Pulsars as Probes of Fundamental Physics

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Outlines

- Tight Constraint on **Photon Mass** from Pulsar Spindown (Yang & Zhang, 2017, ApJ)
- Testing **Einstein's weak equivalence** principle with a 0.4-nanosecond giant pulse of the Crab pulsar (Yang & Zhang, 2016, PRD)
- Conclusions

Constraint on Photon mass

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Tight Constraint on Photon Mass from Pulsar Spindown

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Abstract

Pulsars are magnetized rotating compact objects. They spin down due to magnetic dipole radiation and wind emission. If a photon has nonzero mass, the spin-down rate will be lower than in the zero-mass case. We show that an upper limit of the photon mass, i.e., $m_\gamma \lesssim h/Pc^2$, may be placed if a pulsar with period P is observed to spin down. Recently, a white dwarf (WD)–M dwarf binary, AR Scorpii, was discovered to emit pulsed broadband emission. The spin-down luminosity of the WD can comfortably power non-thermal radiation from the system. Applying our results to the WD pulsar with $P = 117$ s, we obtain a stringent upper limit of the photon mass between $m_\gamma < 6.3 \times 10^{-50}$ g, assuming a vacuum dipole spindown, and $m_\gamma < 9.6 \times 10^{-50}$ g, assuming spindown due to a fully developed pulsar wind.

Key words: pulsars: general – stars: winds, outflows – white dwarfs

Upper limits on photon mass

- Ultimate upper limit (uncertainty principle):

$$m_\gamma \leqslant \hbar/(\Delta t)c^2 \simeq 10^{-66}\ \mathrm{g}$$

- Upper limit adopted by the Particle Data Group (Olive et al. 2014, Solar wind):

$$m_\gamma \leqslant 1.5 \times 10^{-51}\ \mathrm{g}$$

- Most stringent limit (Chibisov 1976, magnetized gas stability, depend on many assumptions):

$$m_\gamma \leqslant 3 \times 10^{-60}\ \mathrm{g}$$

Massive Electrodynamics

- **de Broglie-Proca** Maxwell's Equations:

$$\nabla \cdot \boldsymbol{E} = 4\pi\rho - \mu^2\phi,$$
$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t},$$
$$\nabla \cdot \boldsymbol{B} = 0,$$
$$\nabla \times \boldsymbol{B} = \frac{4\pi}{c}\boldsymbol{J} + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t} - \mu^2 \boldsymbol{A}.$$

Photon-mass terms

$$\mu \equiv m_\gamma c/\hbar$$

- Poynting vector:

$$\boldsymbol{S} = \frac{c}{4\pi}(\boldsymbol{E} \times \boldsymbol{B} + \mu^2\phi\boldsymbol{A}).$$

- The de Broglie-Proca equation reads

$$\partial^\beta F_{\beta\alpha} + \mu^2 A_\alpha = \frac{4\pi}{c}J_\alpha.$$

- In Lorenz gauge, one has

$$(\Box + \mu^2)A_\alpha = \frac{4\pi}{c}J_\alpha.$$

Klein-Gordon equation

where $\Box \equiv \partial^2/c^2\partial t^2 - \nabla^2$

EM wave

- Assume that a point source of strength f(t) resides at the origin. The spherical wave φ(r,t) caused by such a source is given by

$$(\Box + \mu^2)\varphi(r,t) = \delta(\boldsymbol{r})f(t).$$

- For an outgoing wave with f(t) as a function of exp(iωt),

$$\varphi(r,t) \propto \frac{1}{4\pi r} \exp\left[i\omega t - ir\,\underline{\left(\omega^2/c^2 - \mu^2\right)^{1/2}}\right].$$

k: wave vector

- The dispersion relation is given by

Energy-Momentum relation

$$\boxed{\omega^2 = c^2k^2 + \mu^2c^2.} \rightarrow \omega^2 = c^2k^2 + \omega_p^2$$

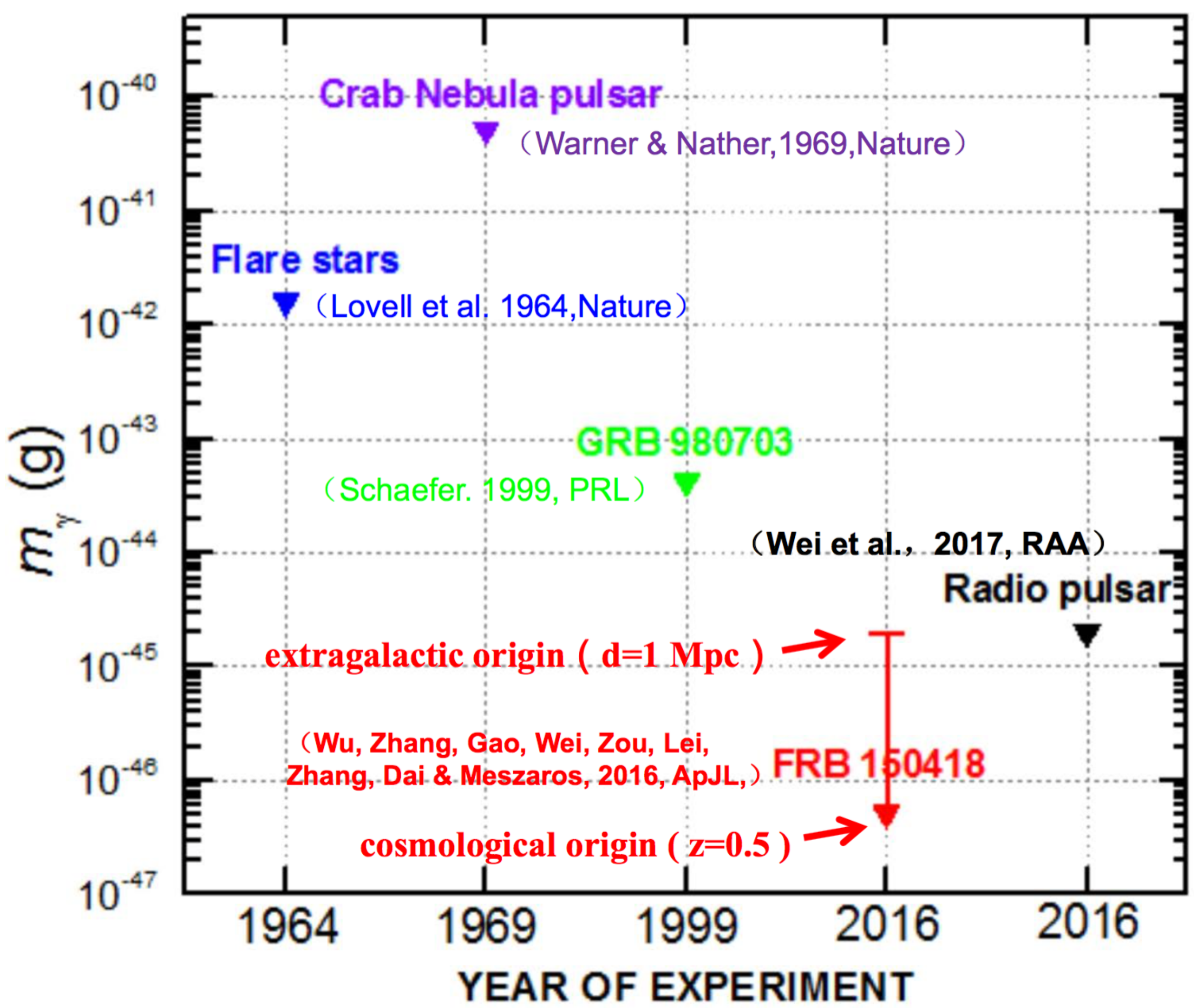
EM wave velocity

- The group velocity of EM wave is variable with frequency:

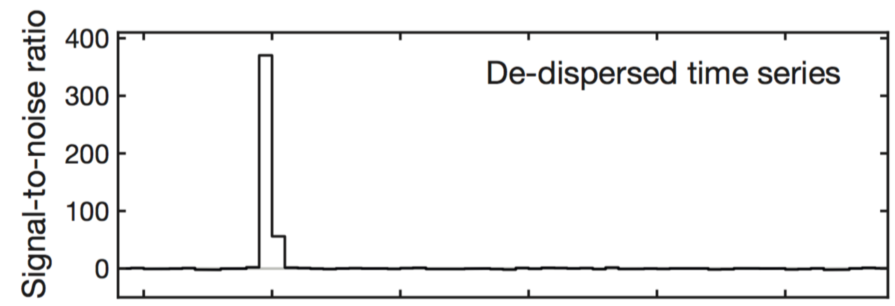
$$v_g = \frac{\partial \omega}{\partial k} = c\left(1 - \frac{\mu^2 c^2}{\omega^2}\right)^{1/2}$$

- Since massive photons with different energies have different velocities, one can use extragalactic sources to constrain the photon mass.

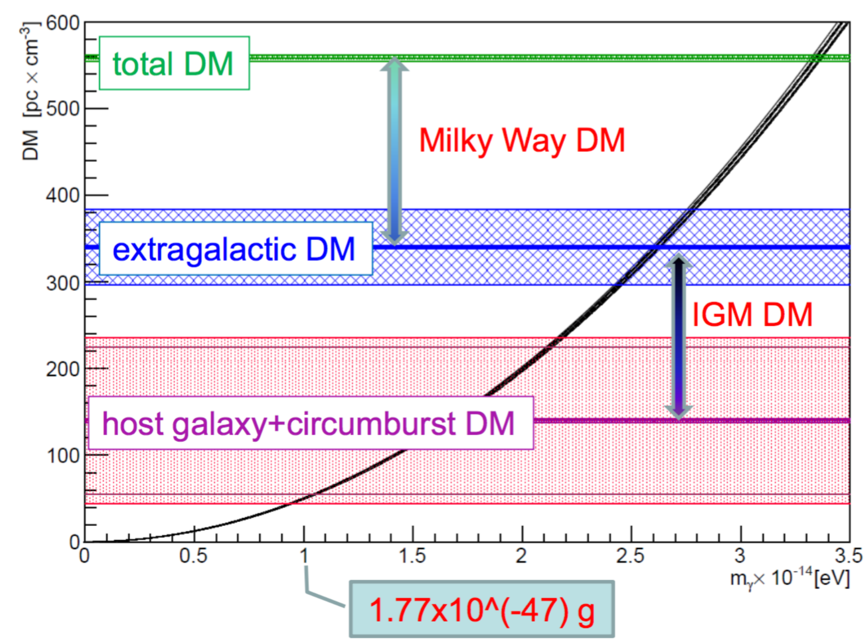
Constraint on photon mass using photons' delay time



Wu's report (2017)



Chatterjee et al. (2017)



Bonetti et al. (2017)

Lowest-frequency photons

$$\omega^2 = c^2k^2 + \mu^2c^2.$$

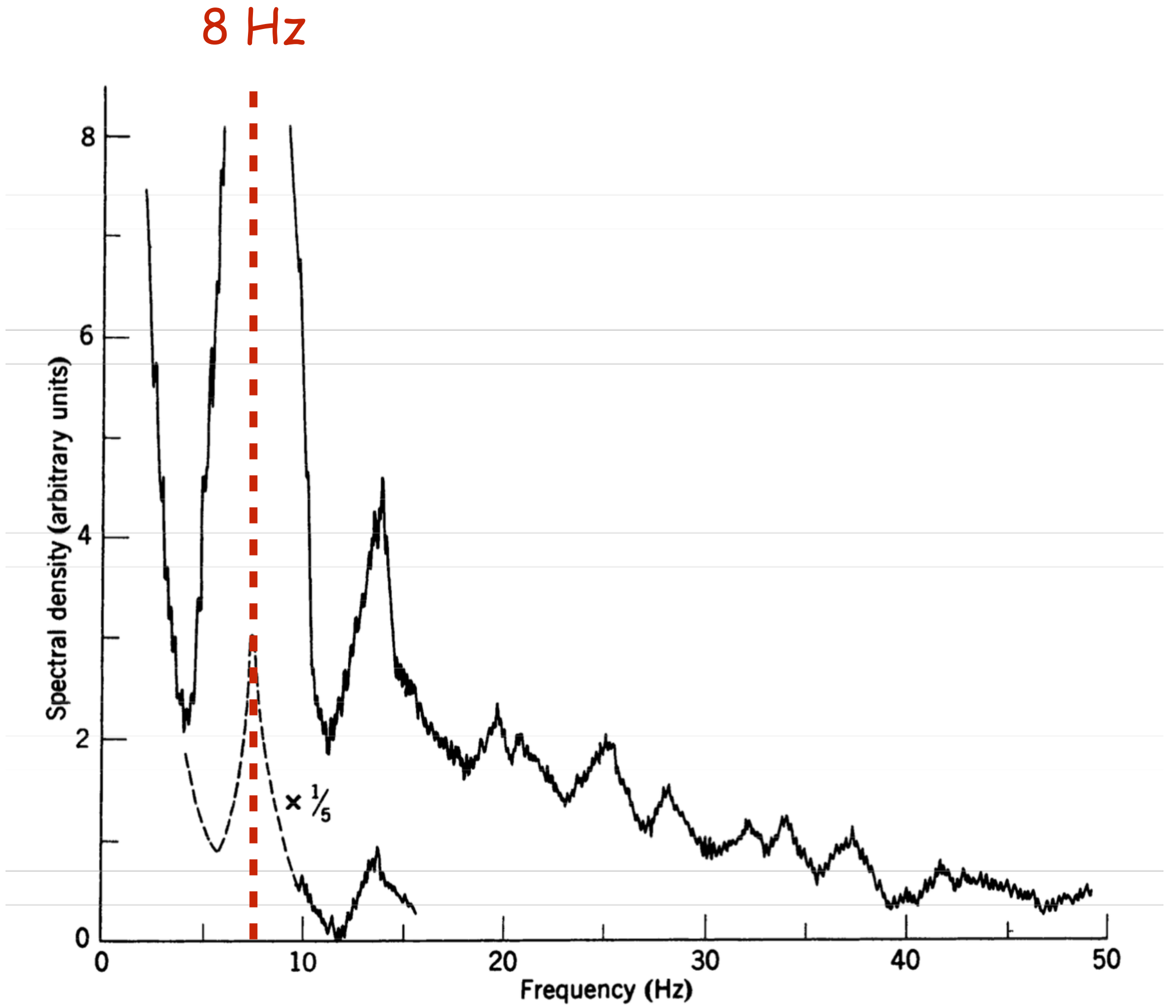
- One important requirement of the Energy-Momentum relation is that the frequency of the free electromagnetic wave must satisfy $\hbar\omega > m_\gamma c^2$
- One direct way to constrain the photon mass is to detect the electromagnetic wave at extremely low frequencies with $m_\gamma < h\nu/c^2 \simeq 7 \times 10^{-47}\ \mathrm{g}\ (\nu/10\ \mathrm{Hz})$

Schumann resonant

- A limit on photon mass can be set by noting the existence of very low frequency modes in earth-ionosphere resonant cavity, so-called Schumann resonant.

- The lowest one is 8 Hz. One has

$$m_\gamma < h\nu/c^2 \simeq 6 \times 10^{-47}\ \mathrm{g}$$



cite: Jackson's book

Massive Dipole Radiation

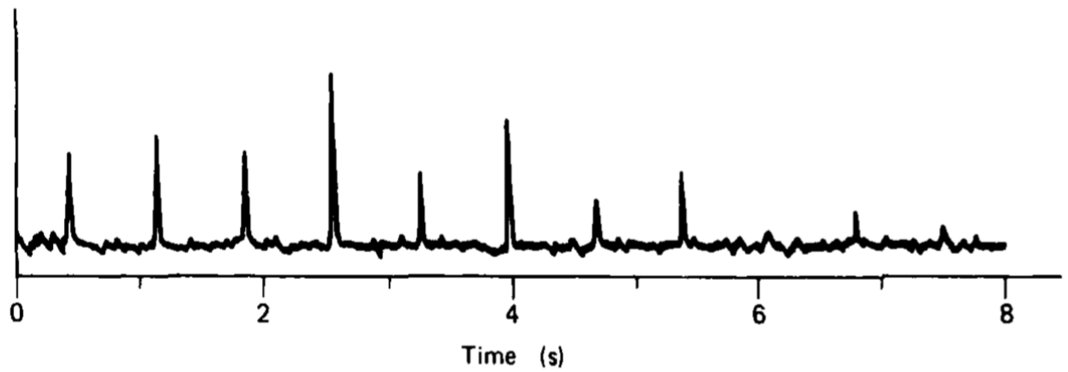
$$\omega^2 = c^2 k^2 + \mu^2 c^2.$$

- One possible method to study massive electrodynamics is through studying the modification of radiation mechanisms at such low frequencies.

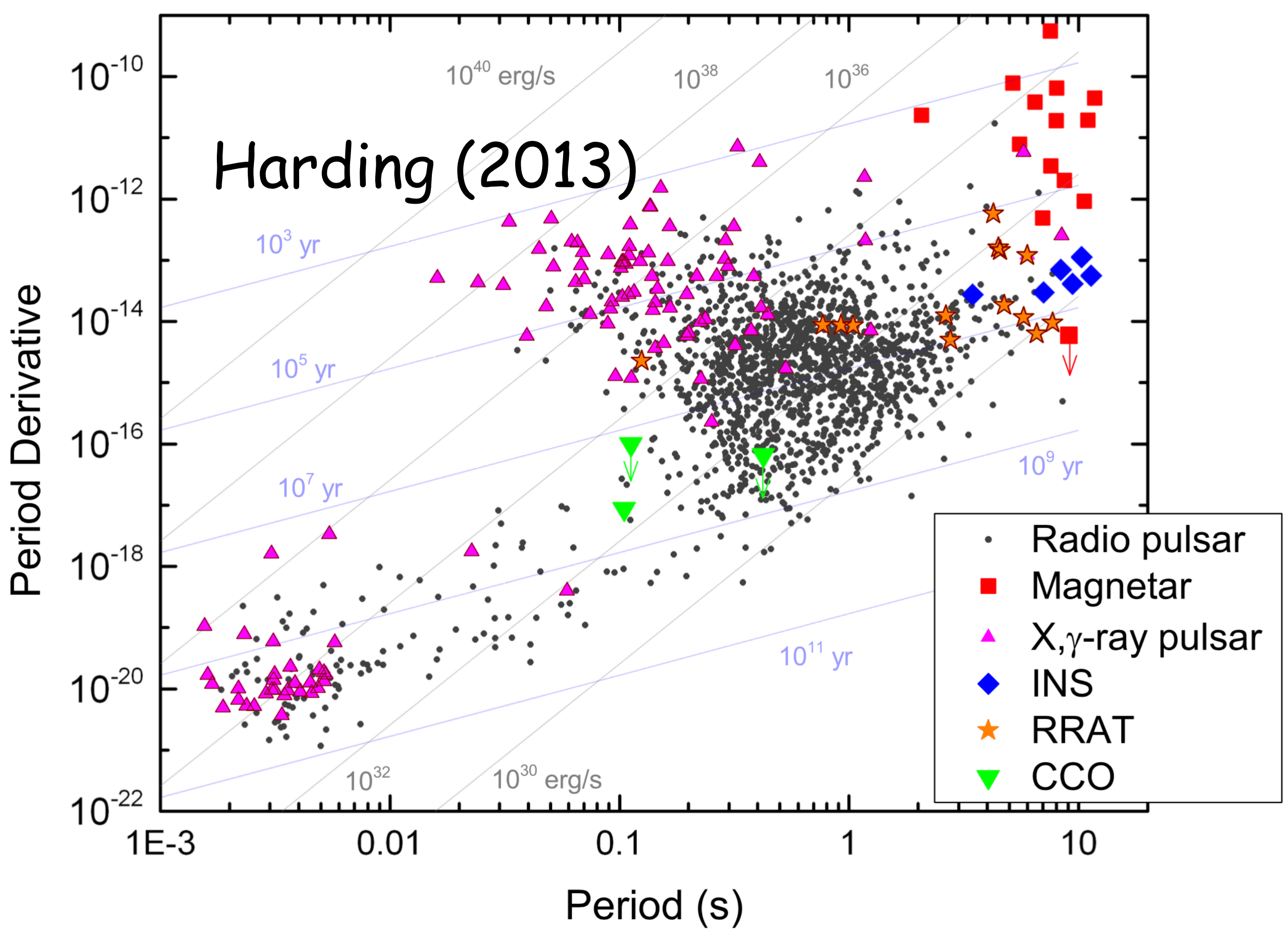
- We note that for the magnetic dipole radiation, the angular frequency of the electromagnetic wave is equal to the angular frequency of rotation, i.e. $\omega \sim \Omega$.

- **One natural question arises: what happens if $\Omega < \mu c$ for a magnetic dipole?**

Pulsar Spindown



Manchester et al. (1977)



Harding (2013)

Magnetic dipole radiation:

$$L_{\rm m} = -\frac{B_p^2 R^6 \Omega^4 \sin^2\theta}{6c^3}$$

Pulsar's spin-down power:

$$\dot{E} = I\Omega\dot{\Omega}$$

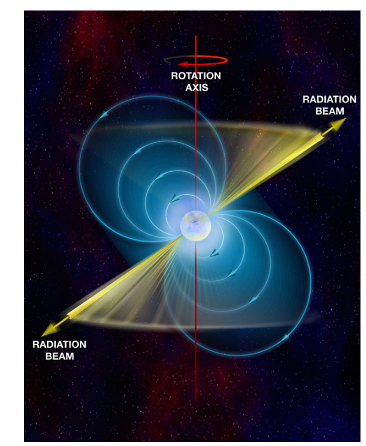
Magnetic field:

$$B_d = \left(\frac{3Ic^3 P\dot{P}}{2\pi^2 R^6}\right)^{1/2} \simeq 2\times 10^{12}{\rm G}\,(P\dot{P}_{15})^{1/2},$$

Magnetic Dipole radiation

- The total power radiated per by the oscillating dipole moment m is (Yang & Zhang, 2017)

$$L_m = \frac{m^2\Omega}{3}\left(\frac{\Omega^2}{c^2} - \mu^2\right)^{1/2}\left(\frac{\Omega^2}{c^2} + \frac{\mu^2}{2}\right)$$



- We define η to characterize the correction of non-zero photon mass effect,

$$\eta \equiv \frac{L_m}{L_{m,0}} = \left(1 - \frac{\mu^2 c^2}{\Omega^2}\right)^{1/2}\left(1 + \frac{\mu^2 c^2}{2\Omega^2}\right)$$

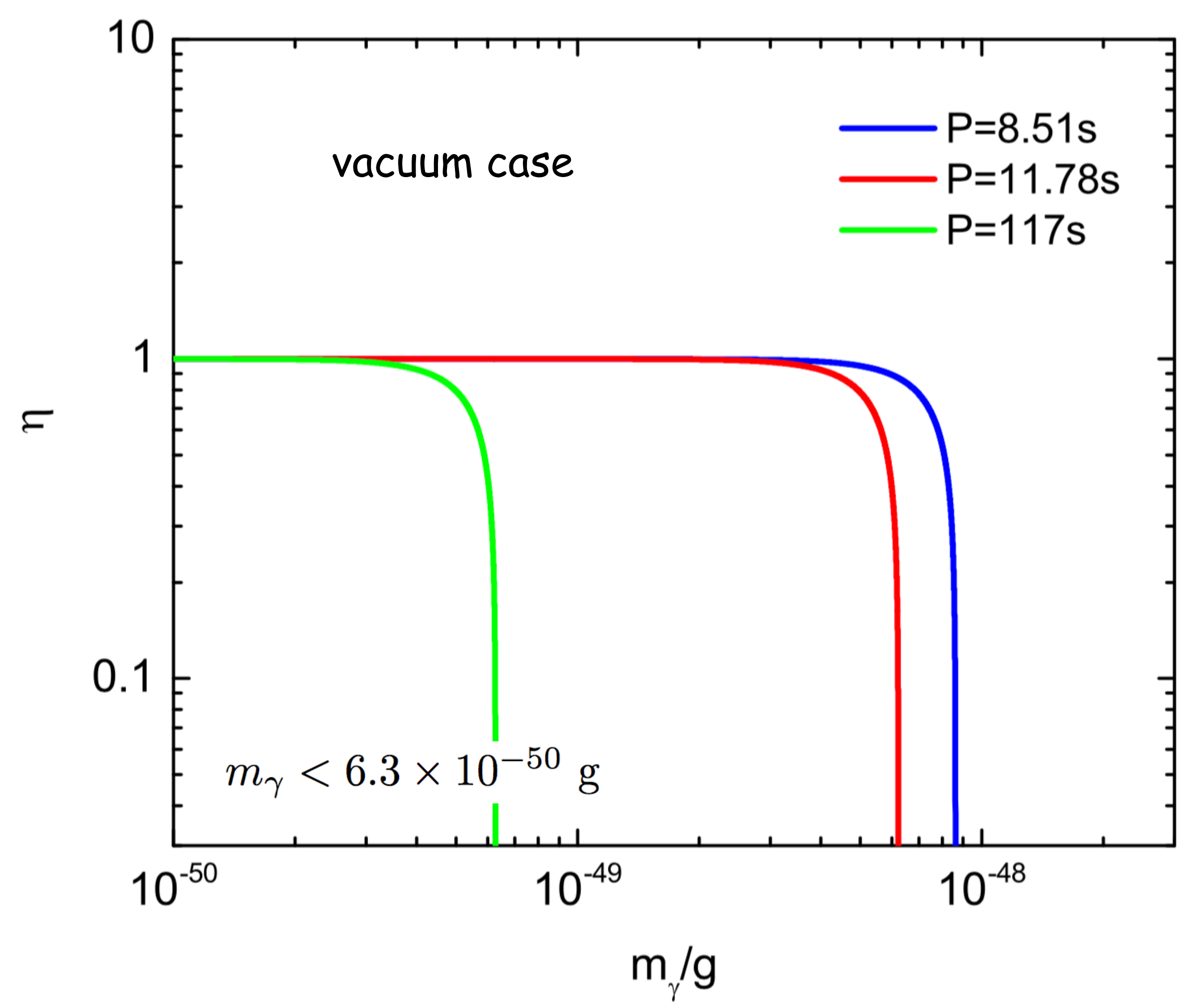
η-mγ relation

- one can see that, as long as η > 0, one has μ < Ω/c. A robust photon mass upper limit can be set to

$$m_\gamma < m_{\gamma,\rm crit} \equiv h/Pc^2,$$

- which is shown as the a sharp cut off. Essentially, this is the result of the standard energy-momentum relation,

$$\omega^2 = c^2k^2 + \mu^2c^2.$$



Yang & Zhang (2017)

Pulsar wind

- Goldreich-Julian density:

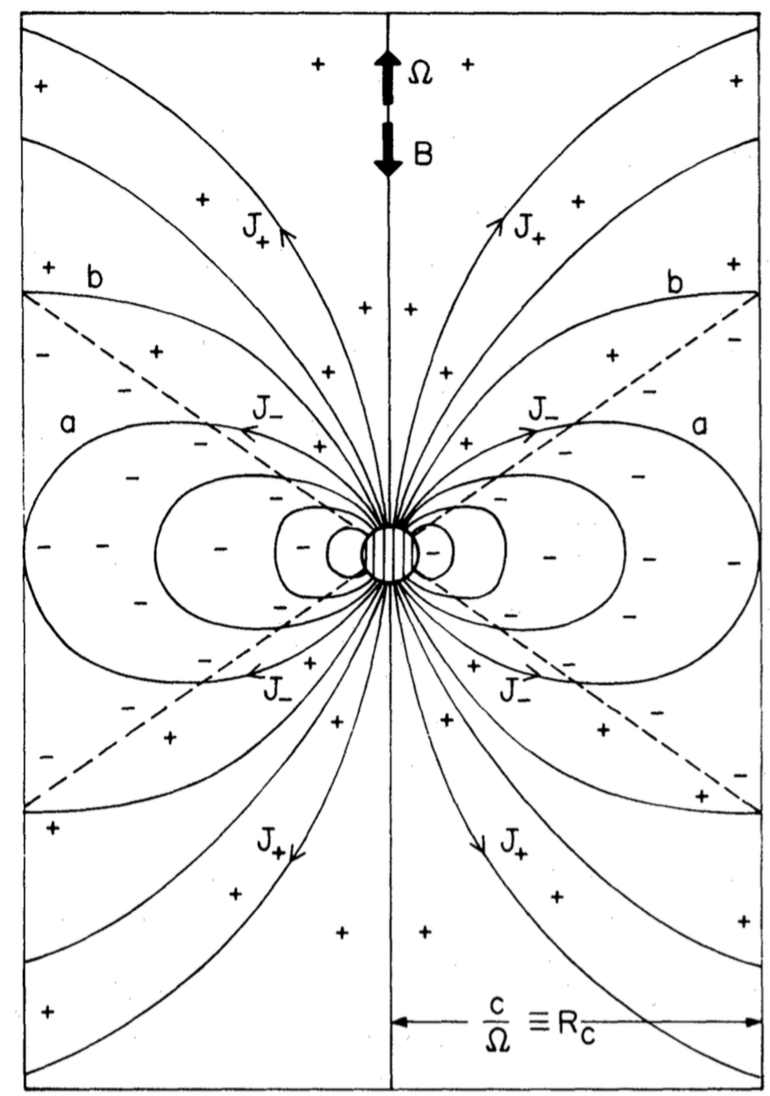
$$\rho_{\rm GJ} \simeq -\frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi c}$$

- The induced potential drop across the open field lines:

$$\Delta V \simeq \Omega r_p^2 B_p / 2c$$

- The wind power:

$$L_{\rm w} \simeq 2e\dot{N}\Delta V = \frac{\chi B_p^2 R^6 \Omega^4}{2c^3}$$



Ruderman & Sutherland (1975)

B-field

- B field equation (e.g. Tu et al. 2006):

exponential decay

$$\boldsymbol{B} = -\nabla \times \left(\boldsymbol{m} \times \nabla \frac{e^{-\mu r}}{r} \right) = [3\boldsymbol{n}(\boldsymbol{n}\cdot\boldsymbol{m}) - \boldsymbol{m}] \left(1 + \mu r + \frac{\mu^2 r^2}{3} \right) \frac{e^{-\mu r}}{r^3} \boxed{- \frac{2}{3}\mu^2 \boldsymbol{m} \frac{e^{-\mu r}}{r}}$$

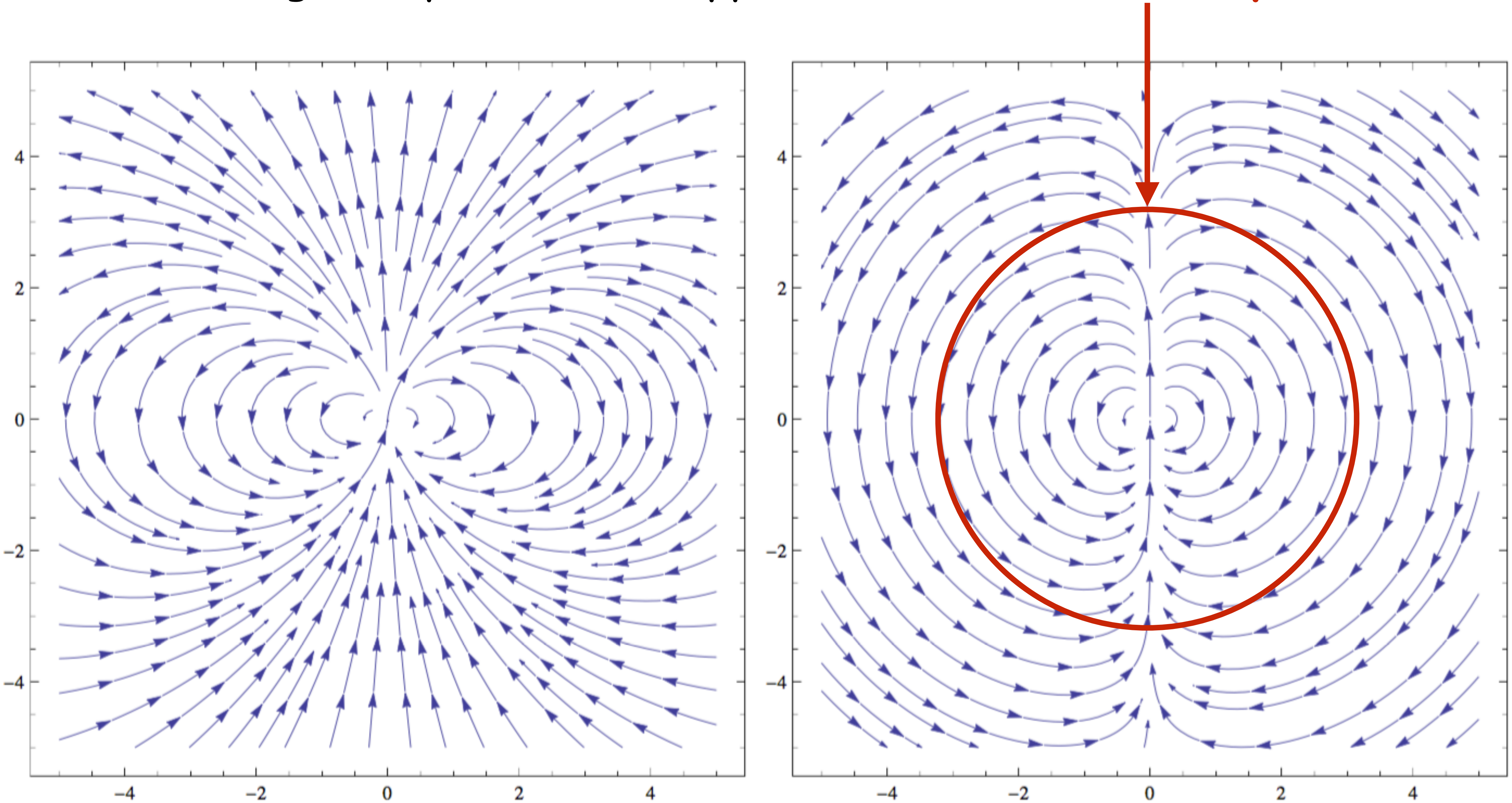
- the B-field appear as dipole angle distribution plus an apparently external magnetic field antiparallel **m**.

- The measurements of the earth magnetic field, both surface and out from the surface by the satellite observation, permit the best direct limits to be set on photon mass (method proposed by Schrodinger, 1943).

$$m_\gamma < 4 \times 10^{-48}\ \mathrm{g}$$

B-field lines

the magnetosphere would approach a **3-dimensional sphere**



Yang & Zhang (2017)

Field lines ➔ $L \sin^2 \theta = r e^{\mu r} / (1 + \mu r)$

Pulsar wind

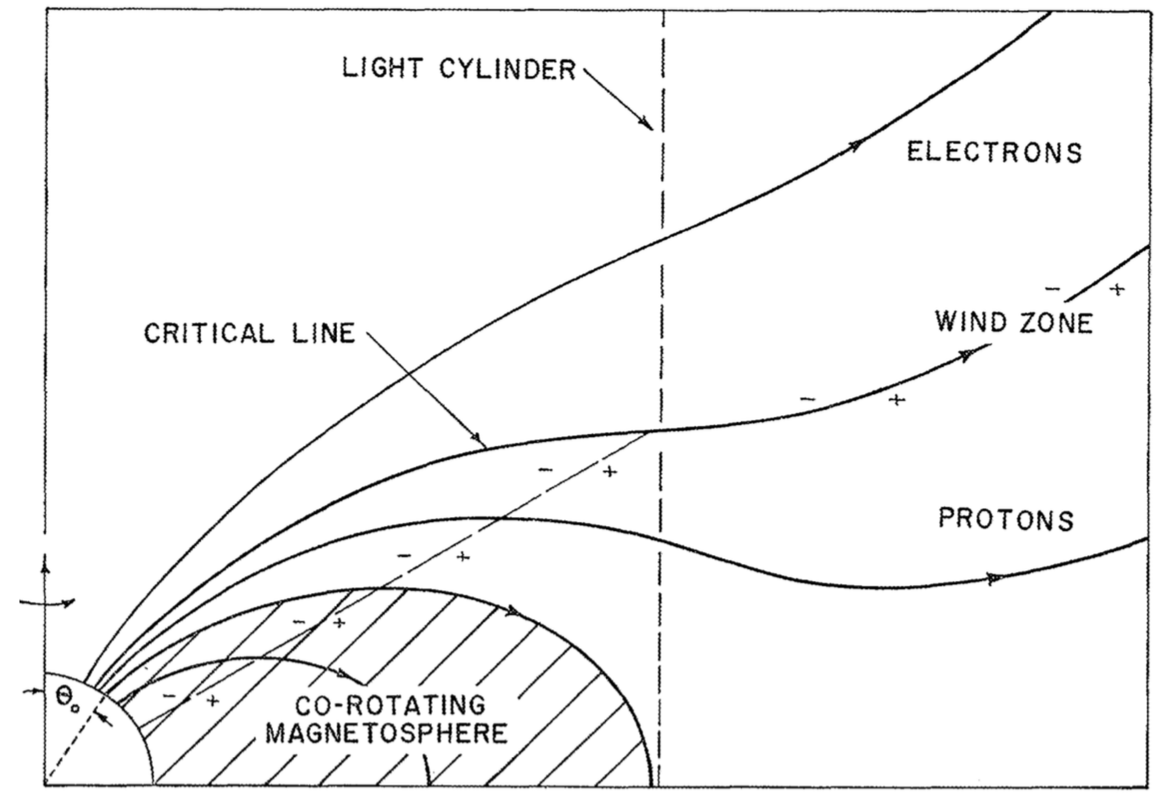
- New Goldreich-Julian density (Yang & Zhang, 2017)

$$\nabla^2 (\rho - \rho_{\rm GJ}) + \mu^2 \rho_{\rm GJ} = 0.$$

- Pulsar wind power

$$L_w \simeq 2e\dot{N}\Delta V = \xi^4 \frac{\chi \Omega^4 R^6 B_p^2}{2c^3} \equiv \eta L_{w,0},$$

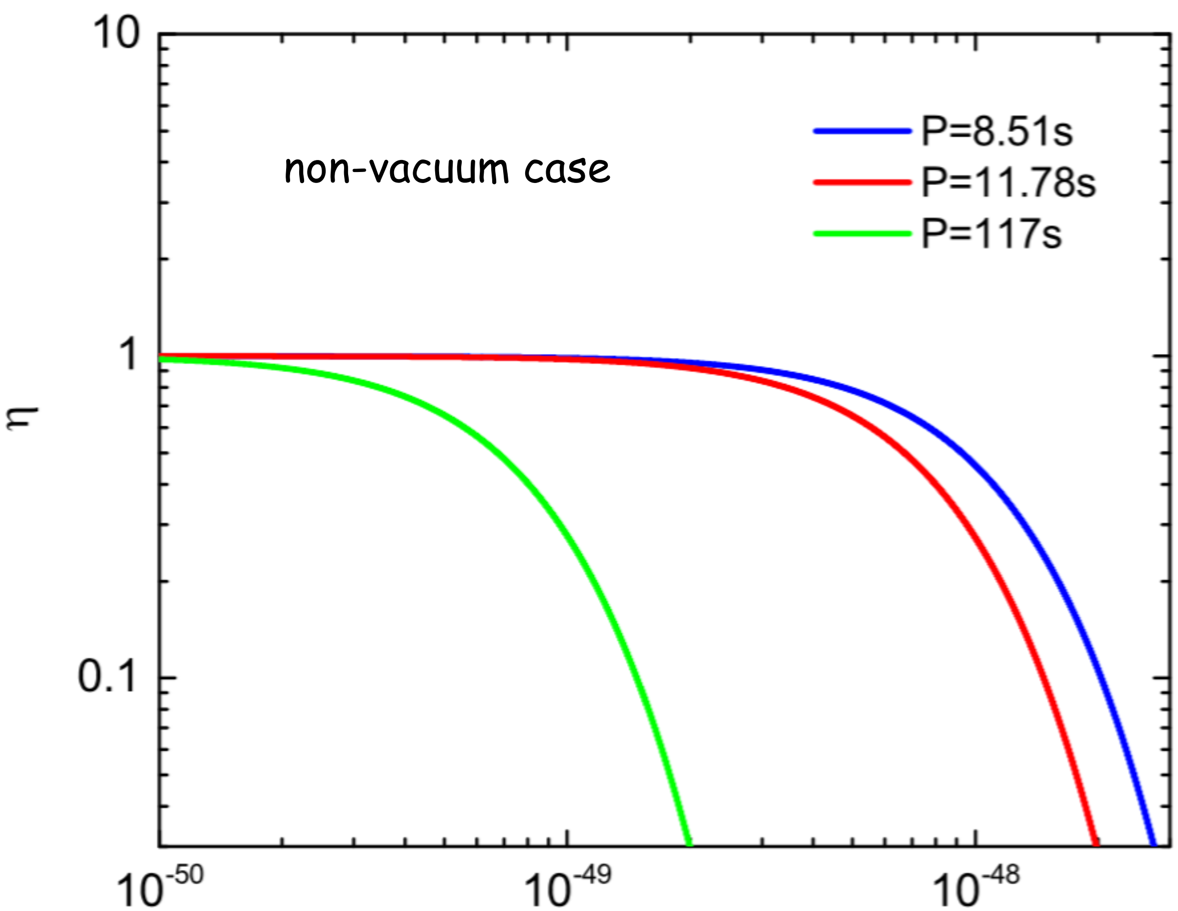
$$\eta = \left(1 + \frac{\mu c}{\Omega}\right)^2 e^{-2\mu c/\Omega}.$$

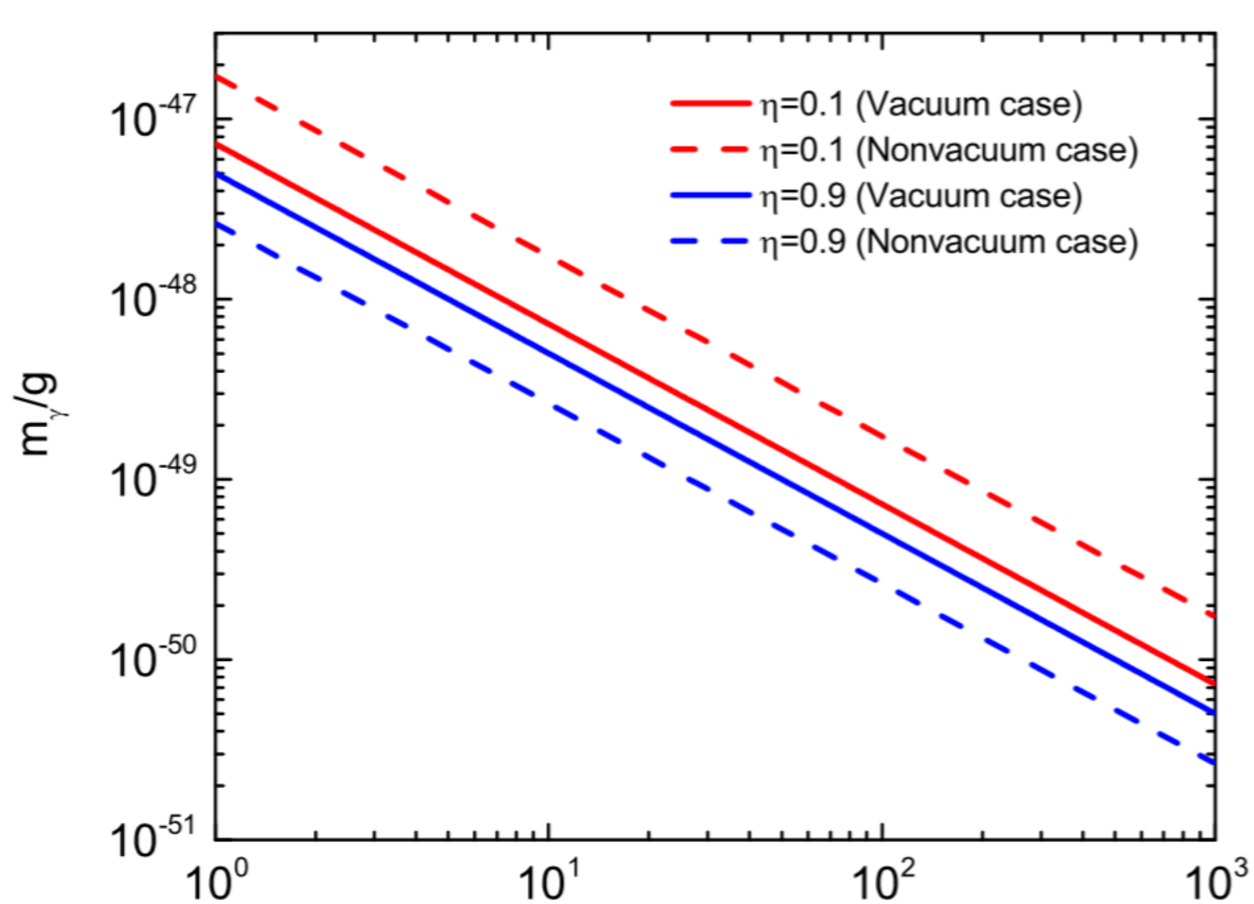


Goldreich & Julian (1969)

$$\rho_{\rm GJ} \equiv -\boldsymbol{\Omega} \cdot \boldsymbol{B} / 2\pi c$$

Constraints on Photon mass





Upper Limits of the Photon Mass

Sources	Period / s	$m_\gamma/10^{-49}$ g in vacuum case				$m_\gamma/10^{-49}$ g in nonvacuum case		
		$\eta > 0$	$\eta > 0.1$	$\eta > 0.5$	$\eta > 0.9$	$\eta > 0.1$	$\eta > 0.5$	$\eta > 0.9$
PSR J2144−3933	8.51	$< m_{\gamma,\rm crit} = 8.6$	<8.5	<8.1	<5.9	<20.3	<9.3	<3.1
1ES 1841−045	11.78	$< m_{\gamma,\rm crit} = 6.2$	<6.2	<5.8	<4.2	<14.7	<6.7	<2.2
WD in AR Scorpii	117	$< m_{\gamma,\rm crit} = 0.63$	<0.62	<0.59	<0.43	<1.48	<0.67	<0.22

Yang & Zhang (2017)

Results

- For the WD pulsar in AR Scorpii with P = 117 s
  - vacuum dipole spindown: $m_\gamma < 6.3 \times 10^{-50}$ g
  - wind spindown: $m_\gamma < 9.6 \times 10^{-50}$ g
- Still valid to order of magnitude for **multipole**
- We strongly urge further observations to **magnetized WD** to detect their spindown behavior and to measure their magnetic field strength independently.

Test EEP

RAPID COMMUNICATIONS

PHYSICAL REVIEW D **94,** 101501(R) (2016)

Testing Einstein's weak equivalence principle with a 0.4-nanosecond giant pulse of the Crab pulsar

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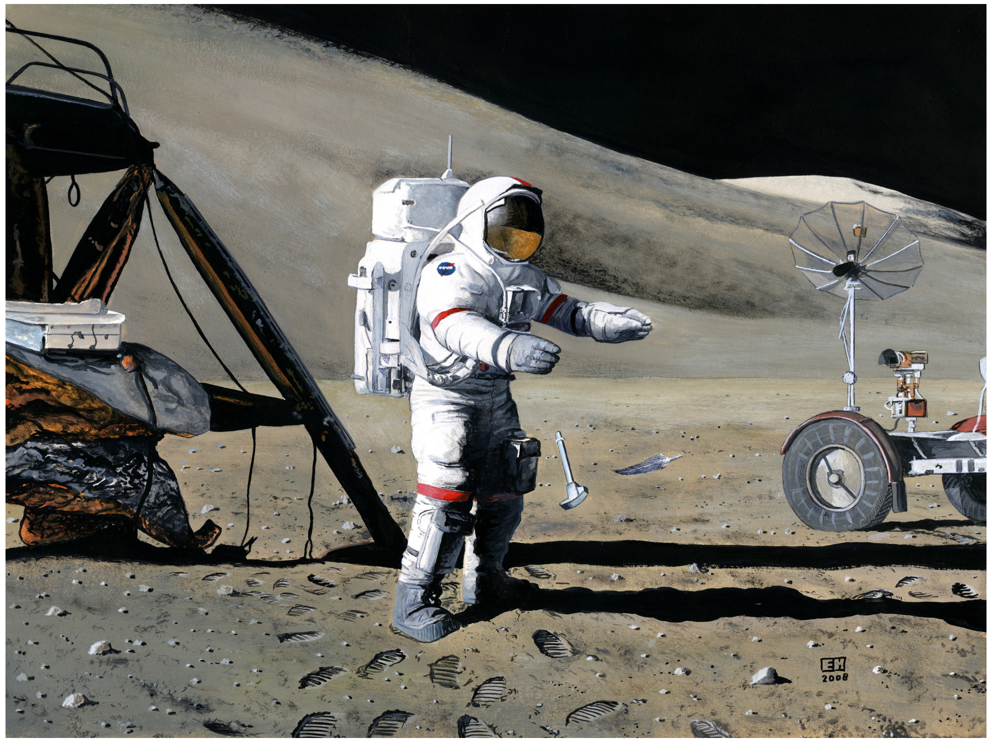
Einstein's weak equivalence principle (EEP) can be tested through the arrival time delay between photons with different frequencies. Assuming that the arrival time delay is solely caused by the gravitational potential of the Milky Way, we show that a "nano-shot" giant pulse with a time delay between energies corrected for all known effects, e.g., $\Delta t < 0.4$ ns, from the Crab pulsar poses a new upper limit on the deviation from the EEP, i.e., $\Delta\gamma < (0.6\text{–}1.8) \times 10^{-15}$. This result provides the hitherto most stringent constraint on the EEP, improving by at least 2 to 3 orders of magnitude from the previous results based on fast radio bursts.

DOI: 10.1103/PhysRevD.94.101501

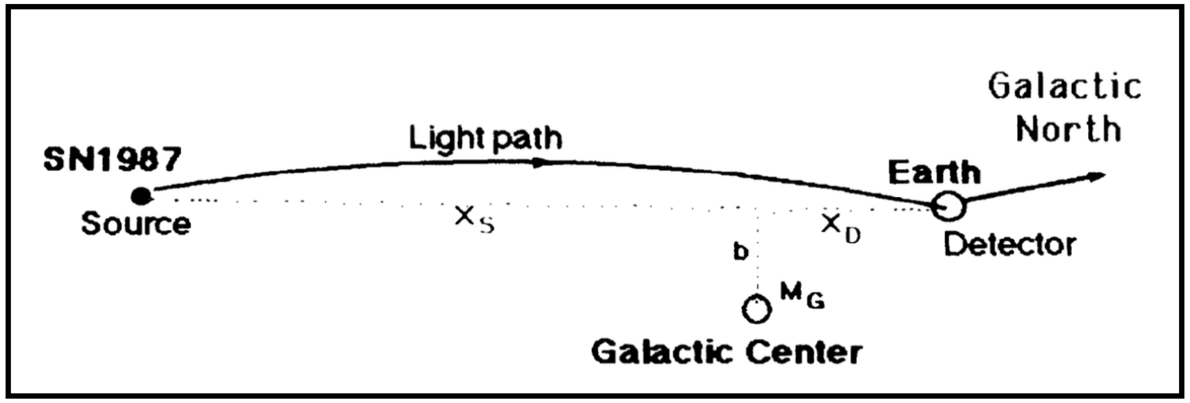
Einstein's weak equivalence

- **The trajectory of a point mass in a gravitational field depends only on its initial position and velocity, and is independent of its composition and structure.**



Test EEP

- Applying the **arrival time delay** to measure the **difference of the γ values** for photons with different energies, or for different species of cosmic messengers.



- The relative Shapiro time delay is given by

$$\Delta t_{\mathrm{gra}} = \frac{\gamma_1 - \gamma_2}{c^3} \int_{r_o}^{r_e} U(r) dr.$$ under Schwarzschild metric

Current Results

TABLE III. The upper limits of the γ discrepancy given by previous works and our work

Source name	Test particles and energy bands	Upper limit of γ	Reference
SN 1987A	photon(eV) - neutrino(MeV)	0.37%	[4]
SN 1987A	neutrino(7.5 MeV) - neutrino(40 MeV)	1.6×10^{-6}	[4]
GRB 090510	photon(GeV) - photon(MeV)	2×10^{-8}	[5]
GRB 080319B	photon(eV) - photon(Mev)	1.2×10^{-7}	[5]
FRB 110220	photon(1.2 GHz) - photon(1.5 GHZ)	2.52×10^{-8}	[6]
GRB 100704A	photon(1.23 GHZ) - photon(1.45 GHz)	4.36×10^{-9}	[6]
Mrk 421	photon(Tev) - photon(keV)	3.86×10^{-3}	[7]
PKS 2155-304	photon(0.2-0.8 TeV) - photon($>$ 0.8 TeV)	2.18×10^{-6}	[7]

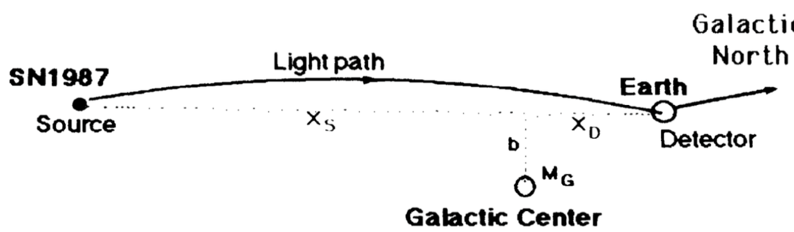
Table 3
The Upper Limits of the γ Discrepancy Given By This Work and Previous Works

Source Name	Test Particles and Energy Bands	Upper Limit of $\Delta\gamma$	$E_{\rm high}/E_{\rm low}$	Reference
Crab Pulsar	photon(radio)–photon(optical)	2.63×10^{-9}	$\sim 10^5$	Equation (9)
Crab Pulsar	photon(radio)–photon(X-ray)	4.01×10^{-9}	$\sim 10^9$	Equation (10)
Crab Pulsar	photon(radio)–photon(γ-ray)	3.28×10^{-9}	$\sim 10^{13}$	Equation (11)
Crab Pulsar	photon(optical)–photon(γ-ray)	3.03×10^{-10}	$\sim 10^8$	Equation (12)
GRB 080319B	photon(eV)–photon(MeV)	$2.3 \times 10^{-10}(3\sigma)$ $1.3 \times 10^{-11}(2\sigma)$	10^6	Nusser (2016)
Crab Pulsar (giant pulse)	photon(8.15 GHz)–photon(10.35 GHz)	$(0.6\text{–}1.8) \times 10^{-15}$	~ 1.2	Yang & Zhang (2016)

Zhang & Gong (2017)

Need extragalactic sources?

- Delay time between two photons



$$\Delta t_{\rm gra} = \frac{\gamma_1 - \gamma_2}{c^3} \int_{r_o}^{r_e} U(r) dr.$$

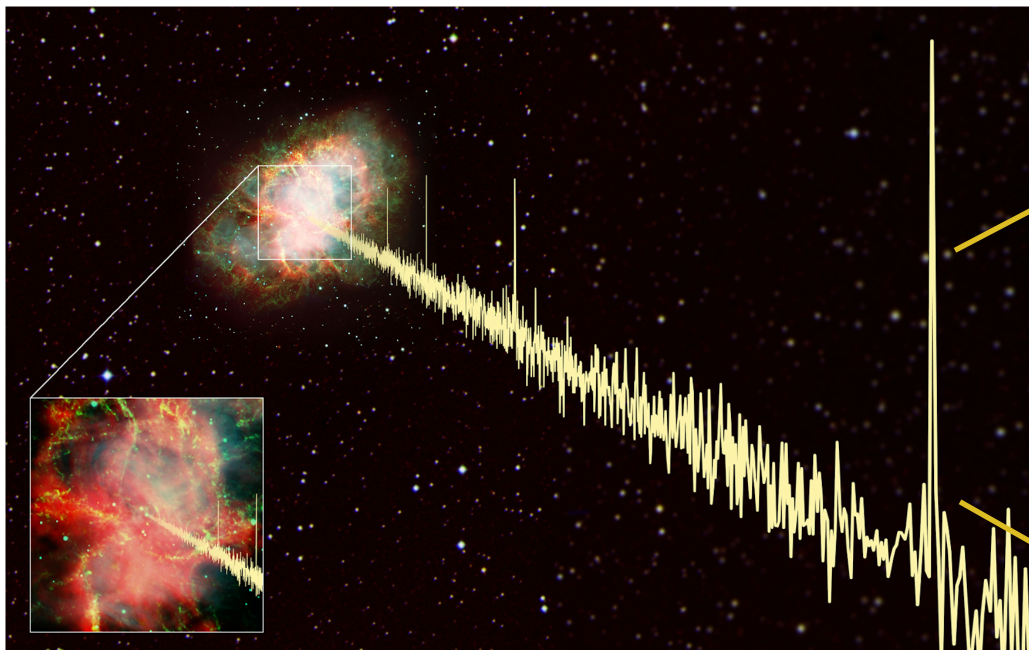
$$= \Delta\gamma \frac{G M_{\rm MW}}{c^3} \boxed{\ln\left(\frac{d}{b}\right)}$$

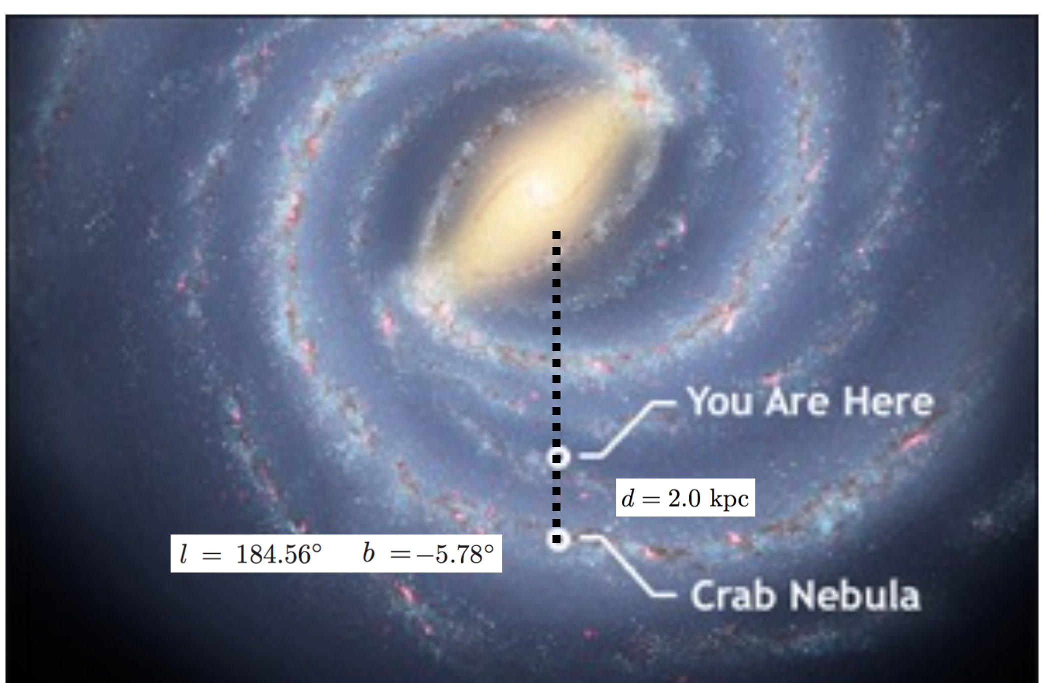
d → Distance to source

b → Impact distance

From kpc to Gpc, the upper limit of $\Delta\gamma$ is only improved six times!!

Crab Giant Pulse





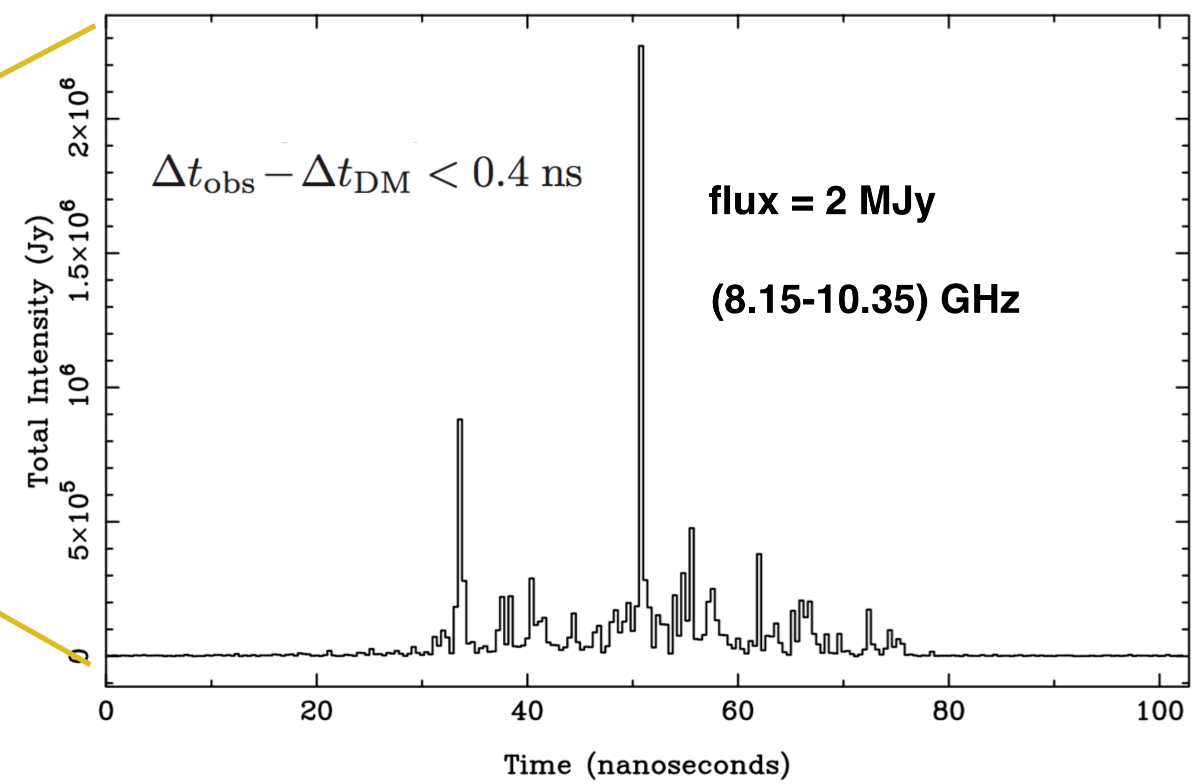


FIG. 5.—Single MP recorded at 9.25 GHz center frequency over a 2.2 GHz bandwidth and optimally dedispersed. The nanopulse shown is unresolved with the 0.4 ns time resolution afforded by our system. Despite the high peak intensity of this pulse, it is unlikely that it saturated the data acquisition system. The dispersion sweep time across the bandwidth is about 1.5 ms, so as sampled by our data acquisition system, the dispersed pulse energy is spread over $\approx 7.5 \times 10^6$ samples.

. Hankins & Eilek, 2007, ApJ

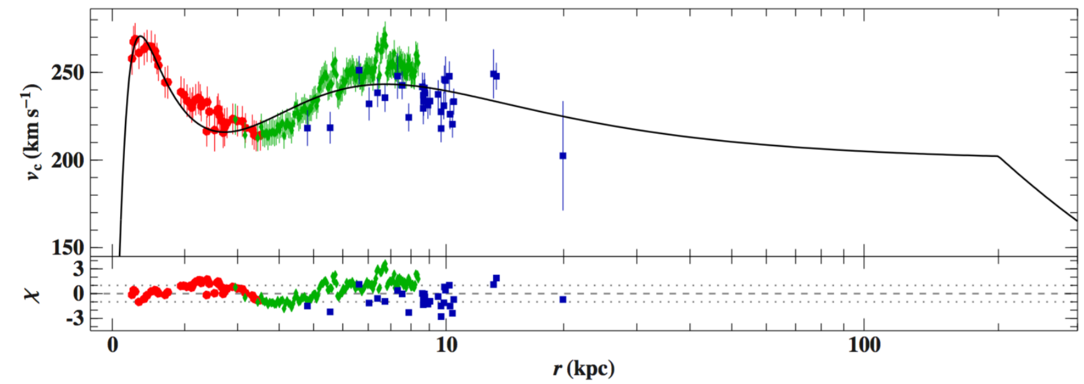
Most Stringent Constraint using MW potential

- Gravitational potential

$$U(r) = U_{\rm MW}(r) + U_{\rm Crab}(r)$$

$$U_{\rm Crab}(x) = -GM/x,$$

Irrgang et al. 2013



- One therefore has

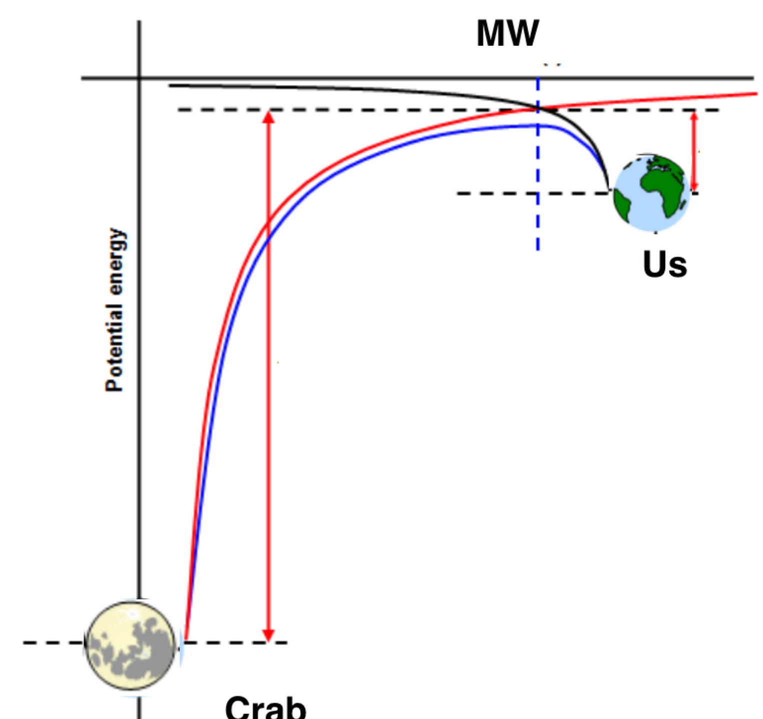
$U_{\rm MW}(r) \simeq -(1-3)\times 10^{15}\ {\rm cm^2 s^{-2}}$ at $r \simeq 8-11$ kpc

$$\Delta\gamma \equiv |\gamma_1(10.35\ {\rm GHz}) - \gamma_2(8.15\ {\rm GHz})|$$

$$< c^3(\Delta t_{\rm obs} - \Delta t_{\rm DM})\left(|U_{\rm MW}|d + GM\ln\frac{d}{x_e}\right)^{-1}$$

$$\simeq (0.6-1.8)\times 10^{-15}$$

$\Delta\gamma < 4.5\times 10^{-11}$	$\Delta\gamma < 1.4\times 10^{-13}$
FRB 110220	FRB 150418



Conclusions

- Pulsars are excellent probes of fundamental physics
  - Photon mass: Pulsars with longest periods
  - EEP: Pulsars with narrowest pulses

Thank You!