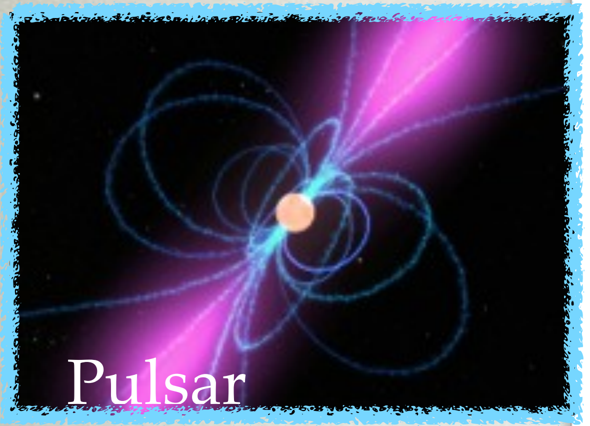
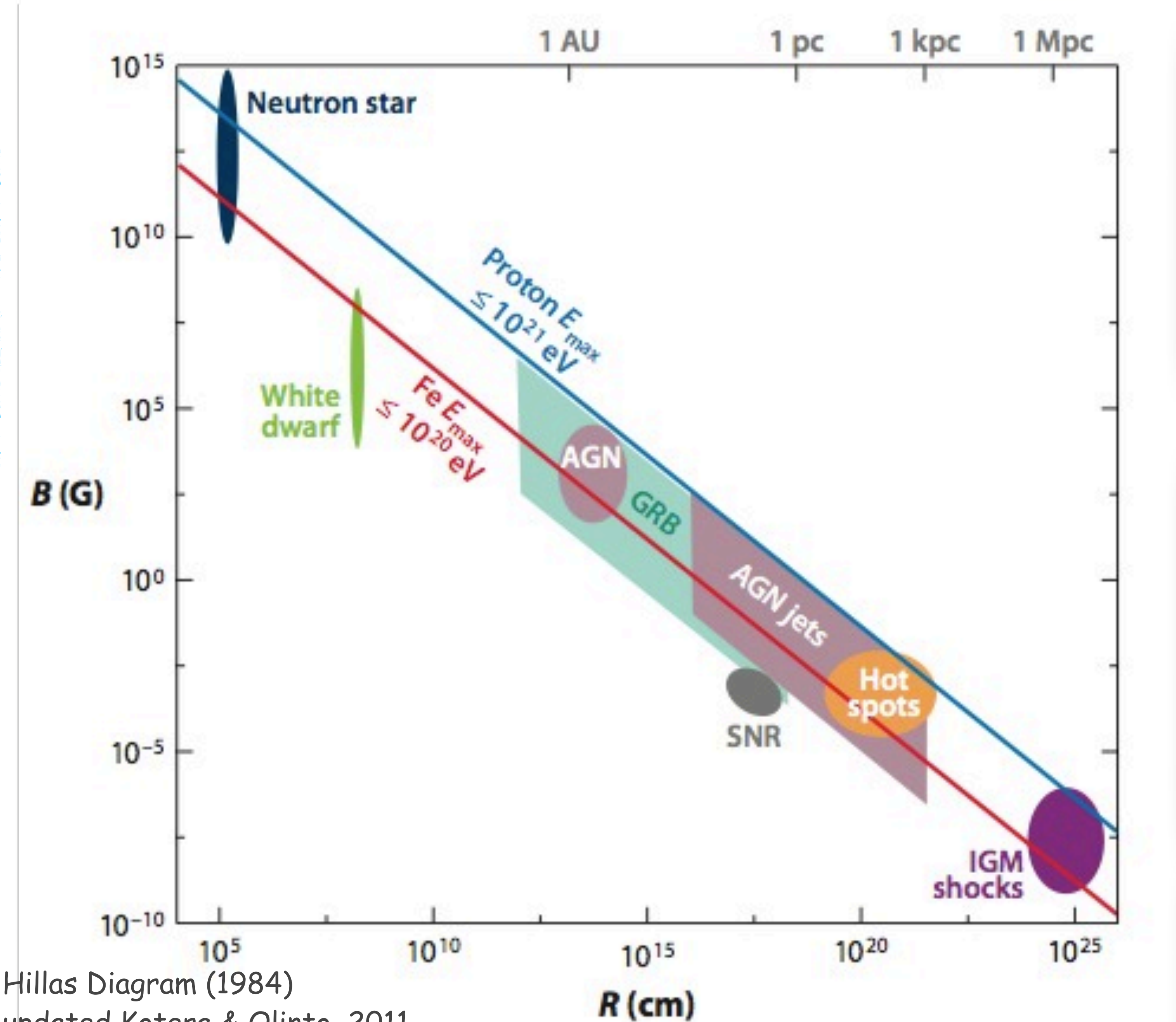
Newborn Pulsars as Sources of UHECRs

Ke Fang
University of Chicago

Cosmic Ray Anisotropy Workshop
Sep 26 2013

Possible Candidates of UHECR Sources





Hillas Diagram (1984)
updated Kotera & Olinto, 2011

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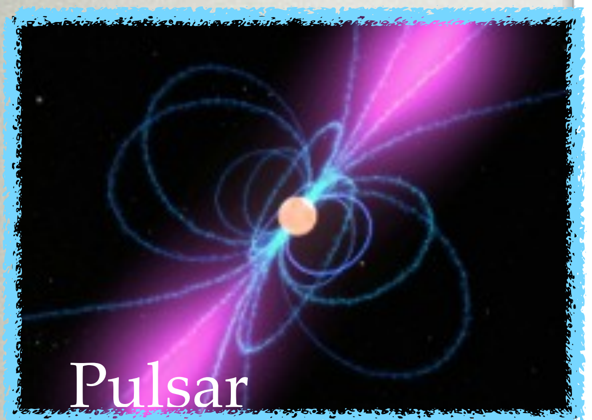

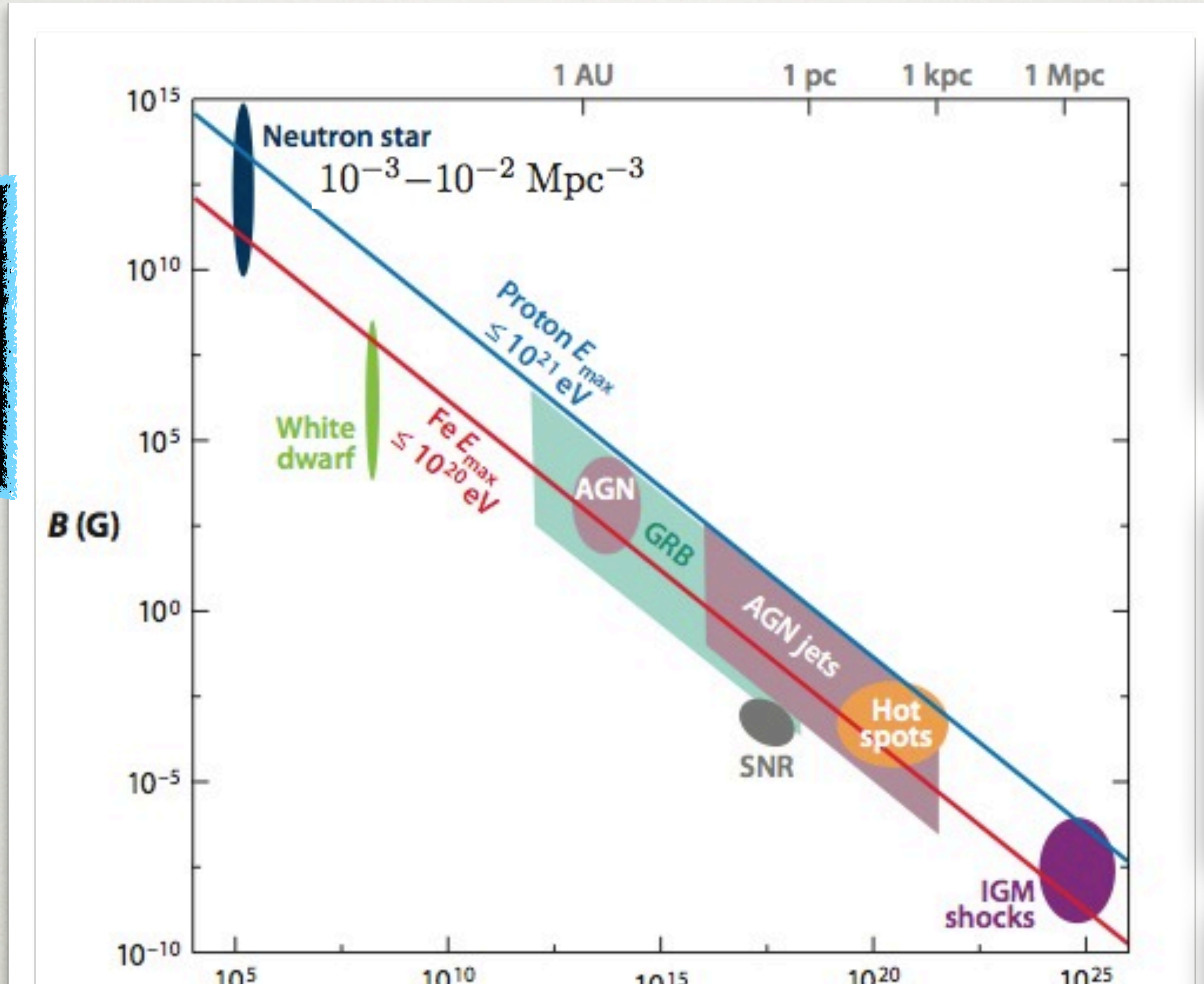

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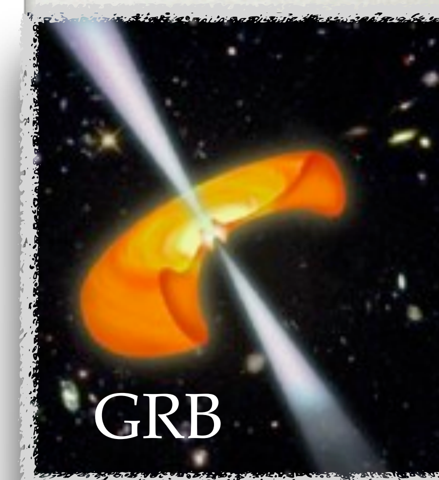

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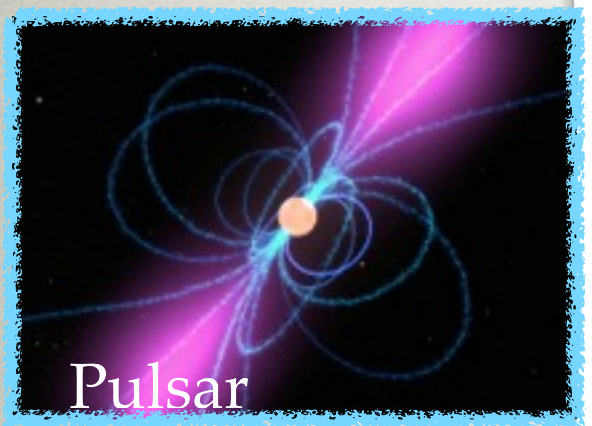

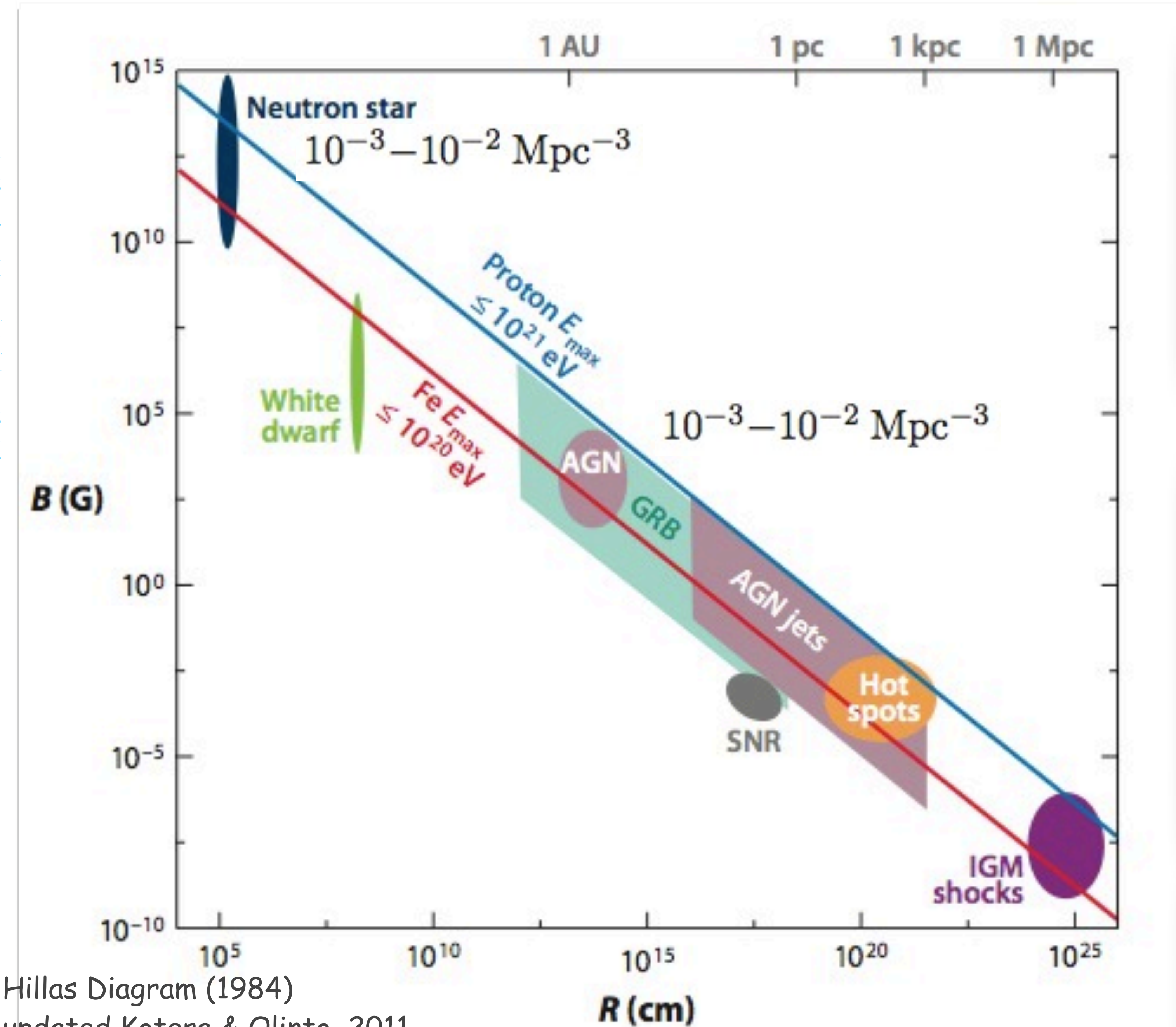

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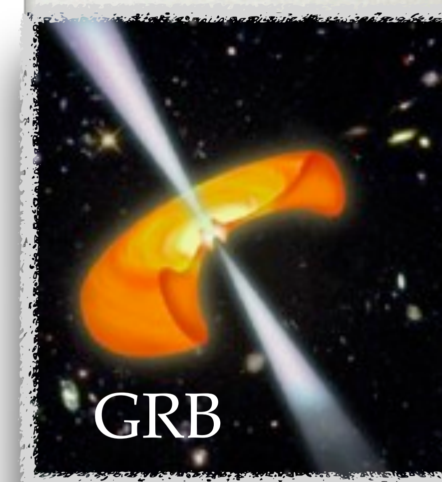

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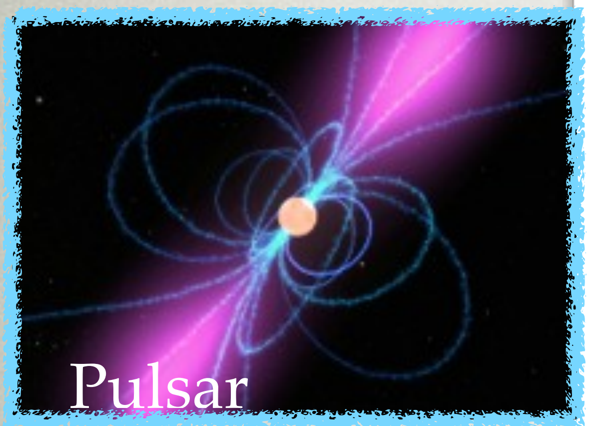

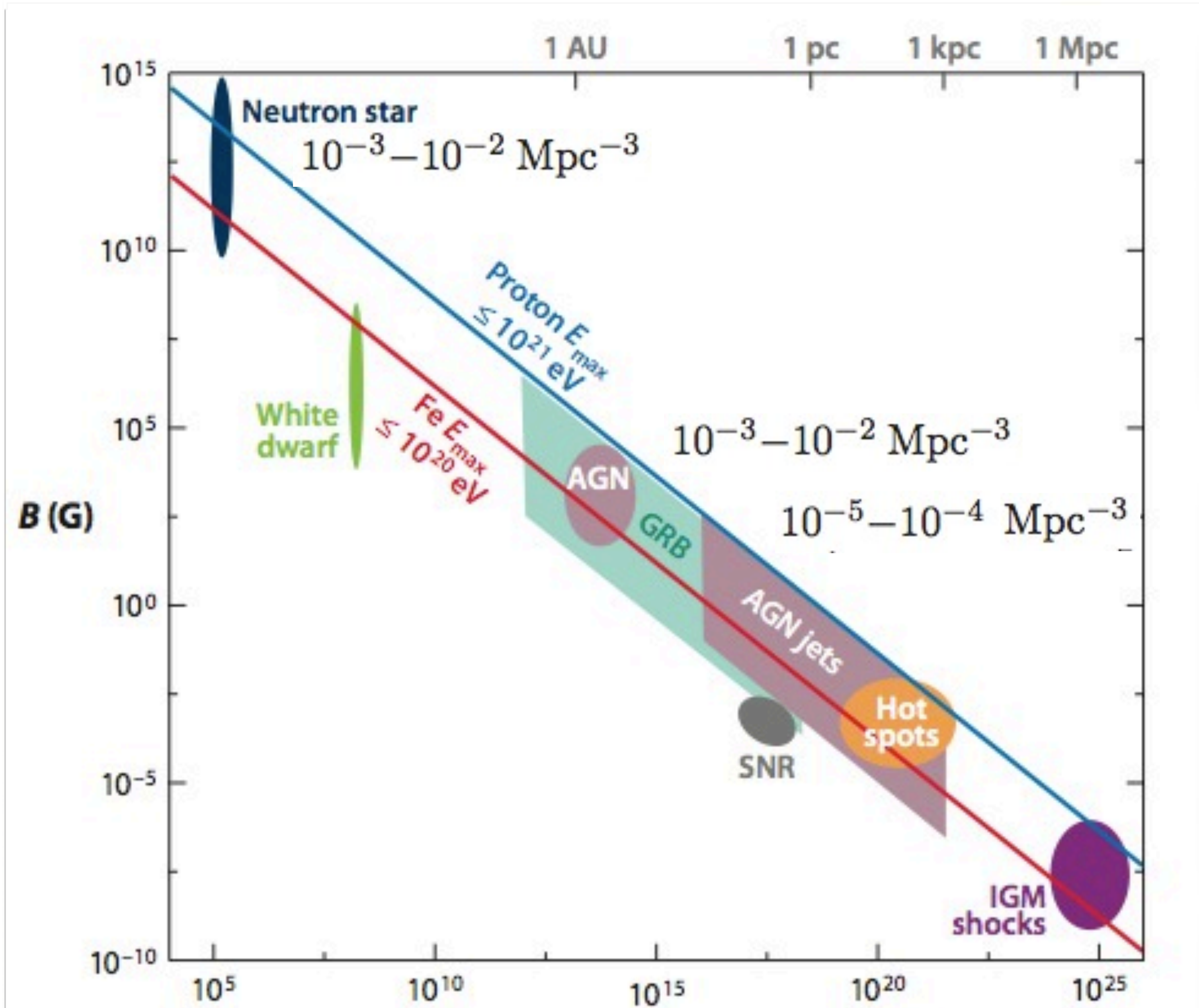

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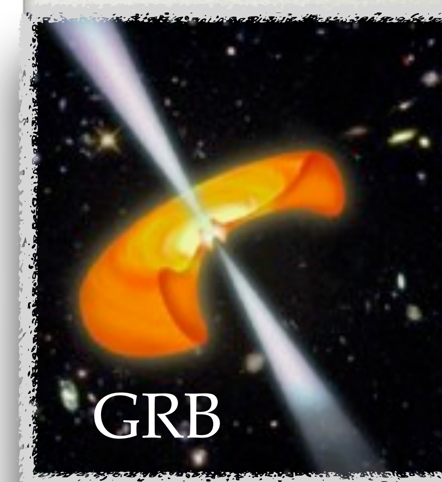

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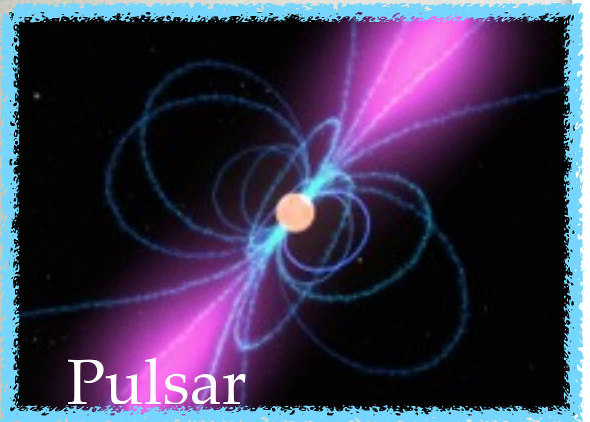

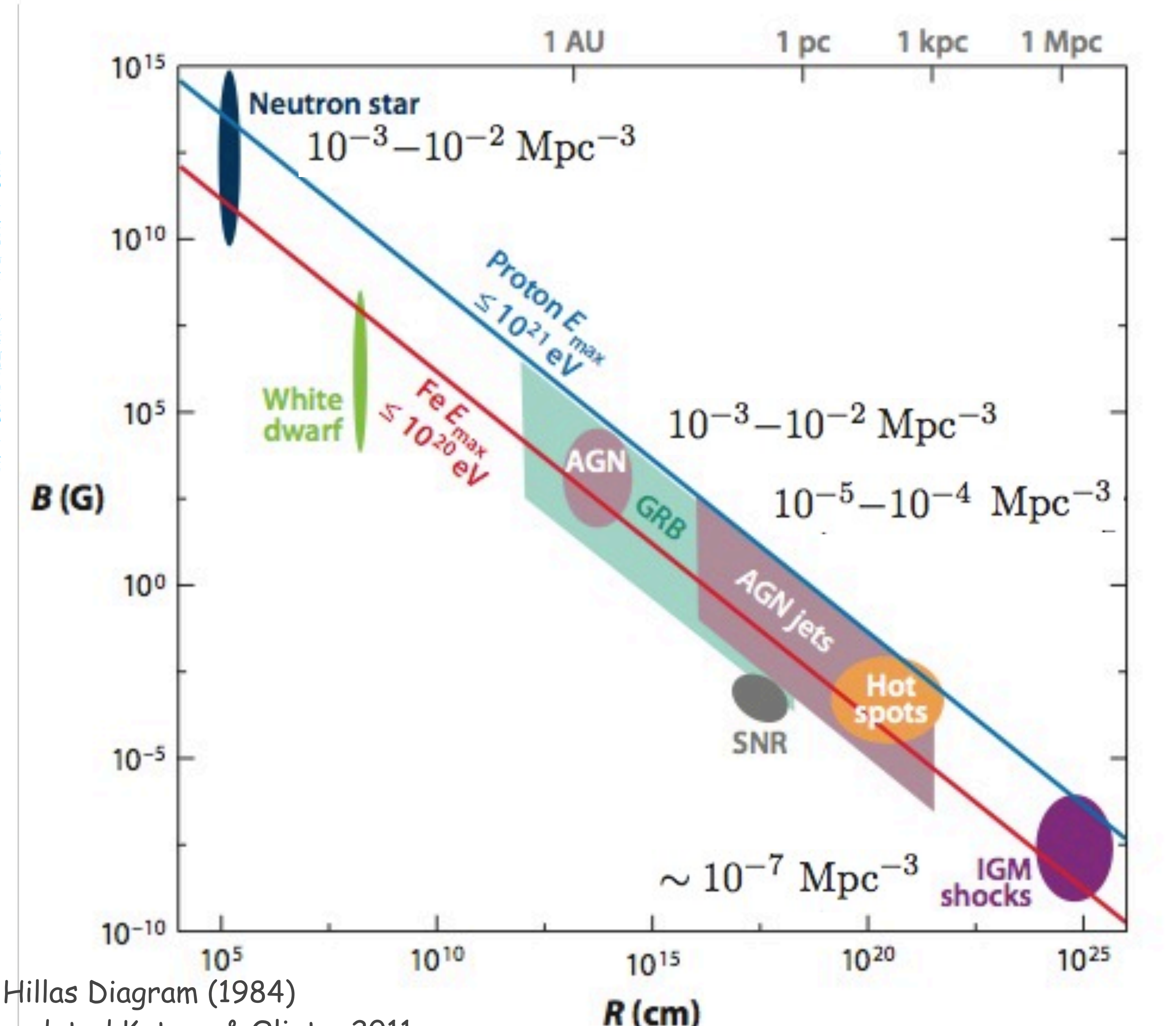

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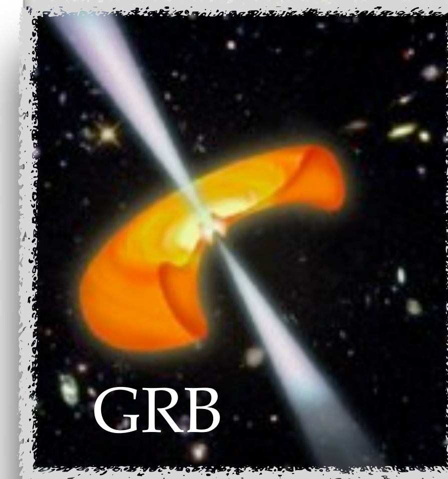

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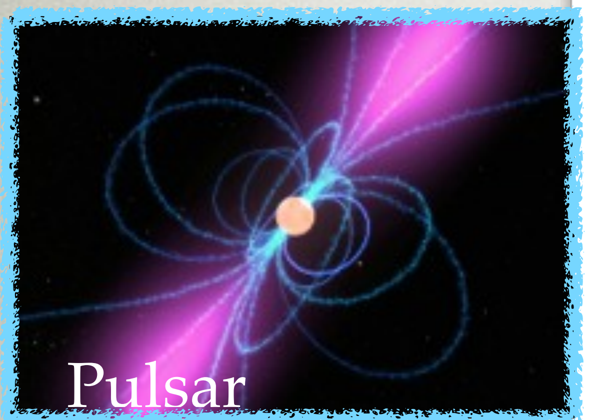

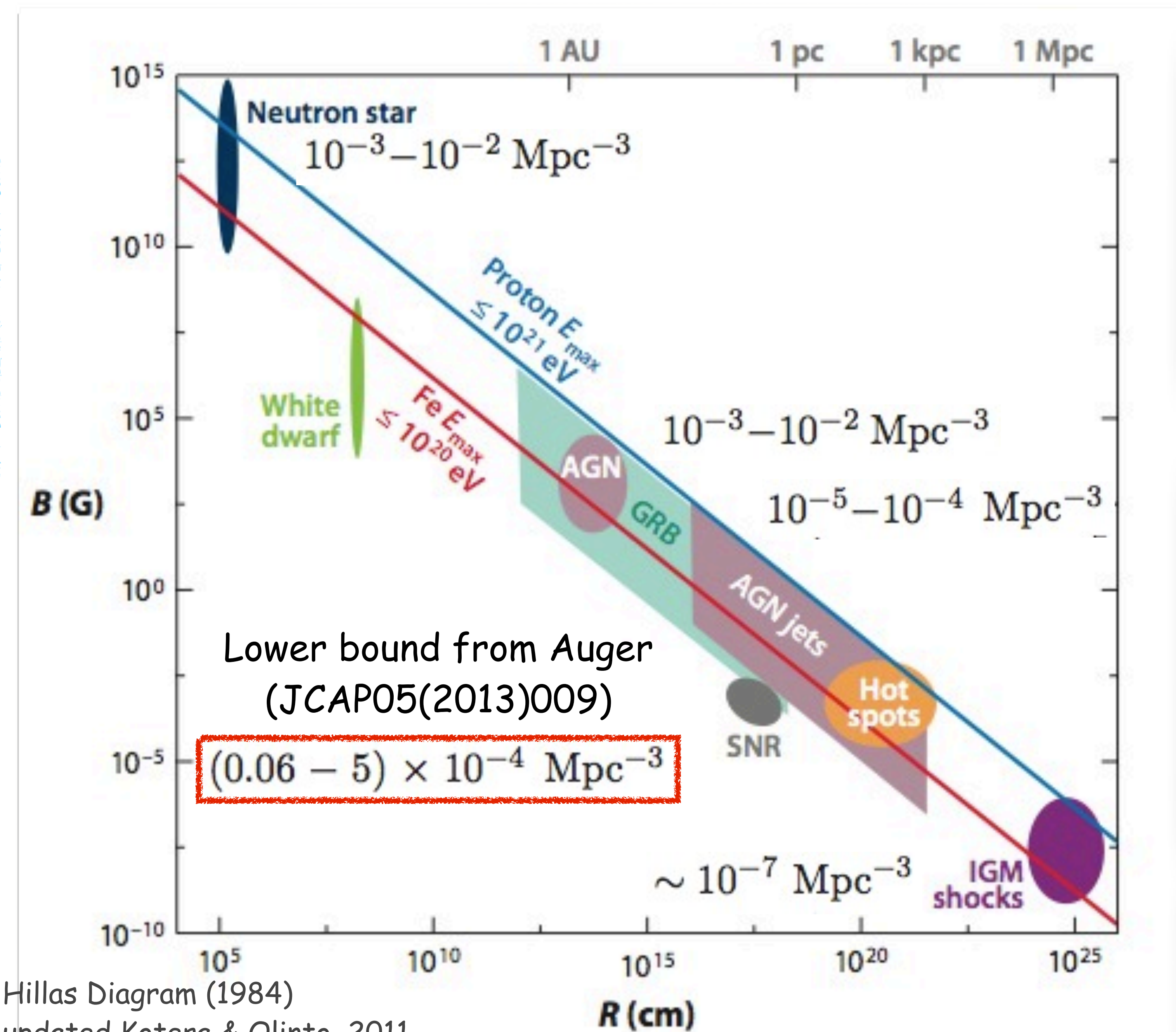

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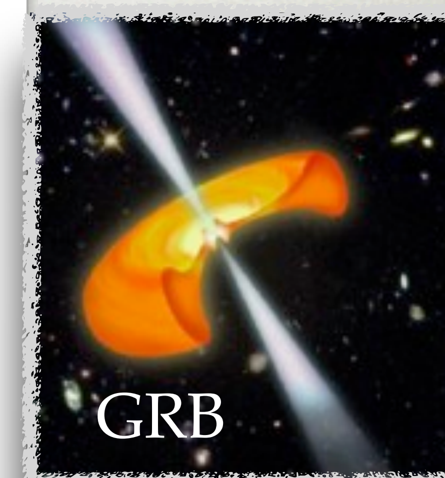
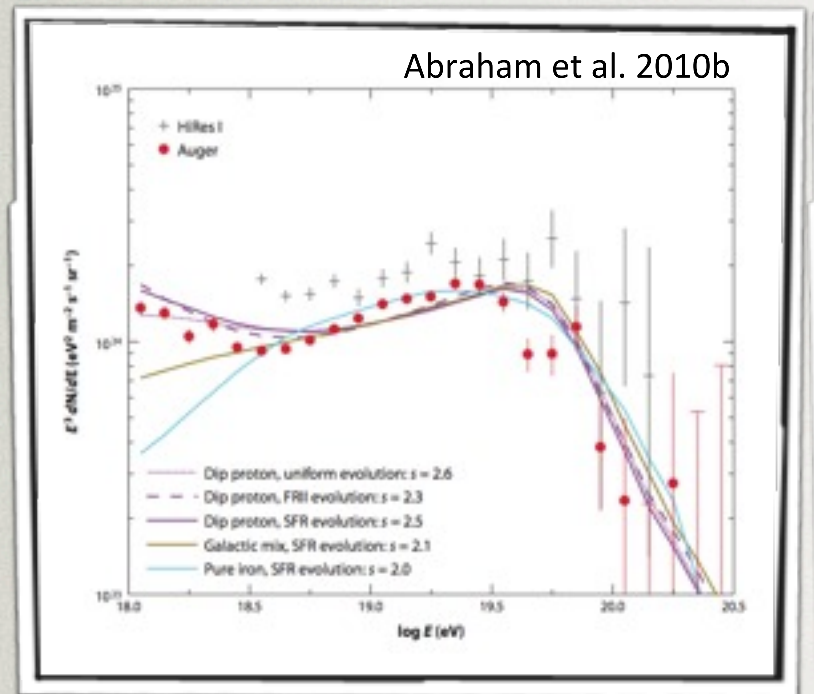
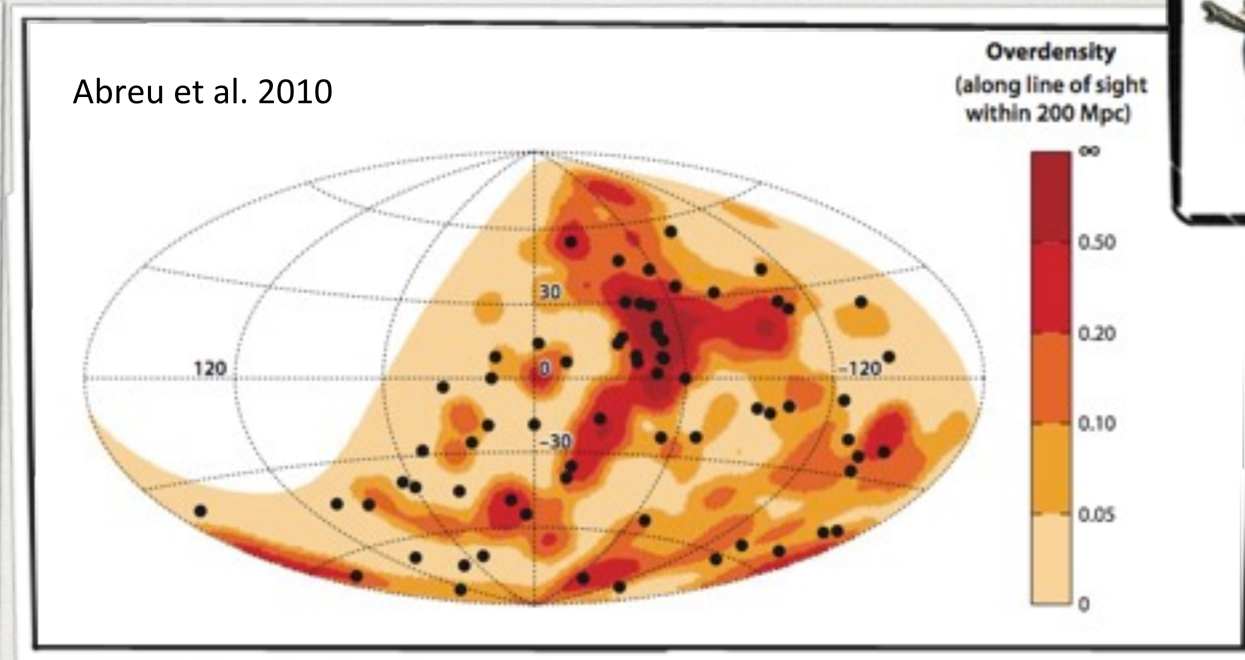


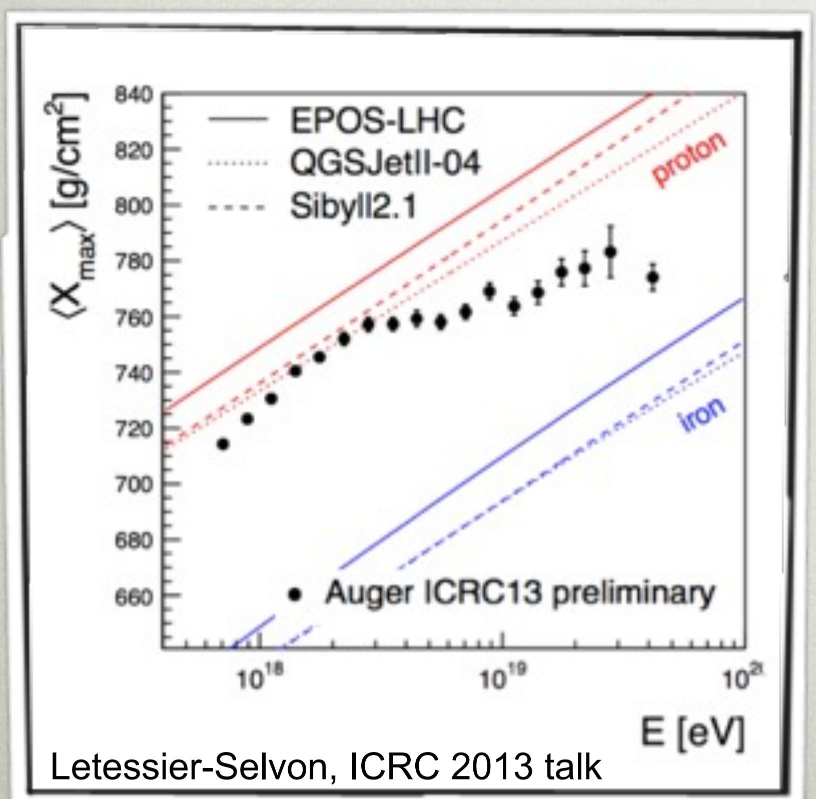
The Source has to explain..

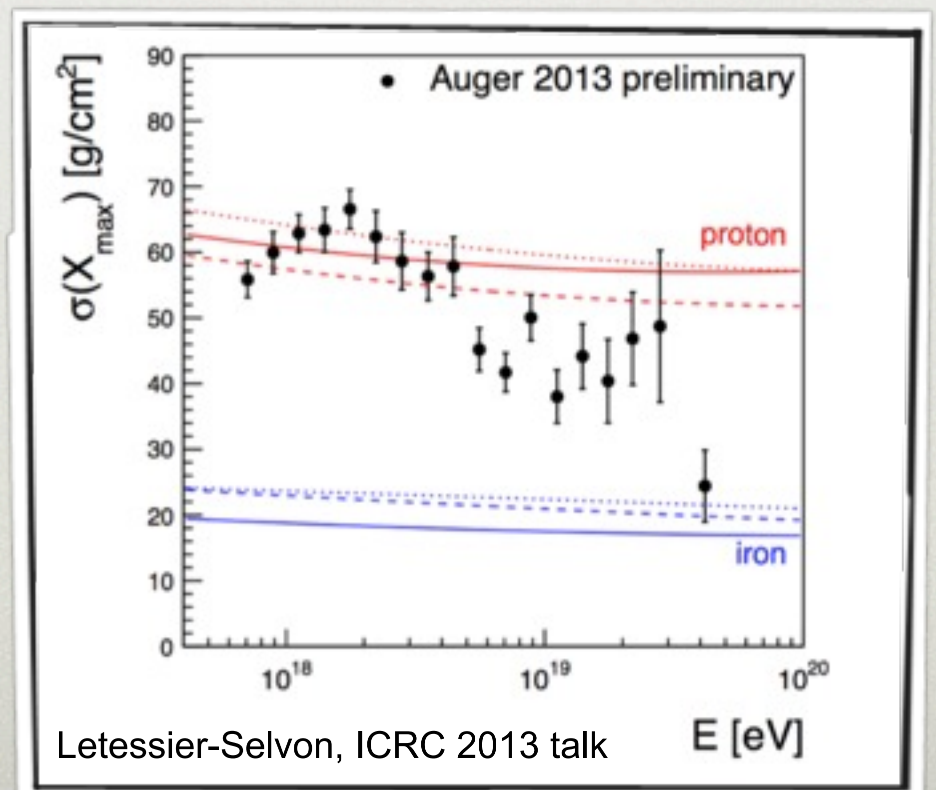




Intrinsic spectrum index ~ 2

no significant anisotropy





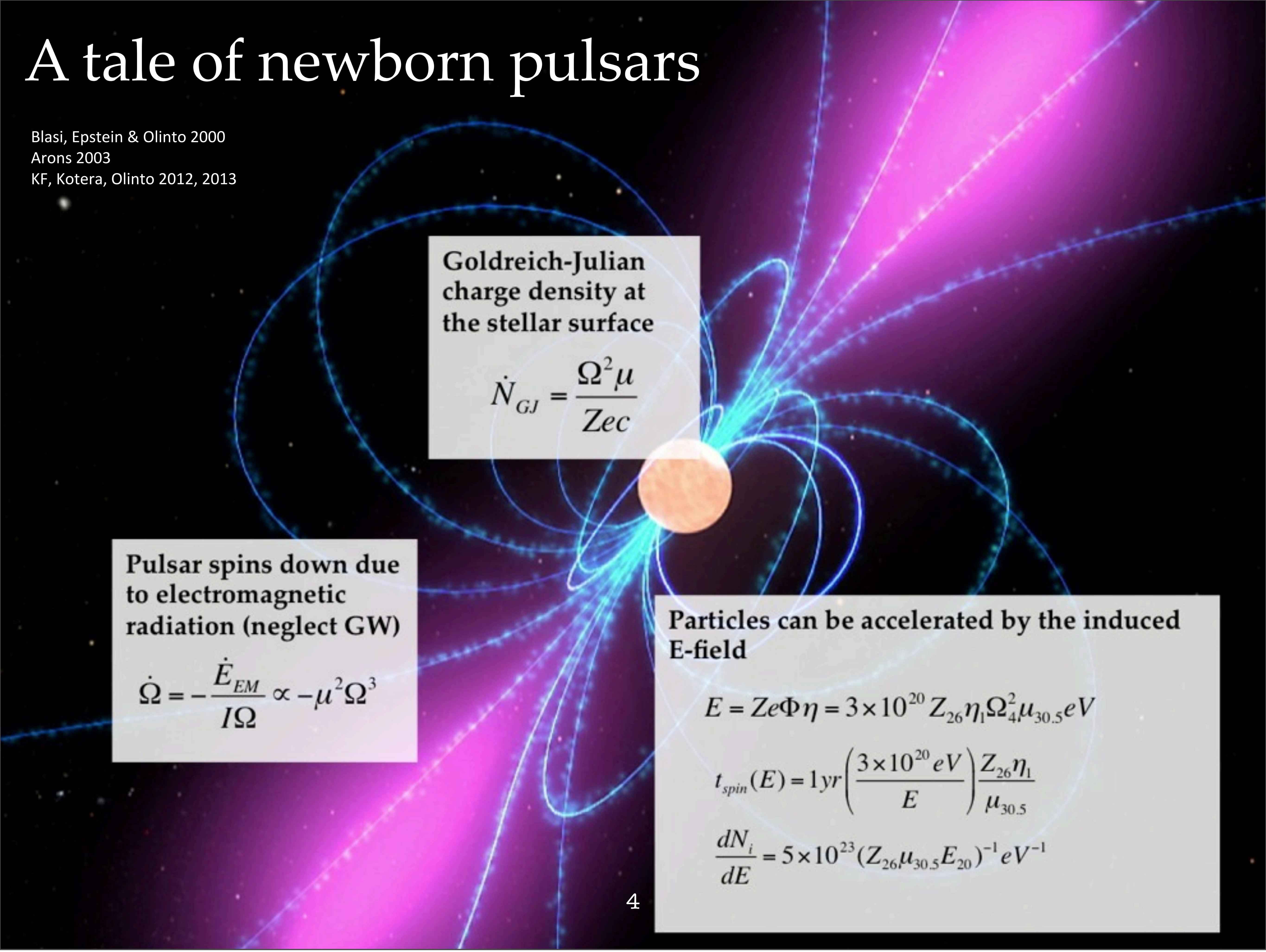
Intermediate and heavy above 10EeV

TA indicates light composition

...

Multi-messenger signatures

A tale of newborn pulsars



Blasi, Epstein & Olinto 2000
Arons 2003
KF, Kotera, Olinto 2012, 2013

Goldreich-Julian charge density at the stellar surface

$$\dot{N}_{GJ} = \frac{\Omega^2 \mu}{Zec}$$

Pulsar spins down due to electromagnetic radiation (neglect GW)

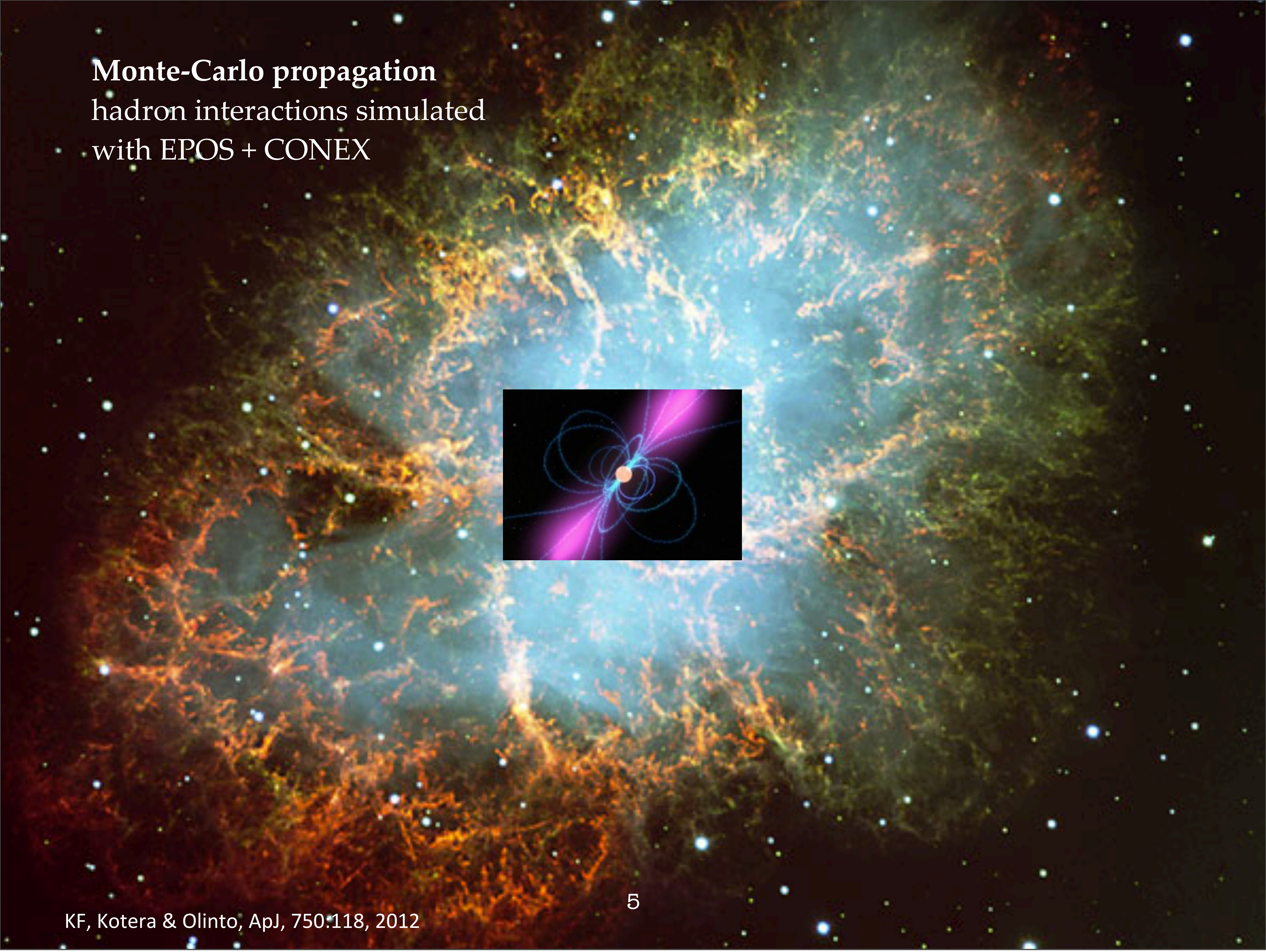
$$\dot{\Omega} = -\frac{\dot{E}_{EM}}{I\Omega} \propto -\mu^2 \Omega^3$$

Particles can be accelerated by the induced E-field

$$E = Ze\Phi\eta = 3\times 10^{20}\, Z_{26}\eta_1 \Omega_4^2 \mu_{30.5}\, eV$$

$$t_{spin}(E) = 1yr \left(\frac{3\times 10^{20}\, eV}{E}\right) \frac{Z_{26}\eta_1}{\mu_{30.5}}$$

$$\frac{dN_i}{dE} = 5\times 10^{23} (Z_{26}\mu_{30.5}E_{20})^{-1}\, eV^{-1}$$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hadron interactions simulated
with EPOS + CONEX
KF, Kotera & Olinto, ApJ, 750:118, 2012

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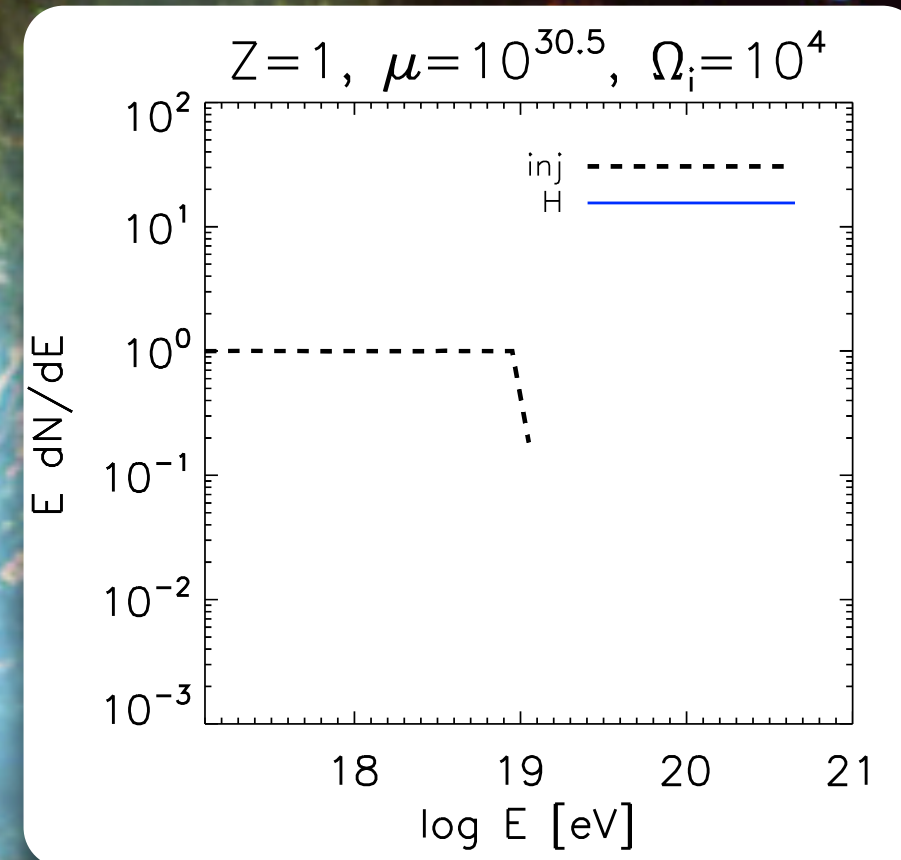

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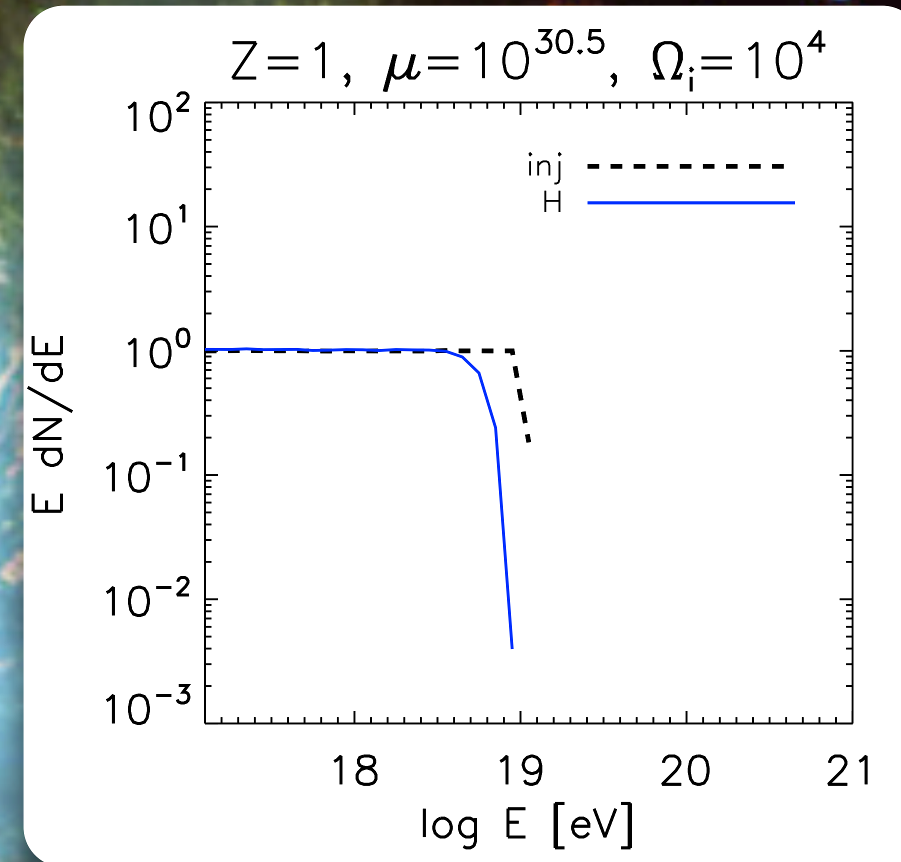

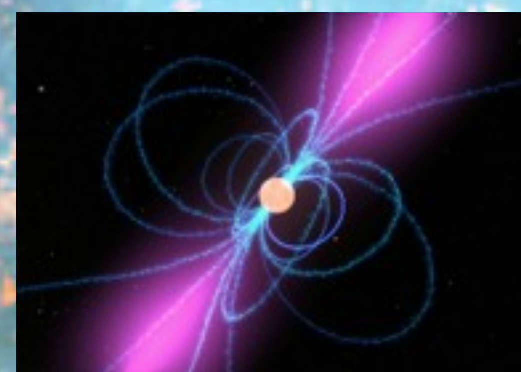

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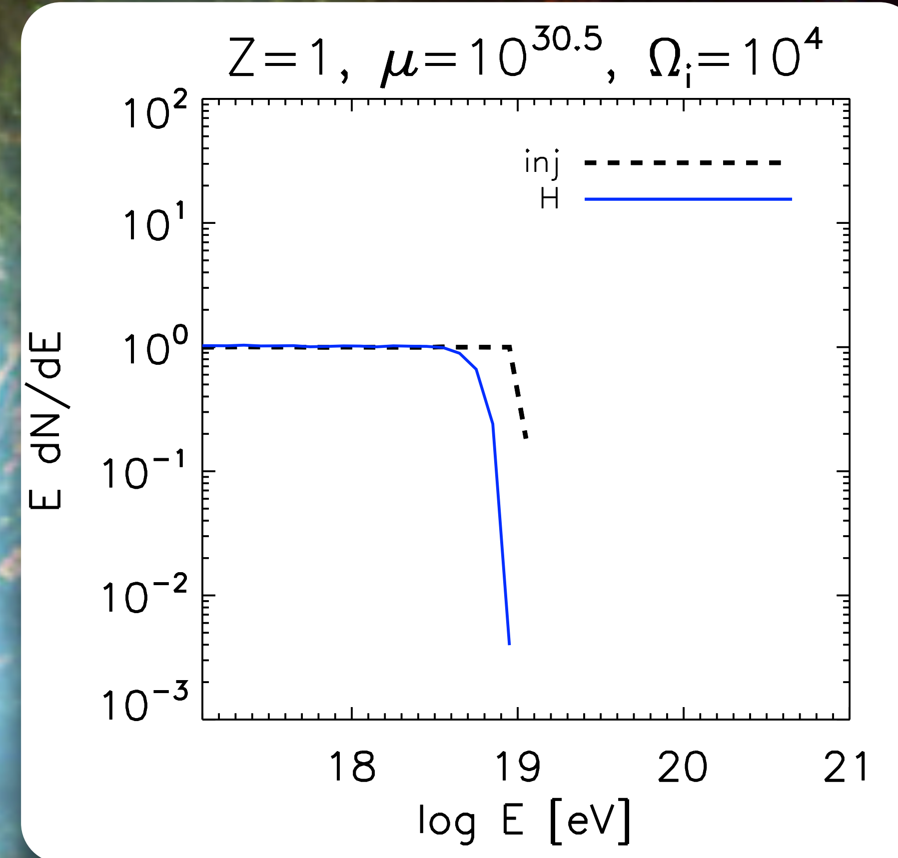

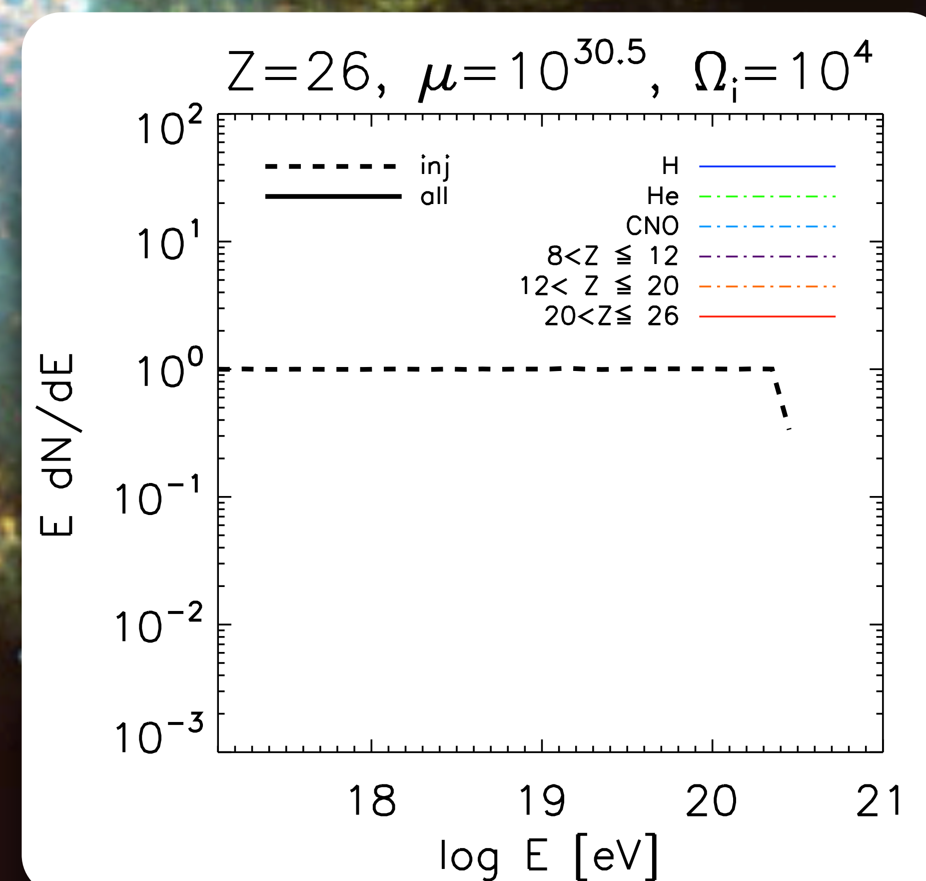

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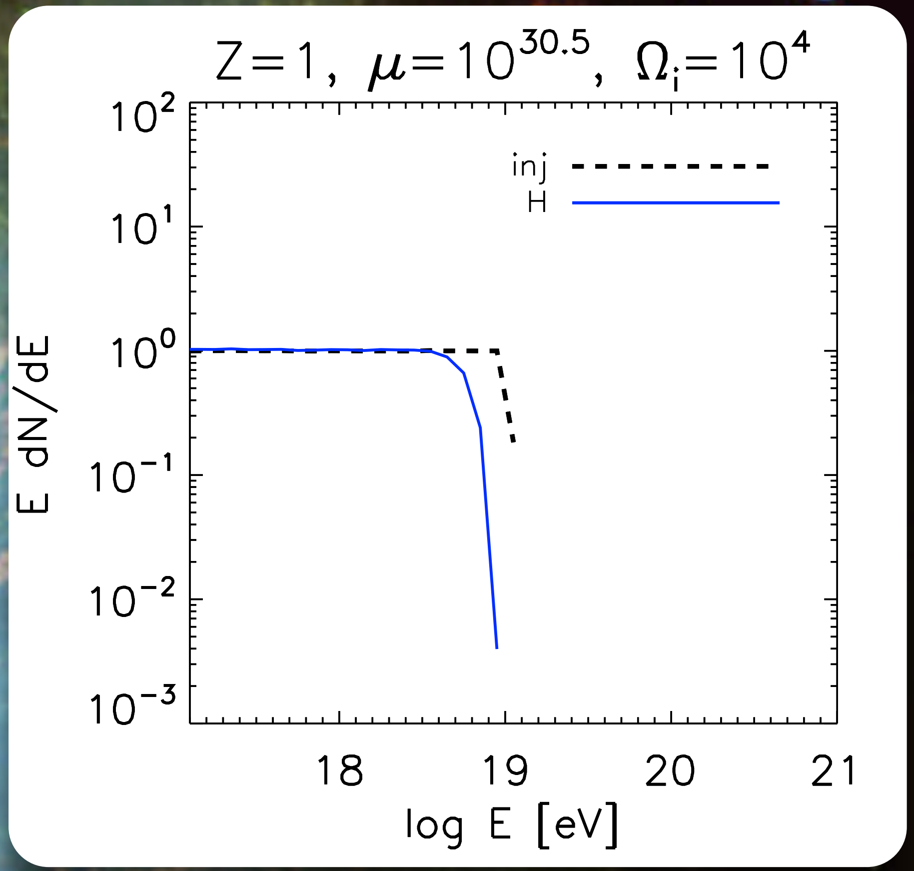

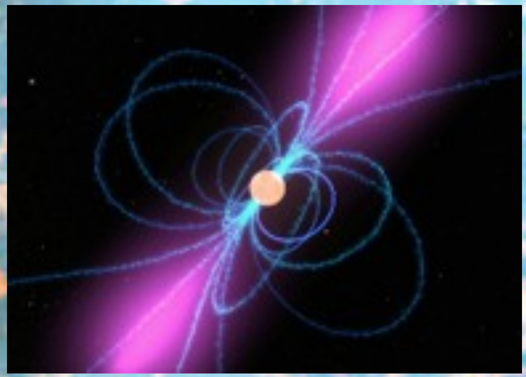

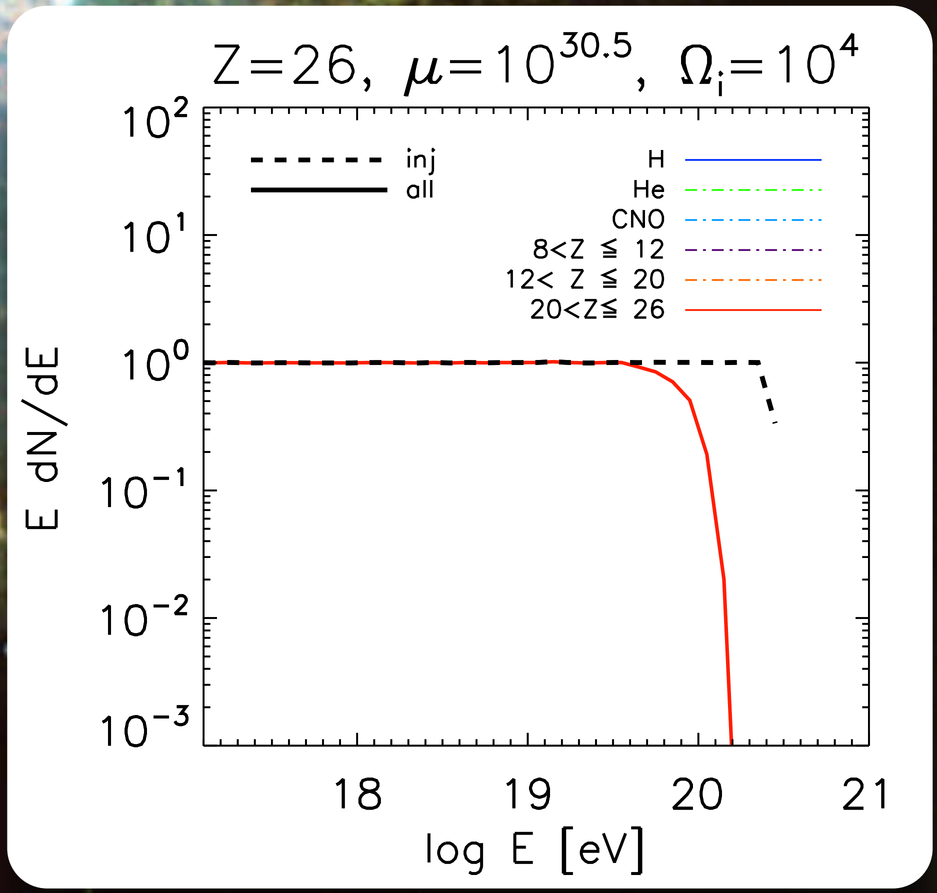

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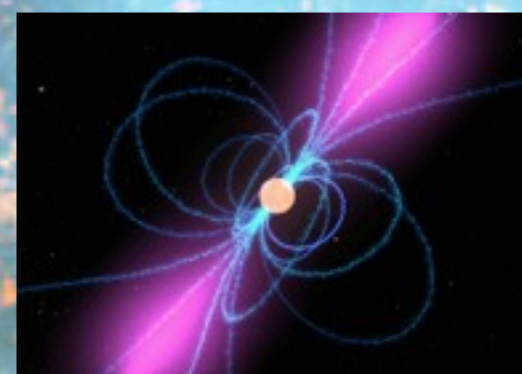

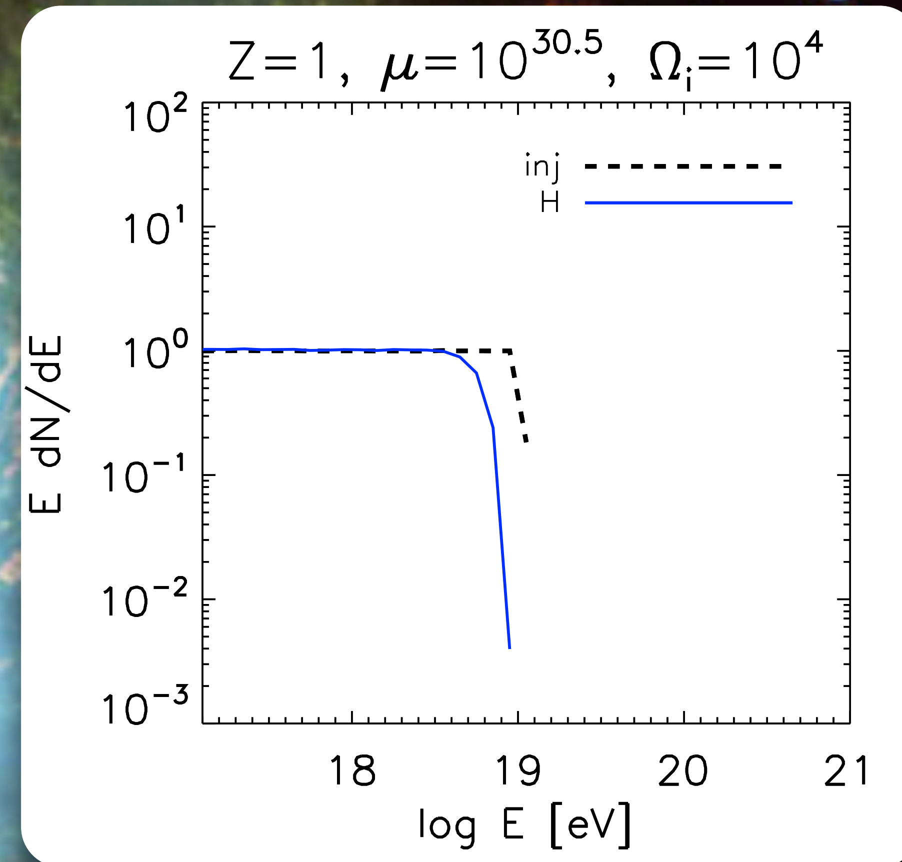

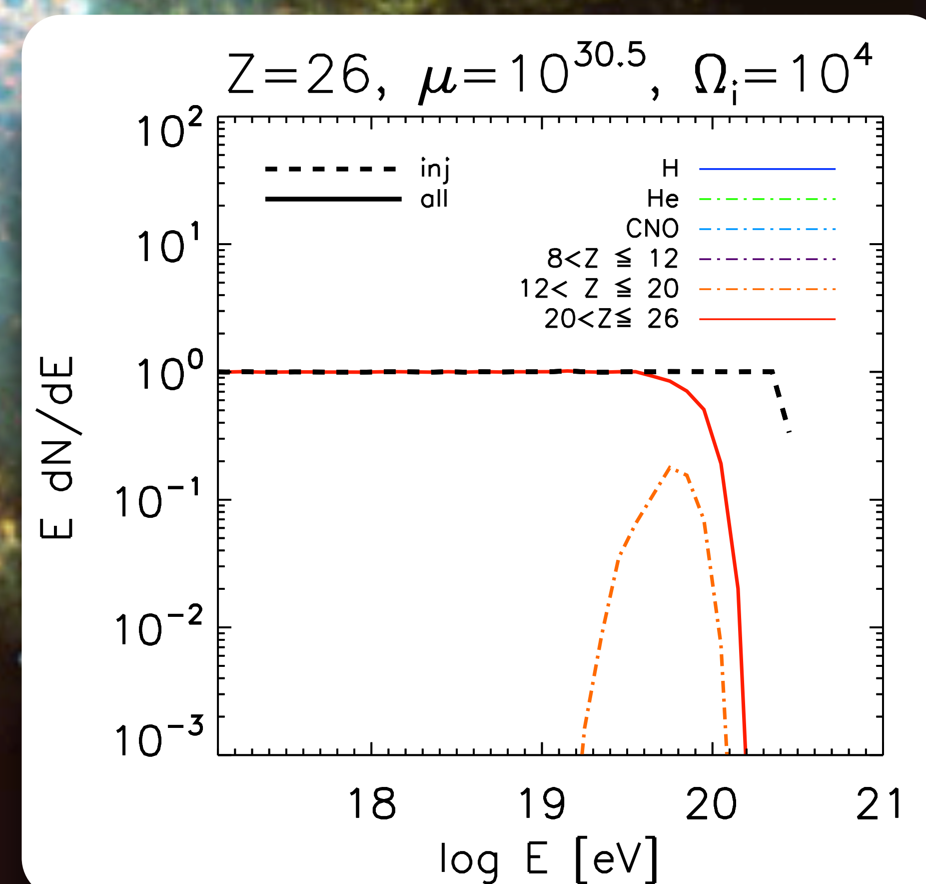

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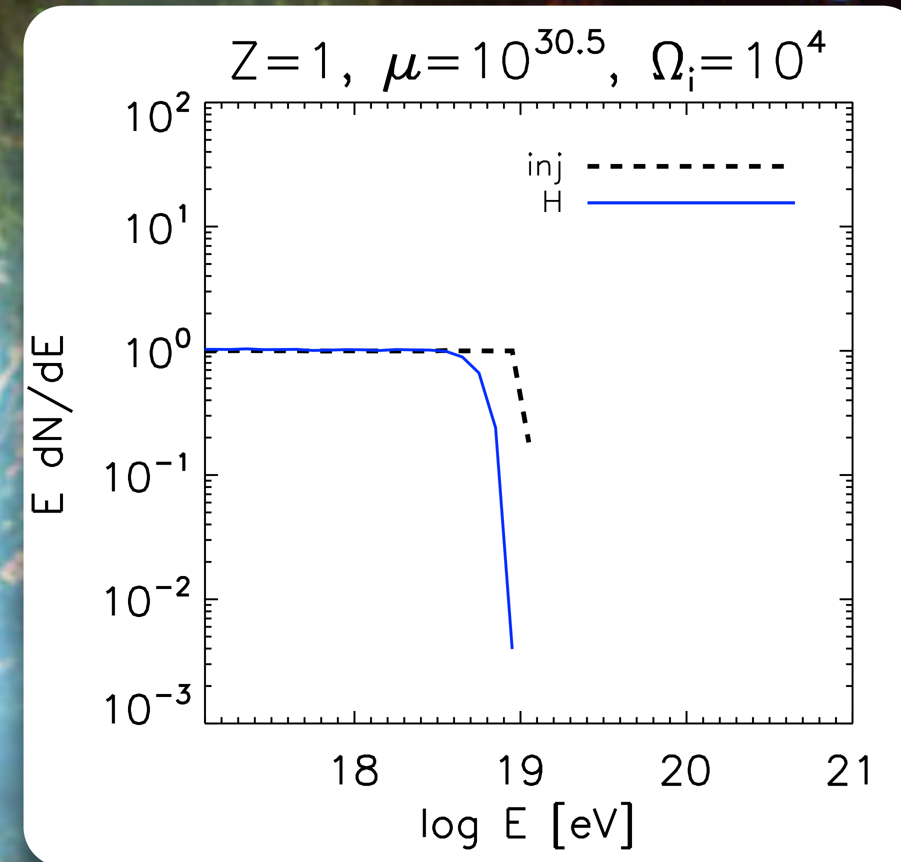

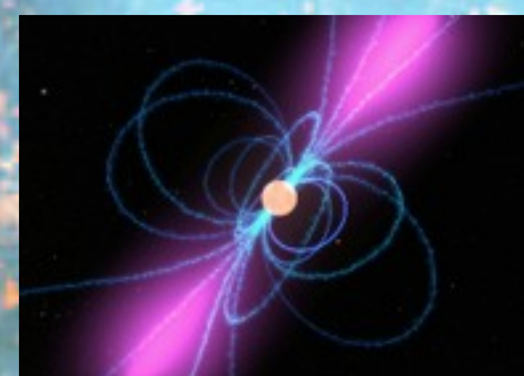

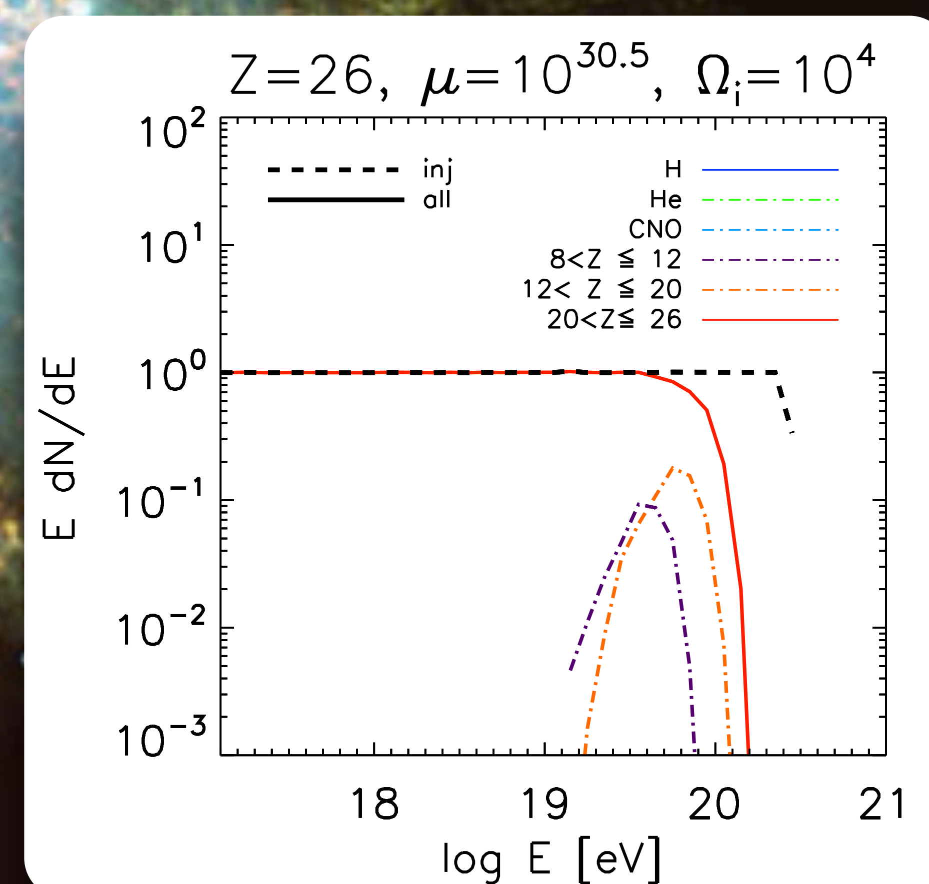

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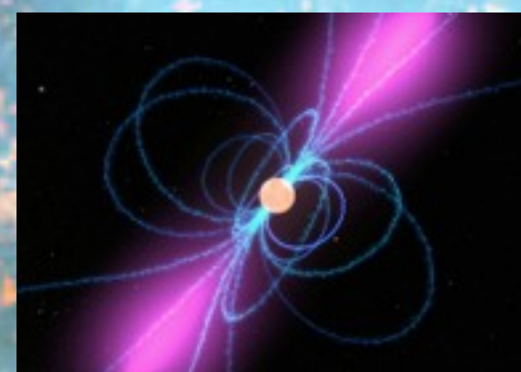

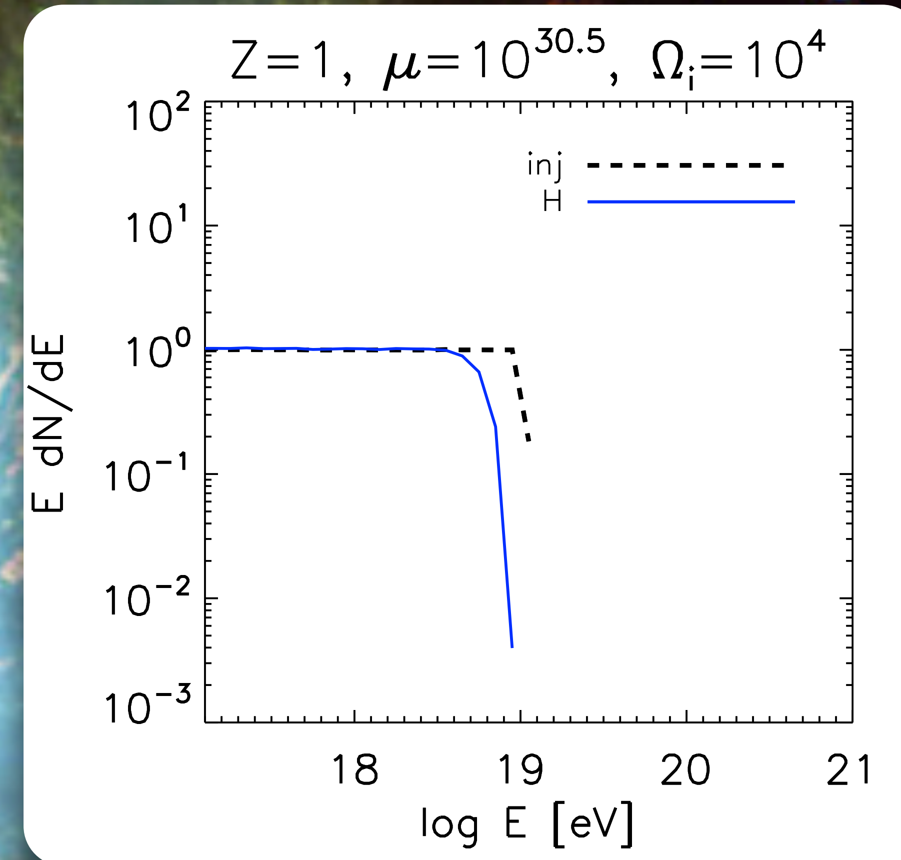

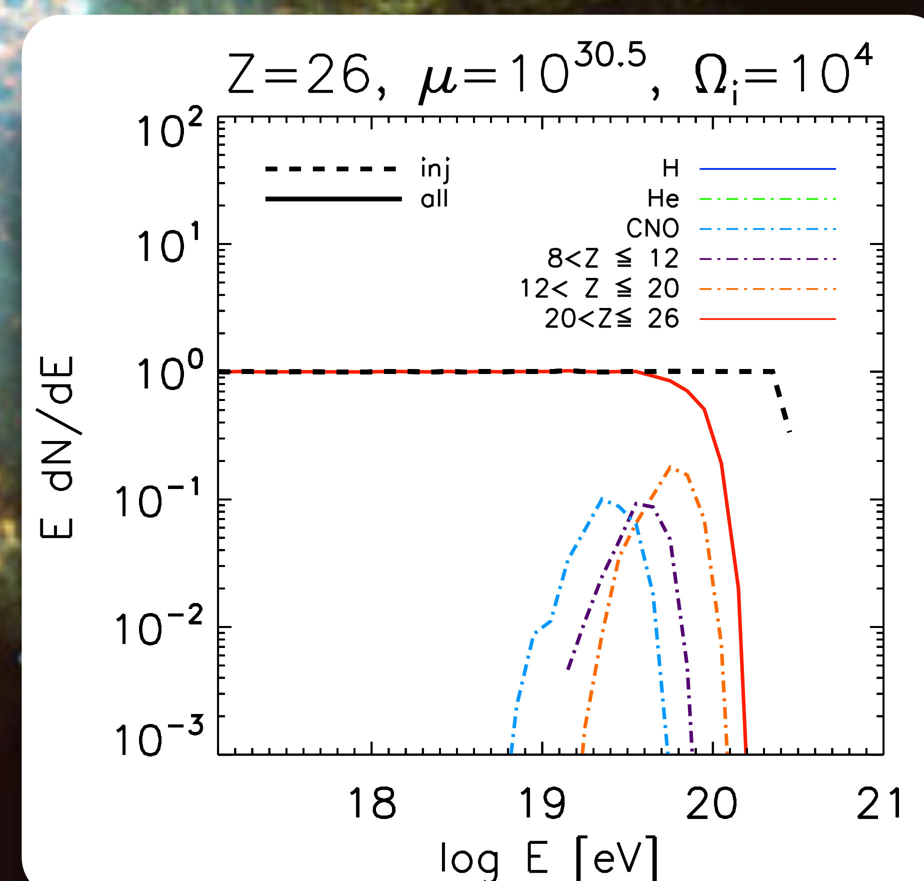

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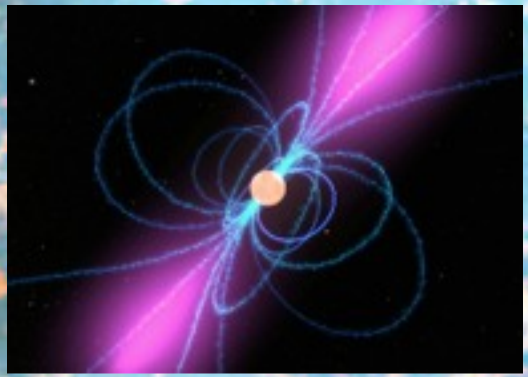

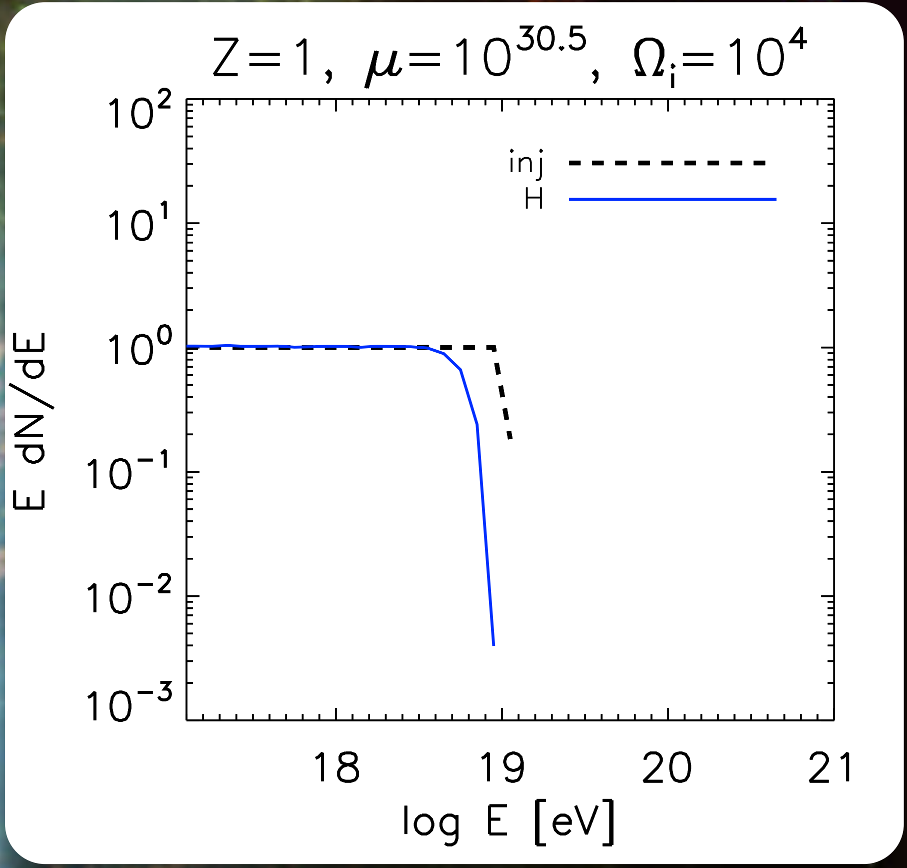

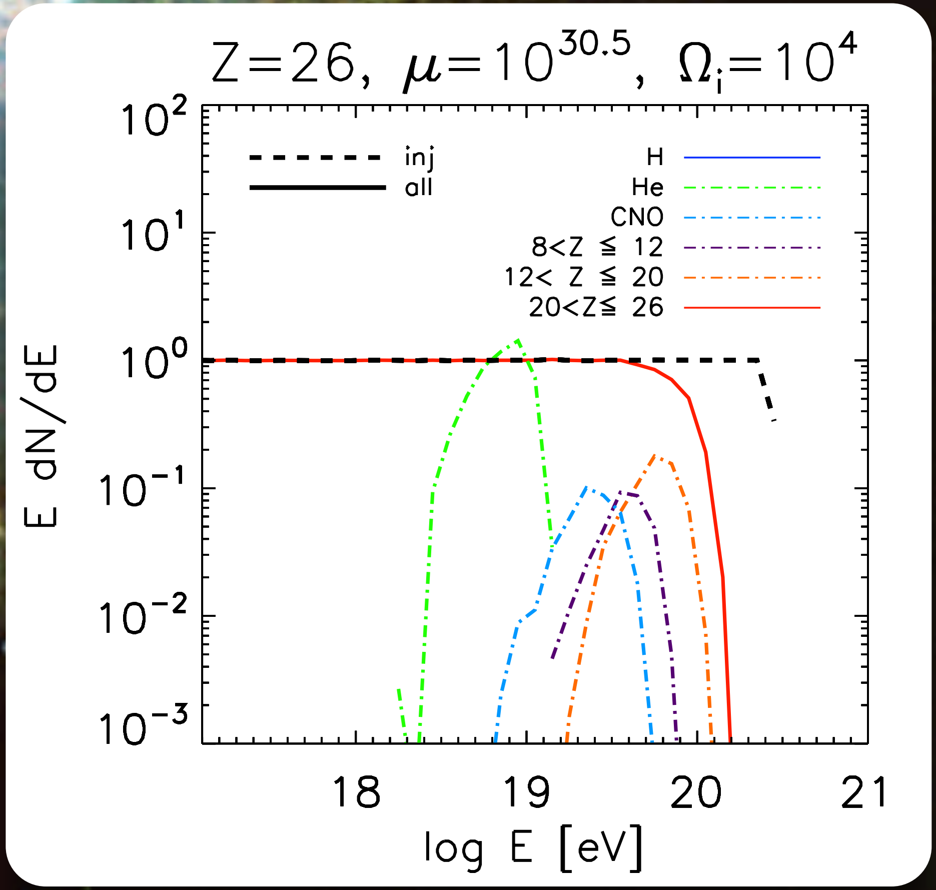

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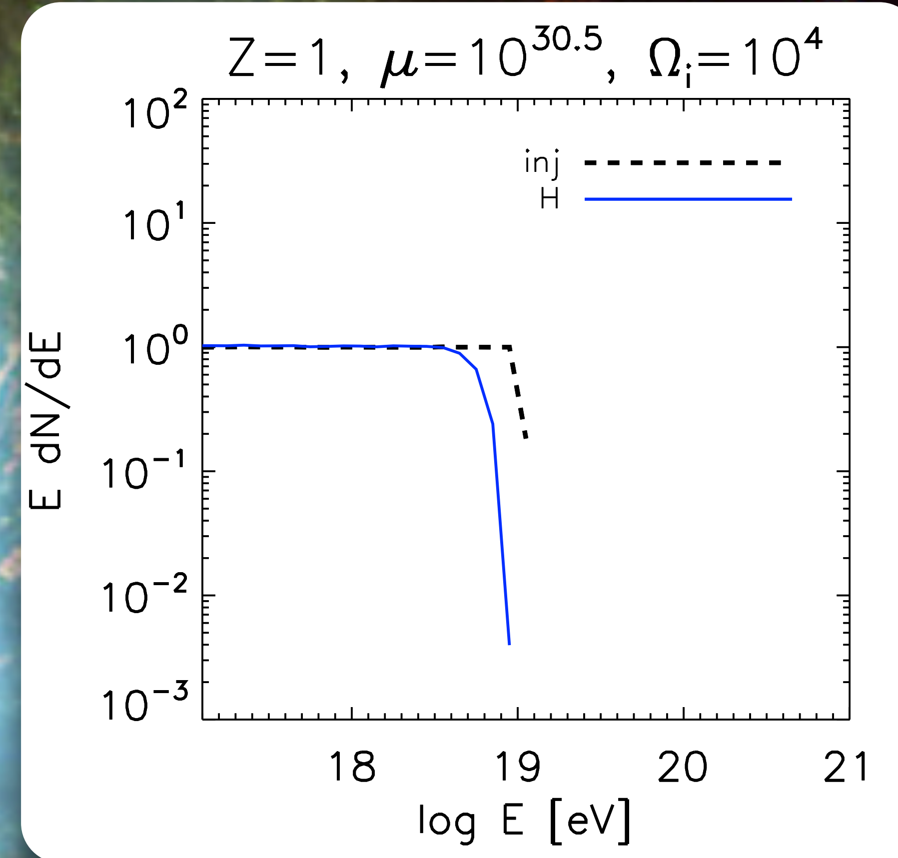

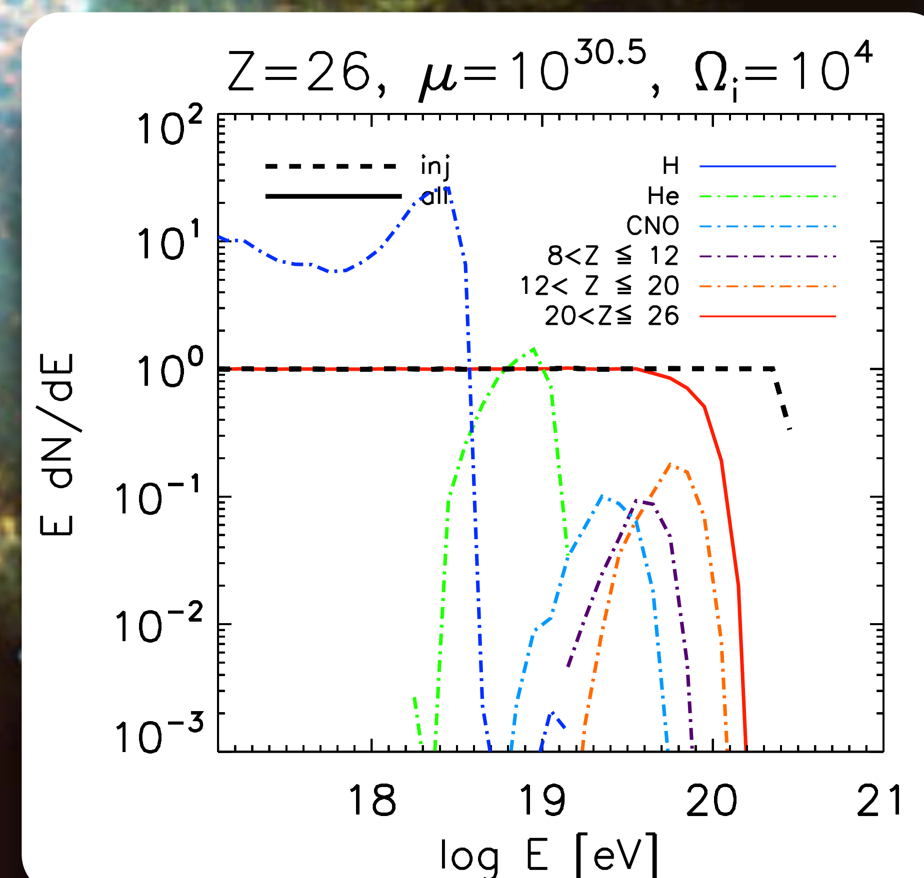

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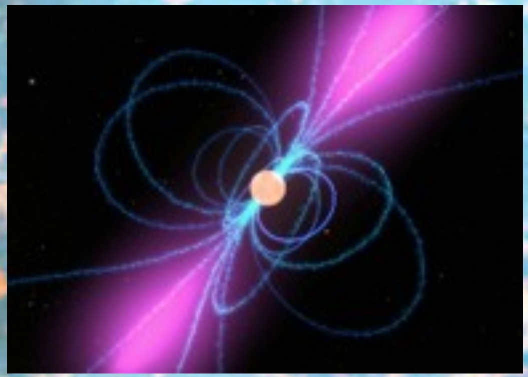

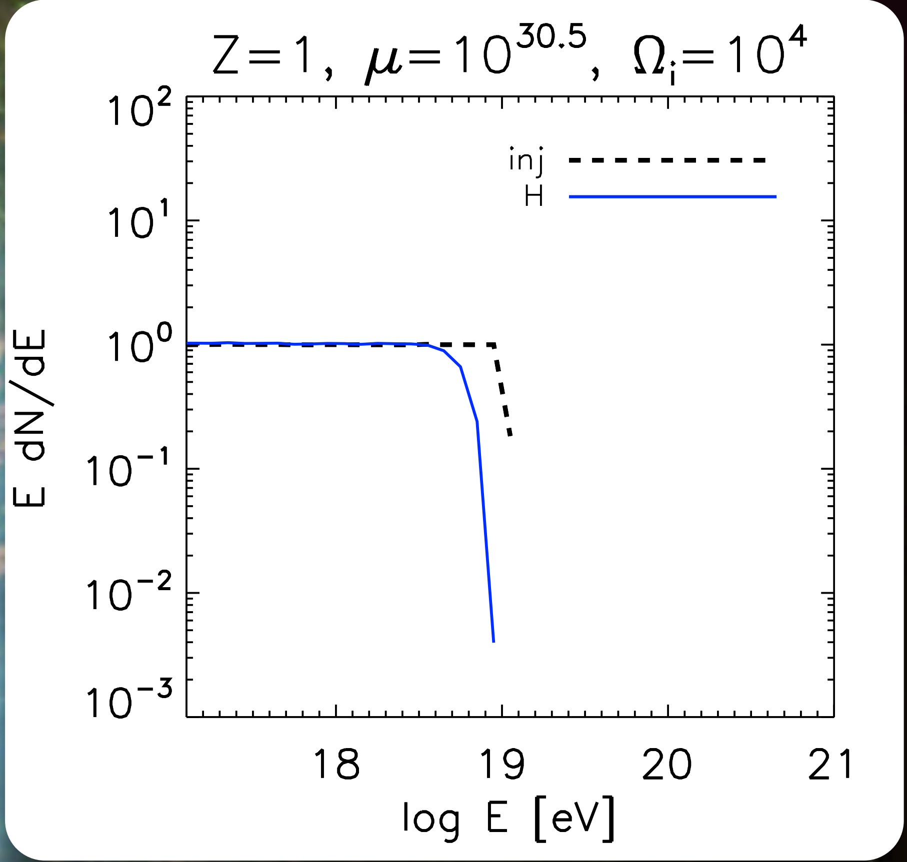

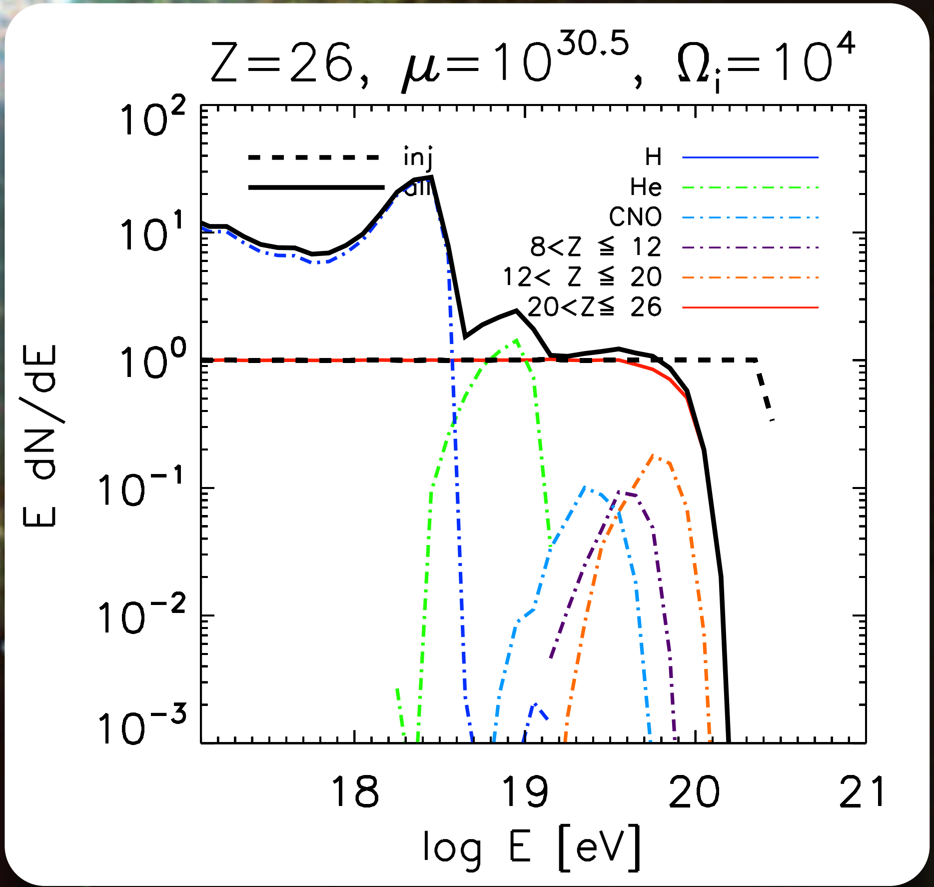

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KF, Kotera & Olinto, ApJ, 750:118, 2012

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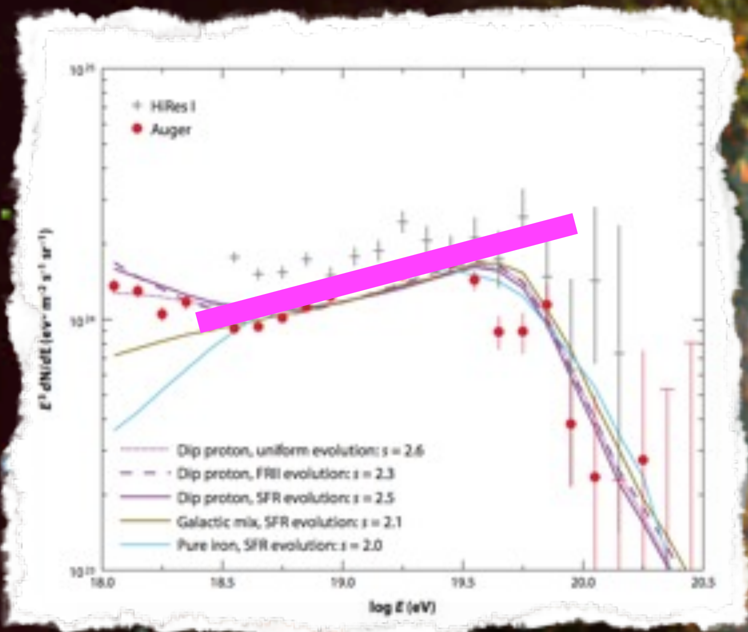

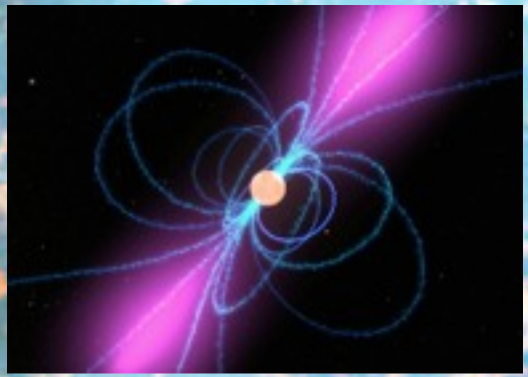

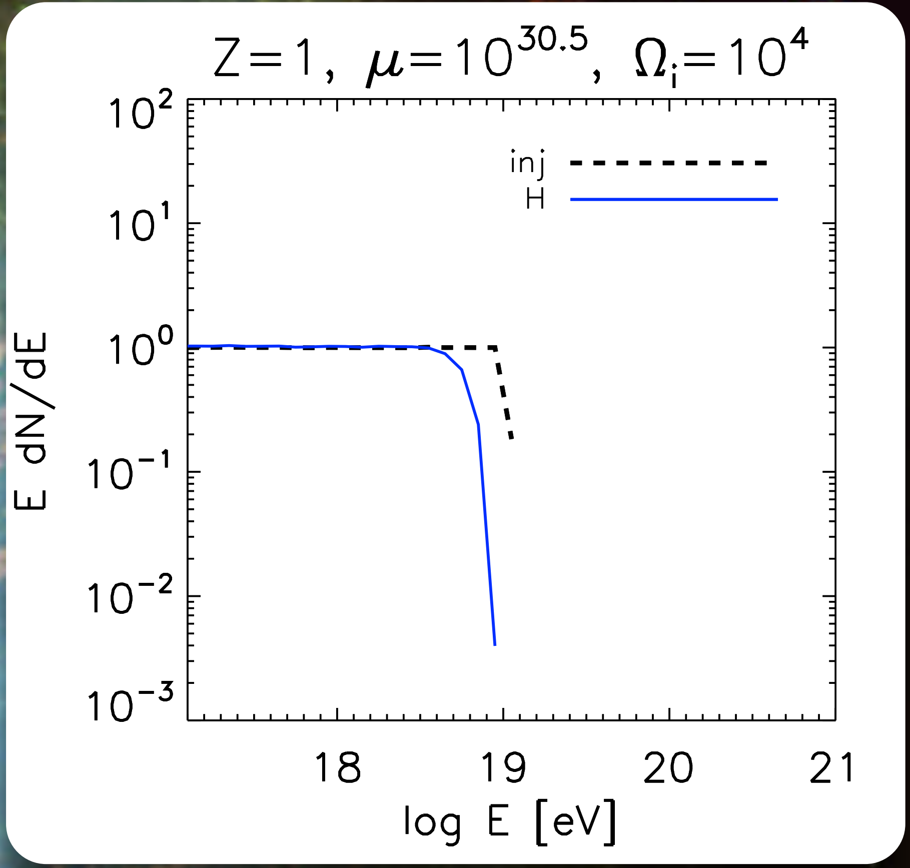

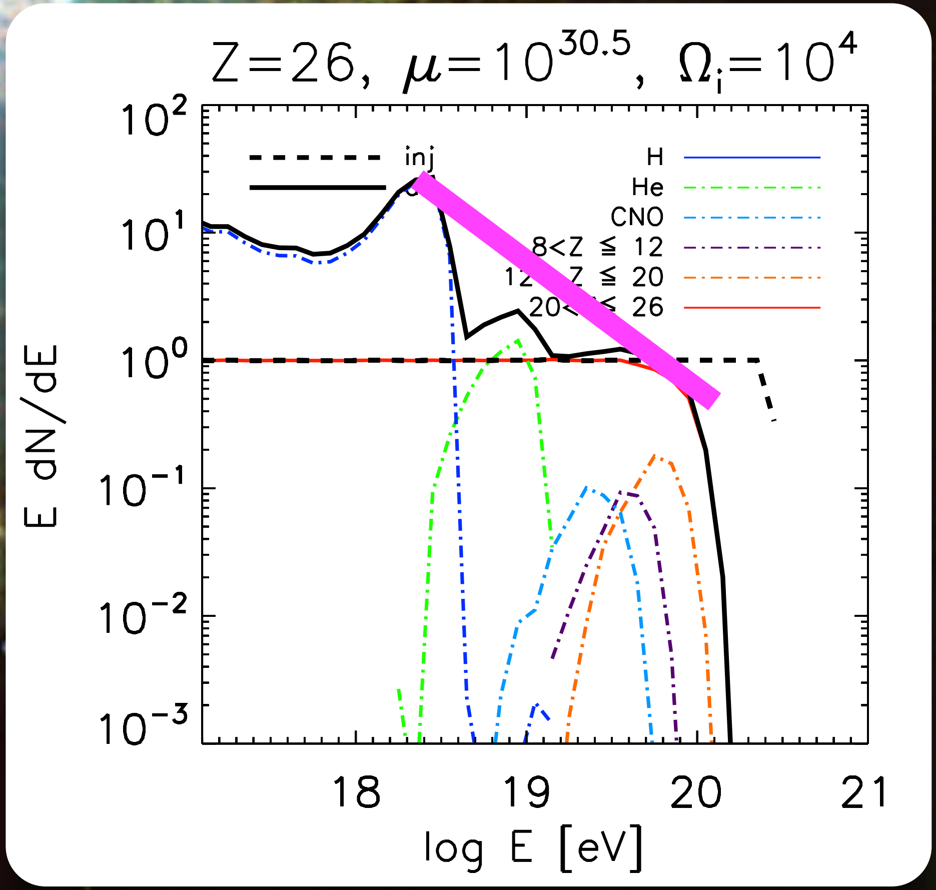

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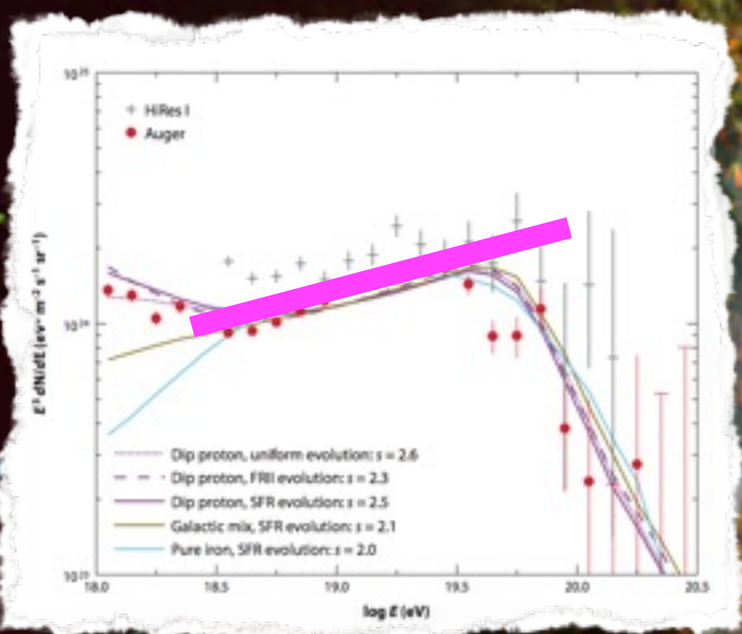

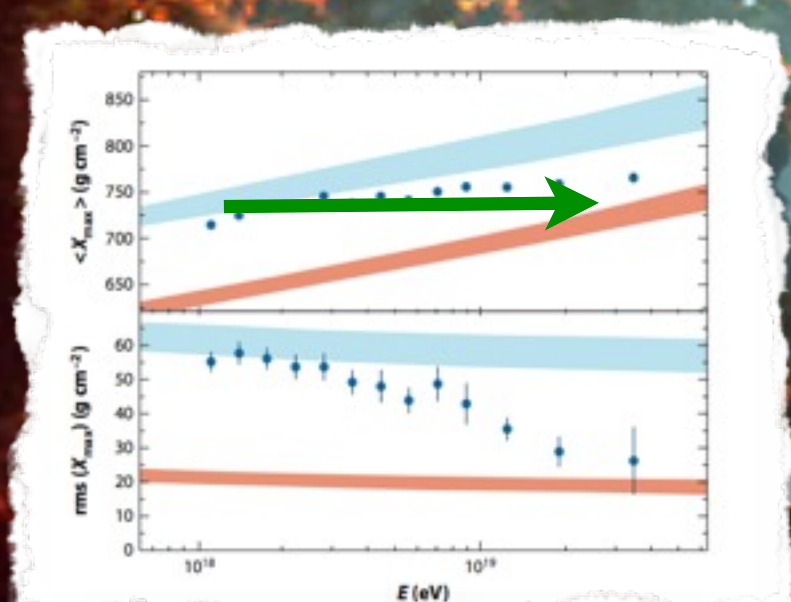

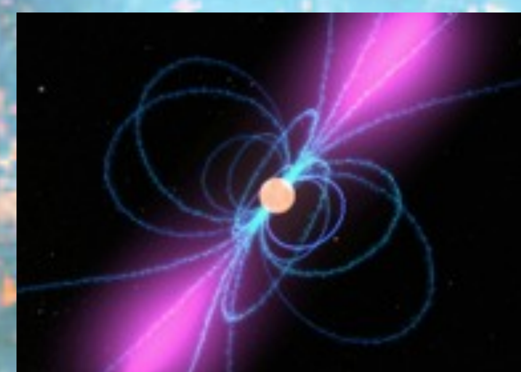

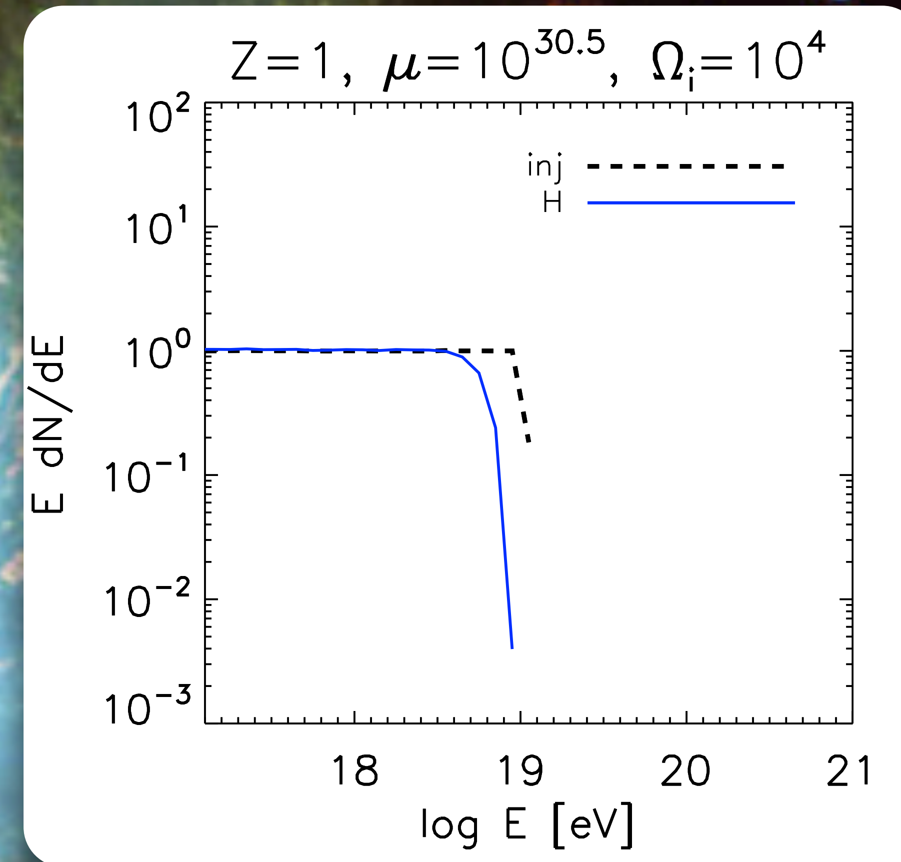

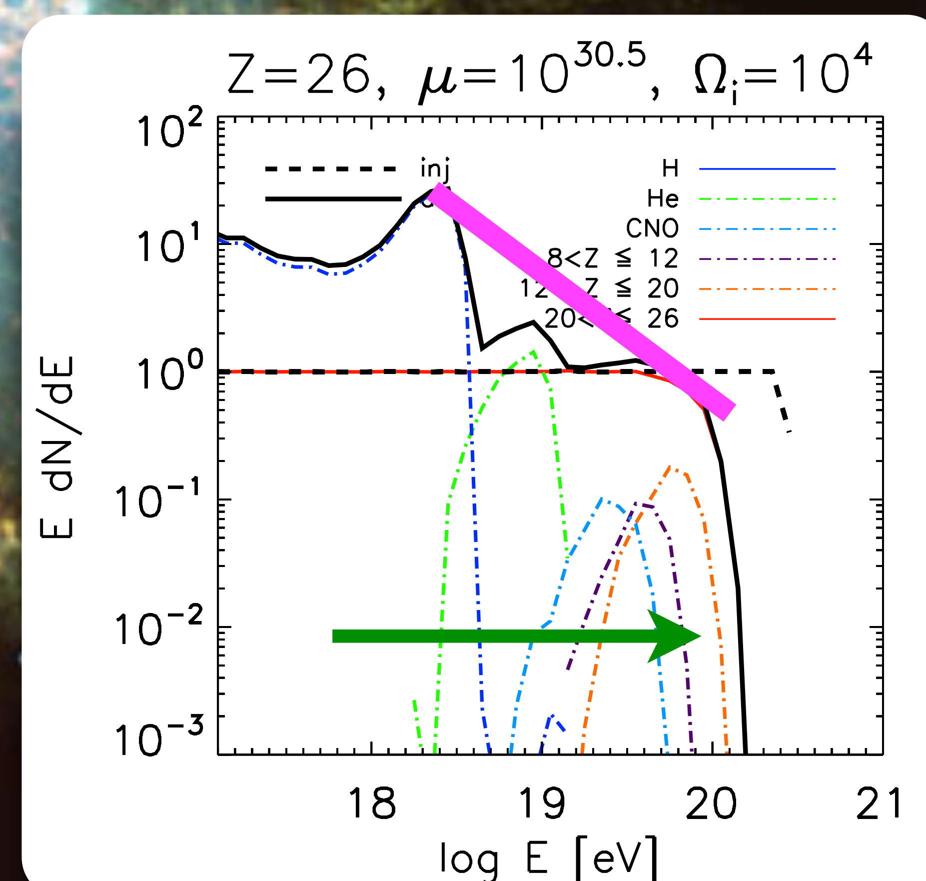

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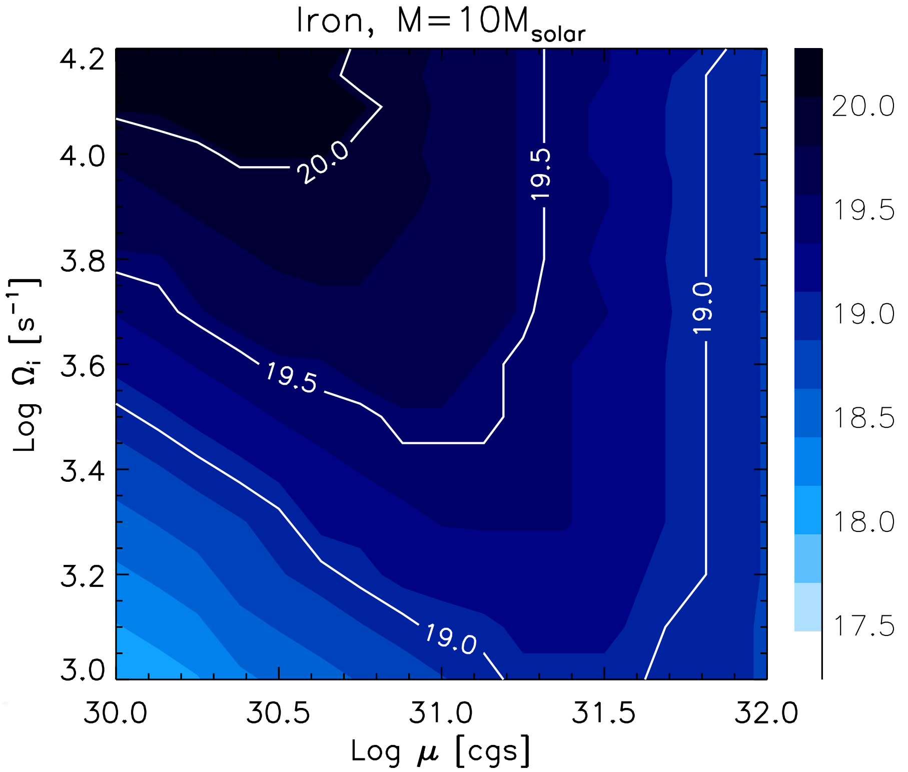
Integrated Extragalactic Pulsars



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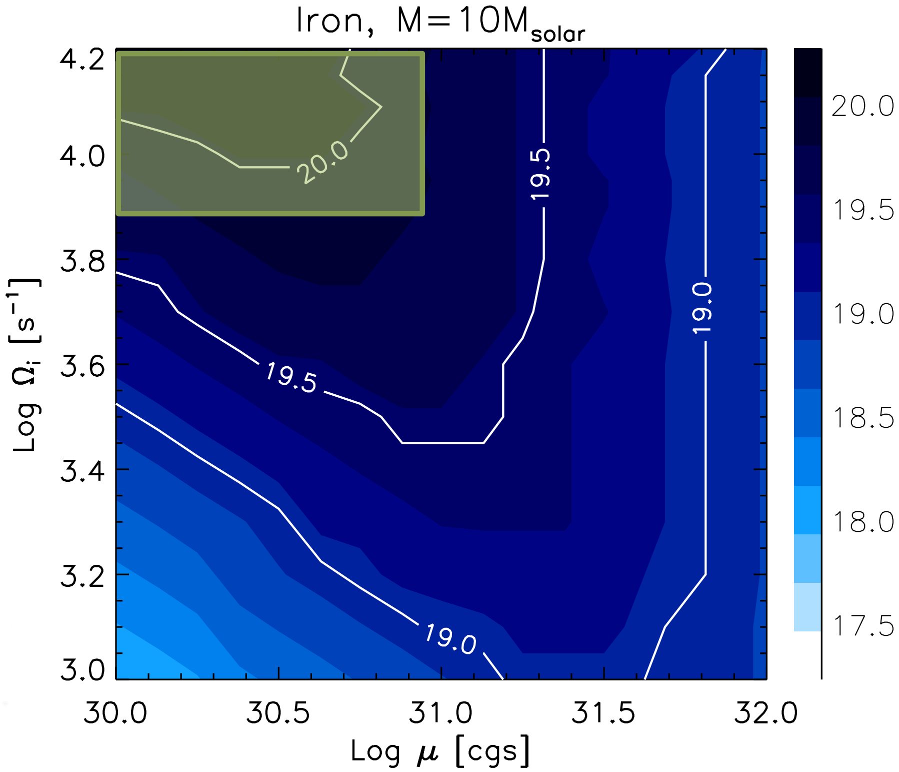
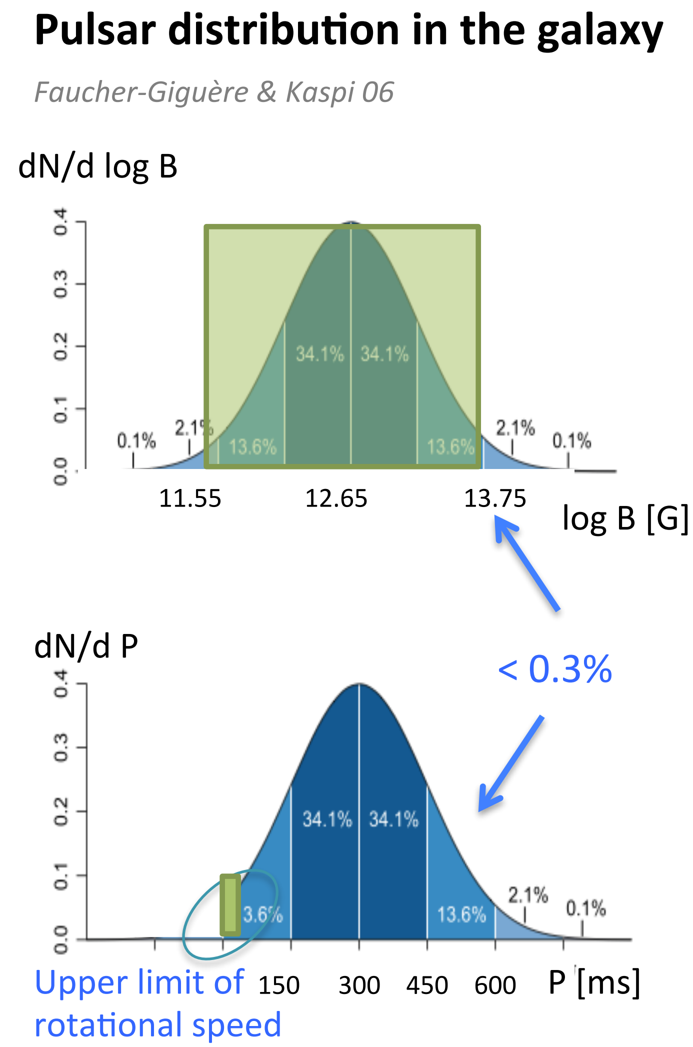


$$\frac{dN}{dE}(Z) = \int \frac{dN_{esc}}{dE}(\mu,\Omega,Z)\, f(\mu)\, f(\Omega)\, d\mu\, d\Omega$$

$$\Re(0) \approx 3.3 \times 10^{-4}\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}$$

50%P + 30%CNO+20%Fe



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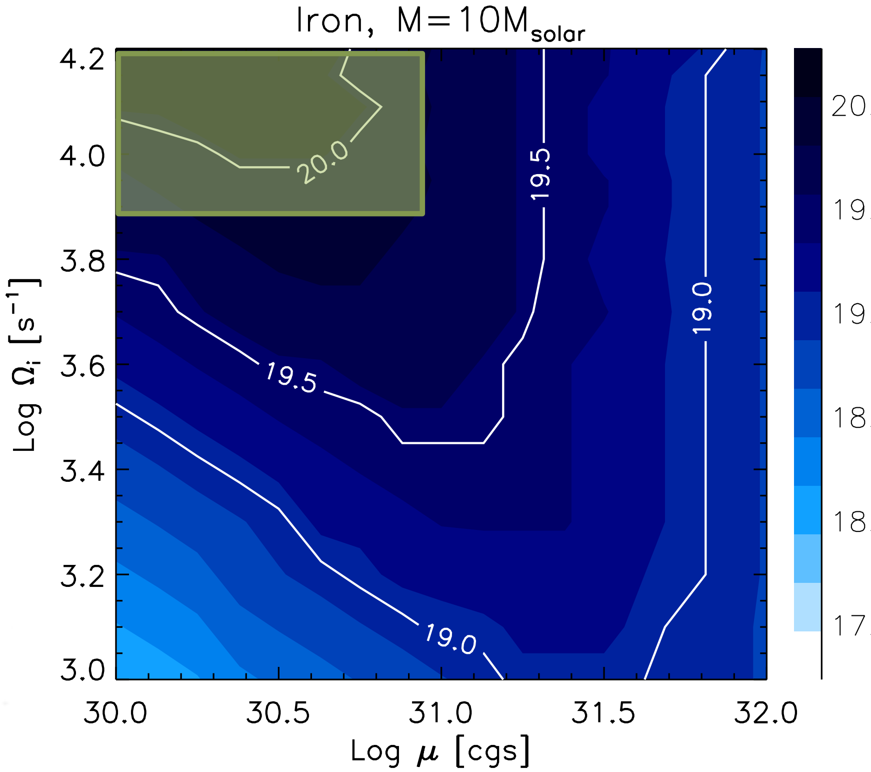
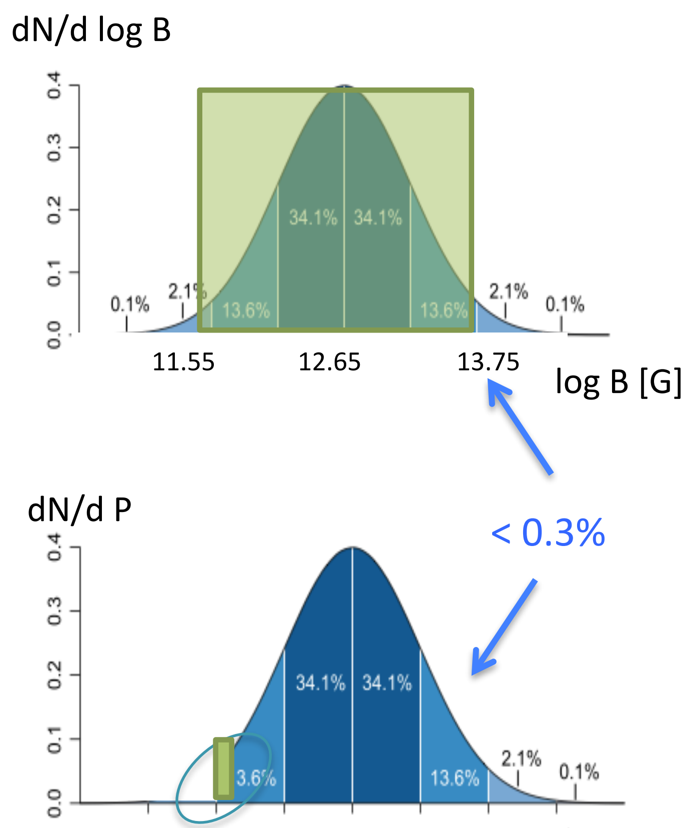


Pulsar distribution in the galaxy

Faucher-Giguère & Kaspi 06



Upper limit of rotational speed

$$\frac{dN}{dE}(Z) = \int \frac{dN_{esc}}{dE}(\mu, \Omega, Z)\, f(\mu)\, f(\Omega)\, d\mu\, d\Omega$$

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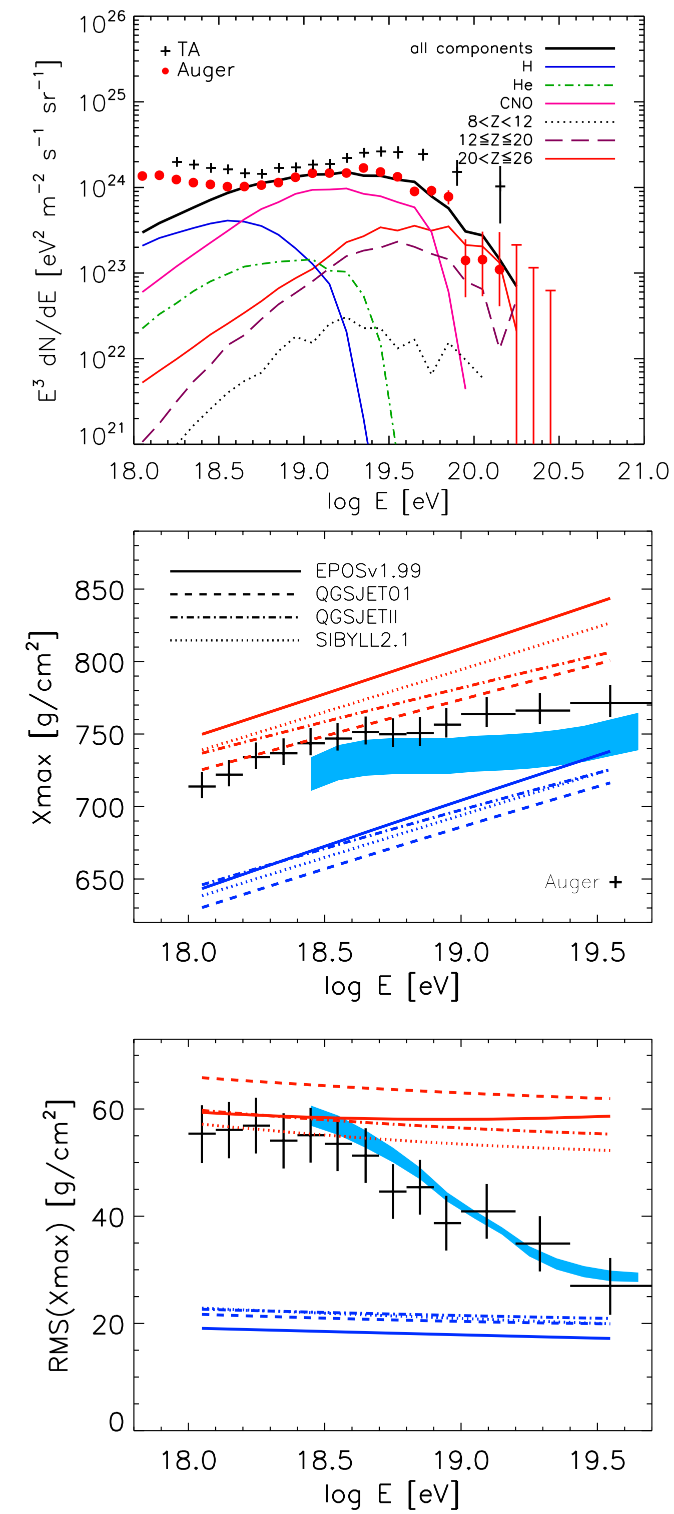


Conclusion I

Newborn pulsars can be successful UHE sources!

Anisotropy Check

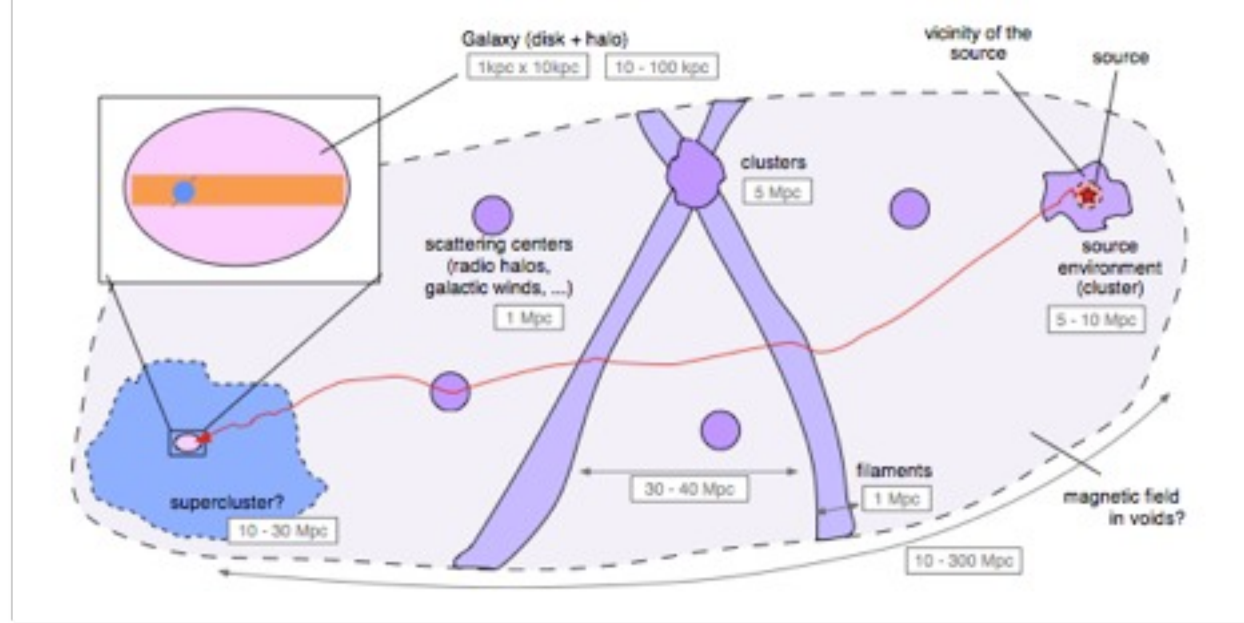
$$r_L = 10\,Mpc \frac{1}{Z} \frac{E}{10^{20}\,eV} \left(\frac{B}{10^{-8}\,G}\right)^{-1}$$

$$\lambda \approx 10 - 100\,kpc << r_L \Rightarrow small \quad deflections$$

$$\delta\theta^2 \approx \frac{r_{structure}}{r_L^2 / l_c}$$

$$\delta\theta_i \simeq 1.7^\circ \left(\frac{\bar{r}_i}{2\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{B_i}{10^{-8}\,\mathrm{G}}\right) \times \left(\frac{\lambda_i}{0.1\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} .$$

Kotera et al 2009



Kotera & Olinto 2011

Time delay after the deflections

$$\delta t_i \simeq 0.93 \times 10^3\,\mathrm{yr} \left(\frac{\bar{r}_i}{2\,\mathrm{Mpc}}\right)^2 \left(\frac{B_i}{10^{-8}\,\mathrm{G}}\right)^2 \times \left(\frac{\lambda_i}{0.1\,\mathrm{Mpc}}\right) \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-2} .$$

Kotera et al 2009

>>

Time the source was lighted

$$t_{spin} = 3yr \left(\frac{10^{20}\,eV}{E}\right) \frac{Z_{26}\eta_1}{\mu_{30.5}}$$

=>

Anisotropy Check

$$r_L = 10\,Mpc \frac{1}{Z} \frac{E}{10^{20}\,eV} \left(\frac{B}{10^{-8}\,G} \right)^{-1}$$

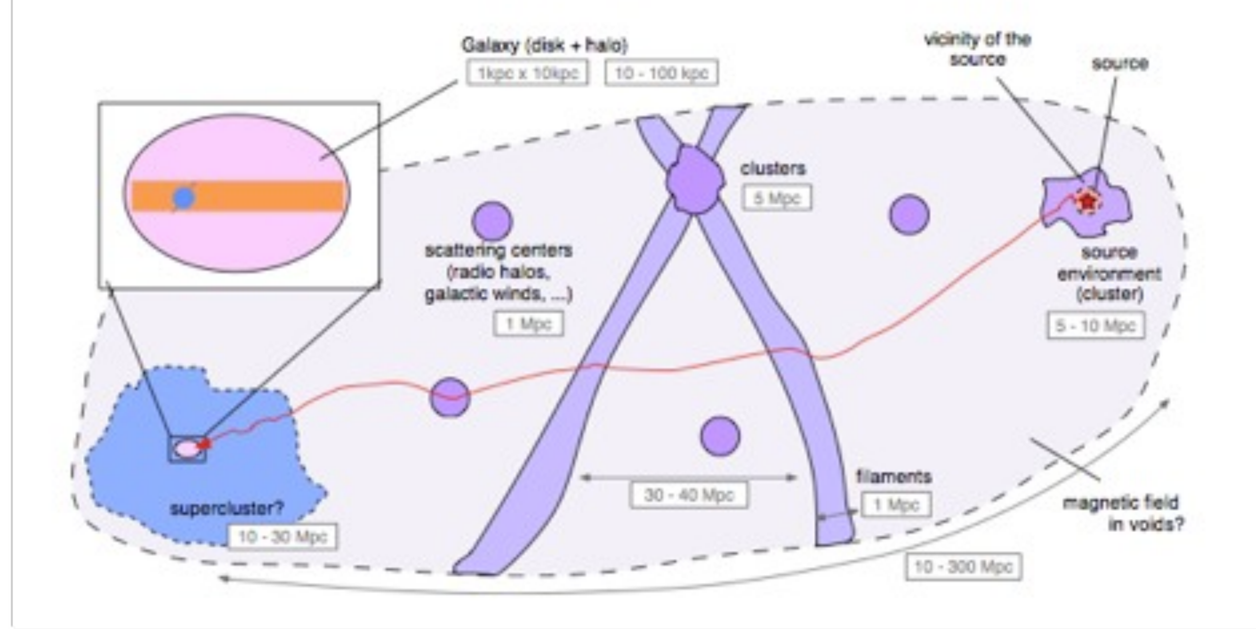
$$\lambda \approx 10 - 100\,kpc << r_L \Rightarrow small \quad deflections$$

$$\delta\theta^2 \approx \frac{r_{structure}}{r_L^2 / l_c}$$

$$\delta\theta_i \simeq 1.7^\circ \left(\frac{\bar{r}_i}{2\,\mathrm{Mpc}} \right)^{1/2} \left(\frac{B_i}{10^{-8}\,\mathrm{G}} \right) \times \left(\frac{\lambda_i}{0.1\,\mathrm{Mpc}} \right)^{1/2} \left(\frac{E}{10^{20}\,\mathrm{eV}} \right)^{-1} .$$

Kotera et al 2009

Kotera & Olinto 2011



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Kotera et al 2009

\>>

Time the source was lighted

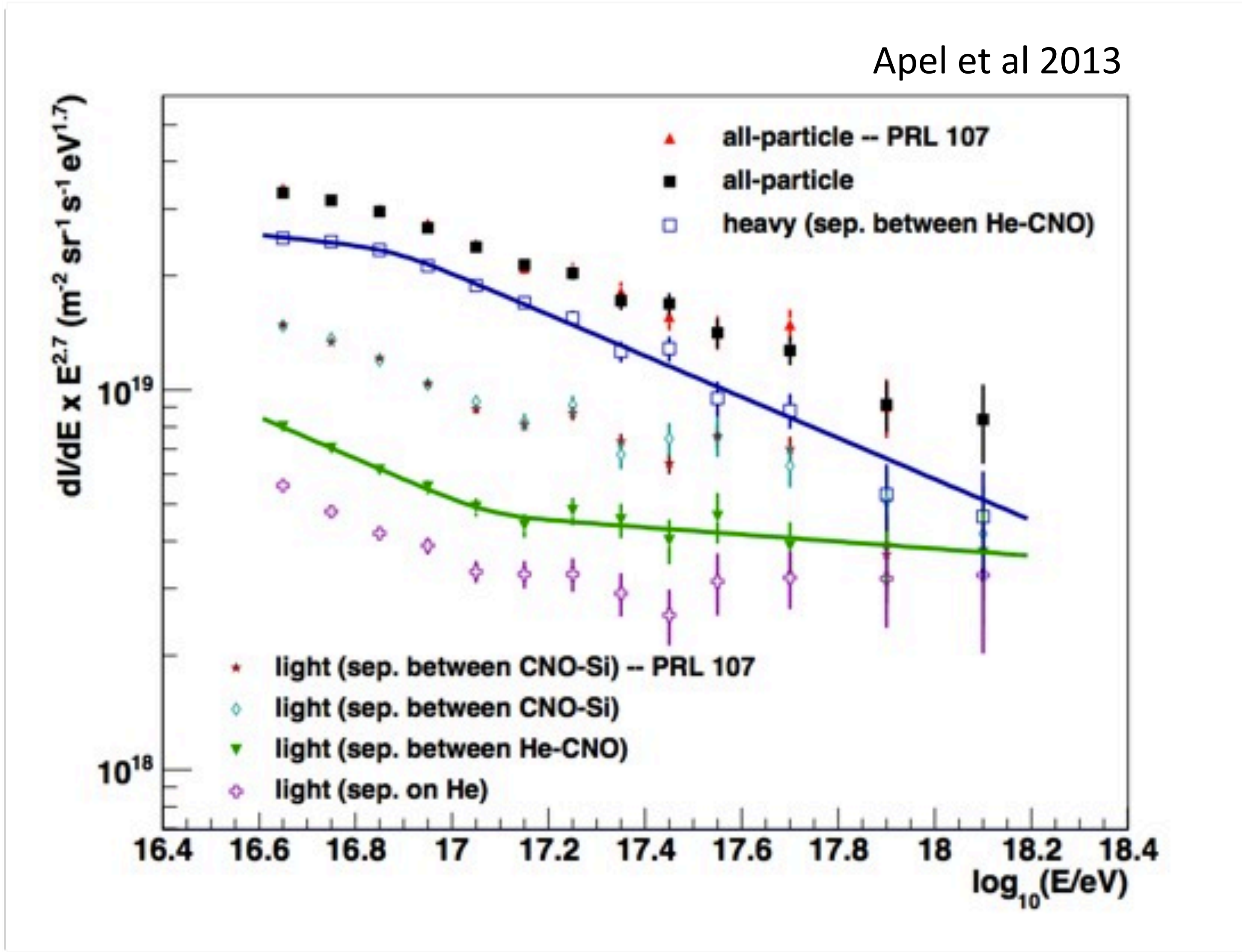
$$t_{spin} = 3yr \left(\frac{10^{20}\,eV}{E} \right) \frac{Z_{26}\eta_1}{\mu_{30.5}}$$

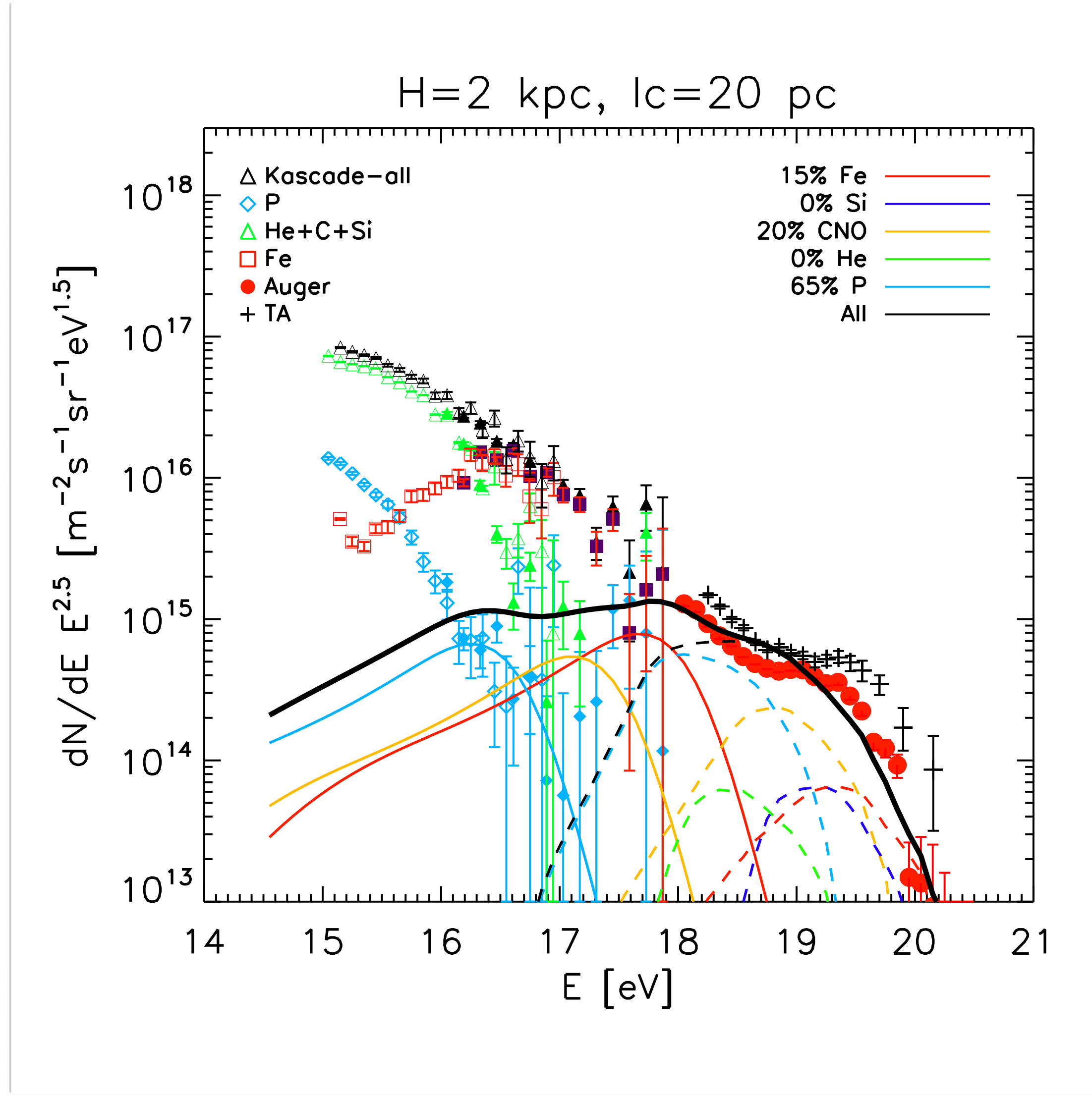
=>

Transients, no source- arrival direction correlation

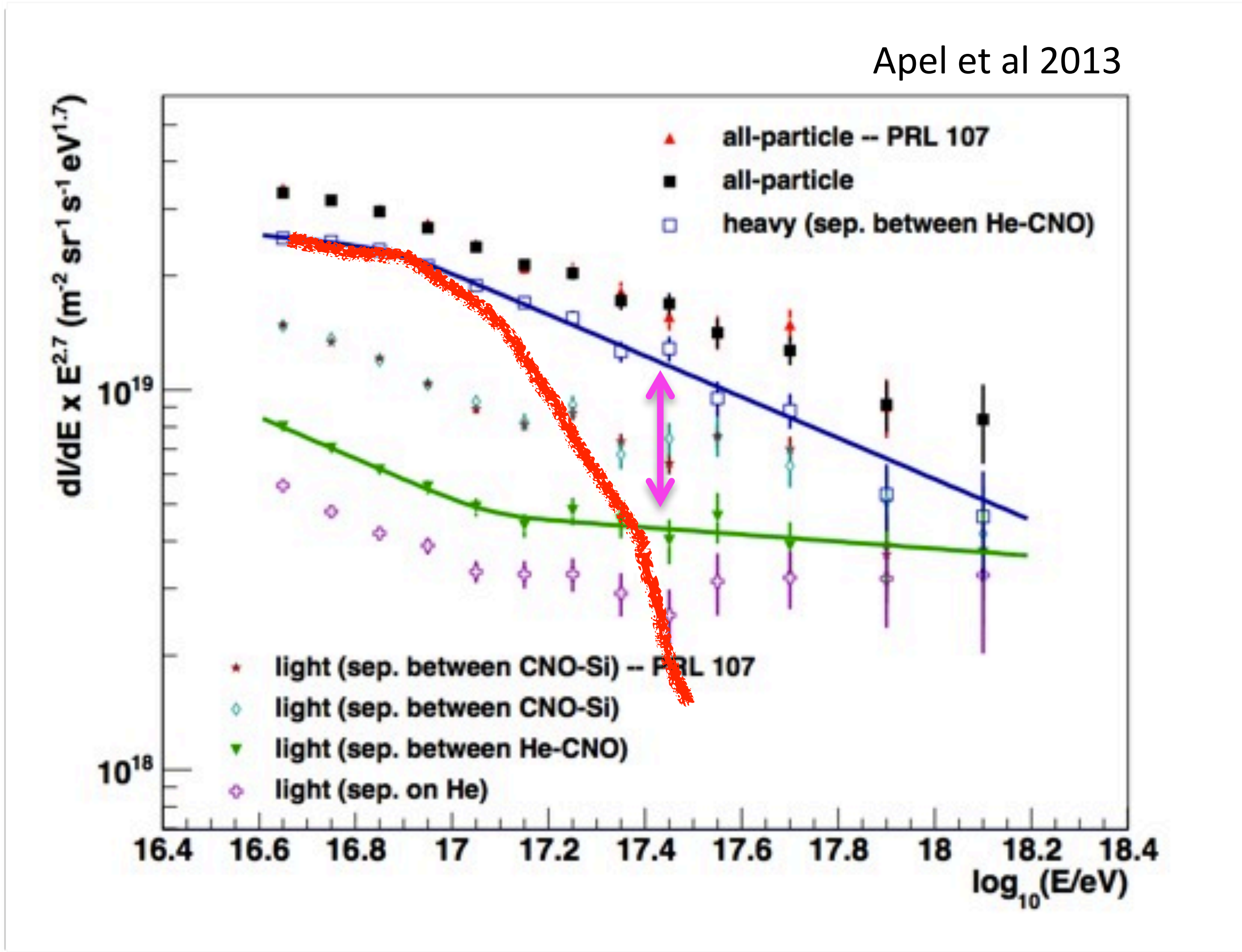
What about their Galactic Counterparts?

Contribution from Galactic pulsars

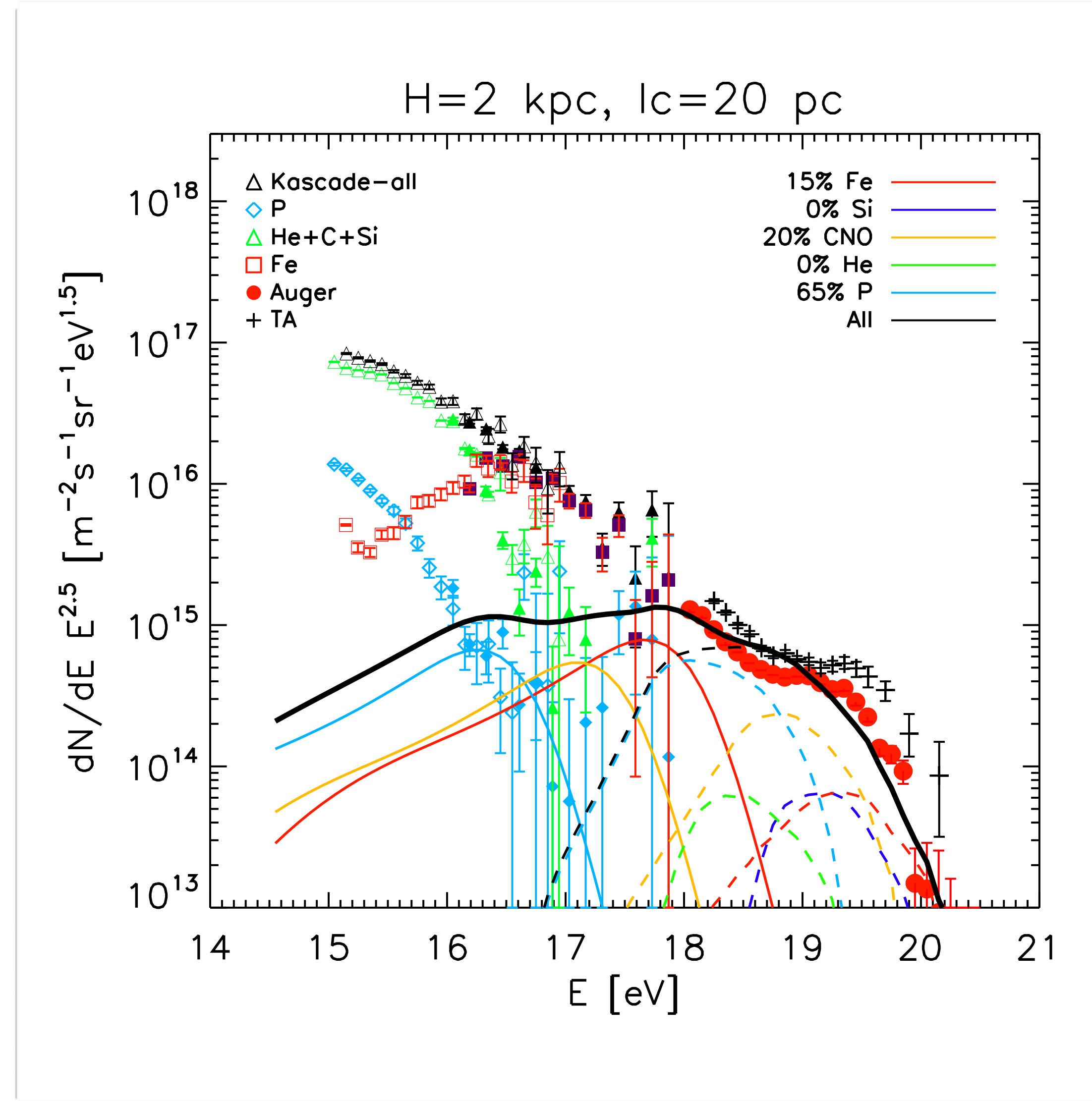




Contribution from Galactic pulsars

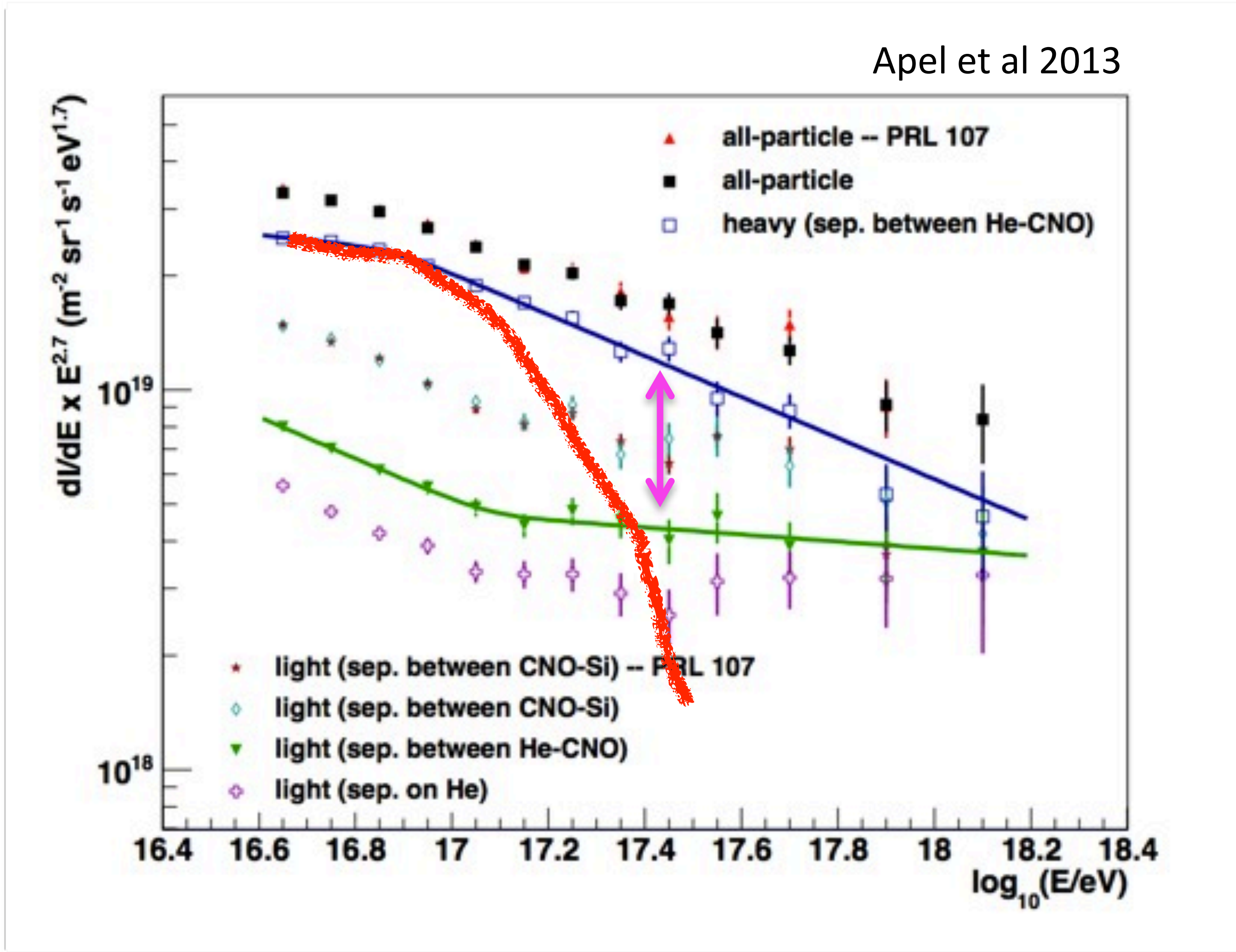


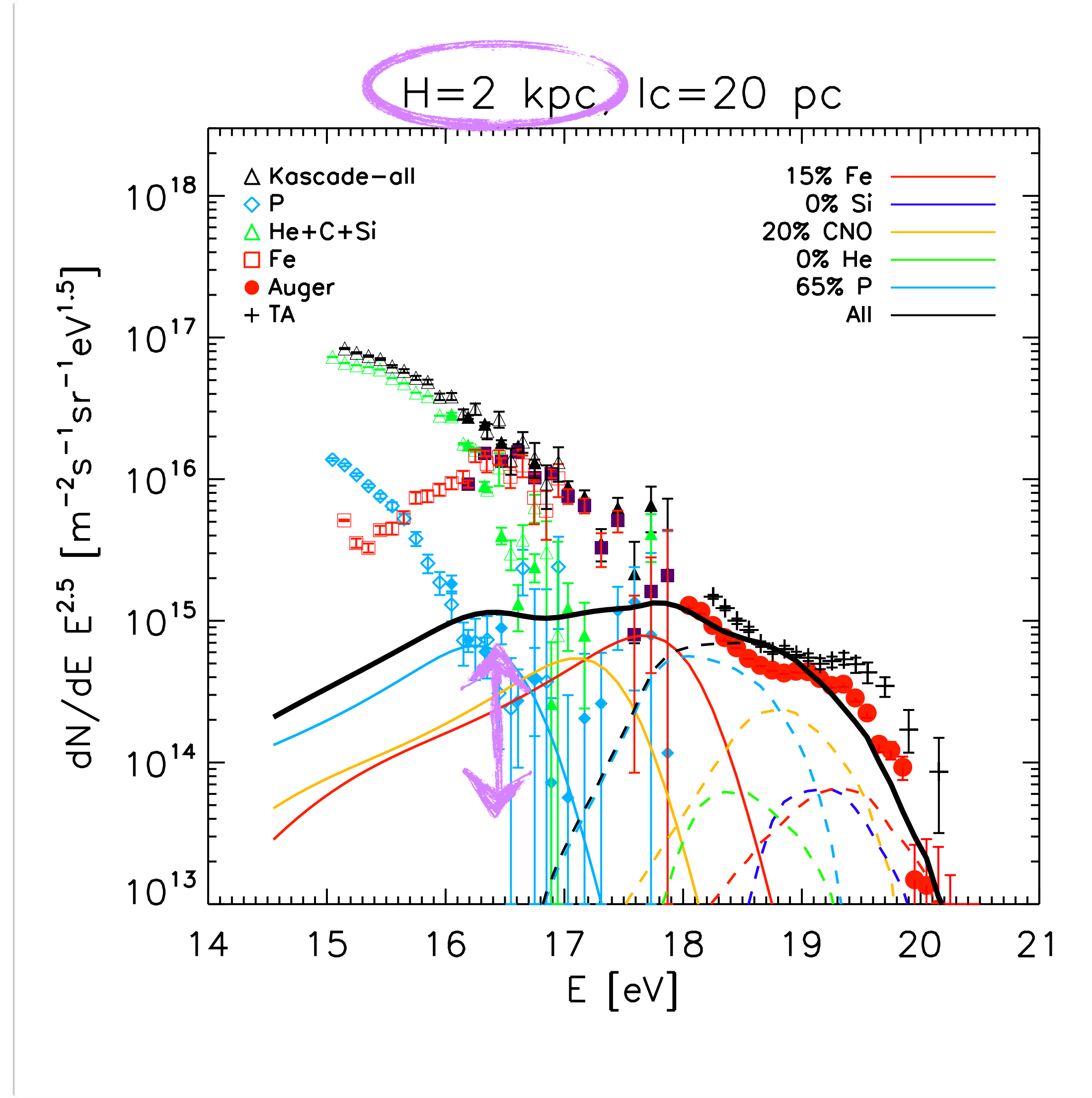
No Cutoff, Mind the Gap!



Galactic pulsars can fill the gap

Contribution from Galactic pulsars





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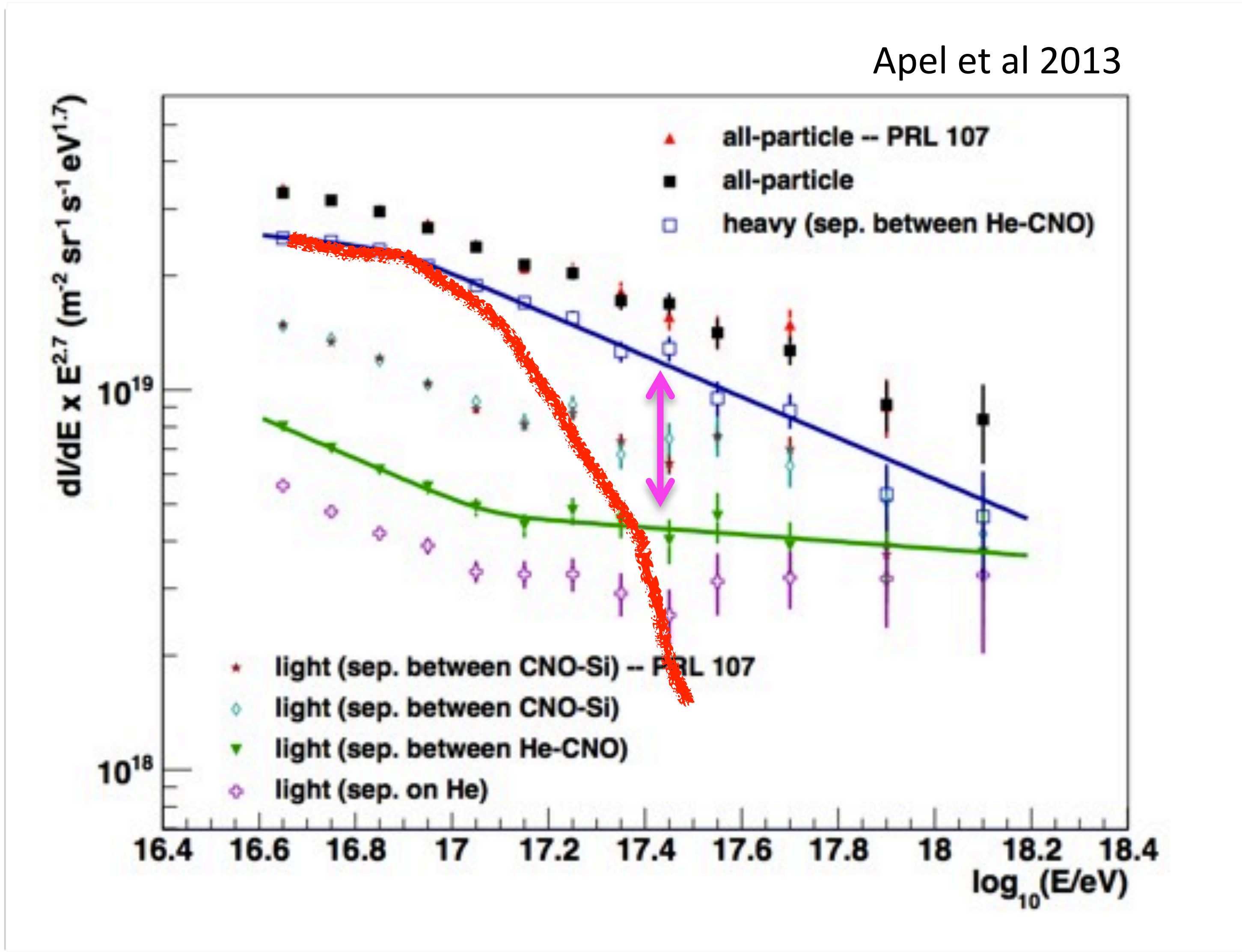

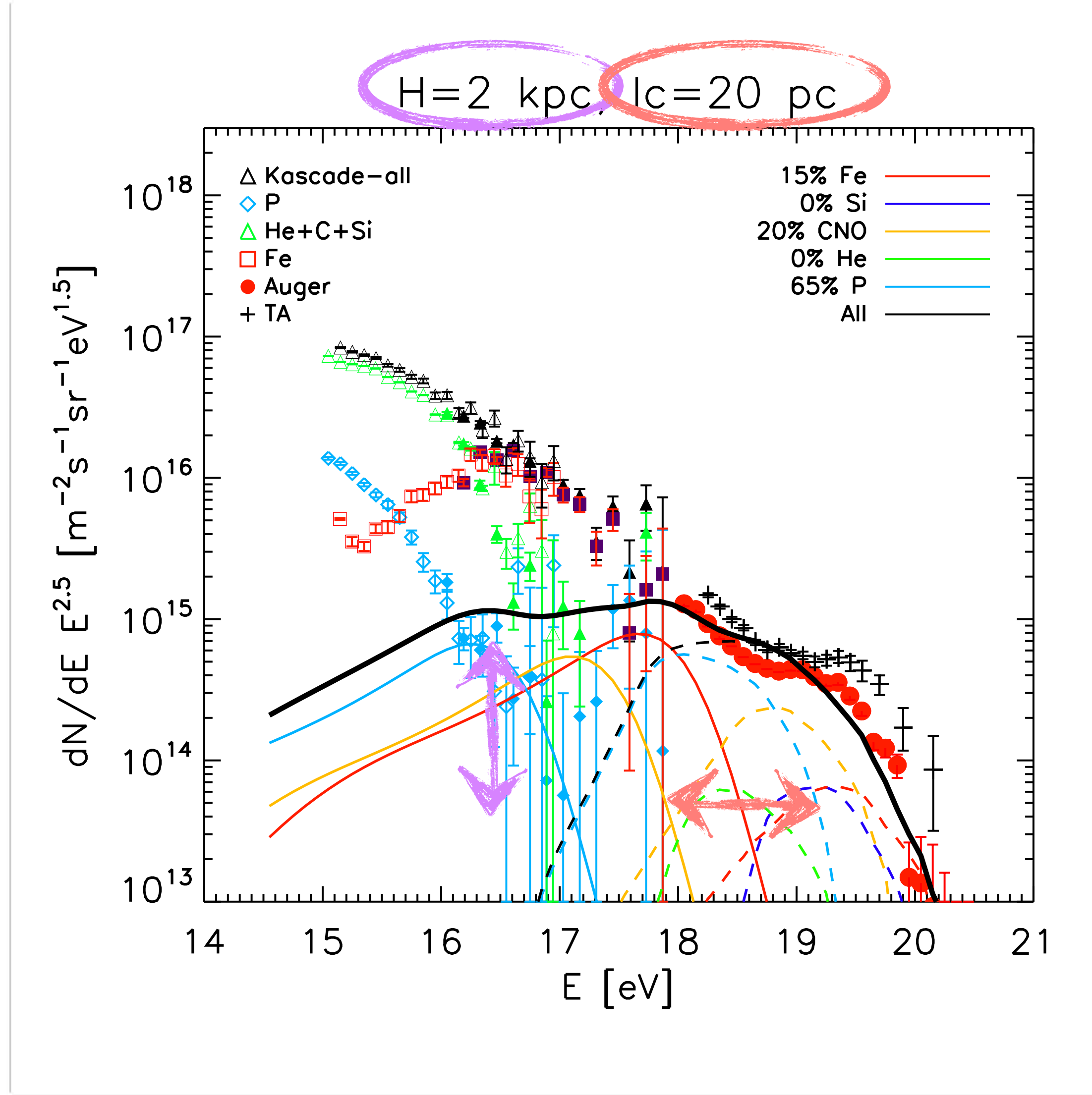

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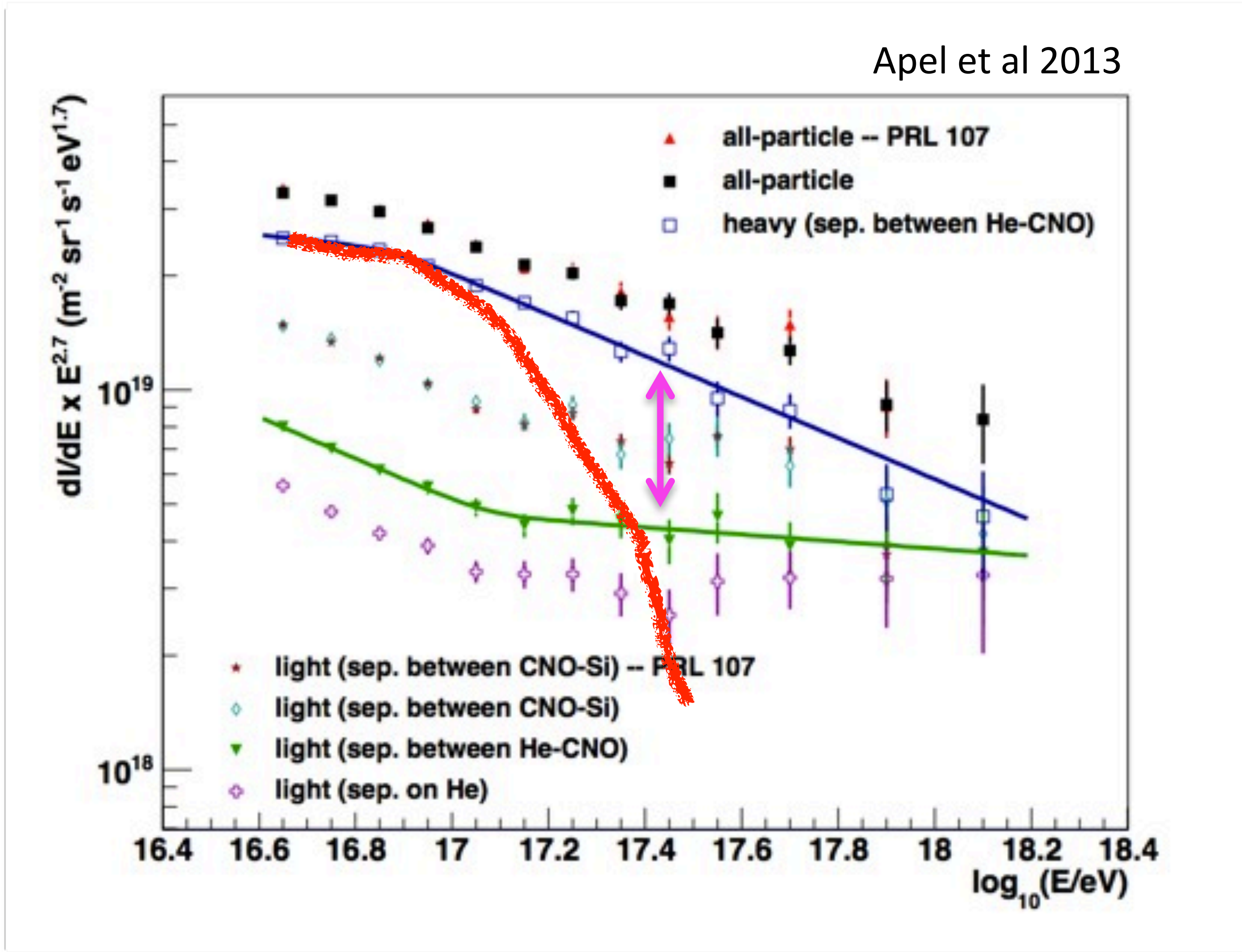
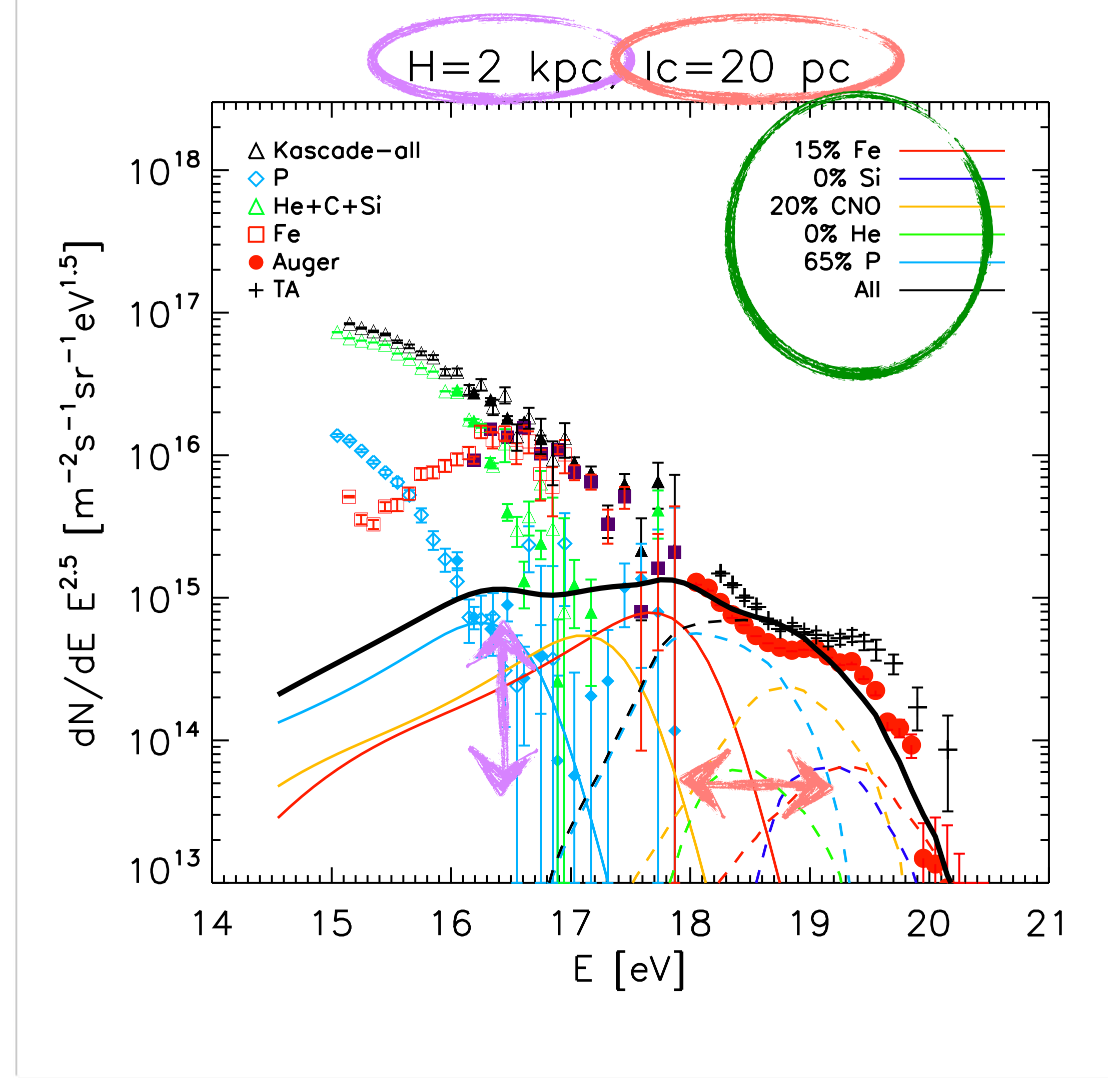
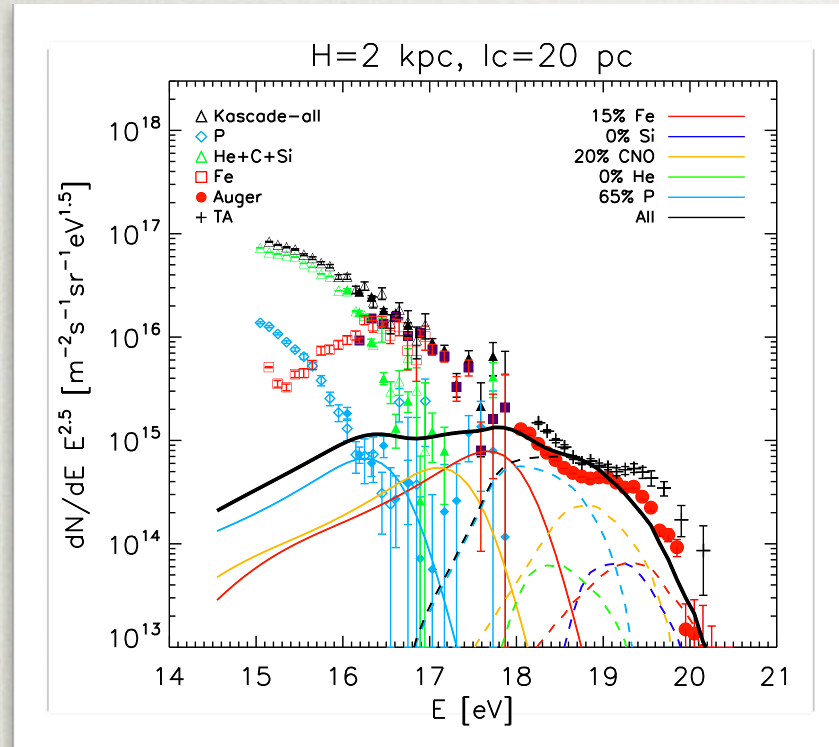


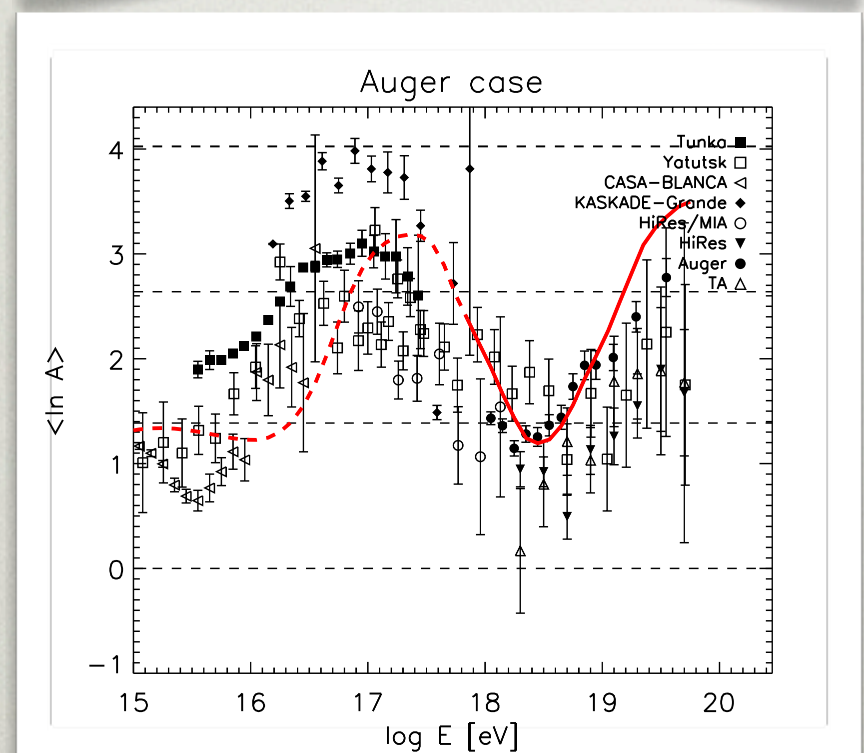


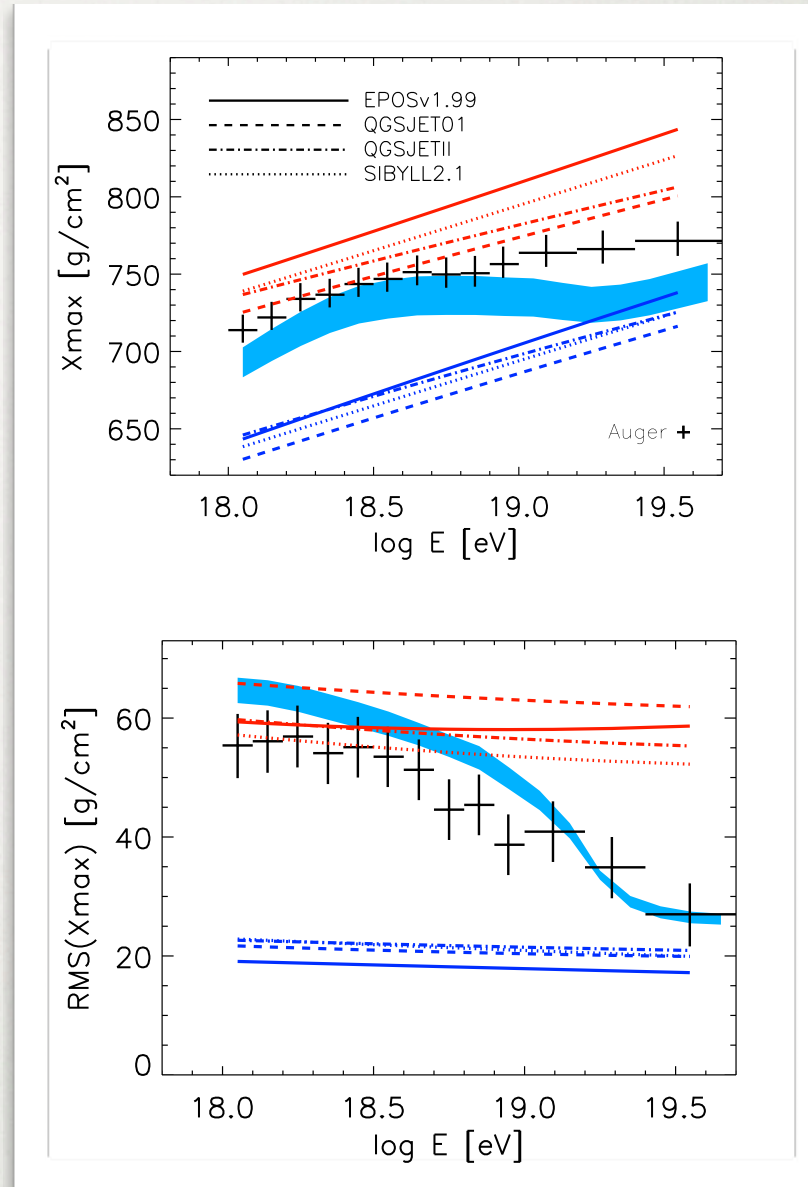
No Cutoff, Mind the Gap!

Galactic pulsars can fill the gap

Composition

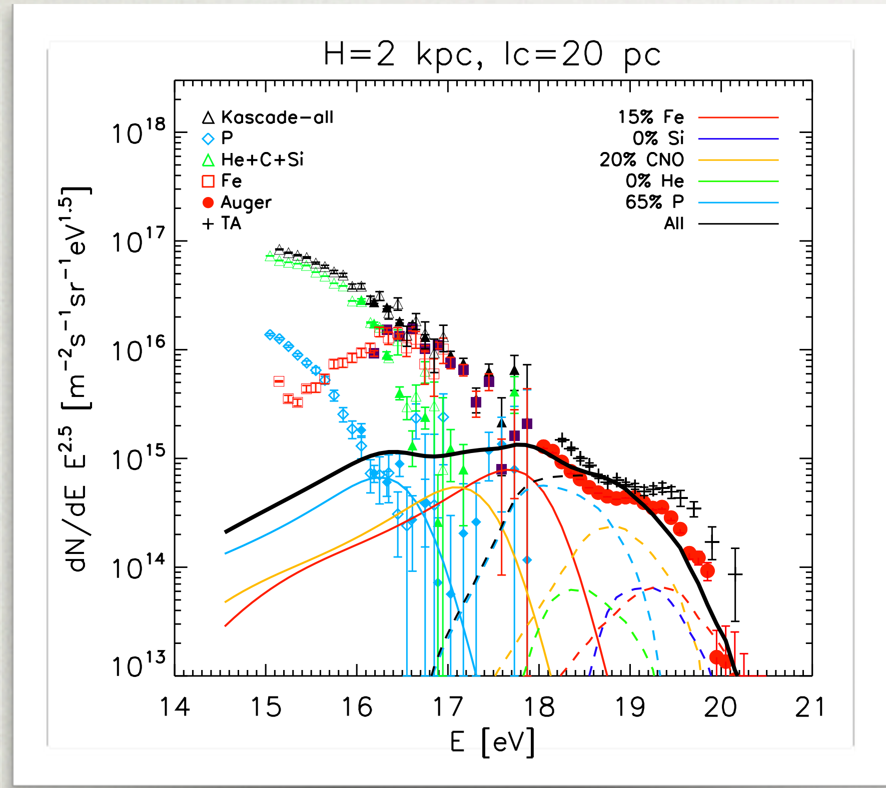






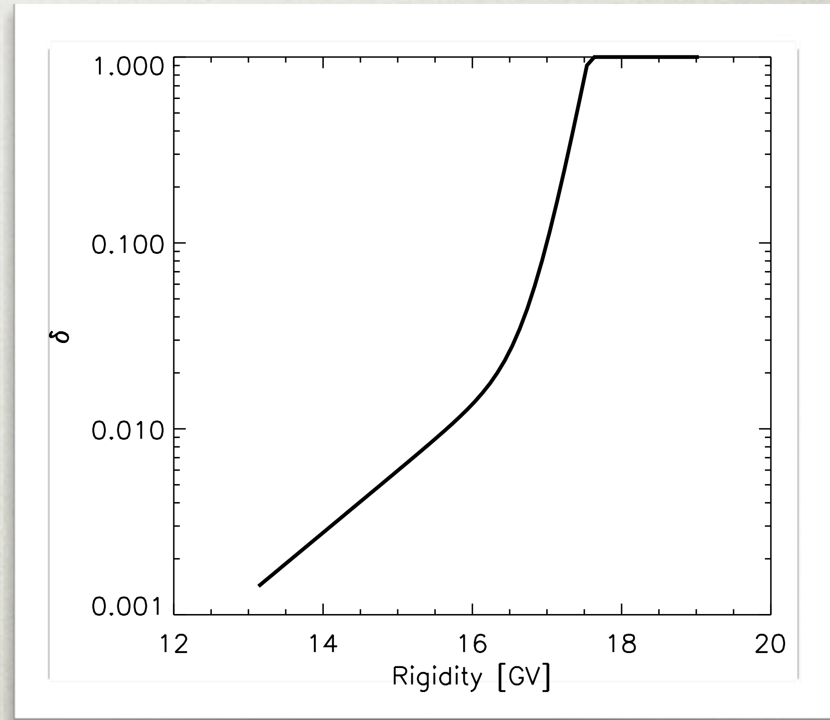
KF, Kotera & Olinto, JCAP, 010: 03, (2013)

Estimation on Anisotropy



Assume sources homogeneously distributed in the disc, small scale anisotropy can be estimated as (Blasi & Amato 2011b)

$$\delta = \frac{3}{2^{3/2}\pi^{1/2}} \frac{D(E)}{Hc}$$



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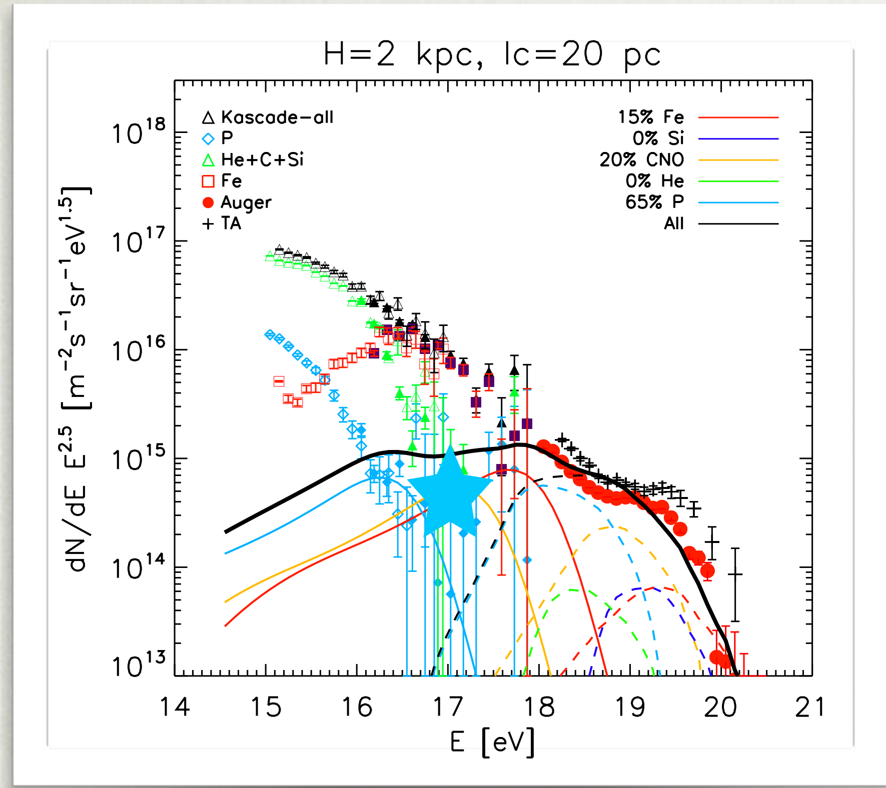

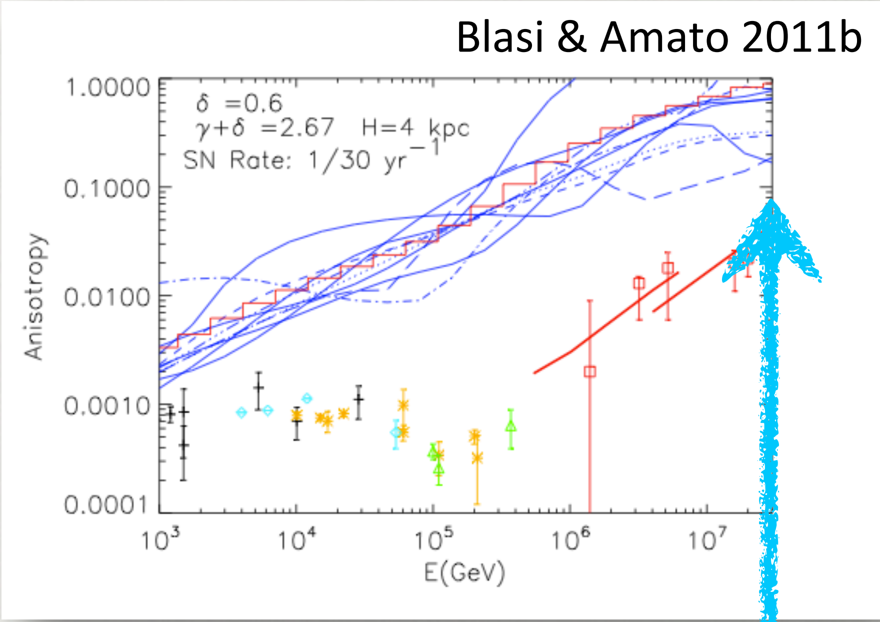

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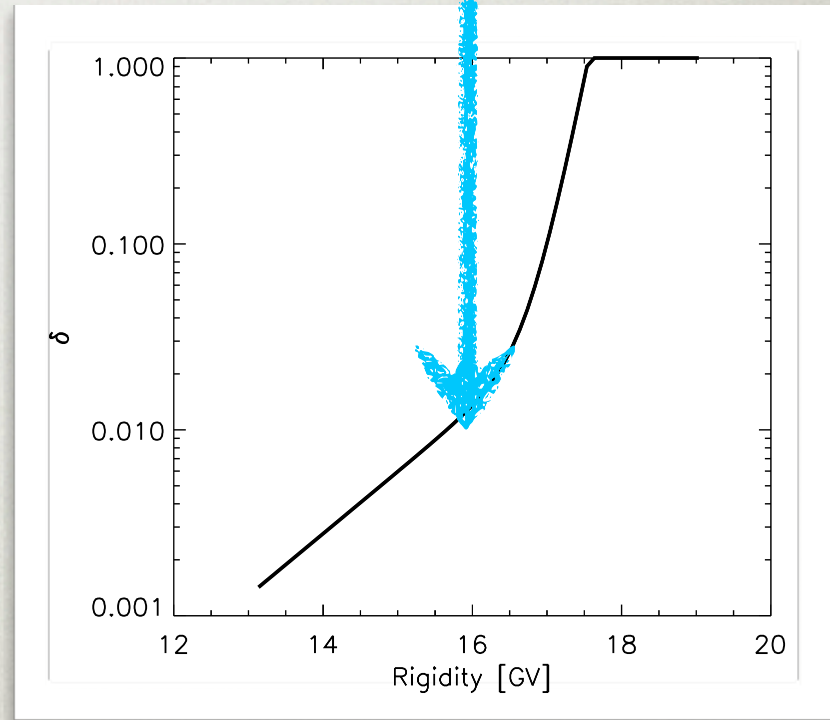
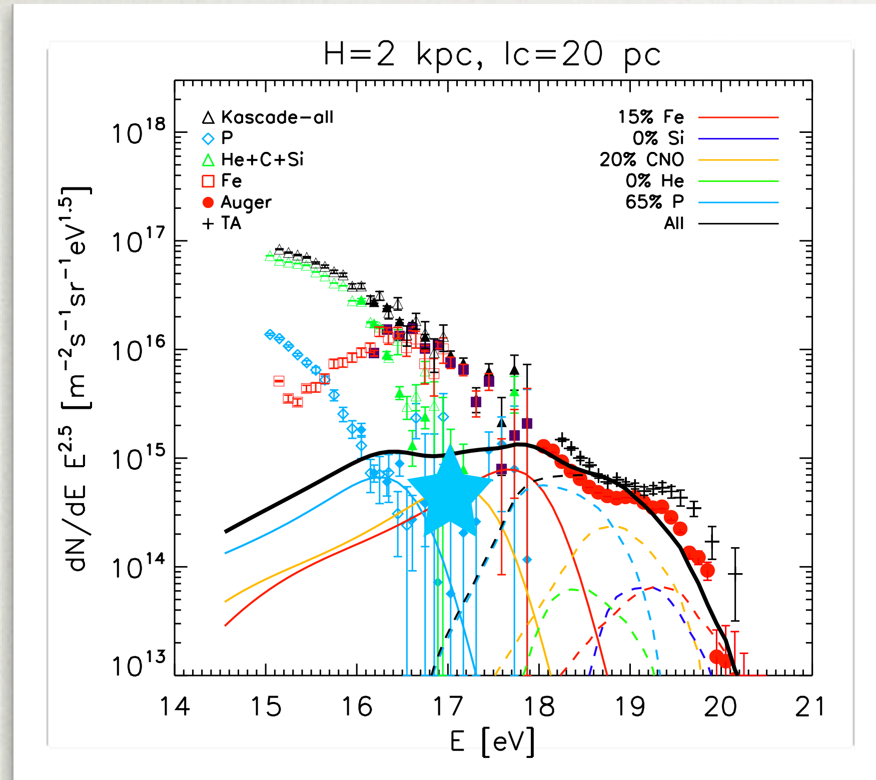
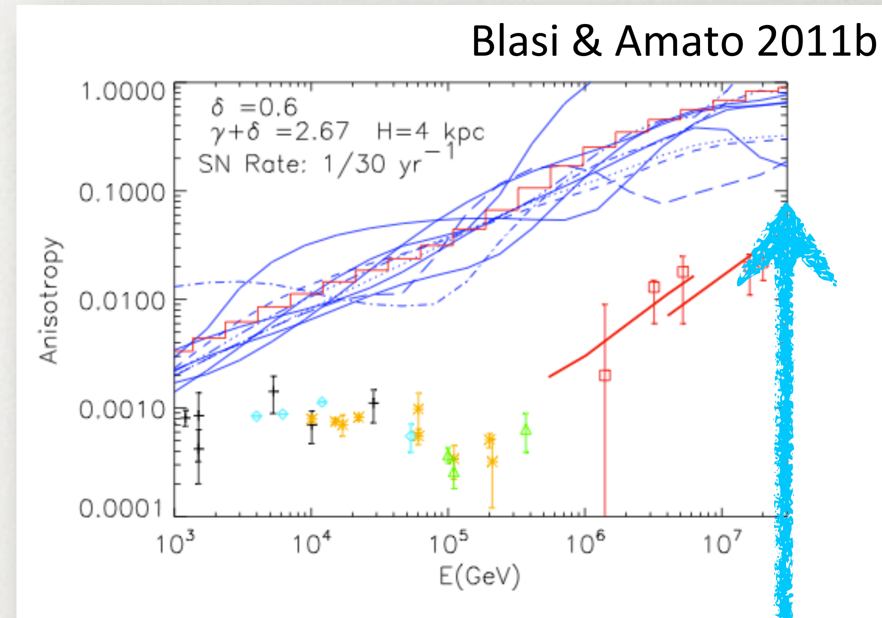


Estimation on Anisotropy





Heavy composition reduces anisotropy levels

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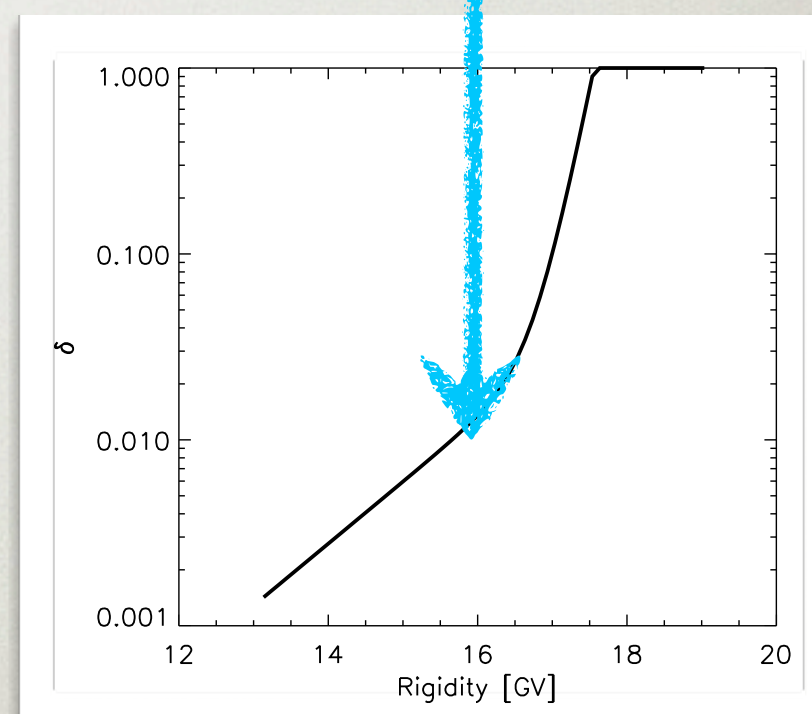
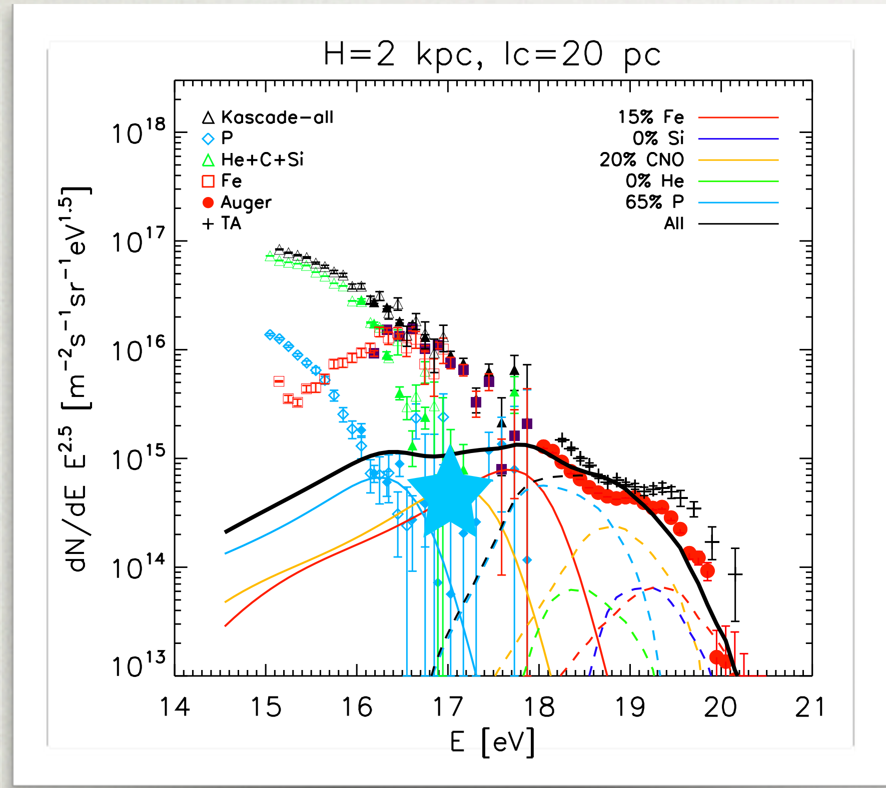
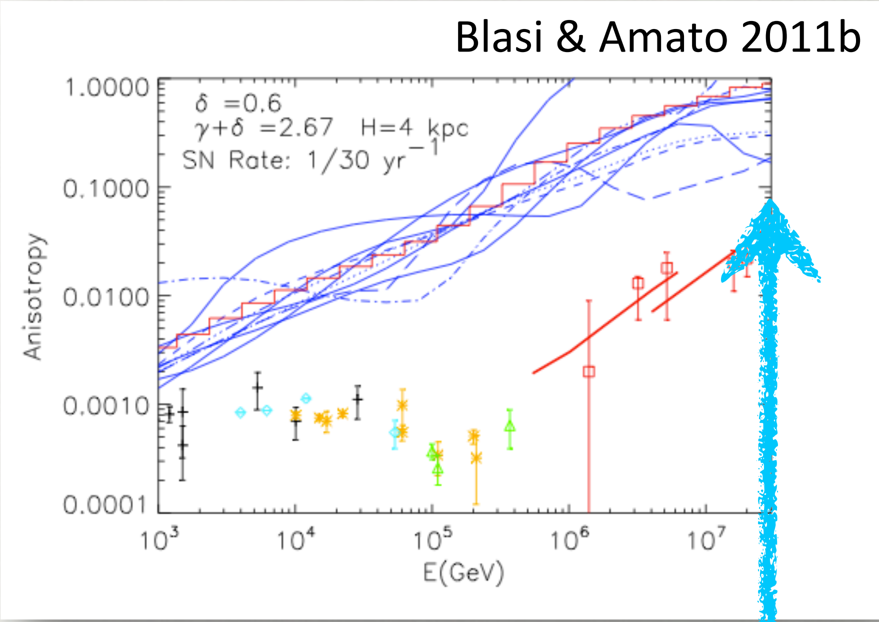


Friday, September 27, 13

Estimation on Anisotropy





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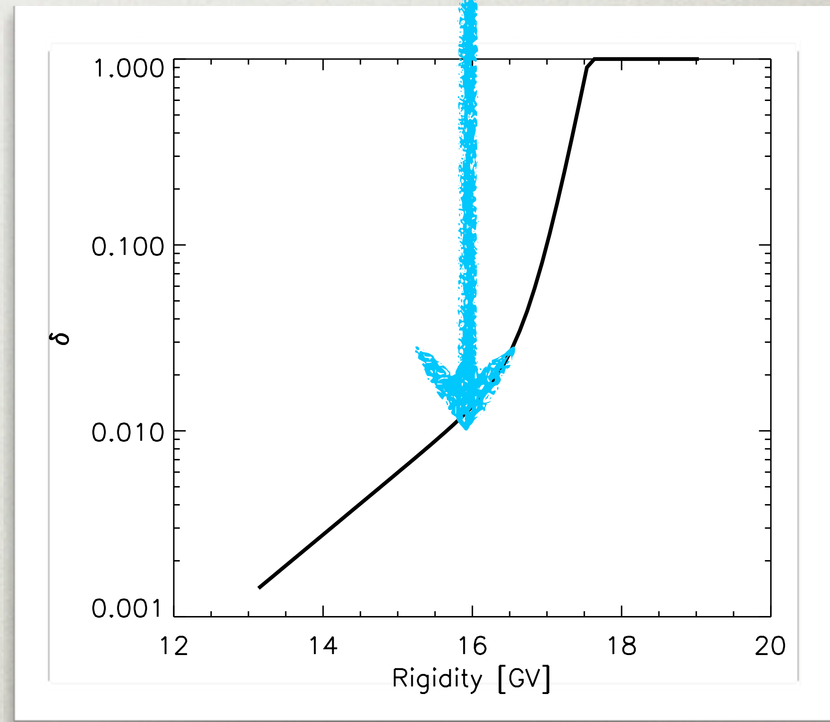

Conclusion II

Galactic pulsars can contribute between the knee and the ankle!

Testable Scenario?

Neutrinos from Integrated Pulsar Sources

$$\Phi_\nu = \frac{f_\mathrm{s}}{4\pi} \int_0^{z_\mathrm{H}} \int_0^{t_\nu} \frac{\mathrm{d}N_\nu}{\mathrm{d}t'\,\mathrm{d}E_\nu\,4\pi D^2}\,\mathrm{d}t'\,\Re(z)\,4\pi D^2\,\frac{\mathrm{d}D}{\mathrm{d}z}\,\mathrm{d}z$$

Neutrinos from Integrated Pulsar Sources

$$\Phi_\nu = \frac{f_s}{4\pi} \int_0^{z_H} \int_0^{t_\nu} \frac{dN_\nu}{dt'\, dE_\nu\, 4\pi D^2}\, dt'\, \Re(z)\, 4\pi D^2 \frac{dD}{dz}\, dz$$

$$\Re(0) \approx 3.3 \times 10^{-4}\, \mathrm{yr}^{-1}\, \mathrm{Mpc}^{-3}$$

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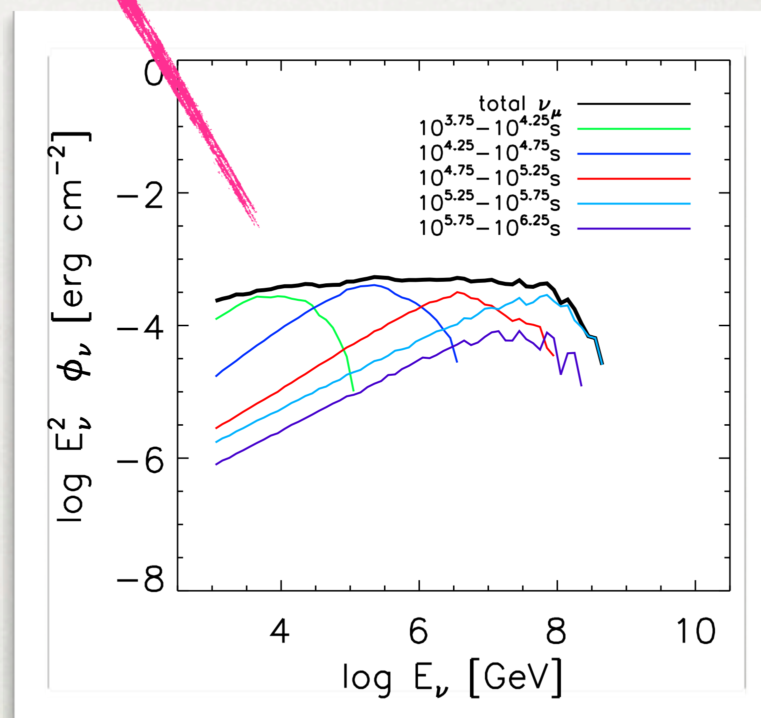

Insensible to injection composition:
Fe~56P/26
CNO~28P/14

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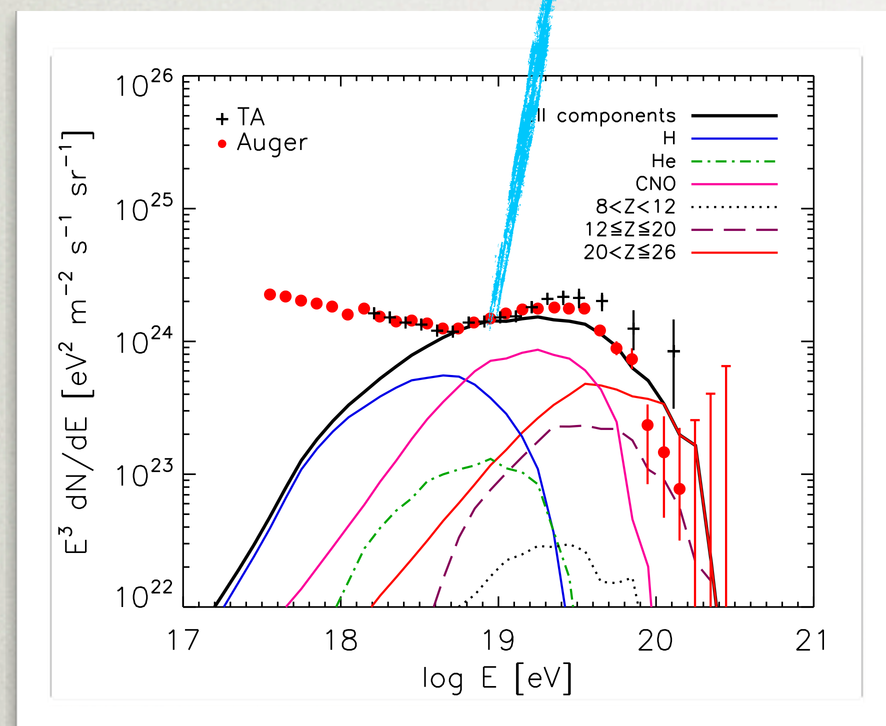

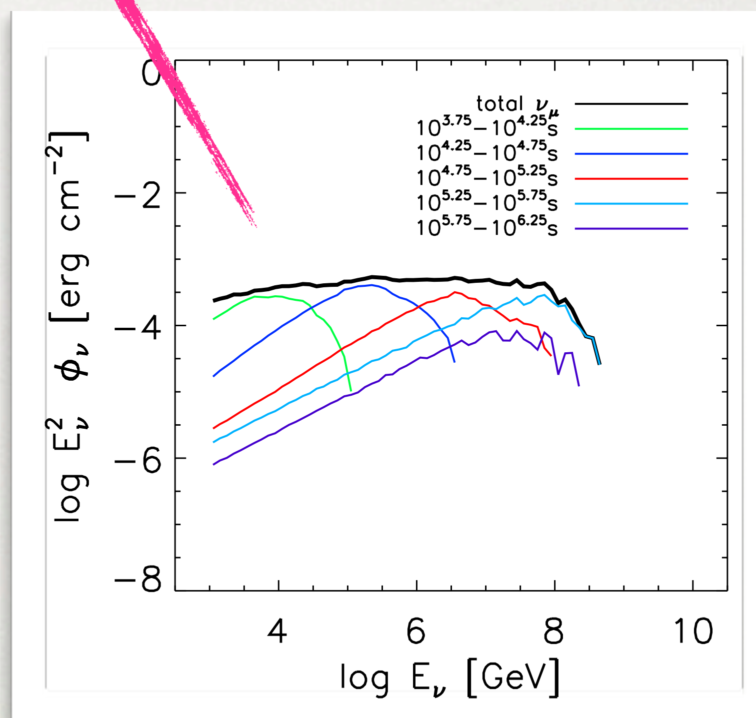

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Fe~56P/26
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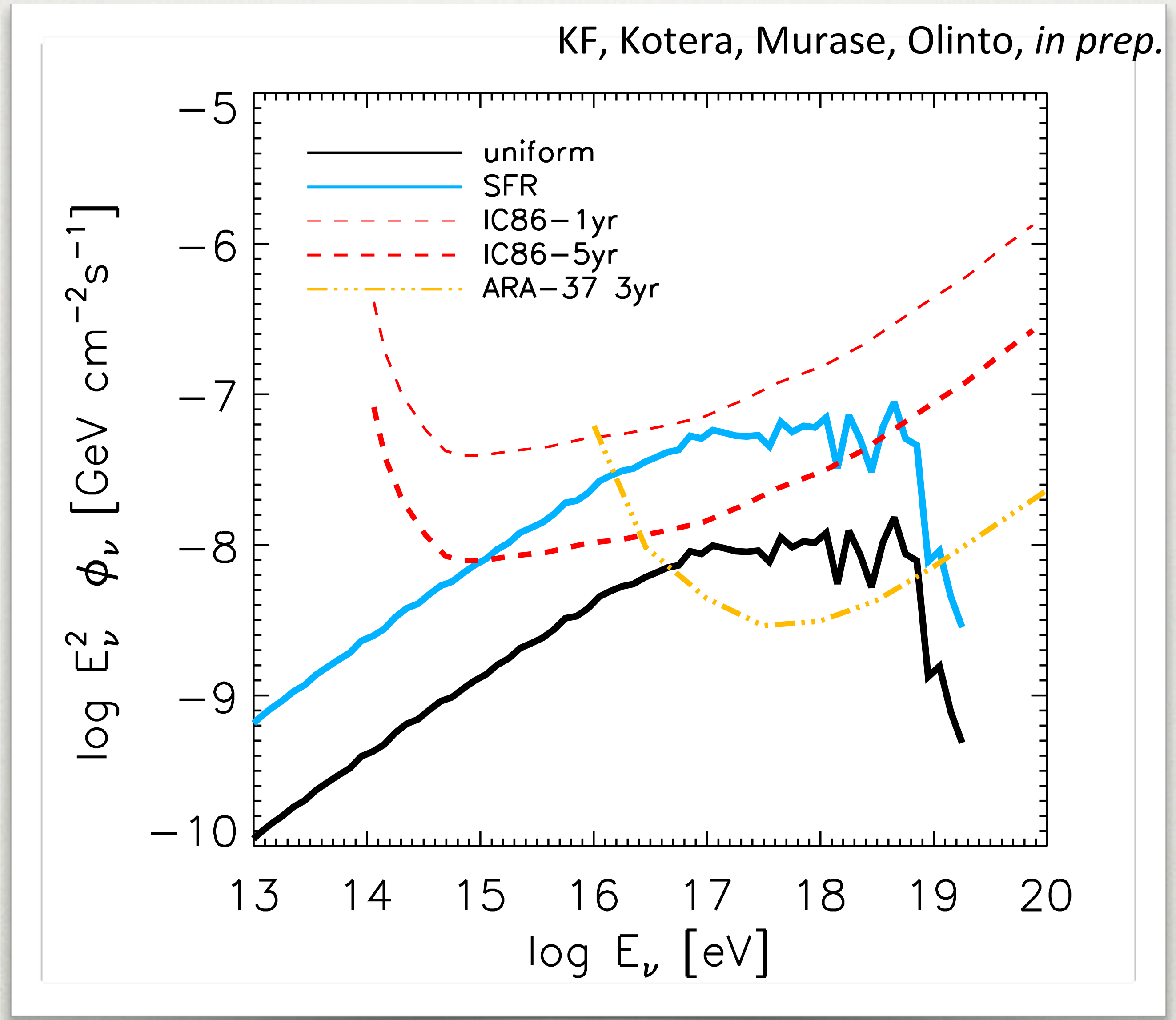
$$\dot{N} = c\left(\frac{\Omega B_{*,\mathrm{dipole}}}{2\pi c}\right)(2\pi A_{\mathrm{cap}})$$ × Neutrino-loud lifetime

Measured UHECR flux → $f_s \approx 0.05$

Neutrinos from Integrated Pulsar Sources



Conclusion III

Consistent with current detection upper limits;

Robustly tested with IC86-5 year and projected ARA-37 3 year operations.