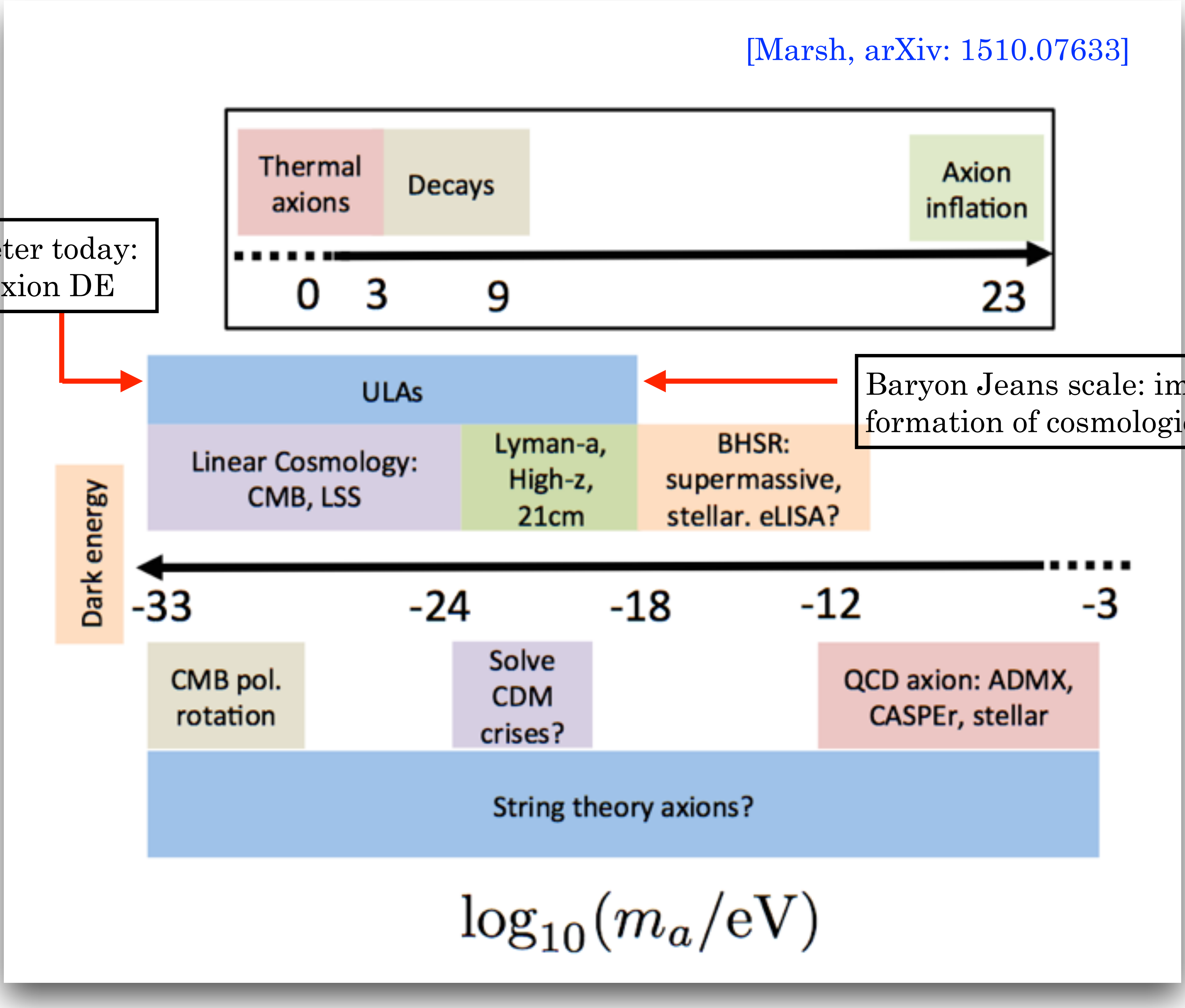
INTERNATIONAL WORKSHOP ON
NEW PHYSICS AT THE LOW ENERGY SCALES
NEPLES-2019

Detecting ULA Dark Matter with Cosmological Birefringence

Tao Liu
The Hong Kong University of Science and Technology

Mainly based on arXiv: 1901.10981 and ongoing project
in collaboration with George Smoot and Yue Zhao

Ultra-Light Axions (ULAs)

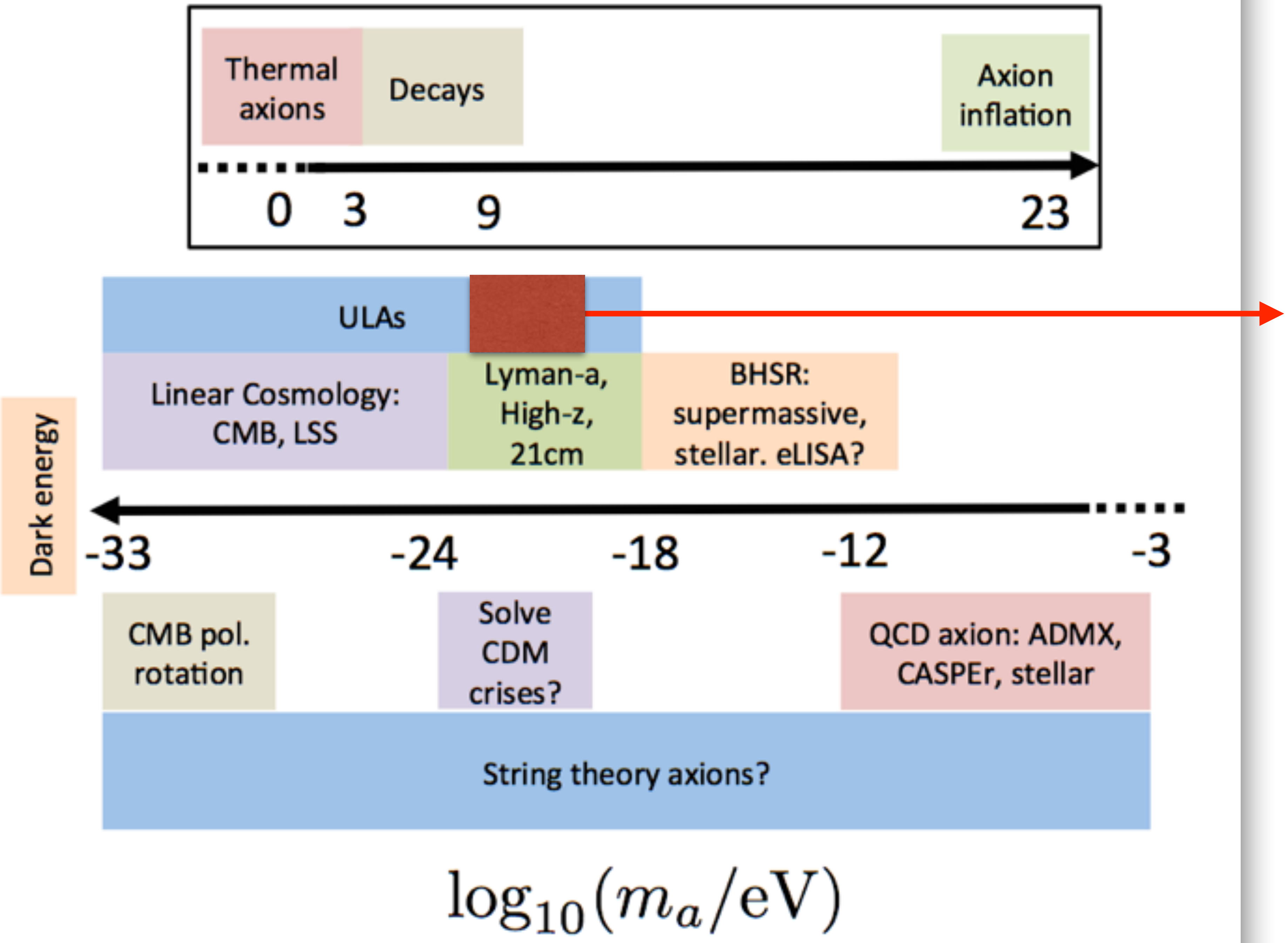


[Marsh, arXiv: 1510.07633]

Hubble parameter today: contraints for axion DE

Baryon Jeans scale: impact for the formation of cosmological structure

Fuzzy Dark Matter



[Marsh, arXiv: 1510.07633]

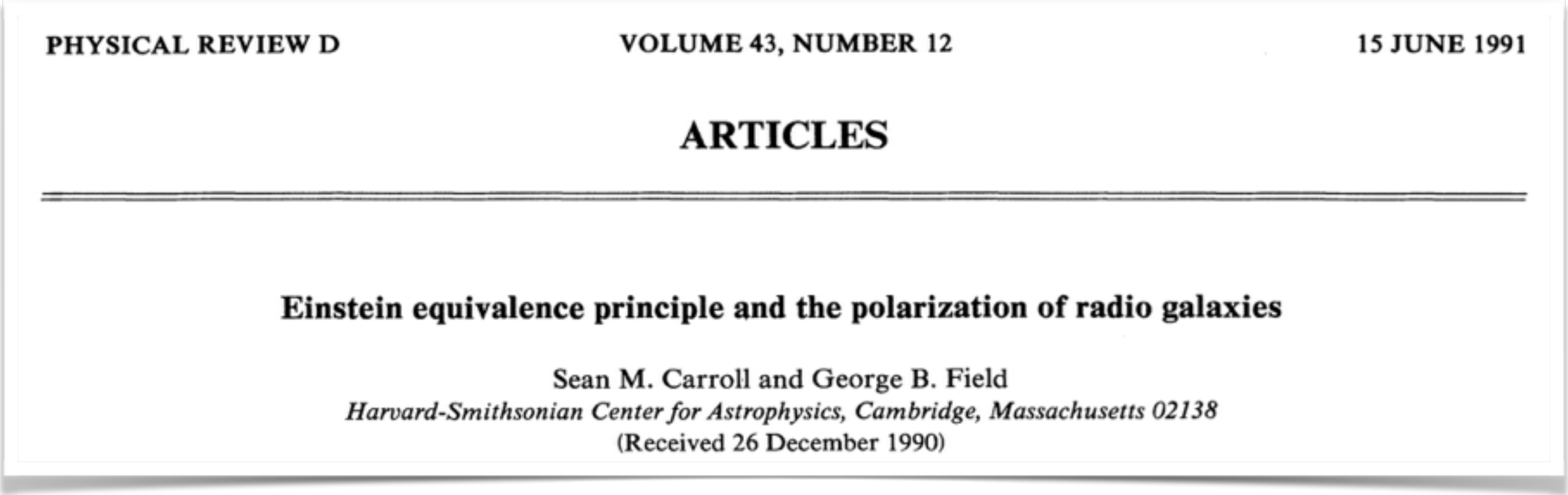
[Hu, Barkana and Gruzinov, astro- ph/0003365]

[Hui, Ostriker, Tremaine and Witten, arXiv:1610.08297]

Fuzzy Dark Matter

Can potentially address “Small Scale Crises” from astronomical observations (cusp-core, missing satellites, etc.) challenging standard CDM paradigm

Cosmological Birefringence



PHYSICAL REVIEW D VOLUME 43, NUMBER 12 15 JUNE 1991

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

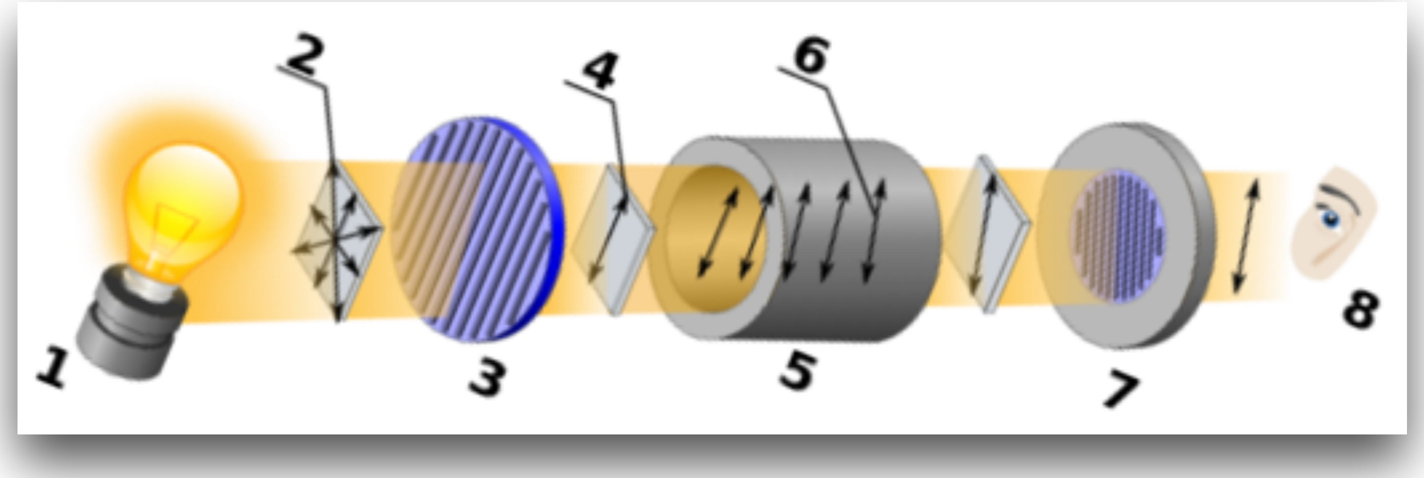
(Received 26 December 1990)

Cosmological Birefringence

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

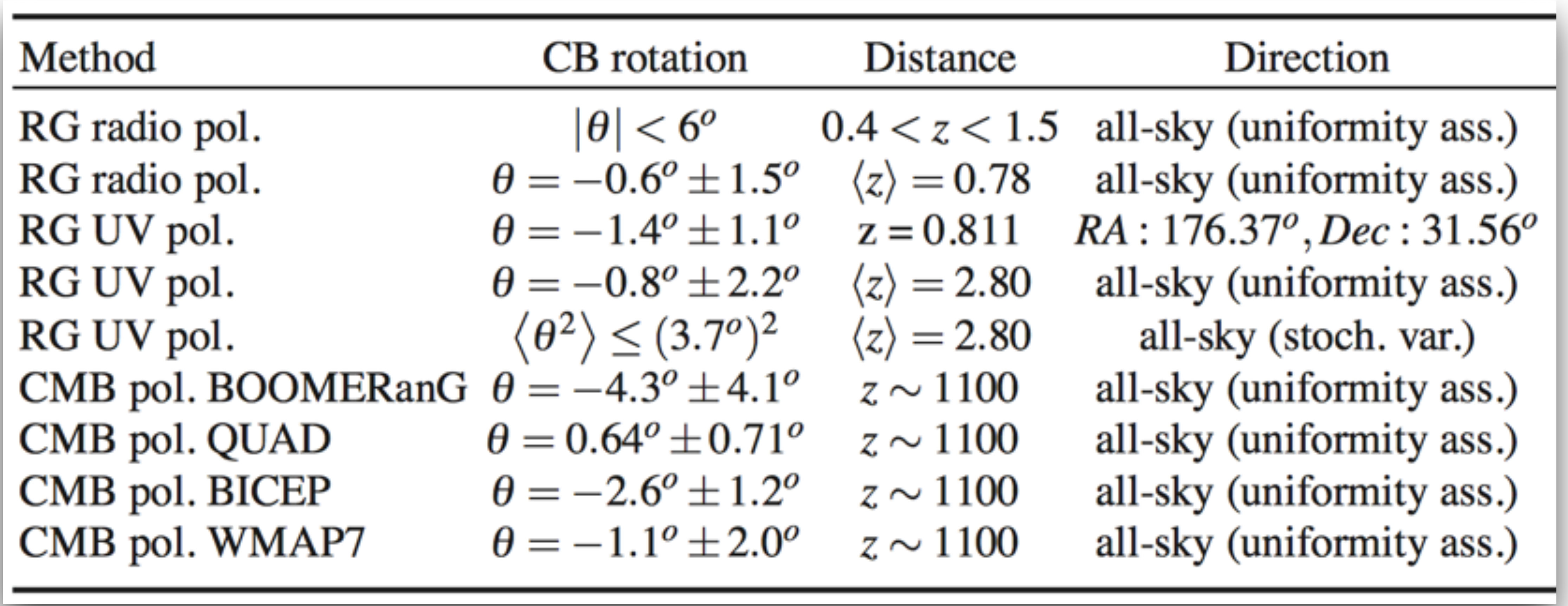
$$\begin{pmatrix} \partial_t^2 + k^2 + m_a^2 & 0 & 0 \\ 0 & \partial_t^2 + k^2 + \eta(t)k & 0 \\ 0 & 0 & \partial_t^2 + k^2 - \eta(t)k \end{pmatrix} \begin{pmatrix} i\hat{a} \\ f_+ \\ f_- \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

Parity-violation => Different dispersion relations for photons with left- and right-circular polarization modes => Potentially observable effect: rotation of linearly polarization angle (LPA)



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

Main Detection Methods



Method	CB rotation	Distance	Direction
RG radio pol.	$\lvert\theta\rvert < 6^o$	$0.4 < z < 1.5$	all-sky (uniformity ass.)
RG radio pol.	$\theta = -0.6^o \pm 1.5^o$	$\langle z \rangle = 0.78$	all-sky (uniformity ass.)
RG UV pol.	$\theta = -1.4^o \pm 1.1^o$	$z = 0.811$	$RA: 176.37^o, Dec: 31.56^o$
RG UV pol.	$\theta = -0.8^o \pm 2.2^o$	$\langle z \rangle = 2.80$	all-sky (uniformity ass.)
RG UV pol.	$\langle \theta^2 \rangle \leq (3.7^o)^2$	$\langle z \rangle = 2.80$	all-sky (stoch. var.)
CMB pol. BOOMERanG	$\theta = -4.3^o \pm 4.1^o$	$z \sim 1100$	all-sky (uniformity ass.)
CMB pol. QUAD	$\theta = 0.64^o \pm 0.71^o$	$z \sim 1100$	all-sky (uniformity ass.)
CMB pol. BICEP	$\theta = -2.6^o \pm 1.2^o$	$z \sim 1100$	all-sky (uniformity ass.)
CMB pol. WMAP7	$\theta = -1.1^o \pm 2.0^o$	$z \sim 1100$	all-sky (uniformity ass.)

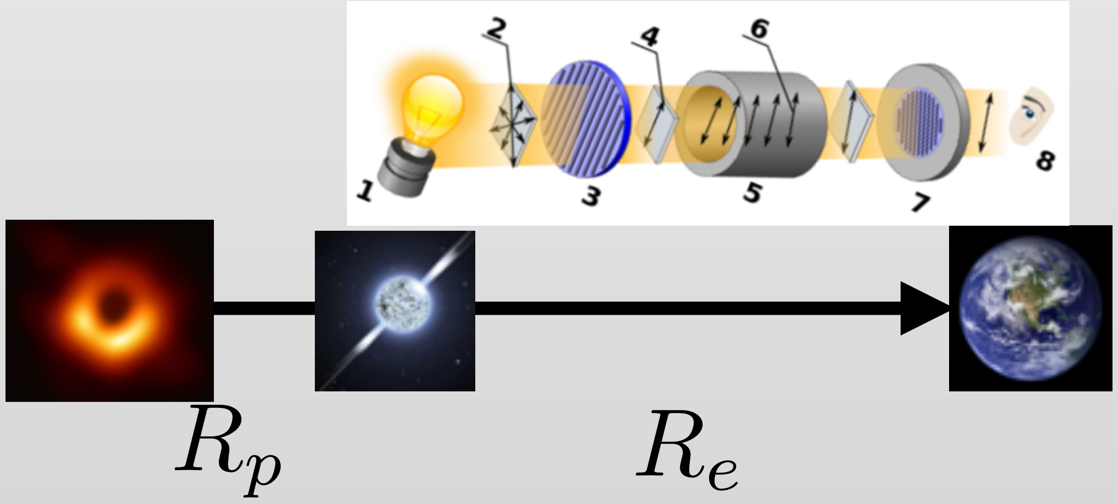
[Di Serego Alighieri, arXiv: 1011.4865]

- Radio polarization of radio galaxies [Carroll, Field and Jackiw, PRD (1990)]
- UV polarization of radio galaxies [Cimatti, Di Serego Alighieri, Field and Fosbury, Astrophys. J. (1994)]
- CMB polarization [Lue, Wang, KamionKowski, PRL (1999)]

These light sources are so distant that the detection is inclusive

Pulsar-Based Detection

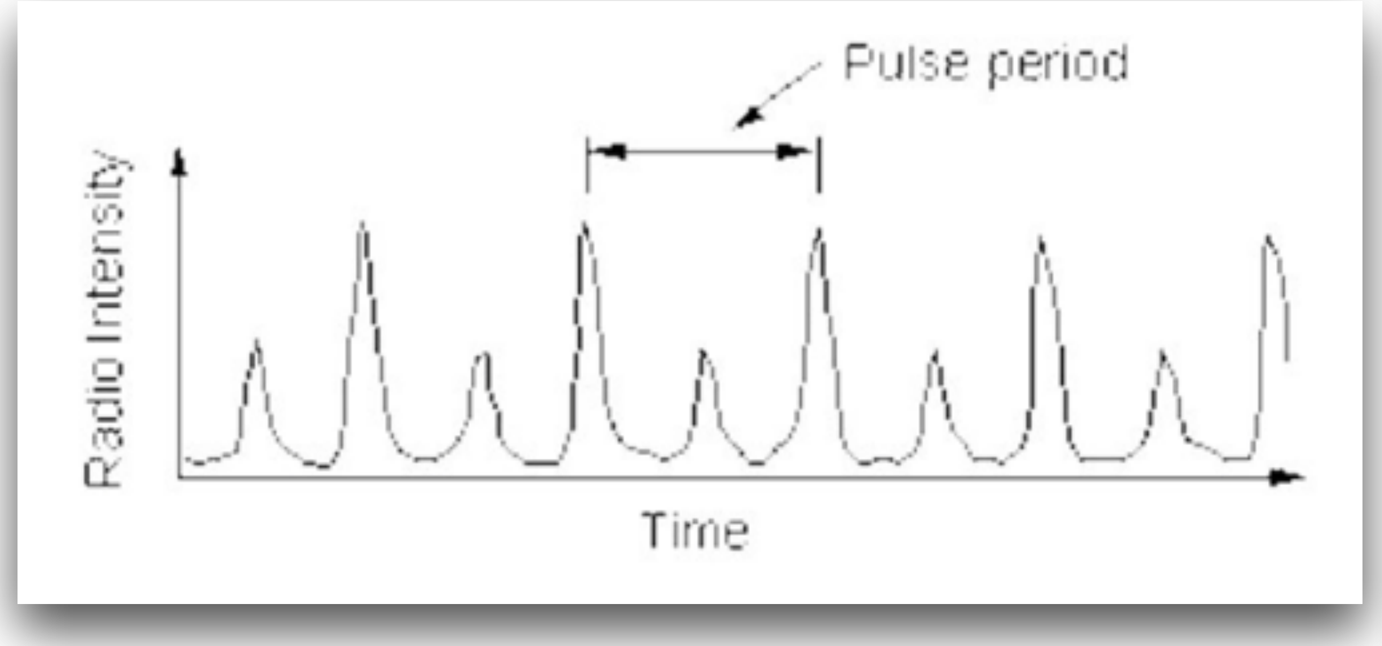
Alternatively, we propose a local measurement to detect ULA DM — using linearly polarized pulsar light as a probe.



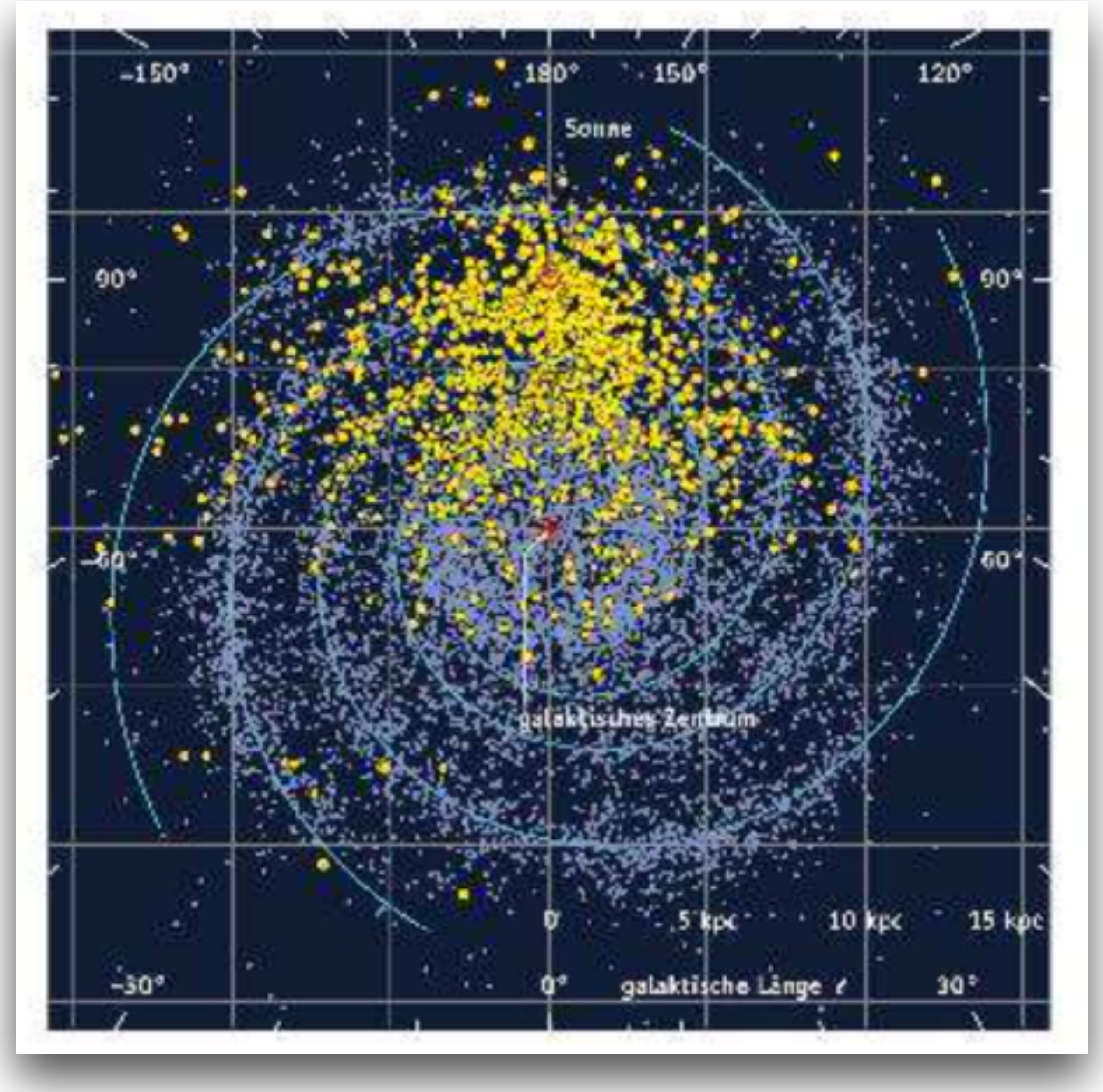
[TL, G. Smoot, Y. Zhao, arXiv:1901.10981]

Why Pulsars?

- Both SP and MSP are stable astrophysical sources of linearly polarized light
- Repeating signals of pulsar light allow reconstructing the temporal shape or profile of the event, with the resolution in time set by the signal/pulse period (recall, for ma~10^{-22} eV, T_osc ~ 1 yr).



Why Pulsars?



[Rauber Beck (2009)]

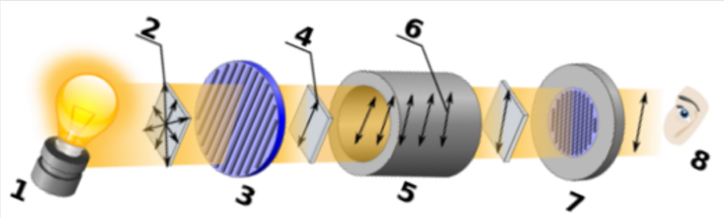
- Rich in Milk Way: simulation (~20000) vs. observation (~2800)
- => Possibility to suppress backgrounds/instrumental errors, by correlating the measurements of multiple pulsars

What to Measure?

Being lack of precise knowledge on the original LPA of pulsar light => measure its time variation instead of its absolute rotation

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

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



- Make Delta-Phi0 valid =>

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

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

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

What to Measure?

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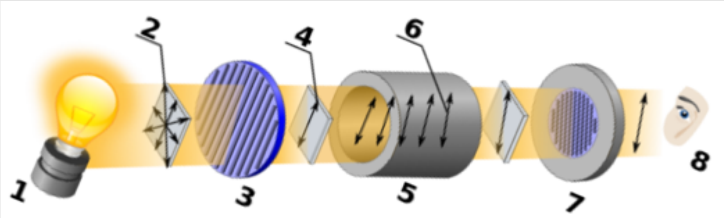

$$\Delta t \ll t_c = \frac{2\pi}{\frac{1}{2} m_a v^2} \qquad \Delta t \ll T = \frac{4\pi}{m_a}$$

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

Both SP and MSP are qualified for probing ULA DM

What to Measure?

Being lack of precise knowledge on the original LPA of pulsar light
=> measure its time variation instead of its absolute rotation

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

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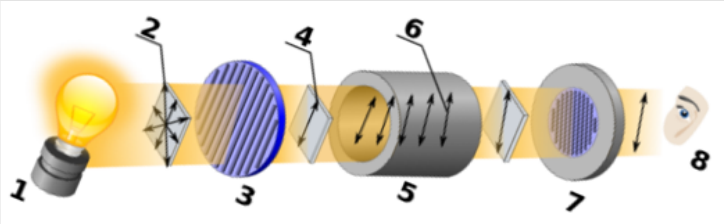
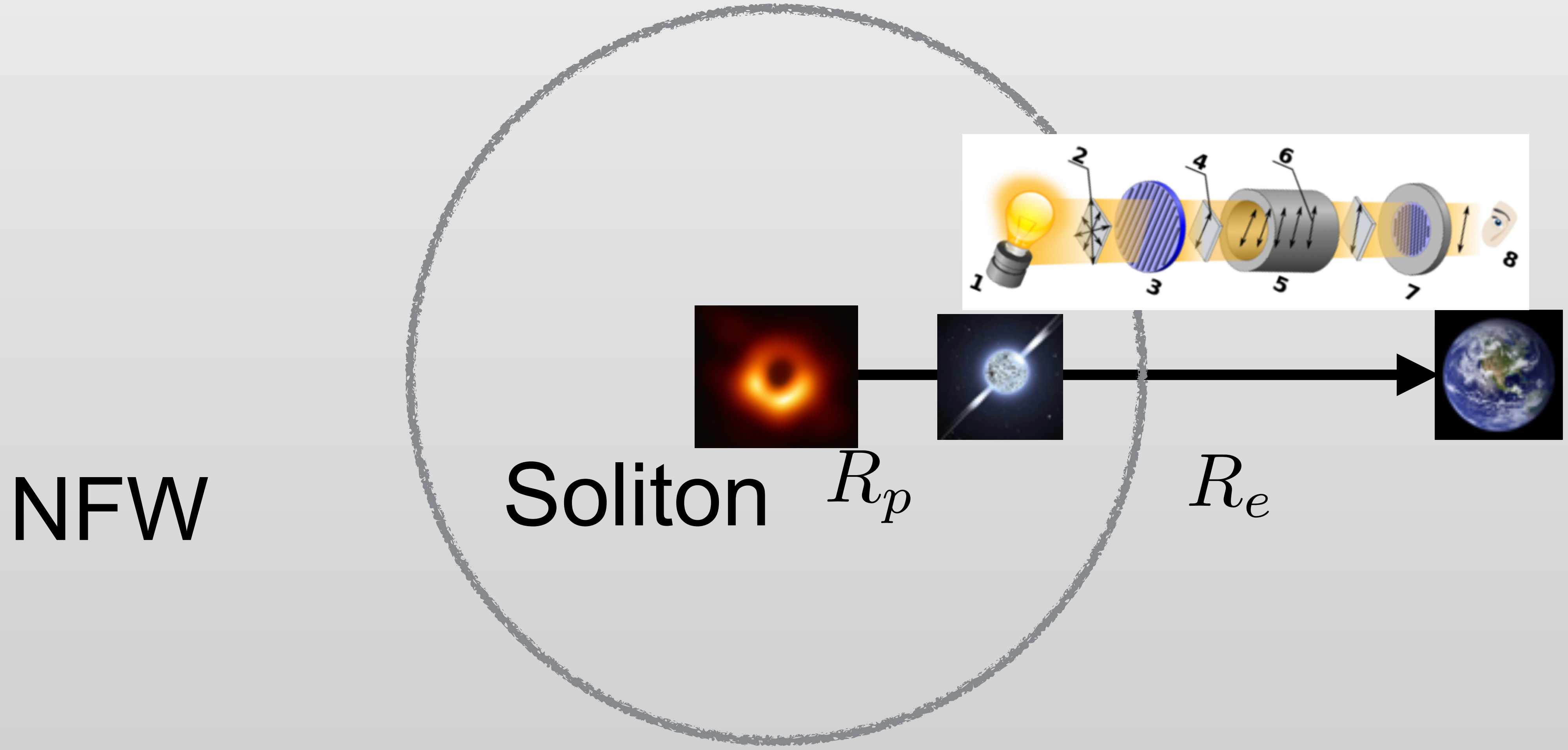


- For qualitatively evaluating the sensitivity of this strategy, we define a characteristic quantity by averaging Delta-Phi0 over temporal coherence regions at ``i'' and ``f''

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

Axion-like DM Density Profile

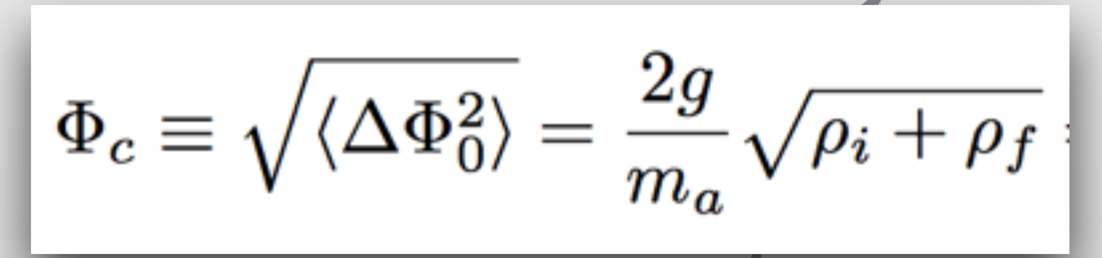
With axion DM condensate,
soliton-like structure could be formed in galactic center
[Schive, Chiueh, Broadhurst, Nature Physics (2014)]



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

Benchmark Pulsars

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



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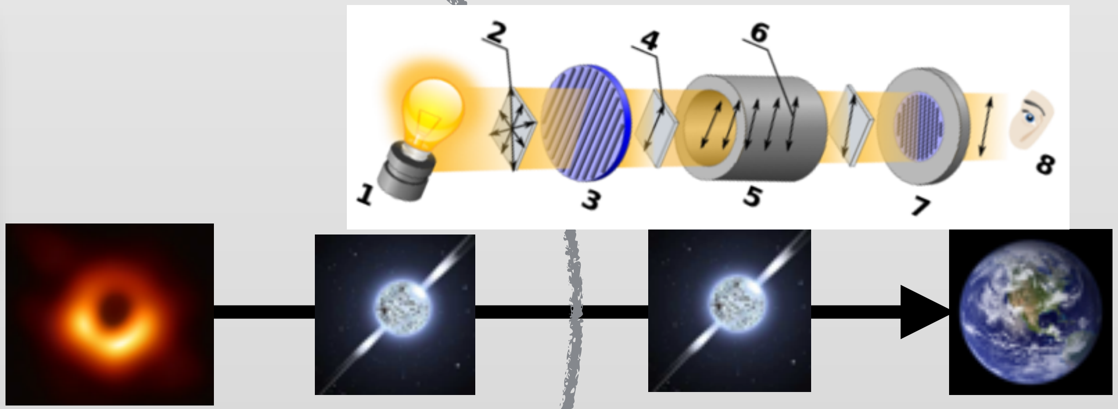
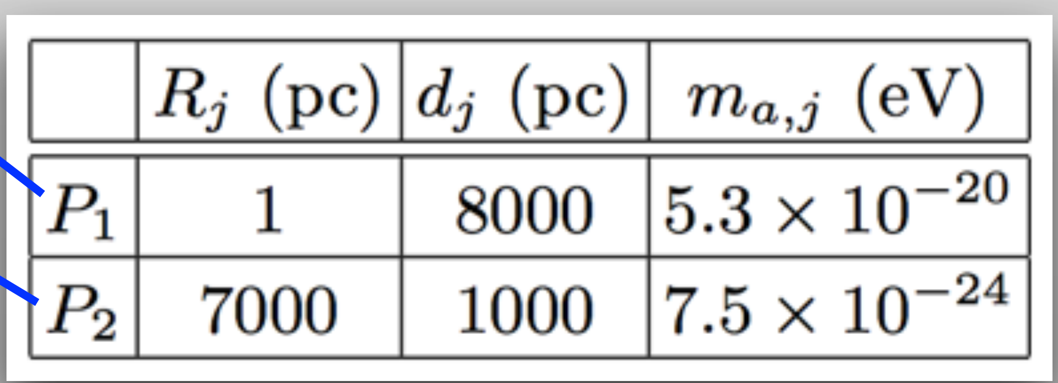


NFW

Soliton

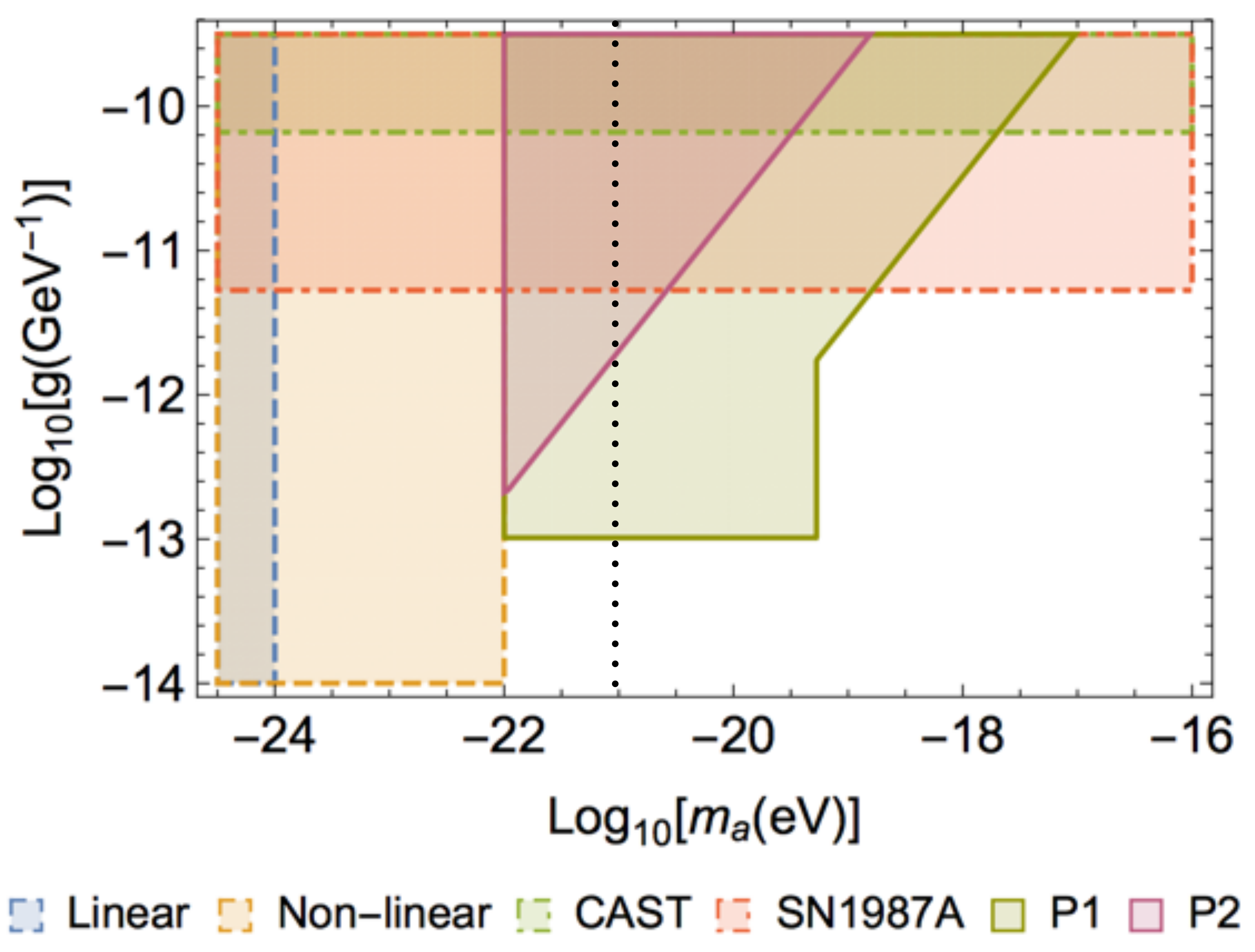
Optimistic

Conservative

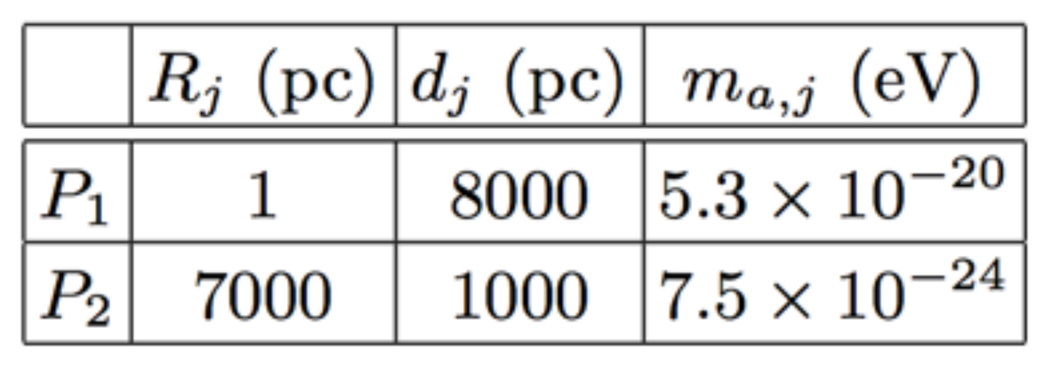


	R_j (pc)	d_j (pc)	$m_{a,j}$ (eV)
P_1	1	8000	5.3×10^{-20}
P_2	7000	1000	7.5×10^{-24}

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



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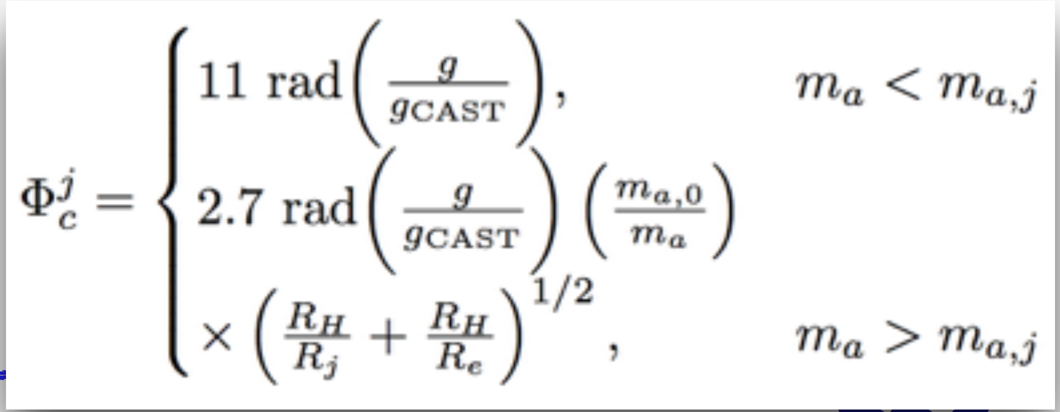
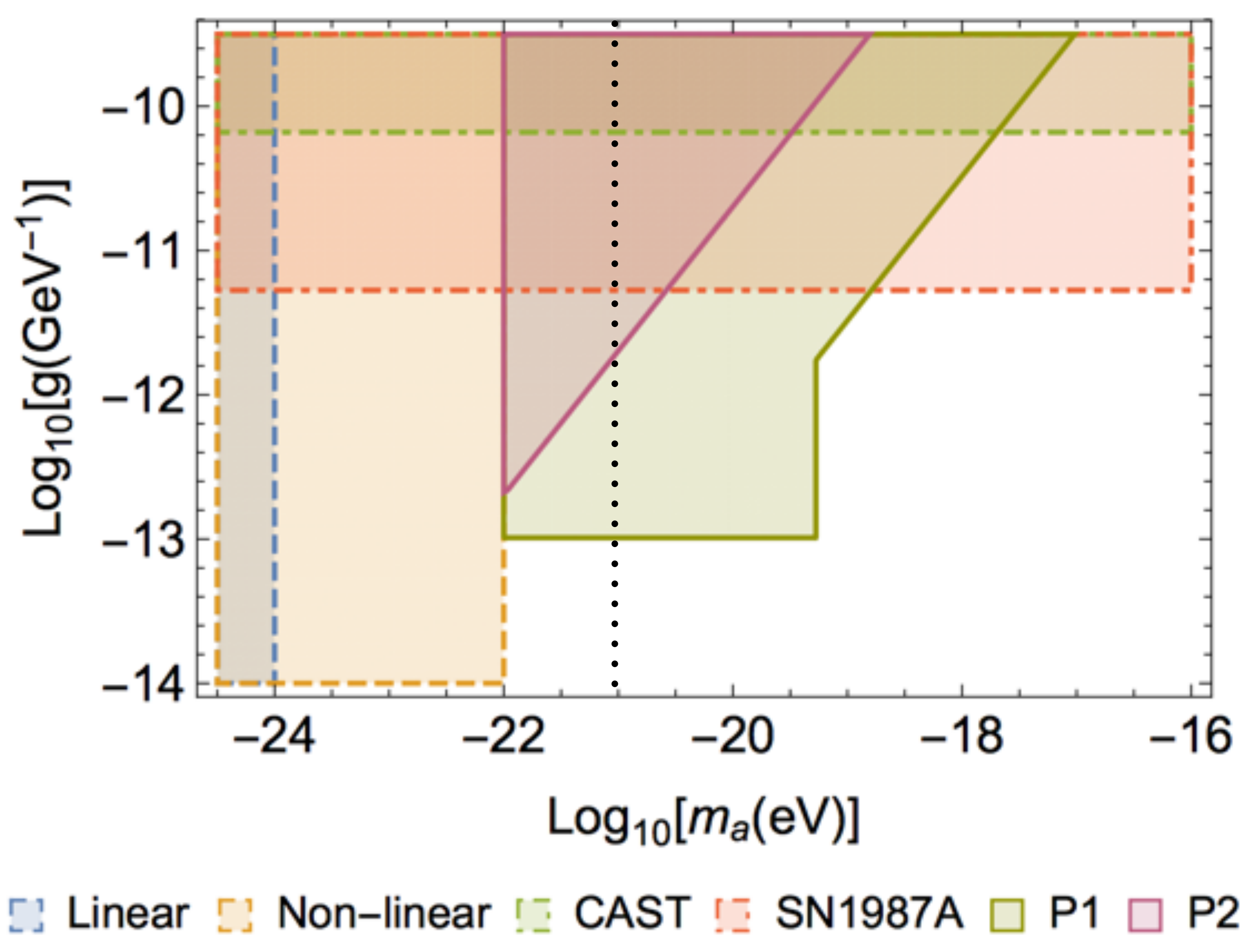
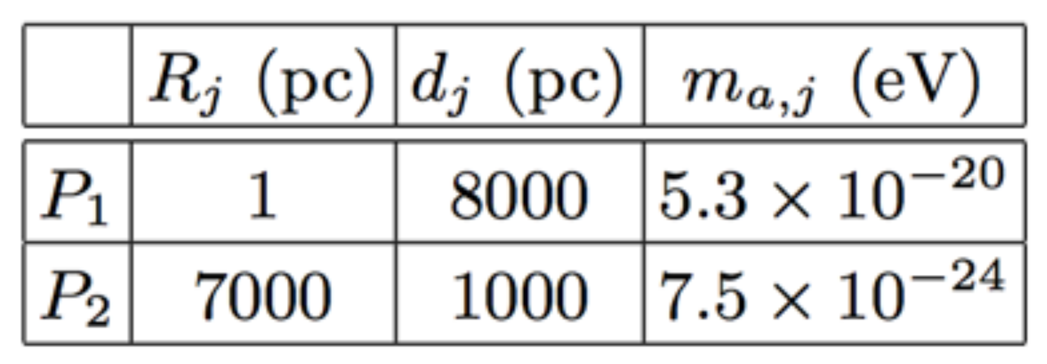


$$\Phi_c^j = \begin{cases} 11\,\text{rad}\left(\frac{g}{g_{\text{CAST}}}\right), & m_a < m_{a,j} \\ 2.7\,\text{rad}\left(\frac{g}{g_{\text{CAST}}}\right)\left(\frac{m_{a,0}}{m_a}\right) & \\ \times\left(\frac{R_H}{R_j}+\frac{R_H}{R_e}\right)^{1/2}, & m_a > m_{a,j} \end{cases}$$

Sensitivity Projection





	R_j (pc)	d_j (pc)	$m_{a,j}$ (eV)
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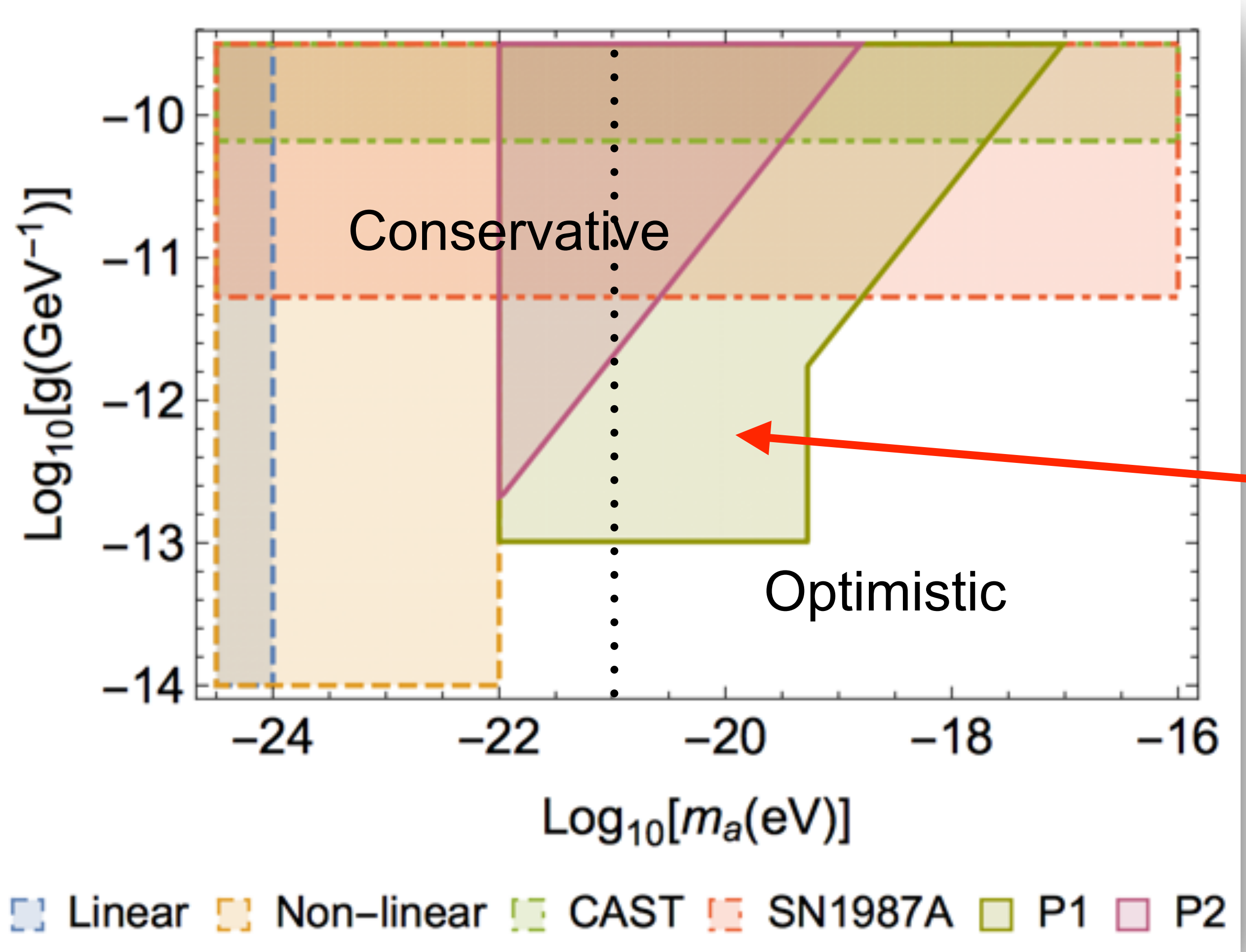
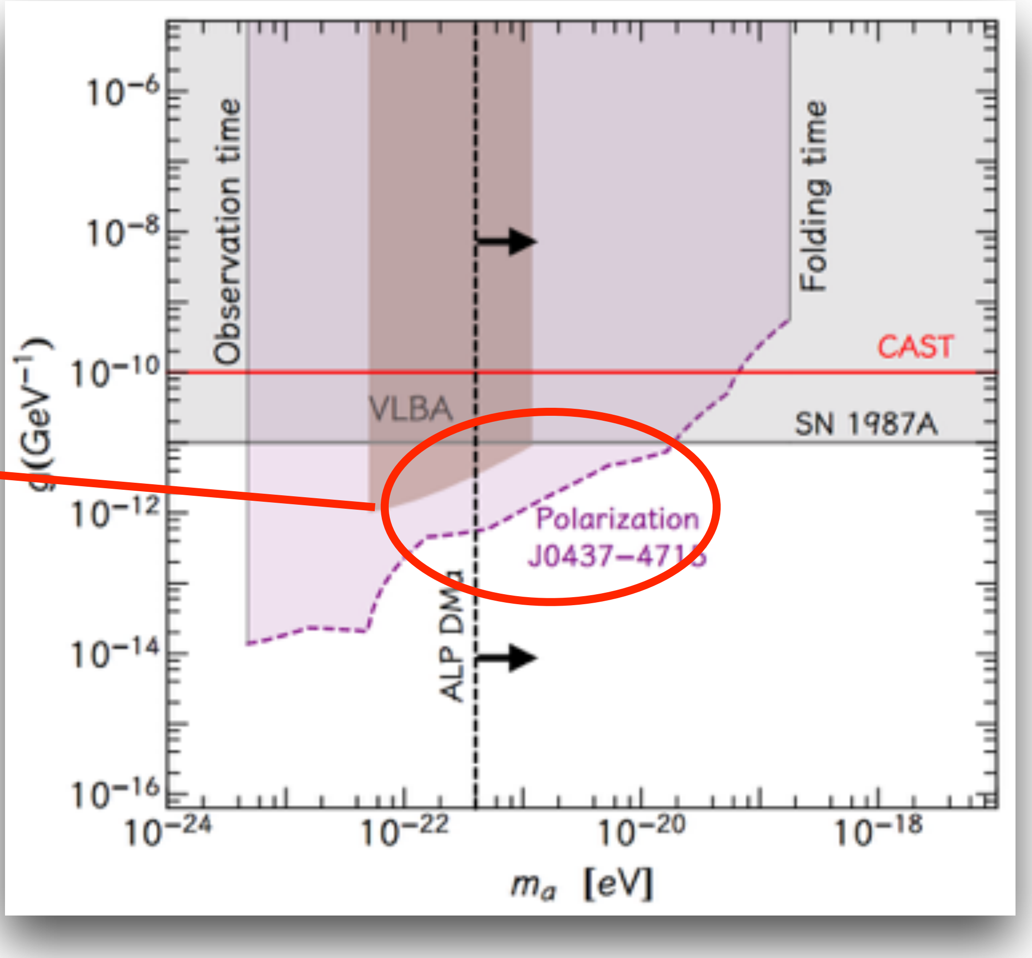
- P1: flat and slope parts result from the scenarios with the pulsar being positioned in the core soliton and NFW regions, respectively, with the threshold set by ~5.3 × 10^{−20} eV
- P2: only slope part is relevant
- Best sensitivity: ~10^{-13} GeV^{-1}, one to two orders better than SN1987A, for axion mass ~ 10^{-22} - 10^{-20} eV

Sensitivity Projection



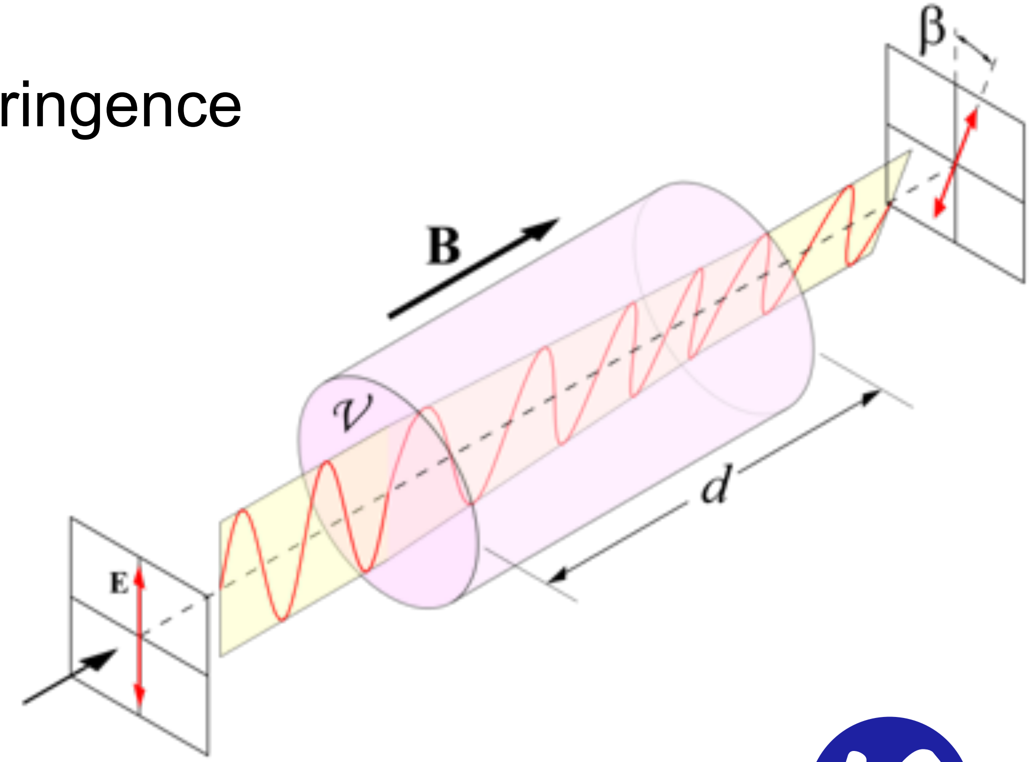
[TL, Smoot, Zhao, arXiv:1901.10981]



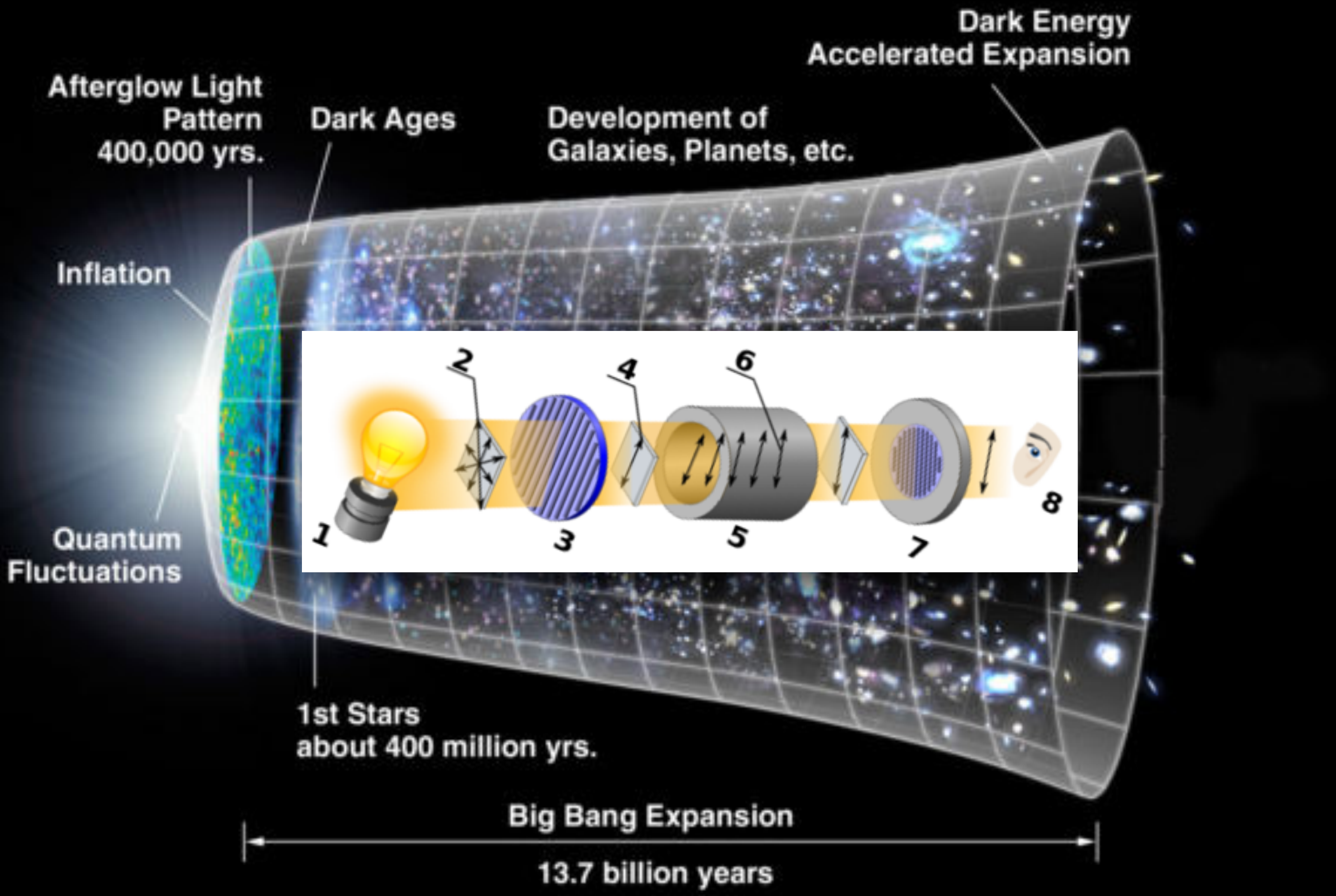
[Caputo et. al., arXiv:1902.02695]

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 of ULA DM is insensitive to frequency, but Faraday rotation is inversely proportional to squared frequency
- Measure time dependence: cosmological birefringence oscillates as sine function



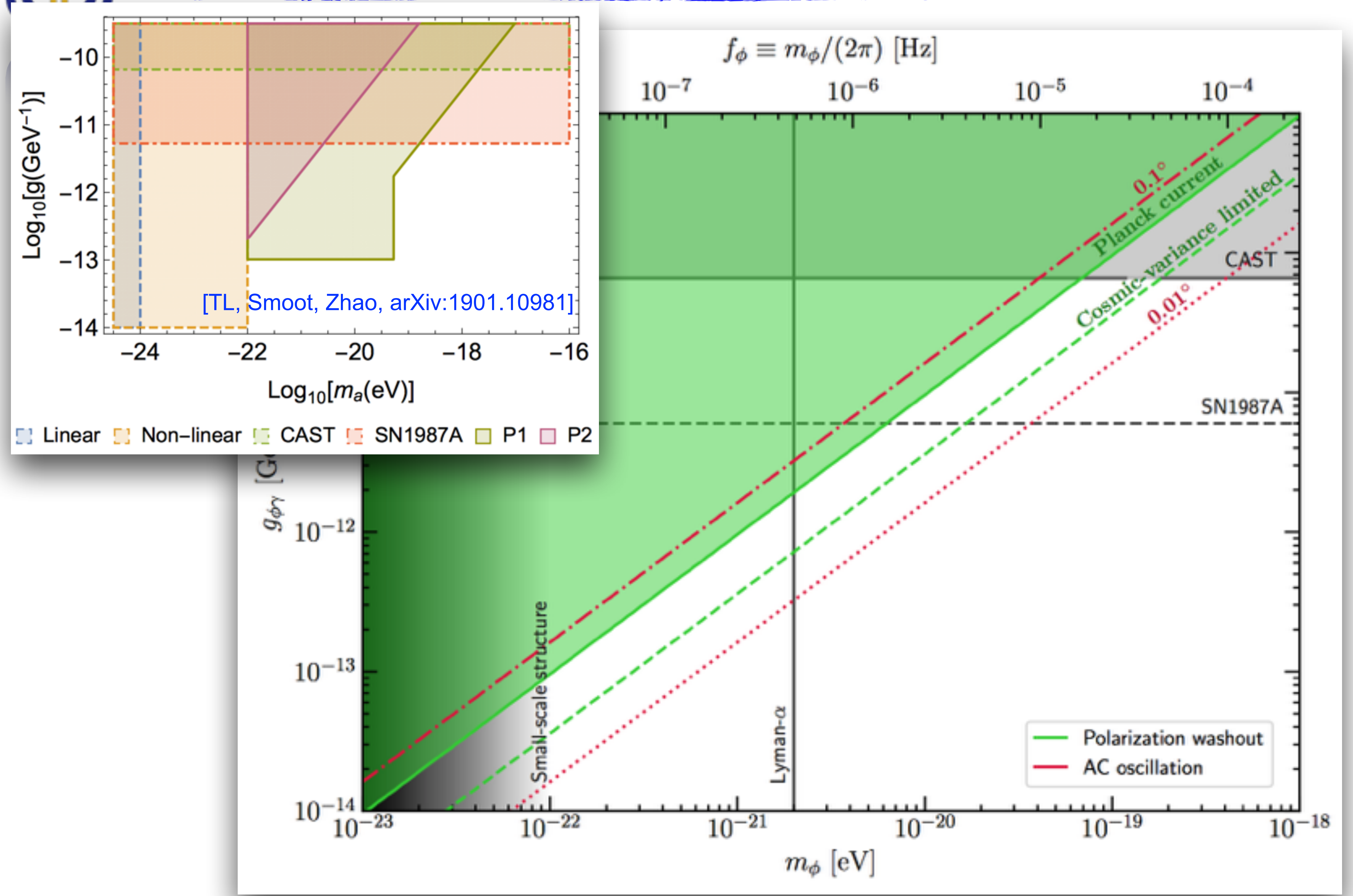
Comparison with CMB-Based Detection



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

NASA/WMAP Science Tea

CMB-Based Detection (A Recent Revisit)



[TL, Smoot, Zhao, arXiv:1901.10981]

[Fedderke, Graham, Rajendran, arXiv: 1903.02666]

Future Detection

However, all of these methods are far from the target sensitivity!

$$\Omega_{\text{axion}} \sim 0.1 \left(\frac{F}{\boxed{10^{17}\,\text{GeV}}}\right)^{2} \left(\frac{m}{10^{-22}\,\text{eV}}\right)^{1/2}$$

[Hui, Ostriker, Tremaine and Witten, arXiv:1610.08297]

Future Detection

However, all of these methods are far from the target sensitivity in the visible future!

$$\Omega_{\text{axion}} \sim 0.1 \left(\frac{F}{\boxed{10^{17}\,\text{GeV}}}\right)^2 \left(\frac{m}{10^{-22}\,\text{eV}}\right)^{1/2}$$

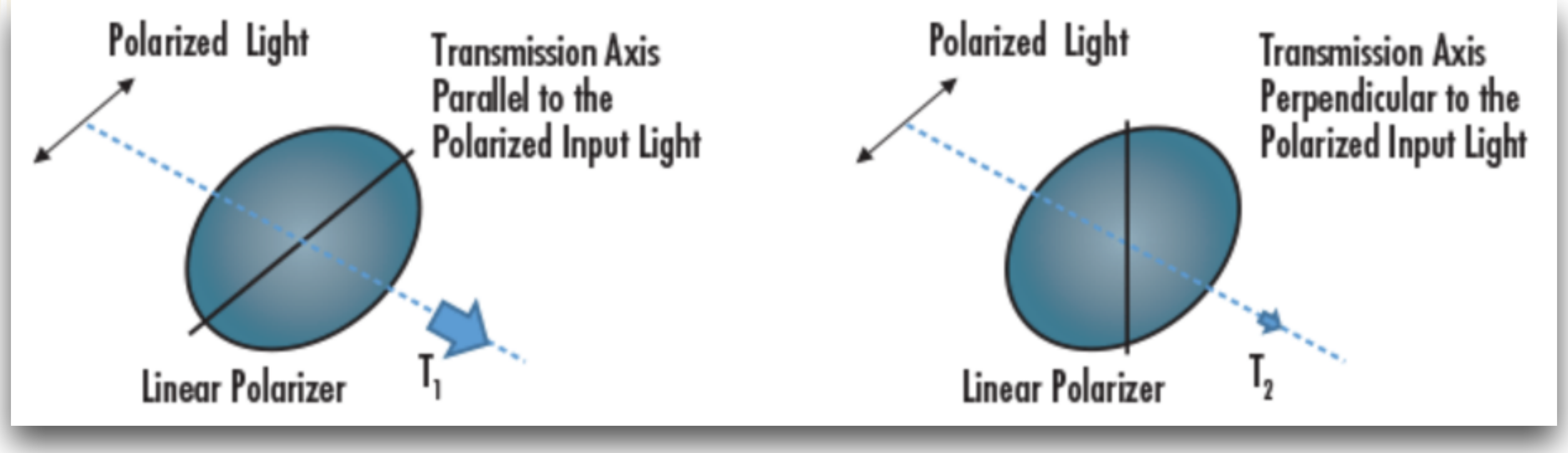
[Hui, Ostriker, Tremaine and Witten, arXiv:1610.08297]

Potential Chance

 - based laser experiment!

[TL, Smoot, Zhao, ongoing]

Gain: High-quality of Linear Polarizers



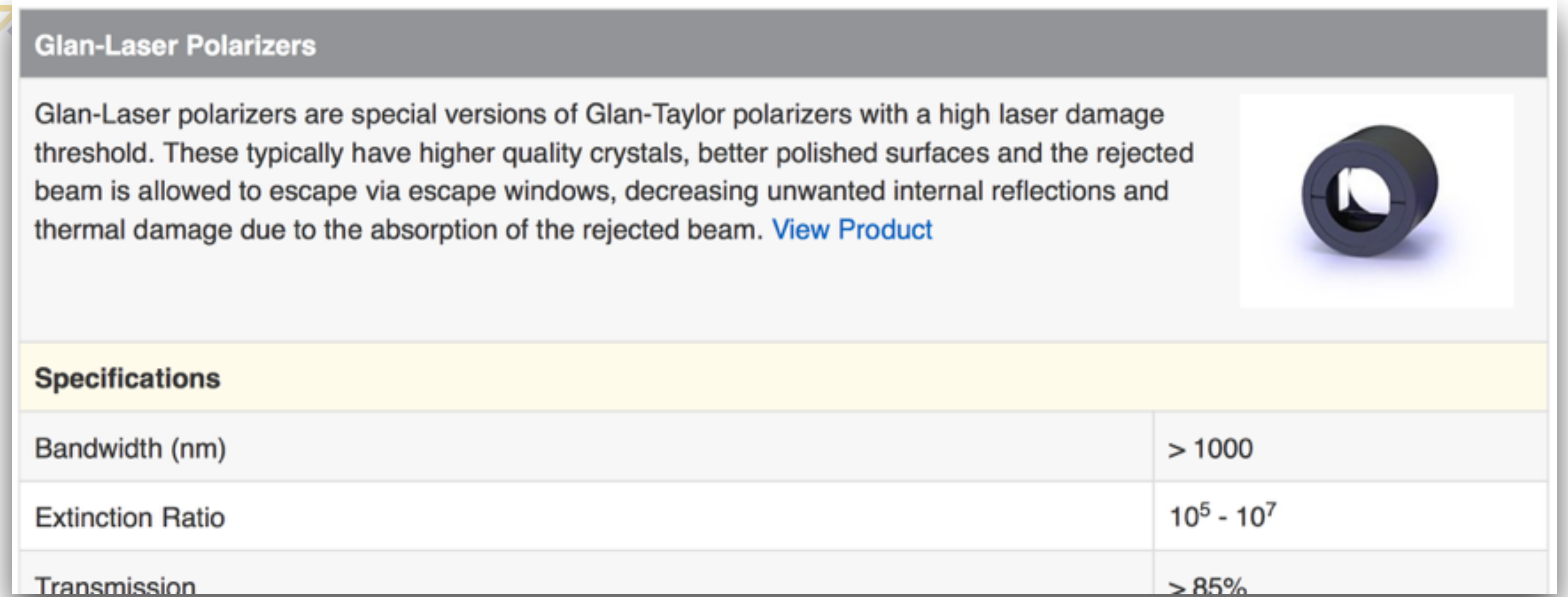
Extinction Ratio of linear polarizers = T1/T2 : 1

=>

(1) Purity of the linearly polarized laser beam

(2) Resolution of the beam signal receiver

Extinction Ratio of Linear Polarizers



Glan-Laser Polarizers

Glan-Laser polarizers are special versions of Glan-Taylor polarizers with a high laser damage threshold. These typically have higher quality crystals, better polished surfaces and the rejected beam is allowed to escape via escape windows, decreasing unwanted internal reflections and thermal damage due to the absorption of the rejected beam. View Product

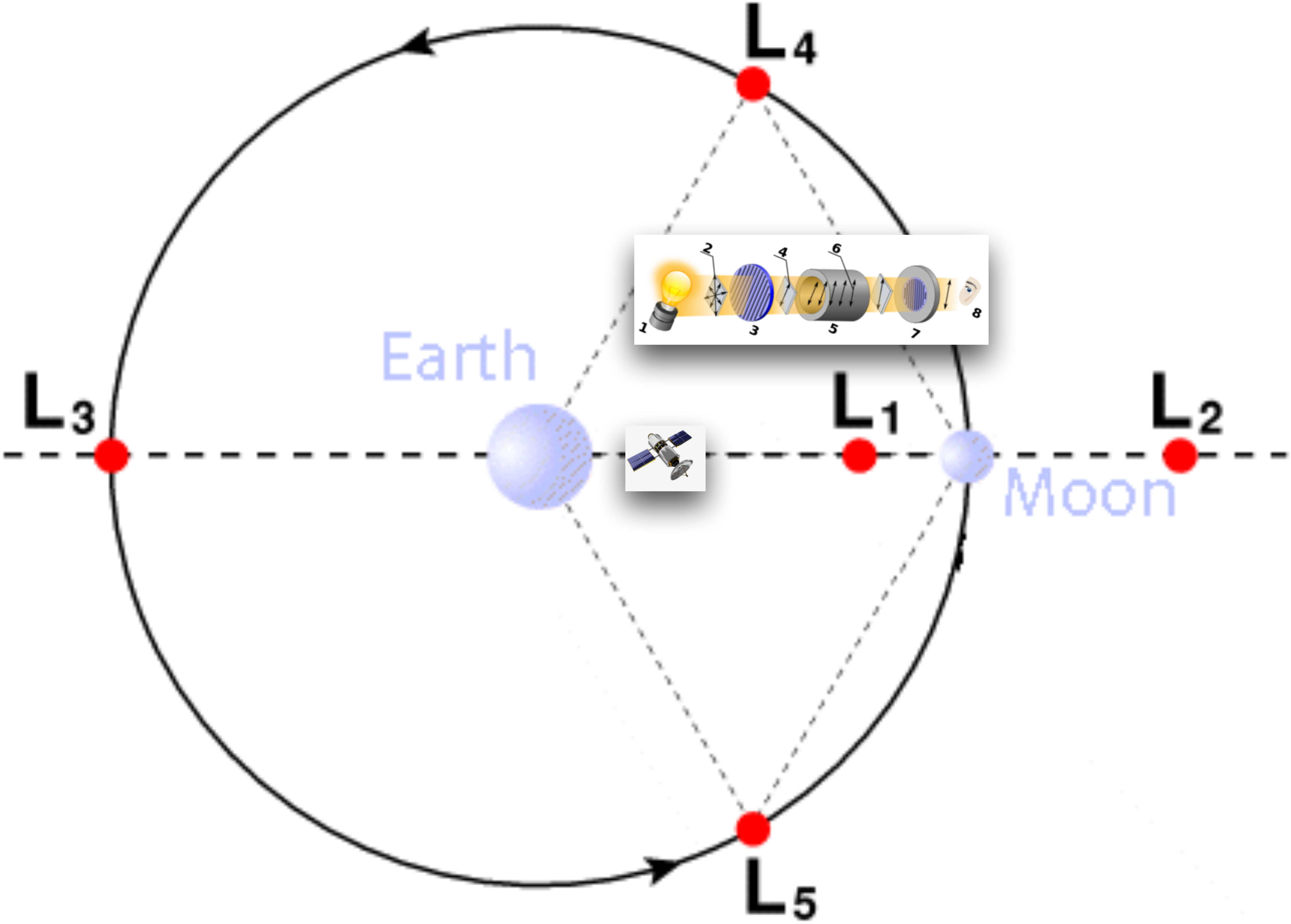
Specifications	
Bandwidth (nm)	> 1000
Extinction Ratio	10^5 - 10^7
Transmission	> 85%

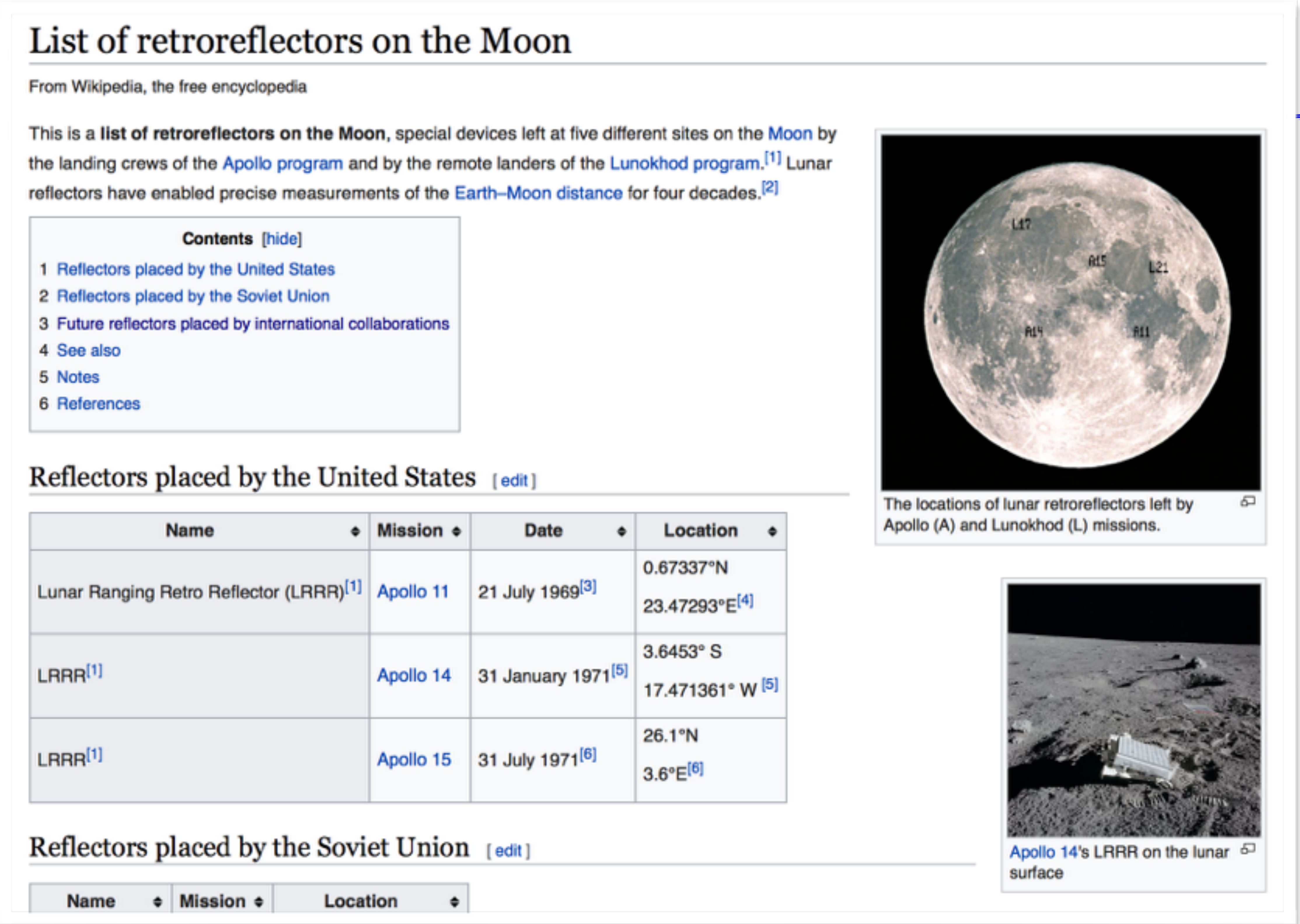
Commercial products: ~ 10^7 : 1

Best laboratory: ~ 10^10 : 1

Near future: > 10^10 : 1

Satellite-Based Detection





List of retroreflectors on the Moon

From Wikipedia, the free encyclopedia

This is a **list of retroreflectors on the Moon**, special devices left at five different sites on the Moon by the landing crews of the Apollo program and by the remote landers of the Lunokhod program.[1] Lunar reflectors have enabled precise measurements of the Earth–Moon distance for four decades.[2]

Contents [hide]

The locations of lunar retroreflectors left by Apollo (A) and Lunokhod (L) missions.

Reflectors placed by the United States [edit]

Name	Mission	Date	Location
Lunar Ranging Retro Reflector (LRRR)[1]	Apollo 11	21 July 1969[3]	0.67337°N 23.47293°E[4]
LRRR[1]	Apollo 14	31 January 1971[5]	3.6453° S 17.471361° W [5]
LRRR[1]	Apollo 15	31 July 1971[6]	26.1°N 3.6°E[6]

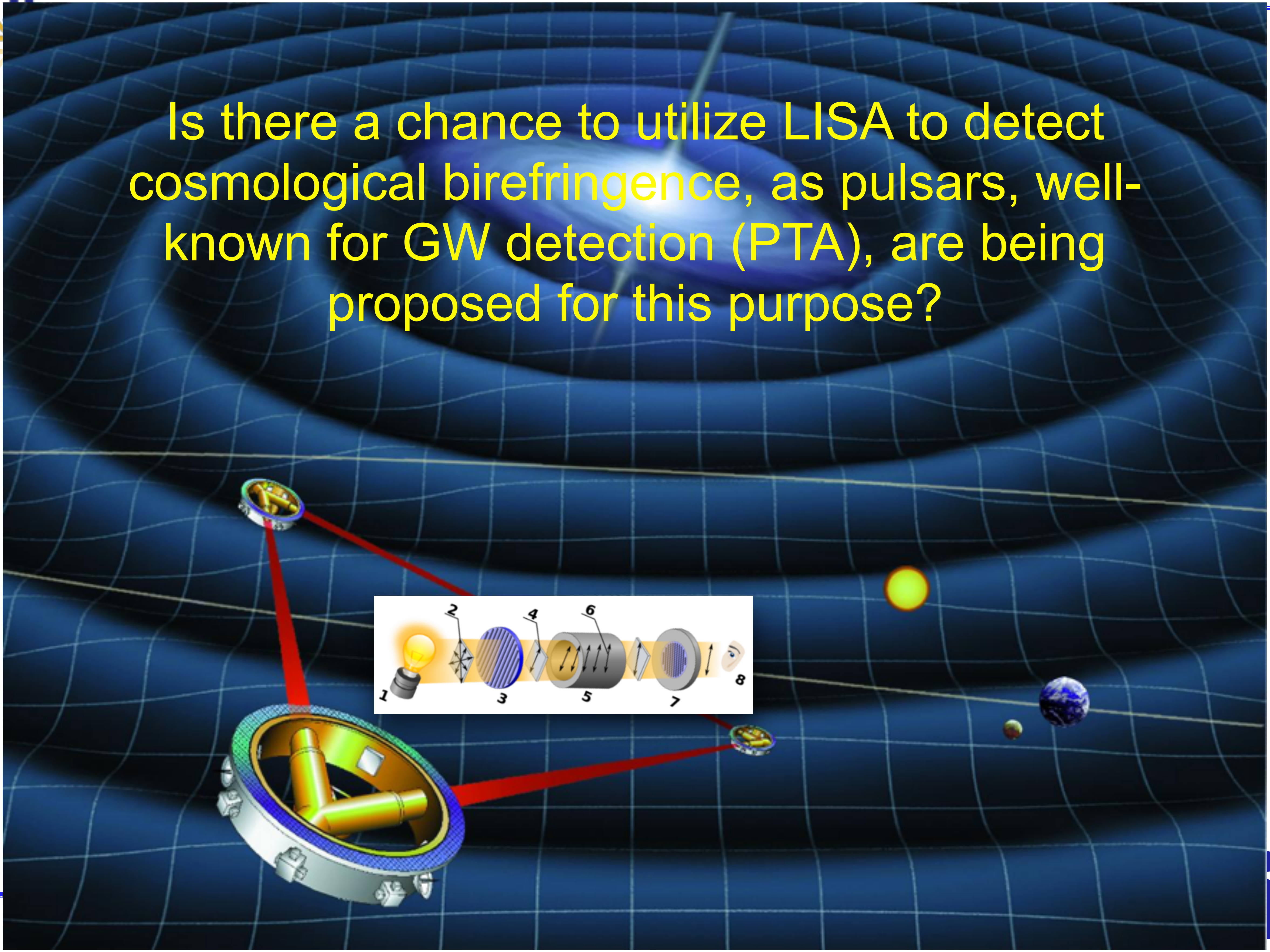
Apollo 14's LRRR on the lunar surface

Reflectors placed by the Soviet Union [edit]

Name	Mission	Location

The idea to use the moon as a base for laser exps is not new.

Or Based at Some Others



Is there a chance to utilize LISA to detect cosmological birefringence, as pulsars, well-known for GW detection (PTA), are being proposed for this purpose?

Summary

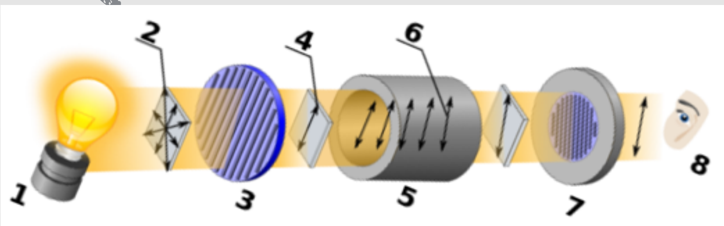
- ULA physics plays a significant role for understanding the puzzle of dark matter
- We propose to detect ULA DM using linearly polarized pulsar light
- Pros: stable repeating signals; rich in Milk Way
- With a soliton+NFW DM density profile and current measurement accuracy, we show that the pulsar-based 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
- Future: satellite-based laser exp? High resolution of linear polarizer VS. Drifting effects of base (ongoing)

Thank you!

Backup: Benchmark Pulsars

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

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

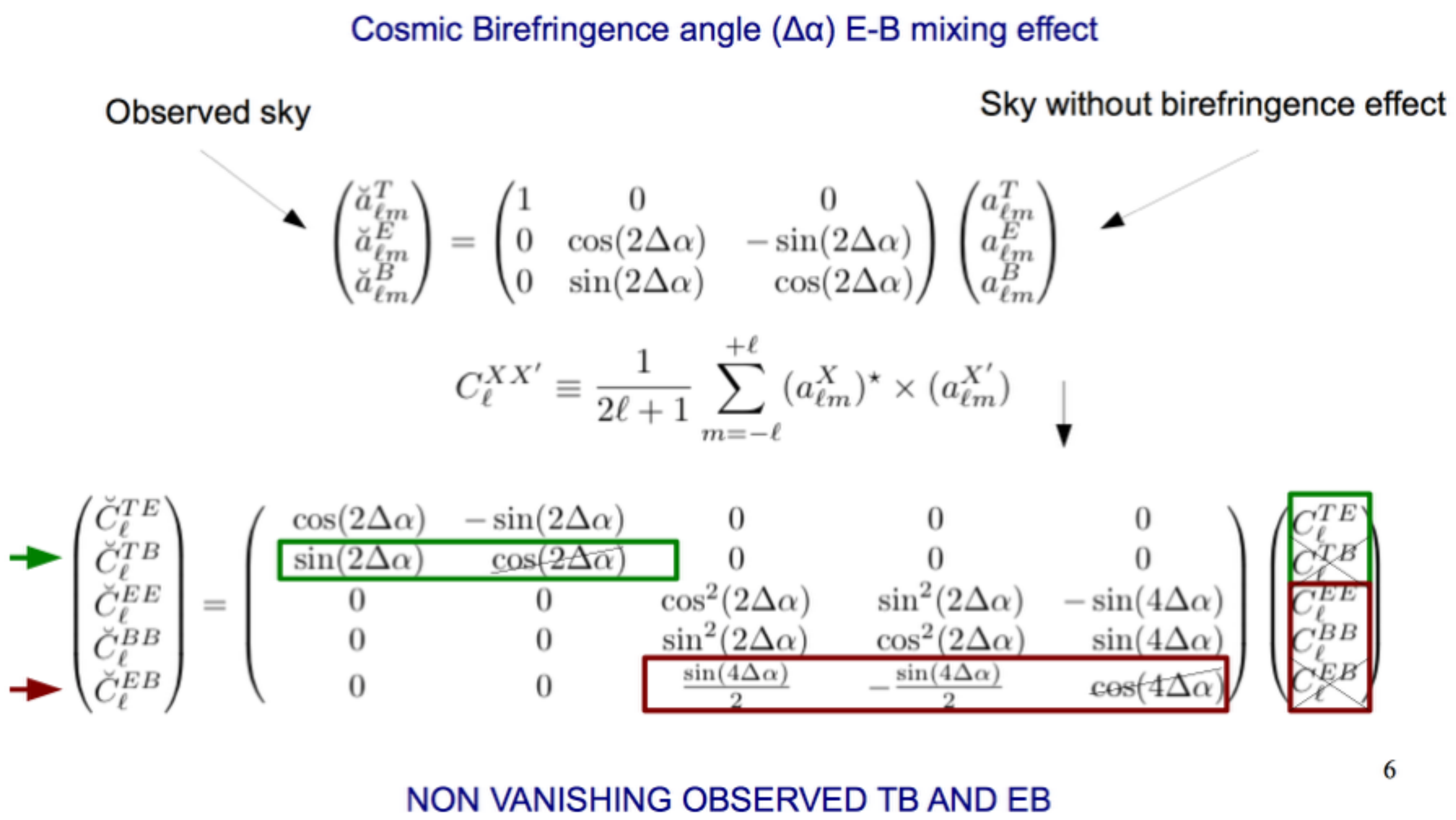


NFW

Soliton

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

Back-up: Comparison with CMB-Based Detection



Cosmic Birefringence angle (Δα) E-B mixing effect

Observed sky

Sky without birefringence effect

$$\begin{pmatrix} \breve{a}^{T}_{\ell m} \\ \breve{a}^{E}_{\ell m} \\ \breve{a}^{B}_{\ell m} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(2\Delta\alpha) & -\sin(2\Delta\alpha) \\ 0 & \sin(2\Delta\alpha) & \cos(2\Delta\alpha) \end{pmatrix} \begin{pmatrix} a^{T}_{\ell m} \\ a^{E}_{\ell m} \\ a^{B}_{\ell m} \end{pmatrix}$$

$$C_\ell^{XX'} \equiv \frac{1}{2\ell+1} \sum_{m=-\ell}^{+\ell} (a^{X}_{\ell m})^\star \times (a^{X'}_{\ell m})$$

$$\begin{pmatrix} \breve{C}_\ell^{TE} \\ \breve{C}_\ell^{TB} \\ \breve{C}_\ell^{EE} \\ \breve{C}_\ell^{BB} \\ \breve{C}_\ell^{EB} \end{pmatrix} = \begin{pmatrix} \cos(2\Delta\alpha) & -\sin(2\Delta\alpha) & 0 & 0 & 0 \\ \sin(2\Delta\alpha) & \cancel{\cos(2\Delta\alpha)} & 0 & 0 & 0 \\ 0 & 0 & \cos^2(2\Delta\alpha) & \sin^2(2\Delta\alpha) & -\sin(4\Delta\alpha) \\ 0 & 0 & \sin^2(2\Delta\alpha) & \cos^2(2\Delta\alpha) & \sin(4\Delta\alpha) \\ 0 & 0 & \frac{\sin(4\Delta\alpha)}{2} & -\frac{\sin(4\Delta\alpha)}{2} & \cancel{\cos(4\Delta\alpha)} \end{pmatrix} \begin{pmatrix} C_\ell^{TE} \\ \cancel{C_\ell^{TB}} \\ C_\ell^{EE} \\ C_\ell^{BB} \\ \cancel{C_\ell^{EB}} \end{pmatrix}$$

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NON VANISHING OBSERVED TB AND EB

[G. Roudier, talk in 2012]