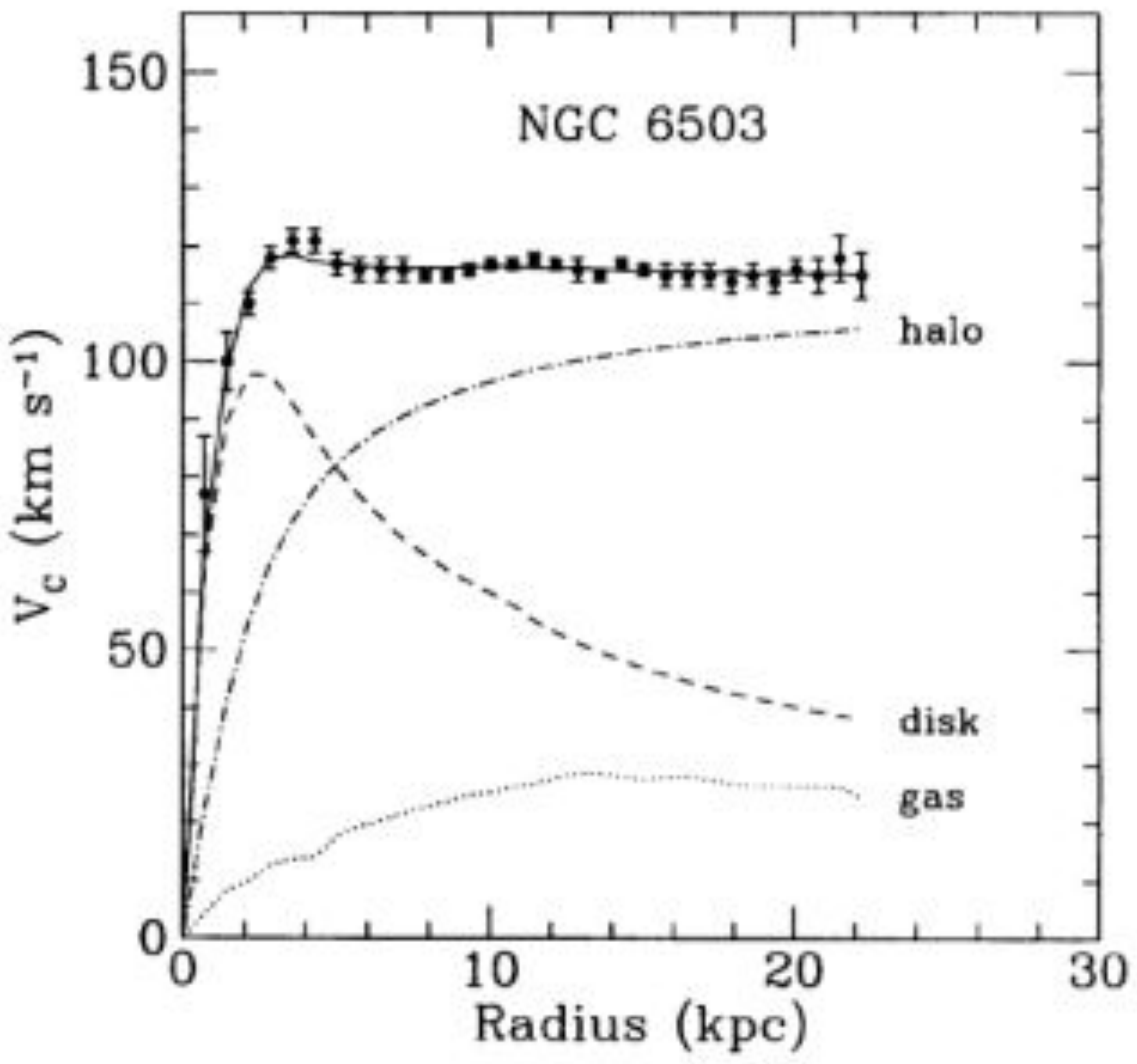
Searching for ultralight Axion/ALP dark matter signal in Parkes PTA polarization data

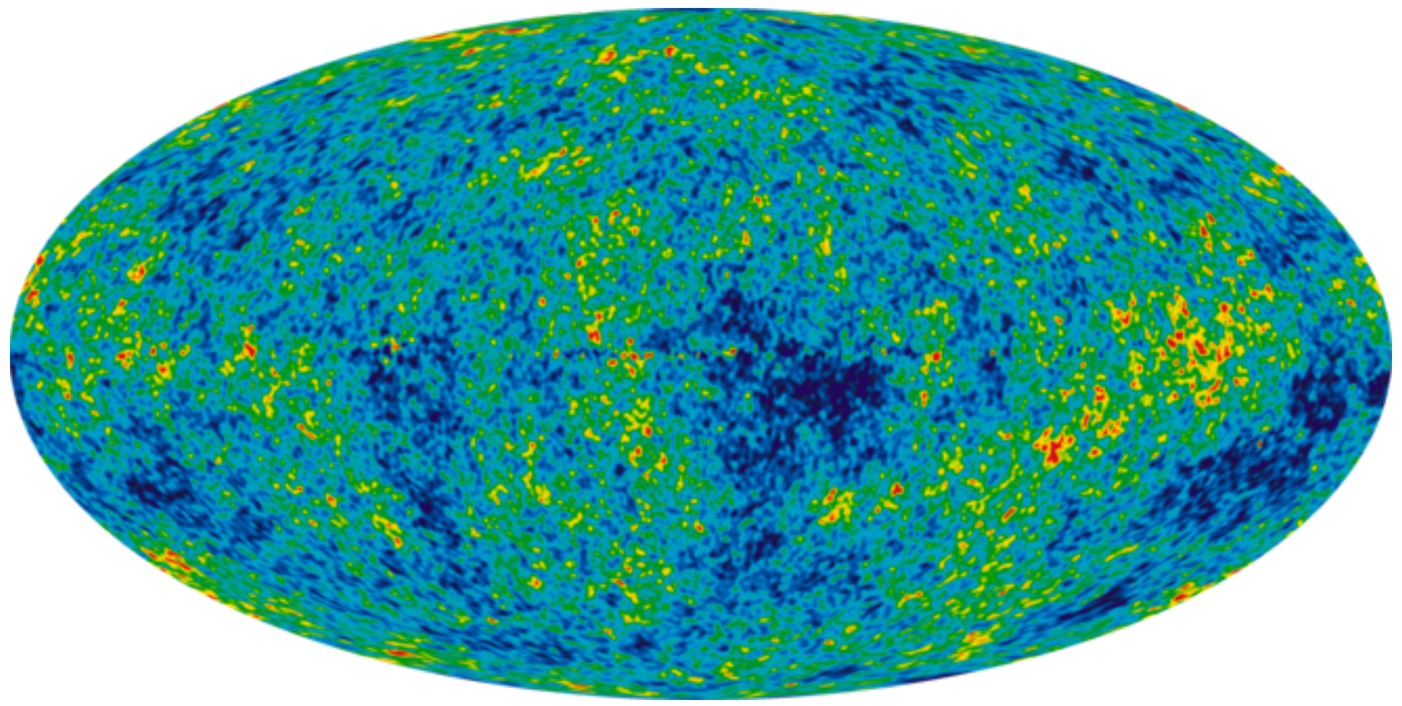
Tao Liu, Hoang Nhan Luu, Jing Ren, Shi Dai, Jing Shu, XX,Yue Zhao and PPTA (in preparation)

Speaker: Xiao Xue
University of Hamburg & DESY, Hamburg, Germany. Sponsored by Quantum Universe.
27.09.2023, Axion++ 2023, LAPTh, Annecy, France

What is the nature of dark matter?

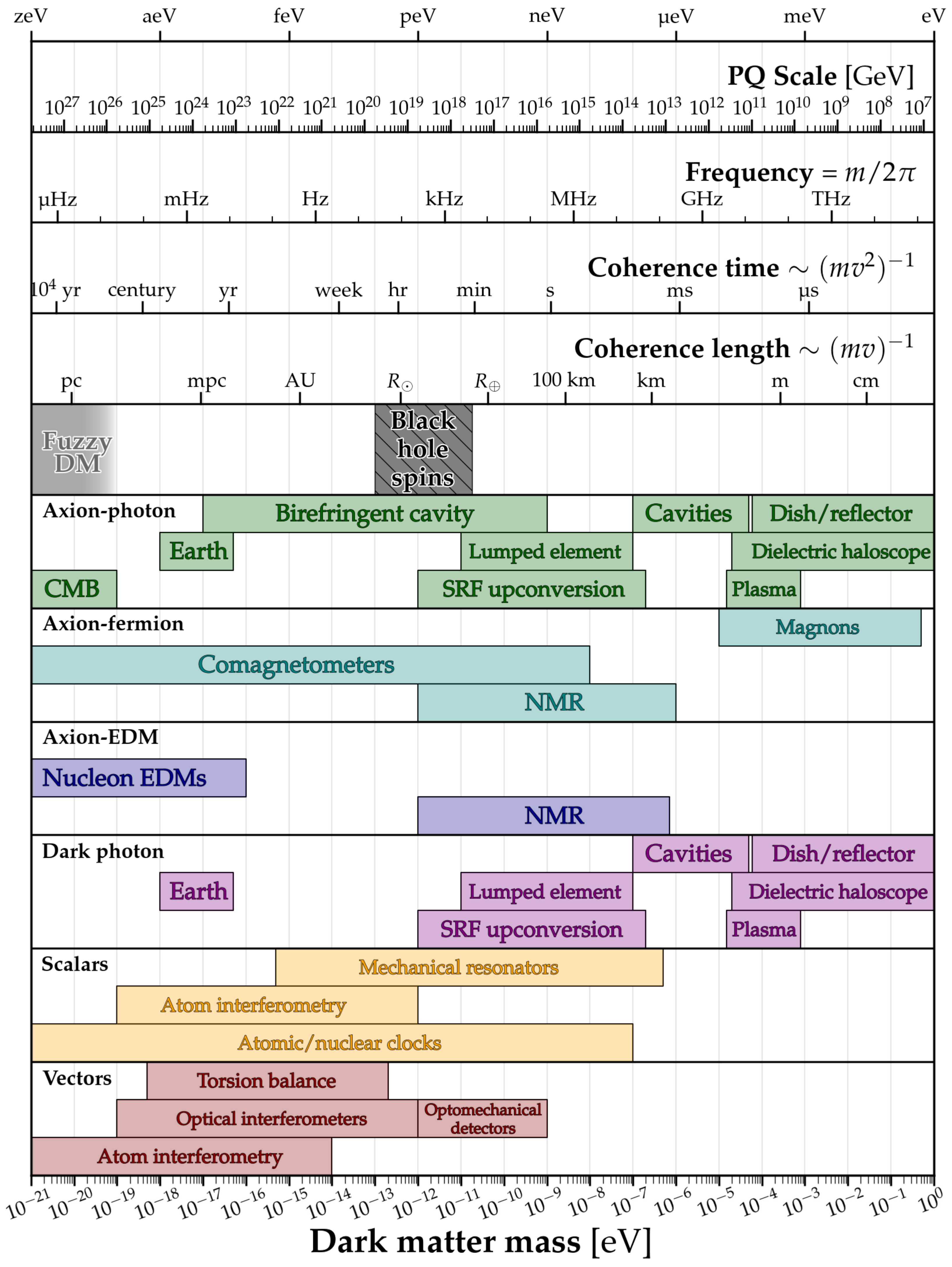


An example of the galaxy rotation curve
Begeman, Broeils and Sanders, 1991.
Originally by Rubin, Ford and Thonnard 1980.



CMB temperature map, Planck 2018

The question:
What is the nature of dark matter?



Credit: AxionLimits, Ciaran O'Hare

Ultralight axion/ALP dark matter

Ultralight Dark Matter

$m \ll 1\mathrm{eV}$

Bosonic,

large occupation number,

stochastic,

soliton core,

substructures,

long coherent time.

Periodic Signal

$f = \frac{m}{10^{-21.88}\mathrm{eV}}\mathrm{yr}^{-1}$

Axion/ALP

$V = m^2 f_a^2 \left(1 - \cos(a/f_a)\right)$

Self interaction

$\mathscr{L} \supset g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$

&with fermion

Coupling with SM particles,

loop level couplings

Constraints:

Lyman alpha forest

Ultralight axion/ALP dark matter

Axion/ALP photon coupling:

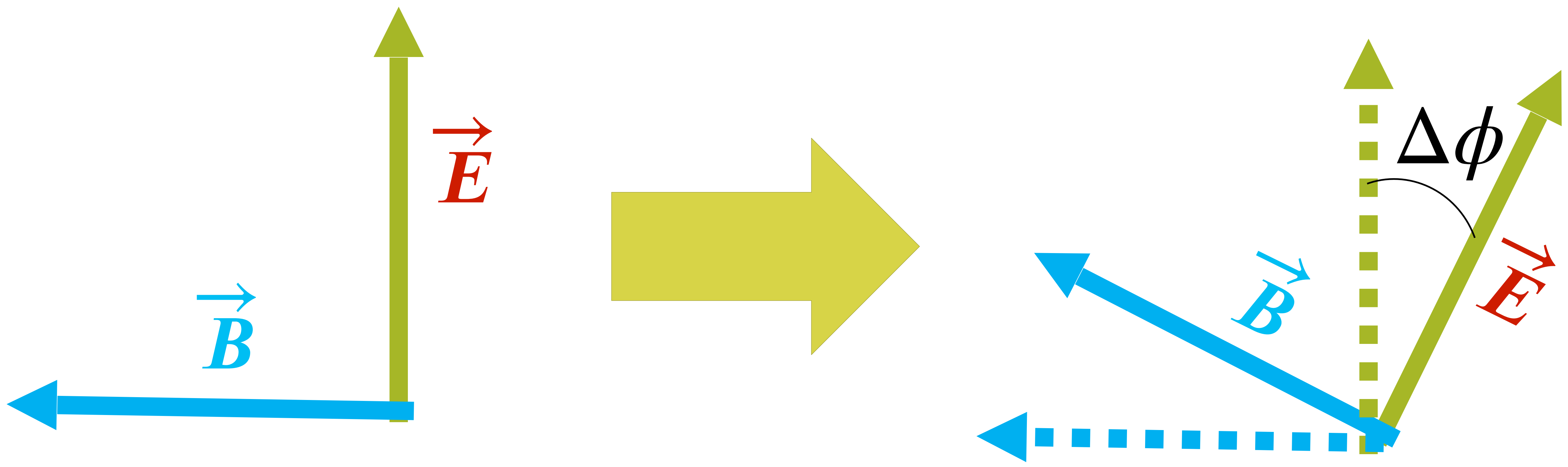
$$\mathscr{L} \supset 2 g_{a\gamma} a \vec{E} \cdot \vec{B}$$

Ultralight Axion/ALP background

Axion birefringence signal

$$\Delta\phi = g_{a\gamma}(a_f - a_i)$$

(Topological effect)



Linearly Polarized Pulsar Light (dark matter)

- Liu, Smoot, Zhao, 19’
- Caputo, Sberna, Frias, Blas, Pani, 19’
- Liu, Lou, Ren, 21’
- Castillo, Martin-Camalich, Terol-Calvo, Blas, Caputo, Santos, Sberna, Peel, Rubiño-Martín 22’
- **Our work (in progress)**

EHT observation of black holes (superradiant cloud)

- Chen, Shu, Xue, Yuan, Zhao, 19’
- Chen, Liu, Lu, Mizuno, Shu, Xue, Yuan, Zhao, 21’
- Chen, Li, Mizuno, Shu, Xue, Yuan, Zhao, Zhou, 22’

Cosmic Birefringence (See Silvia’s talk)

Polarized pulsar light

In radio astronomy the EM observation is described by the Stokes Parameters $\{I, Q, U, V\}$, with

$$Q^2 + U^2 + V^2 = I^2.$$

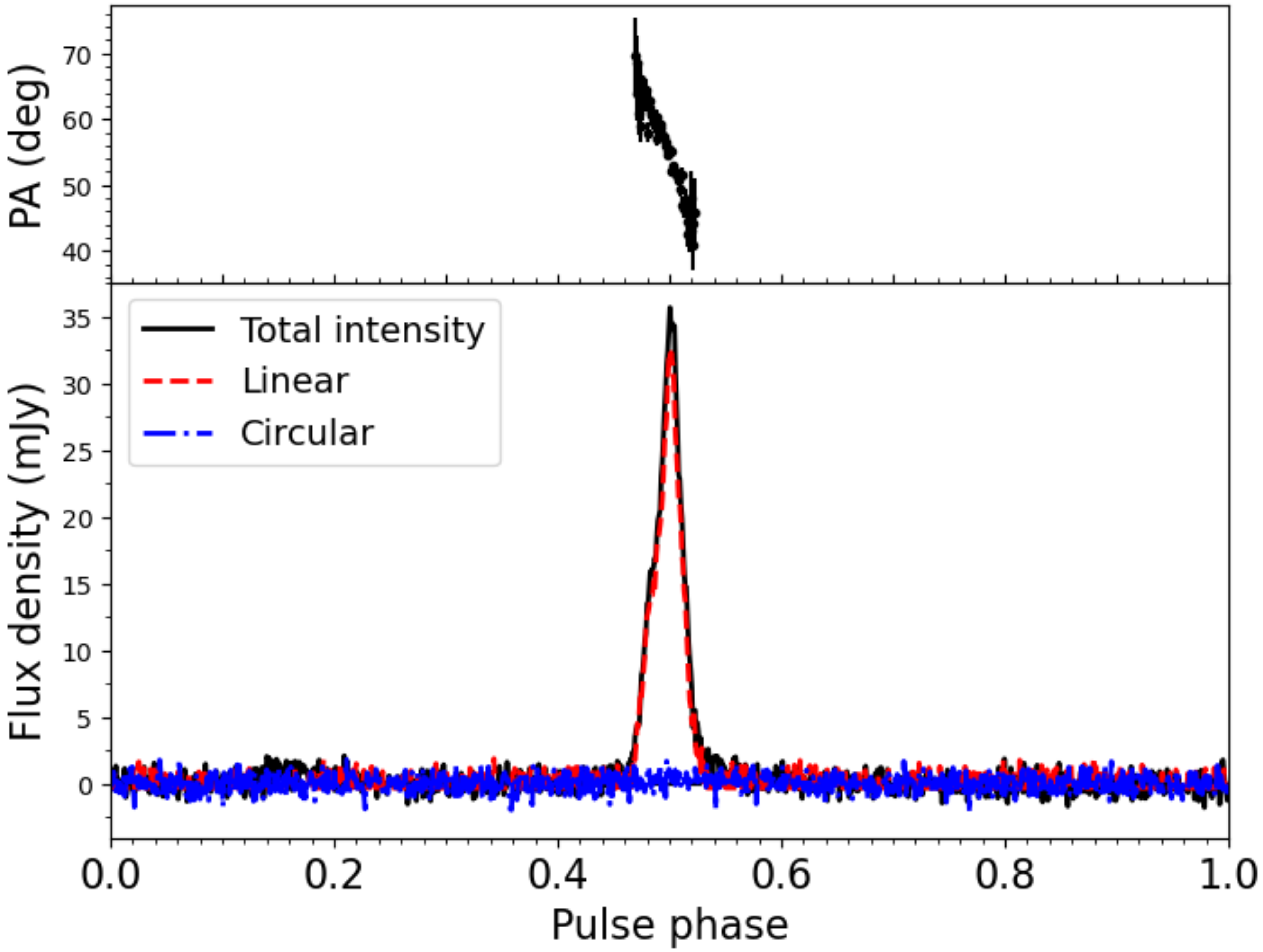
intensity of the linear polarized light.

$$L = \sqrt{Q^2 + U^2}$$

The Polarization Angle (PA).

$$PA \equiv \frac{1}{2} \arctan \frac{U}{Q}$$

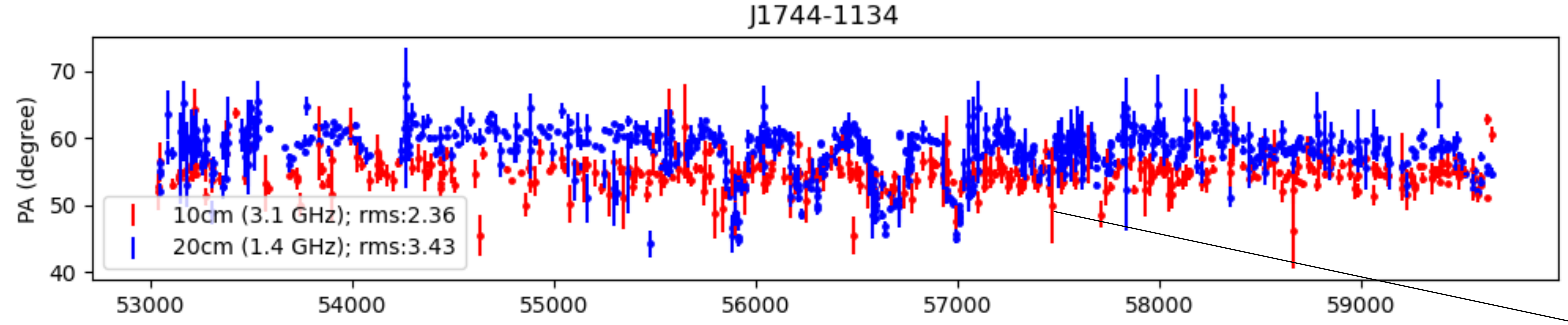
$(2PA = \phi)$

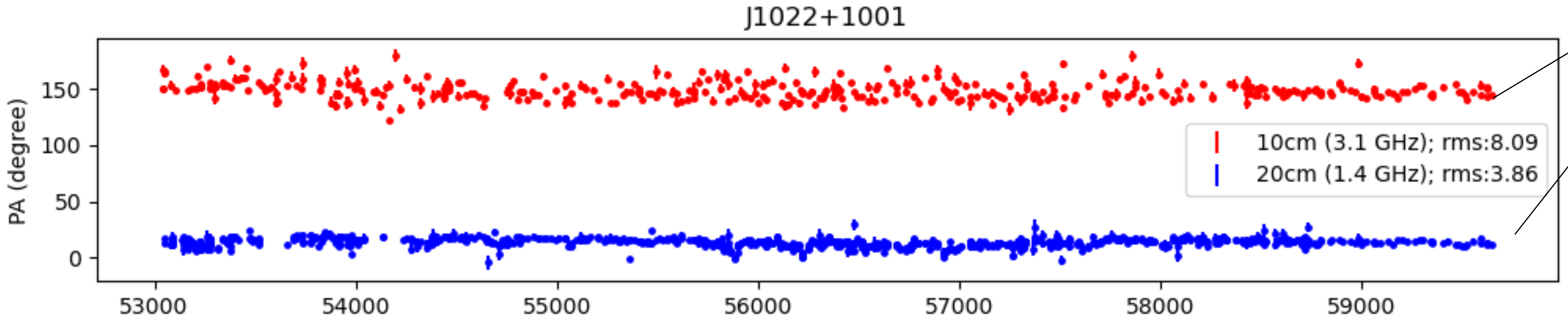


An example of one pulsar profile
Pulsar J1744-1134, 2019-09-17, Ultra Wide band, 10cm sub-band
Provided by Parkes Pulsar Timing Array

Polarization data from millisecond pulsars

Choose the peak of the linear flux intensity, find it's PA then apply a 5-σ stationary cut.





Ionosphere
Faraday rotation

$$\Delta\phi \propto \frac{\int dl(\vec{B}\cdot\vec{l})n_e}{\nu^2}$$

Statistics (4 pulsars):

1954 observations for 3.1GHz band

4338 observations for 1.4GHz band

$$T_{\rm obs} \simeq 18 \rm years$$

Ultralight DM as stochastic background

The axion/ALP DM field follows multivariate normal(Gaussian) distribution
(Foster, Kahn, Nguyen, Rodd, Safdi, 20' "Dark Matter Interferometry")

$$P\left(a(t_1,\vec{x}_1), a(t_2,\vec{x}_2), \ldots, a(t_n,\vec{x}_n)\right) = \mathcal{N}(\vec{0}, \boldsymbol{C}')$$

The axion/ALP DM induced PA change also follows normal distribution
(**Liu, Lou, Ren, "Pulsar polarization arrays" 2111.10615**)

$$P\left(\Delta\mathrm{PA}_1, \Delta\mathrm{PA}_2, \ldots, \Delta\mathrm{PA}_n\right) = \mathcal{N}(\vec{0}, \boldsymbol{C})$$

$$C_{p,n;q,m} = \frac{g_{a\gamma}^2}{m^2}[\rho_e \cos(m(t_{p,n} - t_{q,m}))$$
$$+\sqrt{\rho_p\rho_q}\,\mathrm{sinc}(y_{pq})\cos(m(t_{p,n} - t_{q,m} - (L_p - L_q)))$$
$$-\sqrt{\rho_e\rho_p}\,\mathrm{sinc}(y_{ep})\cos(m(t_{p,n} - t_{q,m} - L_p))$$
$$-\sqrt{\rho_e\rho_q}\,\mathrm{sinc}(y_{eq})\cos(m(t_{p,n} - t_{q,m} + L_q))]$$

Pulsar distance from earth

$$y_{ep} = |\vec{x}_e - \vec{x}_p|/l_c$$

Very similar to Pulsar Timing Arrays for SGWB!

Statistical framework

Likelihood function:

$$\ln L = -\frac{1}{2}(\mathbf{PA} - \mathbf{PA}_{\rm det})^T \boldsymbol{C}^{-1}(\mathbf{PA} - \mathbf{PA}_{\rm det}) - \frac{1}{2}\ln|2\pi \boldsymbol{C}|$$

Parameterize $\boldsymbol{C}$ and $\mathbf{PA}_{\rm det}$:

$$\boldsymbol{C} = \boldsymbol{C}\left(m, \frac{g_{a\gamma}\sqrt{\rho_e}}{m}, L_p^*, \sigma_p^{\rm add}, A_p^{\rm red}(m)\right); \quad \mathbf{PA}_{\rm det} = \mathbf{PA}_{\rm intrinsic} + \Delta\mathbf{PA}_{\rm iono}$$

$L_p^* = L_p/L_p^{\rm est}$: fractional pulsar distance, **prior** taken from ATNF pulsar catalogue.

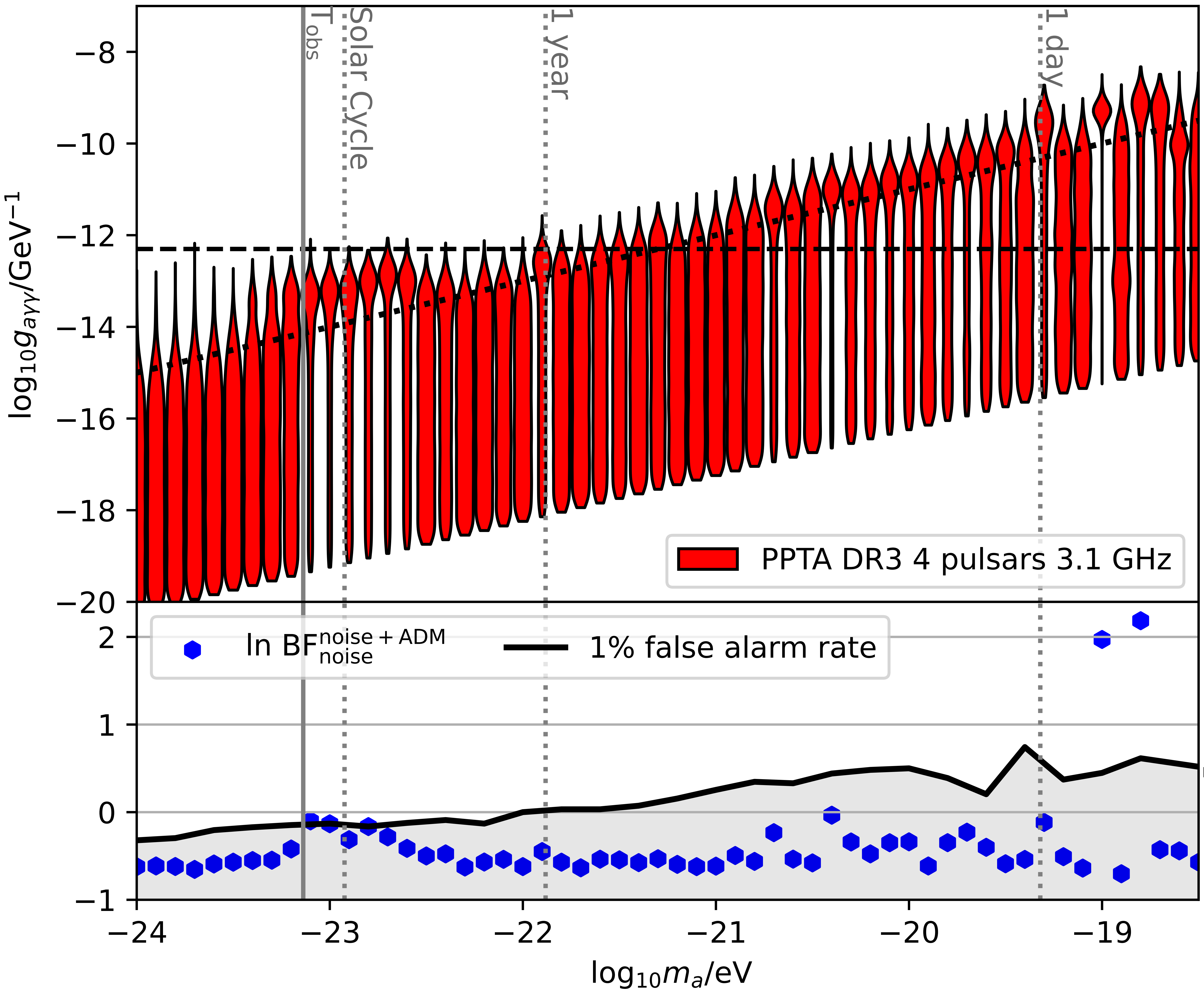
$\sigma_p^{\rm add}$: Additional white noise.

$A_p^{\rm red}(m)$: Additional red noise.

$\mathbf{PA}_{\rm intrinsic}$: Intrinsic PA.

$\Delta\mathbf{PA}_{\rm iono}$: ionosphere Faraday rotation.

Preliminary Results (4 pulsars)



Mass varies within each bin

Excluded by other experiments

Generate data with only white noise 1000 times, derive **BF threshold** that corresponds to **1% false alarm rate** for each m_a.

Undergoing tests

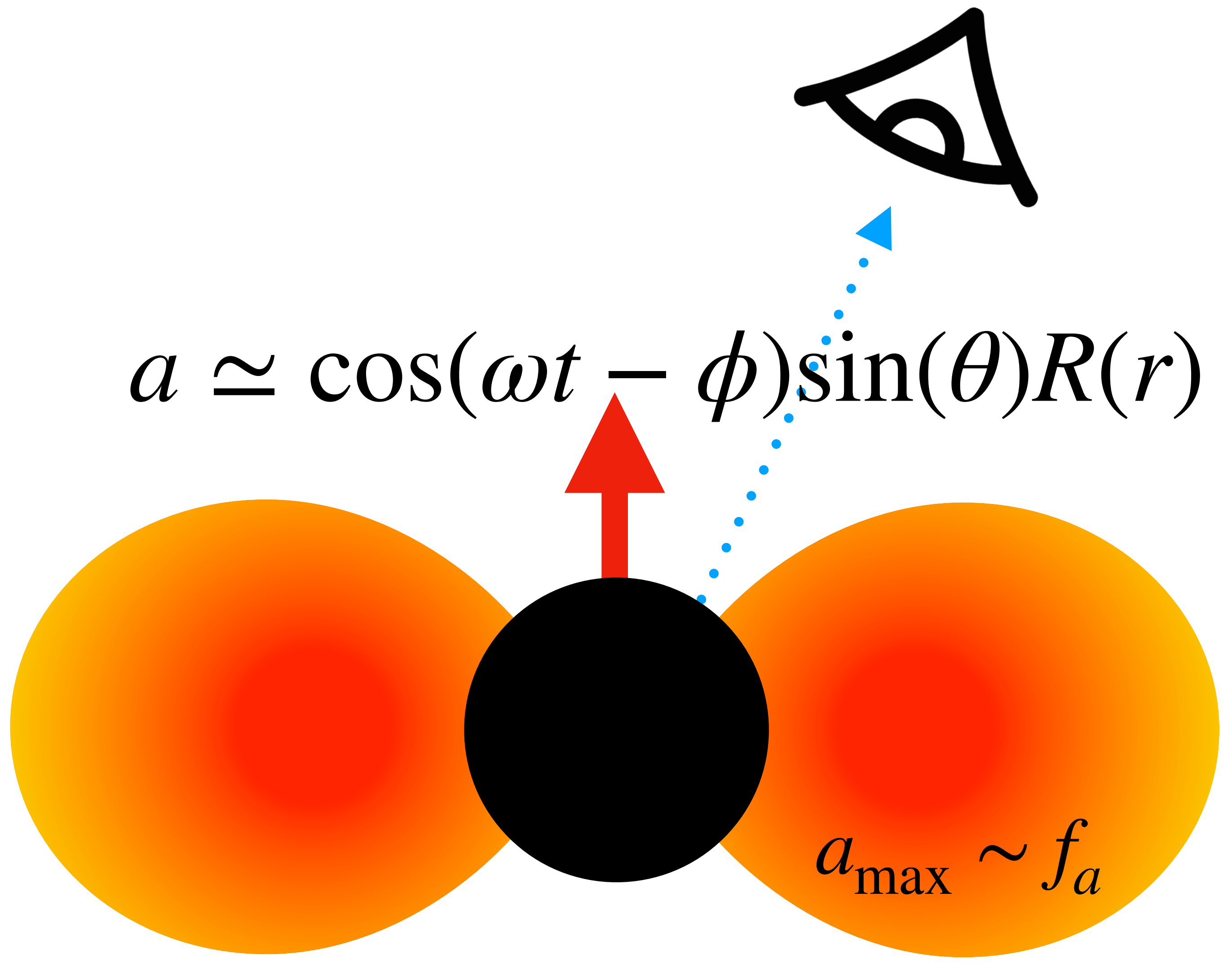
1. More pulsars: From 4 pulsars to all 32 pulsars. Two frequencies: from 3.1GHz to 1.4GHz & 3.1GHz.

2. **Cross correlation** analysis (when we have more pulsars!)

3. Generate ionosphere Faraday rotation to see if it has generation with the axion/ALP DM.

4. Ionosphere corrections.
   - High frequency only analyses + multi-frequency cross examination.
   - Faraday rotation subtraction from **Ultra-wide-band data**.
   - Independent ionosphere subtraction with IONFR.

EHT observation of black holes



[Yoshino et al 12', Baryakht et al 20']

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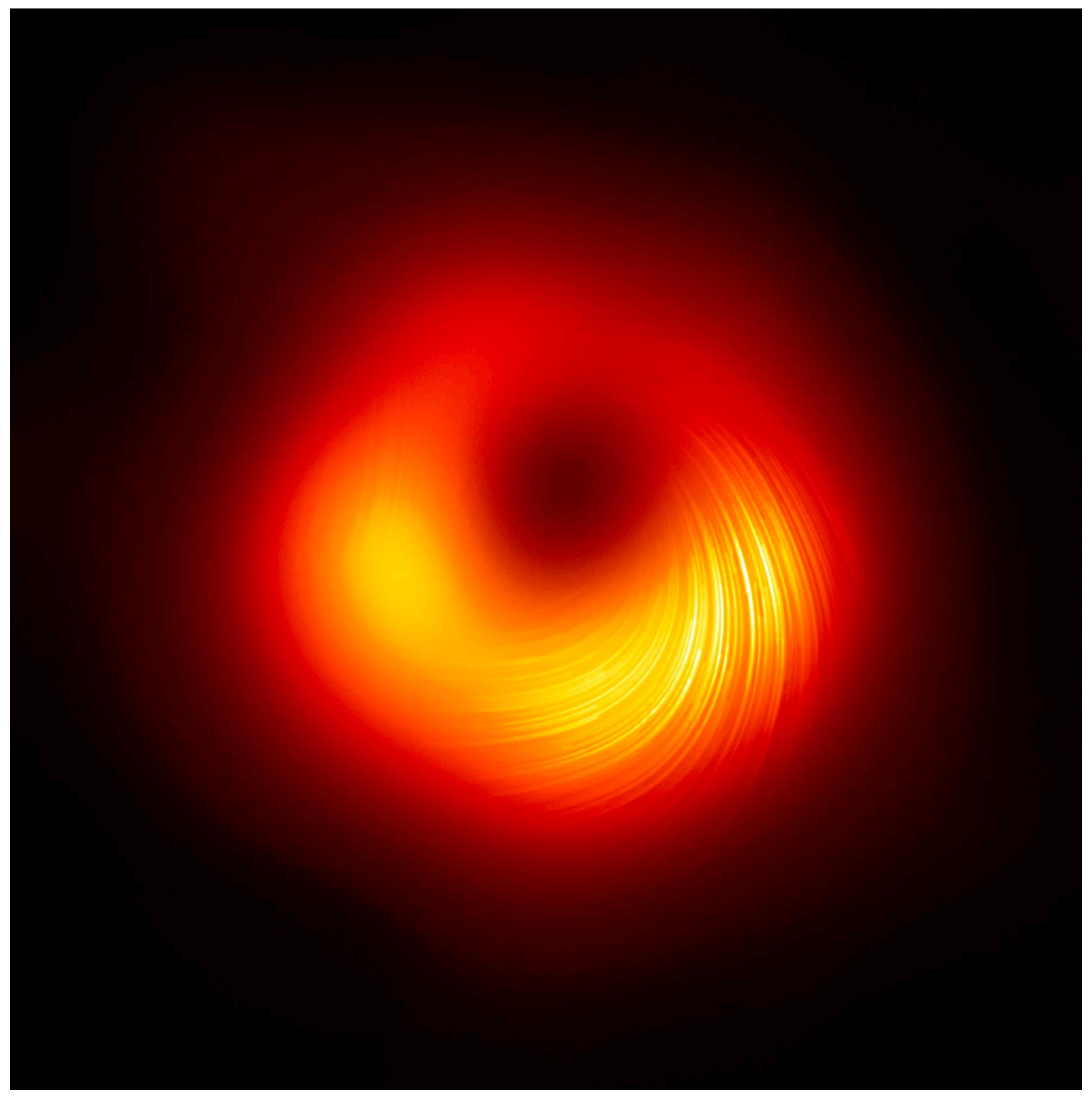

EHT Polarization data of M87* 2021

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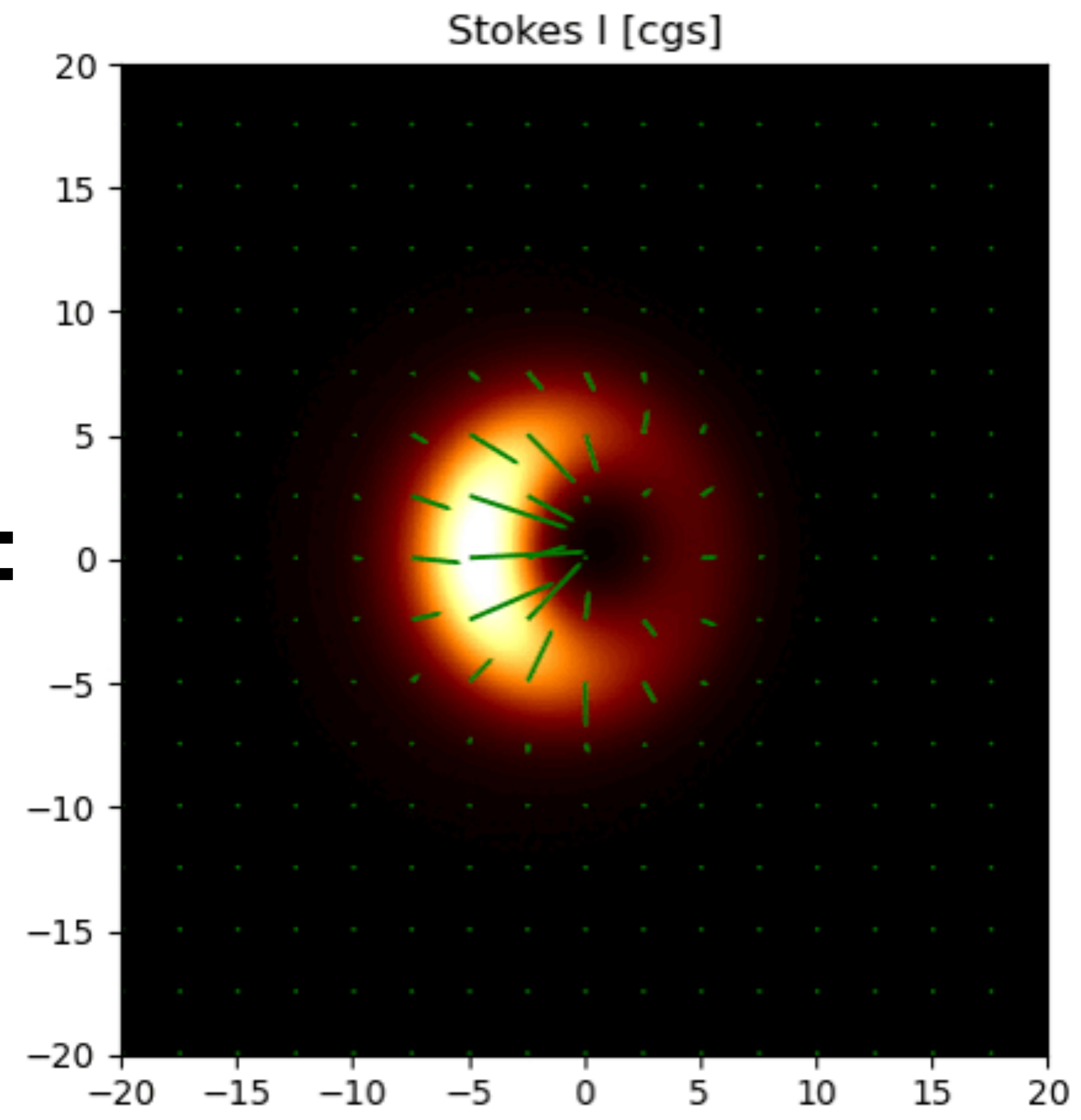


✓Curved space effect

✓Extended emission washout effect

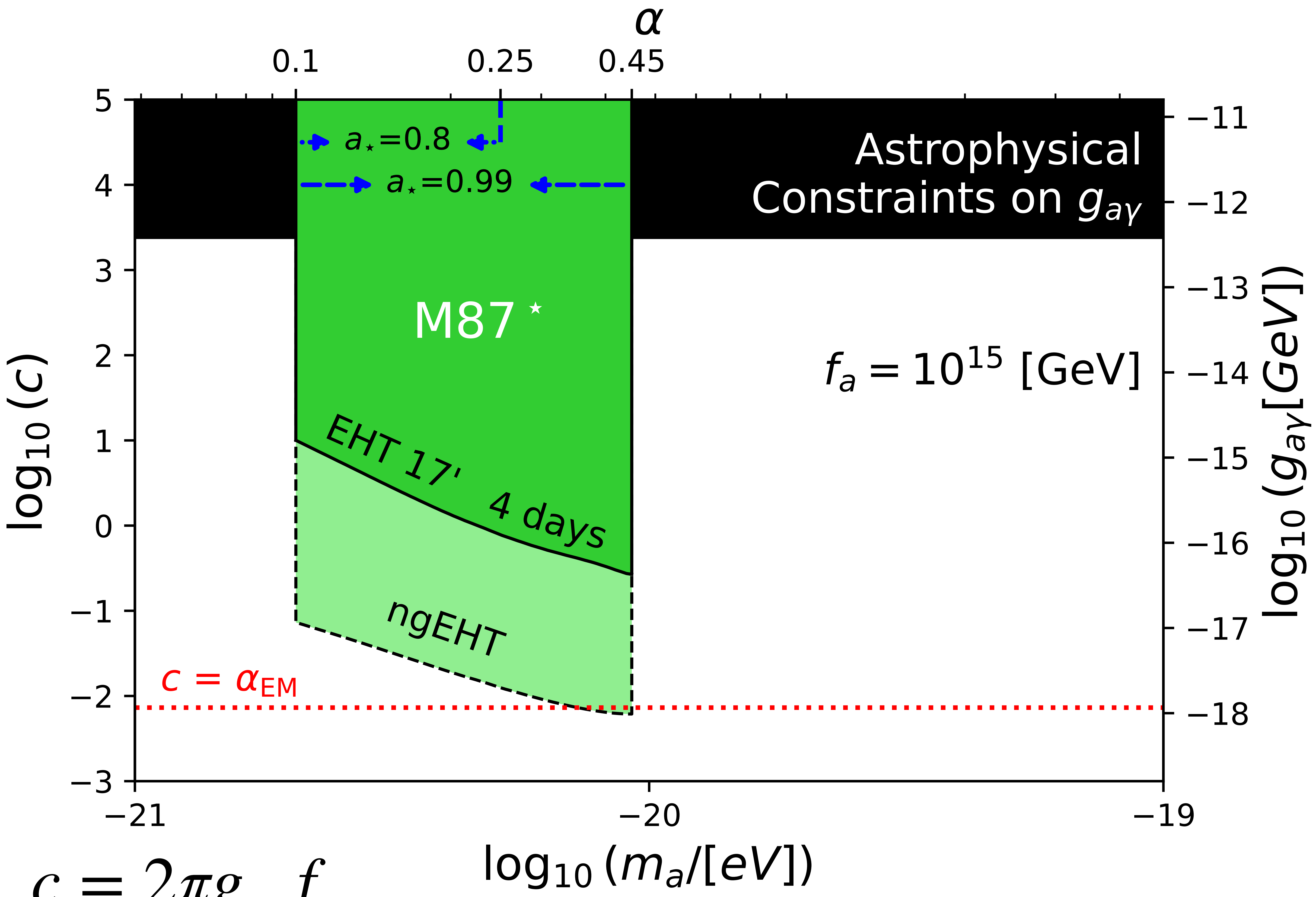
✓Plasma effect

✓Analytic accretion flow *(Yuan, Quataert, Narayan 03'; Pu & Broderick. APJ 18')*

✓**Covariant Radiative transfer** tool IPOLE *(Mościbrodzka & Gammie, 18')*

$$\Delta \mathrm{PA} = A(\rho, \varphi)\sin\left[\omega t + \varphi + \delta(\rho, \varphi)\right]$$

EHT observation of black holes



Chen, Shu, Xue, Yuan and Zhao [1905.02213]

Chen, Liu, Lu, Mizuno, Shu, Xue, Yuan and Zhao [2105.04572]

Chen, Li, Mizuno, Shu, Xue, Yuan, Zhao and Zhou [2208.05724]

$$c = 2\pi g_{a\gamma} f_a$$

Thank you for your attention!