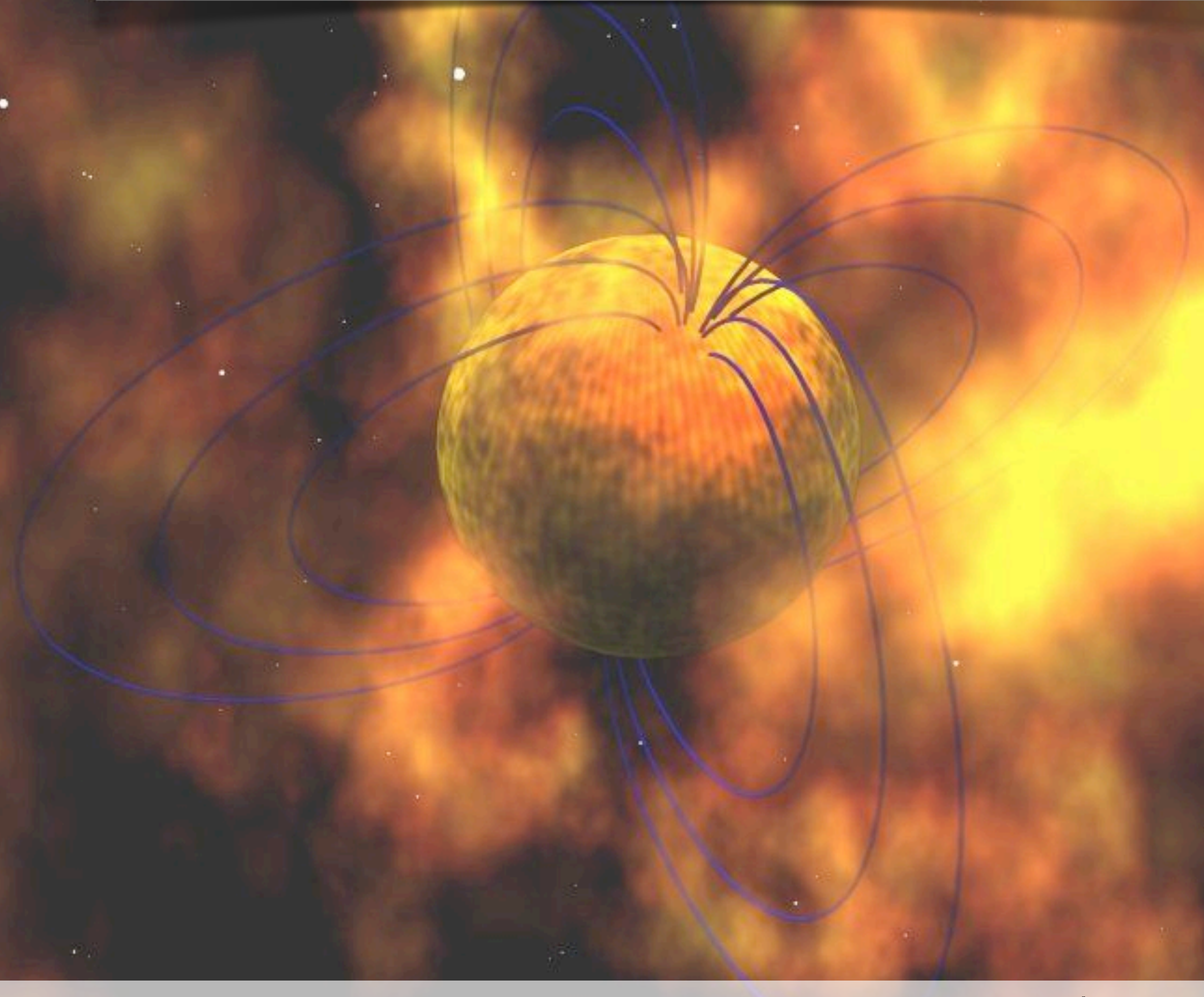
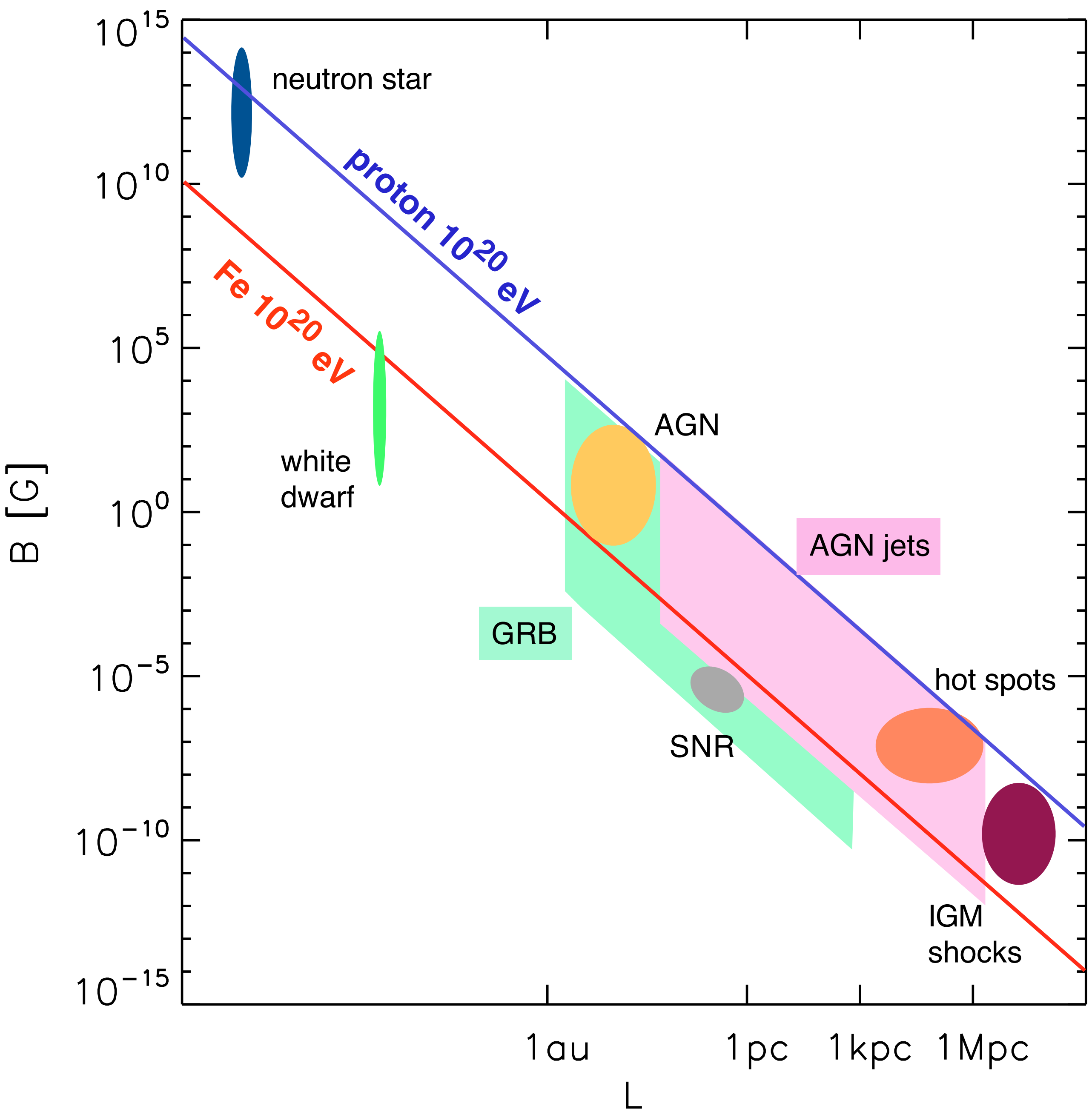
Magnetars as sources of ultrahigh energy cosmic rays



Kumiko Kotera, *University of Chicago*

TeV Particle Astrophysics, Paris - 20/07/10

Possible sources of UHECRs: energetics



updated **Hillas diagram**
taking into account current uncertainties
on source parameters

AGN, jets, hot spots

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

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

only FSRQ/FRII

GRB

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

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

tight energetics

Magnetars

Blasi, Epstein, Olinto 2000
Arons 2003

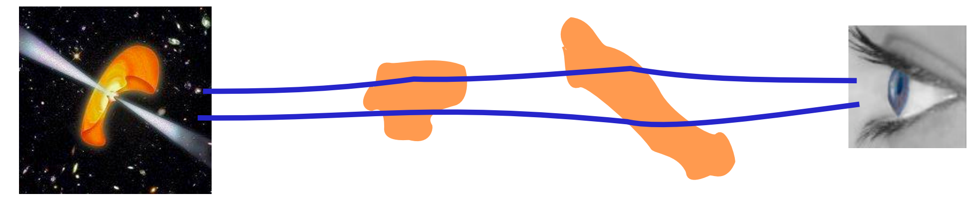
$$E = 3 \times 10^{21} Z \eta_1 \Omega_4^2 \mu_{33} \text{ eV}$$

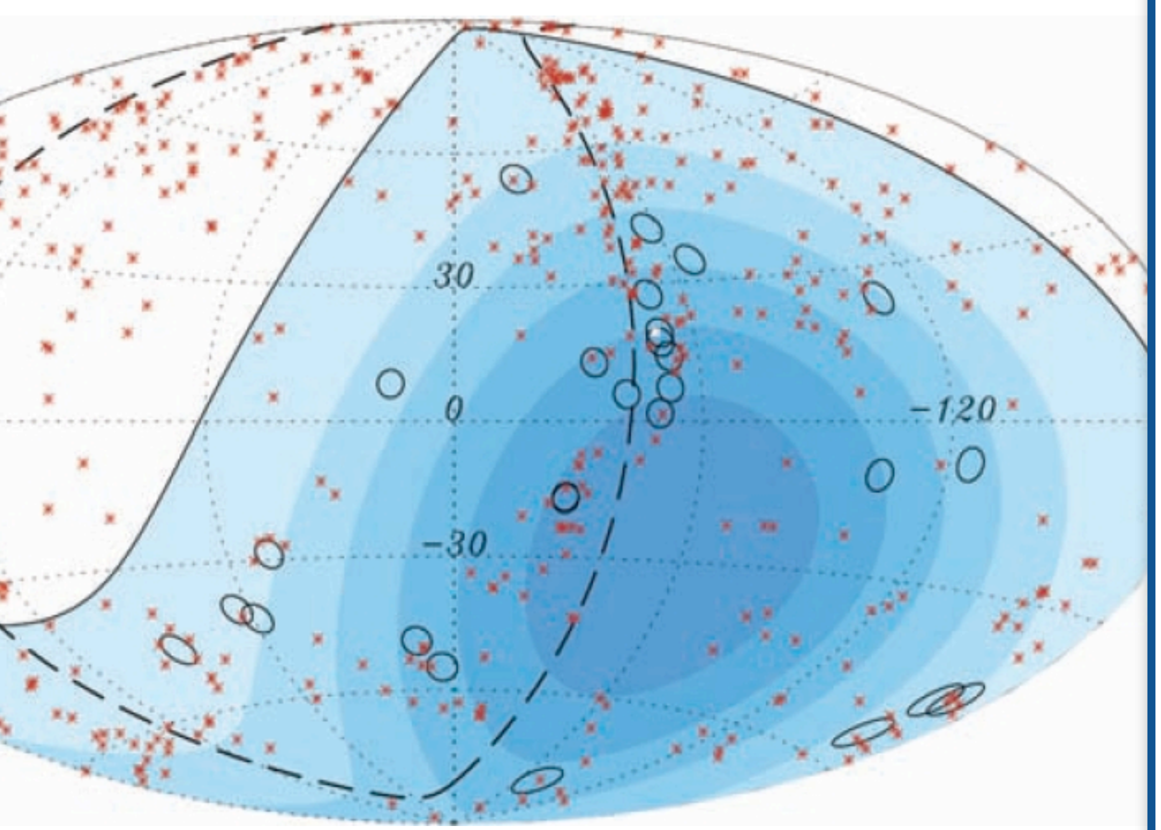
5% of magnetar population would suffice

Possible sources of UHECRs: anisotropy signatures

Continuously emitting sources

FRII in arrival direction of highest energy events *unless*
- particularly strong extragalactic magnetic field
- UHECR = heavy nuclei





Auger Coll. 2008

Transient sources

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

2) low occurence rate (of GRB/magnetars)
low probability of observing events from a source
unless scattering of arrival times due to magnetized regions

enhanced correlation btw UHE events and foreground matter
distortion of arrival direction maps according to LSS

K.K. & Lemoine 2008b
Kalli, Lemoine, K.K., in prep, cf. poster

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

4) magnetars and GRBs have same anisotropy signature

Transient sources: how to distinguish GRBs from magnetars?

UHE neutrinos?

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

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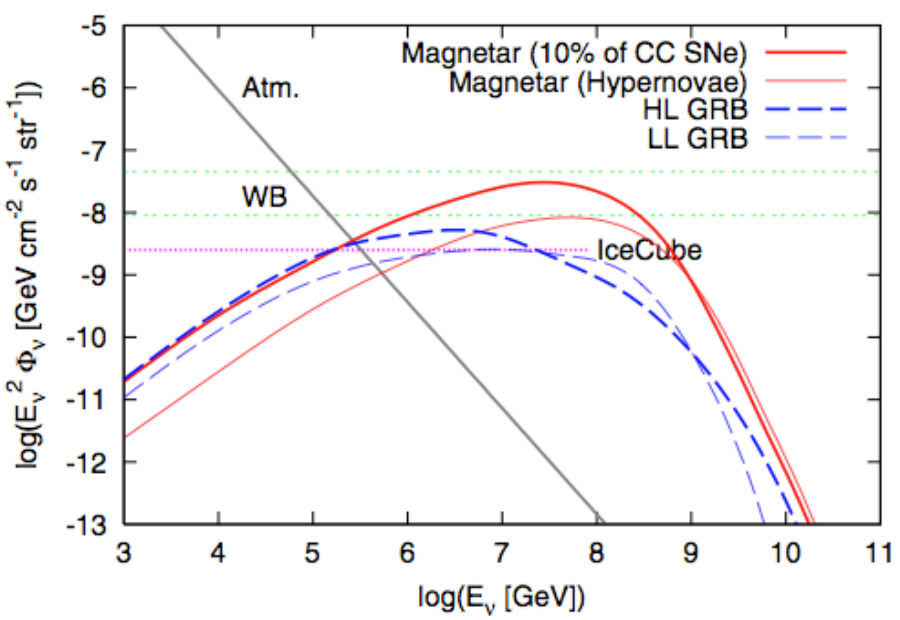

caution: dependency on Physics inside source and in source environment + composition of UHECR

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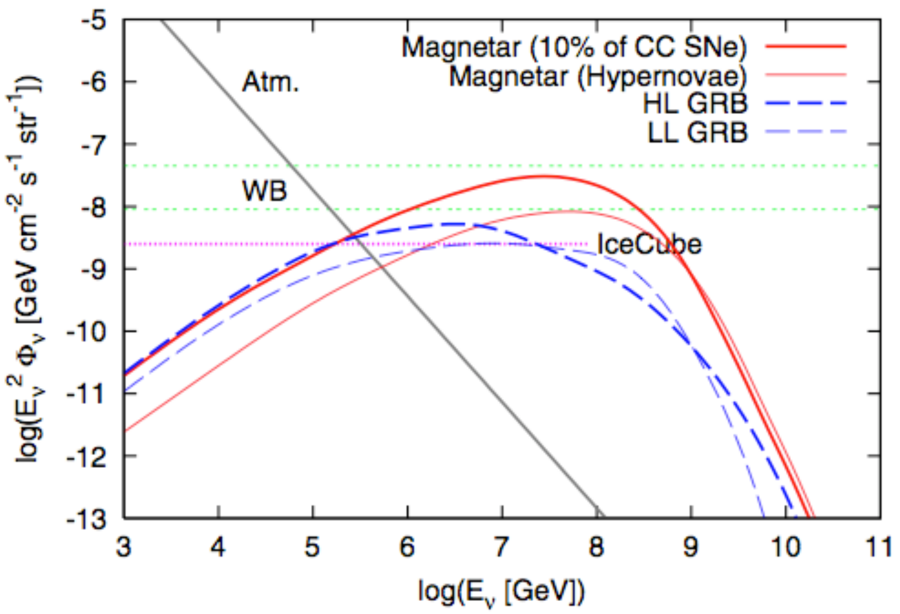

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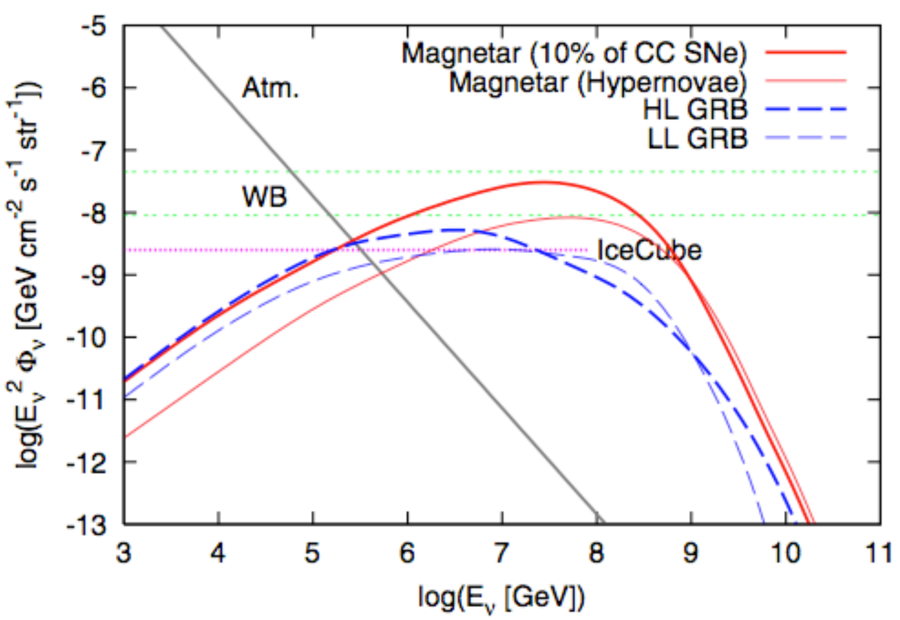

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GRBs: shocks produce only faint GW

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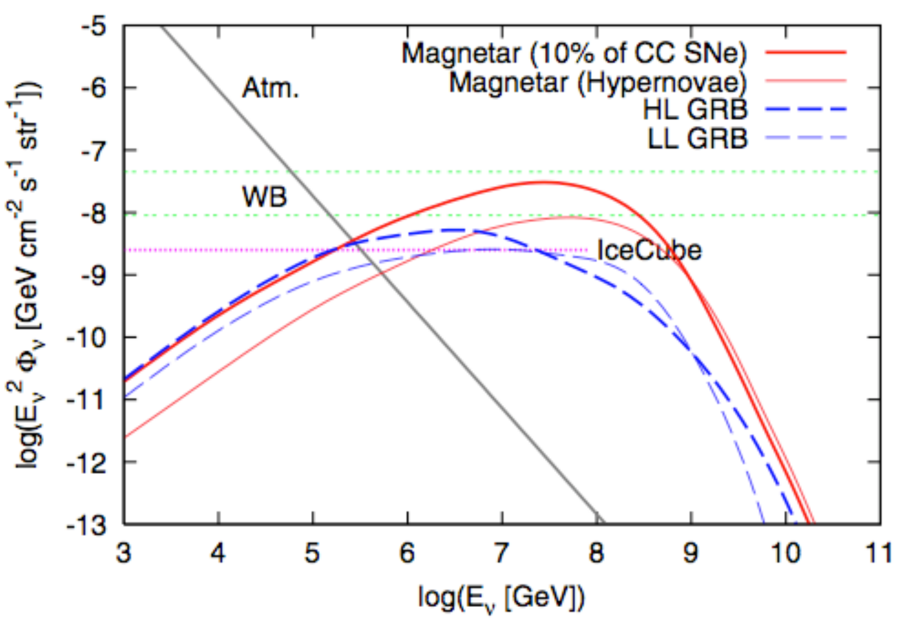

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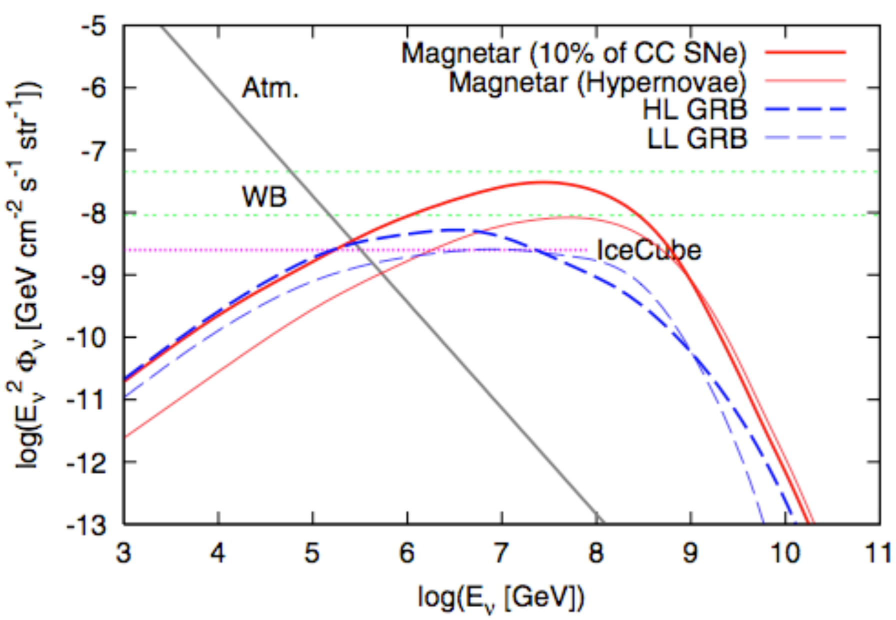

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GW signal
specific spectrum + span in frequency

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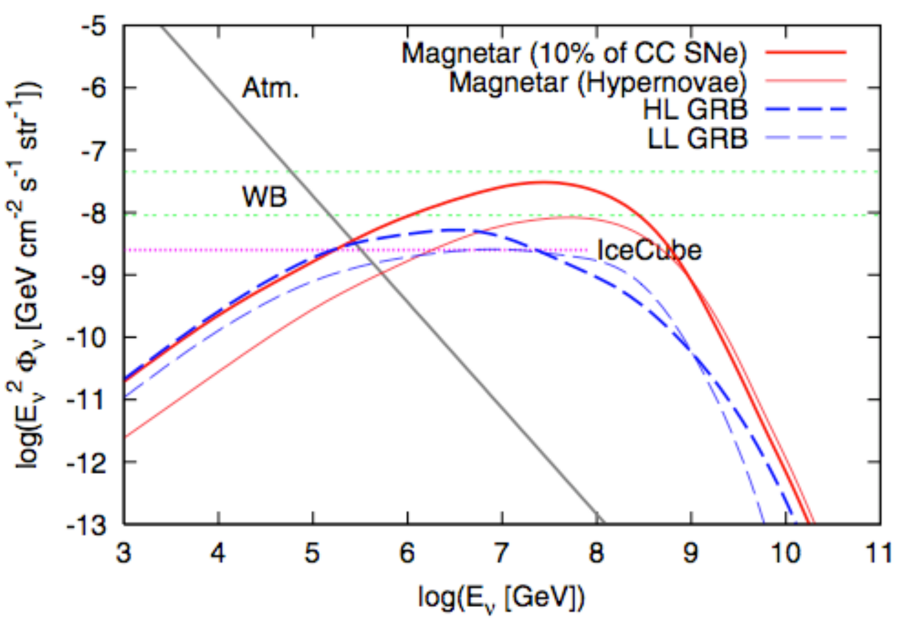

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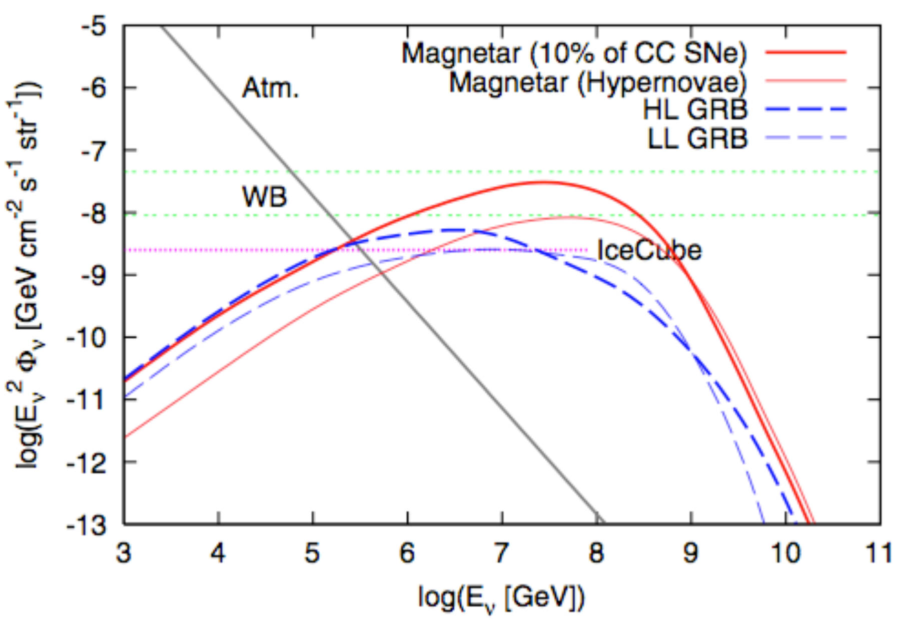

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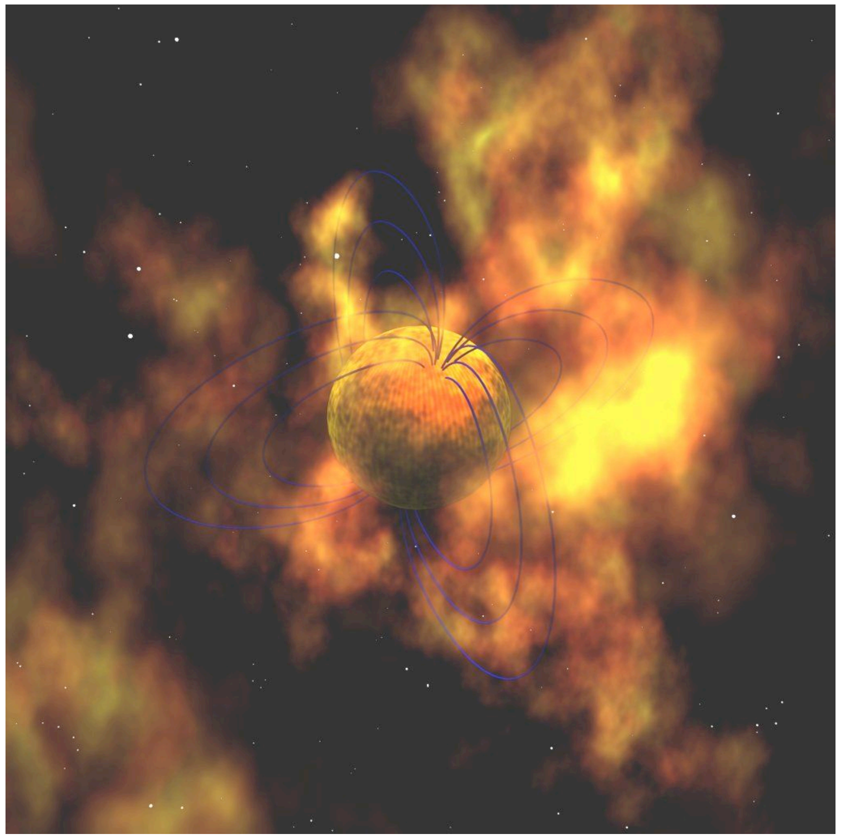
observation of specific spectrum of GW
= evidence of adequate magnetar parameters for acceleration of UHECR

Magnetars and UHECRs



Duncan & Thompson 1992

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

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

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

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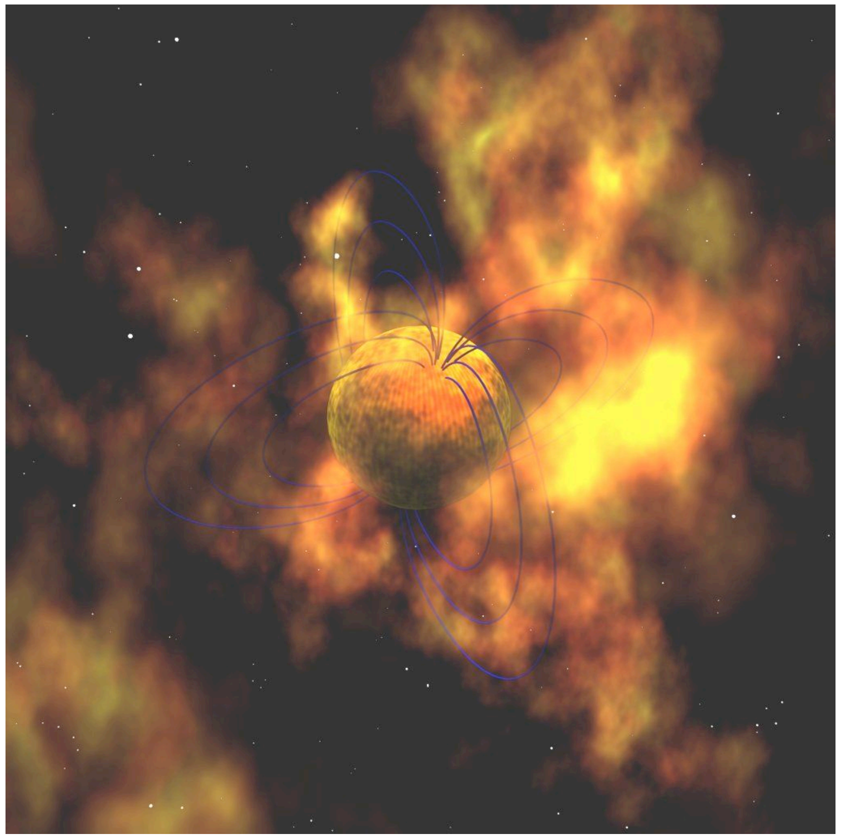

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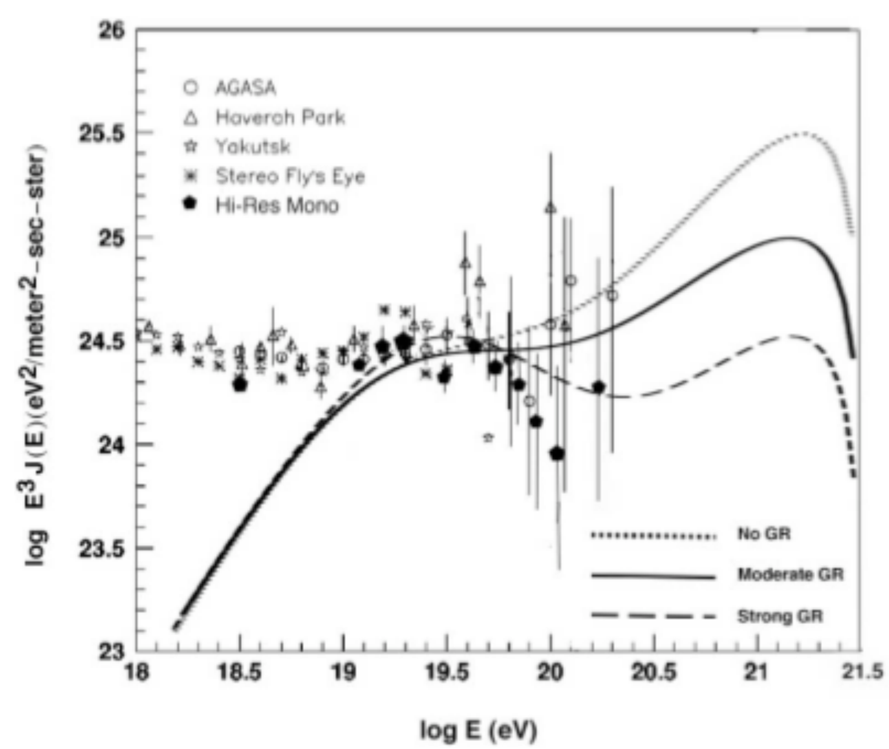
Magnetars as progenitors of UHECRs:
idea introduced during the "AGASA era"

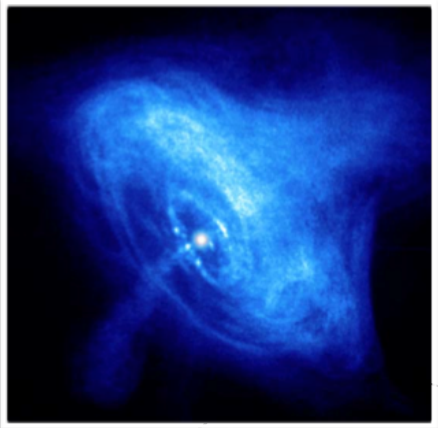
Blasi, Epstein, Olinto 2000

Galactic magnetars + iron particles
aim: isotropic distribution in sky

Arons 2003

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





Acceleration mechanism in magnetars

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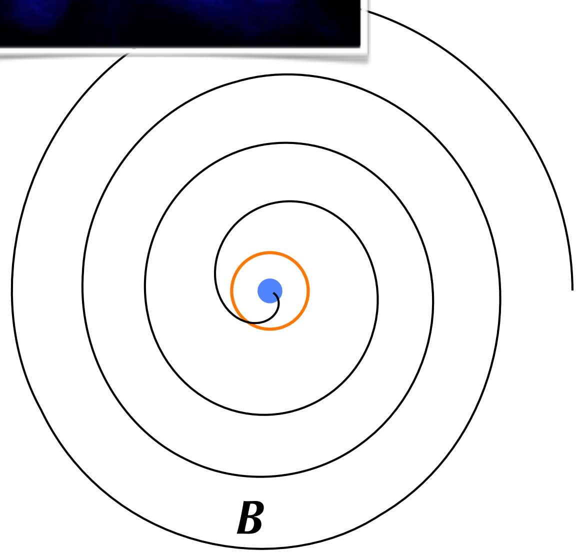

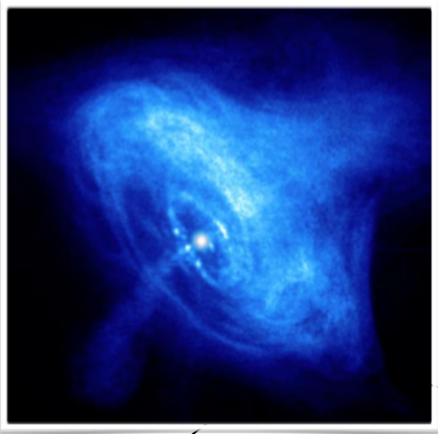

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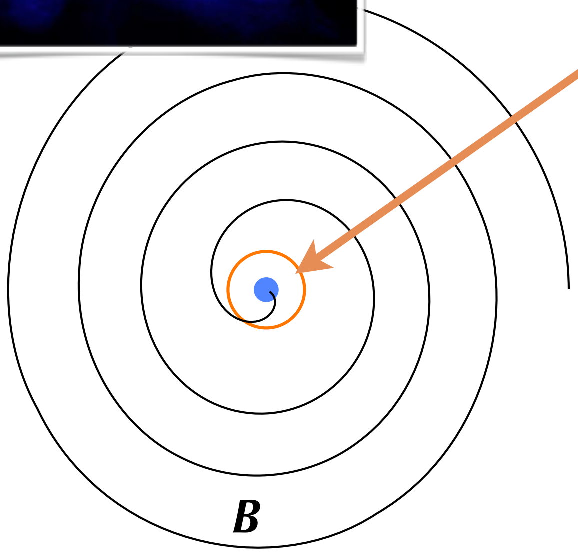

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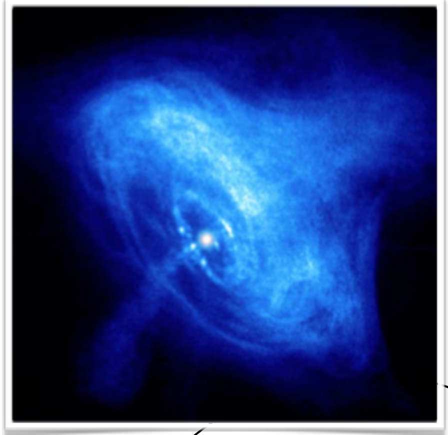

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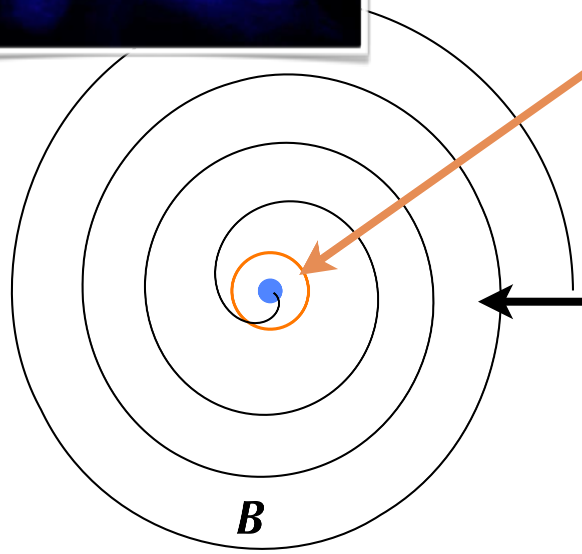

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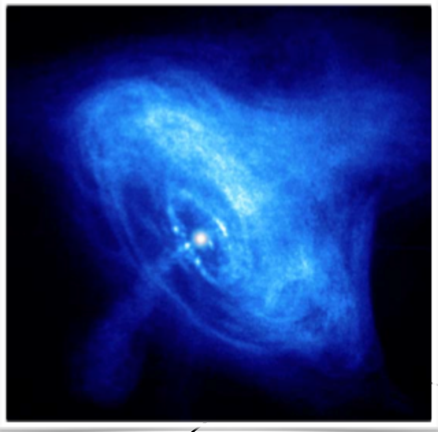

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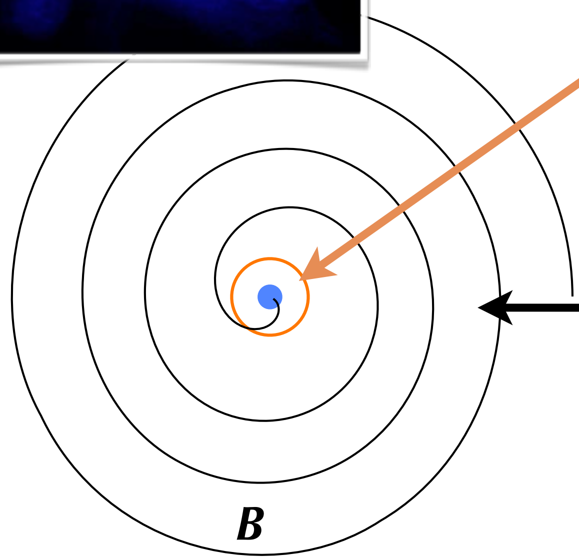

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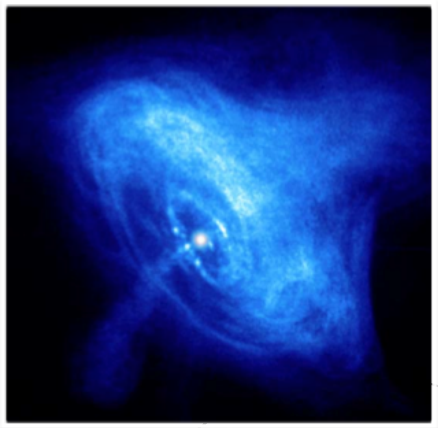

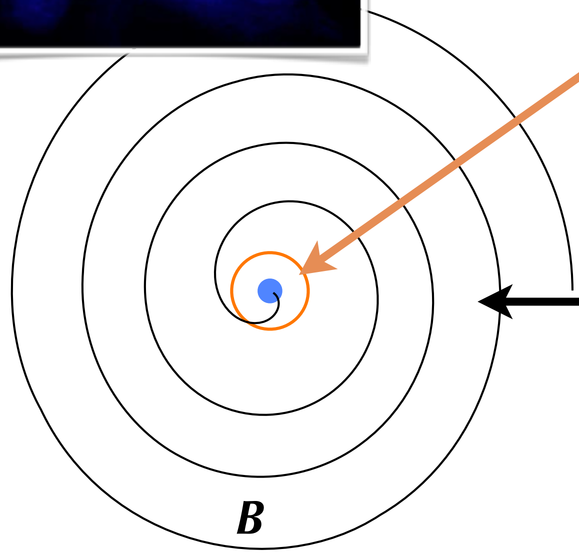

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10%: fraction of voltage experienced by particles

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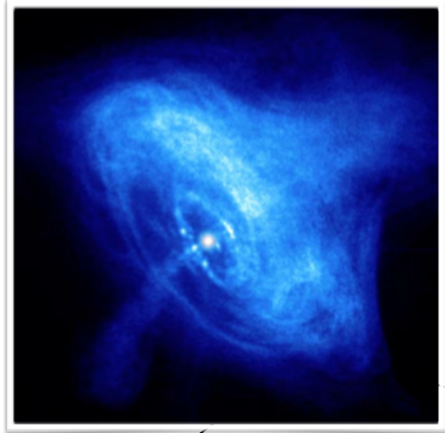

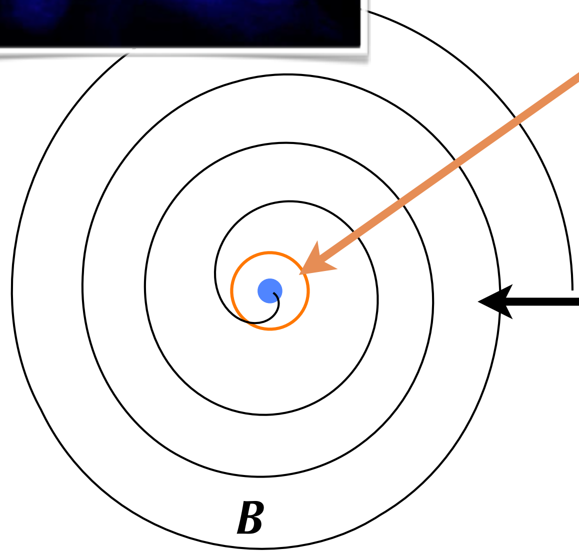

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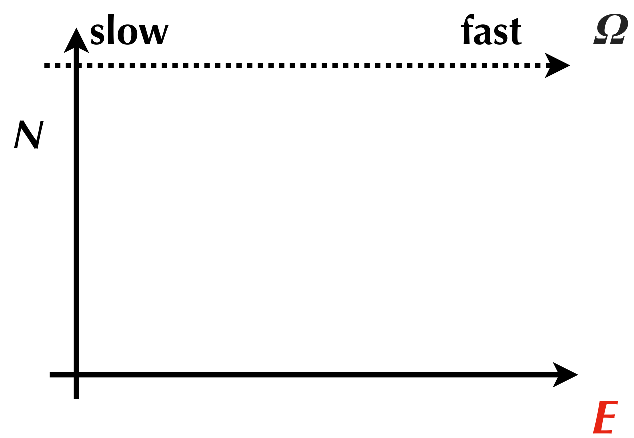

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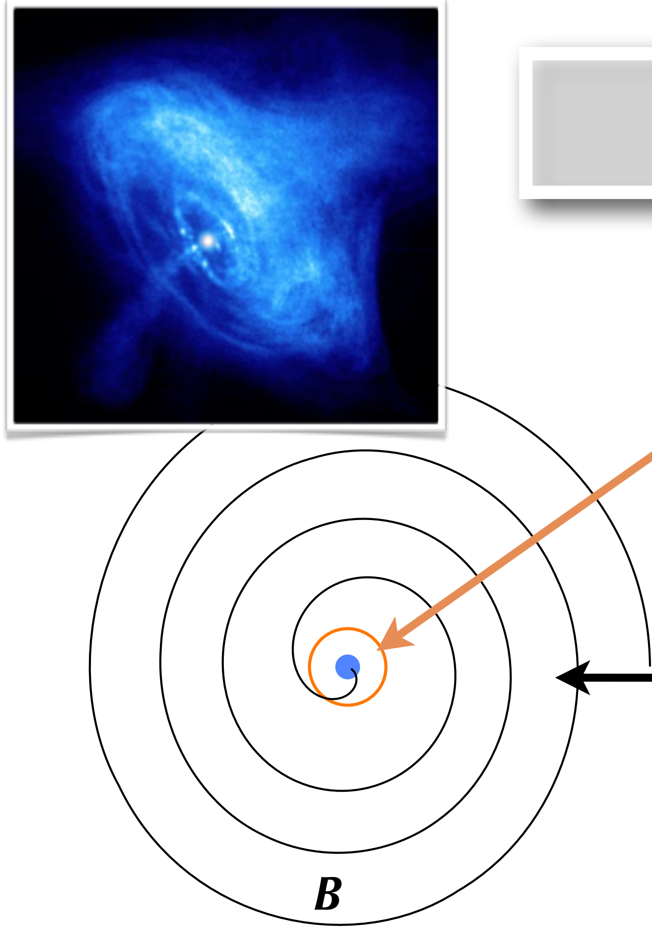

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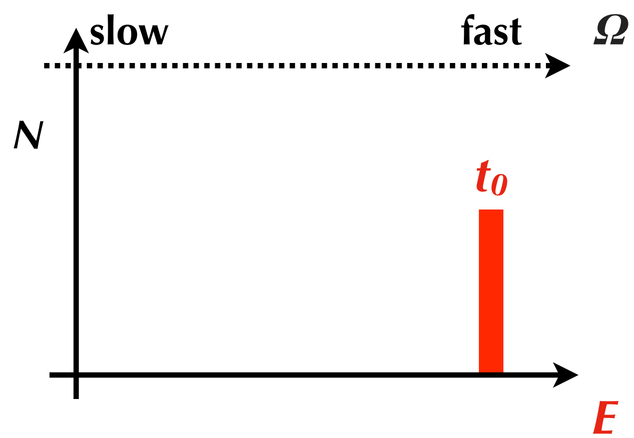

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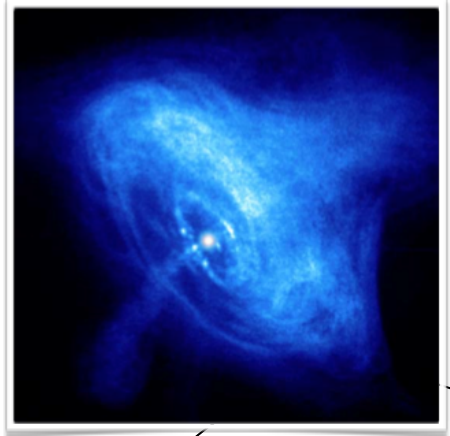

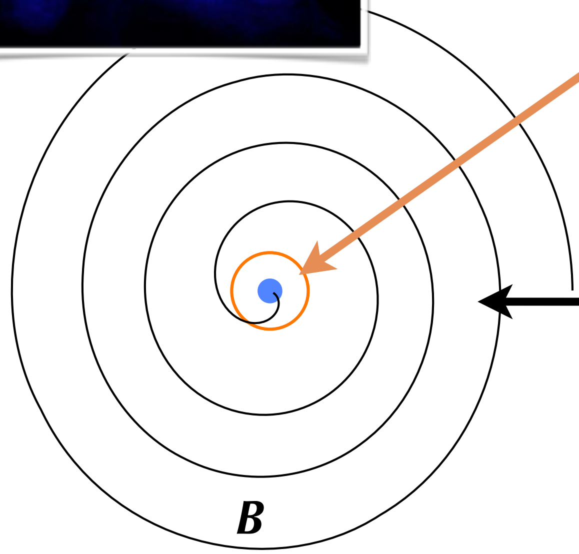

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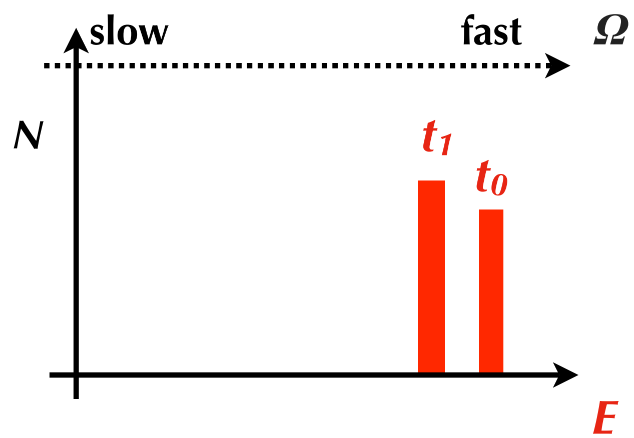

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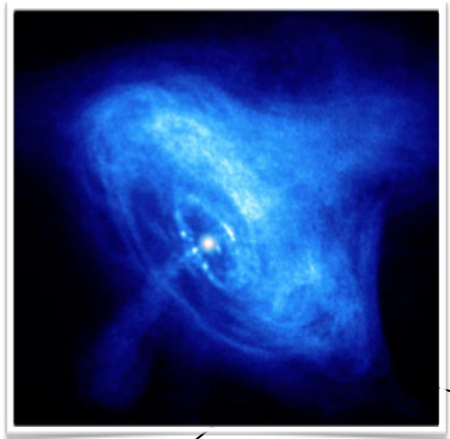

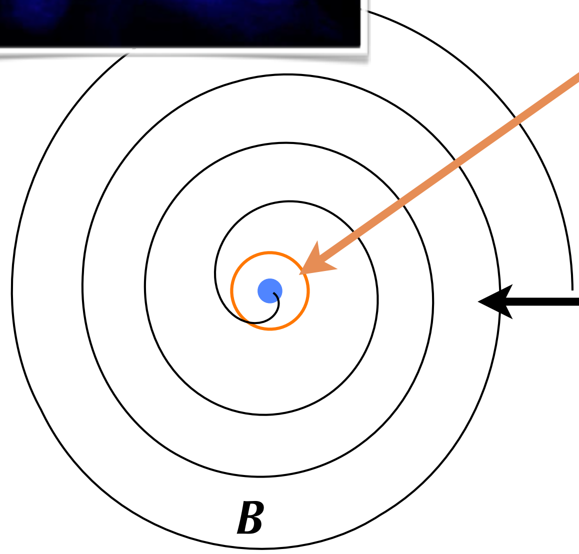

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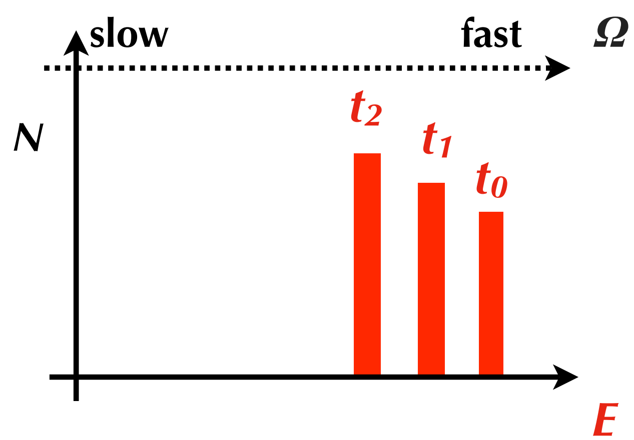

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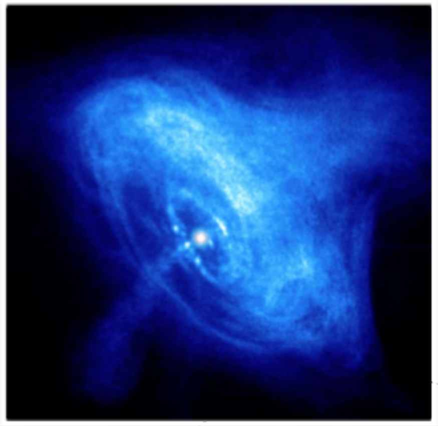

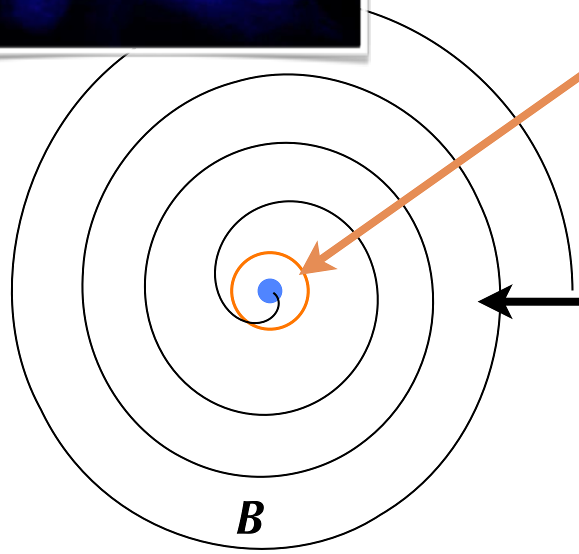

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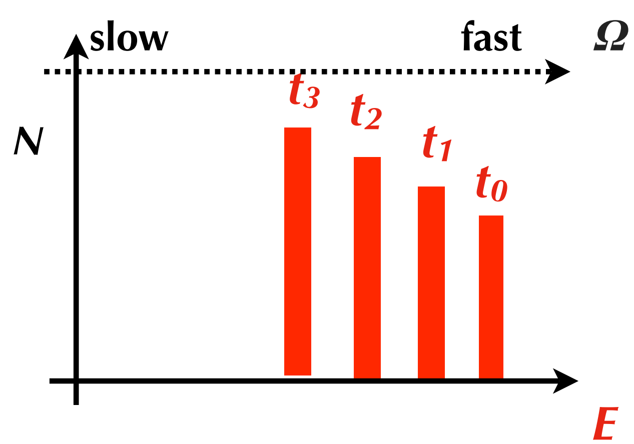

relativistic wind

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

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

leads to voltage drop:

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

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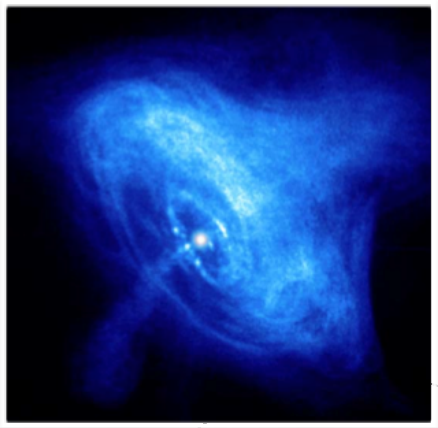

Acceleration mechanism in magnetars

Blasi et al. 2000
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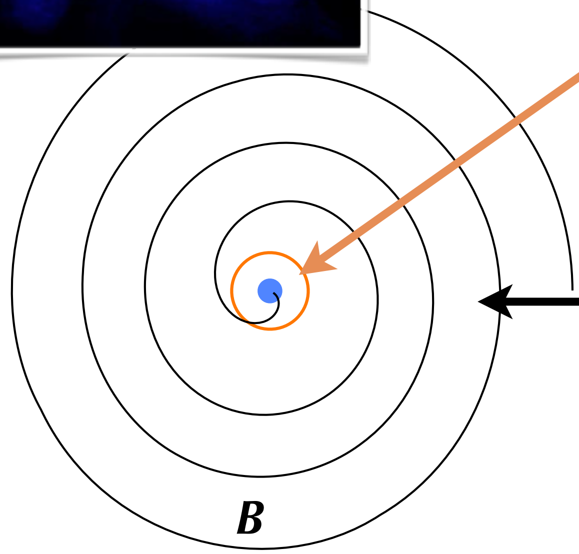

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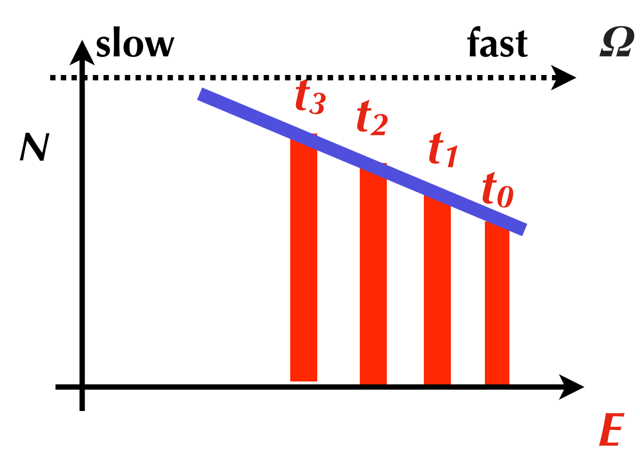

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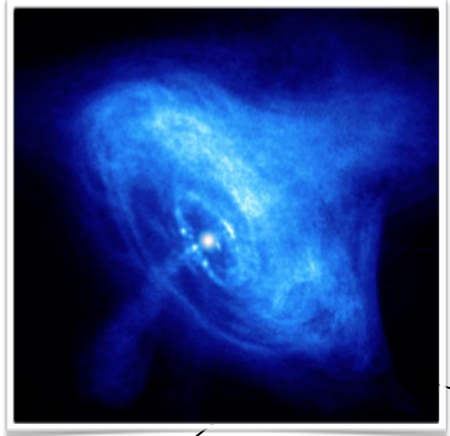

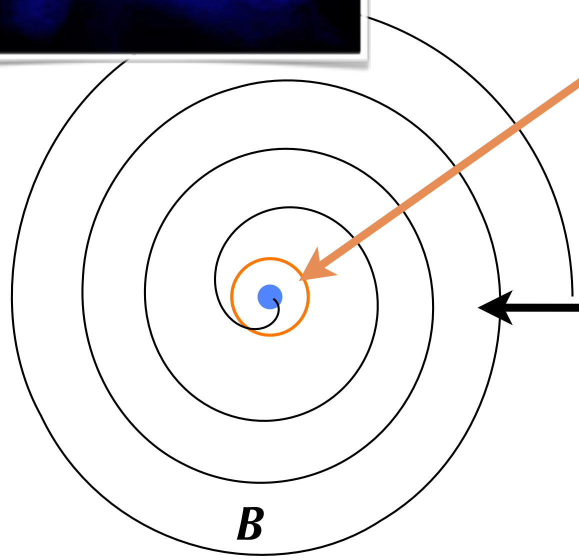

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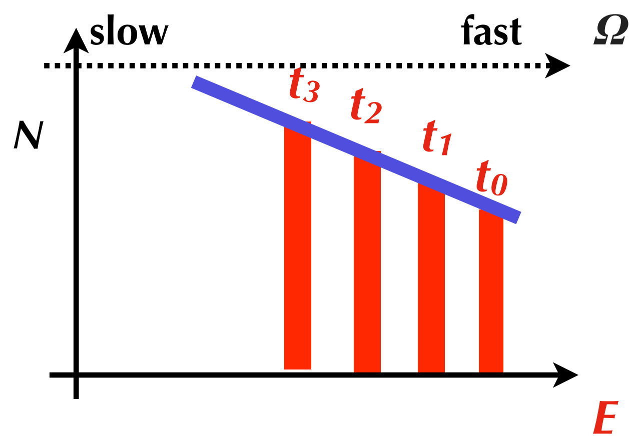

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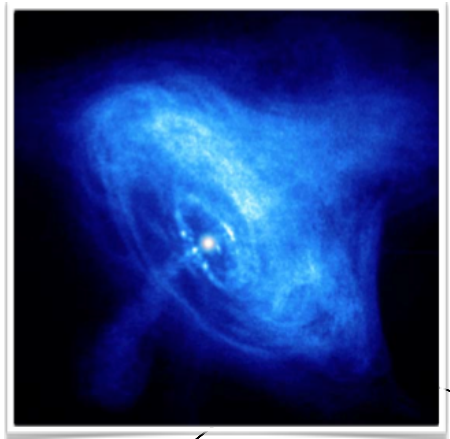
surface of polar cap **Goldreich-Julian density**



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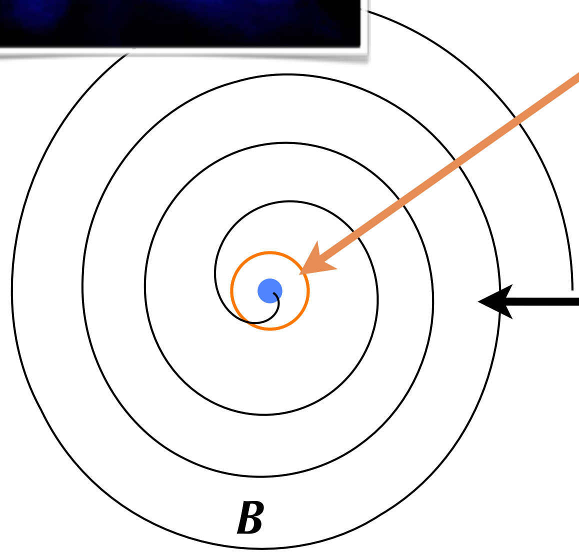

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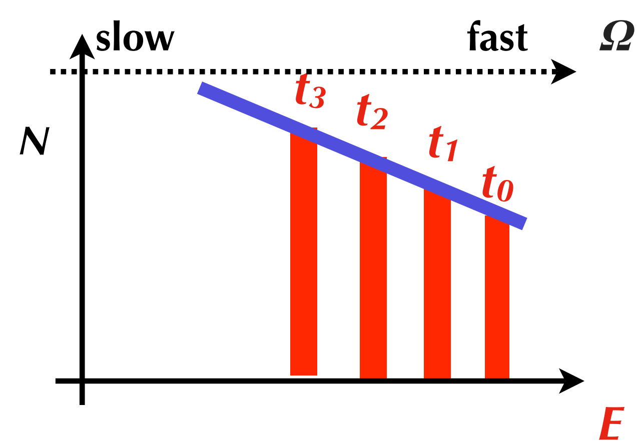

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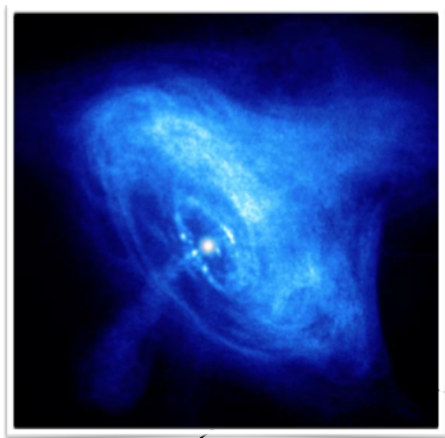

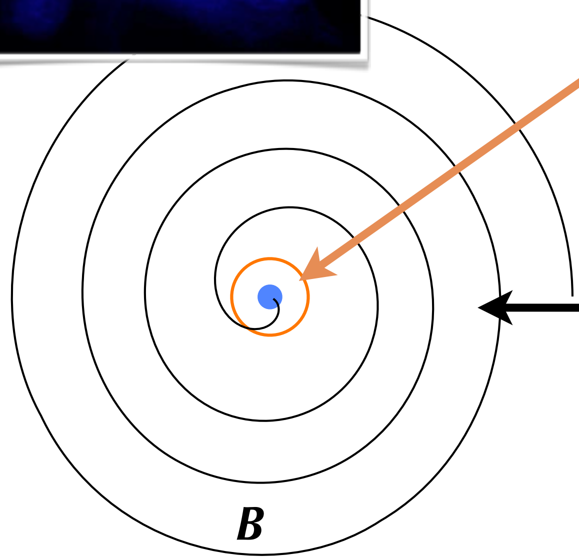

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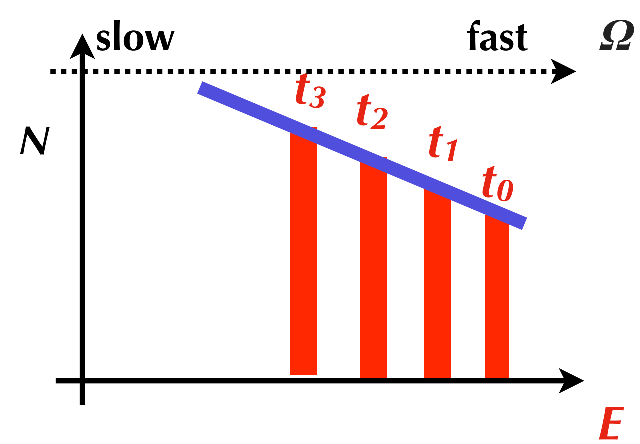

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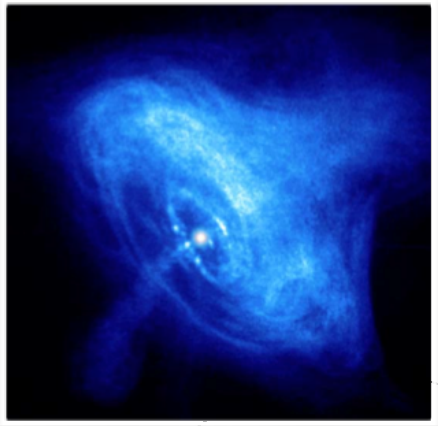

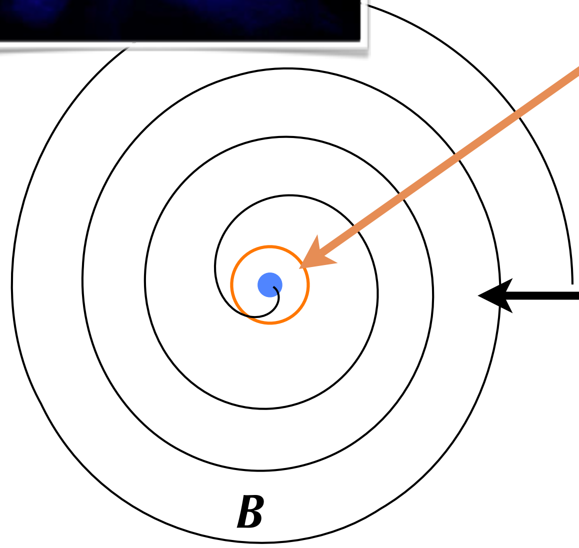

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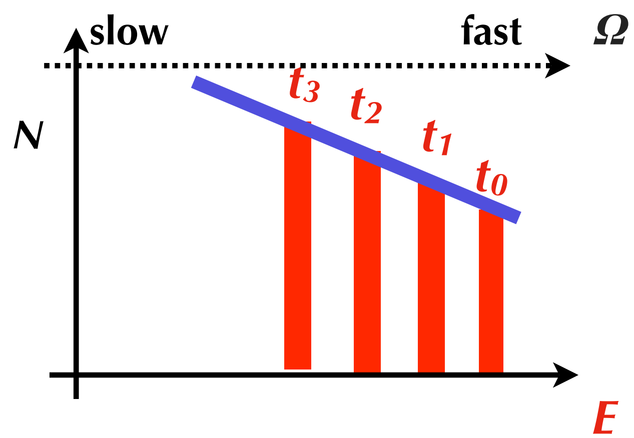

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hard injection spectrum: -1 slope

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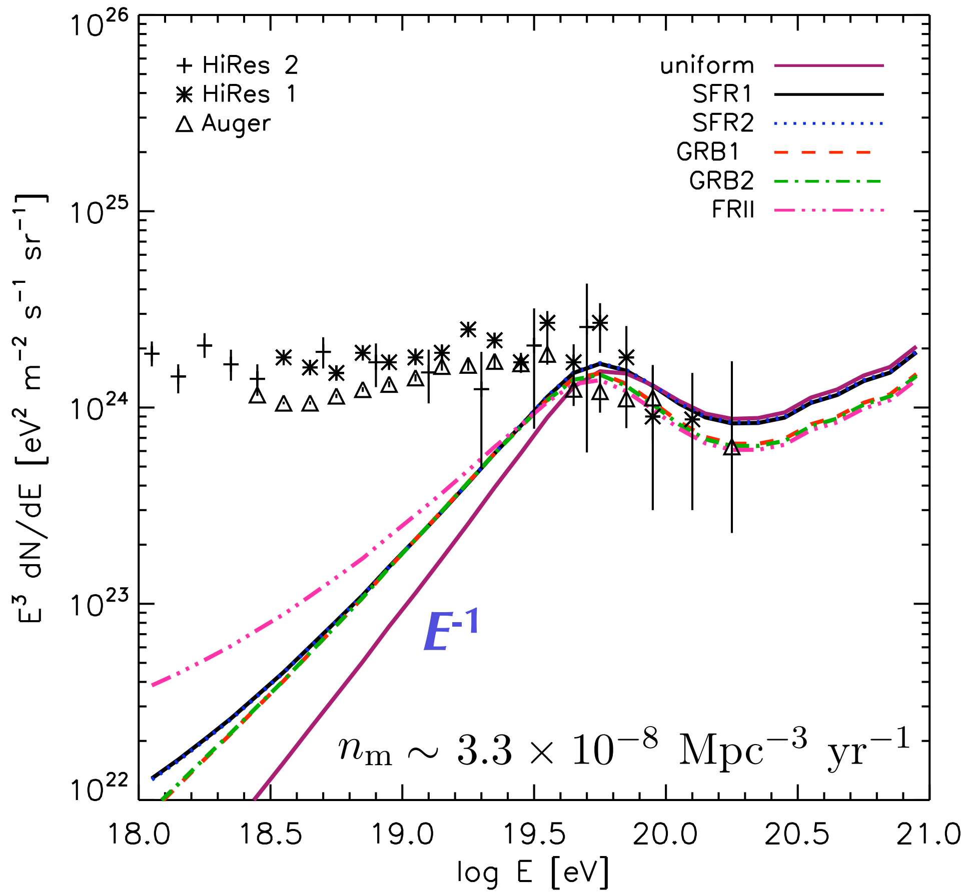
Possible way to reconcile the magnetar spectrum with observed data



distribution of magnetar rates according to starting voltage

$$\frac{dn_{\rm m}}{d\Phi_{\rm i}} = \frac{n_{\rm m}}{\Phi_{\rm i,max}} \frac{s-1}{(\Phi_{\rm i,max}/\Phi_{\rm i,min})^{s-1} - 1} \left(\frac{\Phi_{\rm i}}{\Phi_{\rm i,max}}\right)^{-s}$$

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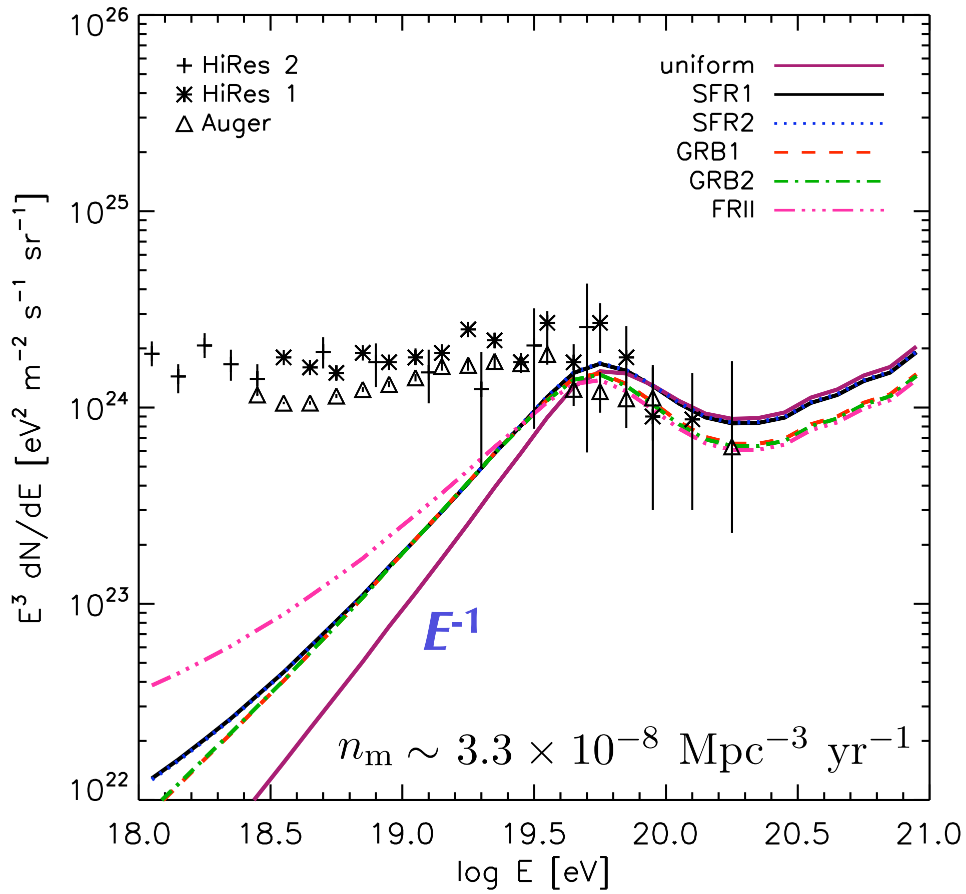

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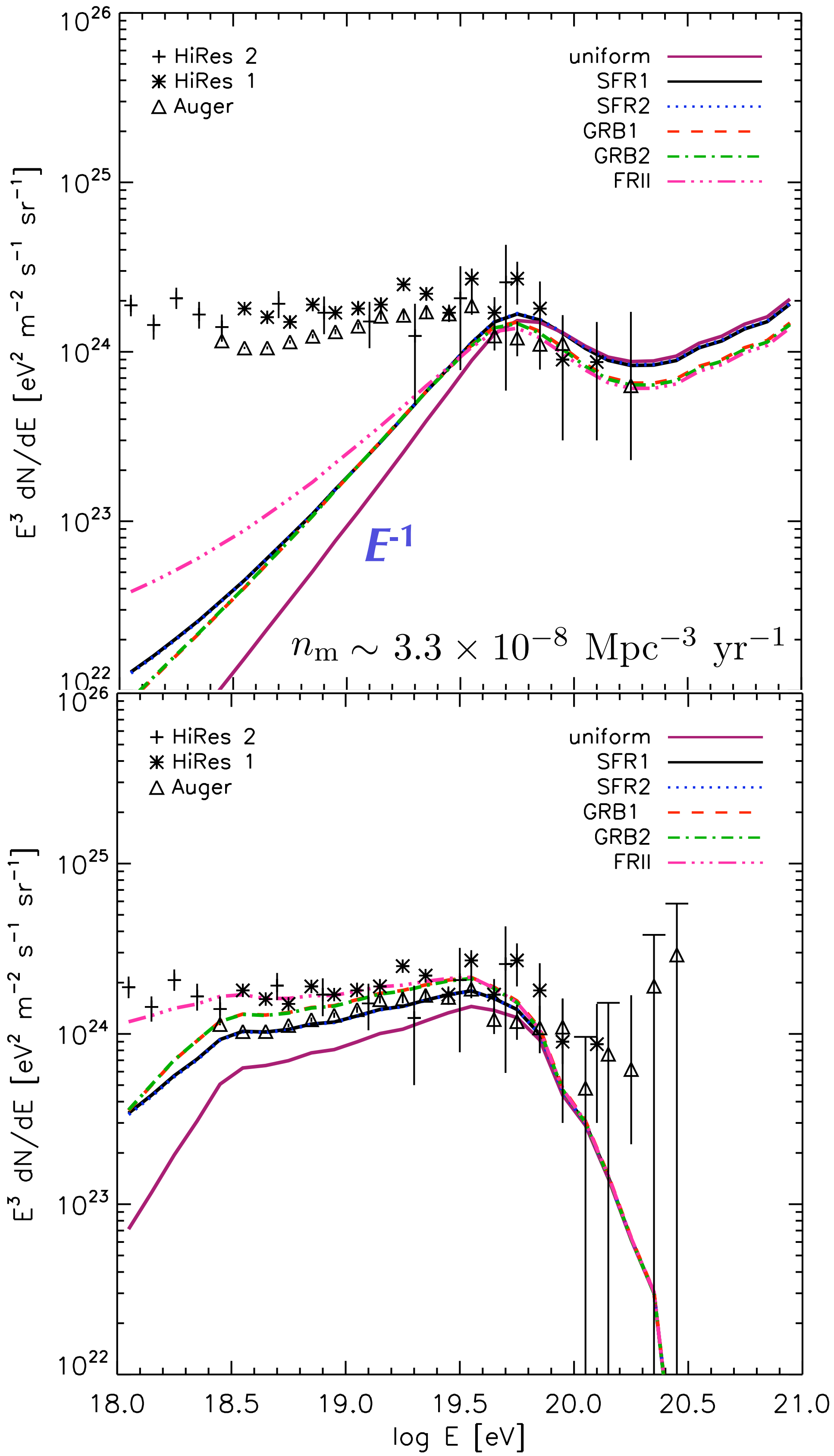

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corrected energy spectrum: **s = 2.2**

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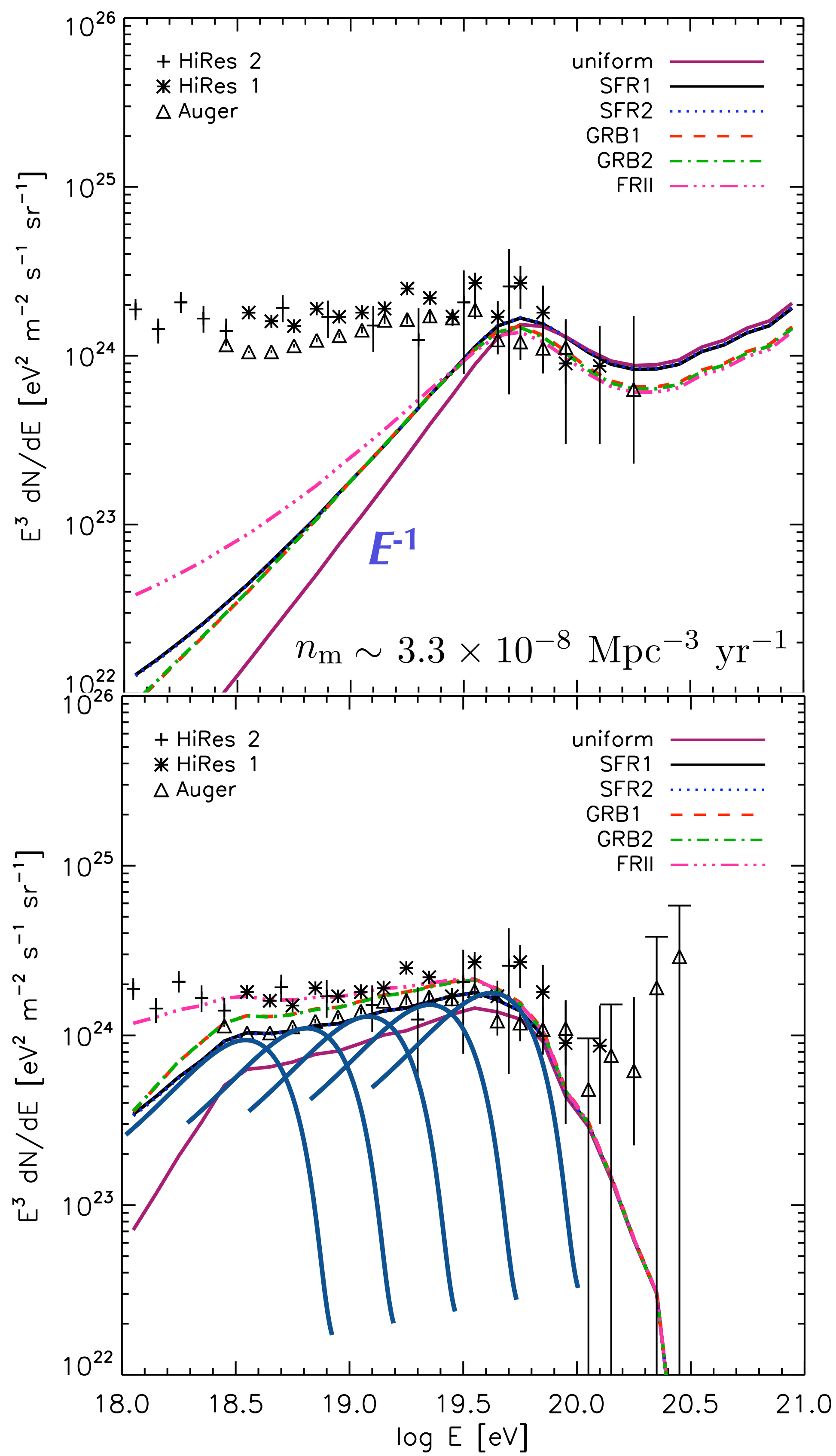

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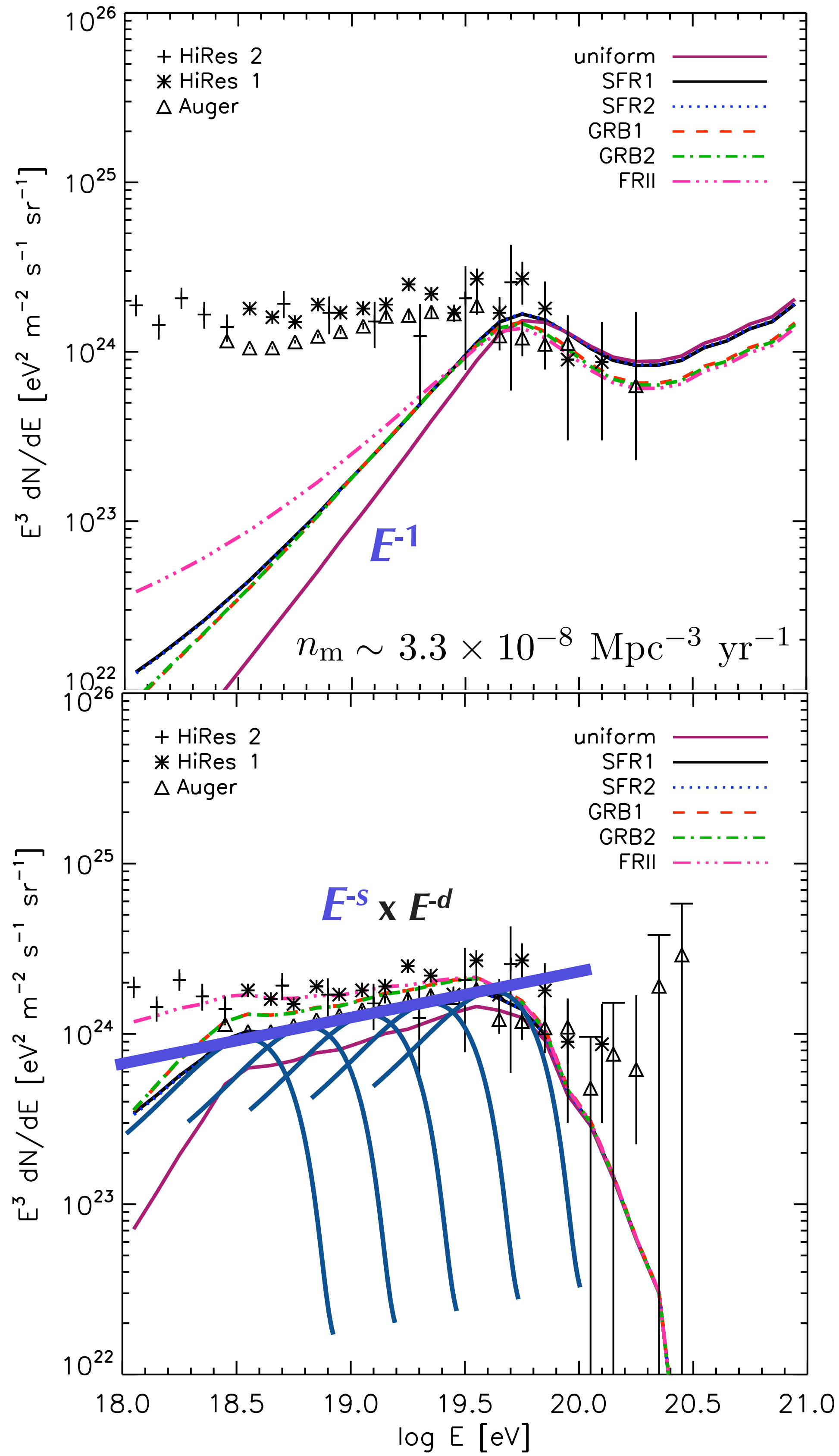

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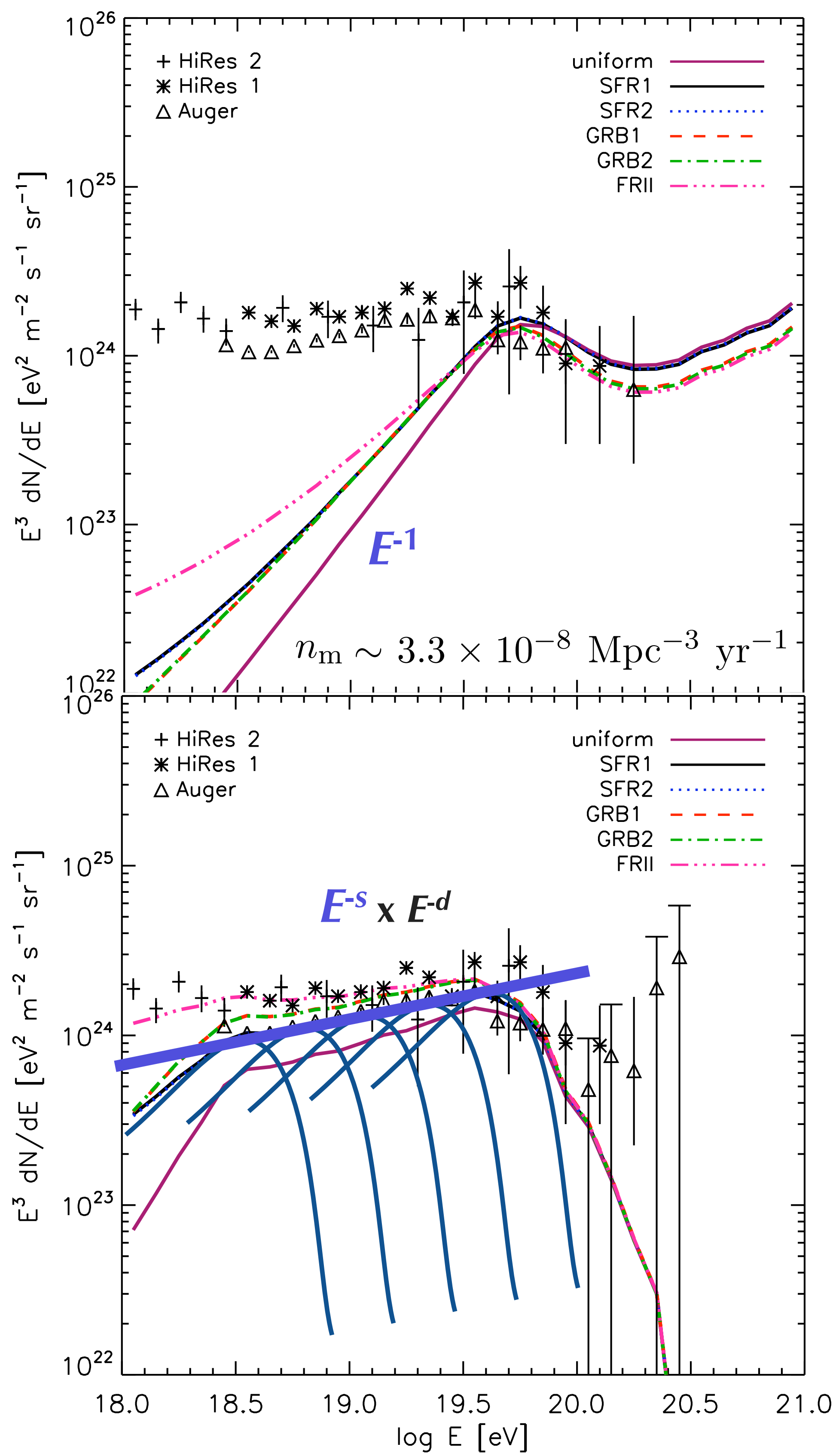

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magnetar rate necessary at z=0:

$$n_{\rm m} = \epsilon_{\rm m} n_{\rm g} \nu_{\rm m}/f \sim 10^{-6} \ {\rm Mpc^{-3}} \ {\rm yr^{-1}}$$

~ hypernovae rate

Implications for the gravitational stochastic background

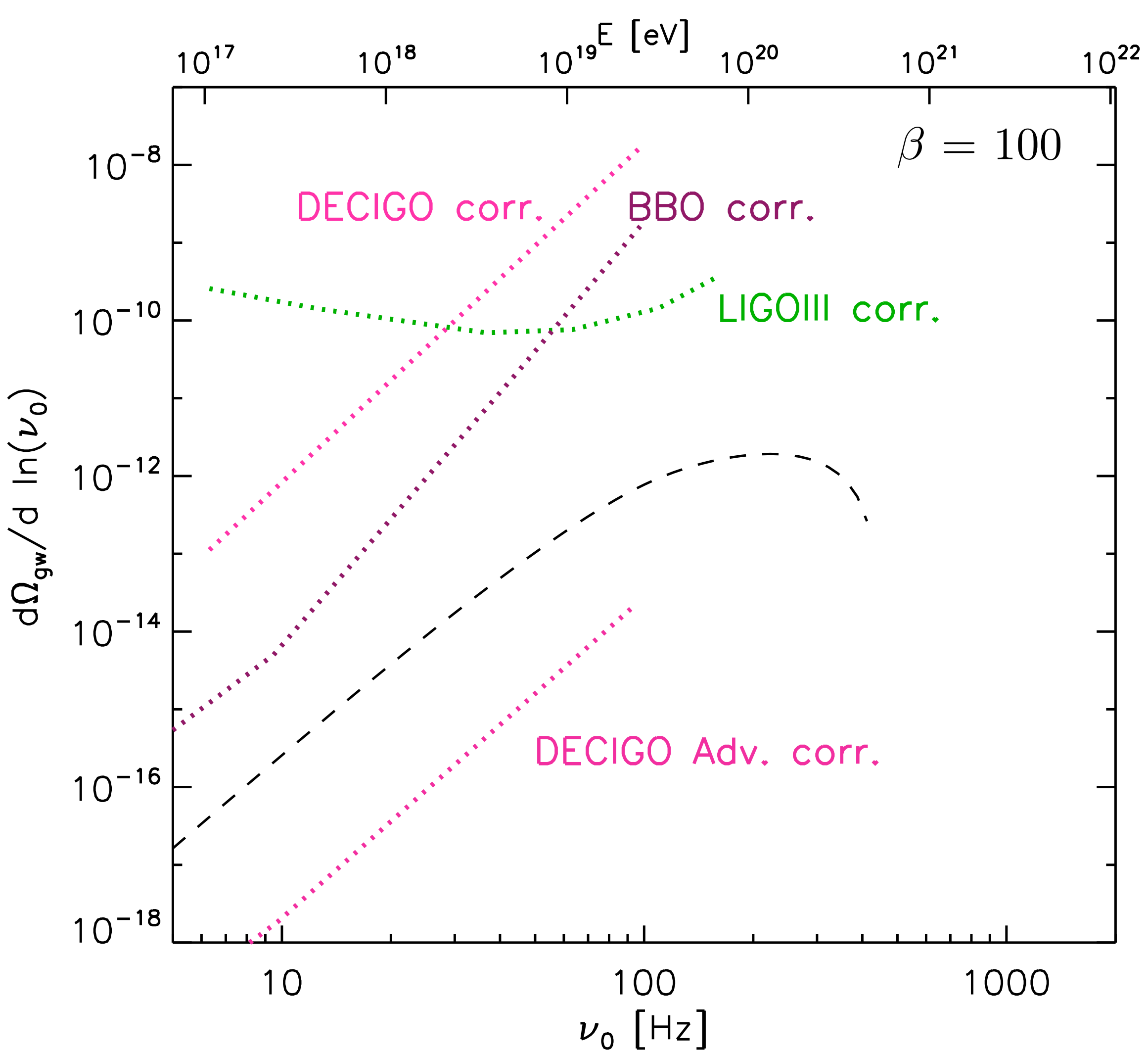
gravitational stochastic background spectrum:

Regimbau & Mandic 2008

$$z_{\rm sup} = \begin{cases} z_{\max} & \text{if } \nu_0 < \dfrac{\nu_{\rm i}}{1+z_{\max}} \\ \dfrac{\nu_{\rm i}}{\nu_0} - 1 & \text{otherwise,} \end{cases}$$

$$\Omega_{\rm gw}(\nu_0) = 5.7 \times 10^{-56} \left(\frac{0.7}{h_0}\right)^2 n_{\rm m,0}\, \nu_0 \int_0^{z_{\rm sup}} \frac{R_{\rm SFR}(z)}{(1+z)^2 \Omega(z)} \frac{{\rm d}E_{\rm gw}}{{\rm d}\nu}[\nu_0(1+z)]\, {\rm d}z$$

cosmological param.



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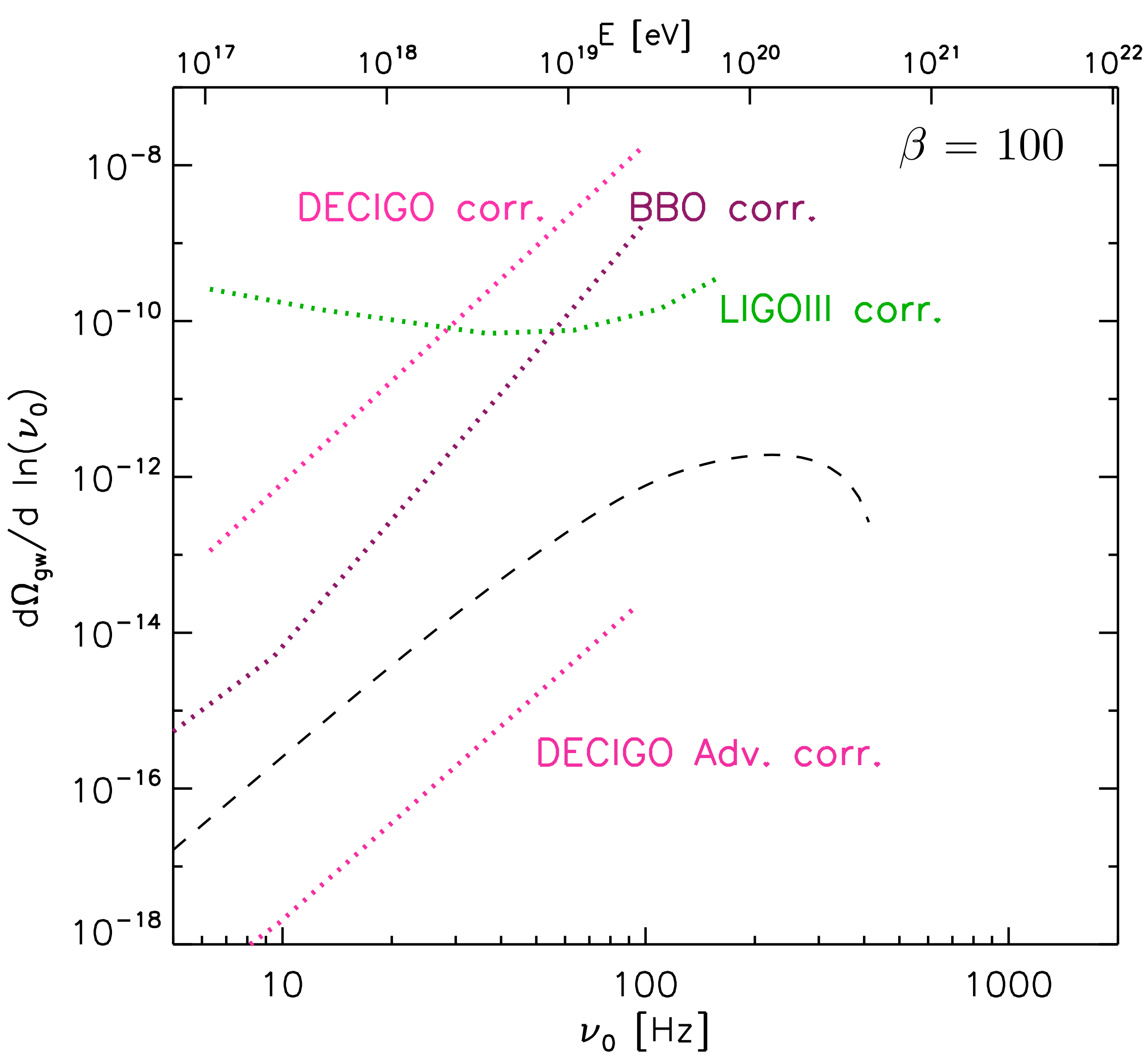
observed frequency
related to rotation velocity

cosmological param.

$$\nu = \Omega/\pi$$



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observed frequency
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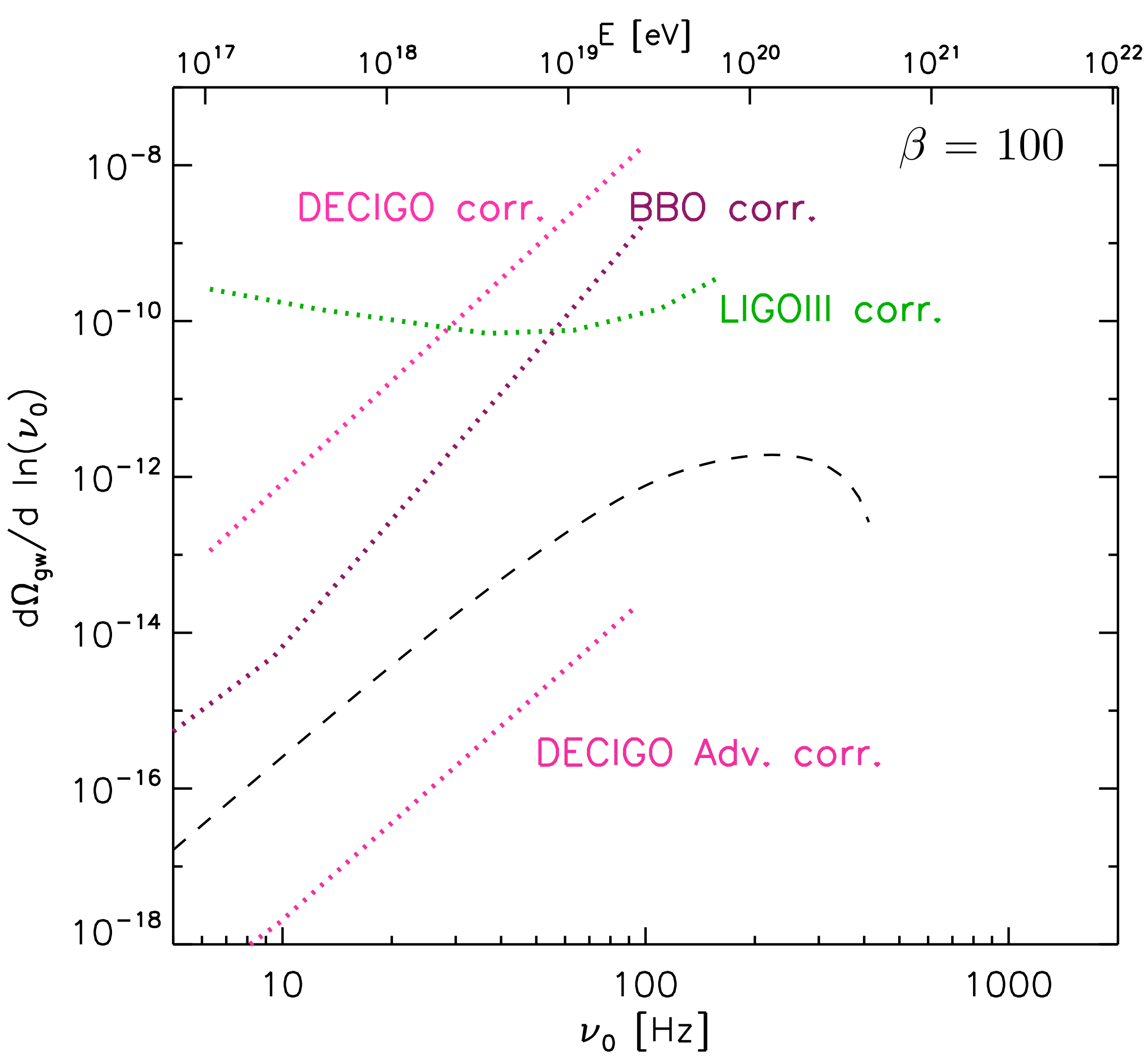
magnetar rate at z=0

cosmological param.



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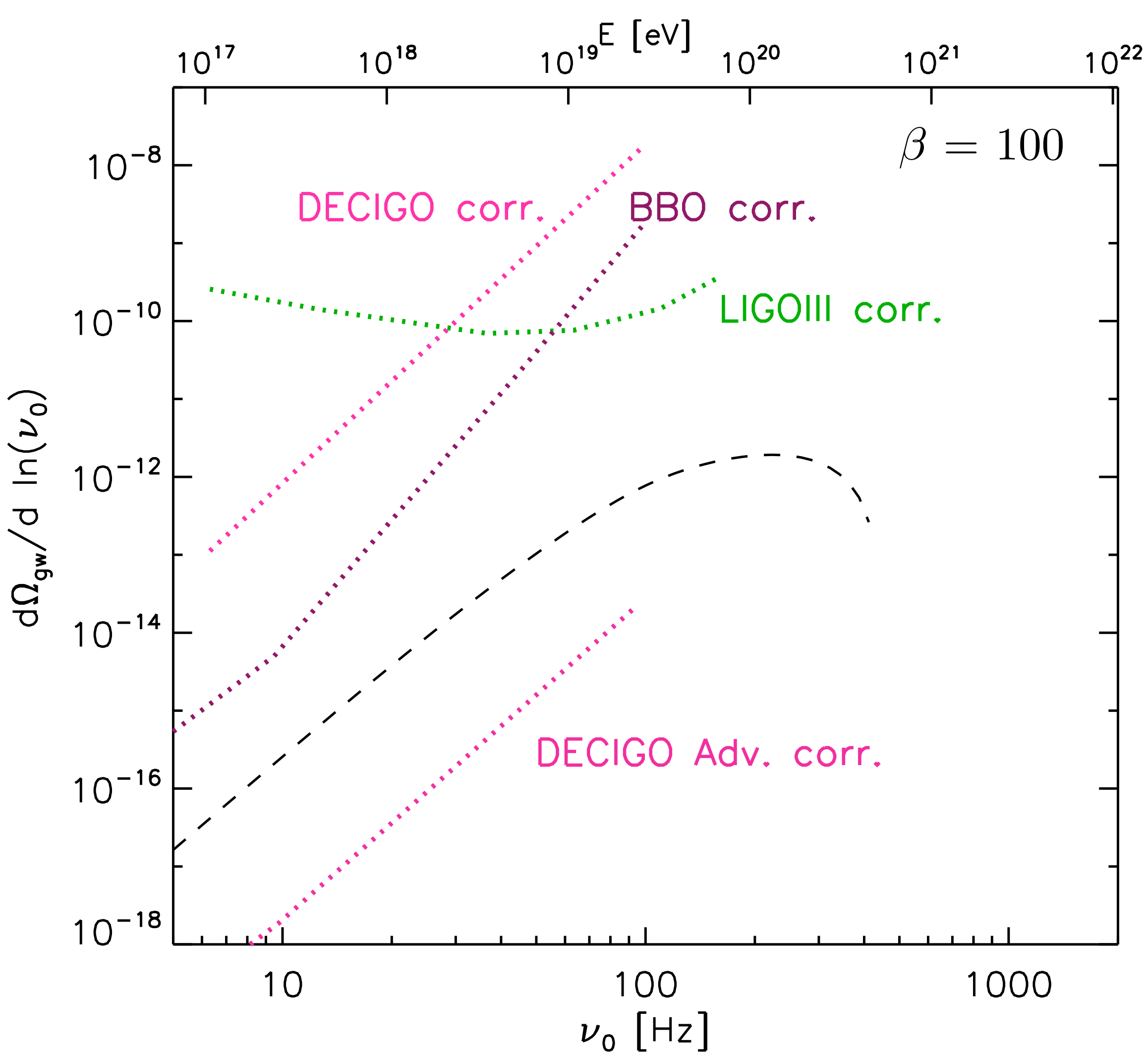

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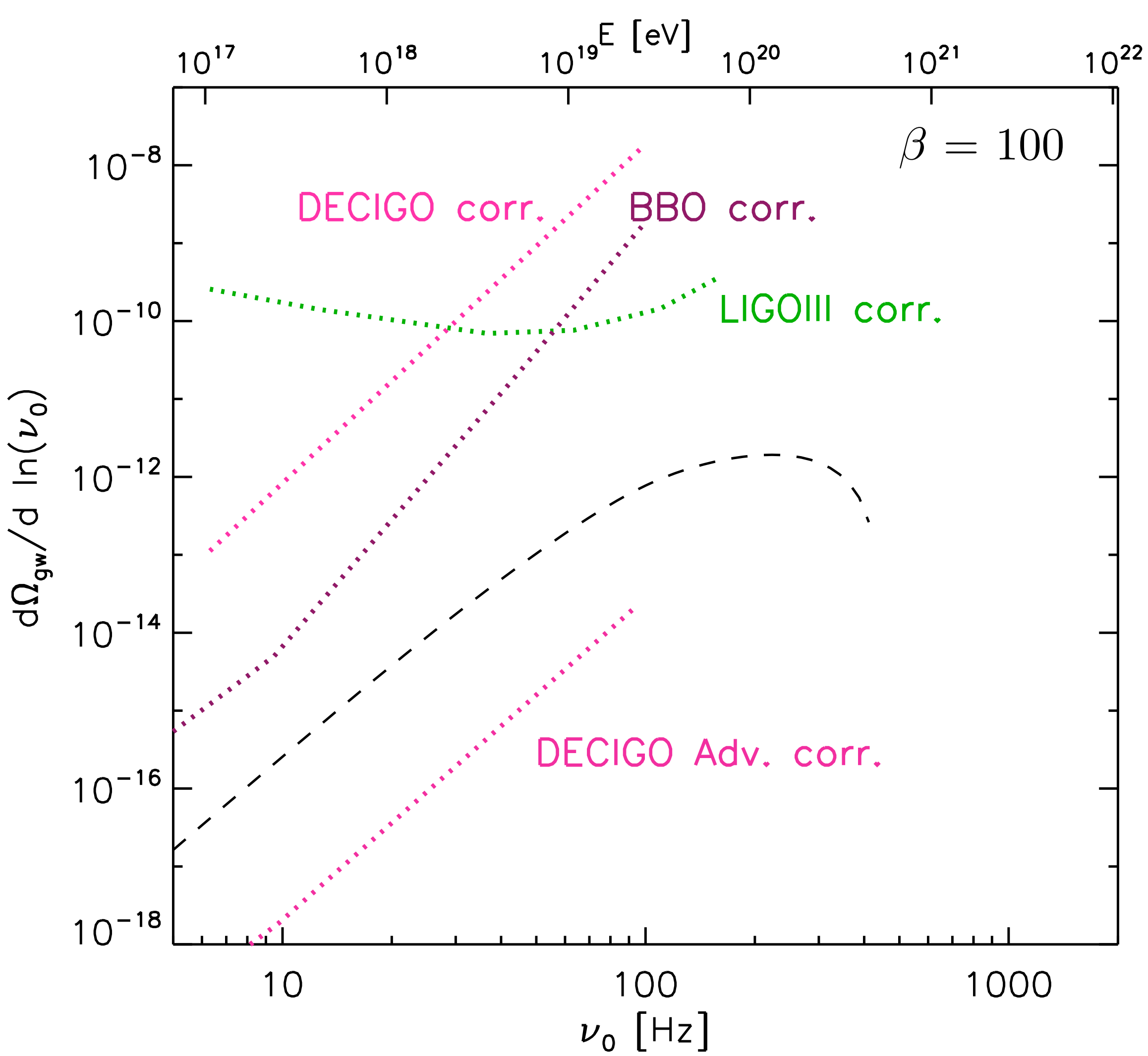

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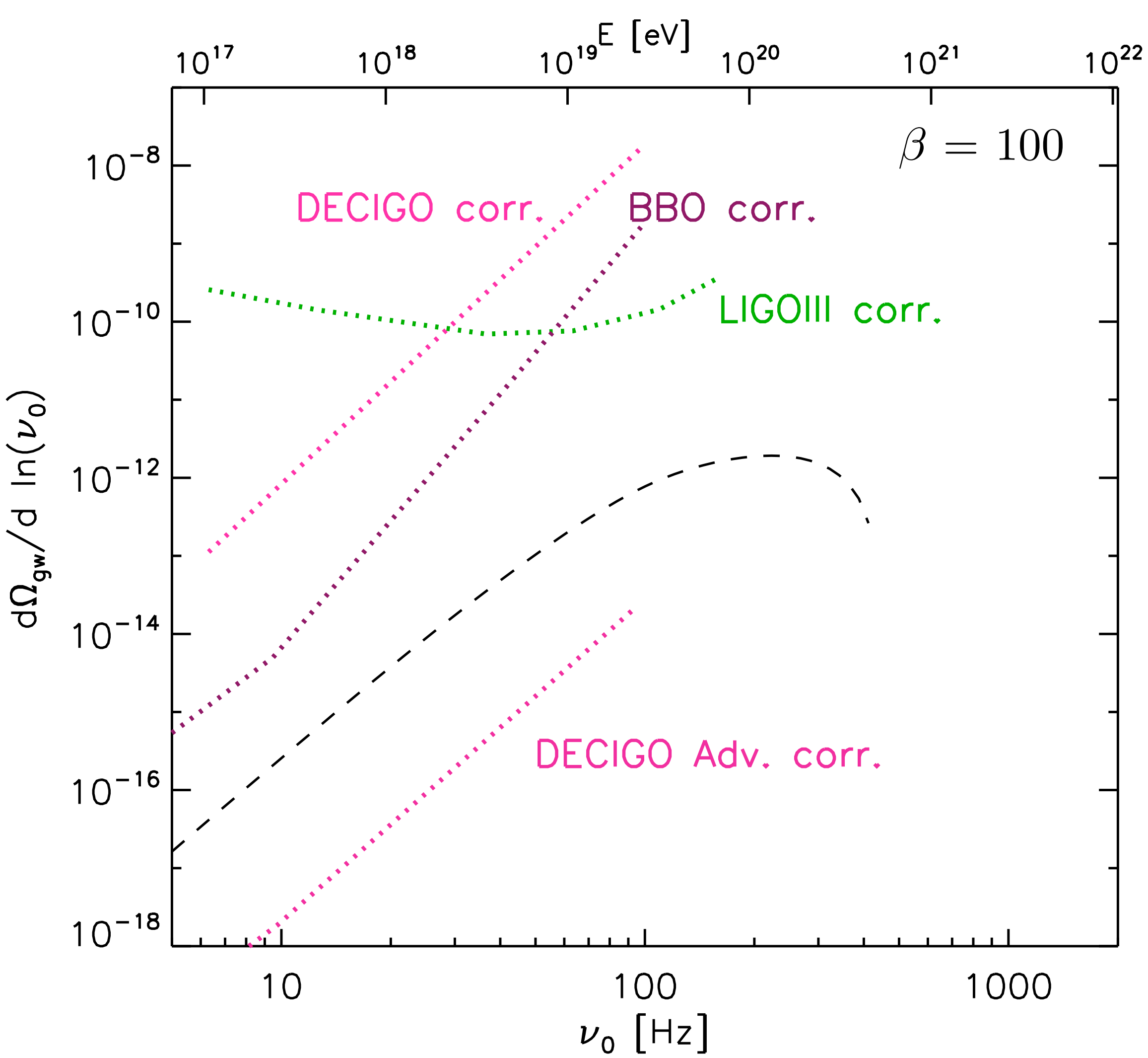

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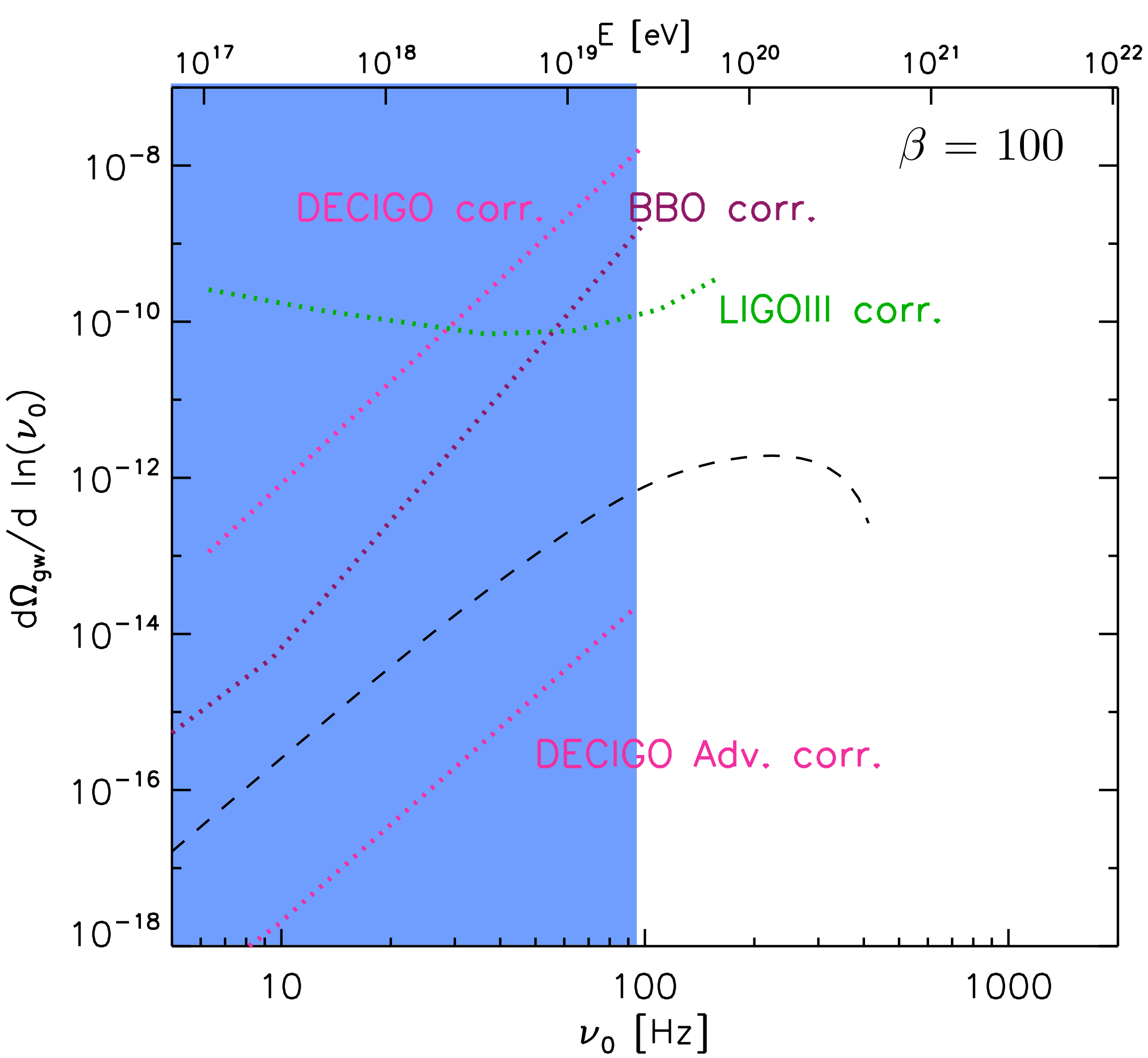

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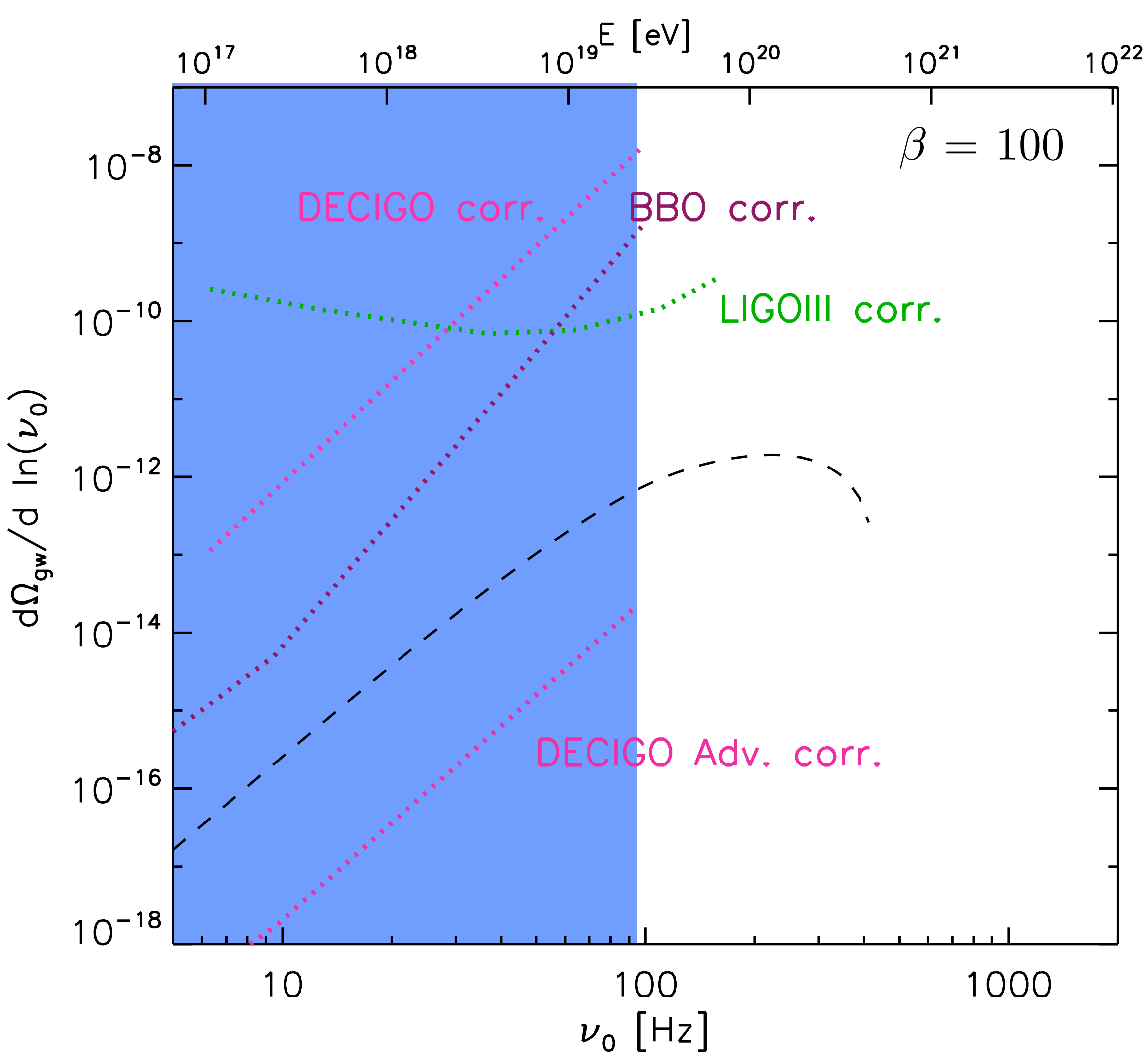

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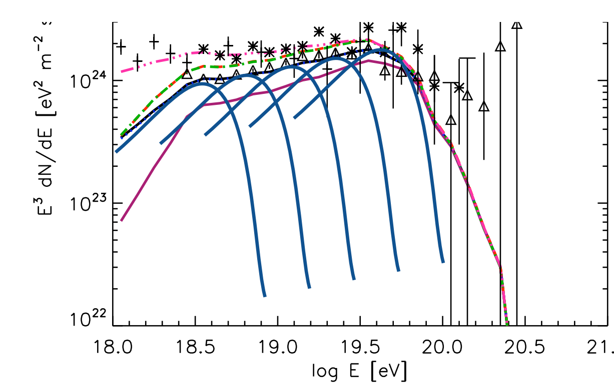

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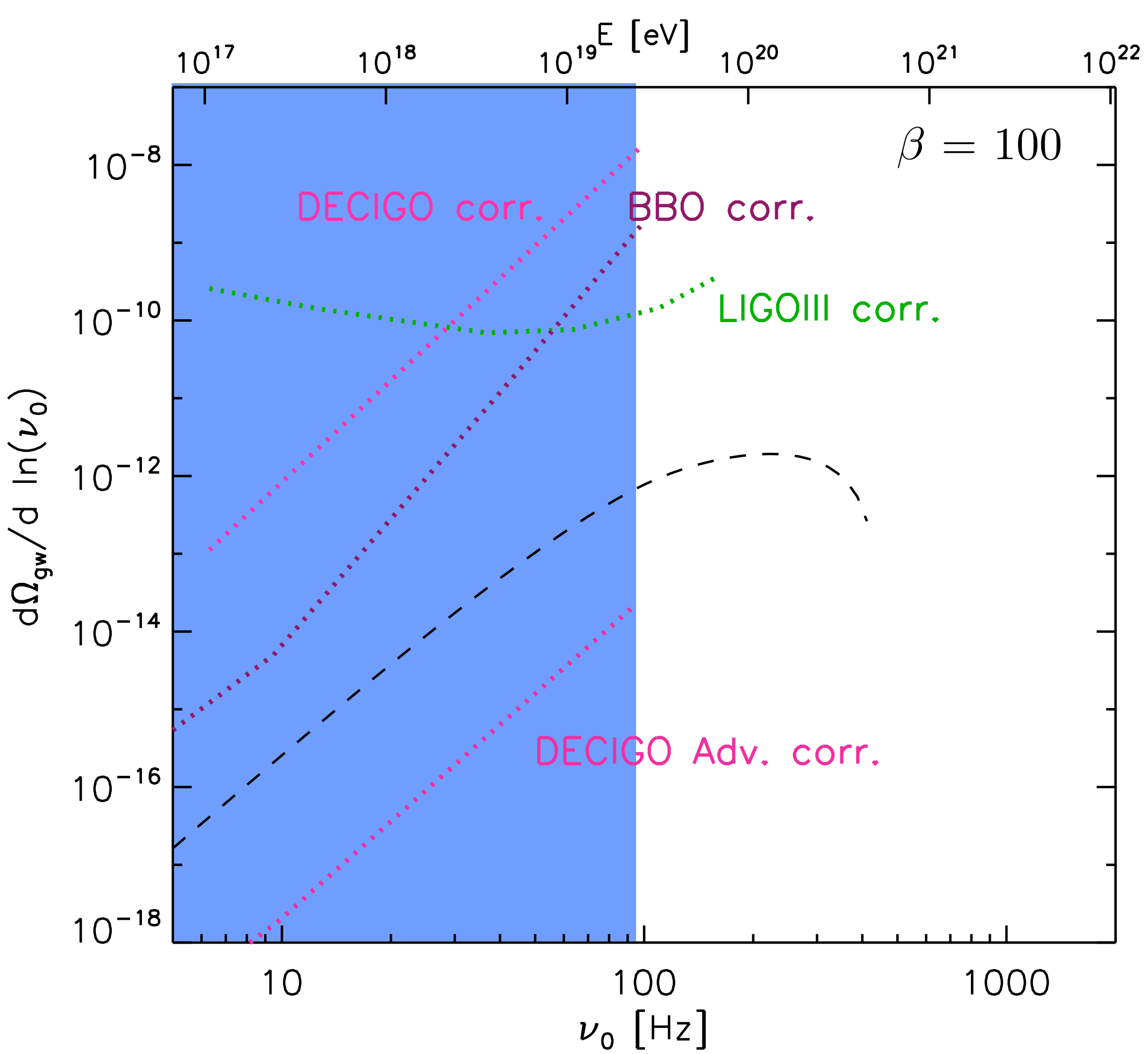

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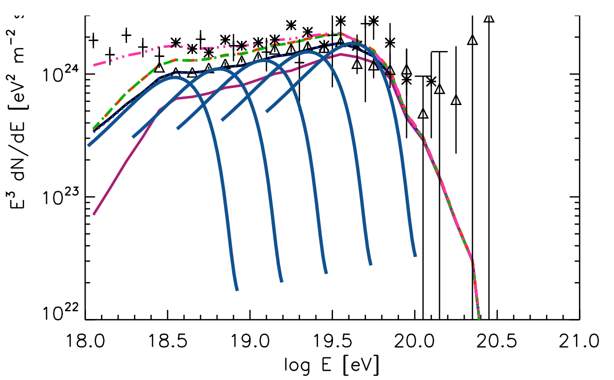

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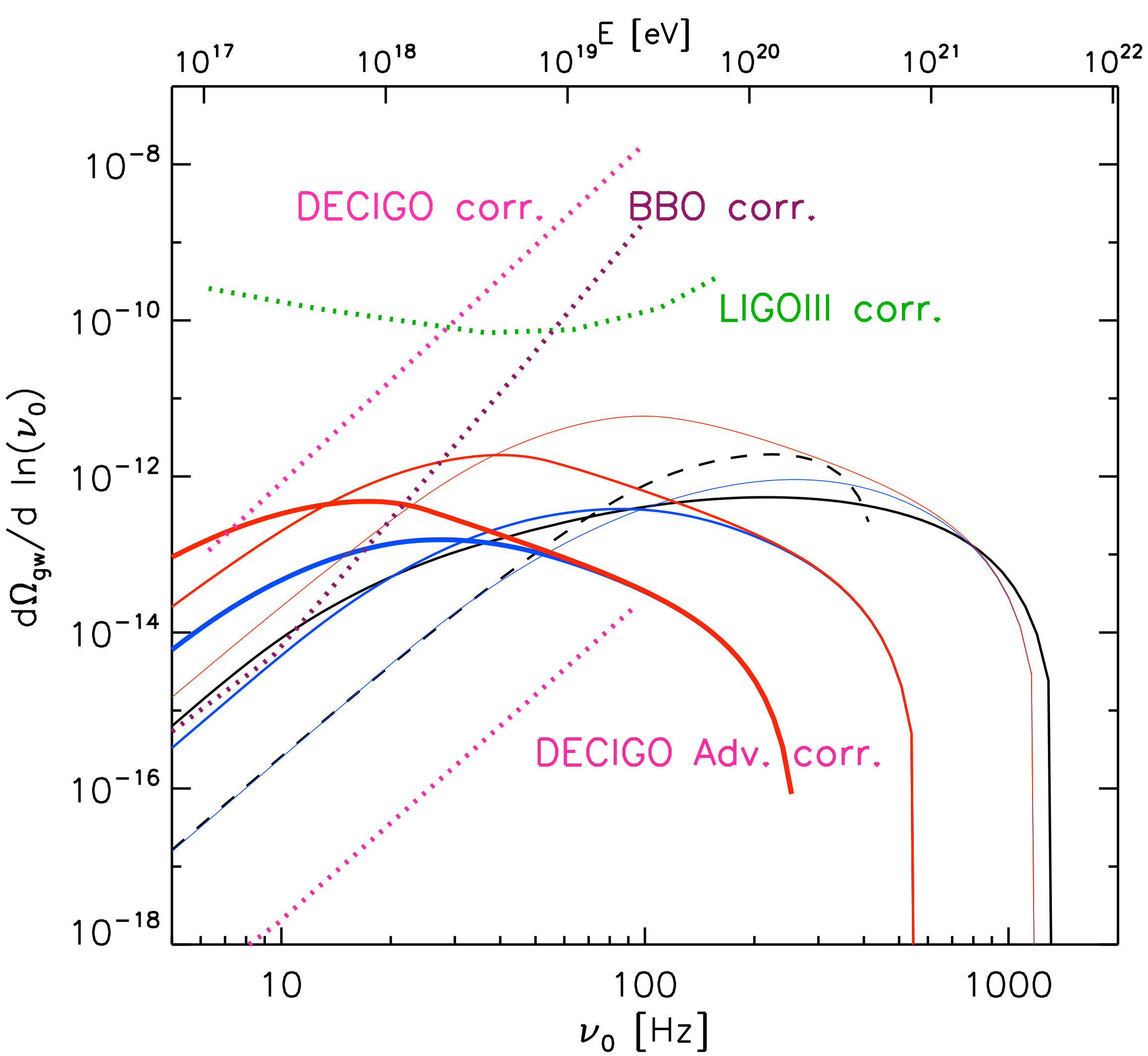

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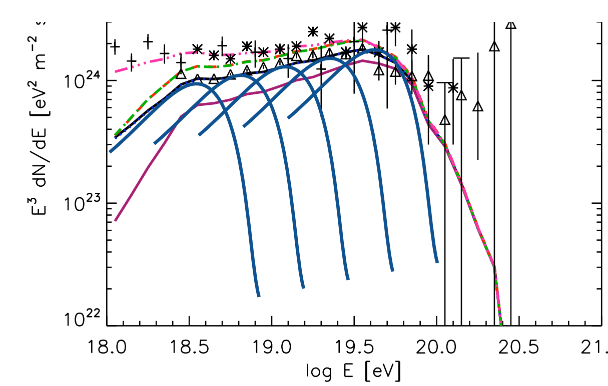

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increasing thickness: $\alpha = 10^{13,14,15}$ G Hz^{-1}

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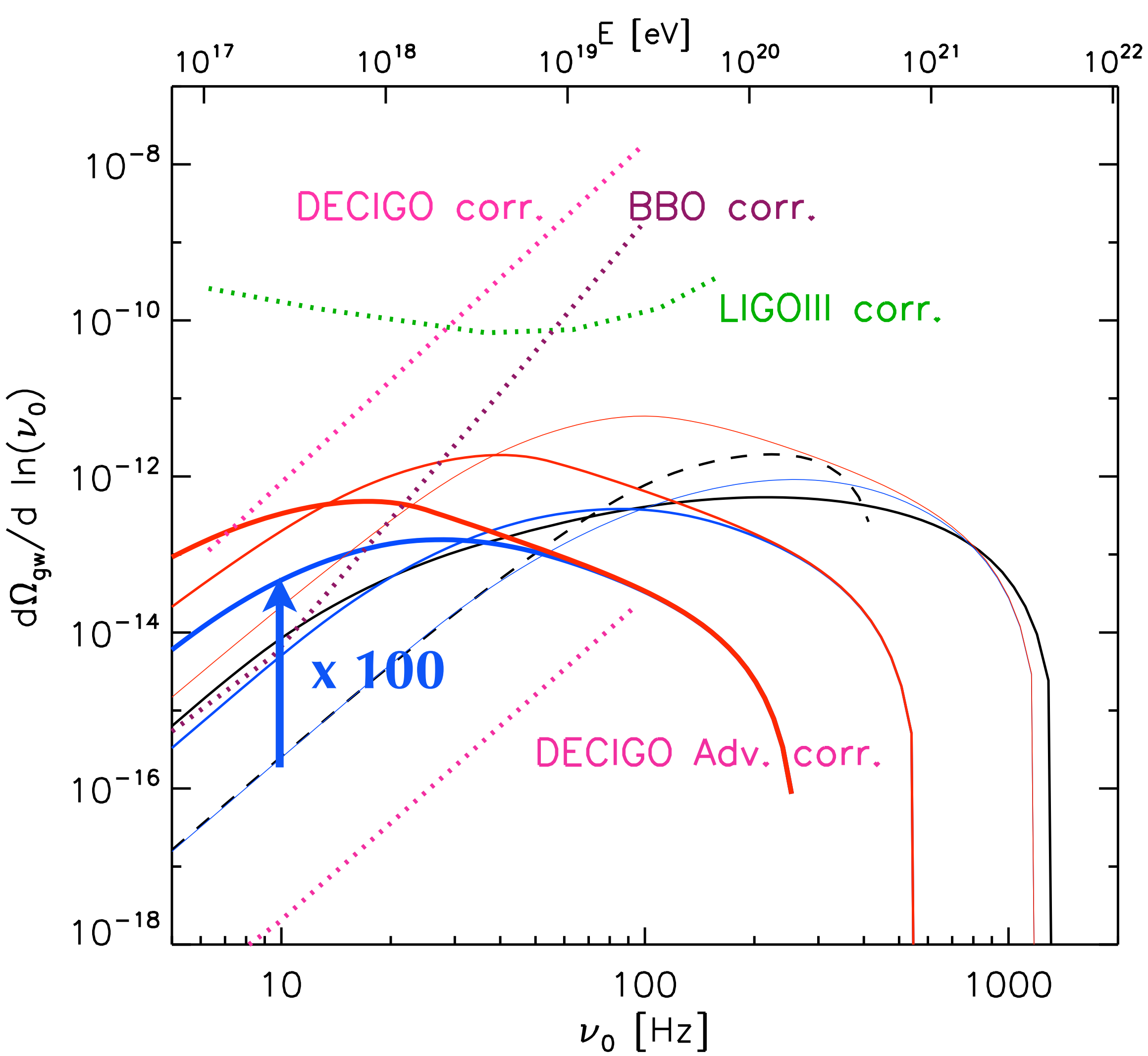

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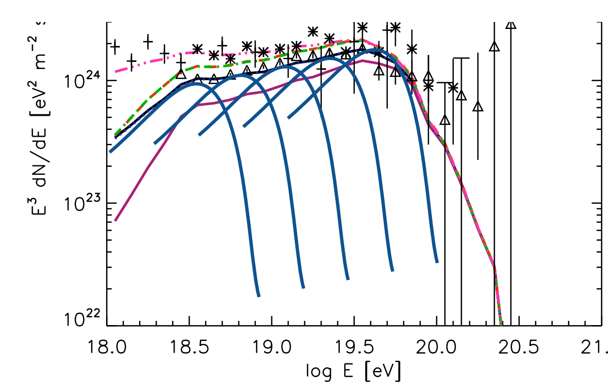

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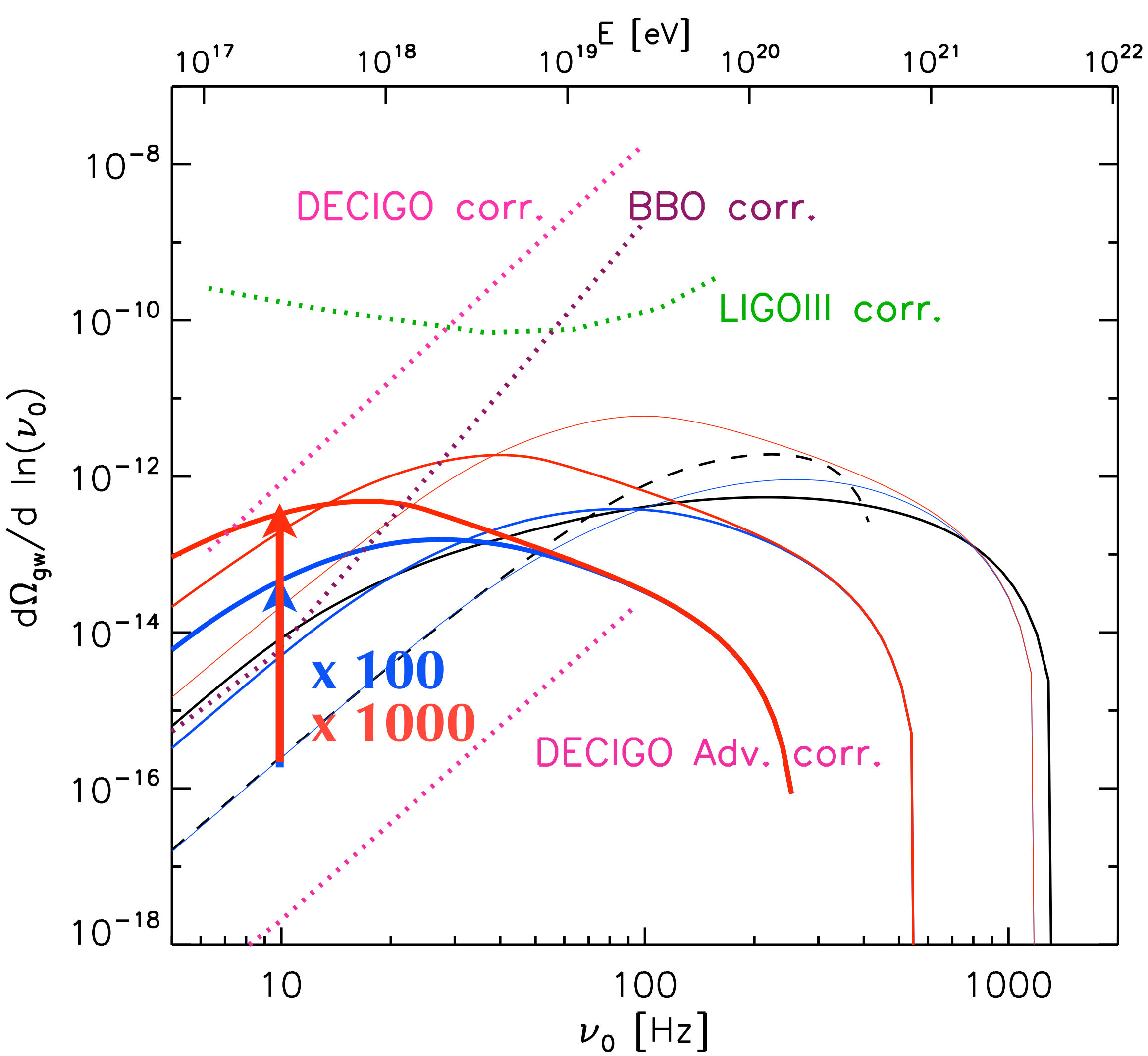

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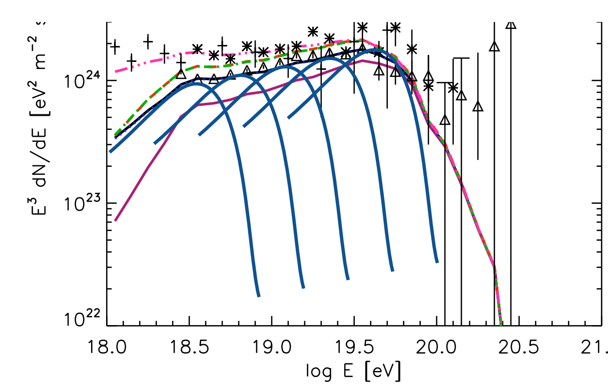

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Summary: recipe to identify UHECR sources

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

How do we discriminate them?

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

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

By looking at **diffuse secondary emissions**:

UHE neutrino spectrum ***Murase et al. 2009***

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

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signal higher of 2-3 orders of magnitude
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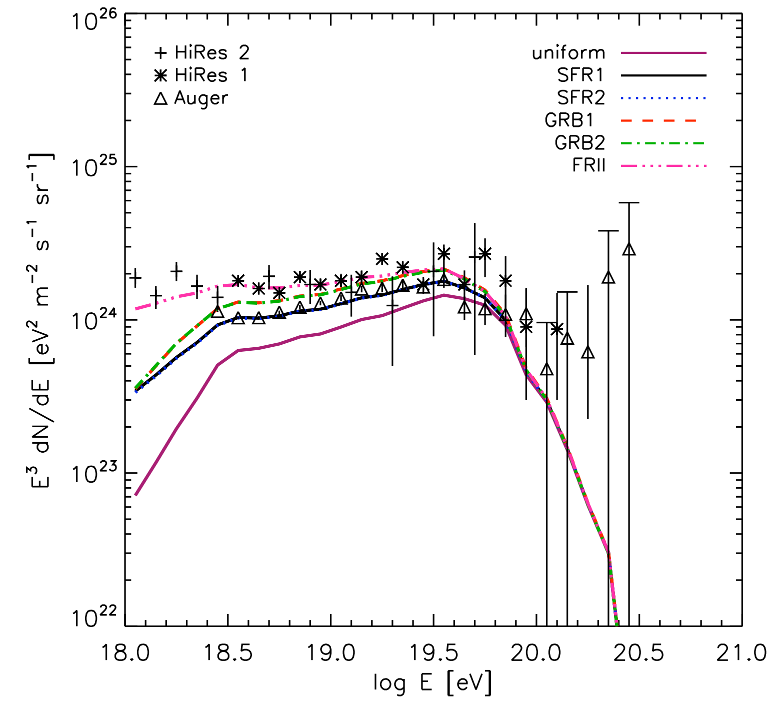

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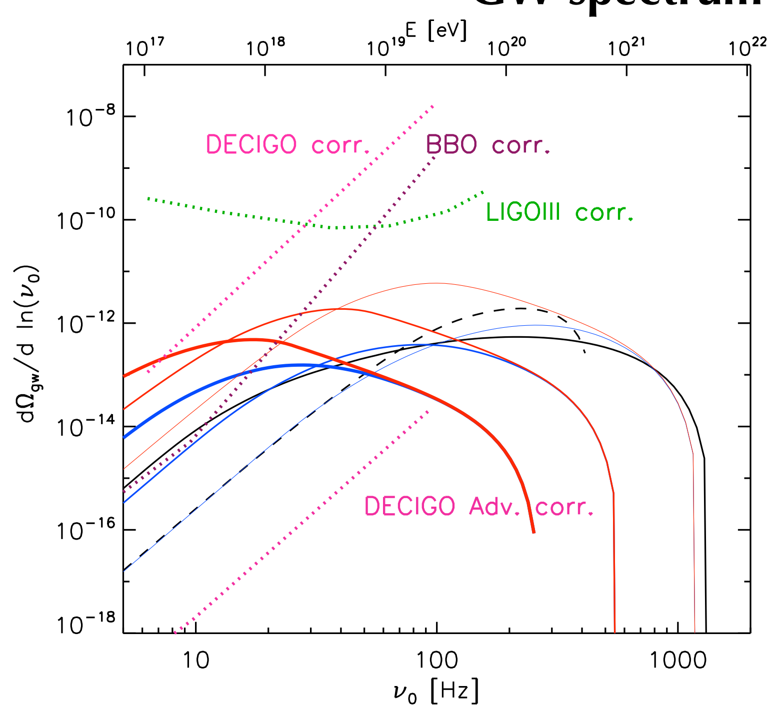

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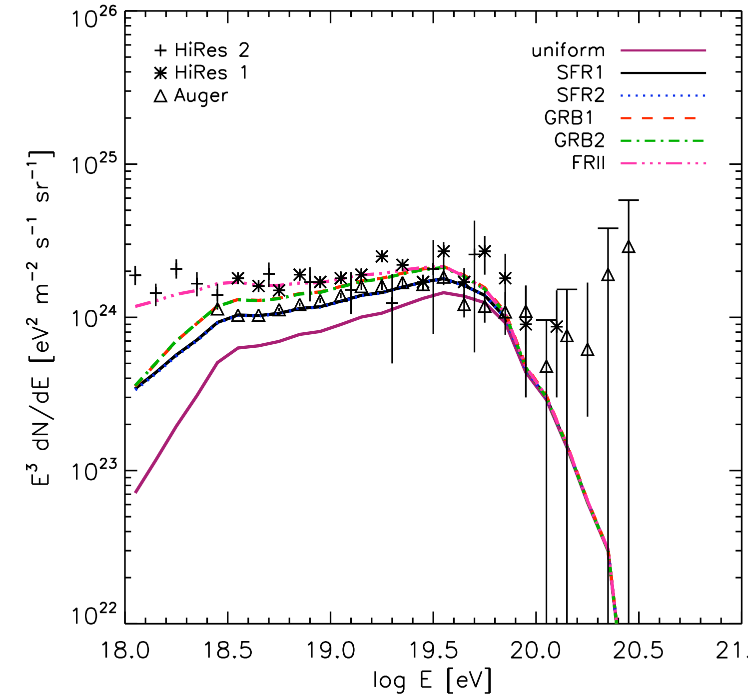

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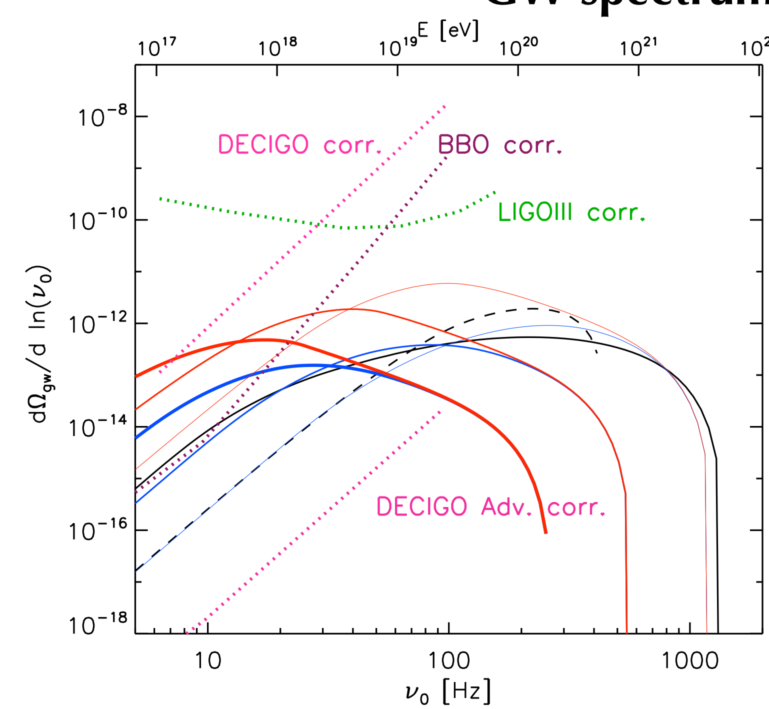

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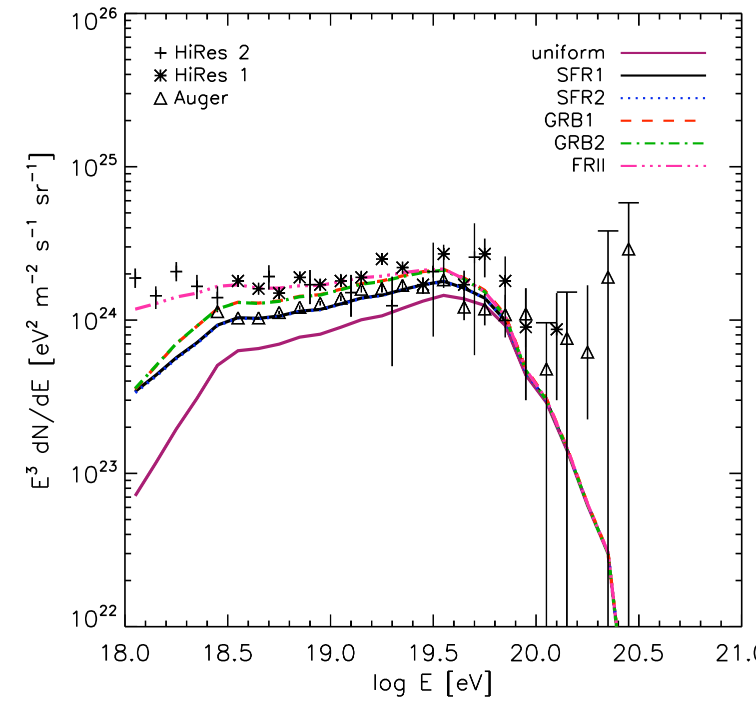

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