Radio Signals of Dark Photons from Compact Stars in the Galactic Center

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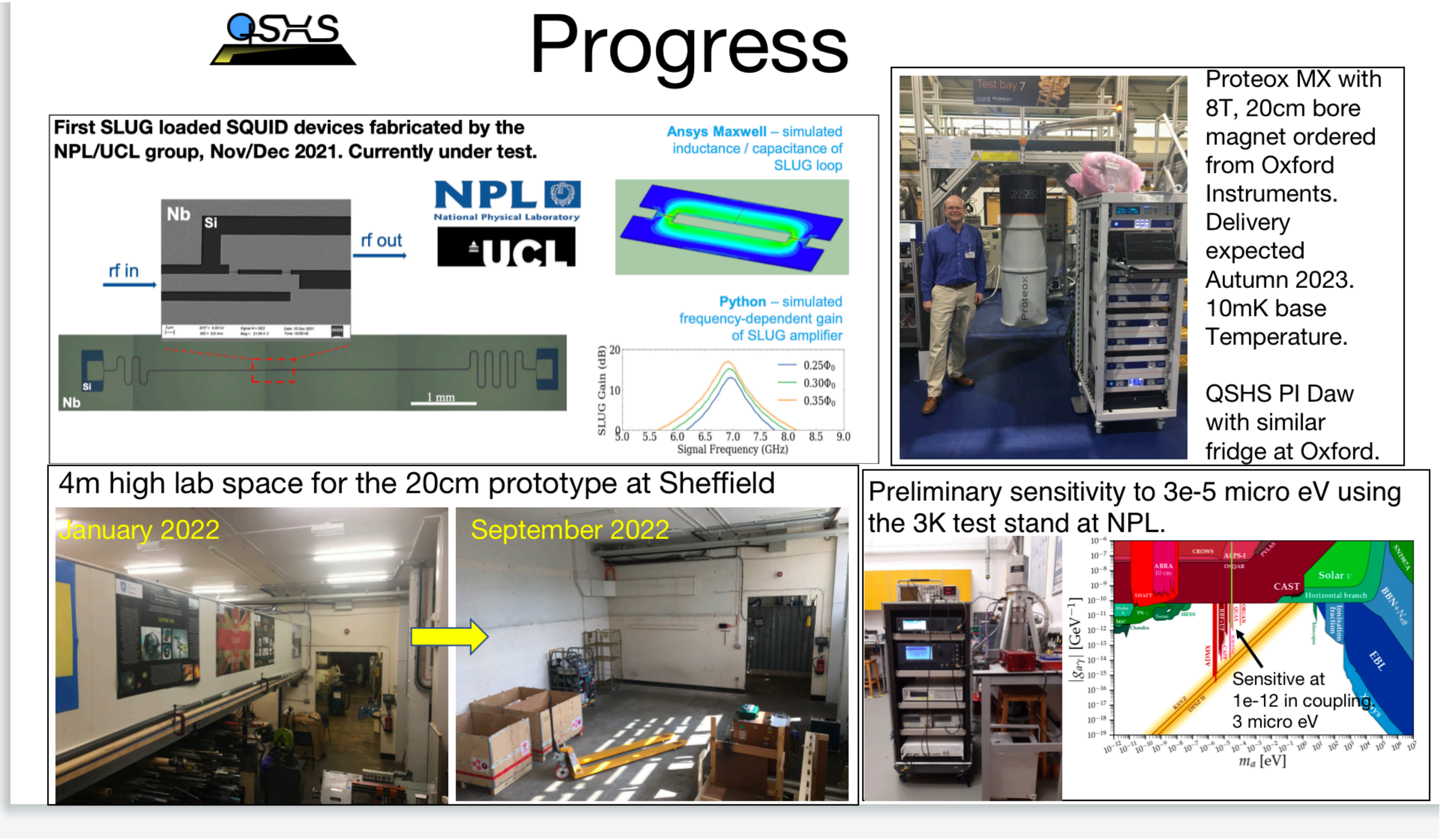
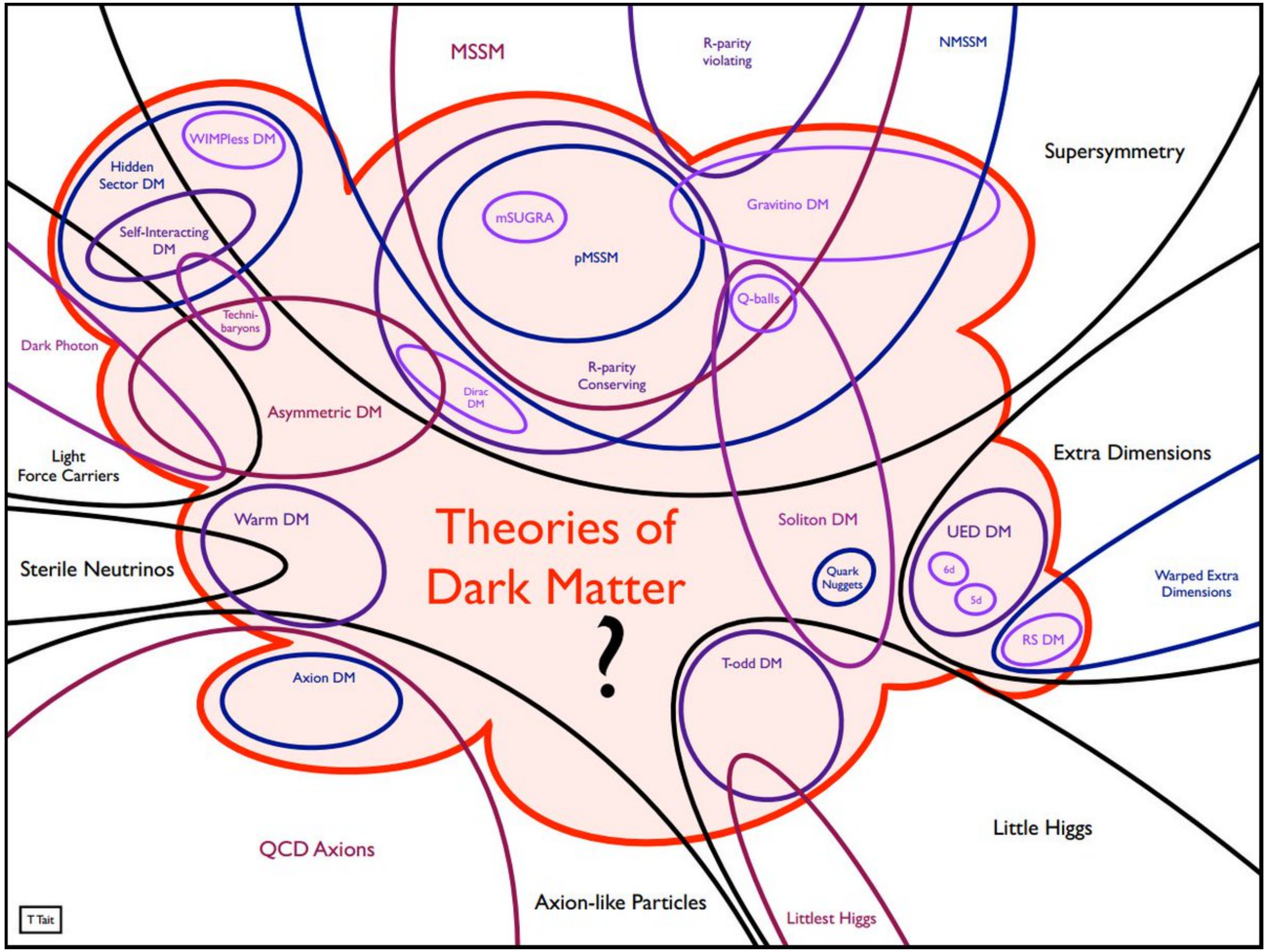


https://qshs.org/

The Dark Matter Landscape



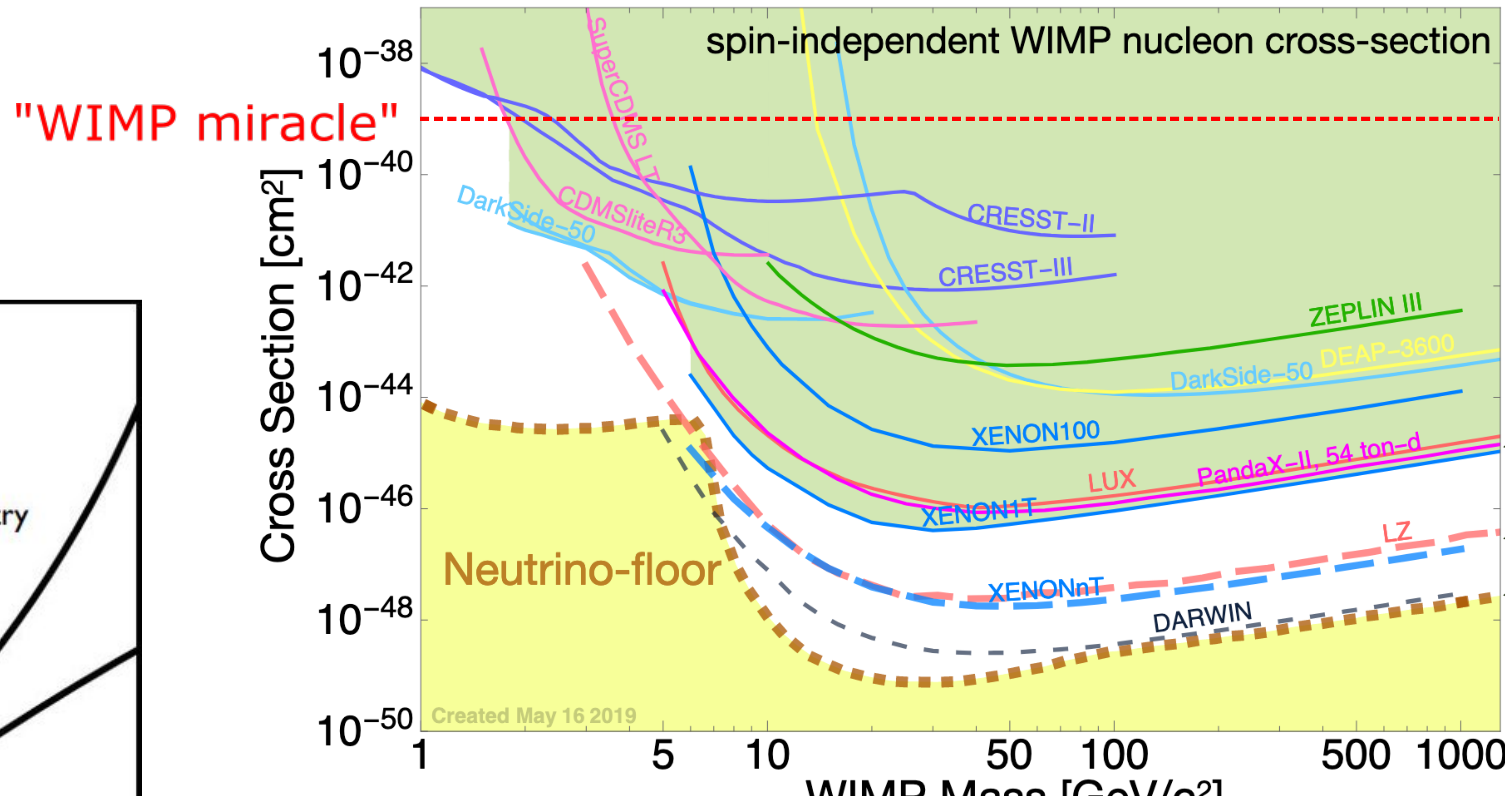
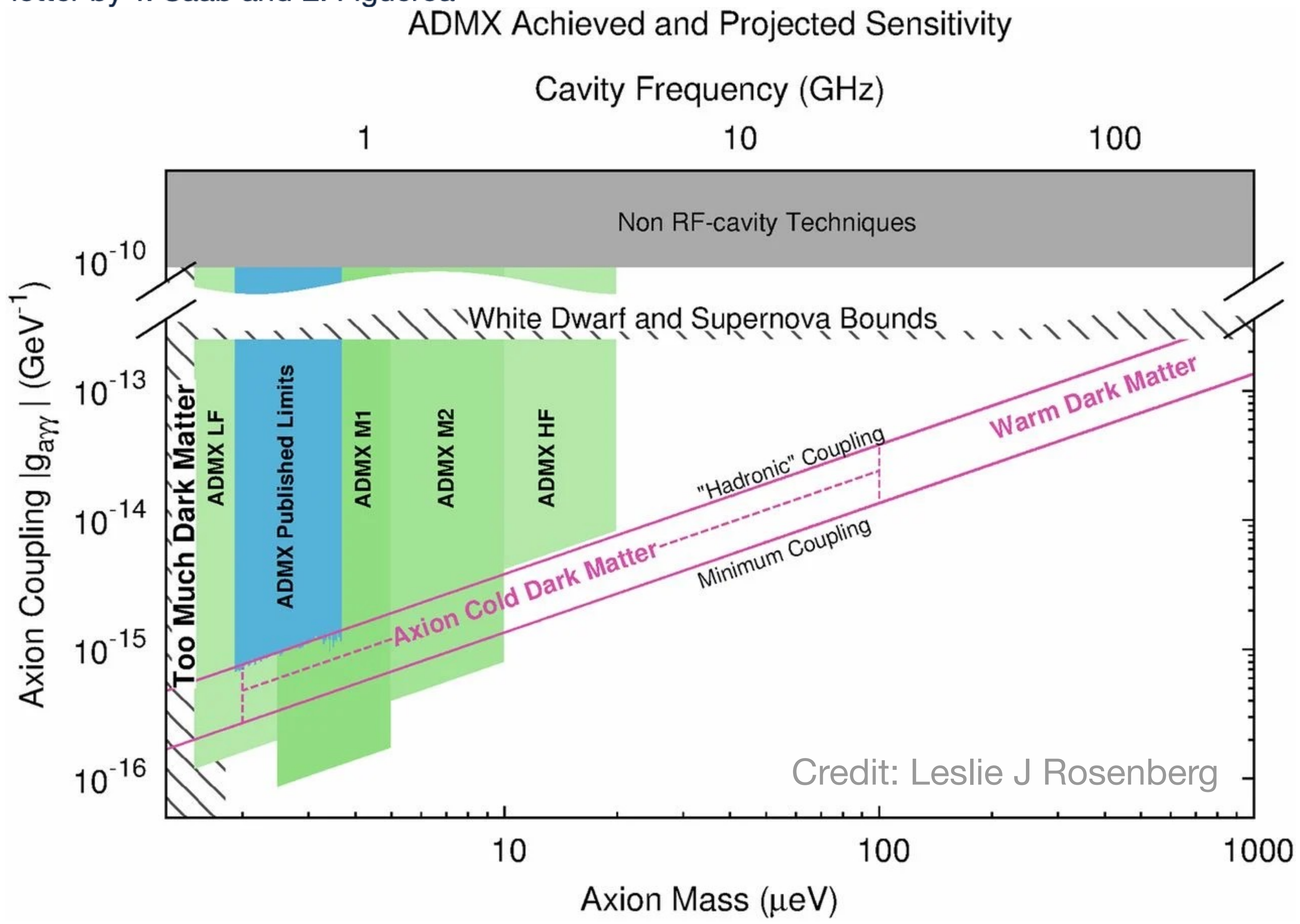


Figure created with the Dark Matter Limit Plotter by T. Saab and E. Figueroa



Dark Photon

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

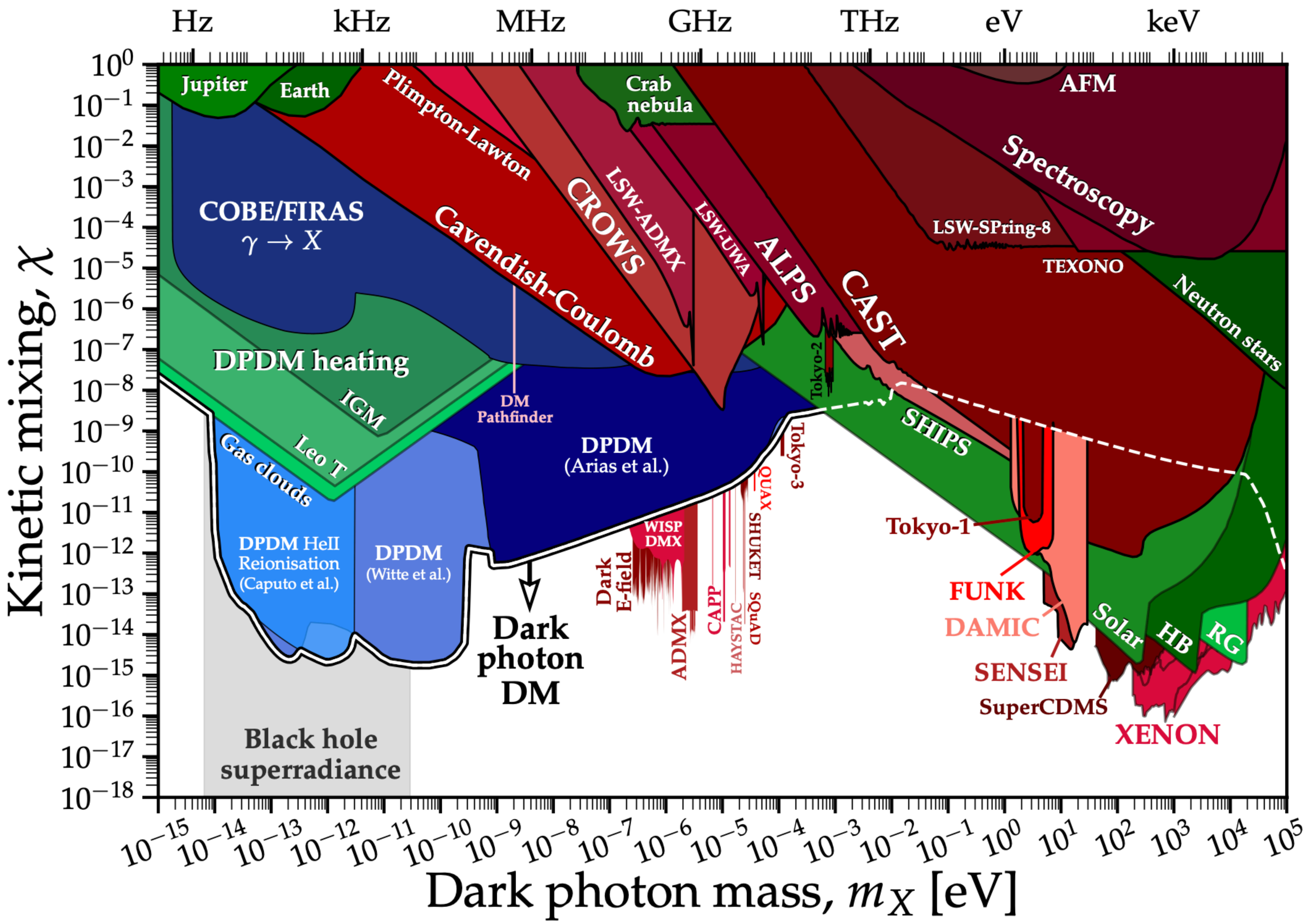
$$\mathscr{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} - 2\kappa F_{\mu\nu}F'^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}) + \frac{m_{A'}^2}{2}A'_\mu A'^\mu - J^\mu A_\mu$$

- 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

Resonant Dark Photon Conversion

- Resonant conversion from axion to photon in the magnetosphere of a neutron star when $m_a \sim \omega_p$

$$-\nabla^2 \vec{E} + \nabla(\nabla \cdot \vec{E}) = -\partial_t^2(\epsilon \cdot \vec{E}) - g_{a\gamma\gamma} \vec{B}_0 \partial_t^2 a\,,$$
$$(\partial_t^2 - \nabla^2 + m_a^2) a = g_{a\gamma\gamma} \vec{E} \cdot \vec{B}_0\,,$$

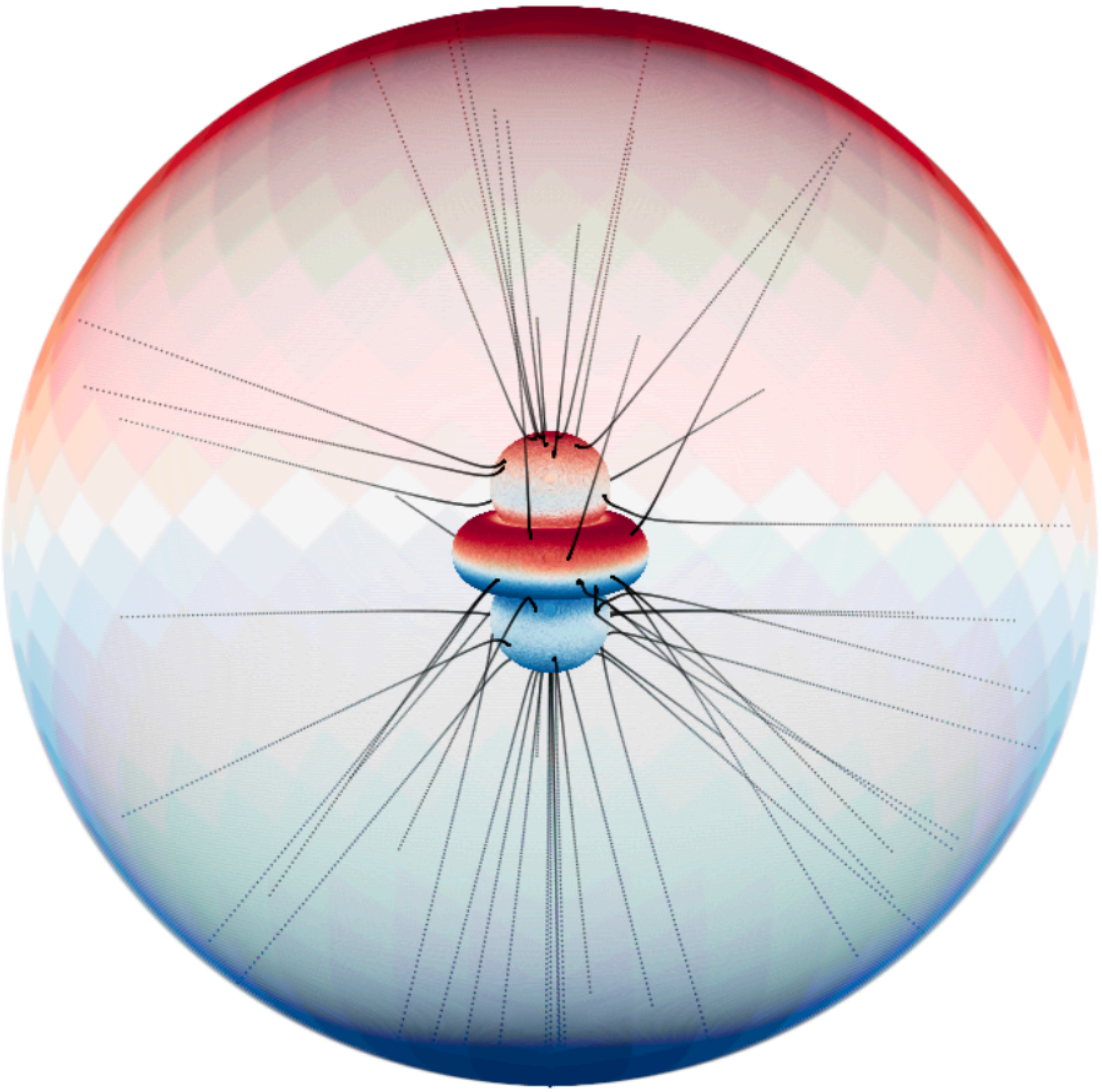
Hook et al 1804.03145

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

Millar et al 2107.07399

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

Dark Photons?



Witte et al 2104.07670

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Resonant Dark Photon Conversion

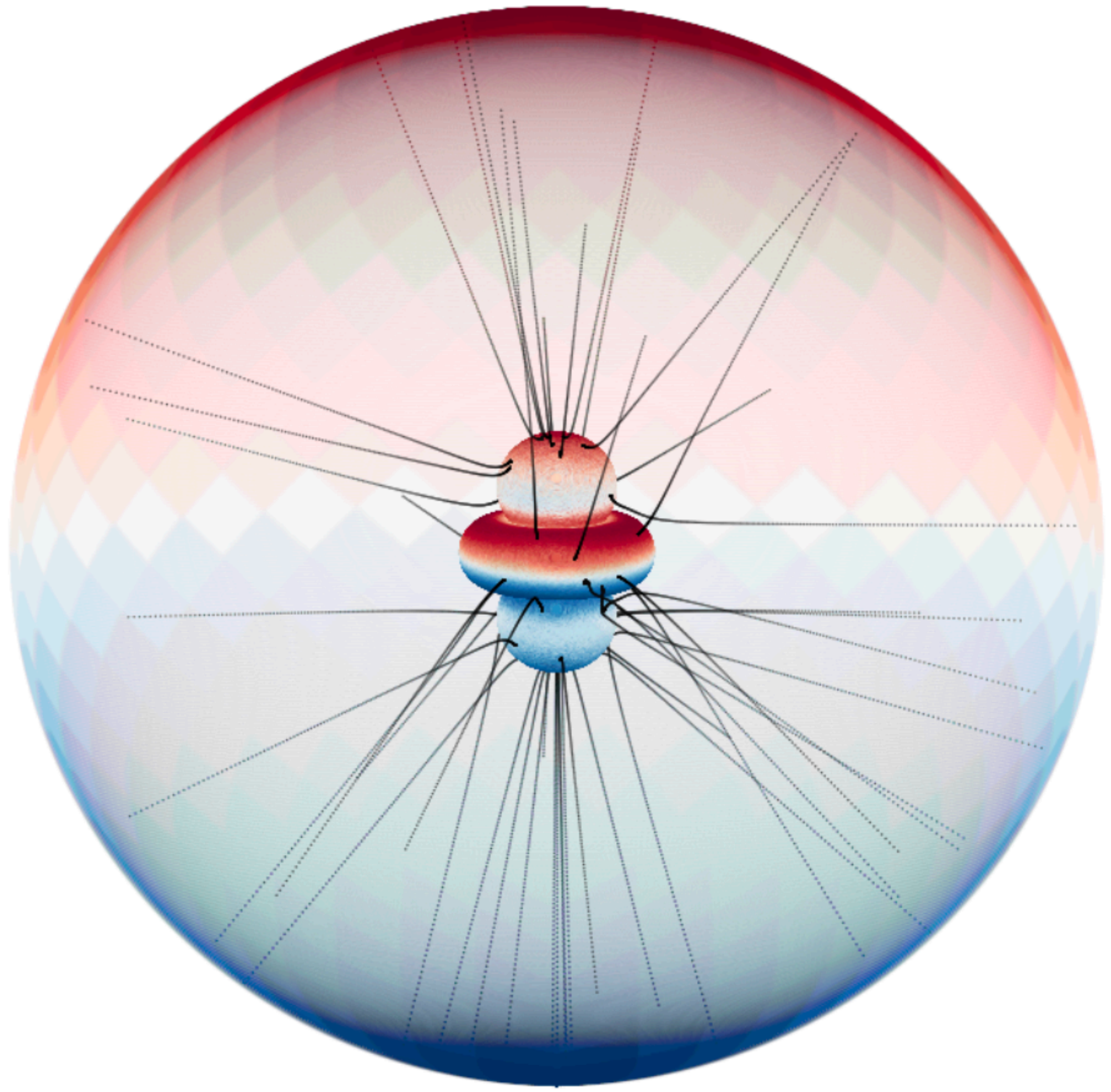
- Resonant conversion from dark photon to photon in the magnetosphere of a neutron star when $m_{A'} \sim \omega_p$
- Redefine $A_\mu \to A_\mu + \kappa A'_\mu$ to remove the mixing,

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

- Equation of motion

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

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



Witte et al 2104.07670

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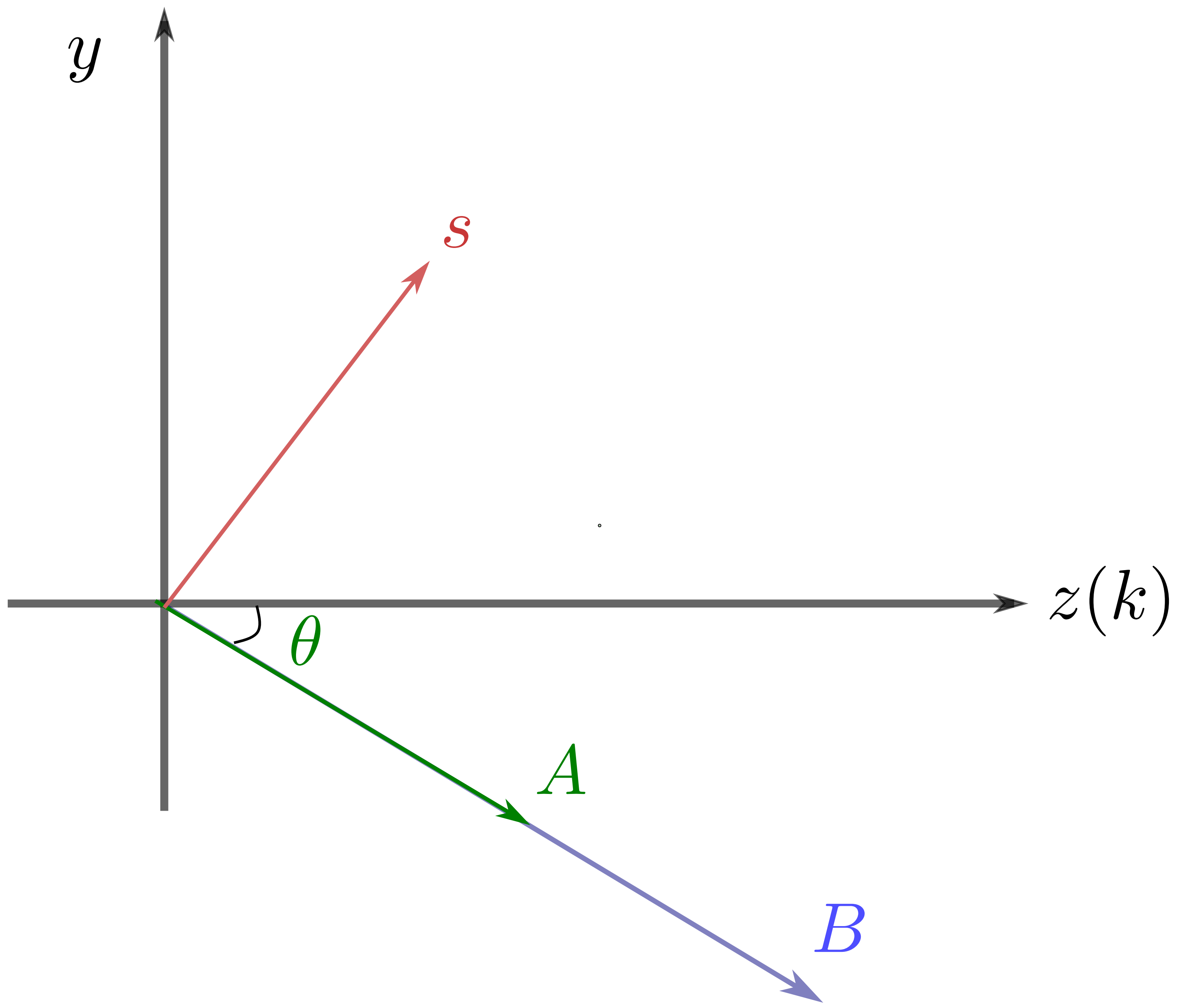
Resonant Dark Photon Conversion

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

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



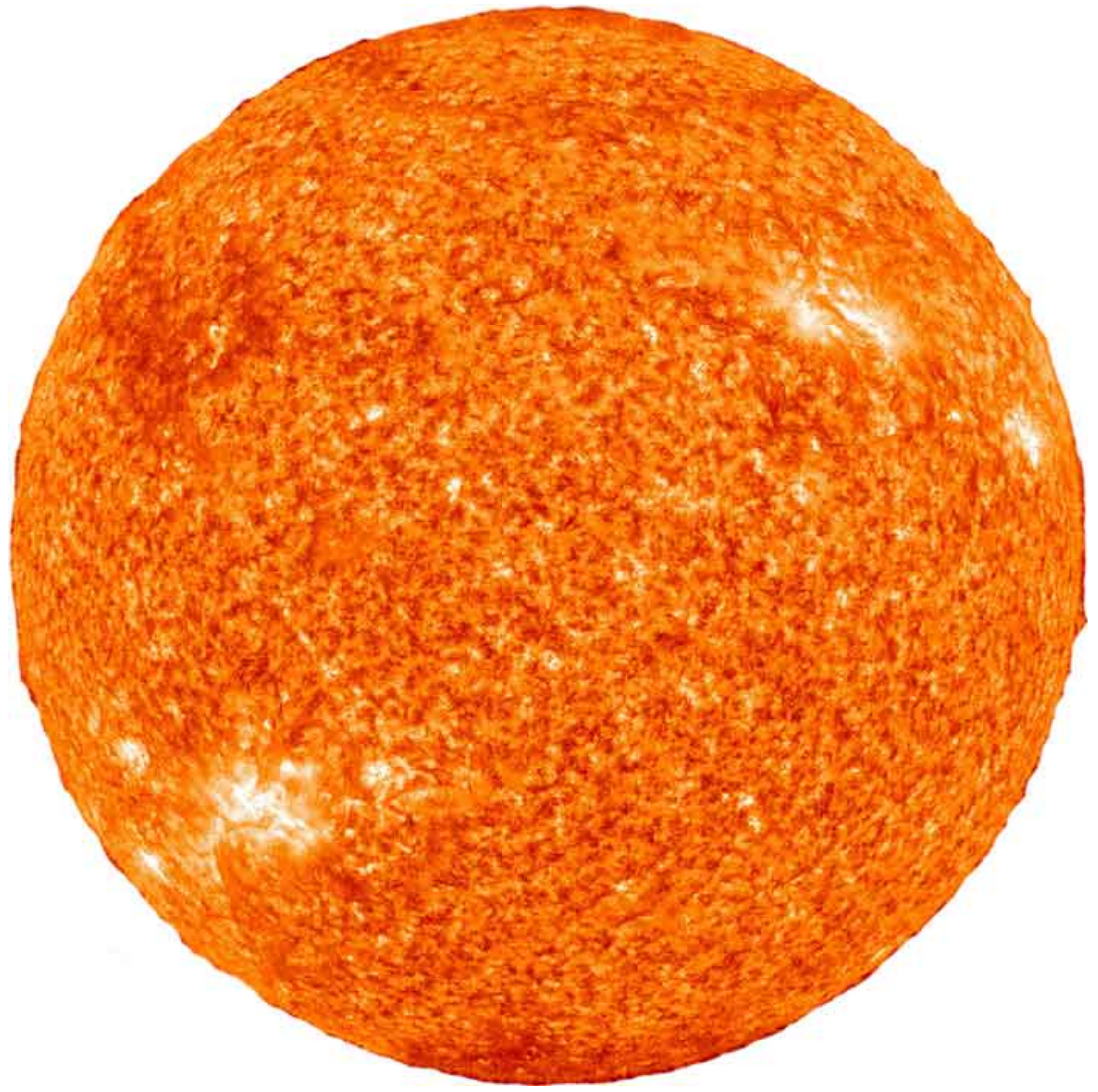
Resonant Dark Photon Conversion in White Dwarf

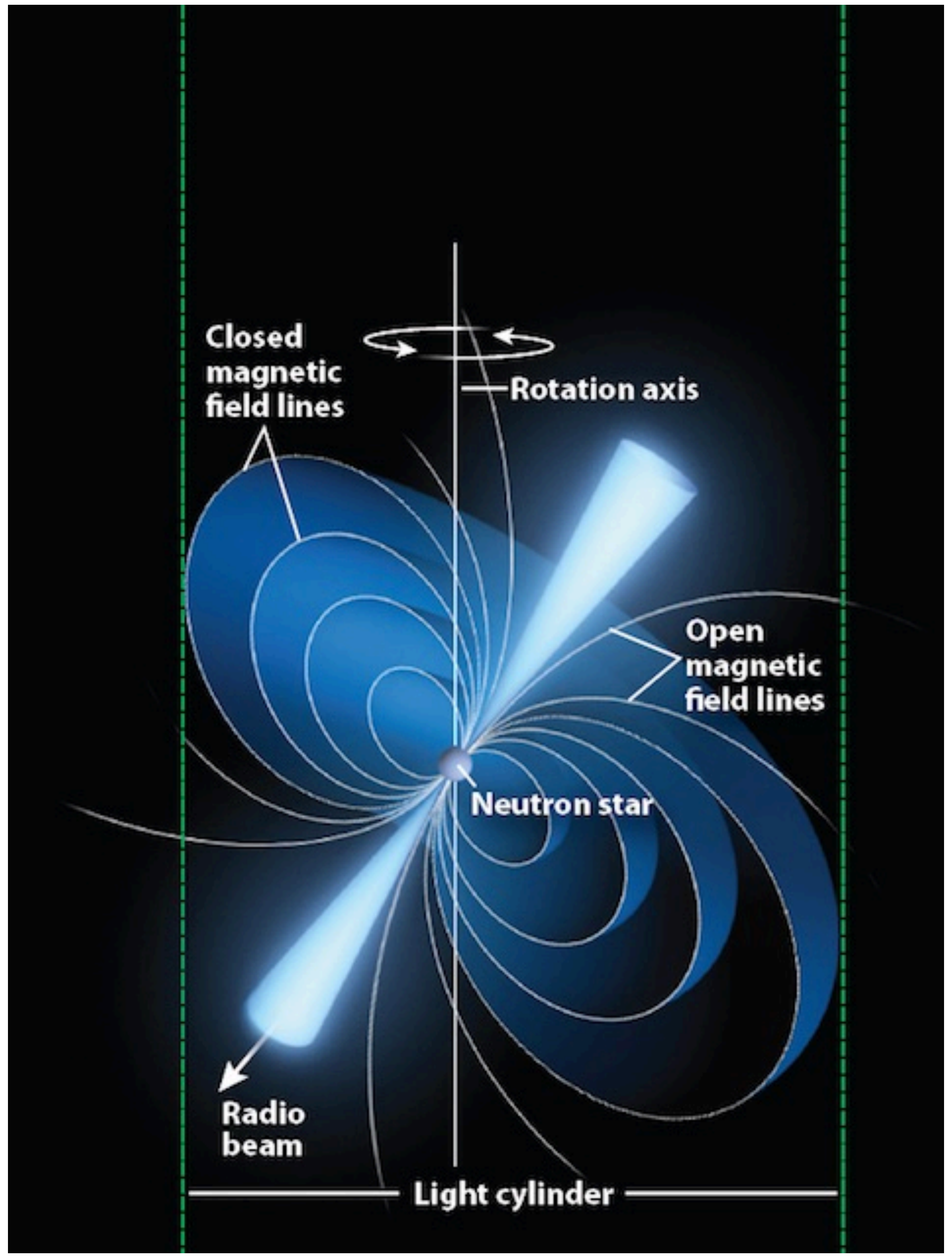
- Magnetic field is NOT required for the conversion
- White dwarf corona with an exponential profile $n_e(r) = n_0 e^{-\frac{r - r_0}{l_c}}$

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

- Conversion probability $p = \frac{2\pi}{3}\frac{\kappa^2 m_{A'}^2}{k} l_c$

Plasma frequencies





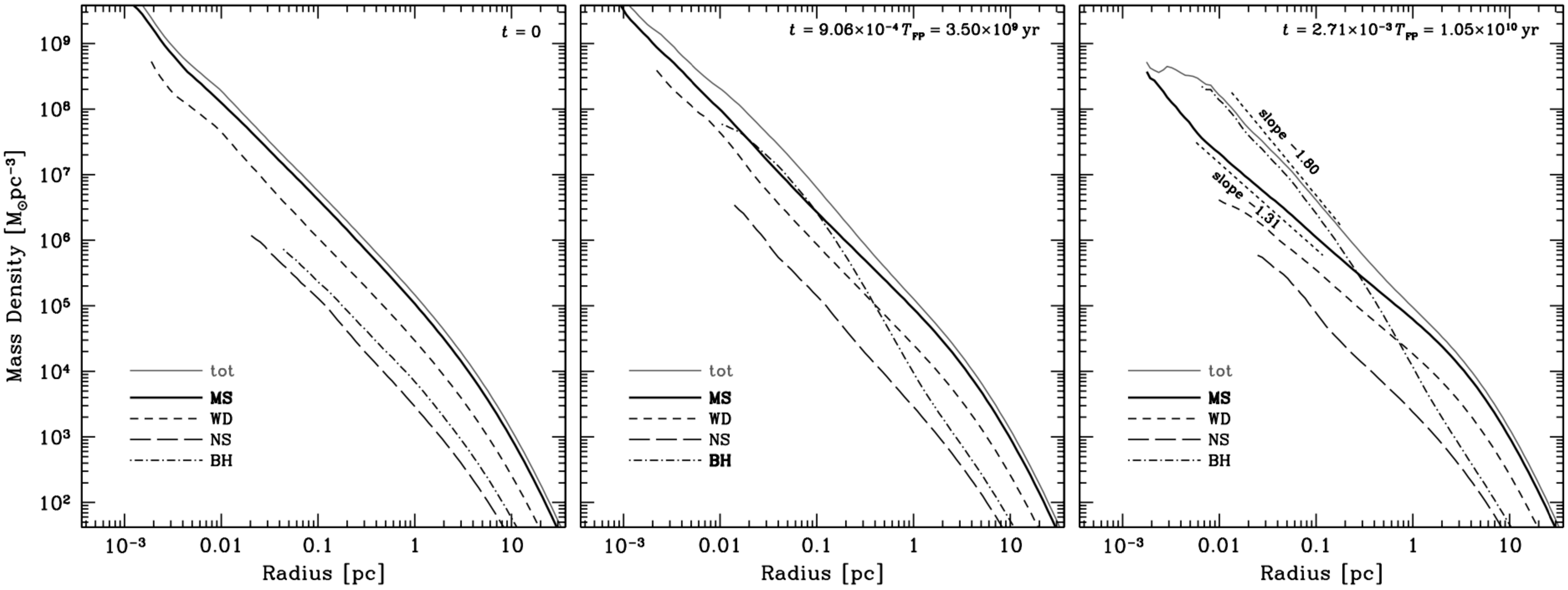
Solar Corona
$n_e \lesssim 10^{10}\ \mathrm{cm}^{-3}$
$\omega_p \lesssim 4 \times 10^{-6}\ \mathrm{eV}$
$f \lesssim \mathrm{GHz}$

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

Compact Stars in the Galactic Centre



Freitag et al 2006

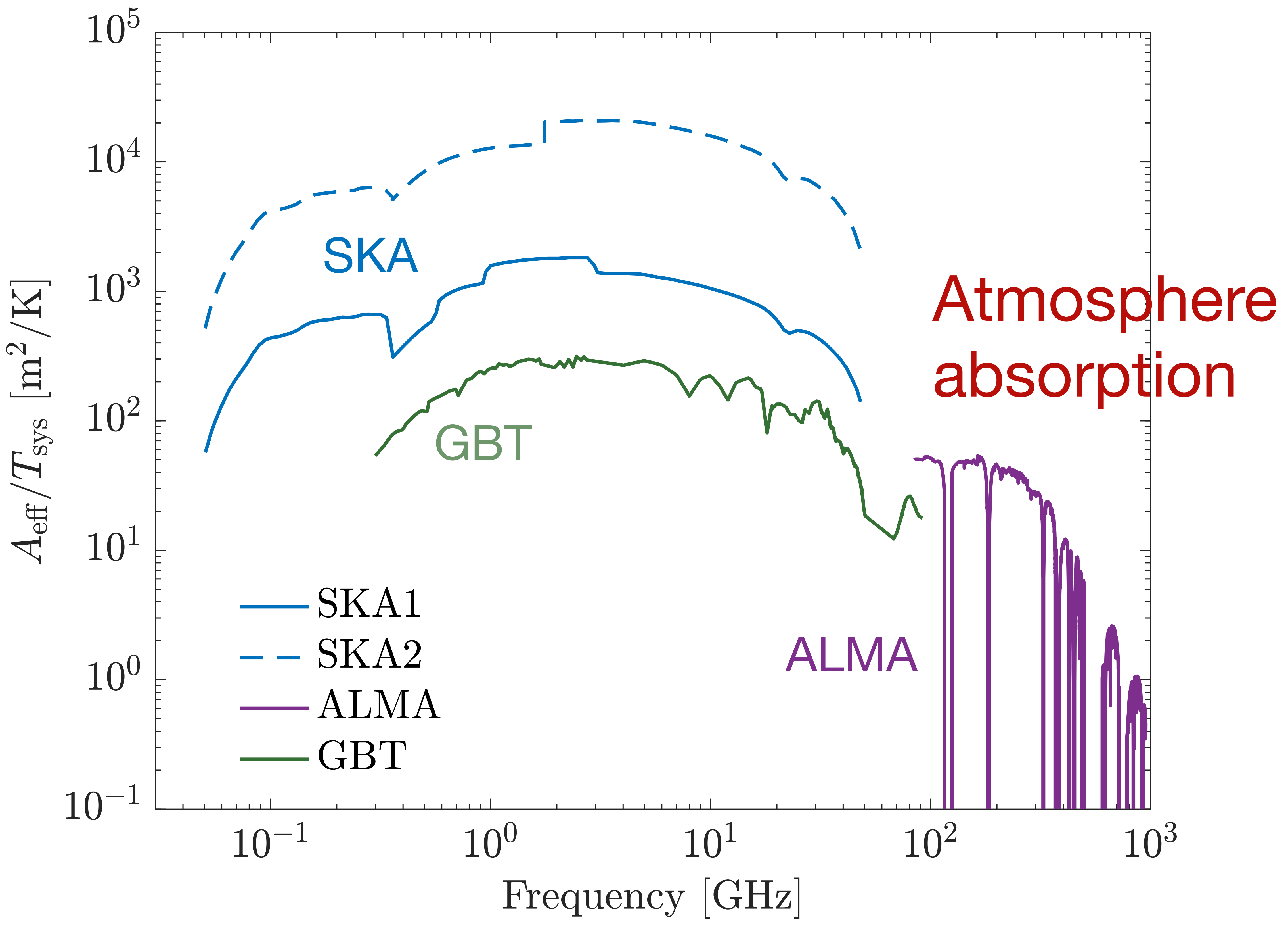
Radio Telescopes

Minimum detectable signal flux density

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

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

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



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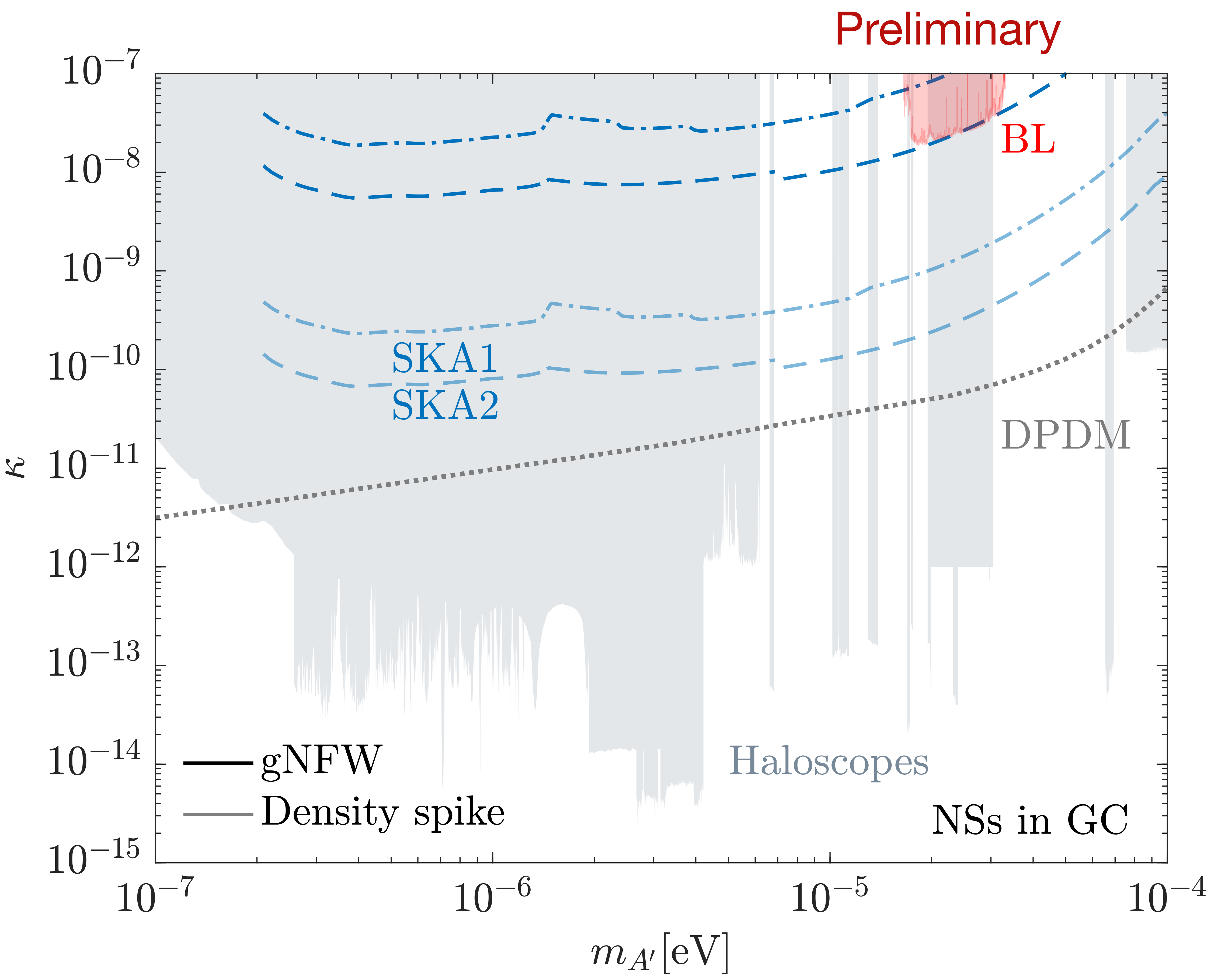
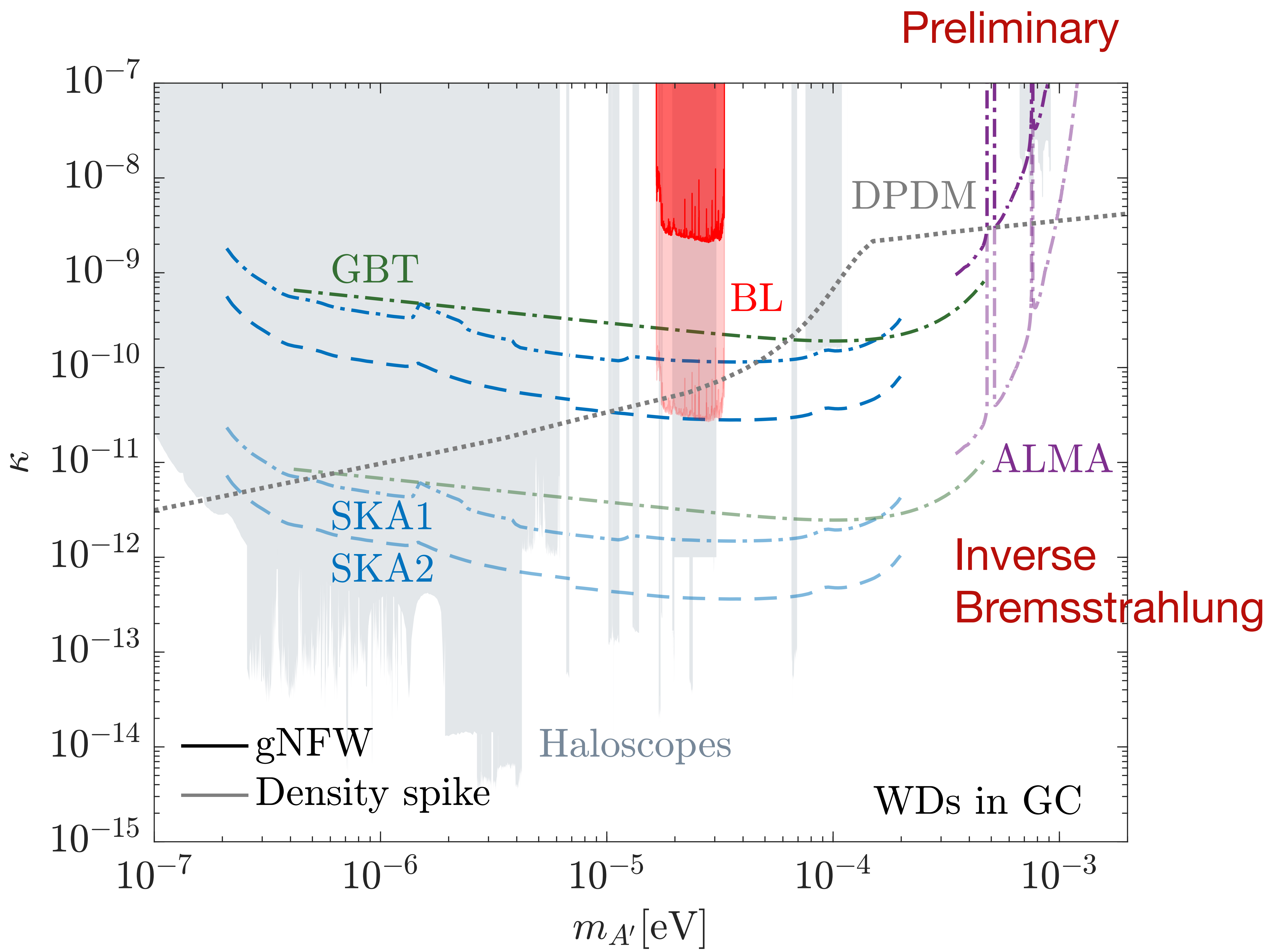
Sensitivities for Galactic Centre Signals



Neutron Stars



White Dwarfs

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Bonus

Signals from the Galactic Centre

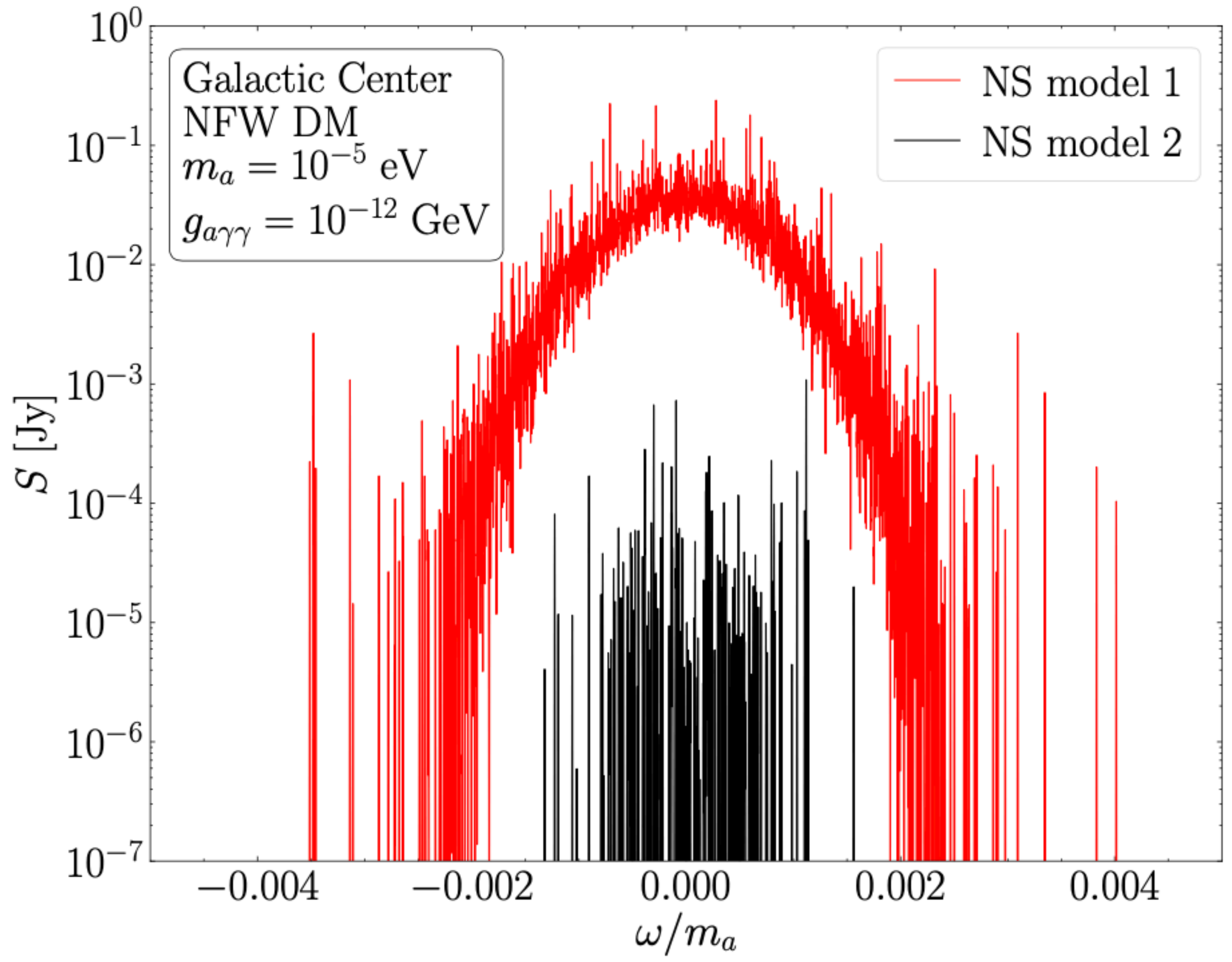
$$S_{\rm sig} = \frac{1}{\mathscr{B} d^2} \frac{dP}{d\Omega} > S_{\rm min}$$

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

Signal 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

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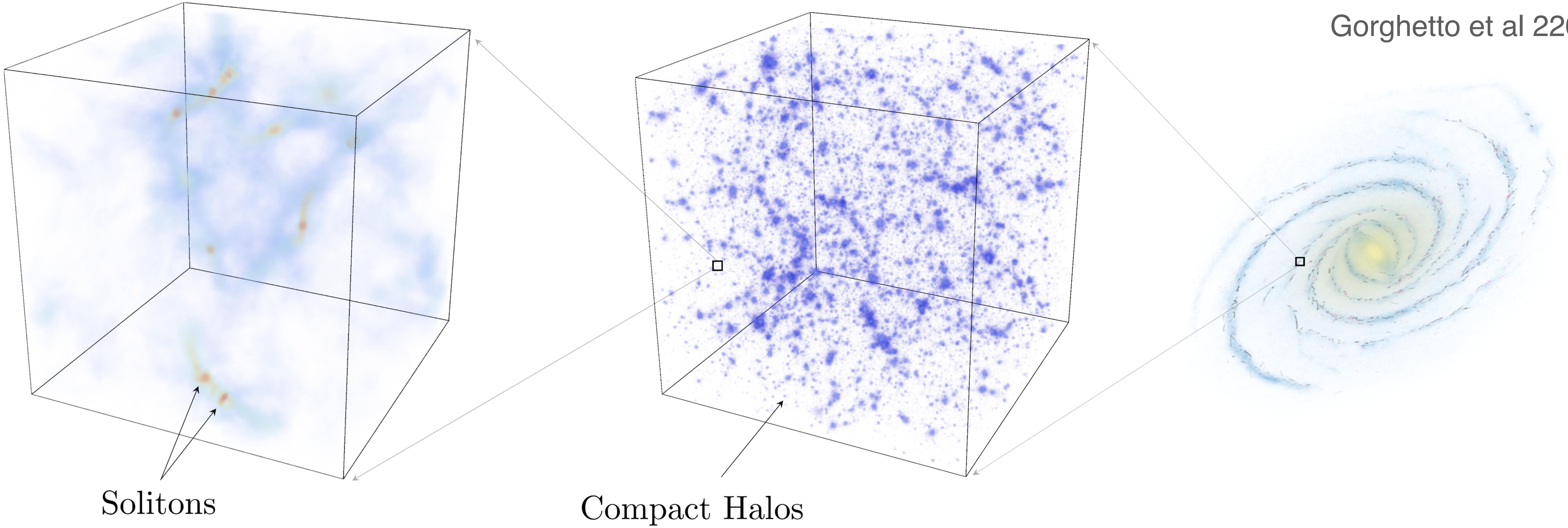
Dark Photon Stars

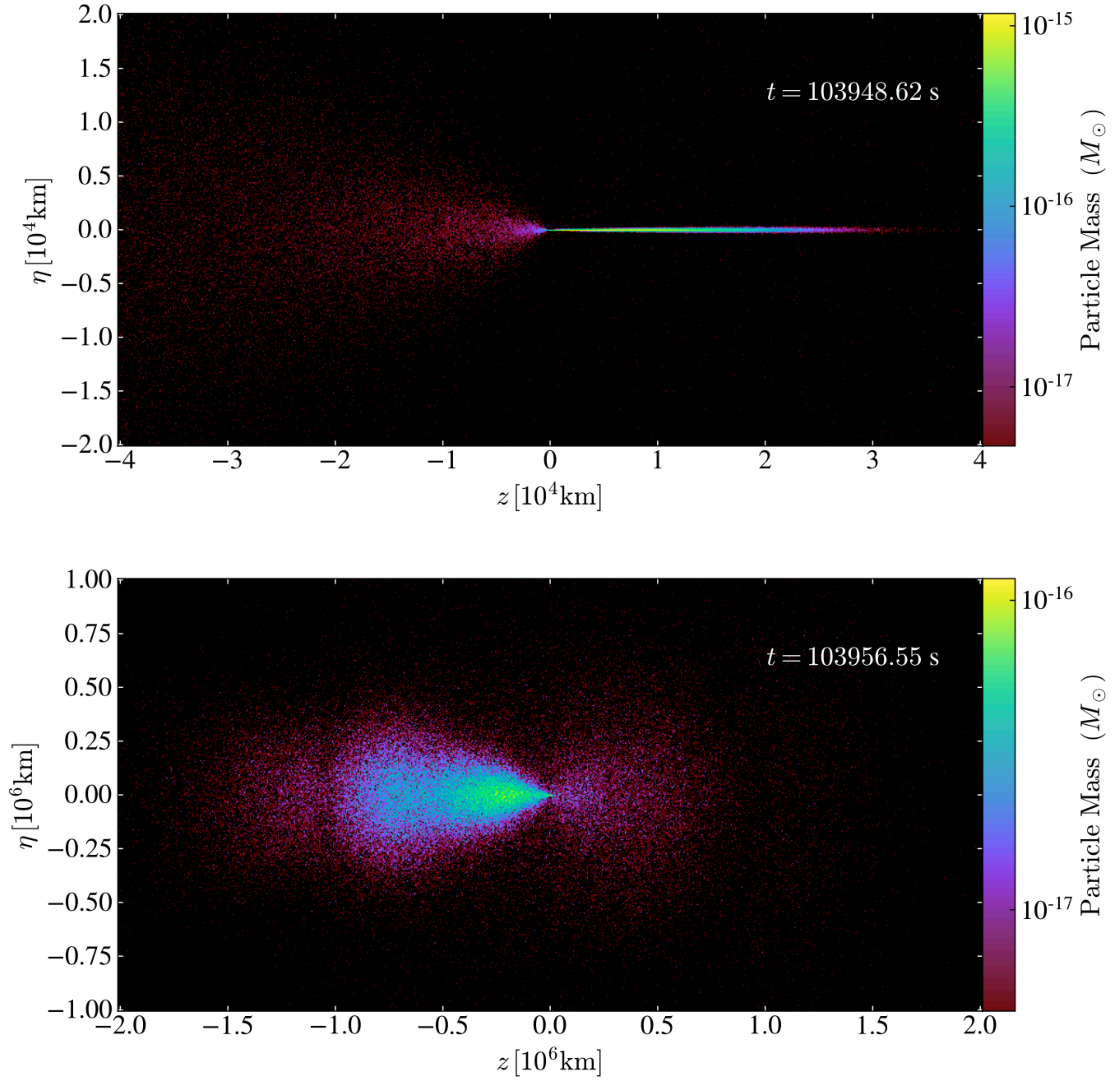
Gorghetto et al 2203.10100



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

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

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