Axion dark matter indirect detection

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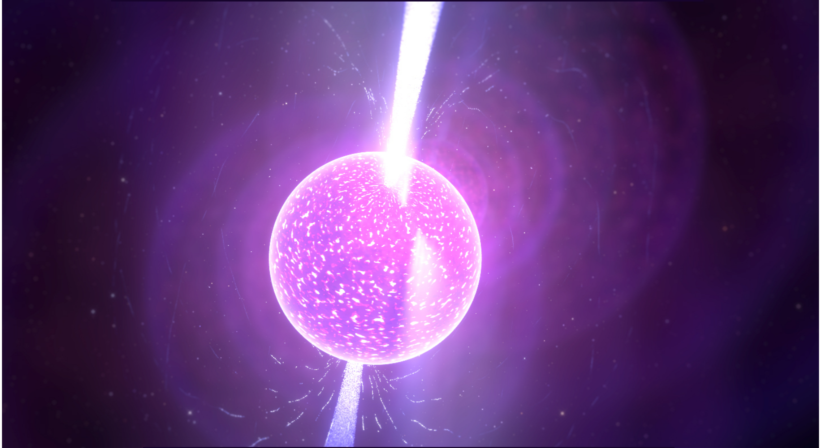
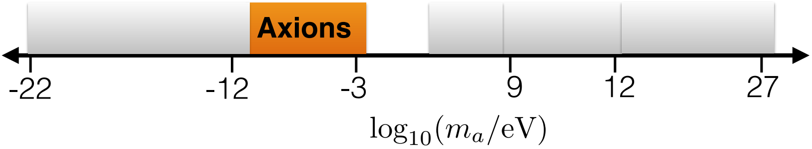
Detecting Axion Dark Matter with Radio Observations of Neutron Stars



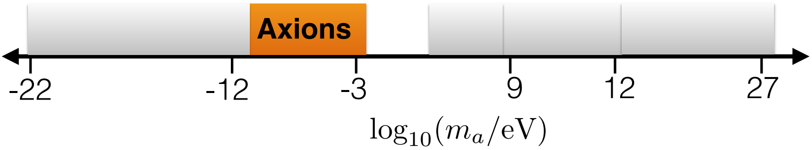
A. Hook, Y. Kahn, **B.S.**, Z. Sun: 1804.03145
A. Chen. **B.S.,** Z. Sun: to appear 2018

Brief Review of Axion-Photon Mixing



- Axion solves strong CP problem (neutron EDM $\propto \bar{\theta}$) Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978

$$\mathcal{L}_{\text{axion}} = -\left(\bar{\theta} + \frac{a}{f_a}\right) \frac{g^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$$



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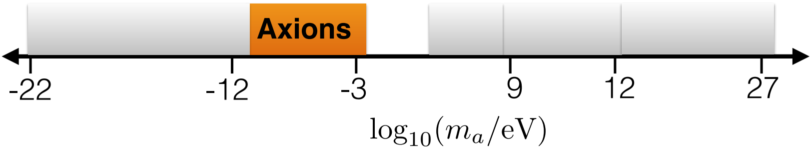

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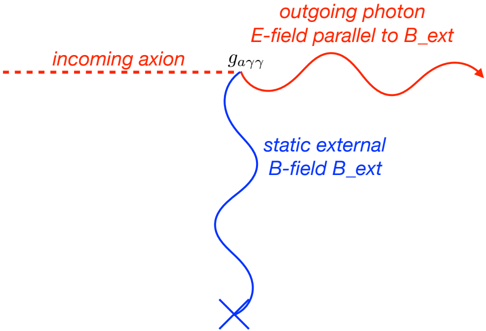
- Axion couples to QED

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad g_{a\gamma\gamma} \propto \frac{\alpha_{\text{EM}}}{f_a}$$

Axion-photon mixing

- $\mathcal{L} = -\frac{g_{a\gamma\gamma}}{4} a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \sim g_{a\gamma\gamma} \underbrace{a}_{\text{dynam.}} \underbrace{\mathbf{E}}_{\text{dynam.}} \cdot \underbrace{\mathbf{B}}_{\text{ext.}}$



- $P_{a\to\gamma} \sim B_{\text{ext}}^2 g_{a\gamma\gamma}^2 L^2$
- L determined by B_{ext} geometry and axion wavelength m_a^{-1}

Example: CAST

Sun

keV plasma produces axions

relativistic axions

X-rays

High B field converts axions -> photons

- $P_{a\to\gamma} \sim B_{\text{ext}}^2 g_{a\gamma\gamma}^2 L^2$: what is L?

Example: CAST

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- $\delta k \ll L_{\text{CAST}}^{-1}$: $L \sim L_{\text{CAST}}$ ☺

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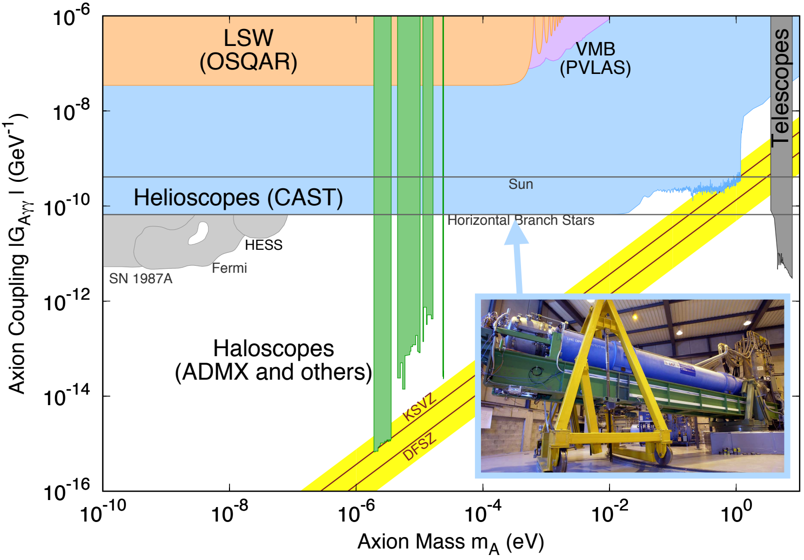
- But if $\delta k \gg L^{-1}_{\text{CAST}}$, $L \sim \delta k^{-1} \ll L_{\text{CAST}}$ ☹
- The CAST fix: at high m_a, give photon a mass $m_\gamma \approx m_a$ with *e.g.* ^{3}He so that $\delta k \sim 0$ and $L \sim L_{\text{CAST}}$ ☺

Existing axion constraints



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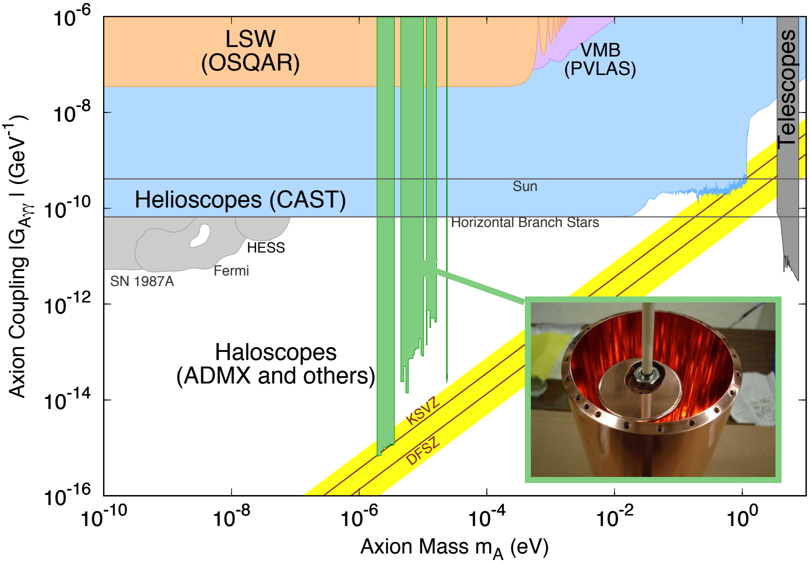
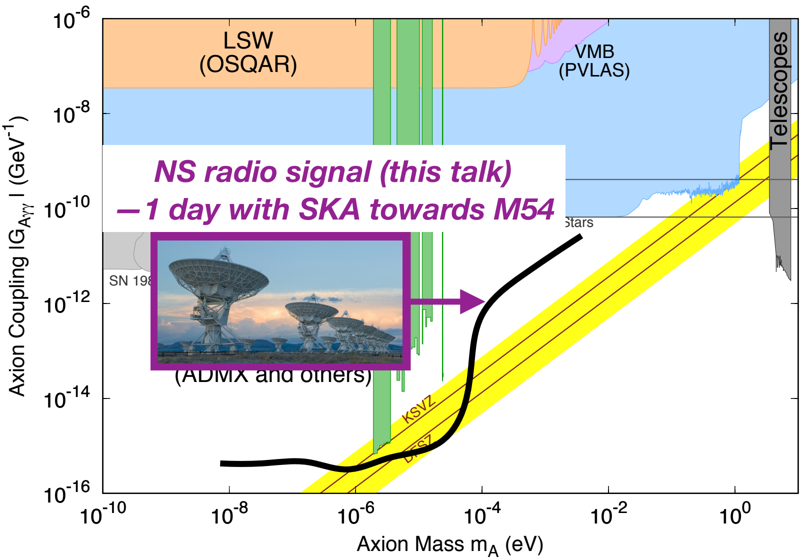
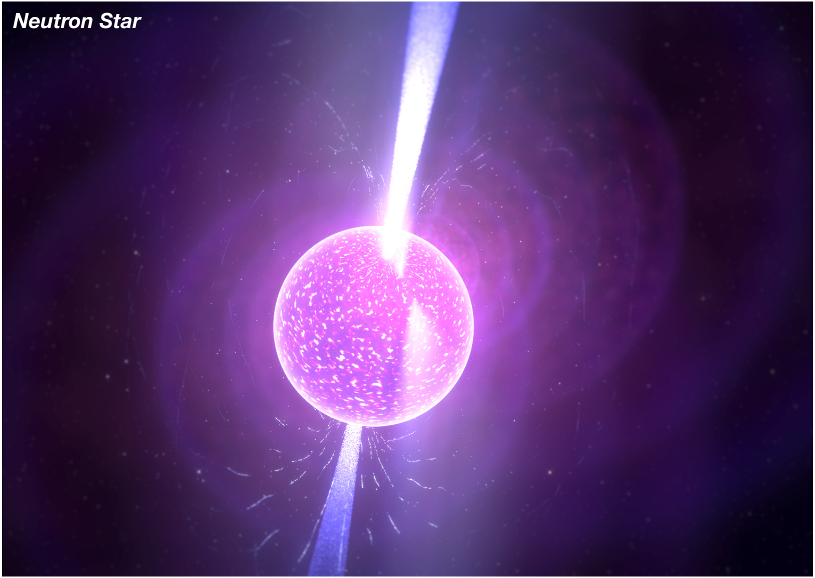
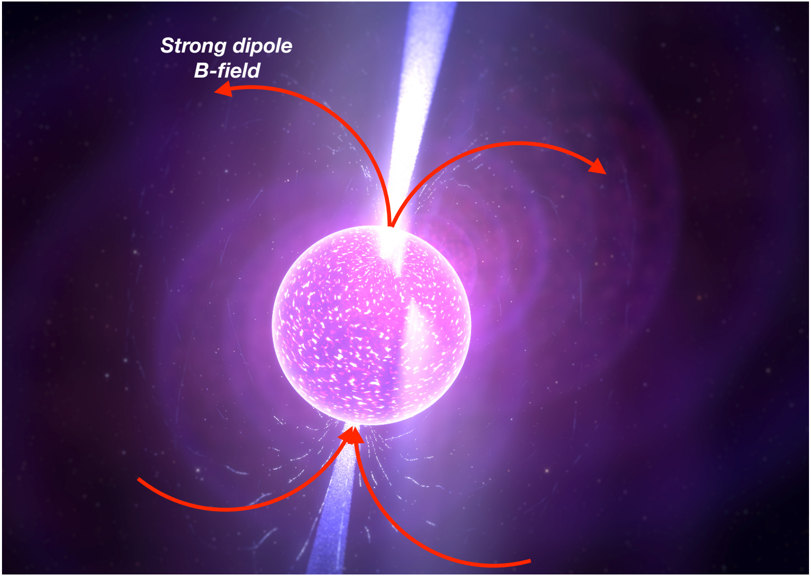


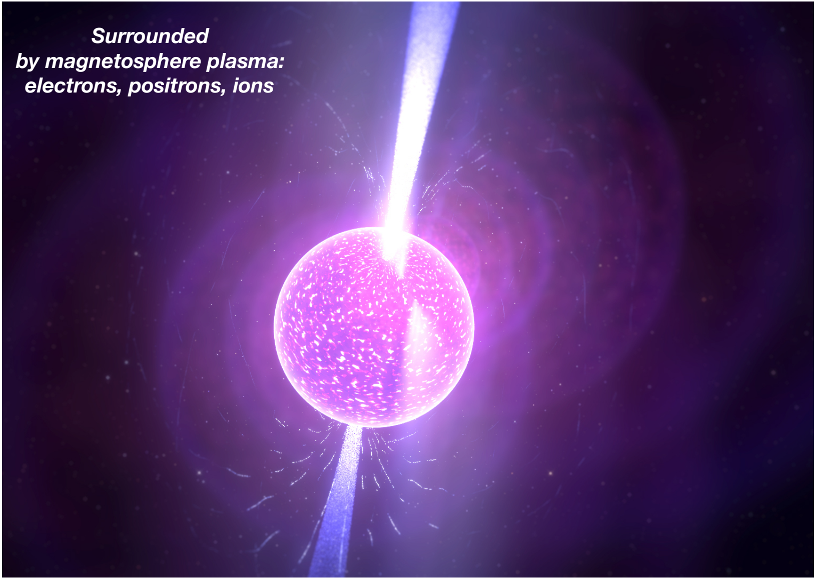
Projected axion sensitivity



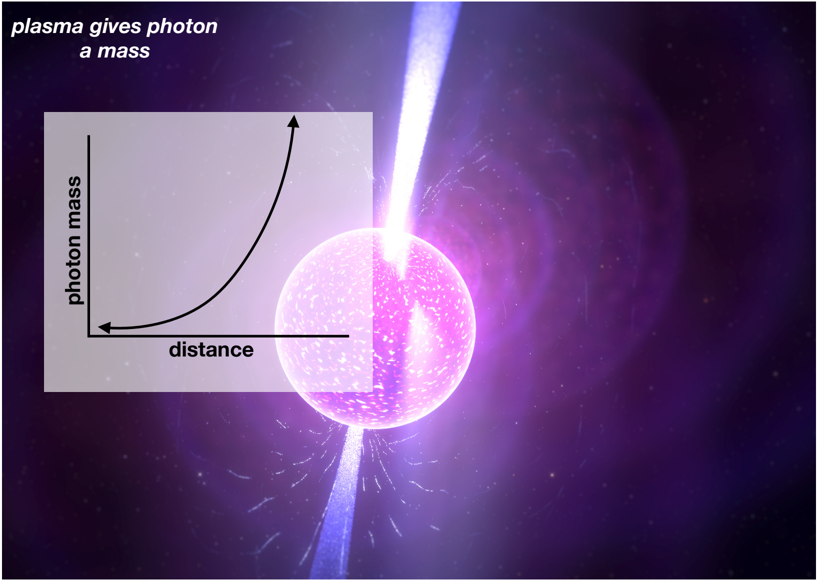
Axion-photon conversion in neutron stars

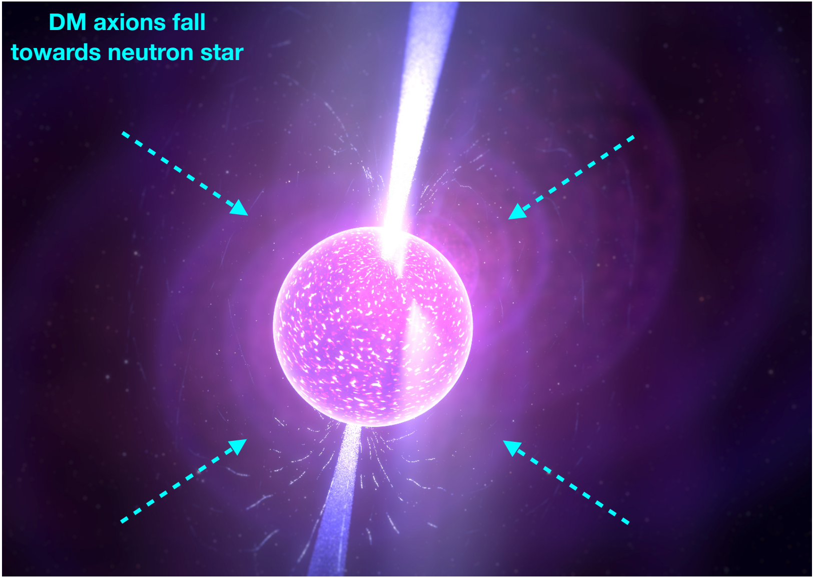

Neutron Star

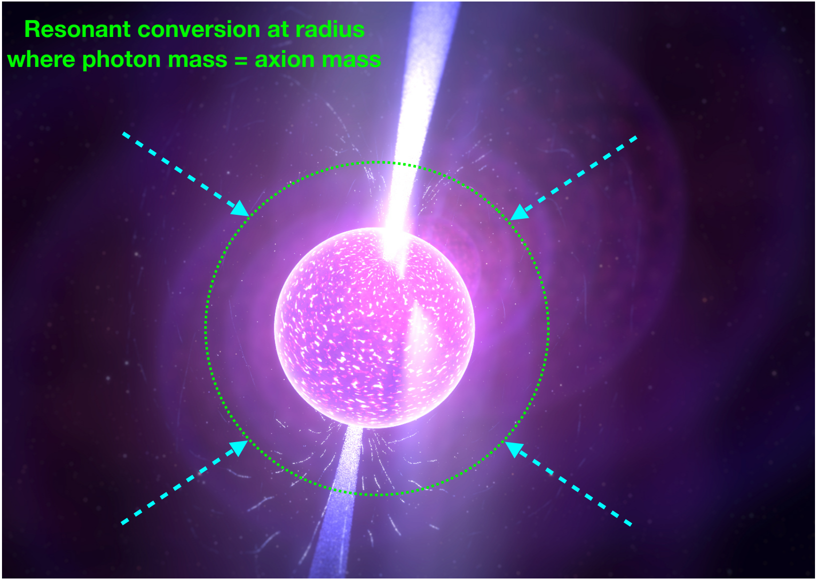

Strong dipole
B-field

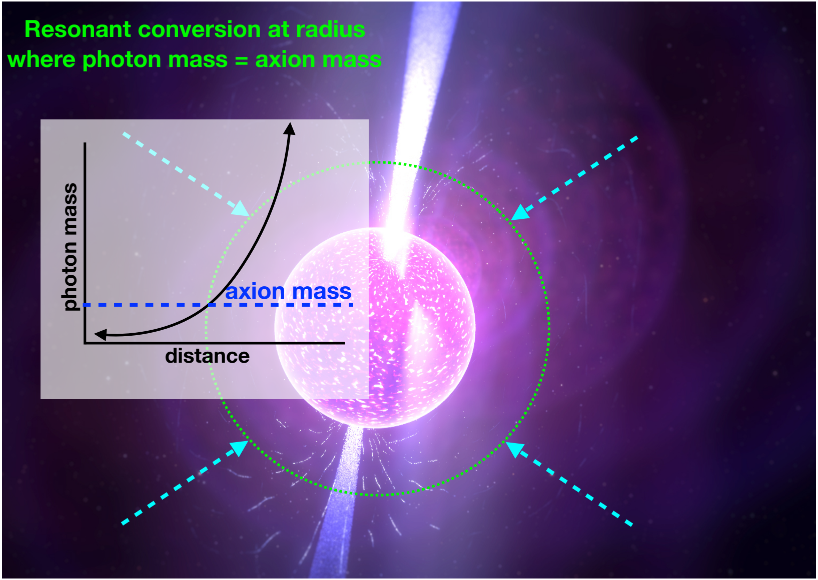


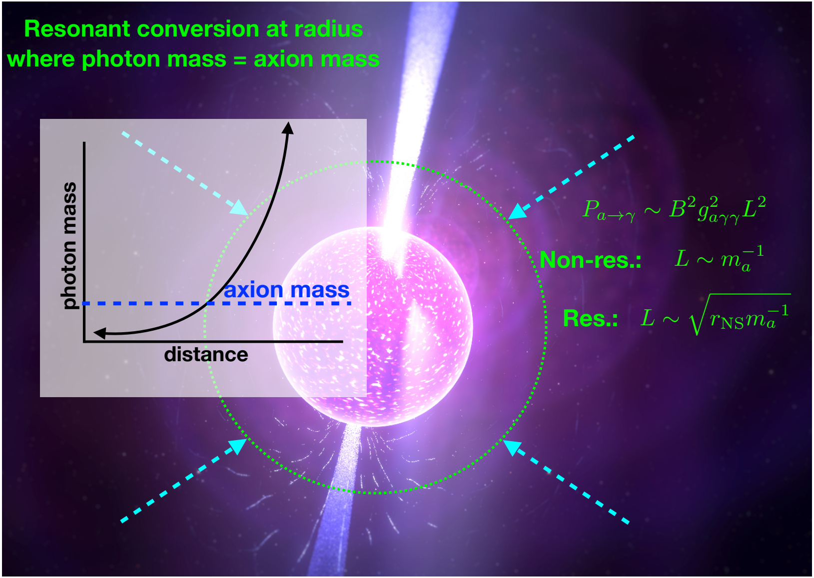
Surrounded
by magnetosphere plasma:
electrons, positrons, ions


plasma gives photon a mass
photon mass
distance


DM axions fall
towards neutron star


Resonant conversion at radius
where photon mass = axion mass


Resonant conversion at radius
where photon mass = axion mass
photon mass
axion mass
distance


Resonant conversion at radius
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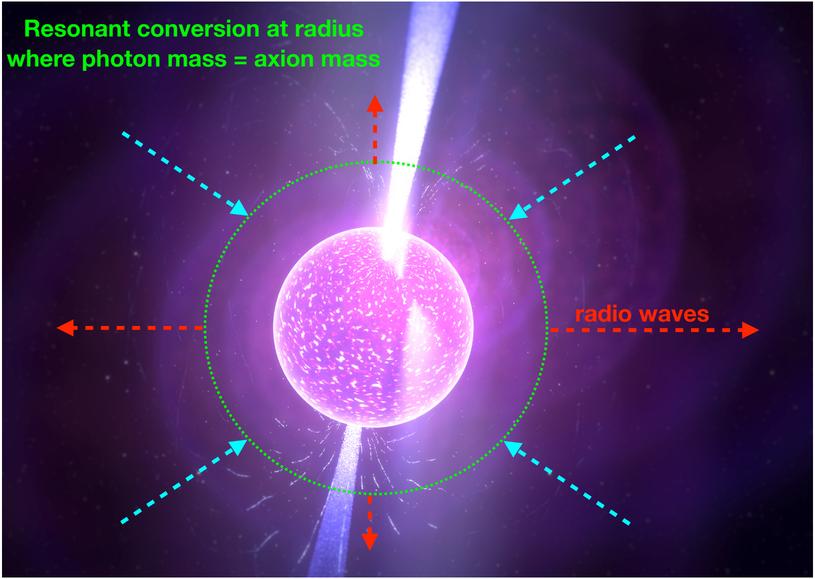
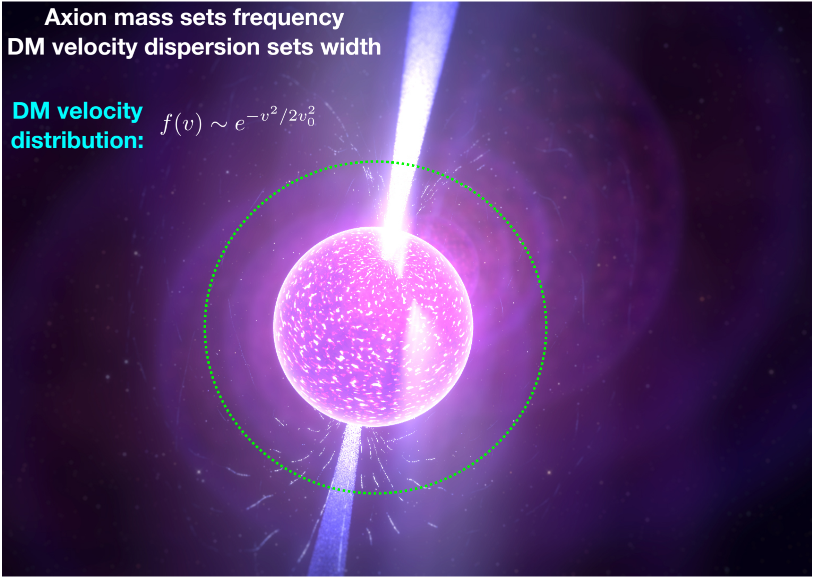
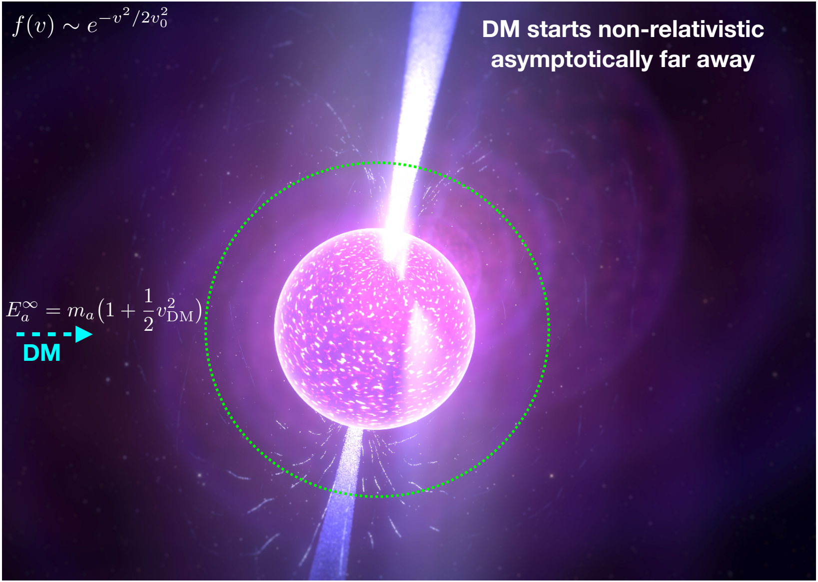
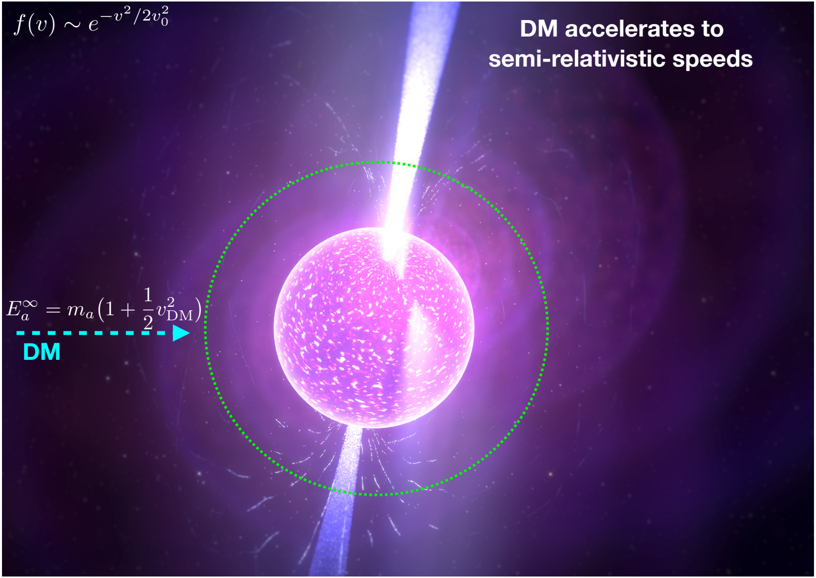
$P_{a\to\gamma} \sim B^2 g_{a\gamma\gamma}^2 L^2$
Non-res.: $L \sim m_a^{-1}$
Res.: $L \sim \sqrt{r_{\rm NS} m_a^{-1}}$

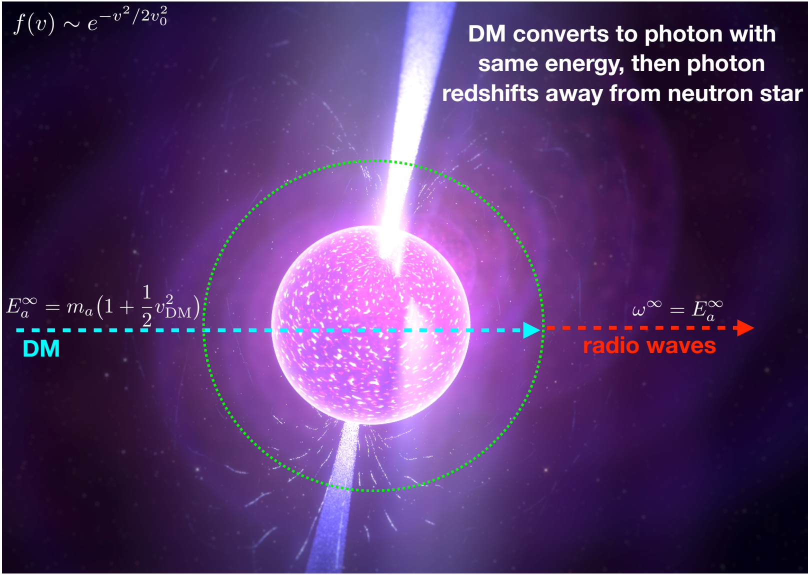

Resonant conversion at radius
where photon mass = axion mass
radio waves

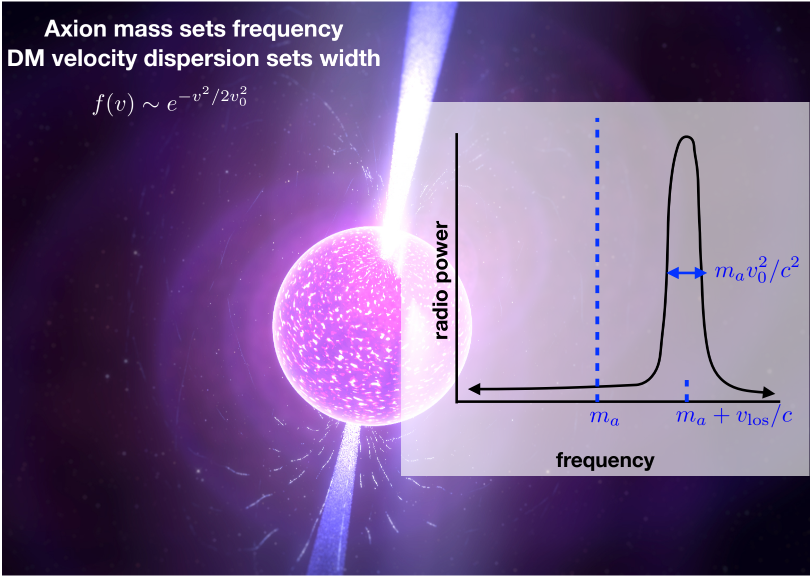

Axion mass sets frequency
DM velocity dispersion sets width
DM velocity distribution:
$f(v) \sim e^{-v^2/2v_0^2}$



$f(v) \sim e^{-v^2/2v_0^2}$
DM starts non-relativistic asymptotically far away
$E_a^\infty = m_a(1 + \frac{1}{2}v_{\rm DM}^2)$
DM

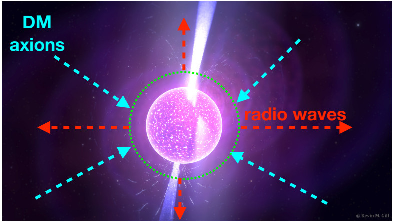

$f(v) \sim e^{-v^2/2v_0^2}$
DM accelerates to
semi-relativistic speeds
$E_a^\infty = m_a(1 + \frac{1}{2}v_{\rm DM}^2)$
DM


$f(v) \sim e^{-v^2/2v_0^2}$
DM converts to photon with same energy, then photon redshifts away from neutron star
$E_a^\infty = m_a(1 + \frac{1}{2}v_{\rm DM}^2)$
DM
$\omega^\infty = E_a^\infty$
radio waves



Axion mass sets frequency
DM velocity dispersion sets width
$f(v) \sim e^{-v^2/2v_0^2}$
radio power
$m_a v_0^2/c^2$
m_a
$m_a + v_{\rm los}/c$
frequency

NS with strong B-field and surrounding plasma



DM axions resonantly convert to radio waves when $m_a = m_\gamma$

radio waves

radio emission propagates to Earth

Narrow radio line detectable at Earth with $f = m_a/(2\pi)$.

Sensitivity Calculation

Conversion radius

- Assume rotation axis $\hat{\mathbf{\Omega}}$ aligned with B-field axis $\hat{\mathbf{z}}$ for simplicity
- Dipole B-field: $B(r,\theta) = \frac{r_{\text{NS}}^3}{r^3}\frac{B_0}{2}(3\cos^2\theta + 1)^{1/2}$

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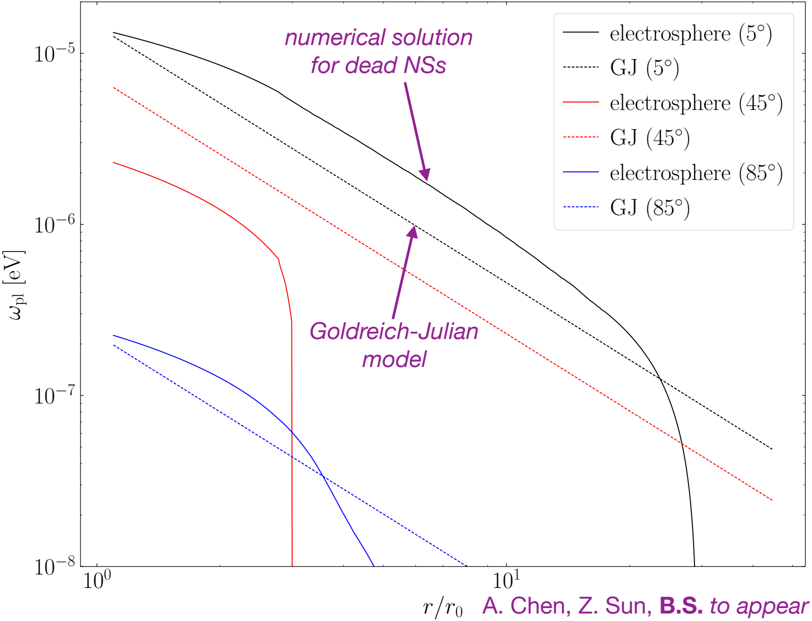
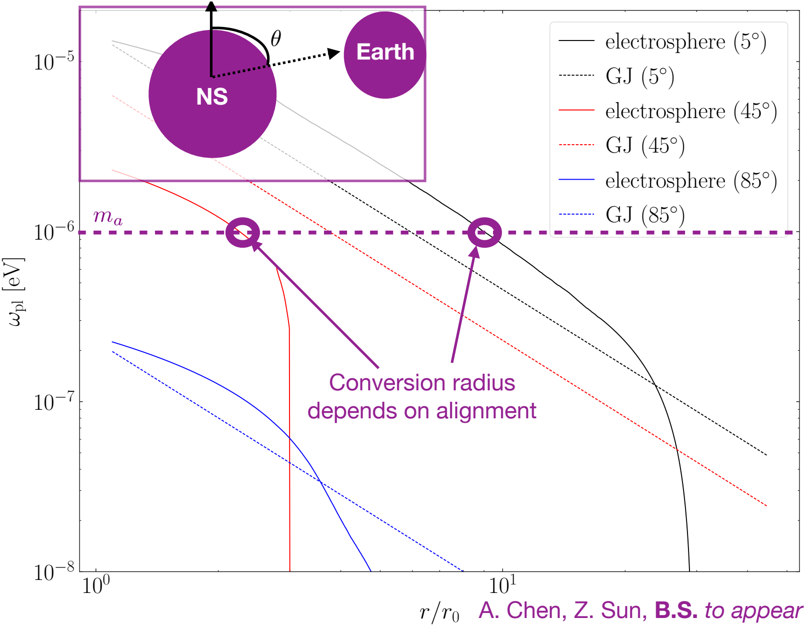
- Plasma mass: $\omega_{\text{pl}} \sim \sqrt{\frac{n_c}{m_c}} \sim \frac{1}{r^{3/2}}$
- Close match to numerical NS simulations away from acceleration regions

Conversion radius



A. Chen, Z. Sun, **B.S.** *to appear*

Conversion radius



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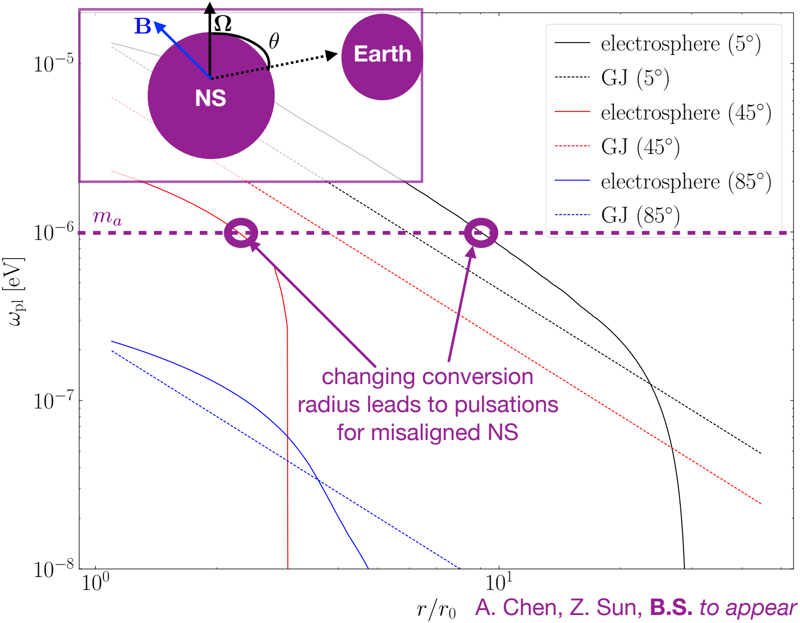

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Radiated power and flux density

- Power: $P \sim g_{a\gamma\gamma}^2 B_0^2 \underbrace{\left(\frac{1}{r_c^4}\right)}_{r_c\text{: conv. rad.}} \times \rho_{\text{DM}}^{\infty} \times \underbrace{\left(\frac{1}{v_0}\right)}_{v_0\text{: DM vel. disp.}}$

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  - Larger m_a, smaller r_c and larger the power

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  - Gain: $G \sim A_{\text{telescope}}$ and $G \approx 2\ K/$Jy at GBT (100 m)

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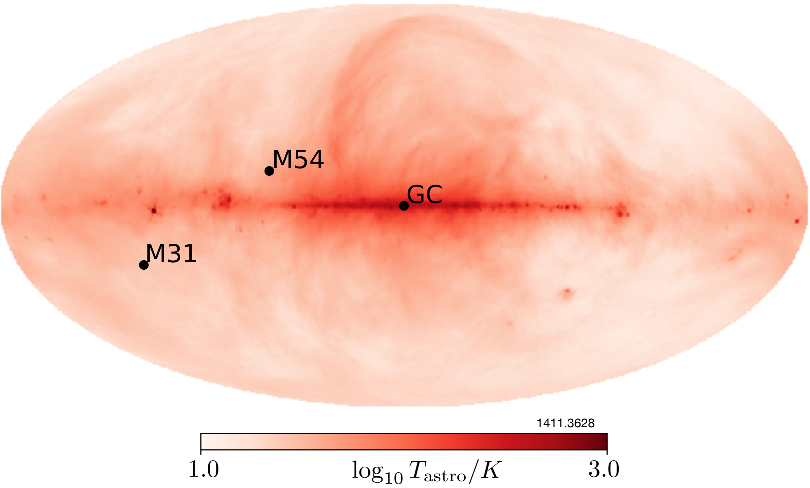
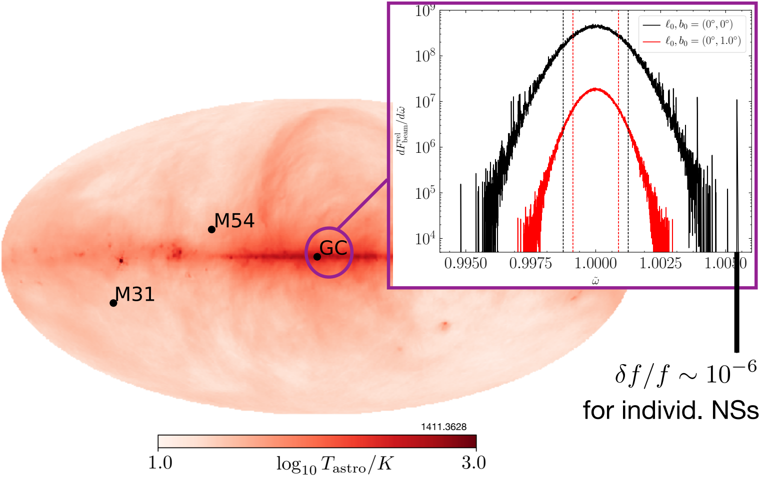
  - $T_{\text{sys}} \approx \underbrace{25\ \text{K}}_{\text{receiver}} + T_{\text{astro}}$

Background temperature



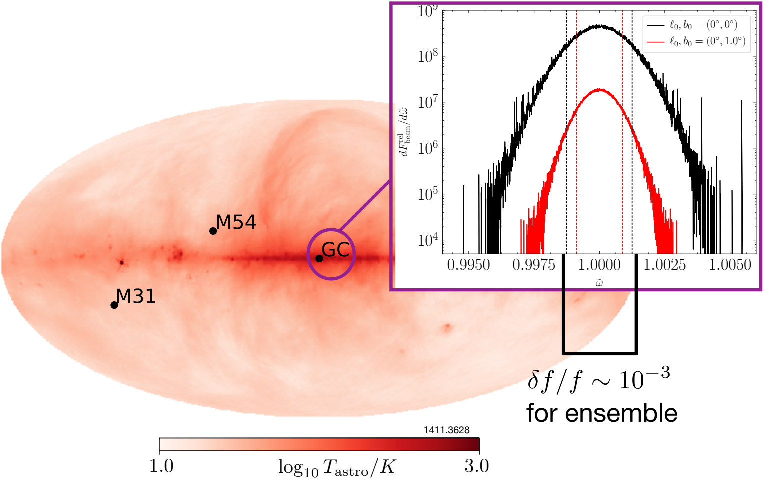
- Above at $f = 408$ MHz (Haslam survey)
- $T_{\text{astro}}(f) \approx T_{\text{astro}}^{408 \text{ MHz}} \left(\frac{408 \text{ MHz}}{f} \right)^{2.75}$

Galactic Center



- High DM density ☺
- Many neutron stars ☺
- High background temperature ☹

Galactic Center



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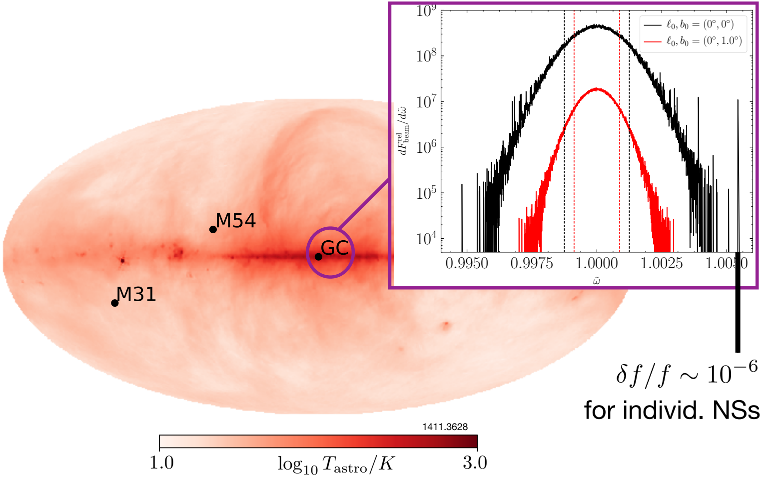
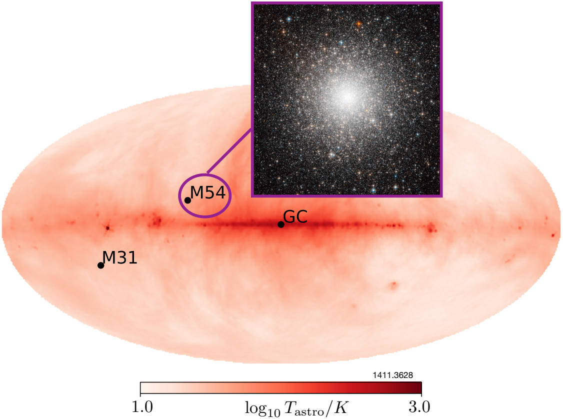


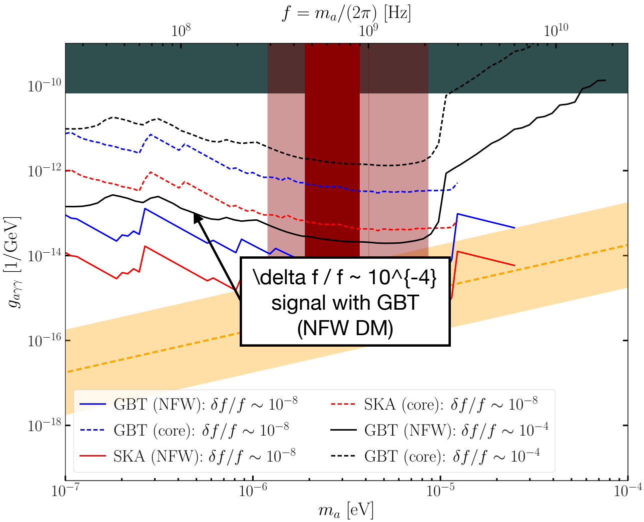
- Beam area shrinks with increasing frequency
- High frequency less NSs have resonant conversion
- Can be useful to search for bright individual NSs

M54



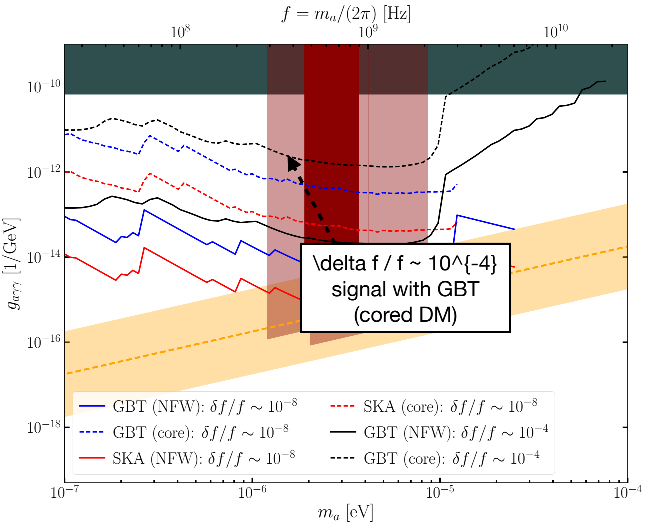
- Globular Cluster within Sagittarius dwarf ($\sim 10^3$ NSs)
- Low background, high DM density, low velocity dispersion, 20 kpc away
- $\delta f/f \sim 10^{-8}$ for individual NSs (or 10^{-4} for all sources)

M54 Sensitivity



- 24 hrs observation
- 5σ detection threshold

M54 Sensitivity



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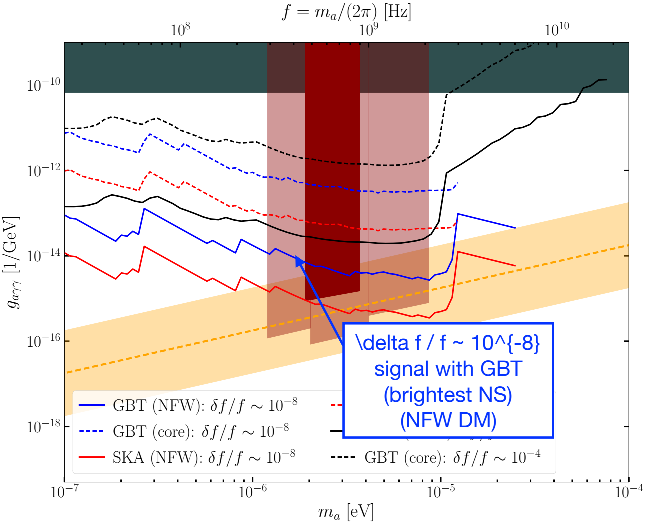

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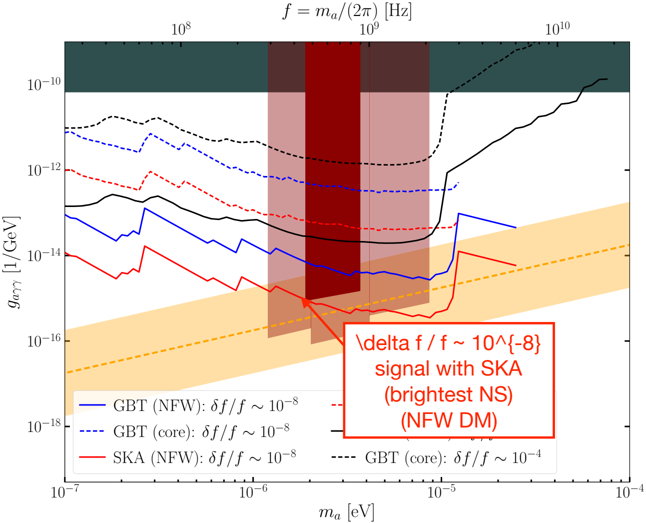

- Caution: current NS model not optimized for active pulsars (underestimate flux at high frequencies)

Summary and Outlook

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Summary and Outlook

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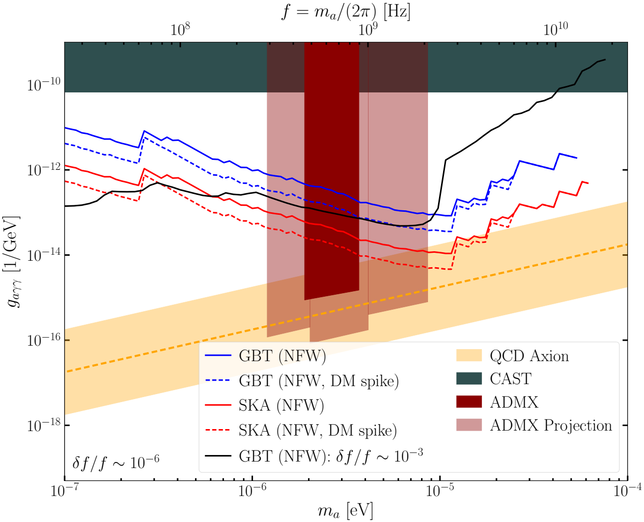
- To do (theory):
  - Closer look at active pulsars (charge acceleration region, population study, etc.)
  - More through analysis of possible extragalactic targets
  - Better joint likelihood combining NSs (in progress with C. Weniger)
  - Account for DM substructure (in progress with J. Foster and K. Zurek)

Questions?

Galactic Center Sensitivity



- 24 hrs observation
- 5σ detection threshold

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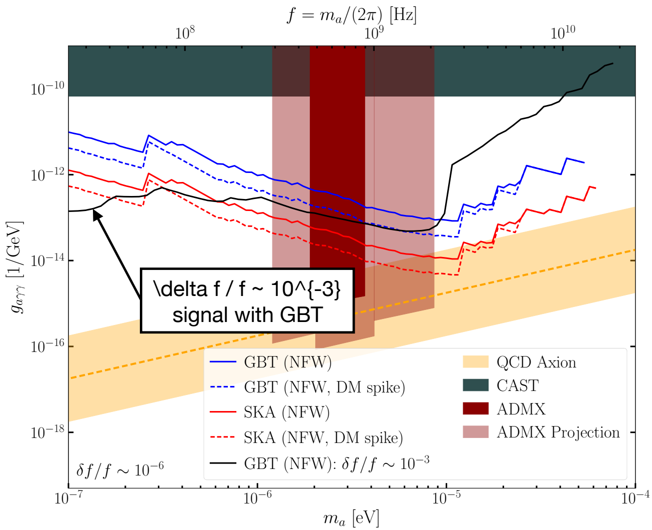

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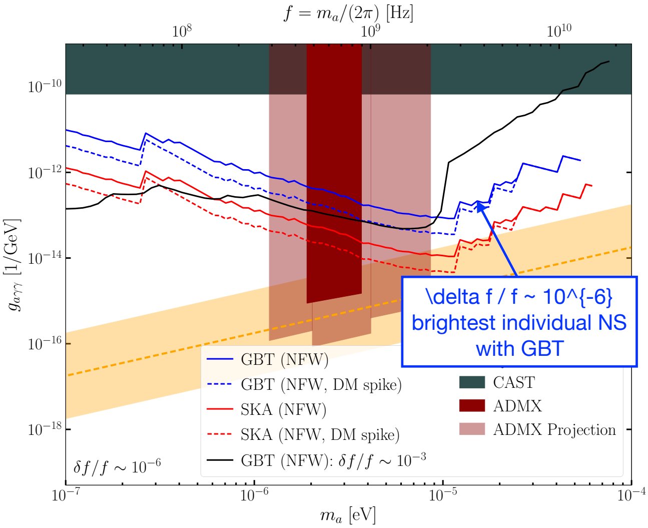

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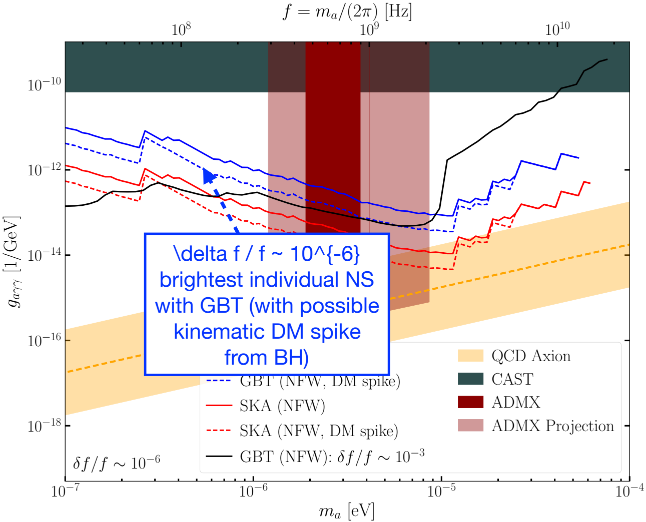

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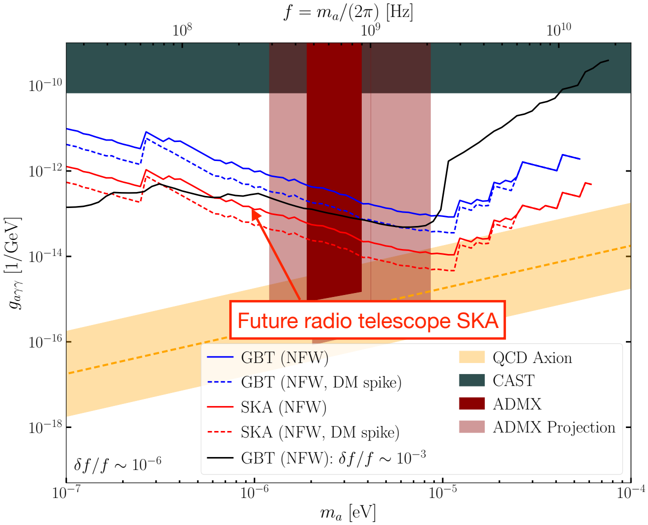

- Caution: current NS model not optimized for active pulsars (underestimate flux at high frequencies)