Neutrino Pulsars

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<u>Bottom line:</u>

Young neutron stars could be the brightest sources of high-energy neutrinos (~50 TeV).

In collaboration with F. Burgio (University of Catania, Italy)

Overview

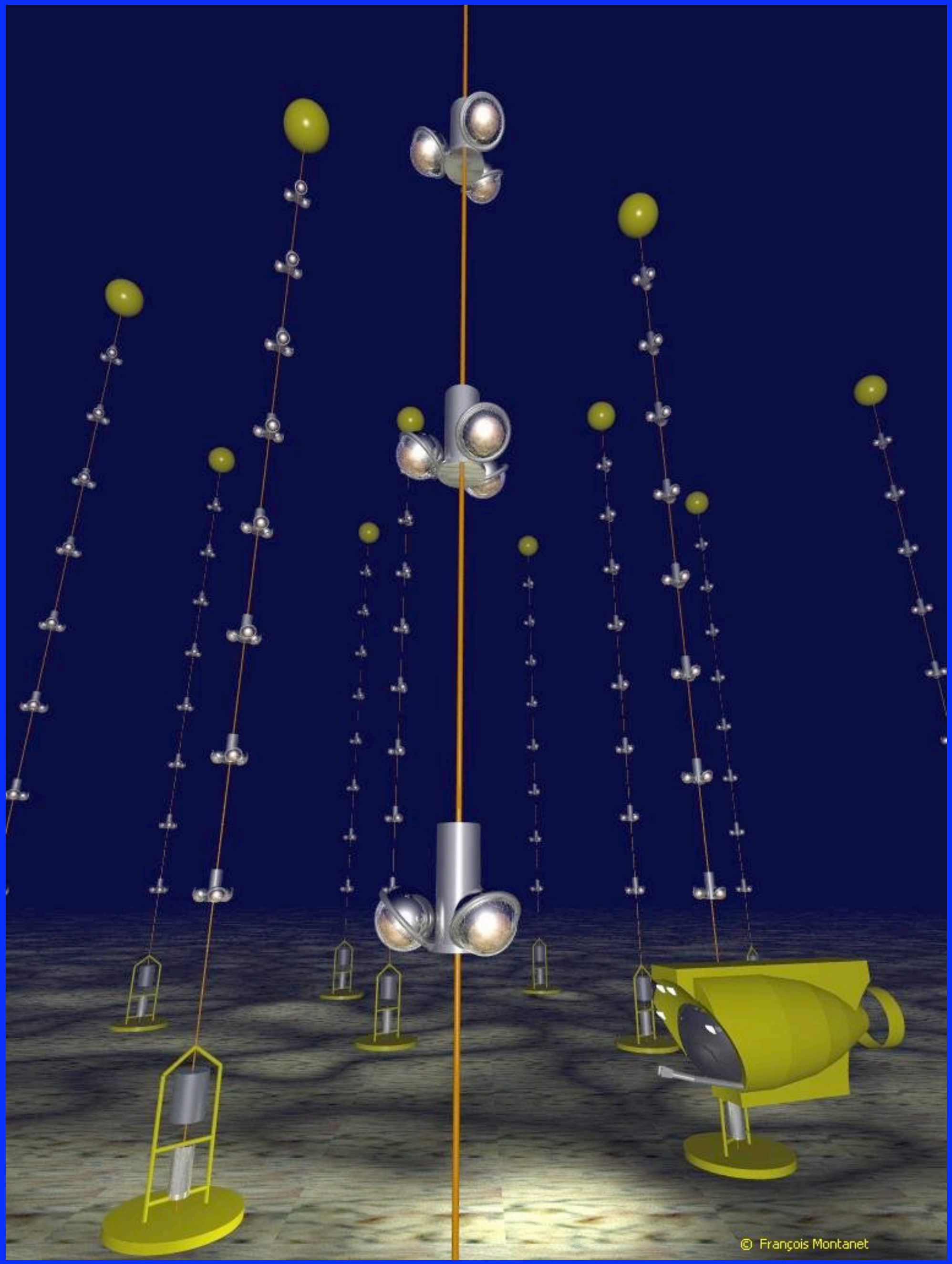
- Neutrino astronomy
- A physical mechanism for high-energy neutrino production from pulsars
- Estimates of neutrino flux rates at Earth
- Prospects for detection

Some models of neutrino production

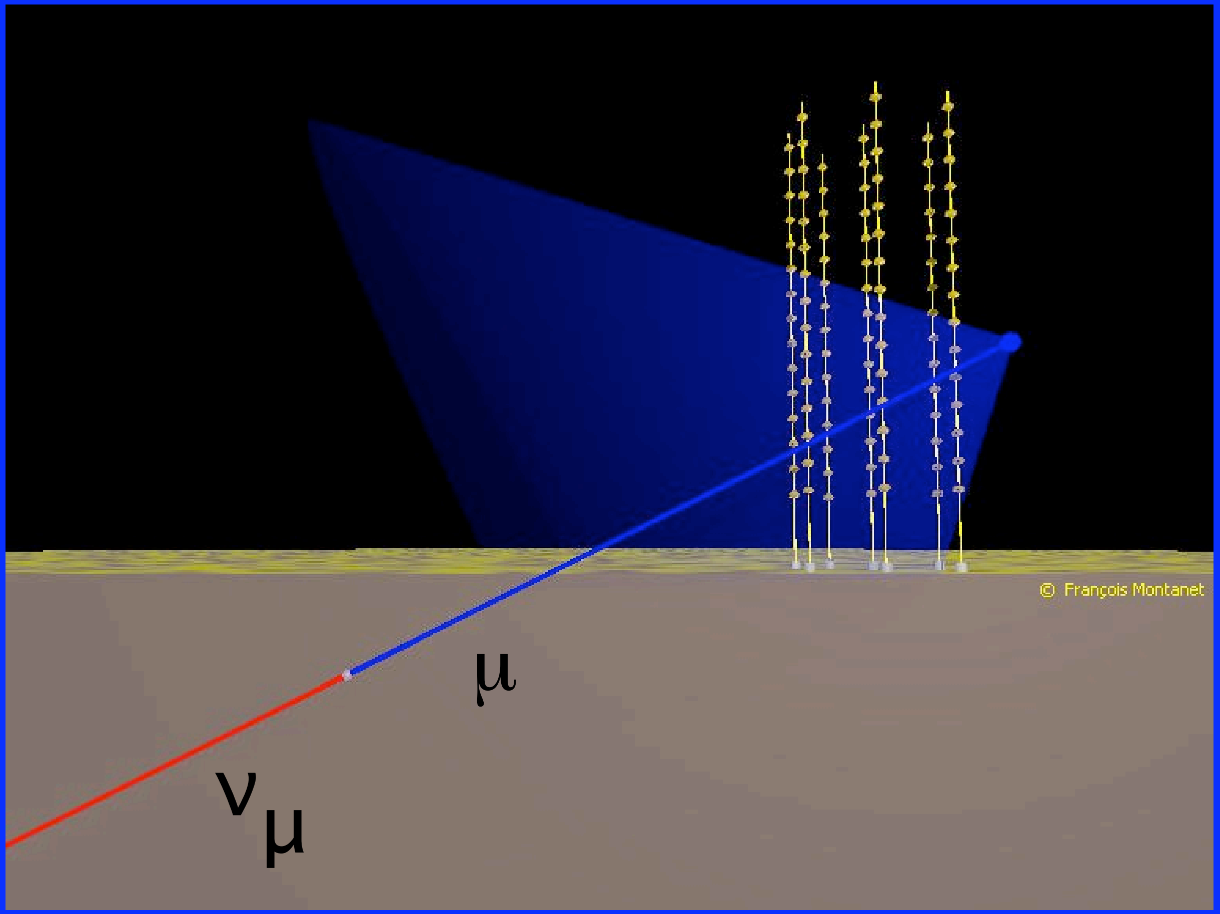
- pp interactions in AGN (Nellen et al. 93)
- pγ in AGN (Stecker & Salamon 96)
- pγ in extragalatic photoproduction sources (Mannheim et al. 00)
- pγ and pp in blazar jets (Mannheim 95)
- pγ due to UHE CR from radio galaxies interacting with the CMBR (Rachen & Biermann 93; Protheroe & Johnson 96)
- Gamma-ray bursts (Waxman & Bahcall 97)
- pγ and pp interactions in plerions (Bednarek & Protheroe 97; Bednarek 03; Guetta & Amato 03)

Neutrino observatories

AMANDA-II, ANTARES, IceCube, NEMO, NESTOR



Detection principle



Angular resolution of ~ 1°!!

Complete list of extraterrestrial sources of high-energy neutrinos by AMANDA-II

Muons from cosmic rays hitting the atmosphere have been seen.

Neutron stars might be sources too

Photomeson production (the "Δ resonance")

$$p\gamma \longrightarrow \Delta^+ \longrightarrow n\pi^+ \longrightarrow n\nu_\mu\mu^+ \longrightarrow ne^+\nu_e\nu_\mu\bar{\nu}_\mu$$

The threshold for this reaction is:

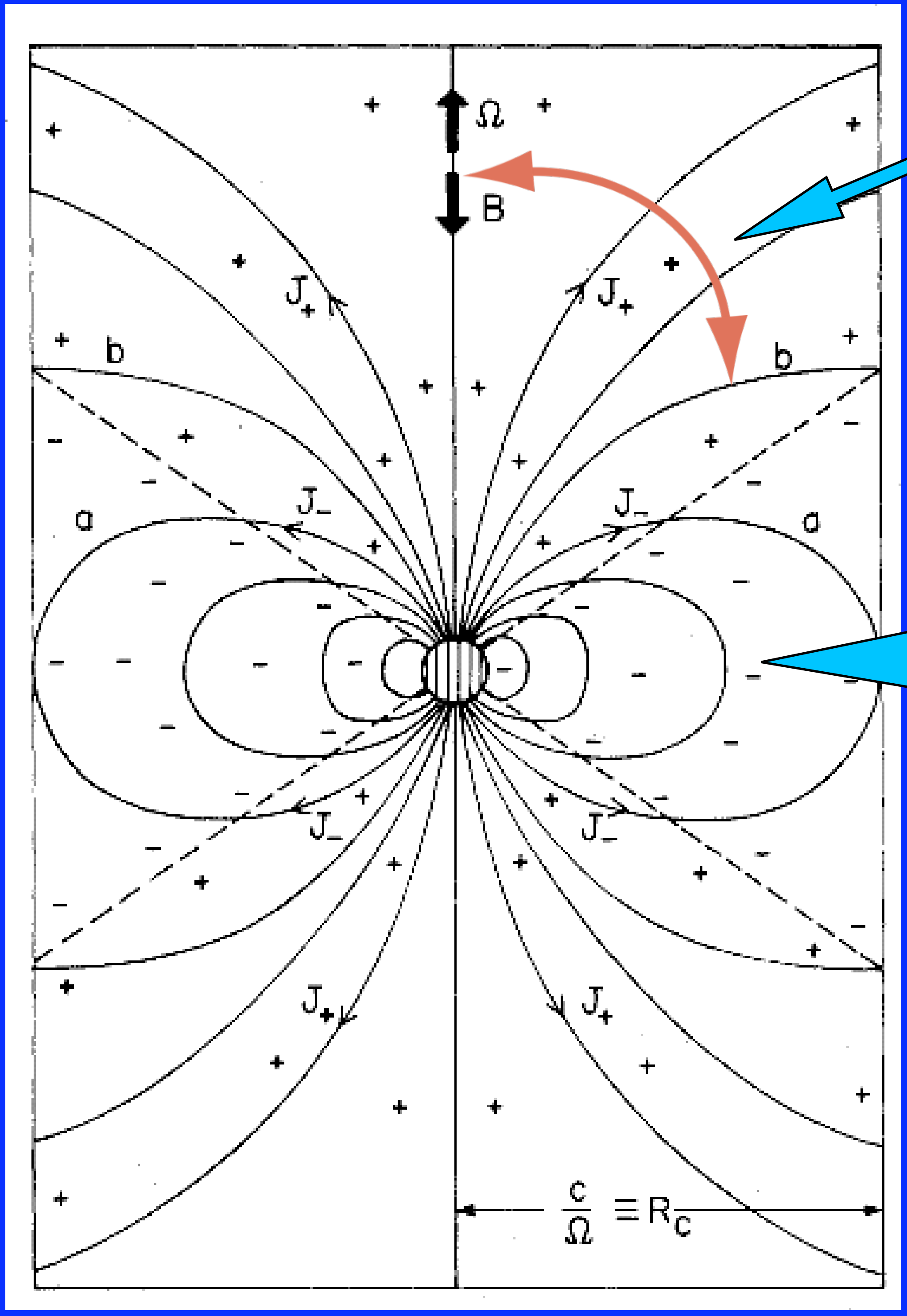
$$\varepsilon_p \geq \left(\frac{T_\infty}{0.1\ \mathrm{keV}}\right)^{-1}\ \mathrm{PeV}$$

Protons accelerated off the surface of a young neutron star could undergo photomeson conversion with the soft x-rays from the surface.
(c.f. Zhang, Dai, Mészáros, Waxman & Harding 03).

Is it possible to get protons to $\sim$1 PeV?

The equilbrium magnetosphere

(Goldreich & Julian 1969)



From Ruderman & Sutherland (76)

Potential drop *across* B of:

$$\varepsilon_\perp \sim 100\, Z B_{12} \left(\frac{p}{10\ \mathrm{ms}}\right)^{-2}\ \mathrm{PeV}$$

Corotating charge of density:

$$n_{GJ} \simeq 10^{13}\, Z B_{12} \left(\frac{p}{10\ \mathrm{ms}}\right)^{-1}\ \mathrm{cm}^{-3}$$

“Light cylinder”

Sign of charges in open-field region is determined by sign of $\mu \bullet \Omega$.

The question of magnetospheric physics

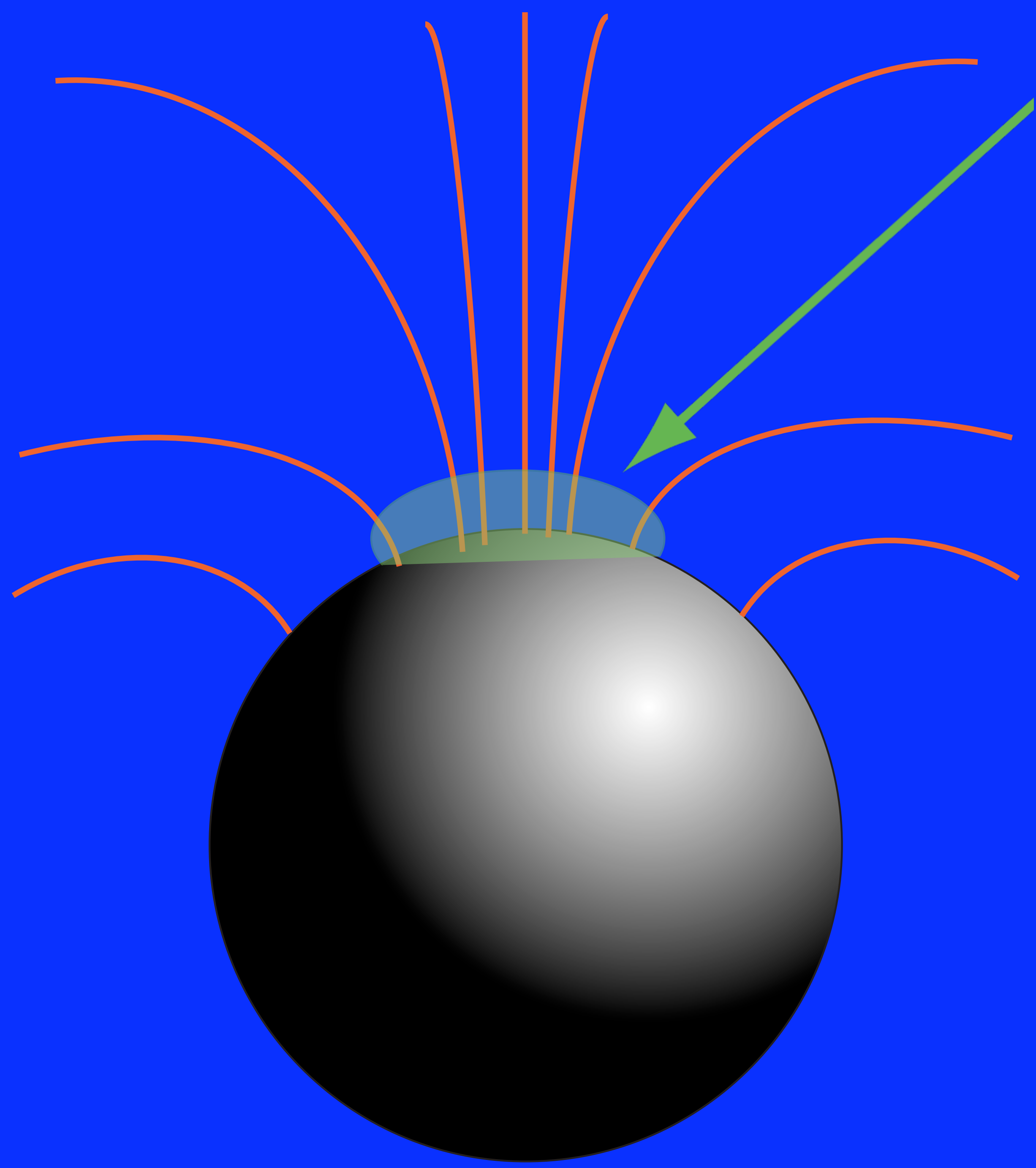
- In the equilibrium magnetosphere, there is no charge acceleration ($E \bullet B \cong 0$).
- For acceleration, need $E \bullet B \neq 0$, which requires $n < n_{GJ}$, somewhere.
- How and where does this *gap* develop?

1. Is it an *inner gap*, close to the star? (see, e.g., Ruderman & Sutherland 75; Arons & Scharlemann 79; Harding & Muslimov 98).
2. Or is it an *outer gap*, far from the star? (Cheng, Ho & Ruderman 86).

Talks later today by Tomokhin and Spitkovsky

Suppose charge depletion occurs near the surface

(Ruderman & Sutherland 75; Arons & Scharlemann 70; Harding & Muslimov 98)



Charge-depleted region

$$n << n_{GJ}$$

$\mathbf{E} \cdot \mathbf{B} \neq 0 \Longrightarrow$ charge acceleration

A significant fraction of

$$\varepsilon_{\Phi} \sim 100\, Z B_{12} \left(\frac{p}{10\ \mathrm{ms}}\right)^{-2} \mathrm{PeV}$$

can be attained.

Conjecture to be tested by neutrino observations

A strong accelerating field exists *near the stellar surface* that is sufficient to bring protons to the Δ resonance:

$$p\gamma \longrightarrow \Delta^{+} \longrightarrow n\pi^{+} \longrightarrow n\nu_{\mu}\mu^{+} \longrightarrow ne^{+}\nu_{e}\nu_{\mu}\bar{\nu}_{\mu}$$

Requirements

- Field is properly oriented: $\mu \cdot \Omega < 0$ (to accelerate positive ions). Half of pulsars.

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- Field is properly oriented: $\mu \cdot \Omega < 0$ (to accelerate positive ions). Half of pulsars.
- Sufficiently strong accelerating field exists to bring protons to resonance.

How strong an accelerating field?

Energy threshold for the proton is

$$\varepsilon_p \geq \left(\frac{T_\infty}{0.1\ \mathrm{keV}} \right)^{-1} \mathrm{PeV}$$

Compare to potential energy across the field:

$$\varepsilon_\perp \sim 100\, Z B_{12} \left(\frac{p}{10\ \mathrm{ms}} \right)^{-2} \mathrm{PeV}$$

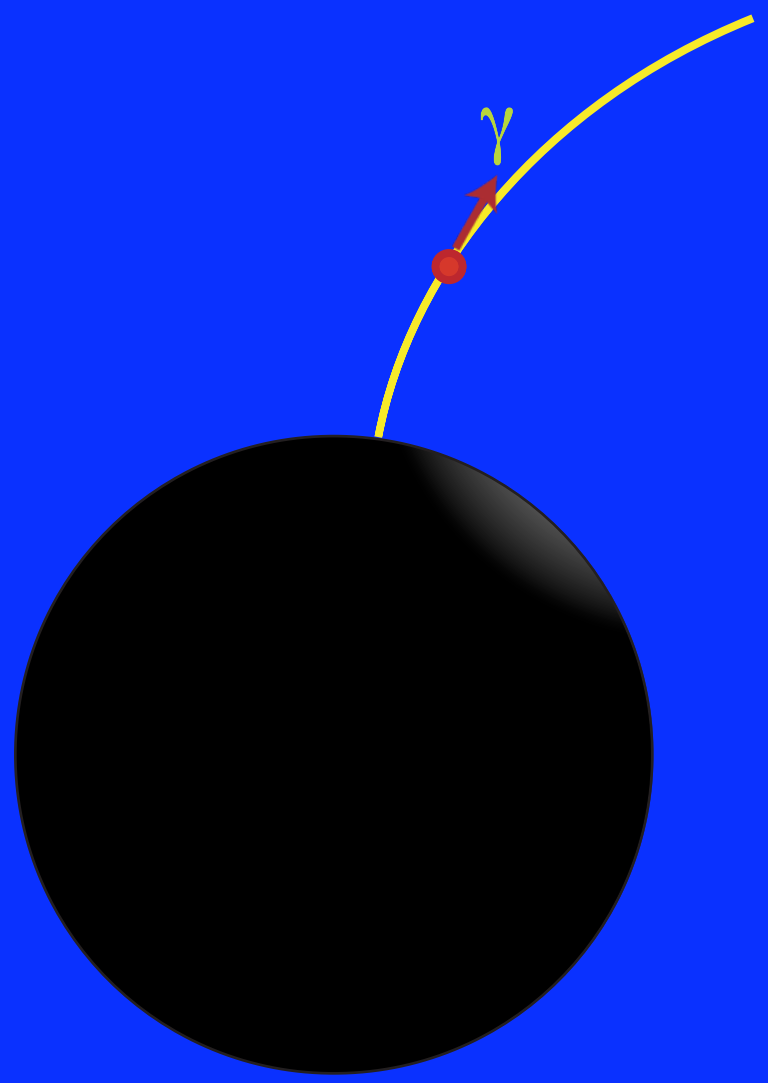
Need an accelerating electric field of strength:

$$E_\| \sim 0.01 E_\perp$$

Can we get protons to ~1 PeV?

- Pair creation will quench the field at some point.
- There will be losses to curvature radiation.

Curvature radiation loss limit



$$\varepsilon_{max} \simeq 20 \left(\frac{A}{Z^2}\right)^{1/3} \text{ PeV}$$

per nucleon

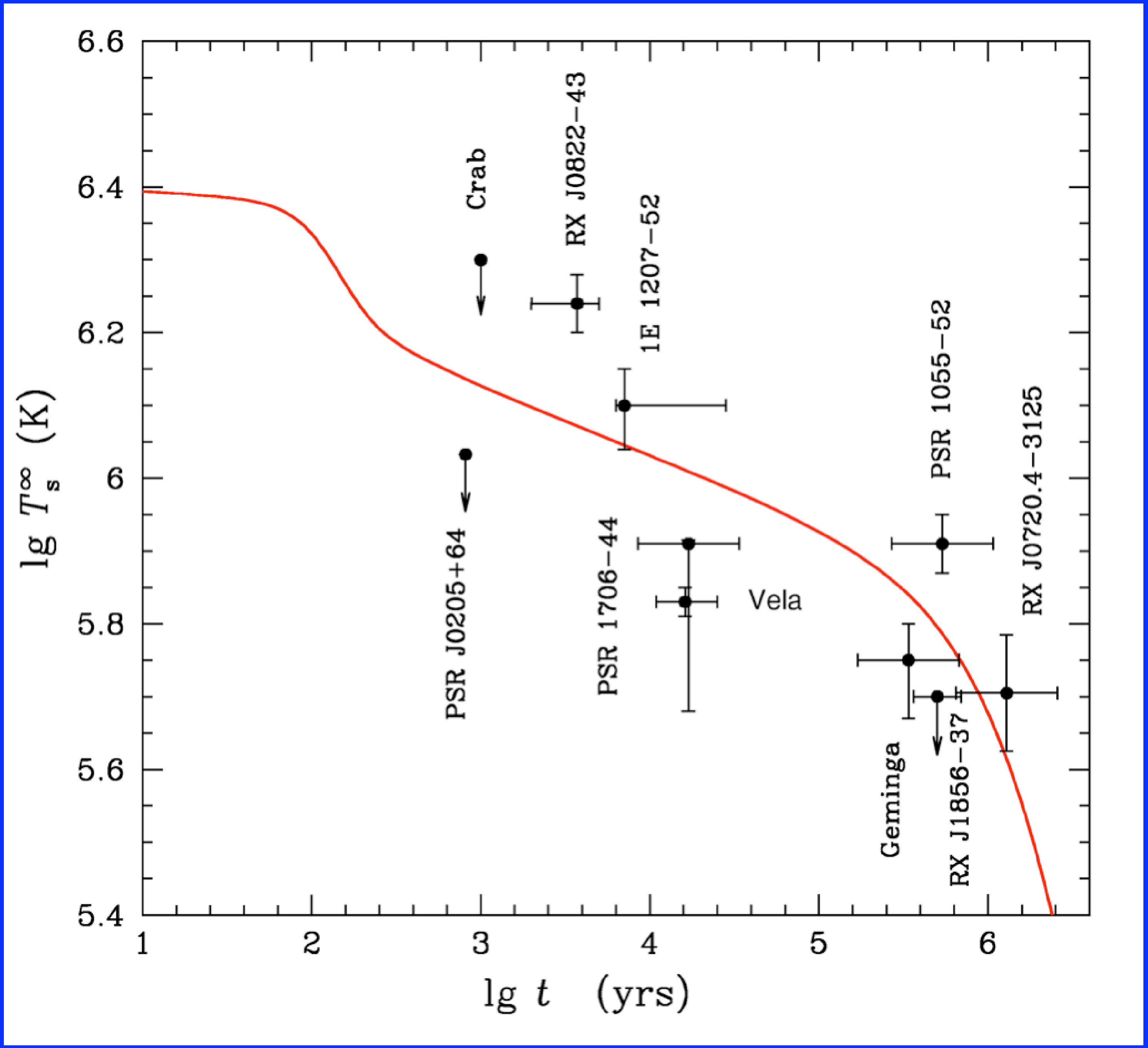
$\Rightarrow$ Not a limitation

Necessary condition on stellar parameters for resonance

$$B_{12}\left(\frac{p}{10\ \mathrm{ms}}\right)^{-2}\left(\frac{T_{surf}}{0.1\ \mathrm{keV}}\right) > 0.03$$

Satisfied by dozens of close pulsars...probably.

Neutron stars stay hot for a long time



Yakovlev & Pethick 04

Necessary condition on stellar parameters for resonance

$$B_{12}\left(\frac{p}{10\ \mathrm{ms}}\right)^{-2}\left(\frac{T_{surf}}{0.1\ \mathrm{keV}}\right) > 0.03$$

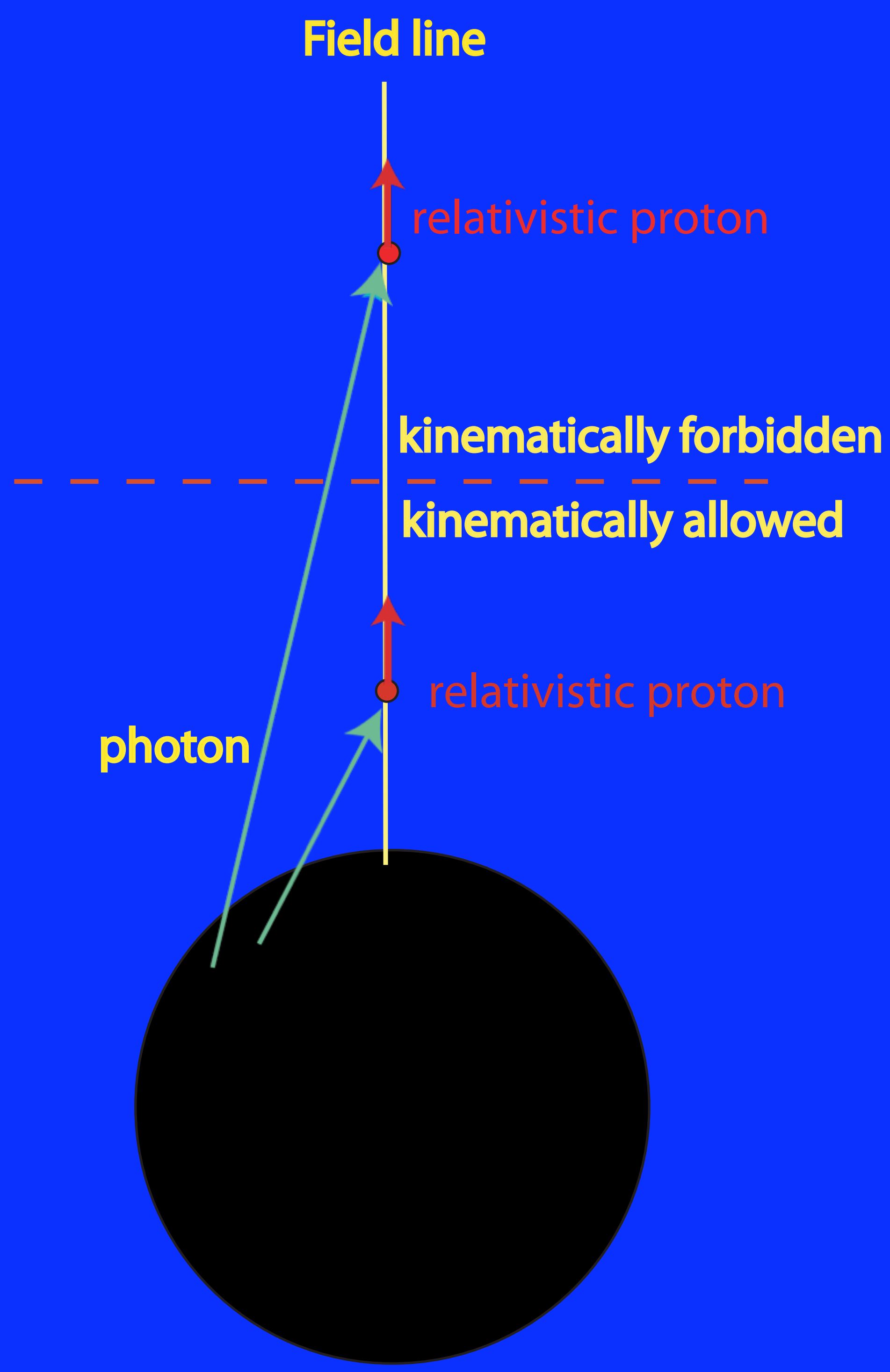
There are 64 known pulsars within 10 kpc younger than 10^5 yr.

There are 9 within 5 kpc, younger than 10^5 yr, and that satisfy this condition if T_{surf}=0.1 keV.

Requirements

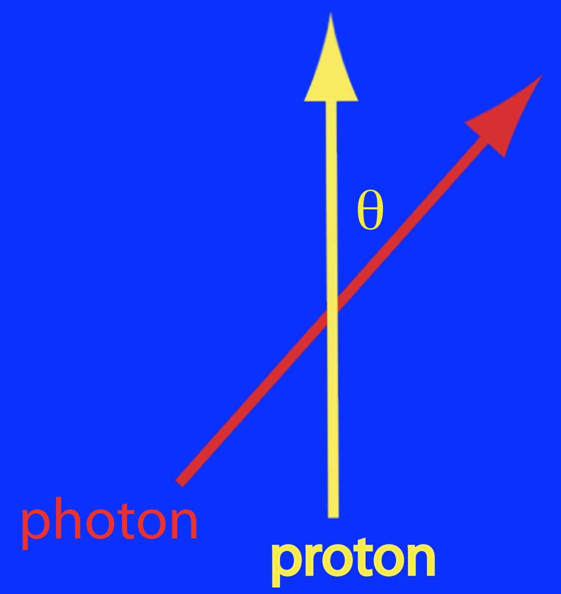
- Field is properly oriented: $\mu \cdot \Omega < 0$ (to accelerate positive ions). Half of pulsars.
- Sufficiently strong accelerating fields exist to bring protons to resonance.
- The acceleration must occur *near the surface* (within ~0.5R).

Resonance can happen only near the surface.



Resonance occurs for:

$$\varepsilon_p = \left(\frac{T_\infty}{0.1\ \mathrm{keV}}\right)^{-1} \frac{1}{1-\cos\theta}\ \mathrm{PeV}$$



Also, the conversion probability is low

$$P_{conv} \simeq 0.02\, T_{0.1keV}^{3}$$

$\Rightarrow$ few protons are affected.

If protons are converted...

$$p\gamma \longrightarrow \Delta^{+} \longrightarrow n\pi^{+} \longrightarrow n\nu_{\mu}\mu^{+} \longrightarrow ne^{+}\nu_{e}\nu_{\mu}\bar{\nu}_{\mu}$$

Pions move along the field lines before decaying...

⇒ a radio pulsar could be a “neutrino pulsar”.

Energies

$$p\gamma \longrightarrow \Delta^{+} \longrightarrow n\pi^{+} \longrightarrow n\nu_{\mu}\mu^{+} \longrightarrow ne^{+}\nu_{e}\nu_{\mu}\bar{\nu}_{\mu}$$

Protons

$$\varepsilon_{p} \simeq T_{0.1keV}^{-1} \text{ PeV}$$

Pions

$$\varepsilon_{\pi} \simeq 200\ T_{0.1keV}^{-1} \text{ TeV}$$

μ neutrinos

$$\varepsilon_{\nu_{\mu}} \simeq 50\ T_{0.1keV}^{-1} \text{ TeV}$$

Best candidate neutron stars are...

- Close
- Hot
- Rapidly spinning

And <u>must</u> have $\mu \bullet \Omega < 0$

A crude flux estimate

(Link & Burgio 2005, PRL, 94, 181101)

depletion factor (<1)

$$\phi_\nu \simeq c f_b f_d n_{GJ} \left(\frac{R}{d}\right)^2 P_{conv}$$

neutrino flux

beam duty cycle

Muon number flux in a large-area detector

$$\frac{dN}{dAdt} = \phi_\nu P_{\nu_\mu \to \mu} \sim 10^5 Z^{-1} f_d f_b B_{12} p_{ms}^{-1} d_{kpc}^{-2} T_{0.1keV}^2 \text{ km}^{-2} \text{ yr}^{-1}$$

at an energy $\varepsilon_{\nu_\mu} \simeq 50\, T_{0.1keV}^{-1}$ TeV

Some promising candidates

Detector area = 0.1 km^2
Observing time = 1 year

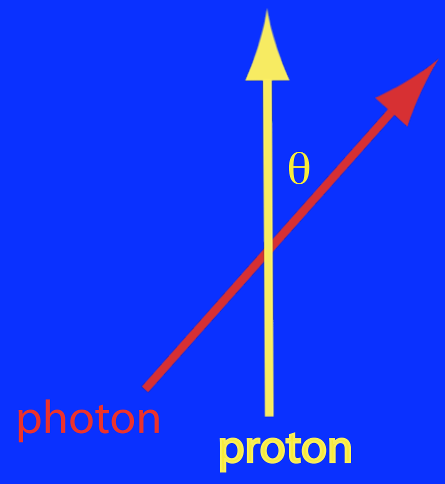
Source	Hemisphere	(muon counts)$*f_d Z^{-1}$
Crab	northern	120
J0205+64	northern	10?
Vela	southern	80
B1509-58	southern	10?

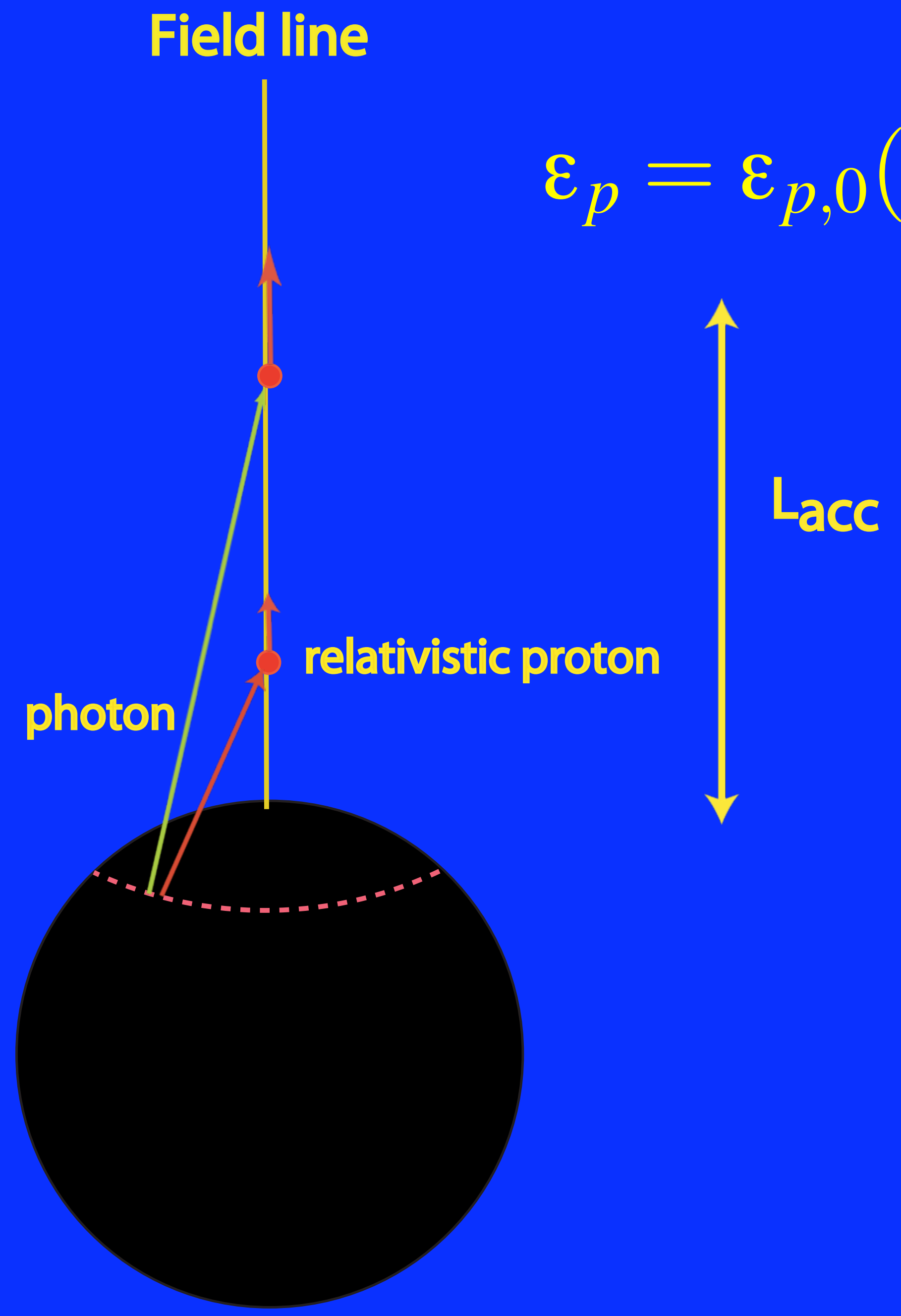
At muon energies ≥ 50 TeV

Calculating the neutrino spectrum

Resonance occurs for:

$$\varepsilon_p = \left(\frac{T_\infty}{0.1\ \mathrm{keV}}\right)^{-1} \frac{1}{1-\cos\theta}\ \mathrm{PeV}$$

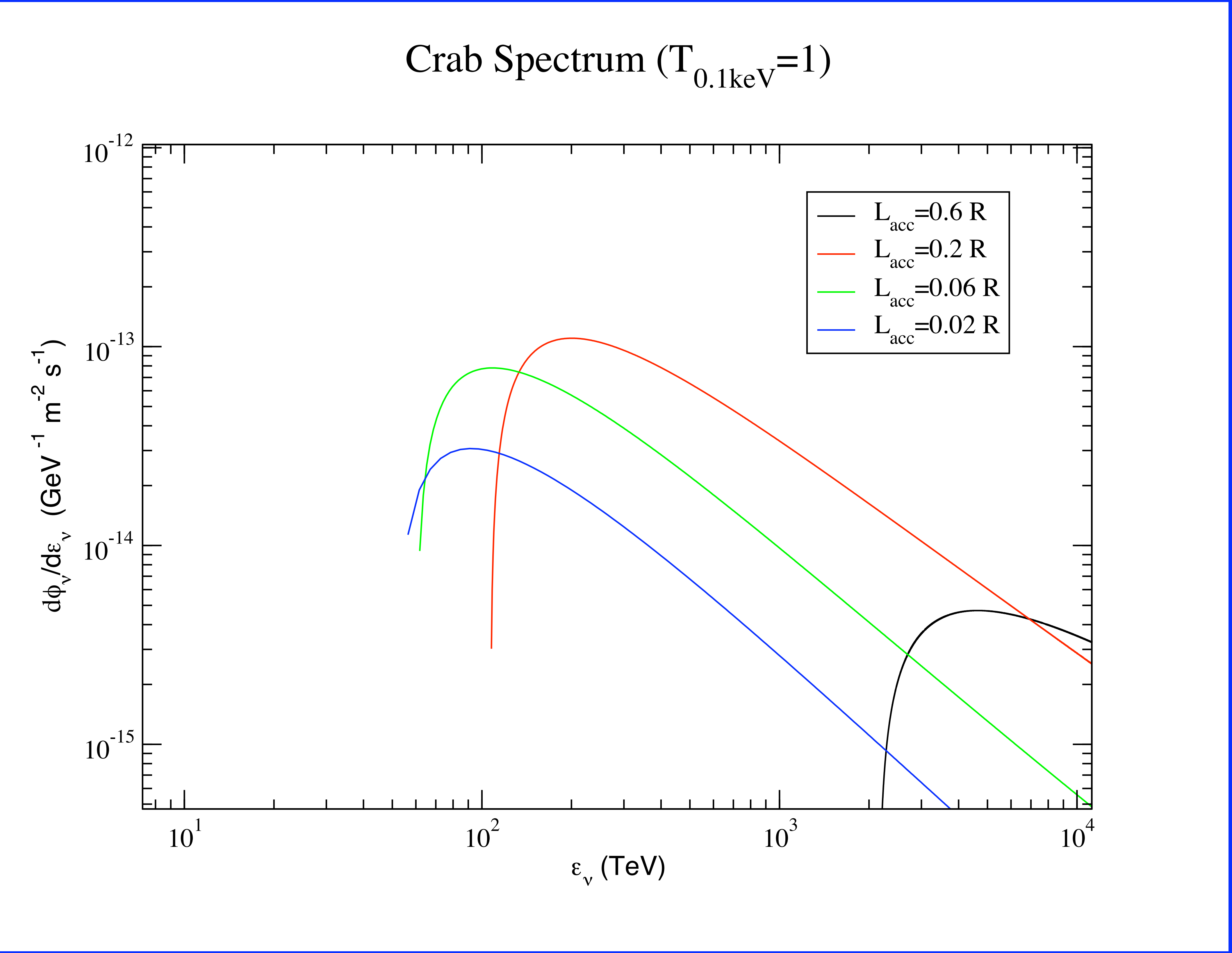




$$\varepsilon_p = \varepsilon_{p,0}(z/L_{acc})^2$$

Predicted neutrino spectrum

(Link & Burgio 05)



Other models

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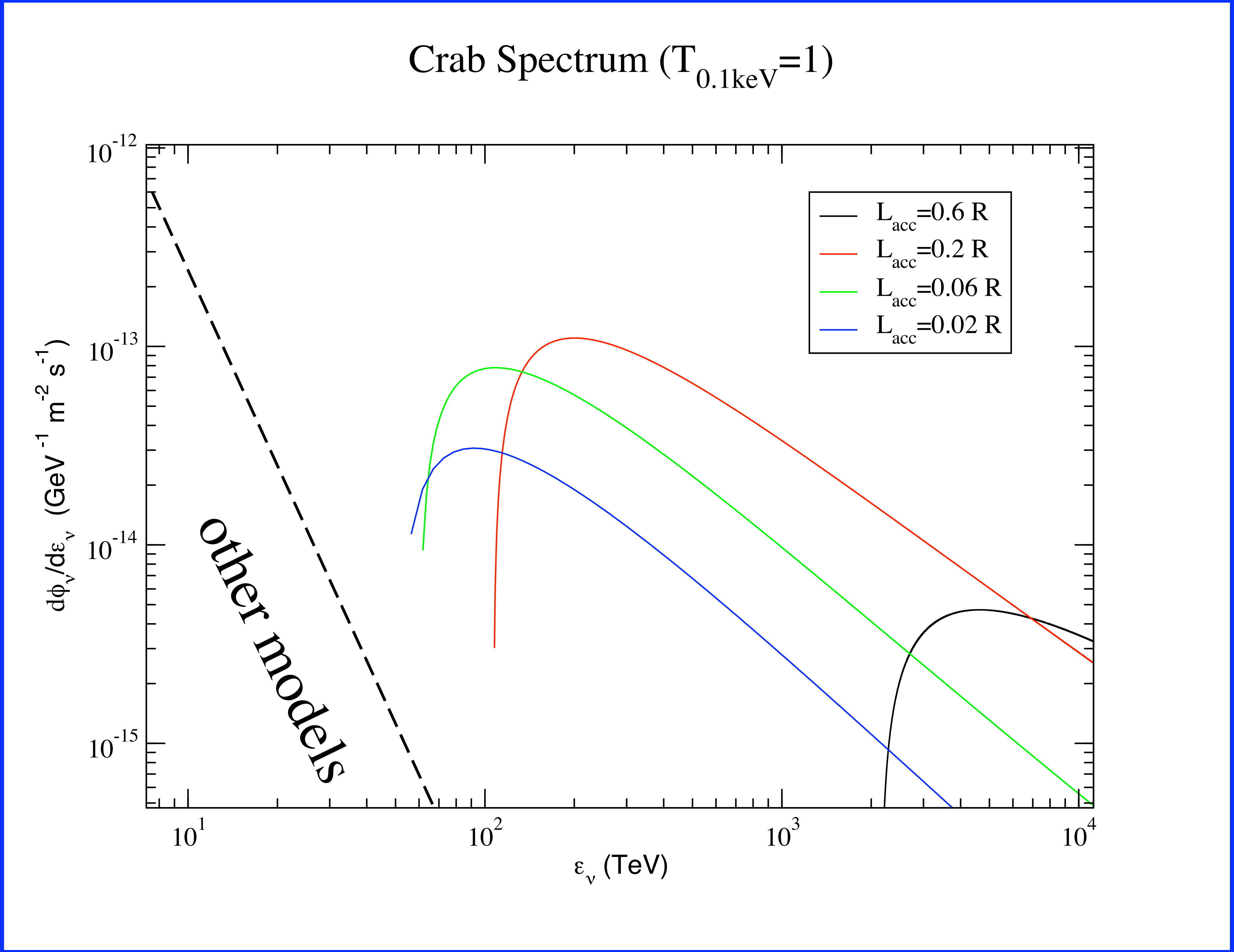

Conclusions

- Neutrino pulsars, *if they exist*, could be the brightest sources in the sky above ~ 50 TeV. They might be the first sources detected.
- Detection would allow direct constraints on the physical conditions in the neutron star magnetosphere.
- Lack of detection would also allow constraints.