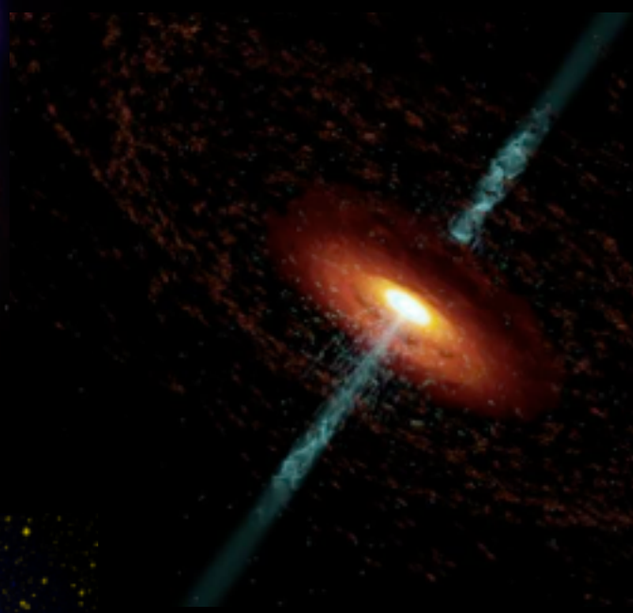
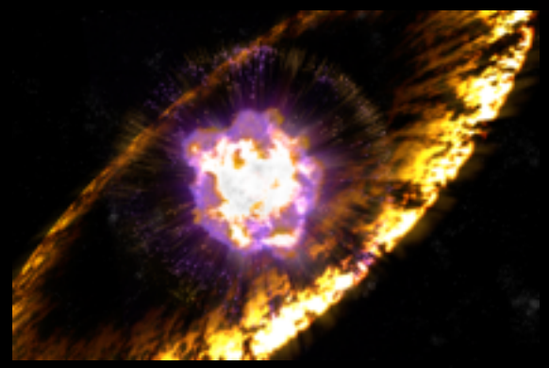
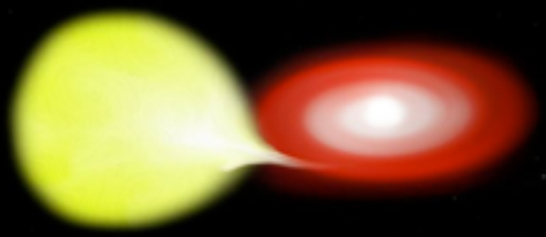
Multi-messengers from transient candidates of UHECRs







UHECRs cannot be protons from steady sources

necessary condition for successful particle acceleration *Lemoine & Waxman 09*

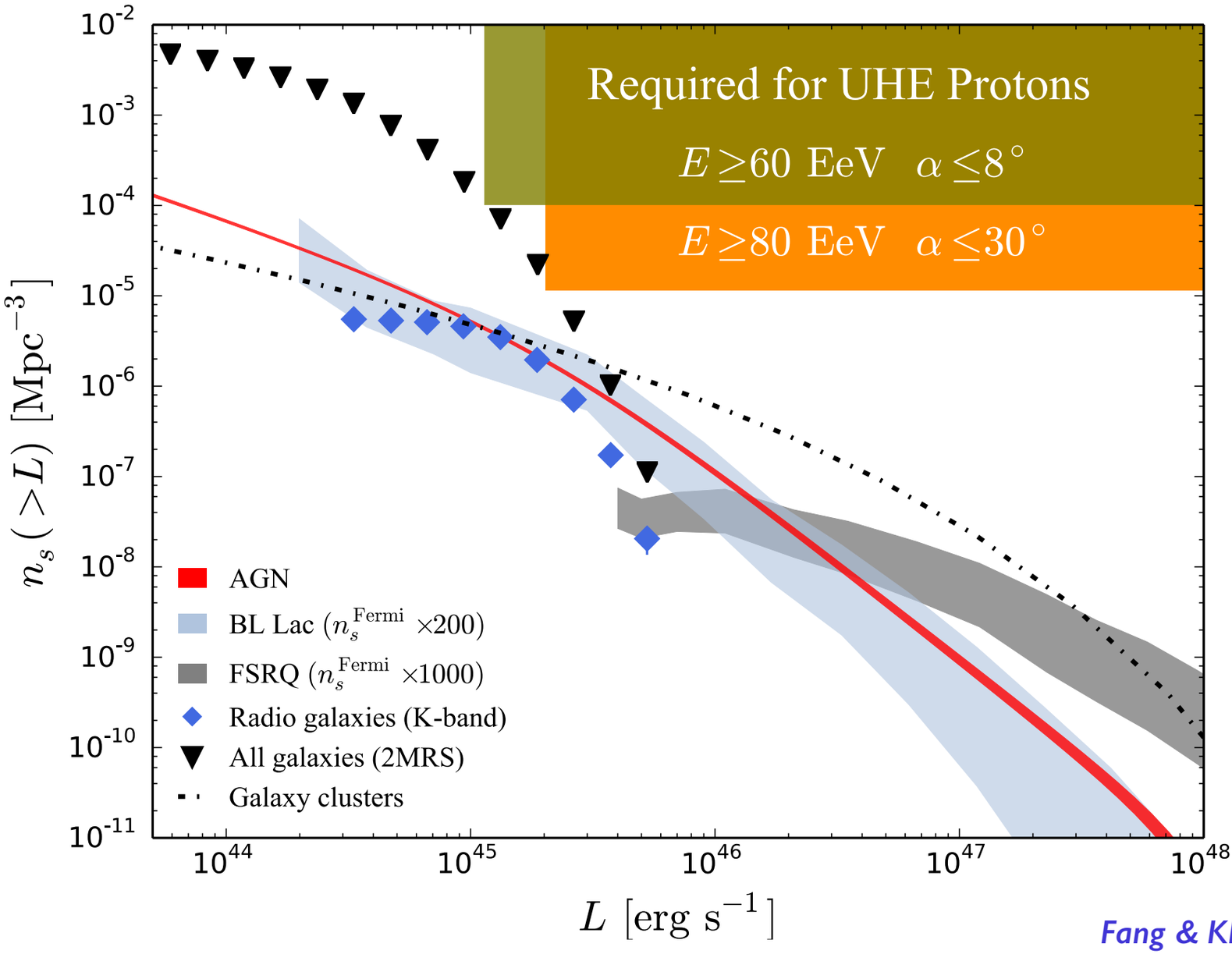
outflow magnetic luminosity $L_B \equiv \Gamma_{\rm w} R^2 B^2/2 > 10^{45}\, Z^{-2} E_{20}^2\ {\rm erg\ s^{-1}}$

➢ **lower bound of the bolometric luminosity of source**

level of anisotropy in the sky in Auger data *Abreu et al. 2013*

➢ **apparent number density of sources** @ given energy and angular deflection α

Ke Fang's talk (Tuesday AM)



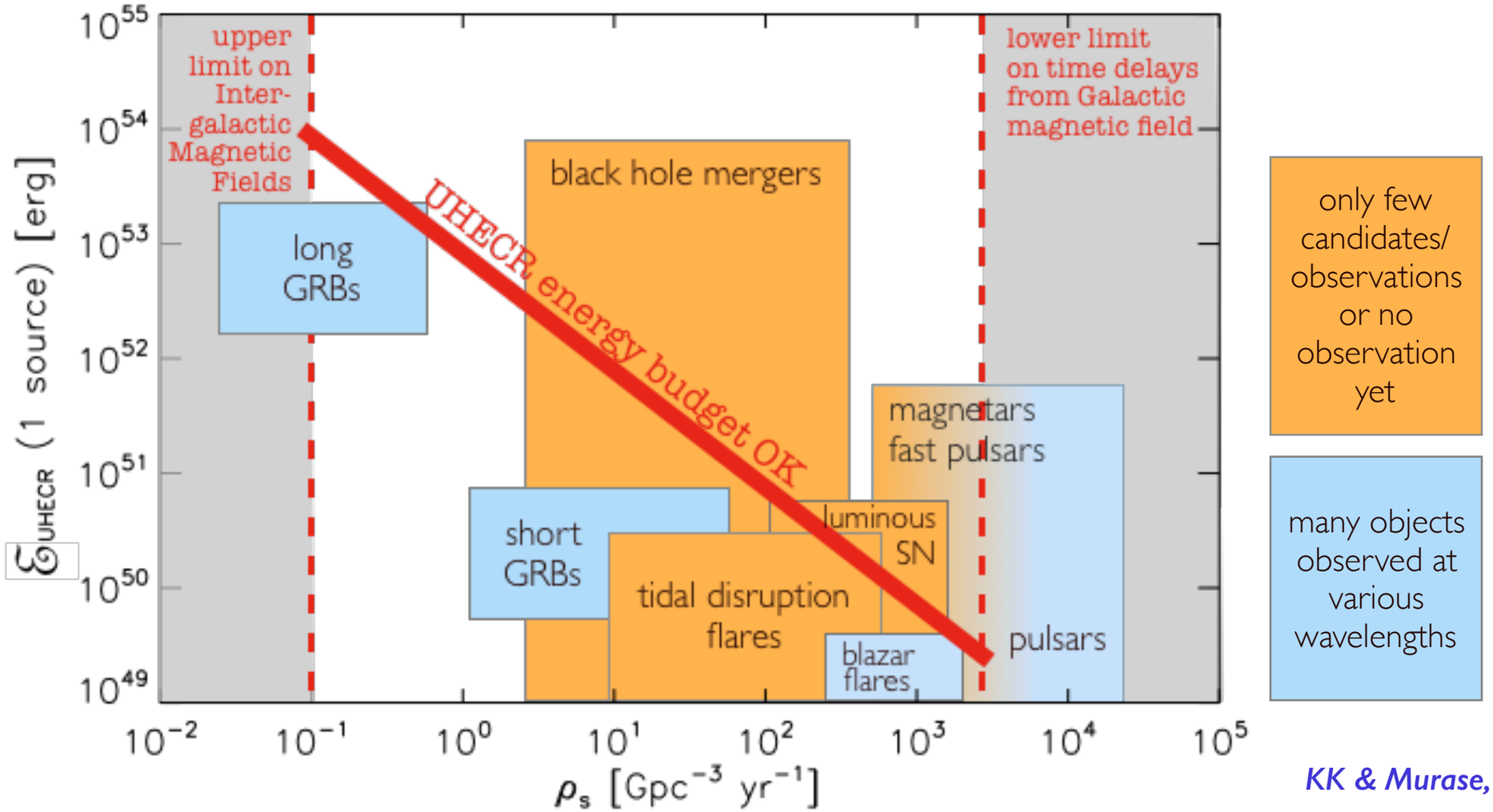
Fang & KK, submitted

The transient energy budget

level of anisotropy in the sky in Auger data
➢ **apparent number density of sources** n_0 @ given energy and angular deflection α

for transient sources: **real number density** of UHE proton sources
$\rho_0 \sim n_0$ / (CR time spread τ_d)
τ_d depends on extragalactic + Galactic magnetic fields (not known) *Murase & Takami 09*

▶ Observed energy budget in UHECRs $E_{\rm UHECR}\,\rho_0 = 10^{44.5}\,{\rm erg\,Mpc^{-3}\,yr^{-1}}$



KK & Murase, in prep.

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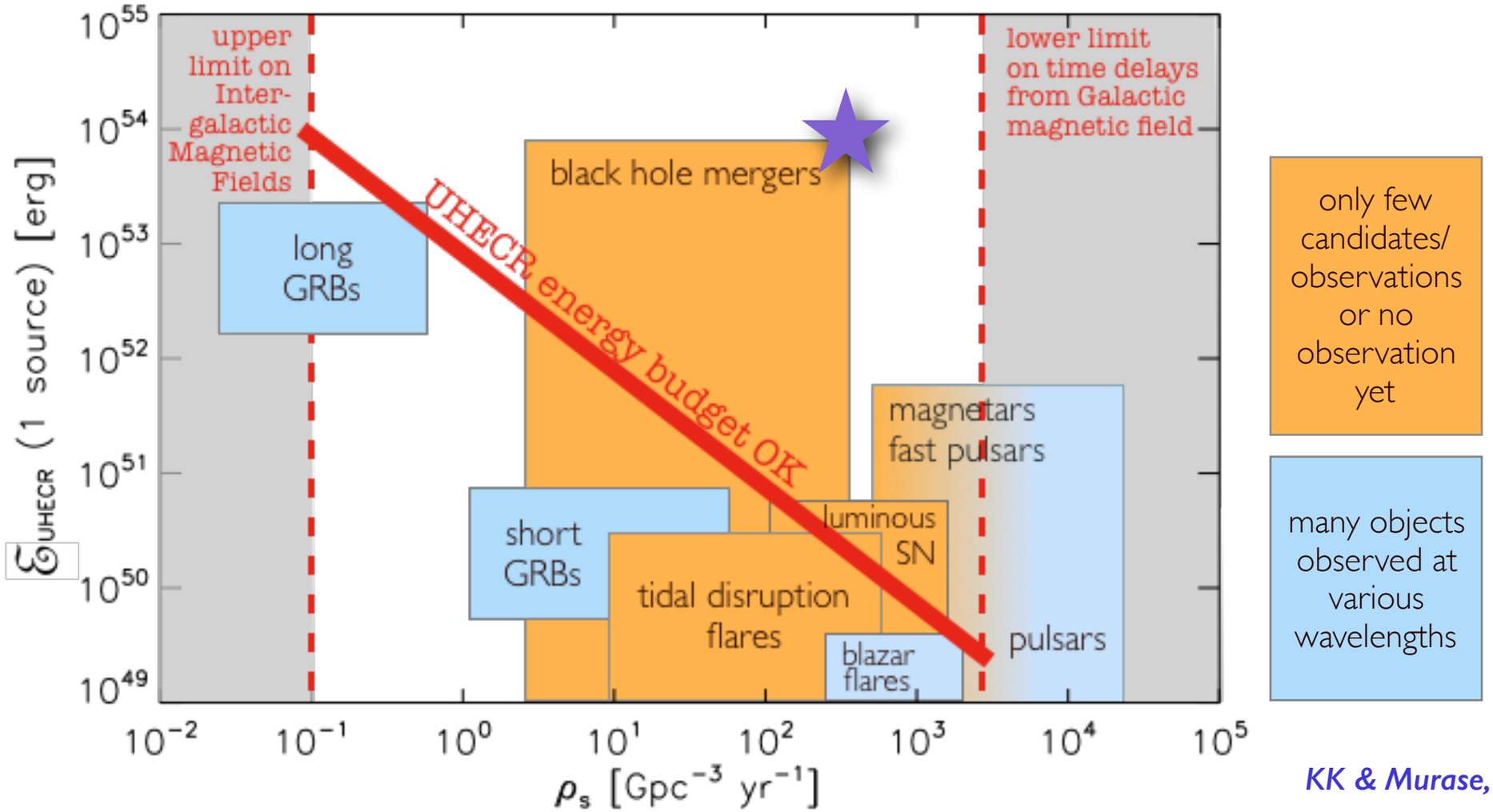

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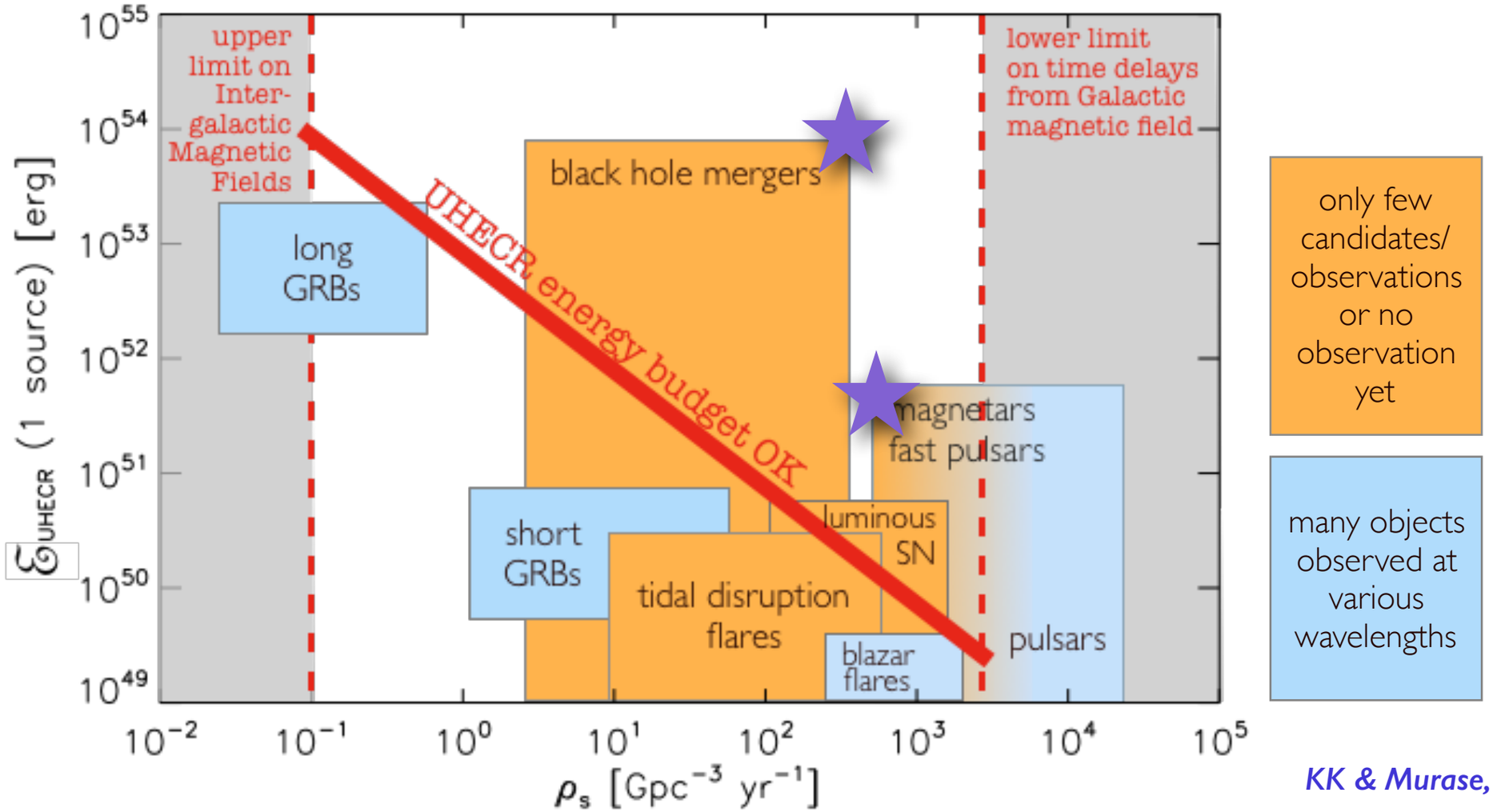

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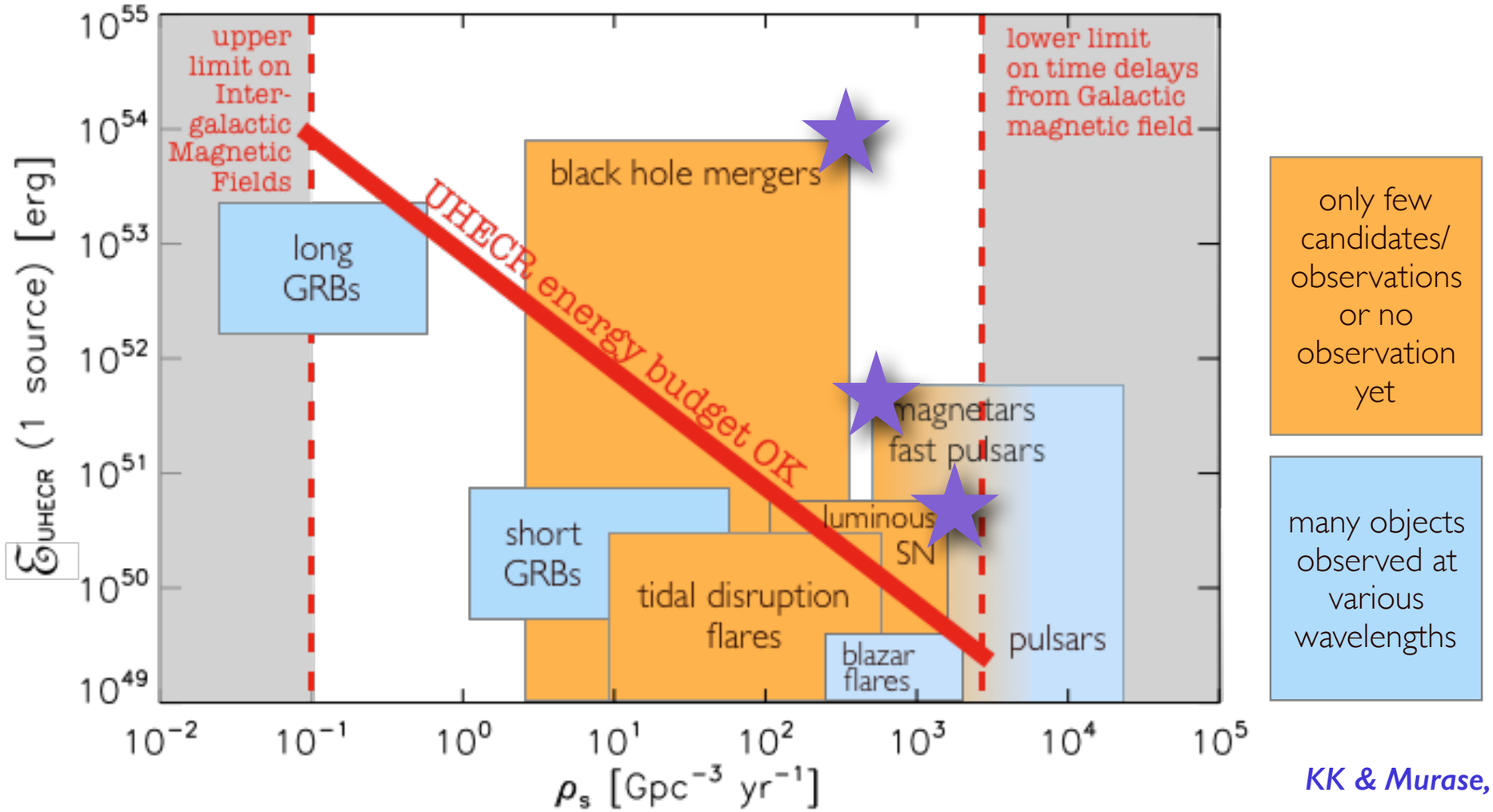


only few candidates/ observations or no observation yet

many objects observed at various wavelengths

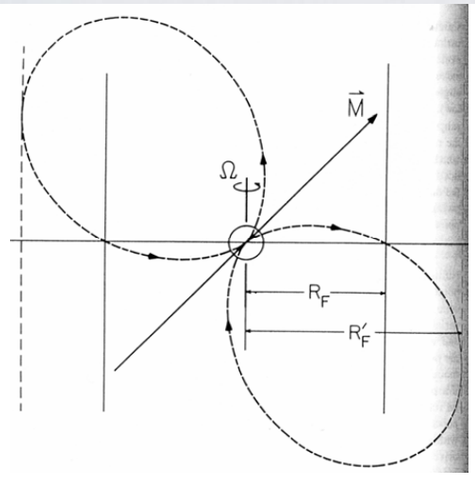
KK & Murase, in prep.

Particle acceleration in pulsars/magnetars

Charge density

Induced electric field

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



Implies a charge density (Goldreich-Julian 69)

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

e.g.
Blasi et al. (2000)
Arons et al. (2003)
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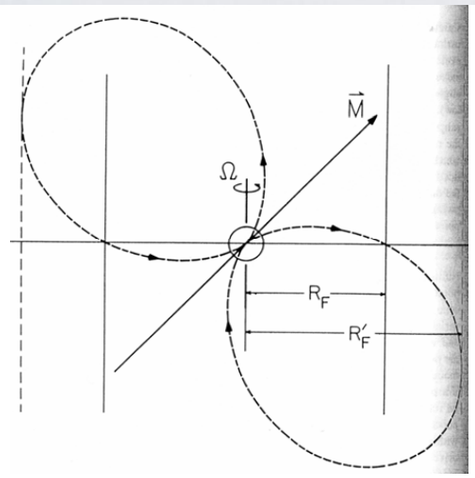

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total energy $E_{\rm p} = \frac{I\Omega_{\rm i}^2}{2} \sim 1.9 \times 10^{52}\,{\rm erg}\, I_{45} P_{\rm i,-3}^2$

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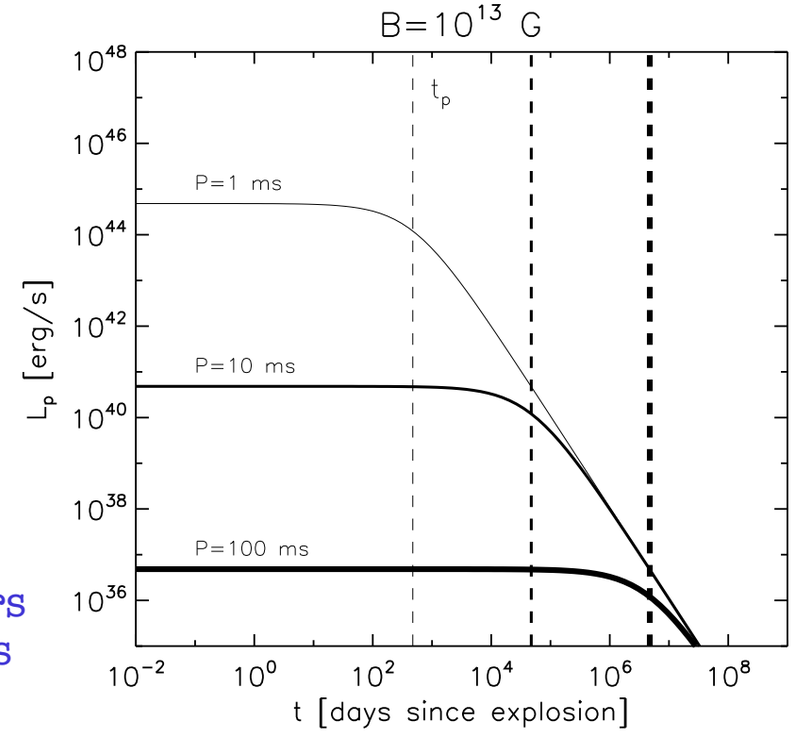

$t_{\rm p}$ ~ a few years for ms pulsars

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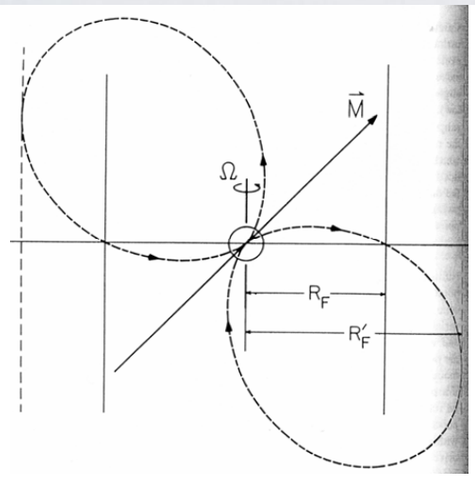

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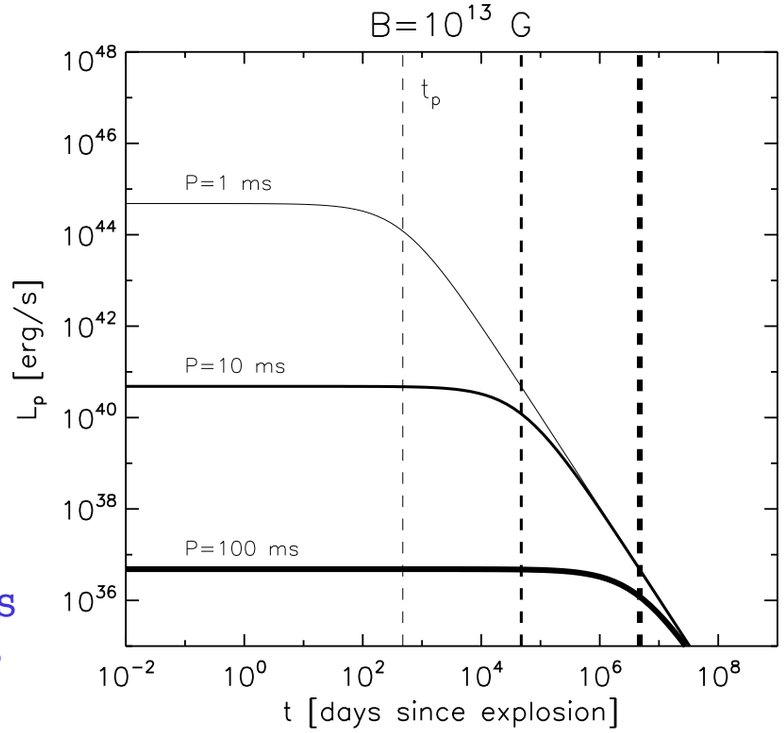

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conversion of pulsar electromagnetic into kinetic energy

particles accelerated to maximum Lorentz factor:

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

← Goldreich-Julian charge density

maximum energy:

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

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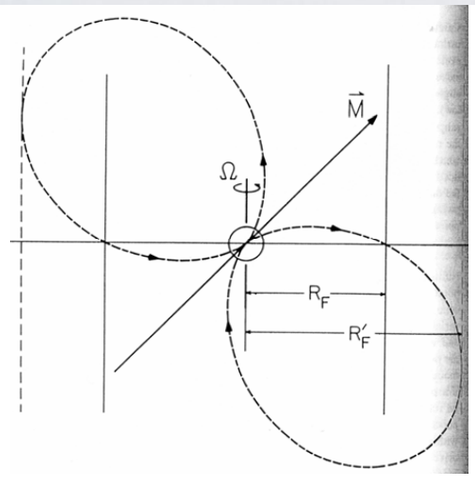

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Pulsars born with ms periods and magnetars are good candidates of UHECR sources

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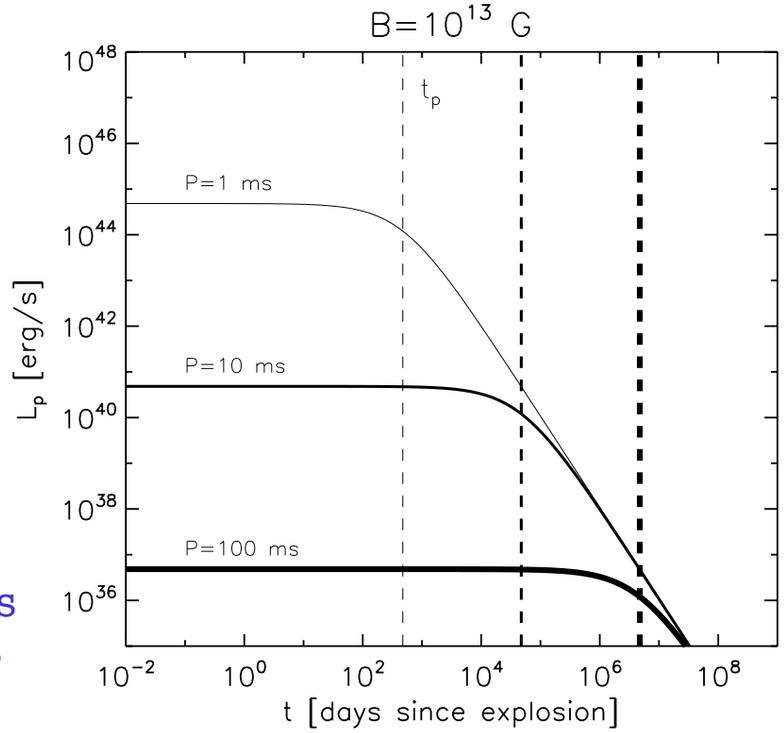

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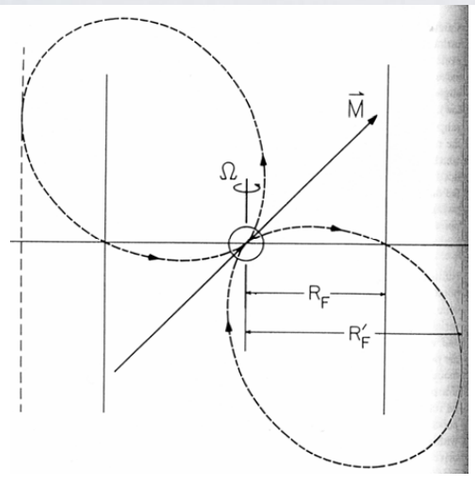

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Lemoine, KK & Pétri (2015)

composition

neutron stars have metal-rich surfaces: ideal site for heavy nuclei production

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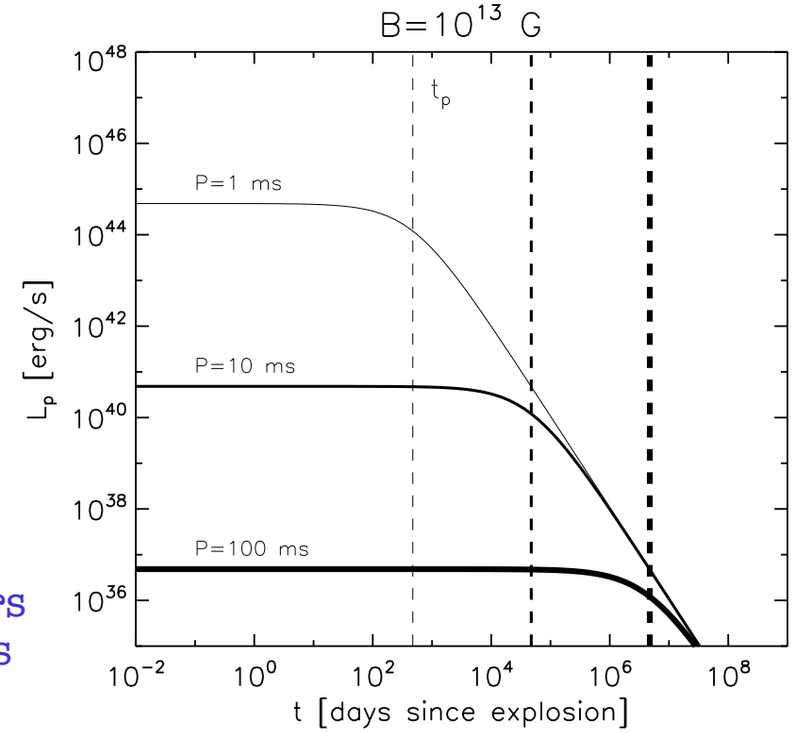

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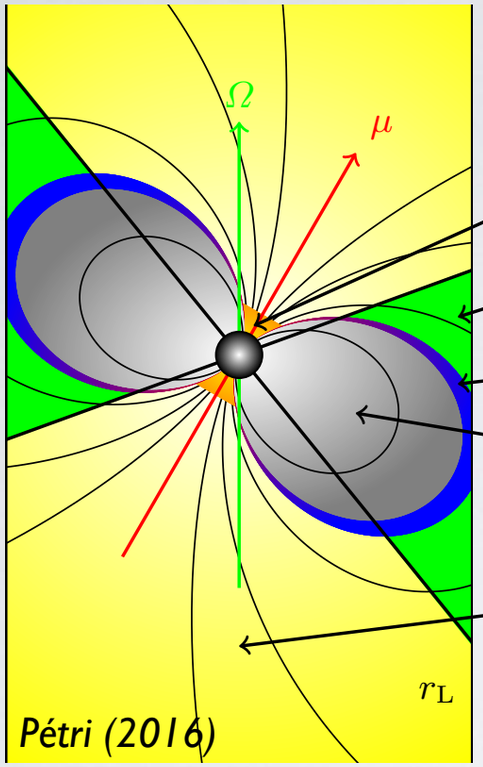
Cosmic ray acceleration in pulsars

- Acceleration region?



Pétri (2016)

polar cap

outer gap

slot gap

closed magnetosphere

open field lines
(base of the wind)

- Gaps close to star

reviews: Harding (2007), Hirotani (2008)

Cosmic ray acceleration in pulsars

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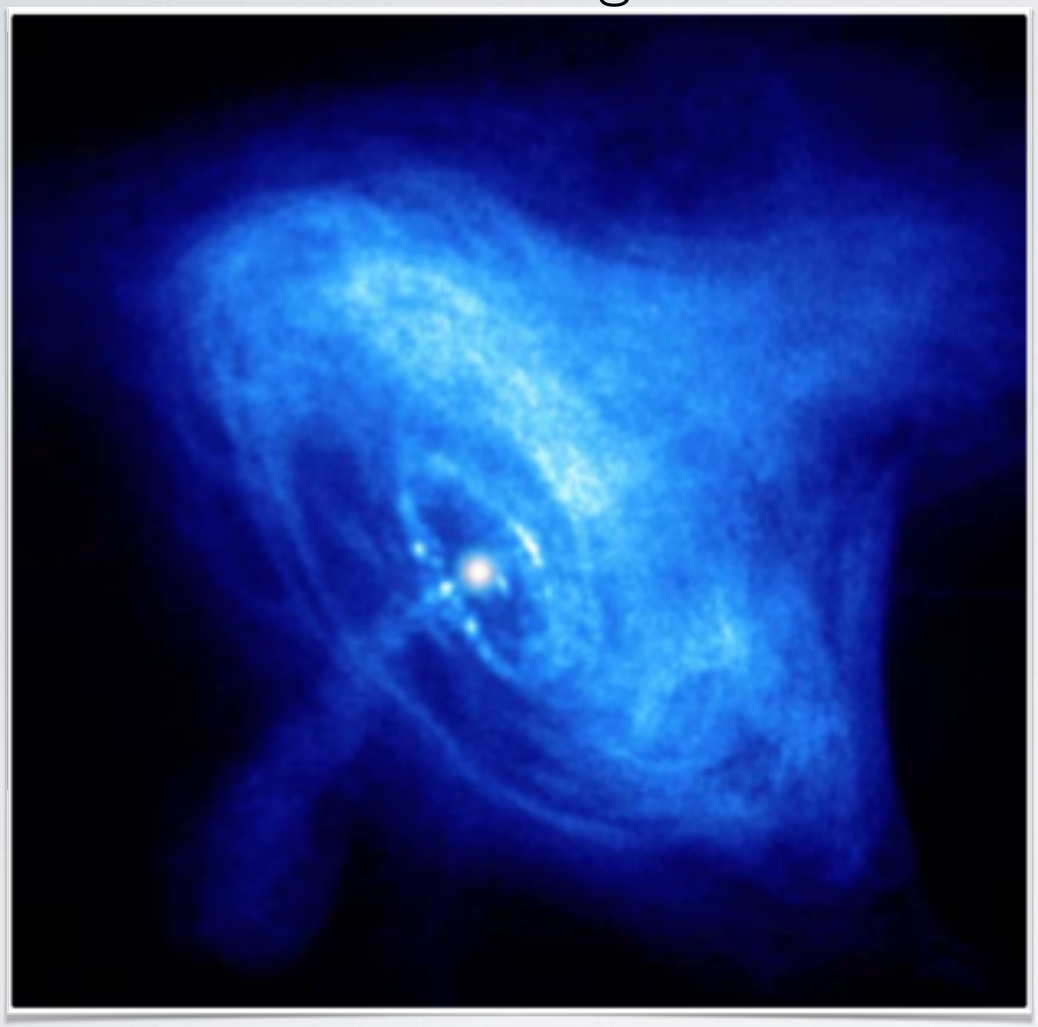

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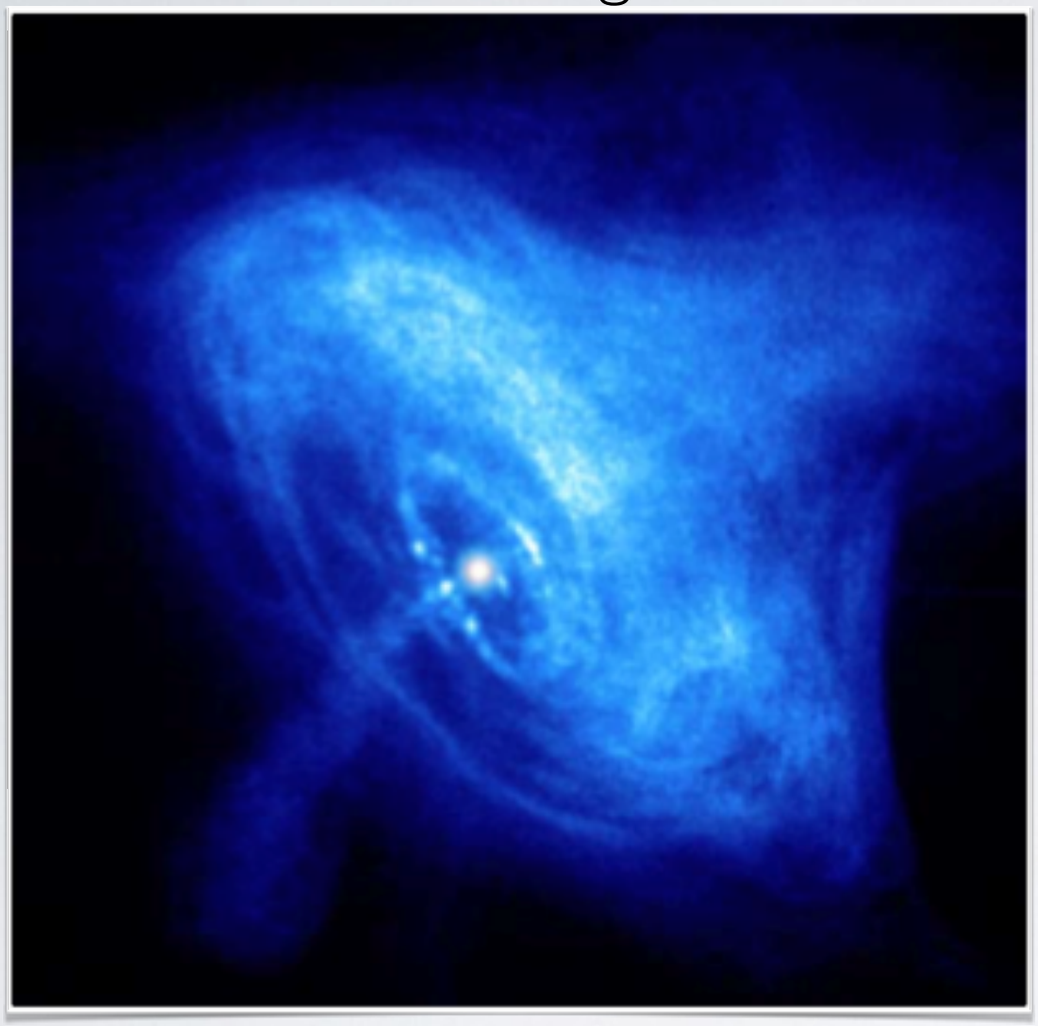

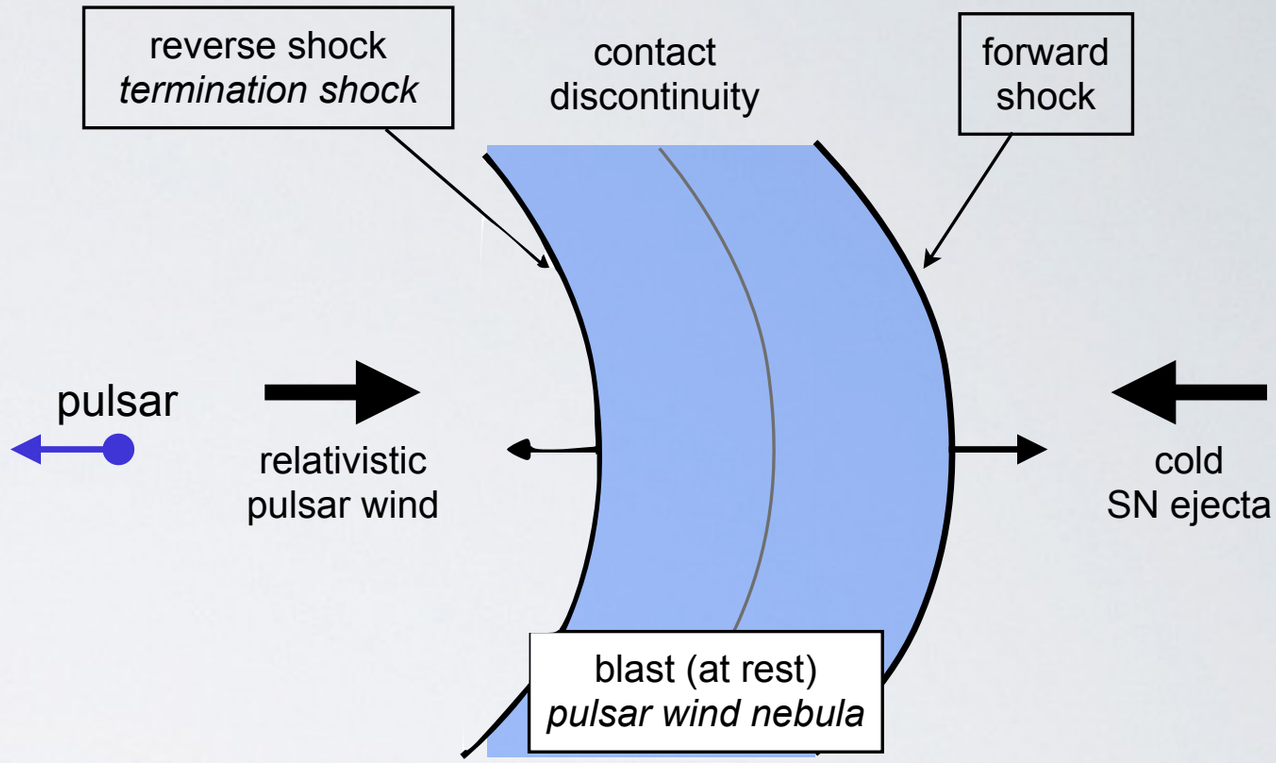

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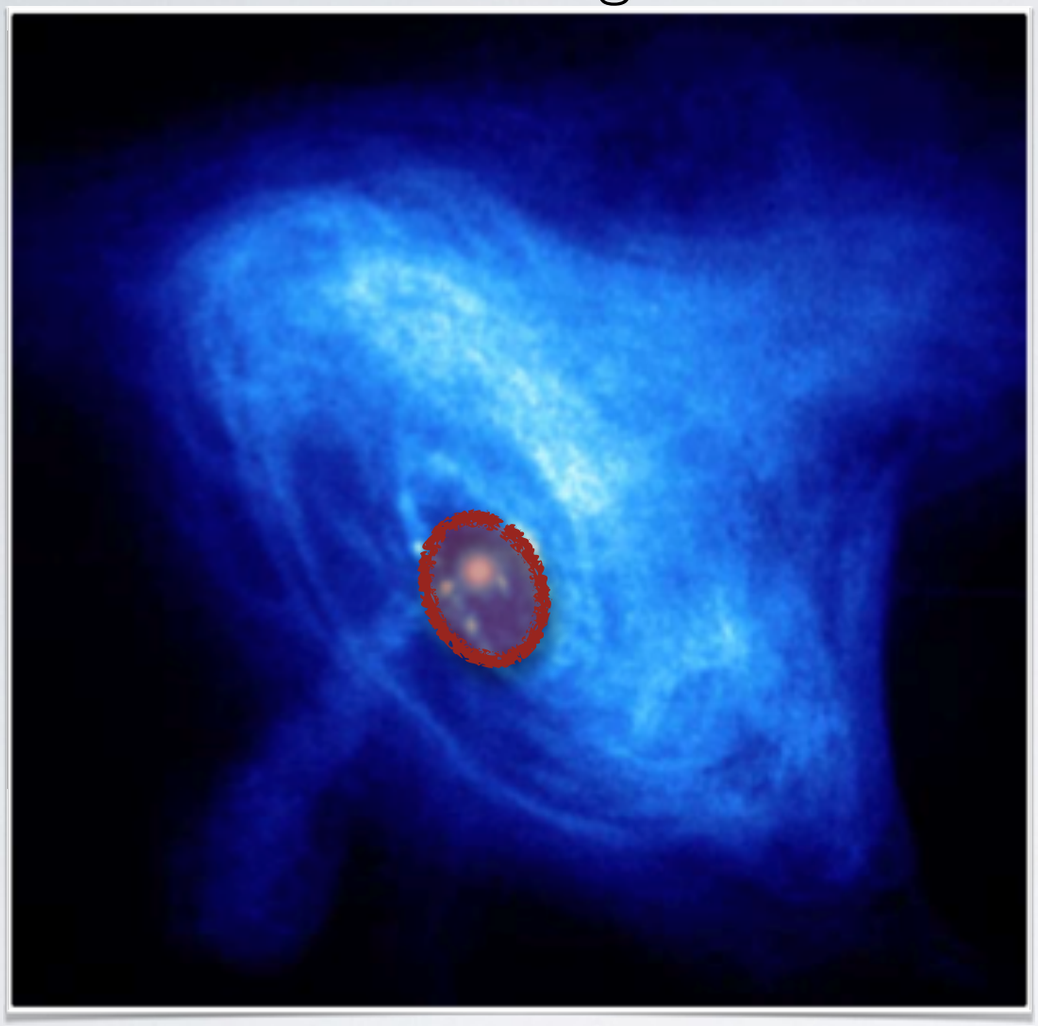

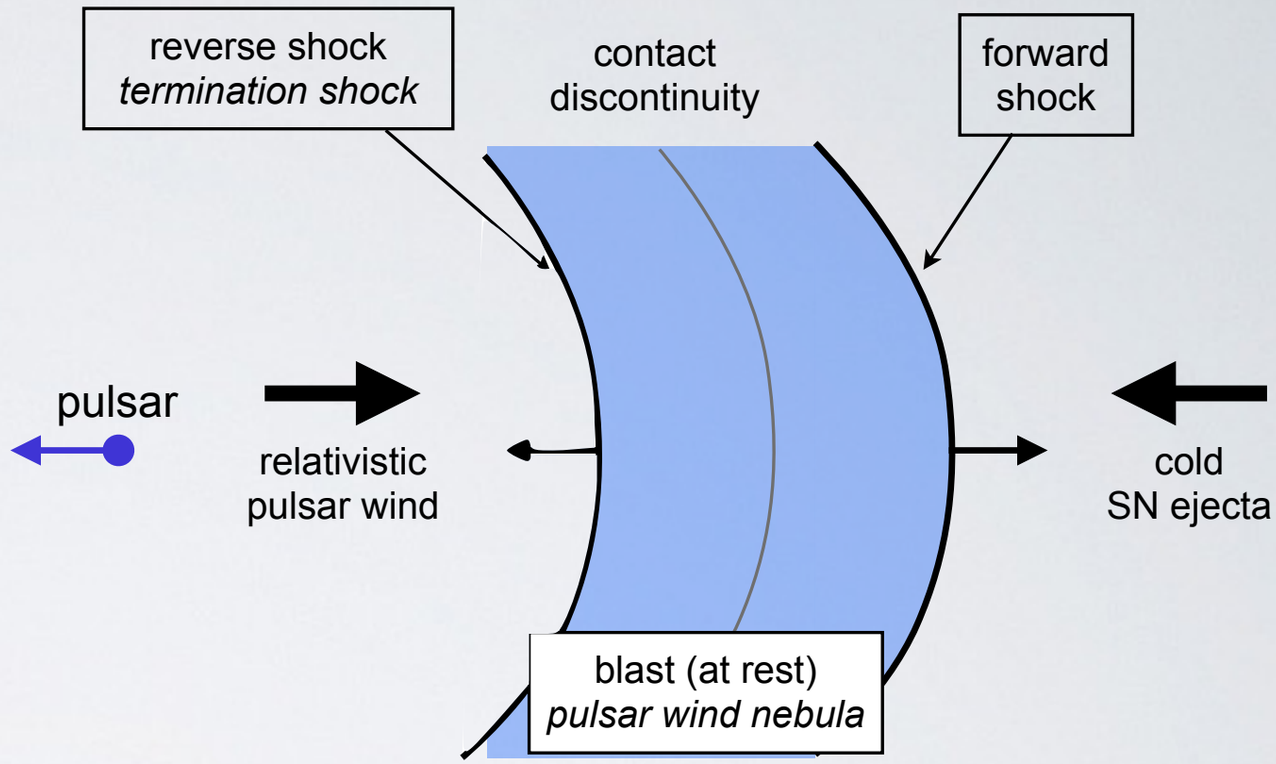

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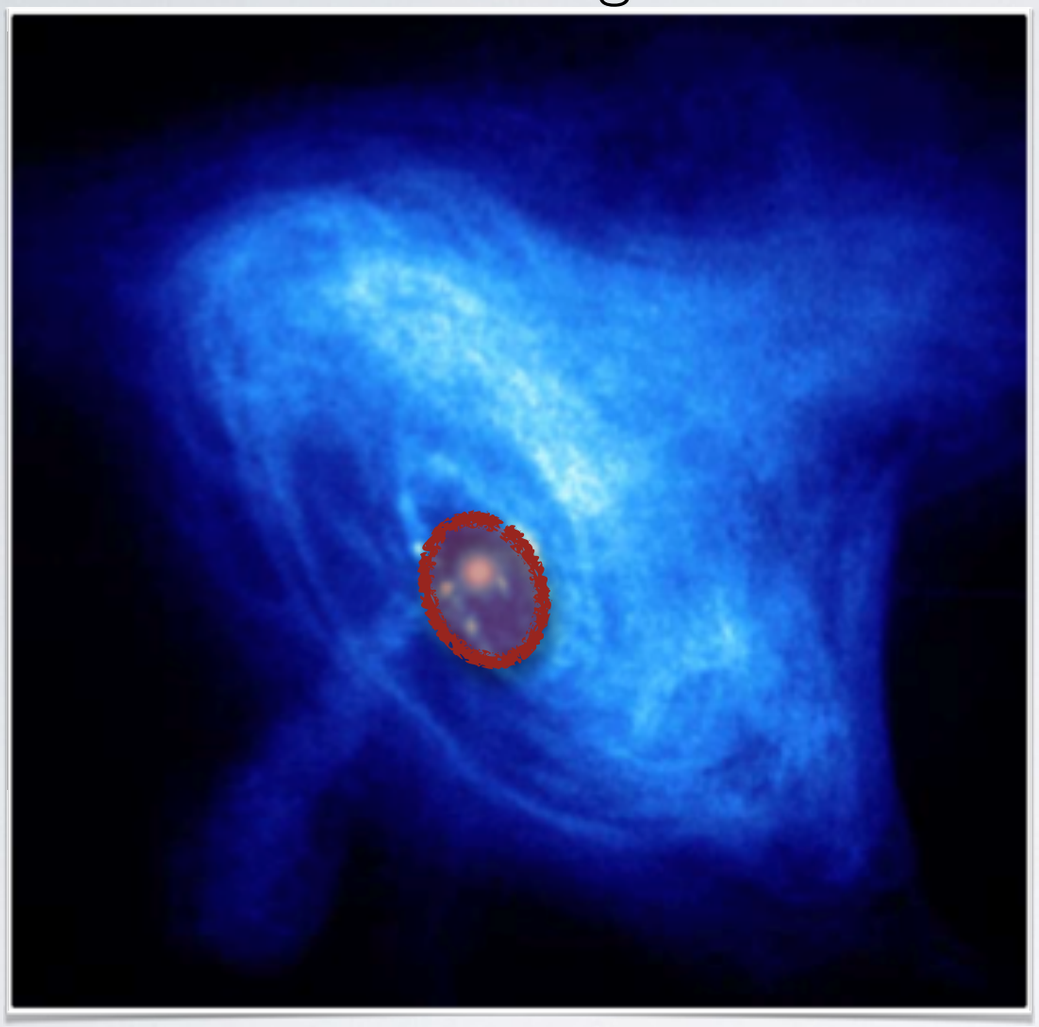

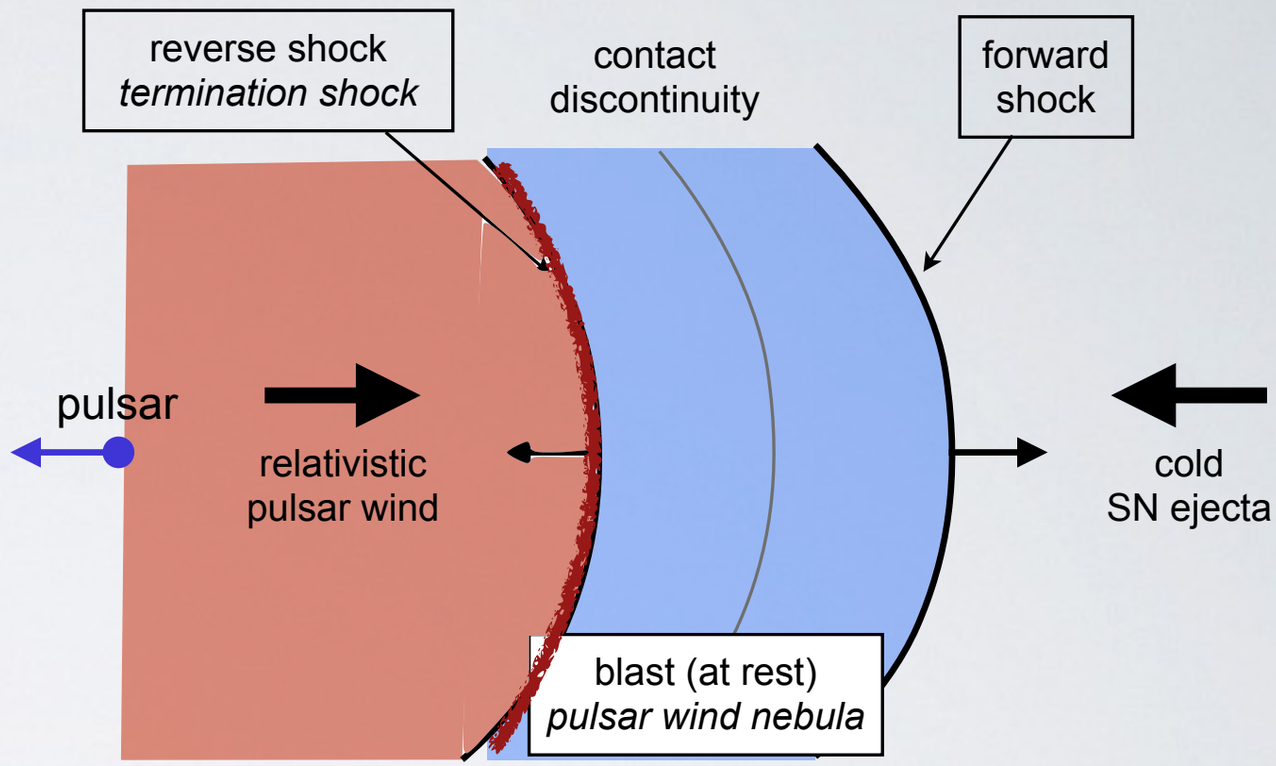

- Wind region

cold
Poynting flux
dominated?

Cosmic ray acceleration in pulsars

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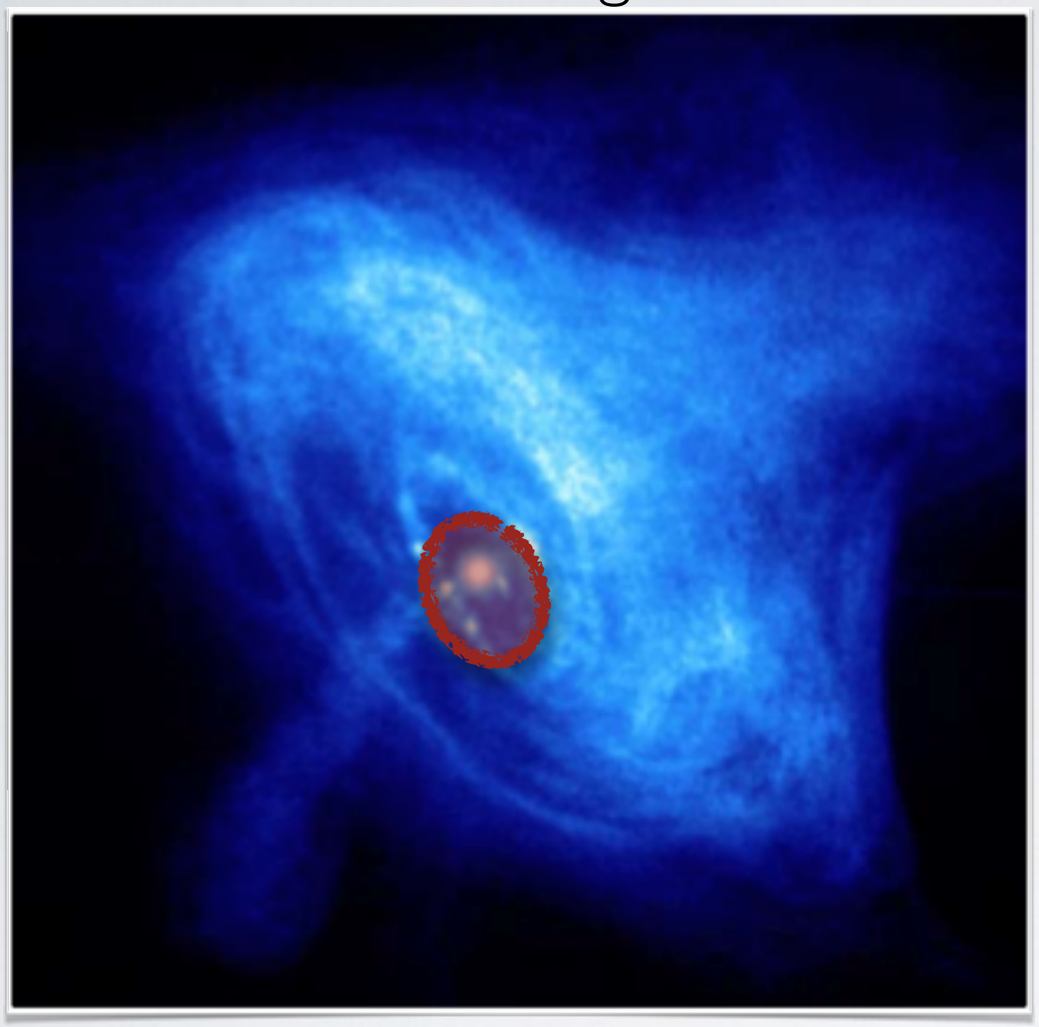

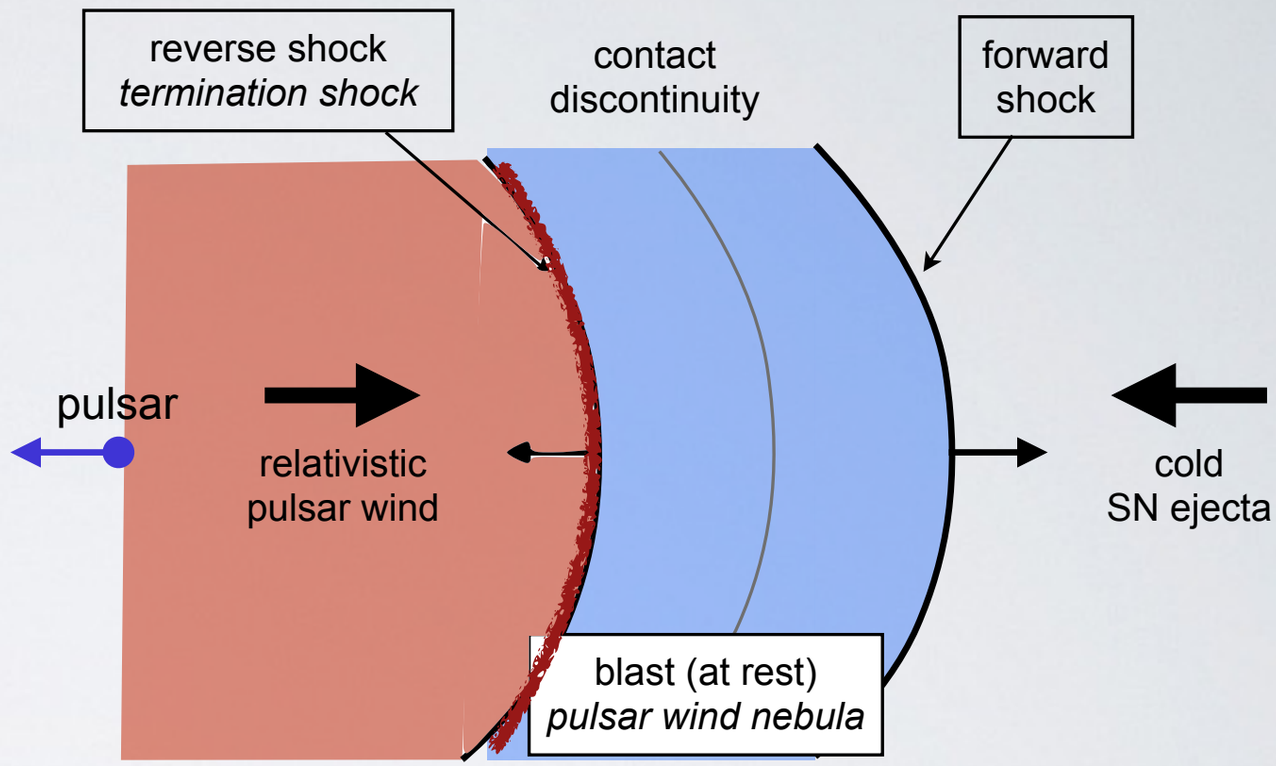

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radiative

kinetic energy

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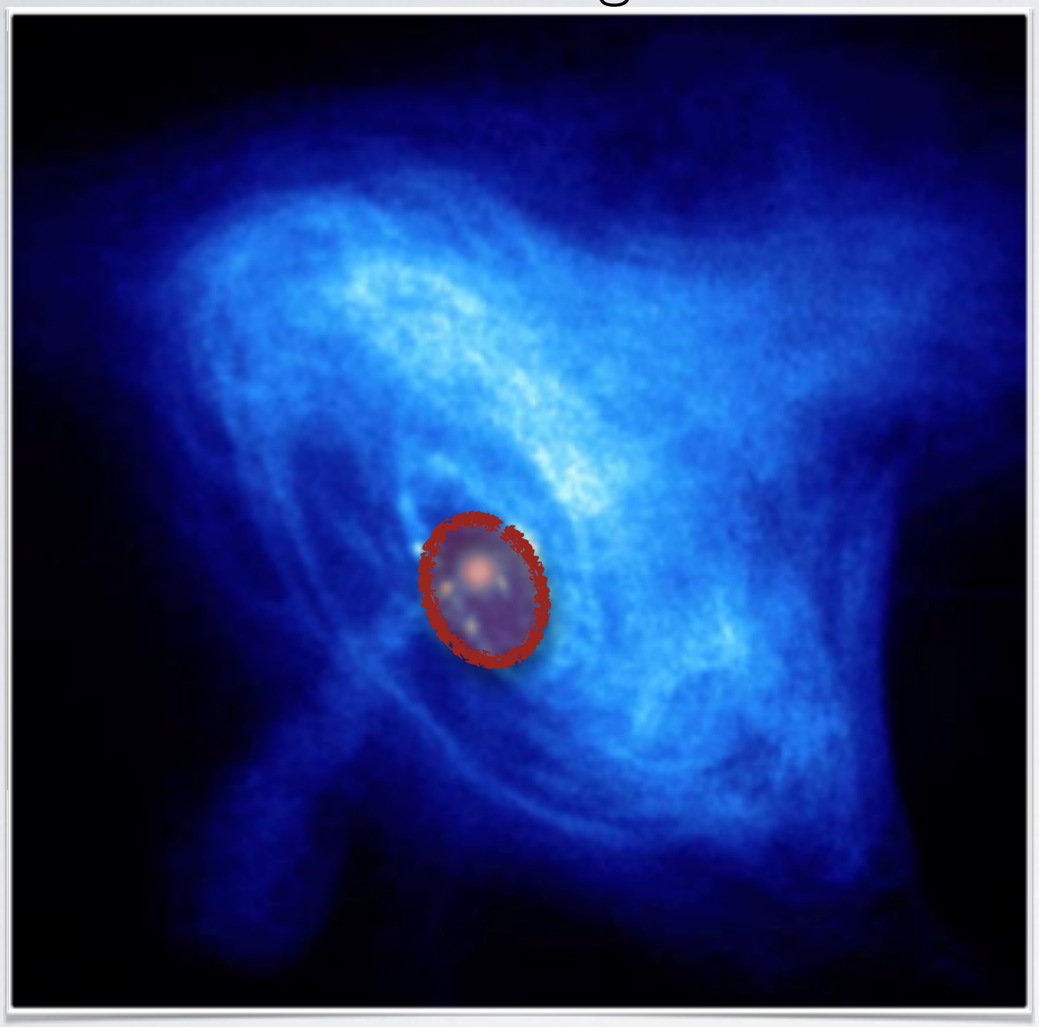

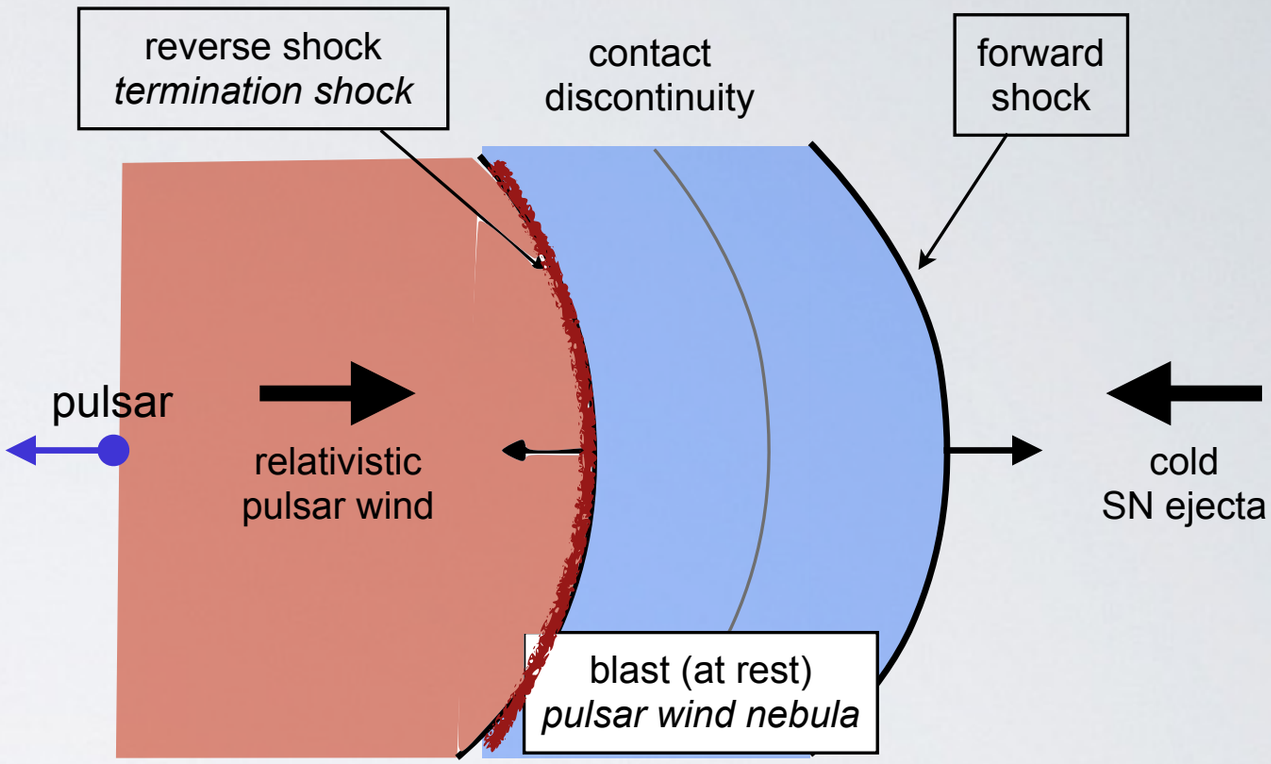

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cold
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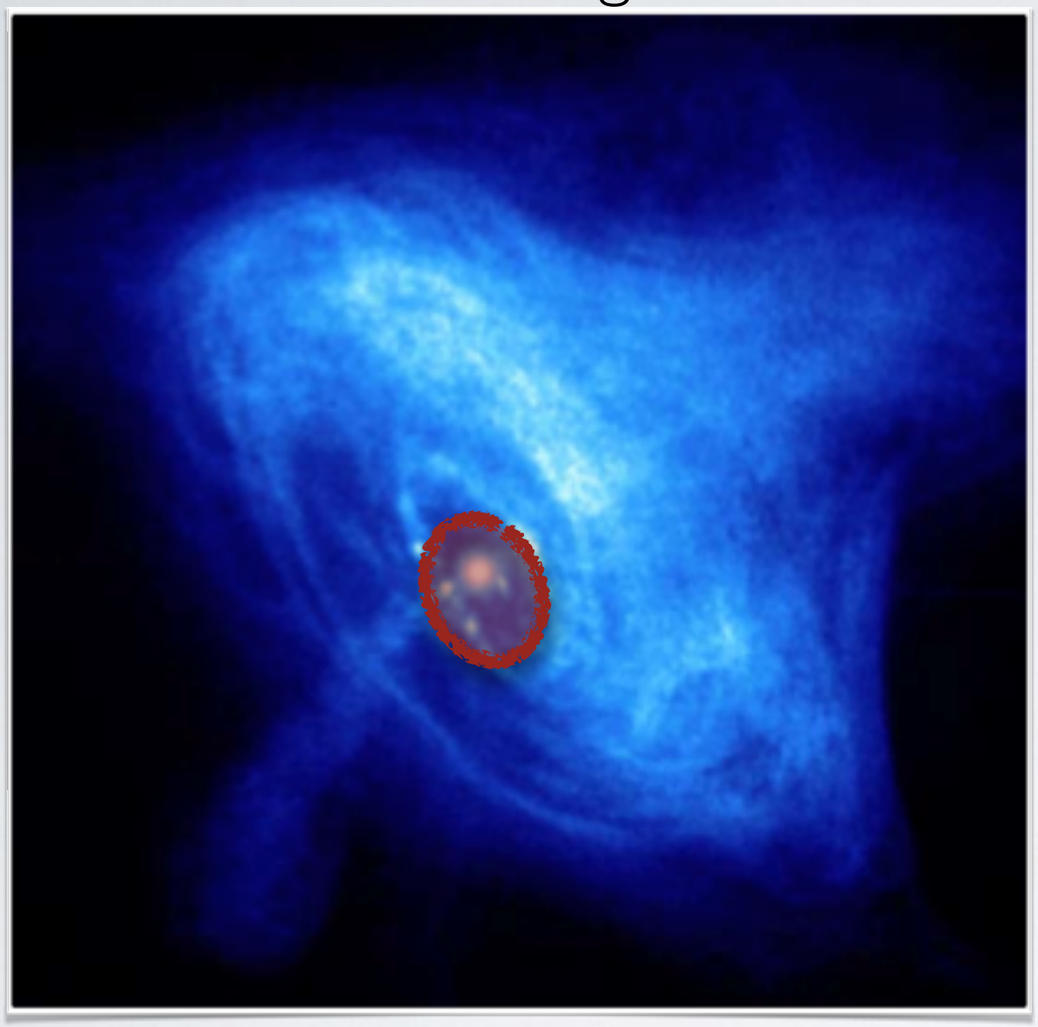
kinetic energy

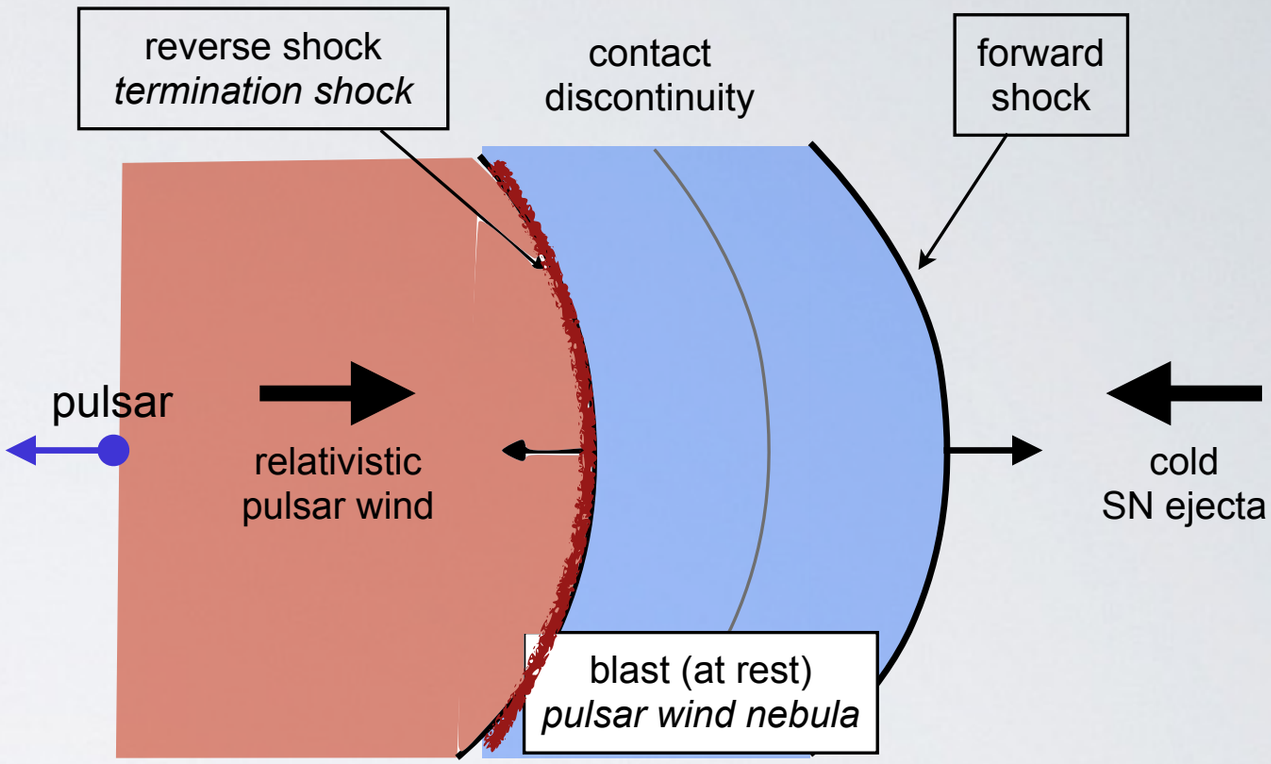
- dissipation of e-m to kinetic energy?
- related to "sigma-problem"

e.g., Kirk et al. 2009

Cosmic ray acceleration in pulsars

- Acceleration region?





- Acceleration mechanism?
  - « linear » E∝r *e.g., Chen et al. 92, Arons 03*
  - Fermi @TS *e.g., Lemoine, KK, Pétri 15*
  - reconnection wind region and/or close to TS in striped wind or in nebula? *e.g., Sironi & Spitkovsky 12, Lemoine, KK, Pétri 15*

- Wind region
  - **cold**
  - **Poynting flux dominated?**
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- Nebula
  - **radiative**
  - **kinetic energy**

Interaction backgrounds for neutrino production

nebula non-thermal γ

Amato et al. (2003)
Lemoine, KK, Pétri (2015)

SN thermal γ

Amato et al. (2003)
Fang, KK, Murase & Olinto (2016)

SN ejecta matter

Amato et al. (2003)
Bednarek (2003)
Murase et al. (2009)
Fang, KK, Murase & Olinto (2015, 2016)

star's thermal γ

Bednarek & Protheroe (1997)
Link & Burgio (2006)

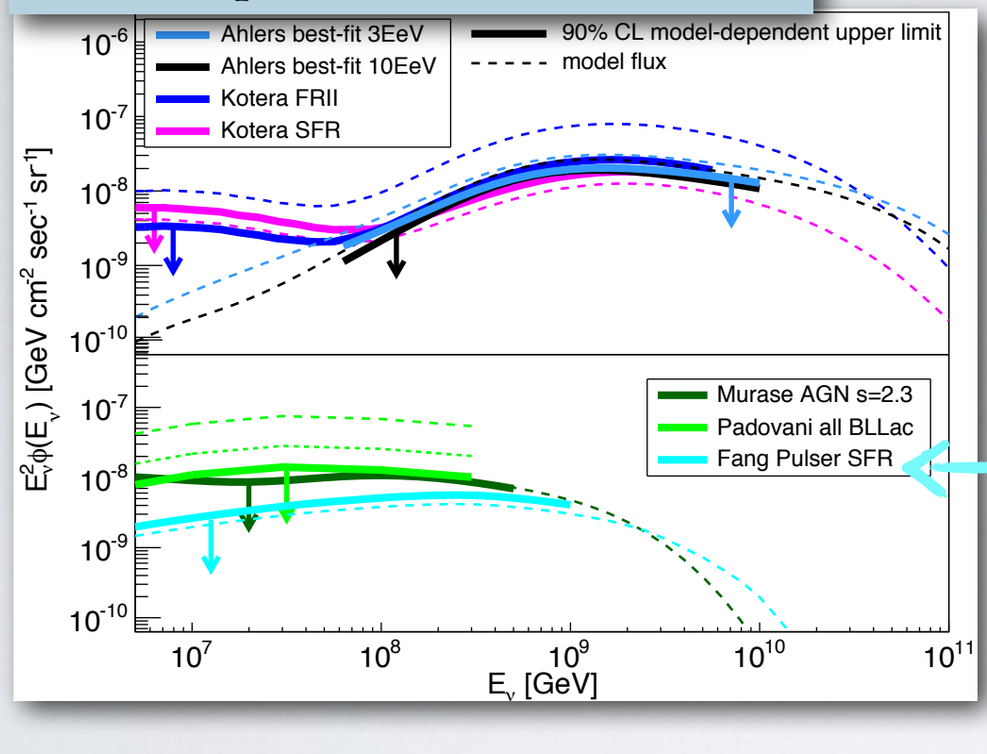
Crab flares non-thermal γ

Guépin & Kotera (in prep.)

- Most promising for UHECRs: interactions in SN

IceCube constraints on neutron stars as sources of UHECRs

model dependent 90% C.L. limits



Aartsen et al. 2016

- Population of newborn pulsars as sources of UHECRs **following star formation rate** excluded at 90% C.L.

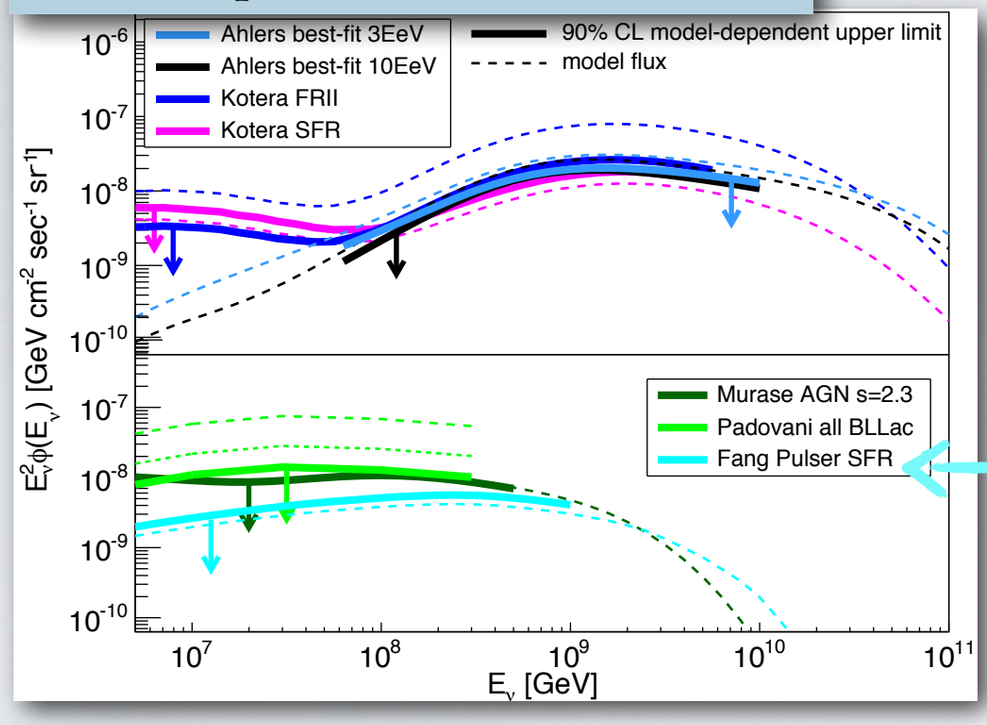
population of pulsars with realistic (P,B) distribution

A. Ishihara's talk

Fang, KK, Murase & Olinto 2013

IceCube constraints on neutron stars as sources of UHECRs

model dependent 90% C.L. limits



Aartsen et al. 2016

- Population of newborn pulsars as sources of UHECRs **following star formation rate** excluded at 90% C.L.

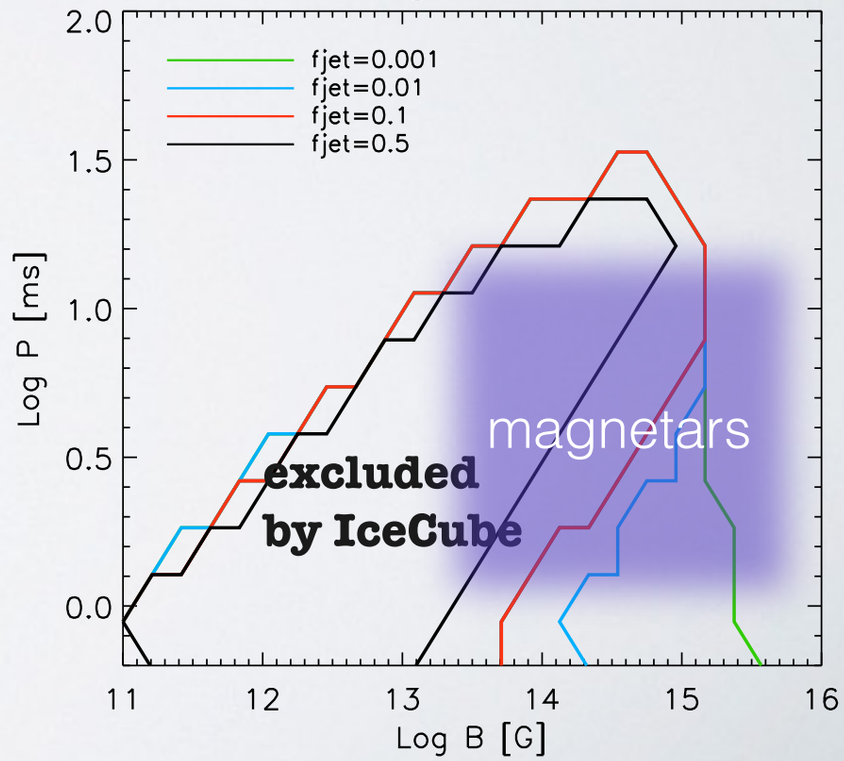
population of pulsars with realistic (P,B) distribution

A. Ishihara's talk

Fang, KK, Murase & Olinto 2013

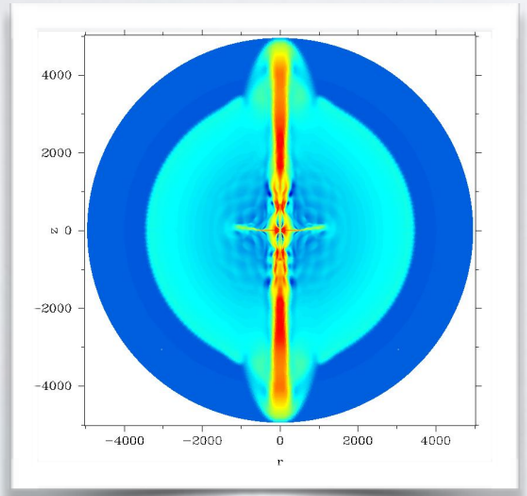
- neutrino fluxes @ break energy, if normalized to UHECR spectrum

Fang, KK, Murase & Olinto 2016



population of neutron stars with same characteristics (P,B)

- magnetar jet puncturing SN ejecta



Komissarov & Barkov (2007)

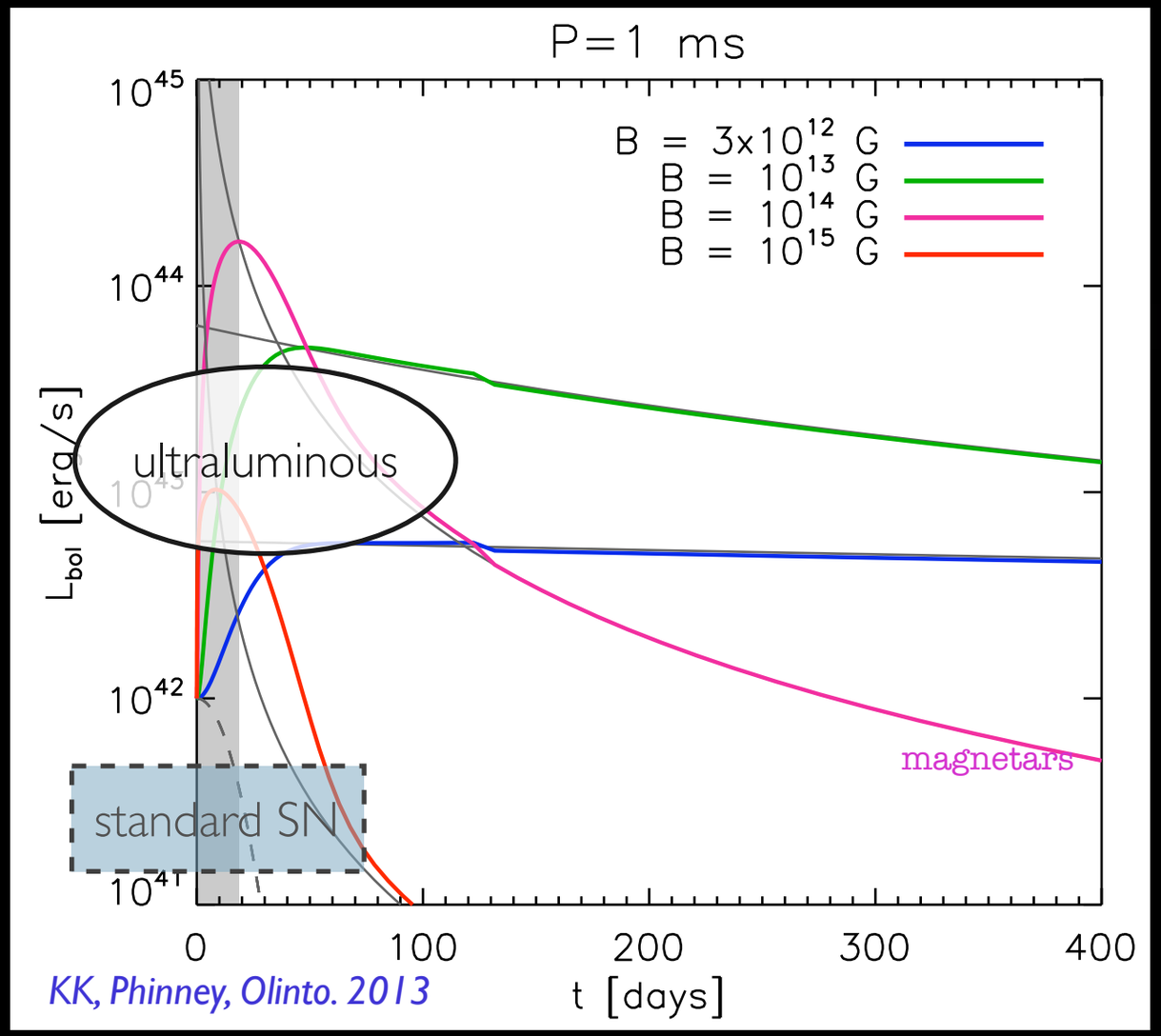
f_{jet} = "jet fraction"

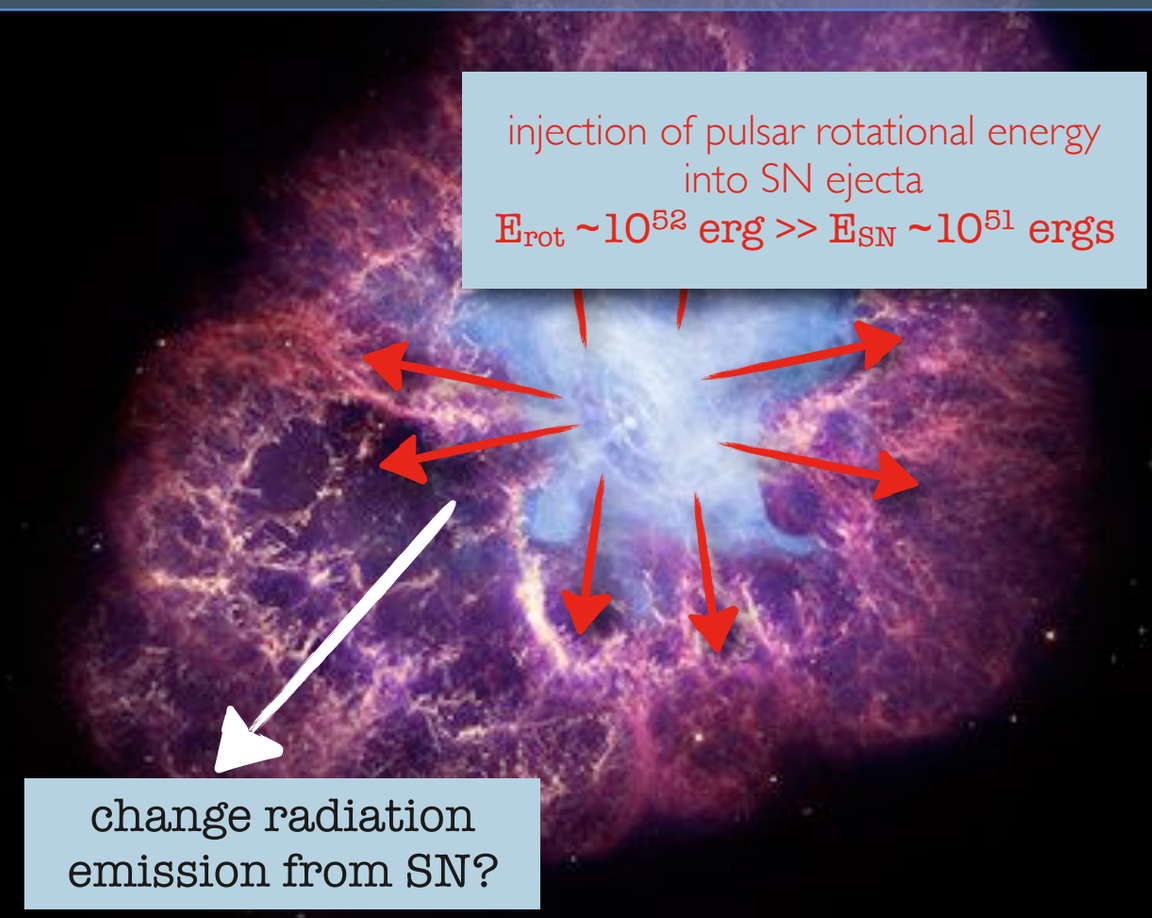
fraction of accelerated particles that can escape without crossing a dense environment

- magnetars not excluded if escape fraction > 10%
- UHECR production and escape possible

Superluminous supernovae due to central pulsar/magnetar

- superluminous supernovae lasting over a few days/months/years





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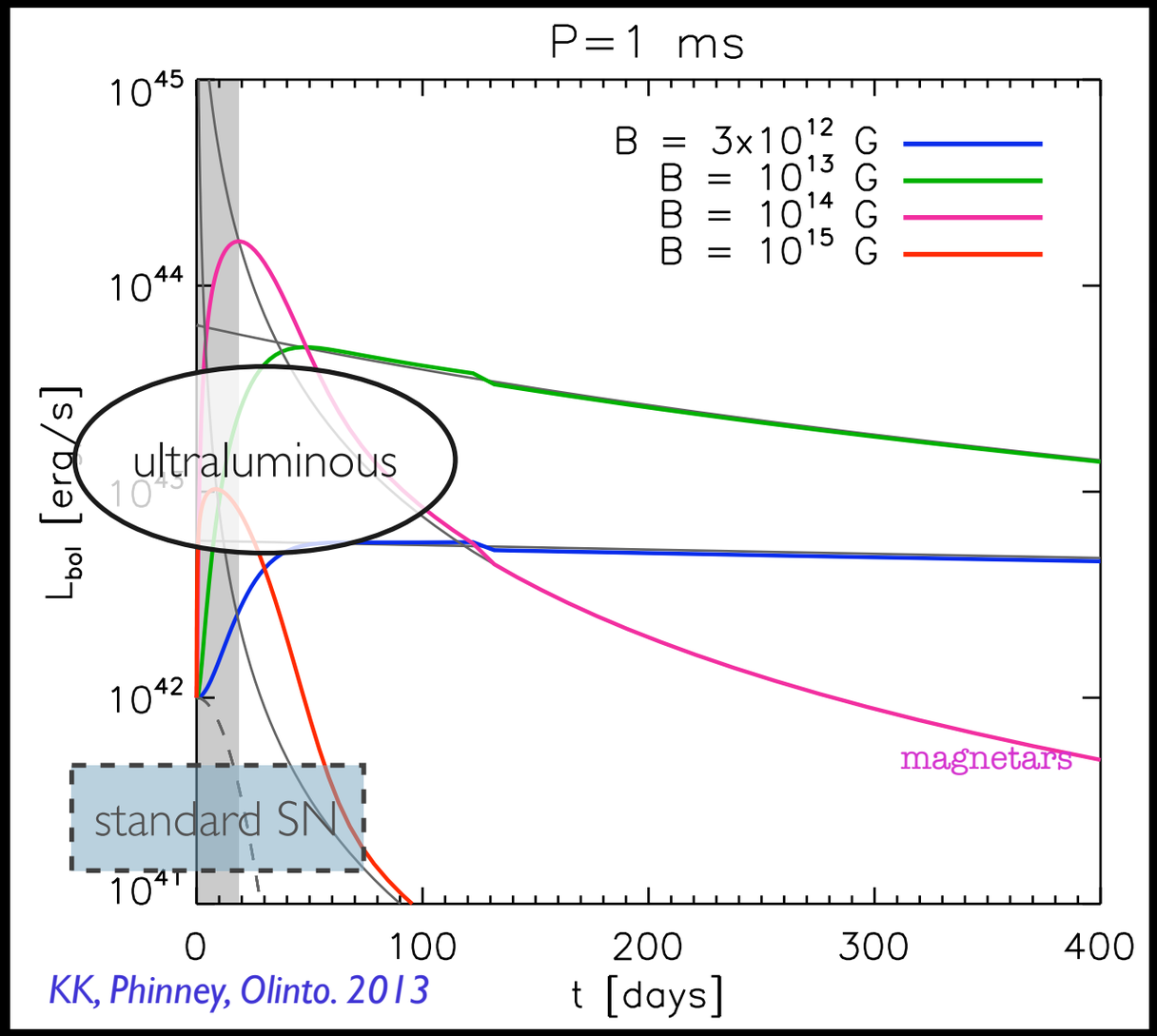

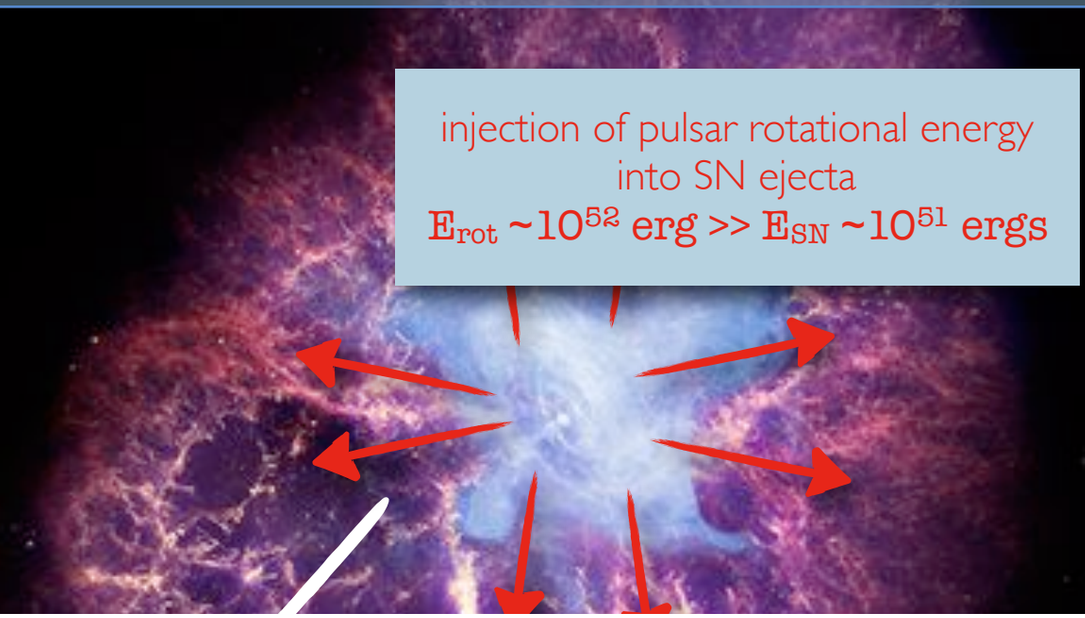

injection of pulsar rotational energy into SN ejecta

$E_{rot} \sim 10^{52}$ erg >> $E_{SN} \sim 10^{51}$ ergs

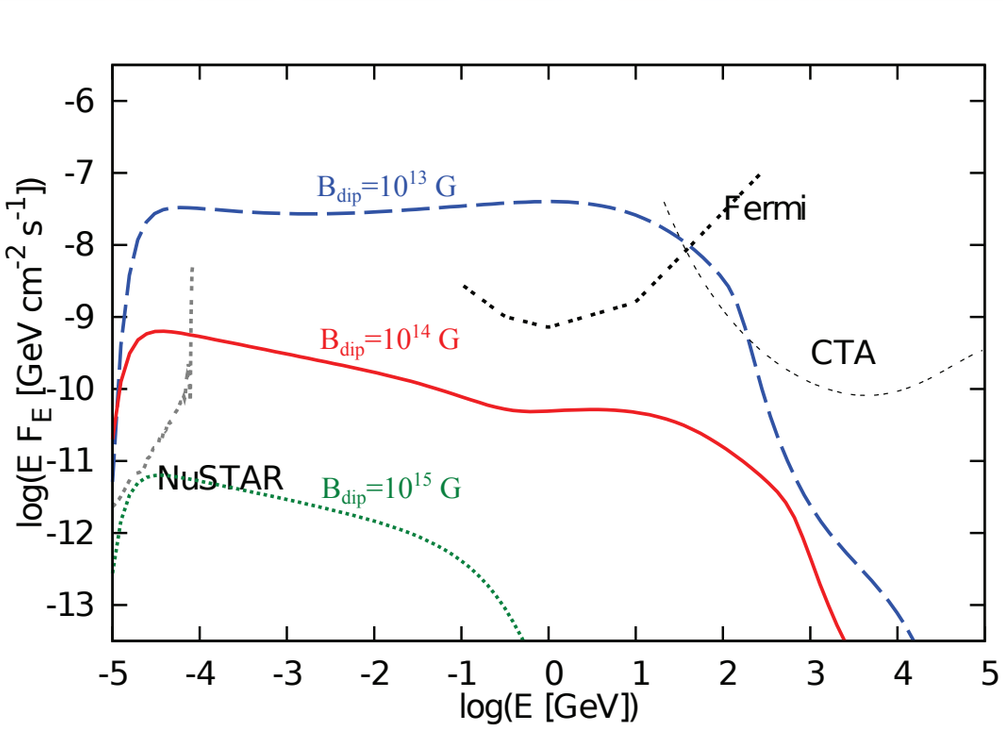

FIG. 7.— High-energy photon spectra of the early PWN embedded in the SN ejecta for $P_i = 2$ ms at $t = 10^{7.5}$ s $\simeq 316$ d. Different magnetic field strengths are considered. Detections with CTA are possible for $B_{\rm dip} = 10^{13}$ G.

Murase et al. 2015

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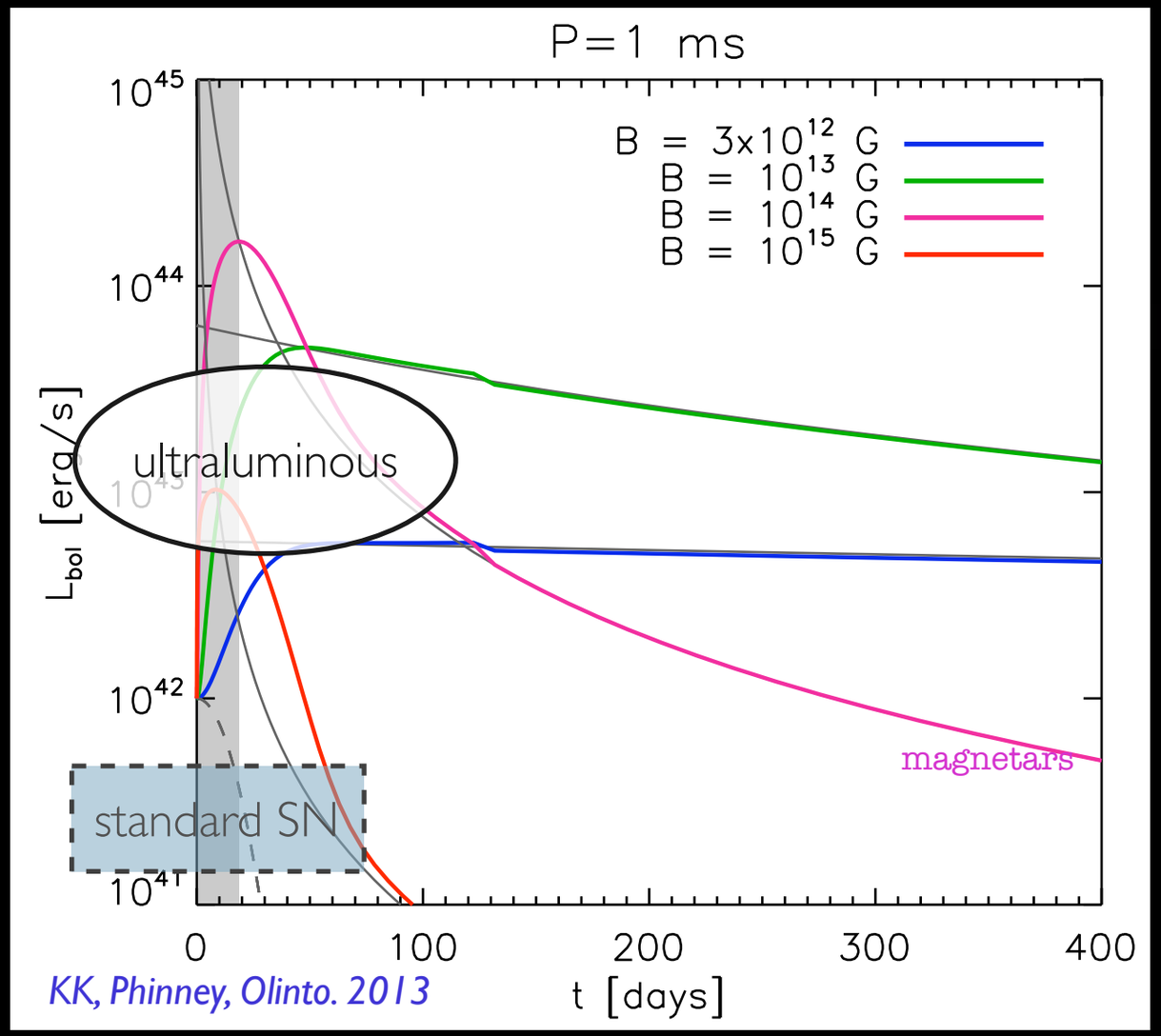
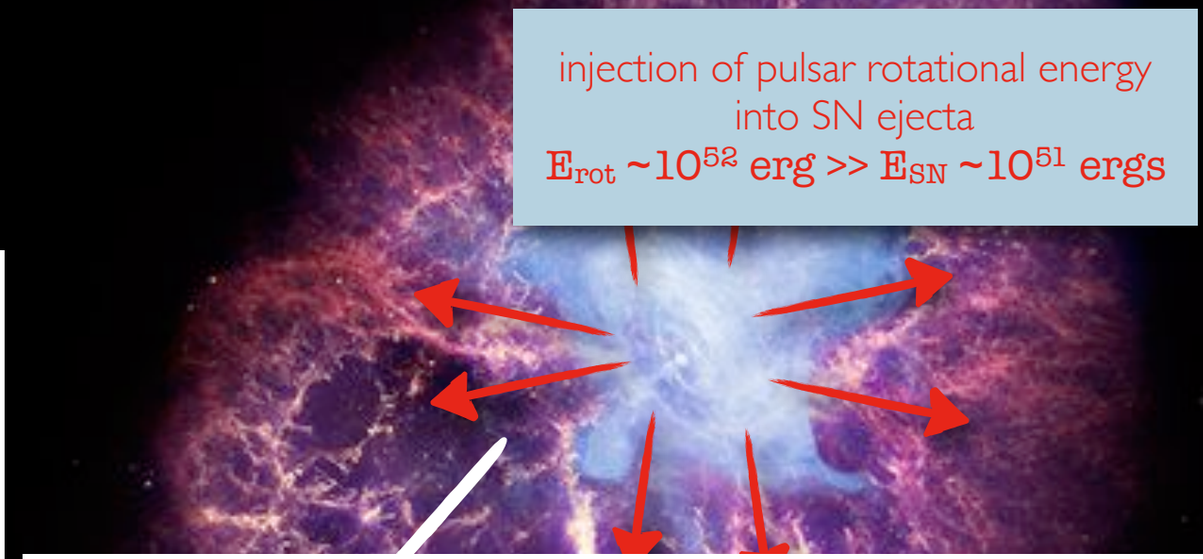


KK, Phinney, Olinto. 2013



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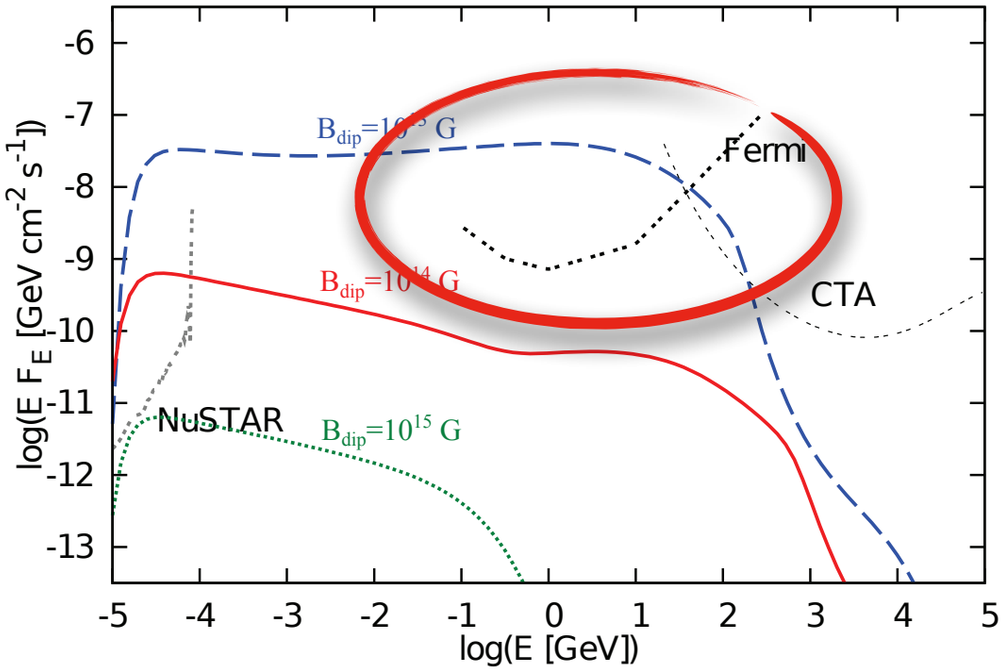

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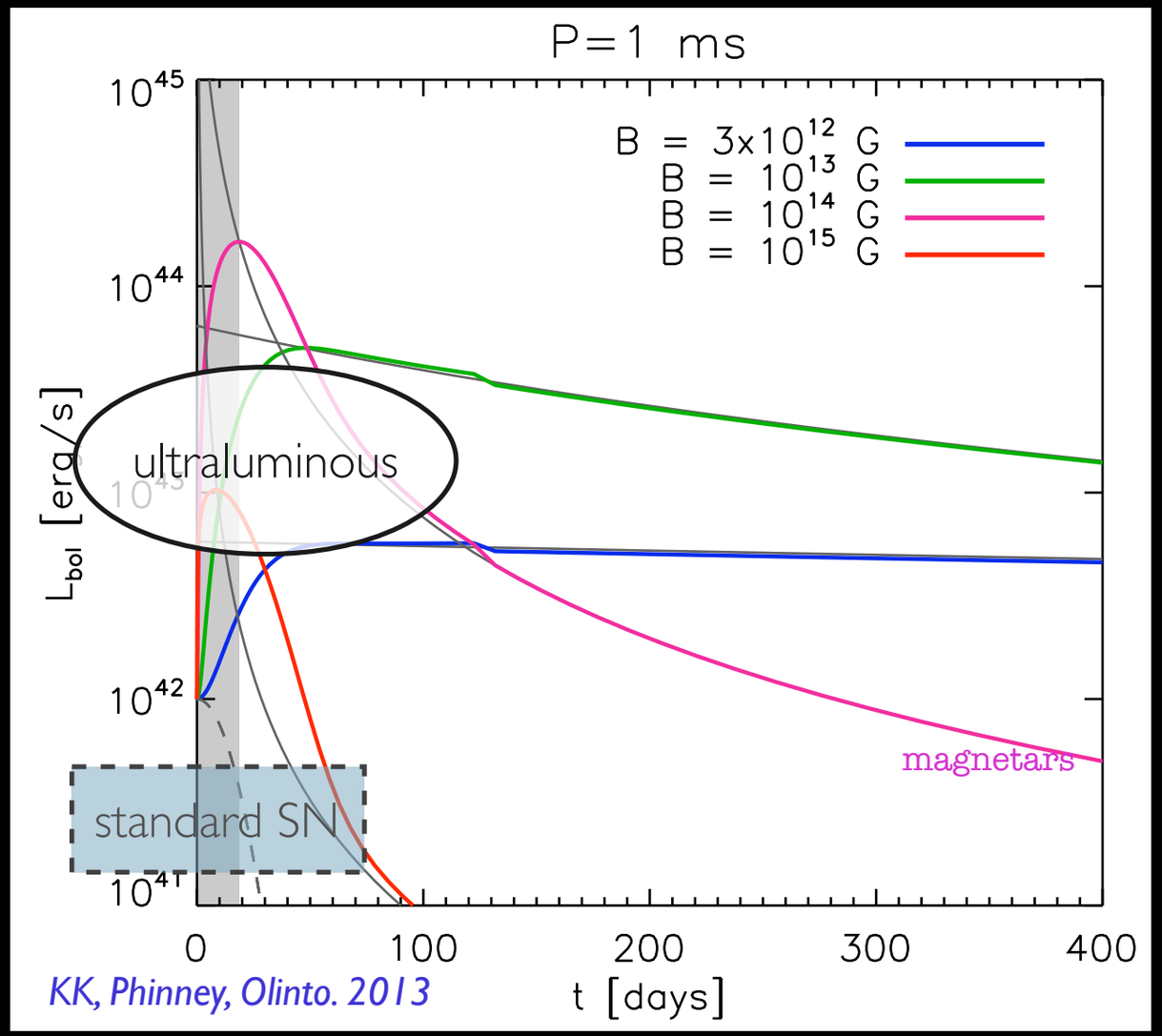

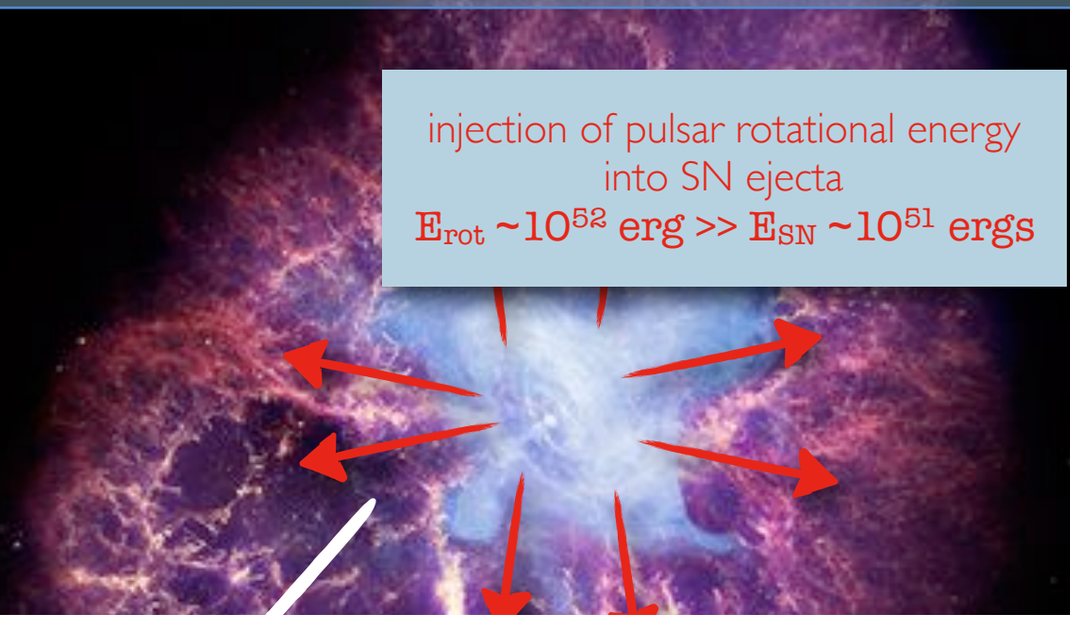

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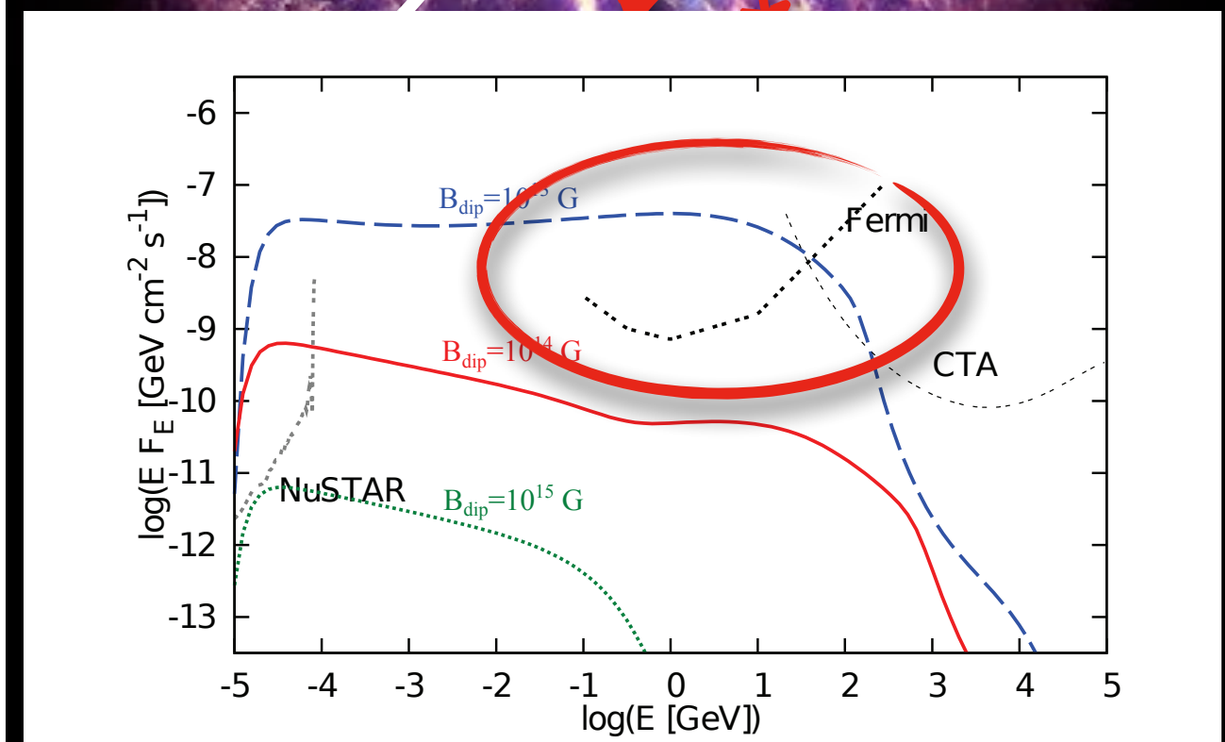

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Murase et al. 2015

- systematic search with Fermi LAT @ location of SLSNe

strong constraints on central object *Renault-Tinacci, KK, et al. for the Fermi Coll., in prep.*

Search for Superluminous Supernovae with Fermi-LAT

Renault-Tinacci, KK, Ando, Neronov, for the Fermi Coll., in prep.

sample of 39 SLSNe
Fermi Pass-8 data
3+1 and 7+1 bands in E: 0.6-600 GeV
4 different time windows

- Individual analysis

  only source detected above 3-sigma level: SN2011ke
  constraints on SLSNe luminosities: $<\sim 10^{44}$ erg/s

- Joint likelihood analysis (stacking)

Table 4: Luminosities from joint likelihood analysis measurements with the 7+1 energy band set and all sources.

Time window	$\mathrm{Sig}_{0.6-600.0\,\mathrm{GeV}}$ σ units	$L_{0.6-10.2\,\mathrm{GeV}}$ erg s^{-1}	$L^{\mathrm{sum}}_{0.6-600.0\,\mathrm{GeV}}$ erg s^{-1}	$\mathrm{Sig}^{\mathrm{best\,bnd}}_{\mathrm{E1-E2}}$ σ units	E1 GeV	E2 GeV
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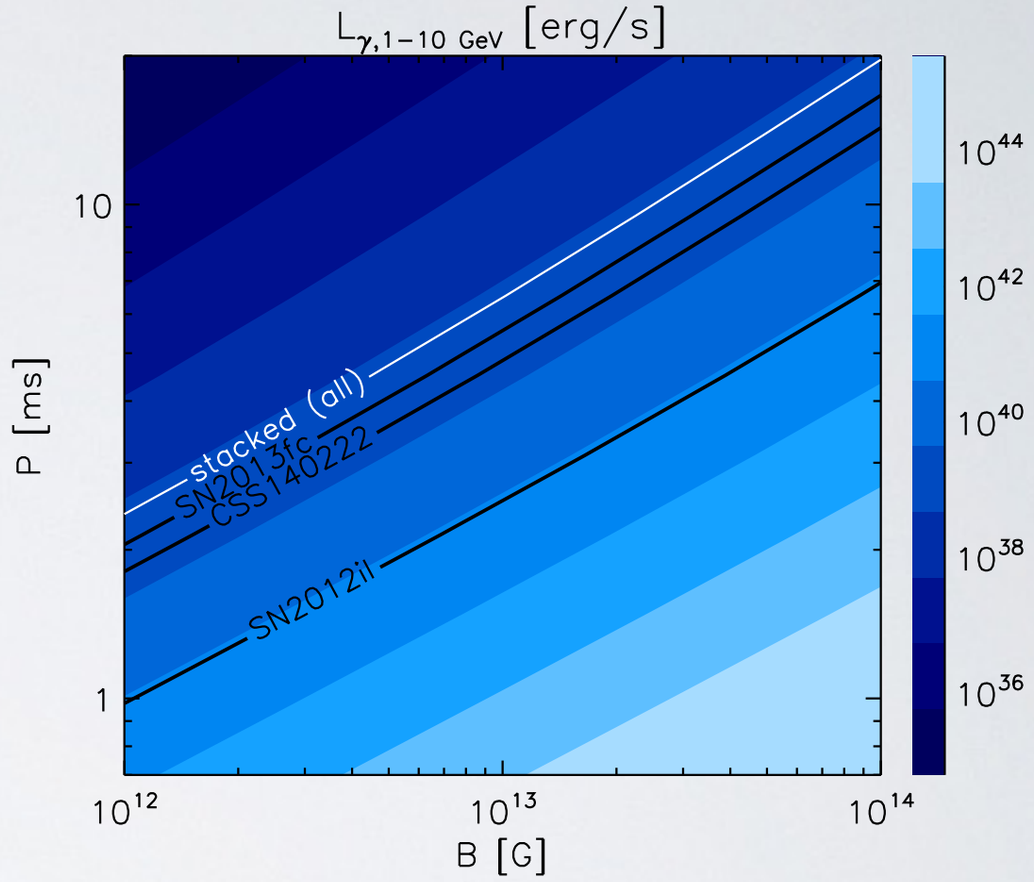

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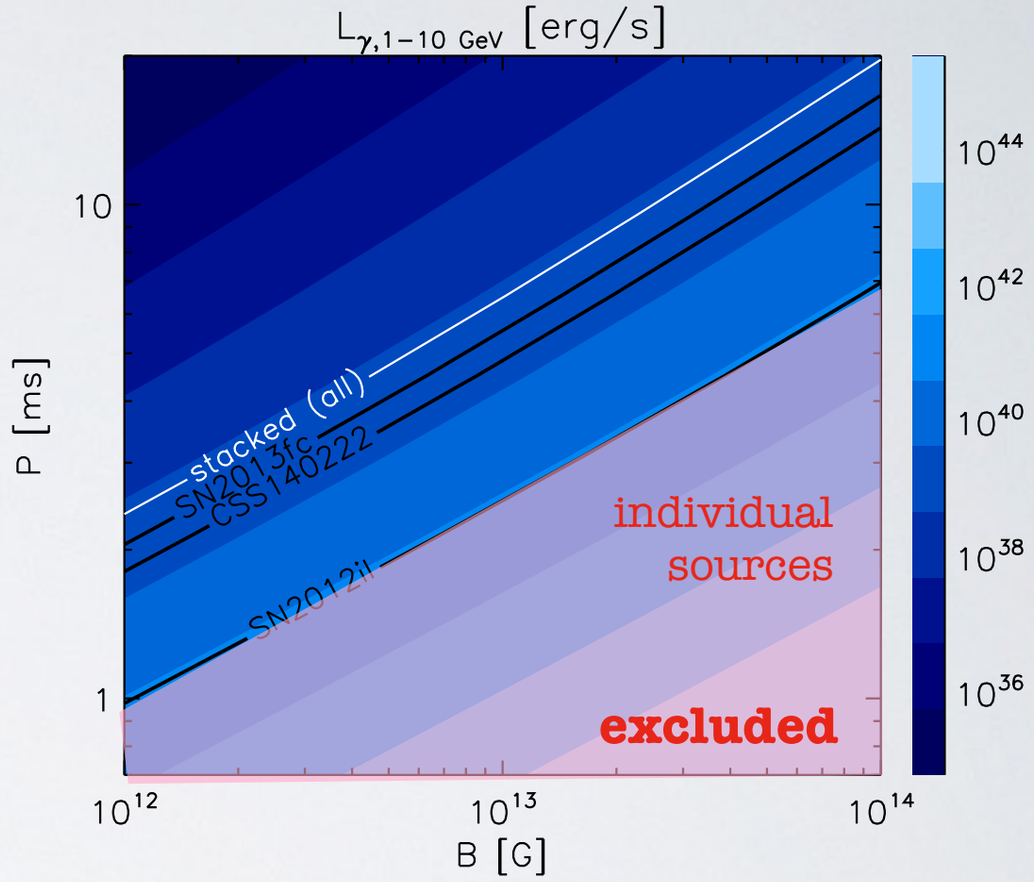

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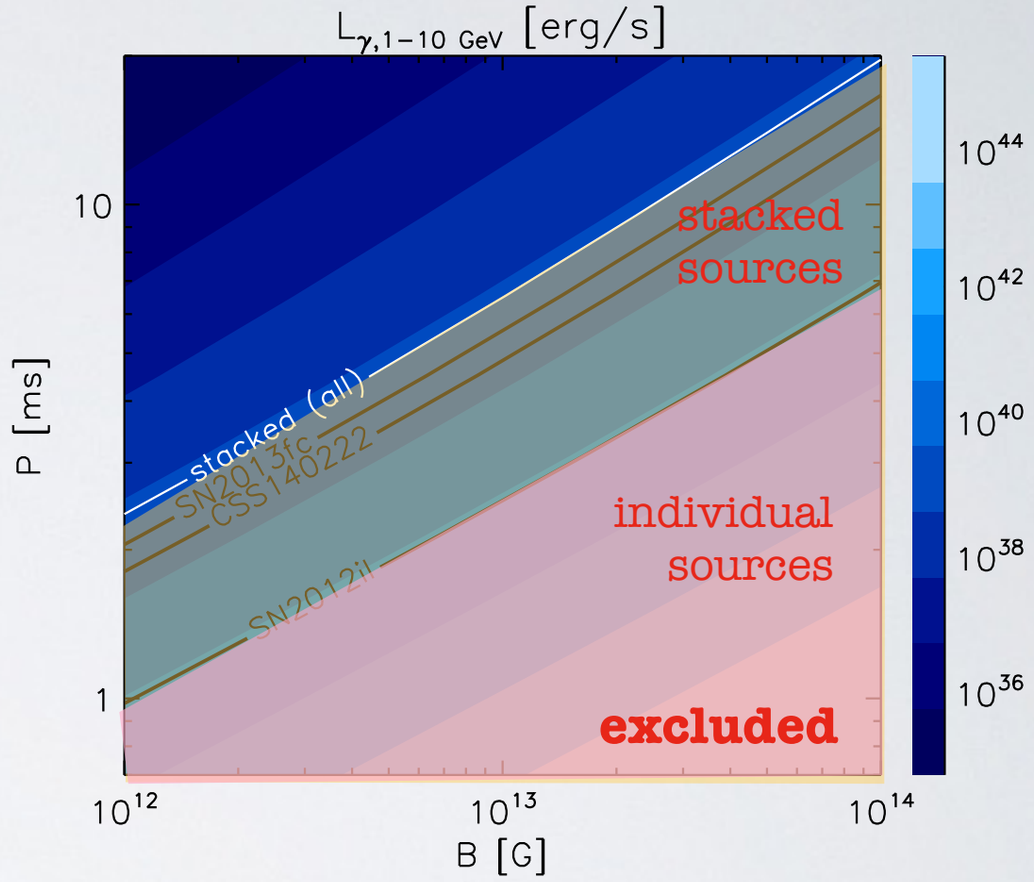

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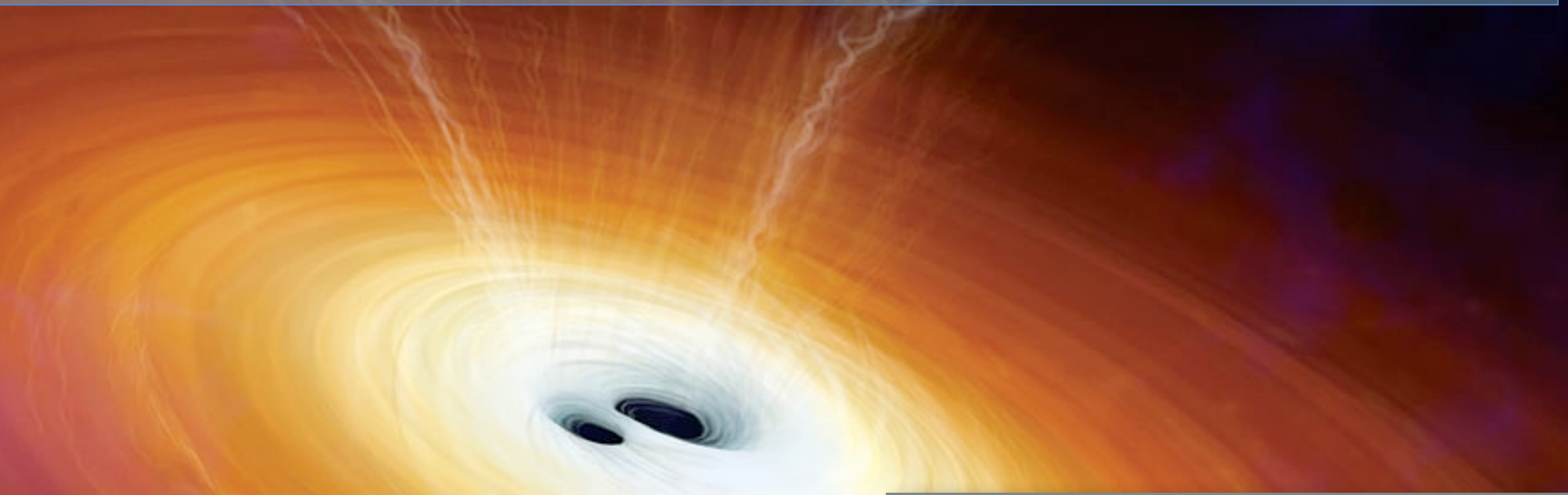
Black Hole mergers as sources of UHECRs: a qualitative model

KK & Silk 2016



$$E_{\rm UHECR} \gtrsim 3.2\times10^{53}\,{\rm erg}\left(\frac{\rho_0}{1\,{\rm Gpc^{-3}\,yr^{-1}}}\right)^{-1}$$

learnt from GW150914

- comfortable energetics:
  - $E_{GW} = 3.0^{+0.5}\ M_{sun}\ c^2 \sim$ **5.4×10^{54} erg** per source
  - population rate $\rho_{BH} \sim 2 - 400\ Gpc^{-3}\ yr^{-1}$
  - **efficiency < 3%** required in UHECRs per event per unit of GW energy release
- heavy composition possible:
  - iron-enriched residual debris around merging BHs

- luminosity extracted via Blandford-Znajek mechanism

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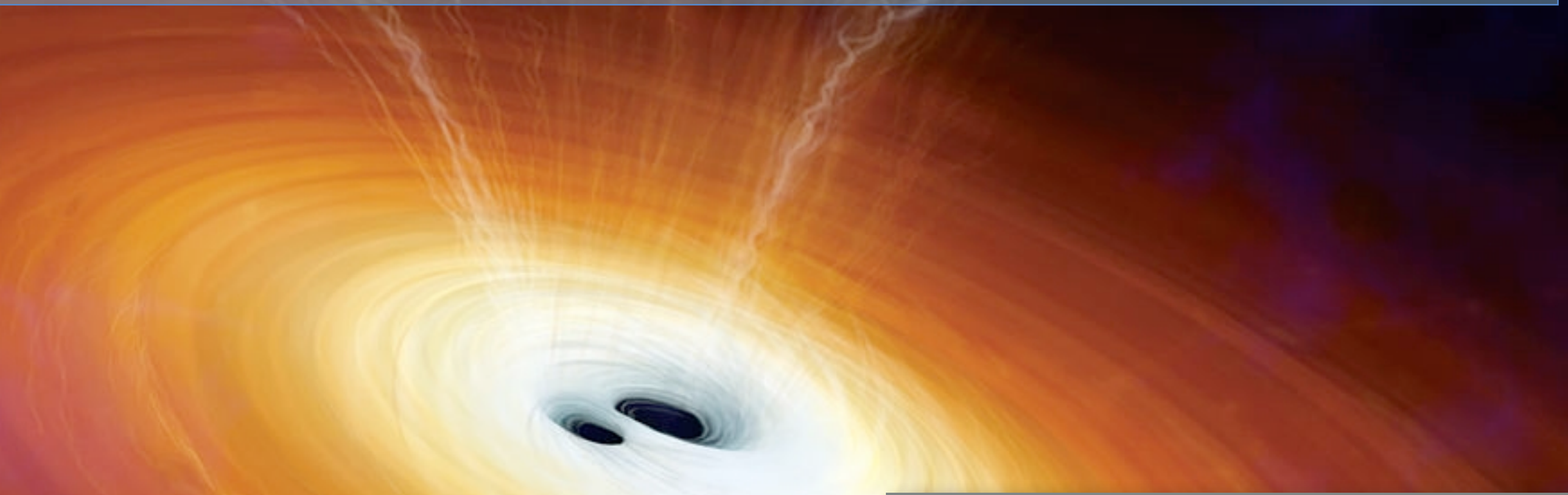

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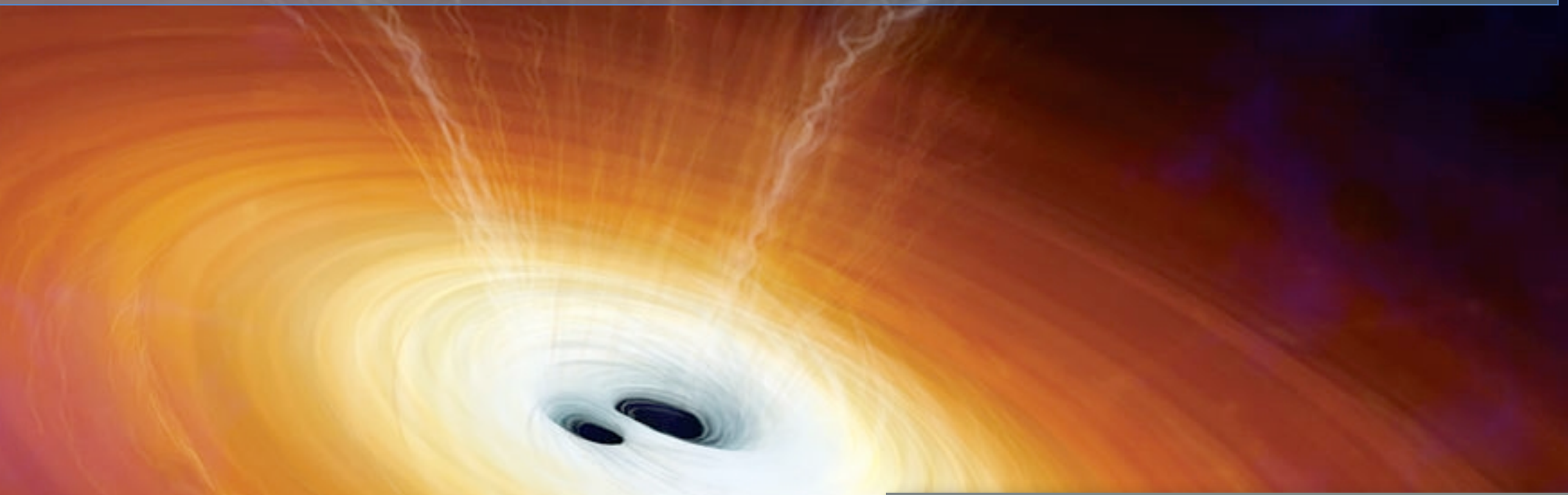

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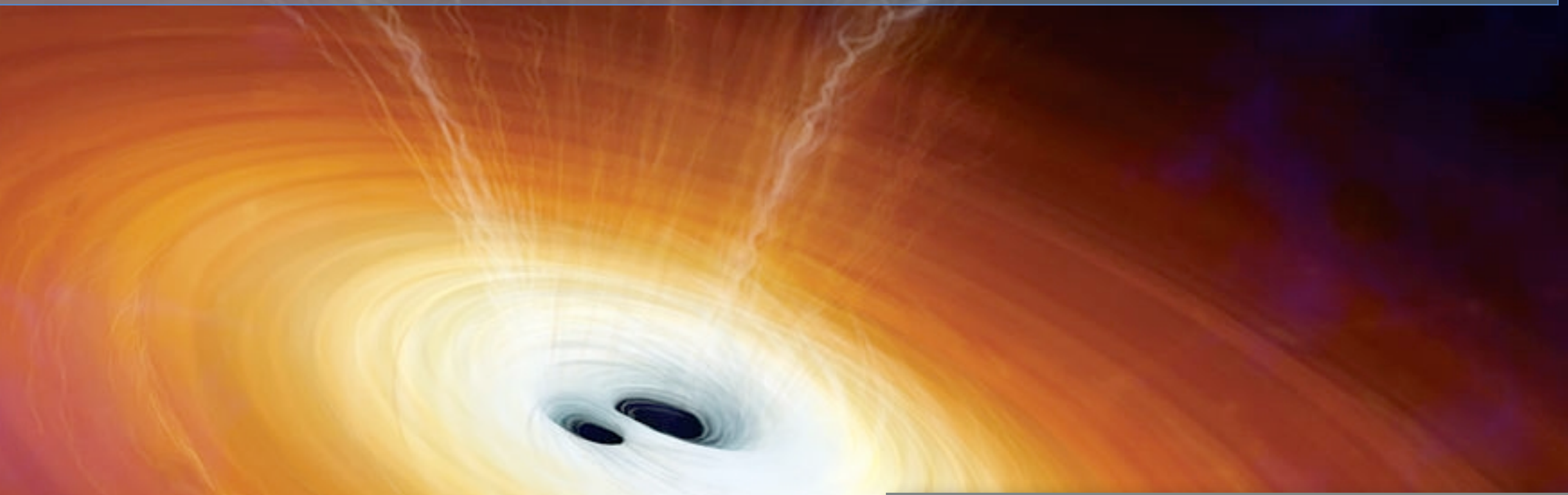

$$E_{\rm UHECR} \gtrsim 3.2\times10^{53}\,{\rm erg}\left(\frac{\rho_0}{1\,{\rm Gpc^{-3}\,yr^{-1}}}\right)^{-1}$$

learnt from GW150914

- comfortable energetics:
  - E_{GW} = 3.0+0.5 M_{sun} c^2 ~ **5.4 ×10^{54} erg** per source
  - population rate ρ_{BH} ~ 2 – 400 Gpc^{-3} yr^{-1}
  - **efficiency < 3%** required in UHECRs per event per unit of GW energy release
- heavy composition possible:
  - iron-enriched residual debris around merging BHs

- luminosity extracted via Blandford-Znajek mechanism

$$L_{\rm BZ} = \frac{(GM)^3B^2}{c^5R} \sim 3.2\times10^{46}\,{\rm erg\,s^{-1}}\,M_{100}^3B_{11}^2\frac{R_{\rm S}}{R}$$

$$R_{\rm S} = 2GM/c^2 \sim 3.0\times10^7\,M_{100}\,{\rm cm}$$

- magnetic field strength via **αω**-dynamo

$$B \sim 10^{12}\,{\rm G}\,(P/300\,{\rm ms})^{-1}$$

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$$t_{\rm BZ} = Mc^2/L_{\rm BZ} \sim 22\,M_{100}B_{11}^{-2}(R_{\rm S}/R)^2\,{\rm yr}$$

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- accretion to source BZ long enough,
- disk to anchor fields and do **αω**-dynamo to generate strong magnetic field

debris ← tidal disruption of asteroids or planets

spin

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Black Hole mergers as sources of UHECRs: neutrinos and FRBs

KK & Silk 2016

- **neutrinos**: similar predictions as for GRBs
  or as for low mass ejecta (AIC type) + pulsar, as in ***Piro et al. (2016)***
  Compatible with non observation of associated neutrinos with IceCube and ANTARES

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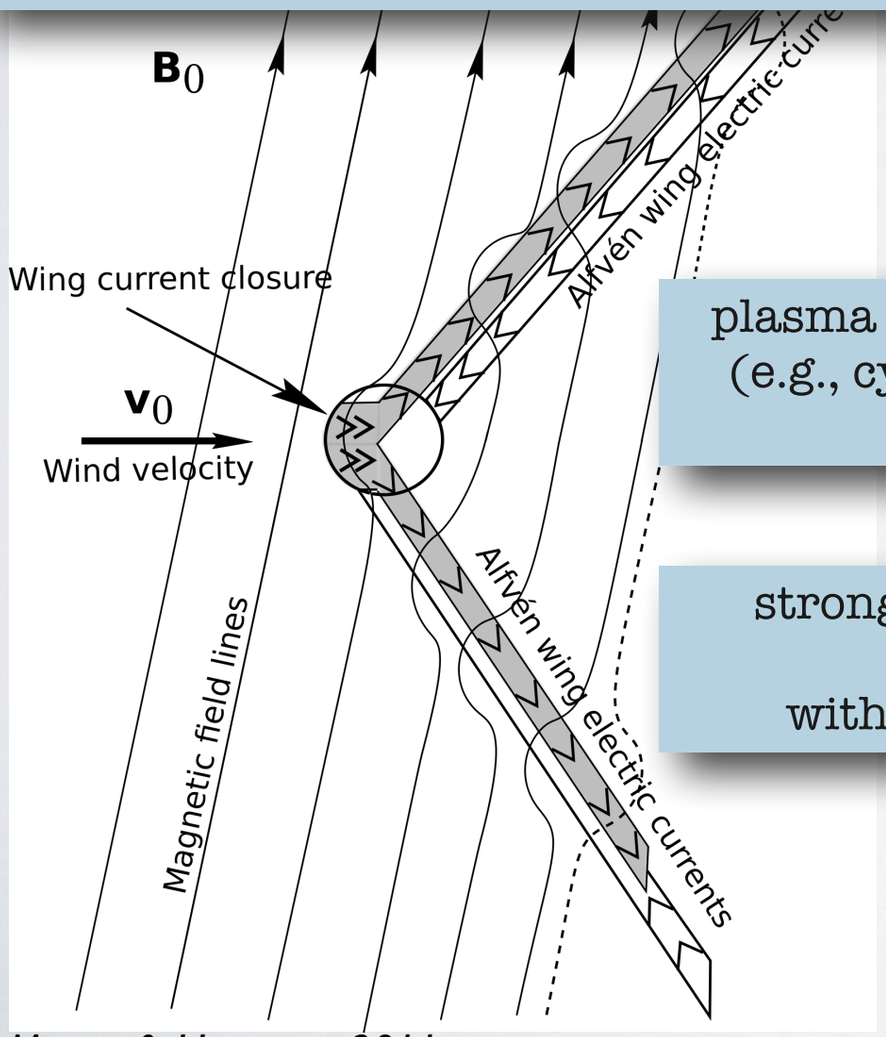
- **Fast Radio Bursts!**
  (very bright radio bursts, routinely detected, of unknown cosmological origin)
  Debris/bodies required around merging black holes/final black hole —> model of ***Mottez & Zarka (2013)***

a body immersed in a highly magnetized outflow generates 2 stationary Alfvén wings



Mottez & Heyvaerts 2011

NB: asteroids and planets can orbit at close distance from the central object without being evaporated/destroyed (Mie Theory)

KK, Mottez, Voisin, Heyvaerts 2016

plasma instabilities in Alfvén wings
(e.g., cyclotron maser instability):
radio emission

strongly beamed radio emission
@ 10 MHz-10^3 GHz
with high flux (Jansky level)

Mottez & Zarka 2013

How to look for multi-messenger transient signals

- UHECRs → a hotspot? TA hotspot?

  hotspot could be signature of Galactic transient source occurred $10^{3\text{-}4}$ yrs ago
  or extragalactic transient at few 10s Mpc 10^5 yrs ago

  Fang et al. 2015
  Fargion 2015
  H. He and D. Ryu's talks — *He et al. 2016*
  Renault-Tinacci, KK, Olinto in prep.

- neutrinos → identify best detector characteristics for neutrino astronomy

  next slide

- photons → boom in time-domain astronomy (PTF, Pann-STARRS, LSST, ...)
  gamma-rays: Fermi, HESS, CTA

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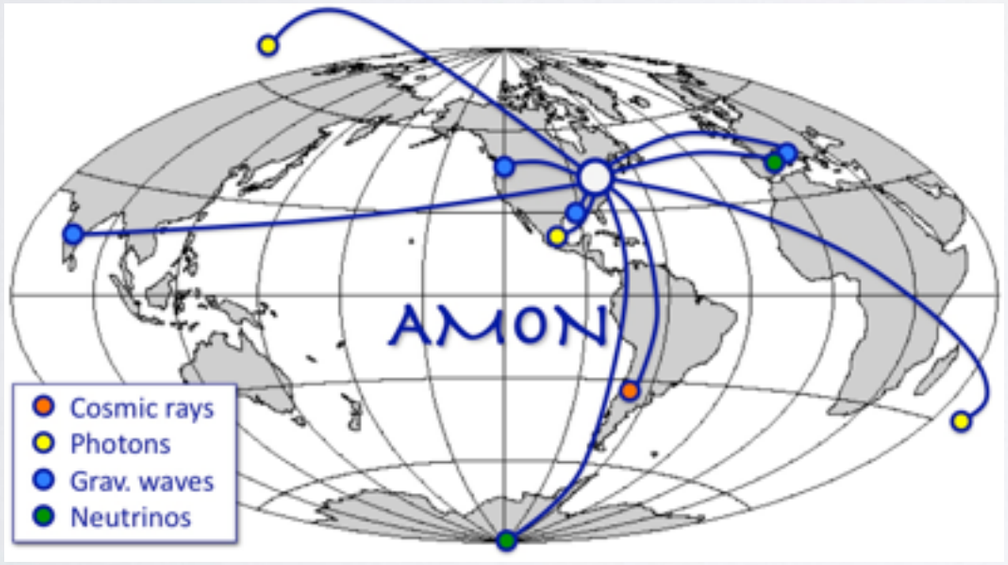


Astrophysical Multimessenger Observatory Network

Example: HESE-160427A , on April 27 2016

05:52:32
event seen in detector

23:24
manual recos give final location, error

05:53:53
automated GCN/AMON notice

16/04/28 22:38, Fermi LAT
GCN 19360, 5 unrelated blazars

16/04/29 12:24, HAWC
GCN 19361, no detection

16/04/29 15:55, MASTER
GCN 19362, no detection

16/04/29 21:08, Fermi GBM
GCN 19364, no detection

16/05/03 00:39, VERITAS
GCN 19377, no detection

16/05/04 18:43, Pan-STARRS
GCN 19381,
24 faint transients, 8 known quasars, six old supernovas,
one new Ic SN candidate(PS16cgx)
at z~0.2 consistent with an explosion on April 27.,
no-correlated low-energy neutrinos found
in follow-up analysis

16/05/06 03:05, iPTF
GCN 19392, 3 transients, all AGN

16/05/12 18:05, Interplanetary Network
GCN 19426, no detection

16/05/13 13:02, FACT
GCN 19427,no detection

Naoko Kurahashi Neilson, Drexel University 25

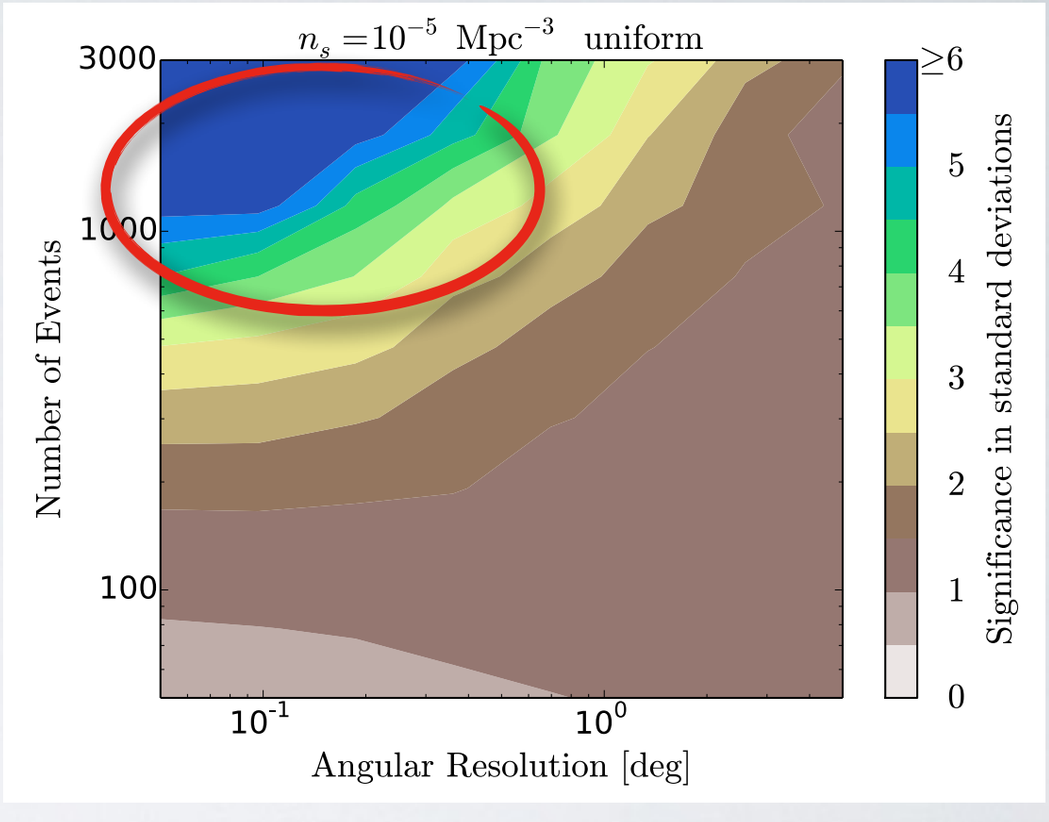
from N. Kurahashi-Neilson, TeVPA 09/2016

How to search for multi-messenger transient signals: neutrino sources?

- no deflection, no time delay, ideal?
- BUT: no horizon —> possible to spot source on top of background?

e.g., difficult to identify sources for IceCube neutrinos…

>1000 events and <1 deg. angular resolution required



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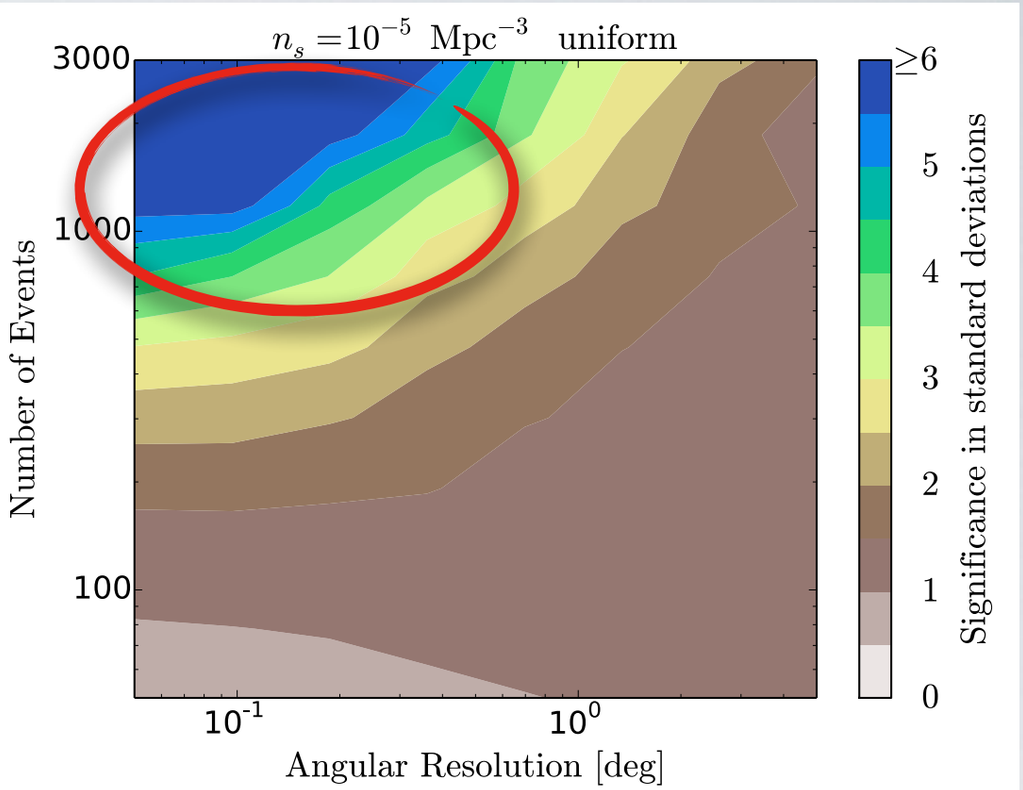

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Giant Radio Array for Neutrino Detection

200'000 radio antennas over 200'000 km^2

>1000 events in 10 yrs (E>10^{17} eV)

< 0.3 deg. angular resolution

- ICRC 2015: ***arXiv:1508.01919***