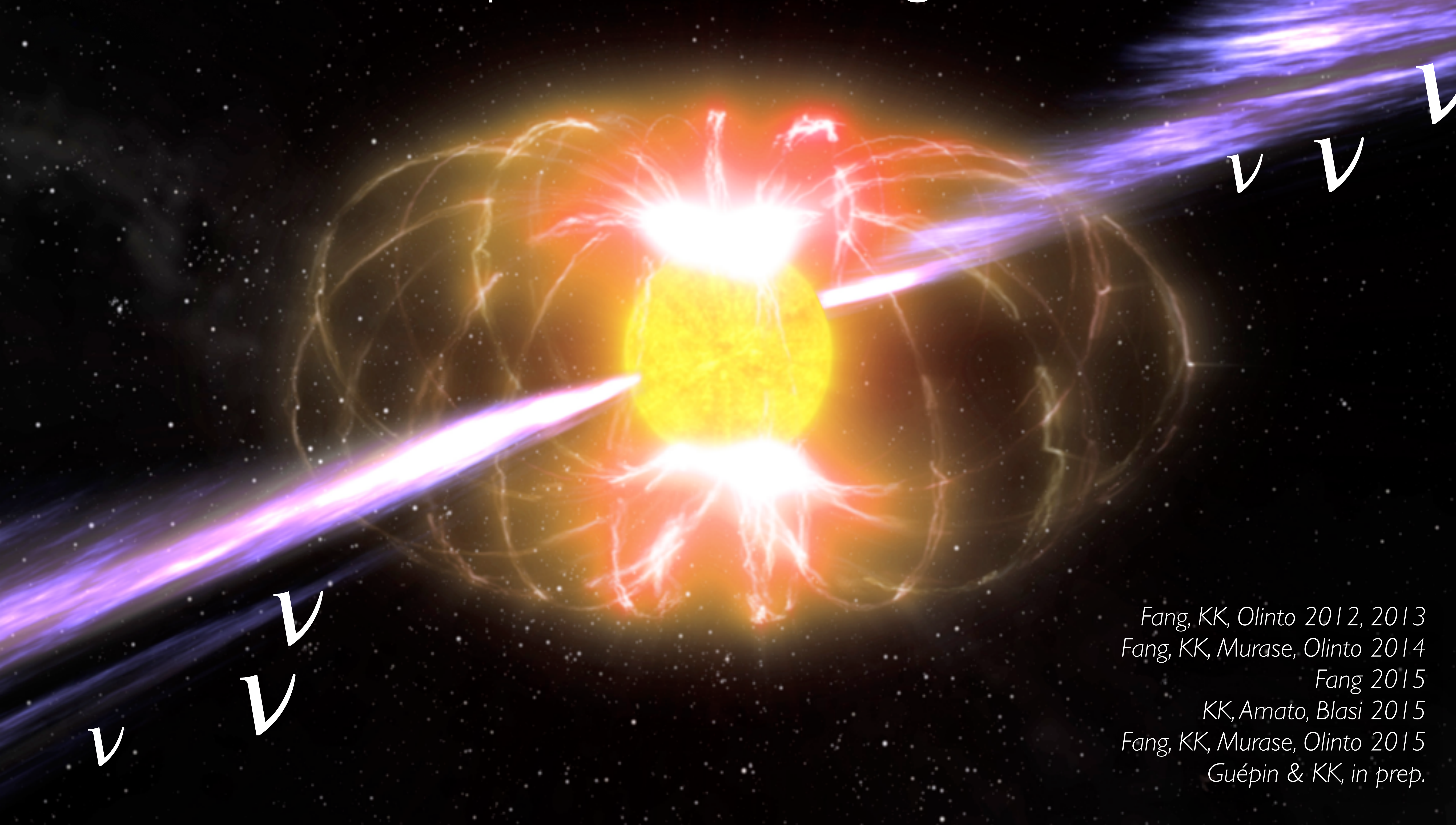
High-energy neutrinos from newborn pulsars and magnetars

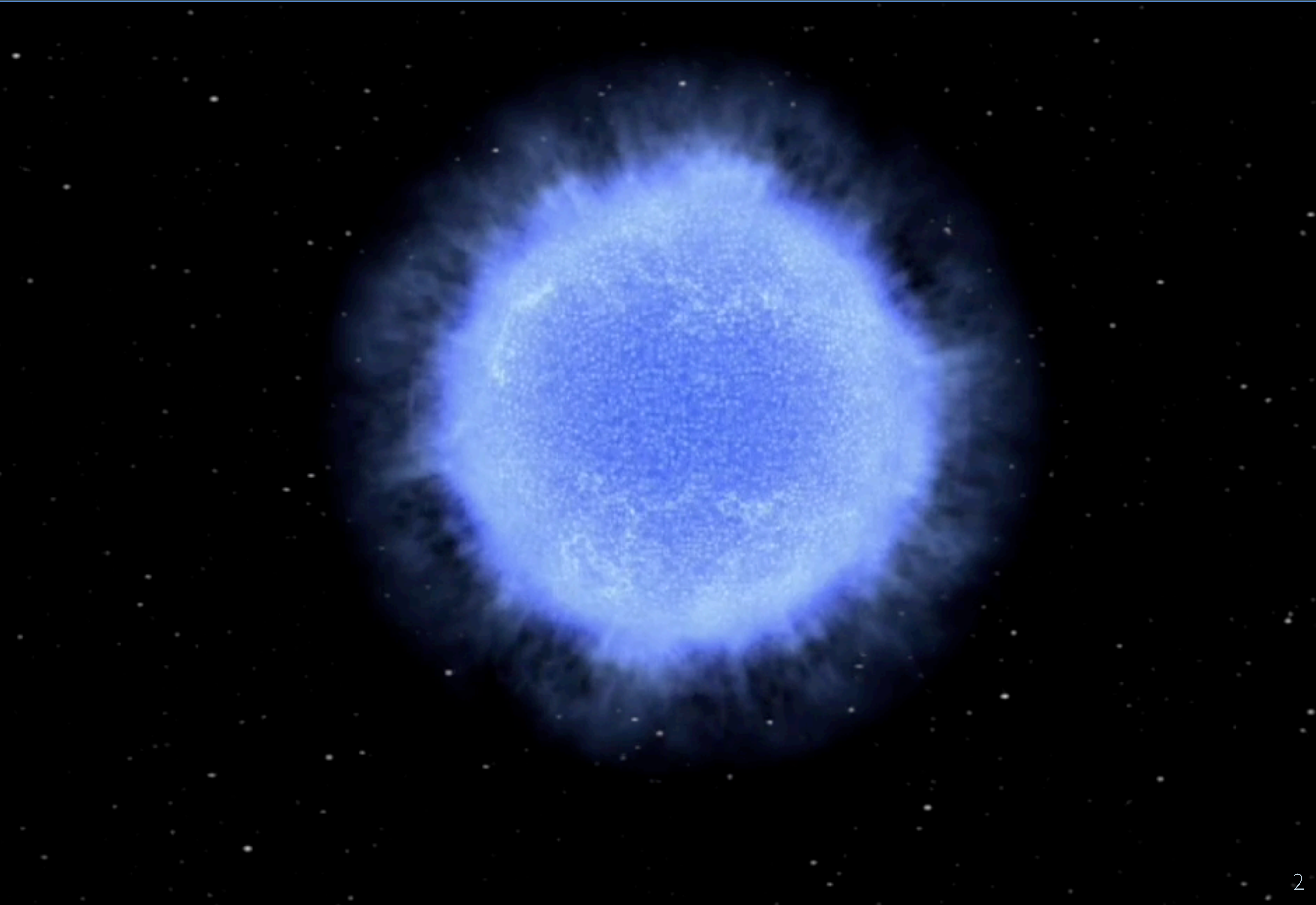


Fang, KK, Olinto 2012, 2013
Fang, KK, Murase, Olinto 2014
Fang 2015
KK, Amato, Blasi 2015
Fang, KK, Murase, Olinto 2015
Guépin & KK, in prep.

Kumiko Kotera - *Institut d'Astrophysique de Paris*

TeV PA, CERN - 13/09/2016

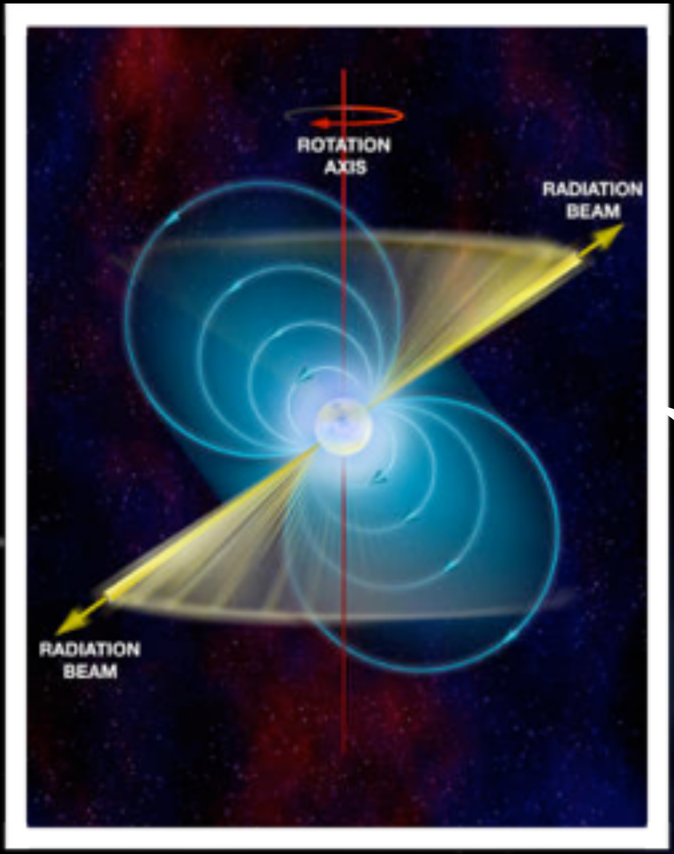
pulsars



pulsars

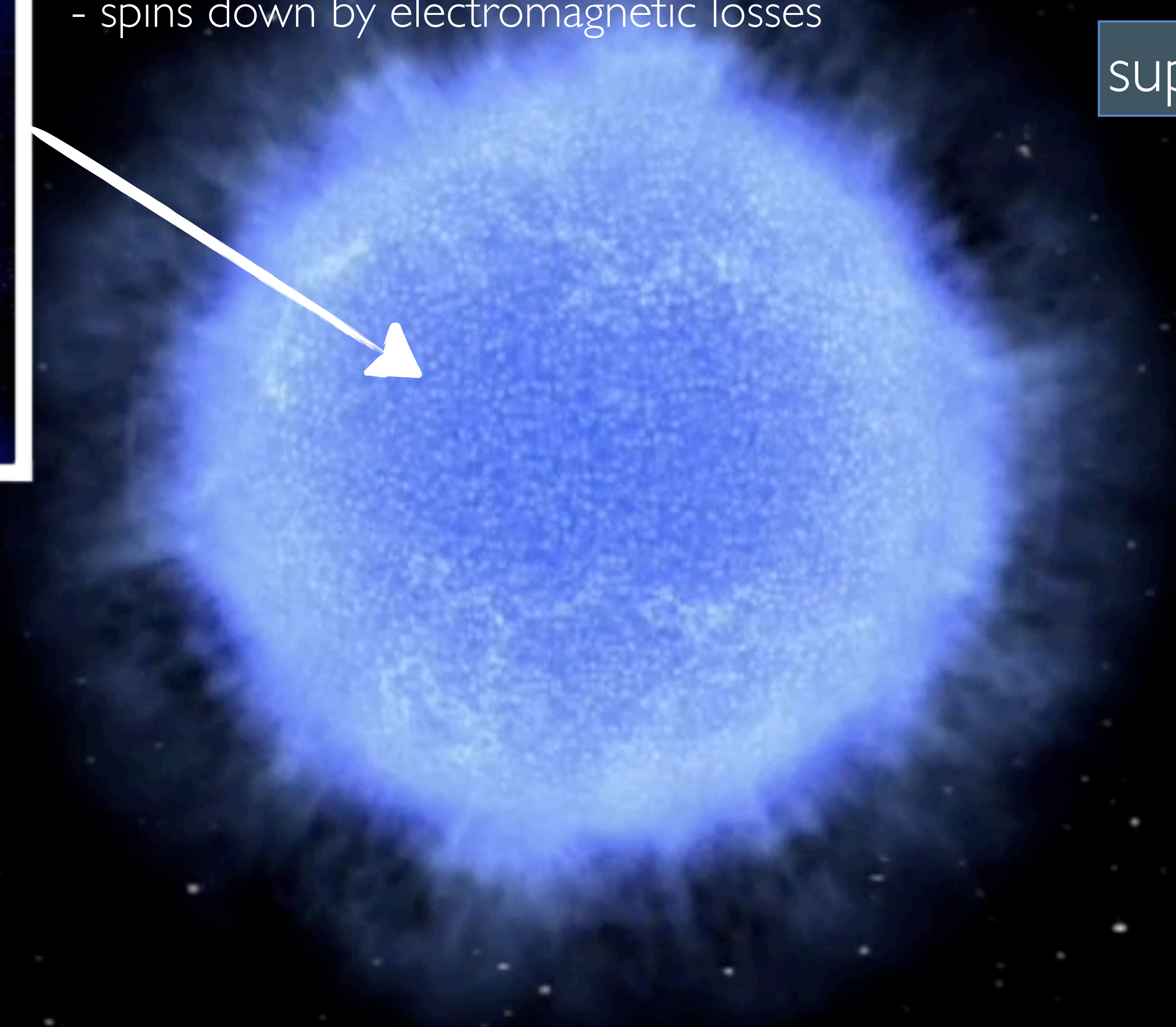
pulsars

pulsars

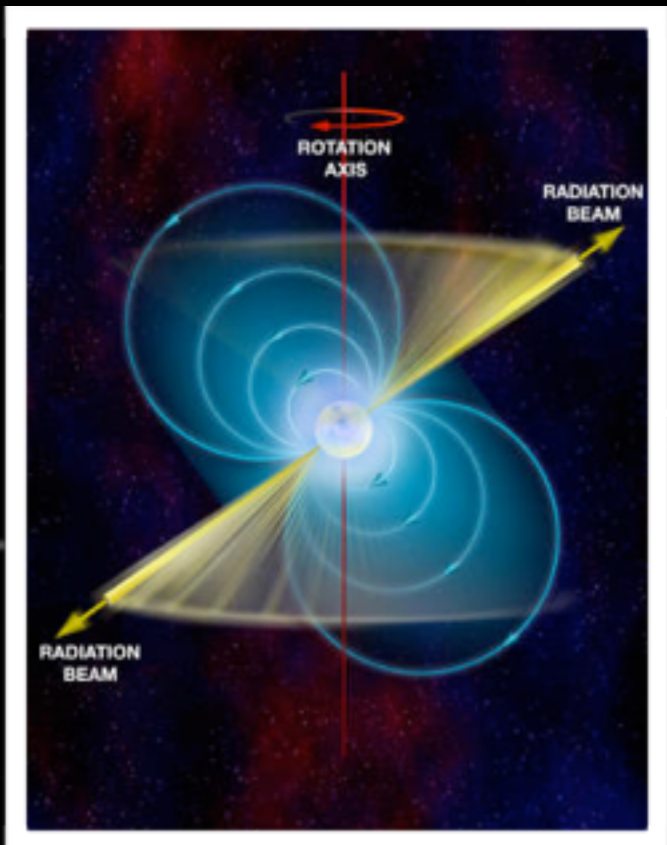


- neutron star
- fast rotation, period P
- strong magnetic field B
- spins down by electromagnetic losses

supernova

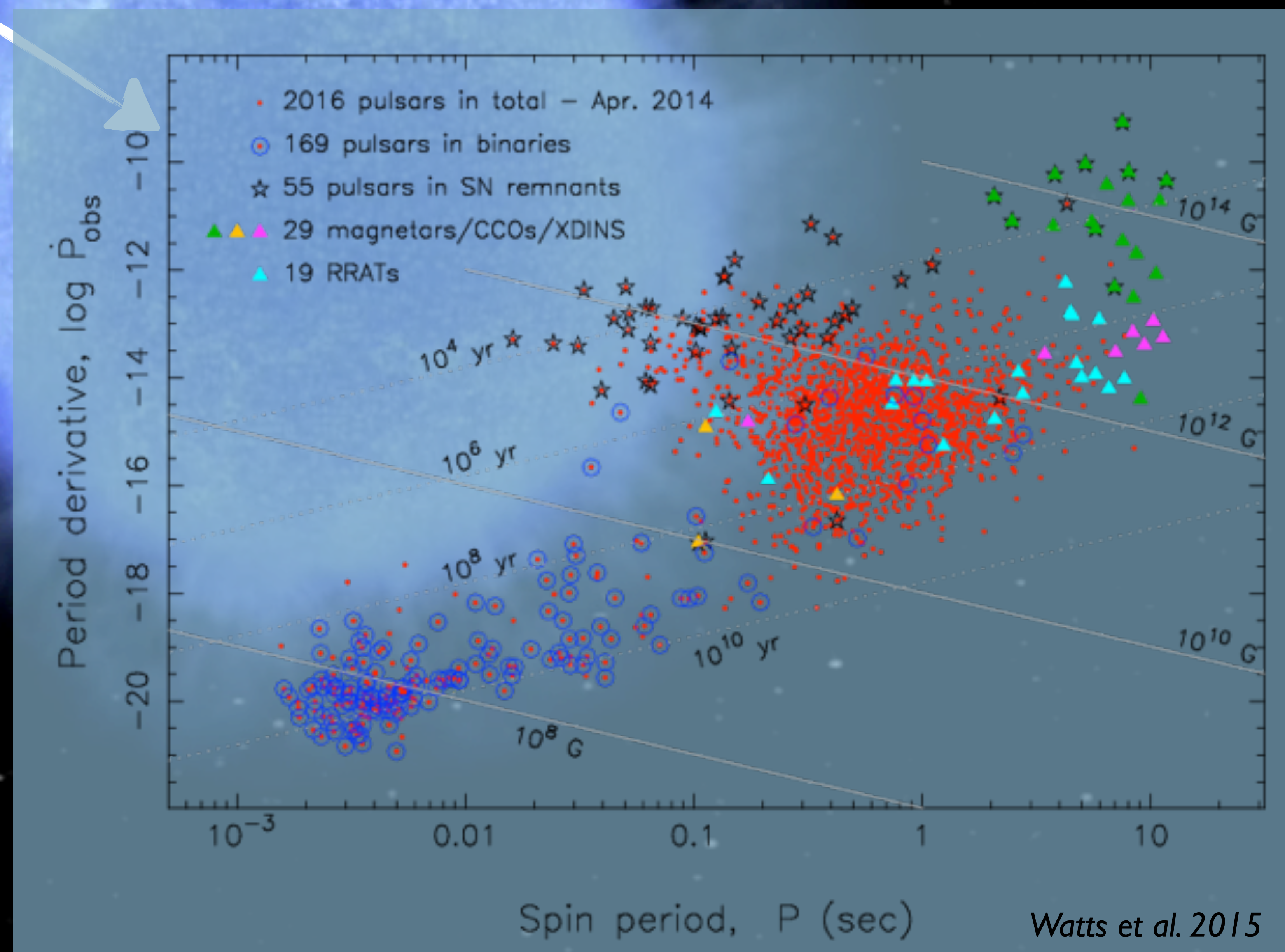


pulsars



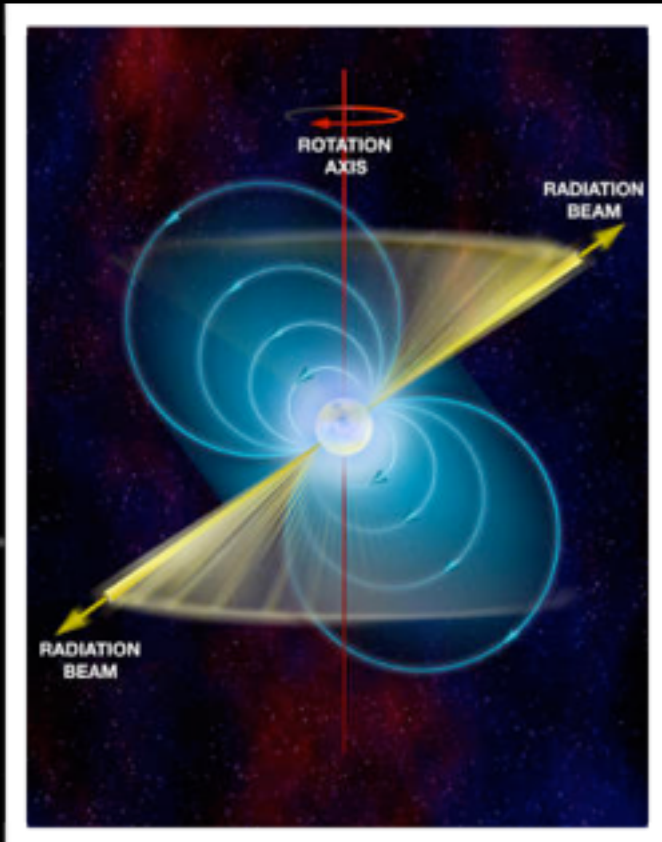
- neutron star
- fast rotation, period P
- strong magnetic field B
- spins down by electromagnetic losses

supernova



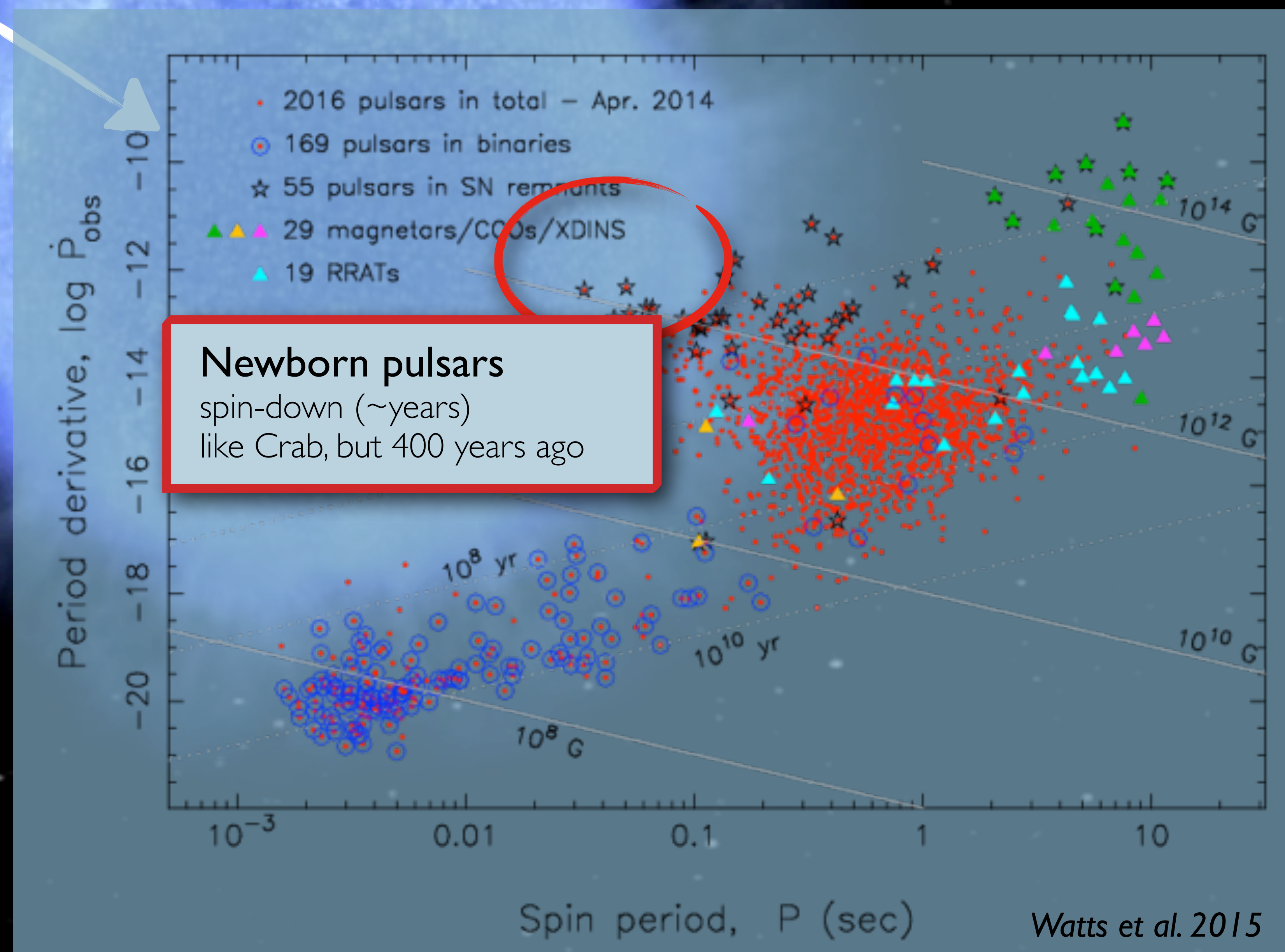
Watts et al. 2015

pulsars



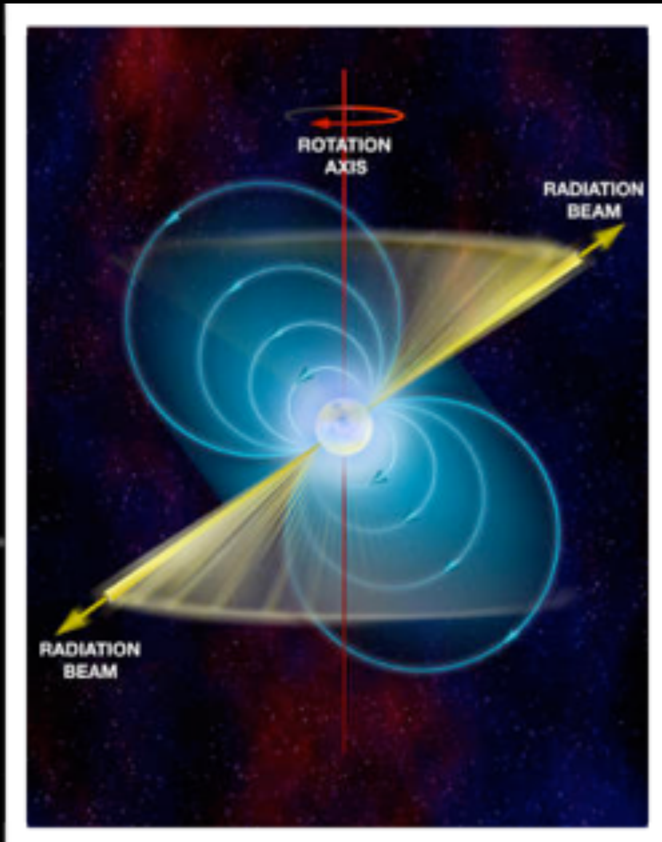
- neutron star
- fast rotation, period P
- strong magnetic field B
- spins down by electromagnetic losses

supernova



Watts et al. 2015

pulsars

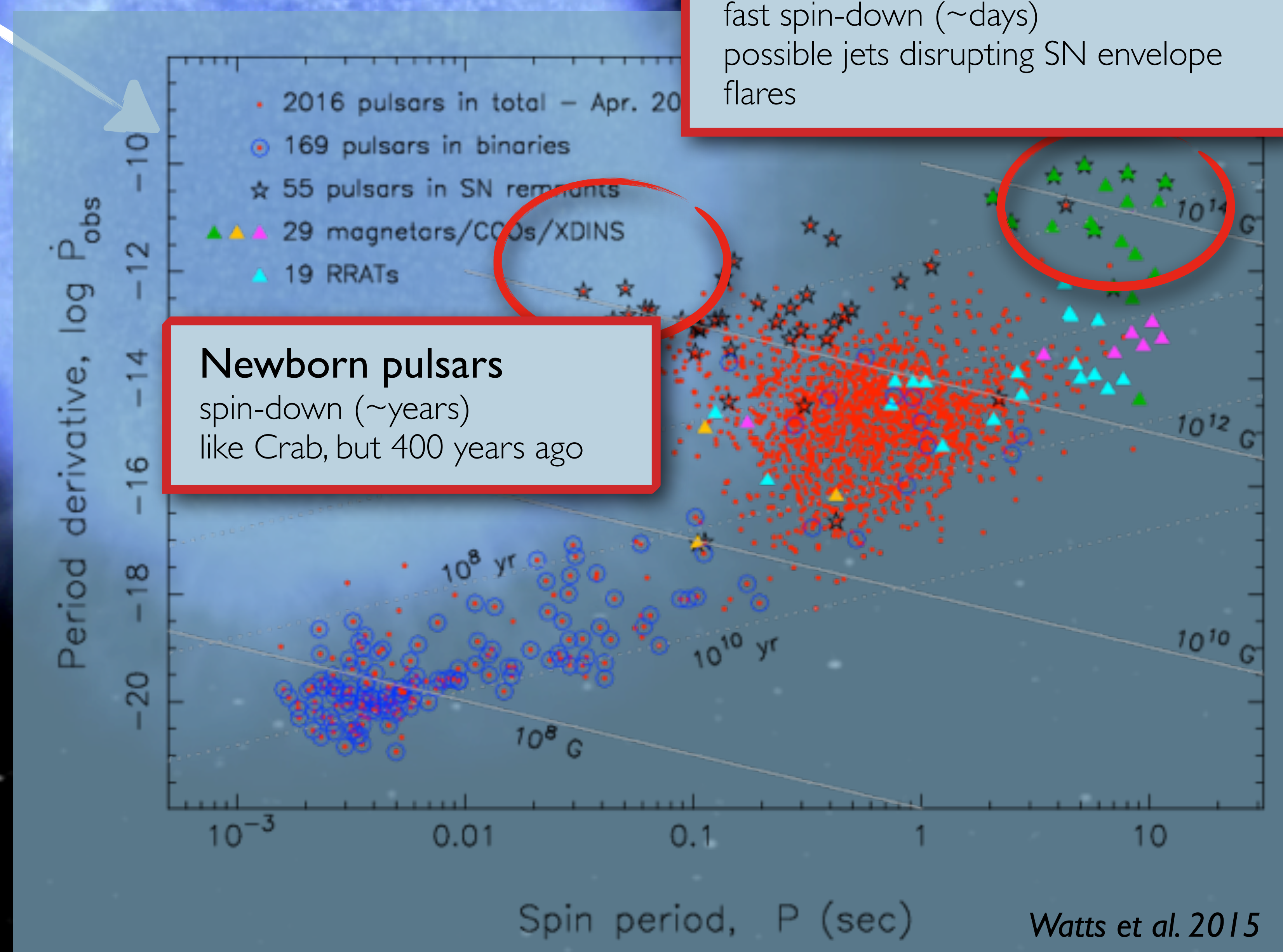


- neutron star
- fast rotation, period P
- strong magnetic field B
- spins down by electromagnetic losses

supernova

Magnetars
fast spin-down (~days)
possible jets disrupting SN envelope
flares

Newborn pulsars
spin-down (~years)
like Crab, but 400 years ago



Watts et al. 2015

Pulsars as neutrino producers

$$p + \gamma \rightarrow n + \pi^+ + \ldots$$

Pulsars as neutrino producers

$$p + \gamma \rightarrow n + \pi^+ + \ldots$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

Pulsars as neutrino producers

$$p + \gamma \to n + \pi^+ + \ldots$$

$$n \to p + e^- + \bar{\nu}_e$$

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

- Cosmic ray acceleration in pulsars
  - Energy budget
  - Magnetic field strength/structure
  - Particle injection

Pulsars as neutrino producers

$$p + \gamma \rightarrow n + \pi^{+} + \ldots$$

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_e + \bar{\nu}_{\mu} + \nu_{\mu}$$

- Cosmic ray acceleration in pulsars
  - Energy budget
  - Magnetic field strength/structure
  - Particle injection

- Background for interaction
  - baryonic density
  - radiative background
  - location: near the star, nebular region, surrounding supernova ejecta

Pulsars as neutrino producers

$$p + p \rightarrow n + \pi^{+} + \ldots$$

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_e + \bar{\nu}_{\mu} + \nu_{\mu}$$

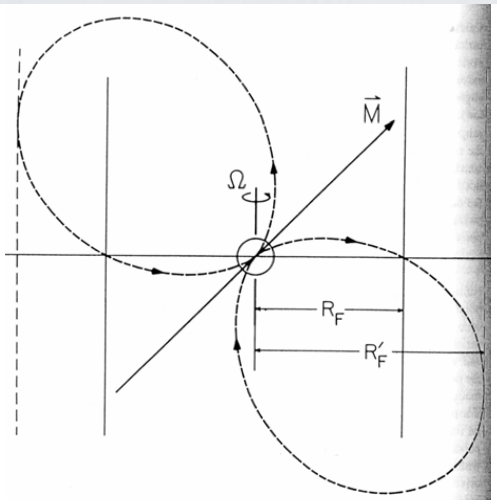
- Cosmic ray acceleration in pulsars
  - Energy budget
  - Magnetic field strength/structure
  - Particle injection
- Background for interaction
  - baryonic density
  - radiative background
  - location: near the star, nebular region, surrounding supernova ejecta

Cosmic ray acceleration in pulsars

Charge density

Induced electric field

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



Implies a charge density (Goldreich-Julian 69)

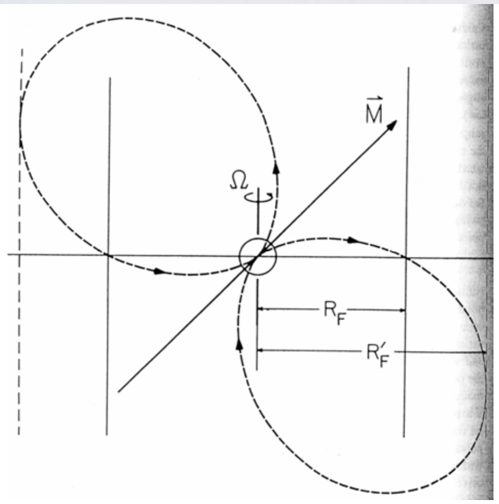
$$\rho = \frac{1}{4\pi}\nabla \cdot \mathbf{E} \approx -\frac{\boldsymbol{\Omega} \cdot \mathbf{B}}{2\pi c} \equiv \rho_{GJ}$$

Cosmic ray acceleration in pulsars

Charge density

Induced electric field

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



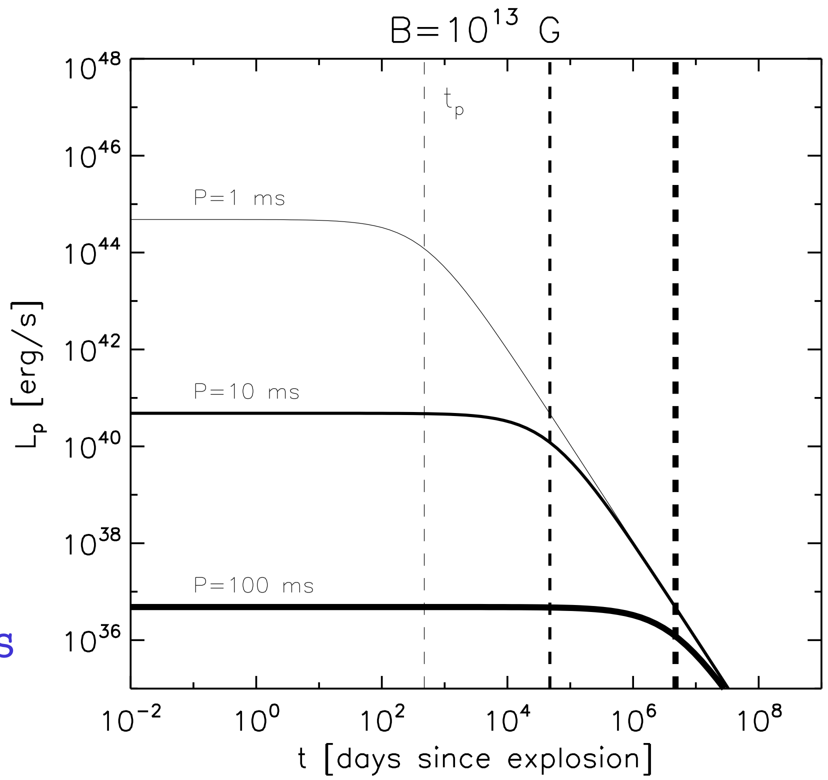
Implies a charge density (Goldreich-Julian 69)

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

pulsar outflow energetics

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

pulsar luminosity $L_\mathrm{p}(t) = \frac{E_\mathrm{p}}{t_\mathrm{p}} \frac{1}{(1+t/t_\mathrm{p})^2}$



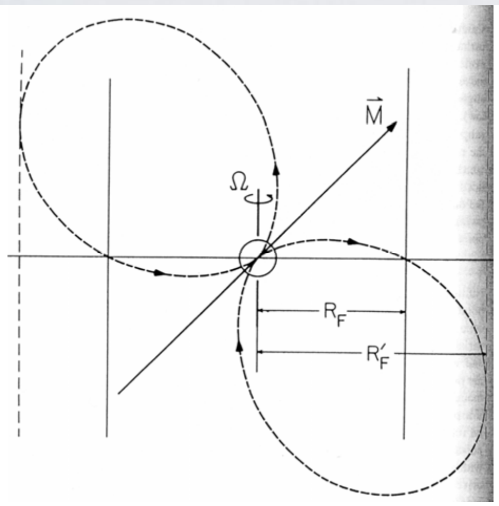
t_p ~ a few years for ms pulsars

Cosmic ray acceleration in pulsars

Charge density

Induced electric field

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



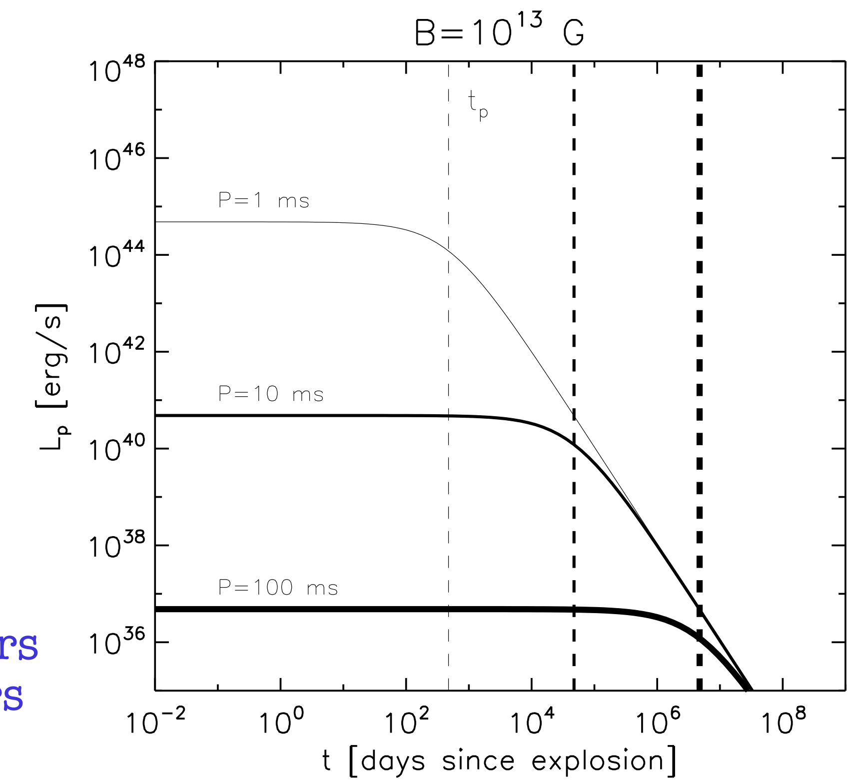
Implies a charge density (Goldreich-Julian 69)

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

pulsar outflow energetics

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

pulsar luminosity $\quad L_{\rm p}(t) = \frac{E_{\rm p}}{t_{\rm p}} \frac{1}{(1+t/t_{\rm p})^2}$



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

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:

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

fraction of luminosity into particle kinetic energy

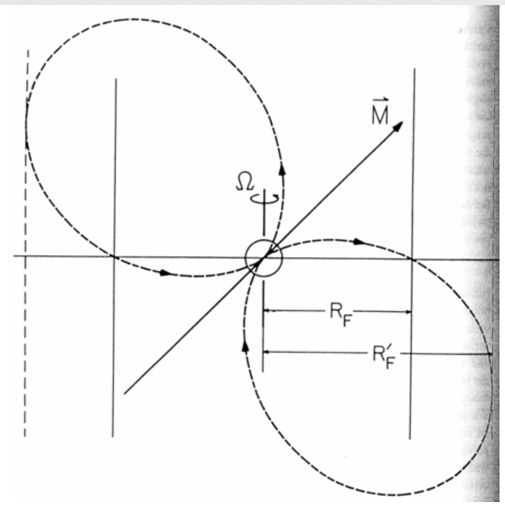
pair multiplicity

Cosmic ray acceleration in pulsars

Charge density

Induced electric field

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



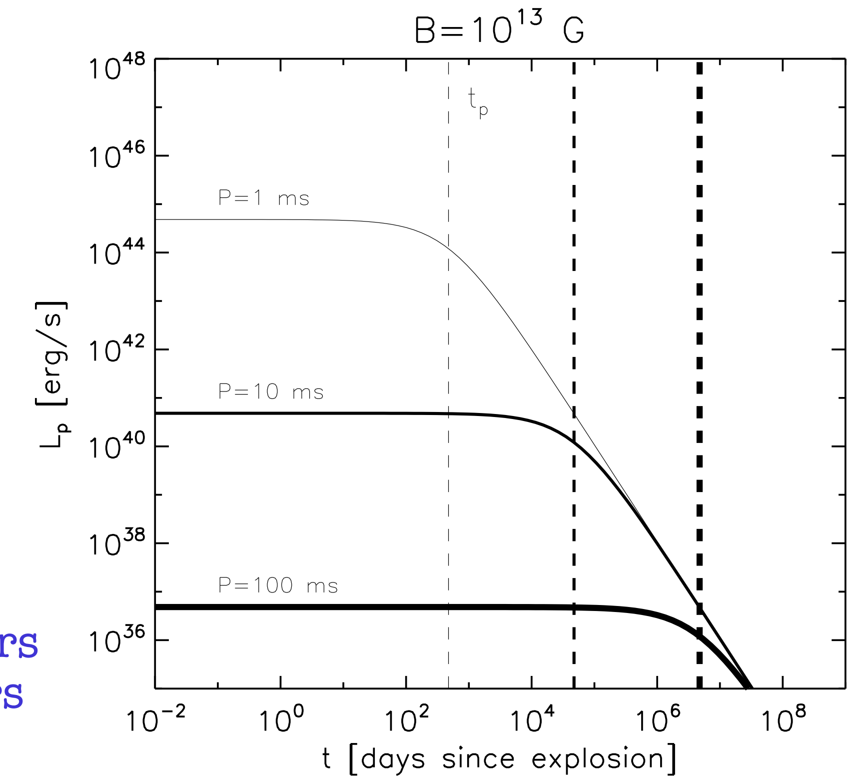
Implies a charge density (Goldreich-Julian 69)

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

pulsar outflow energetics

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

pulsar luminosity $\quad L_\mathrm{p}(t) = \frac{E_\mathrm{p}}{t_\mathrm{p}} \frac{1}{(1+t/t_\mathrm{p})^2}$



$t_\mathrm{p} \sim$ a few years for ms pulsars

pulsar spins down

conversion of pulsar electromagnetic into kinetic energy

particles accelerated to maximum Lorentz factor:

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

Goldreich-Julian charge density

maximum energy:

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

fraction of luminosity into particle kinetic energy

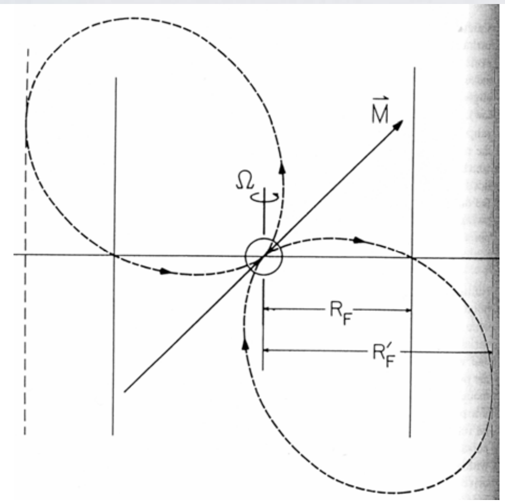
pair multiplicity

Cosmic ray acceleration in pulsars

Charge density

Induced electric field

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



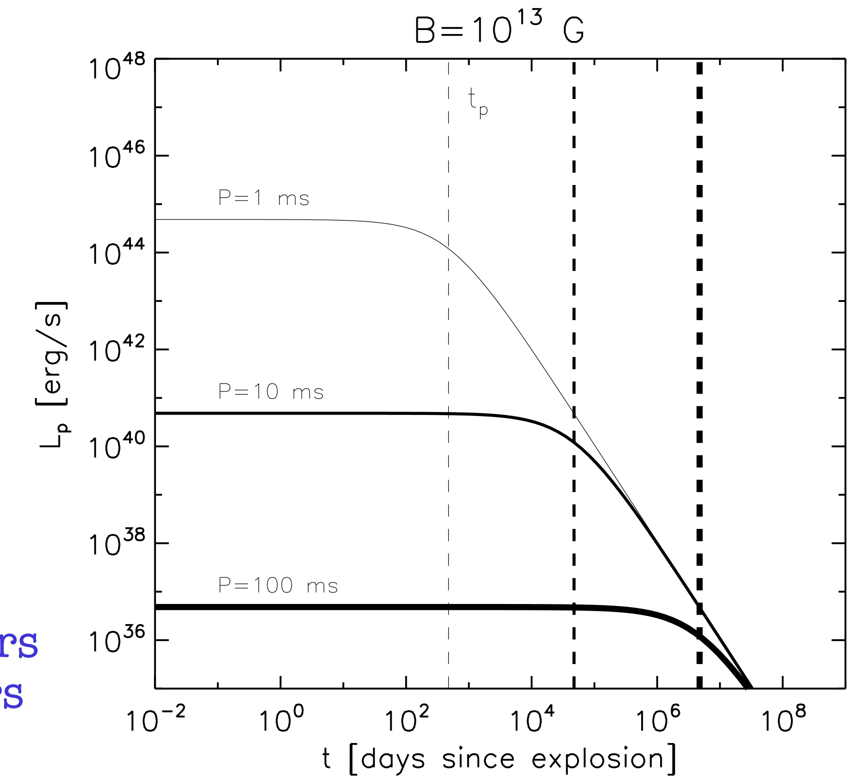
Implies a charge density (Goldreich-Julian 69)

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

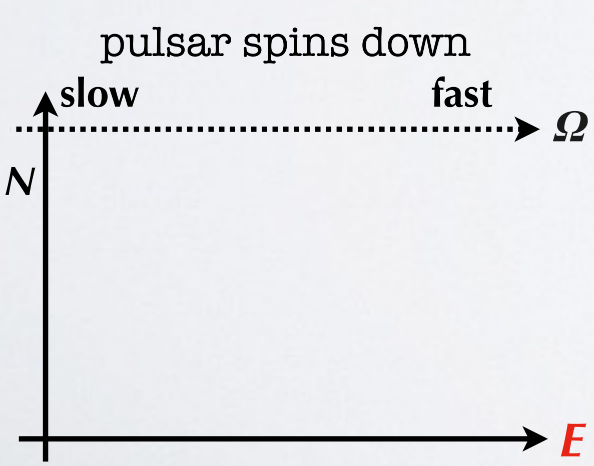
pulsar outflow energetics

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

pulsar luminosity $L_\mathrm{p}(t) = \frac{E_\mathrm{p}}{t_\mathrm{p}} \frac{1}{(1+t/t_\mathrm{p})^2}$



t_p ~ a few years for ms pulsars



conversion of pulsar electromagnetic into kinetic energy

particles accelerated to maximum Lorentz factor:

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

Goldreich-Julian charge density

maximum energy:

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

fraction of luminosity into particle kinetic energy

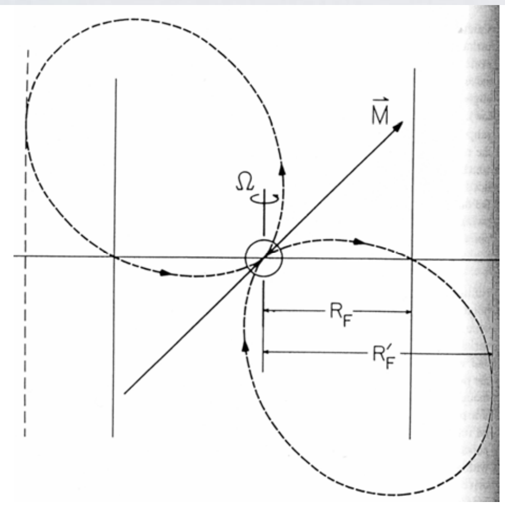
pair multiplicity

Cosmic ray acceleration in pulsars

Charge density

Induced electric field

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



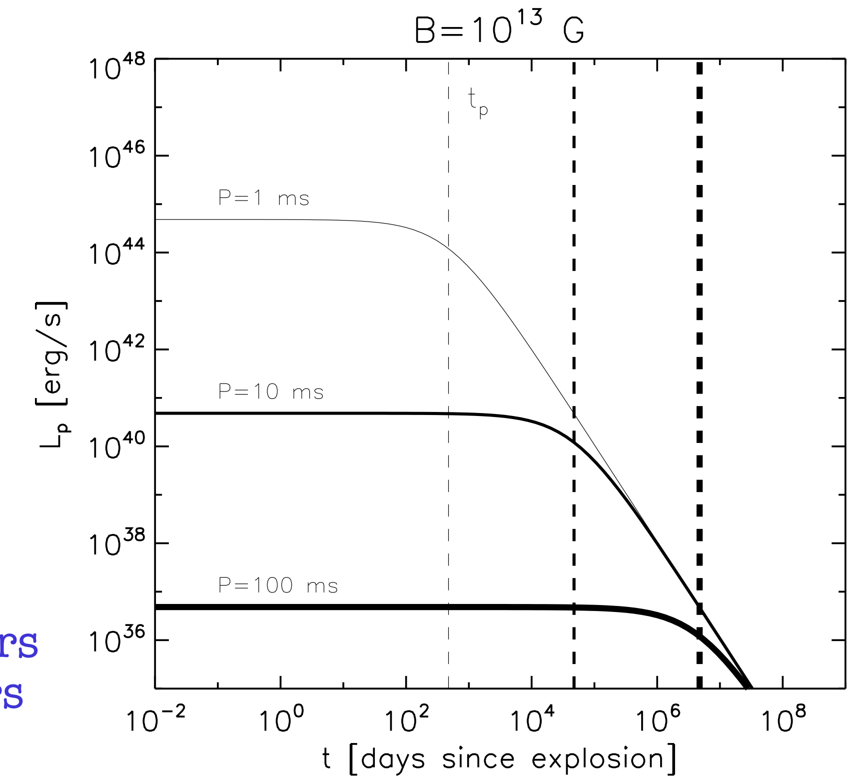
Implies a charge density (Goldreich-Julian 69)

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

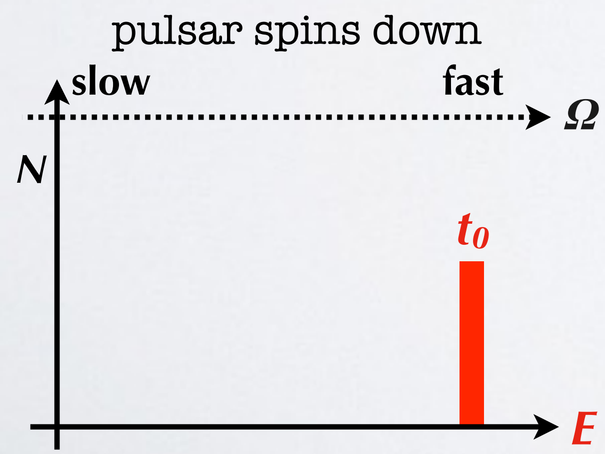
pulsar outflow energetics

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

pulsar luminosity $L_{\rm p}(t) = \frac{E_{\rm p}}{t_{\rm p}} \frac{1}{(1+t/t_{\rm p})^2}$



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



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:

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

fraction of luminosity into particle kinetic energy

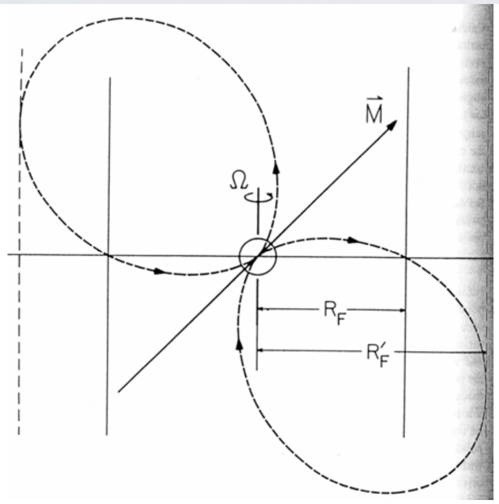
pair multiplicity

Cosmic ray acceleration in pulsars

Charge density

Induced electric field

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



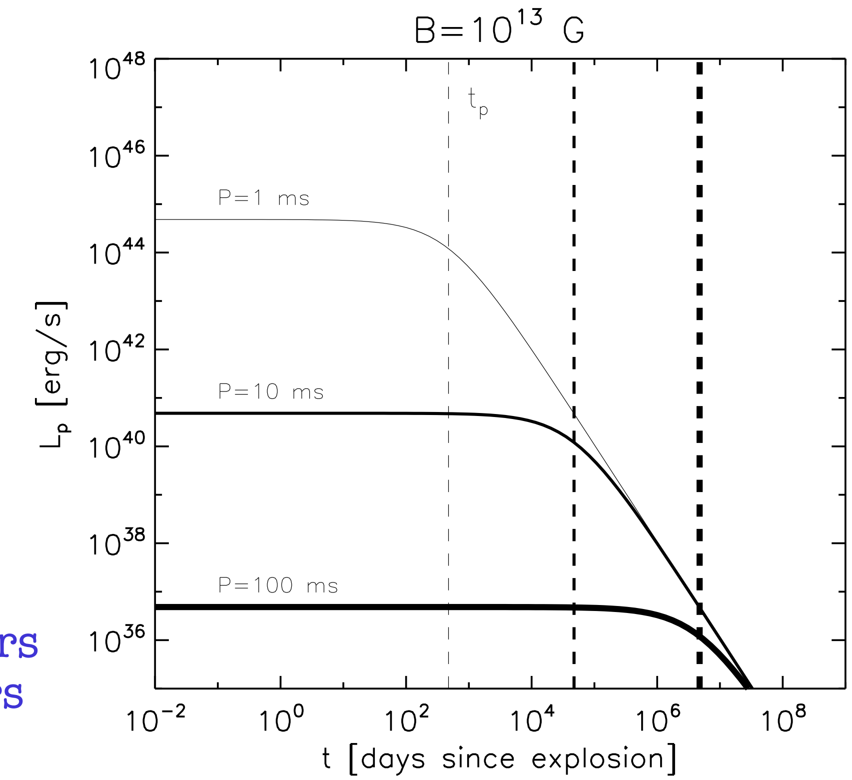
Implies a charge density (Goldreich-Julian 69)

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

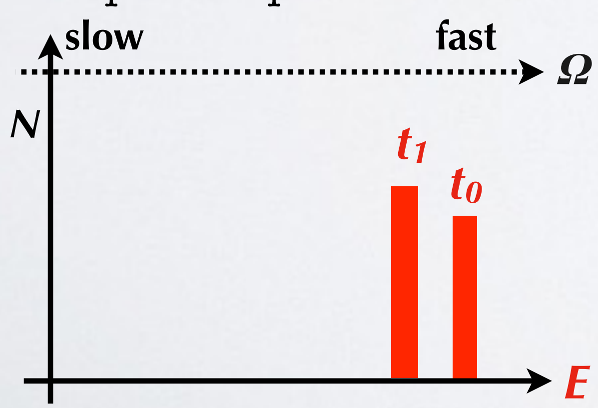
pulsar outflow energetics

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

pulsar luminosity $$L_{\rm p}(t) = \frac{E_{\rm p}}{t_{\rm p}} \frac{1}{(1+t/t_{\rm p})^2}$$



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



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:

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

fraction of luminosity into particle kinetic energy

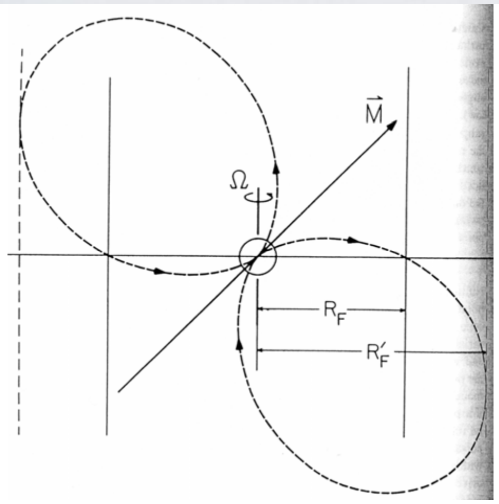
pair multiplicity

Cosmic ray acceleration in pulsars

Charge density

Induced electric field

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



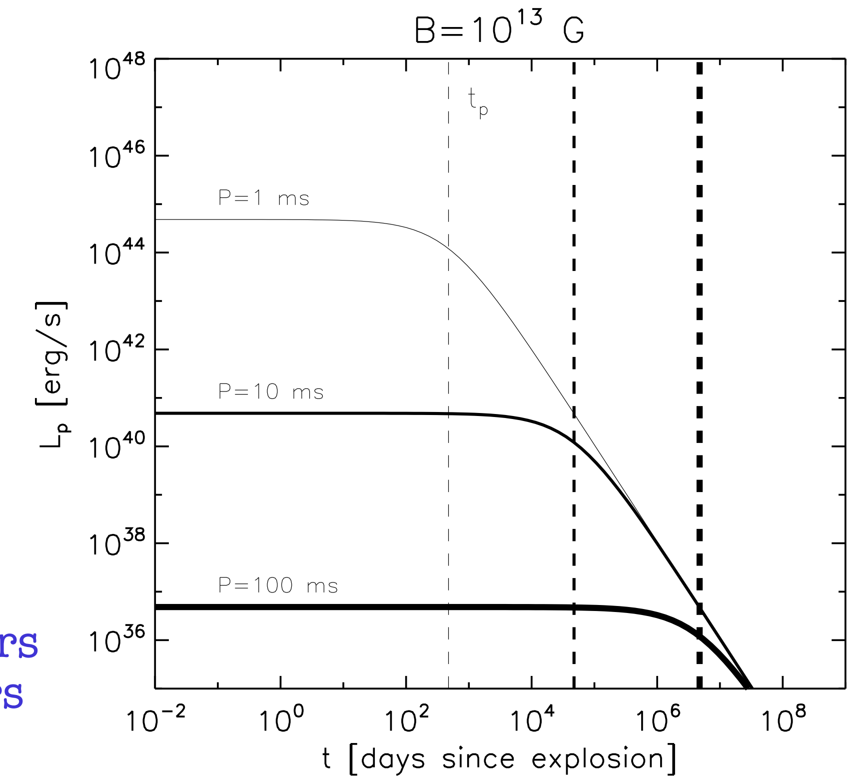
Implies a charge density (Goldreich-Julian 69)

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

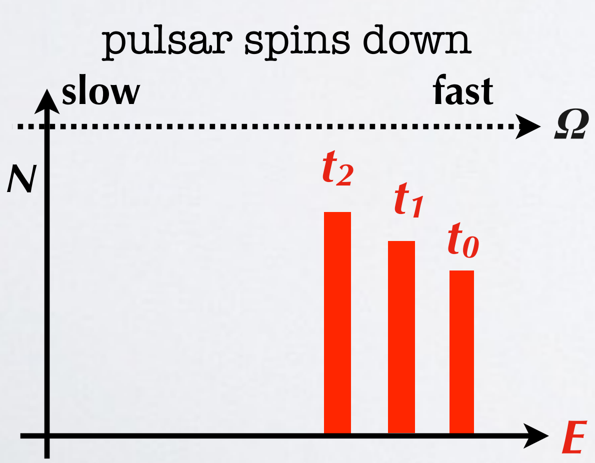
pulsar outflow energetics

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

pulsar luminosity $$L_{\rm p}(t) = \frac{E_{\rm p}}{t_{\rm p}} \frac{1}{(1+t/t_{\rm p})^2}$$



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



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:

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

fraction of luminosity into particle kinetic energy

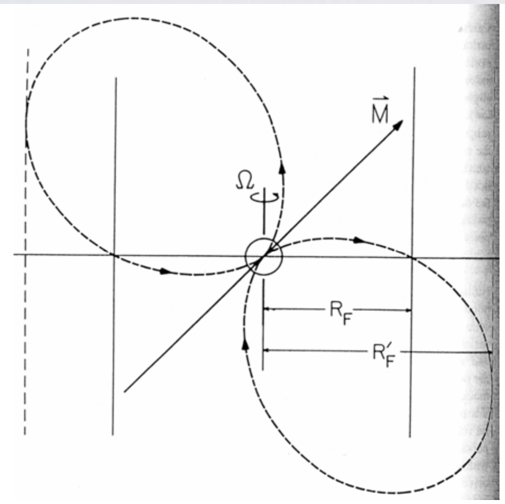
pair multiplicity

Cosmic ray acceleration in pulsars

Charge density

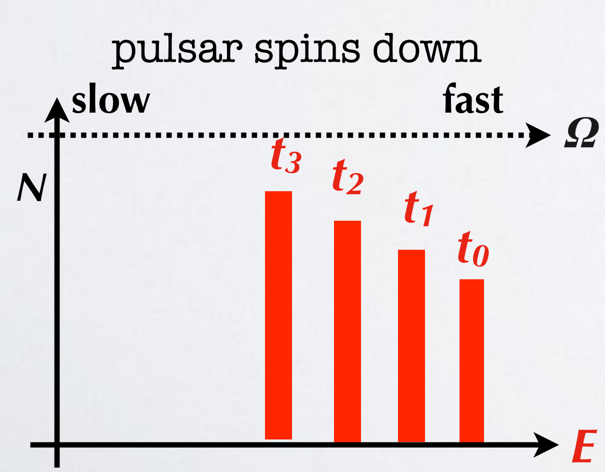
Induced electric field

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



Implies a charge density (Goldreich-Julian 69)

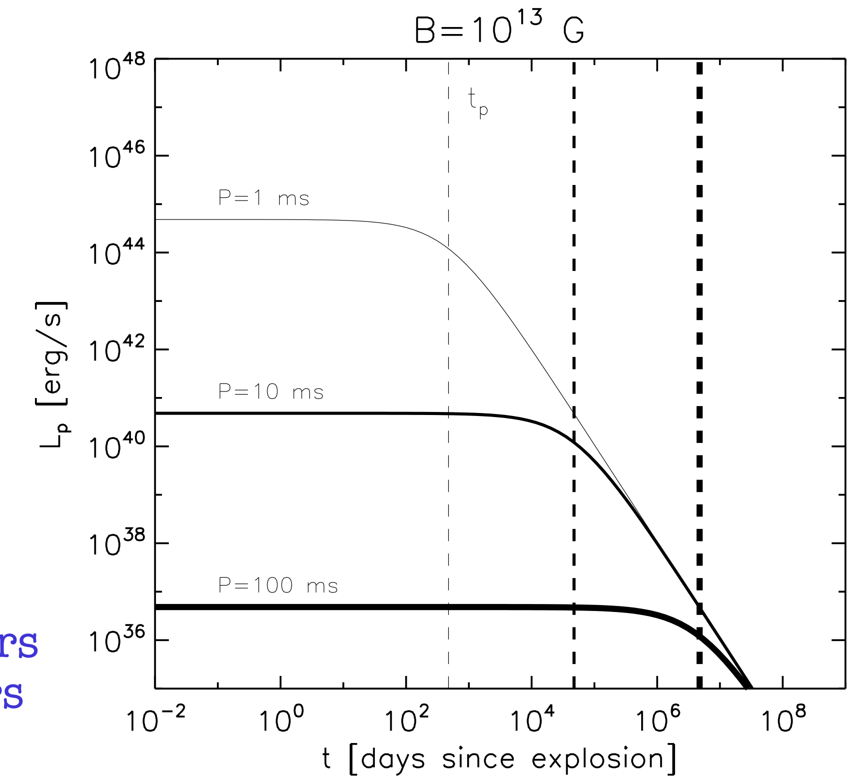
$$\rho = \frac{1}{4\pi}\nabla \cdot \mathbf{E} \approx -\frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi c} \equiv \rho_{GJ}$$



pulsar outflow energetics

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

pulsar luminosity $\quad L_{\rm p}(t) = \frac{E_{\rm p}}{t_{\rm p}} \frac{1}{(1+t/t_{\rm p})^2}$



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

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:

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

fraction of luminosity into particle kinetic energy

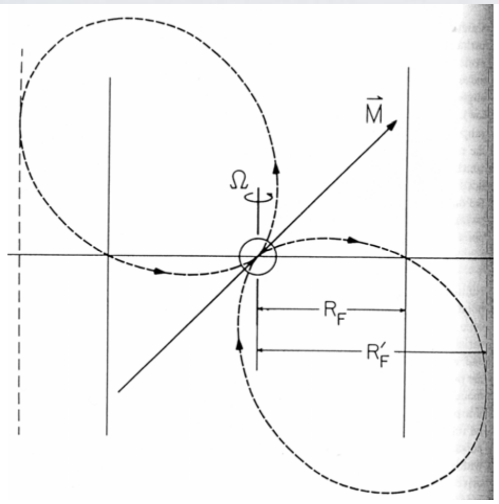
pair multiplicity

Cosmic ray acceleration in pulsars

Charge density

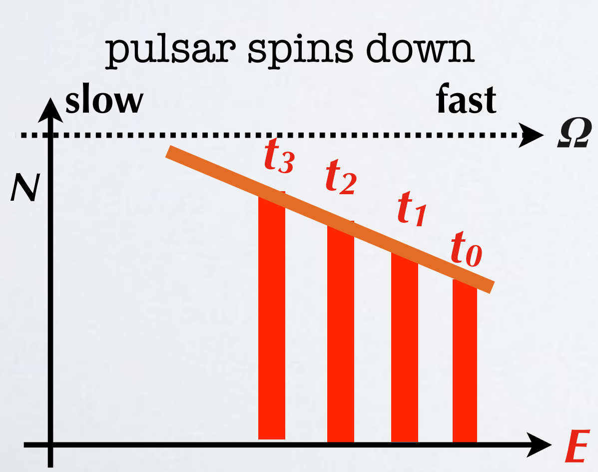
Induced electric field

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



Implies a charge density (Goldreich-Julian 69)

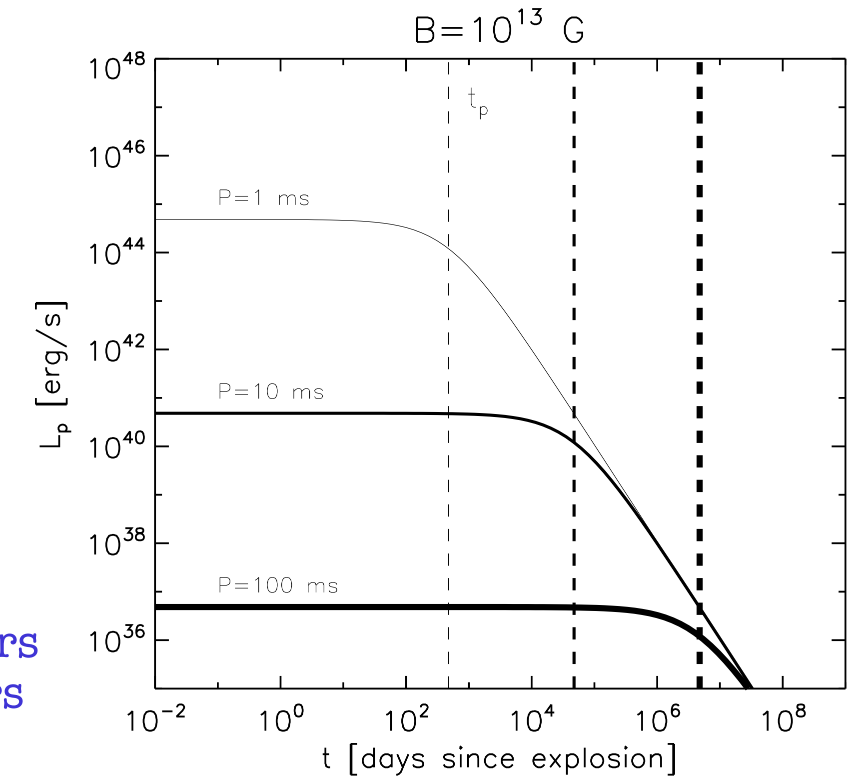
$$\rho = \frac{1}{4\pi}\nabla \cdot \mathbf{E} \approx -\frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi c} \equiv \rho_{GJ}$$



pulsar outflow energetics

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

pulsar luminosity $\quad L_\mathrm{p}(t) = \frac{E_\mathrm{p}}{t_\mathrm{p}} \frac{1}{(1+t/t_\mathrm{p})^2}$



t_p ~ a few years for ms pulsars

conversion of pulsar electromagnetic into kinetic energy

particles accelerated to maximum Lorentz factor:

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

Goldreich-Julian charge density

maximum energy:

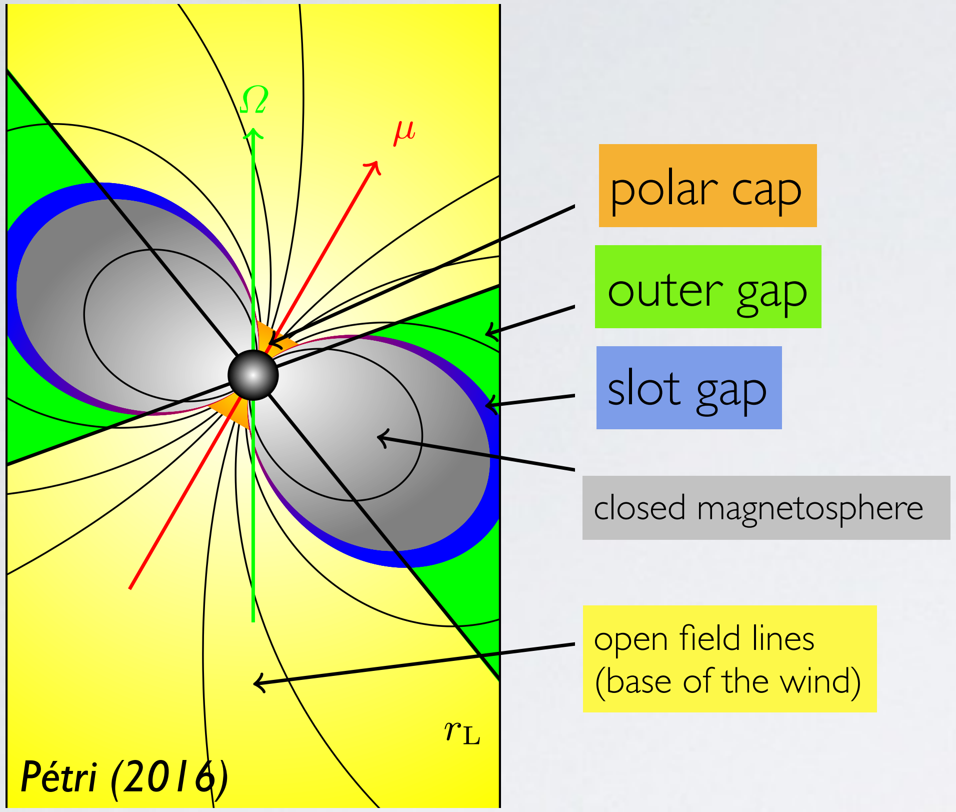
$$E_0 \sim 1.5 \times 10^{20}\,\mathrm{eV}\, A_{56}\, \eta\, \kappa_4^{-1} P_{\mathrm{i},-3}^{-2} B_{13} R_{\star,6}^3$$

fraction of luminosity into particle kinetic energy

pair multiplicity

Cosmic ray acceleration in pulsars

- Acceleration region?

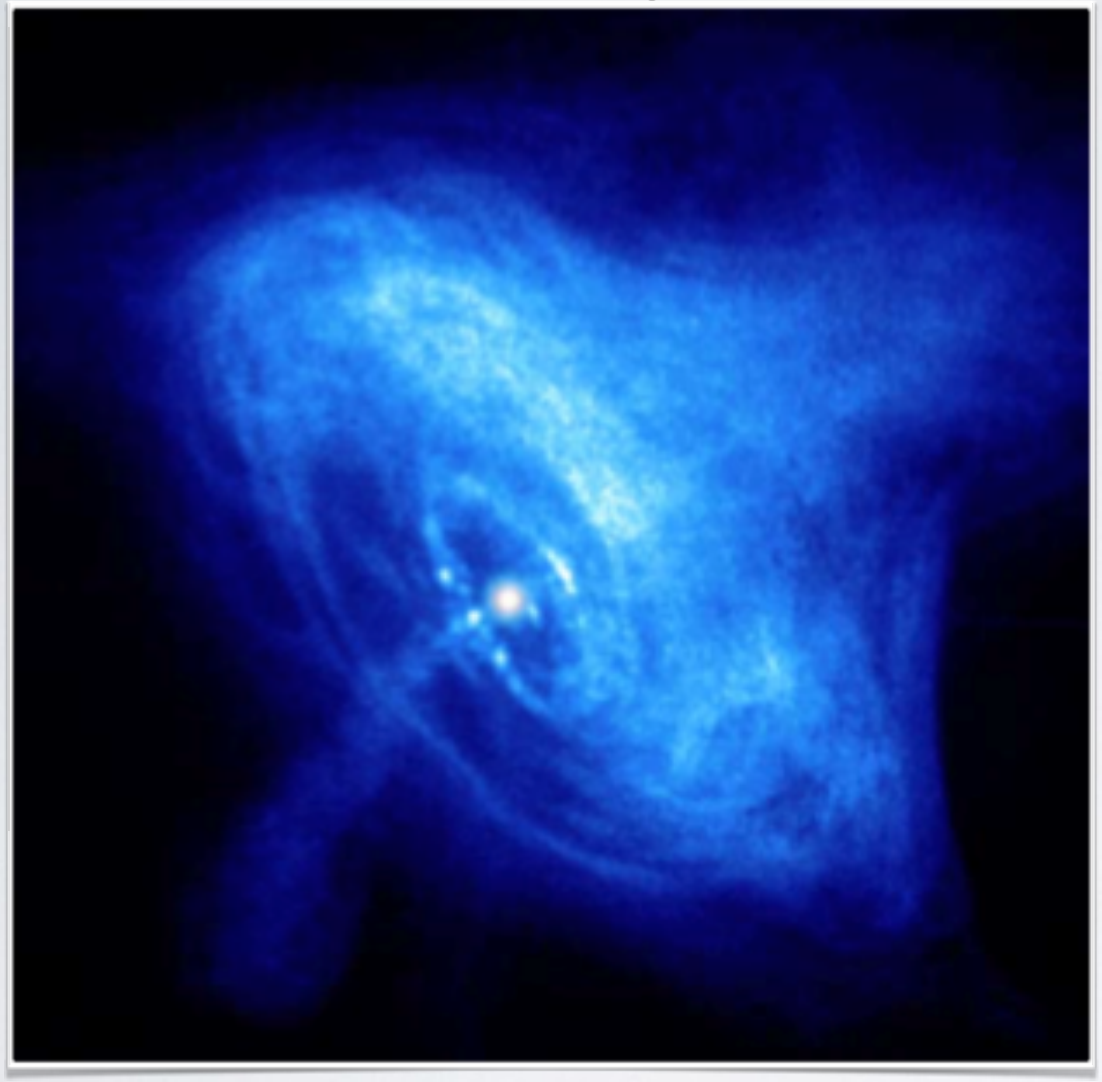


- Gaps close to star

reviews: Harding (2007), Hirotani (2008)

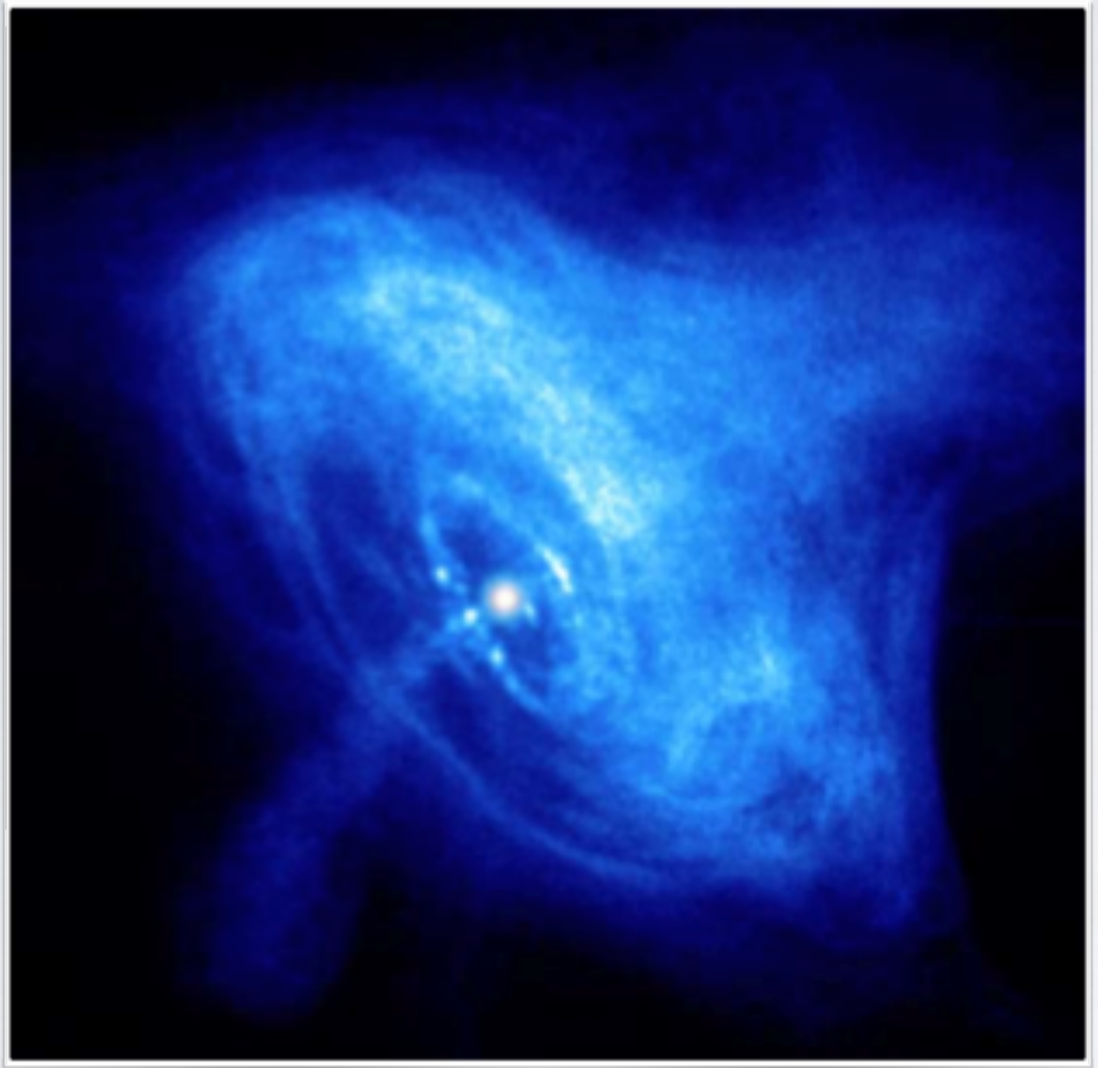
Cosmic ray acceleration in pulsars

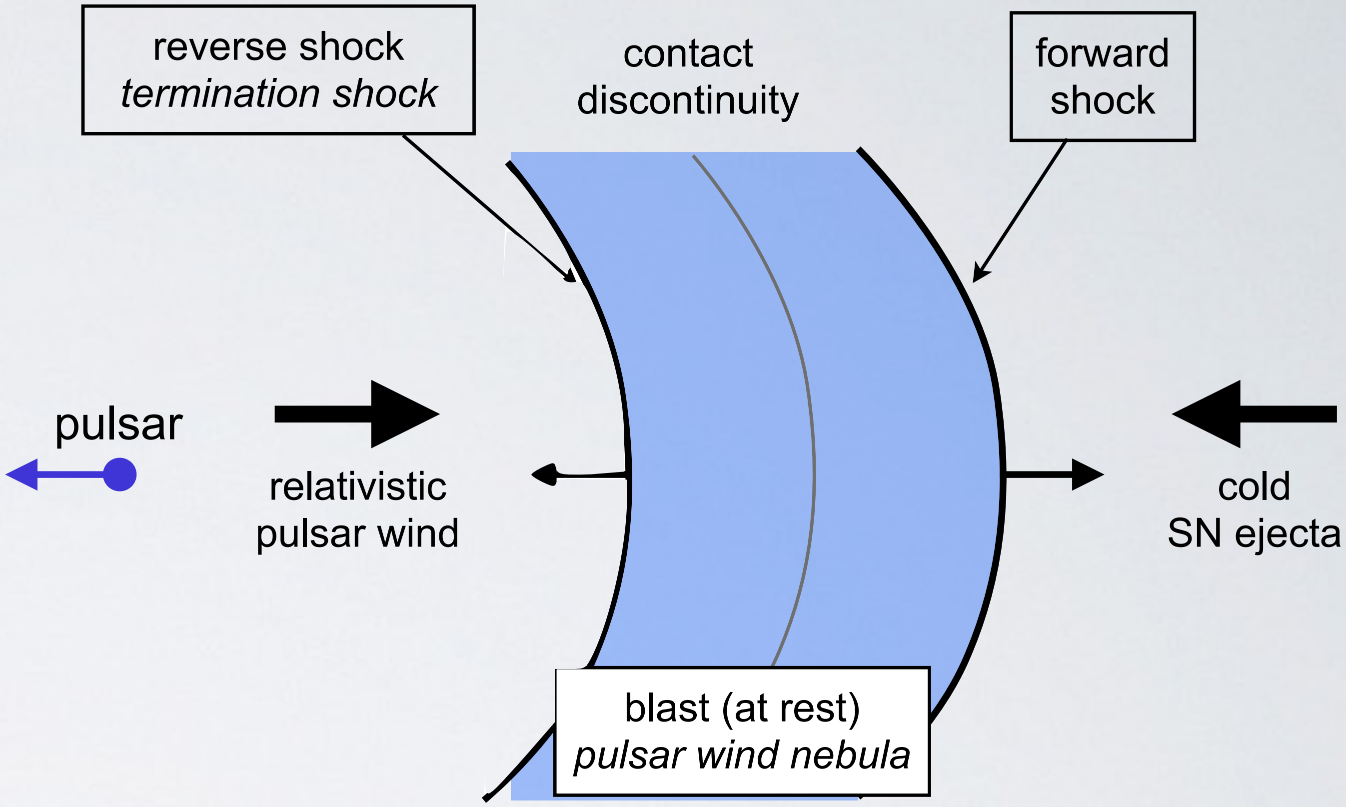
- Acceleration region?



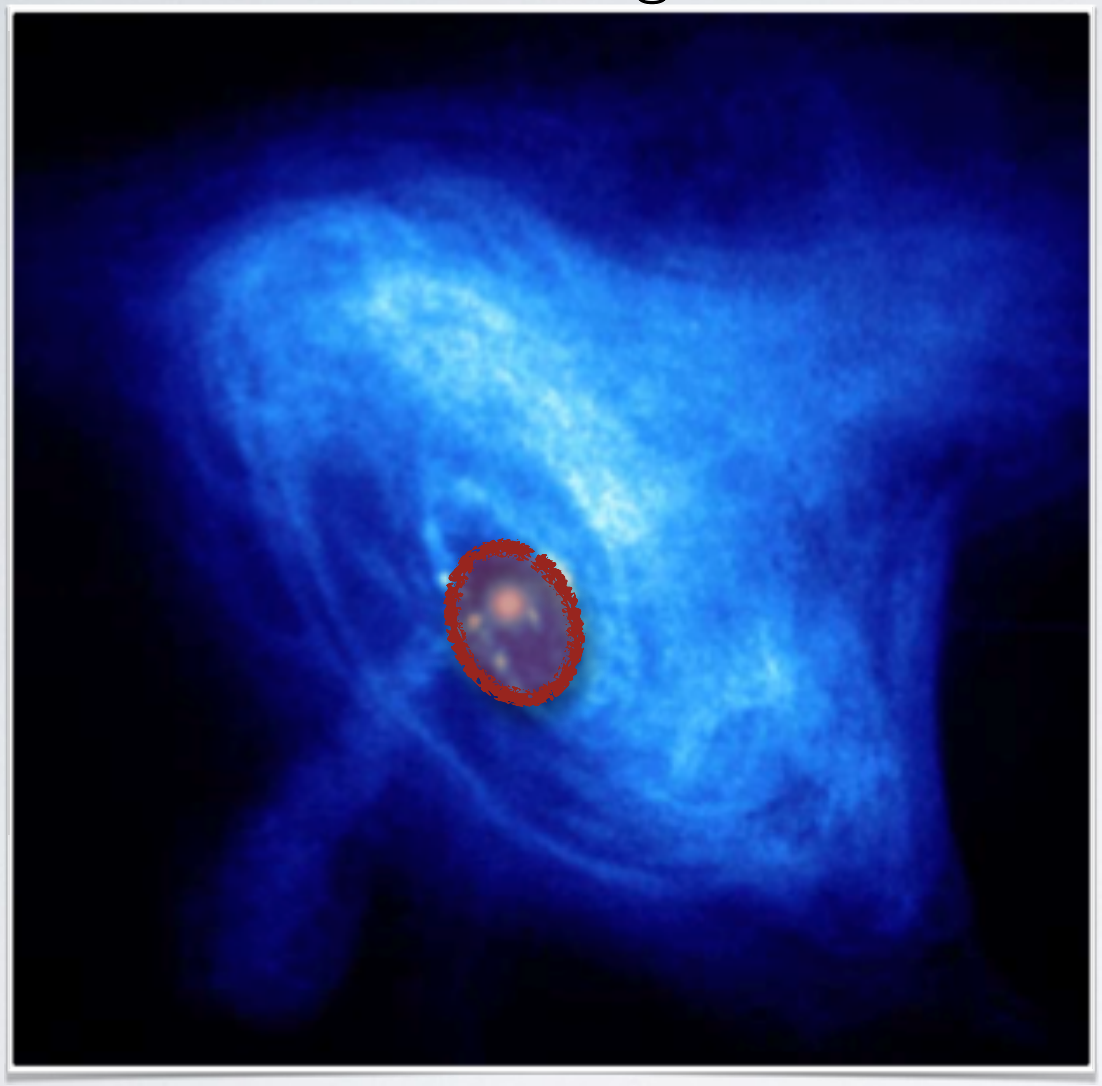
Cosmic ray acceleration in pulsars

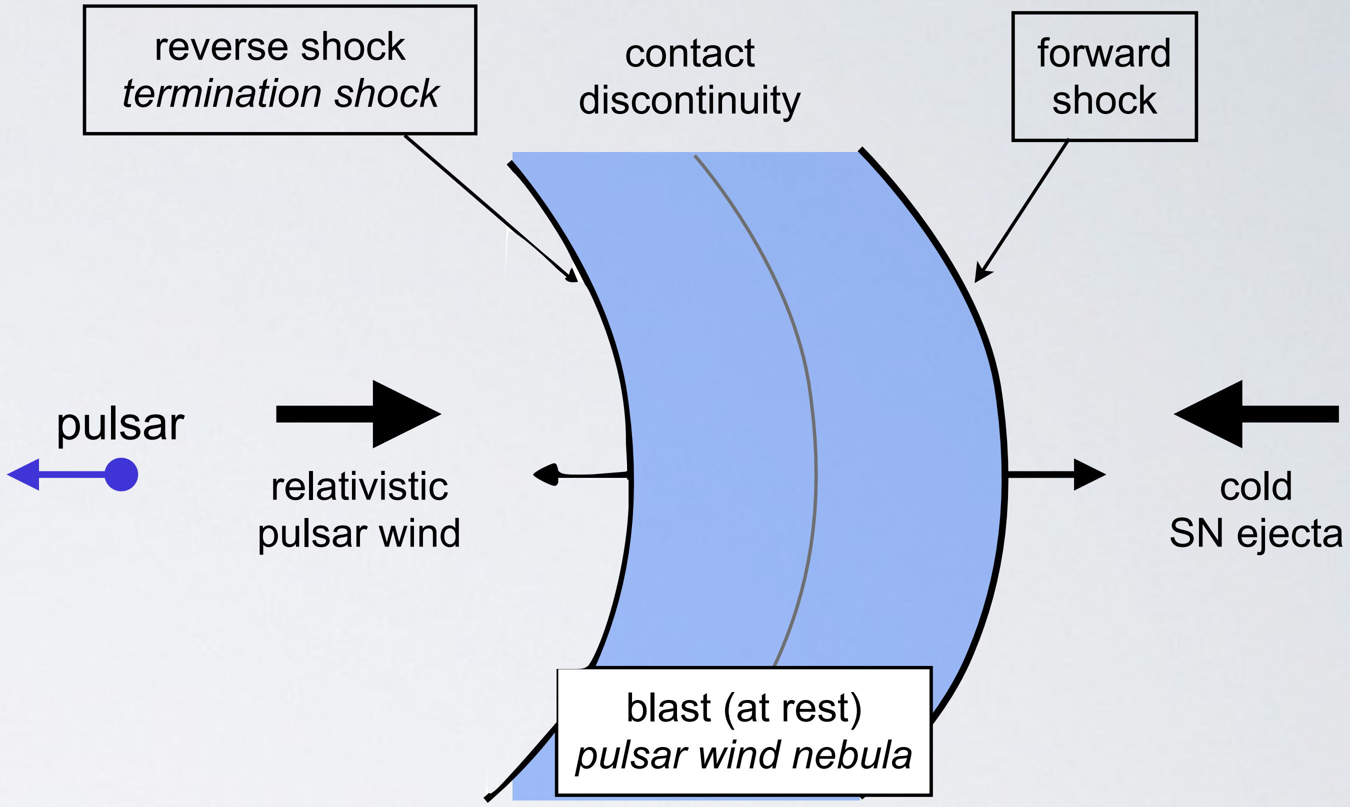
- Acceleration region?



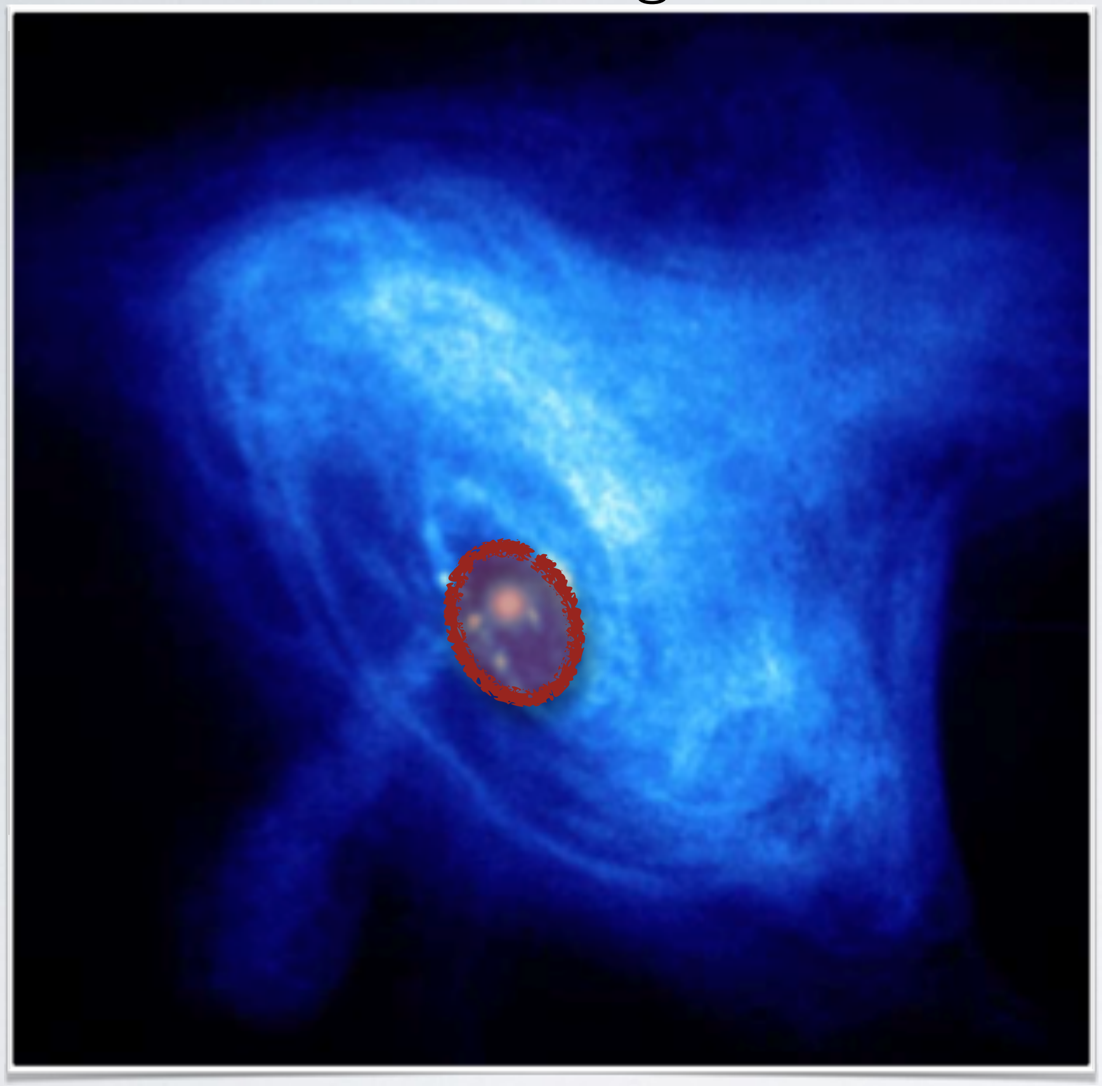


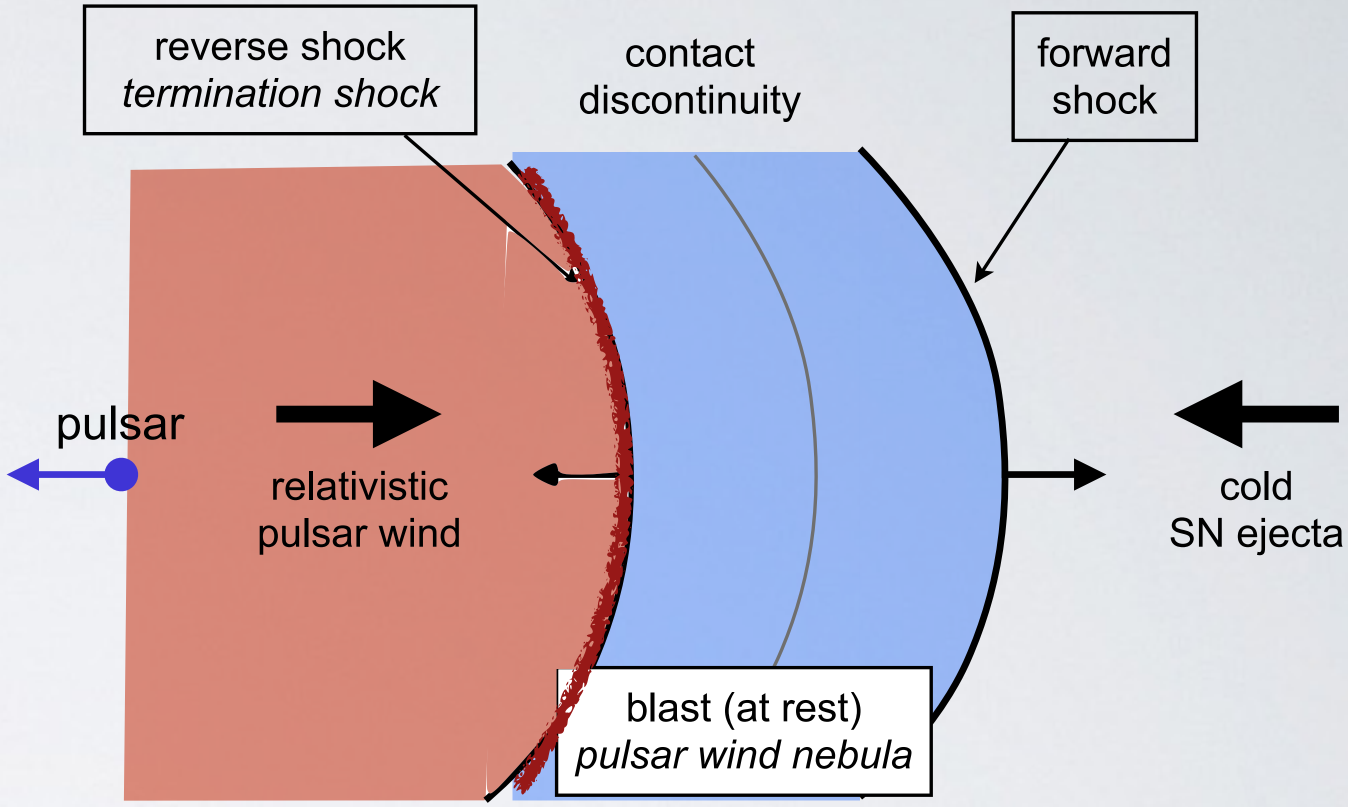
- Acceleration region?





- Acceleration region?



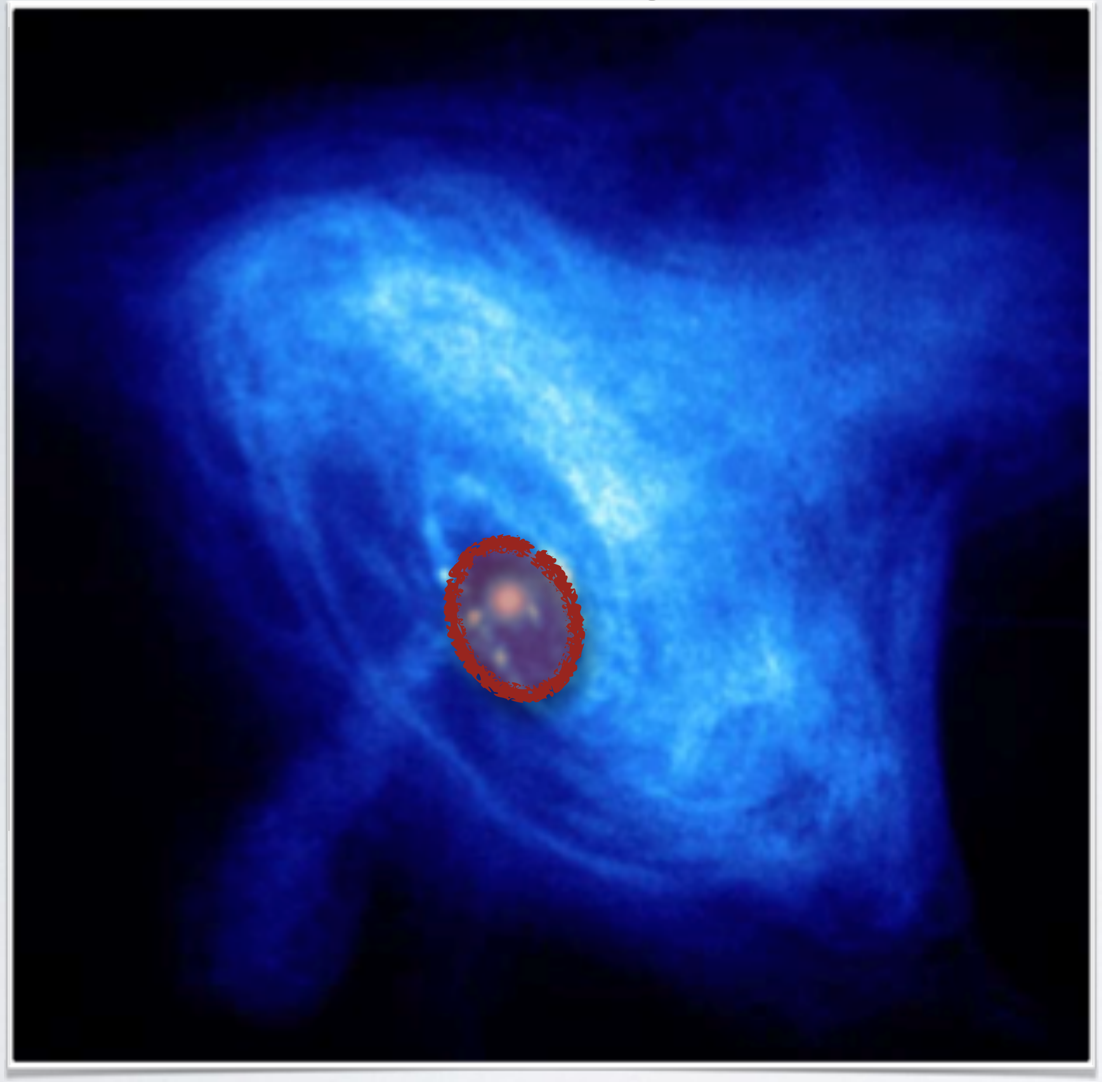


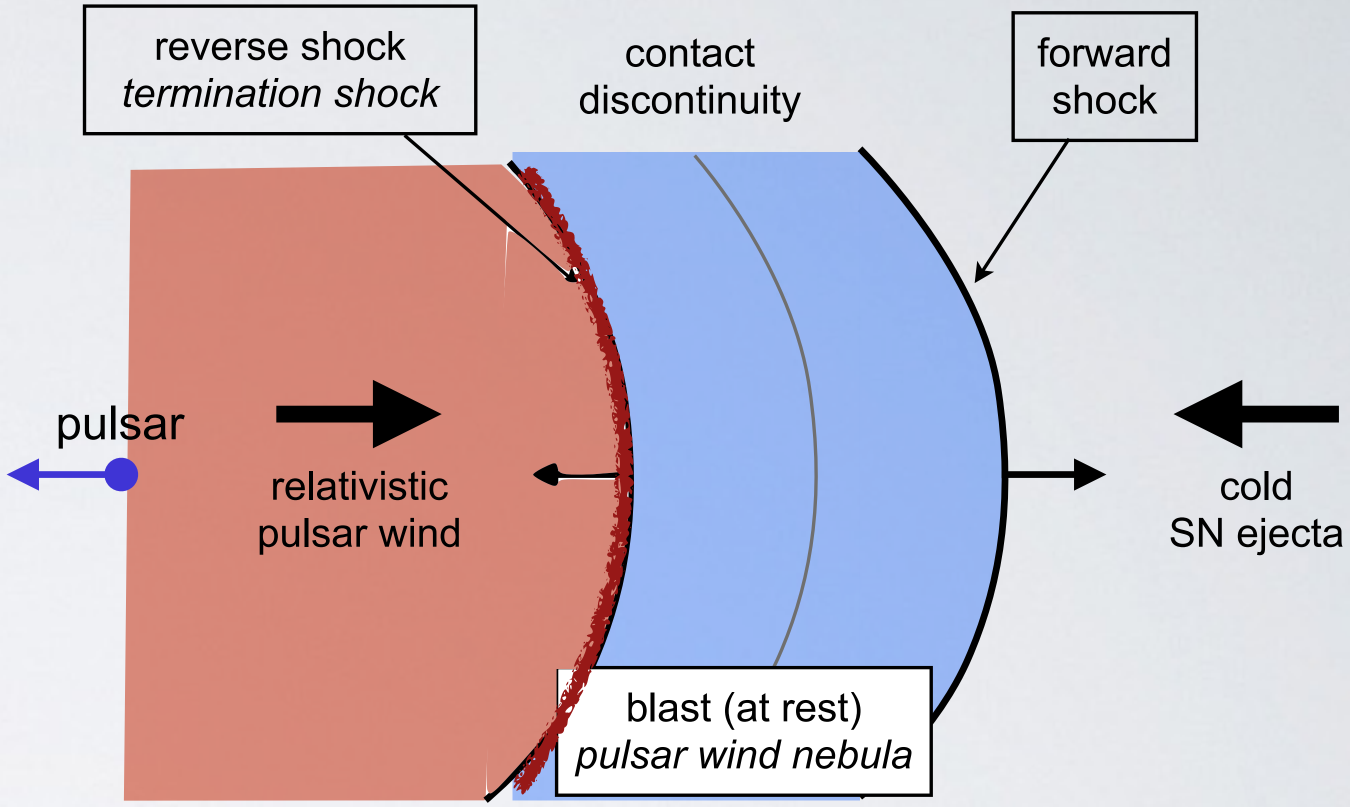
- Wind region

cold

Poynting flux dominated

- Acceleration region?





- Wind region

cold

Poynting flux dominated

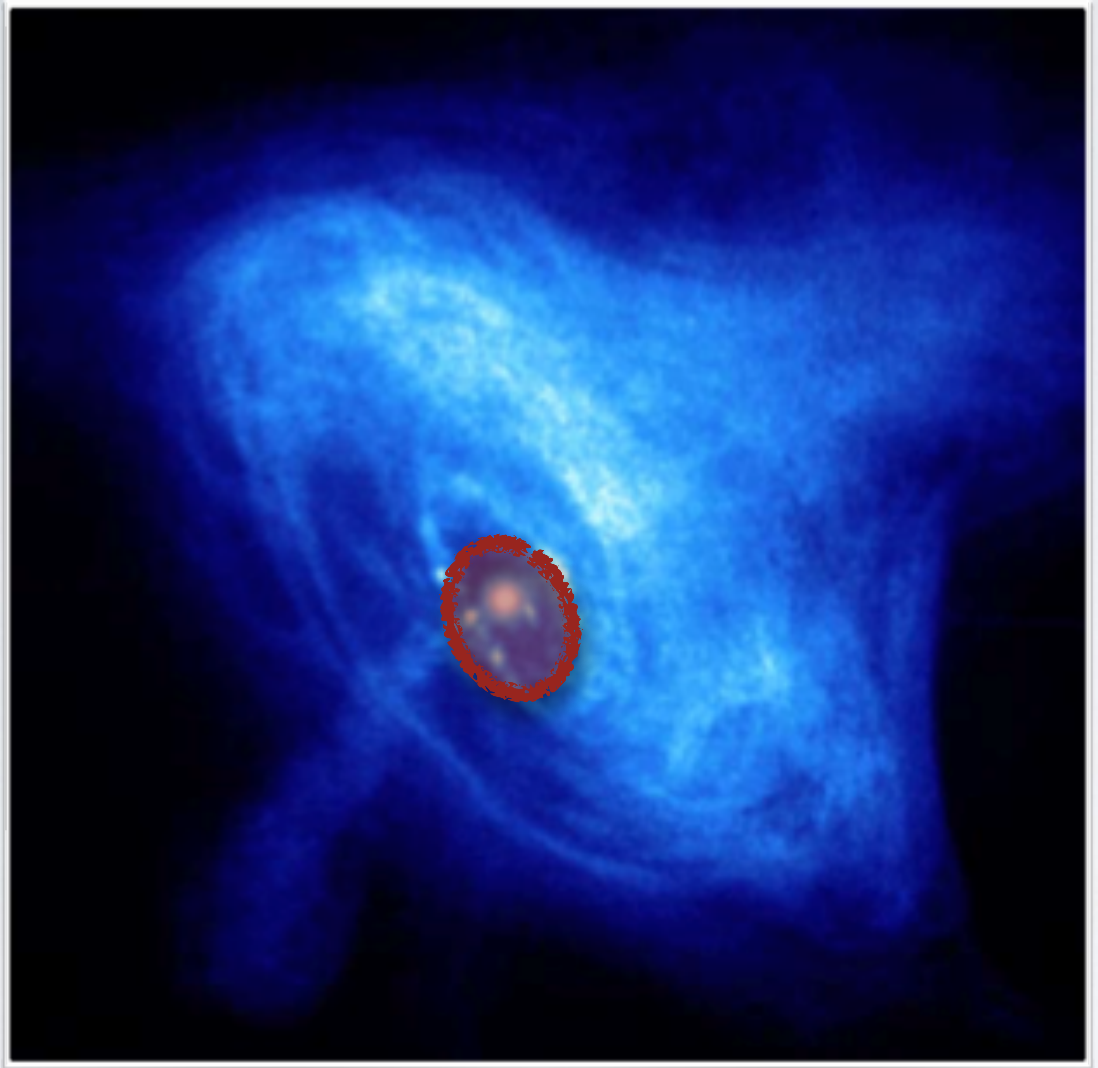
- Nebula

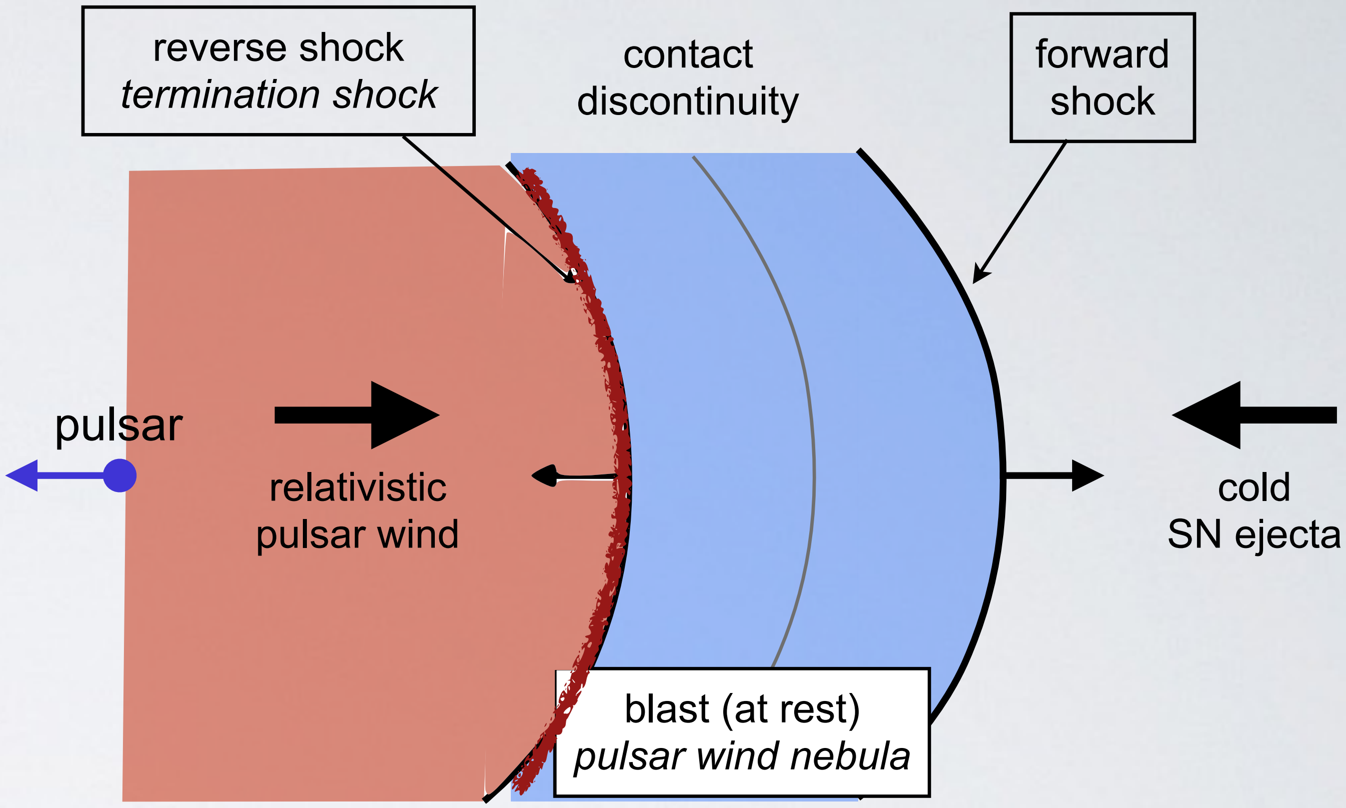
radiative

kinetic energy

Cosmic ray acceleration in pulsars

- Acceleration region?





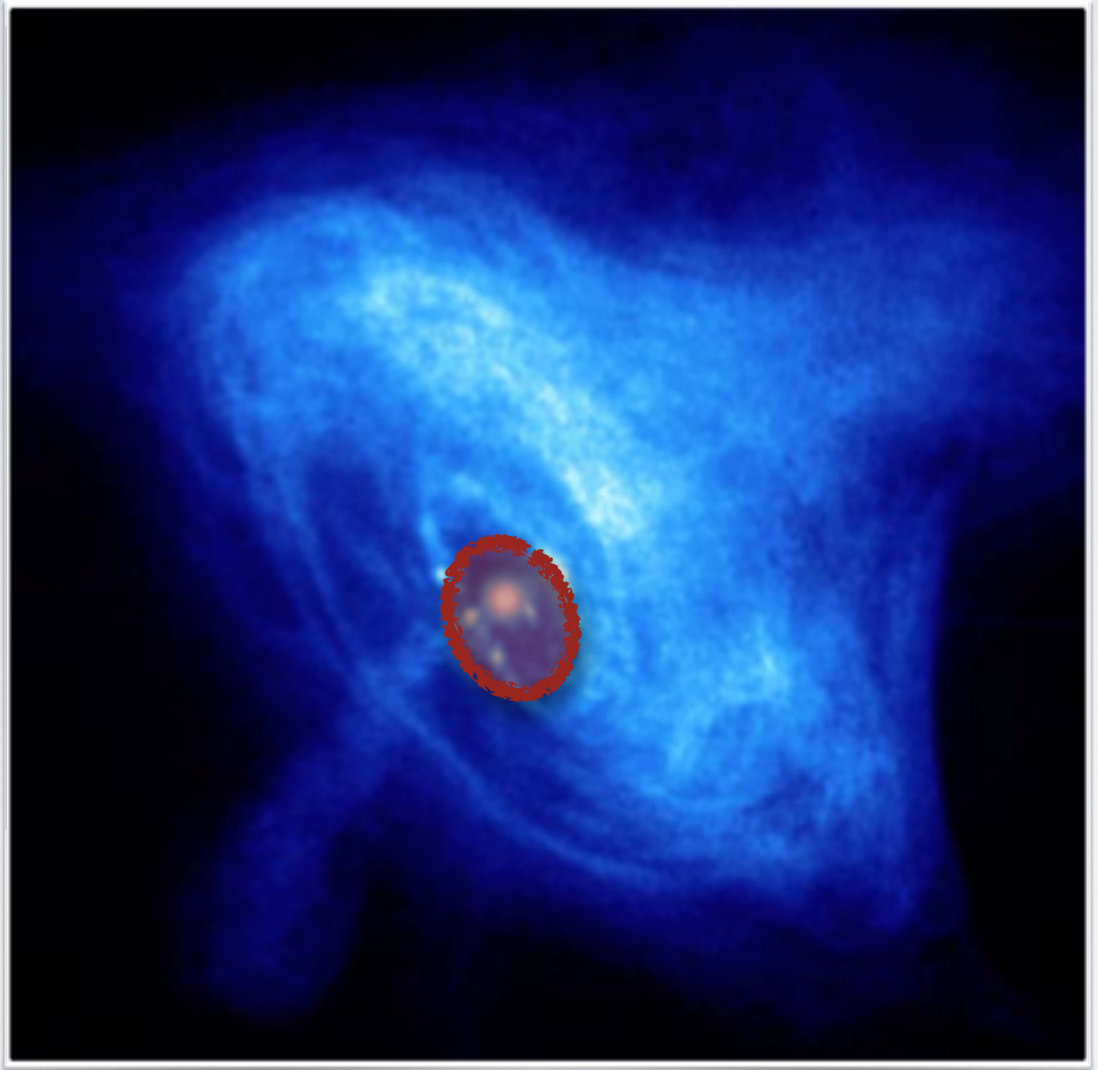
- Wind region
- Nebula

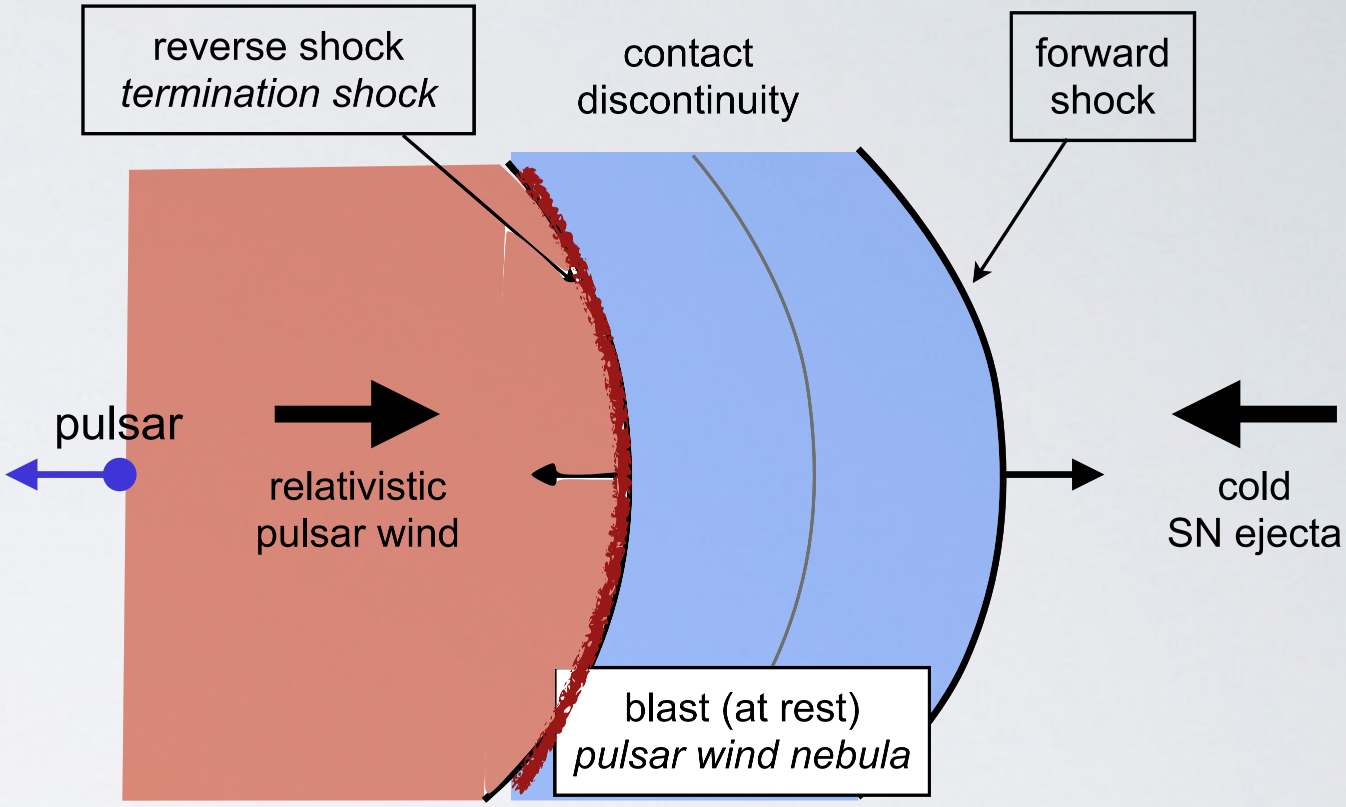
Wind region	Nebula
cold	**radiative**
Poynting flux dominated	**kinetic energy**

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

e.g., *Kirk et al. 2009*

- Acceleration region?





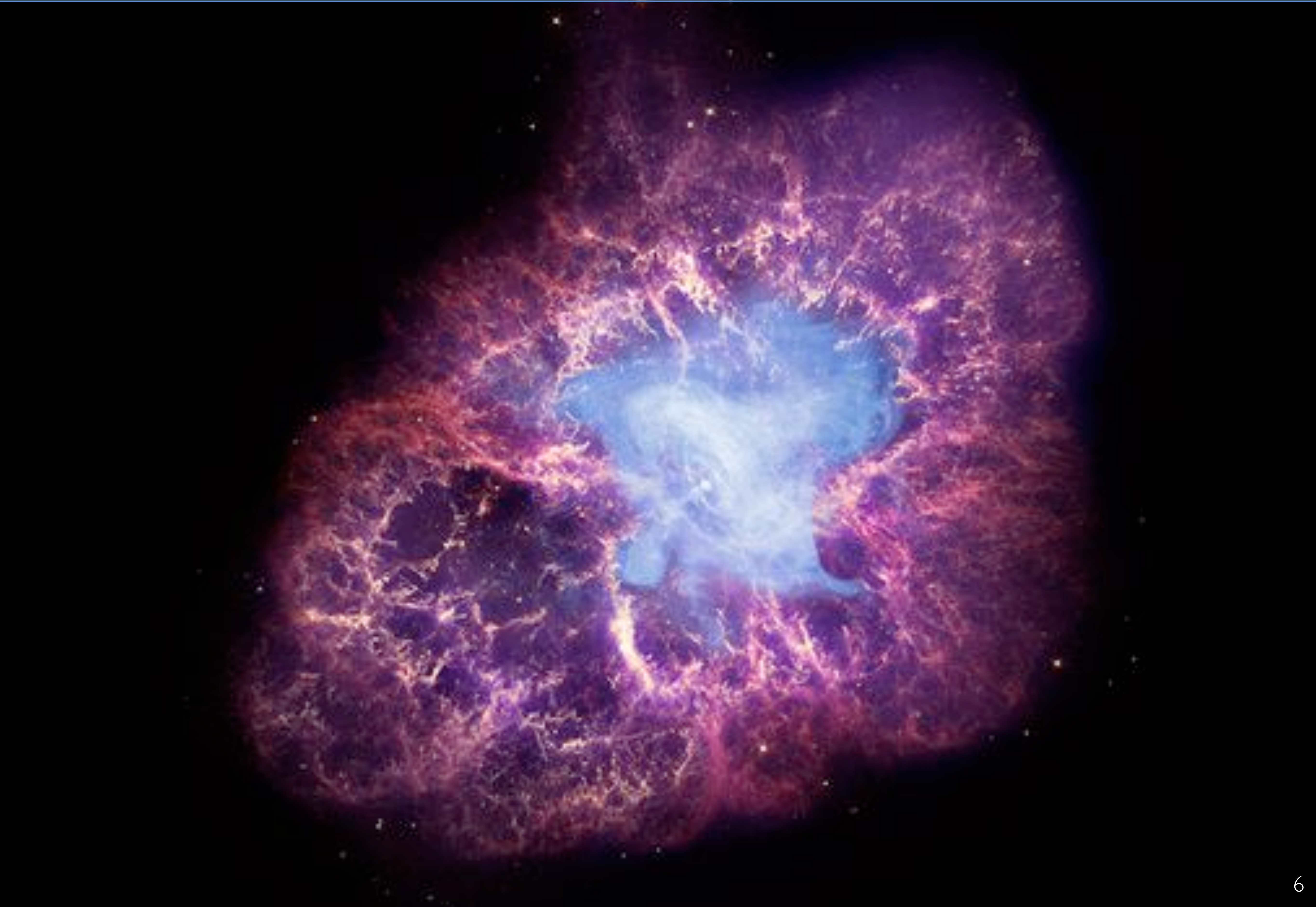
Wind region	Nebula
cold	**radiative**
Poynting flux dominated	**kinetic energy**

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

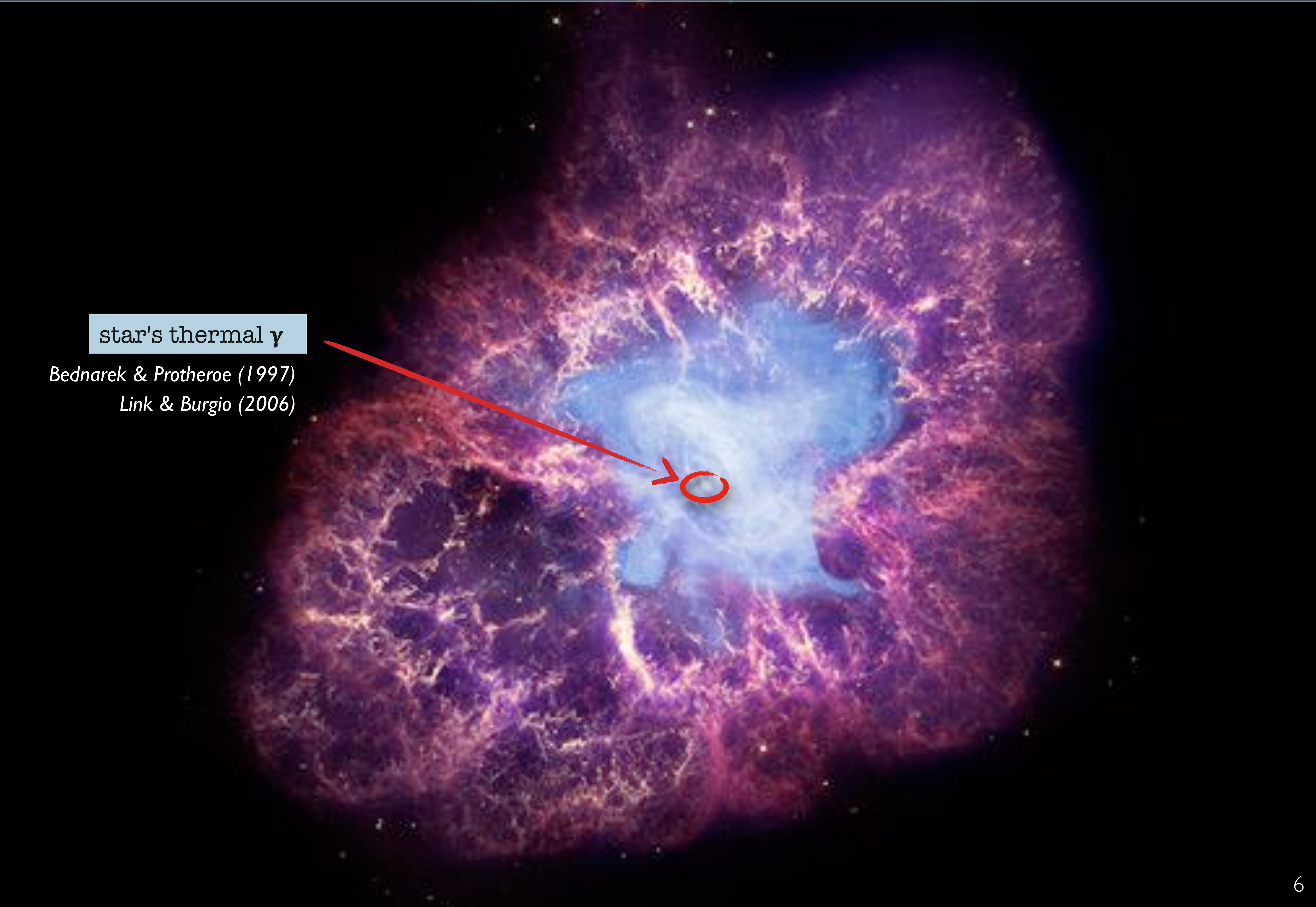
e.g., *Kirk et al. 2009*

- 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*

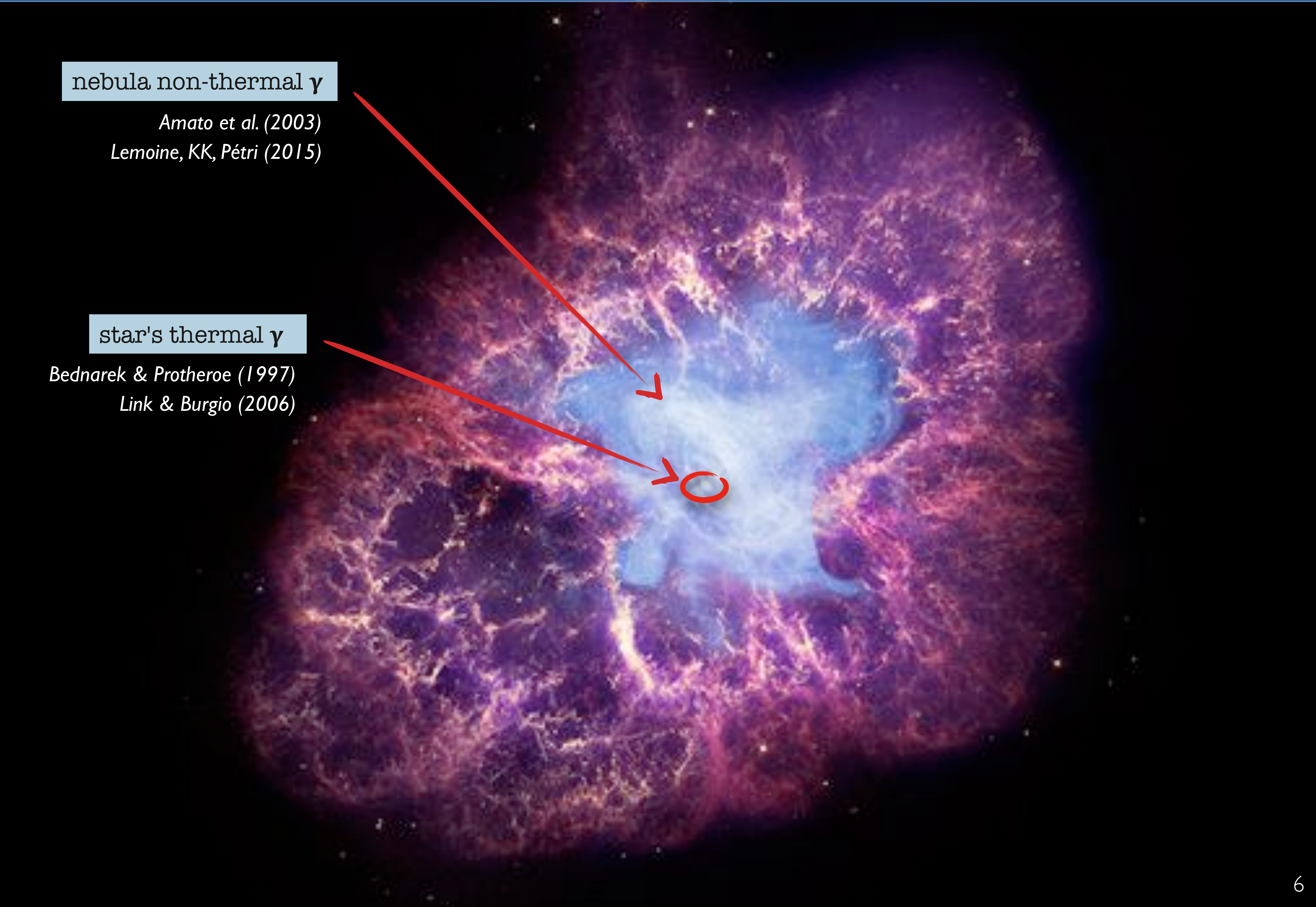
Interaction backgrounds for neutrino production



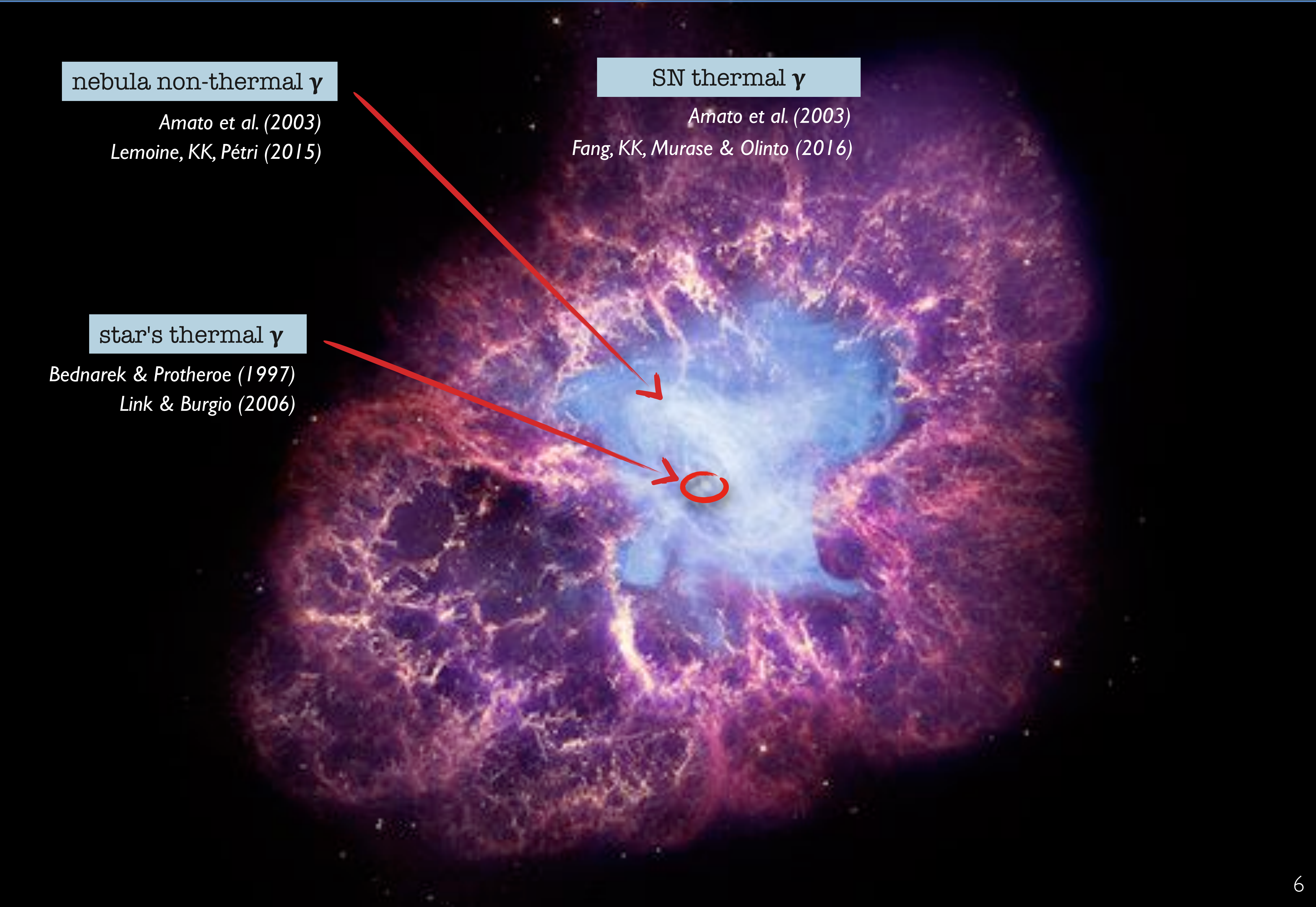
Interaction backgrounds for neutrino production



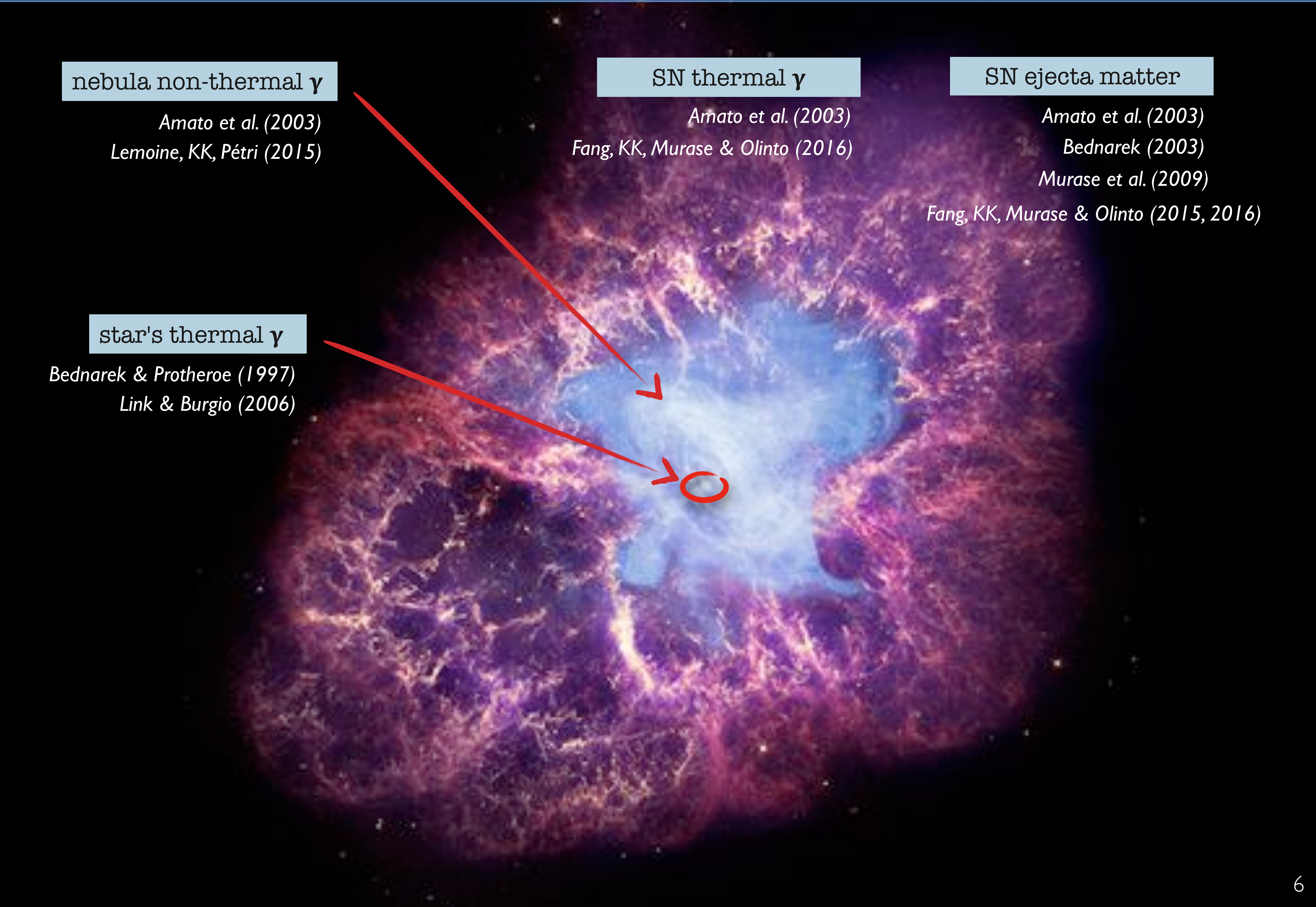
Interaction backgrounds for neutrino production



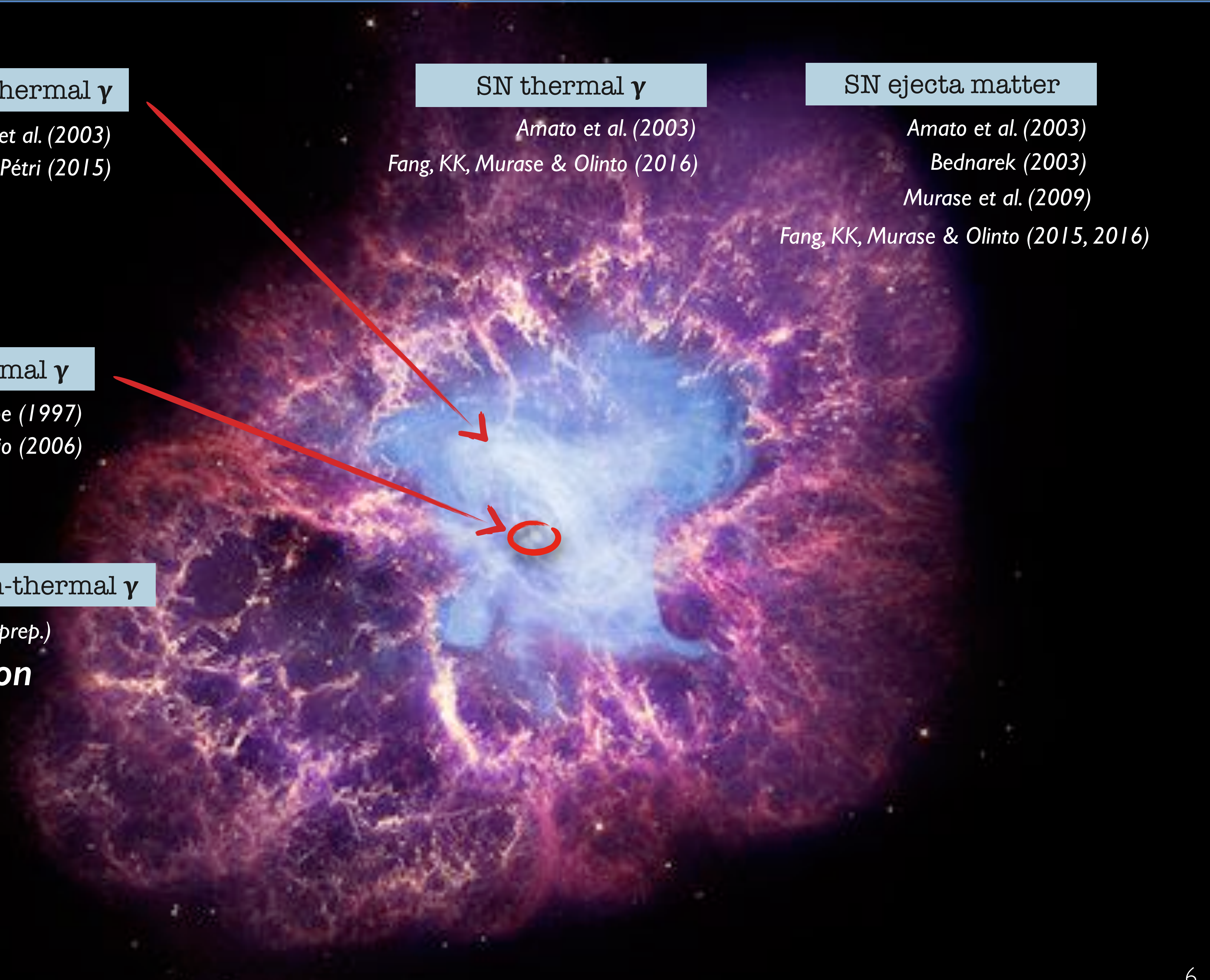
Interaction backgrounds for neutrino production



Interaction backgrounds for neutrino production



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.)

Poster Session

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.)

Poster Session

Aartsen et al. 2014

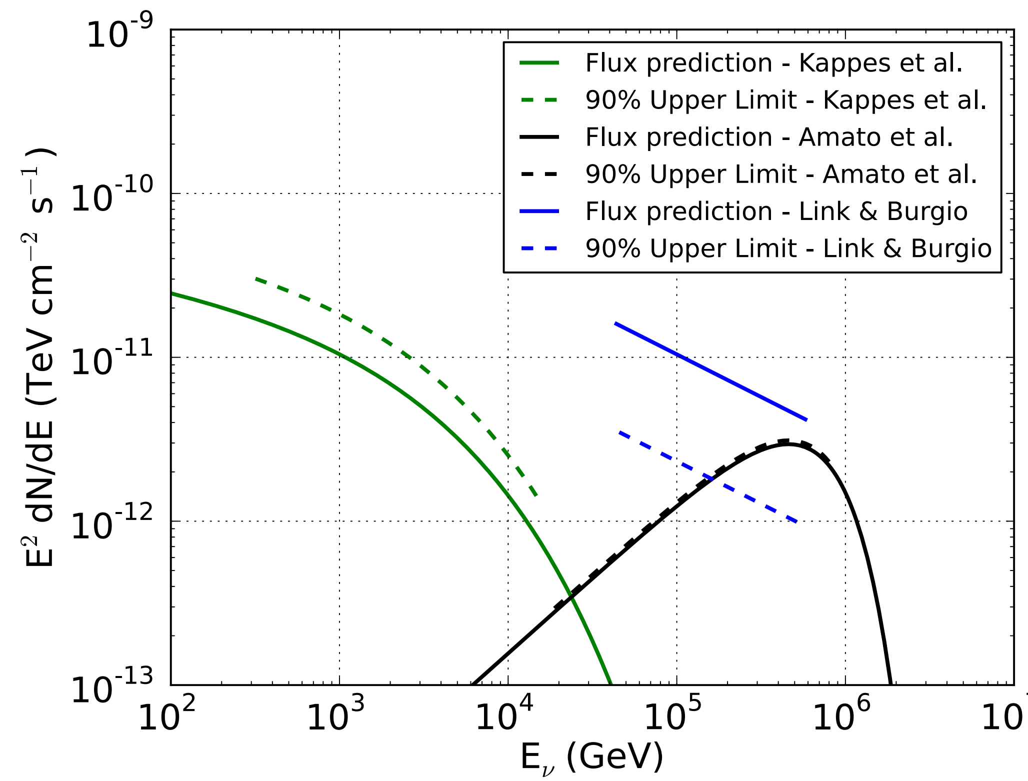


Figure 12. Flux predictions (solid) for three models of neutrino emission from the Crab Nebula, with their associated 90% C.L. upper limits (dashed) for an energy range containing 90% of the signal. Both the model from Amato et al. (2003) and the most optimistic model from Link & Burgio (2005, 2006) are now excluded at 90% C.L. For the gamma-ray-based model from Kappes et al. (2007), the upper limit is still a factor of 1.75 above the prediction.

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.)

Poster Session

Aartsen et al. 2014

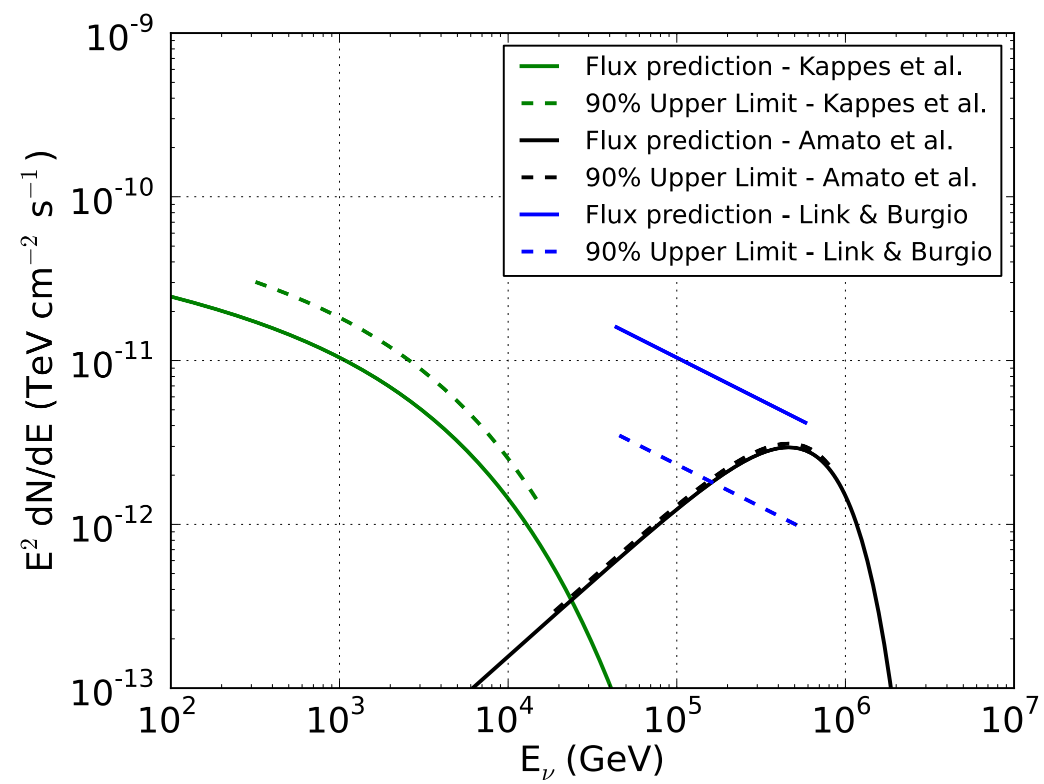


Figure 12. Flux predictions (solid) for three models of neutrino emission from the Crab Nebula, with their associated 90% C.L. upper limits (dashed) for an energy range containing 90% of the signal. Both the model from Amato et al. (2003) and the most optimistic model from Link & Burgio (2005, 2006) are now excluded at 90% C.L. For the gamma-ray-based model from Kappes et al. (2007), the upper limit is still a factor of 1.75 above the prediction.

▶ Most promising for > PeV neutrinos: interactions in SN

Understanding the neutrino spectra from SN region

Murase et al. (2009)
Fang, KK, Murase, Olinto 2016

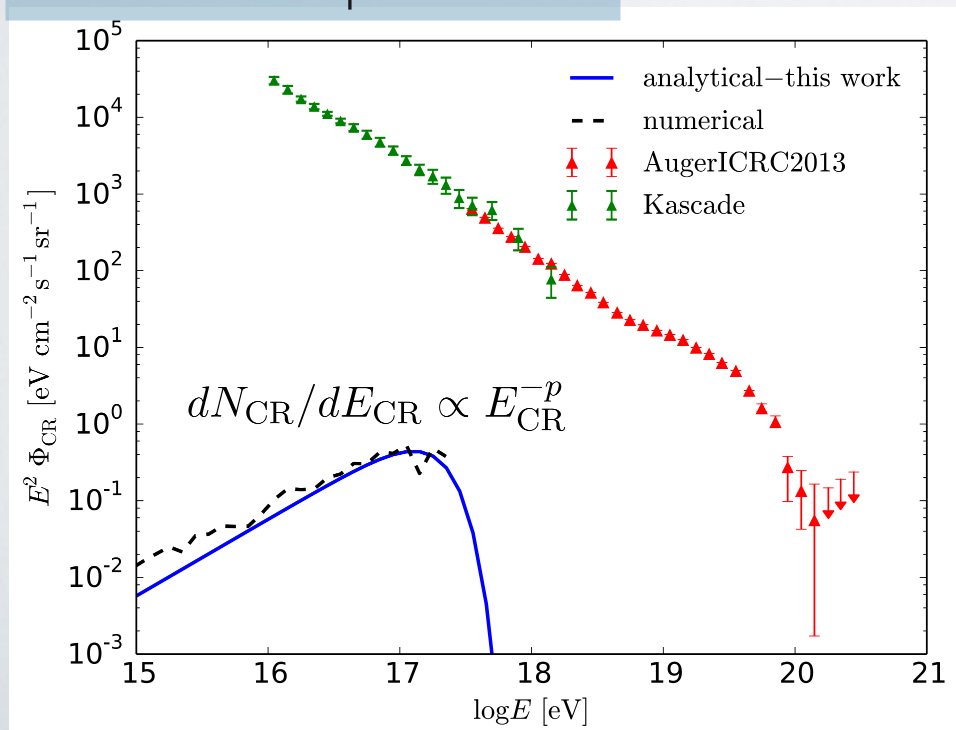
Most promising & robust way to produce observable neutrinos from pulsars/magnetars

$$p + \gamma \rightarrow n + \pi^+ + \ldots$$

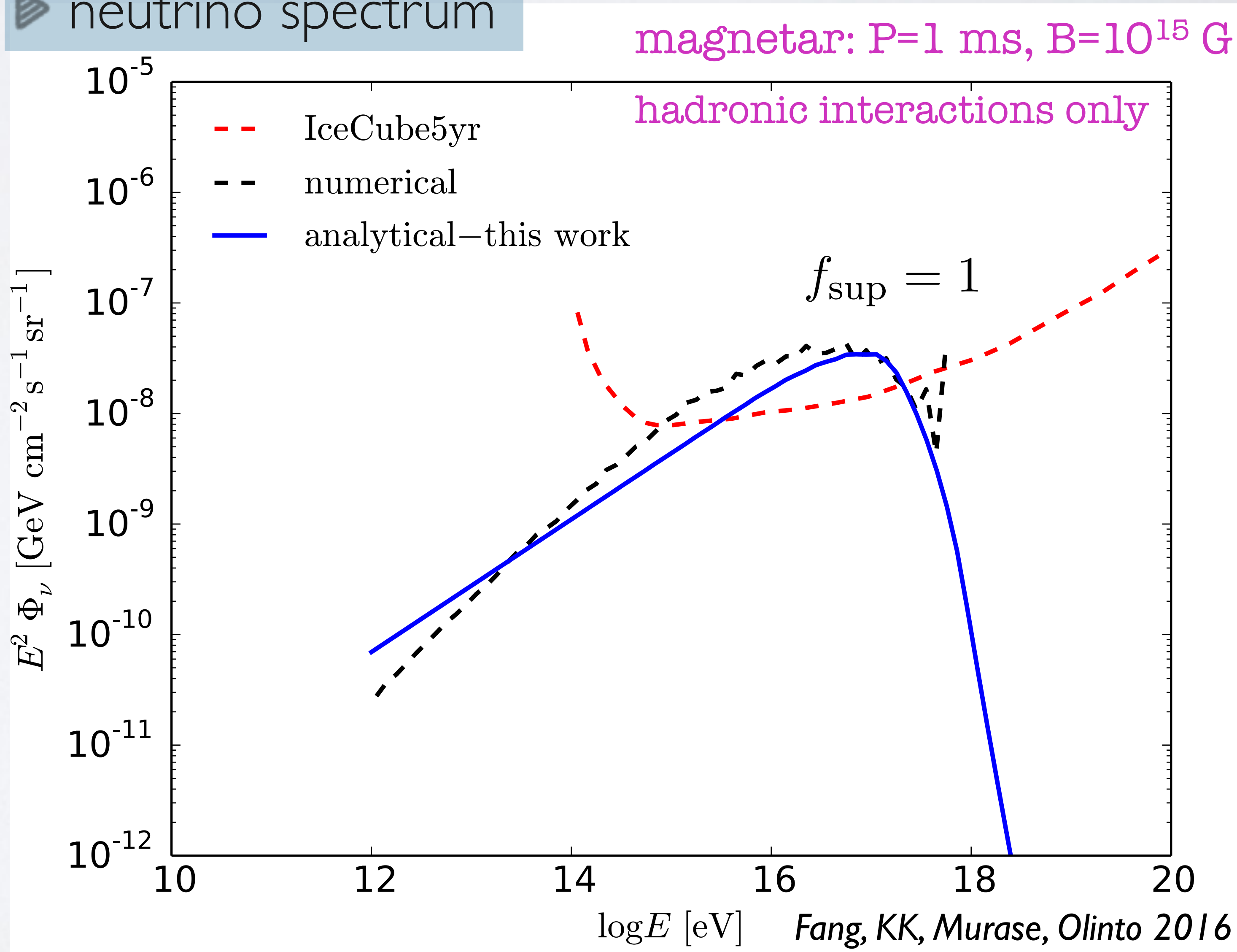
$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

UHECR spectrum



neutrino spectrum

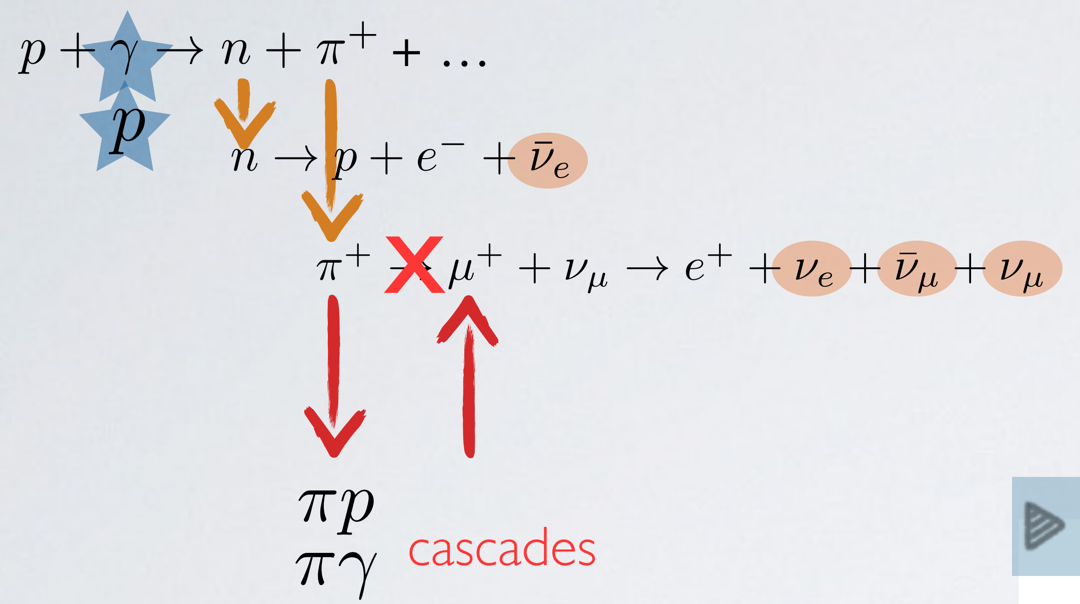


Fang, KK, Murase, Olinto 2016

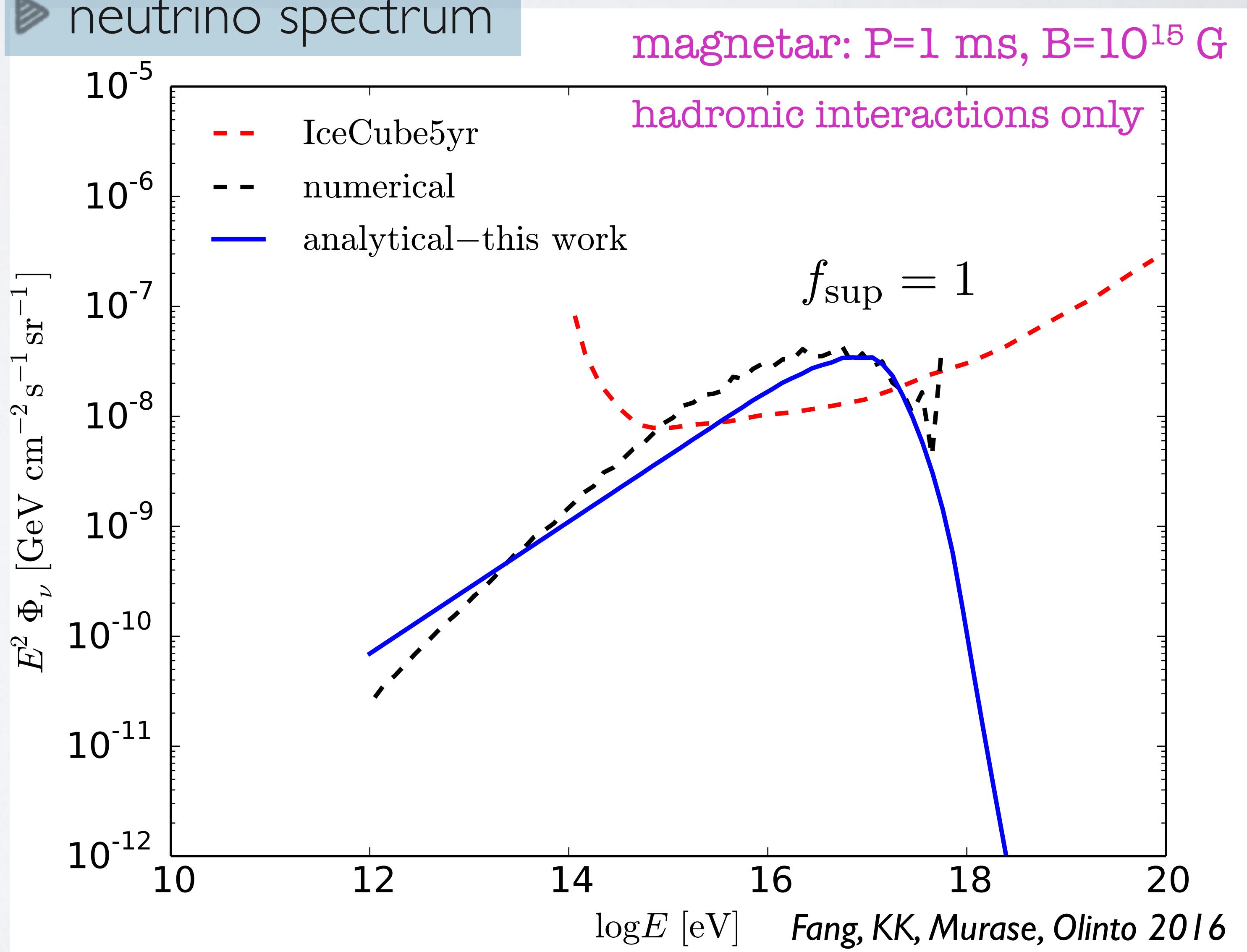
Understanding the neutrino spectra from SN region

Murase et al. (2009)
Fang, KK, Murase, Olinto 2016

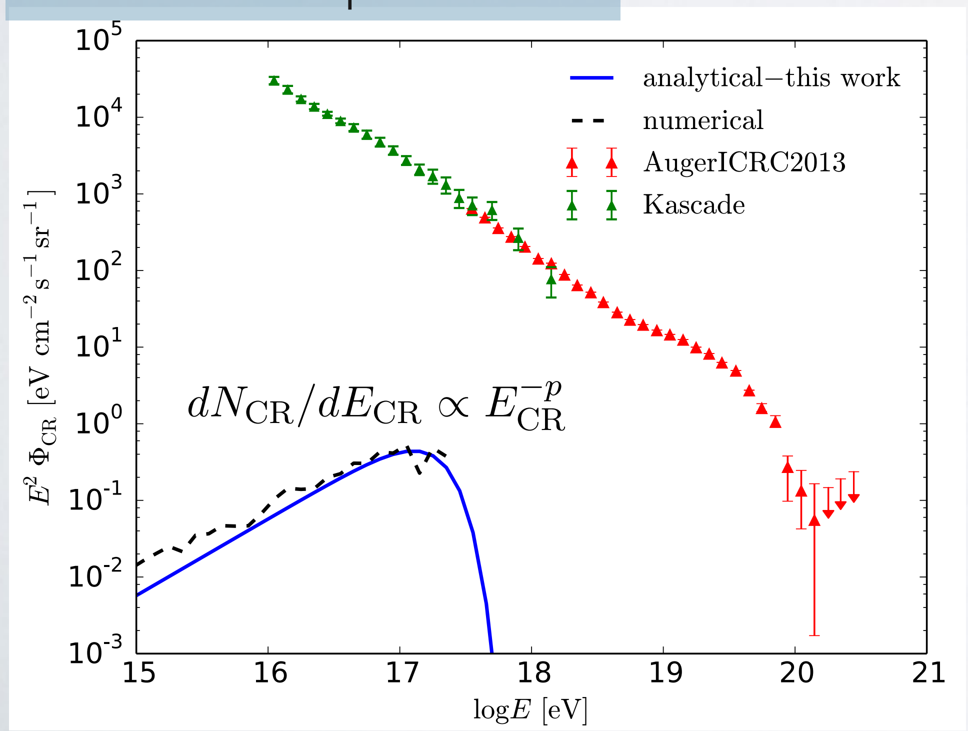
Most promising & robust way to produce observable neutrinos from pulsars/magnetars



neutrino spectrum

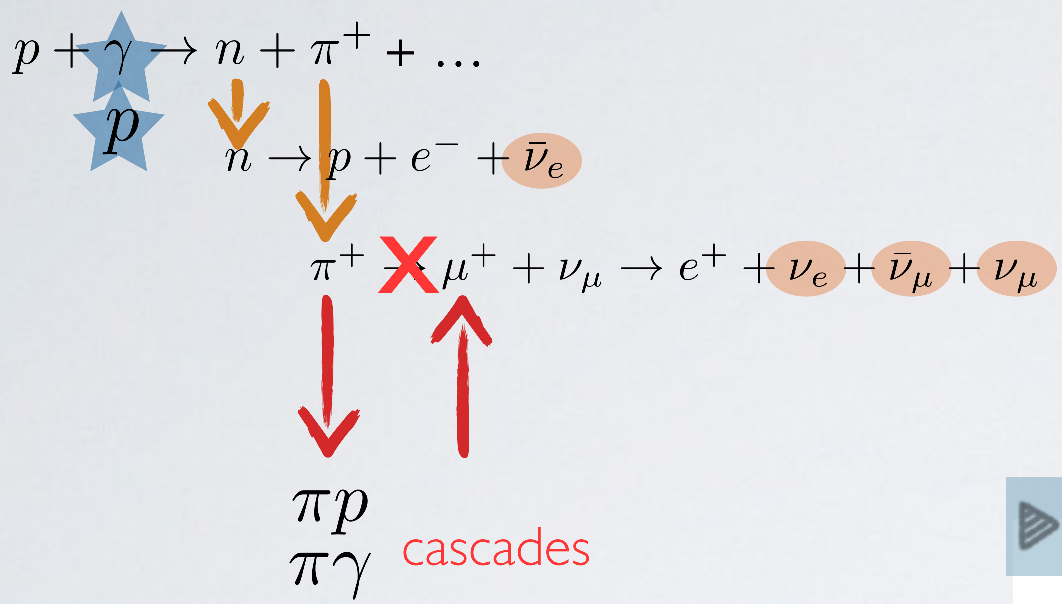


UHECR spectrum



Murase et al. (2009)
Fang, KK, Murase, Olinto 2016

Most promising & robust way to produce observable neutrinos from pulsars/magnetars



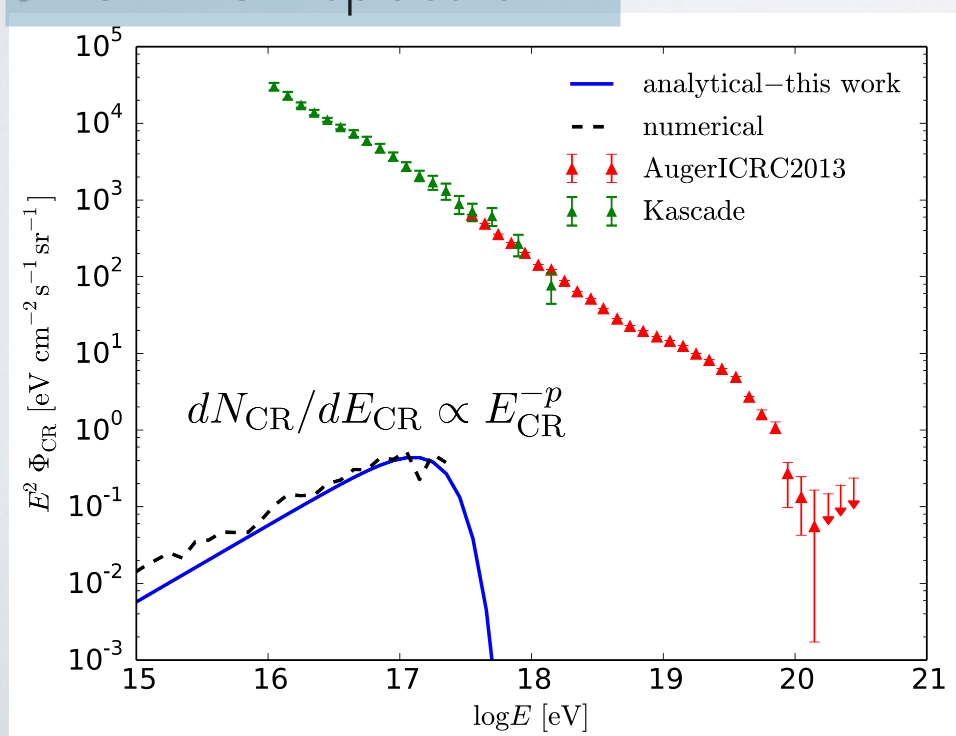
meson production efficiency

$$f_{\rm mes} = \min\left(\tau_{pp} + \tau_{p\gamma}, 1\right)$$

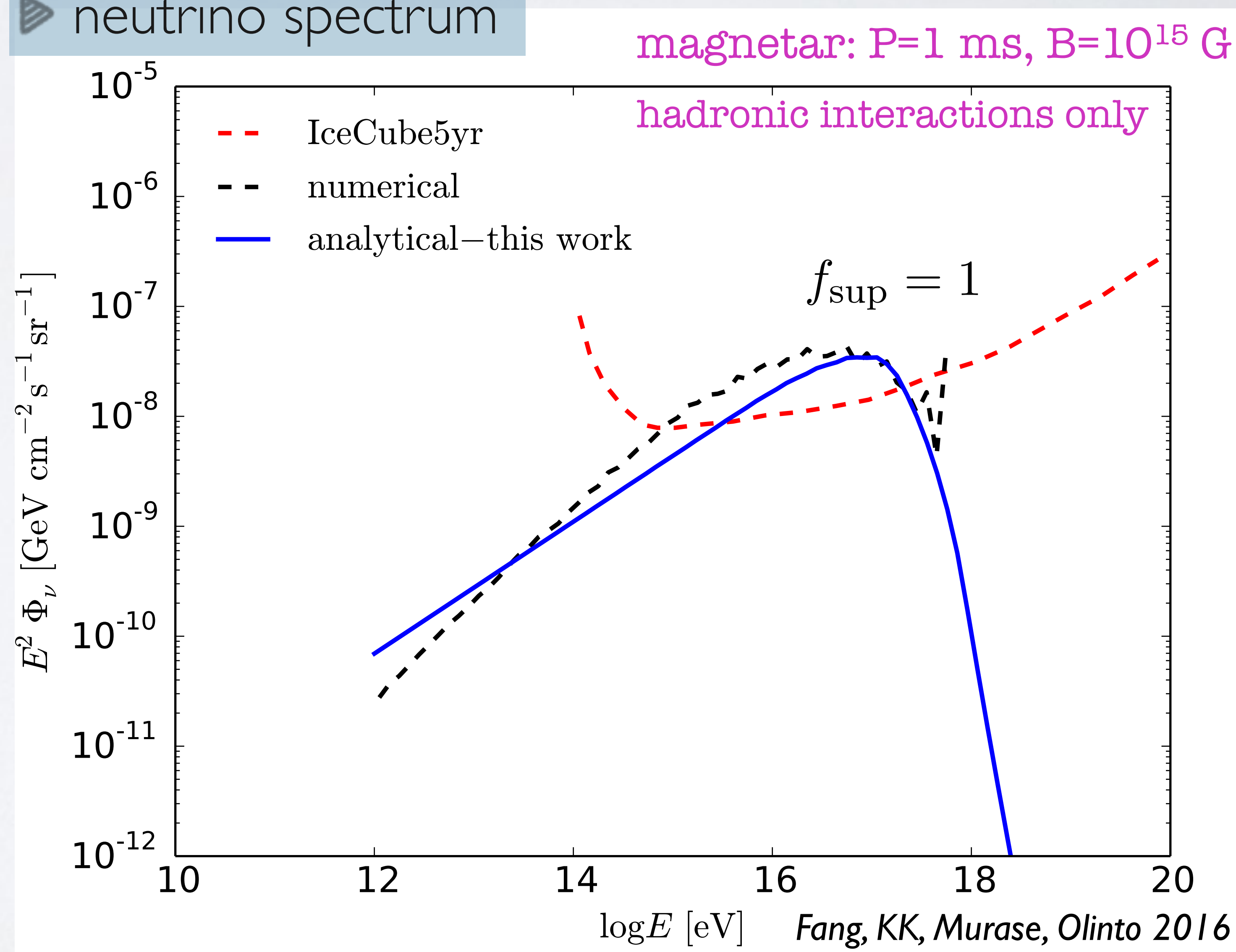
neutrino suppression factor

$$f_{\rm sup} = \min\left[1, \left(\left(\frac{t_{\pi p}}{\gamma_\pi\, \tau_\pi}\right)^{-1} + \left(\frac{t_{\pi\gamma}}{\gamma_\pi\, \tau_\pi}\right)^{-1}\right)^{-1}\right]$$

UHECR spectrum



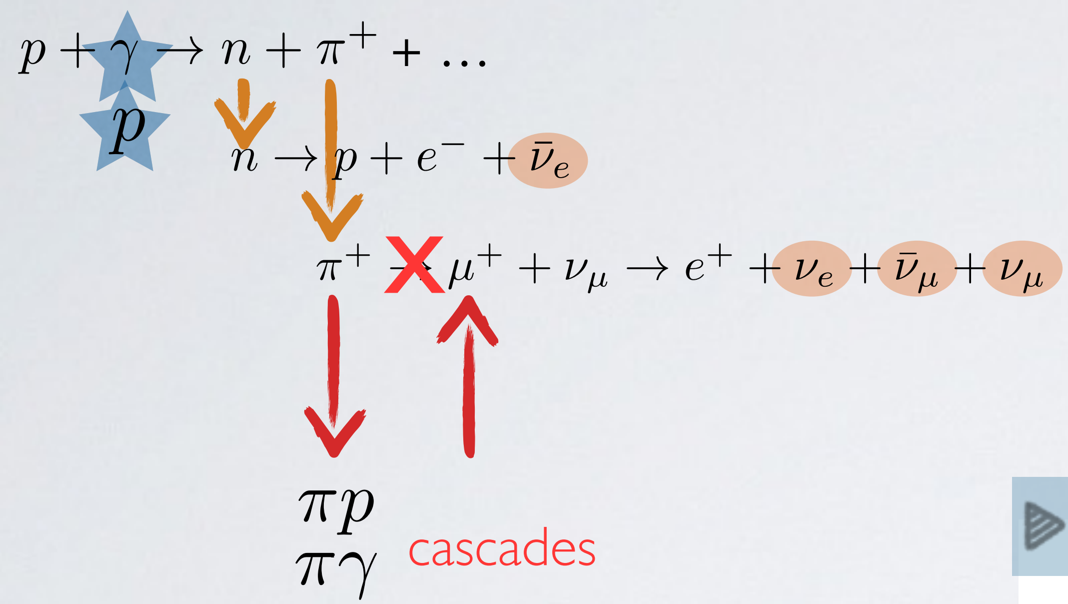
neutrino spectrum



Understanding the neutrino spectra from SN region

Murase et al. (2009)
Fang, KK, Murase, Olinto 2016

Most promising & robust way to produce observable neutrinos from pulsars/magnetars



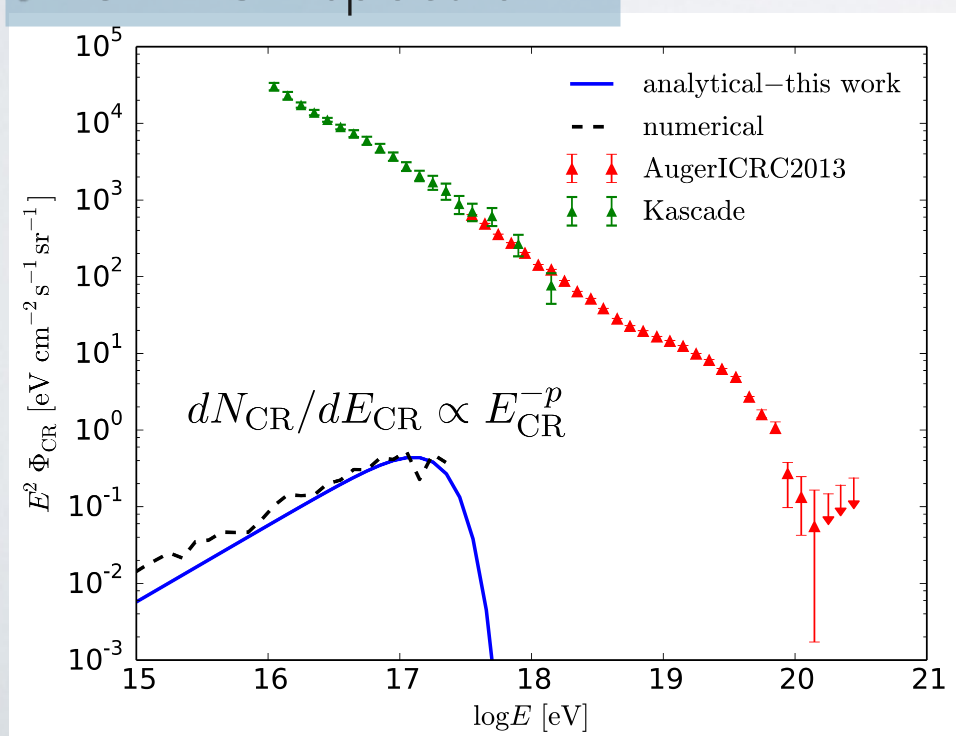
meson production efficiency

$$f_{\rm mes} = \min\left(\tau_{pp} + \tau_{p\gamma}, 1\right)$$

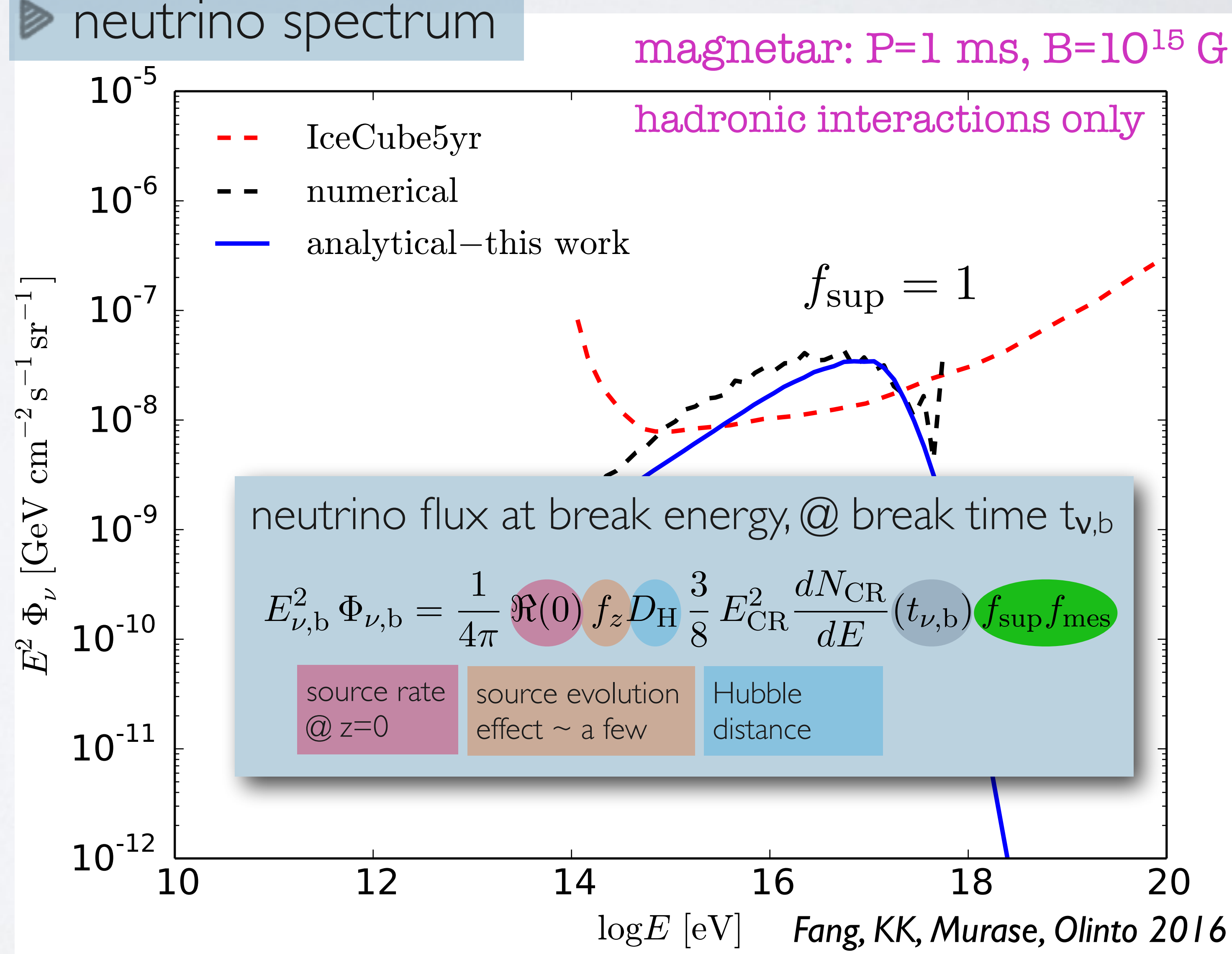
neutrino suppression factor

$$f_{\rm sup} = \min\left[1, \left(\left(\frac{t_{\pi p}}{\gamma_\pi\, \tau_\pi}\right)^{-1} + \left(\frac{t_{\pi\gamma}}{\gamma_\pi\, \tau_\pi}\right)^{-1}\right)^{-1}\right]$$

UHECR spectrum



neutrino spectrum



Fang, KK, Murase, Olinto 2016

Understanding the neutrino spectra from SN region

Murase et al. (2009)
Fang, KK, Murase, Olinto 2016

Most promising & robust way to produce observable neutrinos from pulsars/magnetars

$$p + \gamma \rightarrow n + \pi^+ + \ldots$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

πp, $\pi\gamma$ cascades

meson production efficiency

$$f_{\rm mes} = \min\left(\tau_{pp} + \tau_{p\gamma}, 1\right)$$

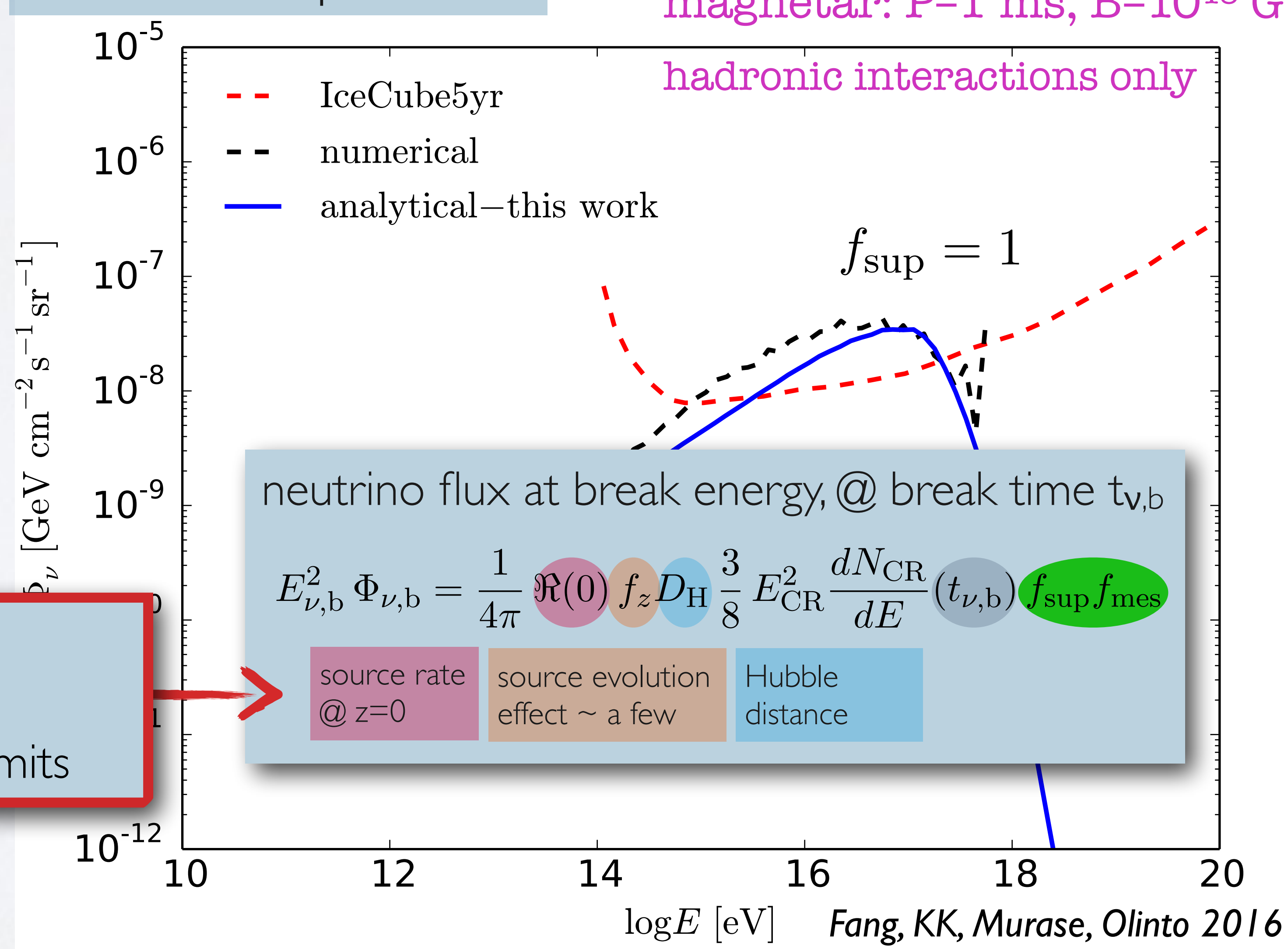
neutrino suppression factor

$$f_{\rm sup} = \min\left[1, \left(\left(\frac{t_{\pi p}}{\gamma_\pi\,\tau_\pi}\right)^{-1} + \left(\frac{t_{\pi\gamma}}{\gamma_\pi\,\tau_\pi}\right)^{-1}\right)^{-1}\right]$$

neutrino spectrum

magnetar: P=1 ms, B=10^{15} G

hadronic interactions only



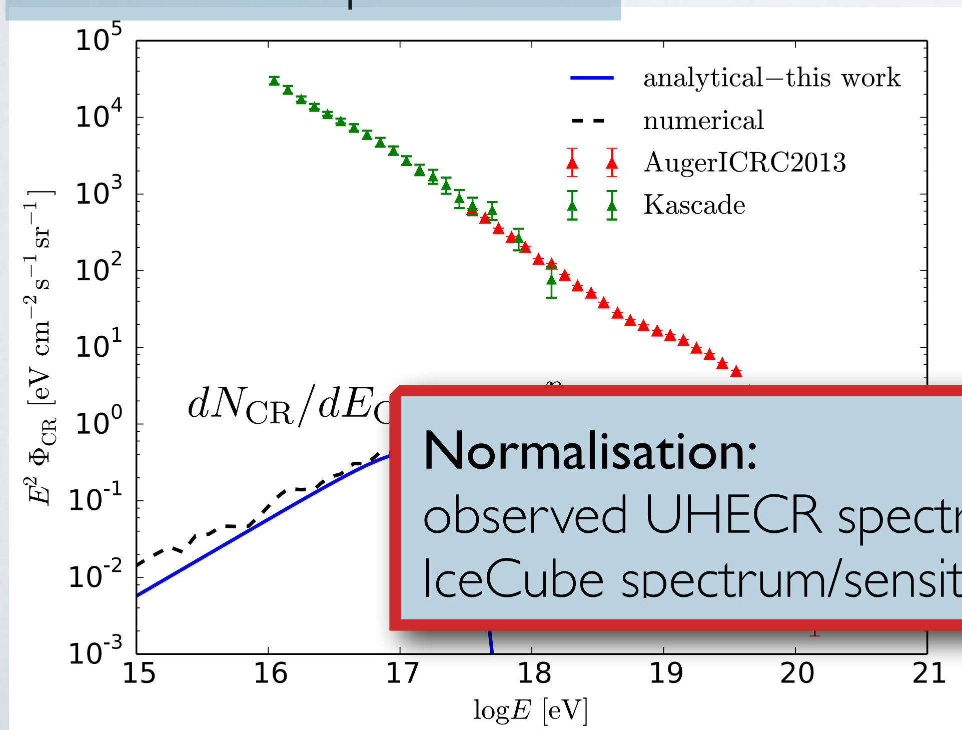
Fang, KK, Murase, Olinto 2016

neutrino flux at break energy, @ break time $t_{\nu,b}$

$$E^2_{\nu,b}\,\Phi_{\nu,b} = \frac{1}{4\pi}\,\Re(0)\,f_z D_{\rm H}\,\frac{3}{8}\,E^2_{\rm CR}\frac{dN_{\rm CR}}{dE}(t_{\nu,b})\,f_{\rm sup} f_{\rm mes}$$

source rate @ z=0	source evolution effect ~ a few	Hubble distance

UHECR spectrum



Normalisation:
observed UHECR spectrum
IceCube spectrum/sensitivity limits

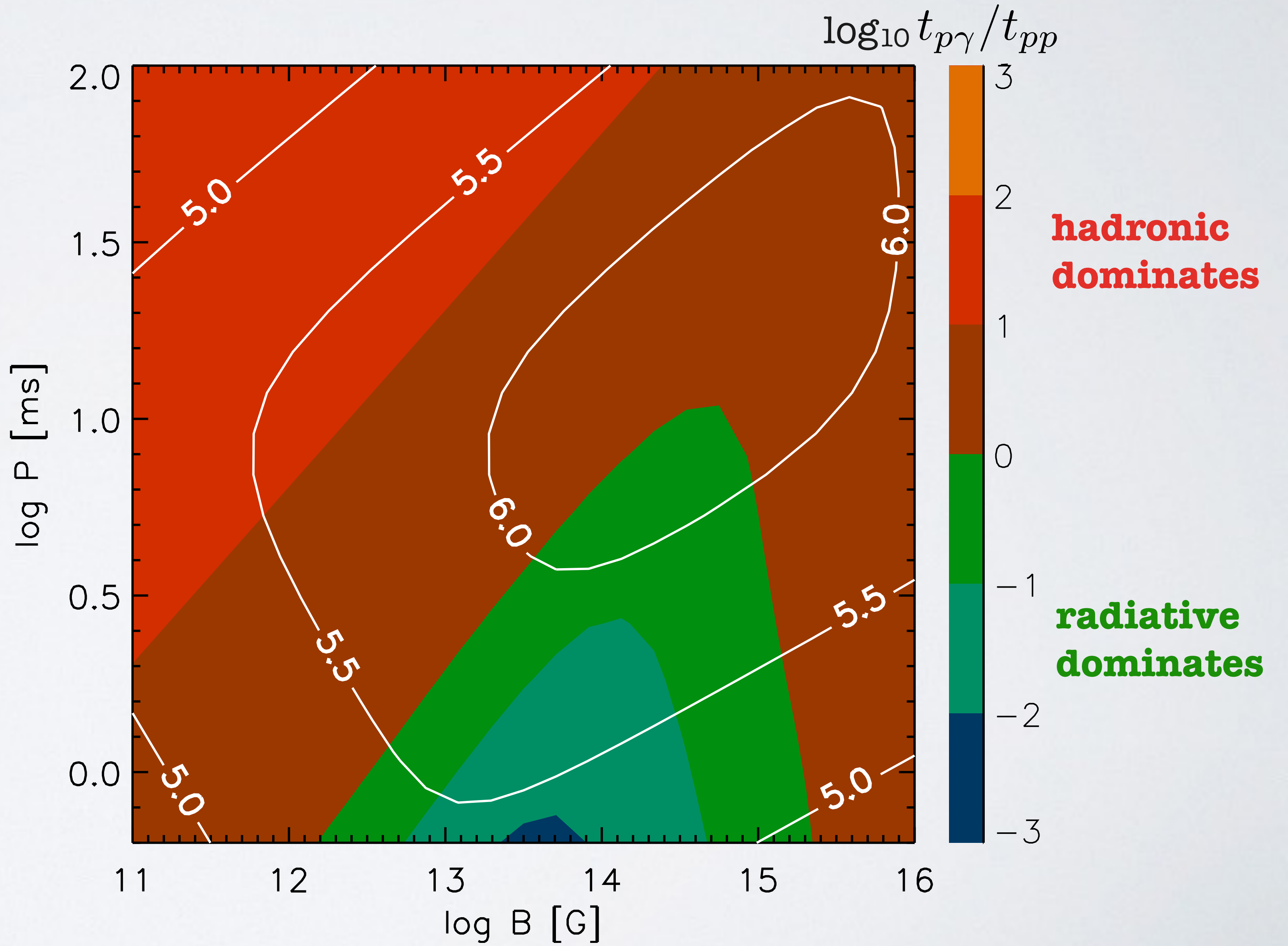
Radiative or Baryonic background in SN ejecta?

Fang, KK, Murase, Olinto 2015

- baryonic, radiative backgrounds evolve in time
- dominant process changes over time
- spectral break time $t_{\nu,b}$ = good reference time

fraction of neutron star rotational energy converted to thermal photons in SN ejecta

$$\eta_{\rm th} = 1$$



- faster rotation: more conversion
- for $\eta < 10^{-3}$ hadronic interactions dominate over whole param. space

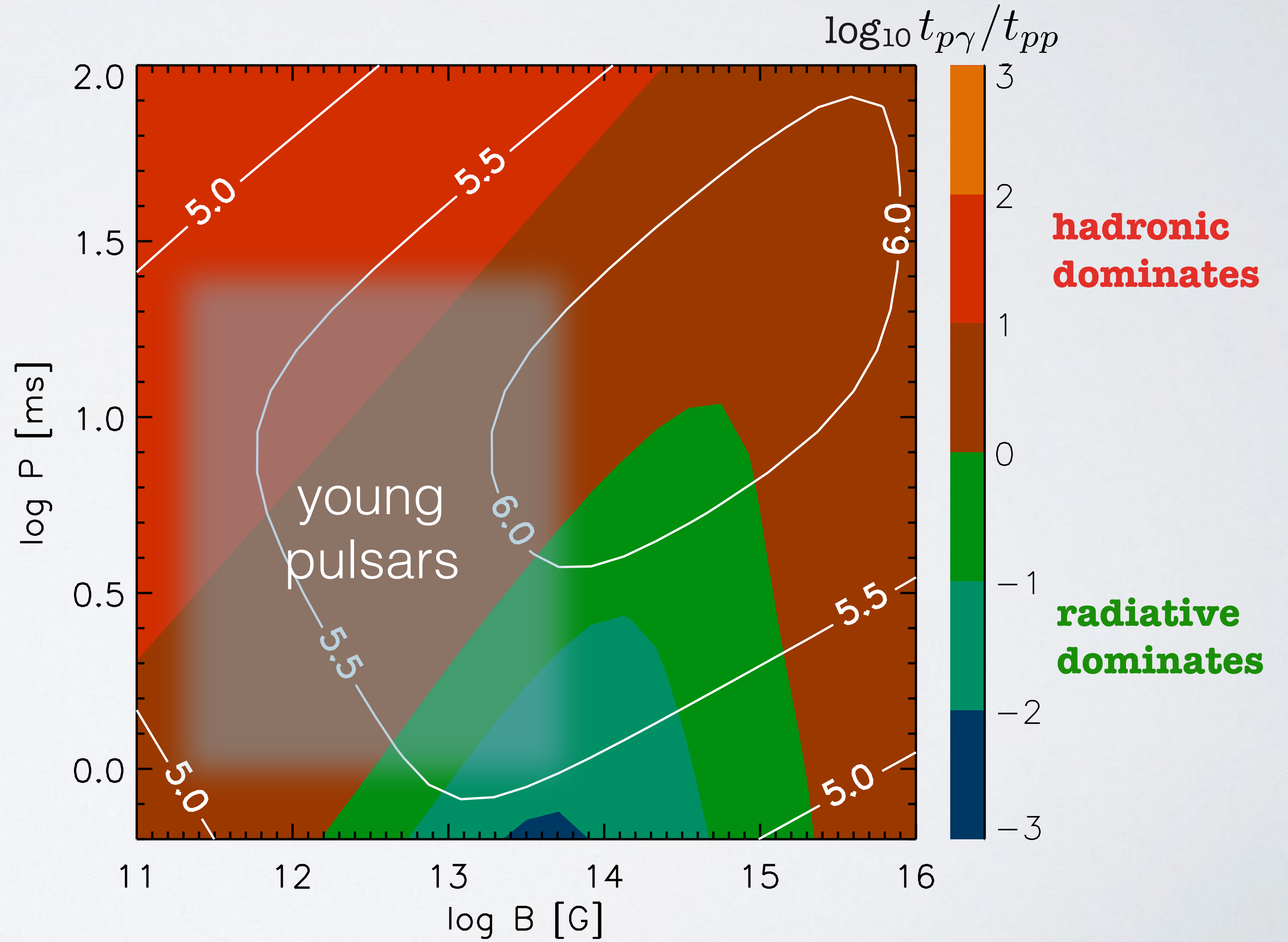
Radiative or Baryonic background in SN ejecta?

Fang, KK, Murase, Olinto 2015

- baryonic, radiative backgrounds evolve in time
- dominant process changes over time
- spectral break time $t_{\nu,b}$ = good reference time

fraction of neutron star rotational energy converted to thermal photons in SN ejecta

$$\eta_{\rm th} = 1$$



- faster rotation: more conversion
- for $\eta < 10^{-3}$ hadronic interactions dominate over whole param. space

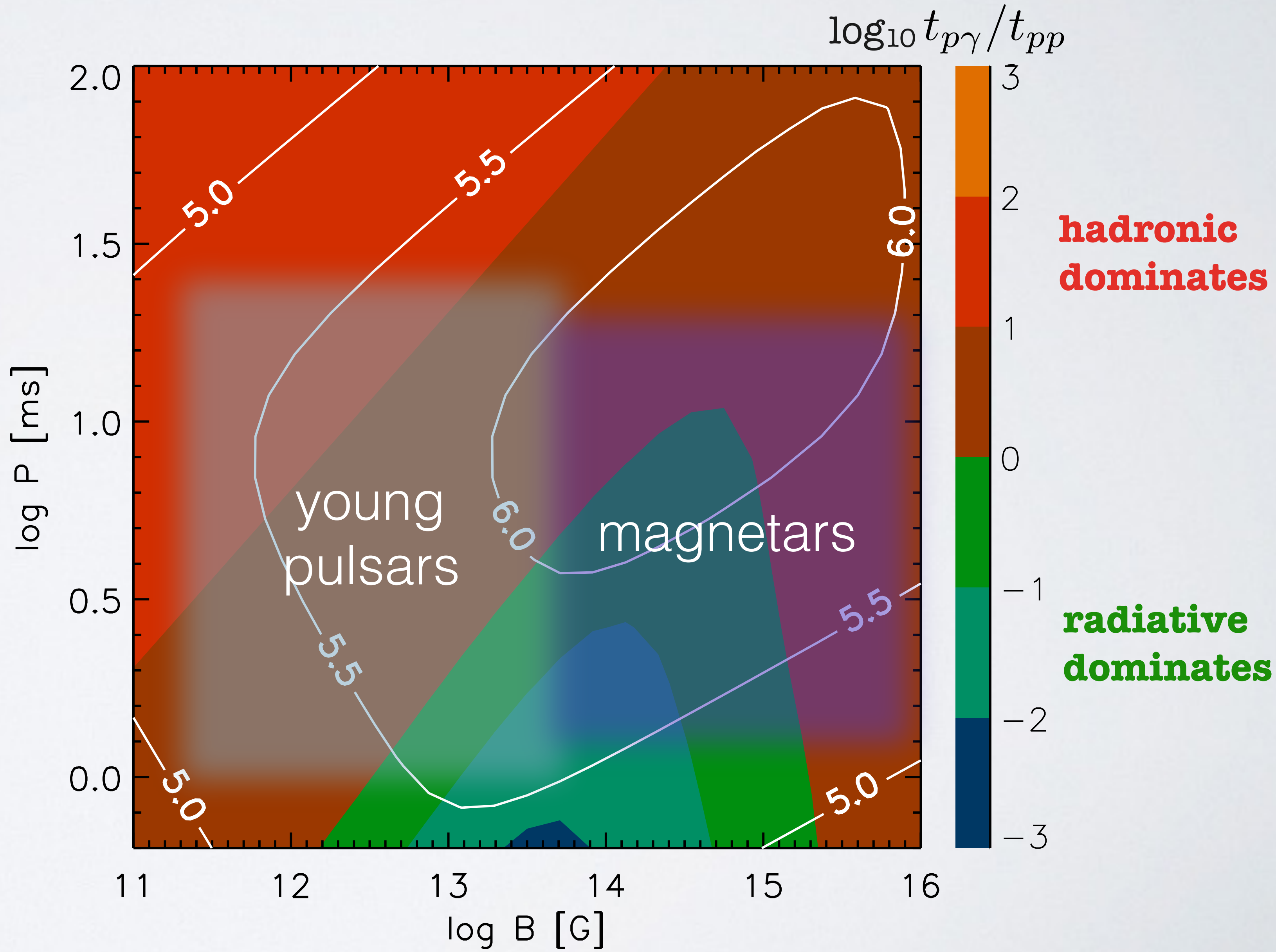
Radiative or Baryonic background in SN ejecta?

Fang, KK, Murase, Olinto 2015

- baryonic, radiative backgrounds evolve in time
- dominant process changes over time
- spectral break time $t_{\nu,b}$ = good reference time

fraction of neutron star rotational energy converted to thermal photons in SN ejecta

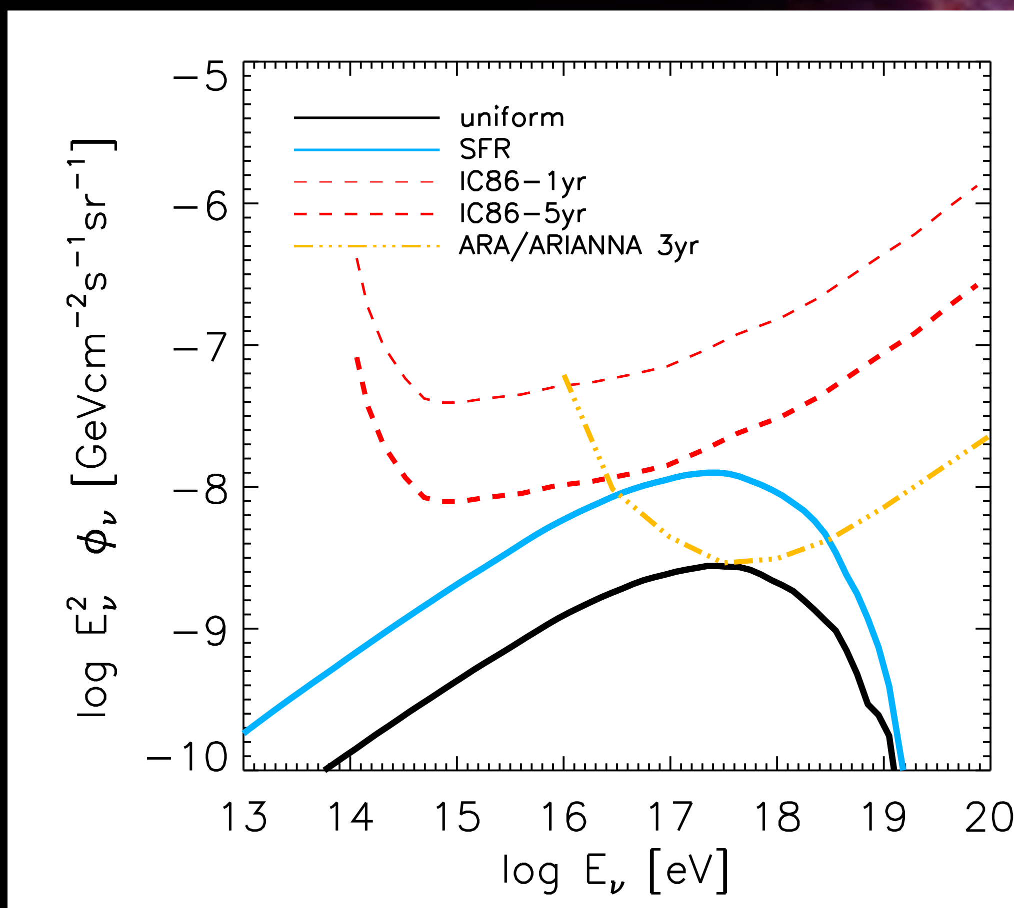
$$\eta_{\rm th} = 1$$



- faster rotation: more conversion
- for $\eta < 10^{-3}$ hadronic interactions dominate over whole param. space

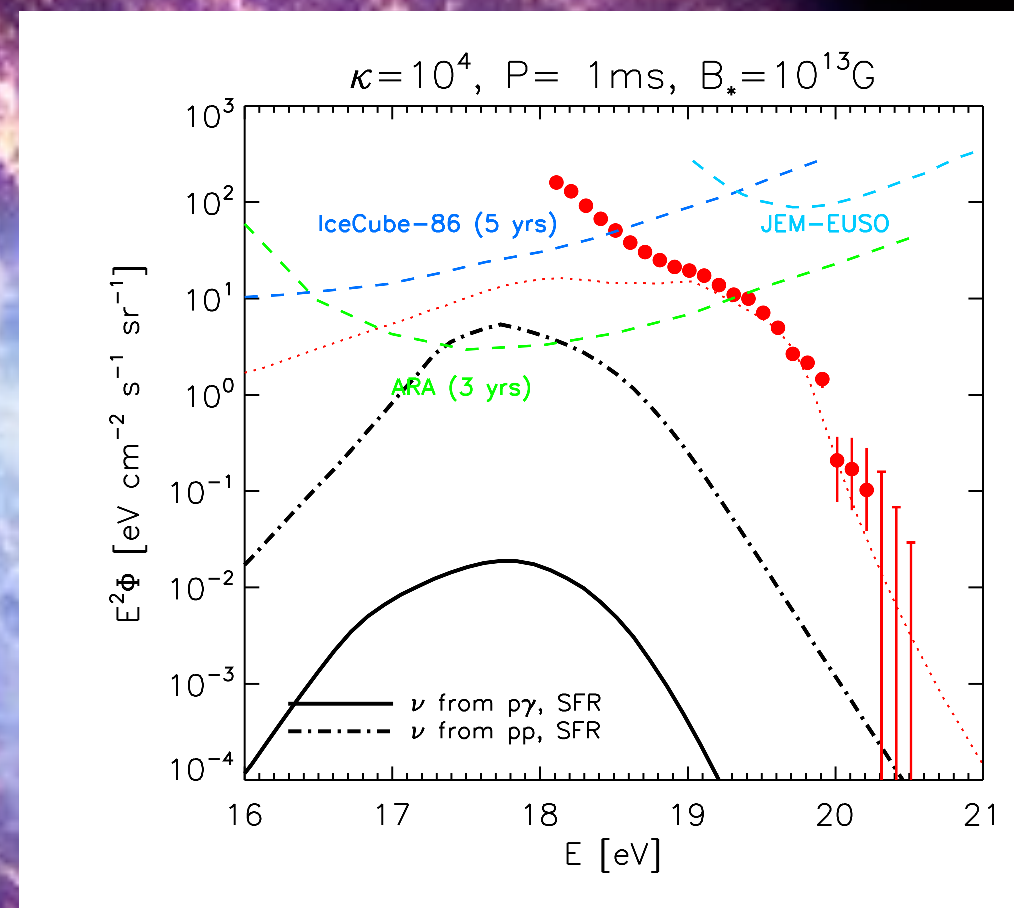
Ultrahigh energy neutrinos from the pulsar model

Neutrino flux for population of pulsars fitting the UHECR spectrum interaction with Supernova ejecta



Fang, KK, Murase, Olinto 2015

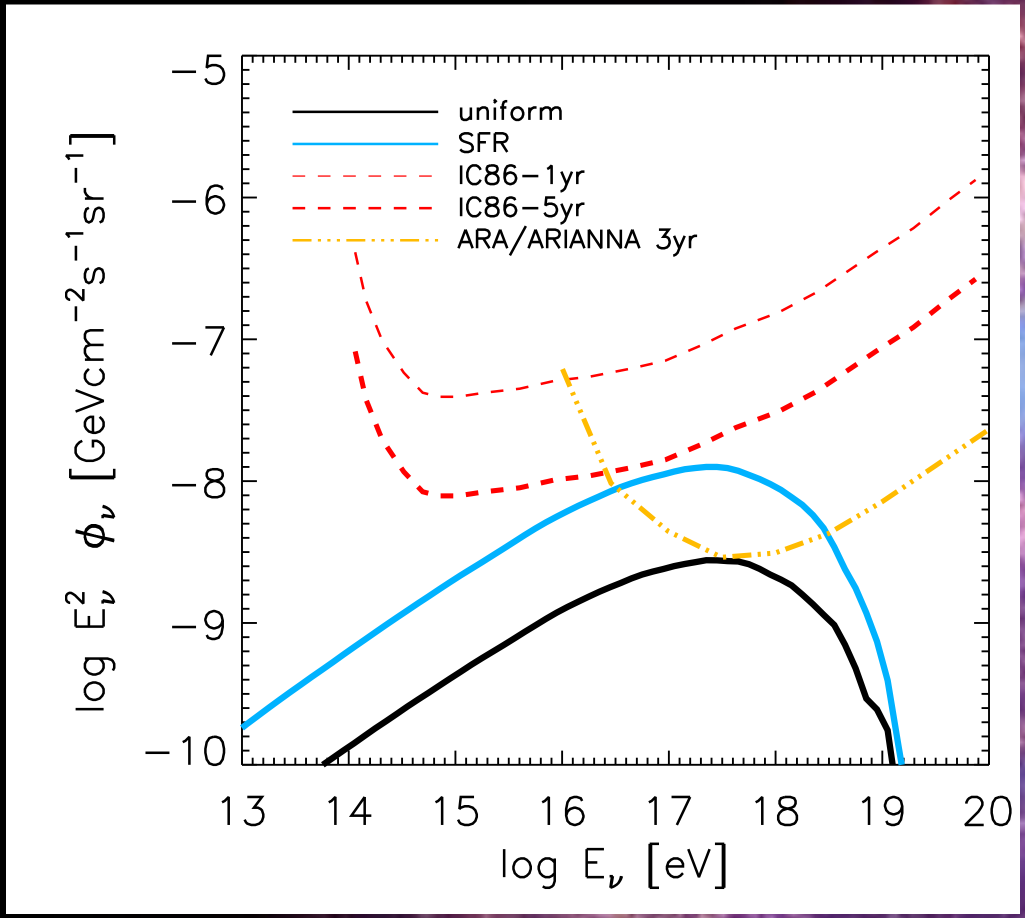
Neutrino flux for population of pulsars fitting the UHECR spectrum interactions in PWN



Lemoine, KK, Pétri 2015

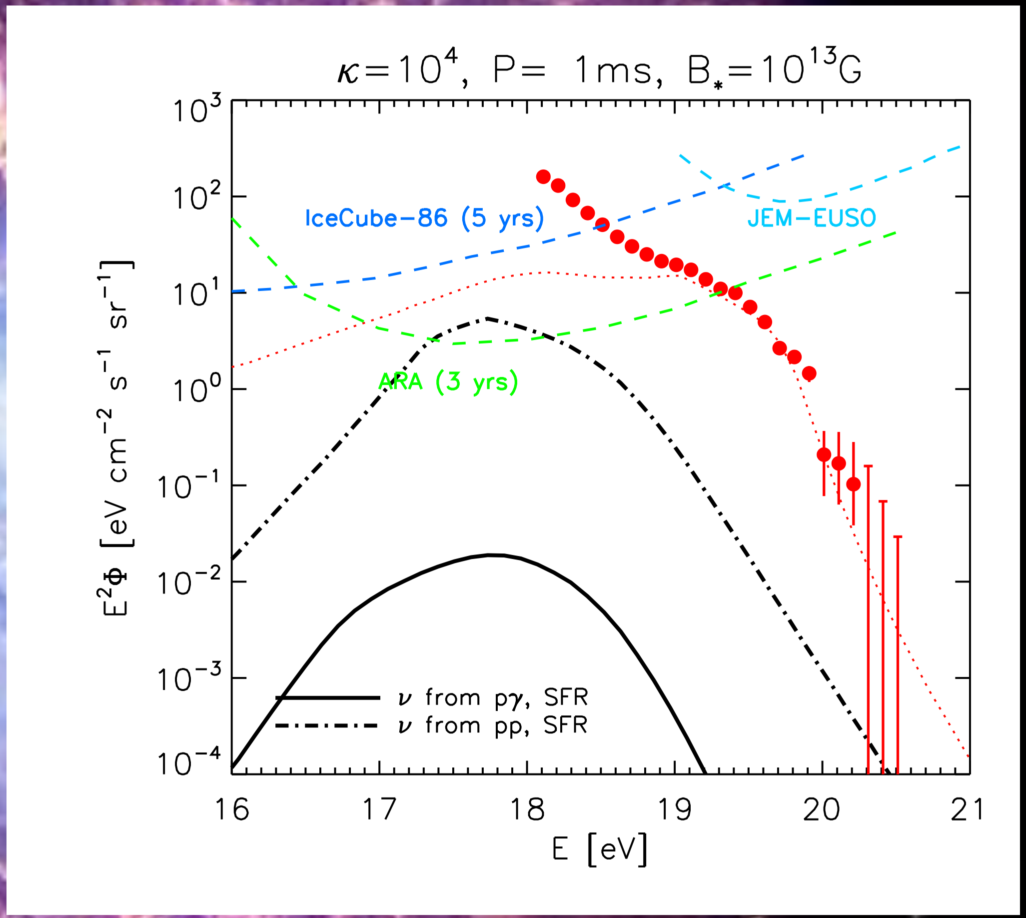
Ultrahigh energy neutrinos from the pulsar model

Neutrino flux for population of pulsars fitting the UHECR spectrum interaction with Supernova ejecta



Fang, KK, Murase, Olinto 2015

Neutrino flux for population of pulsars fitting the UHECR spectrum interactions in PWN



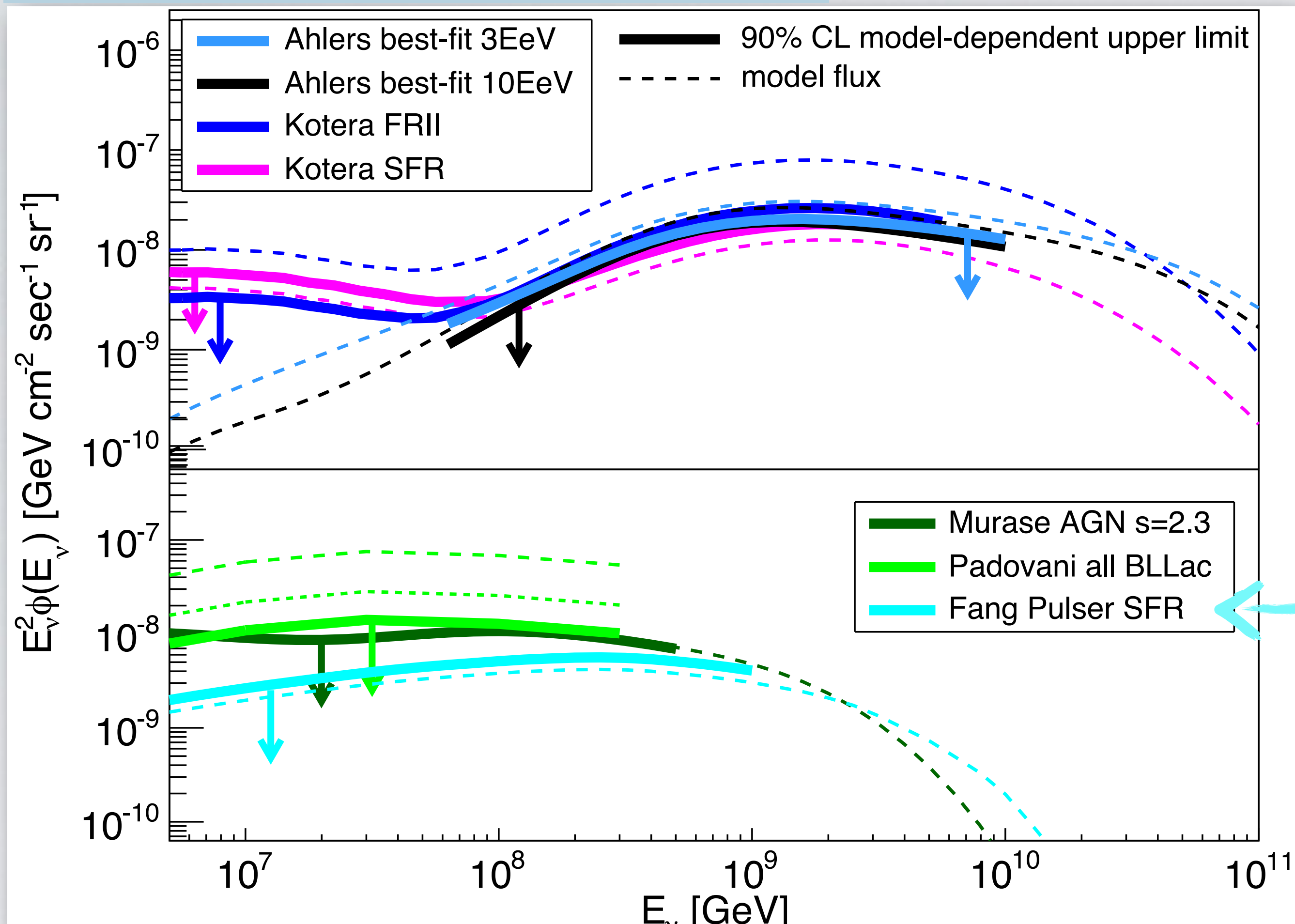
Lemoine, KK, Pétri 2015

- Already constrained with IceCube
- Most pessimistic case: testable with IceCube in the next decade!

IceCube constraints on newborn pulsars as sources of UHECRs

Aartsen et al. 2016

model dependent 90% C.L. limits



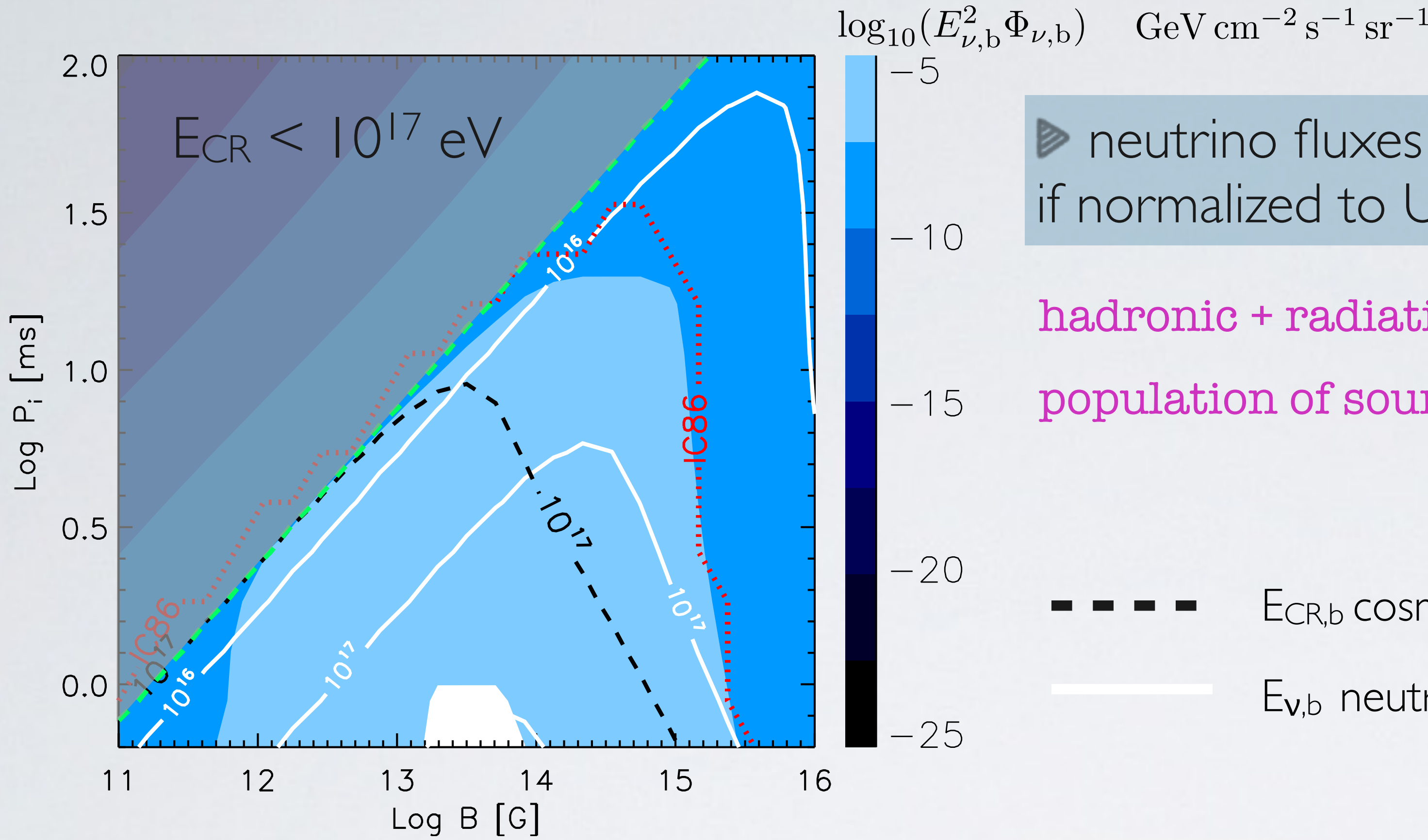
	Expected number of events in 2426 days of effective livetime		Model Rejection Factor
ν Model	Event rate per livetime	p-value	MRF
Murase *et al.* [45] $s = 2.3$, ξ_{CR}=100	$7.4^{+1.1}_{-1.8}$	$2.2^{+9.9}_{-1.4}$%	0.96 ($\xi_{CR} \leq 96$)
Murase *et al.* [45] $s = 2.0$, ξ_{CR}=3	$4.5^{+0.7}_{-0.9}$	$19.9^{+20.2}_{-9.2}$%	1.66 ($\xi_{CR} \leq 5.0$)
Fang *et al.* [48] SFR	$5.5^{+0.8}_{-1.1}$	$7.8^{+14.4}_{-3.7}$%	1.34
Fang *et al.* [48] uniform	$1.2^{+0.2}_{-0.2}$	$54.8^{+1.7}_{-2.7}$%	5.66
Padovani *et al.* [46] $Y_{\nu\gamma} = 0.8$	$37.8^{+5.6}_{-8.3}$	<0.1%	0.19 ($Y_{\nu\gamma} \leq 0.15$)

MRF = ratio of expected average upper limit to expected signal

- Population of newborn pulsars as sources of UHECRs **following star formation rate** excluded at 99.9% C.L.

IceCube constraints on neutrino-producing neutron-stars

Fang, KK, Murase, Olinto 2016



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

hadronic + radiative, no jet

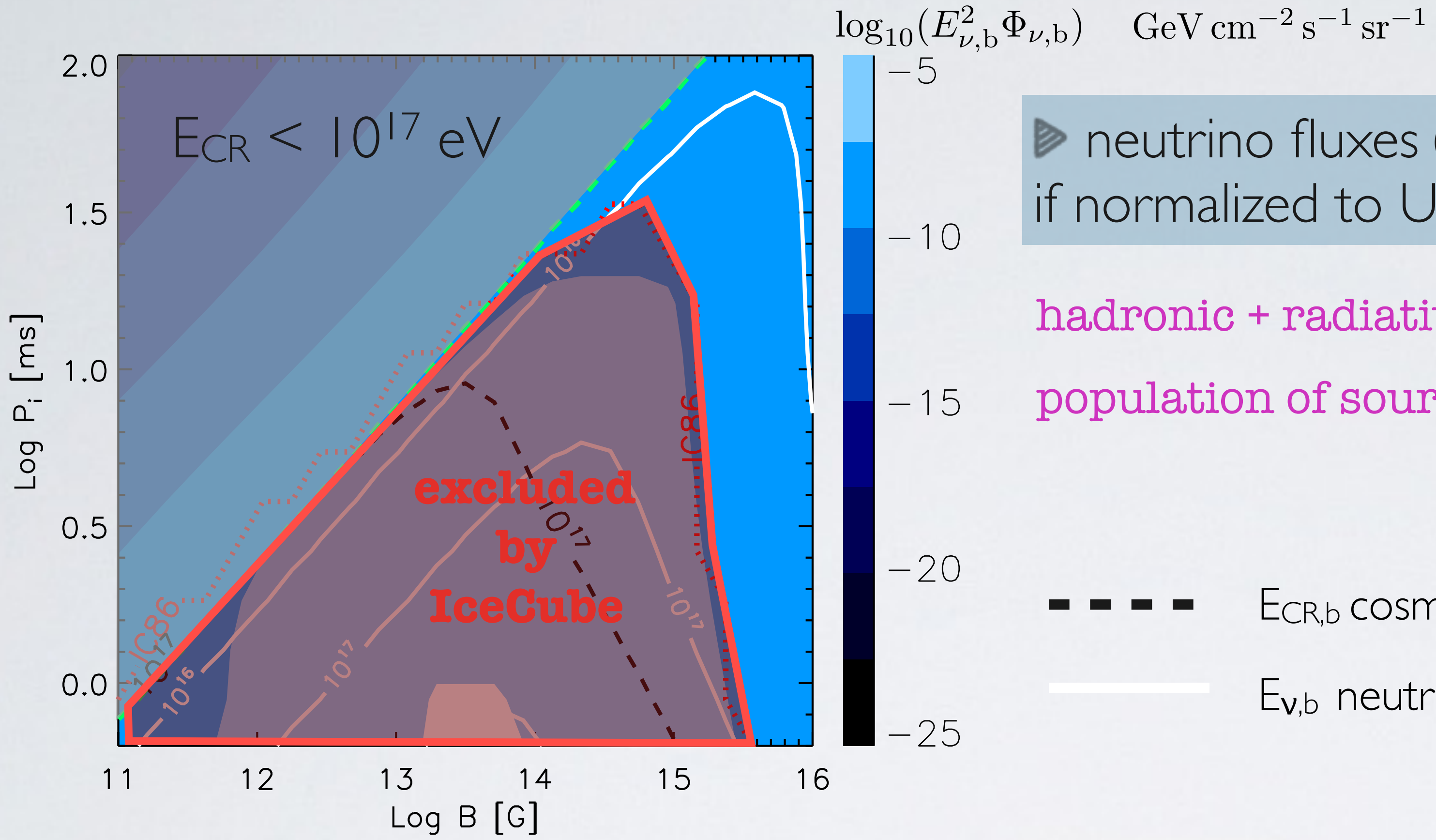
population of sources with same characteristics (P,B)

- - - - $E_{CR,b}$ cosmic-ray break energy [eV]

——— $E_{\nu,b}$ neutrino break energy [eV]

IceCube constraints on neutrino-producing neutron-stars

Fang, KK, Murase, Olinto 2016



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

hadronic + radiative, no jet

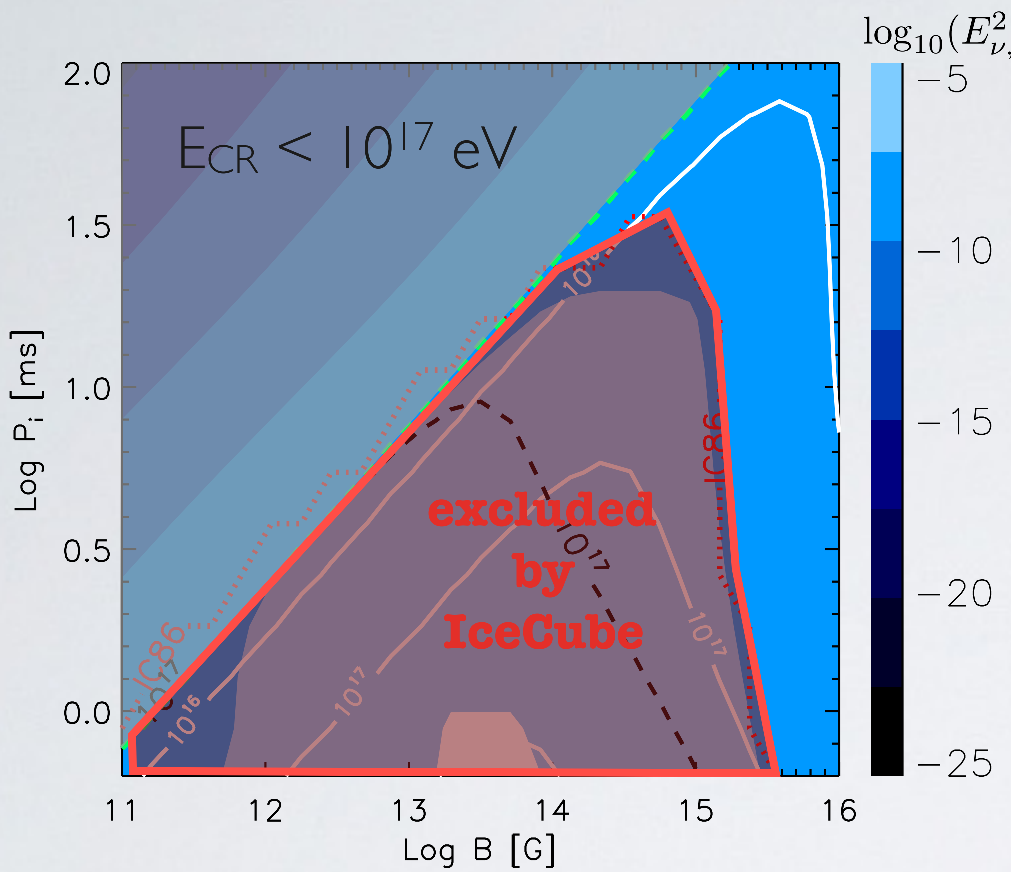
population of sources with same characteristics (P,B)

$E_{CR,b}$ cosmic-ray break energy [eV]

$E_{\nu,b}$ neutrino break energy [eV]

IceCube constraints on neutrino-producing neutron-stars

Fang, KK, Murase, Olinto 2016



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

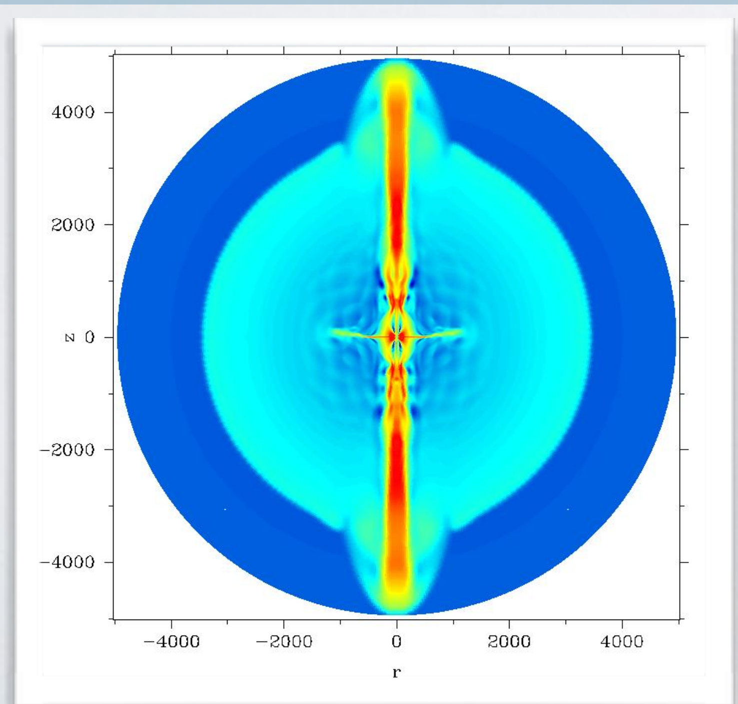
hadronic + radiative, no jet

population of sources with same characteristics (P,B)

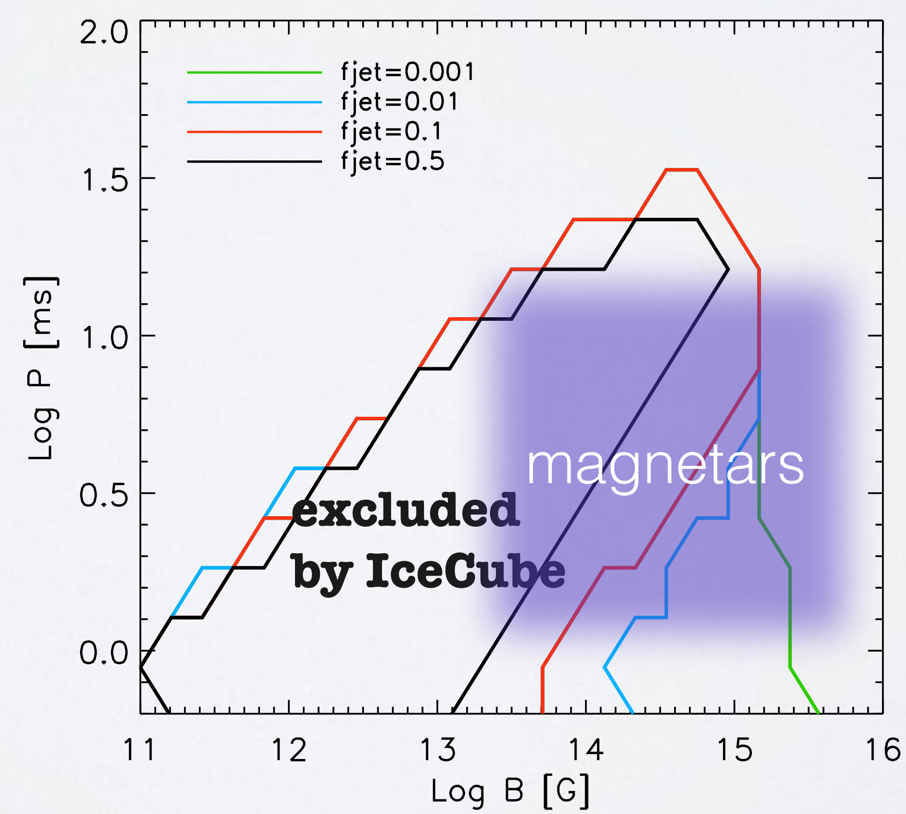
- - - - $E_{CR,b}$ cosmic-ray break energy [eV]

——— $E_{\nu,b}$ neutrino break energy [eV]

▶ 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
▶ UHECR production and escape possible

- pulsars/magnetars should be strong high-energy neutrino emitters
- surrounding SN ejecta material unavoidable to produce neutrinos unless punctured by jet (GRB-like)
- IceCube already strongly constraining pulsar/magnetar scenarios for UHECR production

  - some (P,B) neutron-star populations excluded for UHECR production
  - newborn pulsars with uniform emissivity evolution excluded at 90% C.L. by IceCube as UHECR producers