Dark Photon in Astrophysical Laboratories

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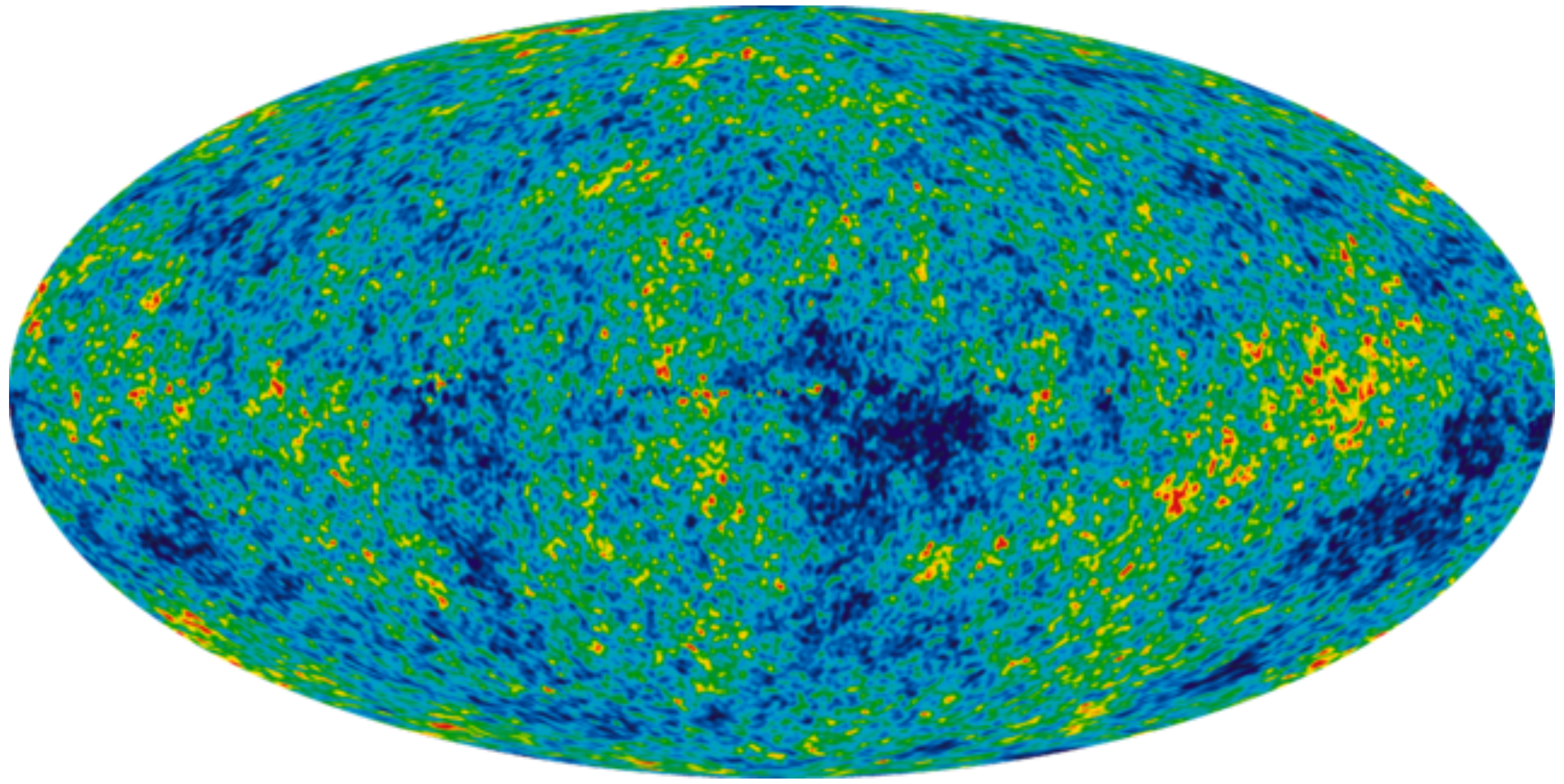
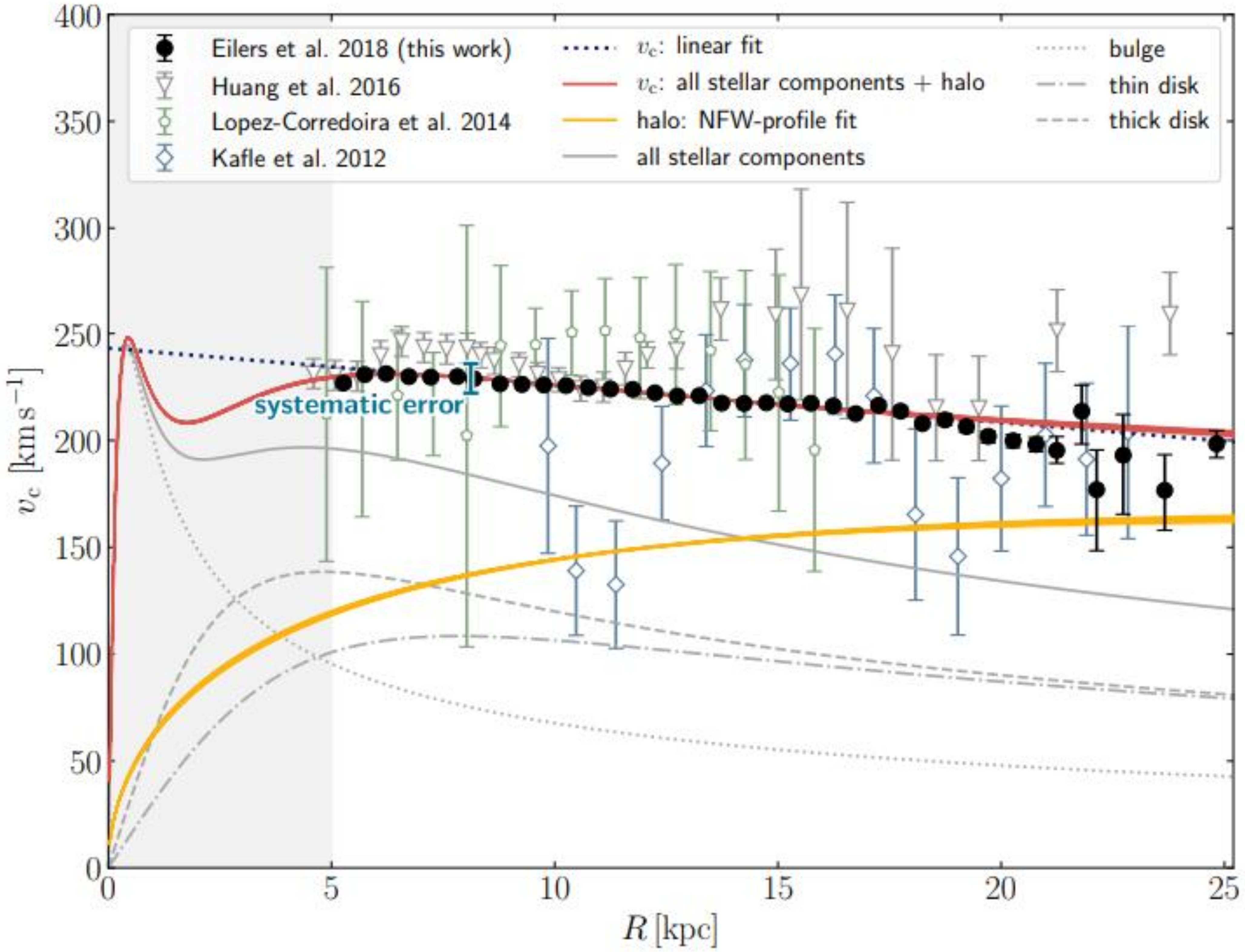
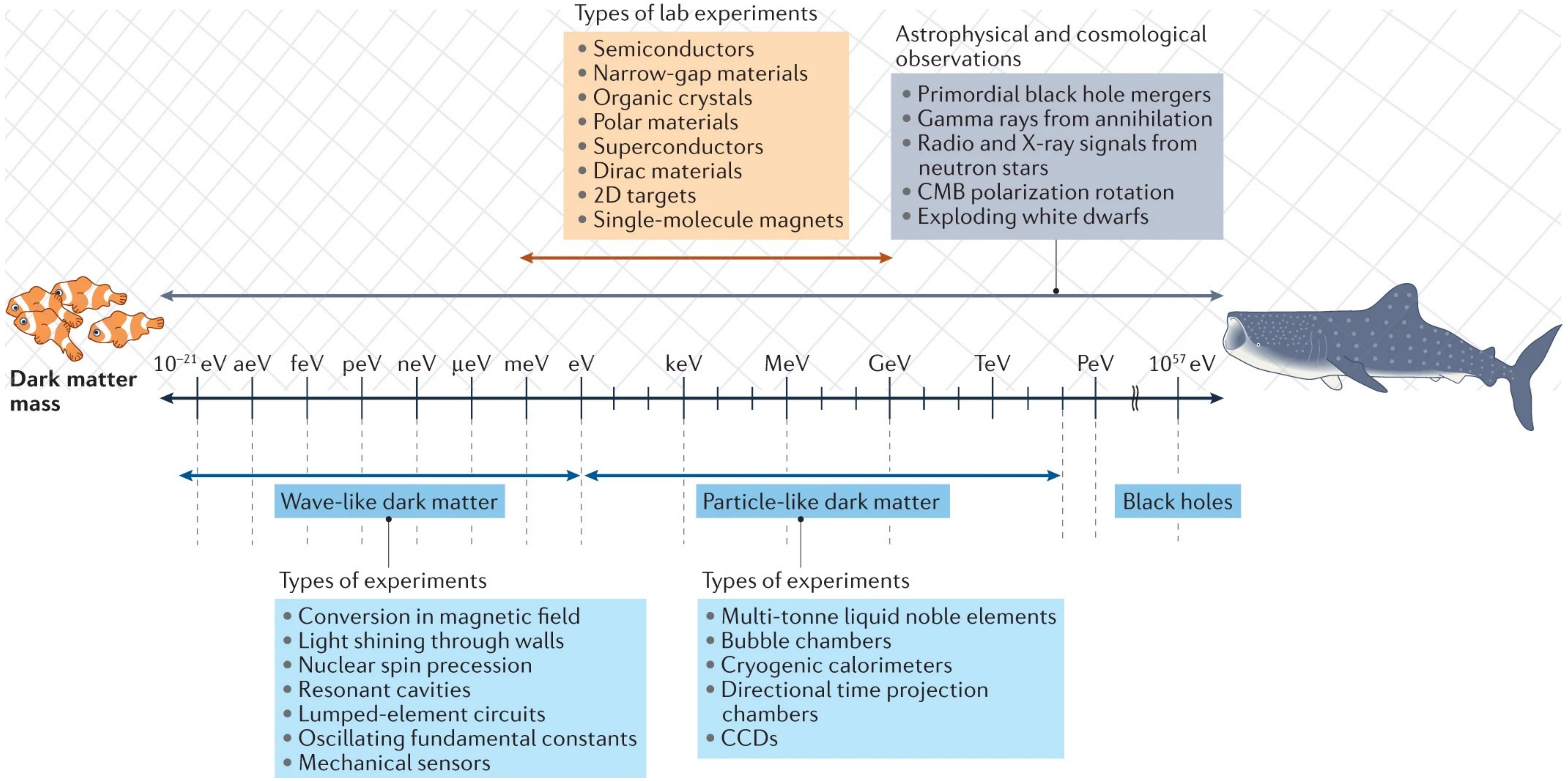
October 20, 2023



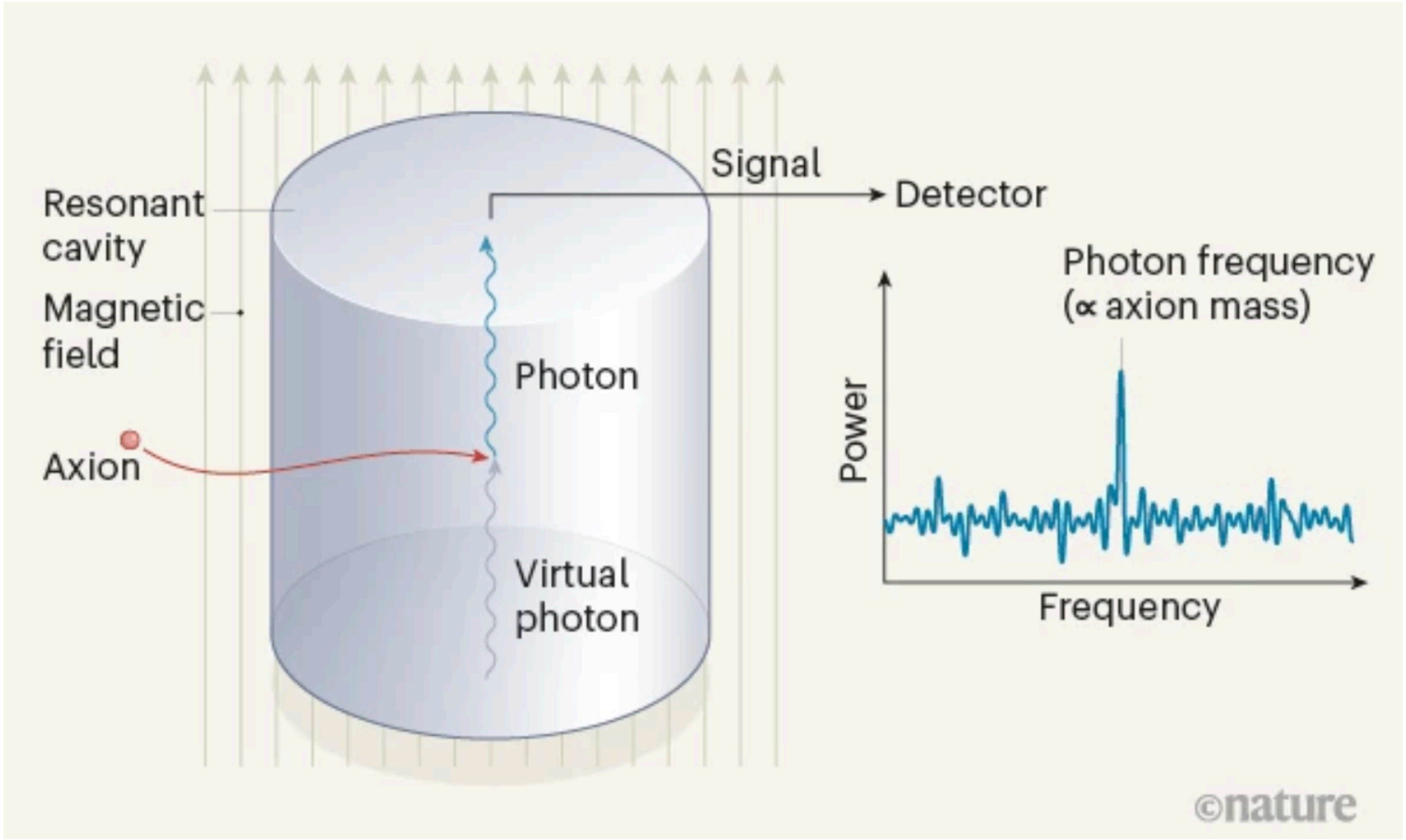


Eilers *et al.*, 1810.09466

Wave-like Dark Matter



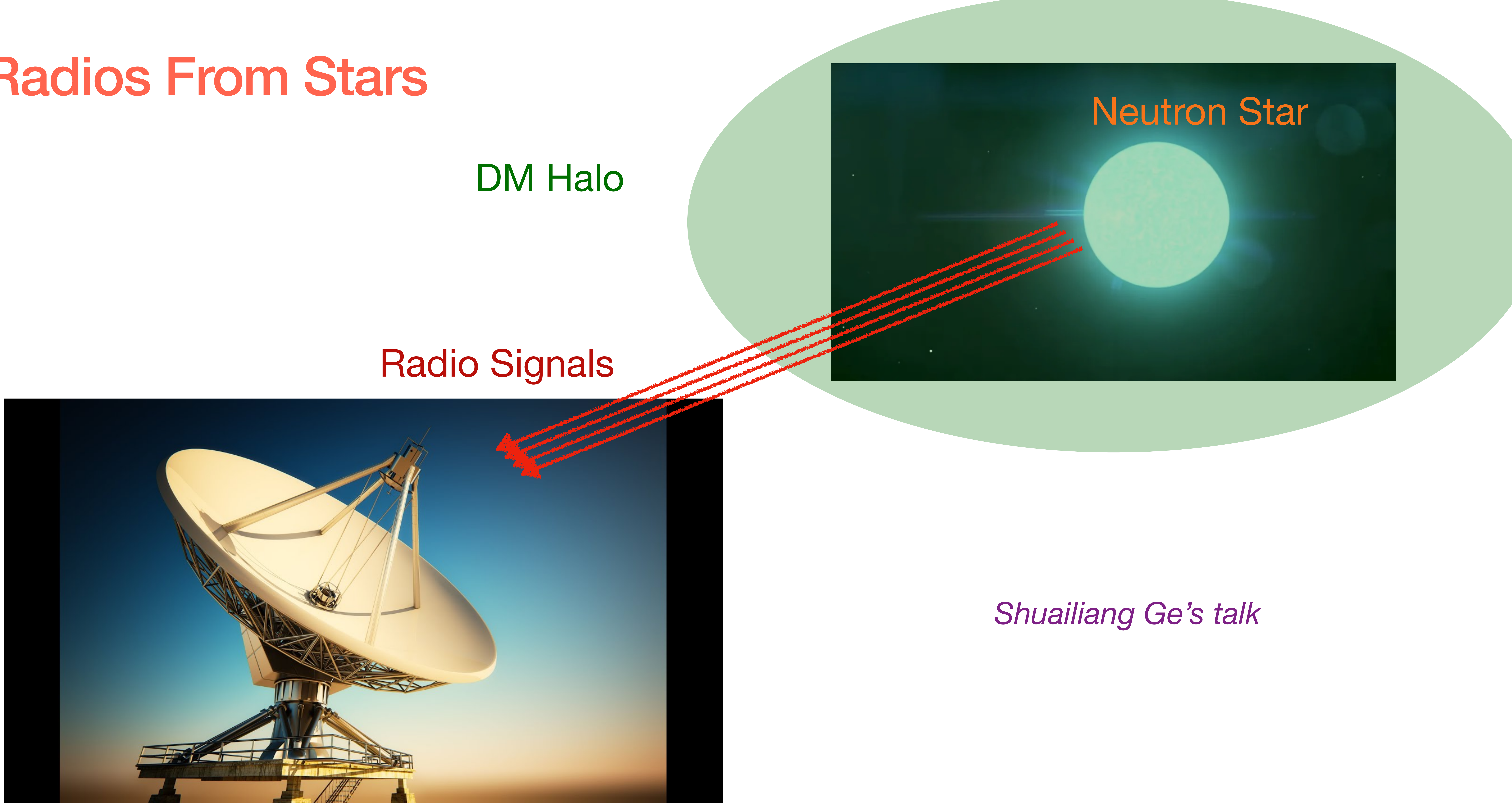
Nature Rev.Phys. 4 (2022) 10, 637-641



Irastorza, Nature 2021

Astrophysical laboratories?

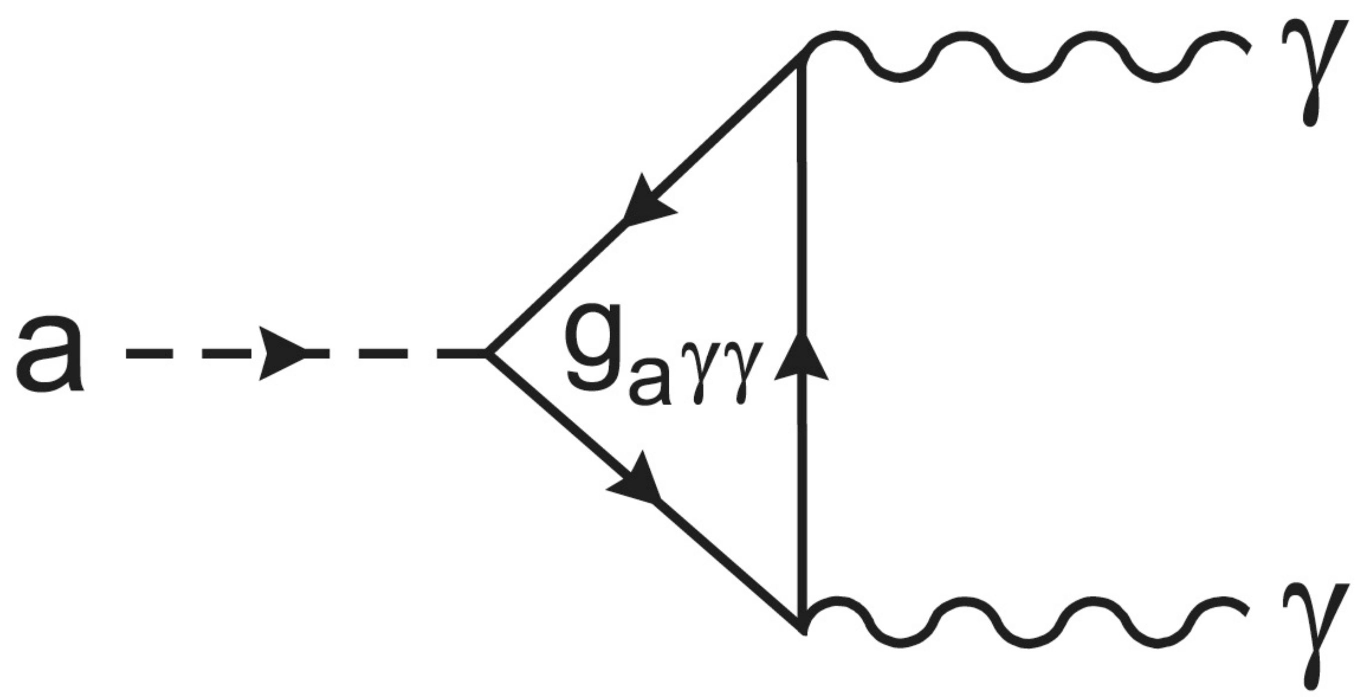
Radios From Stars



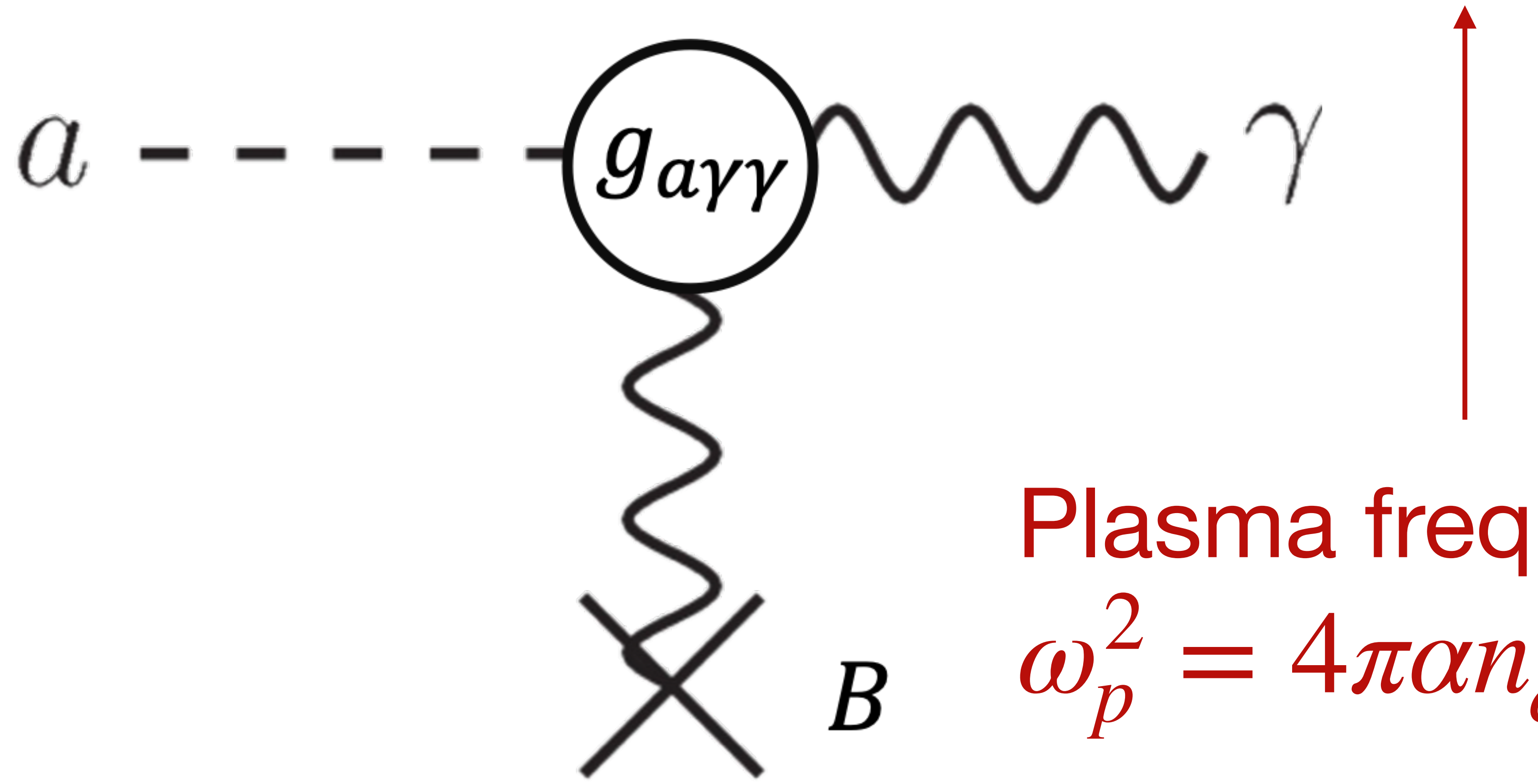
Shuailiang Ge's talk

Axion-Photon Conversion

- CP conserved in QCD ⇒ axion
- $\mathscr{L}_{a\gamma\gamma} = \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$
- Resonant conversion from axion to photon in plasma when $m_a \sim \omega_p$



$\omega^2 = k^2 + m_a^2$ $\omega^2 \sim k^2 + \omega_p^2$



Plasma frequency
$\omega_p^2 = 4\pi\alpha n_e / m_e$

Axion Conversion in Neutron Star

- Magnetized neutron star atmosphere—magnetosphere

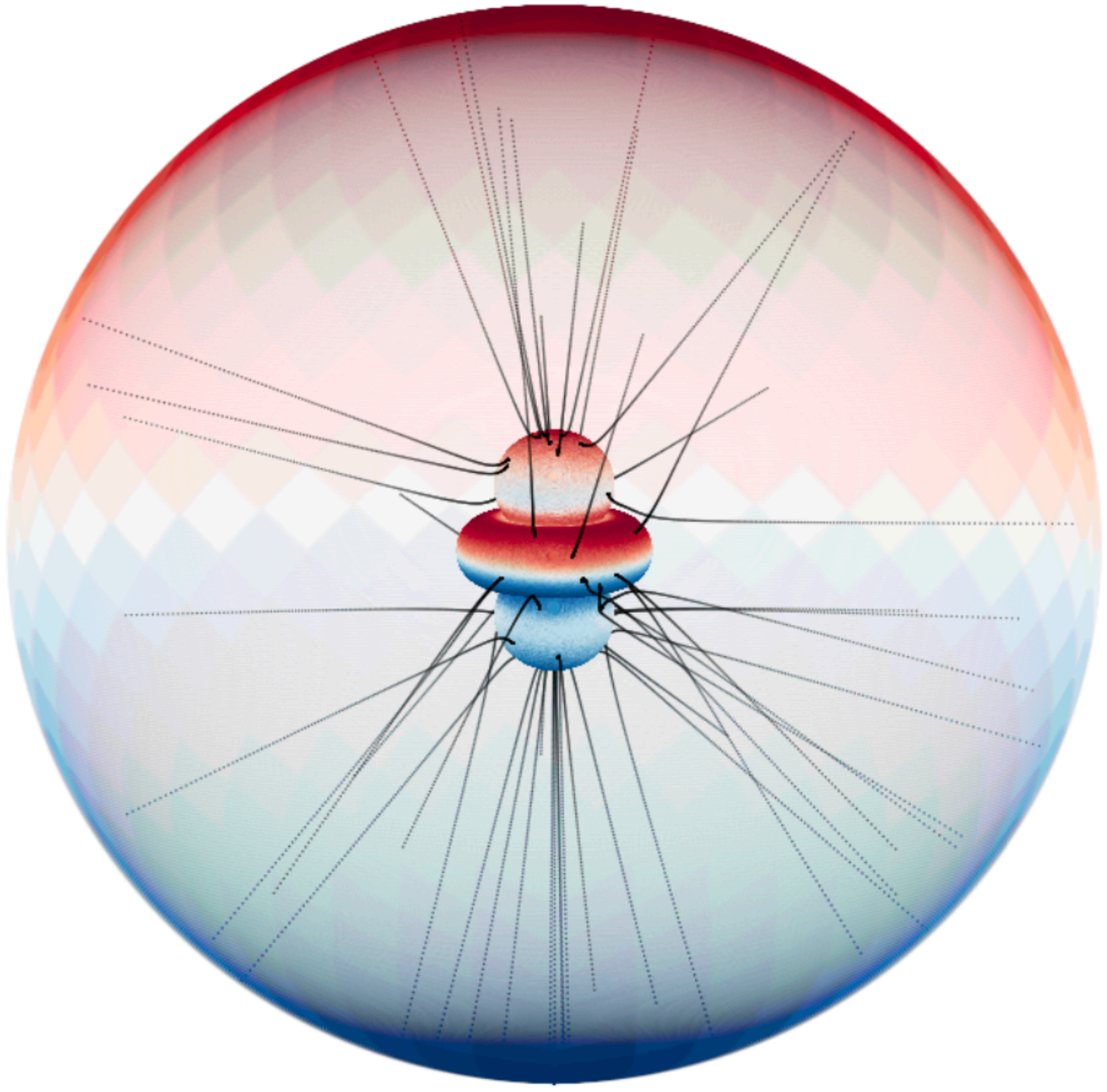
$$n_{\mathrm{GJ}}(\mathbf{r}_{\mathrm{NS}}) = \frac{2\mathbf{\Omega}\cdot\mathbf{B}_{\mathrm{NS}}}{e}\frac{1}{1-\Omega^2 r^2 \sin^2\theta_{\mathrm{NS}}}$$

- Conversion probability

$$p = \frac{g_{a\gamma\gamma}^2 B^2}{2k|\omega_p'|}\frac{\pi m_a^5}{(k^2+m_a^2\sin^2\theta)^2}\sin^2\theta$$

Hook et al 1804.03145

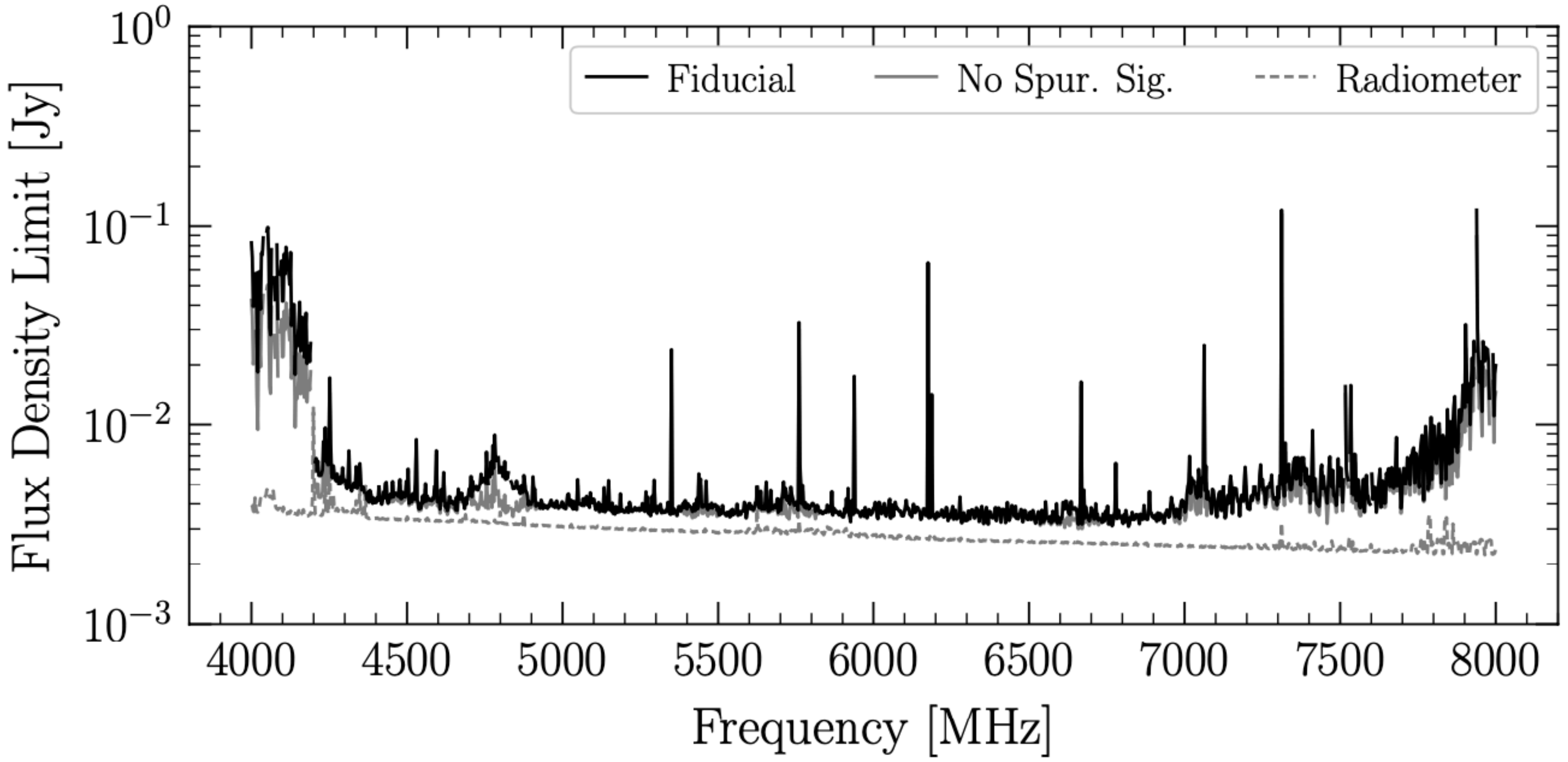
Millar et al 2107.07399

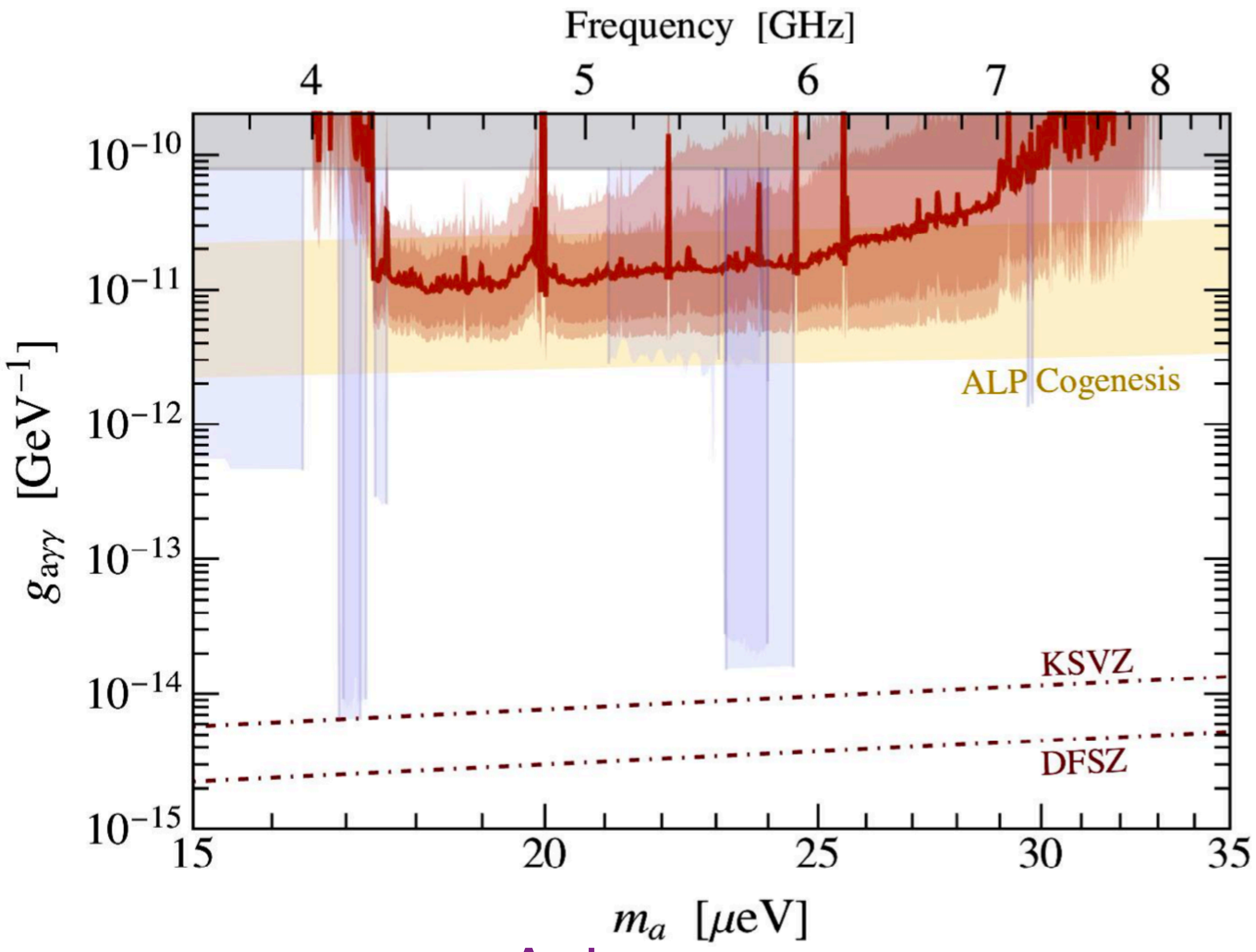


Witte et al 2104.07670

Radio Observation Constraint

Radio flux limit from the galactic center





Axion mass

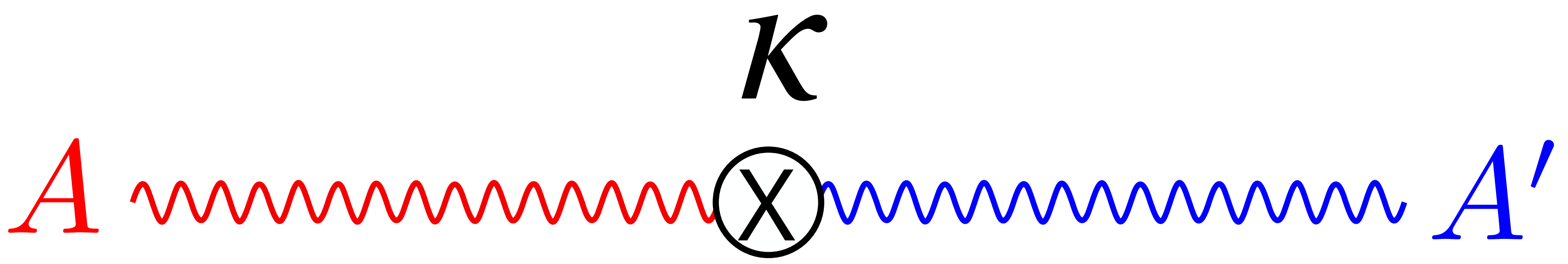
Foster et al 2202.08274

Dark Photon

Extra $U(1)$? $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$

Pospelov' 2008
Ackerman, Buckley, Carrol, Kamionkowsk' 2008
Arkani-Hame, Finkbeine, Slatyer, Weiner' 2008

$$\mathscr{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} - 2\kappa F_{\mu\nu}F'^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}) + \frac{m_{A'}^2}{2}A'_\mu A'^\mu - J^\mu A_\mu$$



$\omega^2 \sim k^2 + \omega_p^2$

$\omega^2 = k^2 + m_{A'}^2$

Resonant Dark Photon Conversion

- Resonant conversion from dark photon to photon in the magnetosphere of a neutron star when $m_{A'} \sim \omega_p$

No magnetic field need!

- Redefine $A_\mu \to A_\mu + \kappa A'_\mu$ to remove the mixing,

$$\mathscr{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}) + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - (A_\mu + \kappa A'_\mu)J^\mu$$

- Equation of motion

$$(\omega^2 + \nabla^2)\boldsymbol{A} - \nabla(\nabla\cdot\boldsymbol{A}) + \omega^2(\boldsymbol{\chi}^p + \boldsymbol{\chi}^{\text{vac}})\cdot(\boldsymbol{A} + \kappa\boldsymbol{A}') = 0$$
$$(\omega^2 + \nabla^2)\boldsymbol{A}' - m_{A'}^2\boldsymbol{A}' + \kappa\omega^2(\boldsymbol{\chi}^p + \boldsymbol{\chi}^{\text{vac}})\cdot\boldsymbol{A} = 0$$

$$\left[\omega^2 + \partial_z^2 + \omega^2\begin{pmatrix}\boldsymbol{\chi}^p + \boldsymbol{\chi}^{\text{vac}} - \mathcal{D}^2 & \kappa(\boldsymbol{\chi}^p + \boldsymbol{\chi}^{\text{vac}}) \\ \kappa(\boldsymbol{\chi}^p + \boldsymbol{\chi}^{\text{vac}}) & -m_{A'}^2/\omega^2\end{pmatrix}\right]\begin{pmatrix}\boldsymbol{A} \\ \boldsymbol{A}'\end{pmatrix} = 0$$

$$\boldsymbol{\epsilon} = 1 + \boldsymbol{\chi}^p = R_\theta^{yz}\cdot\begin{pmatrix}\varepsilon & ig & 0 \\ -ig & \varepsilon & 0 \\ 0 & 0 & \eta\end{pmatrix}\cdot R_{-\theta}^{yz}$$

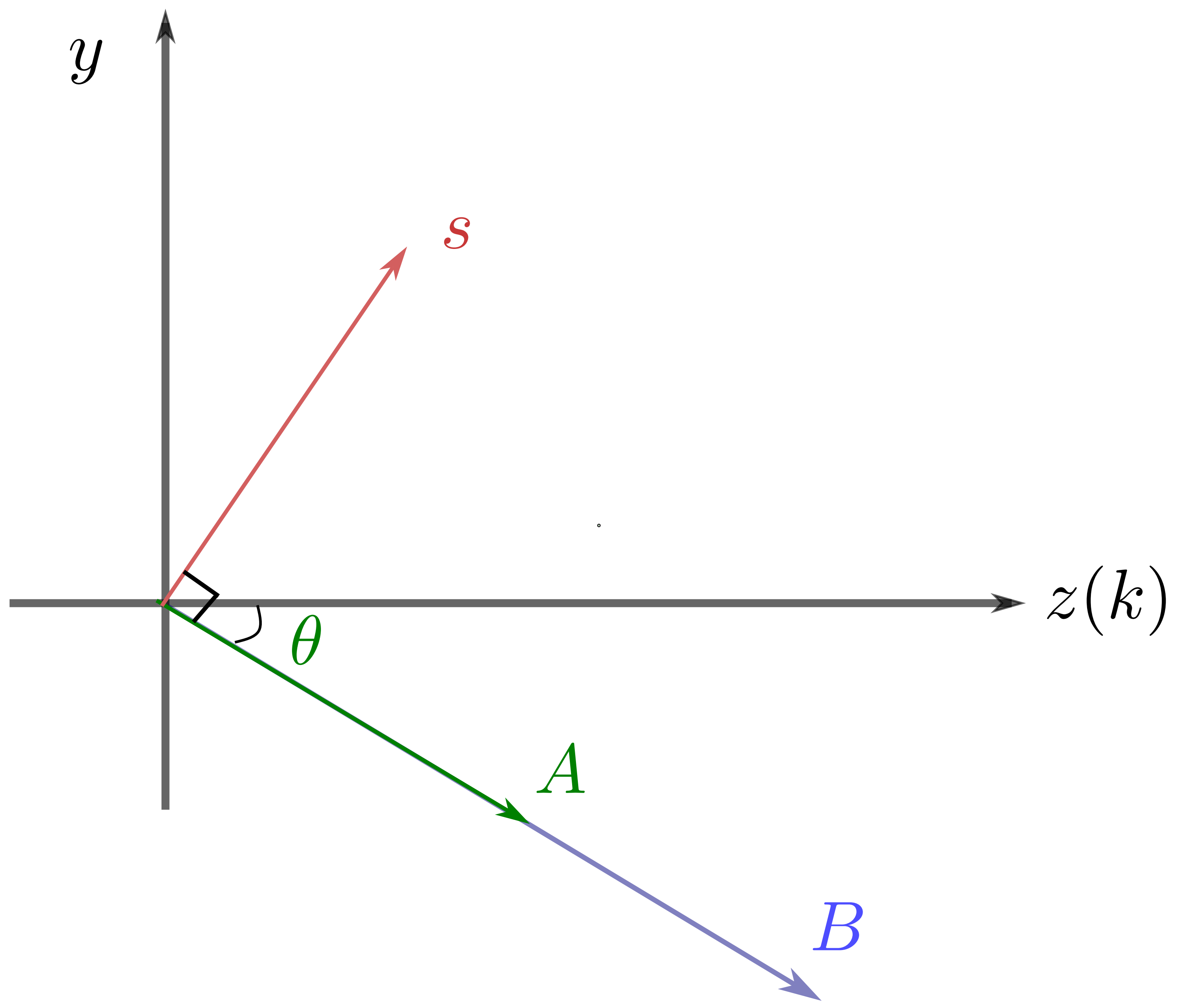
Resonant Dark Photon Conversion

$$(\omega^2 + \partial_z^2)A_x - \partial_x\partial_z A_z + \omega^2 a \bar{A}_x = 0\,,$$
$$(\omega^2 + \partial_z^2)A_y - \partial_y\partial_z A_z + \omega^2[(\eta' \sin^2\theta + a + q\sin\theta^2)\bar{A}_y - (\eta' + q)\cos\theta\sin\theta\bar{A}_z] = 0\,,$$
$$\omega^2 A_z - \partial_x\partial_z A_x - \partial_y\partial_z A_y + \omega^2[-(\eta' + q)\cos\theta\sin\theta\bar{A}_y + (\eta'\cos^2\theta + a + q\cos^2\theta)\bar{A}_z] = 0\,.$$

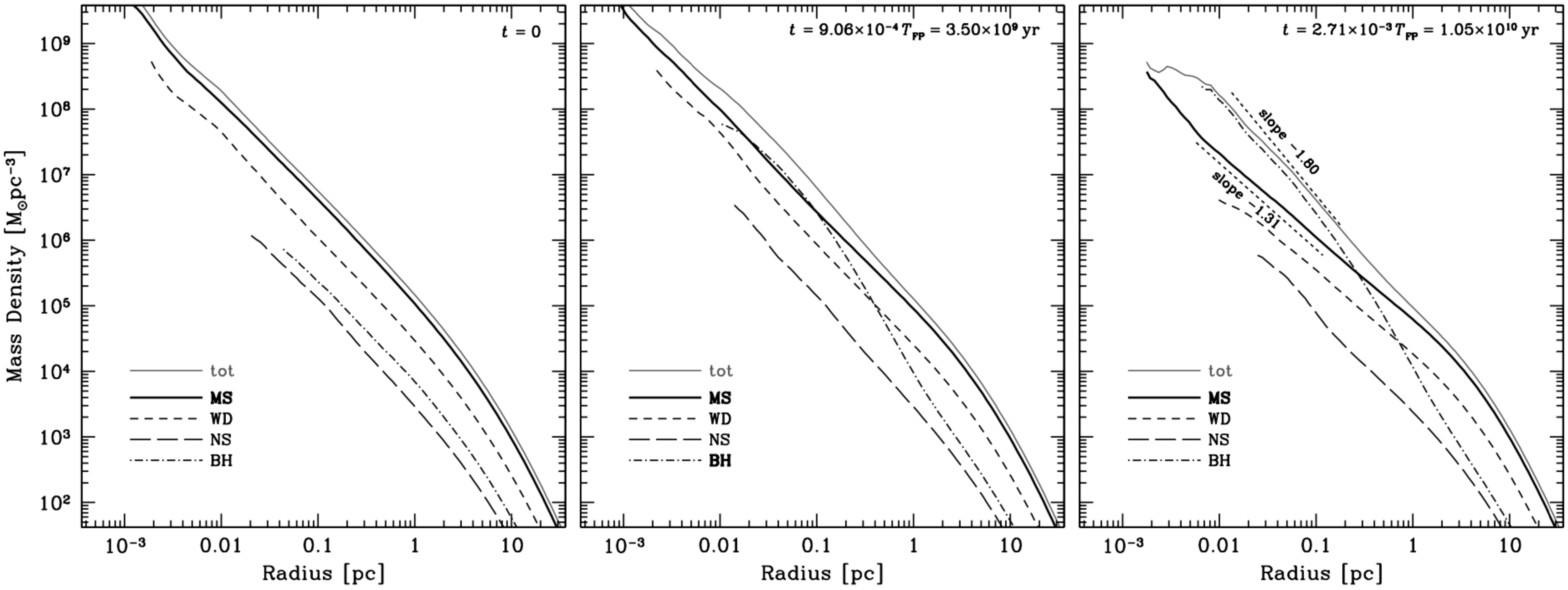
- Conversion probability

$$p \simeq \frac{|\tilde{A}_y|^2 + |\tilde{A}_z|^2}{|\tilde{A}'_x|^2 + |\tilde{A}'_y|^2 + |\tilde{A}'_z|^2} \simeq \frac{\pi\kappa^2\omega_p^3(m_{A'}^2\cos\theta - \omega_p^2\sin^3\theta)^2}{6km_{A'}^4\omega'_p\sin^2\theta}$$

- The converted photon has both transverse and longitudinal polarizations, and evolves in the direction that is perpendicular to the magnetic field



Compact Stars in the Galactic Centre



Freitag et al 2006

Signals from the Galactic Centre

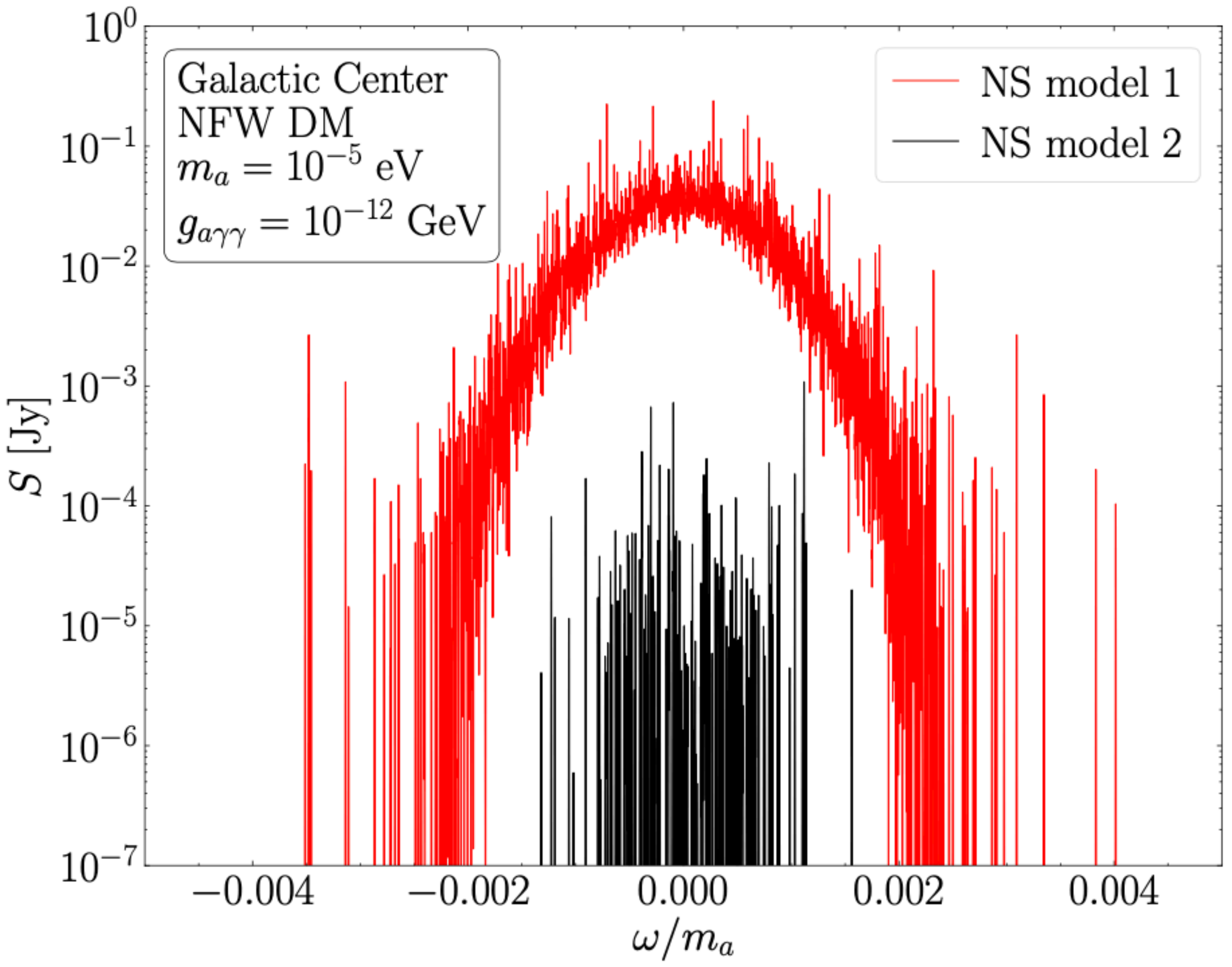
$$S_{\rm sig} = \frac{1}{\mathscr{B} d^2} \frac{dP}{d\Omega} > S_{\rm min}$$

Signals from a single star $\delta f/f \sim v^2 \sim 10^{-6}$

Signals from stellar population $\delta f/f \sim v \sim 10^{-3}$

$$\omega_{\rm obs} = \omega \sqrt{\frac{1 - v_{\rm l.o.s}}{1 + v_{\rm l.o.s}}}$$

Doppler shift can be important!



Safdi et al 1811.01020

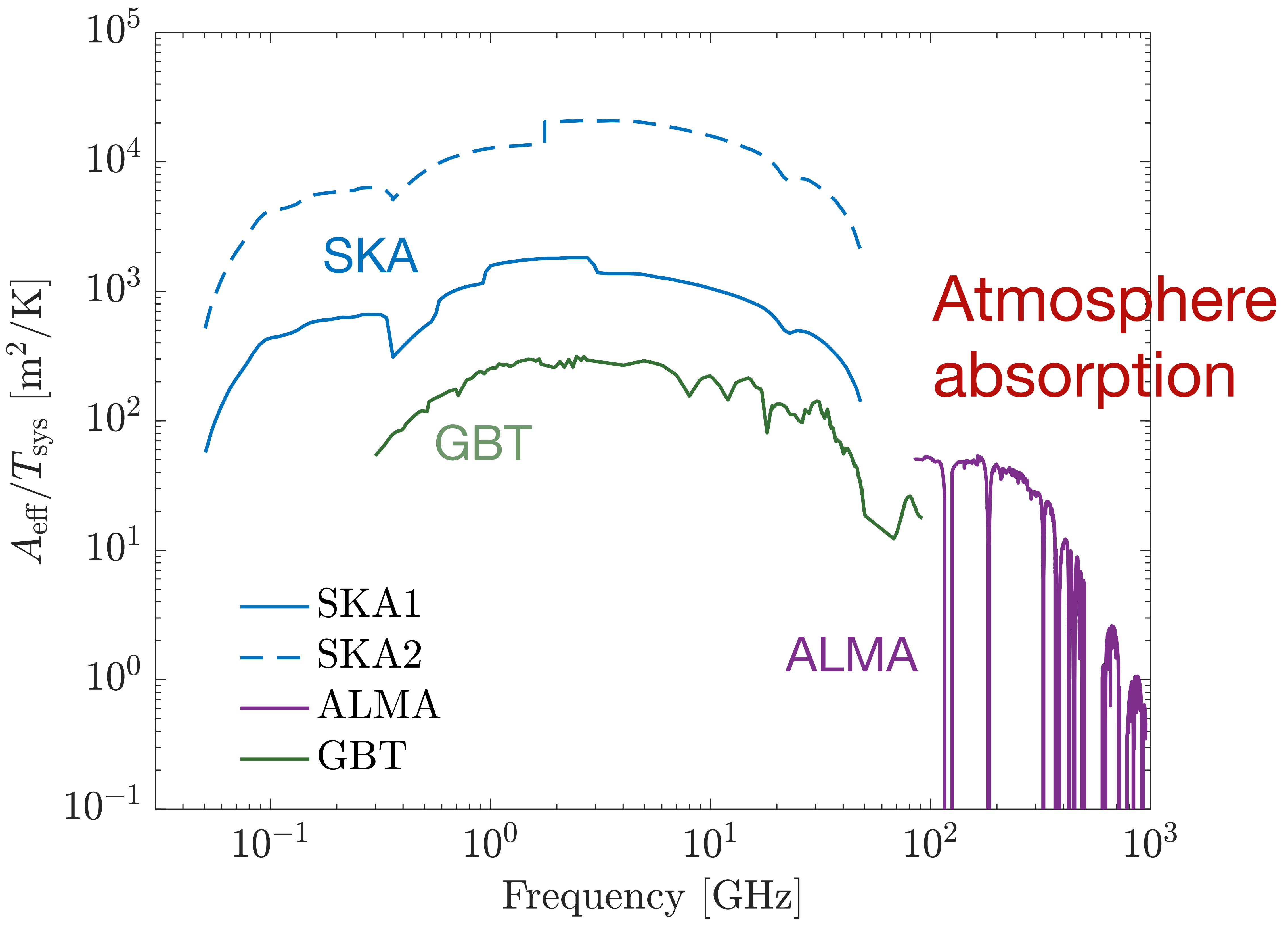
Radio Telescopes

Minimum detectable signal flux density

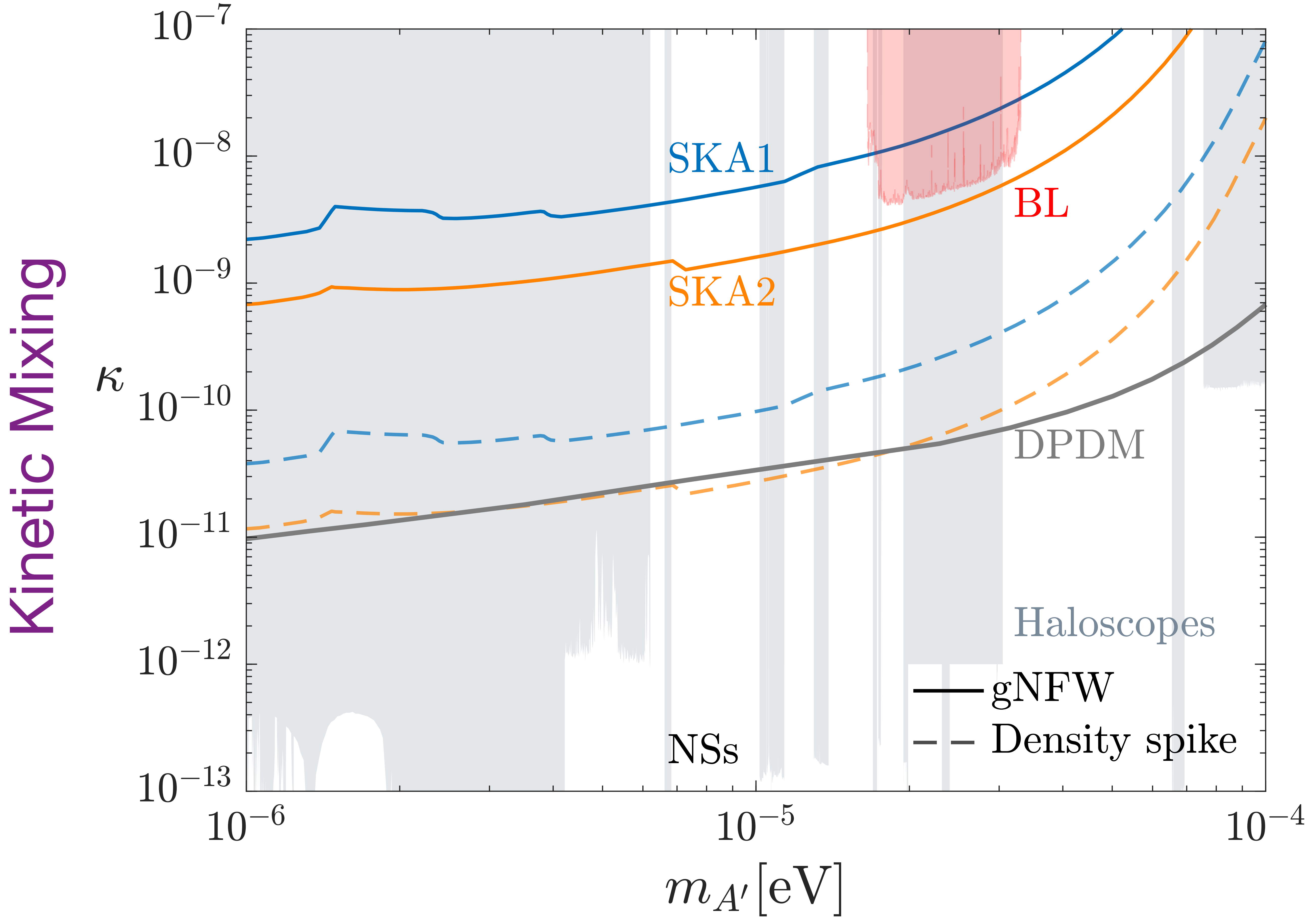
$$S_{\rm min} = \frac{\rm SEFD}{\eta\sqrt{n_{\rm pol}\mathscr{B}t_{\rm obs}}}$$

$${\rm SEFD} = 2k_B\frac{T_{\rm sys}}{A_{\rm eff}} = 2.75\ {\rm Jy}\frac{1000\ {\rm m}^2/{\rm K}}{A_{\rm eff}/T_{\rm sys}}$$

$$S_{\rm sig} = \frac{1}{\mathscr{B}d^2}\frac{dP}{d\Omega} > S_{\rm min}$$



Sensitivities for Galactic Center Signals



Collection of neutron stars

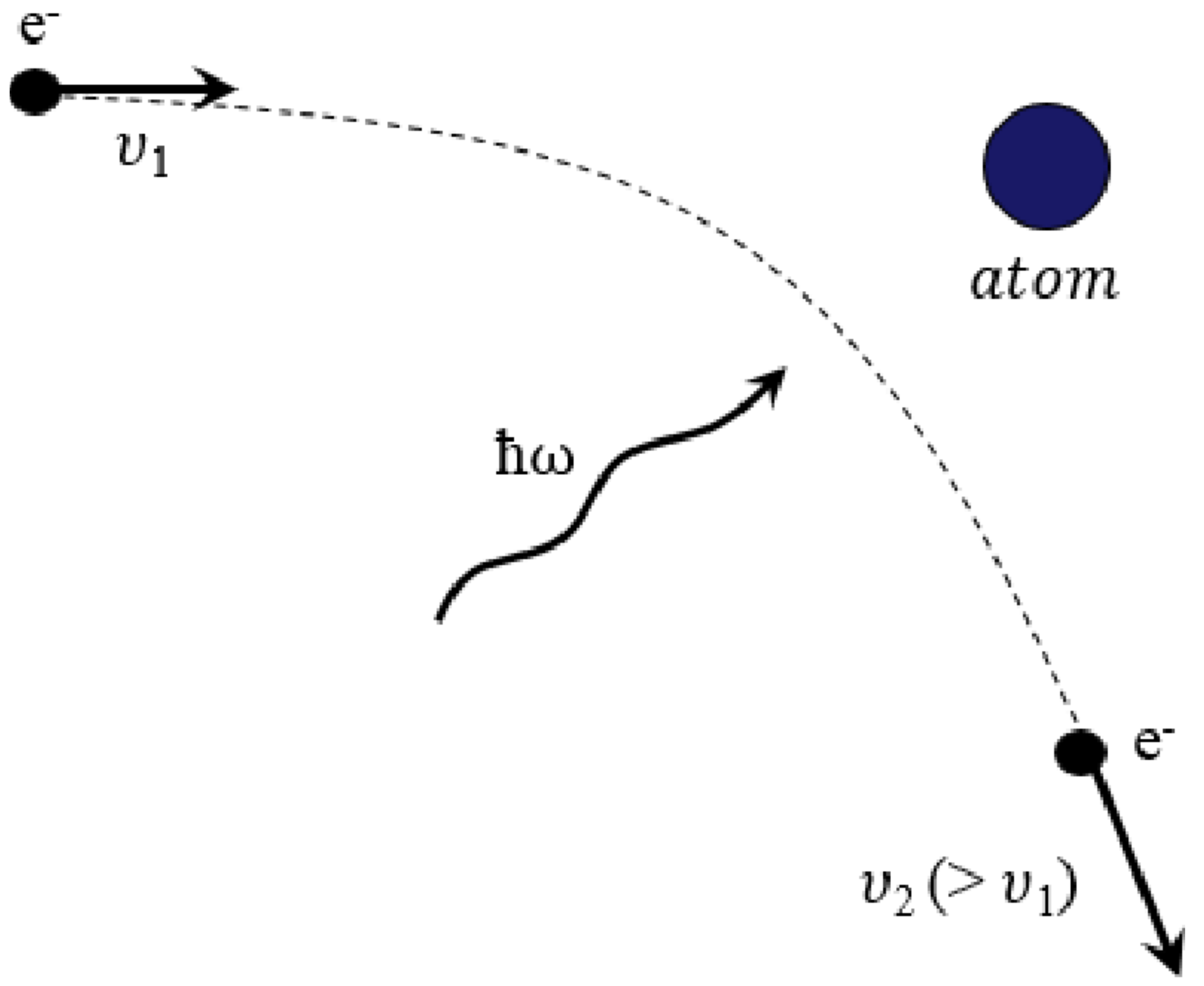
Dark Photon Mass

Edward Hardy, **NS**, PRD/2212.09756

Criteria for Strong Conversion

- Strong magnetic field is NOT required
- Dense plasma ⇒ Larger dark photon mass
- High temperature ⇒ Less Inverse Bremsstrahlung absorption

$$\Gamma_{\mathrm{IB}} = \frac{8\pi\alpha^3 n_e n_{\mathrm{ion}}}{3\omega^3 m_e^2}\sqrt{\frac{2\pi m_e}{T}}\ln\left(\frac{2T^2}{\omega_p^2}\right)\left(1-e^{-\omega/T}\right)$$



White Dwarf Atmosphere

Isotropic plasma ⇒ photon longitudinal polarization does not propagate, only transverse modes convert

$$\left[-i\frac{d}{dr}+\frac{1}{2k}\begin{pmatrix} m_{A'}^2-\omega_p^2 & -\kappa\omega_p^2 \\ -\kappa\omega_p^2 & 0 \end{pmatrix}\right]\begin{pmatrix}\tilde{A} \\ \tilde{A}'\end{pmatrix}=0\,.$$

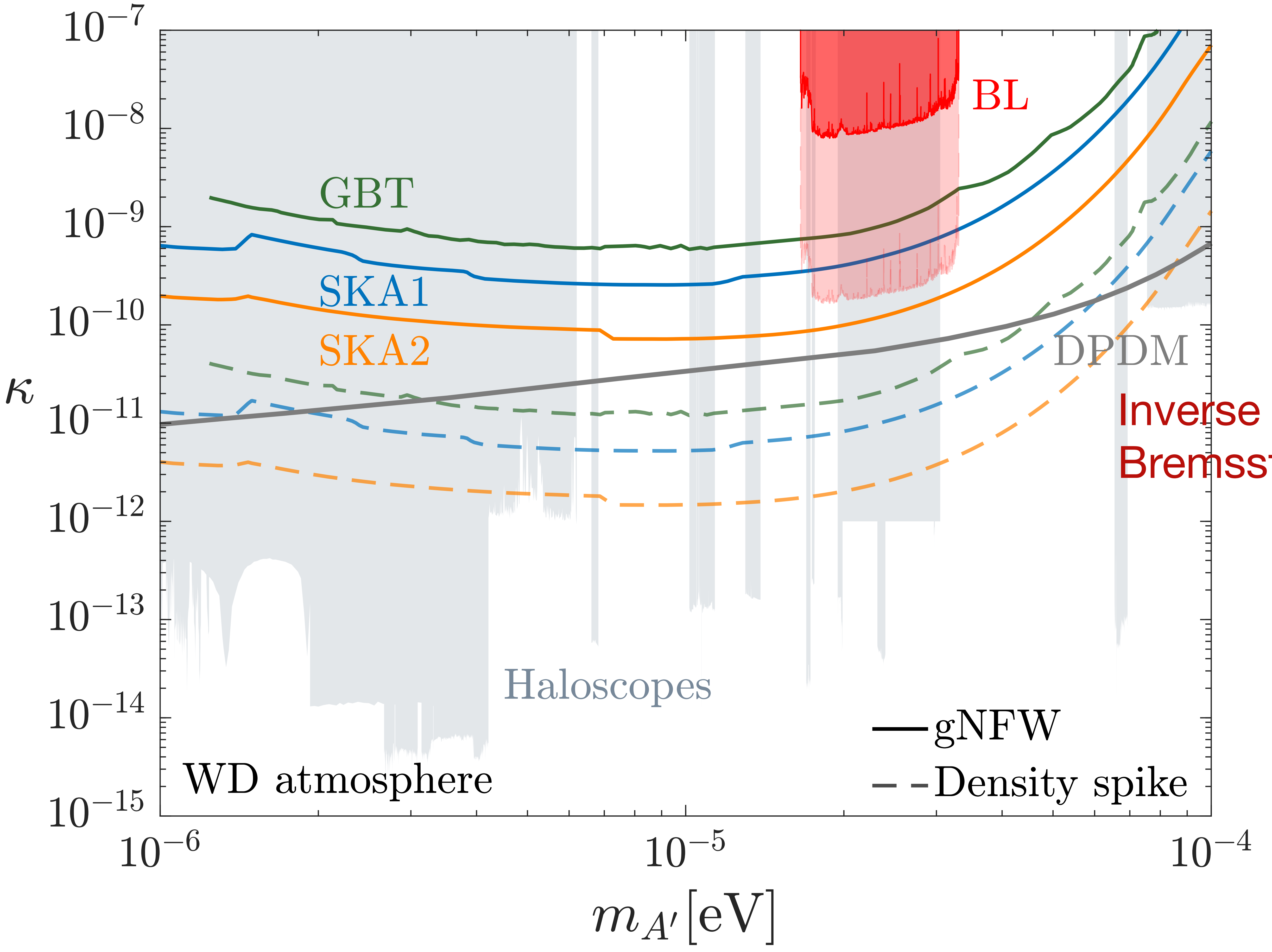
White Dwarf Atmosphere

- Pressure gradient balances gravity $l_a \simeq \frac{kT_a r_0^2}{GM_{\rm WD}\mu m_p} = 0.06\ \mathrm{km}\left(\frac{T_a}{10^4\ \mathrm{K}}\right)\left(\frac{M_{\rm WD}}{M_\odot}\right)\left(\frac{r_0}{0.01\ R_\odot}\right)^2$
- Exponential density profile $n_e(r) = n_0 e^{-\frac{r-r_0}{l_a}}$
- Conversion probability $p = \frac{2\pi}{3}\frac{\kappa^2 m_{A'}^2}{k} l_a$
- Radio emission power $\frac{d\mathcal{P}}{d\Omega} \simeq 2pr_c^2 \rho_{A'}(r_c) v_c$

$$T_a \sim 10^4 - 10^5\ \mathrm{K},\ n_0 \sim 10^{17}\ \mathrm{cm}^{-3}$$

Sensitivities from White Dwarf Atmosphere

Kinetic Mixing



Inverse Bremsstrahlung

Dark Photon Mass

Collection of white dwarfs

Edward Hardy, **NS**, PRD/2212.09756

White Dwarf Corona?

- Higher temperature $10^6 - 10^7$ Kelvins ⇒ less absorption
- Exponential density profile $n_e(r) = n_0 e^{-\frac{r-r_0}{l_a}}$
- No observational evidence for hot corona in isolated white dwarfs

$$T_a \sim 10^6 - 10^7 \text{ K}, n_0 \sim ?$$

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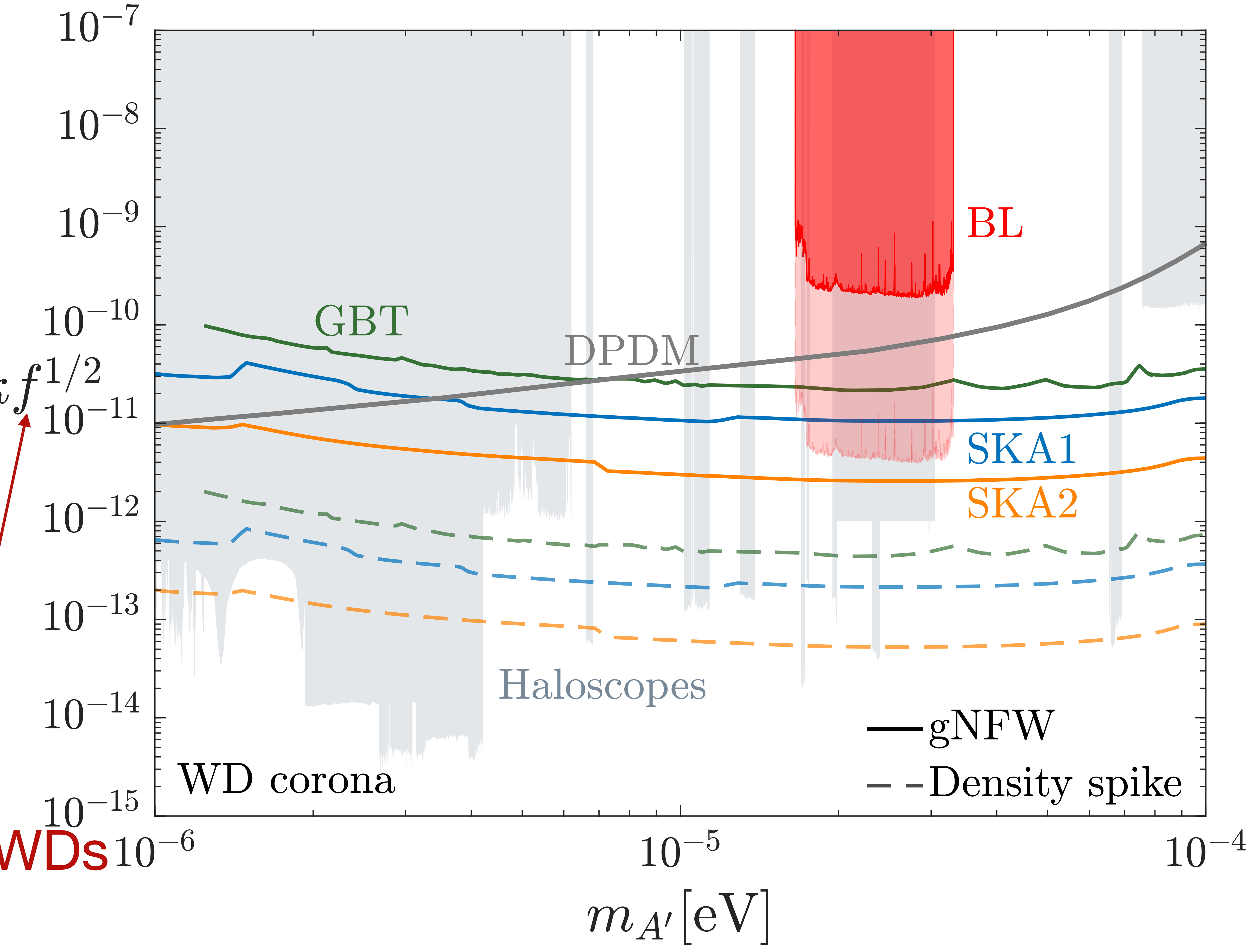
Sensitivities from White Dwarf Corona

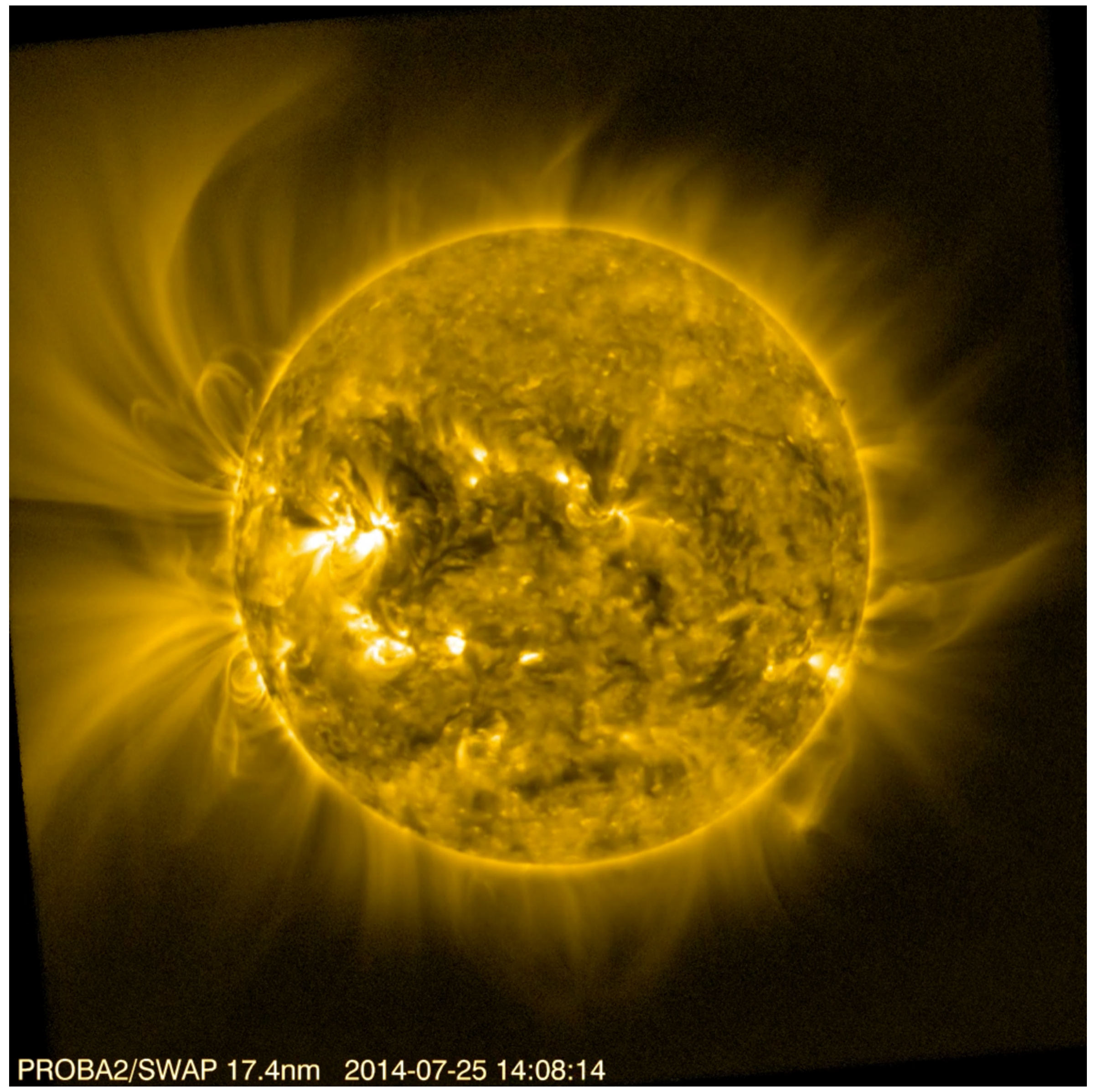
Kinetic Mixing



Fraction of WDs with corona

Collection of white dwarfs

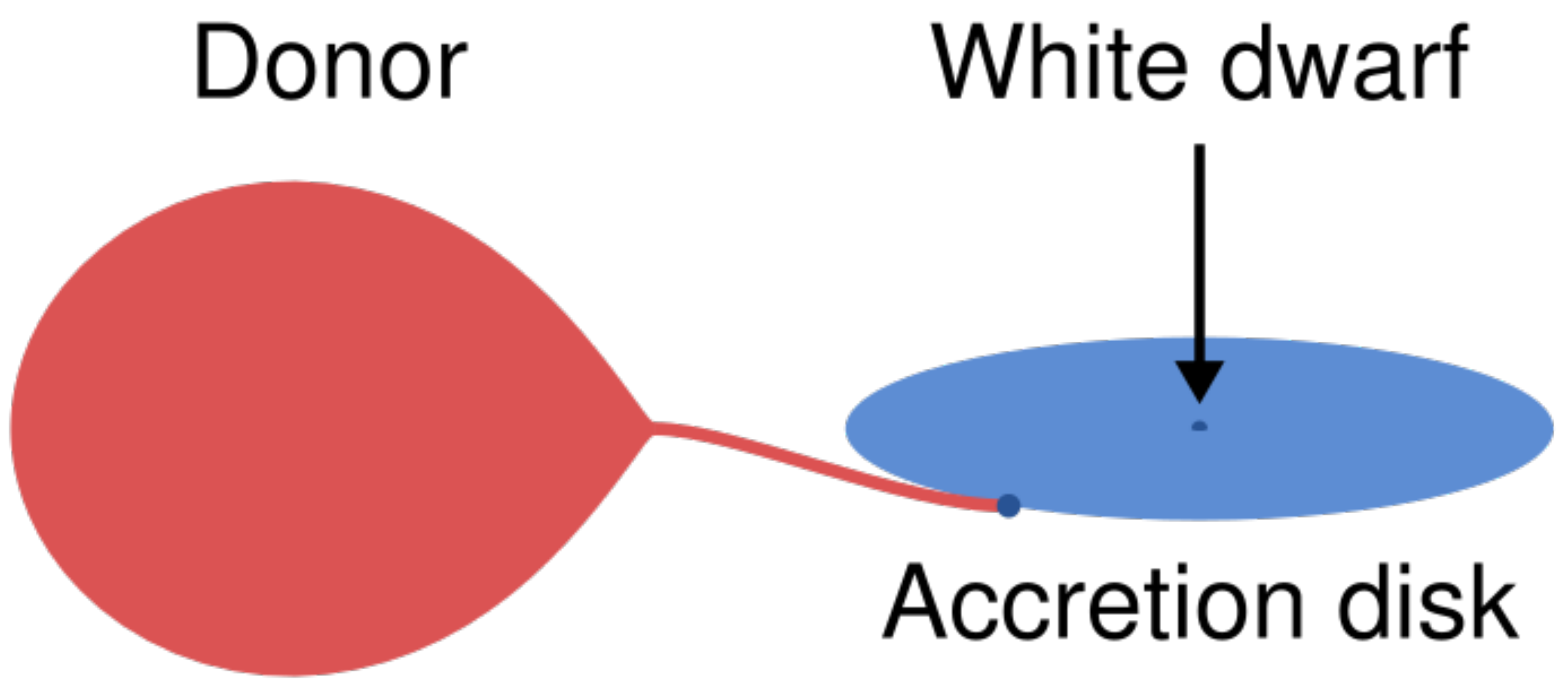
Dark Photon Mass

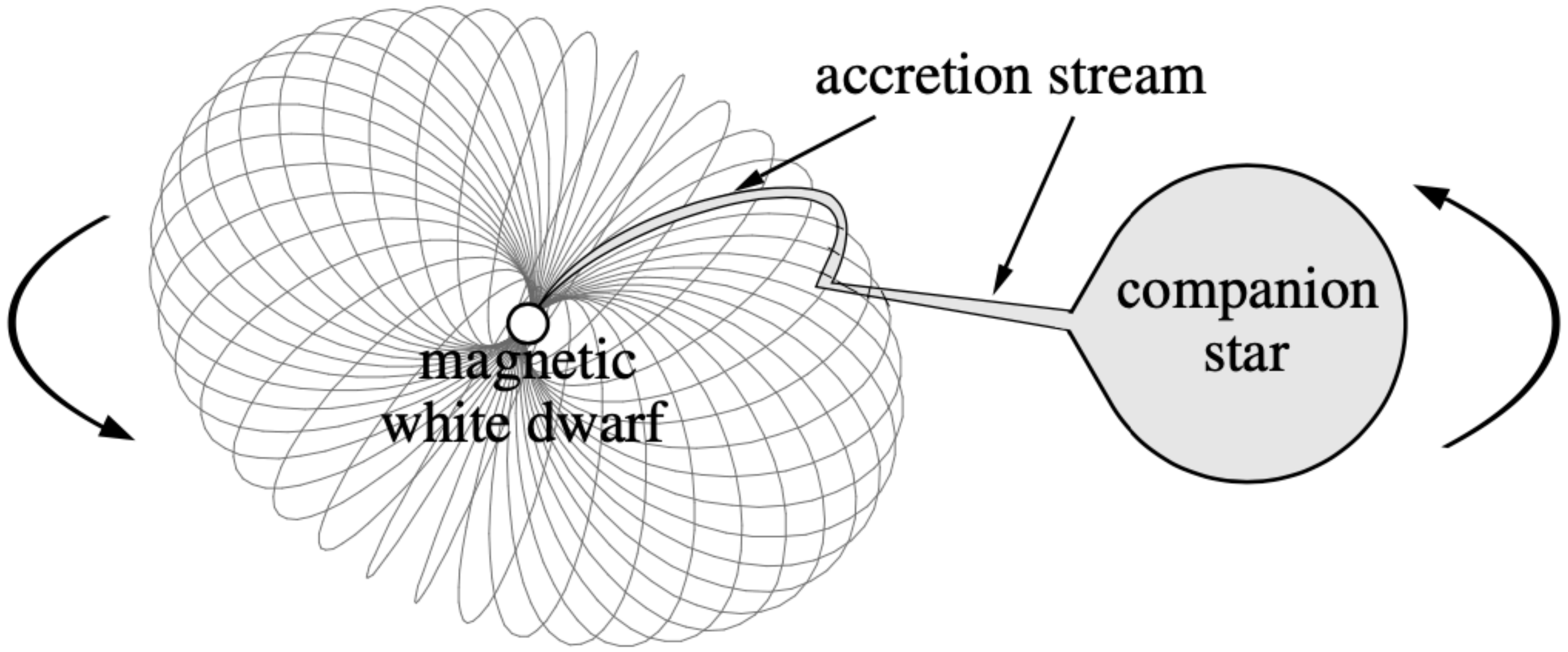


Credit: ESA

Edward Hardy, **NS**, PRD/2212.09756

Accreting White Dwarf



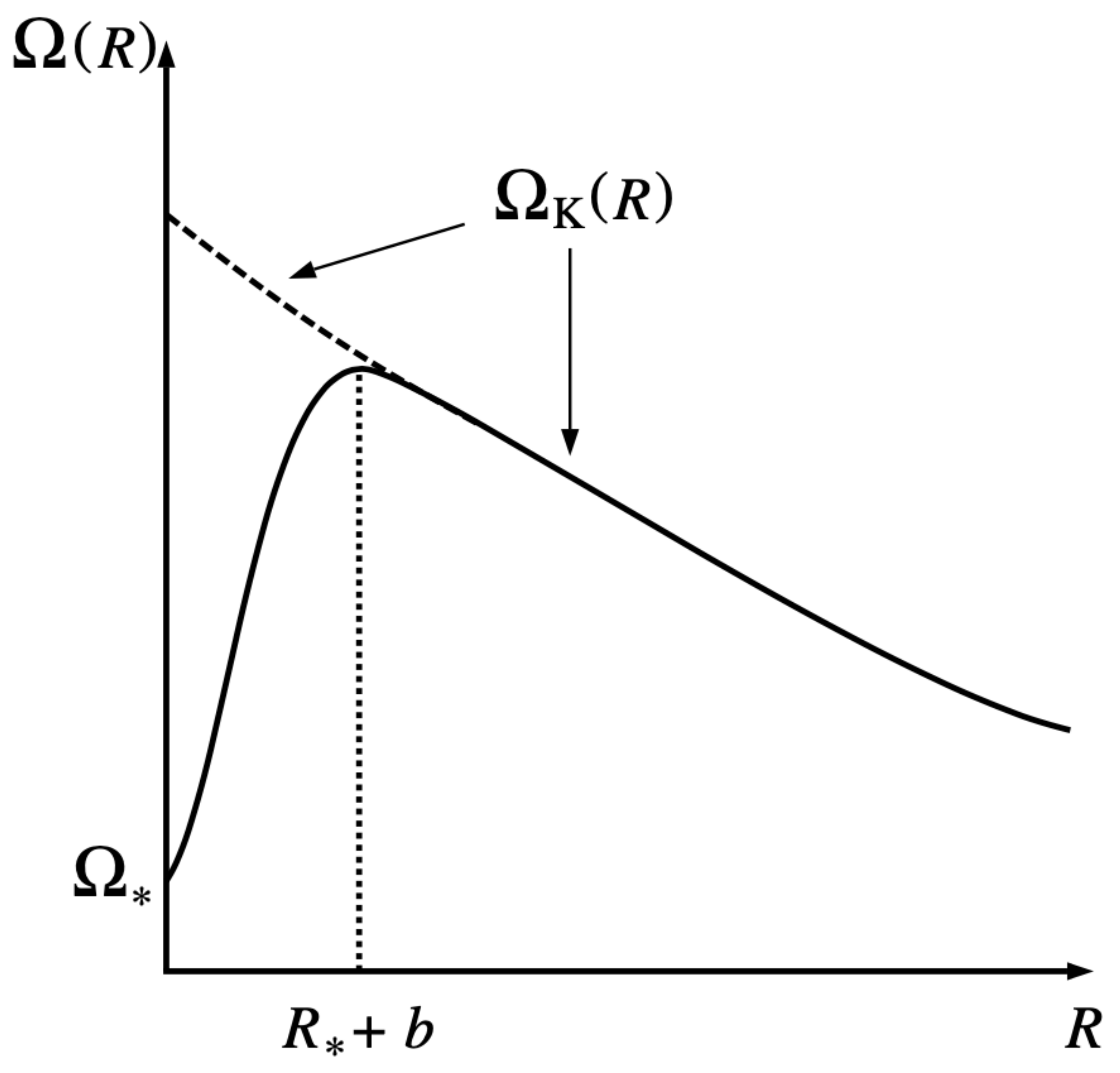


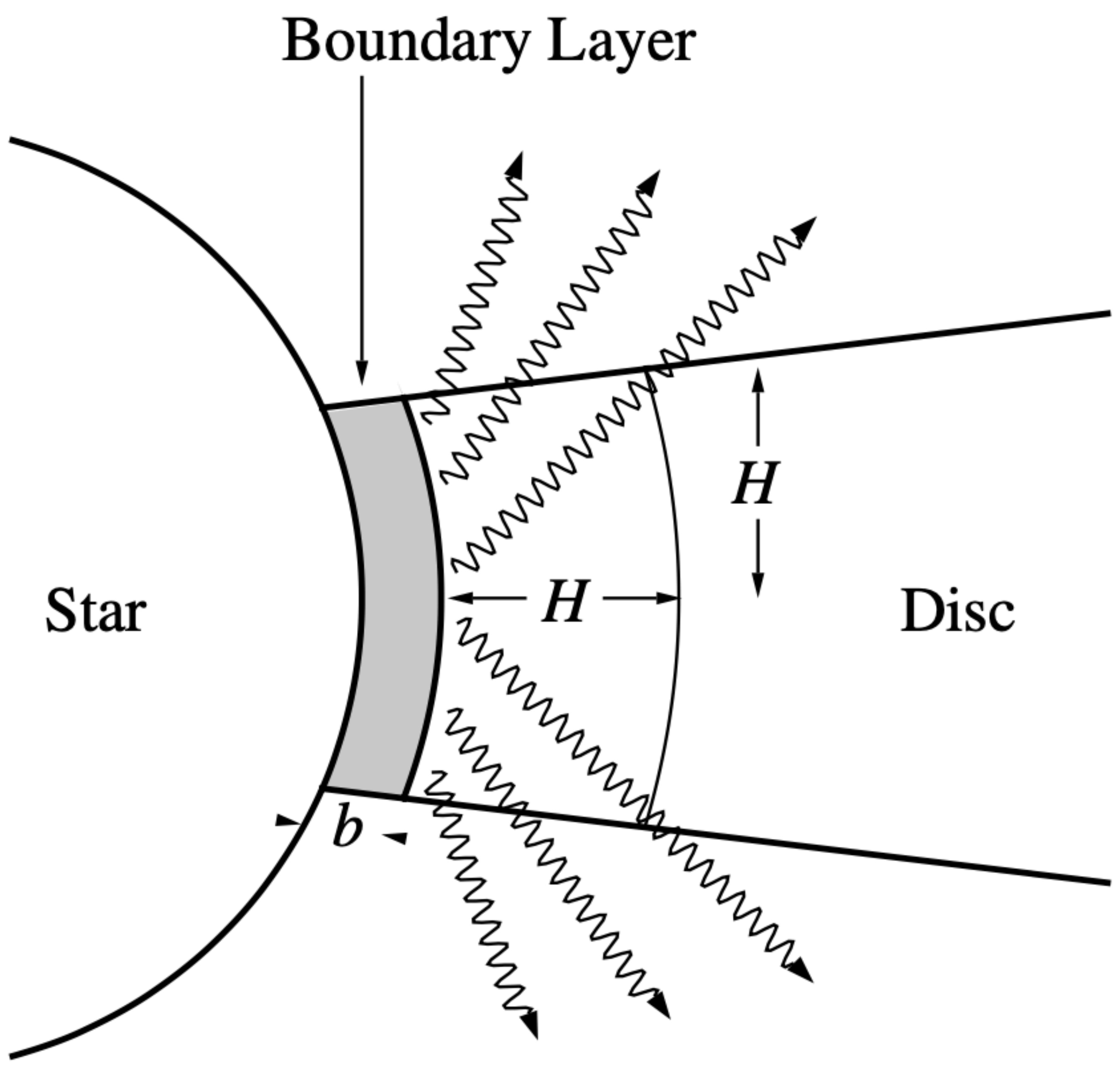
Non-magnetic cataclysmic variable

Magnetic cataclysmic variable

Non-magnetic Cataclysmic Variables

- The inner part of the disk decelerates and forms a hot boundary layer near the white dwarf surface
- High accretion rate ⇒ Black body emission from the optically-thick boundary layer
- Low accretion rate ⇒ Bremsstrahlung emission from the optically-thin boundary layer

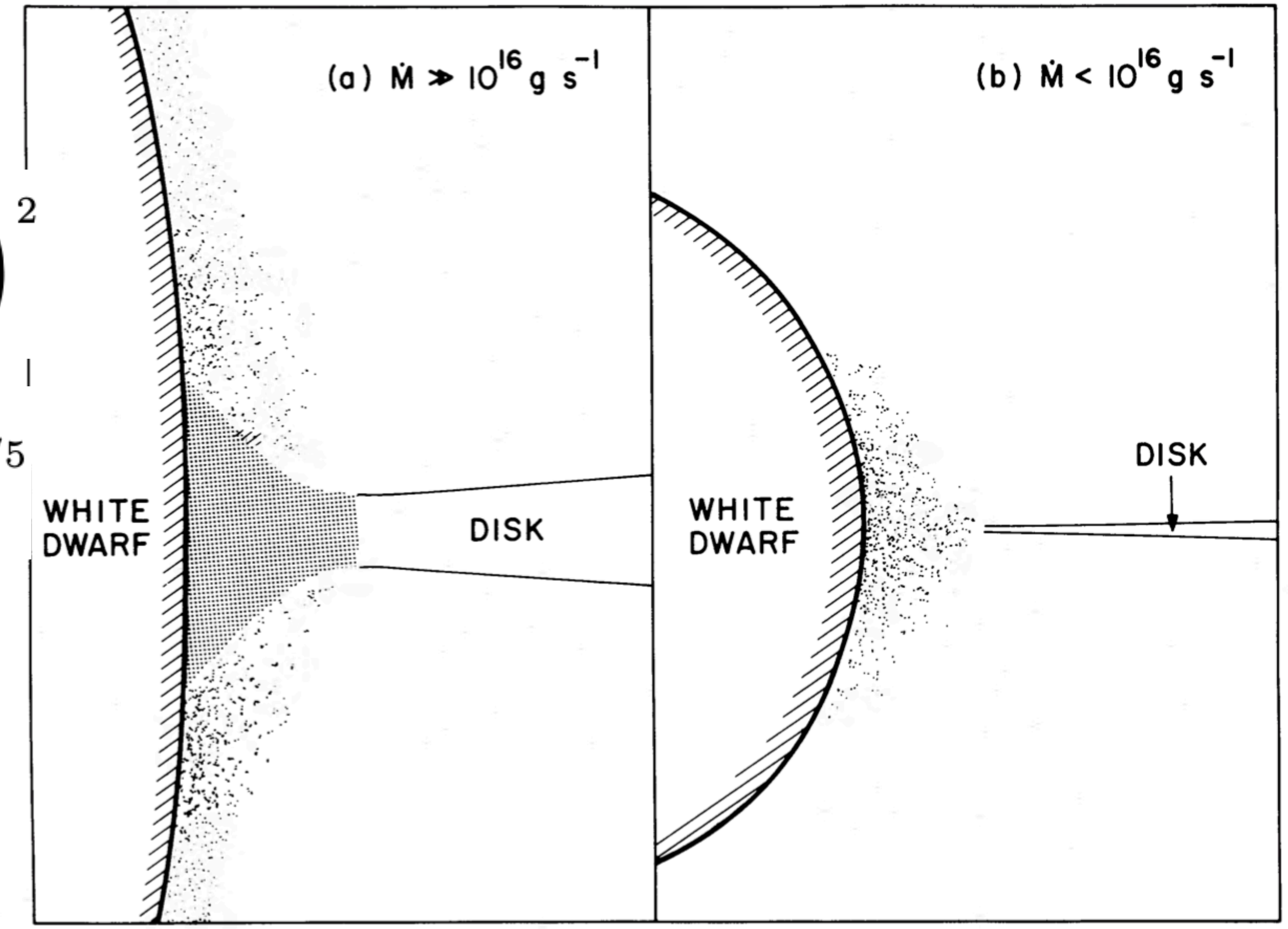




Optically Thin Boundary Layer

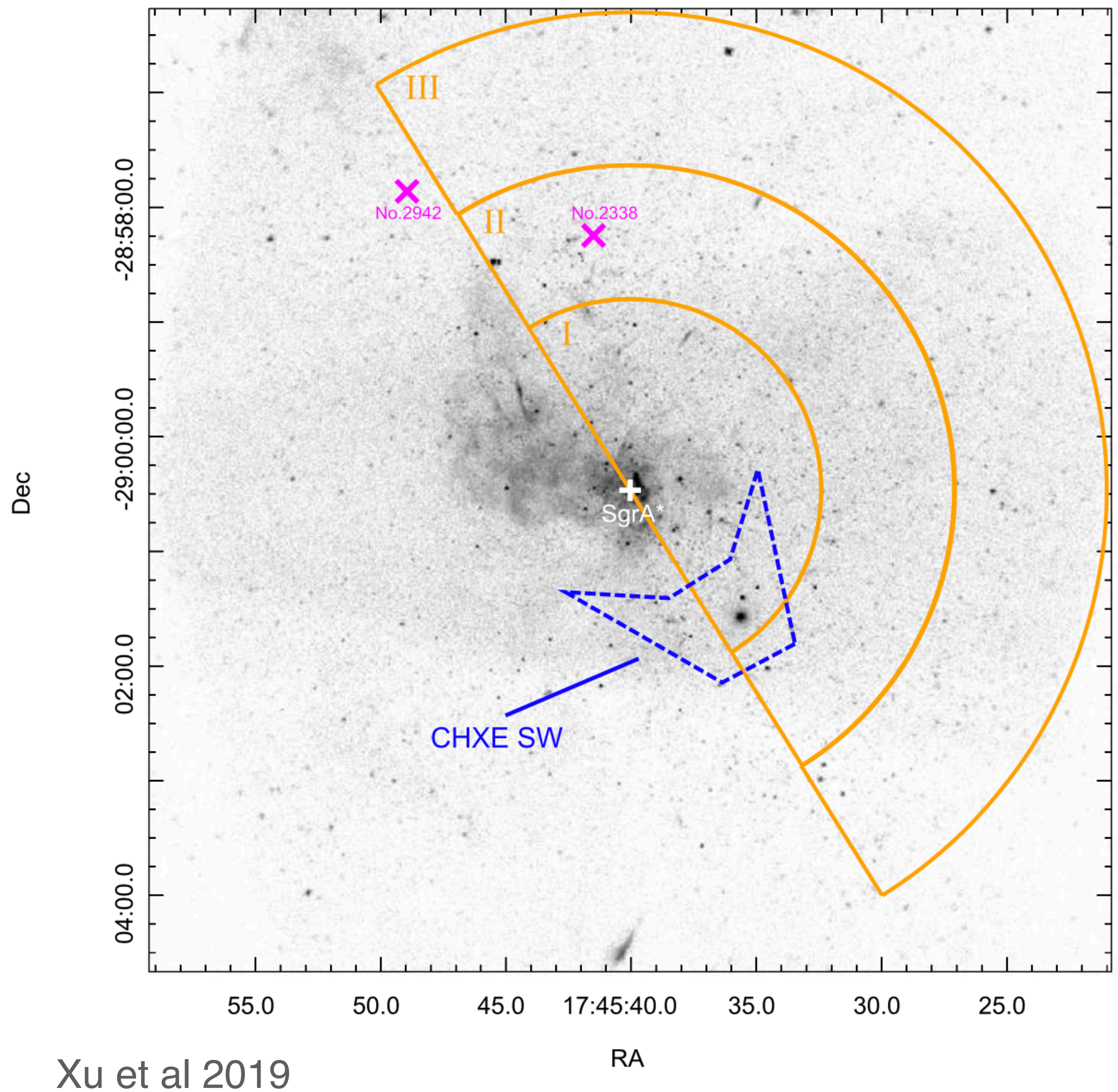
- Temperature $T \simeq \frac{3}{16}\frac{GM\mu m_p}{kR} \sim 10^8\ \mathrm{K}$
- Thickness $b \simeq 600\ \mathrm{km} \left(\frac{T_s}{10^8\ \mathrm{K}}\right)\left(\frac{M_{\mathrm{WD}}}{M_\odot}\right)\left(\frac{r_0}{0.01\ R_\odot}\right)^2$
- Height $H = 2\times10^3\ \mathrm{km}\ \alpha_d^{-1/10}\dot{M}_{16}^{3/20}\left(\frac{r_0+b}{10^5\ \mathrm{km}}\right)^{9/8} f_r^{3/5}$
- Density profile

$$n_e = n_d \exp\left(1 - \frac{r-r_0}{b} - \frac{h^2}{H^2}\right)$$

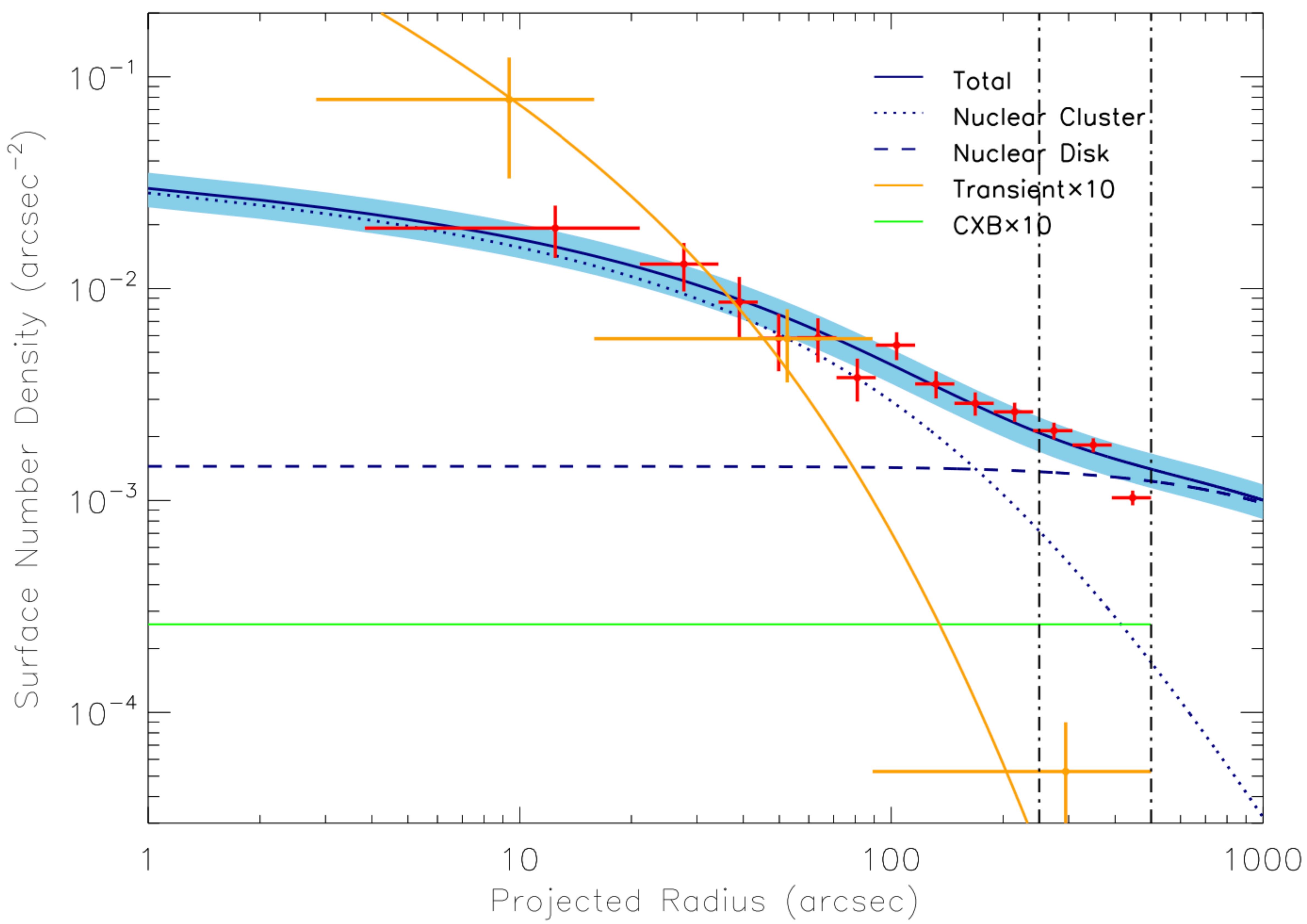


Patterson et al 1985

X-ray Map in the Galactic Center



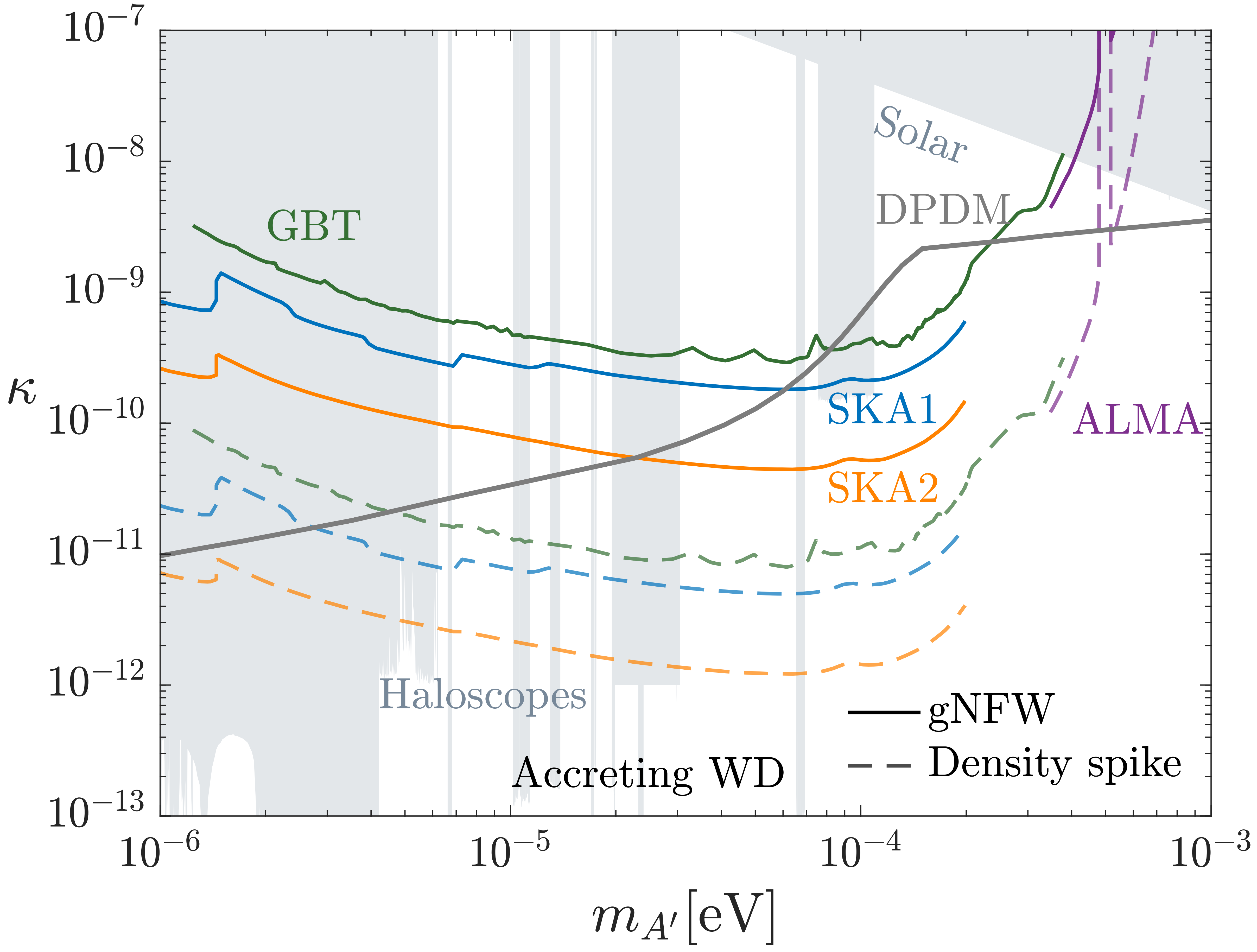
Xu et al 2019



Zhu et al 1802.05073

Sensitivities from Non-magnetic Cataclysmic Variable

Kinetic Mixing



Dark Photon Mass

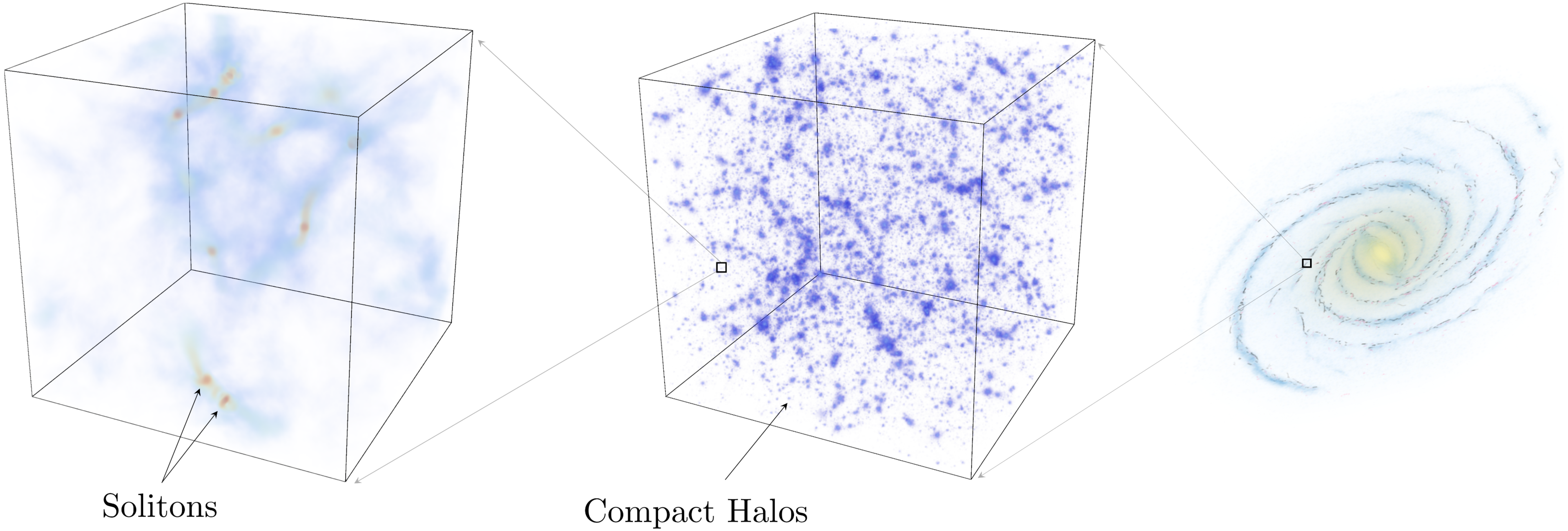
Single accreting white dwarf

Edward Hardy, **NS**, PRD/2212.09756

Dark Photon Stars

At subgalactic scales~pc, dark matter is bound in compact halos that arise from the collapse of small-scale primordial inhomogeneities

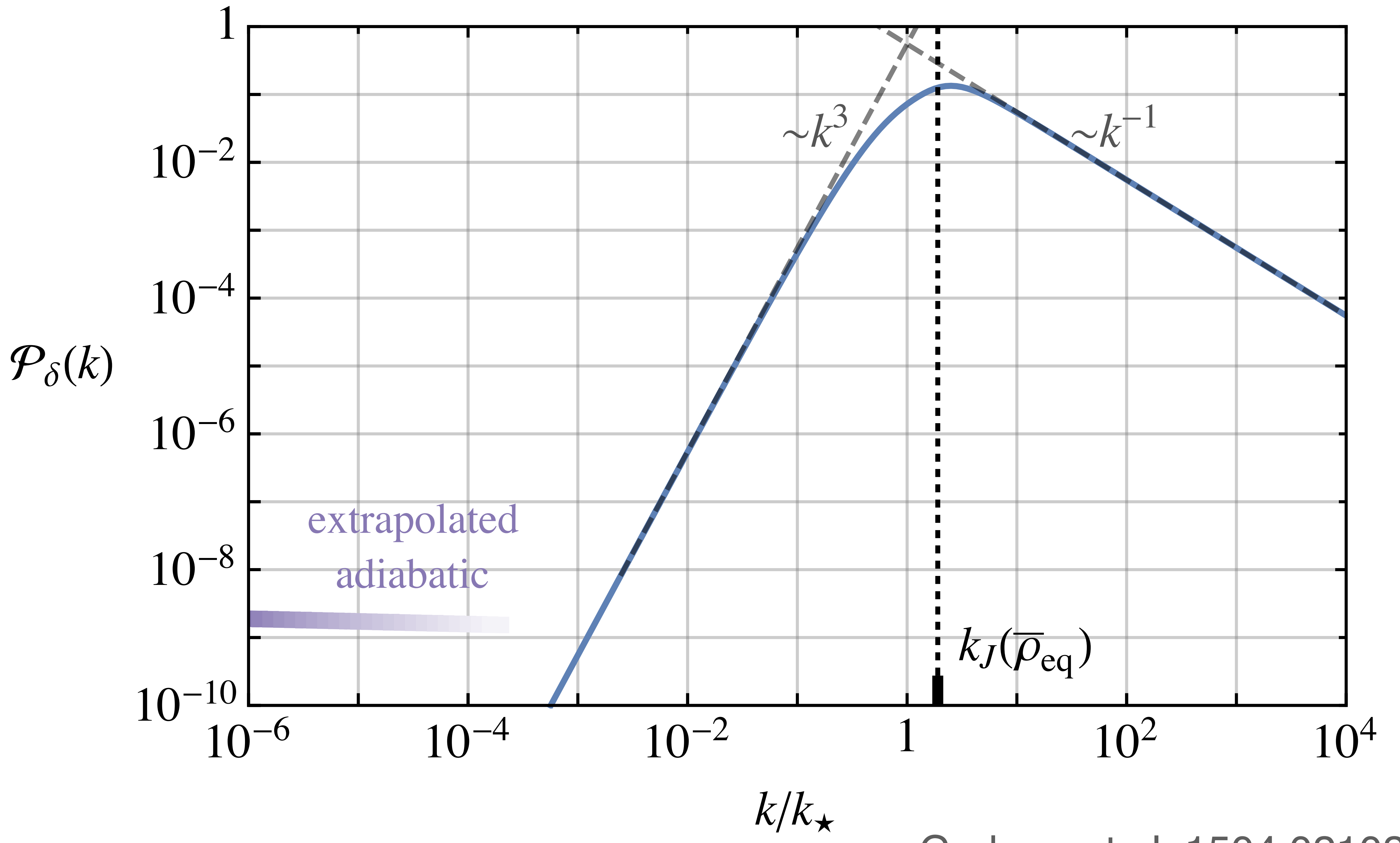
At even smaller scales: solitons, i.e. dark photon stars are surrounded by fuzzy halos, and dark matter filaments connecting them

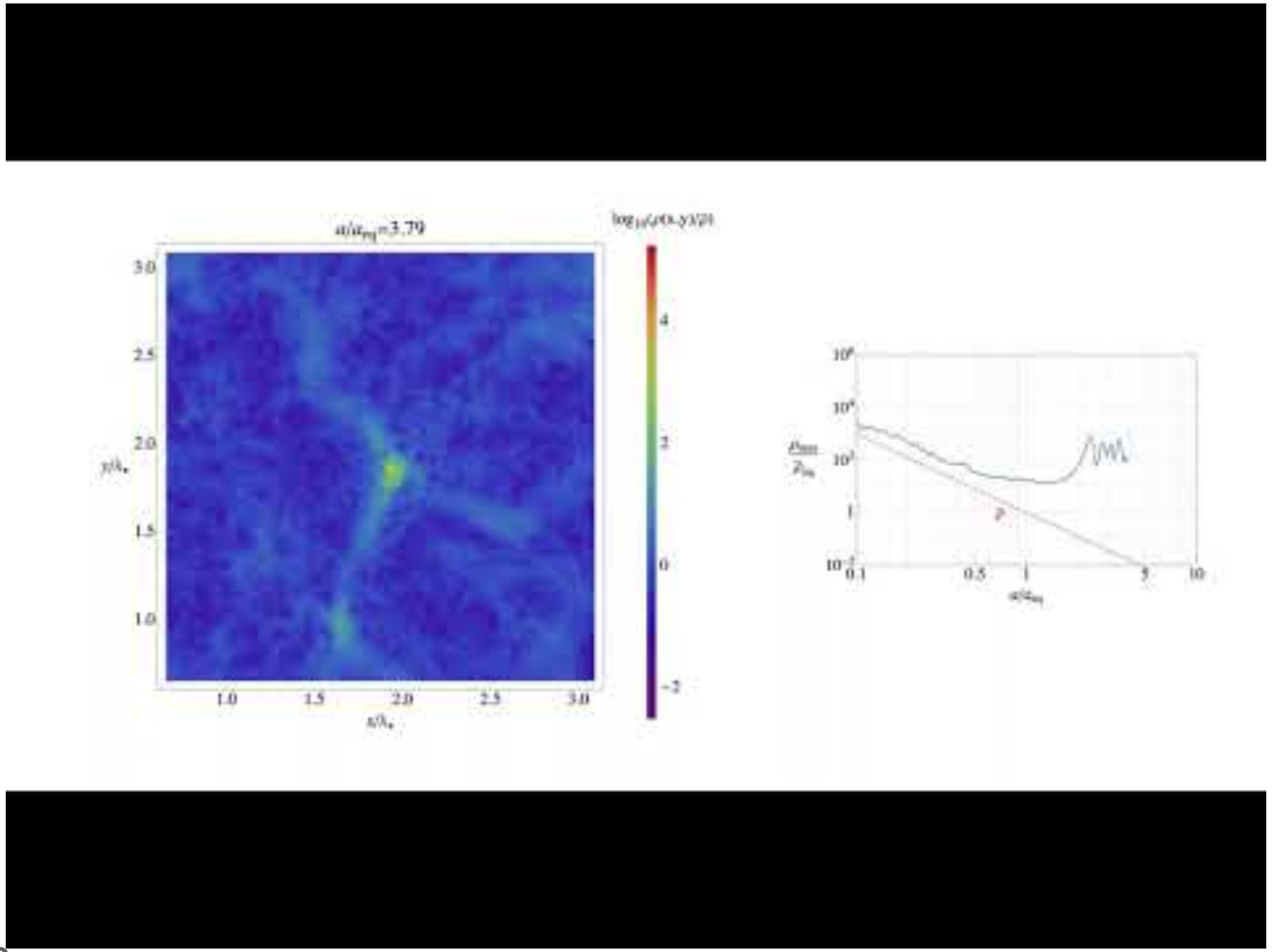


Gorghetto, Hardy, March-Russel, **NS**, West, JCAP/2203.10100

Dark Photon Substructure from Primordial Perturbations

After around matter radiation equality, modes larger than the Jeans scale begins to collapse due to gravity and form solitons, where the quantum pressure is still important





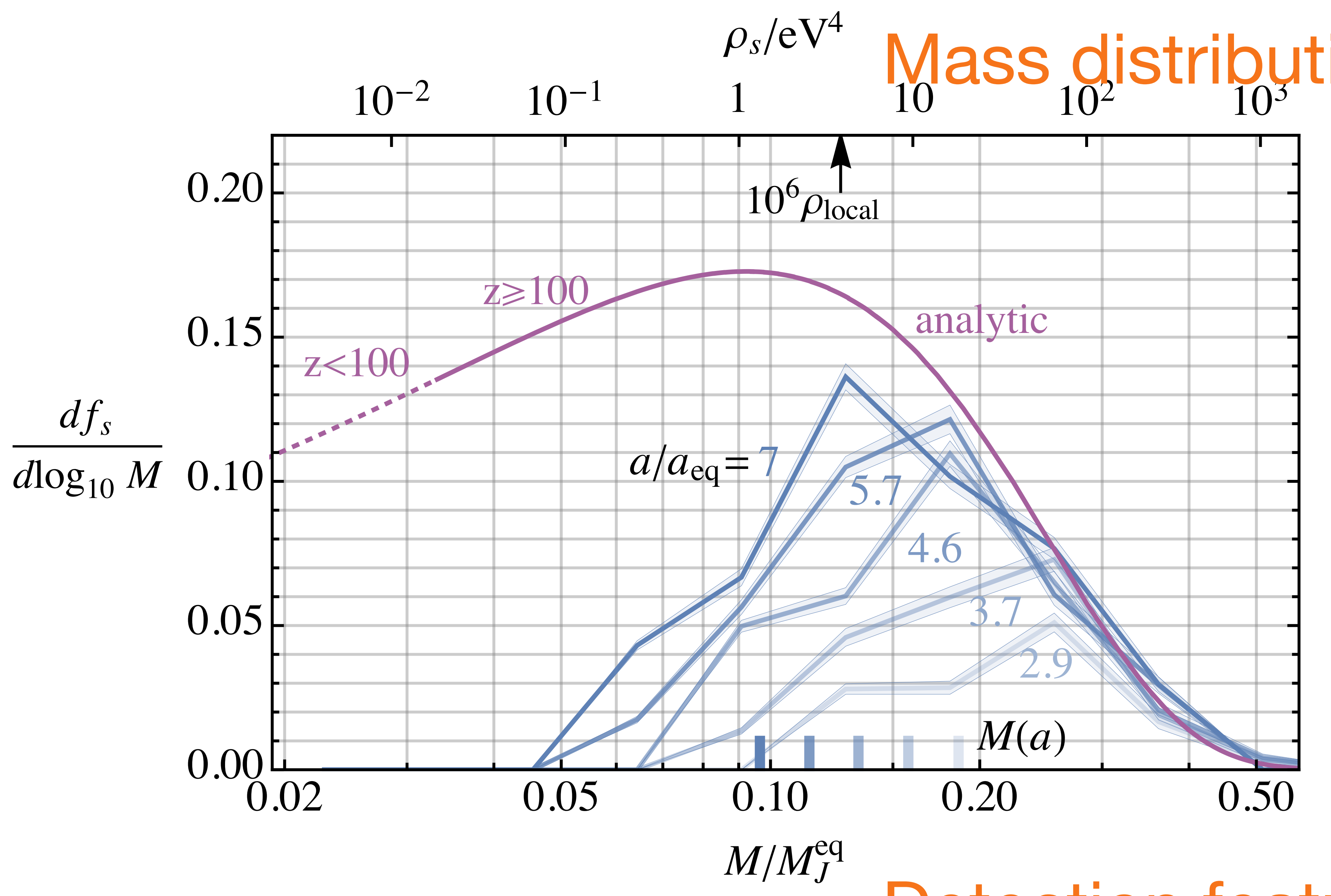
Graham et al, 1504.02102

Other production mechanisms may also apply, e.g. production from topological strings or axions, each predicting a different power spectrum

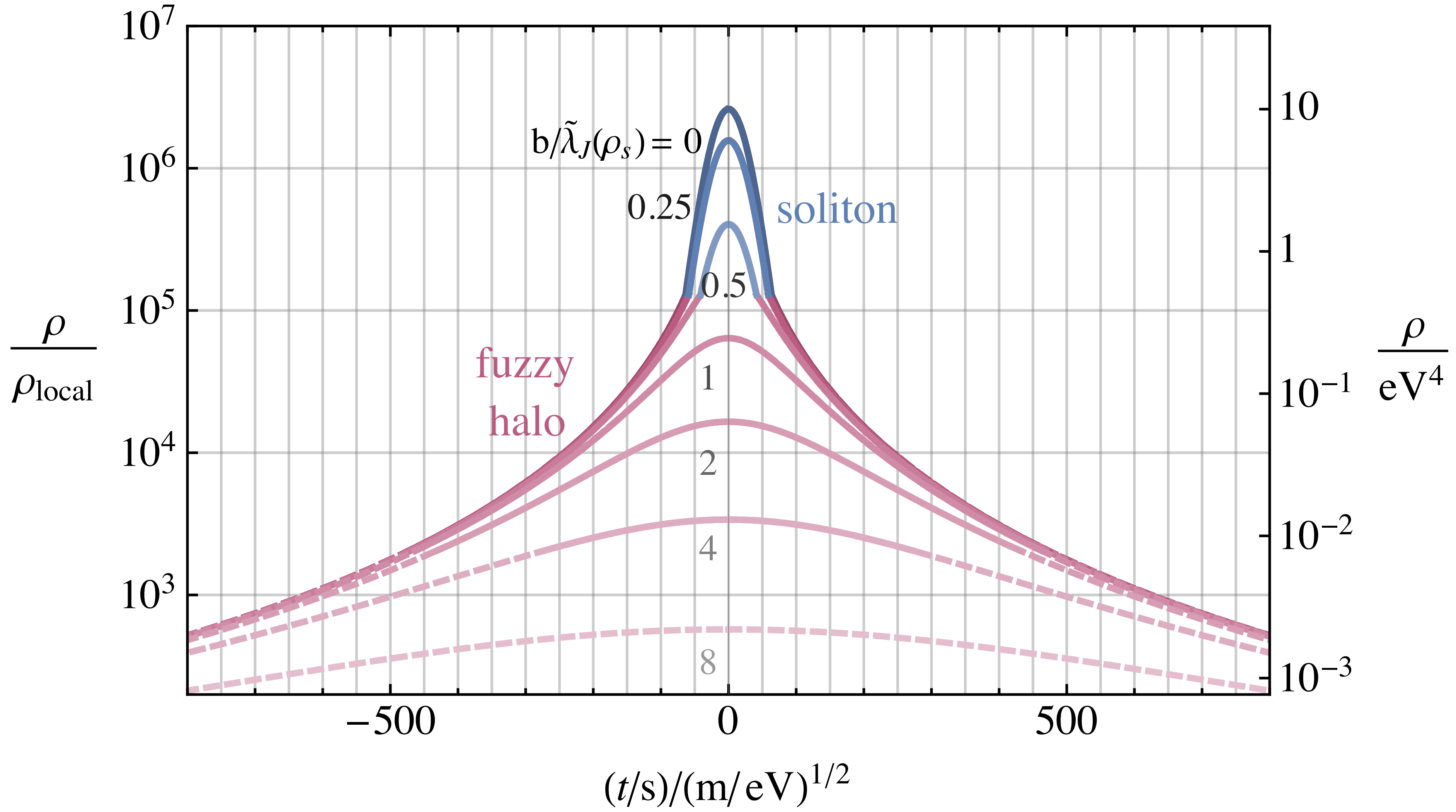
Properties of Dark Photon Stars

- Size: $\lambda_J(\rho_s) = 4.6 \times 10^3\ \mathrm{km} \left(\frac{\mathrm{eV}}{m}\right)^{1/2} \left(\frac{M_J^{\rm eq}}{M}\right)$
- Mass: $M_J^{\rm eq} = 5.2 \times 10^{-23} M_\odot \left(\frac{\mathrm{eV}}{m}\right)^{3/2}$
- Encounters: $N \sim 4.25 \left(\frac{f}{0.05}\right) \left(\frac{m}{\mathrm{eV}}\right)^{1/2} \left(\frac{\Delta t}{\mathrm{yr}}\right)$
- Regions of the clumps within which the mean density larger than 0.05 eV^4 is likely to survive from tidal disruption

Mass distribution



Detection feature



Future Directions

- Signals from compact star and dark photon star encounters
- Magnetic cataclysmic variable, accreting neutron star and black holes
- Axion signal from such systems

Thank you!

Back up

Dark Photon

Extra $U(1)$? $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$

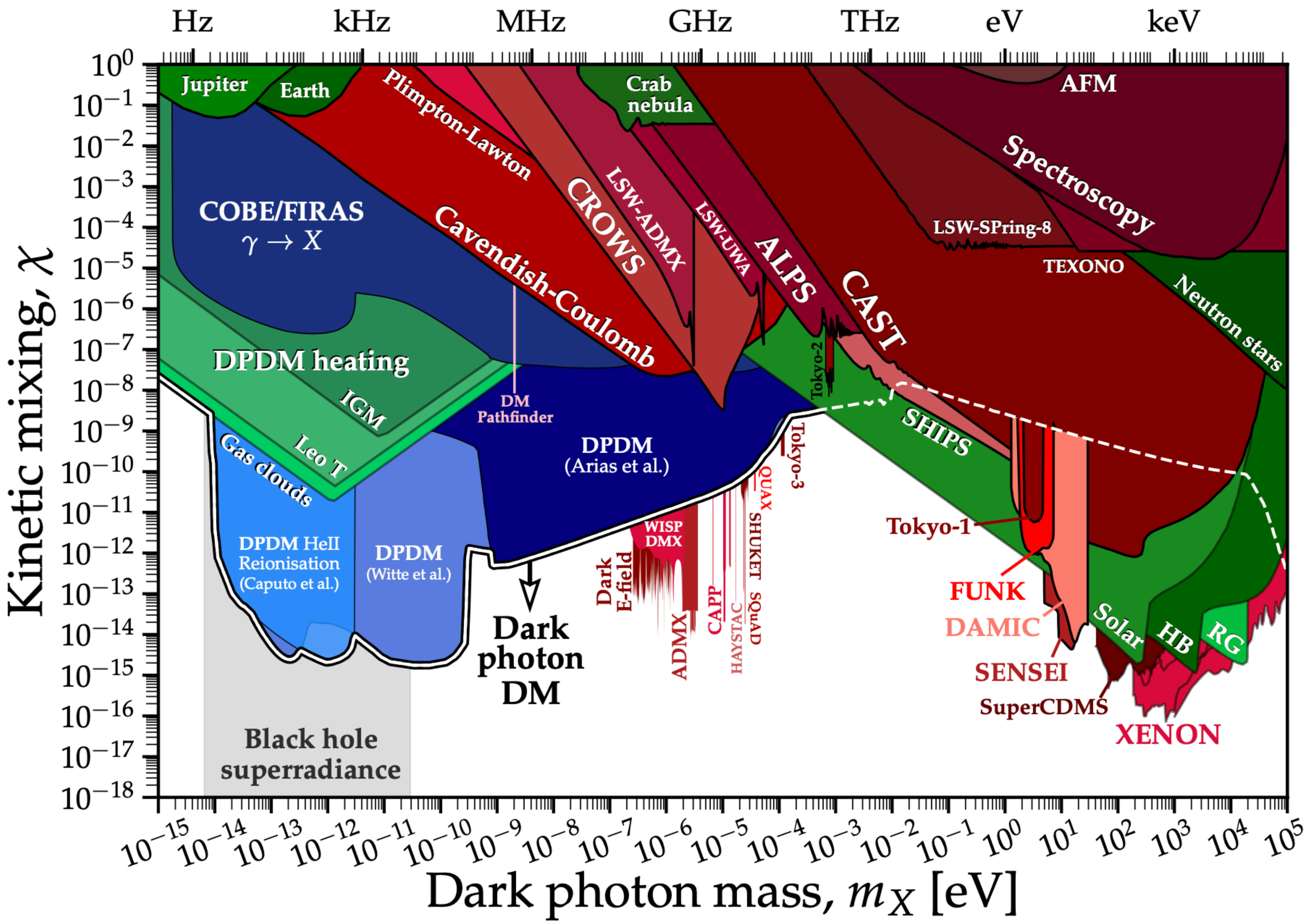
$$\mathscr{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} - 2\kappa F_{\mu\nu}F'^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}) + \frac{m_{A'}^2}{2}A'_\mu A'^\mu - J^\mu A_\mu$$

- Heavy states charged both SM and $U(1)'$
- String compactifications
- Production through misalignment, inflationary perturbation, etc

Pospelov' 2008
Ackerman, Buckley, Carrol, Kamionkowsk' 2008
Arkani-Hame, Finkbeine, Slatyer, Weiner' 2008

Graham et al 1504.02102

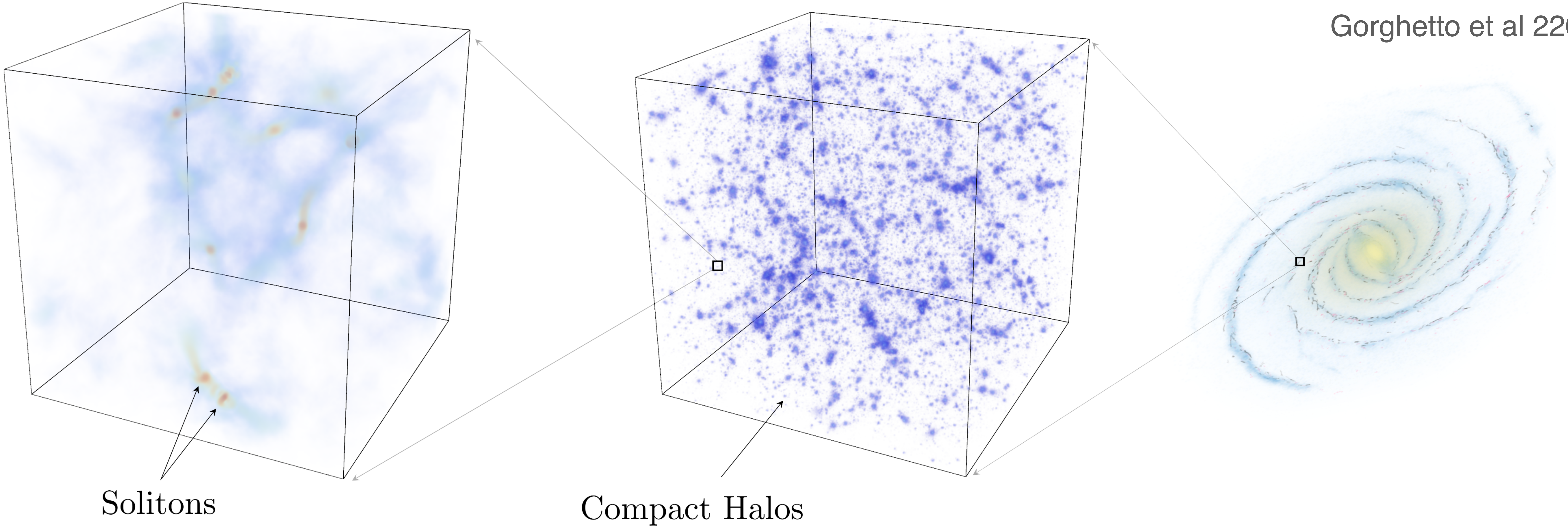
Dark Photon Constraints



Caputo et al 2105.04565

Dark Photon Stars

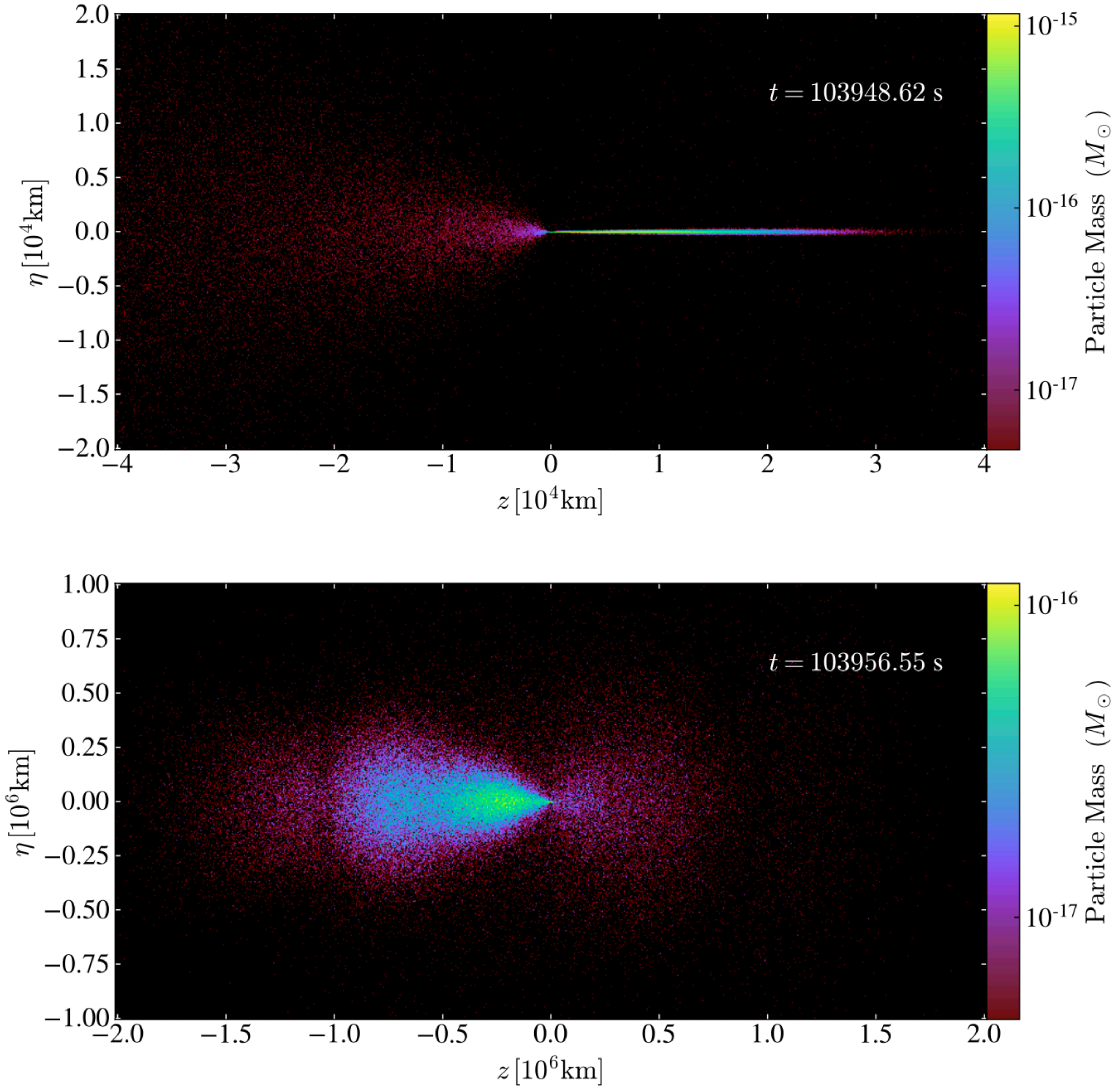
Gorghetto et al 2203.10100



$$\lambda_J = 4.6 \times 10^3 \text{ km} \left(\frac{\text{eV}}{m_{A'}}\right)^{1/2} \left(\frac{M_J^{\text{eq}}}{M}\right) \qquad M_J^{\text{eq}} = 5.2 \times 10^{-23} M_\odot \left(\frac{\text{eV}}{m_{A'}}\right)^{3/2}$$

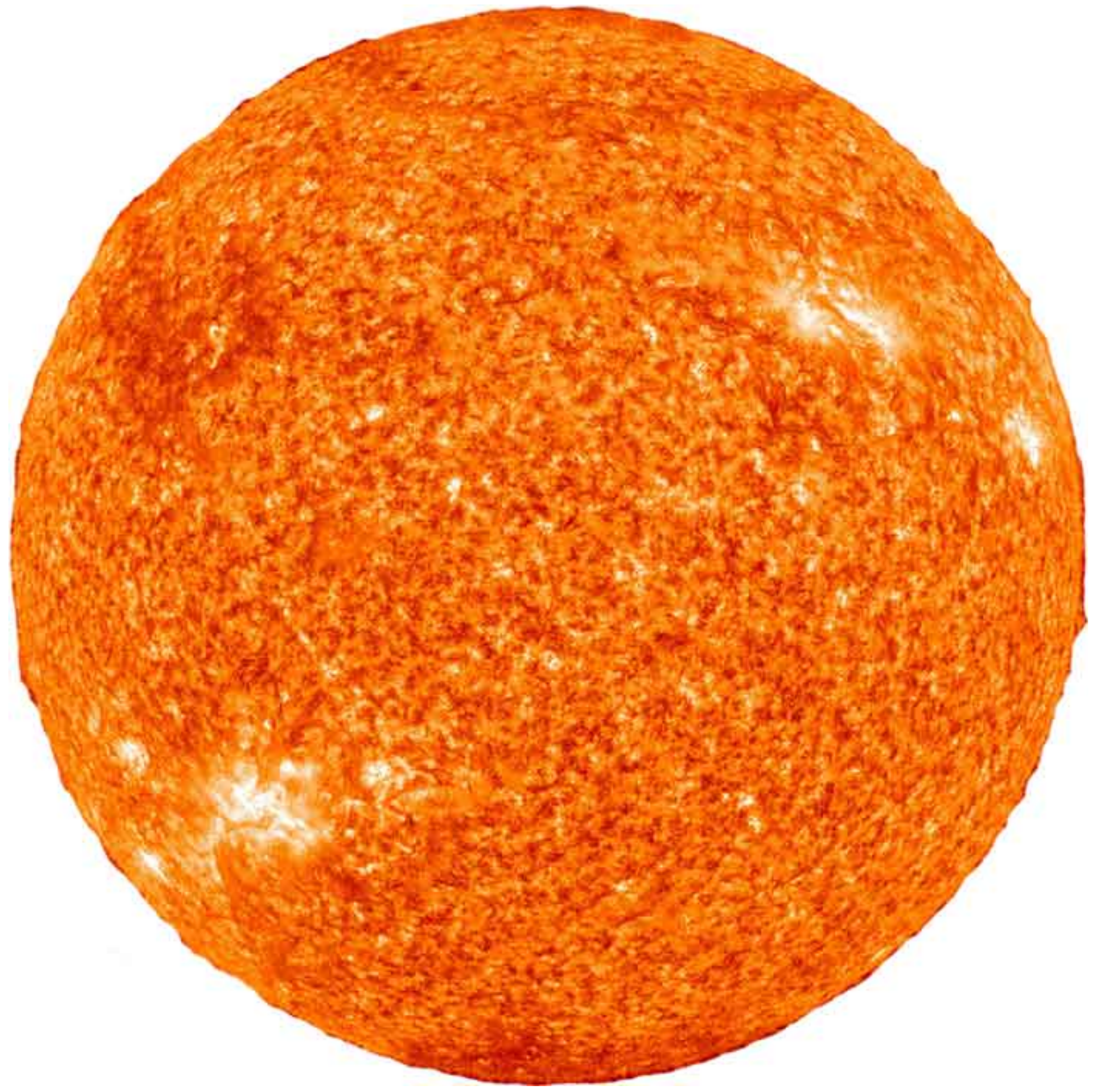
Signal from Dark Photon Star Encounters

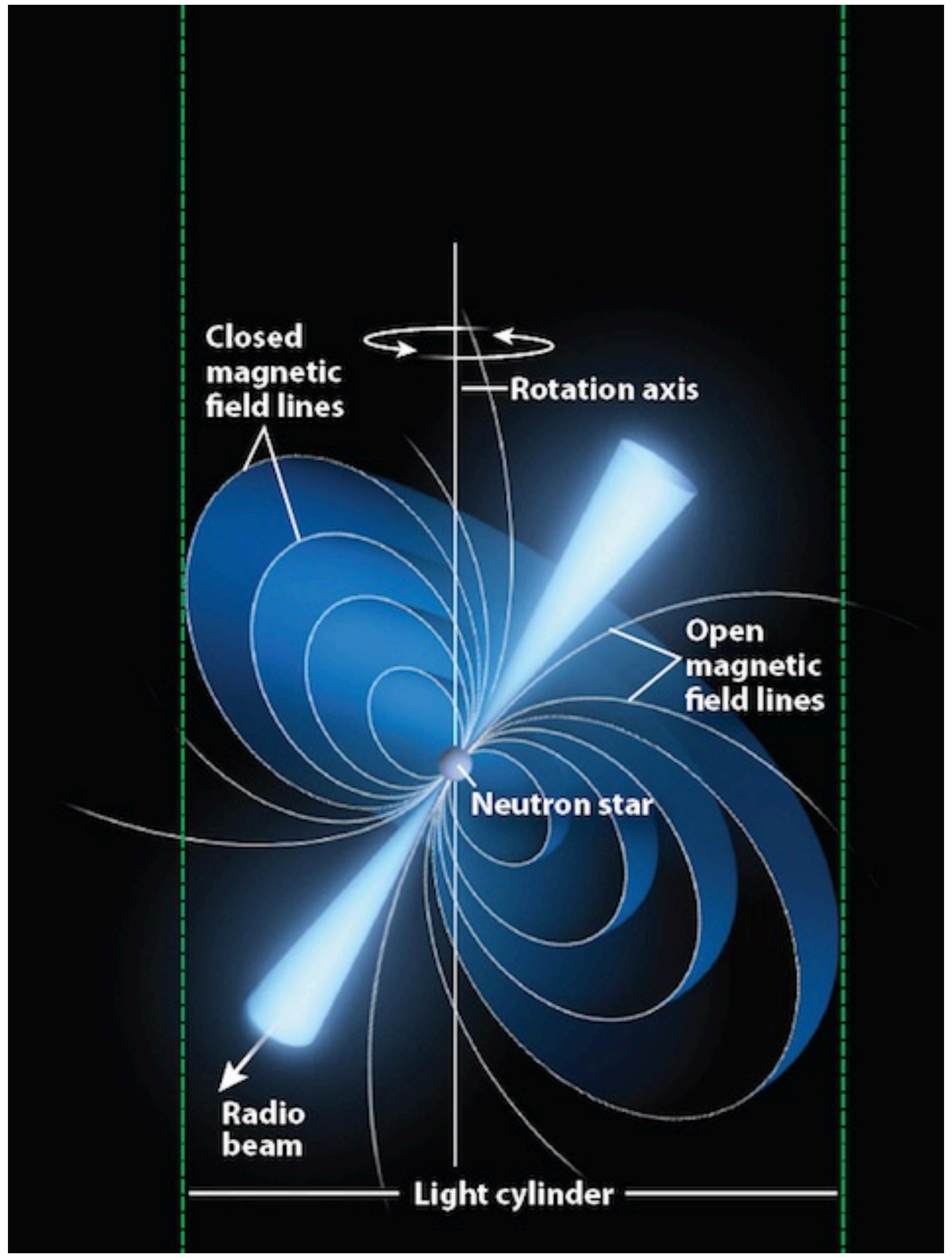
- Dark photon stars are tidally disrupted when colliding with neutron star or white dwarf
- Collision yields a transient signal which lasts a few days
- Density enhancement of around 10^6
- Small velocity dispersion
- More frequent encounter than Earth



Bai et al 2109.01222

Plasma frequencies





Solar Corona
$n_e \lesssim 10^{10}\ \mathrm{cm}^{-3}$
$\omega_p \lesssim 4 \times 10^{-6}\ \mathrm{eV}$
$f \lesssim \mathrm{GHz}$

An et al 2010.15836

Neutron Star Magnetosphere
$n_e \lesssim 10^{13}\ \mathrm{cm}^{-3}$
$\omega_p \lesssim 10^{-4}\ \mathrm{eV}$
$f \lesssim 24\ \mathrm{GHz}$

White Dwarf Corona
$n_e \lesssim 10^{17}\ \mathrm{cm}^{-3}$
$\omega_p \lesssim 10^{-2}\ \mathrm{eV}$
$f \lesssim 2400\ \mathrm{GHz}$

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