Ultra-light dark matter: constraints from observations

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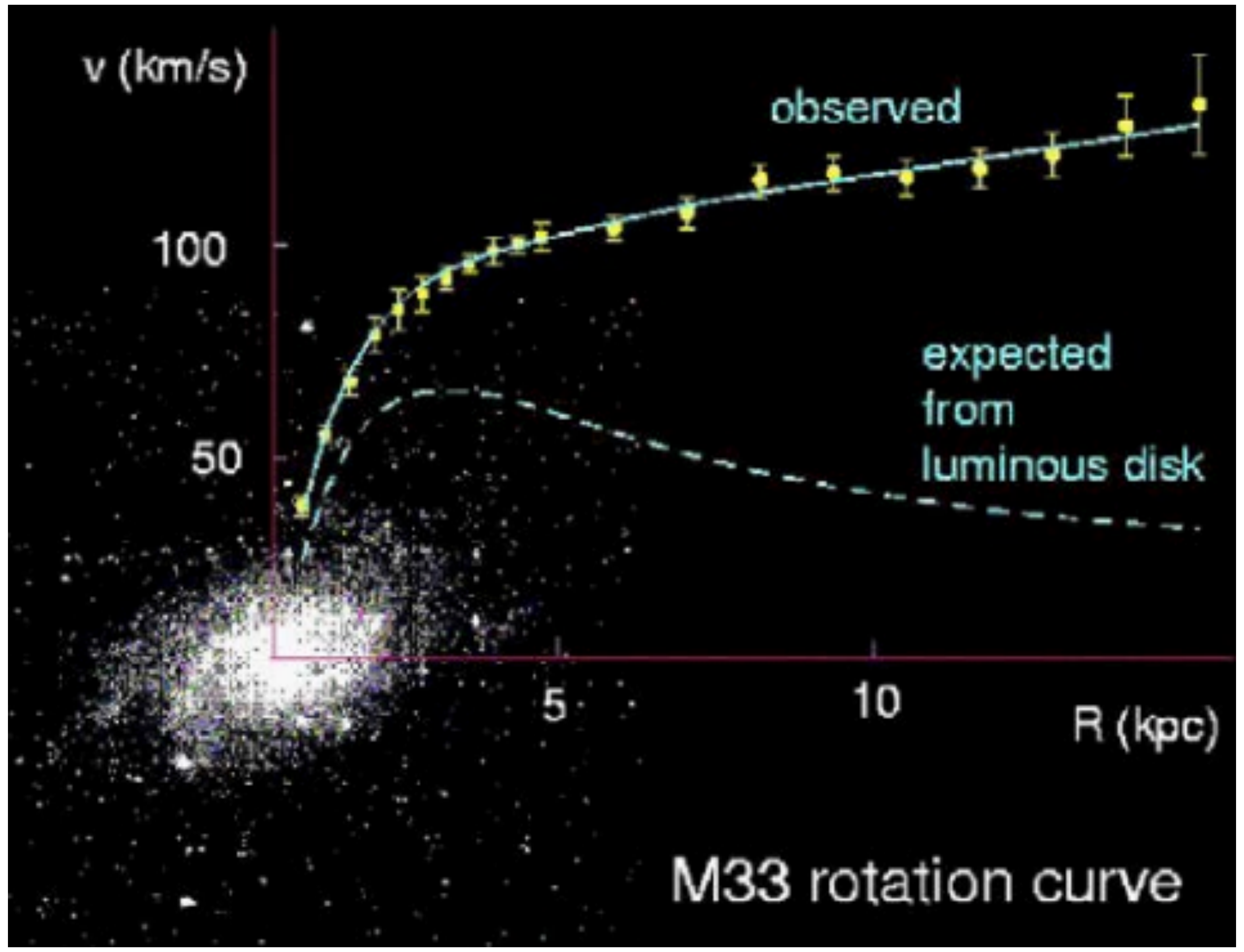
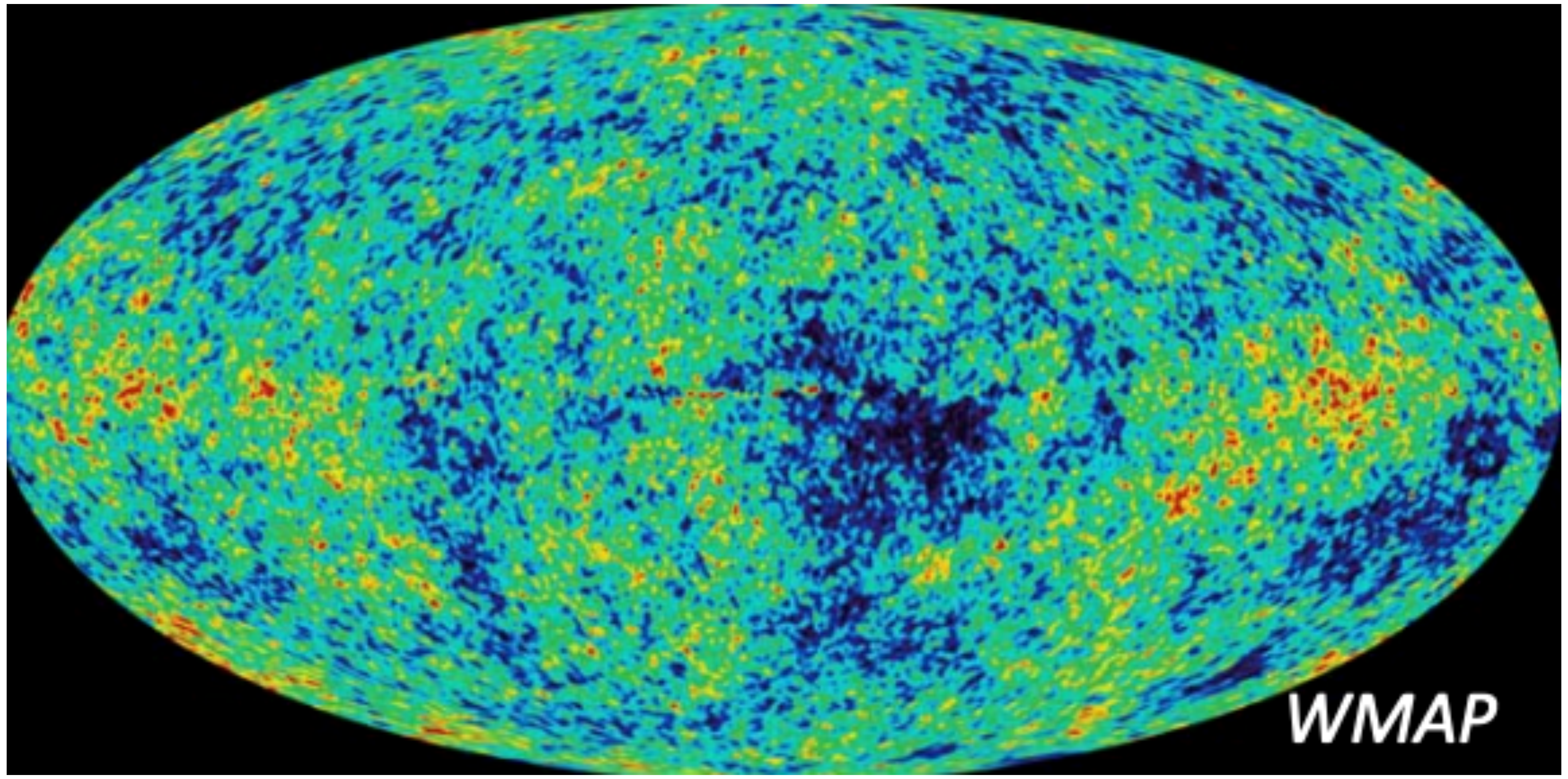
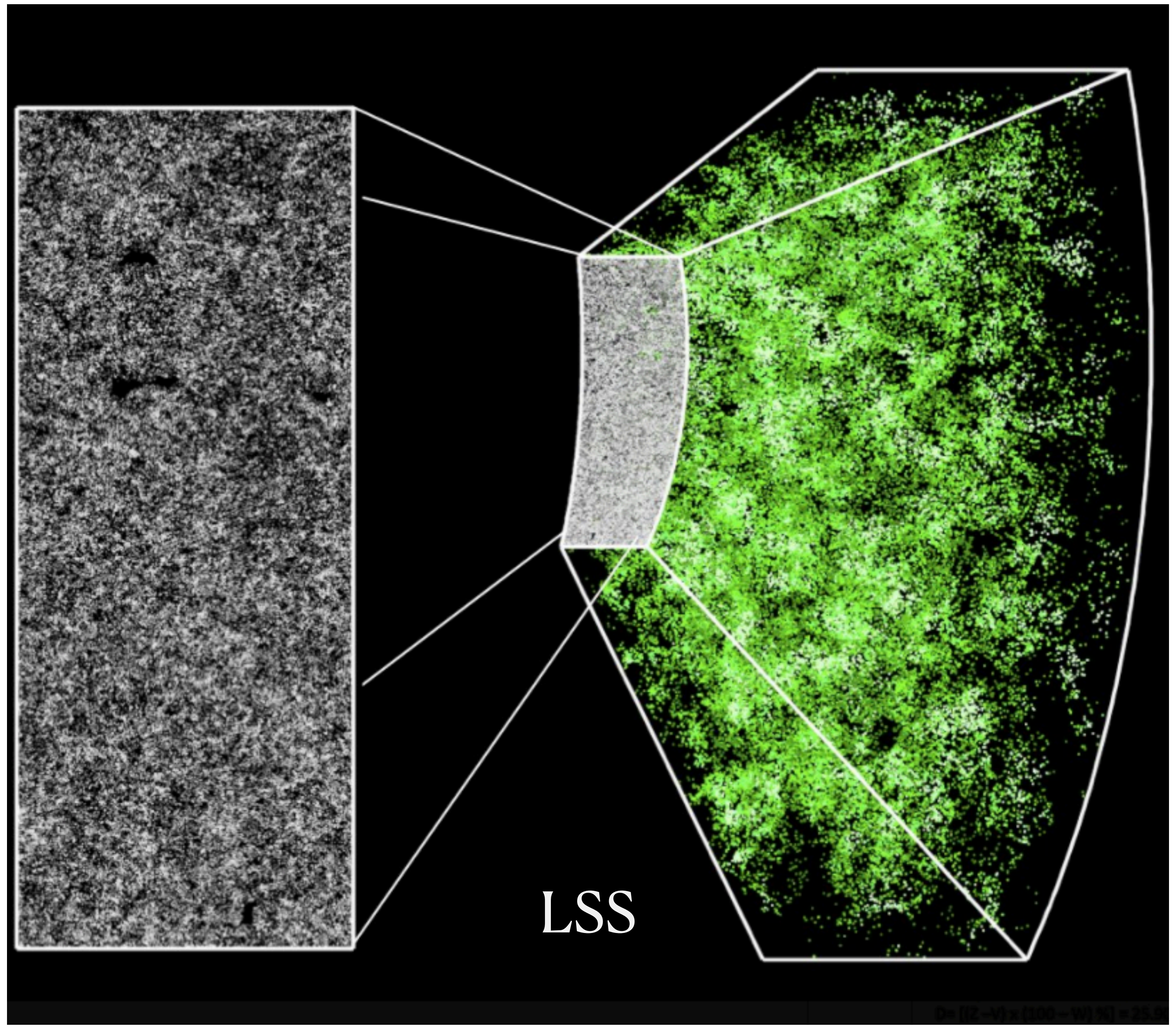
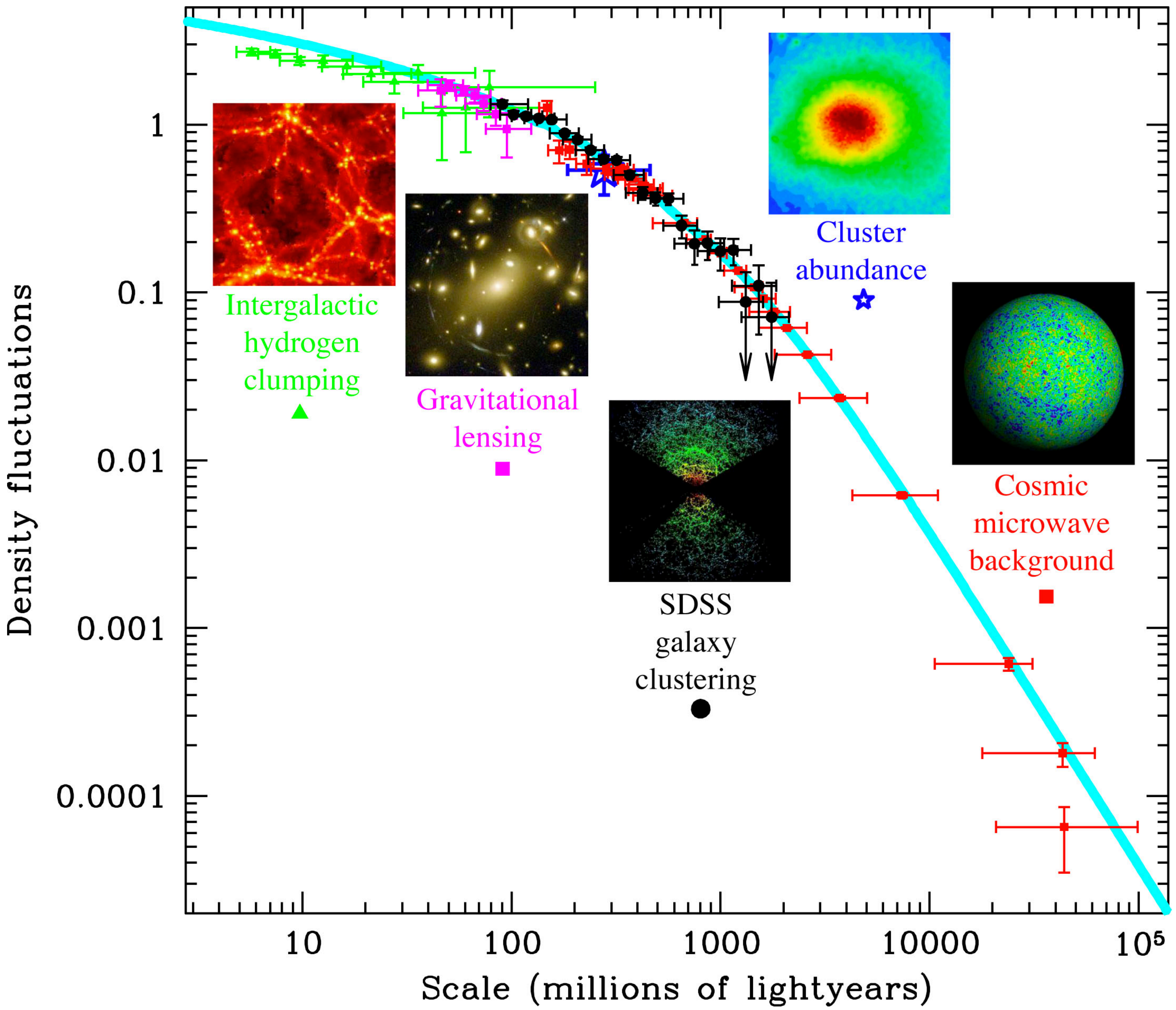
Observational evidence of dark matter







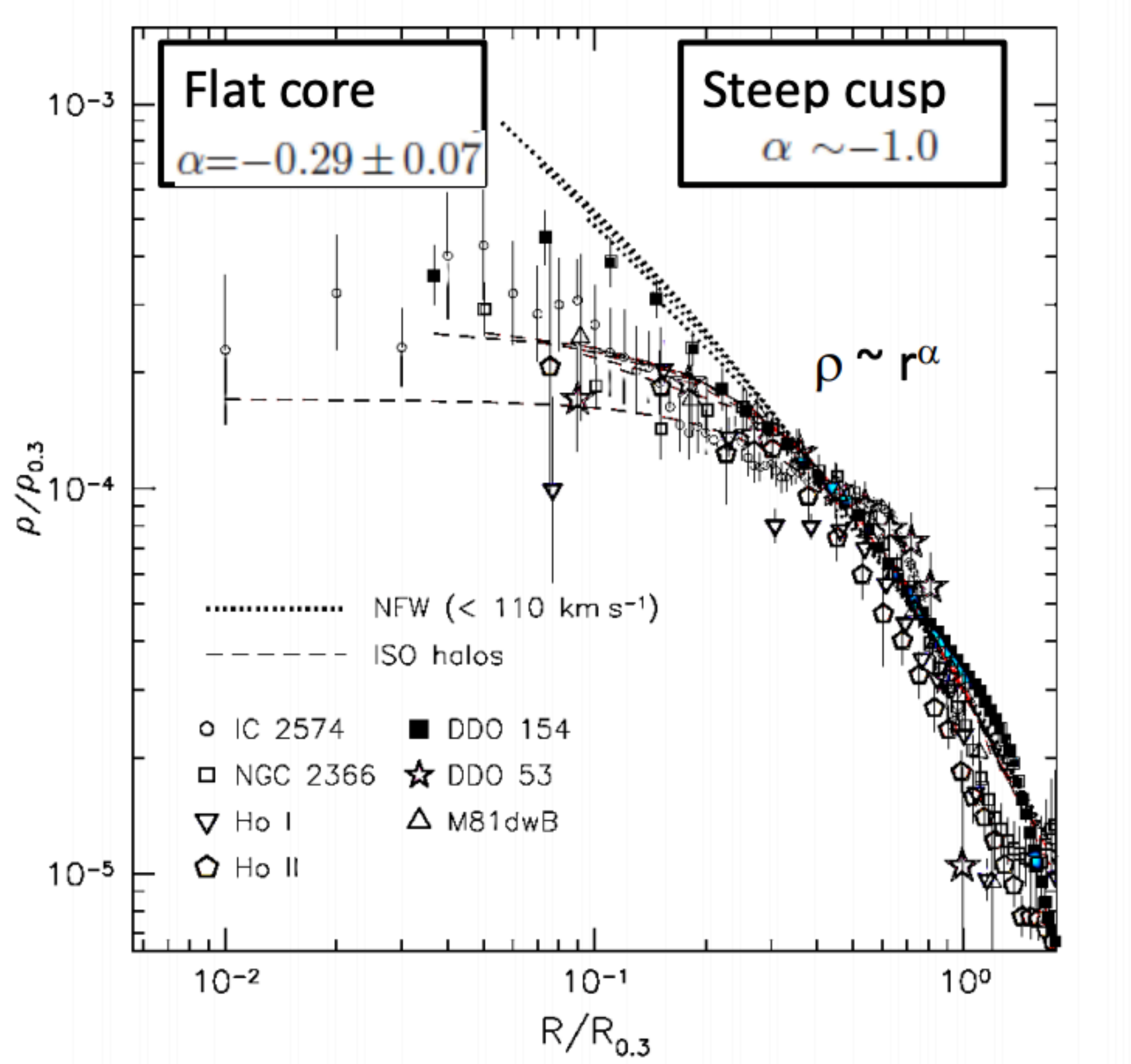
Evidence of dark matter from LSS and CMB



Max Tegmark

https://space.mit.edu/home/tegmark/sdss/

Cuspy Core Problem of Cold Dark matter



CDM simulations predict a NFW profile

$$\rho(r) = \frac{\rho_s r_s^3}{r(r + r_s)^2}$$

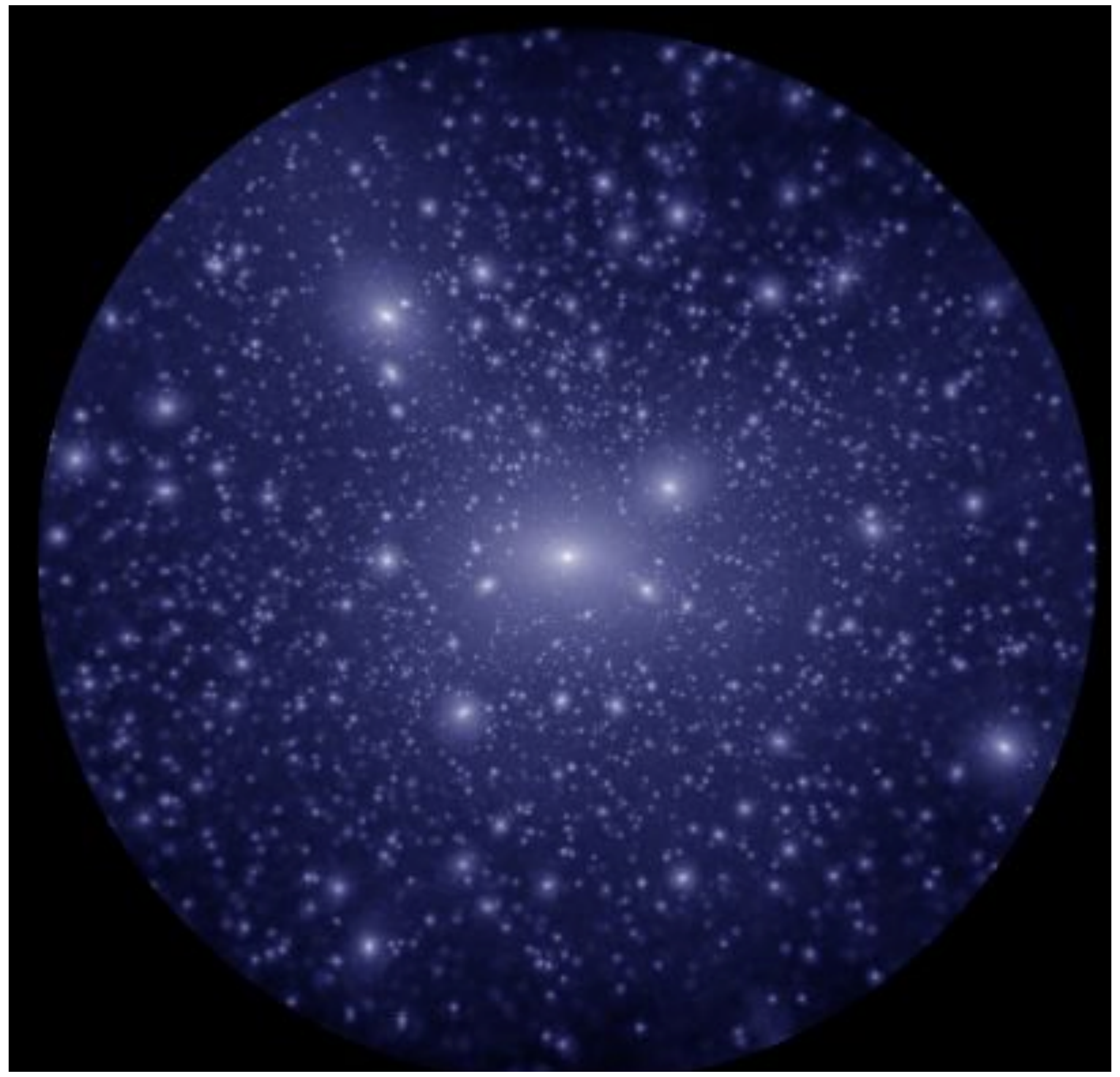
$$\rho(r) \propto r^{-1} \text{ for } r \ll r_s$$

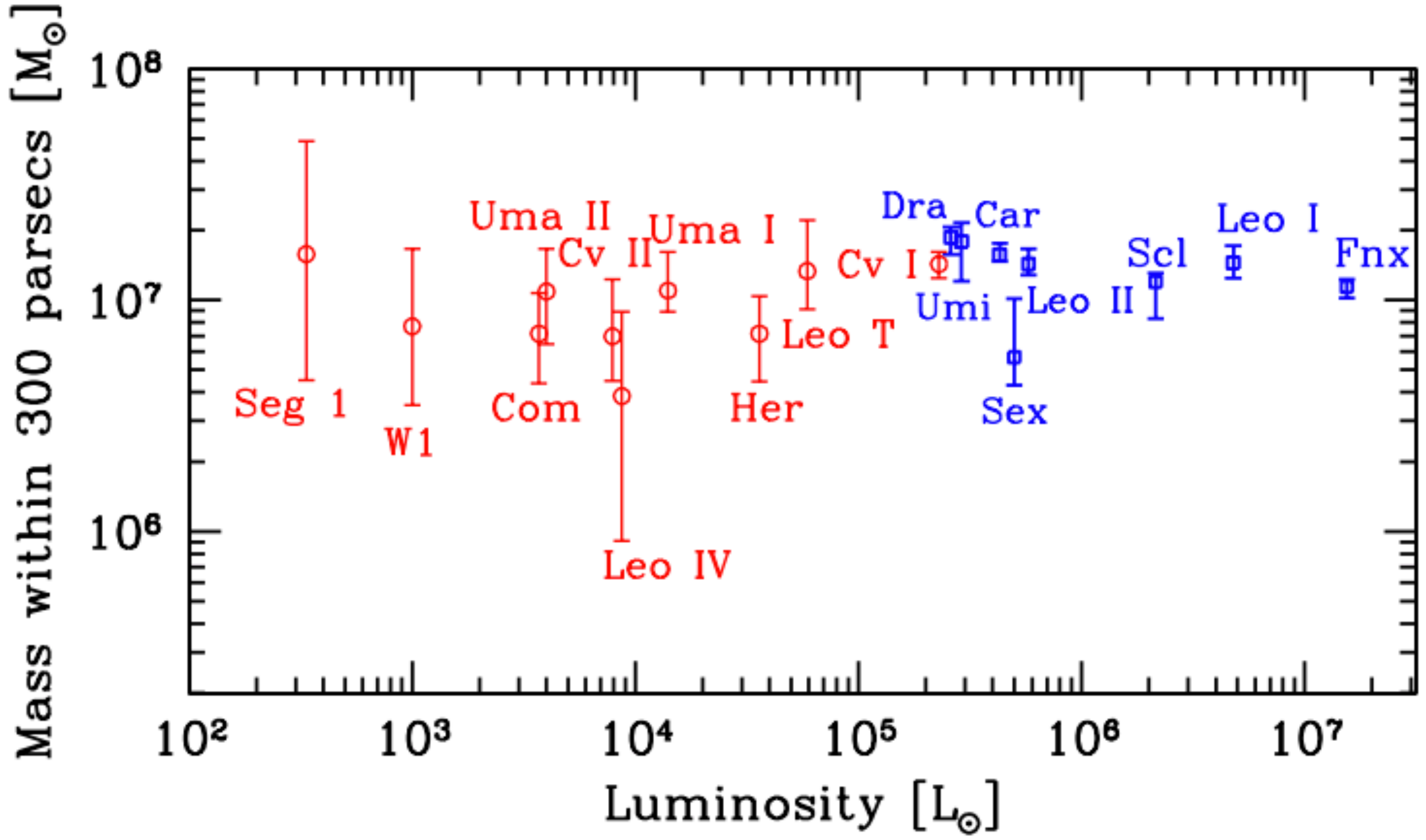
THINGS (dwarf galaxy survey) - Oh et al. (2011)

ArXiv:1011.0899

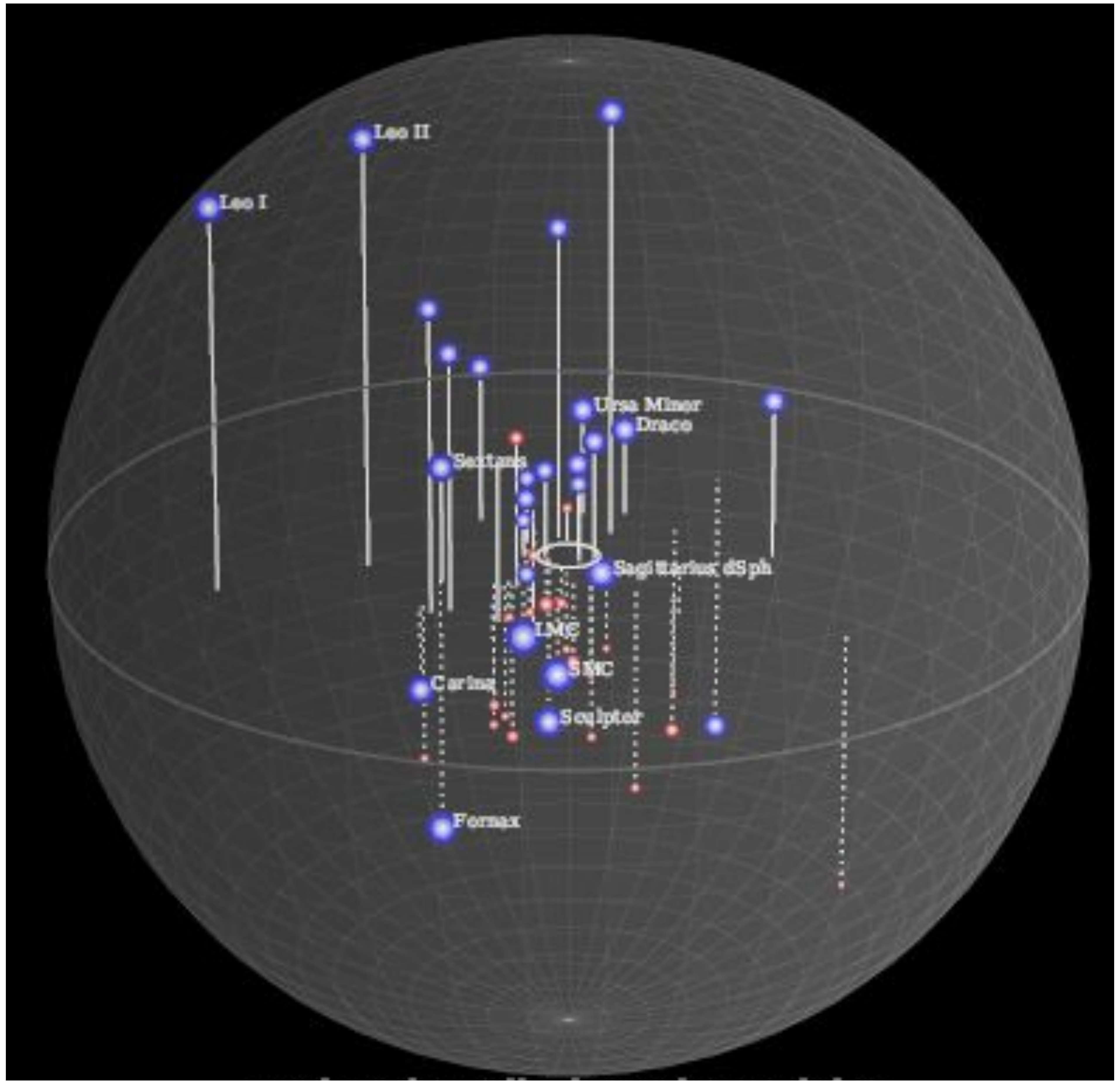
Missing dwarf satellites problem?

CDM simulation





Dwarf satellites around the Milky Way



Bullock, arXiv:1009.4505

- **Fuzzy Dark Matter** -
  Rennan Barkana, Andrei Gruzinov (2000) ;
  Hui, Ostriker, Tremaine, Witten (2017).

de Broglie wavelength of the size of dwarf galaxy

$$\frac{\lambda}{2\pi} = \frac{\hbar}{mv} = 1.92\ \mathrm{kpc}\ \left(\frac{10^{-22}\mathrm{eV}}{m}\right)\left(\frac{10\ \mathrm{km\,s}{-}^{1}}{v}\right)$$

Density perturbations (derived from Schrodinger equations)

$$\ddot{\delta} + 2H\dot{\delta} + \left(\frac{\hbar^2 k^4}{4m^2 a^4} - \frac{4\pi G\bar{\rho}}{a^3}\right)\delta = 0.$$

perturbations with $k < k_J$ collapse to form structures

$$k_J\left(a\right) = \left(\frac{16\pi G\bar{\rho}a^3 m^2}{\hbar^2}\right)^{1/4} a^{1/4}$$

Jeans mass

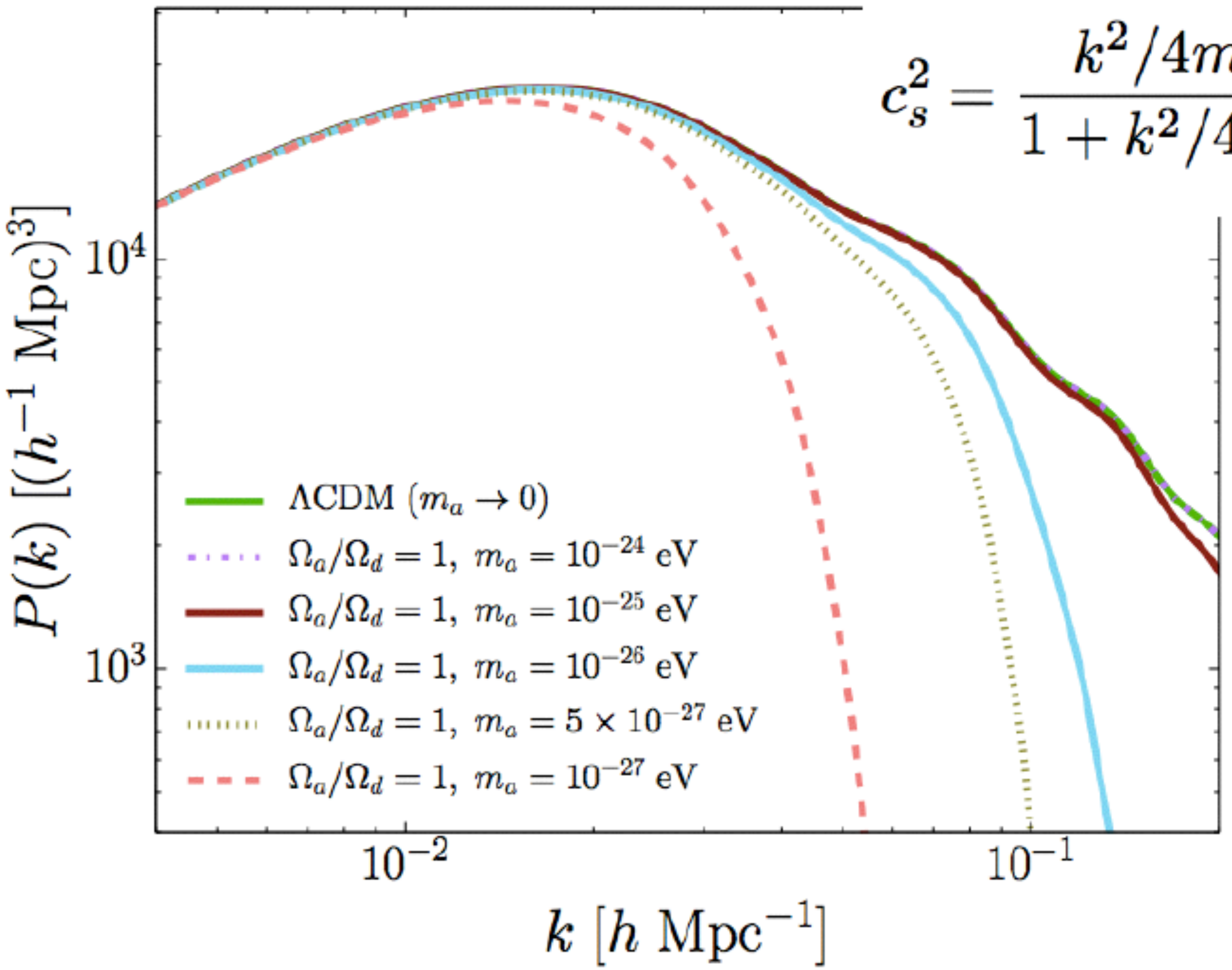
$$M_J = 1.5 \times 10^7\, M_\odot (1+z)^{3/4} \left(\frac{\Omega_{\rm FDM}}{0.27}\right)^{1/4} \left(\frac{H_0}{70\,{\rm km\ s^{-1}\ Mpc^{-1}}}\right)^{1/2} \left(\frac{10^{-22}\,{\rm eV}}{m}\right)^{3/2}$$

Dark-matter halos or sub-halos cannot exist with masses lower than this limit.

FDM solves some fo the standard problems of CDM: Core-cusp, missing satellite galaxies, too big to fail problem.

Matter power spectrum of FDM : power at small length scales suppressed.

$$c_s^2 = \frac{k^2/4m_a^2a^2}{1+k^2/4m_a^2a^2}$$



Hlozek et al 2015

Cosmological relic density of FDM - Hui et al (2017)

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

FDM is a PNGB

$$m_a^2 = \frac{\mu^4}{f^2}$$

mass

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

eom of zero modes

$$\ddot{a} + 3H\dot{a} + m^2 \sin a = 0$$

Oscillations start when $$H = 1.66\sqrt{g_*}\frac{T^2}{M_{pl}} = m$$

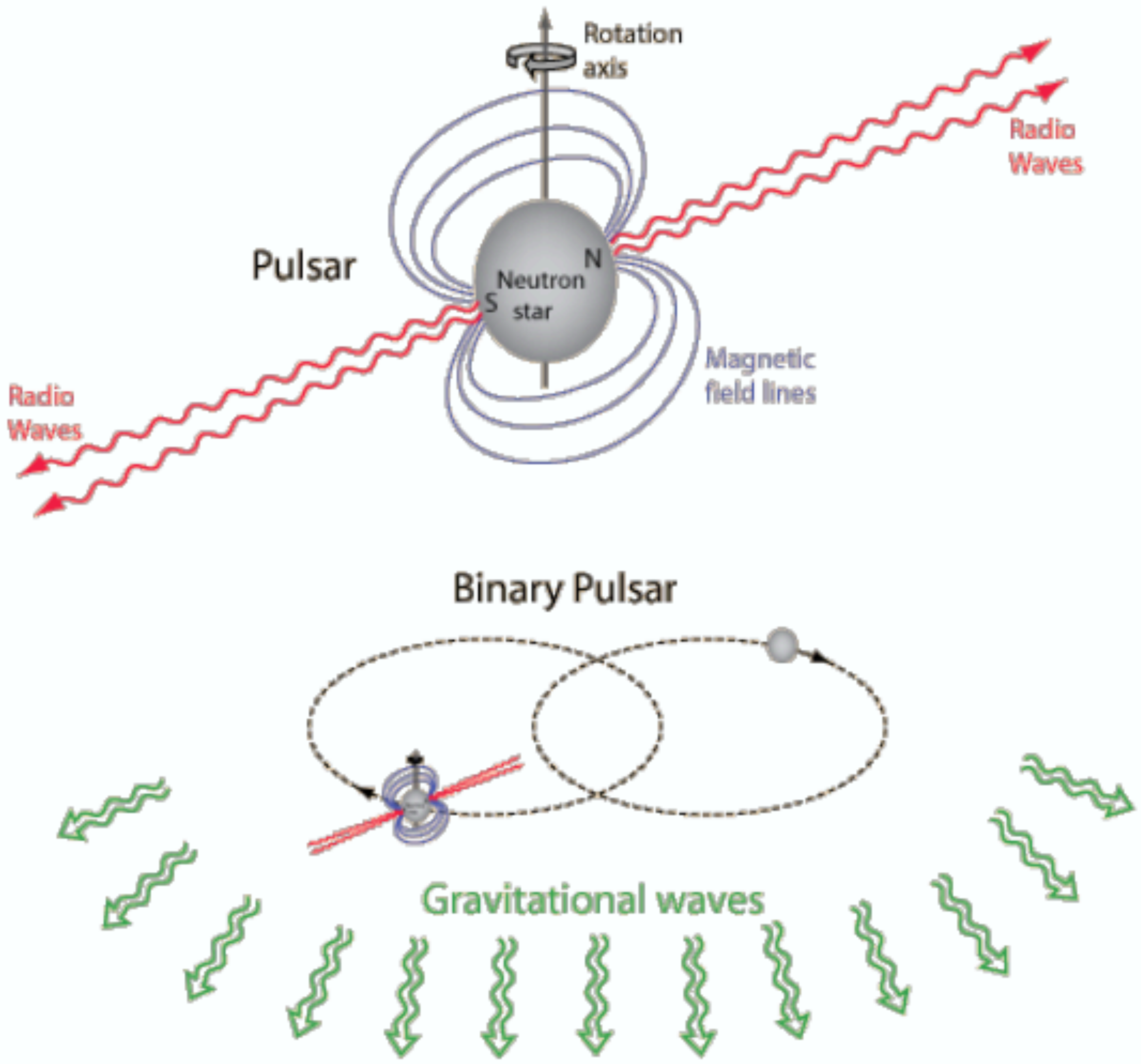
$$T = 500\,\mathrm{eV} \text{ for } m = 10^{-22}\,\mathrm{eV} \Rightarrow \text{No conflict with BBN}$$

Relic density $$\rho_a \sim m_a^2 f^2 \left(\frac{R_i}{R_0}\right)^3$$

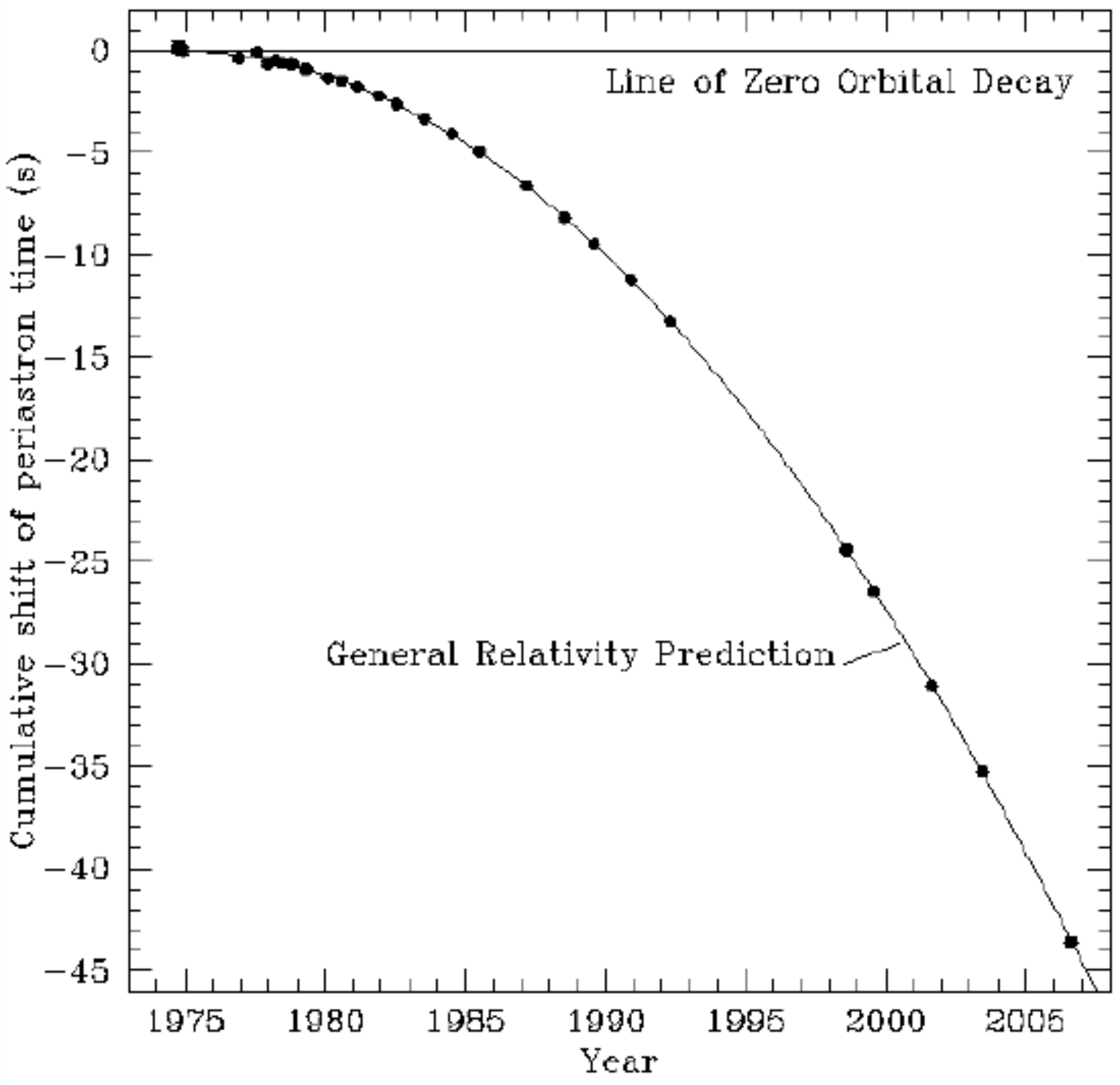
$$\Omega_a \sim 0.1 \left(\frac{f}{10^{17} GeV}\right)^2 \left(\frac{m}{10^{-22} eV}\right)^{1/2}$$

Ultra light dark matter detection from binary pulsar timings

Pulsar timings : First indirect observation of gravitational waves



Orbital time period loss of Hulse-Taylor binary



J.M.WeisbergandY.Huang,Astrophys.J.829,no.1,55(2016)

Rate of energy loss by gravitational radiation

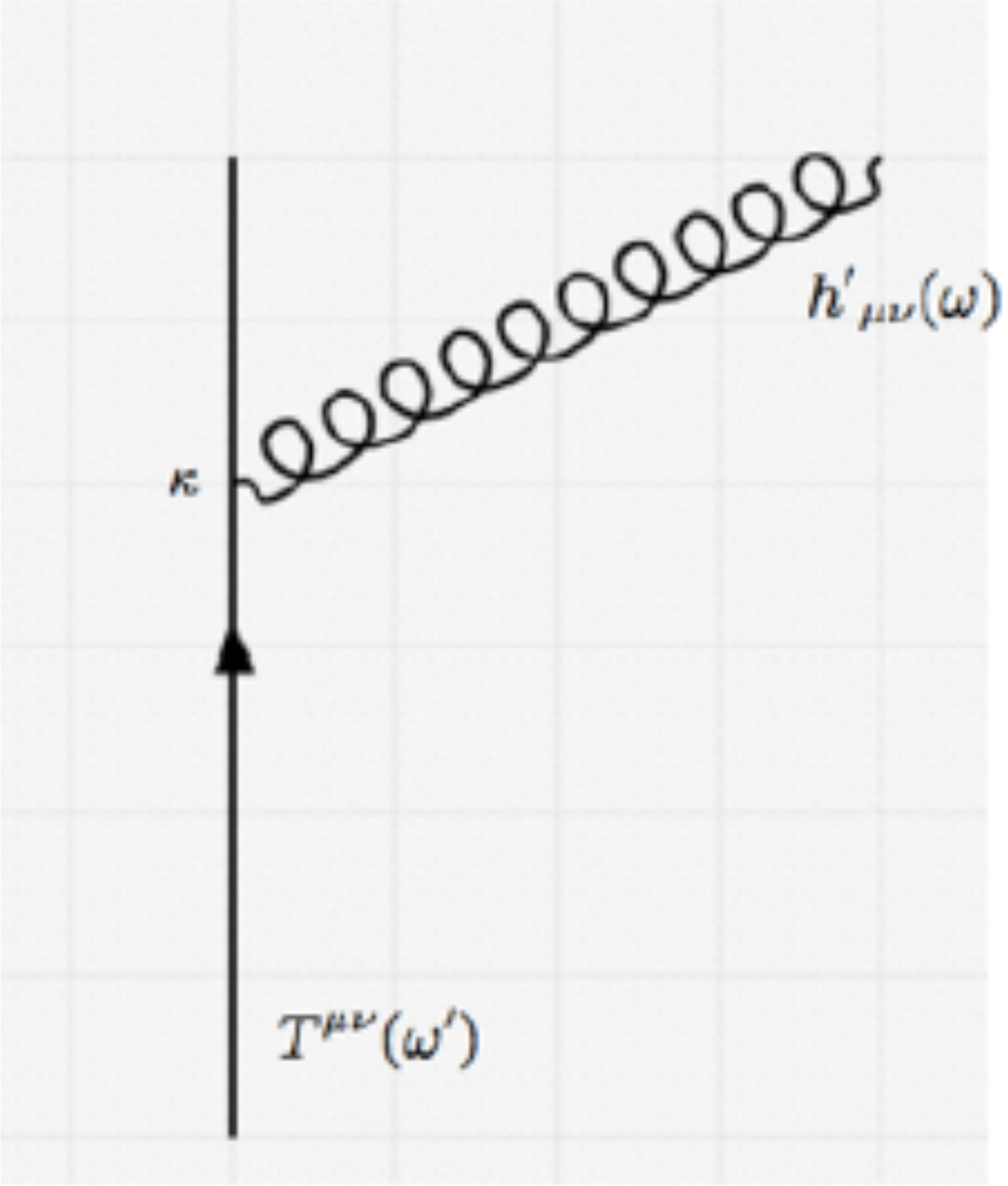
$$\frac{dE}{dt} = \frac{32}{5} G\Omega^6 \left(\frac{m_1 m_2}{m_1 + m_2}\right)^2 a^4 (1 - e^2)^{-7/2} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)$$

P.C. Peters and J. Mathews, Phys. Rev. 131, 435 (1963).

$$\Omega \equiv (G(m_1 + m_2)/a^3)^{1/2} \sim 10^{-19}\ eV$$

Compact binaries can emit particles with mass smaller than $10^{-19}\ eV$

Field theory calculation of Peter Mathew radiation formula



$$g_{\mu\nu}(x) = \eta_{\mu\nu} + h_{\mu\nu}(x)$$

$$\mathcal{L} = \frac{1}{2}\partial_\alpha h'^{\mu\nu}\partial^\alpha h'_{\mu\nu} + \frac{1}{2}\kappa\, h'^{\mu\nu}\,\tilde{T}_{\mu\nu}$$

$$\kappa = \sqrt{32\pi G}$$

$$T_{\mu\nu}(x') = \mu\delta^3(\mathbf{x}' - \mathbf{x}(t))U_\mu U_\nu$$

$$\mu = m_1 m_2/(m_1 + m_2)$$

Rate of graviton emission

$$d\Gamma = \kappa^2 \sum_{\lambda=1}^{2} |T_{ij}(k')\, \epsilon^{TT\,ij}_{(\lambda)}(k)|^2\, 2\pi\, \delta(\omega - \omega')\, \frac{d^3k}{(2\pi)^3}\, \frac{1}{2\omega}$$

$$\sum_{\lambda=1}^{2} \epsilon^{TT\,ij\;*}_{(\lambda)}(k)\, \epsilon^{TT\,lm}_{(\lambda)}(k) = 2\Lambda^{TT}_{ij,lm}$$

$$\frac{dE}{dt} = \int \frac{\kappa^2}{5\pi}\, \omega^2 \left[T_{ij}(\omega')T^*_{ji}(\omega') - \frac{1}{3}|T^{\,i}{}_{i}(\omega')|^2 \right] \delta(\omega - \omega')\, d\omega$$

$$\frac{dE}{dt} = \frac{32}{5} G\Omega^6 \left(\frac{m_1 m_2}{m_1 + m_2} \right)^2 a^4\, (1 - e^2)^{-7/2} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right)$$

Peter- Mathews formula

S. Mohanty and P.K. Panda, Phys.Rev.D53,5723(1996).[hep-ph/9403205]

Rate of time period loss of compact binaries

$$\frac{dP_b}{dt} = -6\pi G^{-3/2}(m_1 m_2)^{-1}(m_1+m_2)^{-1/2}a^{5/2}\left(\frac{dE}{dt}\right)$$
$$= -\frac{192\pi}{5}G^{5/3}\Omega^{5/3}\frac{m_1 m_2}{(m_1+m_2)^{1/3}}(1-e^2)^{-7/2}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)$$

For the Hulse-Taylor binary pulsar

$$dE/dt = 3.2 \times 10^{33} \text{ erg/sec}$$

$$\dot{P}_b = -2.40263 \pm 0.0005 \times 10^{-12}$$

$$\dot{P}_b(observed) = -2.40262 \pm 0.00005 \times 10^{-12}$$

Binary Pulsars can radiate light scalars of gauge bosons

Radiation of long range fifth force scalars

$$\mathcal{L}_s = g_s\, \phi\, \bar{\psi}\, \psi\ = g_s\, \phi\, q(x)$$

$$\frac{dE}{dt} = \frac{1}{24\pi}\left[\left(\frac{N_1}{m_1} - \frac{N_2}{m_2}\right) M\, g_s\right]^2 \Omega^4\, a^2\, \frac{(1+e^2/2)}{(1-e^2)^{5/2}}$$

$$\frac{dE}{dt} = g_s^2 \times 9.62 \times 10^{67}\ \text{ergs/sec}$$

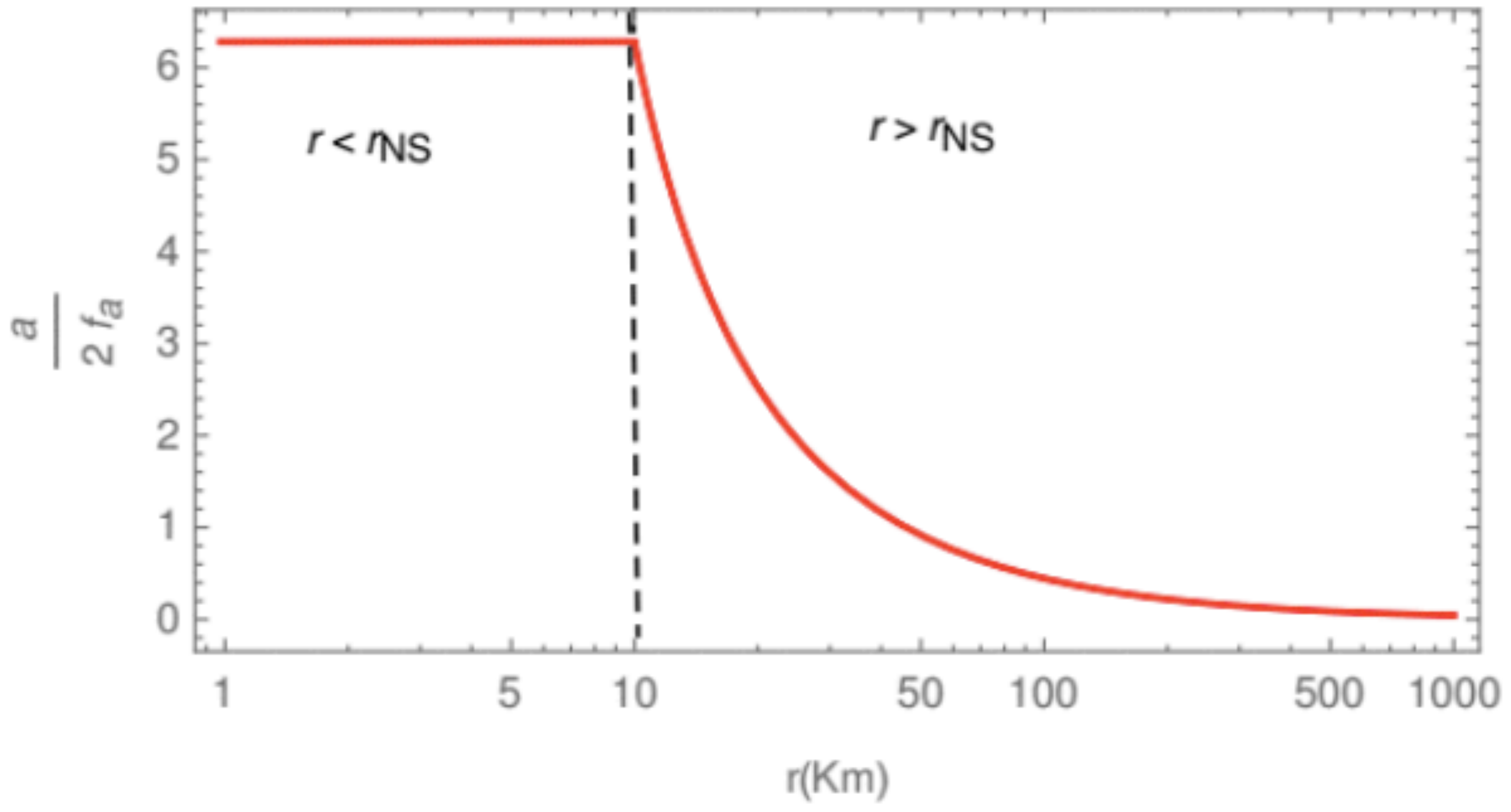
$$g_s < 3 \times 10^{-19}$$

S. Mohanty and P.K. Panda, Phys.Rev.D53,5723(1996).[hep-ph/9403205]

Ultra light Axion dark matter

Neutron stars immersed in axionic FDM have axion charge

$$q_{eff} \sim 4\pi f_a r_{NS}$$ axion charge of NS



A. Hook, J. Huang
J. High Energy. Phys. (2018) 2018:36.

Constraints on ultralight axions from compact binary systems

Tanmay Poddar, Soumya Jana, SM , Phys.Rev.D 101 (2020) 8, 083007

$$q_{eff} = -\frac{8\pi G M f_a}{\ln\left(1 - \frac{2GM}{r_{NS}}\right)}$$

Compact binary system	f_a (GeV)
PSR J0348+0432	$\lesssim 1.66 \times 10^{11}$
PSR J0737-3039	$\lesssim 9.69 \times 10^{16}$
PSR J1738+0333	$\lesssim 2.03 \times 10^{11}$
PSR B1913+16	$\lesssim 2.07 \times 10^{17}$

FDM which couple with quarks ruled out

Ultra light leptonic vector bosons

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

Gauging any one of these quantum numbers is anomaly free

These give rise to long range forces which can be probed by neutrino oscillations.

$L_e - L_\mu,$ $L_e - L\tau$ Joshipura, SM (2004)

$L_\mu - L_\tau$ $$\mathcal{L} \supset g' V_\alpha \left(\bar{\mu}\gamma^\alpha \mu - \bar{\tau}\gamma^\alpha \tau + \bar{\nu}_\mu \gamma^\alpha \nu_\mu - \bar{\nu}_\tau \gamma^\alpha \nu_\tau \right)$$

Difficult to probe by neutrino oscillations experiments

Muon charge in NS $Q_1 \sim Q_2 \sim 10^{55}$ Garani, Heek (2019)

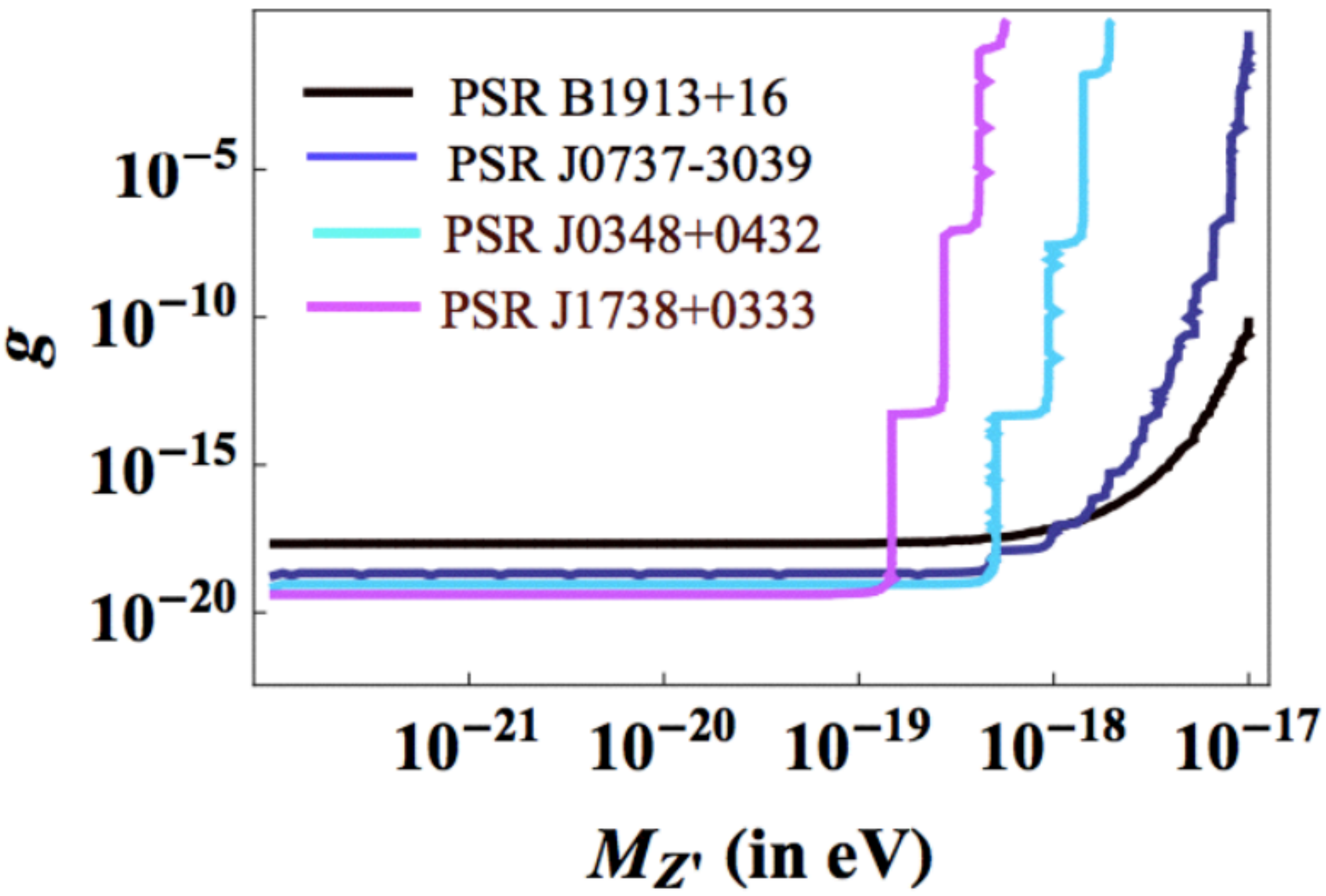
Energy loss of binary stars by vector boson radiation

$$\frac{dE}{dt} = \frac{g^2}{6\pi} a^2 M^2 \left(\frac{Q_1}{m_1} - \frac{Q_2}{m_2}\right)^2 \Omega^4 \frac{(1 + \frac{e^2}{2})}{(1 - e^2)^{\frac{5}{2}}}$$

Constraints on ultralight gauge bosons from compact binary systems

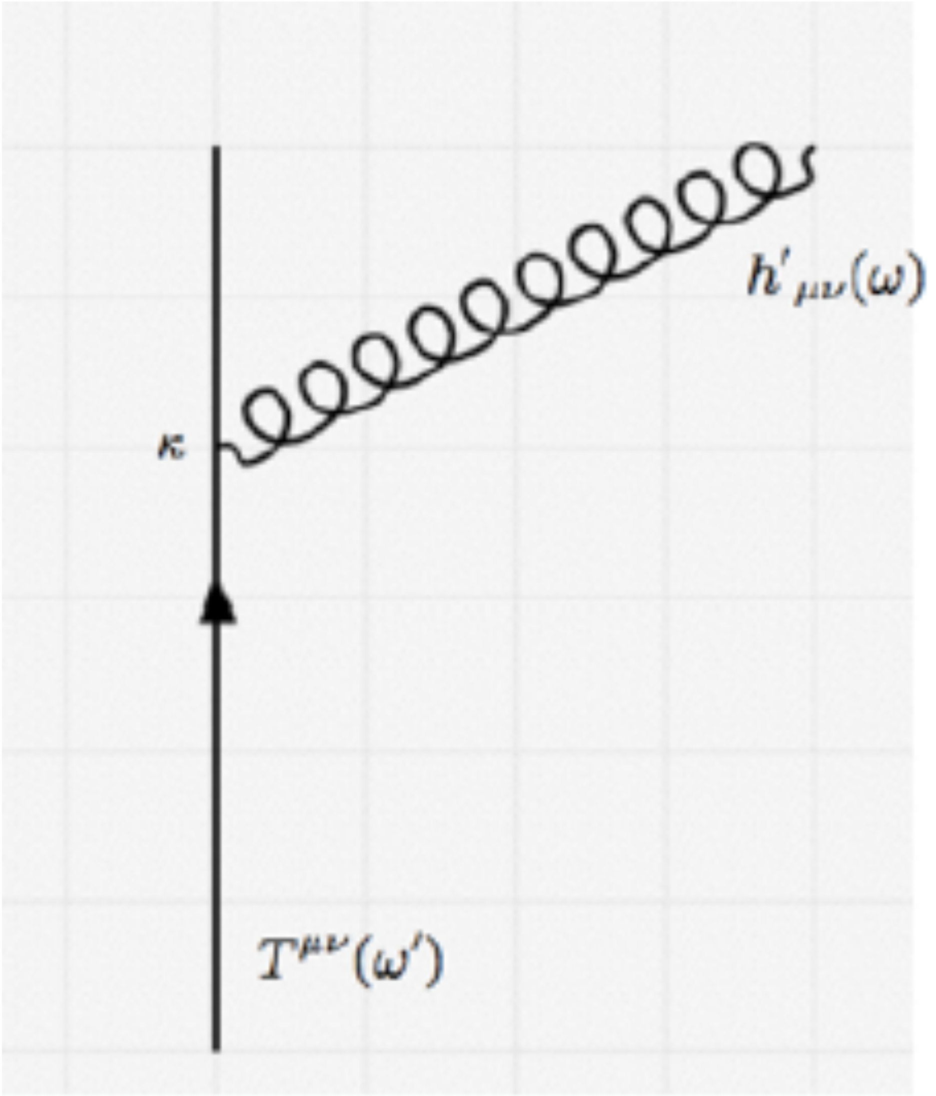
Tanmay Poddar, Soumya Jana, SM , *Phys.Rev.D* 100 (2019) 12, 123023

Tanmay Poddar, Soumya Jana, SM , *Phys.Rev.D* 100 (2019) 12, 123023

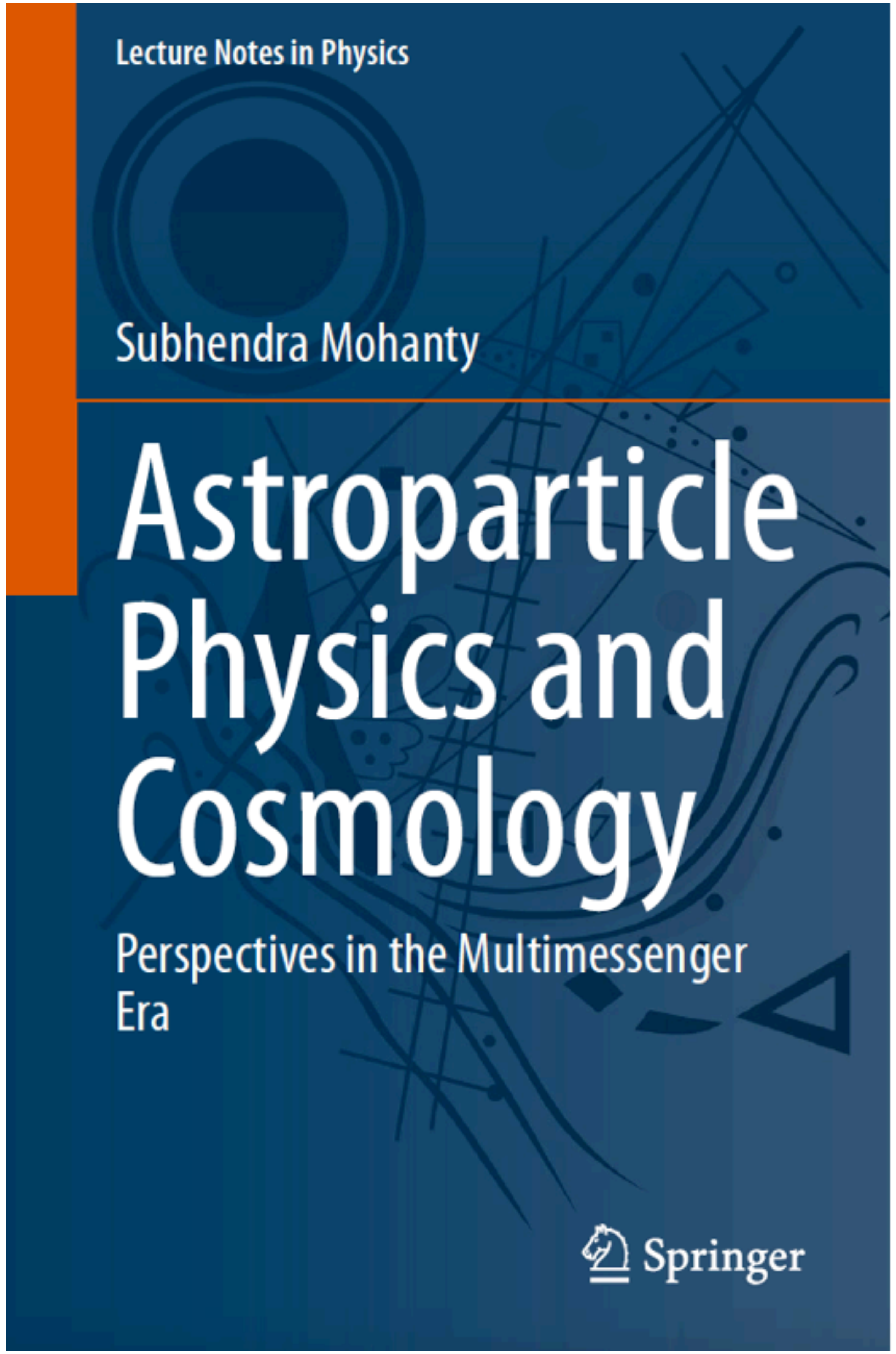


Dror, Laha, Opferkuch (2019) - GW signal

Effective field theory of spin-0, 1, 2 particle radiation from binary stars



Application in binary pulsar timings and gravitational wave signals



Thank You