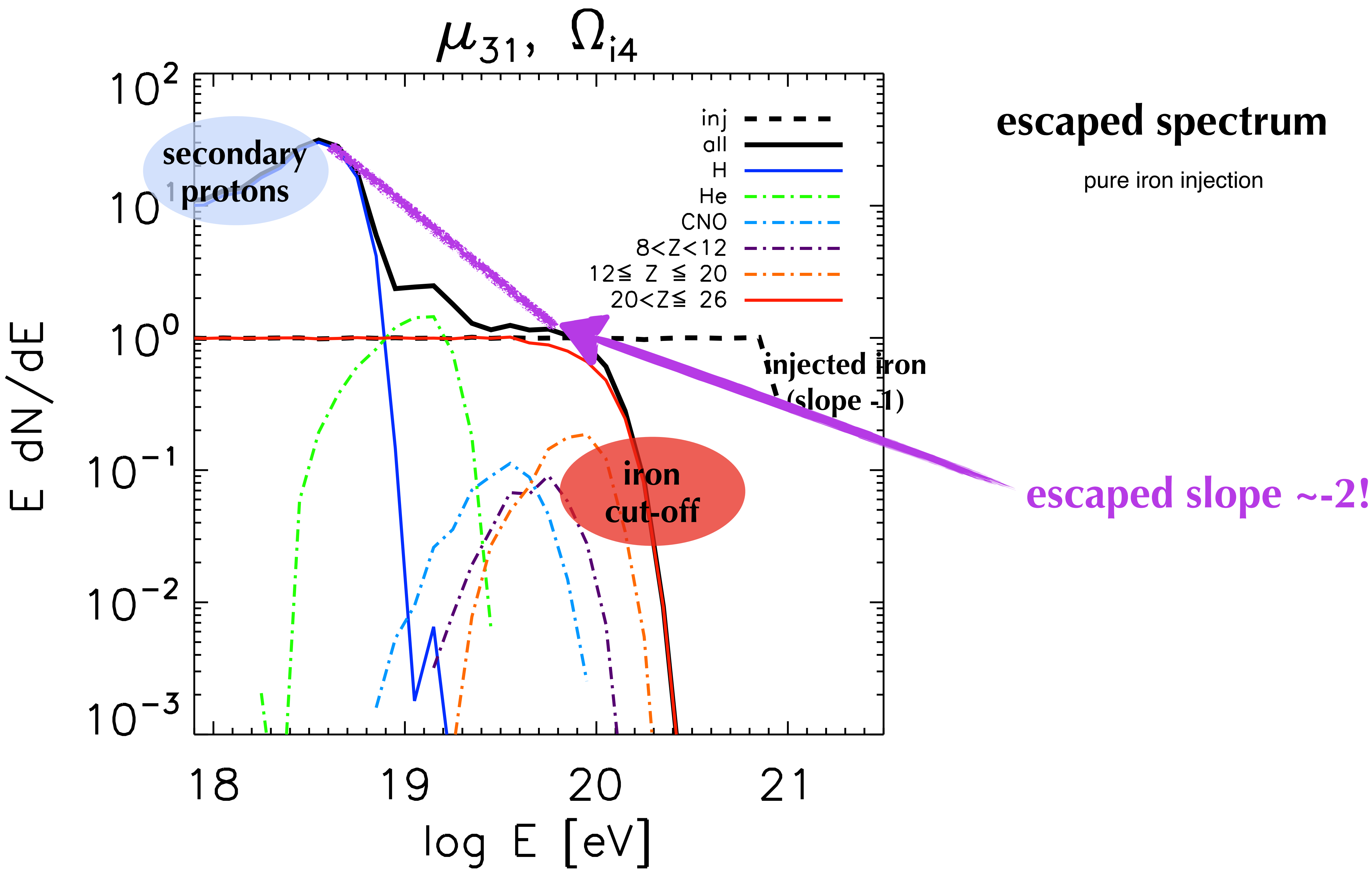

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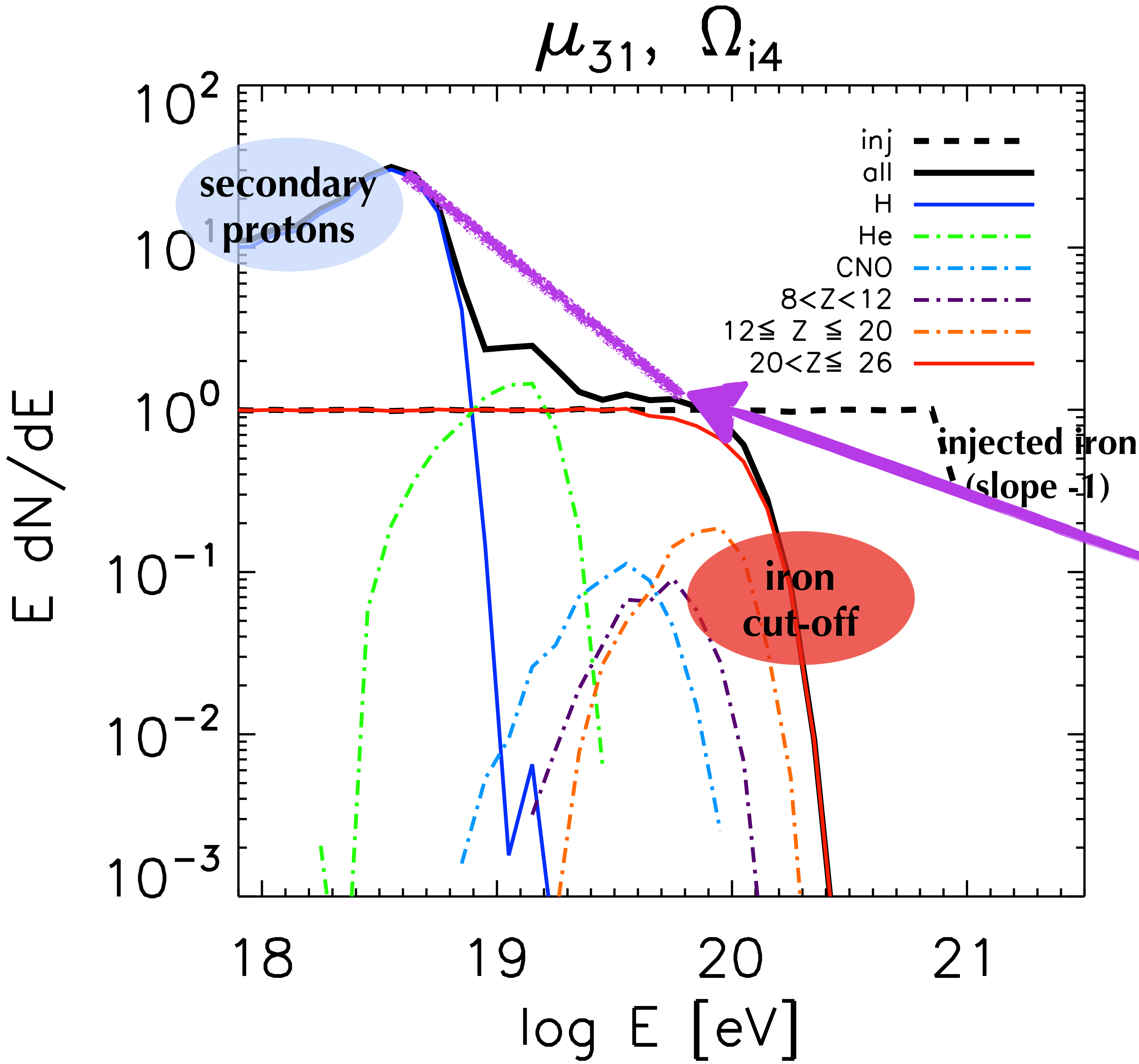


escaped spectrum

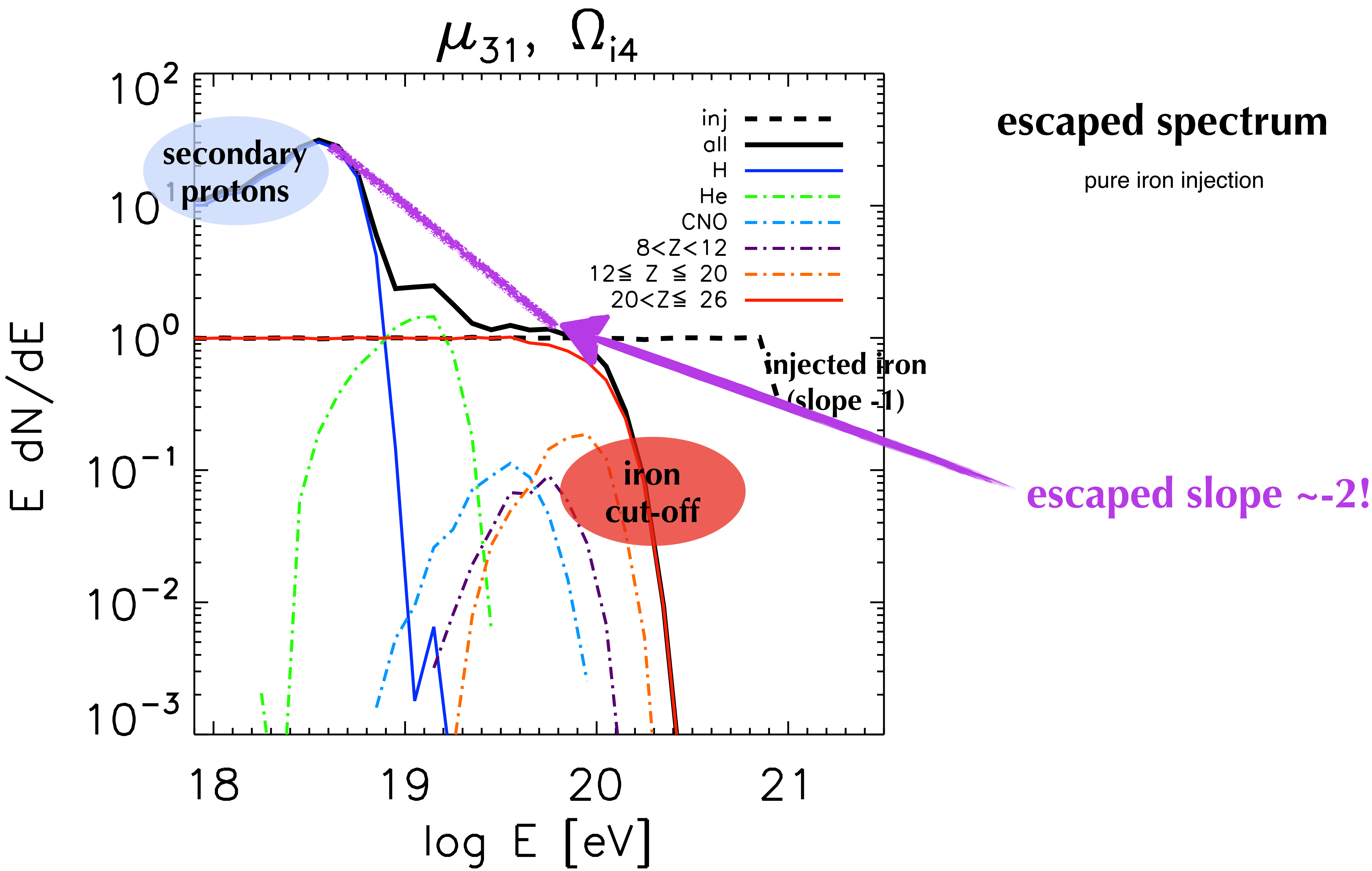
pure iron injection

escaped slope ~-2!

light → heavy

Collateral good news: spectrum, composition!

Fang, KK, Olinto 2012



escaped spectrum

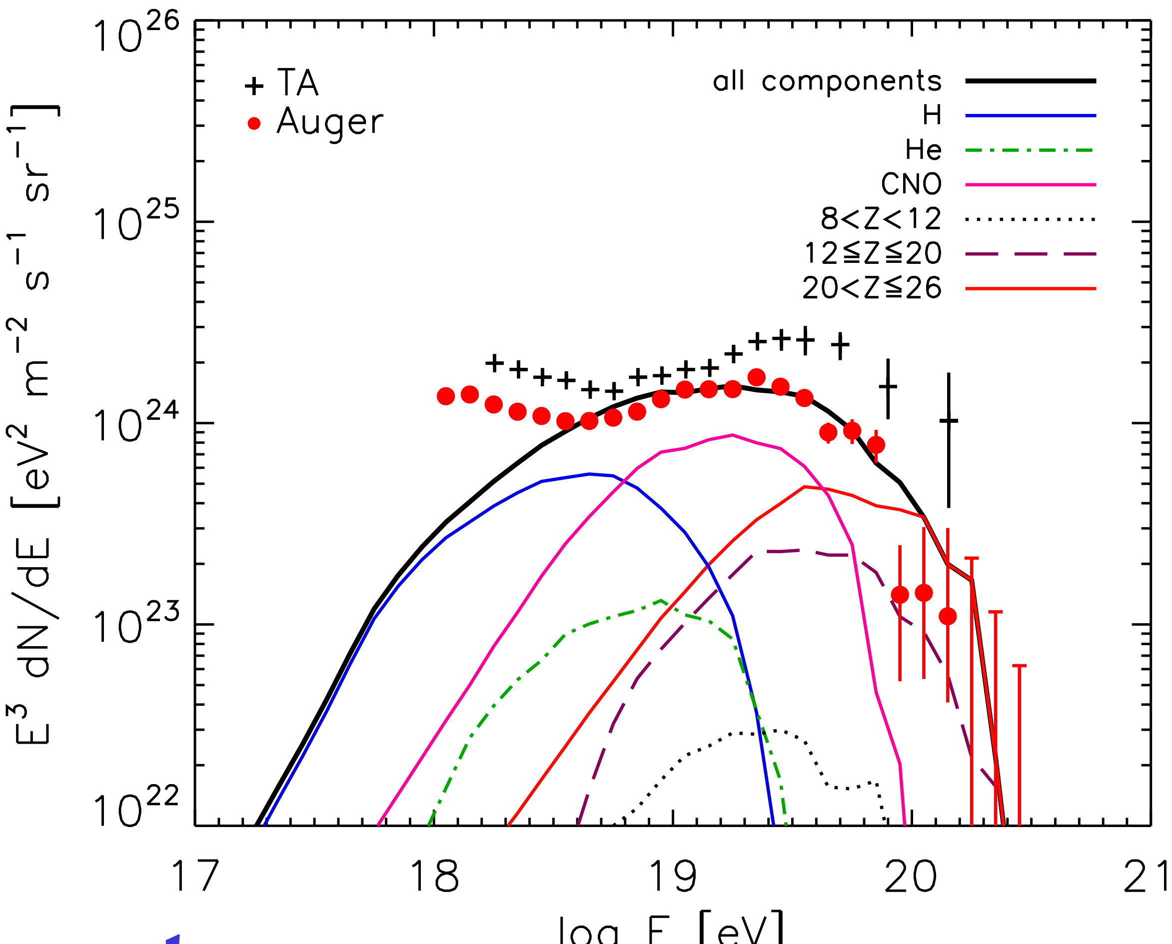
pure iron injection

light → heavy

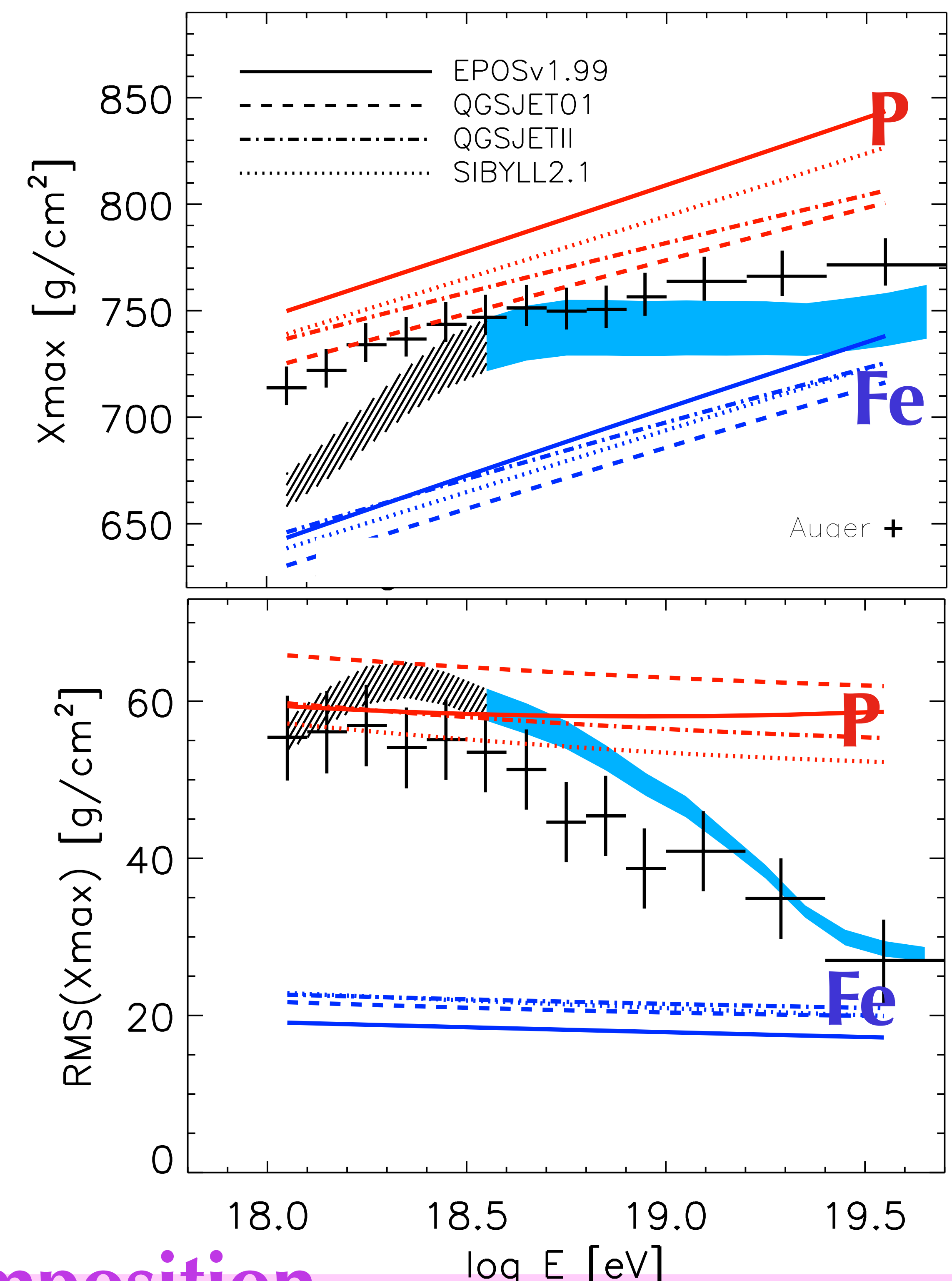
... and after propagation in the Universe with EXTRAGALACTIC pulsar population:

A scenario that fits UHECR Auger data (rare)

Fang, KK, Olinto 2012
Fang, KK, Olinto, 2013



spectrum



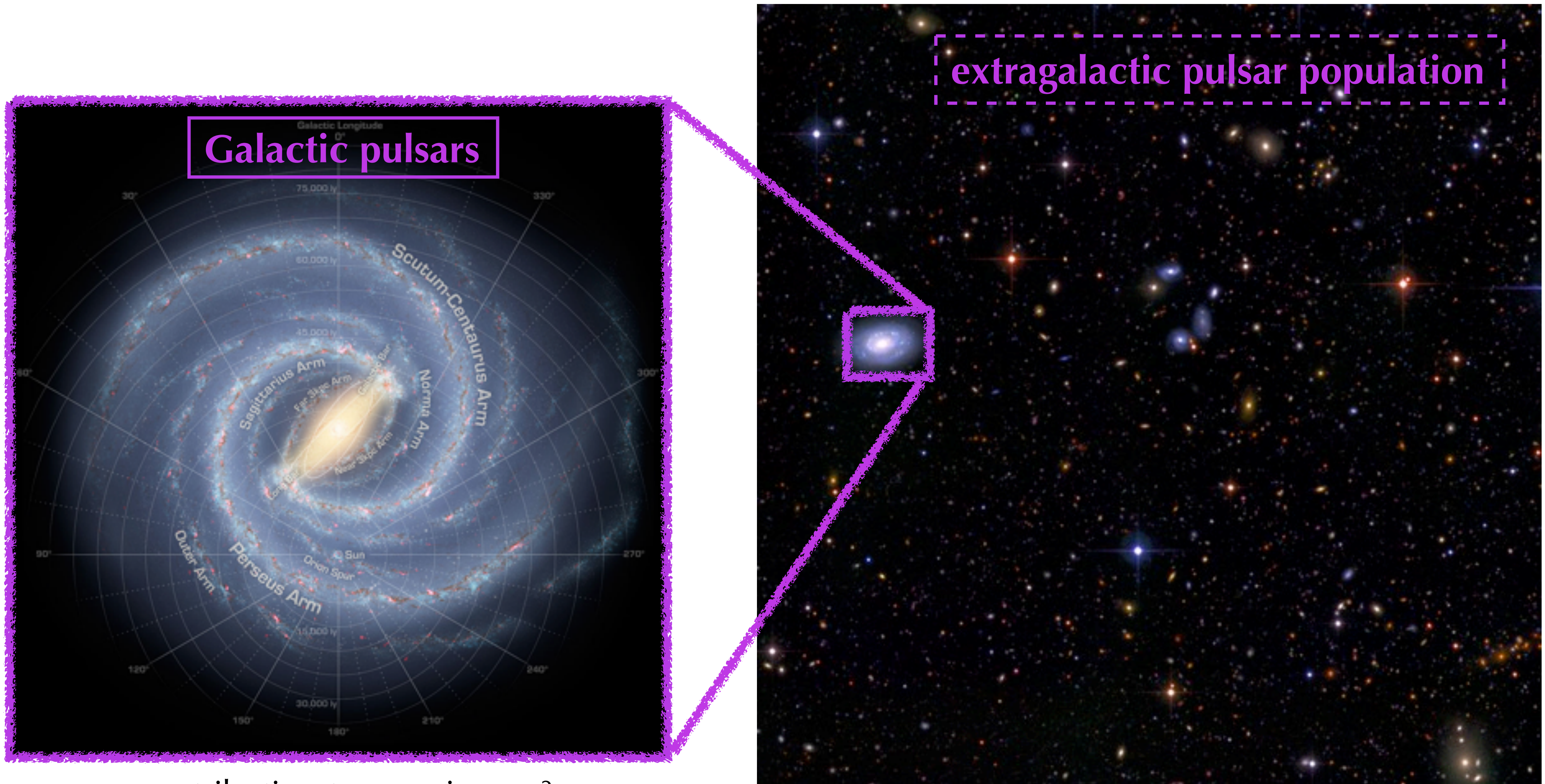
composition

propagated in the IGM

uniform source emissivity evolution
@injection: 50%P, 30%CNO, 20%Fe

Contribution of all Galactic+extragactic pulsars?

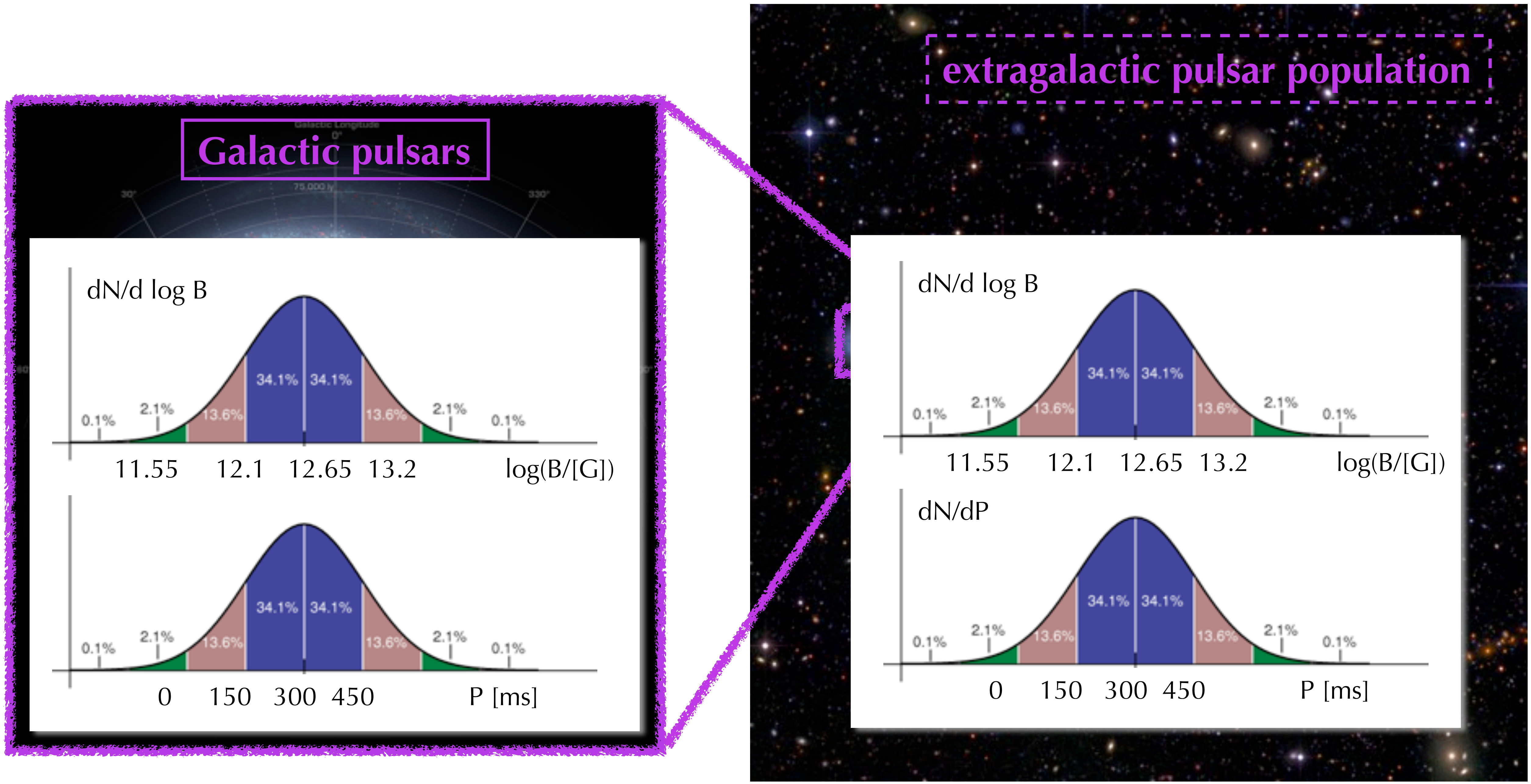
Fang, KK, Olinto, 2013



contribution to cosmic rays?

Contribution of all Galactic+extragactic pulsars?

Fang, KK, Olinto, 2013



identical distribution of pulsar parameters in any galaxy,
distribution following ***Faucher-Giguère & Kaspi 06***

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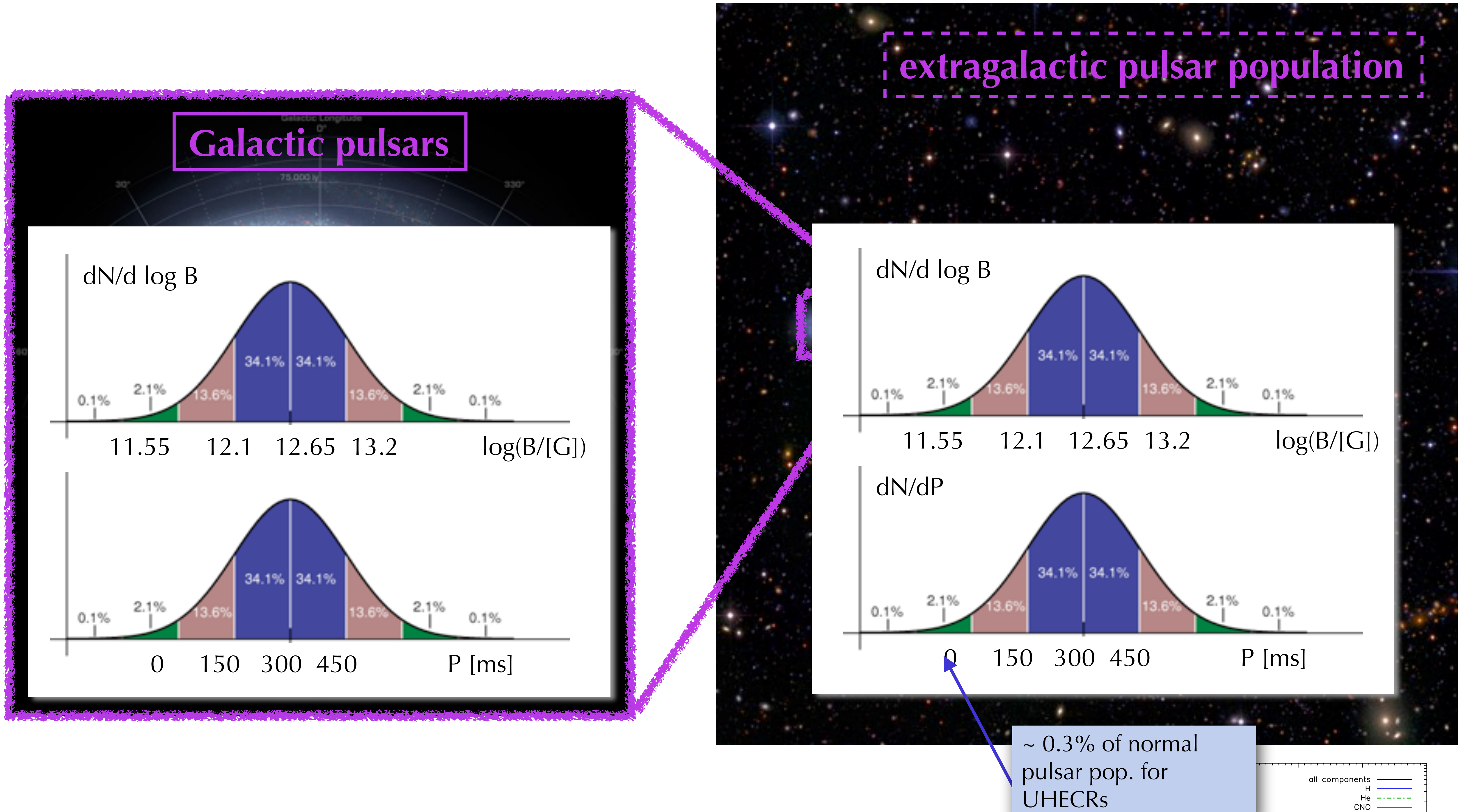
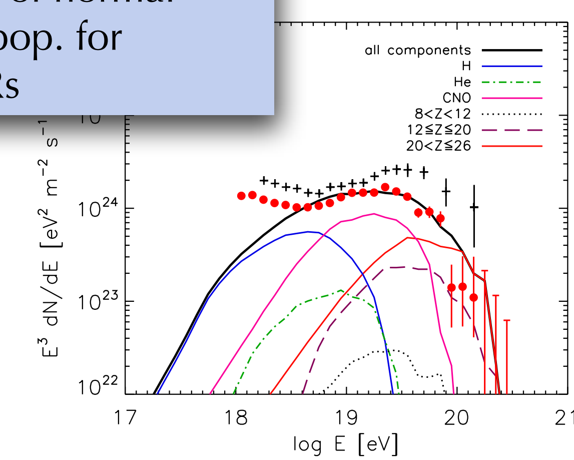
Fang, KK, Olinto, 2013





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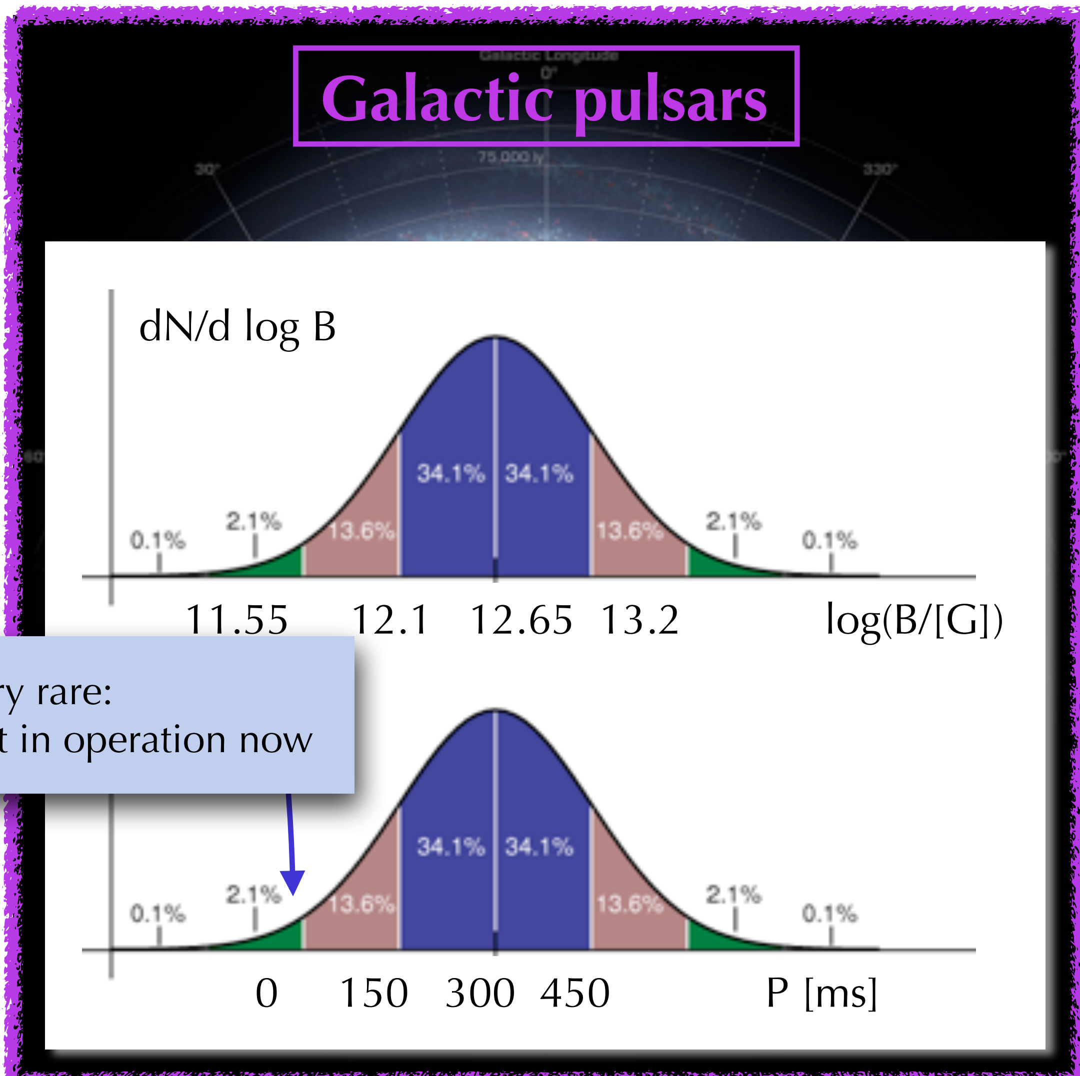
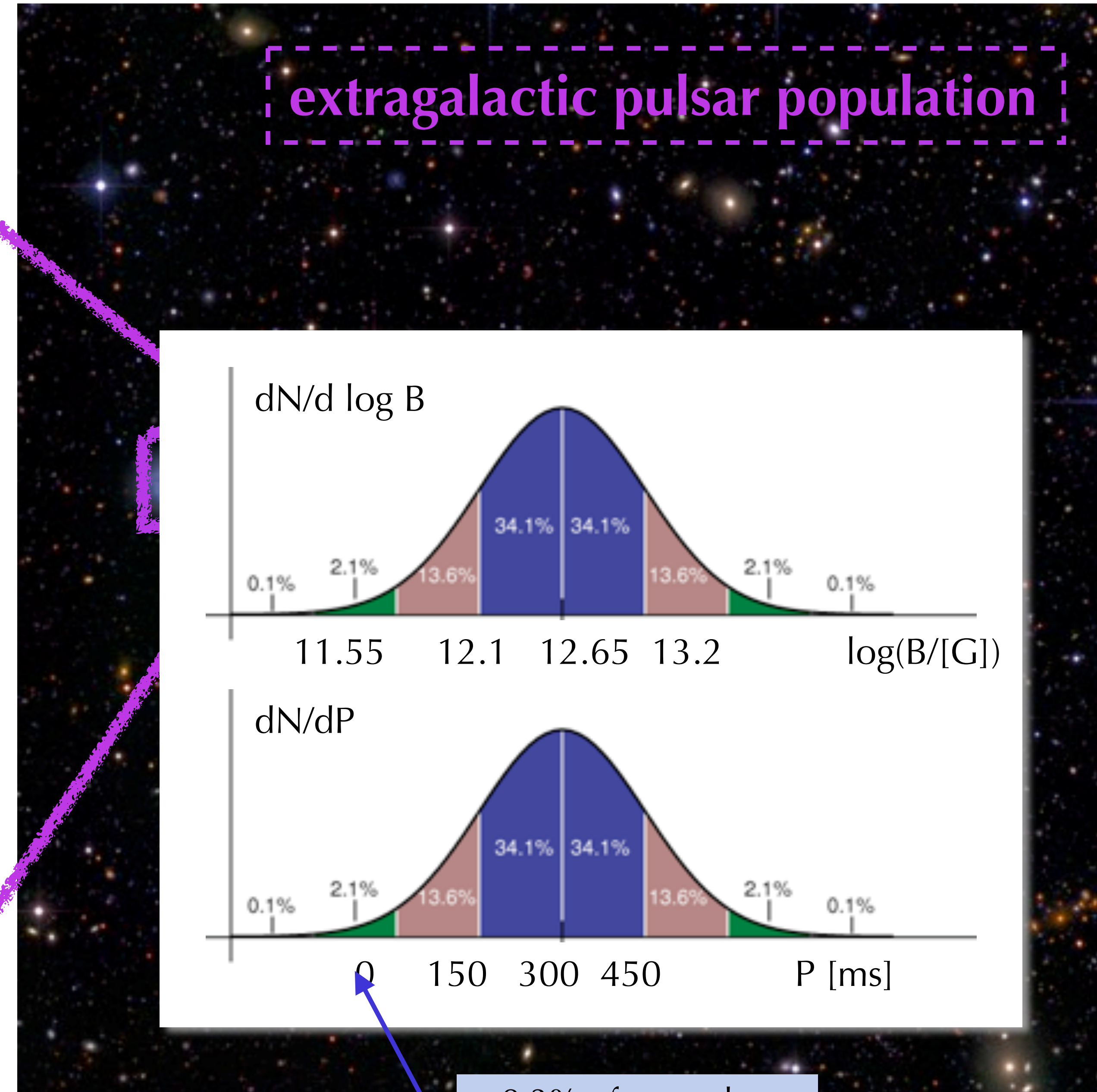
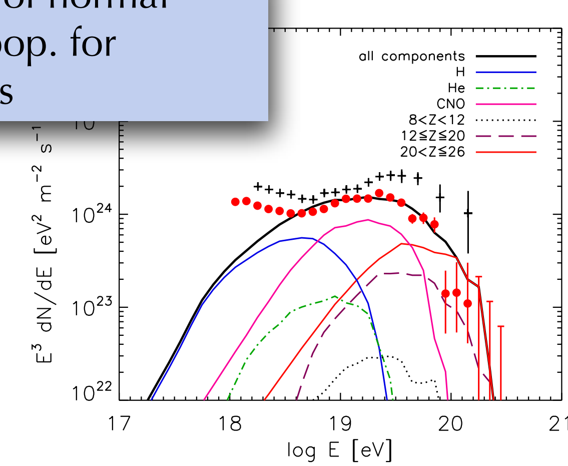


very rare:
not in operation now



~ 0.3% of normal pulsar pop. for UHECRs



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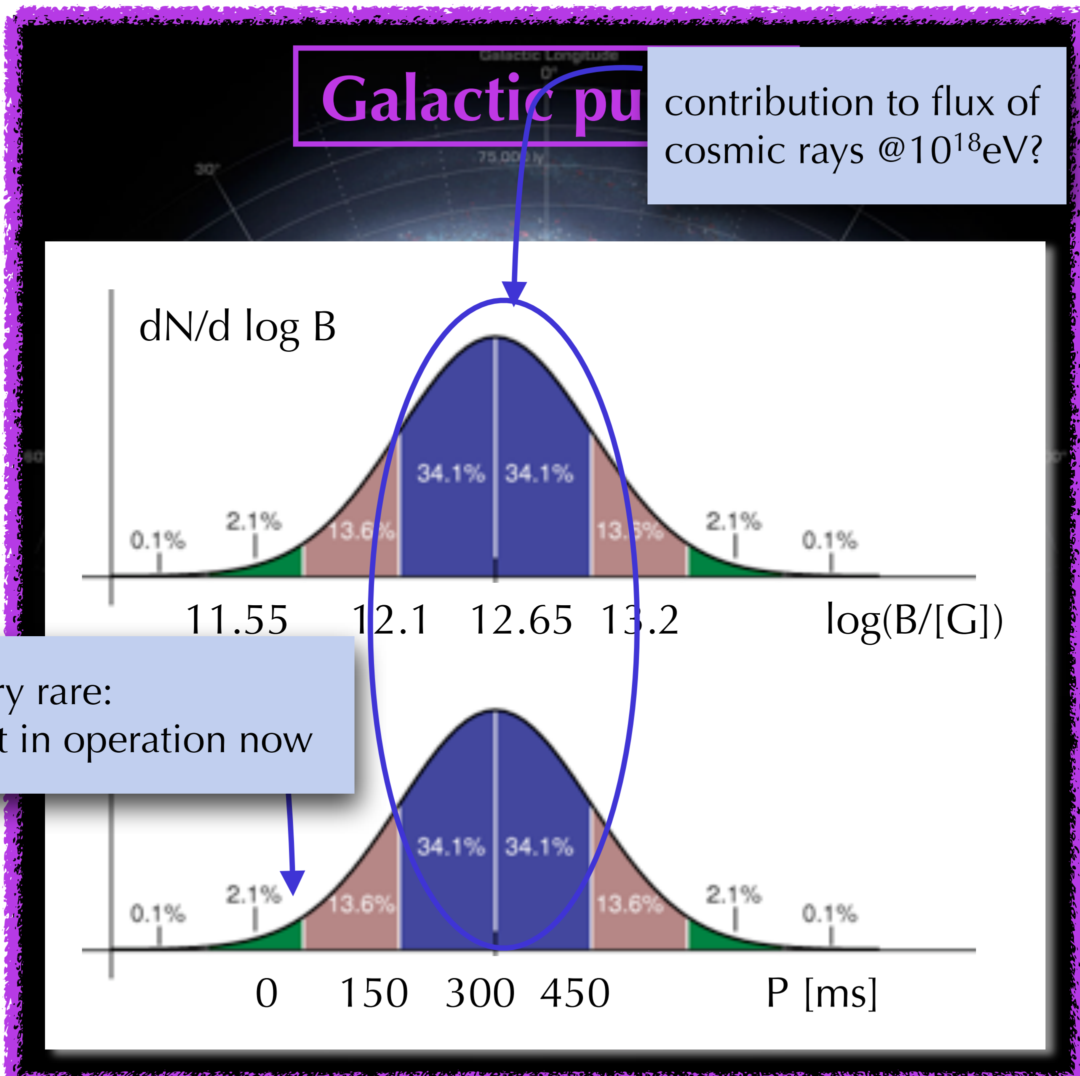
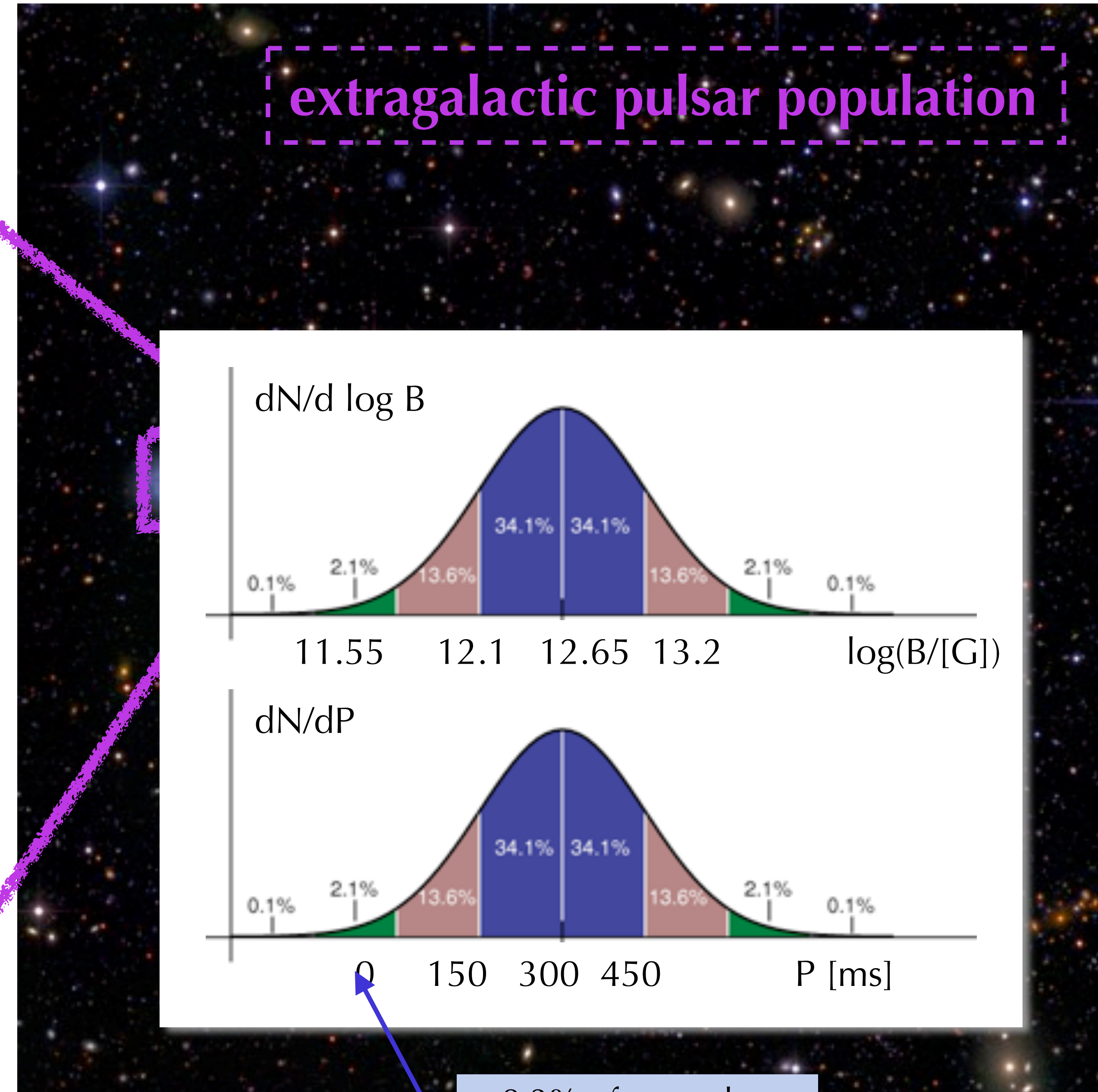


contribution to flux of cosmic rays @10^{18}eV?

very rare:
not in operation now



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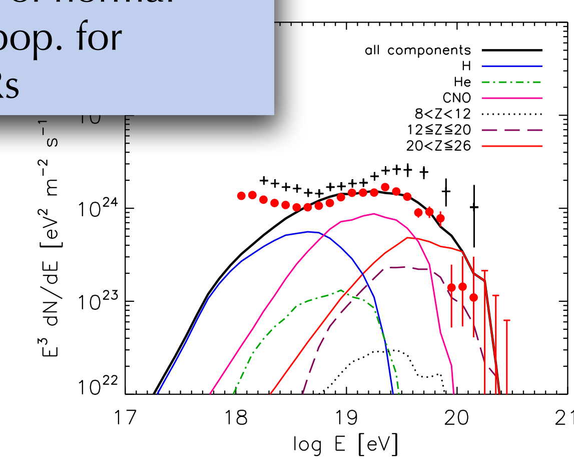

identical distribution of pulsar parameters in any galaxy,
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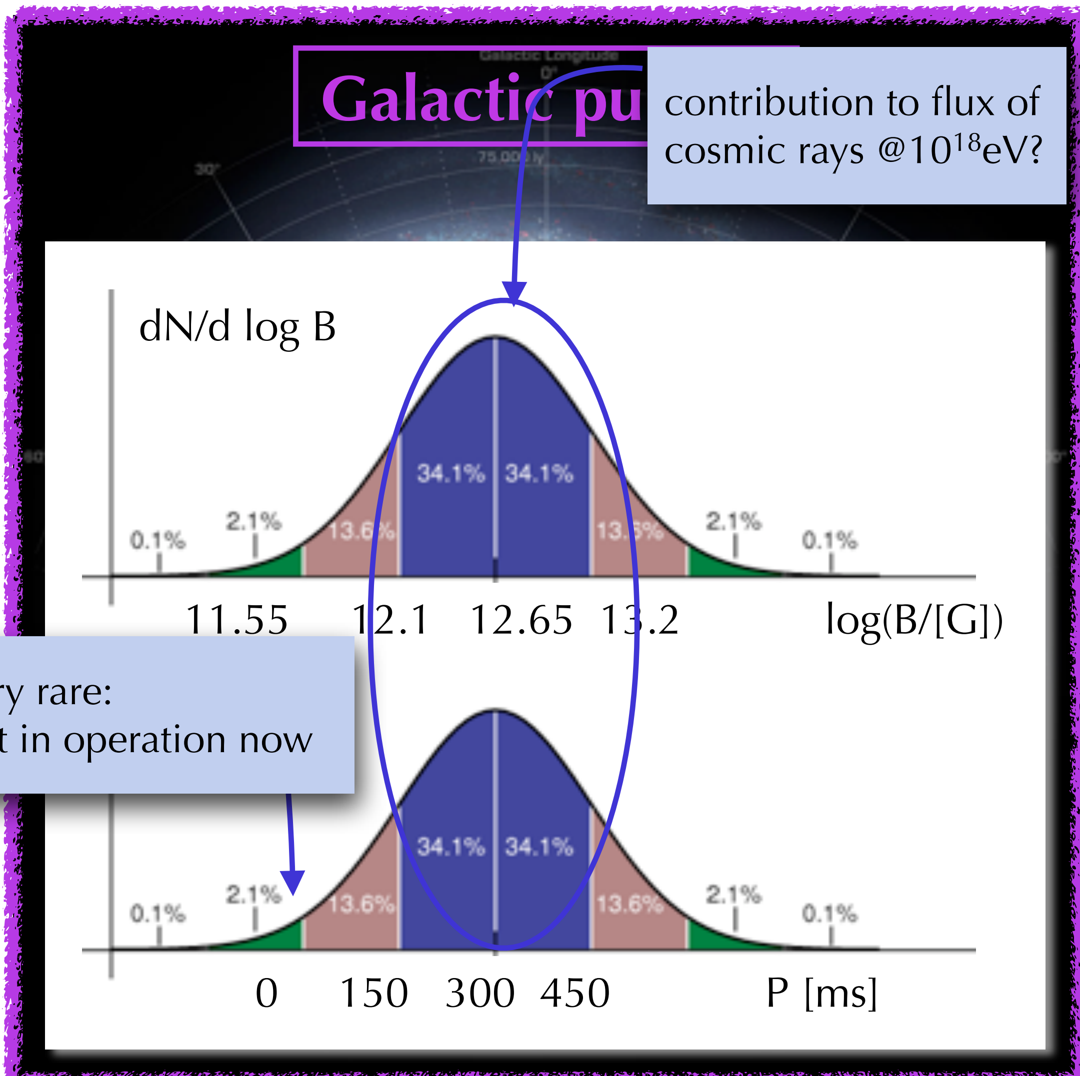
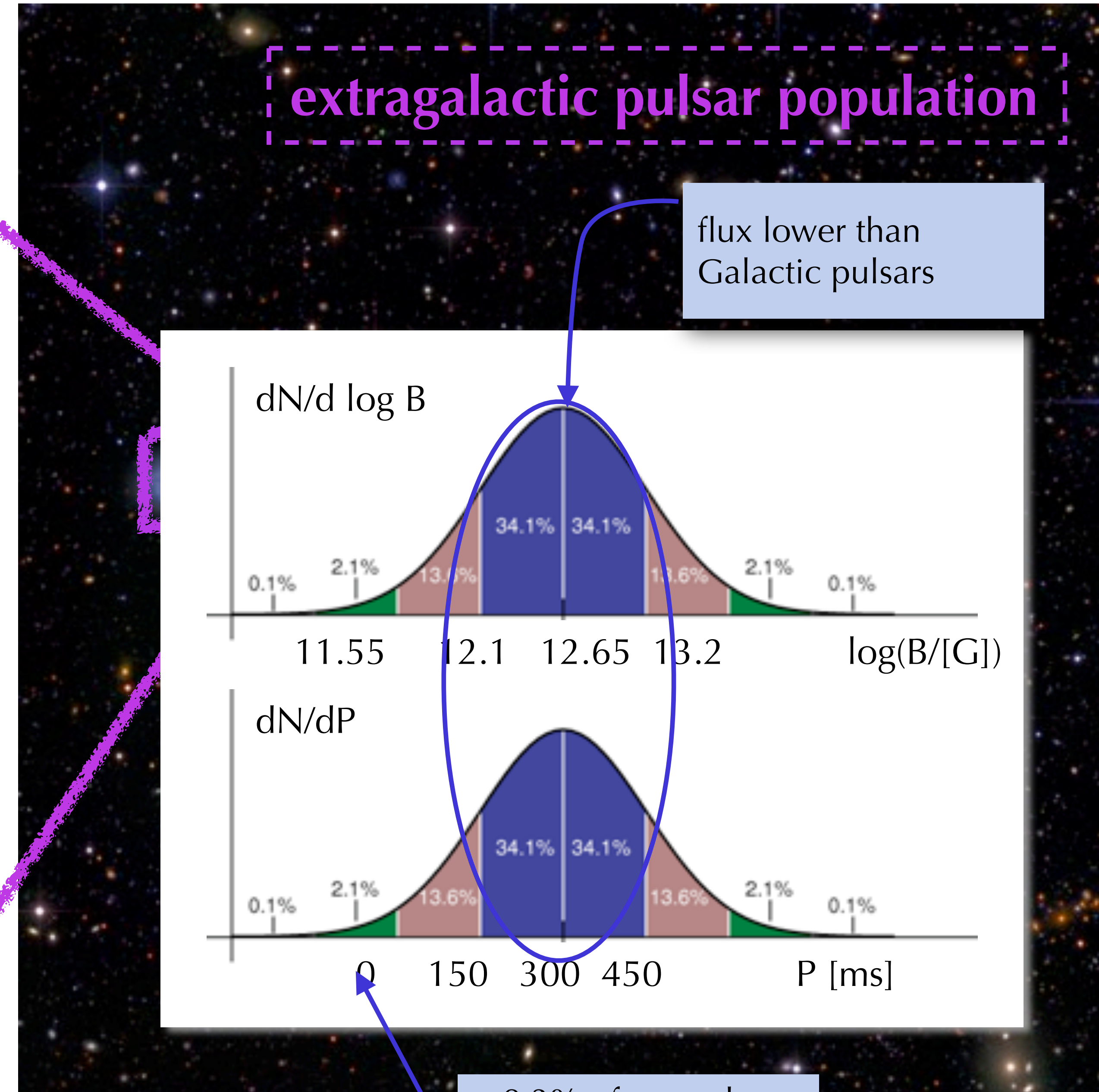
Contribution of all Galactic+extragactic pulsars?

Fang, KK, Olinto, 2013



contribution to flux of cosmic rays @10^{18}eV?

very rare:
not in operation now



flux lower than Galactic pulsars

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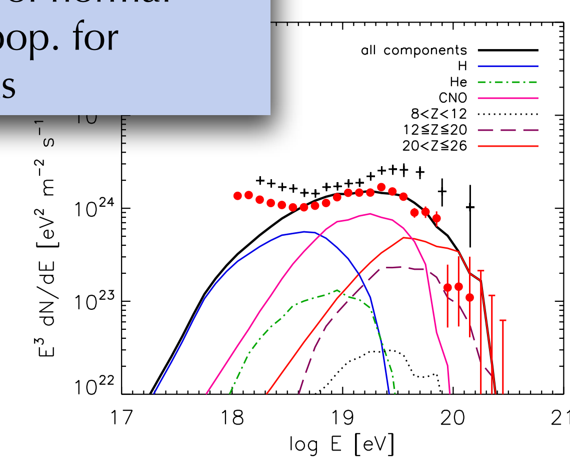

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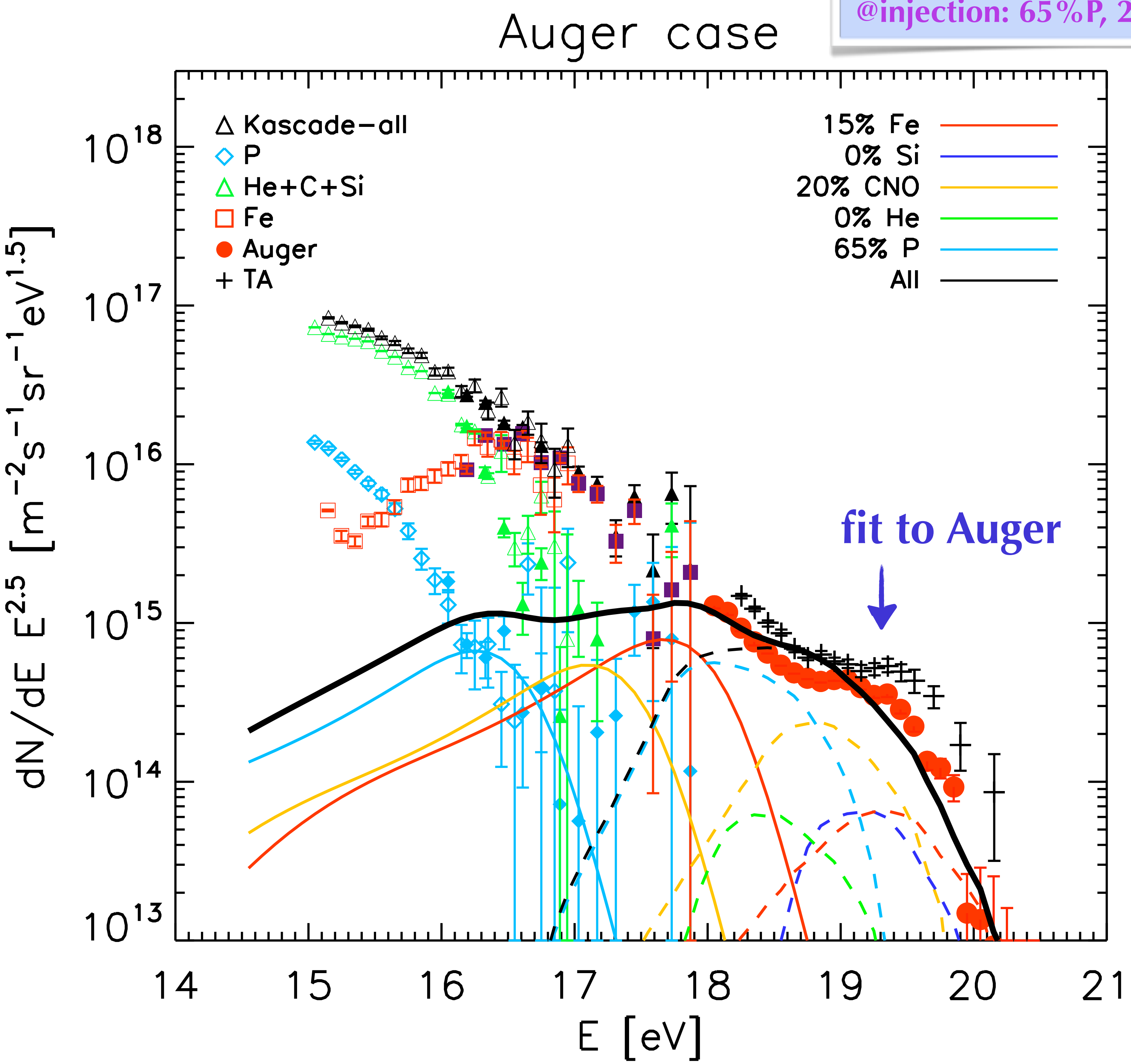

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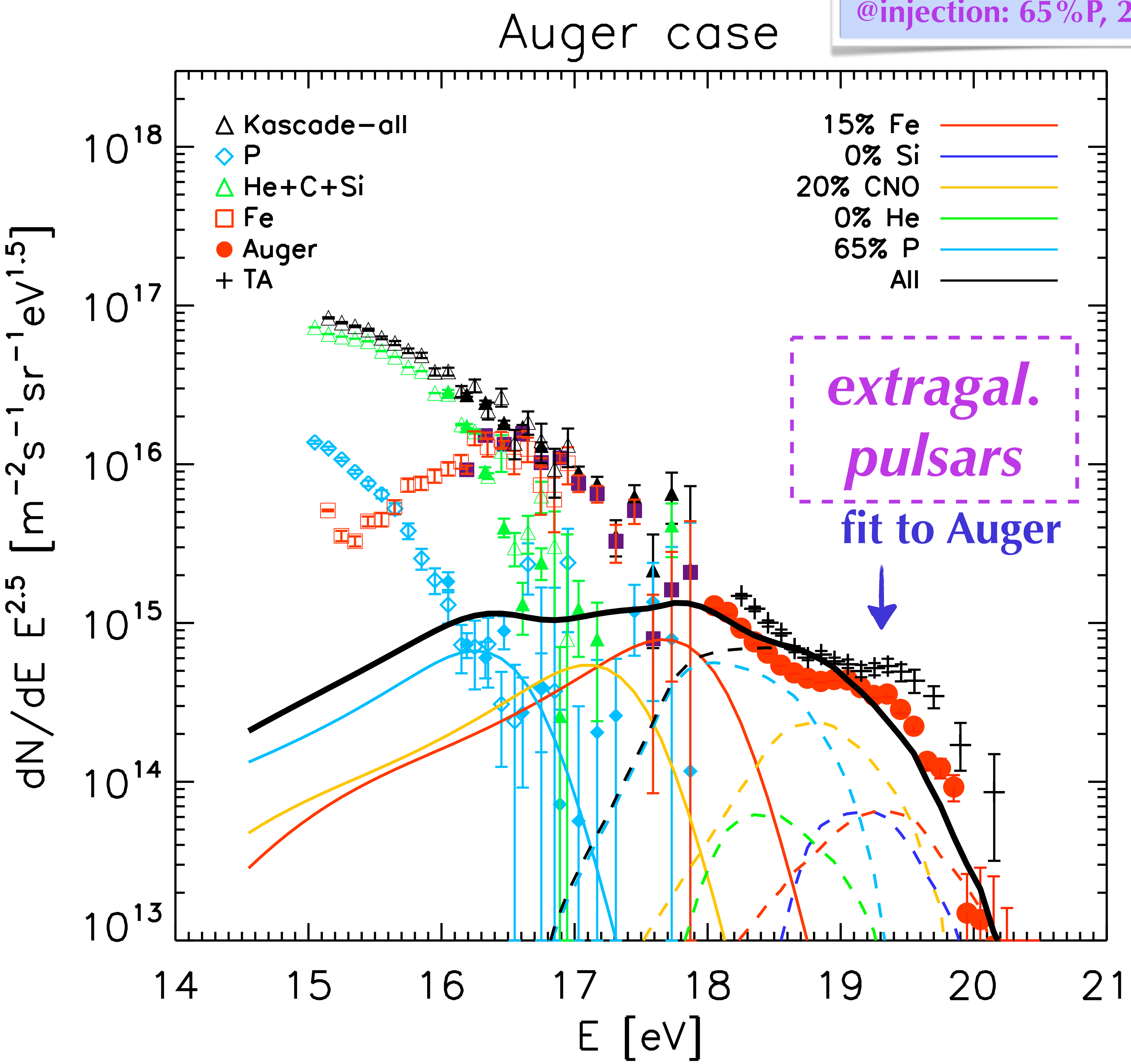

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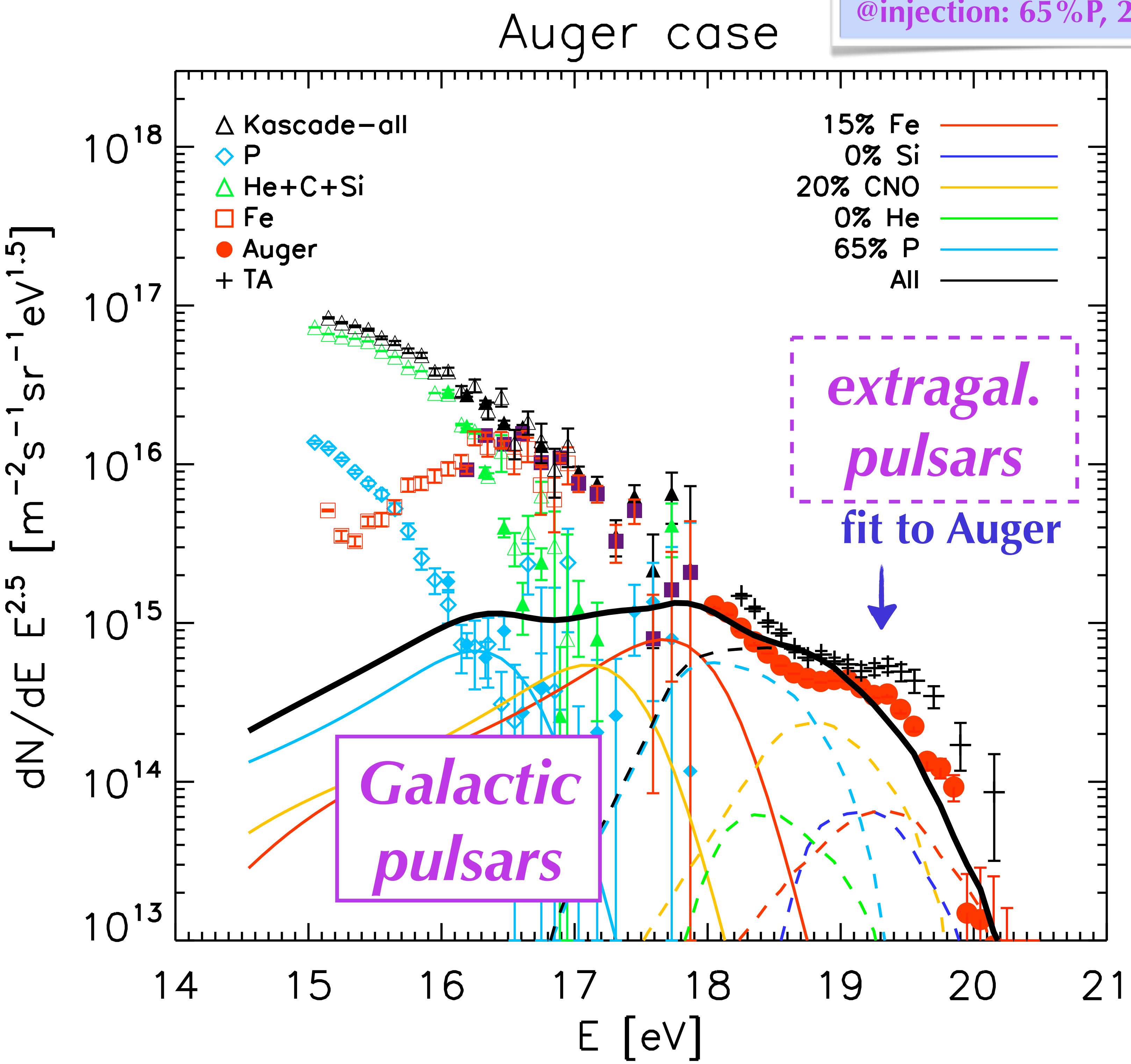

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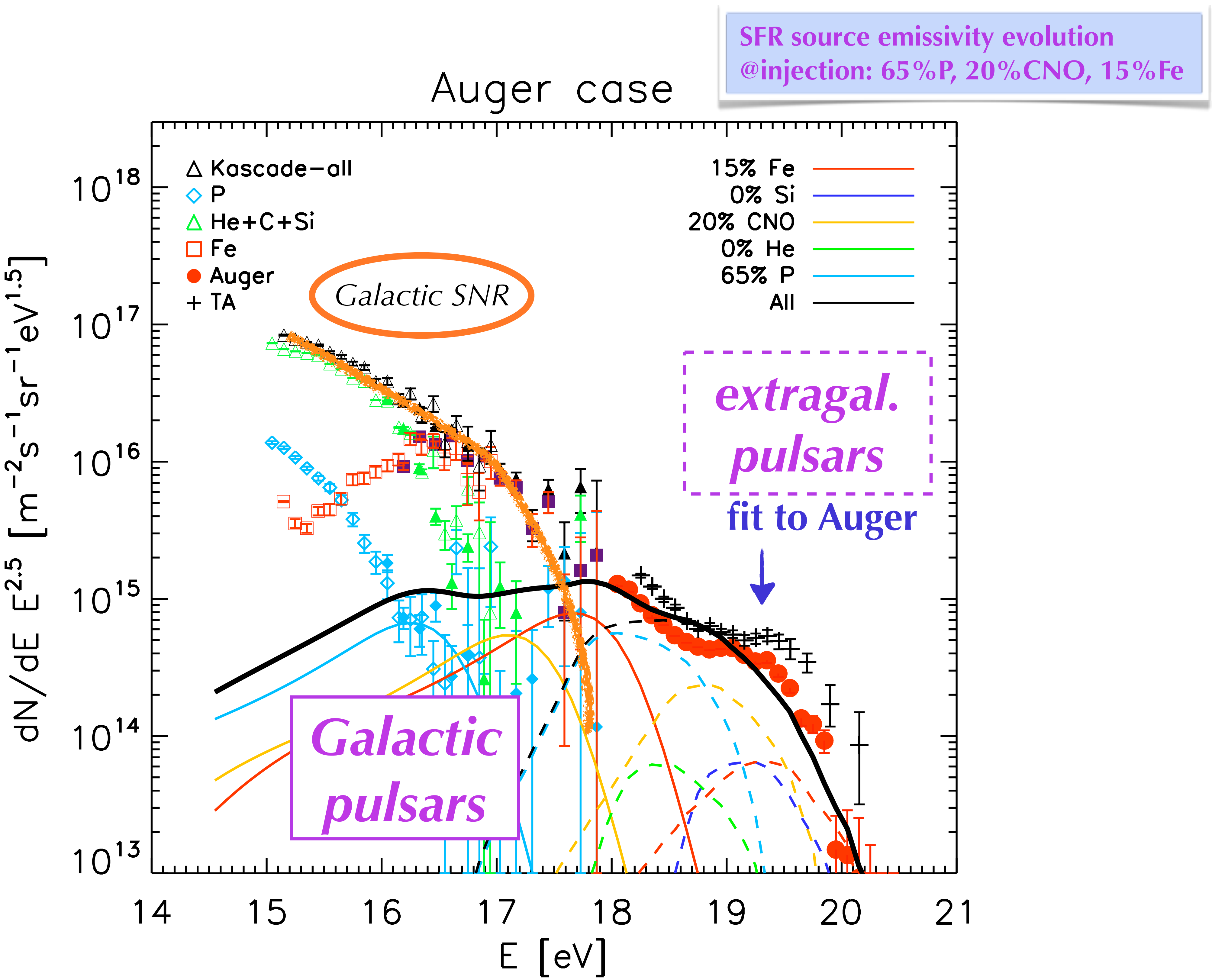

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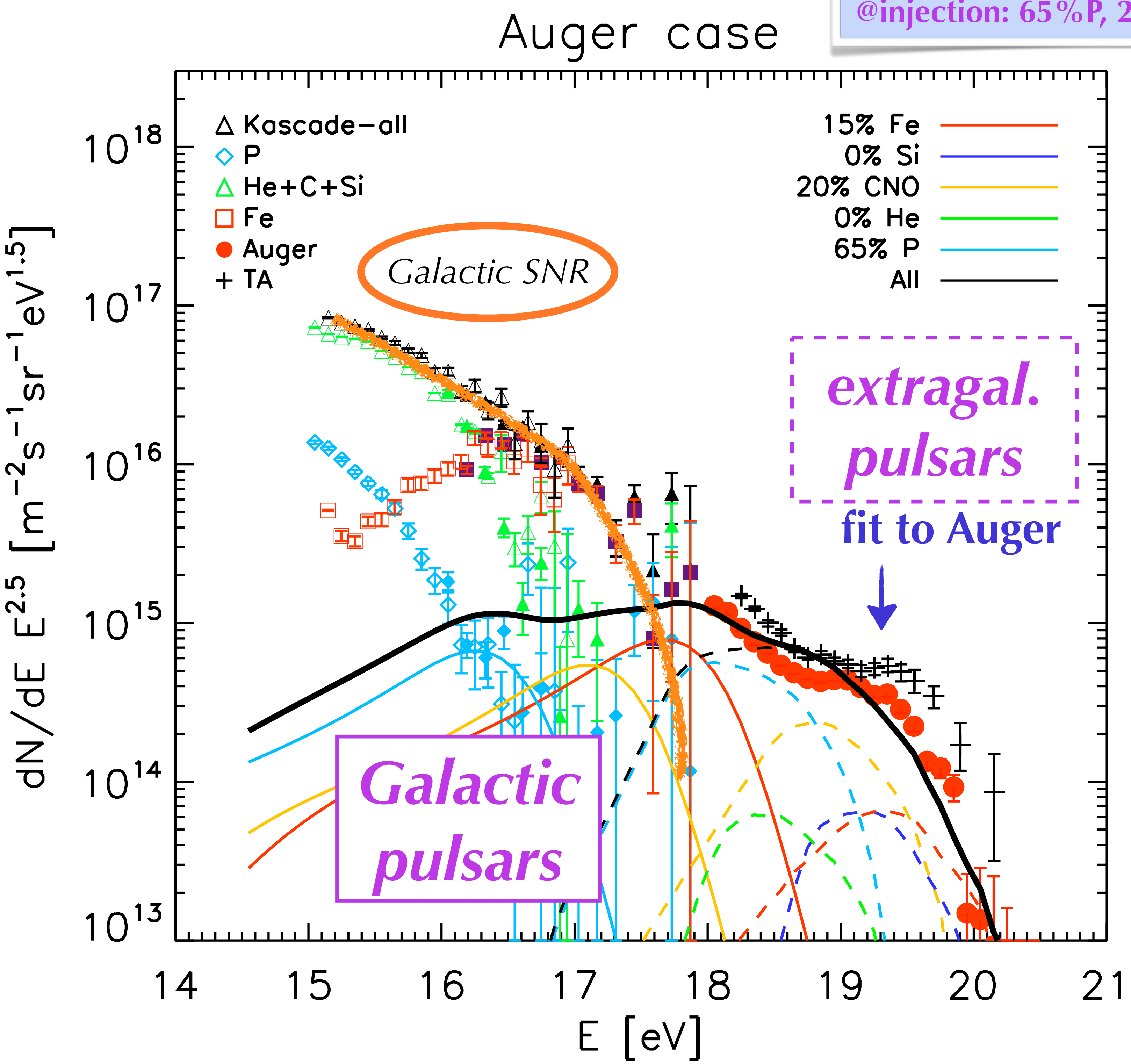

UHE spectrum
UHE composition
UHE anisotropy

ankle spectrum + transition
ankle composition
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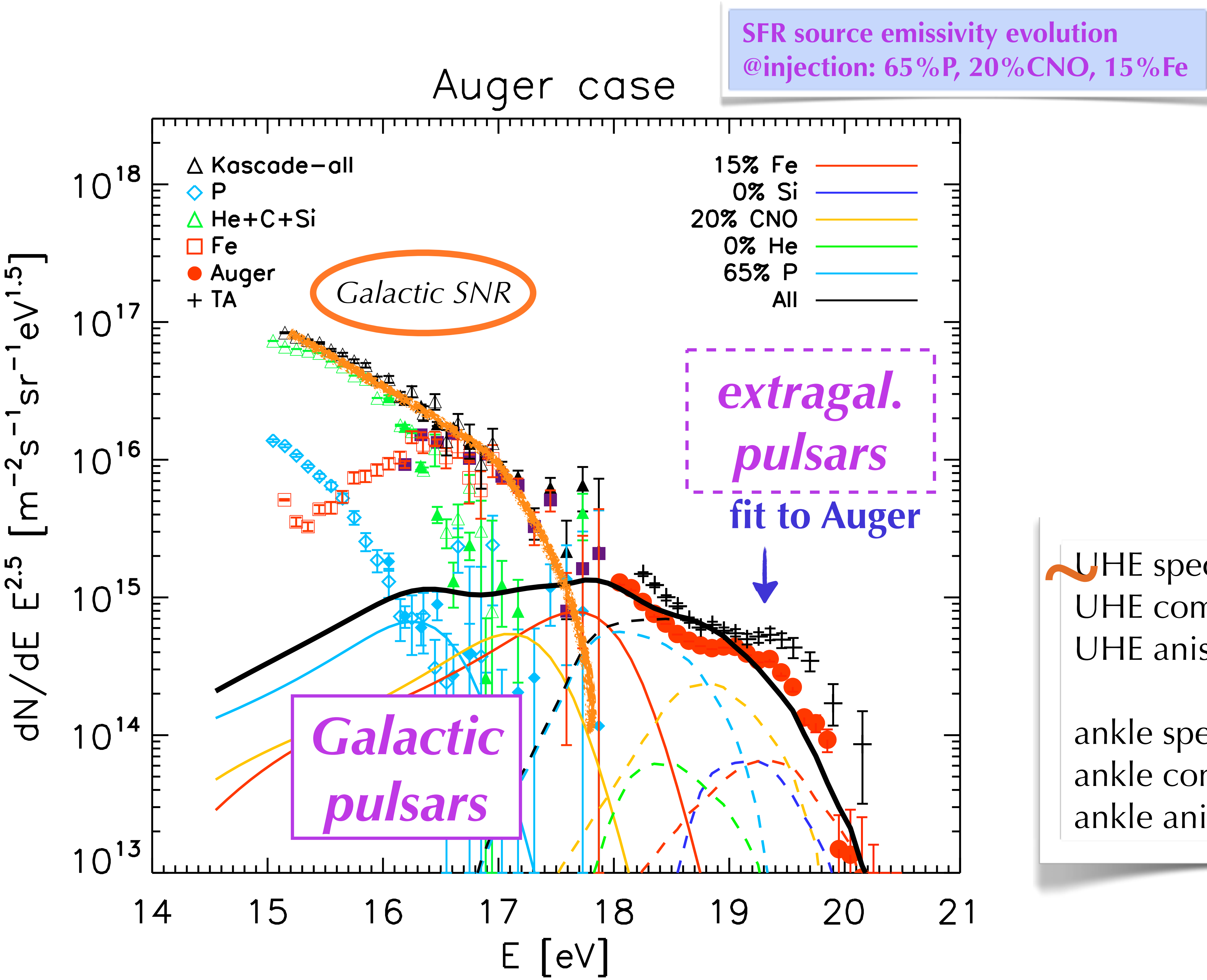

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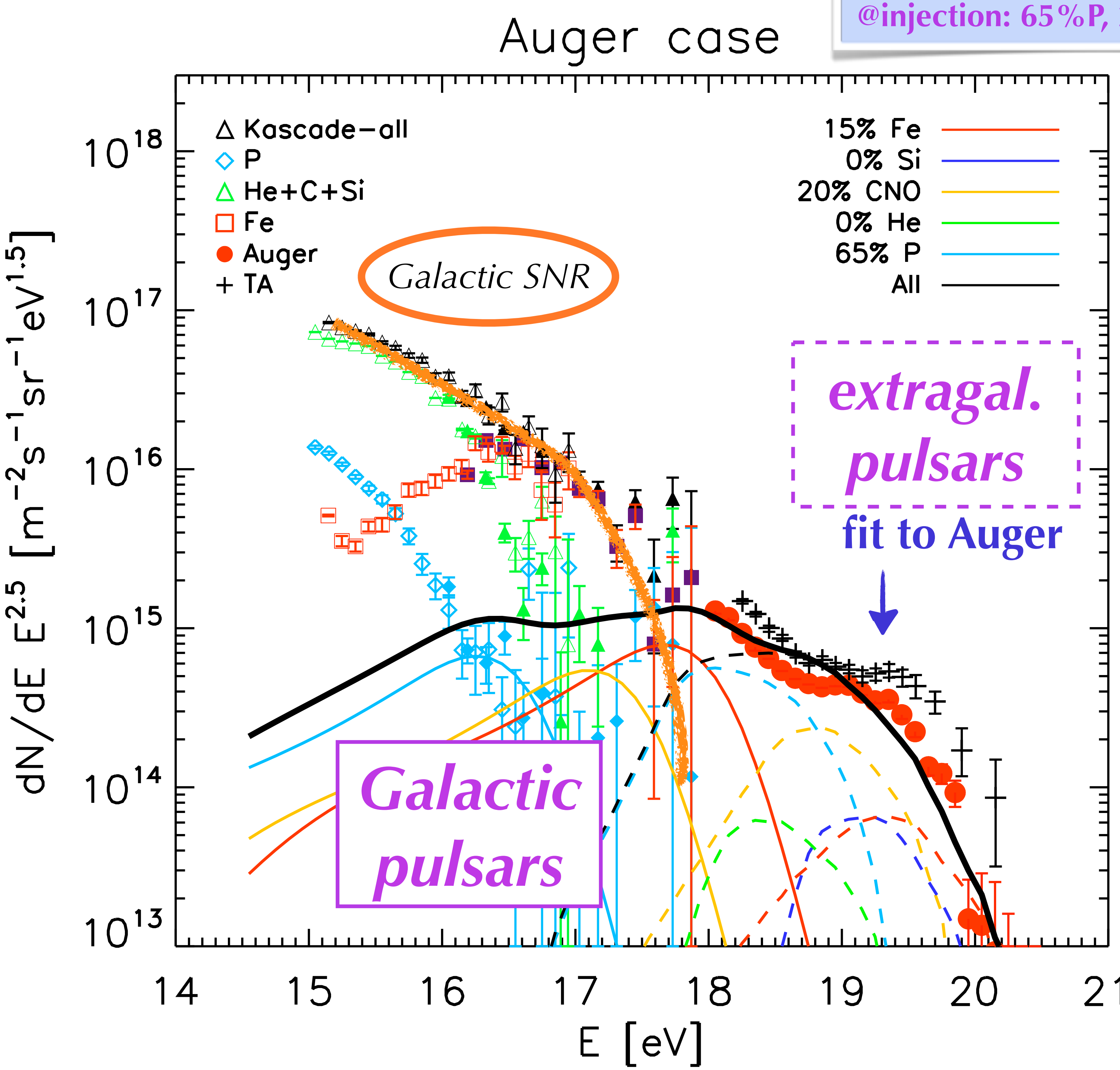

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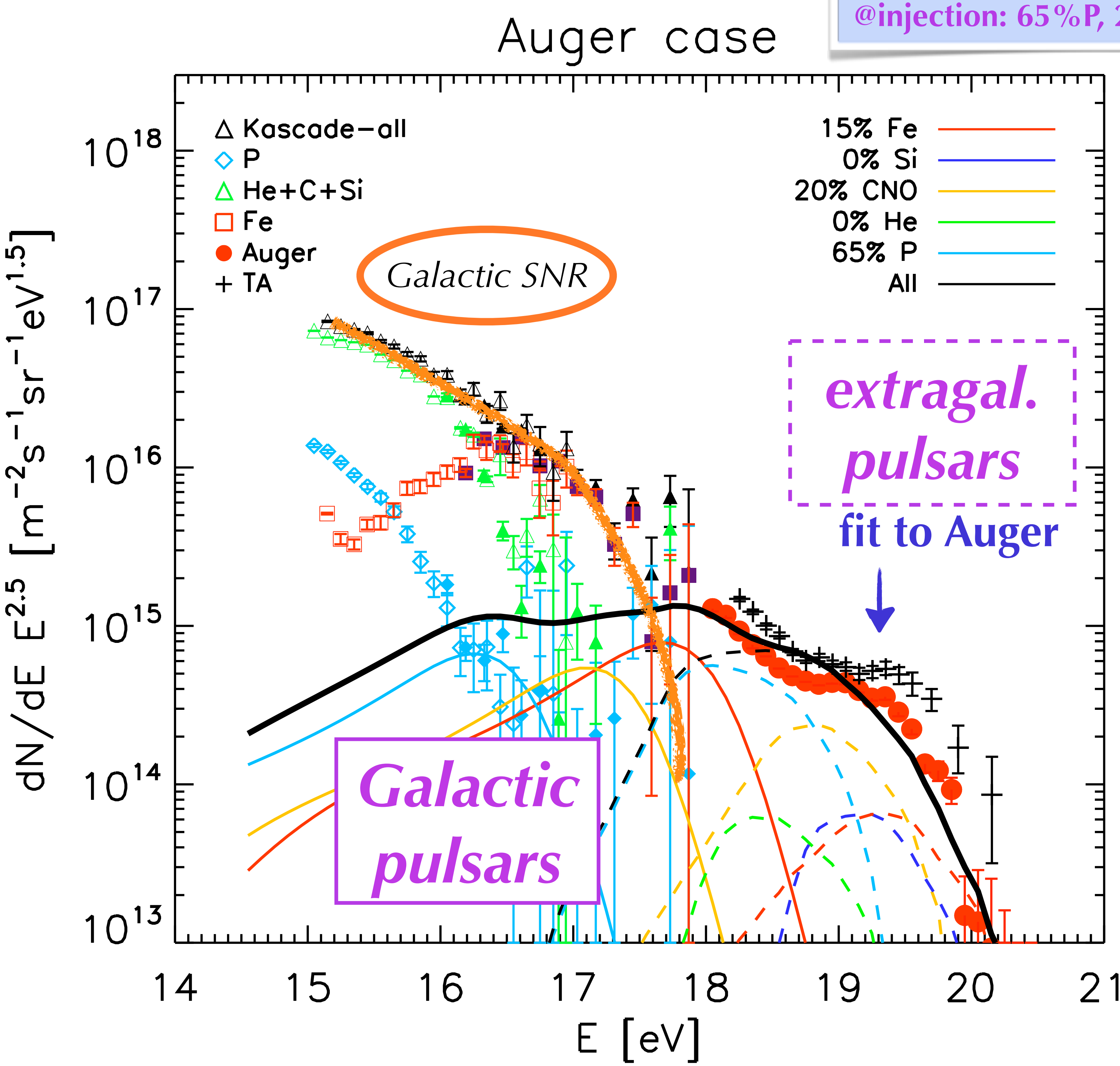

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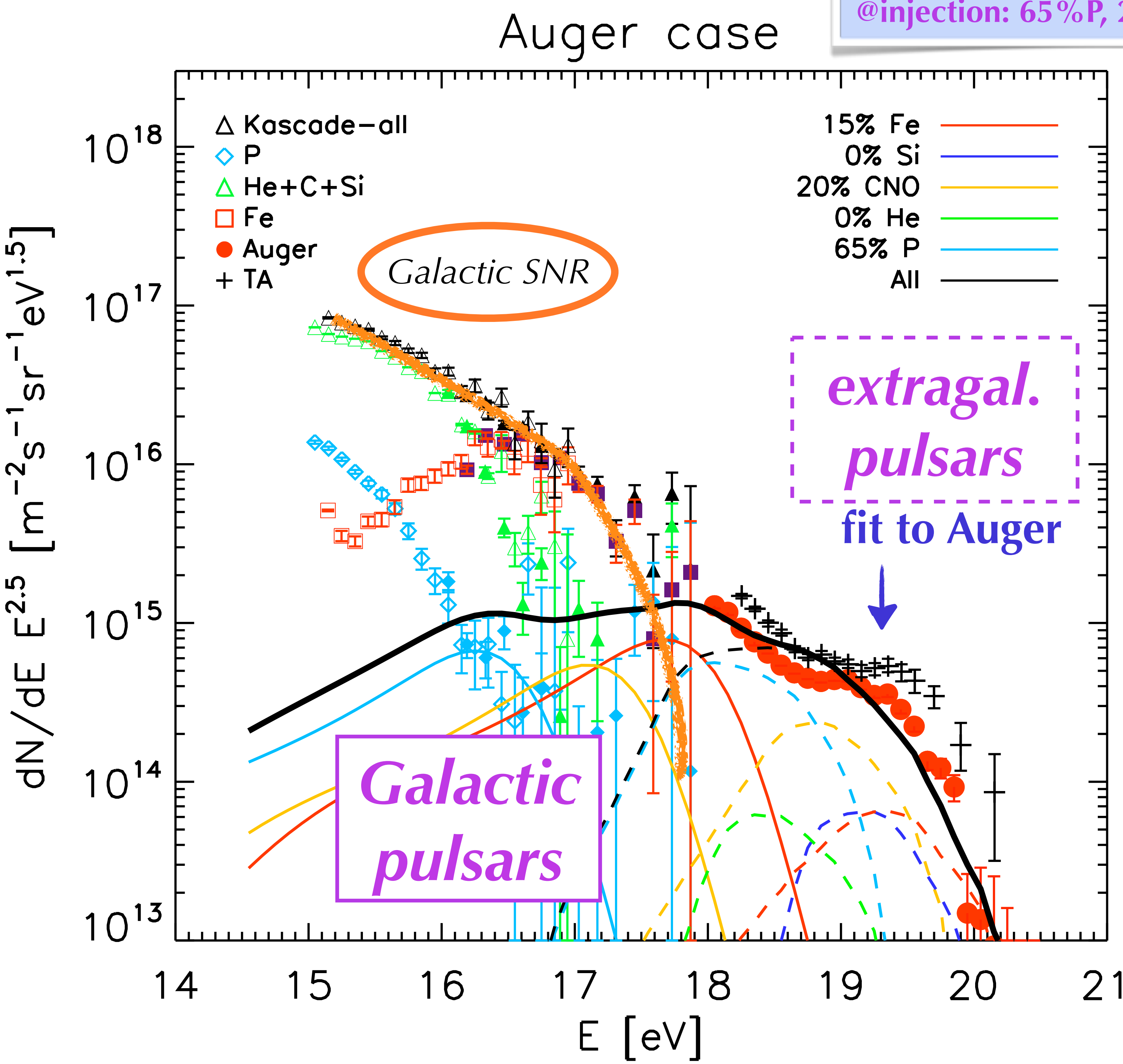

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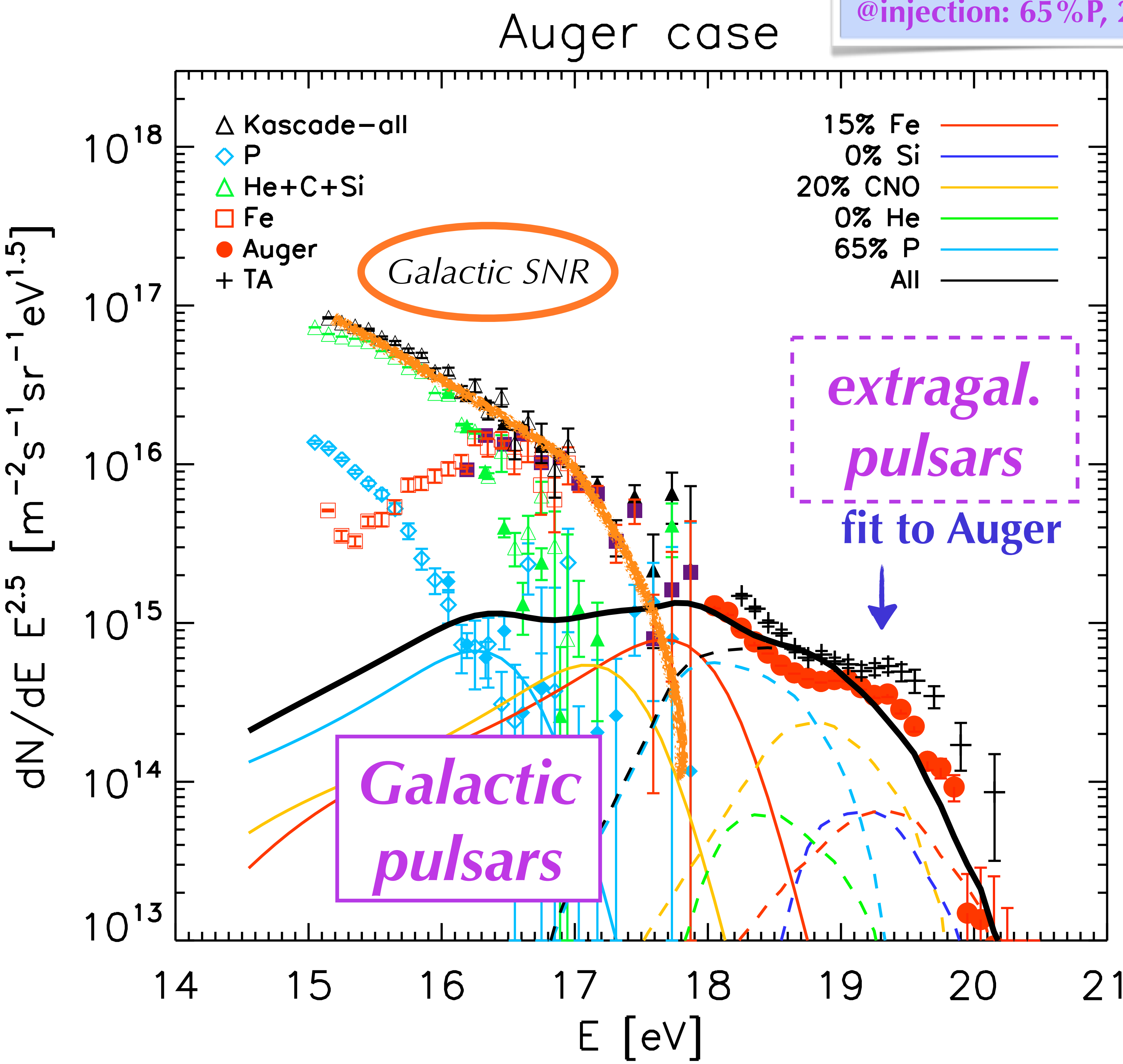

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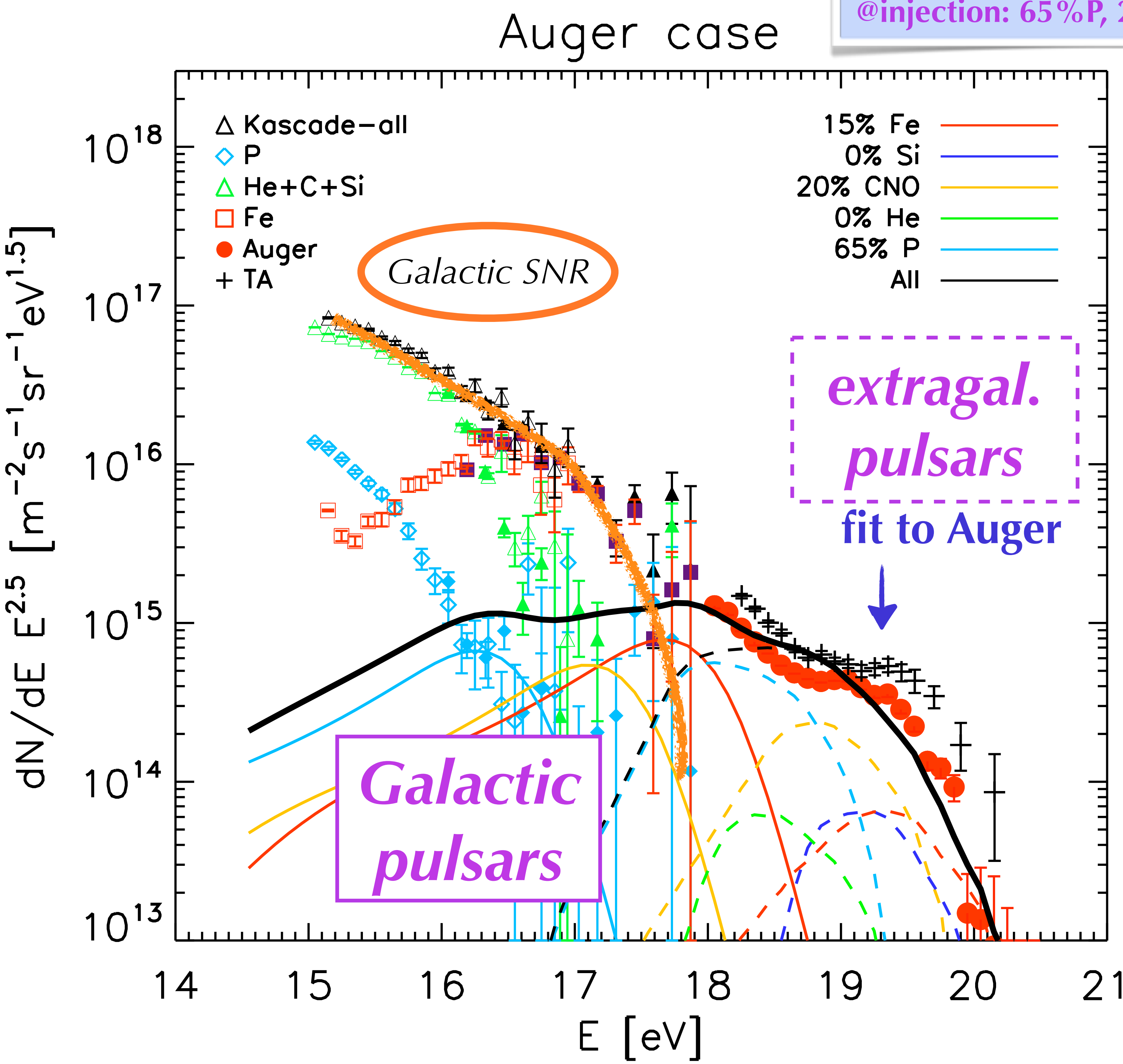

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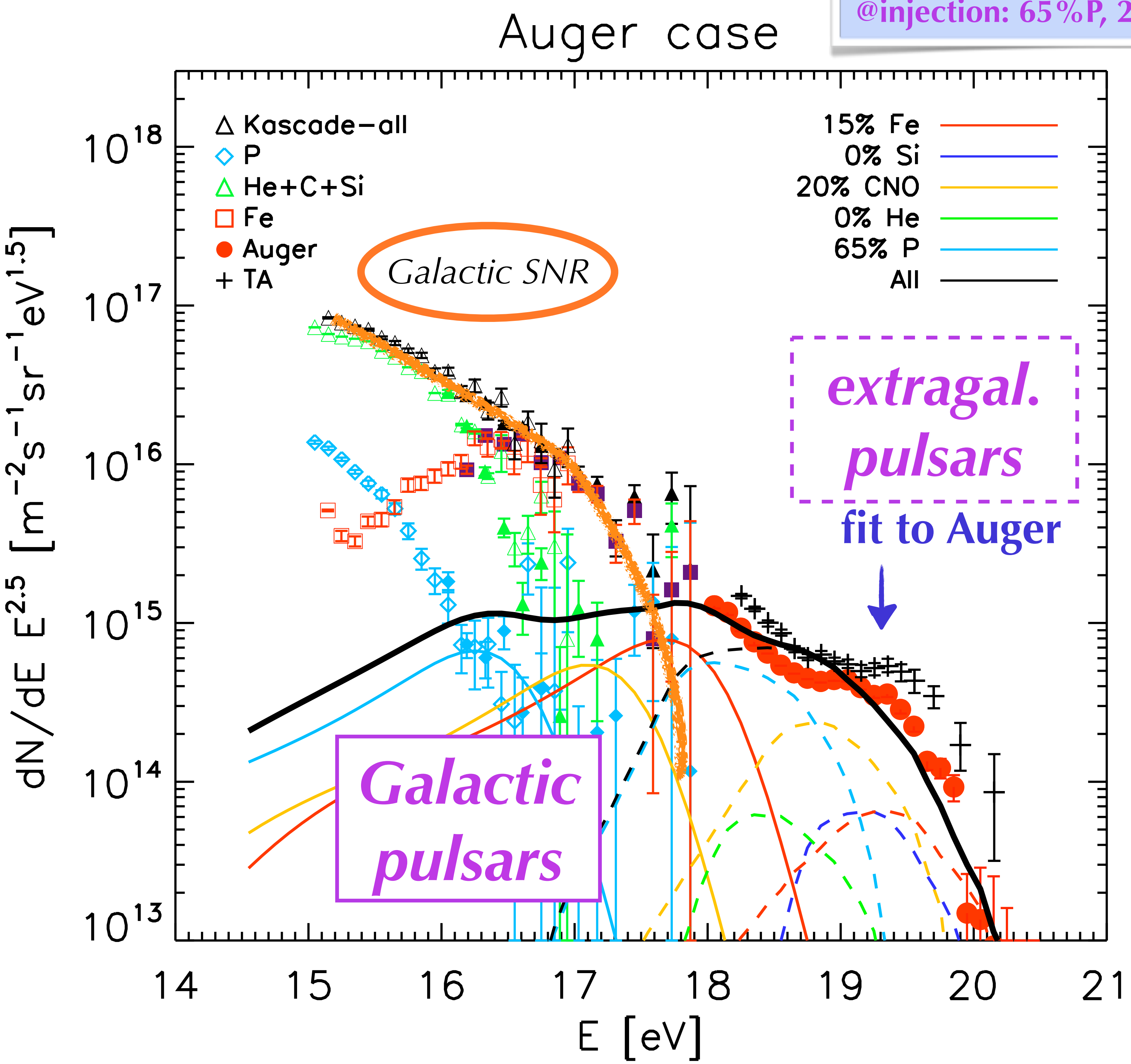

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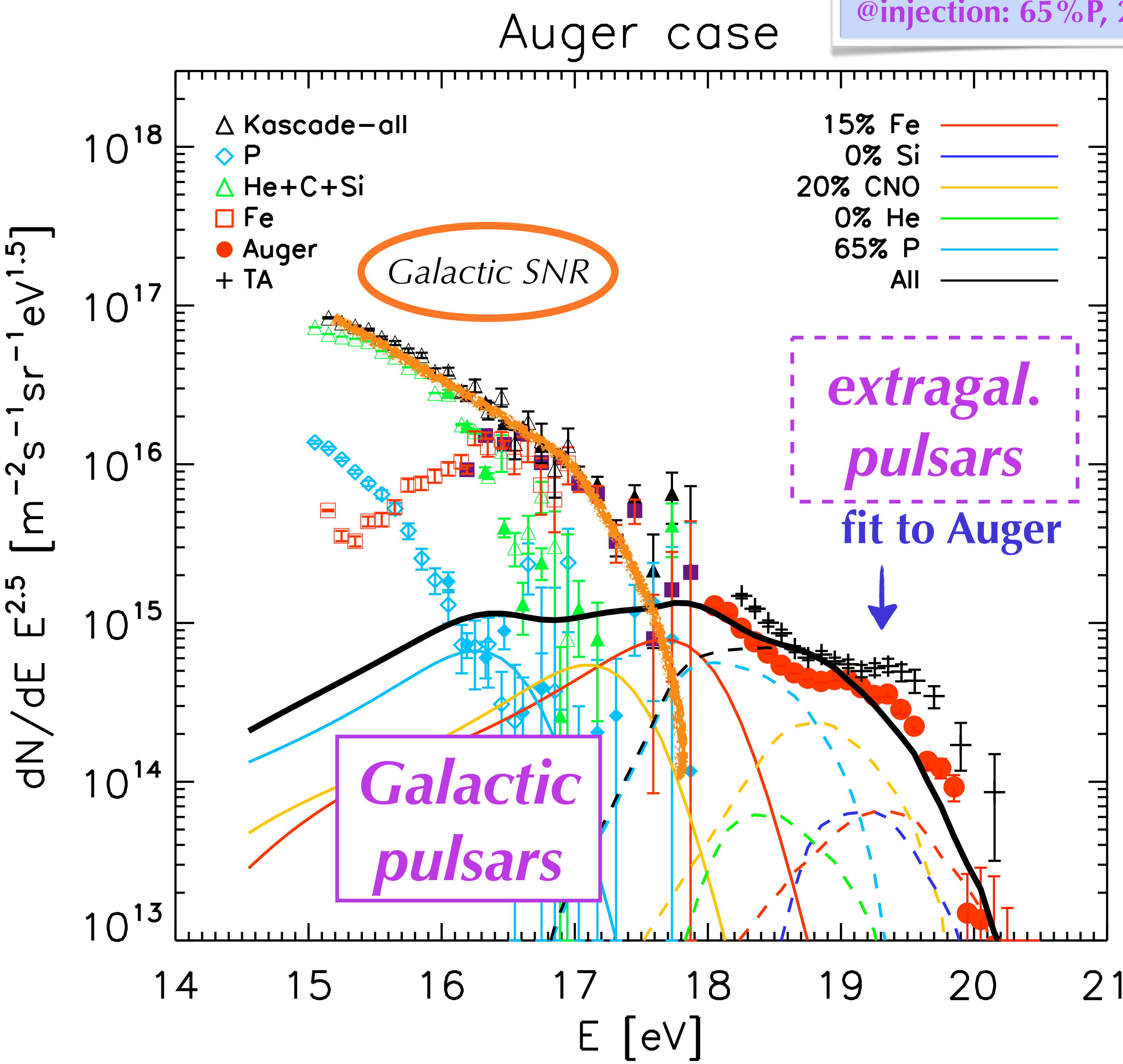

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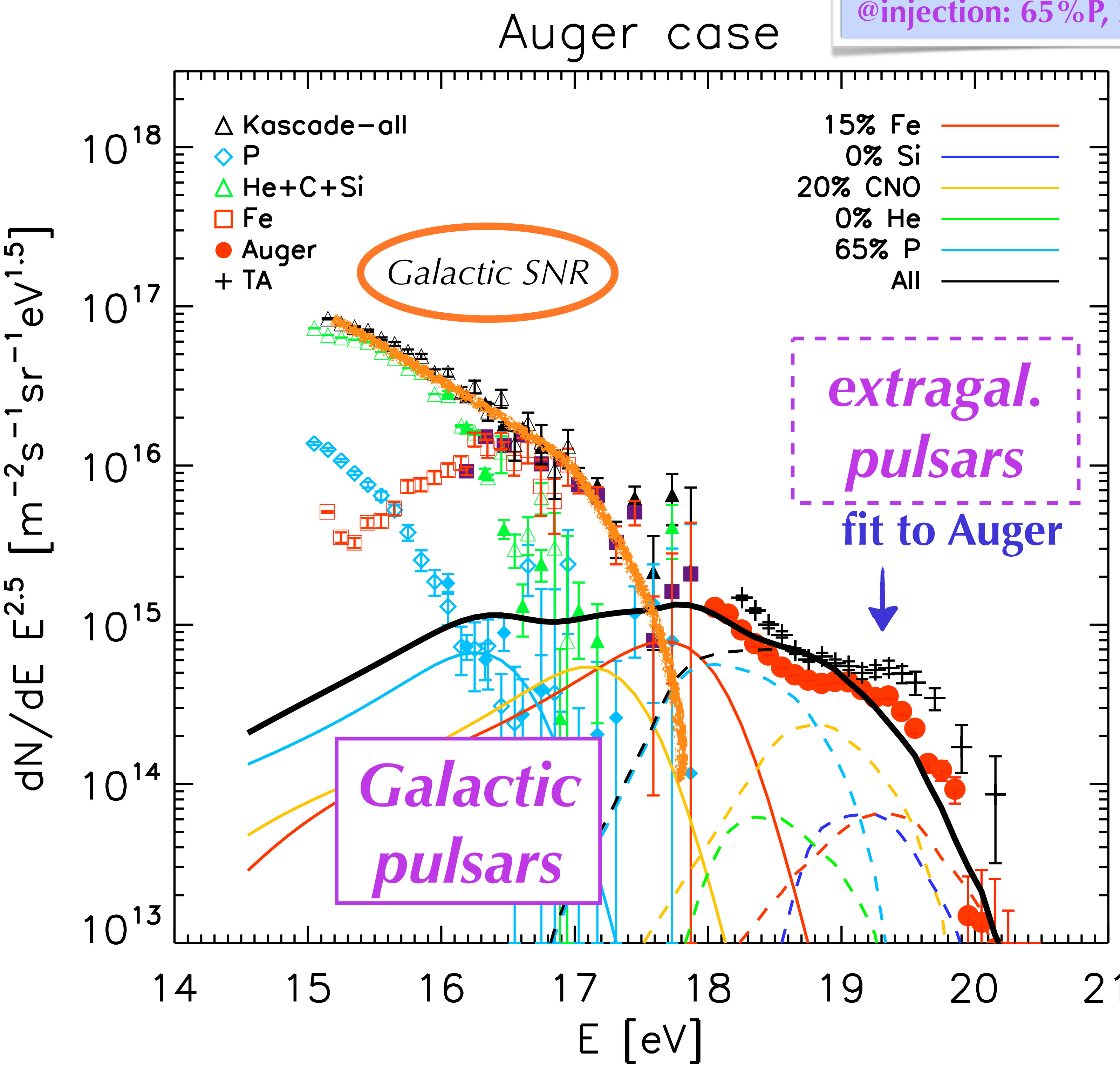

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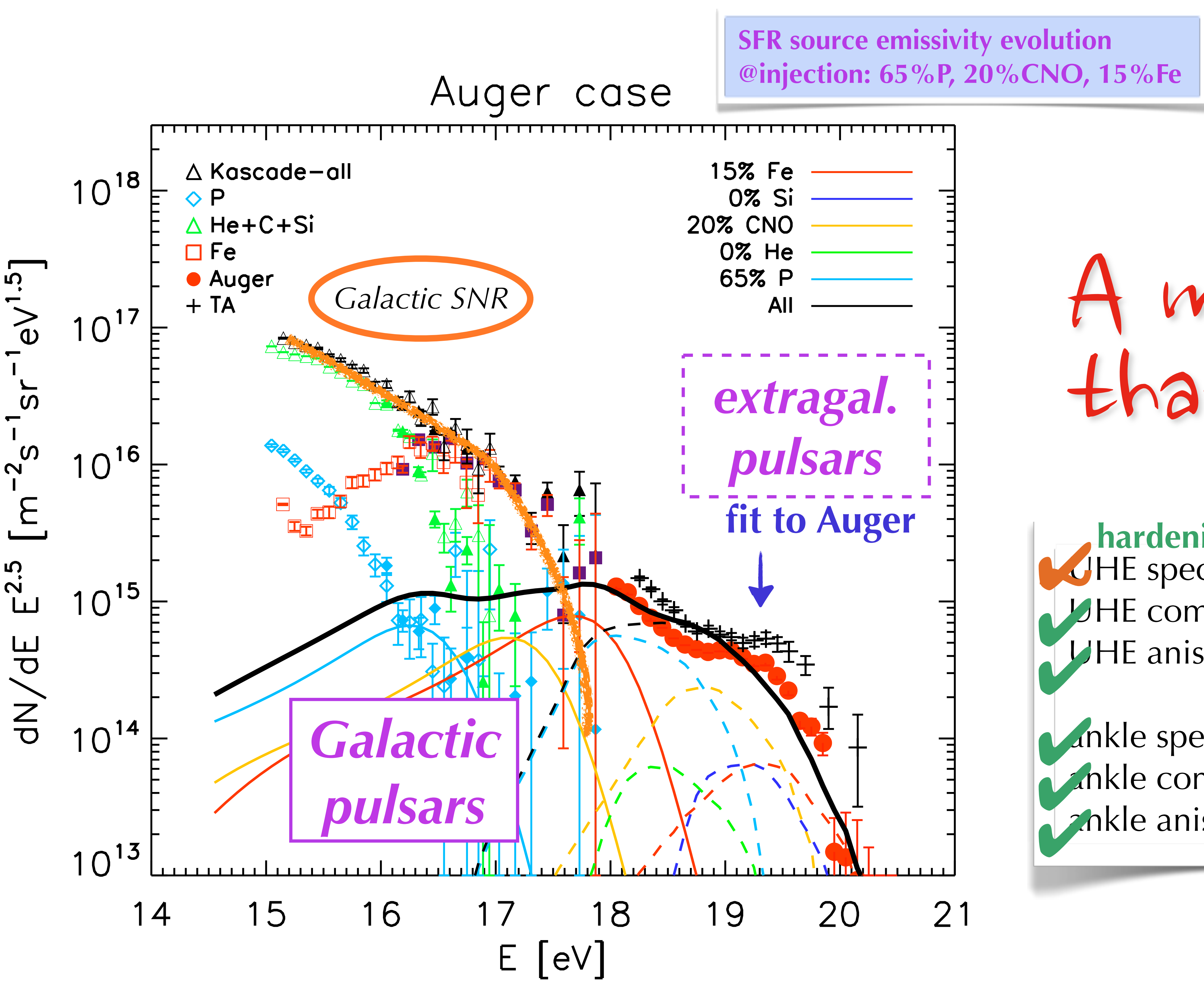

A model that works!

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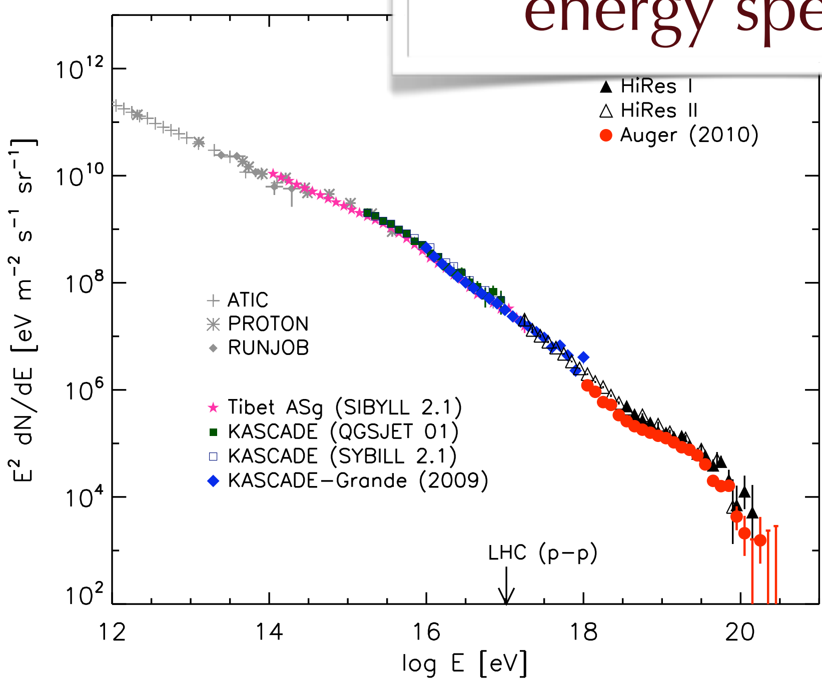
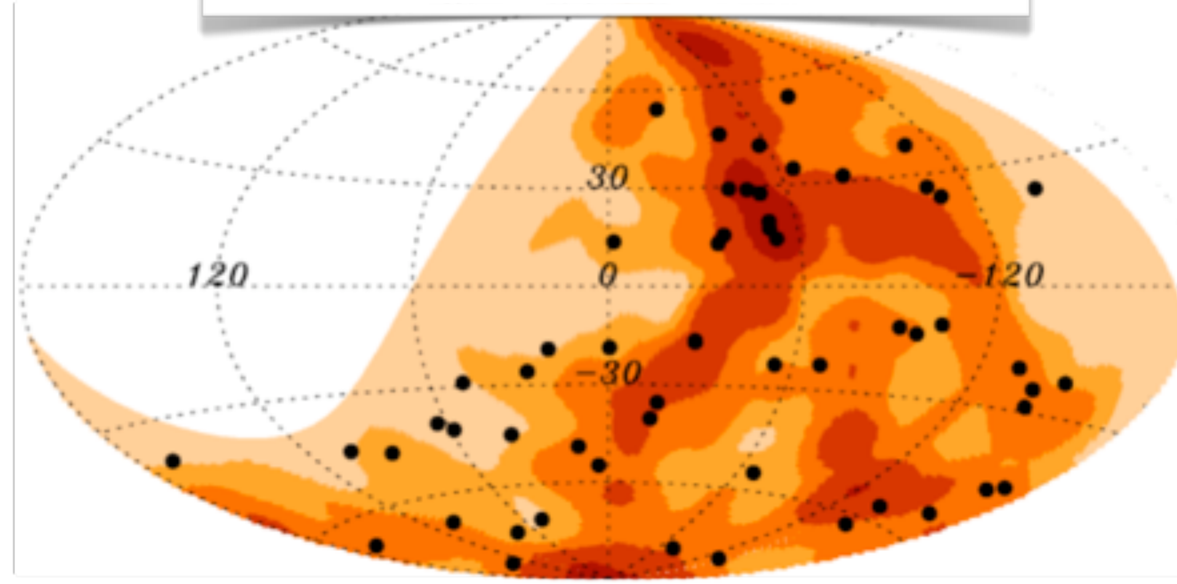
What observational information do we have?

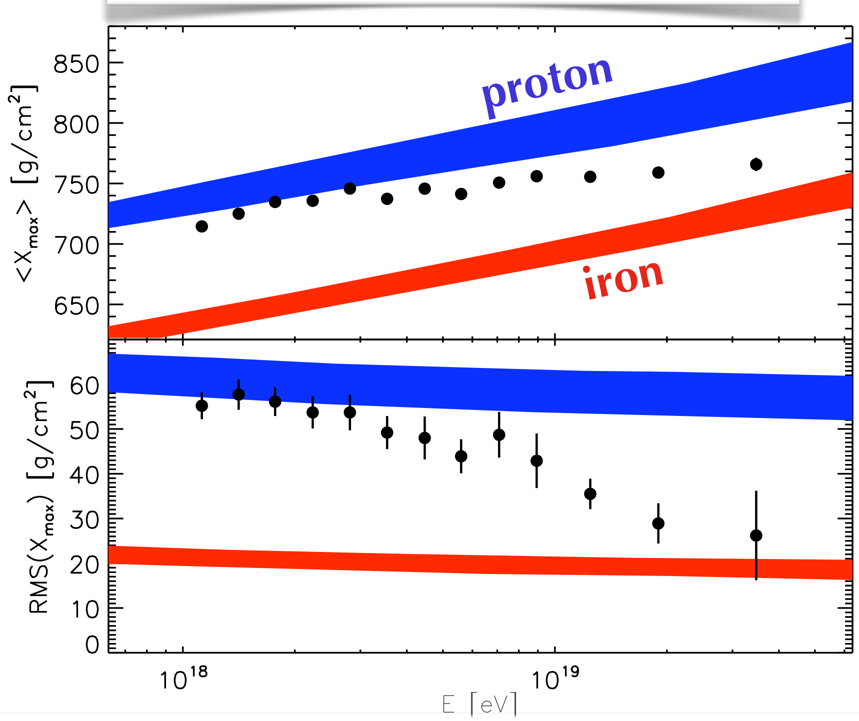
energy spectrum



arrival directions in the sky



chemical composition



other messengers:
secondary gamma-rays,
neutrinos, etc.

Proofs and signatures of the pulsar model?

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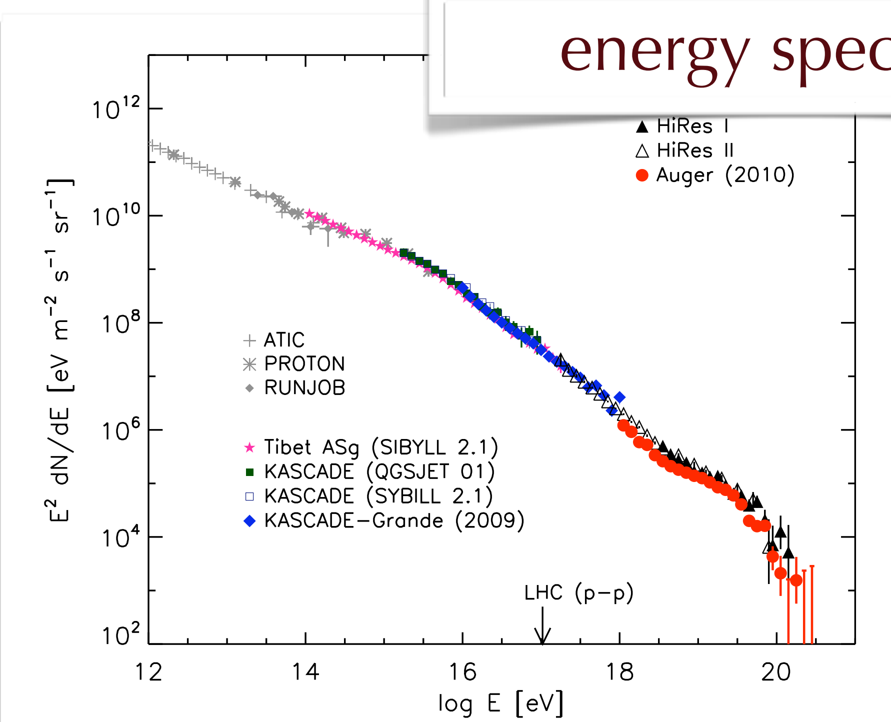

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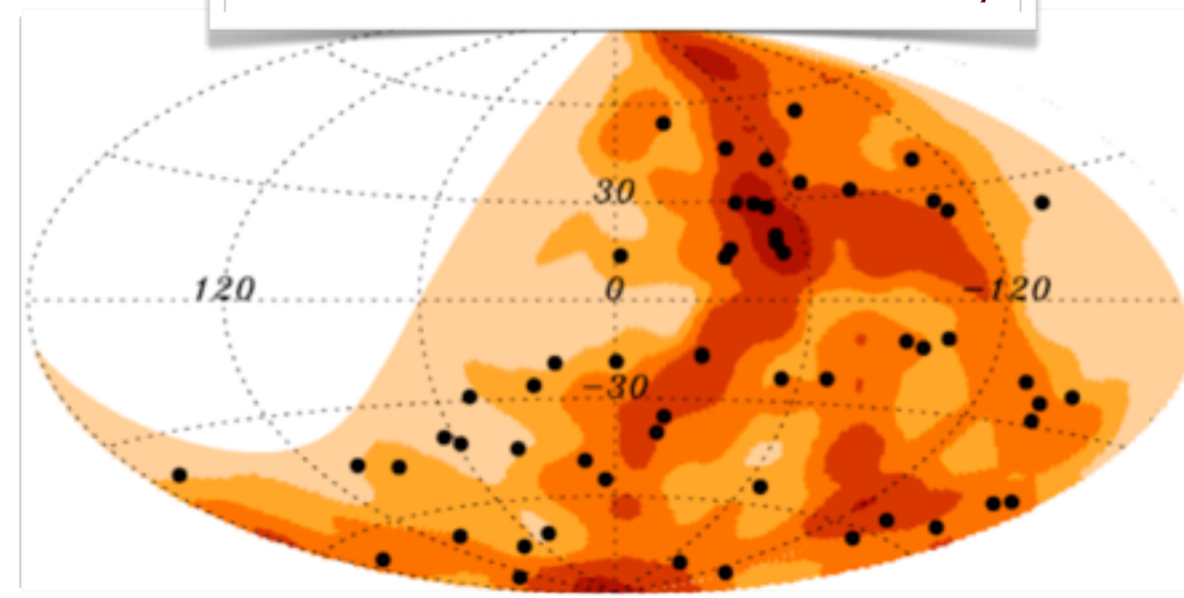

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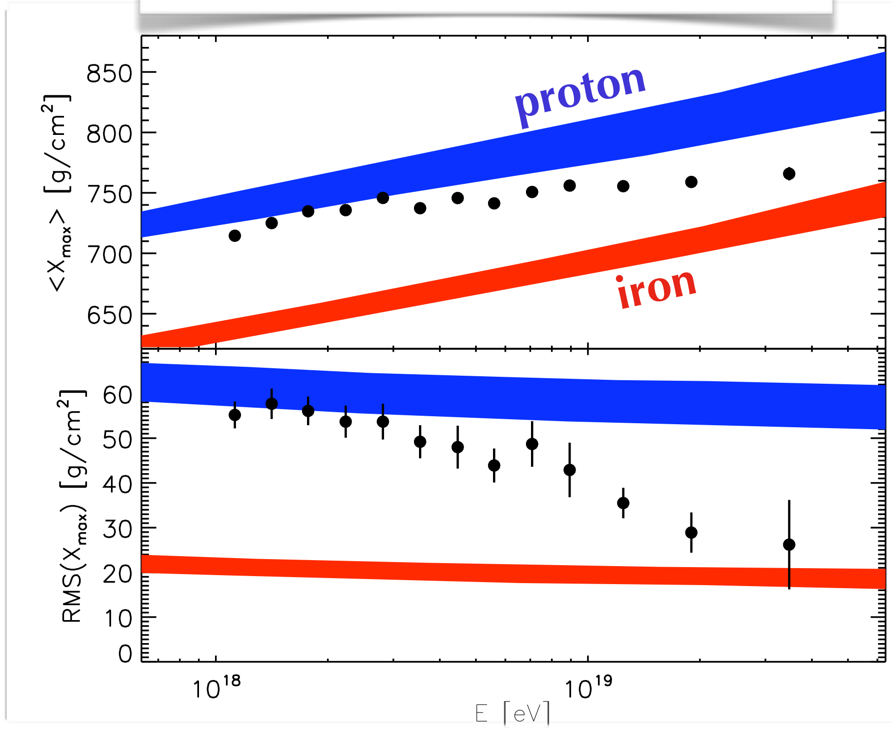

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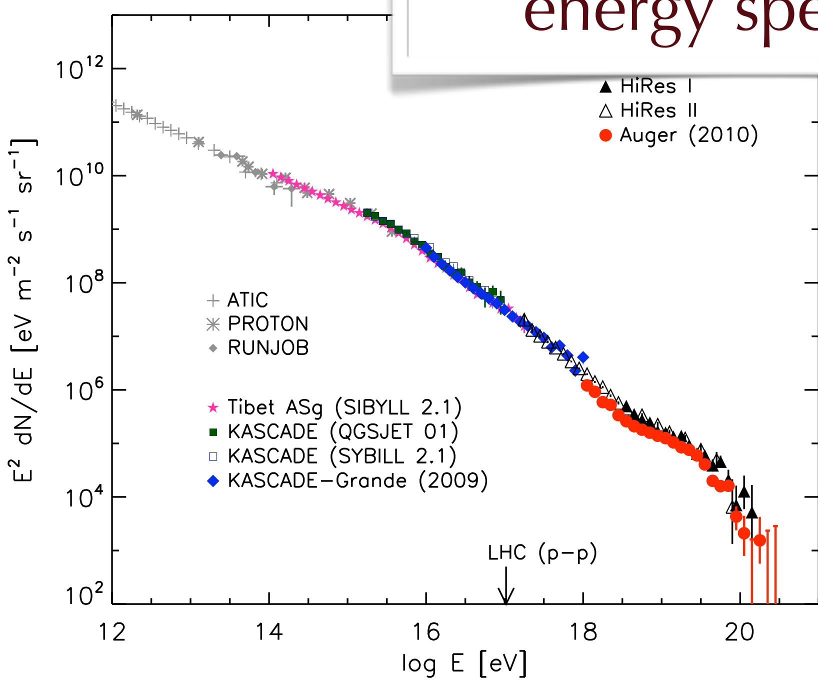

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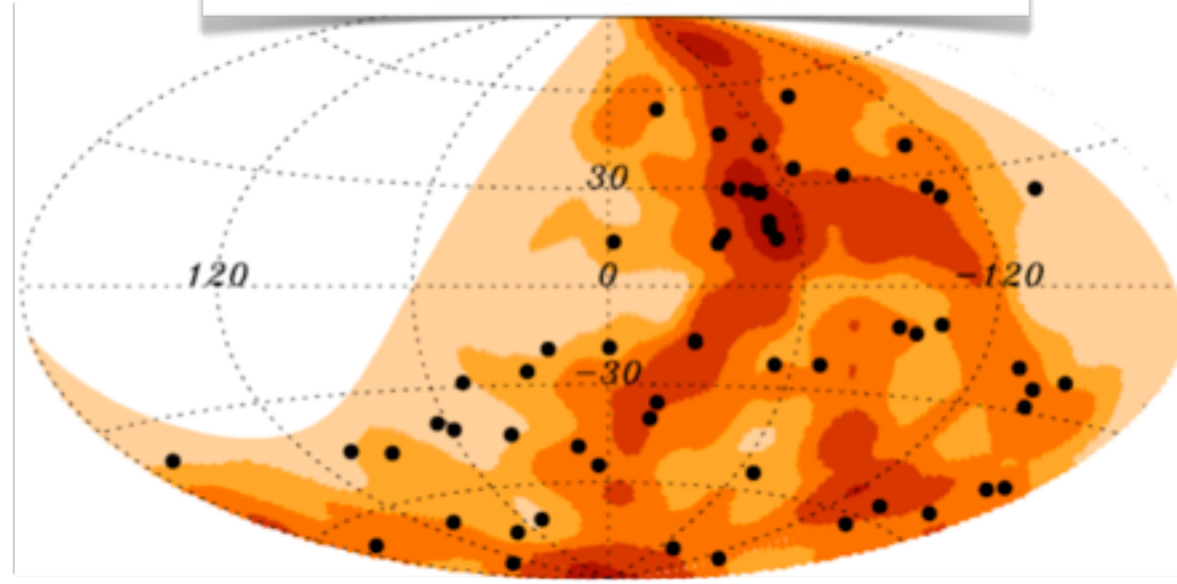

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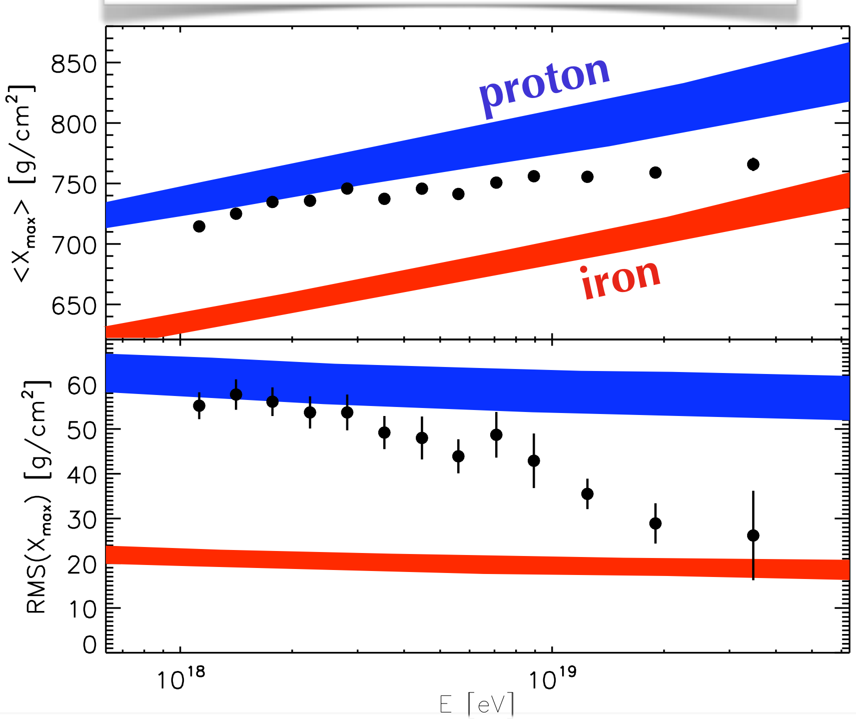

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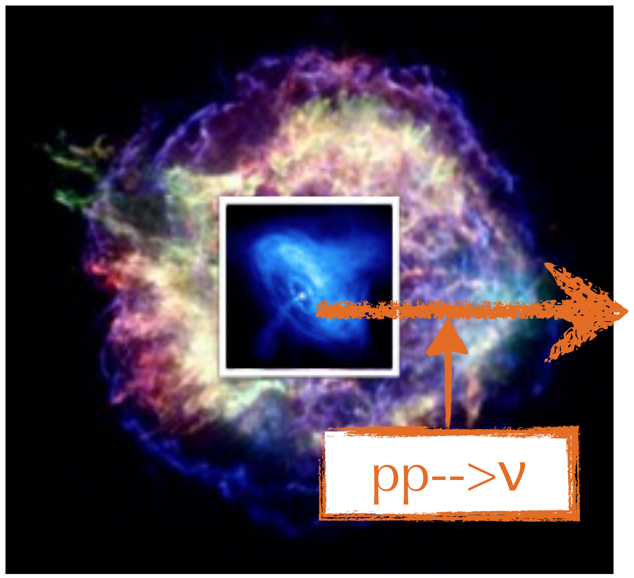
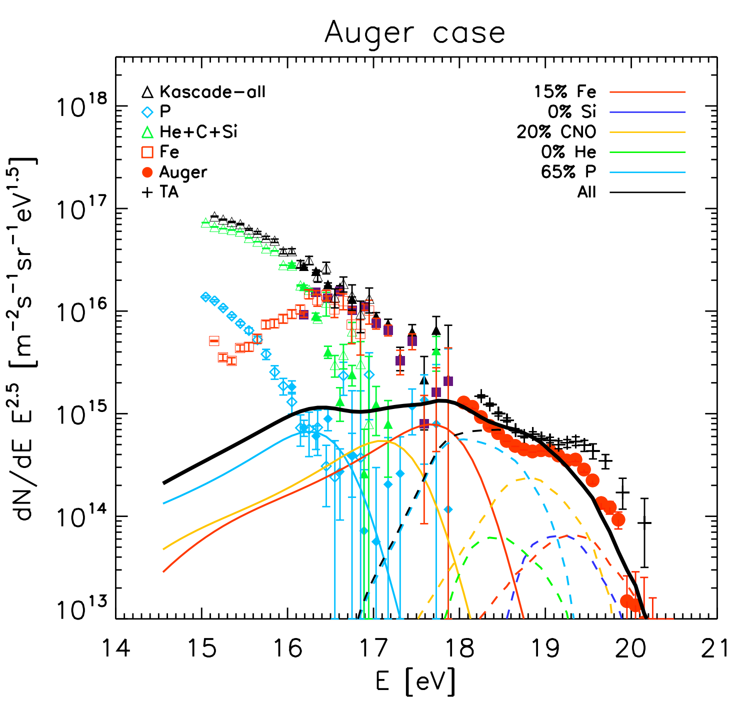
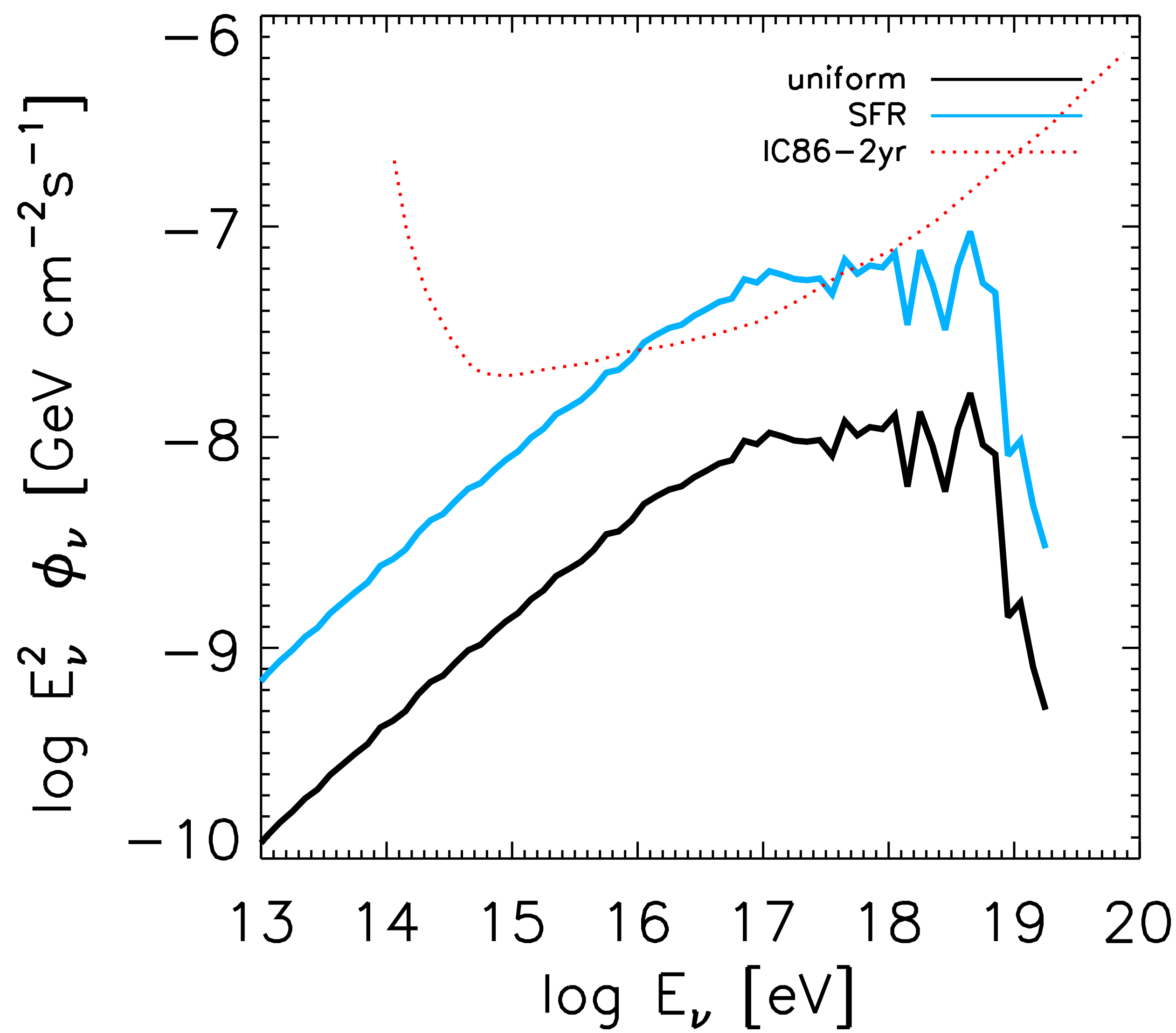




Neutrino flux for population of pulsars fitting the UHECR spectrum @injection: 65%P, 20%CNO, 15%Fe



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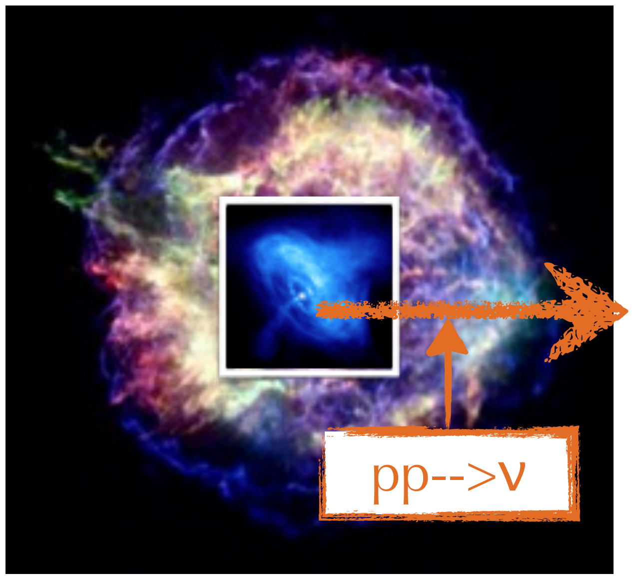

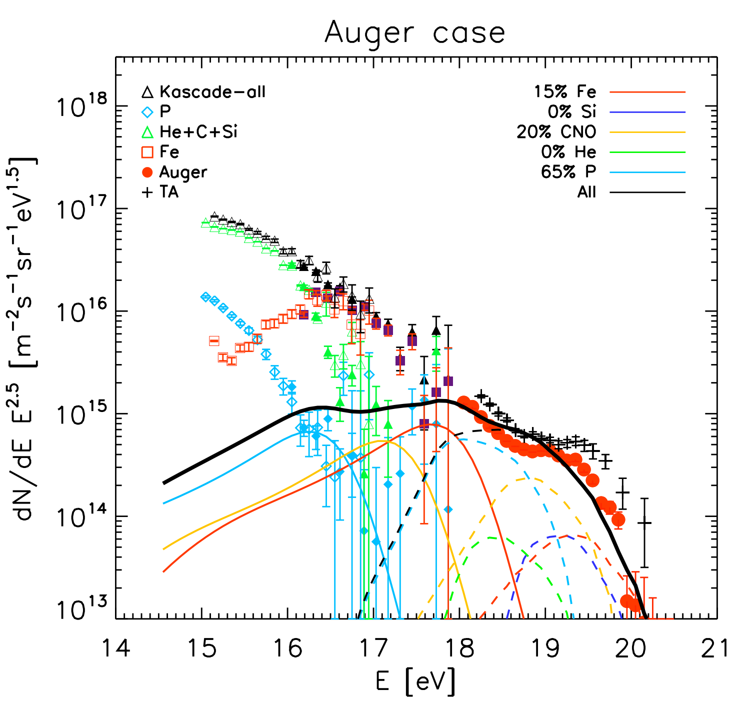

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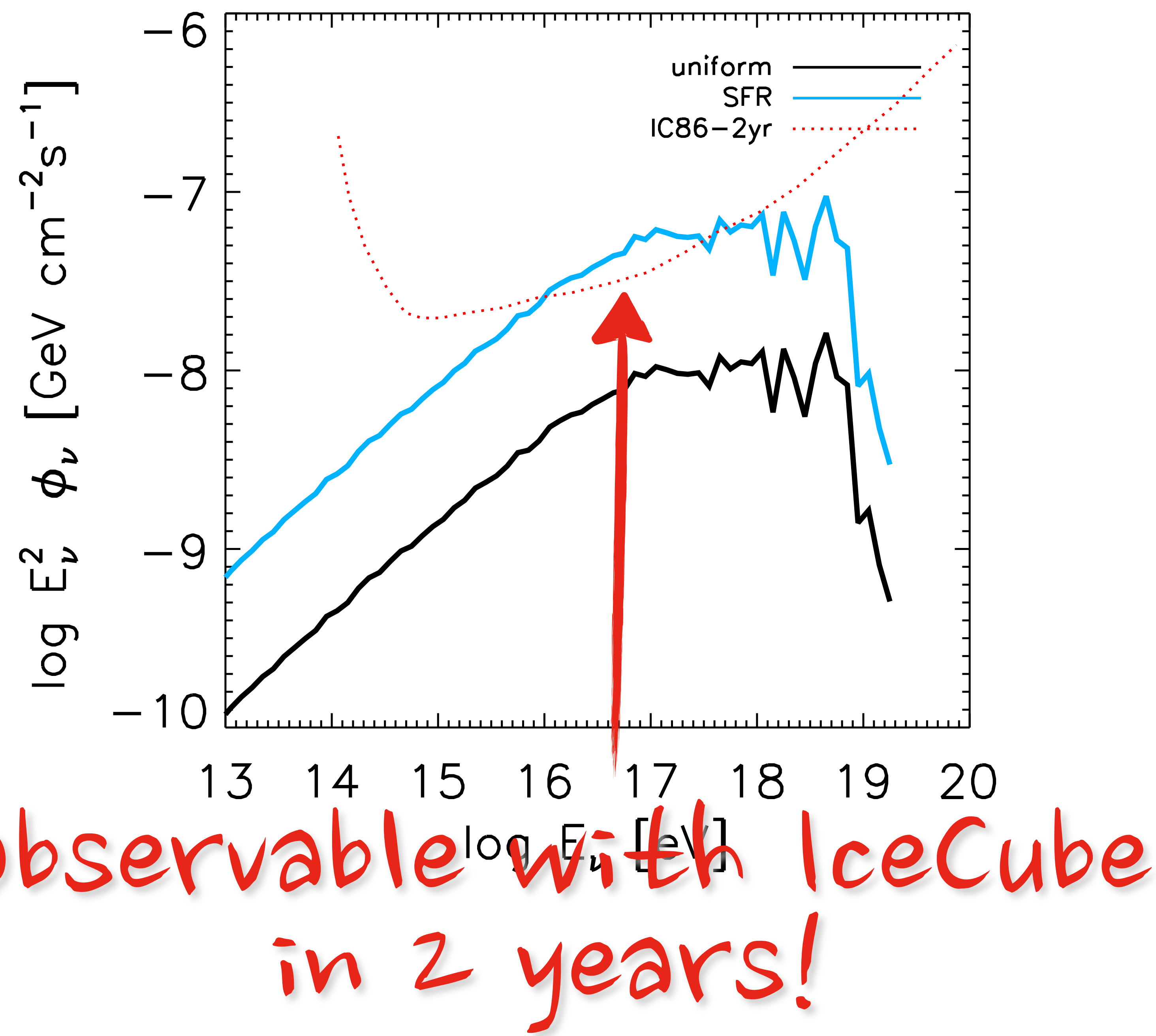
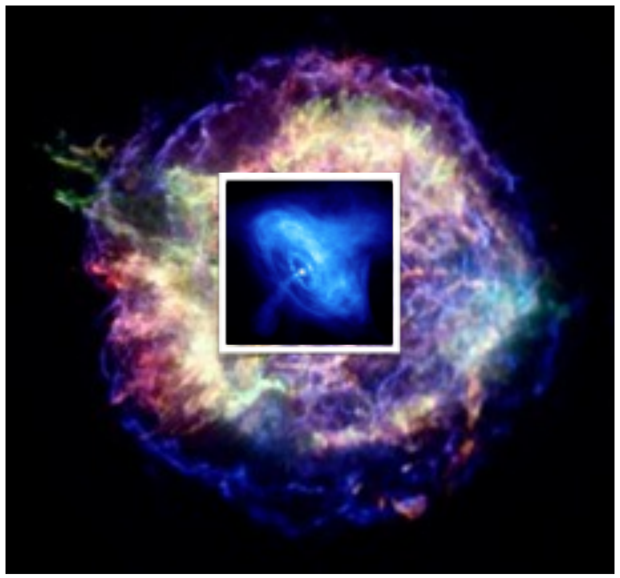


Signatures in supernova lightcurves

KK, Phinney, Olinto 2013



related works
Gaffet et al. 77: can a pulsar power the SN?
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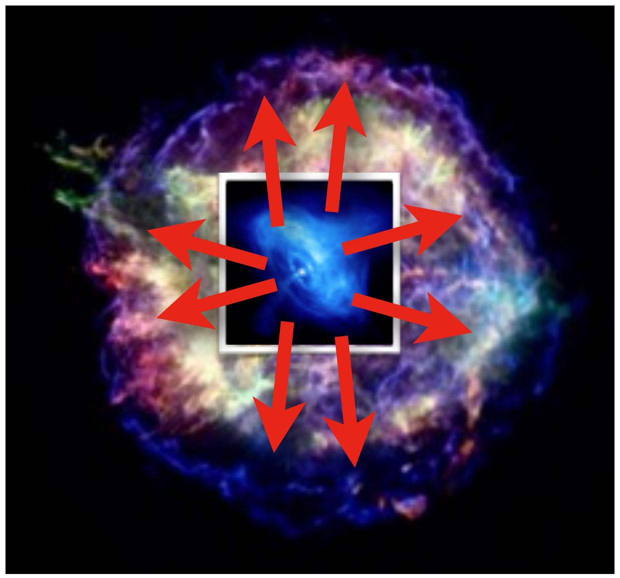

injection of
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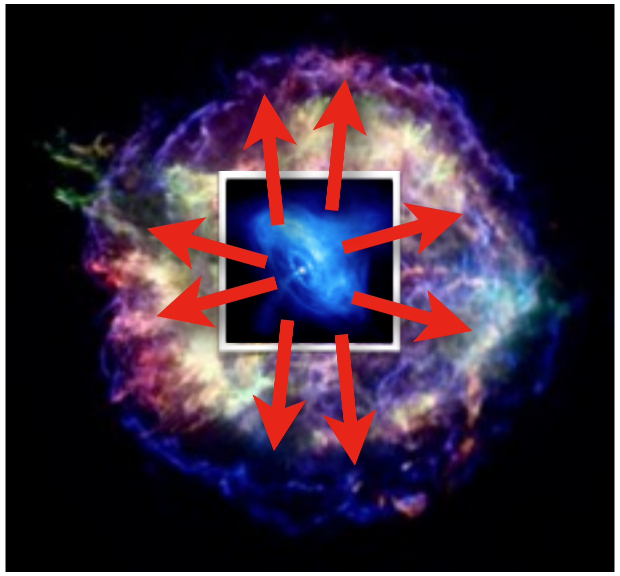

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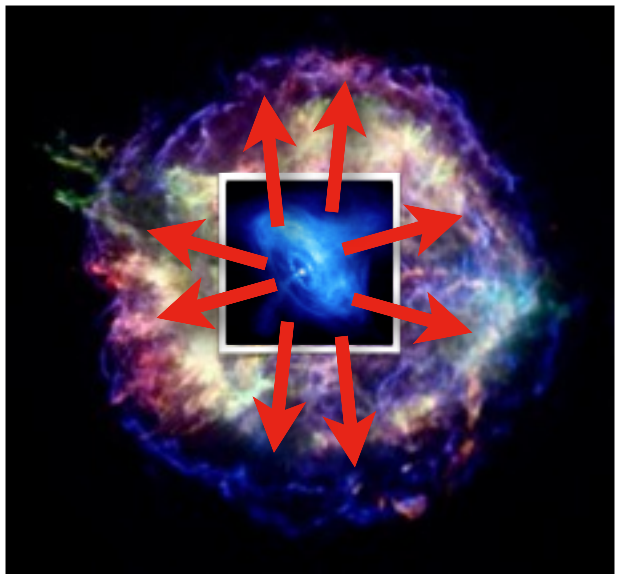

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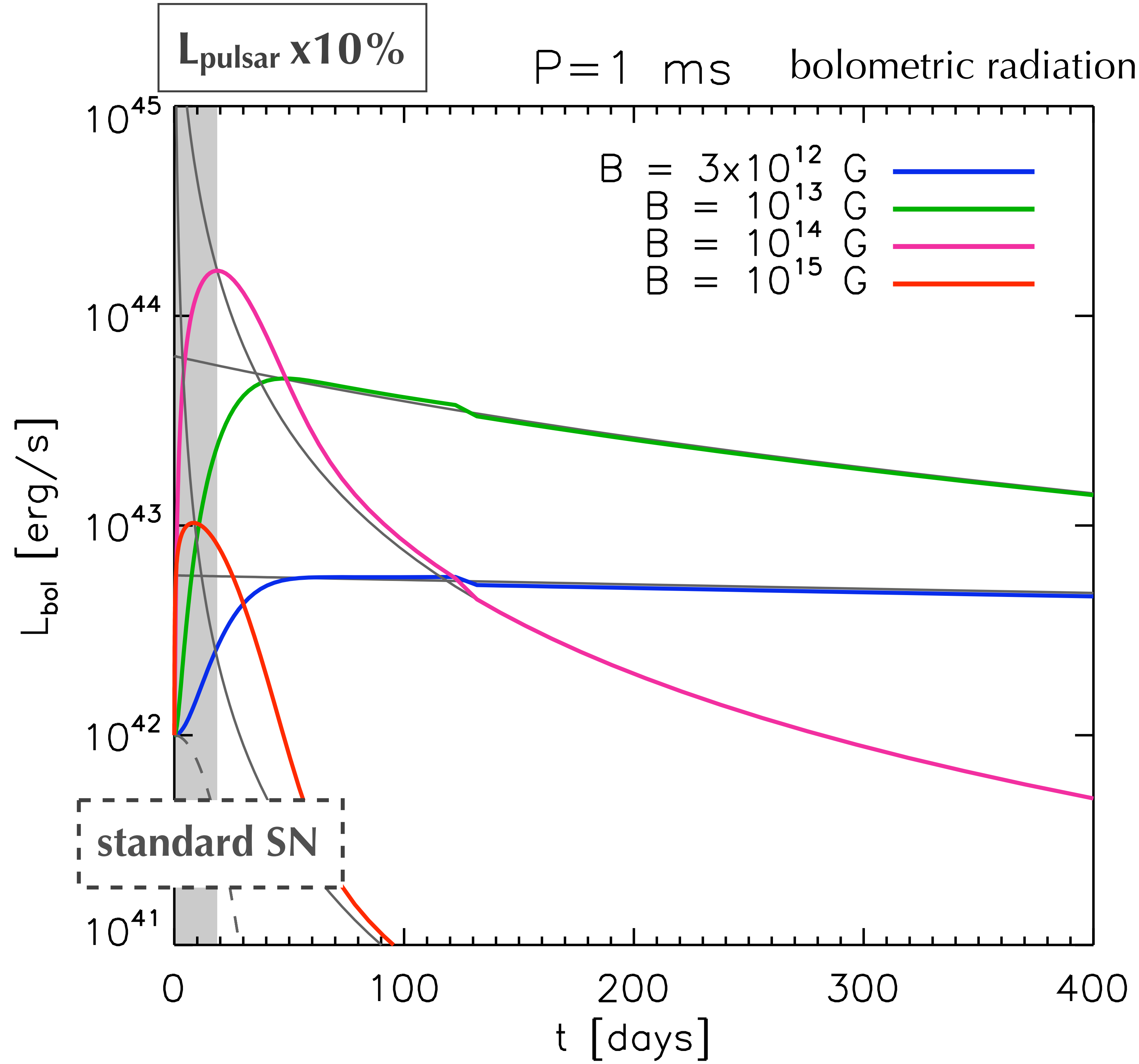

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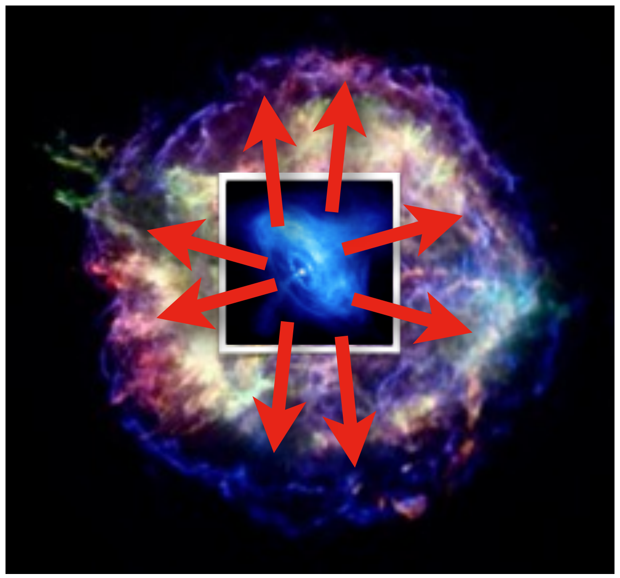

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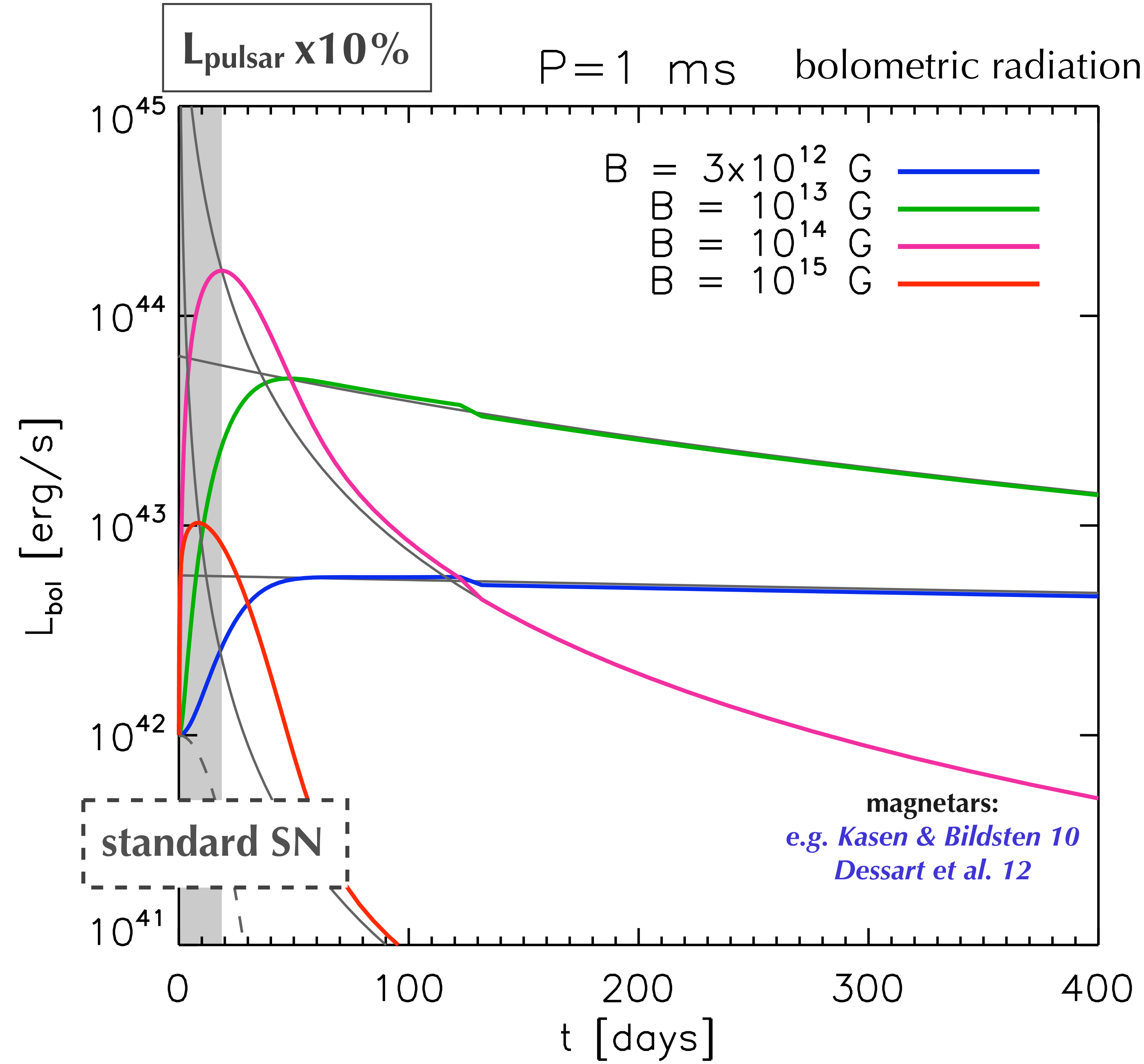

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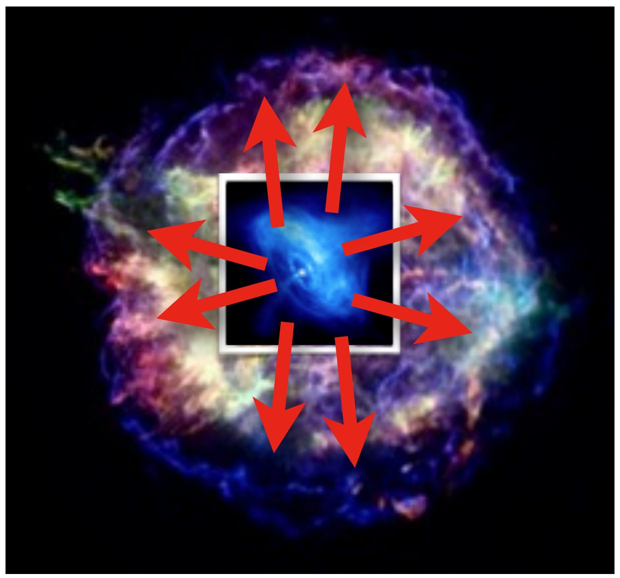

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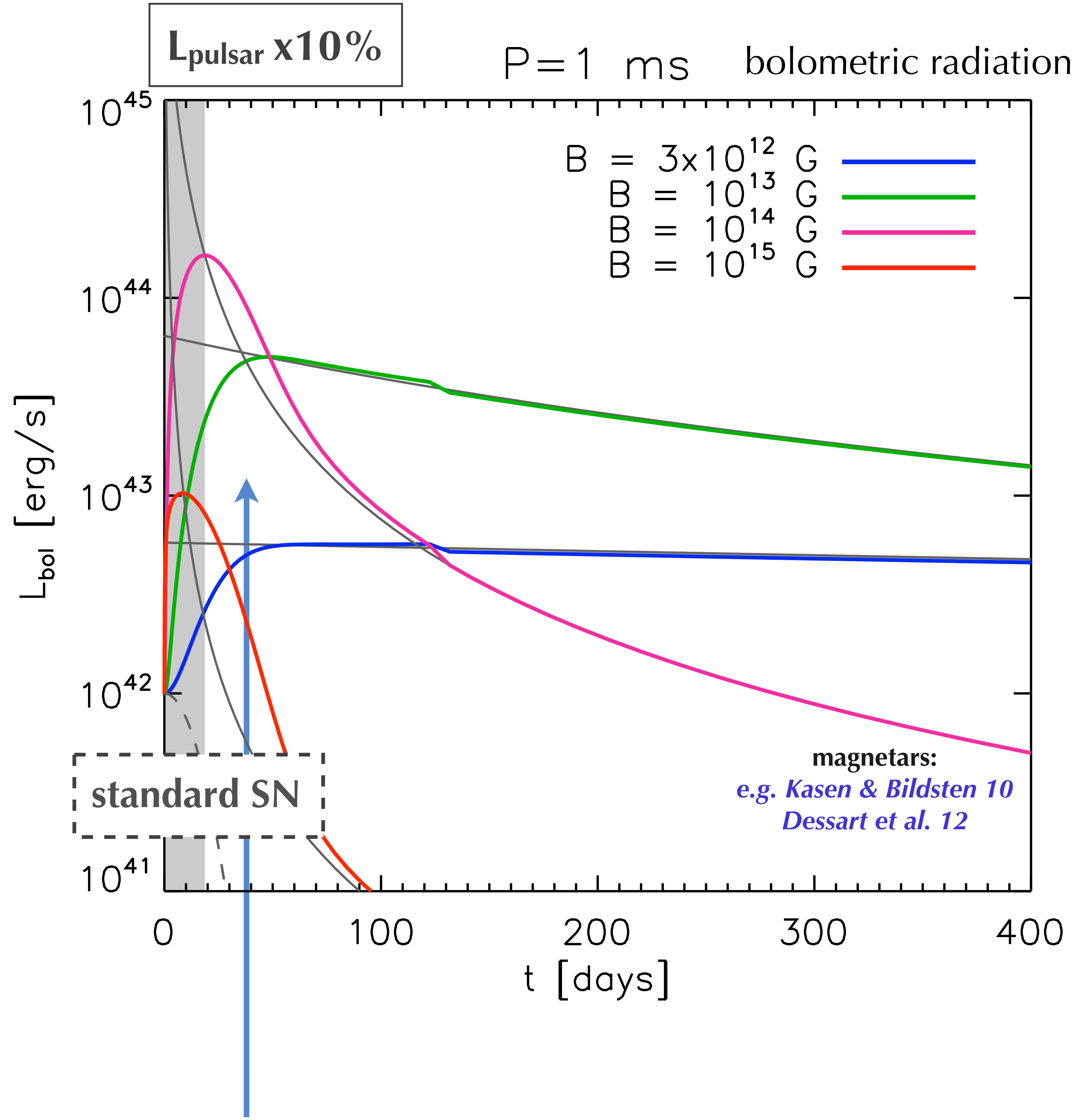

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- interesting lightcurve @ few years high plateau (in bol.)

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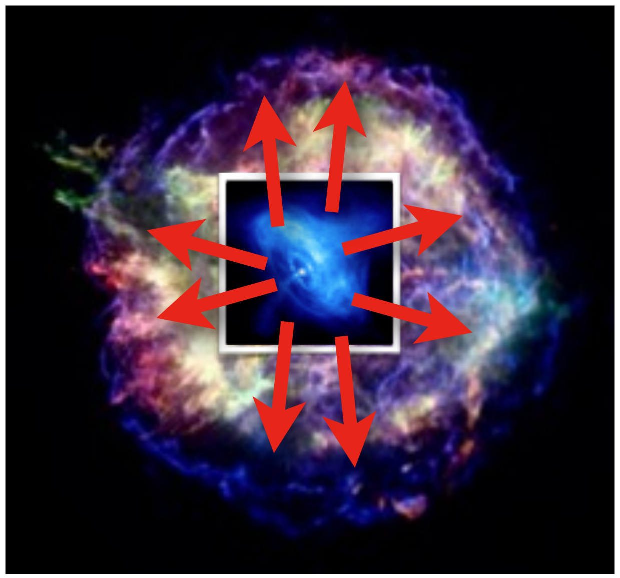

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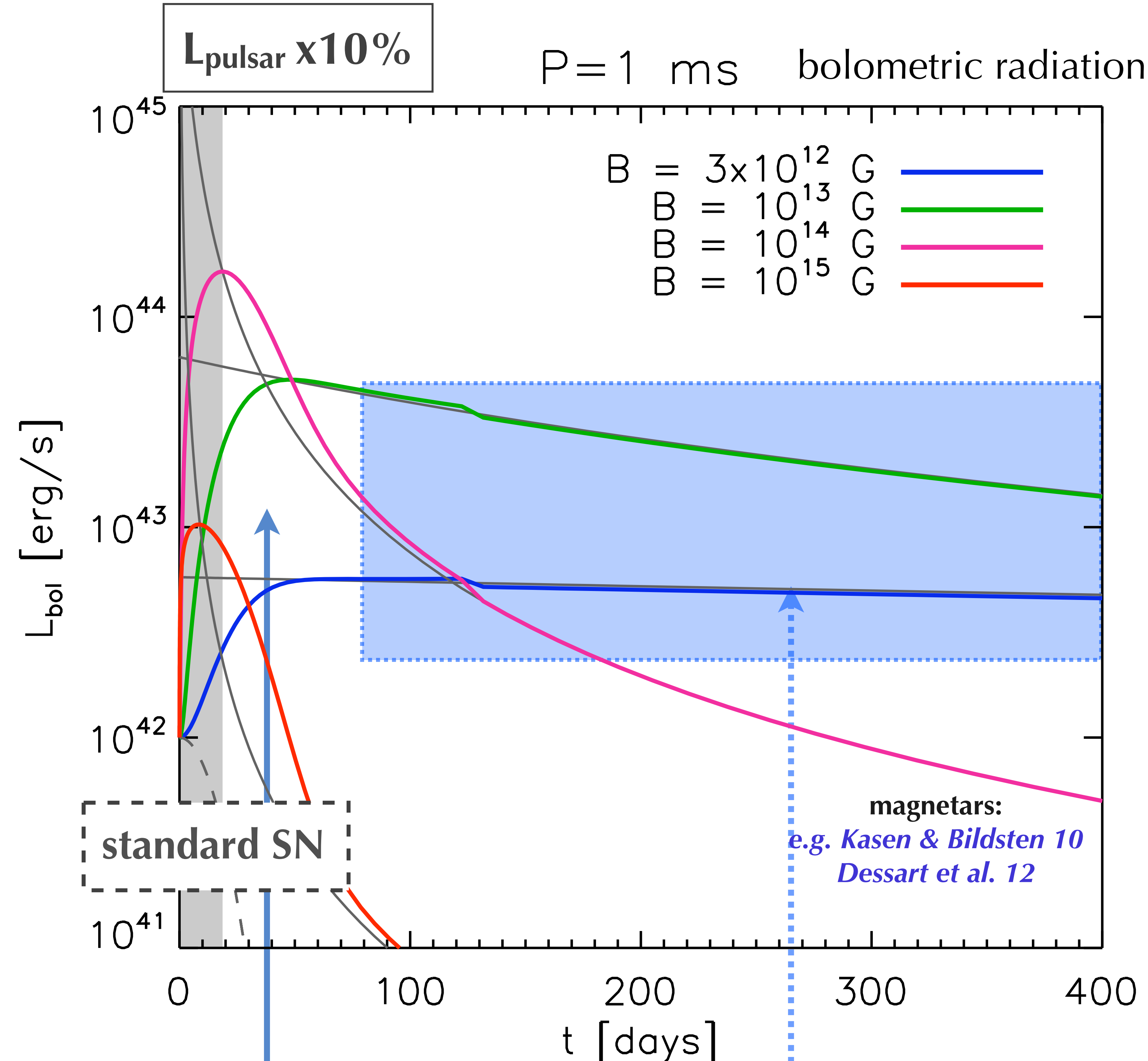

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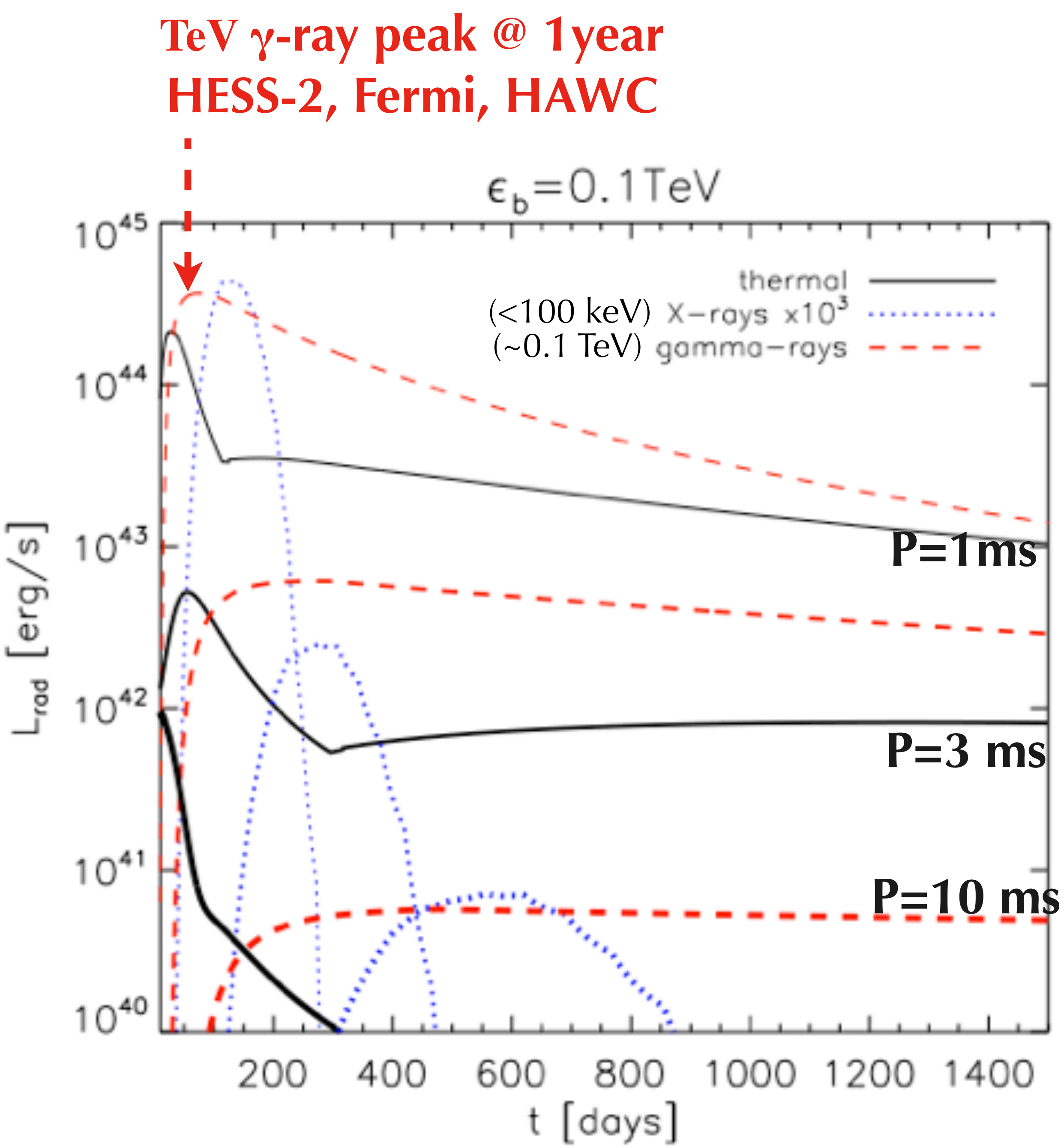

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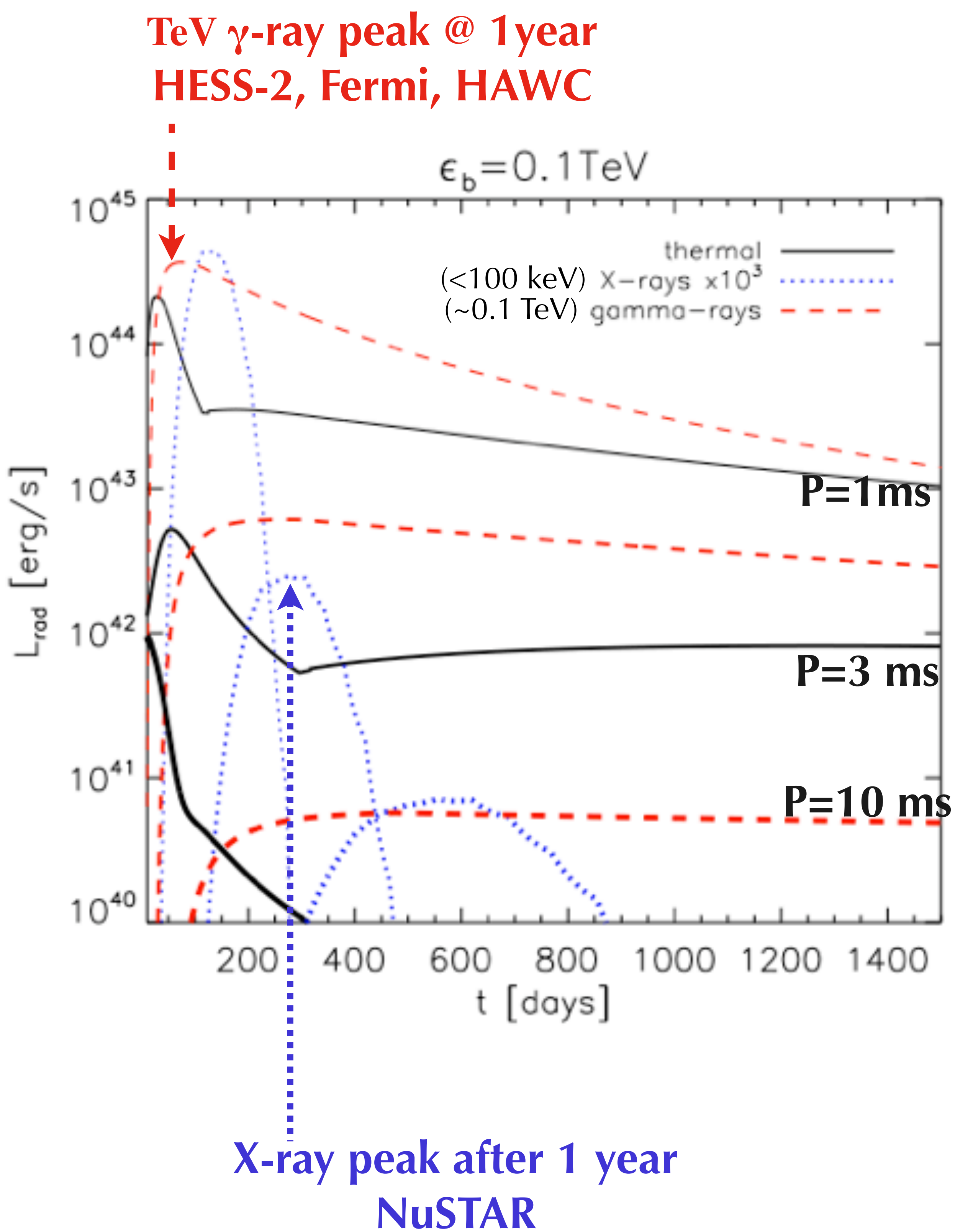

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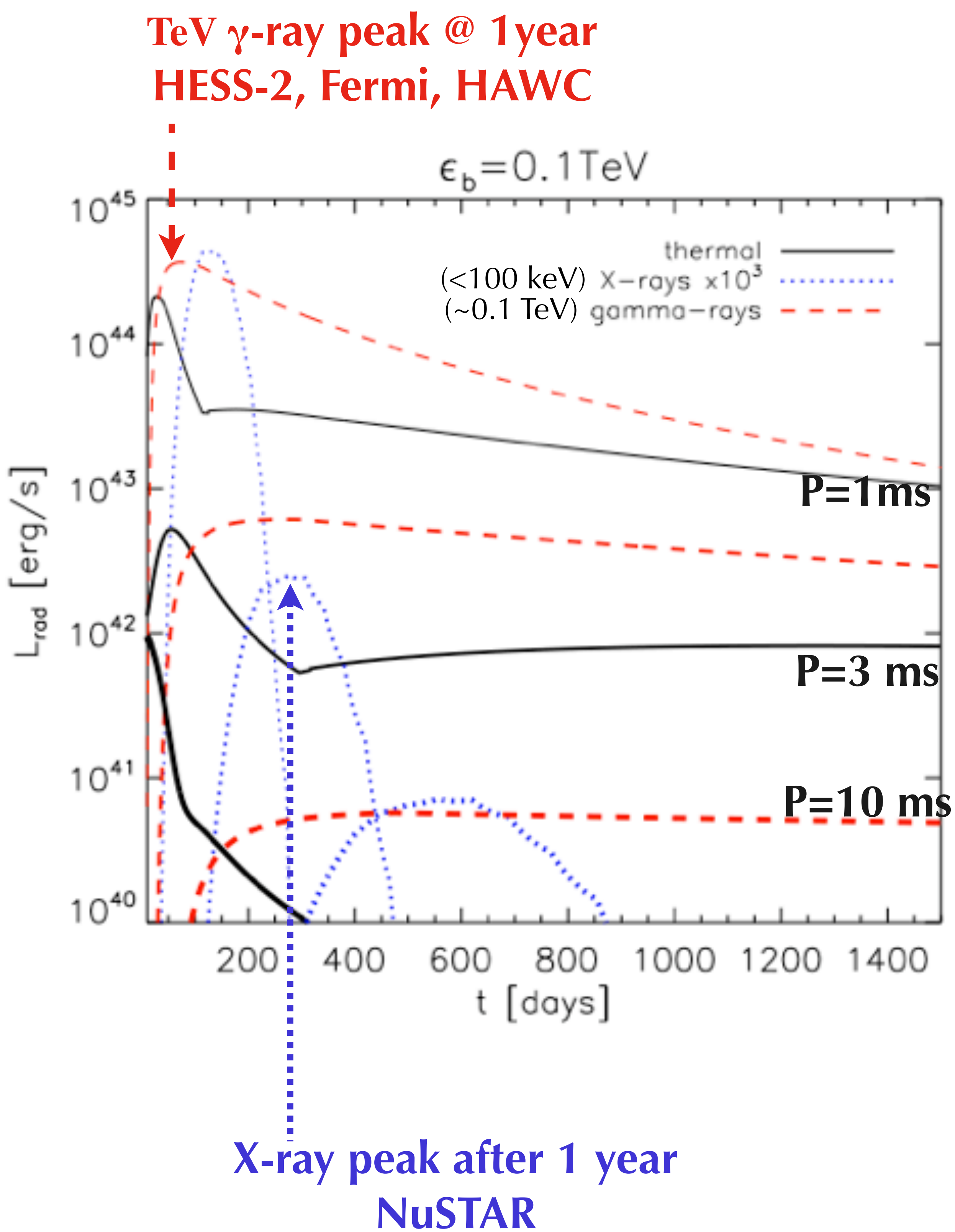
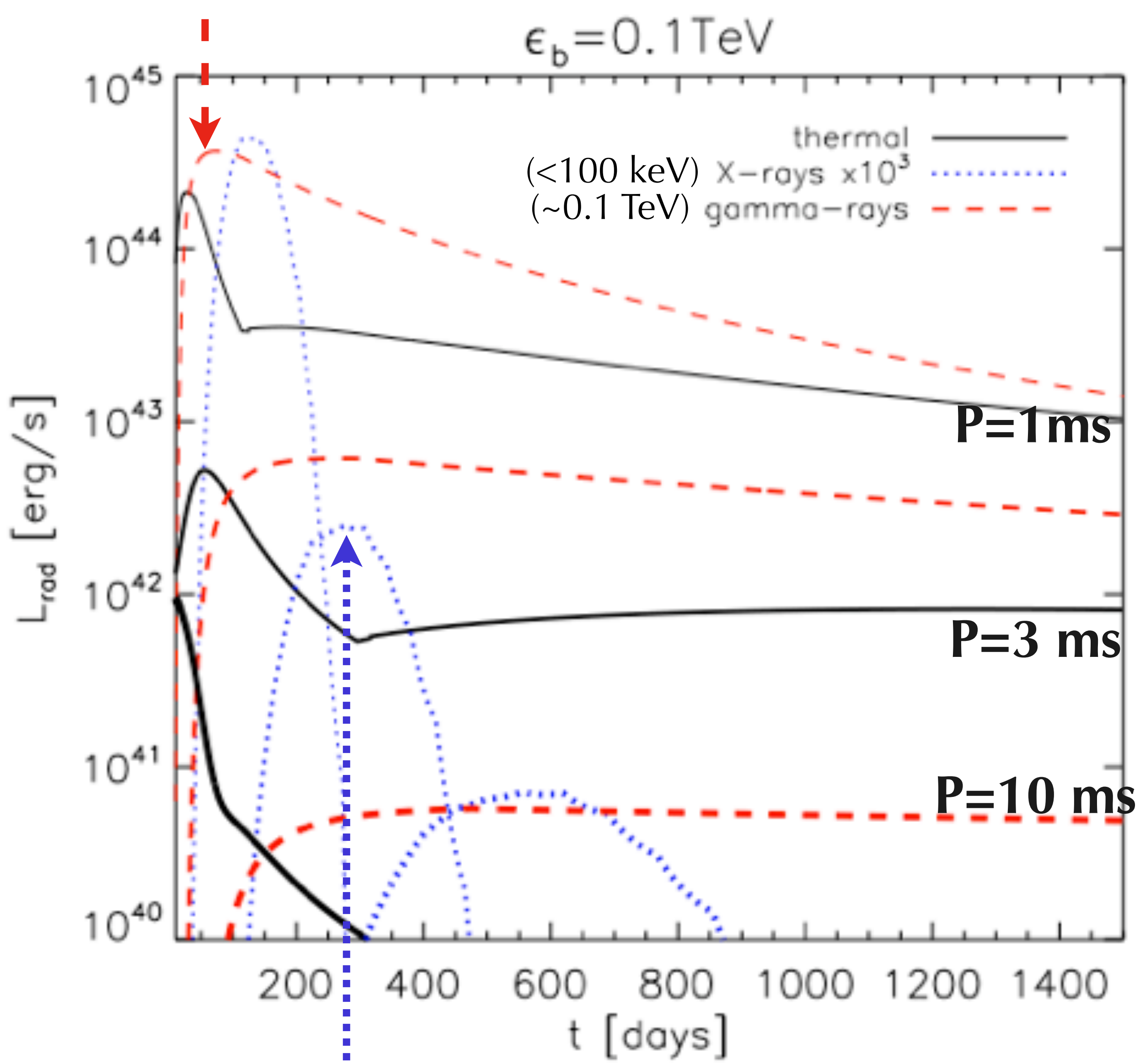


Follow up of SN lightcurves over **a few years** in **all wavelengths** will be crucial

KK, Phinney, Olinto 2013

TeV γ-ray peak @ 1year
HESS-2, Fermi, HAWC



X-ray peak after 1 year
NuSTAR

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Observable with NuSTAR or HAWC

Pulsars as sources of High and Ultrahigh Energy CR?

Surprisingly promising candidate: pulsars

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more statistics for shape of energy spectrum at highest E
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JEM-EUSO

Pulsars as sources of High and Ultrahigh Energy CR?

Surprisingly promising candidate: pulsars

acceleration? *Lemoine, KK, Pétri, in prep.*

successful escape from acceleration region and source
good adequacy with UHECR observables *Fang, KK, Olinto 2012*

Galactic+extragalactic pulsar populations ---> explain cosmic rays from 10^{17} eV to UHE
Fang, KK, Olinto 2013

signatures: UHE neutrinos! *Fang, KK, Murase, Olinto, in prep.*
signatures if birth in our Local Group
look for signatures in SN light curves @ few months-years after explosion *KK, Phinney, Olinto 2013*

UHECR data to improve

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
shower development, parameters for hadronic interactions

JEM-EUSO

Auger upgrades, radio detection, etc.