Ultralight particle radiation from compact stars and the effect of neutrinos

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Neutrino Frontiers

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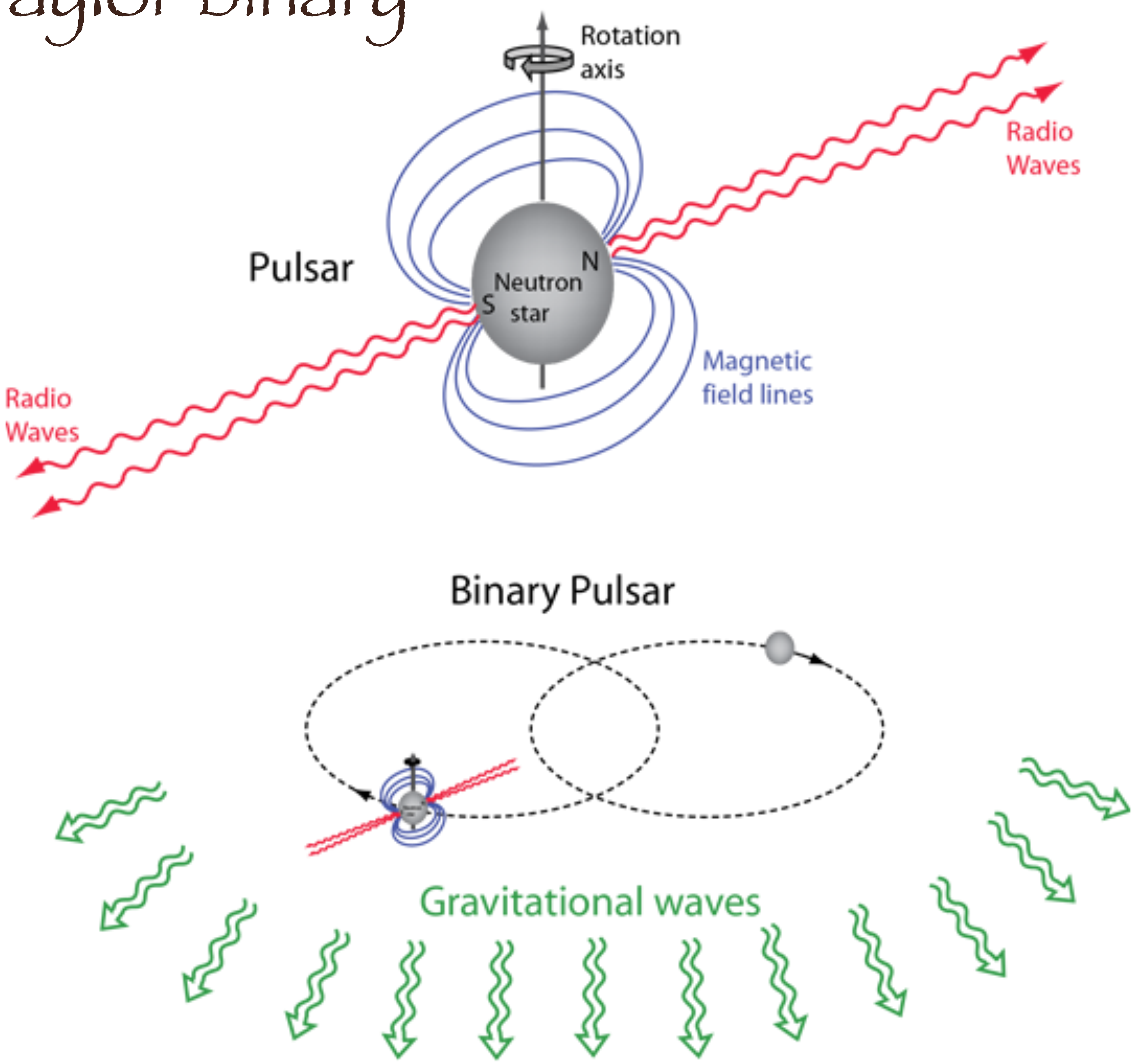
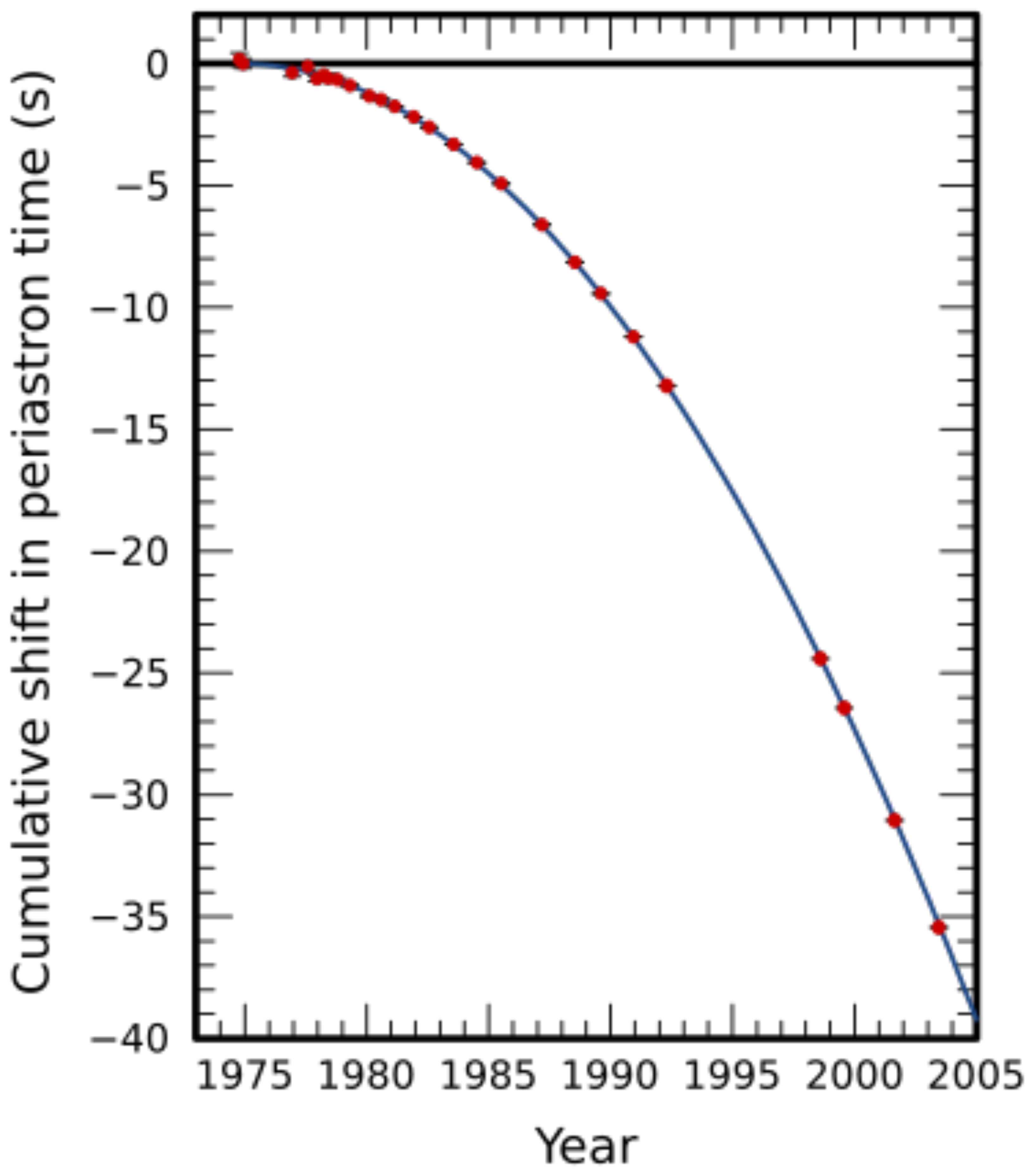
Istituto Nazionale di Fisica Nucleare

Orbital period loss of binary systems

Hulse-Taylor binary

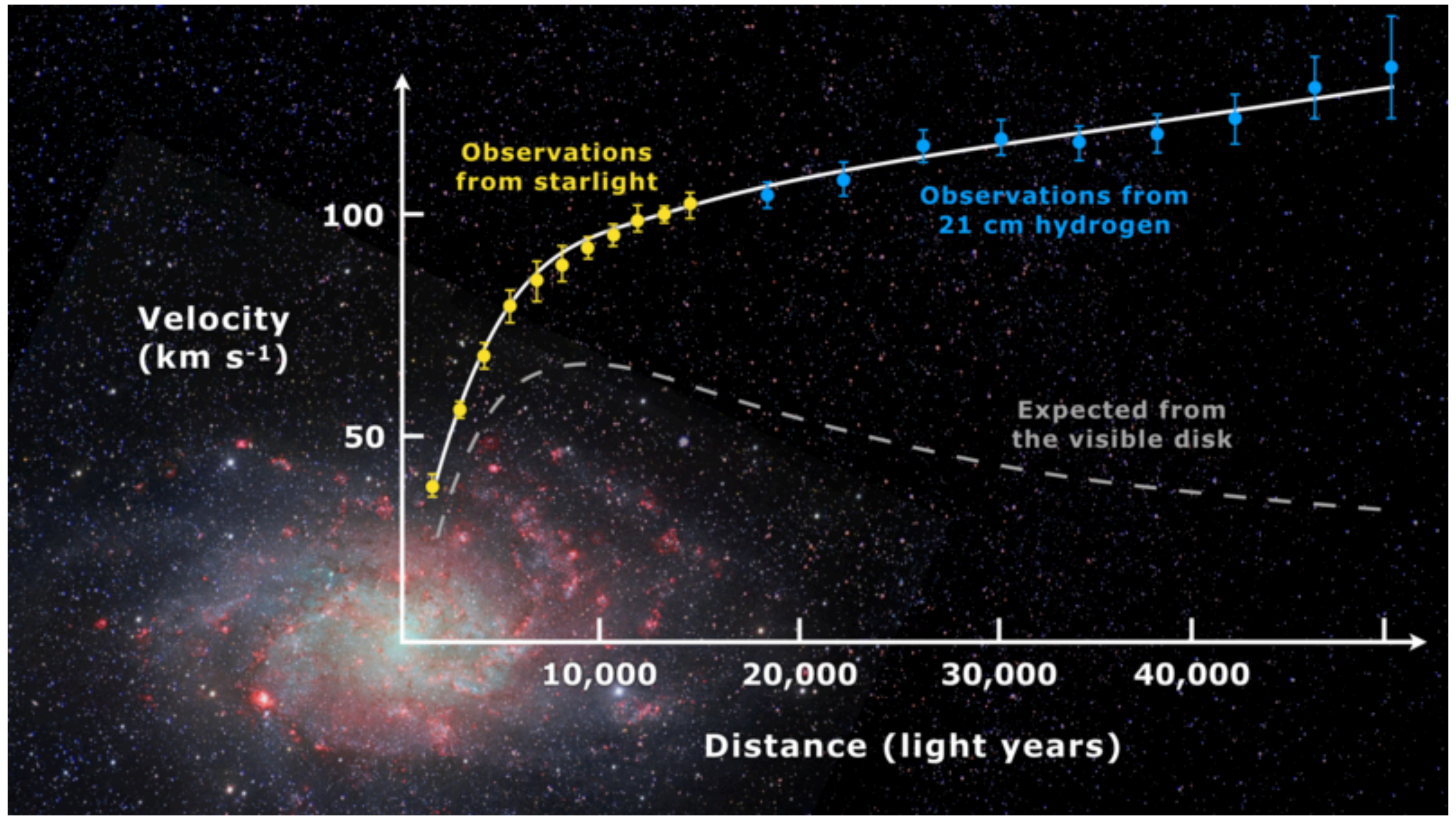


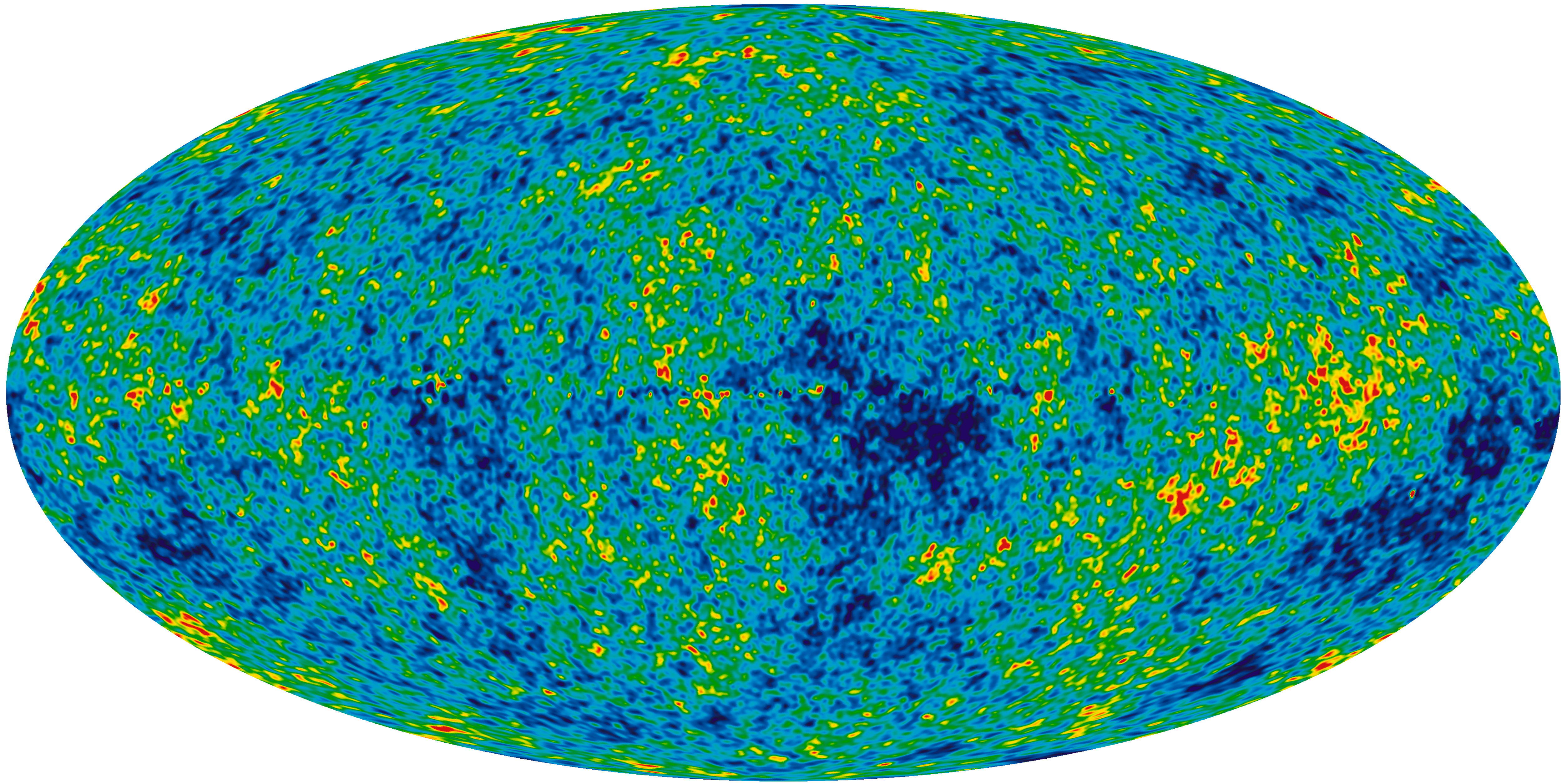


$P_b \sim 8\text{h}, \ \ \Omega \sim 10^{-19}$ eV   ballpark for FDM

arXiv: astro-ph/0407149

Dark matter signatures





Images credit: wikipedia

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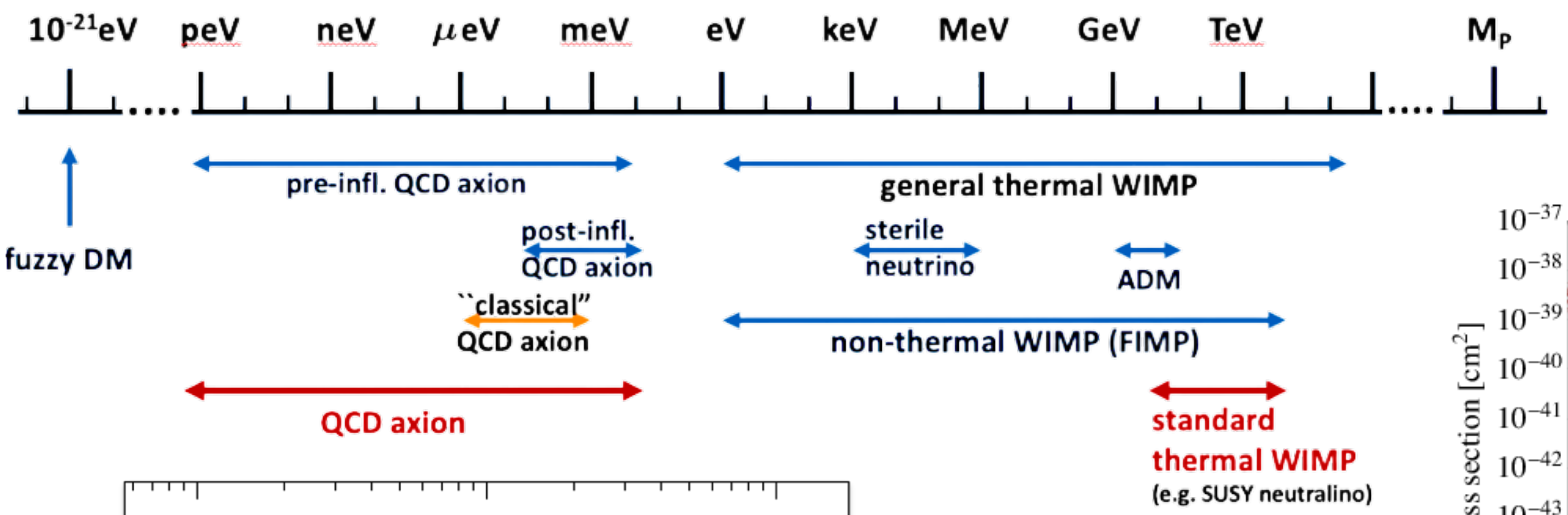
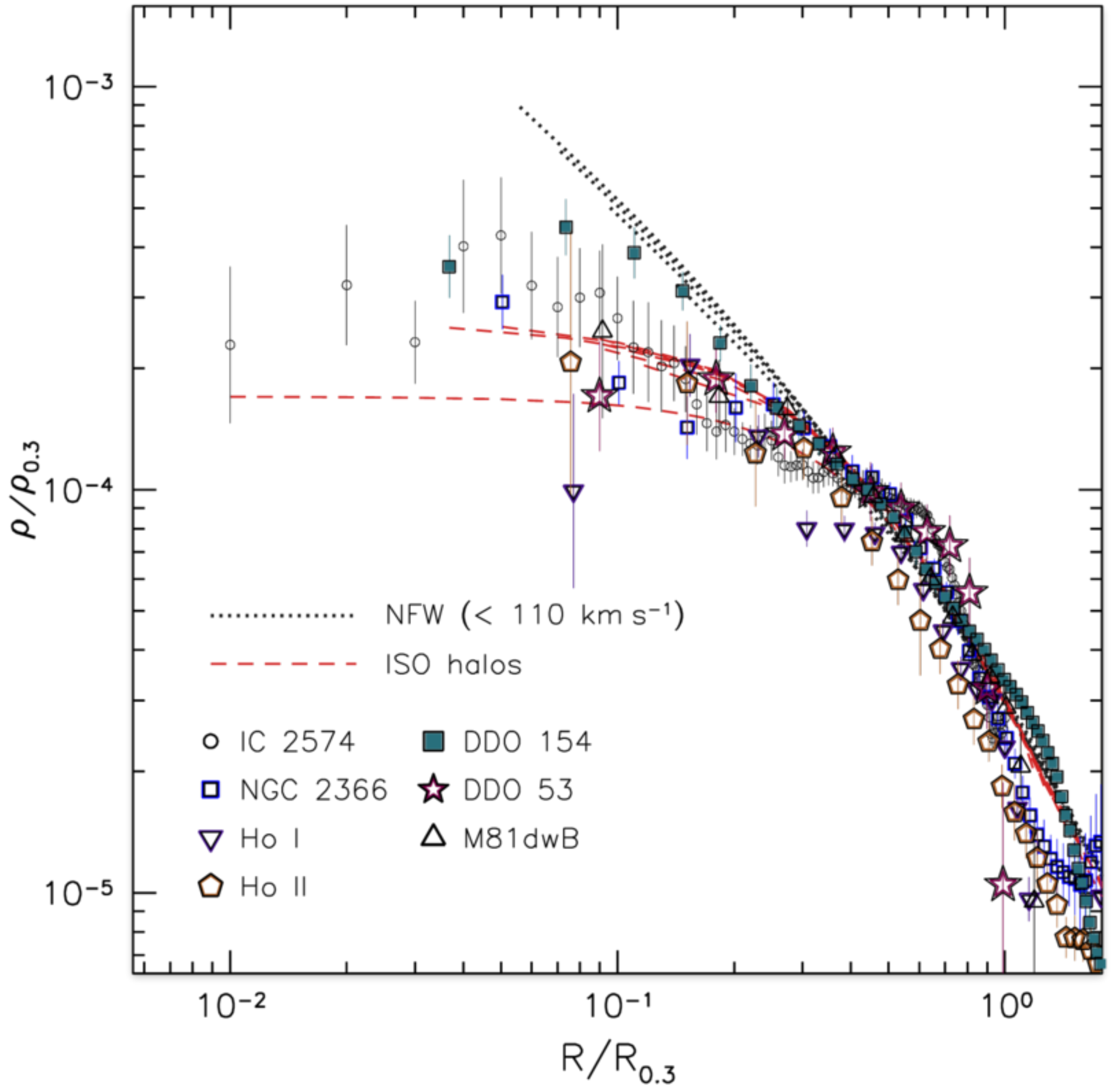
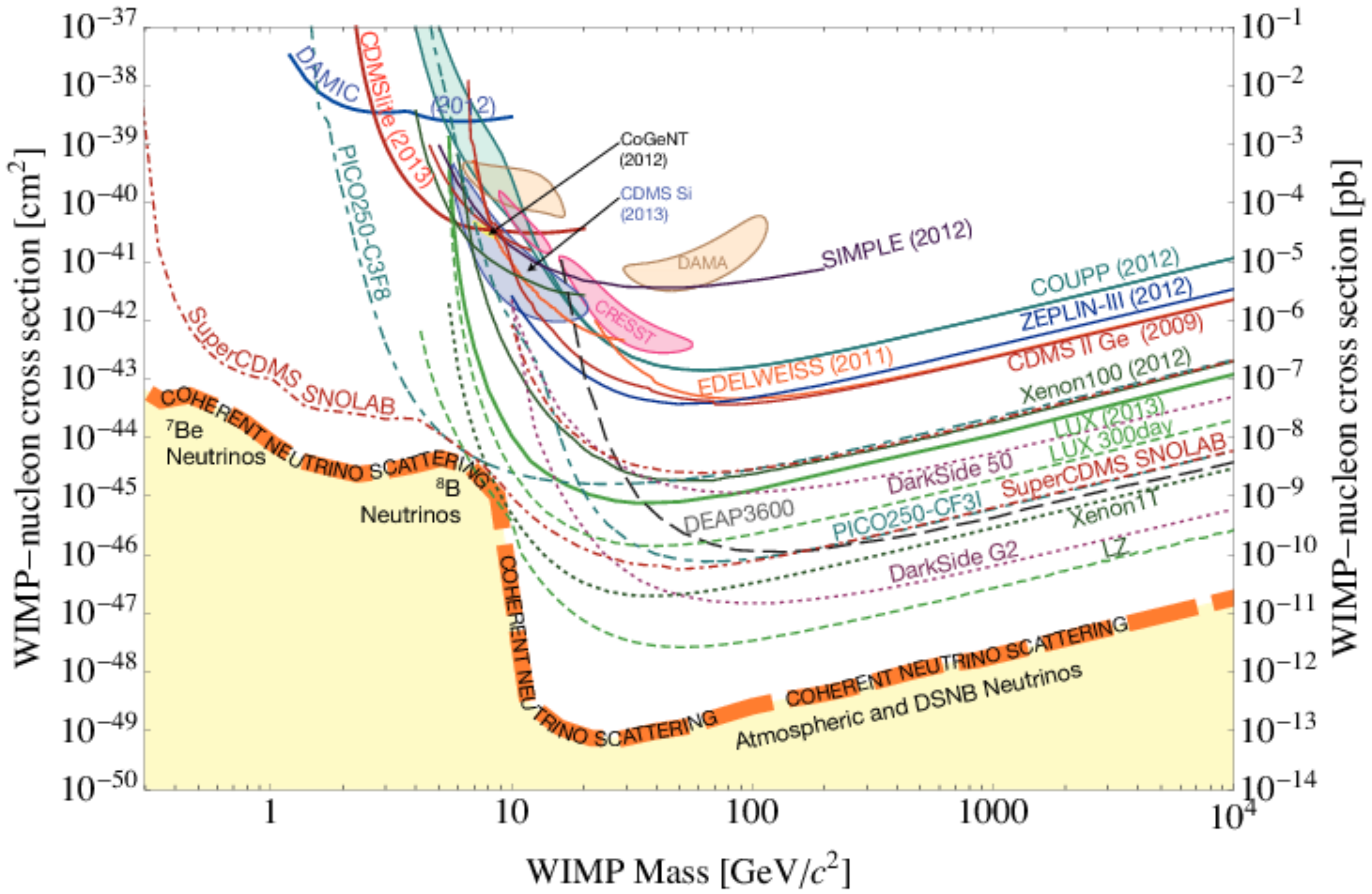






Problems with WIMPs

The Astronomical Journal, 141:193 (45pp), 2011 June

Phys.Rev.D 89 (2014)2,023524

Fuzzy Dark Matter

de Broglie wavelength ~ size of a dwarf galaxy

$$\frac{\lambda}{2\pi} = \frac{\hbar}{m_a v} = 1.92\mathrm{kpc}\left(\frac{10^{-22}\mathrm{eV}}{\mathrm{m_a}}\right)\left(\frac{10\mathrm{km/s}}{\mathrm{v}}\right)$$

$$\rho_\odot \sim 0.4\ \mathrm{GeV/cm^3},\ \mathrm{n_{DM}} \sim 10^{30}/\mathrm{cm^3},\ \mathrm{m_{DM}} \sim 10^{-22}\ \mathrm{eV}$$

$$V(a) = \mu^4\left(1 - cos\left(\frac{a}{f_A}\right)\right)$$ PNGB

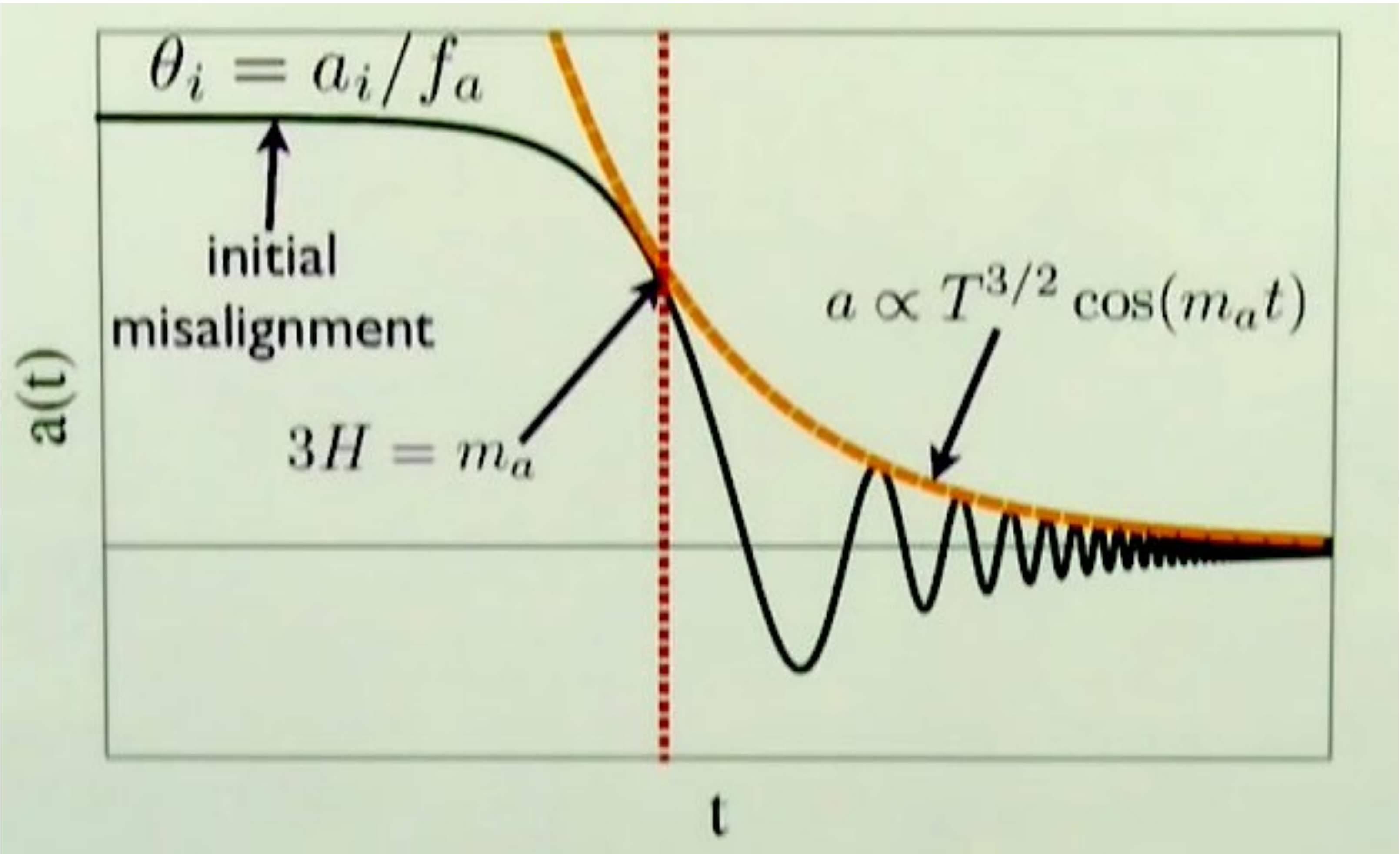
$$m_a^2 = \frac{\mu^4}{f_a^2}$$ Mass

Phys . Rev.Lett. 85 (2000)1158-1161

Phys.Rev.D 95, 043541 (2017)

EOM

$$\ddot{a}_k + 3H\dot{a}_k + m_a^2 a_k = 0$$



Slide from B. Safdi

Oscillation starts at $H \sim m_a$

$T \sim 500$ eV, $m_a \sim 10^{-22}$ eV

Late time energy density $\rho \sim m_a^2 a^2$

So at the late time the axion field redshifts like a cold dark matter

$$\Omega_{DM} \sim 0.12\left(\frac{a_0}{10^{17}GeV}\right)^2\left(\frac{m_a}{10^{-22}eV}\right)^{\frac{1}{2}}$$

L. Hui et al, Phys. Rev. D 95,043541

Motivation of FDM

- Constraints from dark matter direct detection experiments
- Solve small scale structure problems of the universe

Muon content in NS

One can construct three combinations of Lepton numbers in an anomaly-free way

Three gauge symmetries

$$L_e - L_\mu, \quad L_e - L_\tau, \quad L_\mu - L_\tau$$

beta stability demands the muon decay is Pauli blocked

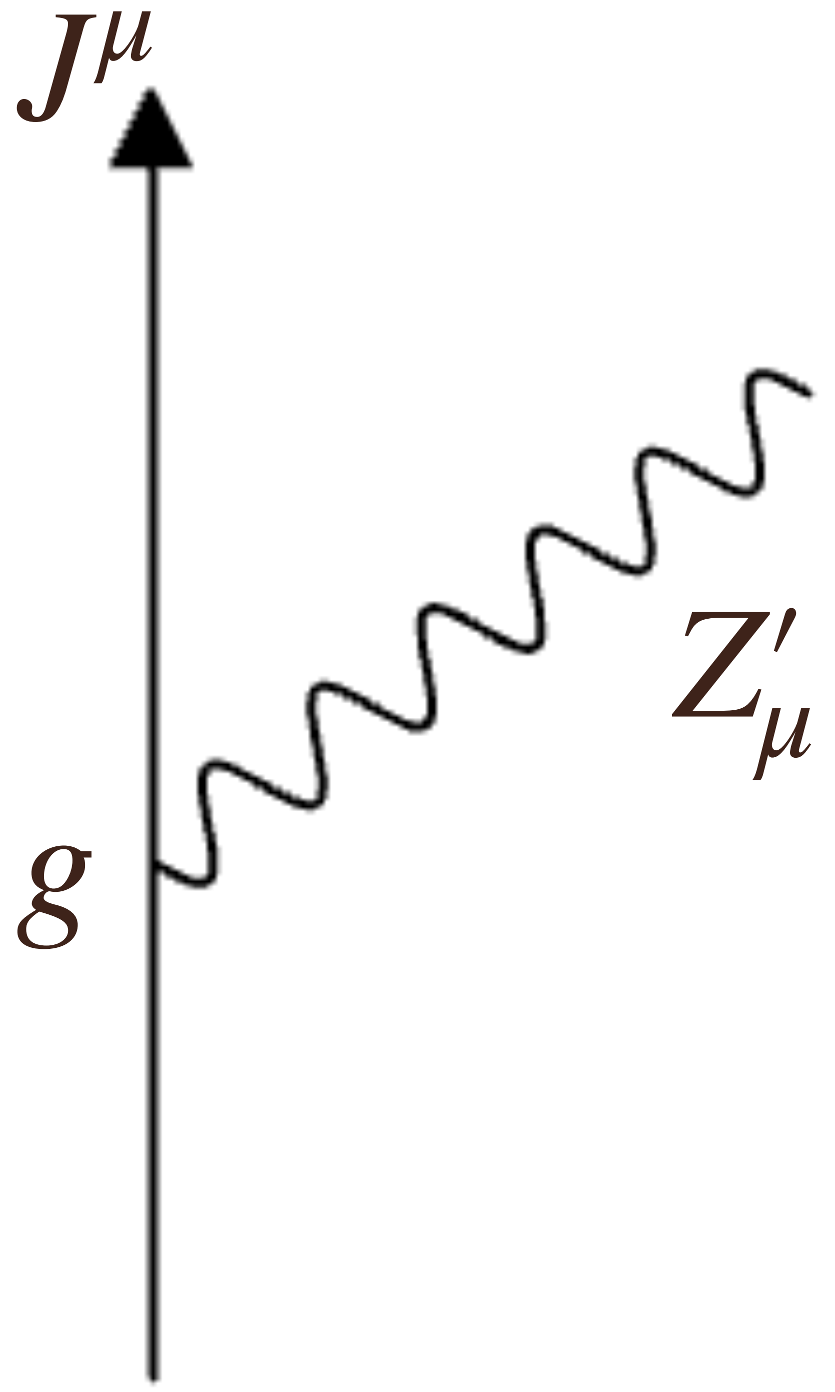
$$N_\mu \approx 10^{55}$$

Garani, Heeck, Phys Rev D 100, 035039 (2019)

Energy loss due to the radiation of vector field coupled with Muons

The interaction Lagrangian

$$\mathscr{L} \supset g Z'_{\mu} J^{\mu}$$



Rate of massive Z' boson radiation

$$d\Gamma = g^2 \sum_{\lambda=1}^{3} [J^{\mu}(k')J^{\nu *}(k')\epsilon_{\mu}^{\lambda}(k)\epsilon_{\nu}^{\lambda *}(k)] 2\pi\delta(\omega - \omega')\frac{d^3k}{(2\pi)^3 2\omega}$$

The polarization sum is

$$\sum_{\lambda=1}^{3} \epsilon_{\mu}^{\lambda}(k)\epsilon_{\nu}^{\lambda *}(k) = -g_{\mu\nu} + \frac{k_{\mu}k_{\nu}}{M_{Z'}^2}$$

Contd…

Rate of energy loss

$$\frac{dE}{dt} = \frac{g^2}{2\pi}\int\Big[-|J^0(\omega')|^2 + |J^i(\omega')|^2 + \frac{\omega^2}{M_{Z'}^2}|J^0(\omega')|^2 + \frac{\omega^2}{3M_{Z'}^2}|J^i(\omega')|^2\Big(1-\frac{M_{Z'}^2}{\omega^2}\Big)\Big]$$

$$\times\,\delta(\omega-\omega')\omega^2\Big(1-\frac{M_{Z'}^2}{\omega^2}\Big)^{\frac{1}{2}}d\omega$$

Fundamental frequency

$$\Omega = G\Big(\frac{m_1+m_2}{a^3}\Big)^{\frac{1}{2}}$$

The current density for the binary system

$$J^\mu(x) = \sum_{a=1,2} Q_a\delta^3(\mathrm{x}-\mathrm{x}_a(t))u_a^\mu$$

The Keplerian orbit in the $x-y$ plane can be parametrized as

$$x = a(\cos\xi - e),\quad y = a\sqrt{1-e^2}\sin\xi,\quad \Omega t = \xi - e\sin\xi$$

Contd...

Sum over the harmonics $n\Omega$ of the fundamental mode

The velocities in the Fourier space

$$\dot{x}_n = -ia\Omega J'_n(ne), \quad \dot{y}_n = \frac{a\sqrt{1-e^2}\Omega}{e} J_n(ne)$$

The components of the current

$$|J^i(\omega')|^2 = a^2\Omega^2 M^2 \left(\frac{Q_1}{m_1} - \frac{Q_2}{m_2}\right)^2 \left[J_n'^2(ne) + \frac{(1-e^2)}{e^2} J_n^2(ne)\right]$$

$$|J^0(\omega)|^2 = \frac{1}{3} a^2 M^2 \Omega^2 \left(1 - \frac{M_{Z'}^2}{n^2\Omega^2}\right) \left(\frac{Q_1}{m_1} - \frac{Q_2}{m_2}\right)^2 \left(J_n'^2(ne) + \frac{1-e^2}{e^2} J_n^2(ne)\right)$$

Contd…

Energy loss due to $L_\mu - L_\tau$ vector gauge boson radiation

$$\frac{dE}{dt} = \frac{g^2}{6\pi}a^2M^2\left(\frac{Q_1}{m_1} - \frac{Q_2}{m_2}\right)^2\Omega^4 \sum_{n>n_0} 2n^2\left[J_n'^2(ne) + \frac{(1-e^2)}{e^2}J_n^2(ne)\right]\left(1 - \frac{n_0^2}{n^2}\right)^{\frac{1}{2}}\left(1 + \frac{1}{2}\frac{n_0^2}{n^2}\right)$$

$\frac{dE}{dt} \neq 0$ for non-zero charge to mass asymmetry of the binary stars

$\frac{dE}{dt} \propto \Omega^4$ The radiation is dipolar

Radiation happens for $n\Omega > M_{Z'}$

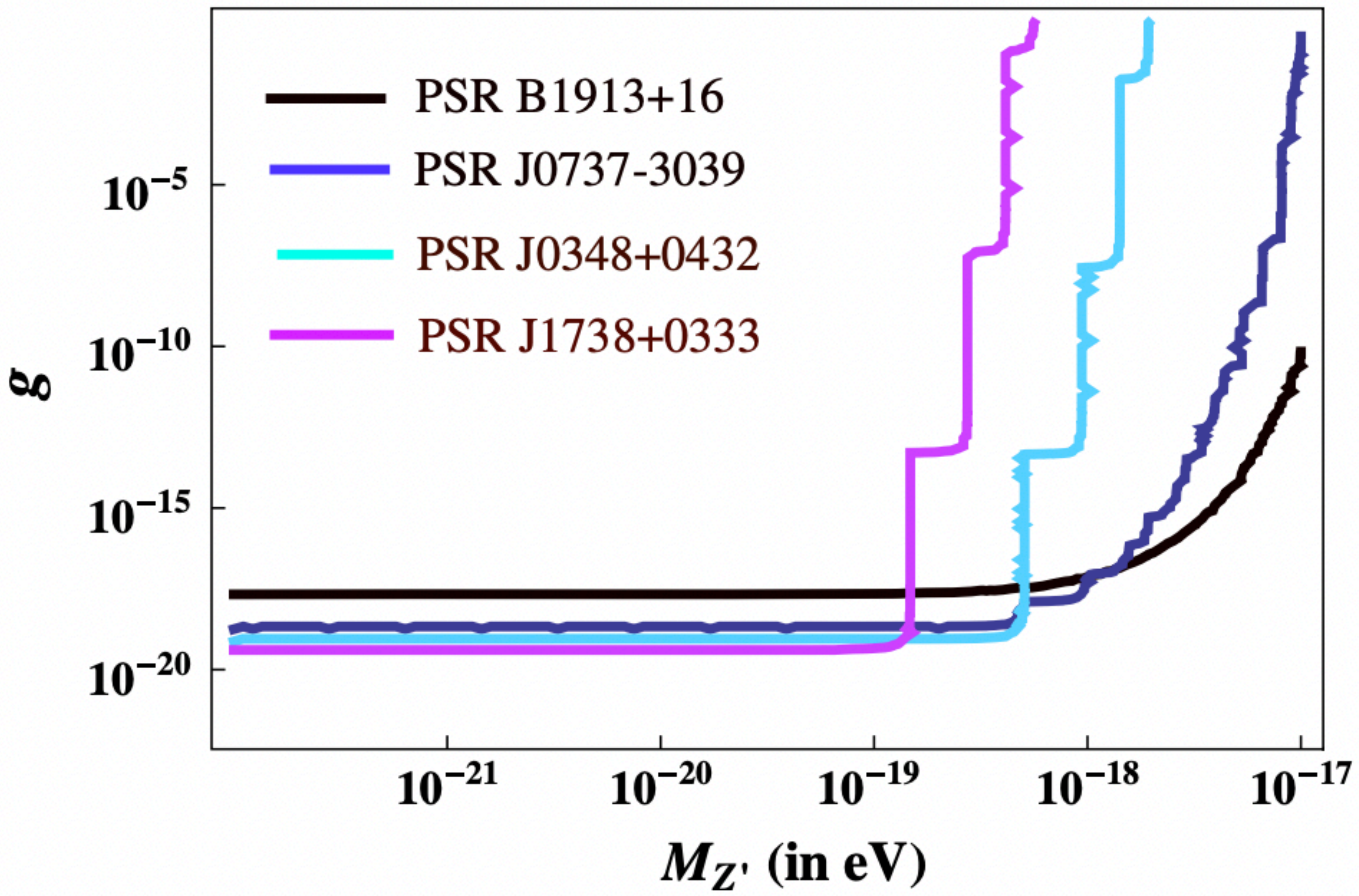
Compare with rate of energy loss due to GW

$$\frac{dE_{GW}}{dt} = \frac{32}{5}G\Omega^6M^2a^4(1-e^2)^{-7/2}\left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)$$

Orbital period loss

$$\frac{dP_b}{dt} = -6\pi G^{-3/2}(m_1 m_2)^{-1}(m_1 + m_2)^{-1/2} a^{5/2}\left(\frac{dE}{dt} + \frac{dE_{GW}}{dt}\right)$$

Compact binary system	g (fifth force)	g (orbital period decay)
PSR B1913 + 16	$\leq 4.99 \times 10^{-17}$	$\leq 2.21 \times 10^{-18}$
PSR J0737 – 3039	$\leq 4.58 \times 10^{-17}$	$\leq 2.17 \times 10^{-19}$
PSR J0348 + 0432	⋯	$\leq 9.02 \times 10^{-20}$
PSR J1738 + 0333	⋯	$\leq 4.24 \times 10^{-20}$



$M_{Z'} < 10^{-19}$ eV

Candidate for FDM

Phys Rev D 100, 123023 (2019)

T.K.P, S. Mohanty, S.Jana

Other particle radiation from the binary system

Massive Scalar (spin-0) radiation:

Phys. Rev. D 101, 083007 (2020) (T.K.P,++), 2404.18309 (T.K.P,+),........

$$\mathscr{L} \supset g_e \phi n(r) \qquad n(r) = \sum_{j=1,2} N_j \delta^3(\mathbf{r} - \mathbf{r}_j(t))$$

Massive tensor (spin-2) radiation:

JCAP 03 (2022) 019 (T.K.P,++),....

$$\mathscr{L} \supset \frac{\kappa}{2} h_{\mu\nu} T^{\mu\nu} \qquad T_{\mu\nu} = \mu \delta^3(\mathbf{x} - \mathbf{x}_j(t)) U_\mu U_\nu$$

What happens to ν radiation from a binary system?

$$\mathcal{L} \supset -i\frac{g}{2\cos\theta_W}[\bar{\psi}\gamma^\mu(c_V^\psi - c_A^\psi)\psi + \bar{\nu}\gamma^\mu(c_V^\nu - c_A^\nu)\nu]Z_\mu$$

Power loss due to ν pair radiation (SM)

$$P_\nu \sim G_F^2\frac{({c^\nu}_V{}^2 + {c^\nu}_A{}^2)}{105\pi^3\cos^2\theta_W}M^2a^2\Omega^8 c_V^{\psi 2}\left(\frac{Q_1}{m_1} - \frac{Q_2}{m_2}\right)^2 \sim 10^{-56}\ \mathrm{eV}^2 \ll 10^8\ \mathrm{GeV}^2\ (P_{\mathrm{GW}})$$

BSM

$$\mathcal{L} \supset gZ'_\mu J^\mu + gZ'_\mu\bar{\psi}\gamma^\mu\psi$$

$g \lesssim 10^{-18}$ PSR B1913+16

JHEP 10 (2023) 002 (Ghosh, Grossman, Tangarife,++)

Leptophilic scalar field profile for a NS

The Goldreich-Julian (GJ) charge density on the surface of the star

$$\rho_{GJ} = -2\Omega B/e$$

Ω is the angular velocity of the star and B is the surface magnetic field

Interaction of a massive scalar field ϕ with the GJ charge density:

$$\mathscr{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - g_e\phi\rho_{GJ}$$

E.O.M

$$(\Box + m_\phi^2)\phi = g_e\rho_{GJ}$$

Contd…

For a spherically symmetric matter density distribution

Smirnov, Xu
JHEP 12(2019)046

Considering GJ charge density is constant and confined within NS

$$\rho_{GJ}(r) = \rho_{GJ}^0 = -\frac{2\Omega B}{e} \quad r \le R$$

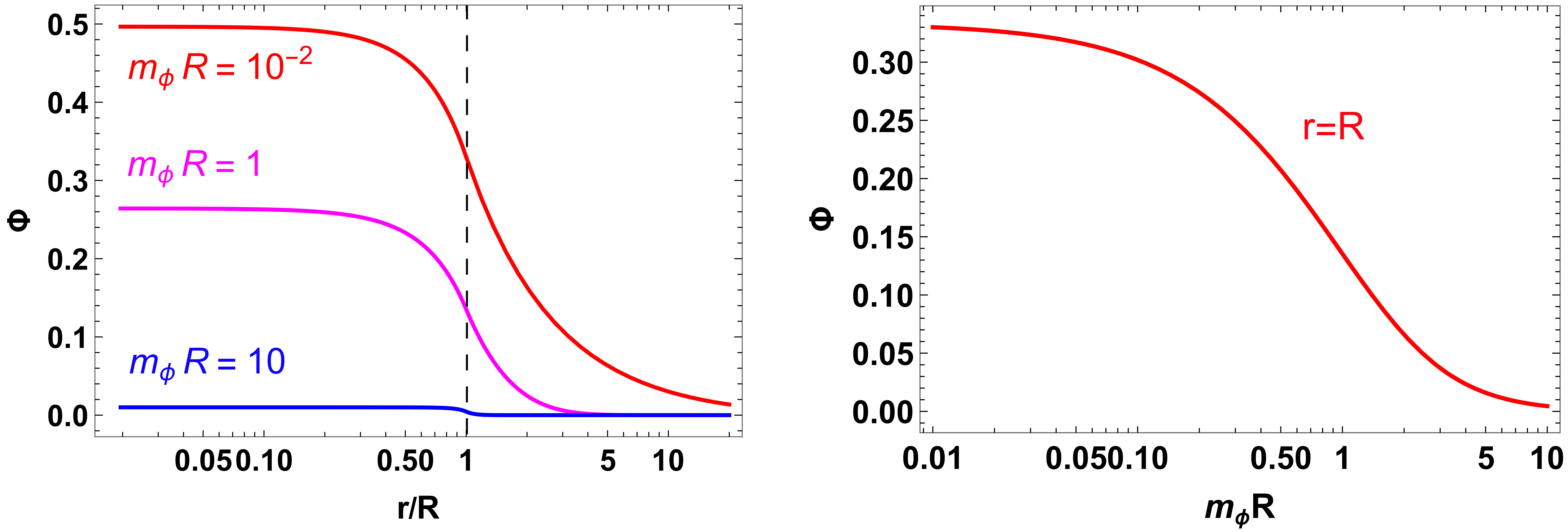
$$= 0 \quad r > R$$

Solution

$$\phi(r) = \frac{2g_e \Omega B}{e m_\phi^2}\left[-1 + \frac{1 + m_\phi R}{m_\phi r} e^{-m_\phi R} \sinh(m_\phi r)\right], \quad r \le R$$

$$= \frac{2g_e \Omega B}{e m_\phi^2} \frac{e^{-m_\phi r}}{m_\phi r}(\sinh(m_\phi R) - m_\phi R \cosh(m_\phi R)), \quad r > R$$

Contd...



0.5
0.4
0.3
0.2
0.1
0.0
Φ
$m_\phi R = 10^{-2}$
$m_\phi R = 1$
$m_\phi R = 10$
0.05
0.10
0.50
1
5
10
r/R
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Φ
r=R
0.01
0.05
0.10
0.50
1
5
10
m_ϕR

Contd…

Small scalar mass limit

$$\phi(r) \approx \frac{g_e B\Omega}{3e}(r^2 - 3R^2), \quad r \leq R$$

$$\approx -\frac{2g_e B\Omega R^3}{3er}, \quad r > R$$

If ϕ coupled with net electron charge of NS:

NS can be treated as a point source with $n(r) = N\delta^3(r)$

$$\phi(r) = -\frac{g_e N}{4\pi r}e^{-m_\phi r}$$

Scalar field radiation from a binary systems

$1/\Omega_{\rm orb} \sim 10^9$ km $\gg R \sim 10$ km The stars behave as point sources

The interaction Lagrangian

$$\mathscr{L} \supset g_e \phi n(r) \qquad n(r) = \sum_{j=1,2} N_j \delta^3(\mathbf{r} - \mathbf{r}_j(t))$$

The coordinates in the frequency space

$$x(\omega) = \frac{aJ_n'(ne)}{n}, \quad y(\omega) = \frac{ia\sqrt{1-e^2}J_n(ne)}{ne}$$

The emission rate

$$d\Gamma = g_e^2 |n(\omega')|^2 2\pi\delta(\omega - \omega')\frac{d^3k'}{(2\pi)^3 2\omega'}$$

Contd...

Rate of energy loss due to scalar emission

$$\frac{dE}{dt} = \frac{g_e^2}{6\pi}\left(\frac{N_1}{M_1} - \frac{N_2}{M_2}\right)^2 M^2 a^2 \Omega_{\text{orb}}^4 \sum_{n>m_\phi/\Omega} n^2 \left[J_n'(ne)^2 + \frac{1-e^2}{e^2} J_n(ne)^2\right]\left(1 - \frac{m_\phi^2}{n^2\Omega_{\text{orb}}^2}\right)^{\frac{3}{2}}$$

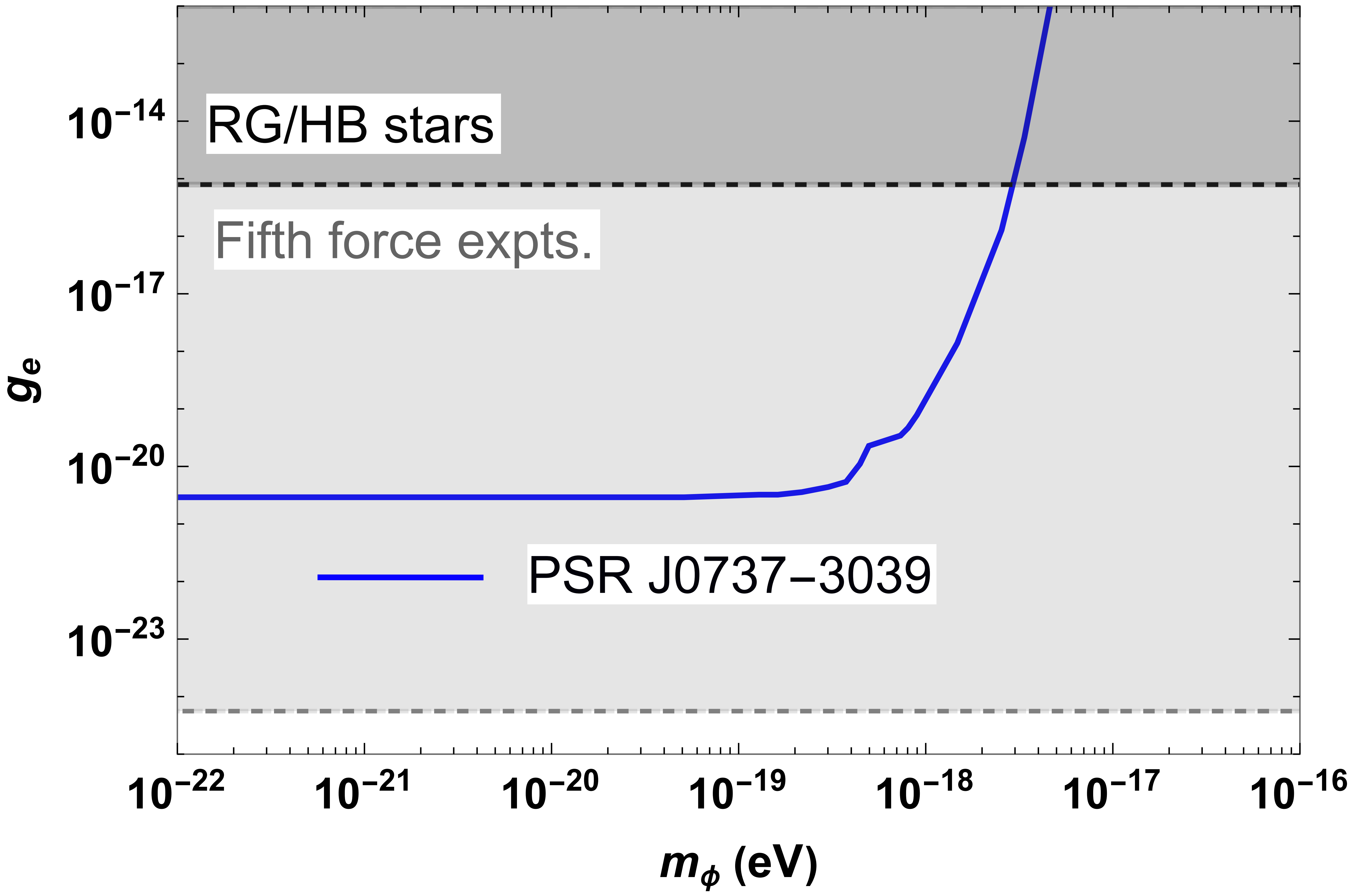
Rate of energy loss sourced by GJ charge density

$$\frac{dE}{dt} = \frac{32\pi g_e^2}{27e^2}\left(\frac{B_1 R_1^3 \Omega_1}{M_1} - \frac{B_2 R_2^3 \Omega_2}{M_2}\right)^2 M^2 a^2 \Omega_{\text{orb}}^4 \sum_{n>m_\phi/\Omega} n^2 \left[J_n'(ne)^2 + \frac{1-e^2}{e^2} J_n(ne)^2\right]\left(1 - \frac{m_\phi^2}{n^2\Omega_{\text{orb}}^2}\right)^{\frac{3}{2}}$$

Contd…

Compare with GW energy loss

$$\frac{dE_{GW}}{dt} = \frac{32}{5} G\Omega^6 M^2 a^4 (1-e^2)^{-7/2}\left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)$$



2404.18309

T.K.P, G. Lambiase

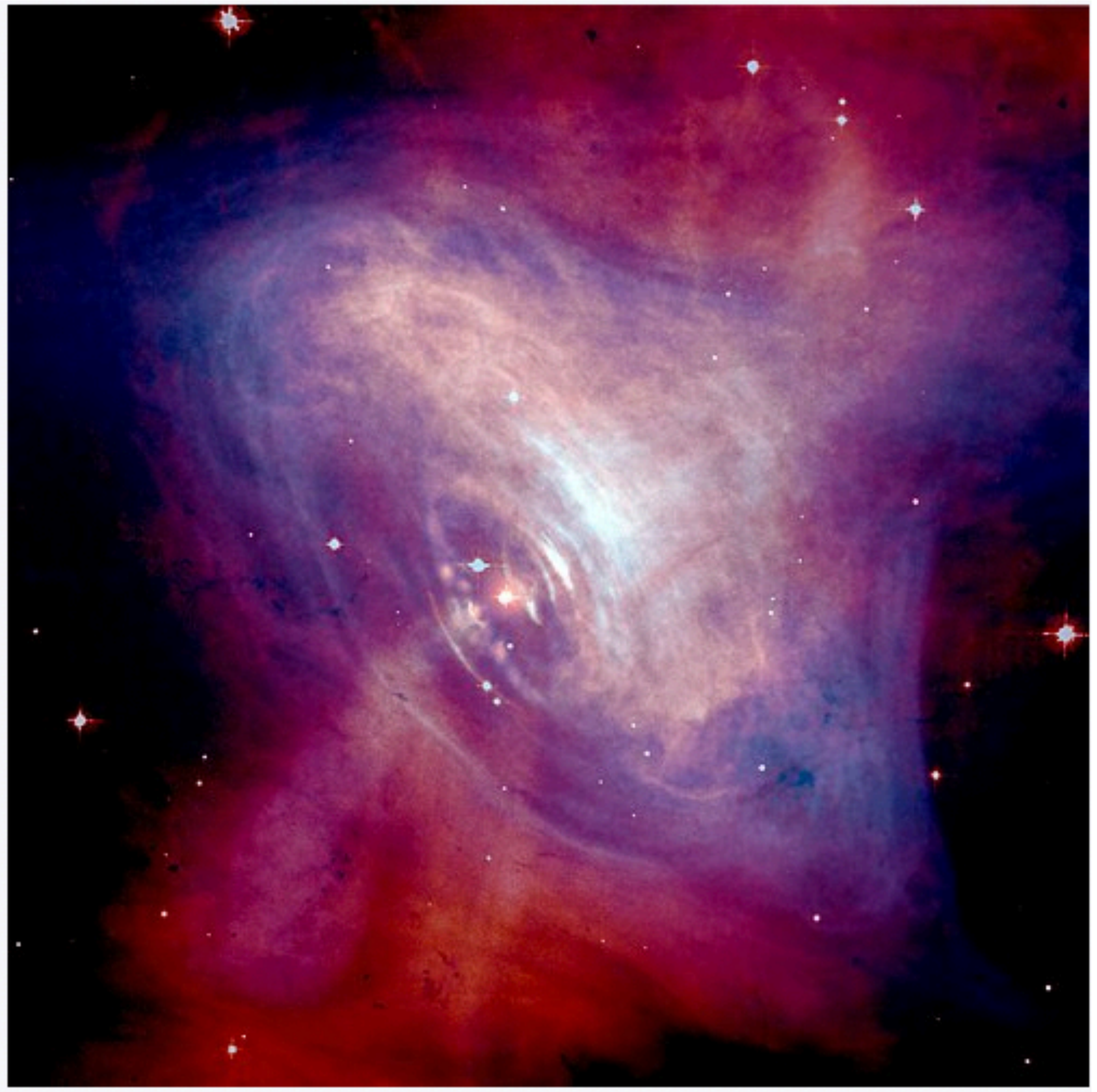
Energy loss from an isolated pulsar

Pulsar periodically rotates with a spin angular frequency Ω

Solution of scalar field

$$\phi(\mathbf{r}, t) = \sum_{n=-\infty}^{\infty} e^{i\omega t}\phi_n(\mathbf{r})$$

$$\omega = n\Omega$$



The source current can be written as

$$\rho_n(\mathbf{r}) = \frac{1}{T}\int_0^T e^{i\omega t}\rho(\mathbf{r}, t)dt$$

The wave equation of the scalar field

$$(\nabla^2 + k^2)\phi_n(\mathbf{r}) = -\rho_n(\mathbf{r})$$

Image credit: wikipedia

Contd...

Using Green's function method

$$\phi_n(\mathbf{r}) = \frac{1}{4\pi}\int \frac{e^{ik|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|}\rho_n(\mathbf{r}')d^3r'$$

The dipole scalar field solution in the limit $|\mathbf{r}| \gg |\mathbf{r}'|$ and $k|\mathbf{r}'| \ll 1$

For the fundamental mode

$$\phi(\mathbf{r}, t) = \frac{ik}{4\pi r}(\hat{\mathbf{n}}\cdot\mathbf{p}_+ e^{-i(\Omega t - kr)} - \hat{\mathbf{n}}\cdot\mathbf{p}\_e^{i(\Omega t - kr)})$$

Rate of energy loss

$$\frac{dE}{dt} = \frac{1}{8\pi^2}\Omega k^3 \int d\Omega_n |\mathbf{p}_+\cdot\hat{\mathbf{n}}|^2 \qquad\qquad \mathbf{p}_+ = \frac{1}{T}\int e^{i\Omega t}dt \int d^3r'\rho(\mathbf{r}', t)\mathbf{r}'$$

Contd…

The scalar-induced GJ number density for a dipolar magnetic field

$$\rho(r,t) \approx \frac{2g_e B_0 R^3 \Omega}{er^3} \tan\alpha \cos\theta_m \cos(\phi - \Omega t)$$

$$\cos\theta_m = \cos\alpha\cos\theta + \sin\alpha\sin\theta\cos(\phi - \Omega t)$$

Energy loss for the pulsar spindown

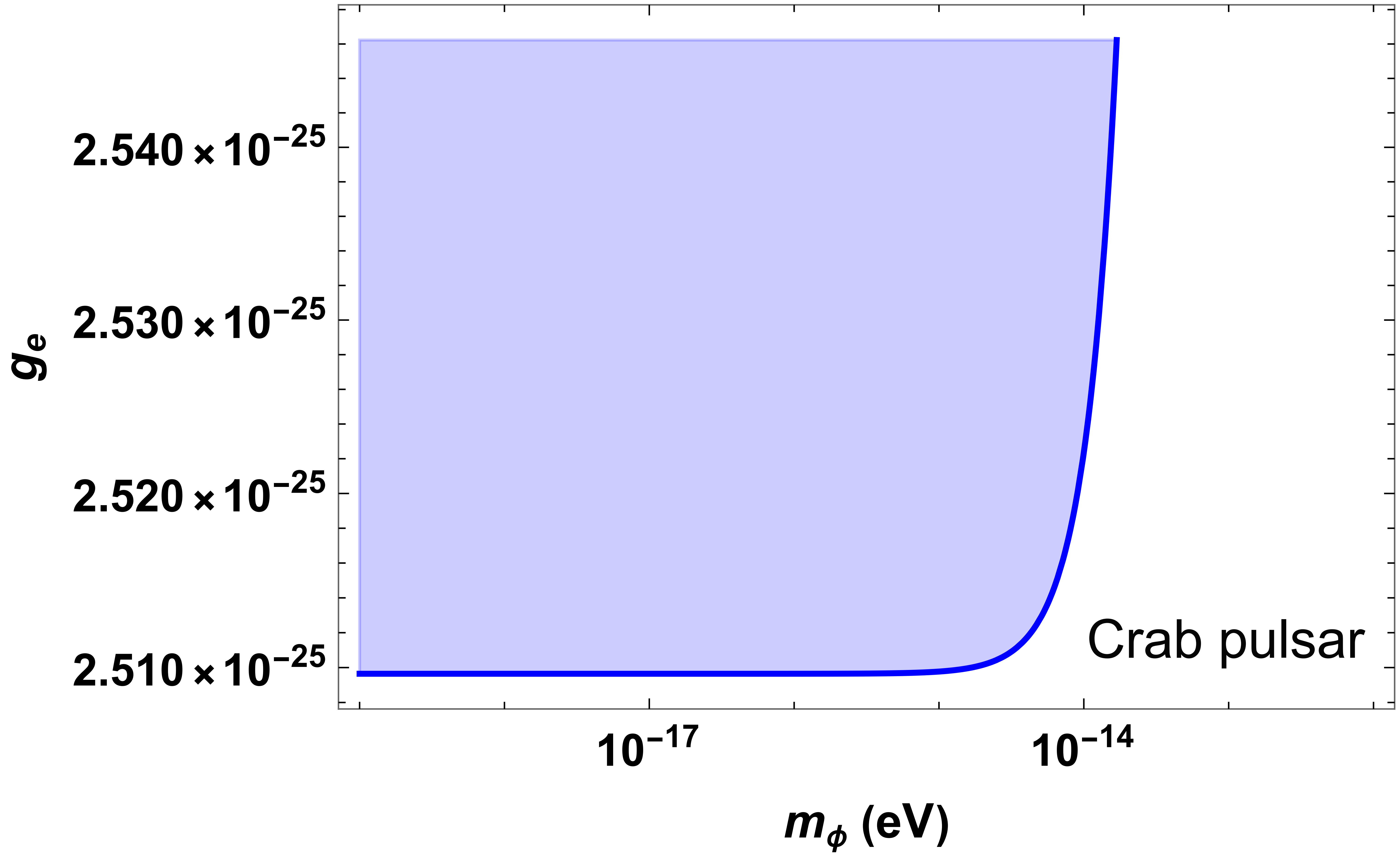
$$\frac{dE}{dt} = \frac{1}{8\pi^2}\Omega k^3 \int\!\!\int d\Omega_n |\hat{\mathbf{n}}\cdot\mathbf{p}_\Omega|^2 \approx \frac{\pi^3}{8e^2} g_e^2 B_0^2 R^8 \Omega^6 \sin^2\theta_m \left(1 - \frac{m_\phi^2}{\Omega^2}\right)^{\frac{3}{2}}$$

For the net electron charge N

$$\frac{dE}{dt} = \frac{1}{8\pi^2}\Omega k^3 \int\!\!\int d\Omega_n |\hat{\mathbf{n}}\cdot\mathbf{p}_\Omega|^2 = \frac{1}{12\pi} g_e^2 R^2 \Omega^4 N^2 \sin^2\theta_m \left(1 - \frac{m_\phi^2}{\Omega^2}\right)^{\frac{3}{2}}$$

Constraints from pulsar spindown

$L_{\text{spindown}} \sim 4.5 \times 10^{38}$ erg/s



Radiation happens for $\Omega > m_\phi$

2404.18309

T.K.P, G. Lambiase

Effects of $C\nu B$

Very low energy $\rightarrow 10^{-4} - 10^{-6}$ eV   Difficult to detect

Decouple much earlier than photon→ can probe universe before CMB

At present epoch $T_\nu \sim 1.95\ K \sim 1.68 \times 10^{-4}$ eV

Standard cosmological model predicts $n_\nu \sim 336/\ \mathrm{cm}^3$

Oscillation data gives two of the neutrino mass eigenstates are NR today

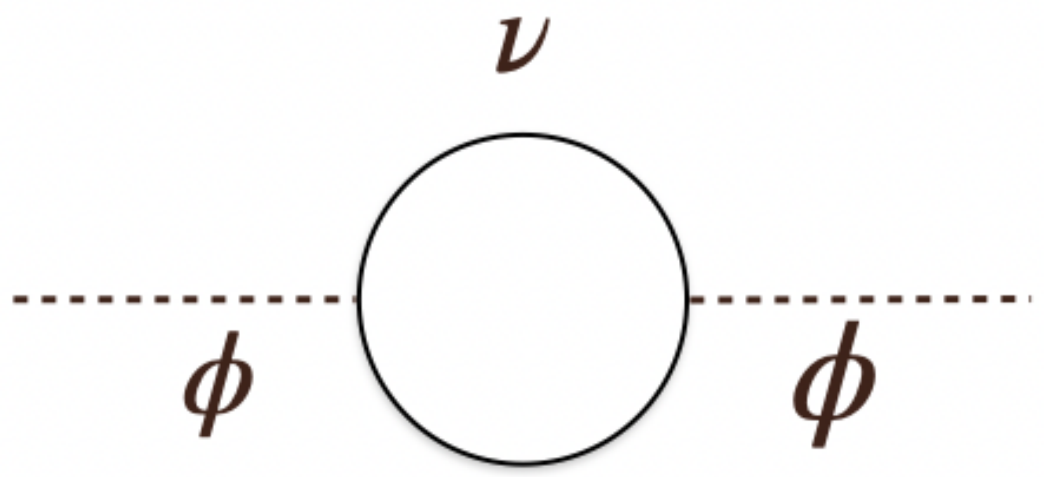
PTOLEMY can detect through inverse β decay of tritium

Affects CMB fluctuations→ indirect probe

Contd…

Mass of ultralight scalar increases when it propagates through $C\nu B$

$$m_\phi^2 \to m_\phi^2 + y_\nu^2 \frac{n_\nu}{m_\nu}$$ For NR ν

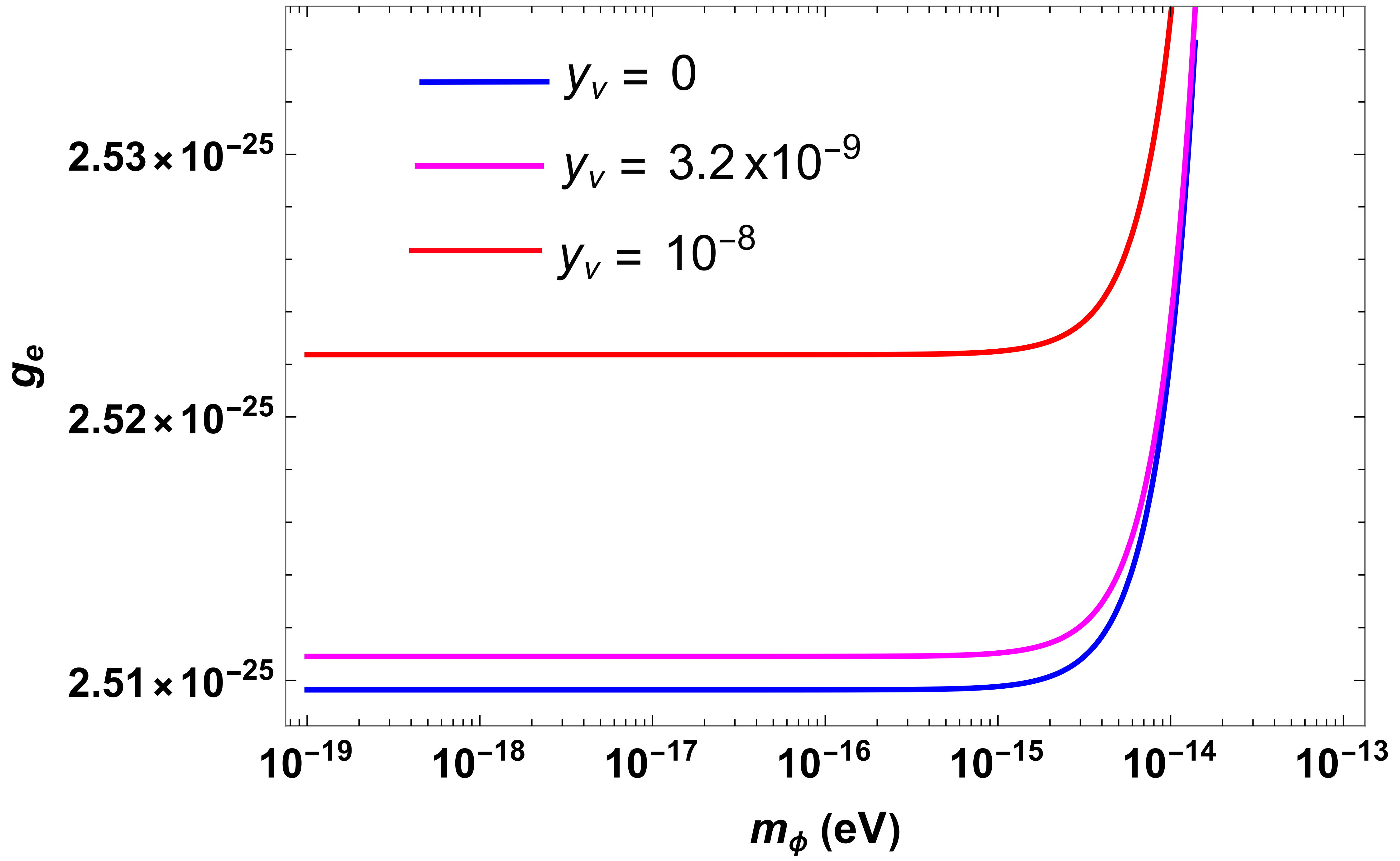


Scalar mass correction for NR ν

$$\Delta m_\phi^2 = y_\nu^2 \frac{n_\nu}{m_\nu} \sim 10^{-32}\ \text{eV}^2 \left(\frac{y_\nu}{10^{-10}}\right)^2 \left(\frac{n_\nu}{56/\text{cm}^3}\right)\left(\frac{0.1\ \text{eV}}{m_\nu}\right)$$

Phys. Rev.D 101, 095029

Babu, Chauhan, Dev



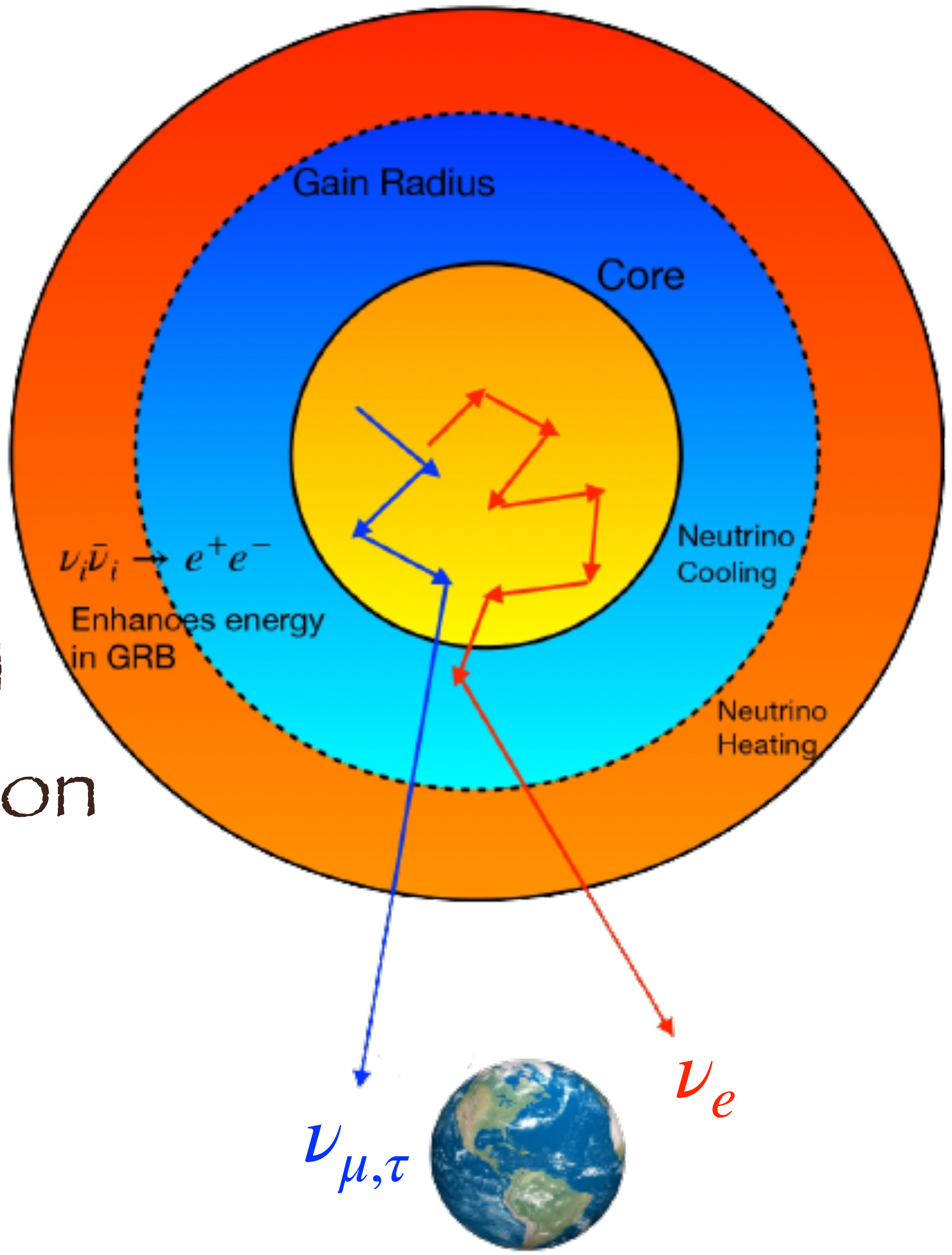
2404.18309

T.K.P, G. Lambiase

Motivations

- Neutrino Cooling: Emission of a huge number of neutrinos make stellar objects cool, $L_\nu \sim 10^{53}\mathrm{erg/s}$

- Neutrino Heating: Neutrino flux can also deposit energy into the stellar envelope through neutrino pair annihilation



$$\nu_i\bar{\nu}_i \to e^+e^-, i = e, \mu, \tau$$ Energizes GRB

$E_{\mathrm{GRB}} \sim 10^{52}\mathrm{erg}$ (Observation)

$E_{GRB}^{\mathrm{Theory}} \sim 1.5 \times 10^{50}\mathrm{erg}$ (Newtonian)

$E_{GRB}^{\mathrm{Theory}} \sim 4.3 \times 10^{51}\mathrm{erg}$ (Schwarzschild)

Contd…

The energy deposition rate

$$\dot{q}_{\nu_e}(r) = \frac{21}{2(2\pi)^6}\pi^4(kT_{\nu_e}(r))^9\zeta(5) \times \Big[\frac{G_F^2}{3\pi}(1 + 4\sin^2\theta_W + 8\sin^4\theta_W) + \frac{4g'^4}{6\pi M_{Z'}^4} + \frac{4G_F g'^2}{3\sqrt{2}\pi M_{Z'}^2}\Big(-\frac{1}{2} + 2\sin^2\theta_W\Big) + \frac{4G_F g'^2}{3\sqrt{2}\pi M_{Z'}^2}\Big]\Theta_{\nu_e}(r),$$

$$\dot{q}_{\nu_{\mu,\tau}}(r) = \frac{21}{2(2\pi)^6}\pi^4(kT_{\nu_{\mu,\tau}}(r))^9\zeta(5) \times \Big[\frac{G_F^2}{3\pi}(1 - 4\sin^2\theta_W + 8\sin^4\theta_W) + \frac{4g'^4}{6\pi M_{Z'}^4} + \frac{4G_F g'^2}{3\sqrt{2}\pi M_{Z'}^2}\Big(-\frac{1}{2} + 2\sin^2\theta_W\Big)\Big]\Theta_{\nu_{\mu,\tau}}(r).$$

in $\frac{g'}{M_{Z'}} \to 0$ limit,

Goodman, Dar, Nussinov, APJ (1987)

$$\dot{q}(r) = \frac{7G_F^2\pi^3\zeta(5)}{2(2\pi)^6}(kT)^9\Theta(r)(1 \pm 4\sin^2\theta_W + 8\sin^4\theta_W)$$

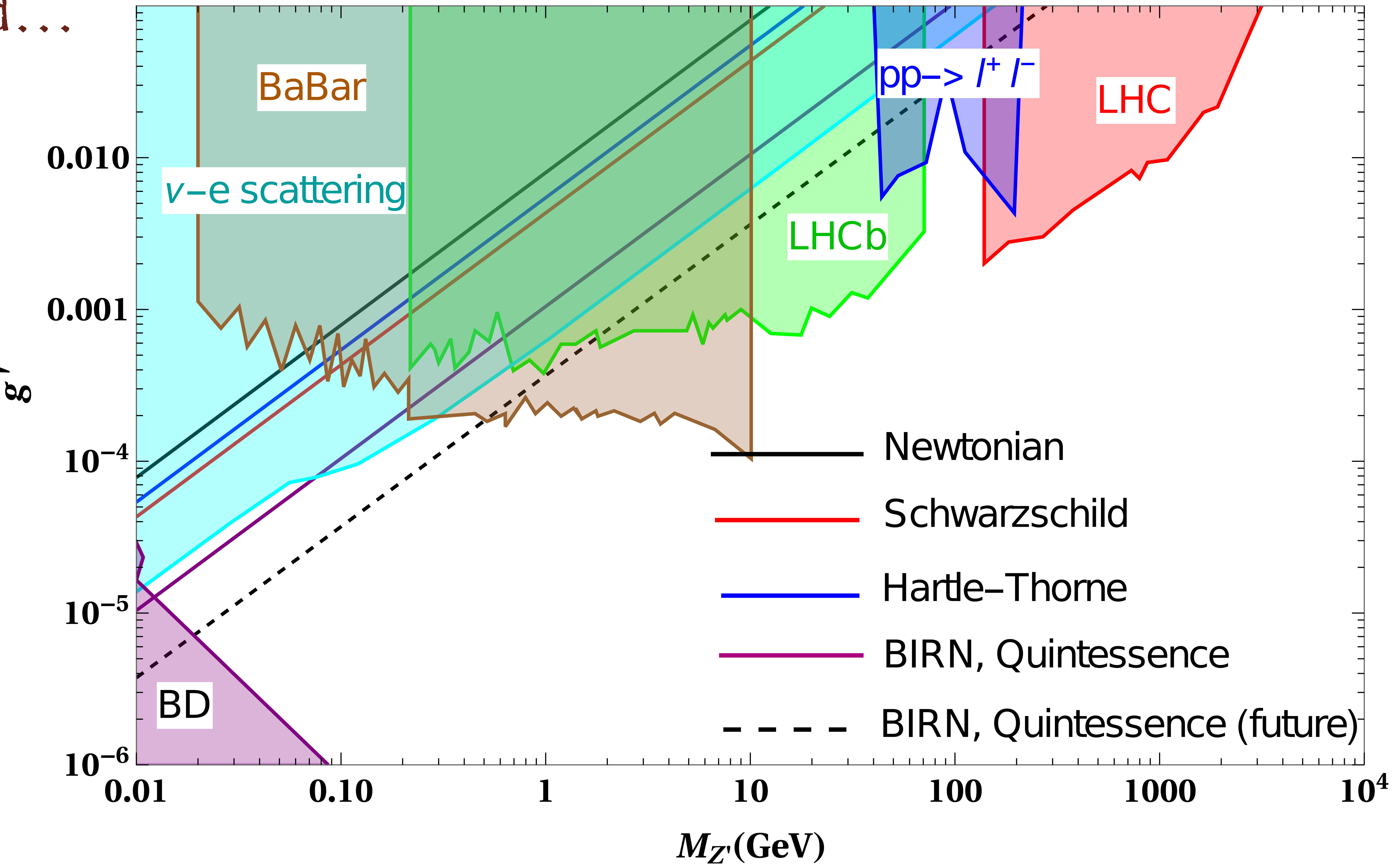
→ SM

where,

$$\Theta(r) = \int\int(1 - \Omega_\nu.\Omega_{\overline{\nu}})^2 d\Omega_\nu d\Omega_{\overline{\nu}}$$

depends on background geometry

Contd...



T.K.P, S. Goswami, A.K. Mishra, Eur. Phys. J.C 83 (2023) 223

Thank You !!!