``Light scalars: origin, cosmology, astrophysics and experimental probes" Workshop
April 2019, Benasque, Spain

Detecting Axion-like Dark Matter Using Linearly Polarized Pulsar Light

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Based on arXiv: 1901.10981
in collaboration with George Smoot and Yue Zhao

Cosmological Birefringence

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ARTICLES

Einstein equivalence principle and the polarization of radio galaxies

Sean M. Carroll and George B. Field
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138
(Received 26 December 1990)

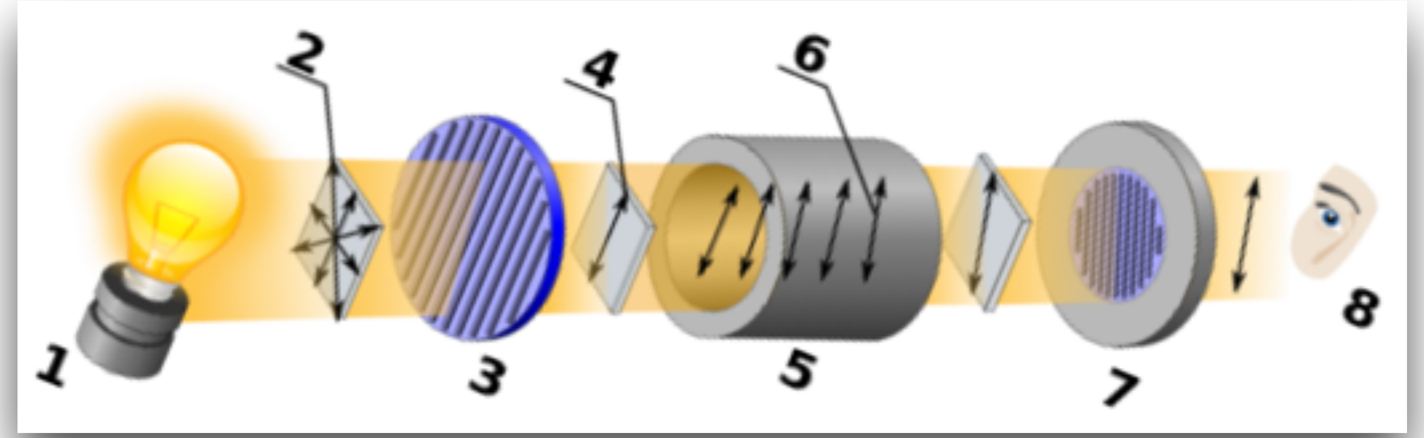
Cosmological Birefringence

$$L \sim -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 + \frac{g}{2} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\begin{pmatrix} \partial_t^2 + k^2 + m_a^2 & 0 & 0 \\ 0 & \partial_t^2 + k^2 + \eta(t)k & 0 \\ 0 & 0 & \partial_t^2 + k^2 - \eta(t)k \end{pmatrix} \begin{pmatrix} i\hat{a} \\ f_+ \\ f_- \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

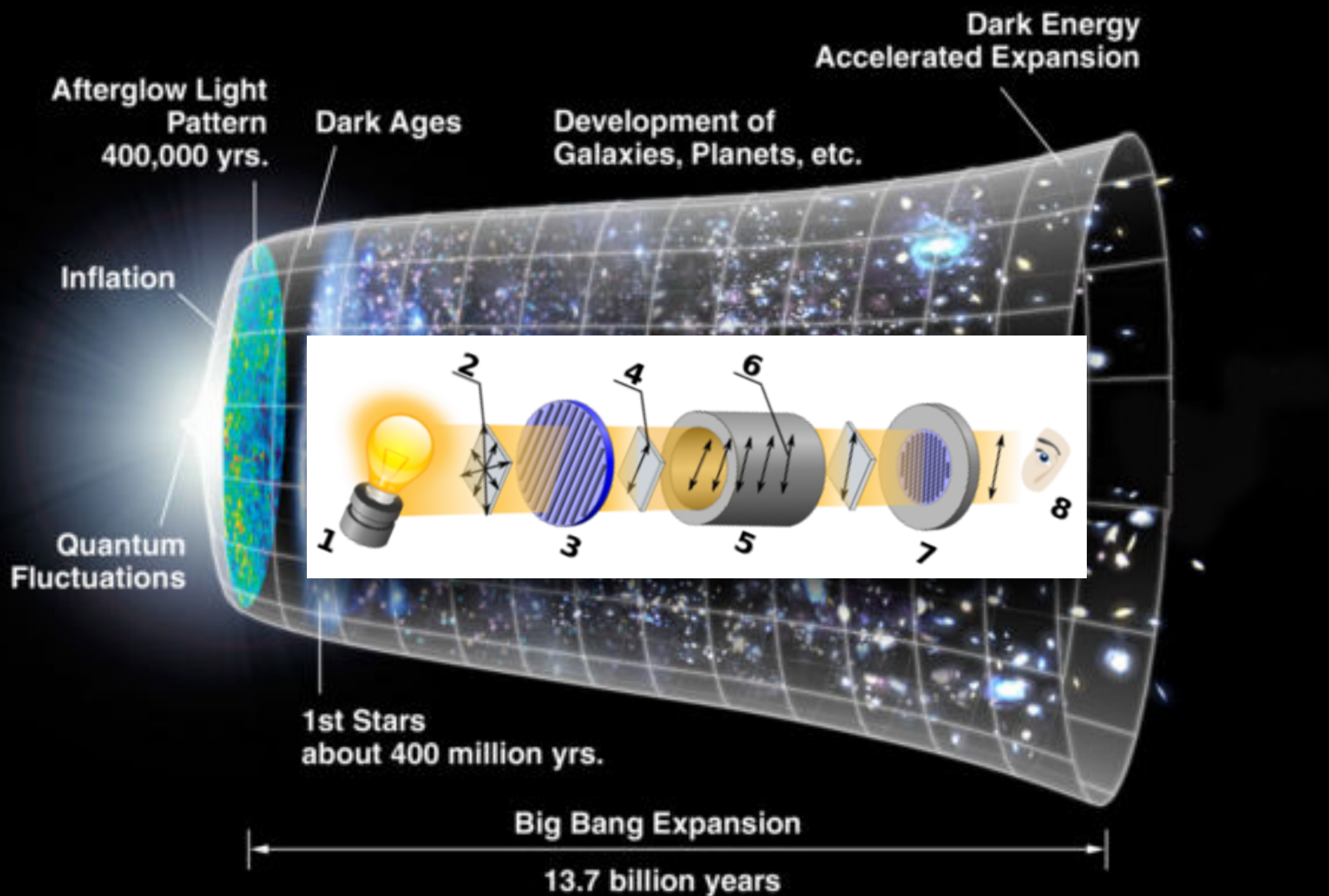
=> Different dispersion relations for light with left- and right-circular polarization modes

=> Potentially observable effect: rotation of linearly polarization angle (LPA)



$$\Delta\phi = g\int_{t_i}^{t_f} \partial_t a(x,t) = g\int_{t_i}^{t_f} \partial_t [a_0(x,t)\cos(m_a t + \theta(x,t))]$$

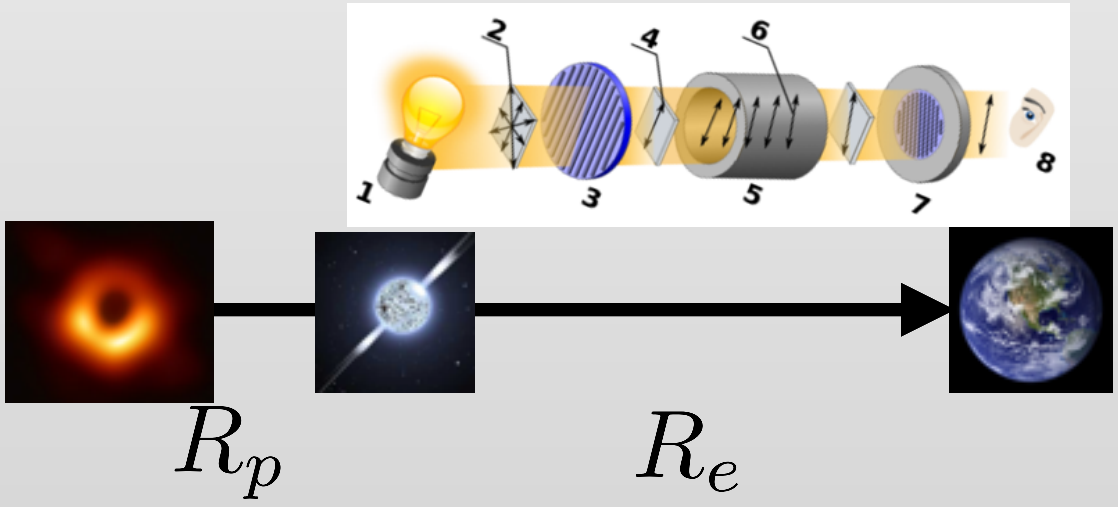
CMB-Based Detection



[Lue, Wang, KamionKowski, PRL(1999)]

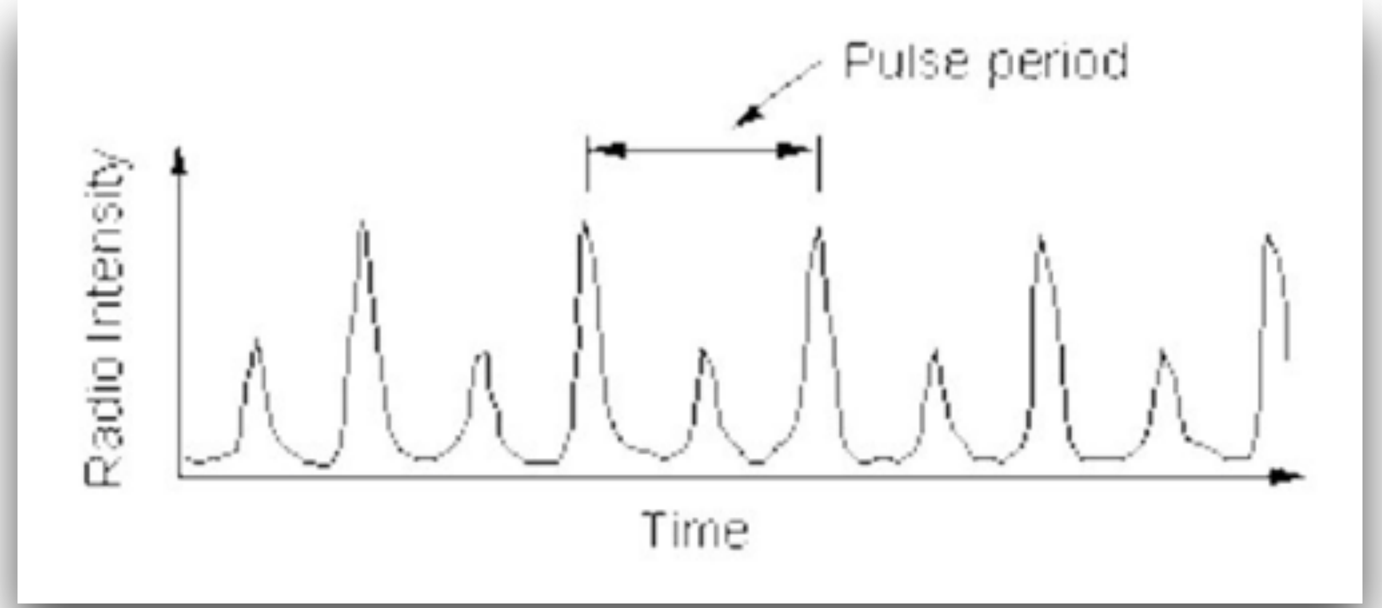
The Proposal — Pulsar-Based Detection

Alternatively, we propose a local measurement to detect axion-like DM — using linearly polarized pulsar light as a probe.



Why Pulsars?

- Both MSP and non-MSP are stable astrophysical sources of linearly polarized light
- Repeating signals of pulsar light may allow reconstructing the temporal shape or format of the event (e.g., the LPA), with the resolution in time being mainly determined by the signal/pulse period.



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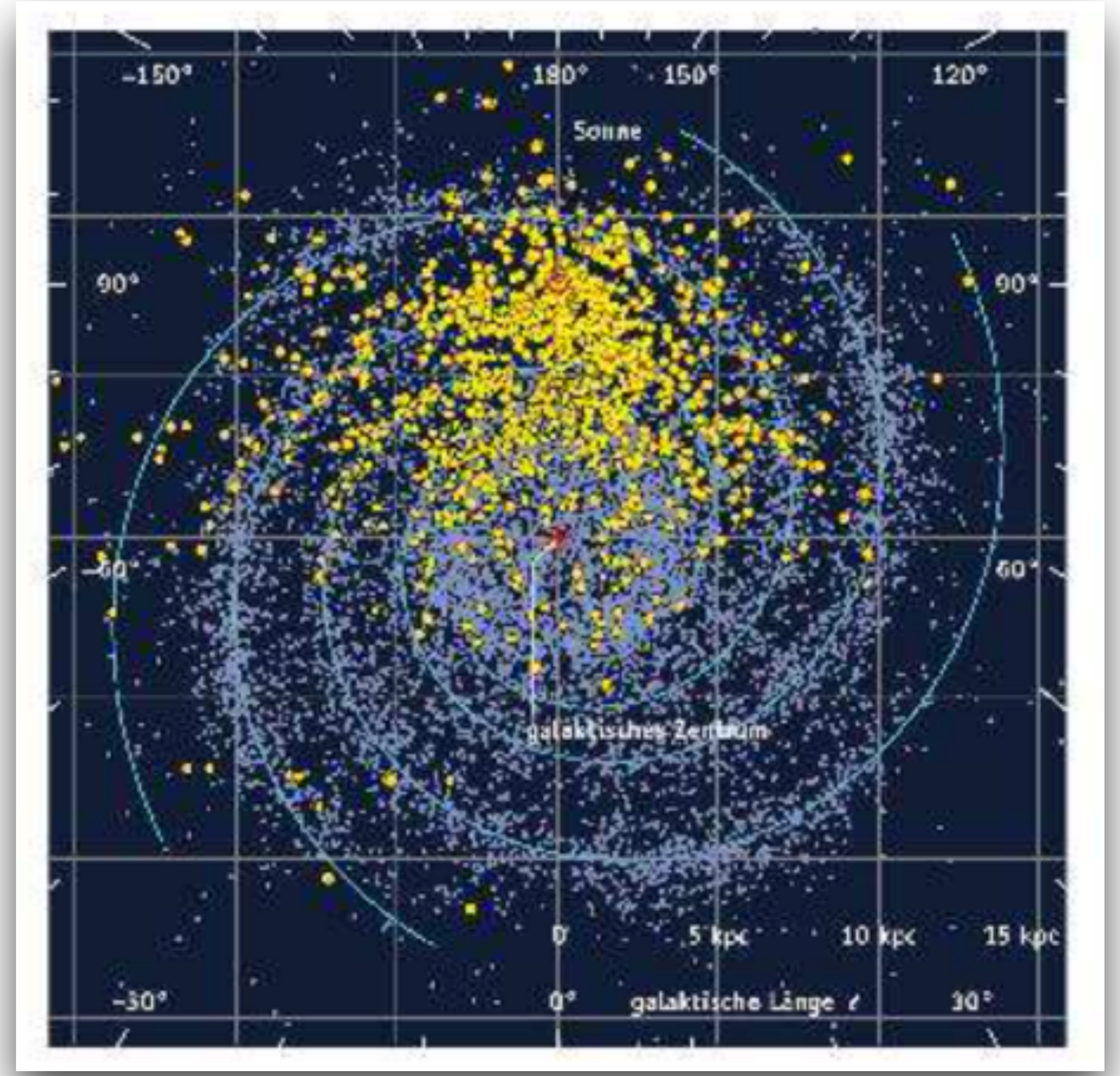


[Rauber Beck (2009)]

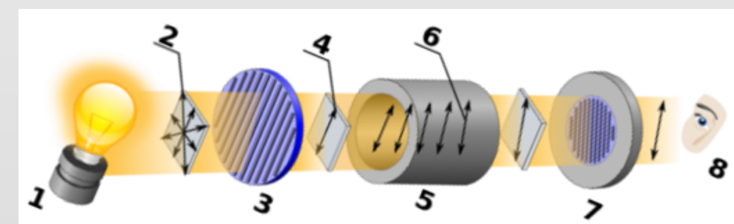
- Rich in Milk Way: simulation (~20000) vs. observation (~2800)
- May suppress backgrounds/ instrumental errors, by correlating the measurements of multiple pulsars

What to Measure?

Being lack of knowledge on the original LPA of pulsar light => measure its time variation or oscillation

$$\Delta\Phi = \Delta\phi_2 - \Delta\phi_1 = \Delta\Phi_0 \sin\left(\frac{m_a \Delta t}{2}\right)$$

$$\Delta\Phi_0 = -\frac{2\sqrt{2}g}{m_a}\Big(\sqrt{\rho_f}\sin(m_a t_{f,+} + \theta_f) - \sqrt{\rho_i}\sin(m_a t_{i,+} + \theta_i)\Big)$$



- Make Delta-Phi0 meaningful =>

$$\Delta t \ll t_c = \frac{2\pi}{\frac{1}{2} m_a v^2}$$

- The time-varying effect is mainly picked up by the Sine factor in Delta-Phi. Requirement of resolution in time =>

$$\Delta t \ll T = \frac{4\pi}{m_a}$$

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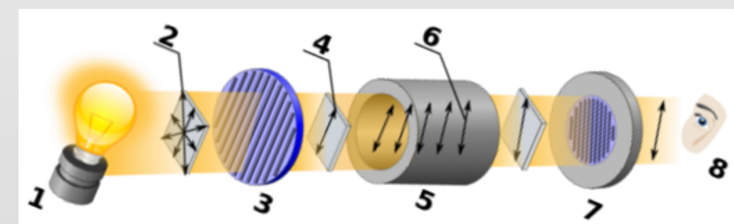

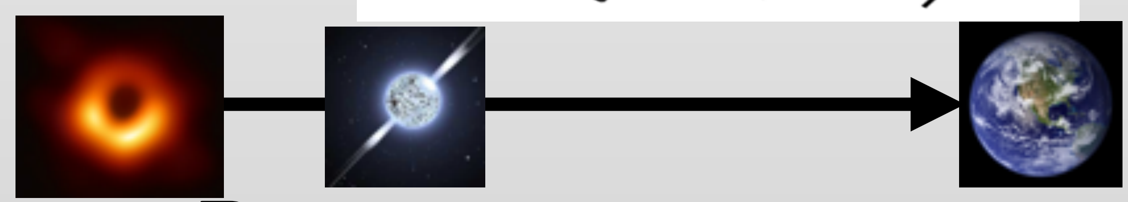

R_p R_e

$$\Delta t \ll t_c = \frac{2\pi}{\frac{1}{2} m_a v^2} \qquad \Delta t \ll T = \frac{4\pi}{m_a}$$

$$\Delta t = 100 \times \Delta t_{\mathrm{pulse}}$$
$$\Rightarrow m_a \ll 8.3 \times 10^{-17}\ \mathrm{eV\ for\ SPs}$$
$$m_a \ll 8.3 \times 10^{-14}\ \mathrm{eV\ for\ MSPs}$$

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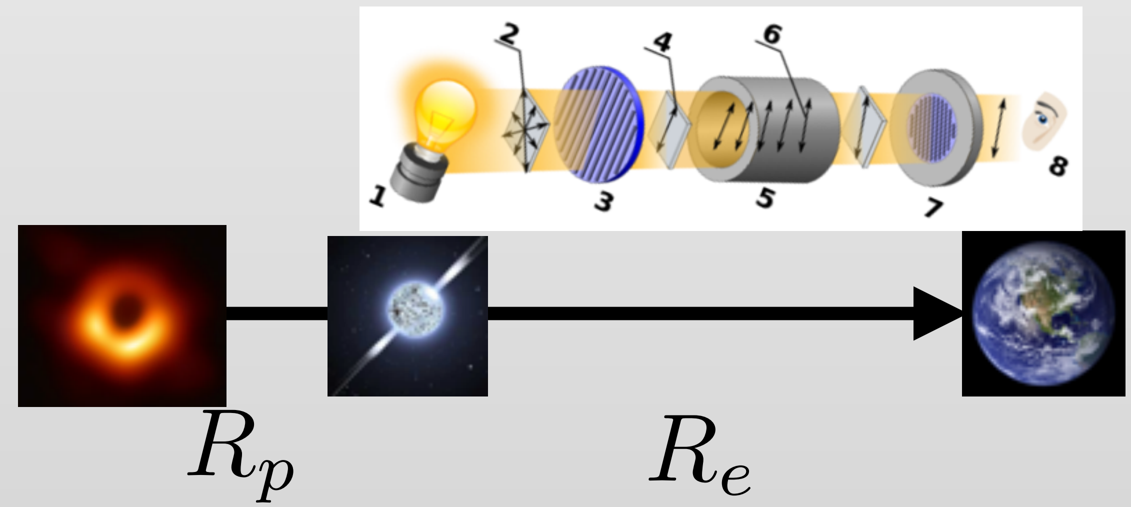
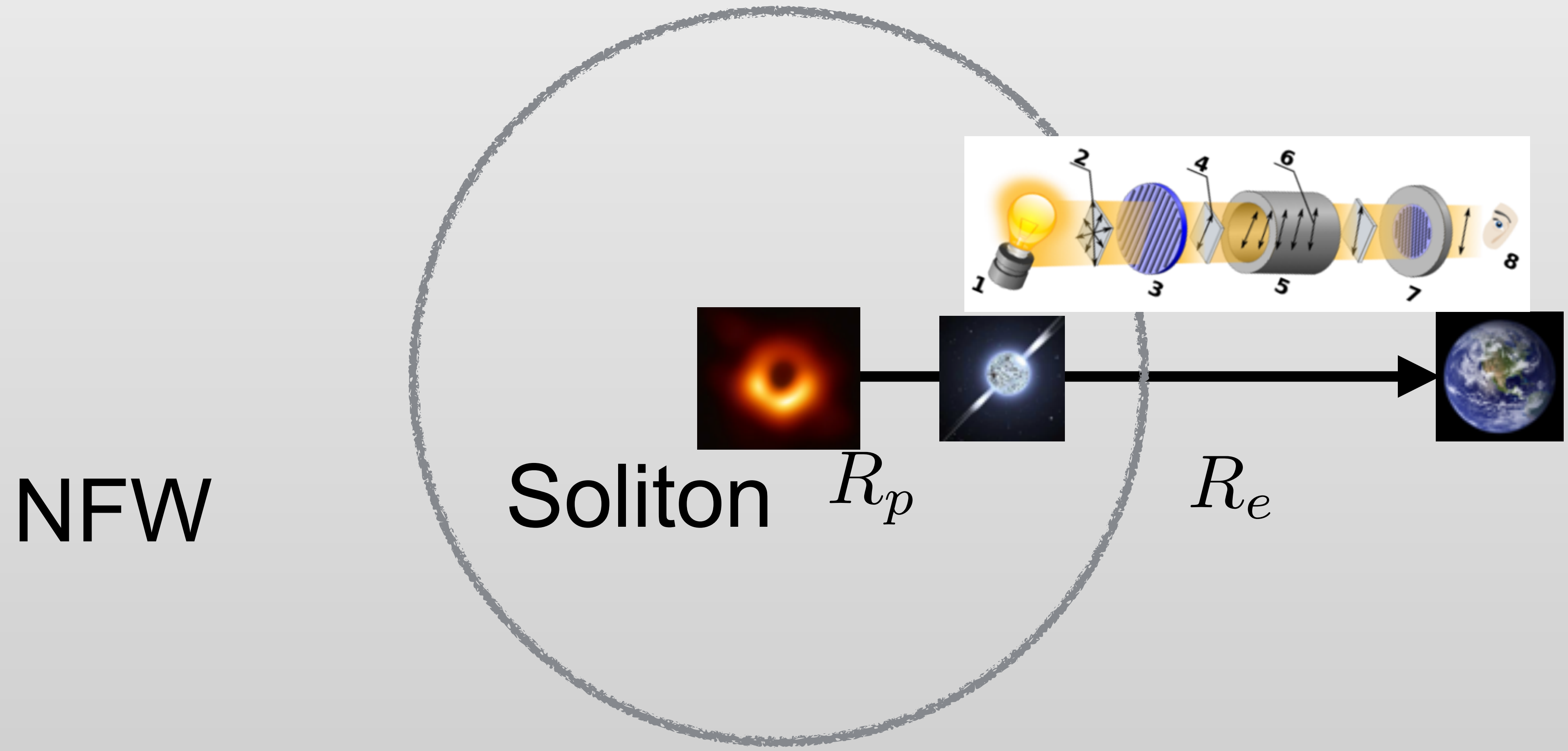


- For qualitatively evaluating the sensitivity of this strategy, we define a characteristic quantity by averaging Delta-Phi0 over temporal coherence regions at ``i'' and ``f''

$$\Phi_c \equiv \sqrt{\langle \Delta\Phi_0^2 \rangle} = \frac{2g}{m_a}\sqrt{\rho_i + \rho_f}$$

Axion-like DM Density Profile

With axion DM condensate,
soliton-like structure is formed in galactic center
[Schive, Chiueh, Broadhurst, Nature Physics (2014)]



$$\rho(x) = \begin{cases} 0.019\left(\frac{m_a}{m_{a,0}}\right)^{-2}\left(\frac{l_c}{1\mathrm{kpc}}\right)^{-4} M_\odot \mathrm{pc}^{-3}, & \text{for } r < l_c \\ \frac{\rho_0}{r/R_H(1+r/R_H)^2}, & \text{for } r > l_c \end{cases}$$

Benchmark Pulsars

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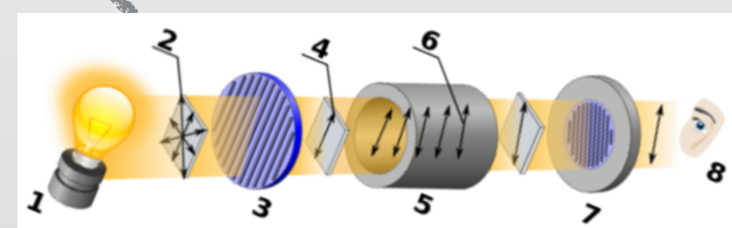

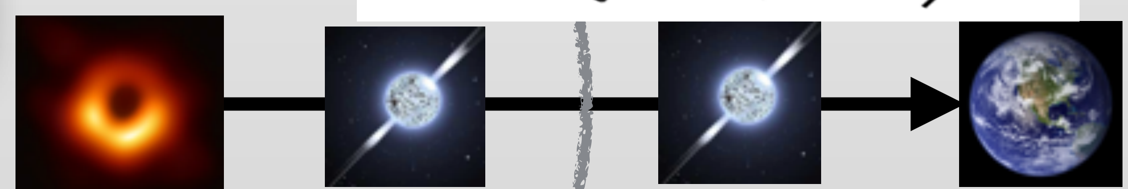

NFW

Soliton

Optimistic

Conservative

	R_j (pc)	d_j (pc)	$m_{a,j}$ (eV)
P_1	1	8000	5.3×10^{-20}
P_2	7000	1000	7.5×10^{-24}

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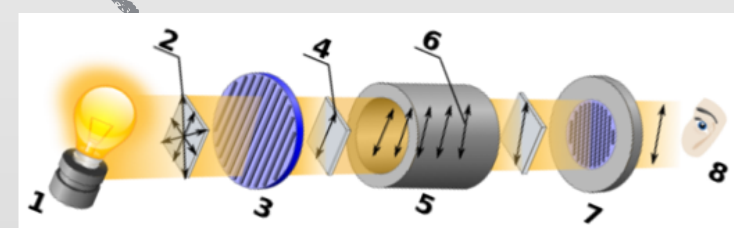
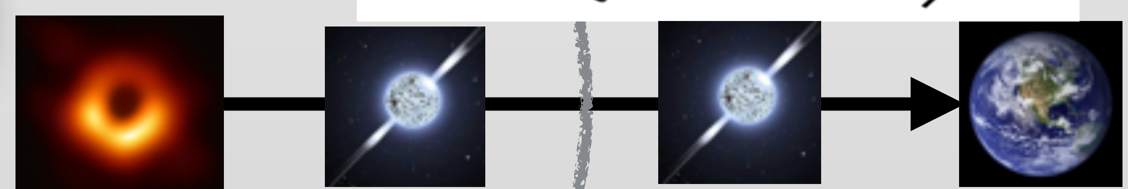


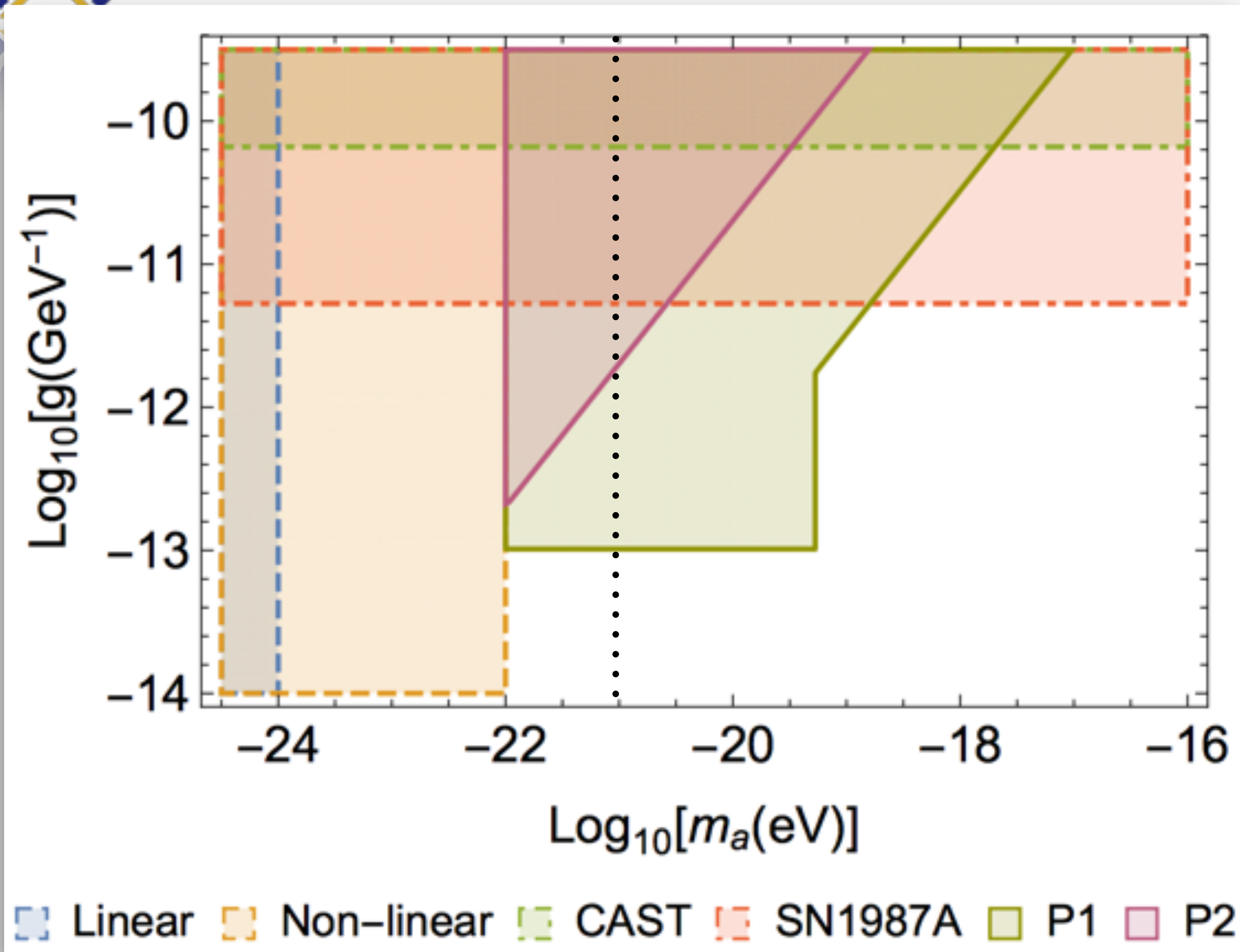


NFW

Soliton

$$\Phi_c^j = \begin{cases} 11 \text{ rad} \left(\frac{g}{g_{\text{CAST}}} \right), & m_a < m_{a,j} \\ 2.7 \text{ rad} \left(\frac{g}{g_{\text{CAST}}} \right) \left(\frac{m_{a,0}}{m_a} \right) & \\ \times \left(\frac{R_H}{R_j} + \frac{R_H}{R_e} \right)^{1/2}, & m_a > m_{a,j} \end{cases}$$

Sensitivity Projection



- Projected sensitivity is generated by comparing characteristic oscillation magnitude and current LPA accuracy (~1^o)
- P1: flat and slope parts result from the scenarios with the pulsar being positioned in the core soliton and NFW regions, respectively, with the threshold set by ~5.3 × 10^{−20} eV
- P2: only slope part is relevant

	R_j (pc)	d_j (pc)	$m_{a,j}$ (eV)
P_1	1	8000	5.3×10^{-20}
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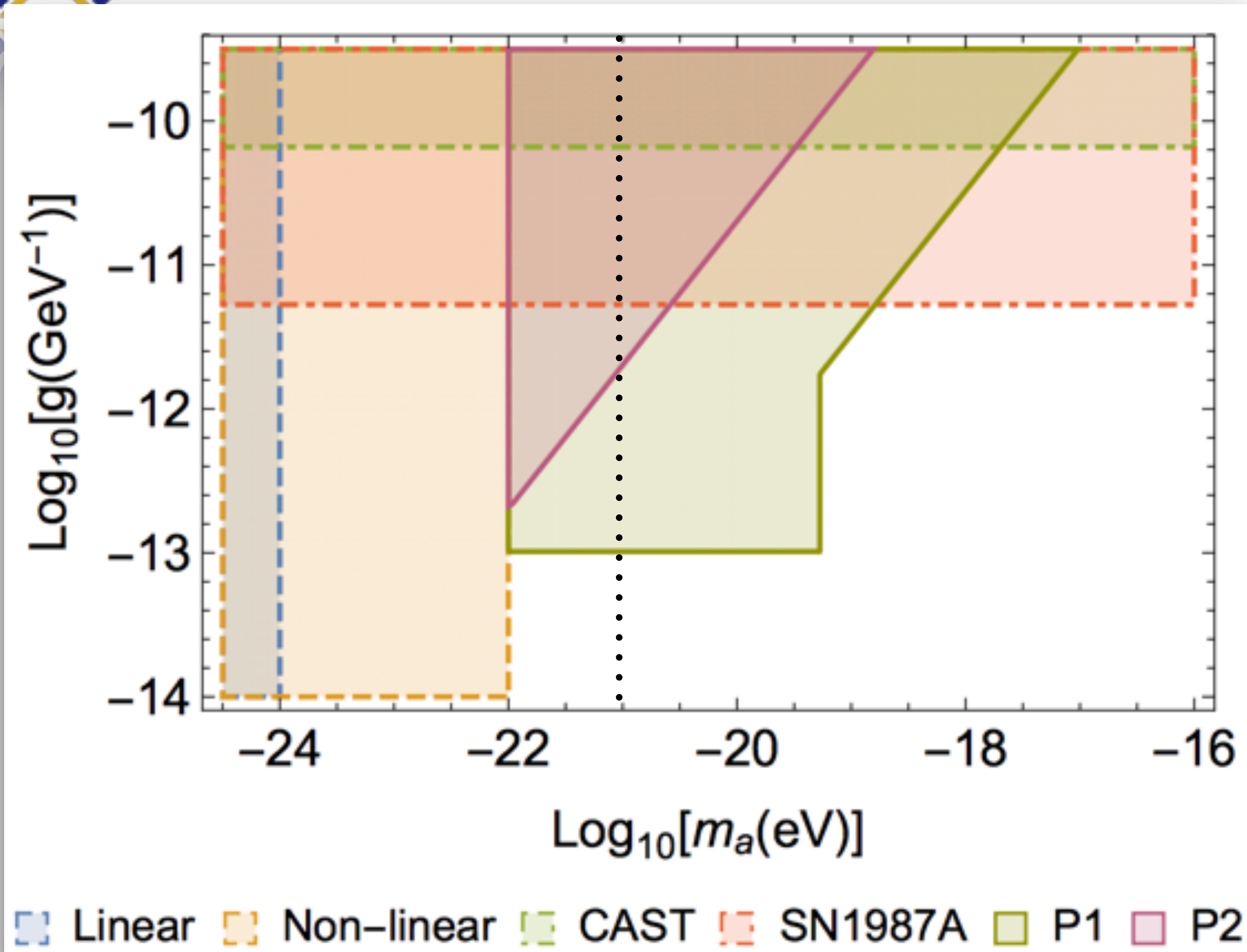

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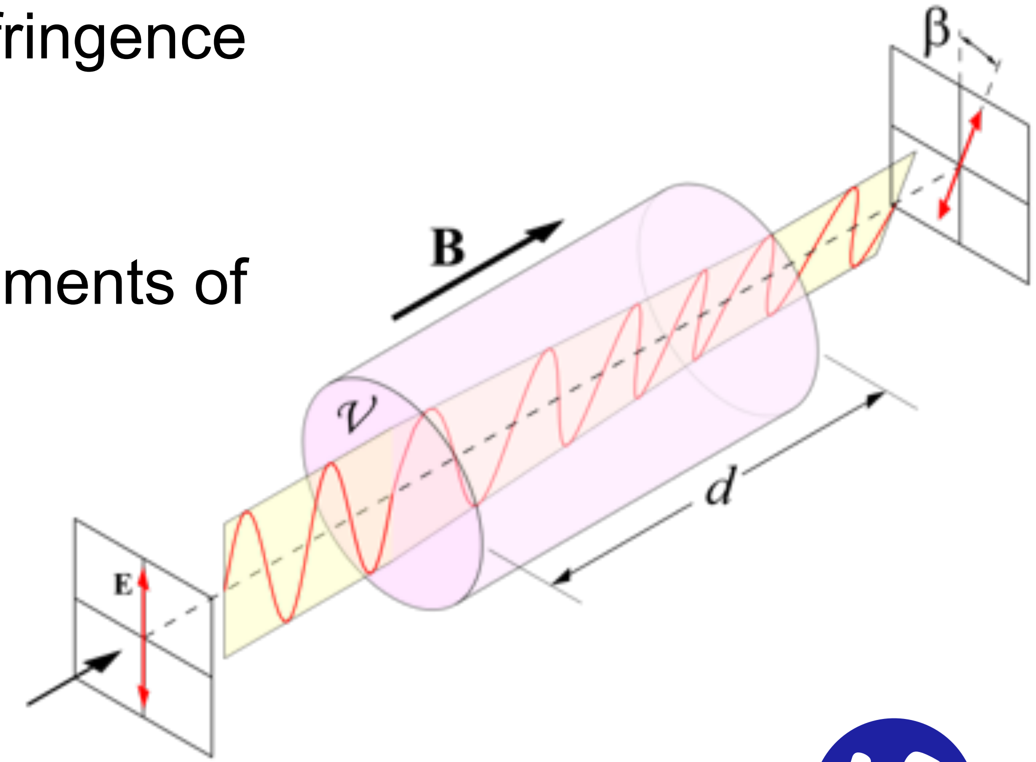
- Projected sensitivity is generated by comparing characteristic oscillation magnitude and current LPA accuracy (~1^o)
- P1: flat and slope parts result from the scenarios with the pulsar being positioned in the core soliton and NFW regions, respectively, with the threshold set by ~5.3 × 10^{−20} eV
- P2: only slope part is relevant
- Best sensitivity: ~10^{-13} GeV^{-1}, one to two orders better than SN1987A, for axion mass ~ 10^{-22} - 10^{-20} eV

Faraday Rotation

- Galactic magnetic field and the magnetic field in solar system may yield optical rotation - Faraday rotation. How to distinguish cosmological birefringence from it?
- Measure frequency dependence: cosmological birefringence is insensitive to frequency, Faraday rotation is inversely proportional to squared frequency
- Measure time dependence: cosmological birefringence oscillates as sine function
- Could be achieved by correlating the measurements of multiple pulsars



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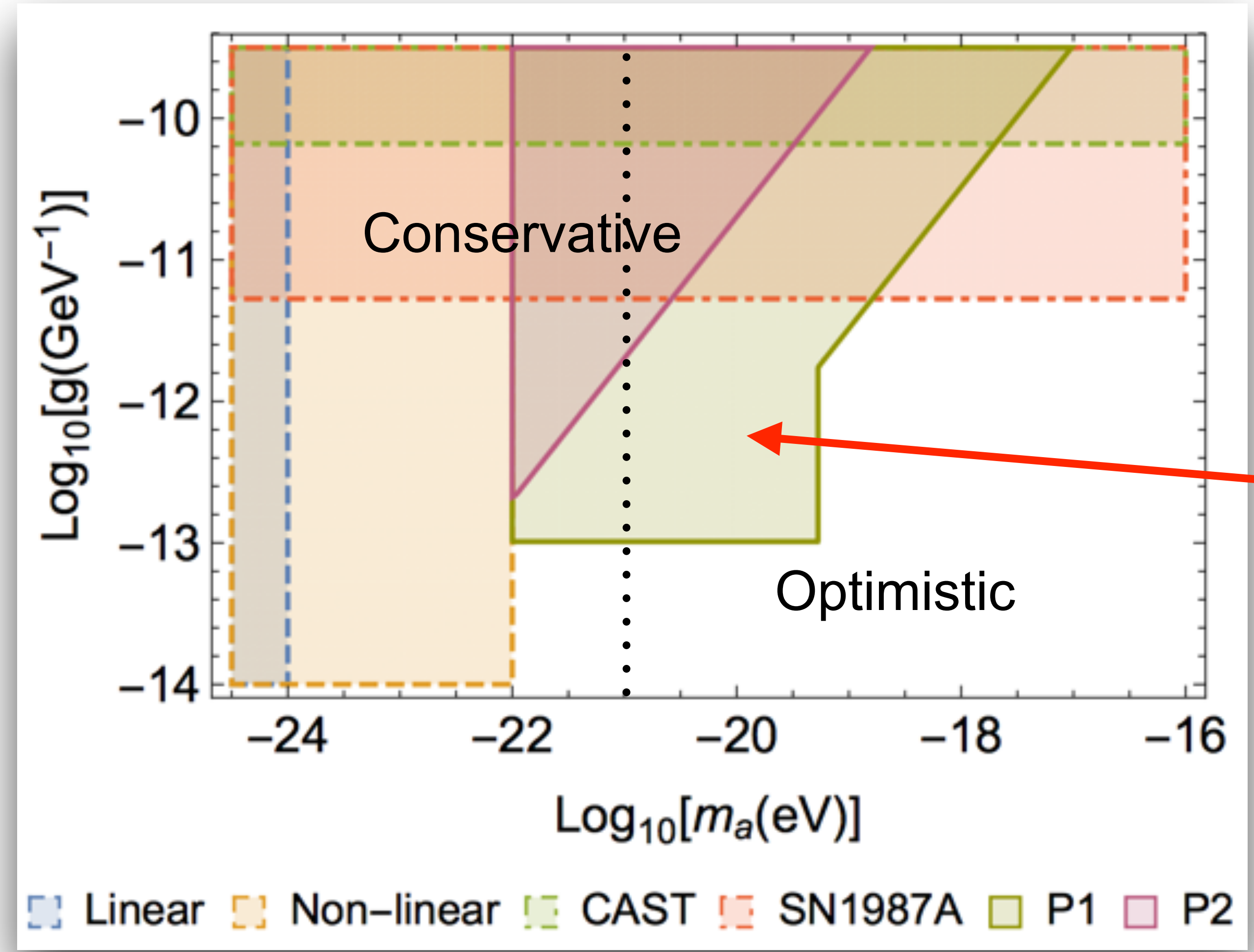

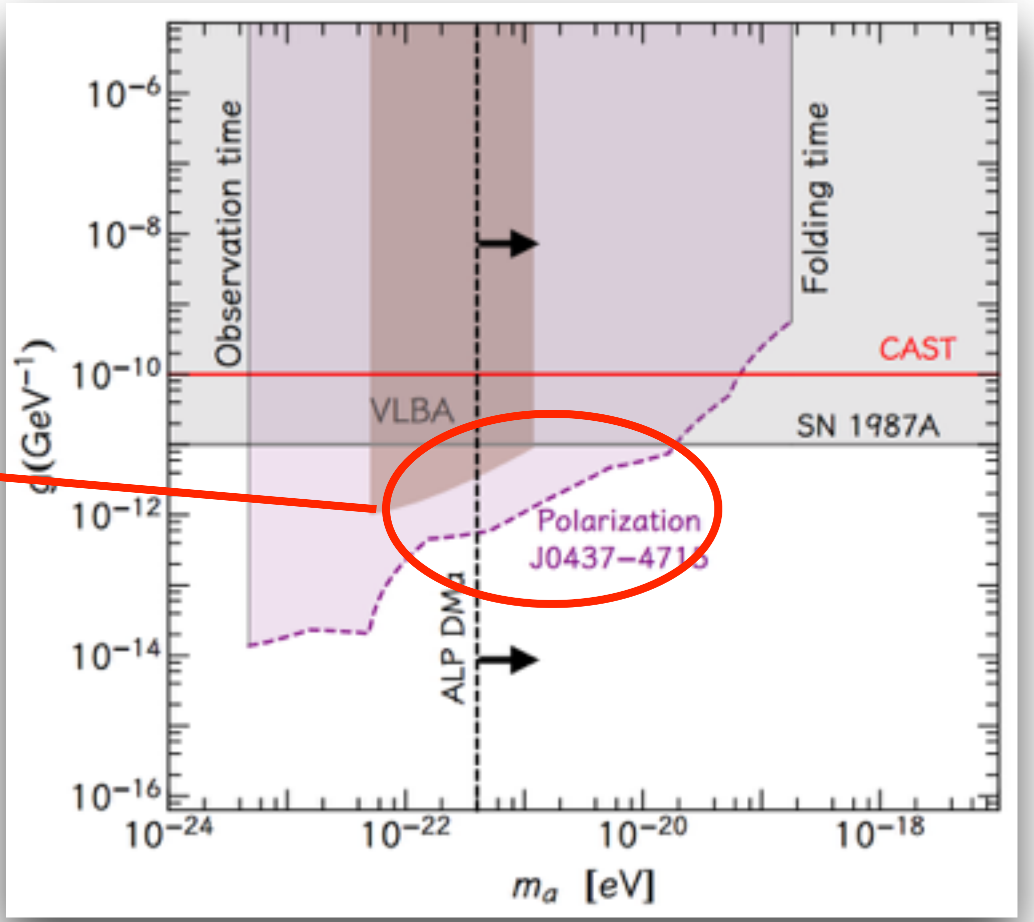

[TL, Smoot, Zhao, arXiv:1901.10981]

[Caputo et. al., arXiv:1902.02695]

Summary

- Axion or ALP physics play a significant role for understanding cosmological puzzles, such as dark matter
- We propose to detect axion-like DM using linearly polarized pulsar light
- Pros: stable repeating signals; rich in Milk Way
- With a soliton+NFW DM density profile and current measurement accuracy, we show that the pulsar-based detection potentially can probe an axion-photon coupling ~10^{-13} GeV^{-1}, one to two orders better than SN1987A, for axion mass ~ 10^{-22} - 10^{-20} eV
- Systematic real-data analysis is ongoing in collaboration with Smoot and Zhao .....


Thank you!