Axion like particles- cosmological and astrophysical probes

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Interesting axion ideas in the in recent years…

- Fuzzy Dark Matter -
  Hui, Ostriker, Tremaine, Witten (2017);
  Hu, Rennan Barkana, Andrei Gruzinov (2000)
- Superradiance in black holes.
- Binary pulsars -energy loss by ULDM radiation and gravitational waves.

- **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

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

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.

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 = m , T= 500 eV

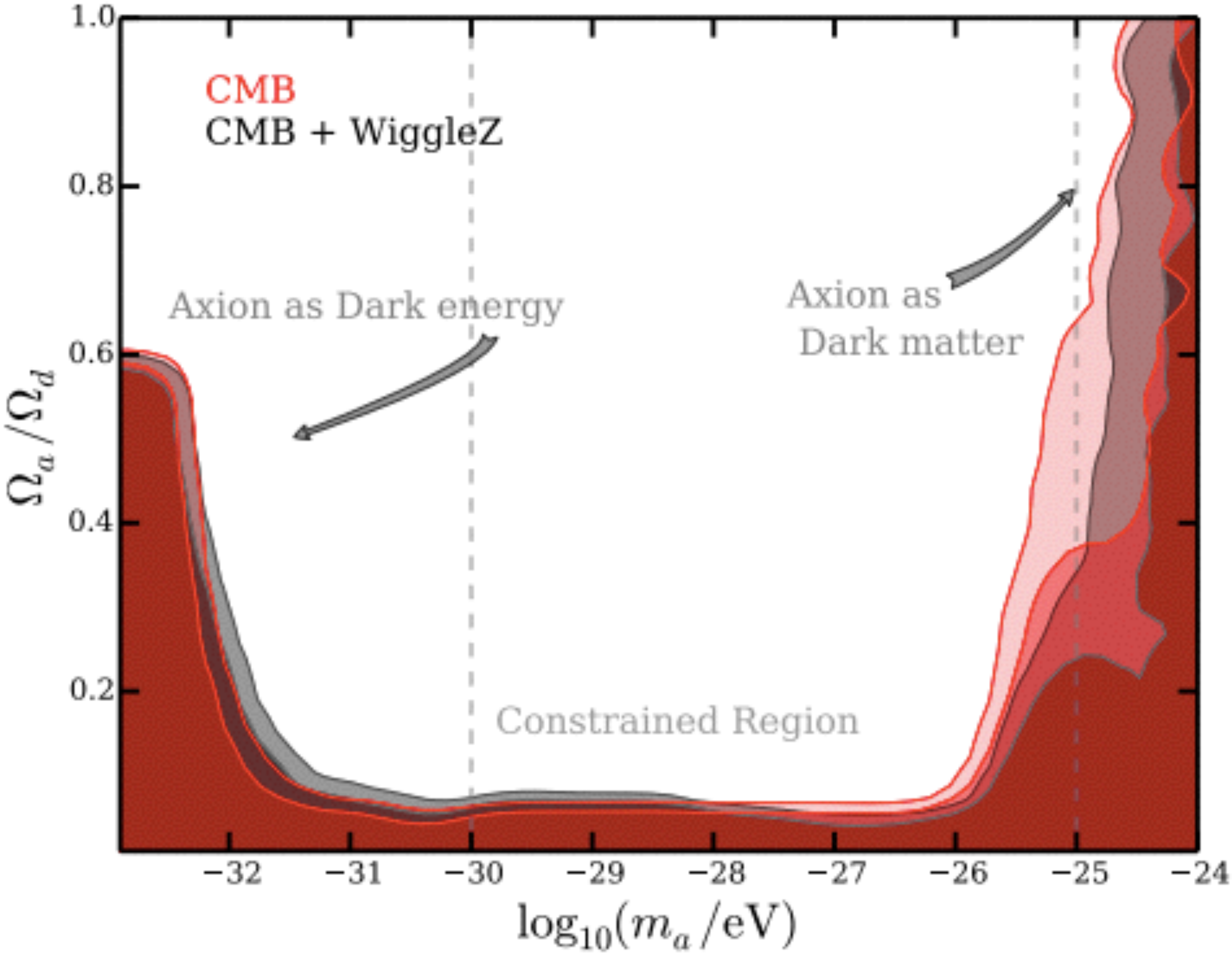
$$\rho_a \sim m_a^2 f^2 \left(\frac{R_i}{R_0}\right)^3$$

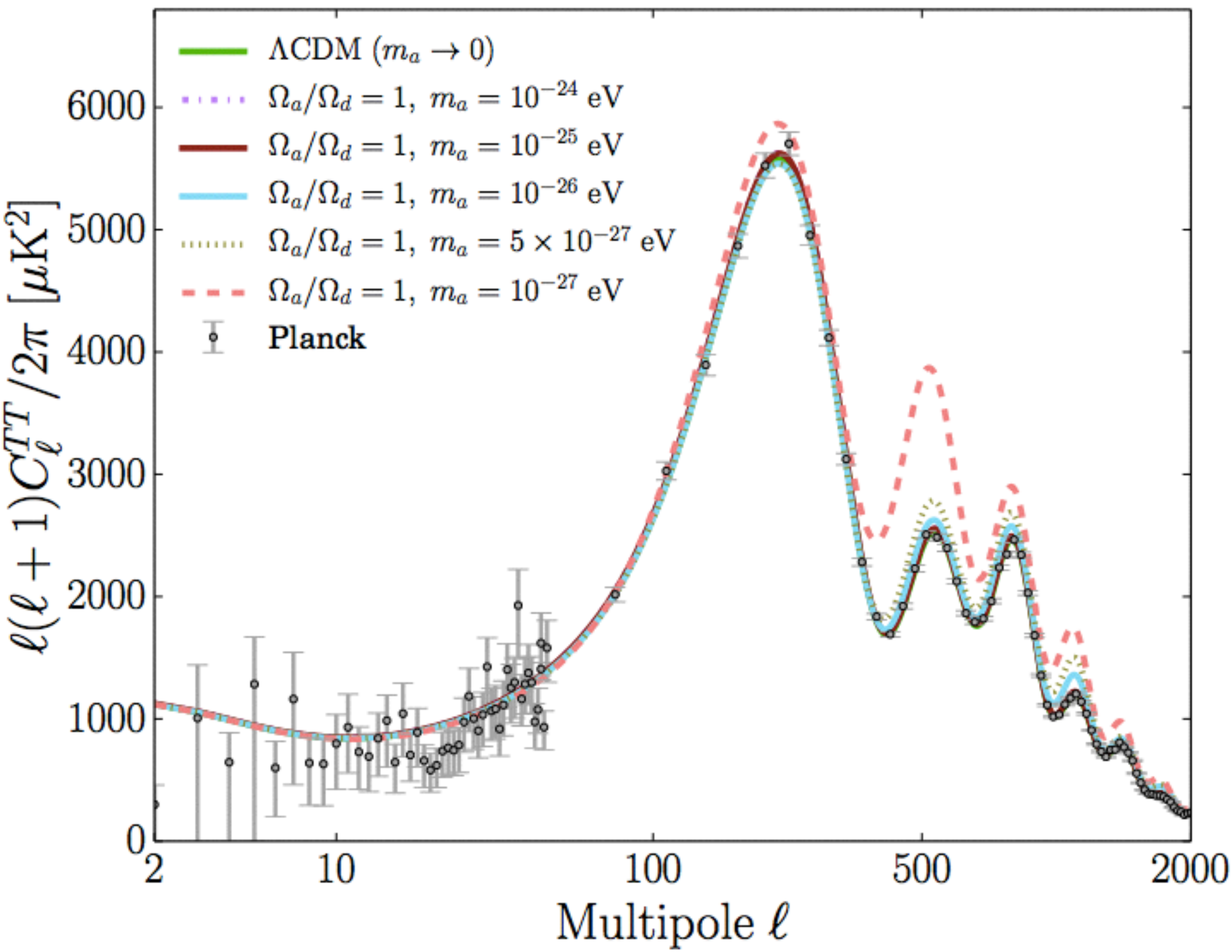
Energy density of Fdm

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

Relic density

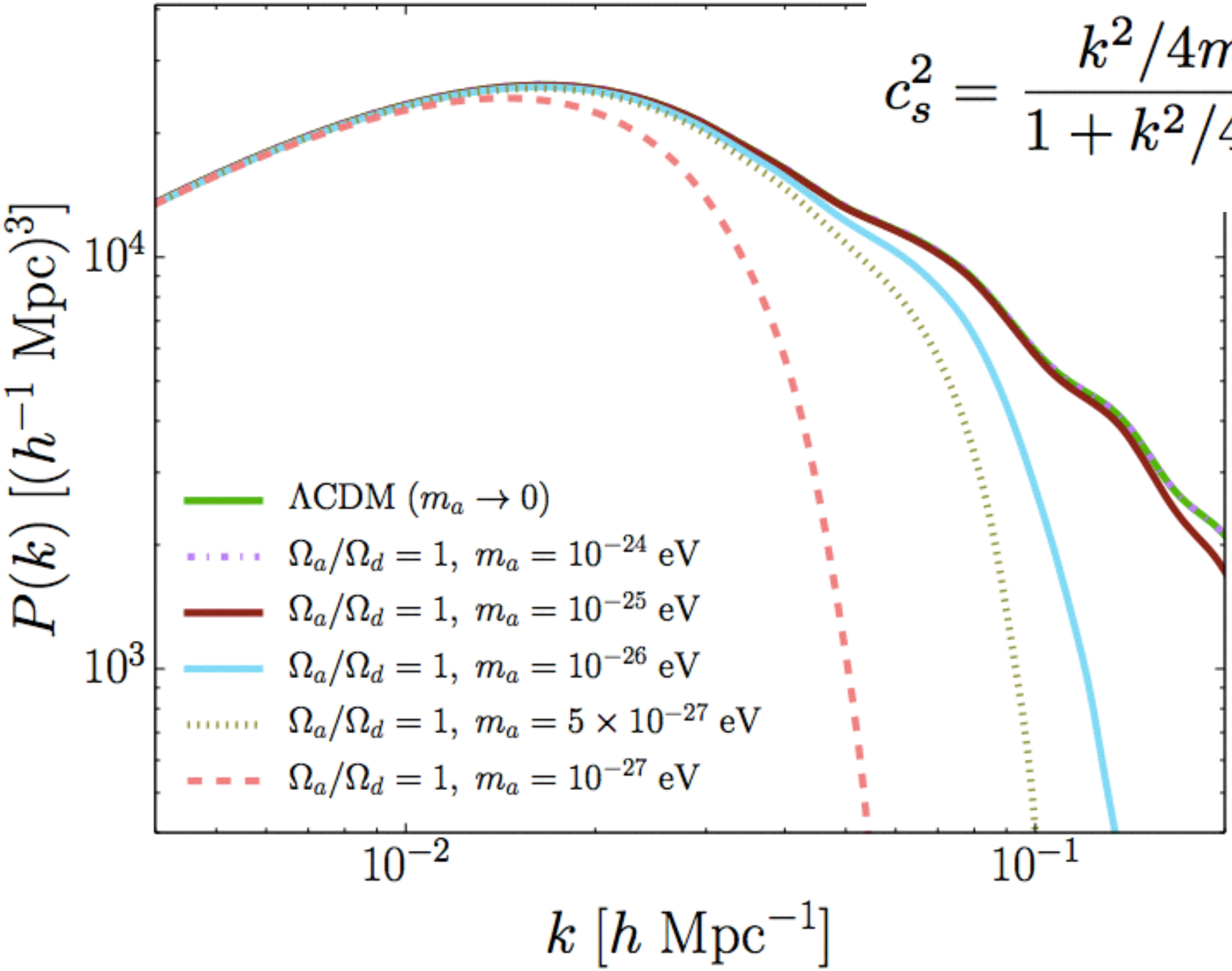
Constraints from CMB - Hlozek et al (2015).



ΛCDM ($m_a \to 0$)
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-24}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-25}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-26}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 5 \times 10^{-27}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-27}$ eV
Planck
$\ell(\ell+1)C_\ell^{TT}/2\pi\ [\mu\mathrm{K}^2]$
6000
5000
4000
3000
2000
1000
0
2
10
100
500
2000
Multipole ℓ

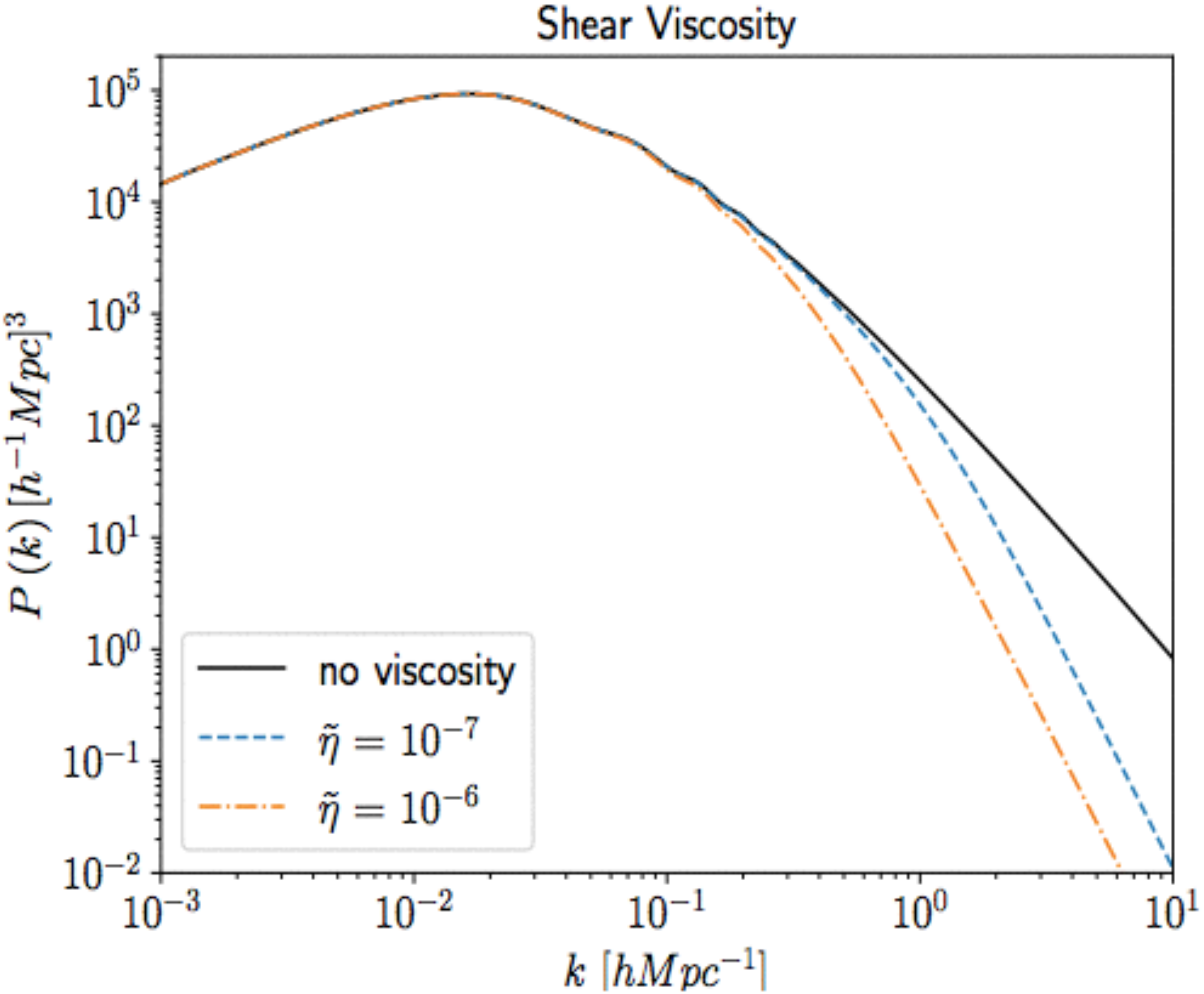
Matter power spectrum of FDM : power at small length scales suppressed.

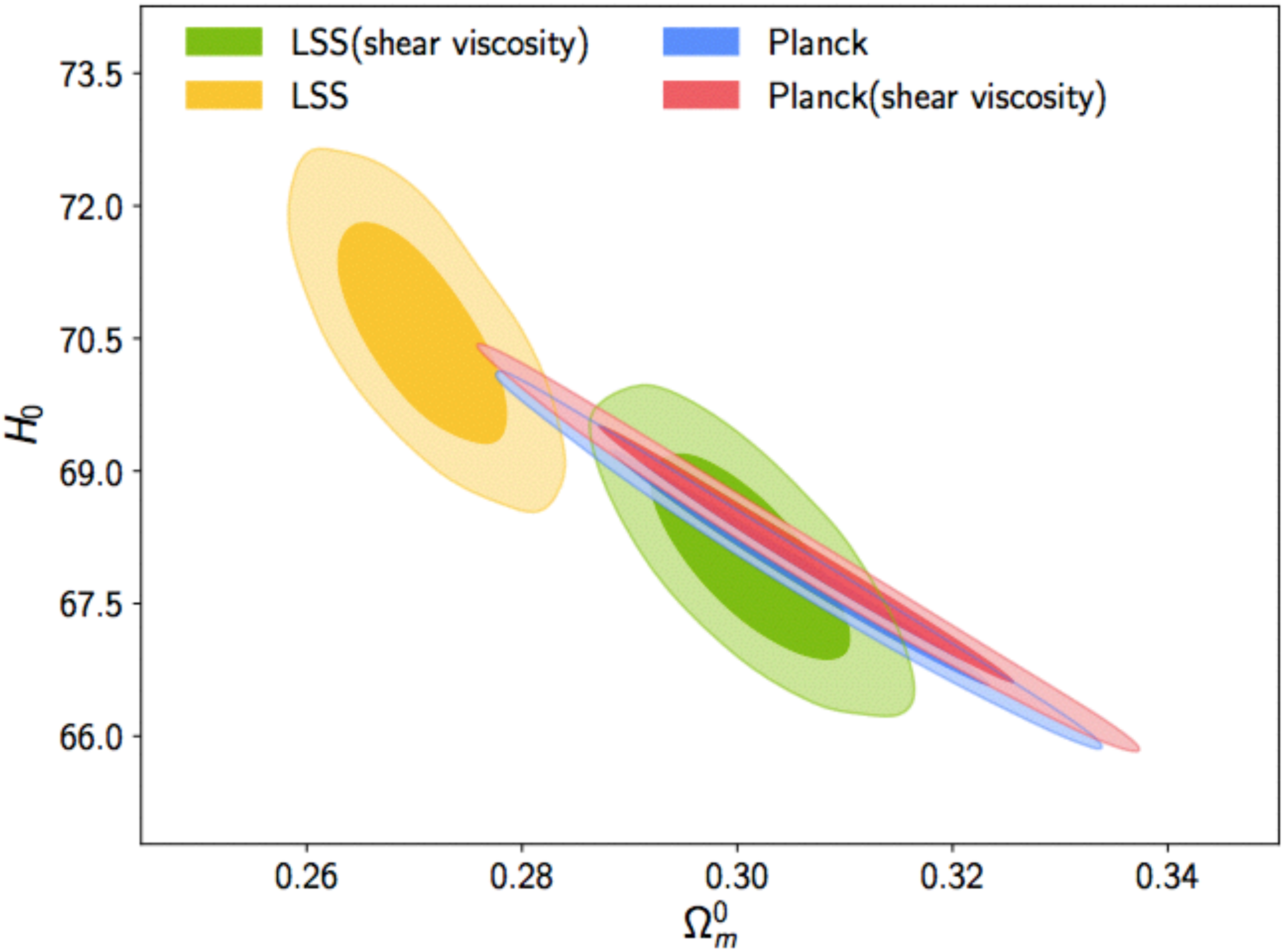
$$c_s^2 = \frac{k^2/4m_a^2a^2}{1+k^2/4m_a^2a^2}$$



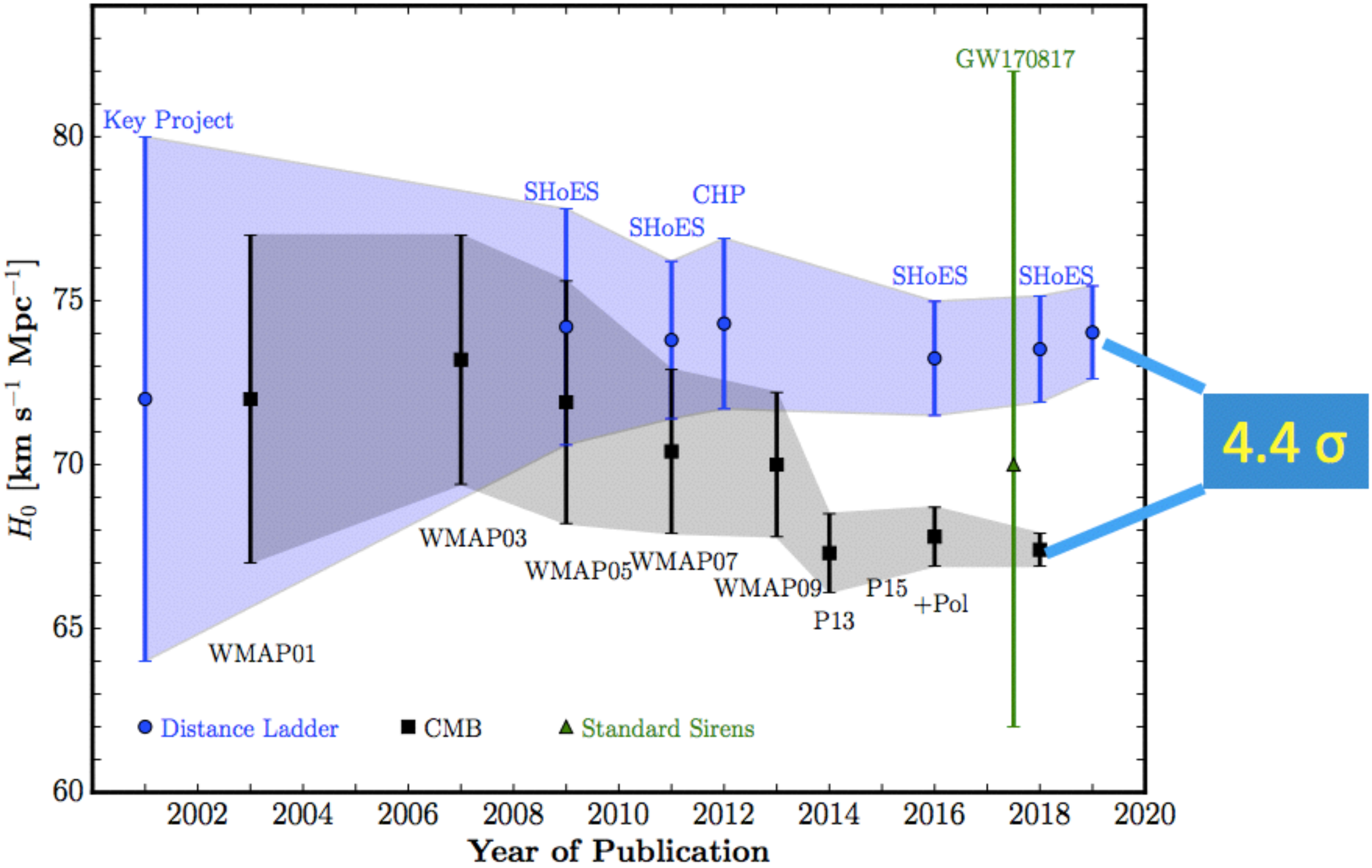
Hlozek et al 2015

Viscous ΛCDM cosmology: S.Anand, P.Chaubal, A.Mazumdar, SM (2017)





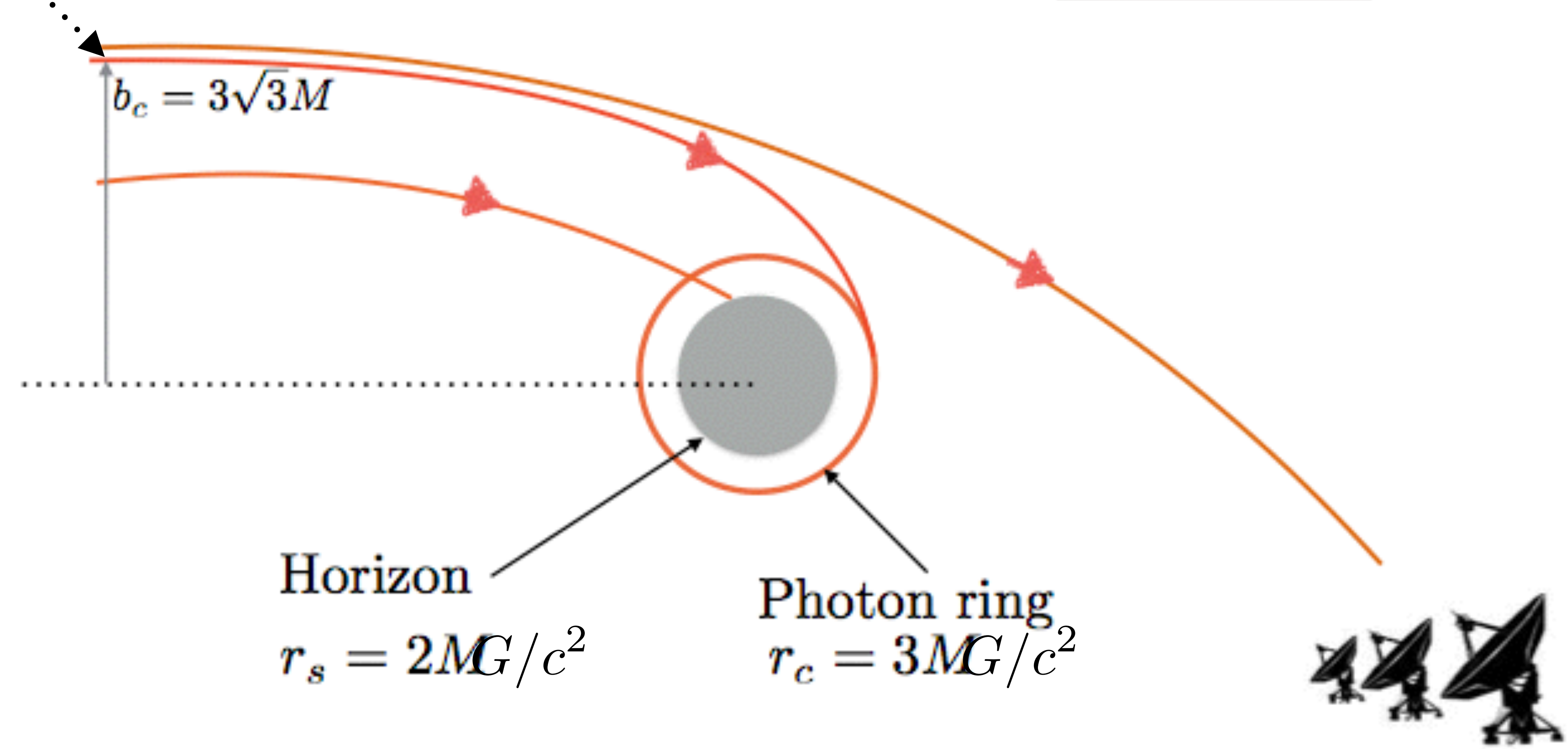
S.Anand, P.Chaubal, A.Mazumdar, SM (2017)



Wendy Freedman, 2019

M87* : The photon shadow is not the event horizon

Photon shadow $r_{shadow} = 3\sqrt{3}MG/c^2$



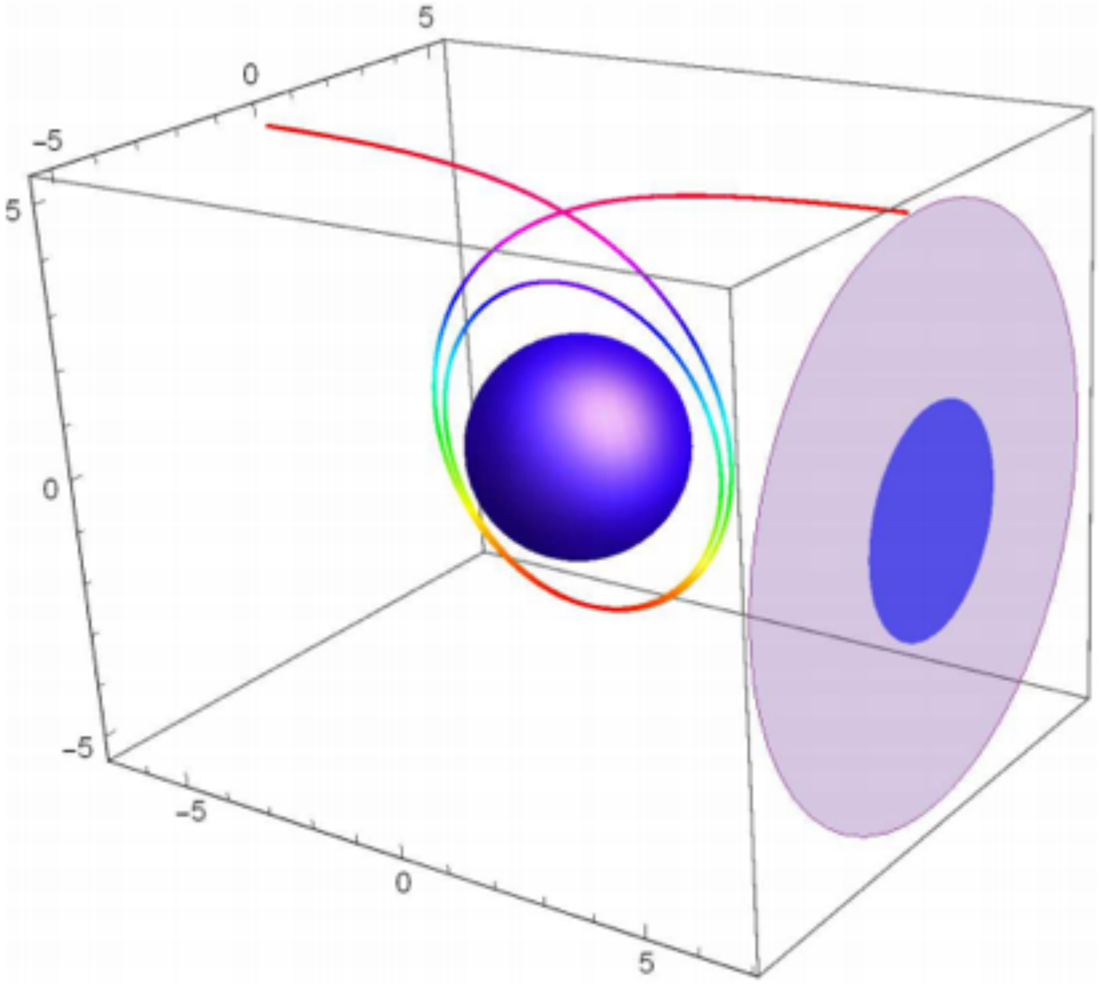
Horizon

$r_s = 2MG/c^2$

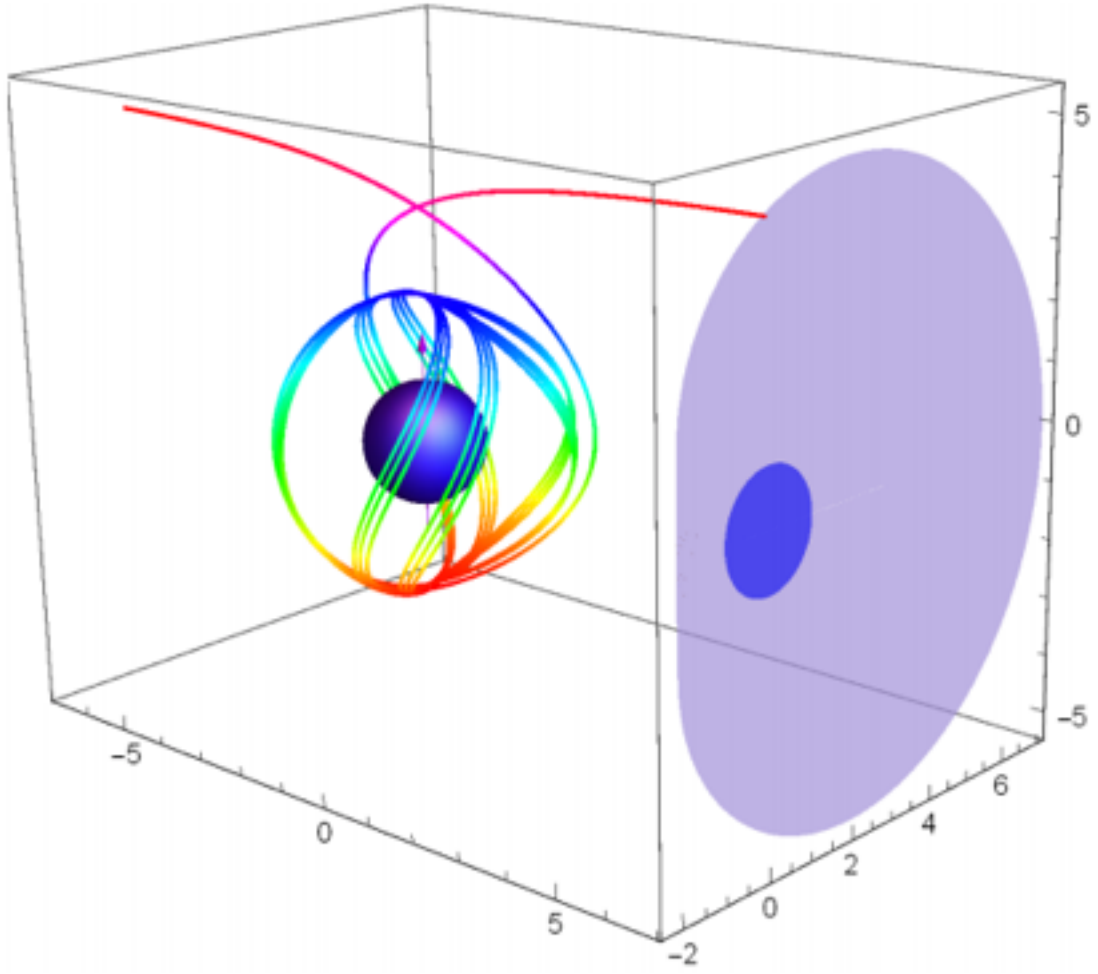
Photon ring

$r_c = 3MG/c^2$

Black hole shadow



Non-rotating BH



Rotating BH (a=1)

First M87 Event Horizon Telescope Results. VI.
The Shadow and Mass of the Central Black Hole

10 April 2019 ApJL

$$M = (6.6 \pm 0.4) \times 10^9\, M_\odot \quad from\ stellar\ dynamics\,(2011)$$

$$M = (3.5 \pm 0.9) \times 10^9\, M_\odot \quad from\ gas\ dynamics\,(2013)$$

EHT observations:

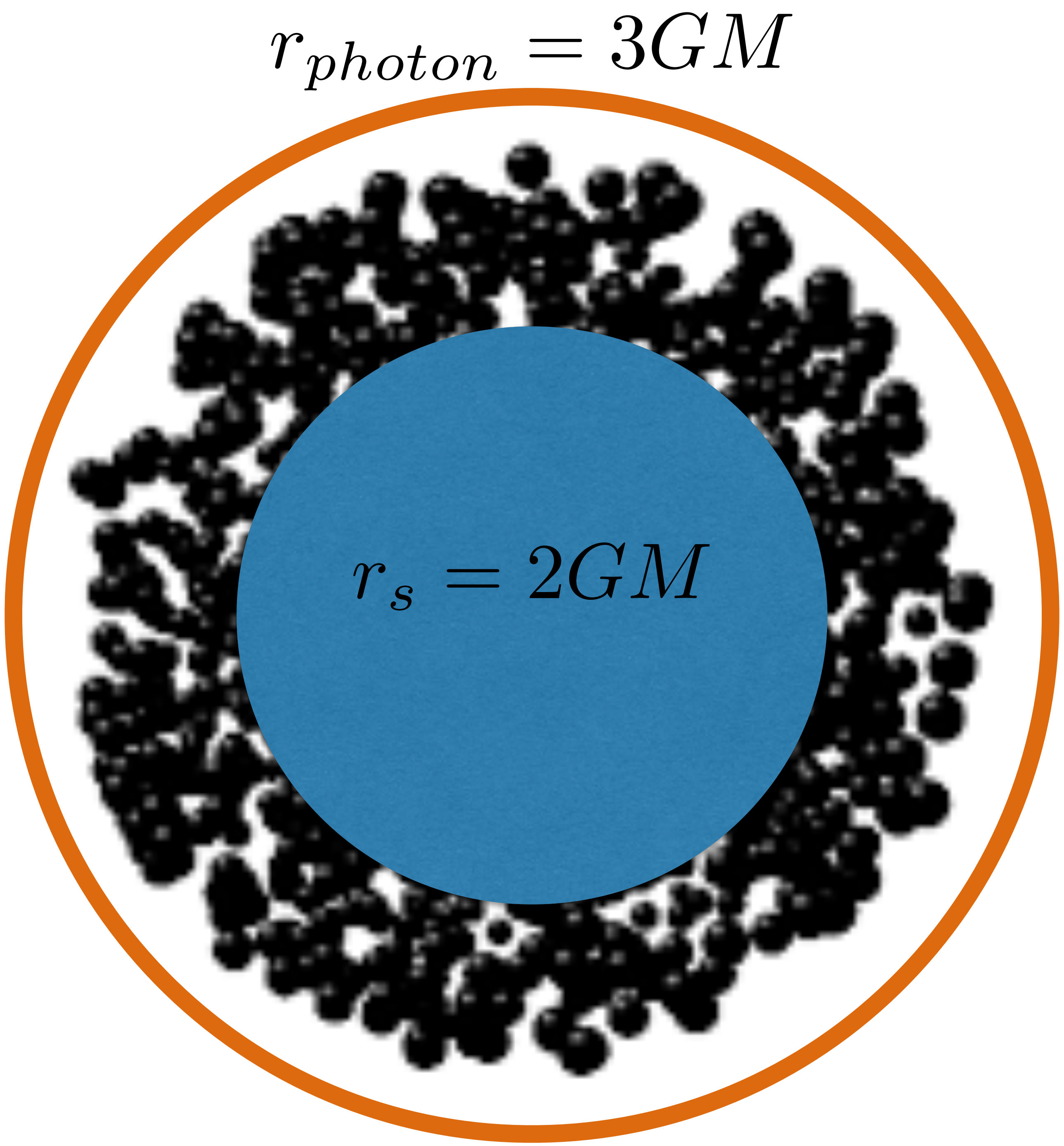
Shadow diameter $d = \dfrac{2r_{shadow}}{D} = 42 \pm 3\ \mu as$

$$\Longrightarrow\ M = (6.5 \pm 0.2|_{stat} \pm 0.7|_{sys}) \times 10^9 M_\odot$$

$$r_s = 6 \times 10^{-4}\, pc$$

Motion of stars and gas around Milky Way center Sgr A*

Mass of Sgr A* $= 4 \times 10^6 M_\odot$



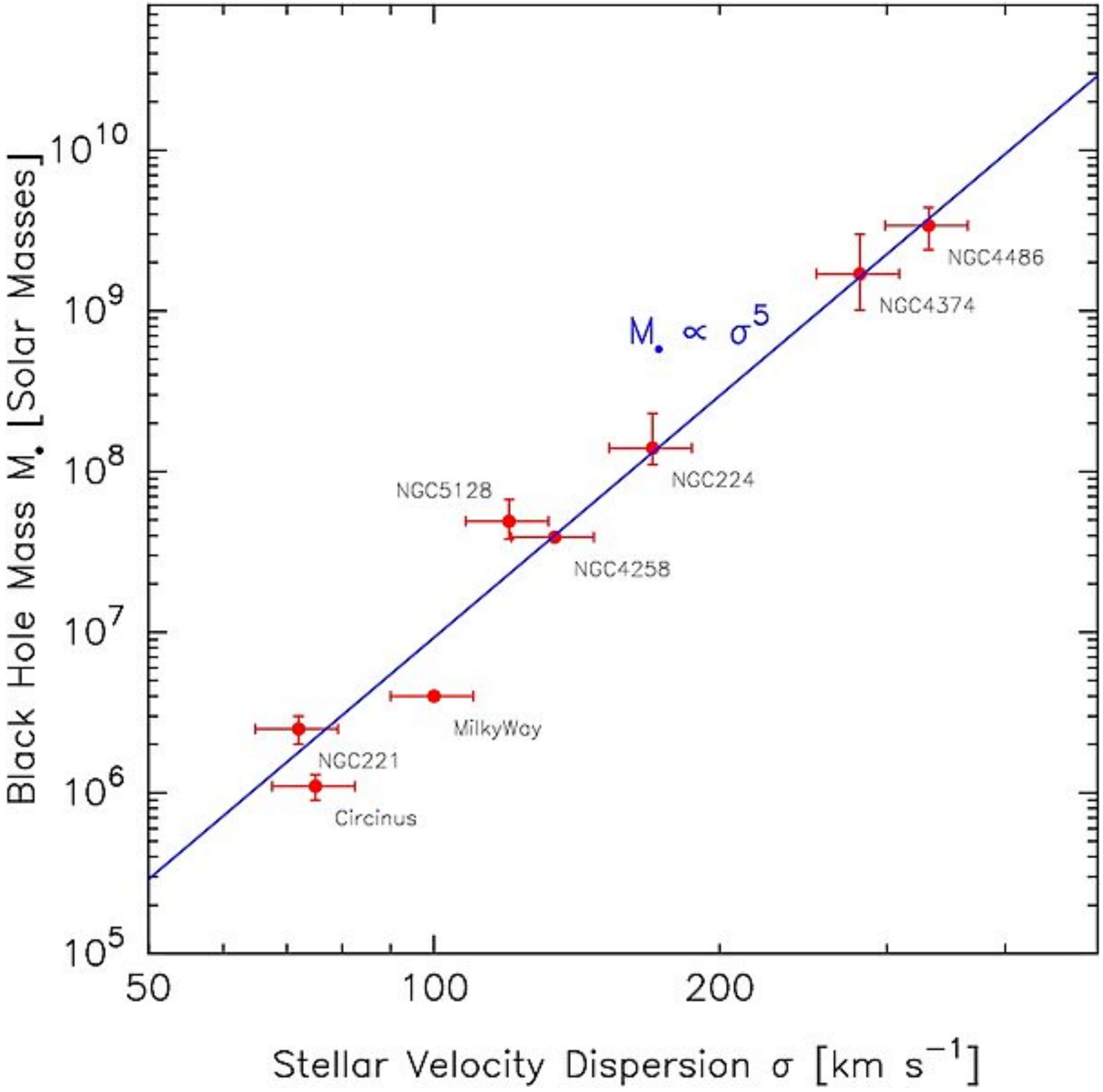
Buchadahl Theorem:
minimum packing
radius of normal matter

$$R_{min} = \frac{9}{8} r_s$$

$$\rho = \frac{M}{(\frac{4\pi}{3})(GM)^3} = 0.00016 \quad gm/cm^3$$

Density of M87 ‘BH’

MBH - sigma relation between galactic BH mass and velocity dispersion



FDM constraints from Black Hole observation

Ultralight Boson Dark Matter and Event Horizon Telescope Observations of M87* - Davoudiasl and Denton (2019)

Superradiant instability of a Kerr black hole

$$\frac{\omega_b}{n} < \Omega_H$$

Energy of gauge boson ω_b

$$\Omega_H = \frac{1}{2r_g}\frac{a^*}{1+\sqrt{1-a^{*2}}}$$

Angular momentum of outer horizon

$$a^* \equiv J_{\rm BH}/(G_N M_{\rm BH}^2)$$

Spin parameter

Instability rate for scalars

$$\Gamma_s = \frac{1}{24} a^* \, r_g^8 \, m_a^9$$

Detweiler (1980)

Instability rate for vectors

$$\Gamma_V = 4 a^* \, r_g^6 \, m_a^7$$

No instability for fermions

M87* BH has mass $M \sim 6.5 \times 10^9 M_\odot$

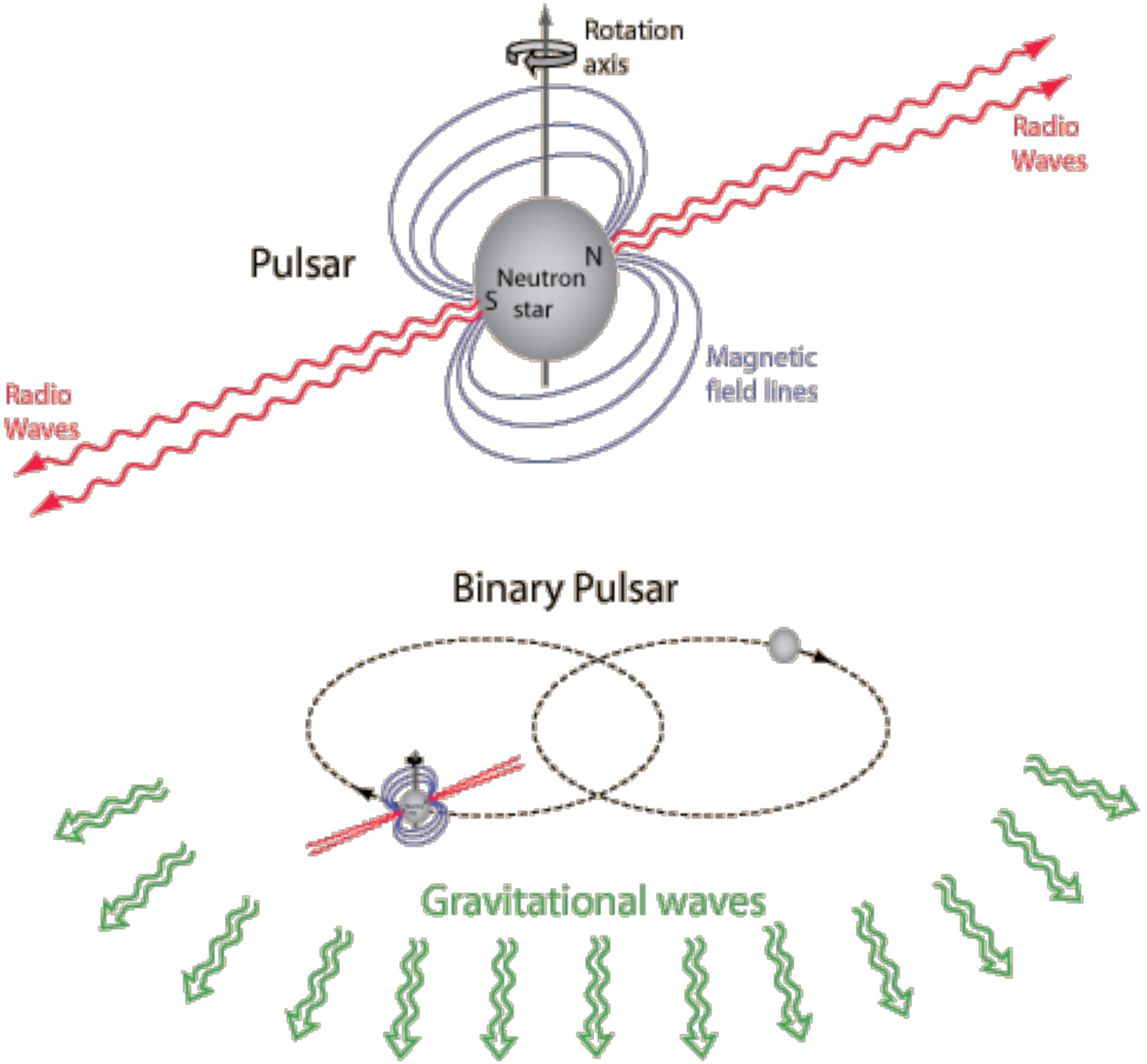
Spin parameter $a^* \sim 0.9$

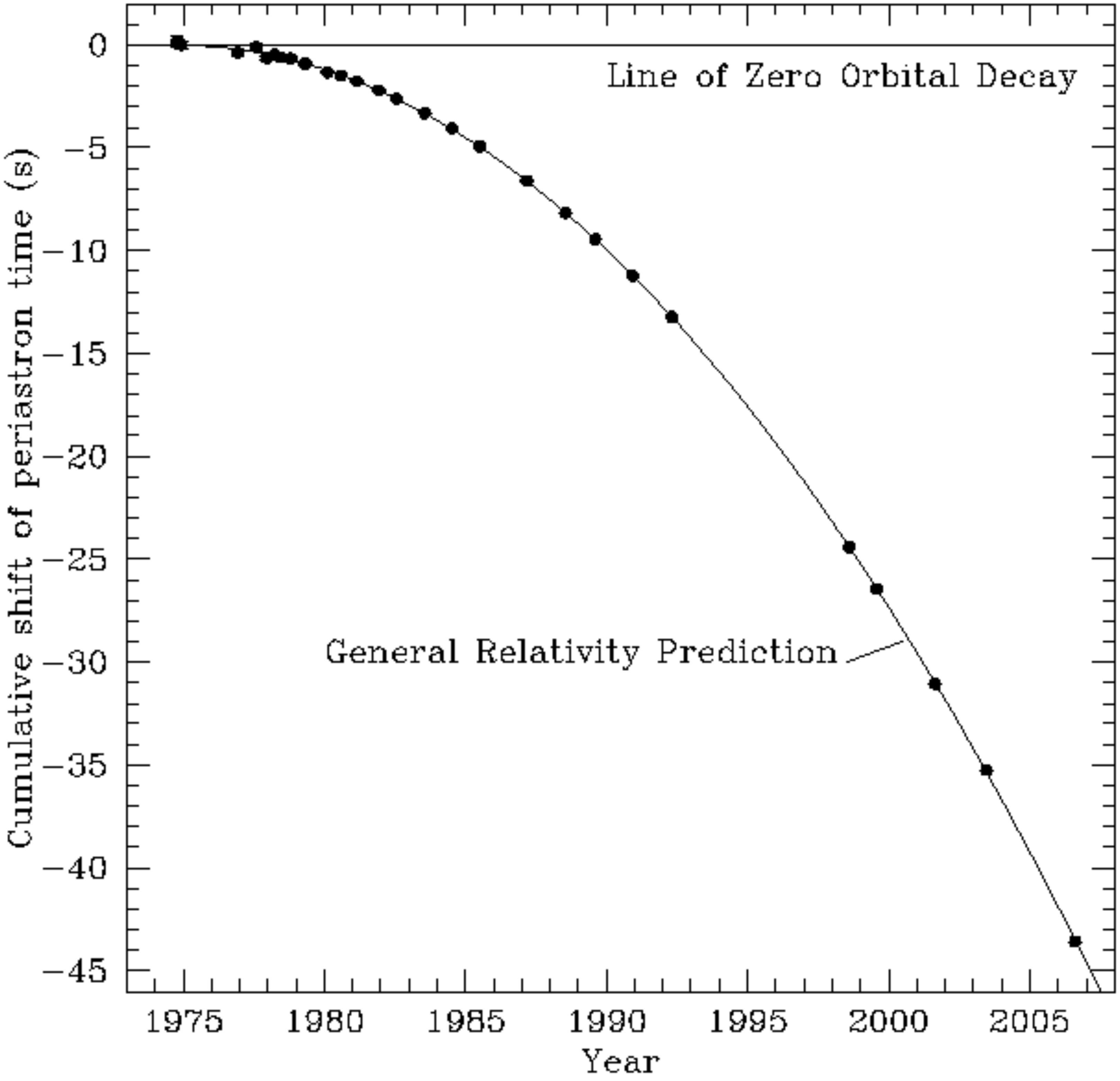
Ruled out parameter space

$$2.9 \times 10^{-21}\ \mathrm{eV} < \quad m_a \quad < 4.6 \times 10^{-21}\ \mathrm{eV}$$

$$8.5 \times 10^{-22}\ \mathrm{eV} < \quad m_V \quad < 4.6 \times 10^{-21}\ \mathrm{eV}$$

Pulsar timings : First indirect observation of gravitational waves





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

Rate of energy loss by gravitational radiation

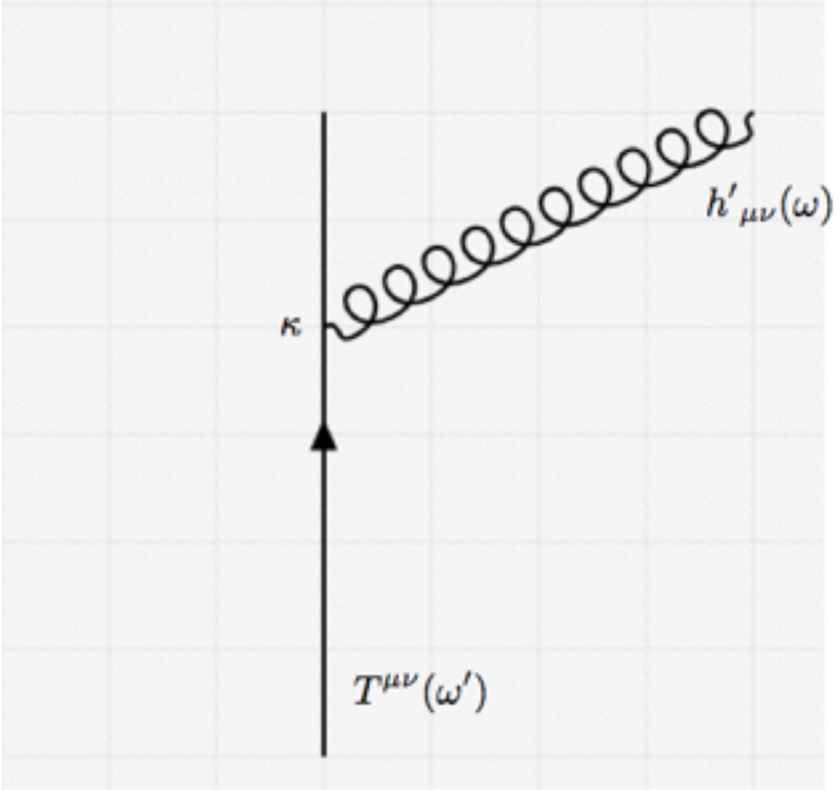
$$\frac{dE}{dt} = \frac{32}{5} G \Omega^6 \left(\frac{m_1 m_2}{m_1 + m_2} \right)^2 a^4 \left(1 - e^2\right)^{-7/2} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right)$$

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

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

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

Feynman diagram calculation of Peters Mathews formula



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

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

$$h'_{\mu\nu} = \kappa^{-1} h_{\mu\nu}$$

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

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

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

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

Rate of graviton emission

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

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

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

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

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

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

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

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

Radiation of long range fifth force scalars

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

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

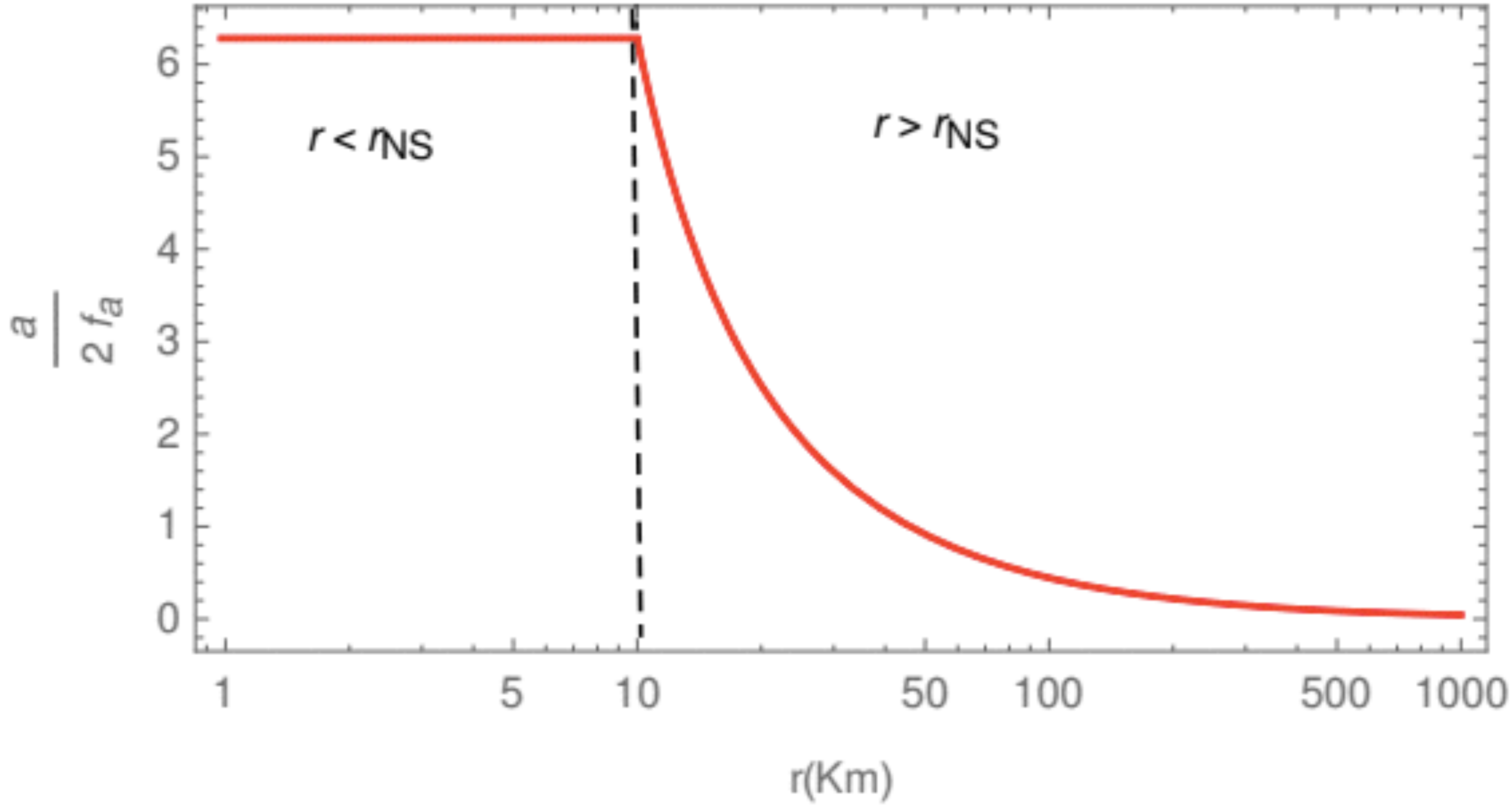
$$\frac{dE}{dt} = g_s^2 \times 9.62 \times 10^{67} \text{ ergs/sec}$$

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

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

Neutron stars immersed in axionic FDM have axion charge

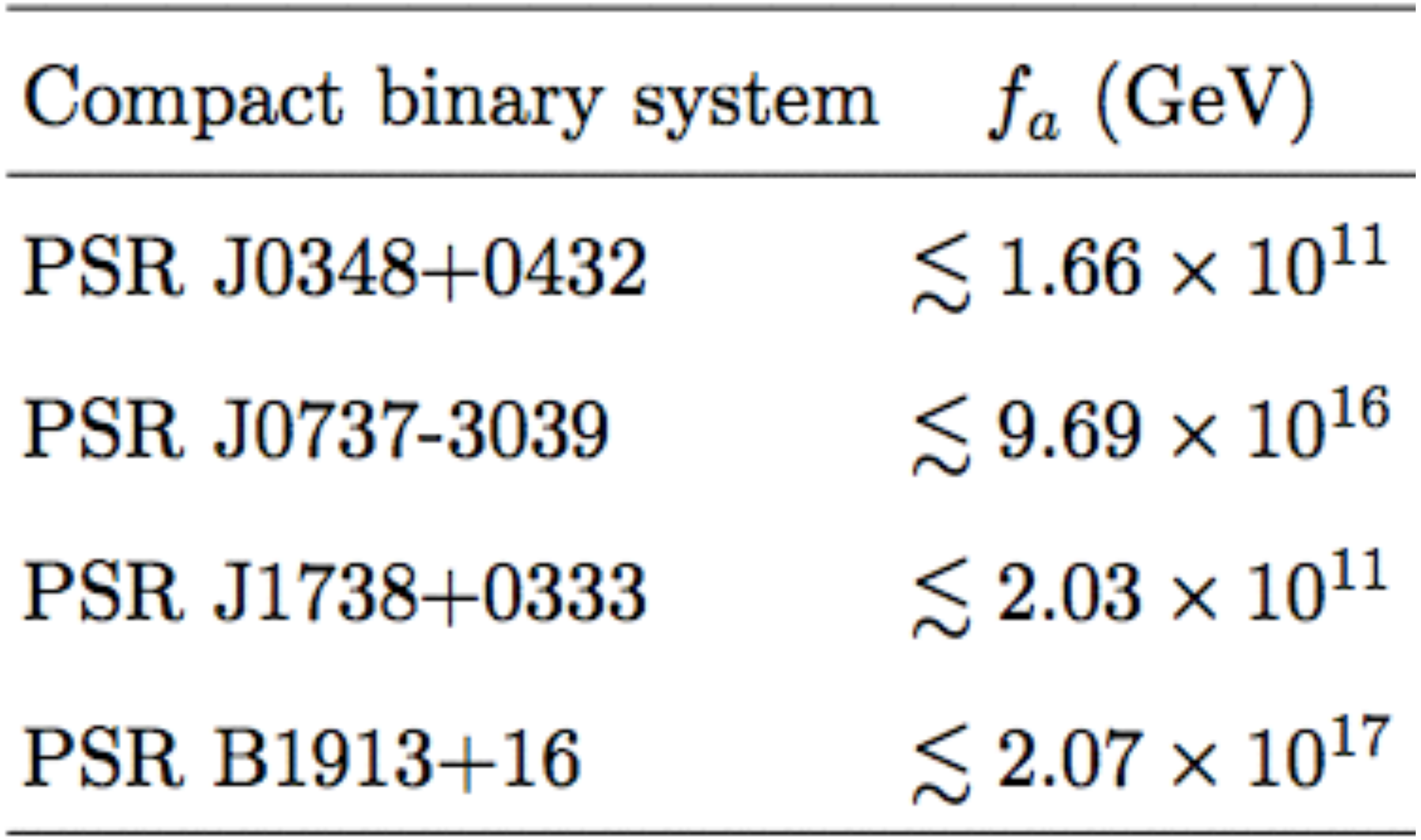
$q_{eff} \sim 4\pi f_a r_{NS}$ axion charge of NS



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

Soumya Jana, Tanmoy Poddar, SM 1906.00666

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



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.

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

Vector gauge boson radiation from neutron star binaries in a gauged $L\mu{-}L\tau$ scenario

Soumya Jana , Tanmoy Poddar , SM (2019)

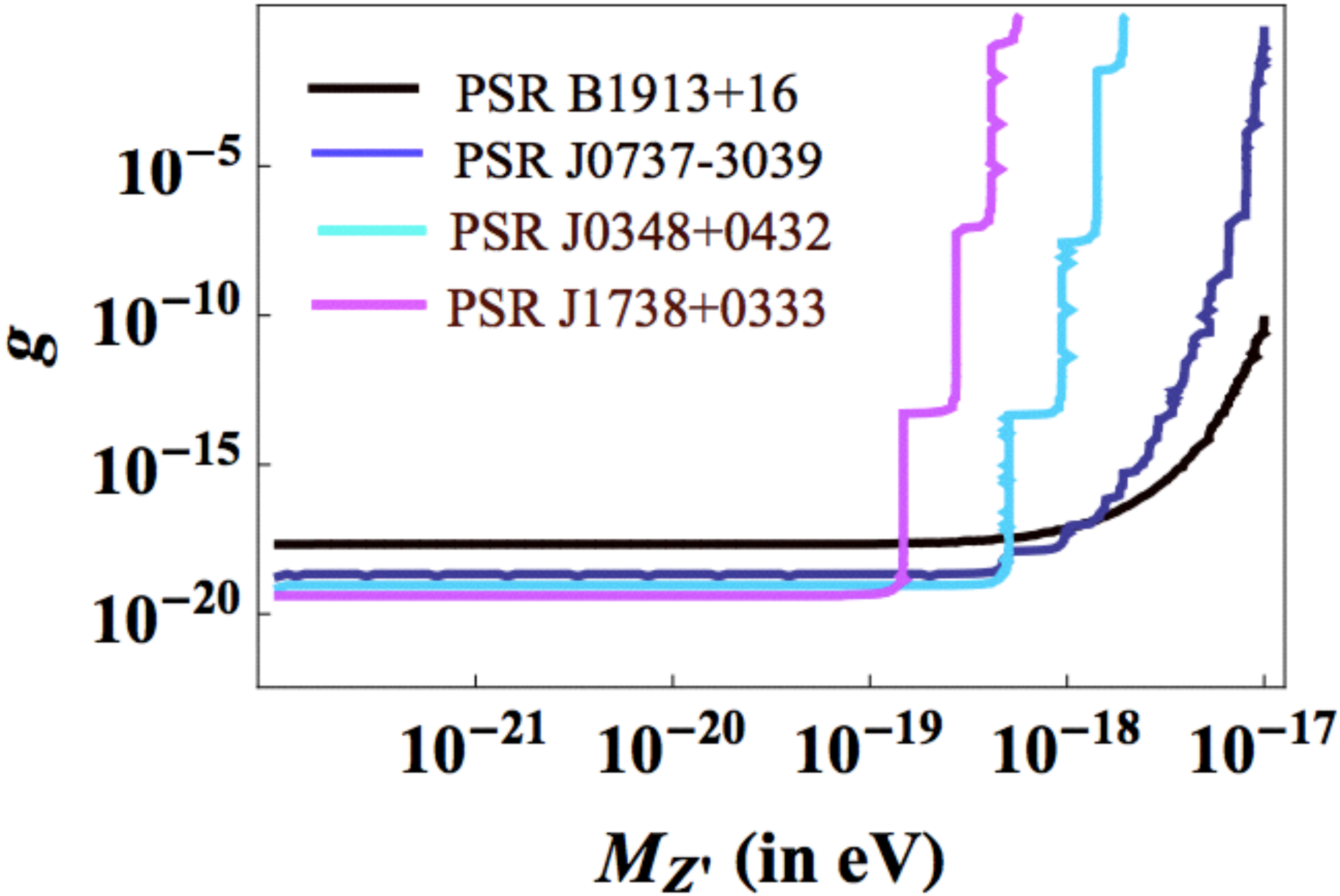
$$\frac{dE}{dt} = \frac{g^2}{6\pi} a^2 M^2 \left(\frac{Q_1}{m_1} - \frac{Q_2}{m_2}\right)^2 \Omega^4 \frac{(1 + \frac{e^2}{2})}{(1 - e^2)^{\frac{5}{2}}}$$

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

Energy loss by vector boson radiation in binary stars

Constraints from binary NS timings

Soumya Jana , Tanmoy Poddar , SM (2019)



Dror, Laha, Opferkuch (2019) - GW signal

Thank You