Searching for axionlike particles with radio observations

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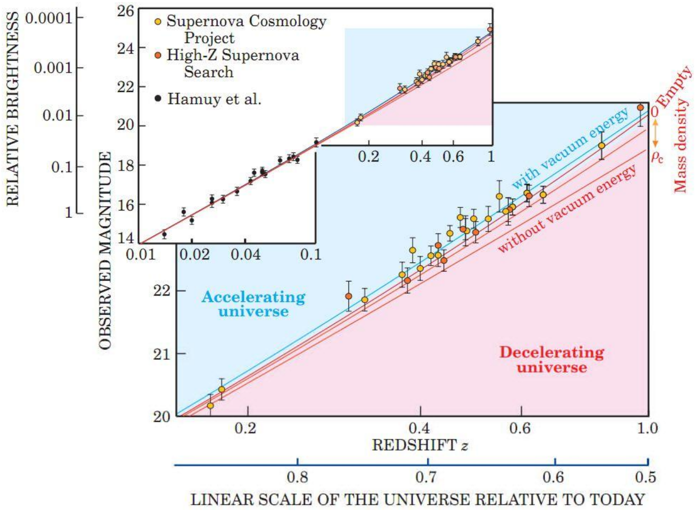
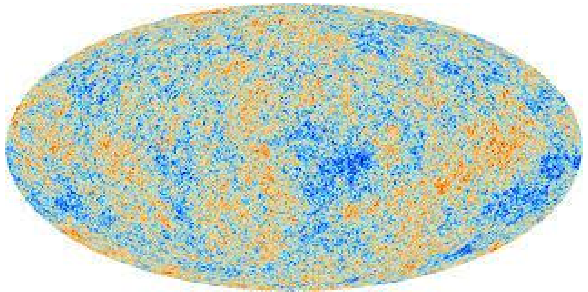
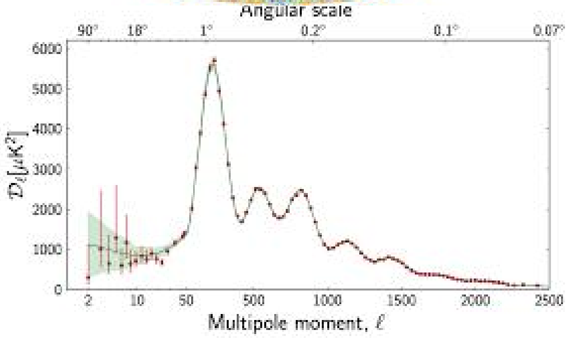
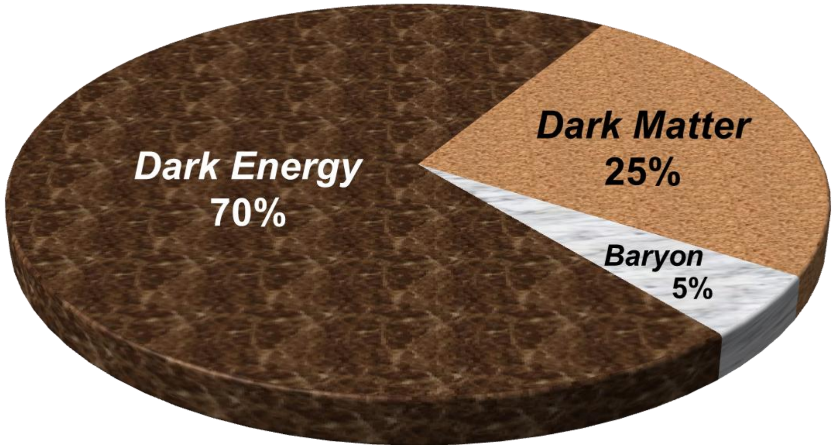
First International Conference on Axion Physics and Experiment (Axion 2022), 2022-11-23

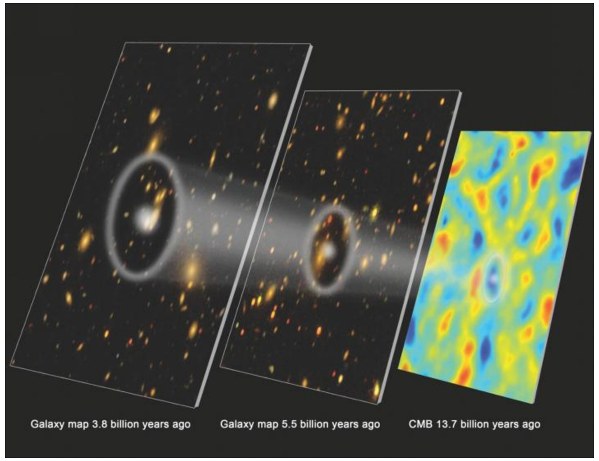
Composition of the Universe

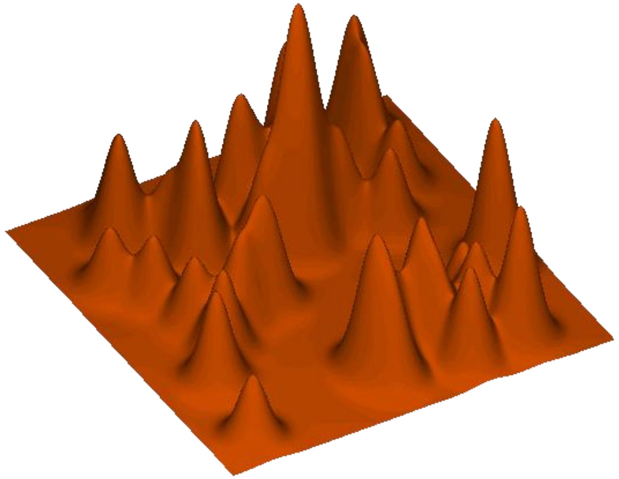








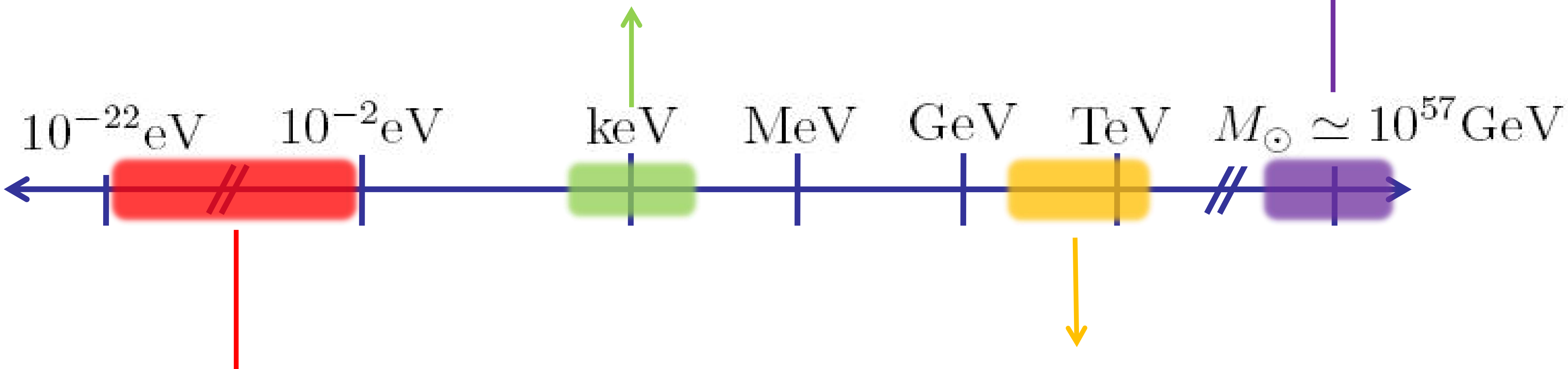




Candidates of dark matter

Sterile neutrinos
Neutrino oscillation
X-ray astronomy

Black holes (MACHOs):
Astrophysical detection



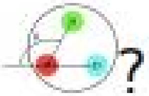
Very light dark matter
Axion, ALP, dark photon …

WIMPs:
direct detection,
indirect detection,
collider detection

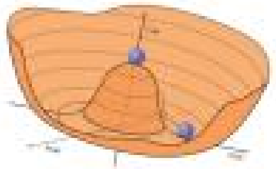
Axion: motivation and detection

- Hypothetical pseudoscalar initially motivated by strong CP problem: **Neutron electric dipole** $|\bar{\theta}|10^{-16}$ **e.cm is smaller than** 10^{-26} **e.cm.**

$$\bar{\theta} = \theta_{\mathrm{QCD}} + \arg\,\det M_u M_d, \qquad \text{Fine tuning!}$$

Why is $\bar{\theta}$ so small? Why  instead of ?
Solution: introducing an **dynamical** field with effective potential

$$V \sim -m_\Phi^2 f_\Phi^2 \cos(\bar{\theta} + \frac{\Phi}{f_\Phi}).$$

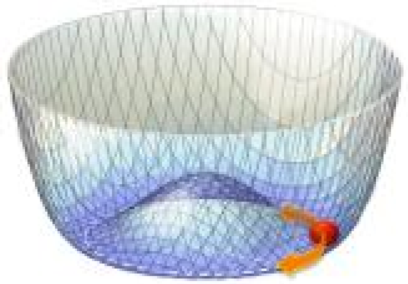


- Cold dark matter candidate behaving like **coherent wave**:

$$\Phi(x^\mu) \simeq \Phi_0(\mathbf{x}) \cos\omega t; \qquad \Phi_0 \simeq \frac{\sqrt{\rho}}{m_\Phi}; \qquad \omega \simeq m_\Phi.$$

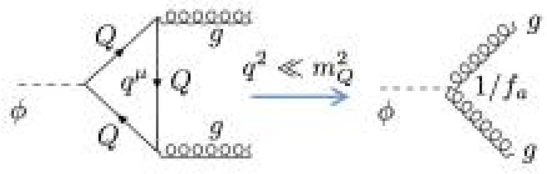
From Y. Chen

Axion: motivation and detection



- **Axion Fermion coupling**: $\partial_\mu \Phi \bar{\psi} \gamma^\mu \gamma_5 \psi / f_\Phi$,
  non-linearization of a chiral global symmetry $\sim \partial_\mu \Phi J_5^\mu / f_\Phi$.
  Stellar cooling, DM wind/gradient.

- **Axion Gluon coupling**: $\mathcal{C}_g \Phi \mathrm{Tr}\, G_{\mu\nu} \tilde{G}^{\mu\nu} / f_\Phi$,
  generated from anomaly/triangle loop diagram.
  Oscillating EDM.



- **Axion Photon coupling**: $\mathcal{C}_\gamma \Phi F_{\mu\nu} \tilde{F}^{\mu\nu} / f_\Phi$,
  from mixing with neutral π_0.
  Photon conversion to axion, inverse Primakoff, birefringence.

From Y. Chen

Content of this talk

- **Constraining axion (ALP) -photon coupling with polarimetric radio observations**
  - Yuan G.-W. et al., 2021, JCAP, 03, 018 (arXiv:2008.13662)
  - Chen Y. et al., 2020, PRL, 124, 061102 (arXiv:1905.02213)
  - Chen Y. et al., 2022, Nat. Astron., 6, 592 (arXiv:2105.04572)

- **Search for resonant conversion of photons from axion (ALP) dark matter with MeerKAT observations of a neutron star**
  - Zhou Y.-F. et al., 2022, PRD, 106, 083006 (arXiv:2209.09695)

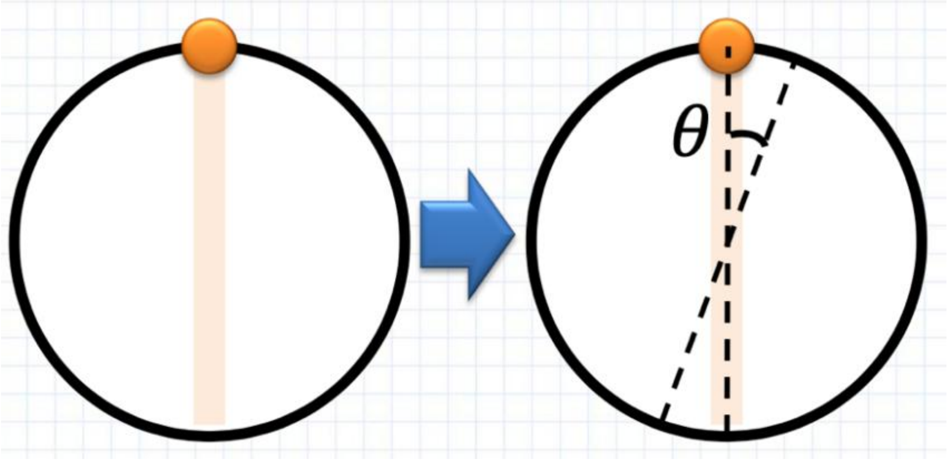
Axion-induced birefrangence

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\nabla^{\mu}a\nabla_{\mu}a - V(a)$$

$$\Box A_{\pm} = \pm 2ig_{a\gamma}[\partial_z a\dot{A}_{\pm} - \dot{a}\partial_z A_{\pm}]$$

$$A_{\pm}(t,z) = A_{\pm}(t',z')\exp\{-i\omega_{\gamma}(t-t') + i\omega_{\gamma}(z-z') \pm ig_{a\gamma}[a(t,z) - a(t',z')]\}.$$

$$\begin{aligned}\Delta\Theta &= g_{a\gamma}\Delta a(t_{\rm obs}, \mathbf{x}_{\rm obs}; t_{\rm emit}, \mathbf{x}_{\rm emit}) \\ &= g_{a\gamma}\int_{\rm emit}^{\rm obs} ds n^{\mu}\partial_{\mu}a \\ &= g_{a\gamma}[a(t_{\rm obs}, \mathbf{x}_{\rm obs}) - a(t_{\rm emit}, \mathbf{x}_{\rm emit})].\end{aligned}$$



- The equation of motion of photons get modified in the axion background, resulting in periodic oscillation of position angle of linearly polarized photons

- A large axion field is important!

Carroll et al., 1990, PRD, 41, 1231

Constraints from pulsar polarization measurements

arXiv:1901.10981

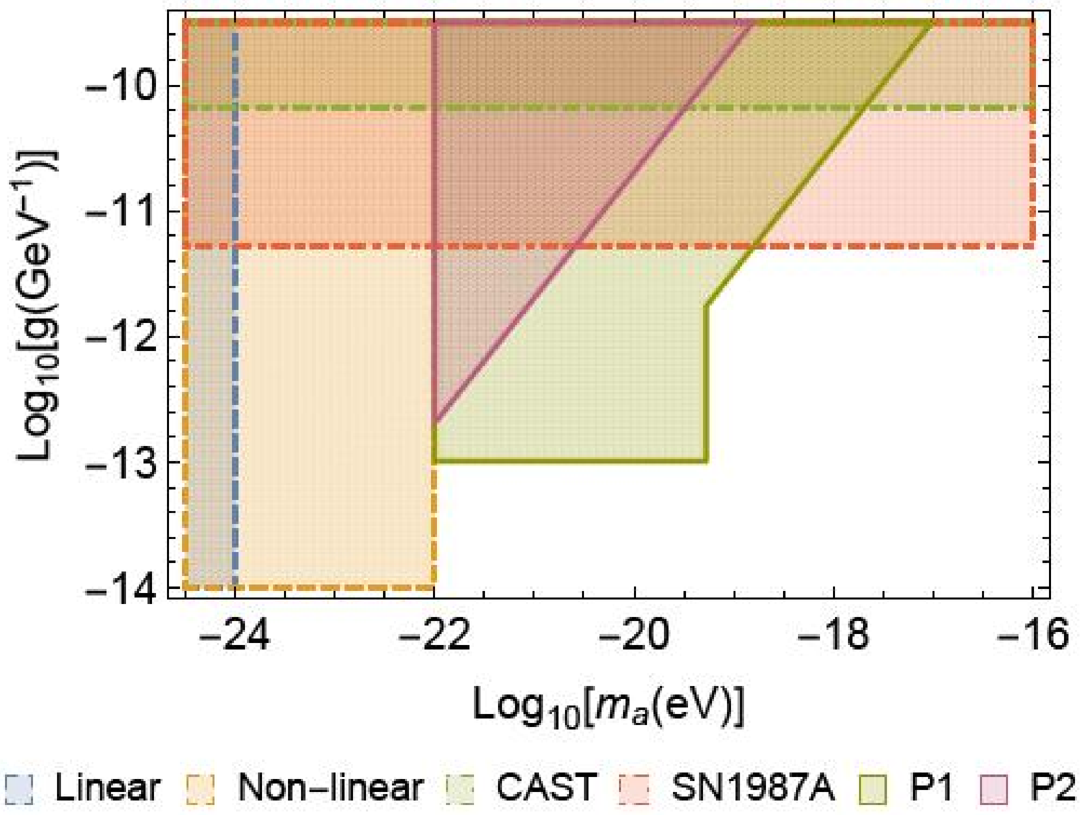
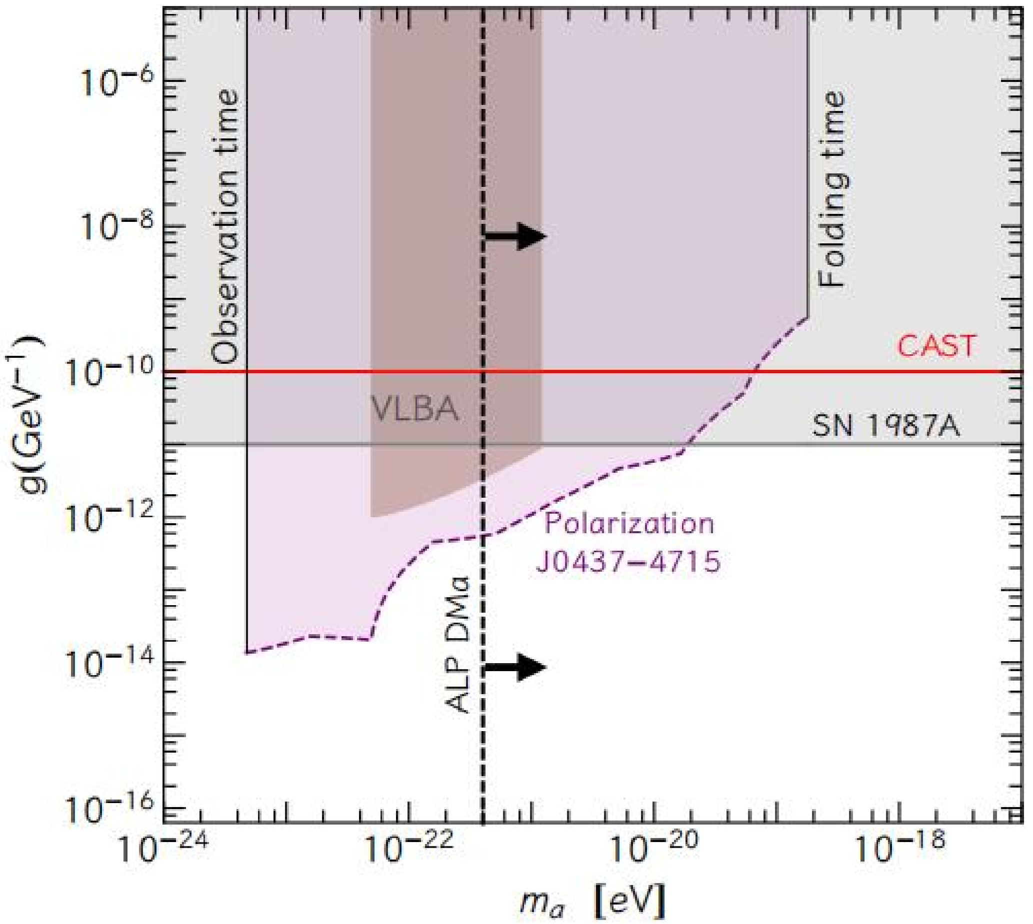


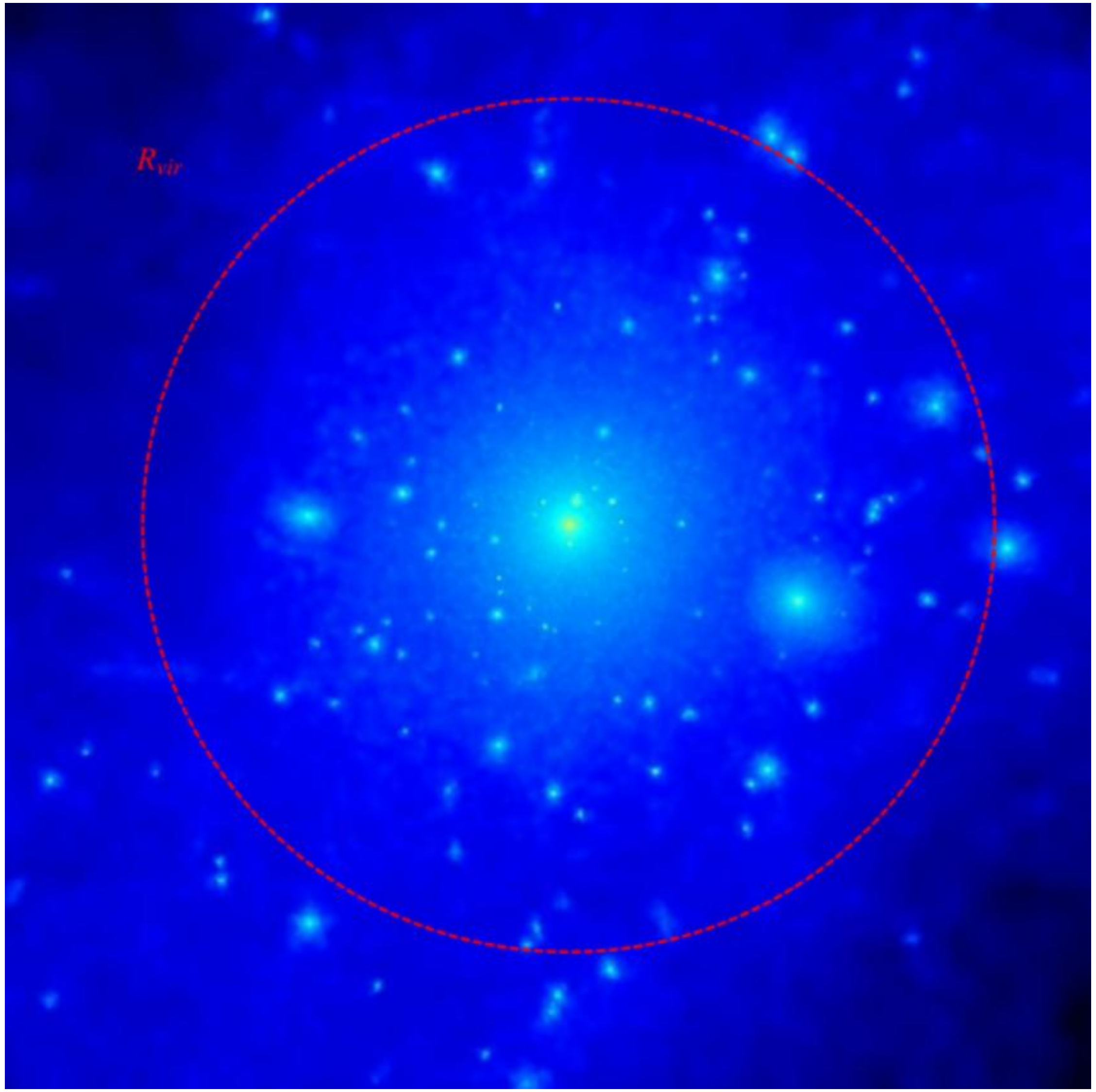
FIG. 1: Projected sensitivities to detect the CAB, using linearly polarized pulsar light as a probe, in the two benchmark scenarios: P_1 and P_2.

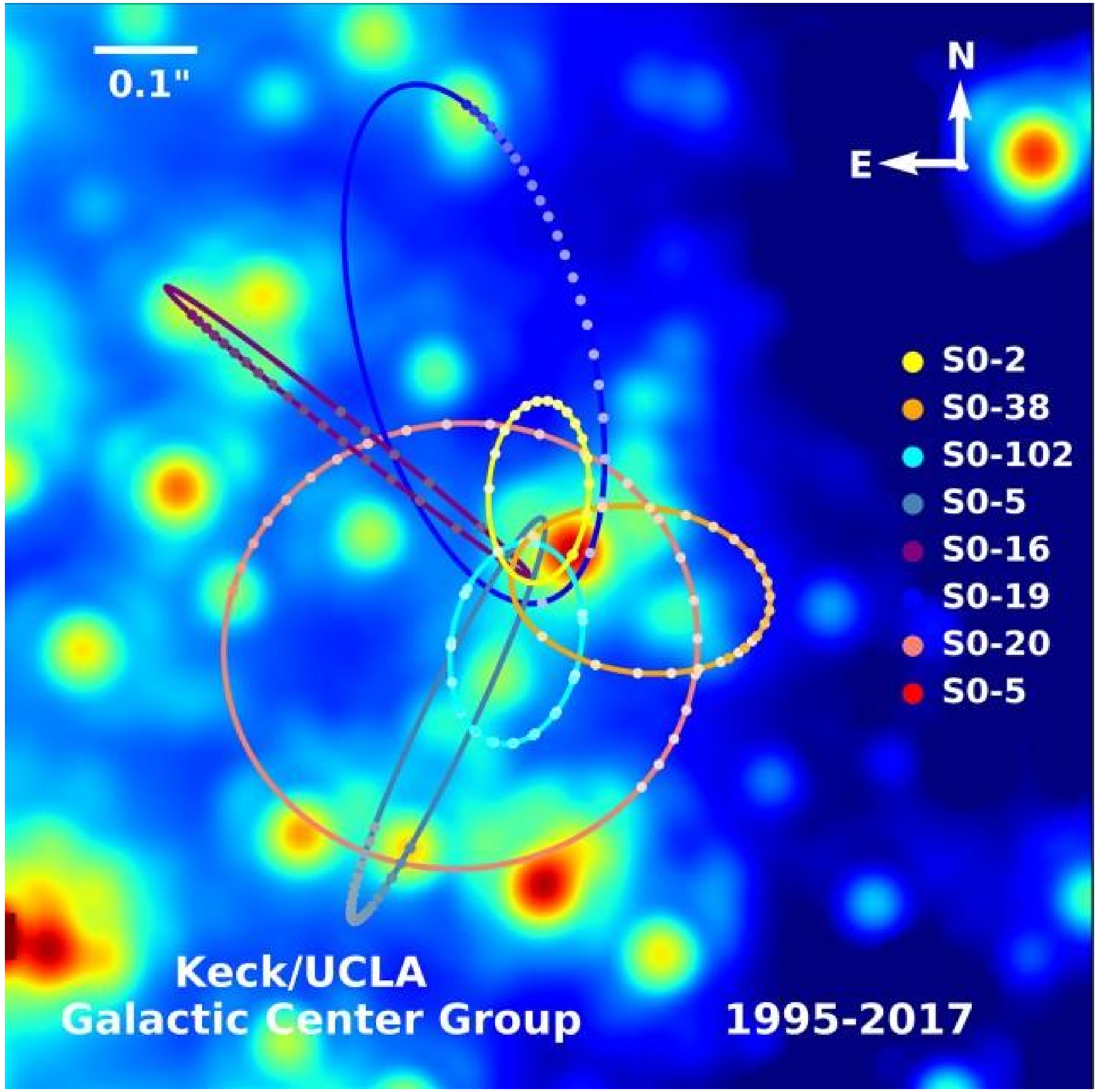
arXiv:1902.02695



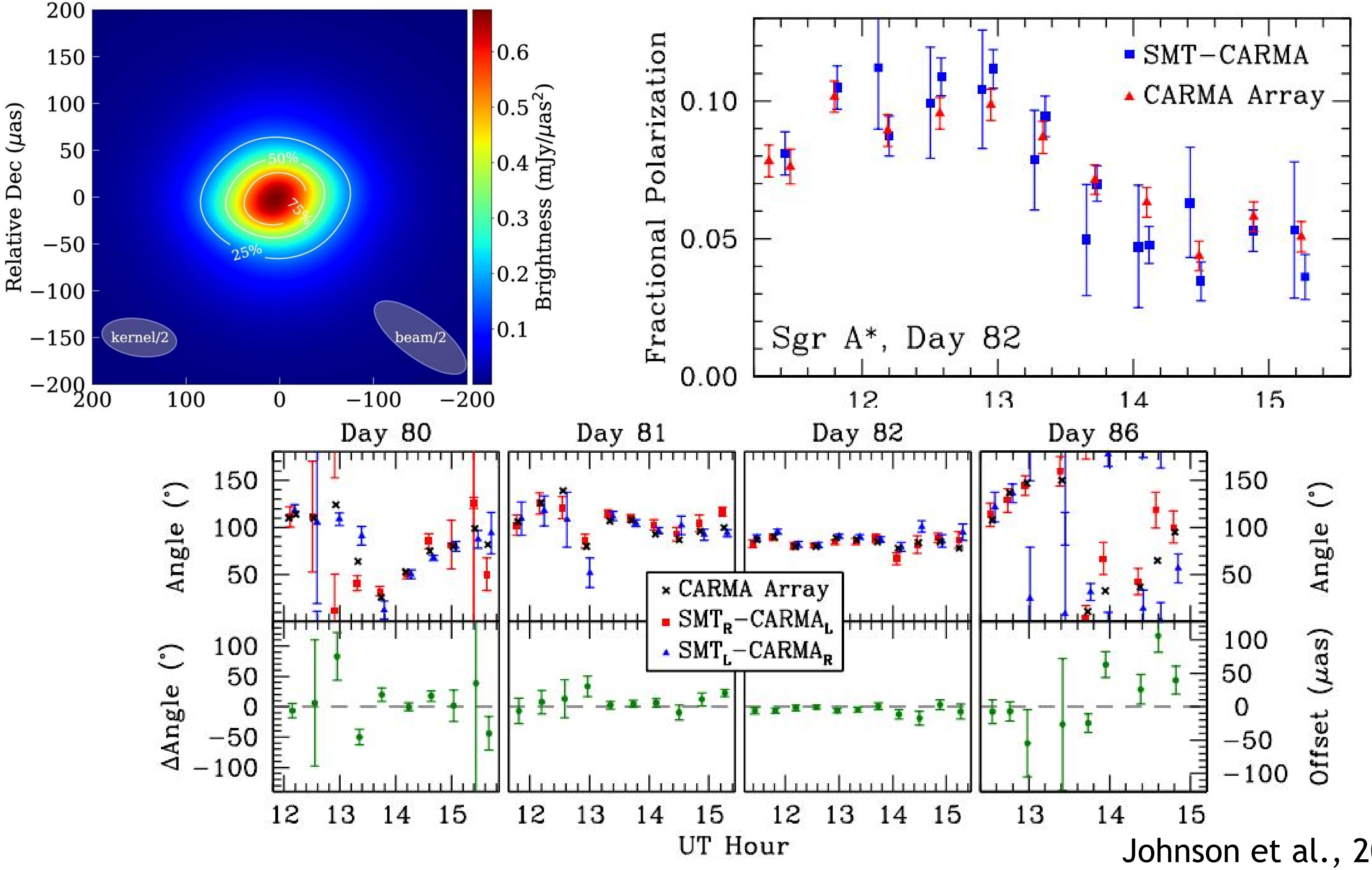
Parkes observations of PSR J0437-4715

Galactic center: a high DM site





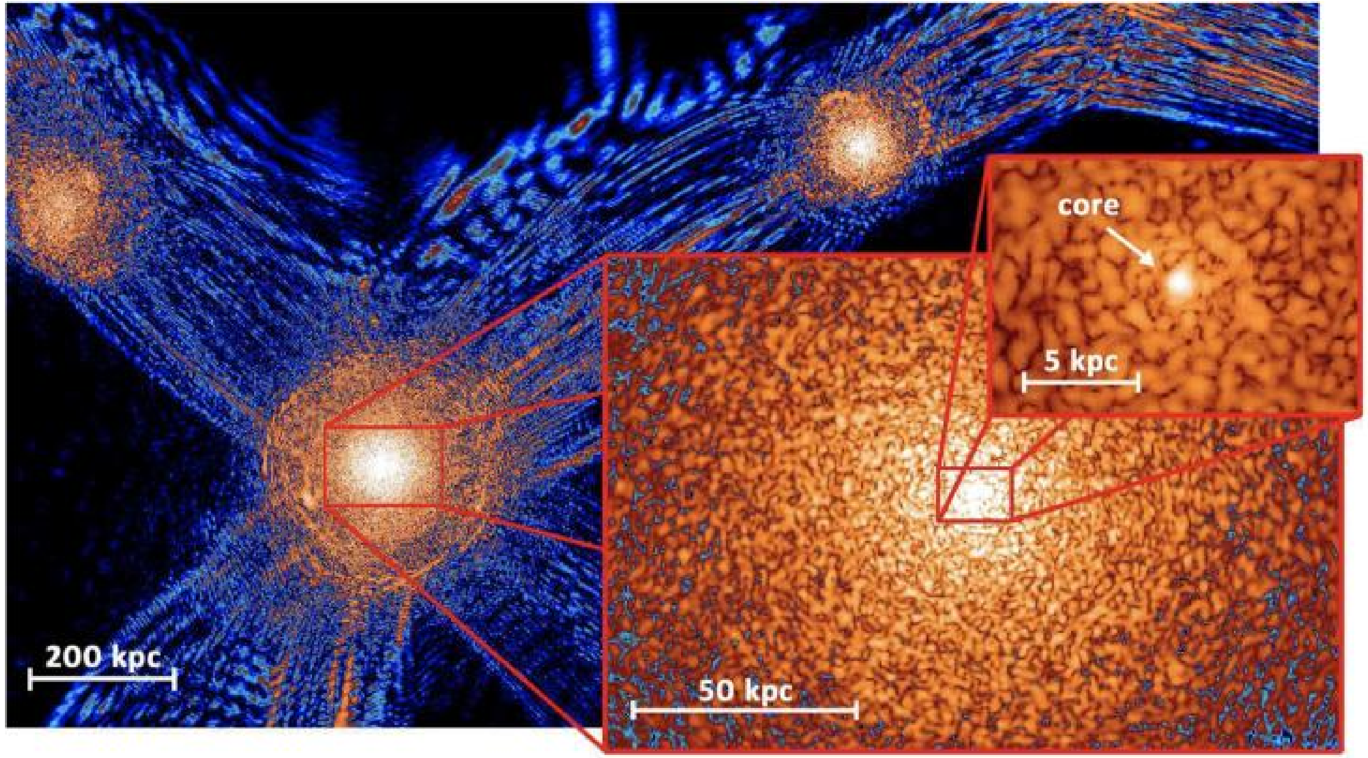
Galactic center: EHT sub-array imaging



Johnson et al., 2015, Science

Profile of wave DM in the Galactic center

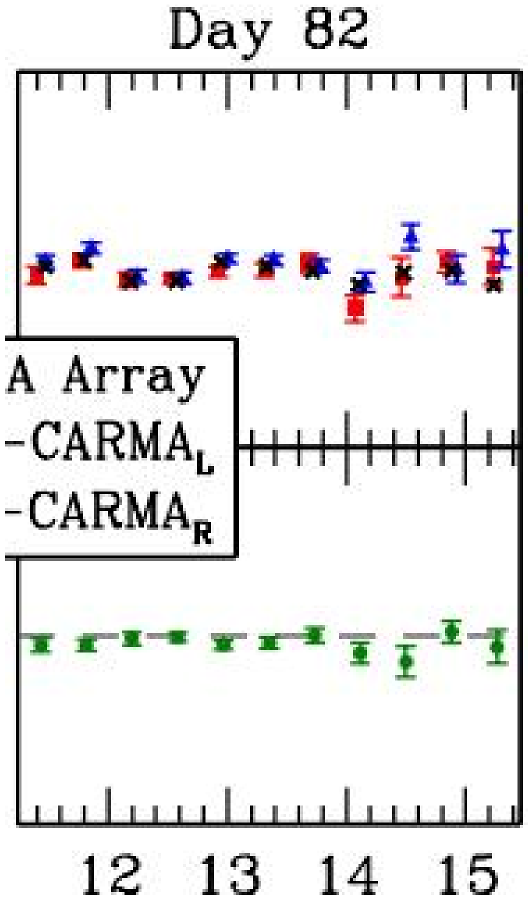
The remarkable wave property of ultralight DM suppresses its density in the central region, forming a soliton core

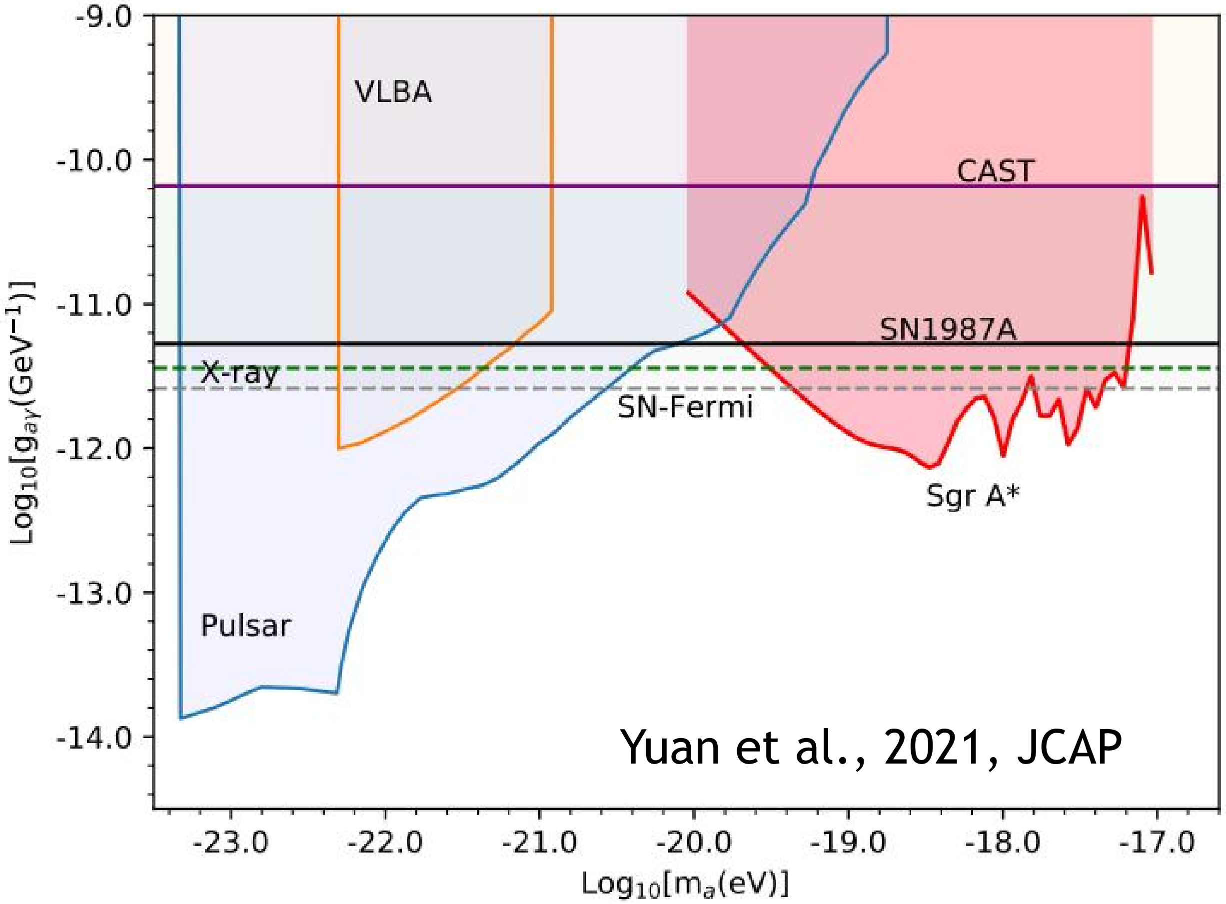


$$\rho_{\rm DM} = \begin{cases} 190 \times \left(\frac{m_a}{10^{-18}\rm eV}\right)^{-2} \left(\frac{r_c}{1\rm pc}\right)^{-4} M_\odot {\rm pc}^{-3}, & \text{for } r < r_c \\ \frac{\rho_0}{r/R_g(1+r/R_g)^2}, & \text{for } r > r_c \end{cases}$$

Schive et al., 2014, Nature Physics

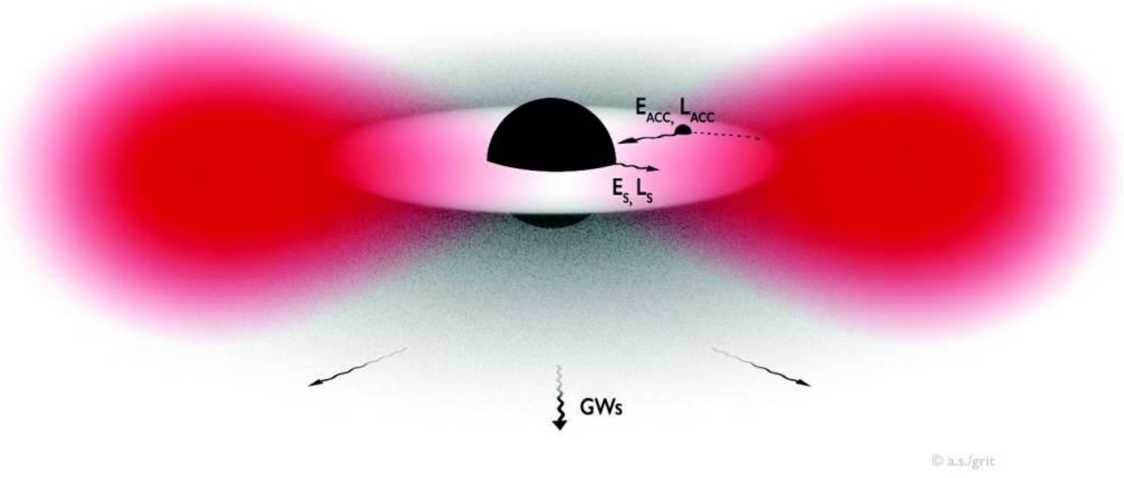
Constraints on axion coupling for 10^{-20}~10^{-17} eV





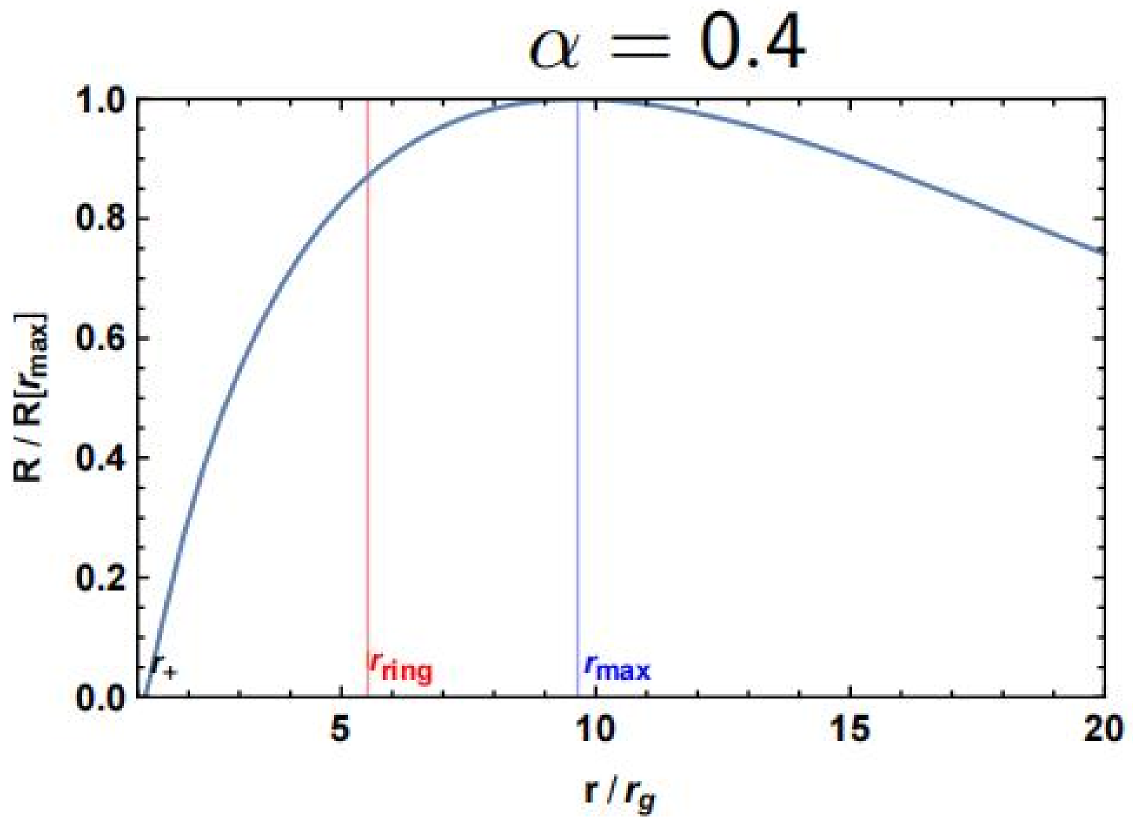
- The polarization fractions and position angles vary significantly, due to the small size and instabilities of the accretion disk
- The day with relatively stable polarized emission (Day 82) can in turn constrain the ALP model parameters

Superradiance around Kerr BH



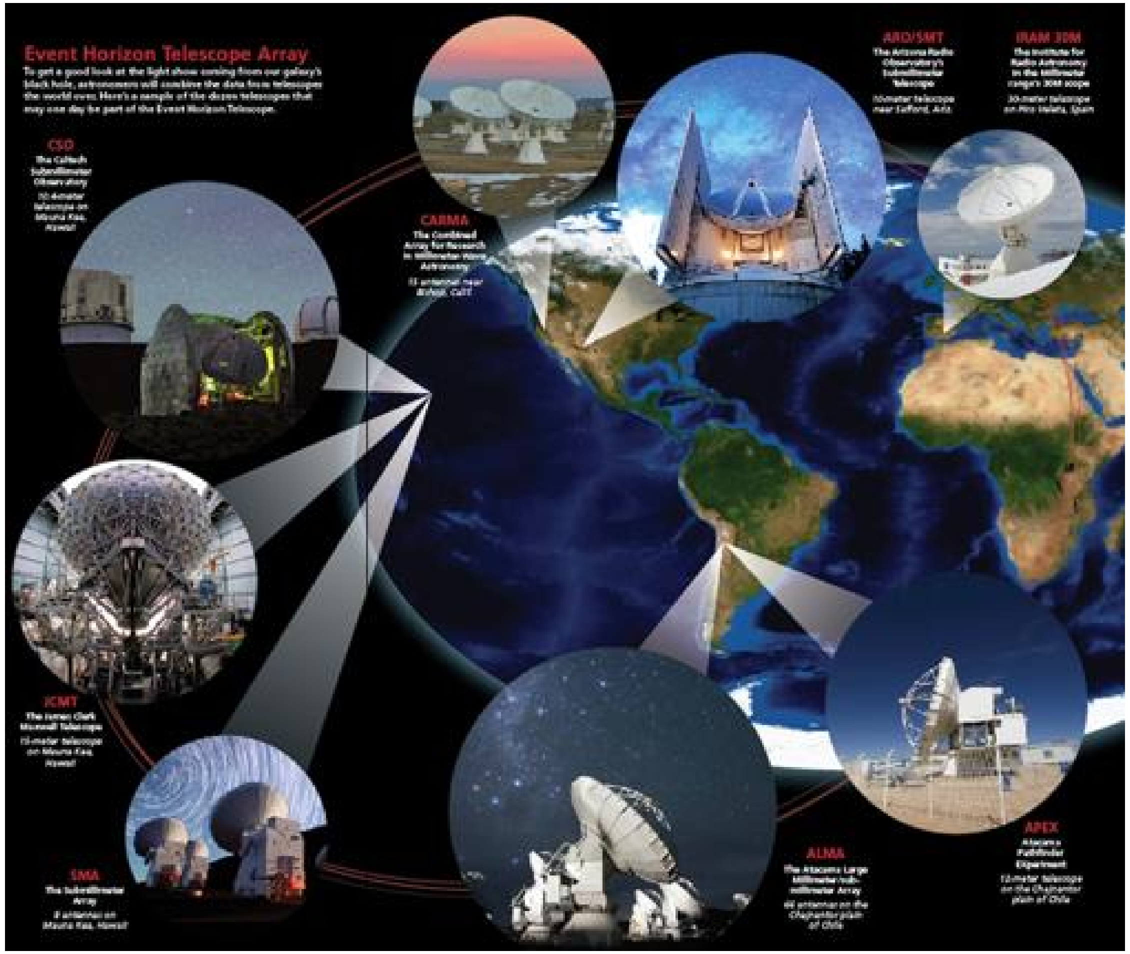
Superradiance condition

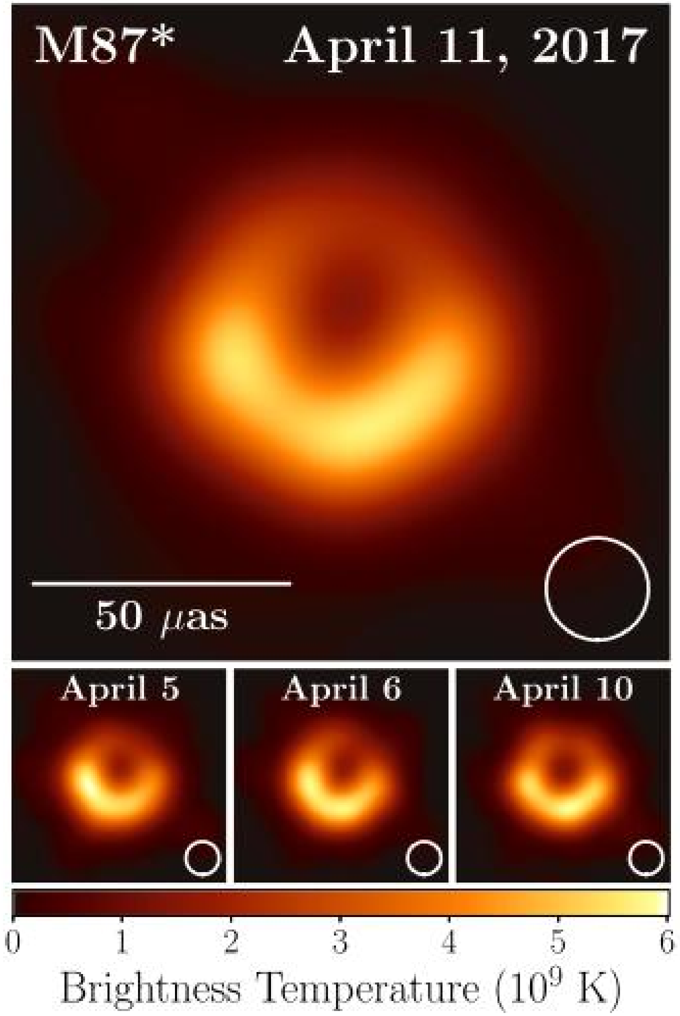
$$\omega < \omega_c = \frac{a_J m}{2r_+}$$

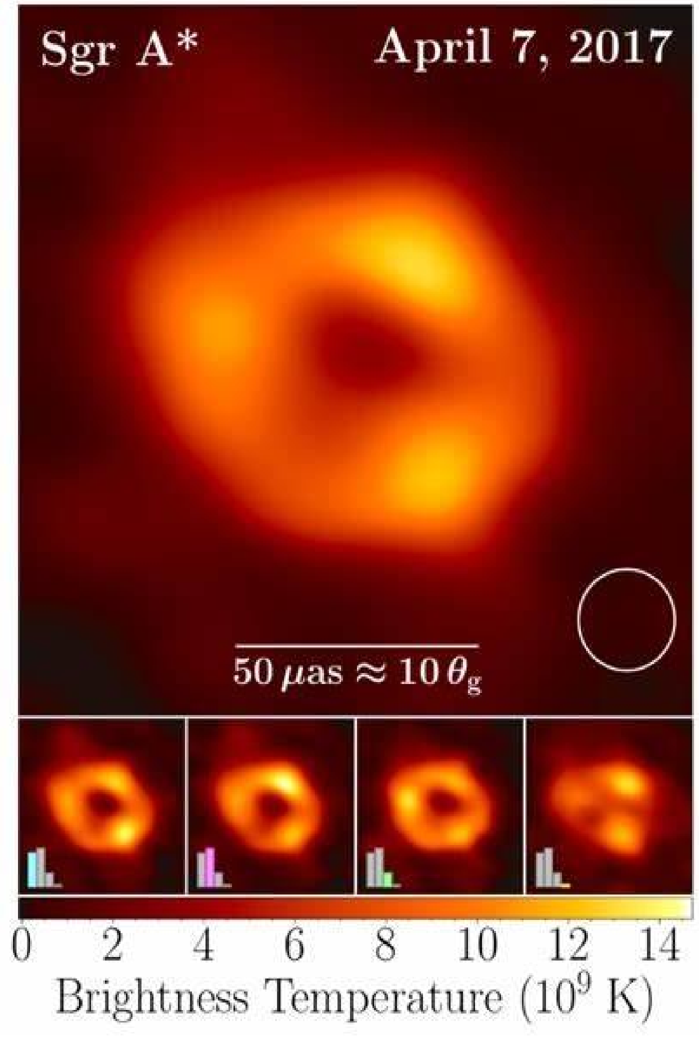


- The wave function grows exponentially through extracting BH rotation energy (Penrose process)
- The radial distribution reaches maximum at a few r_g, can just be resolved by EHT!

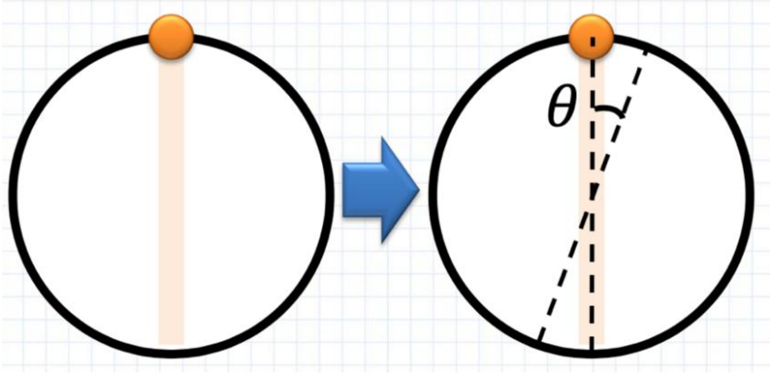
Event Horizon Telescope (EHT)



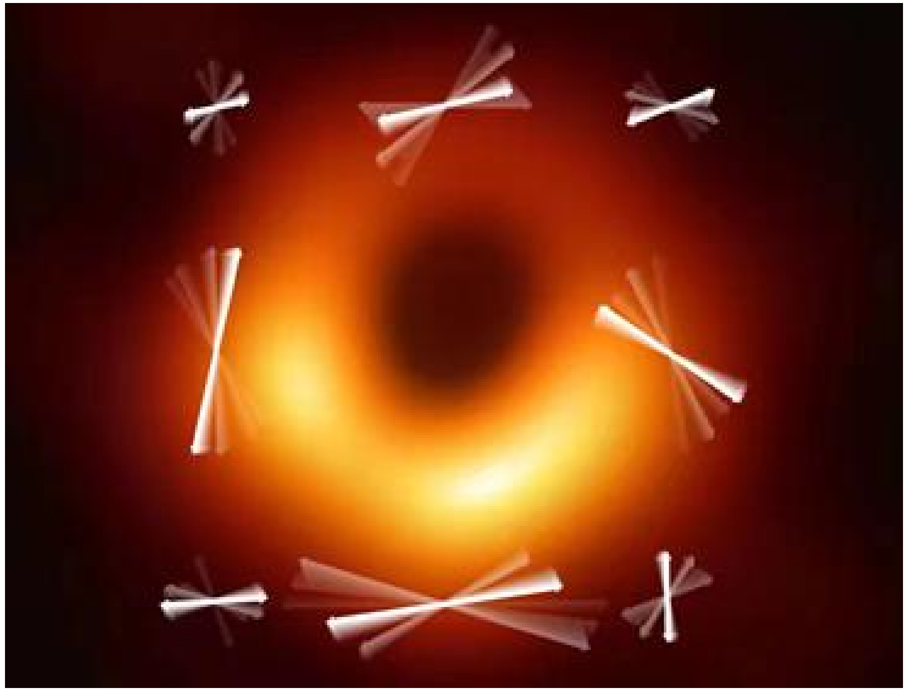




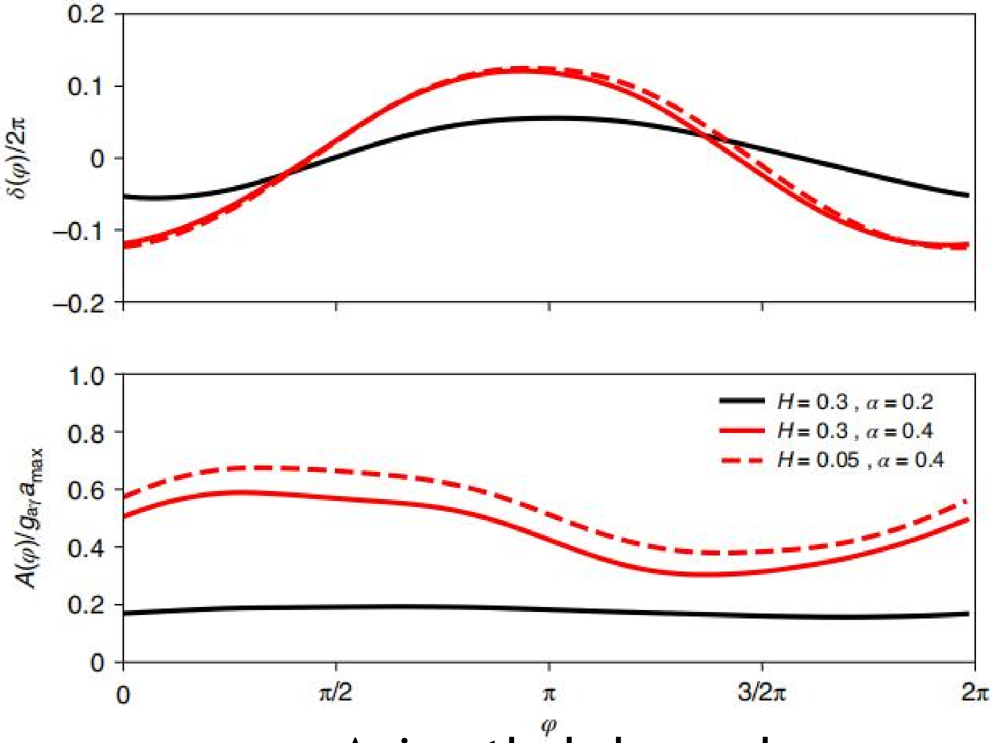
Search for axions with EHT polarimetric imaging



$$\begin{aligned}\Delta\Theta &= g_{a\gamma}\Delta a(t_{\rm obs},\mathbf{x}_{\rm obs};t_{\rm emit},\mathbf{x}_{\rm emit})\\ &= g_{a\gamma}\int_{\rm emit}^{\rm obs} ds\; n^\mu\;\partial_\mu a\\ &= g_{a\gamma}[a(t_{\rm obs},\mathbf{x}_{\rm obs})-a(t_{\rm emit},\mathbf{x}_{\rm emit})],\end{aligned}$$

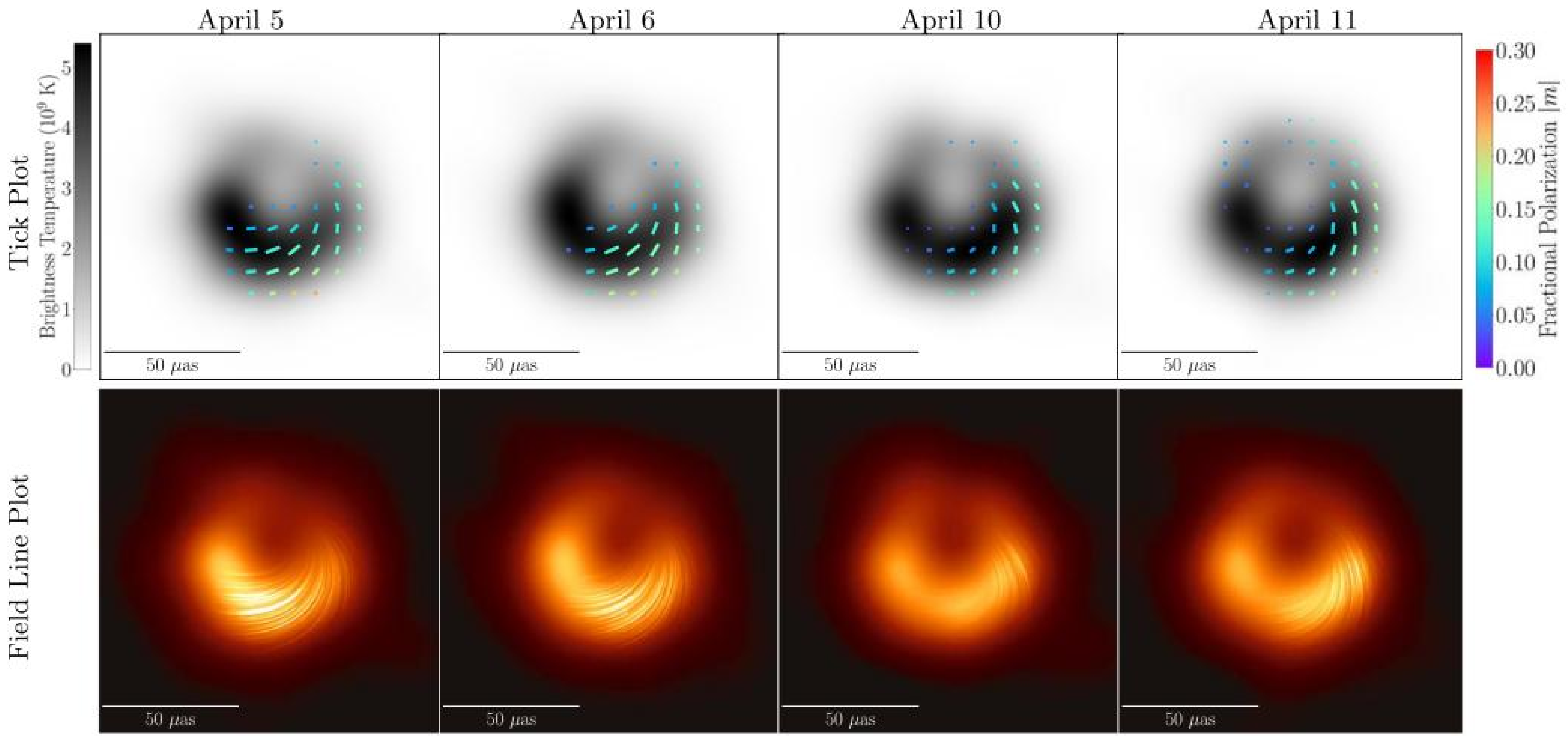


Time dependence



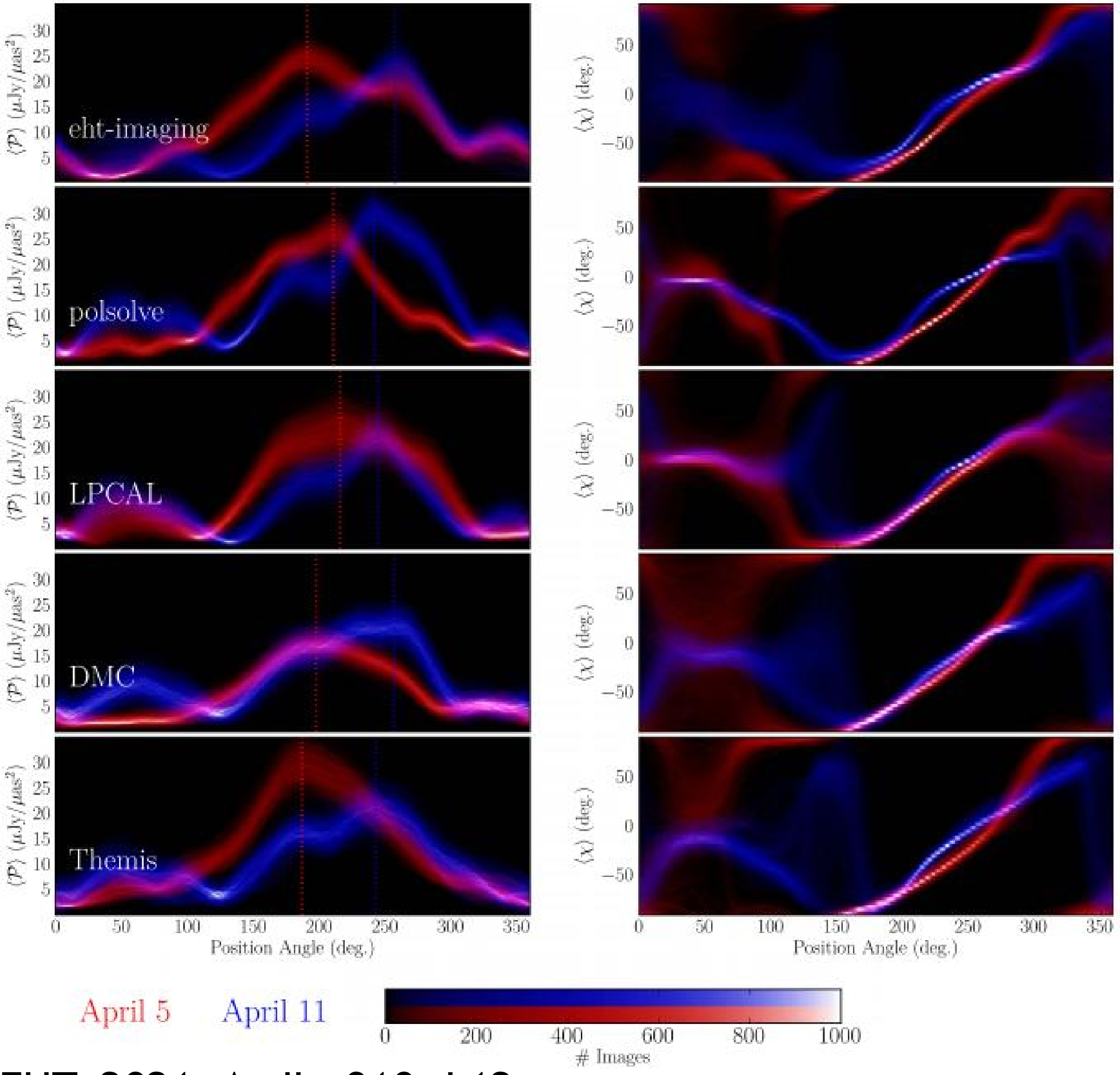
Azimuthal dependence

EHT polarimetric imaging of M87*



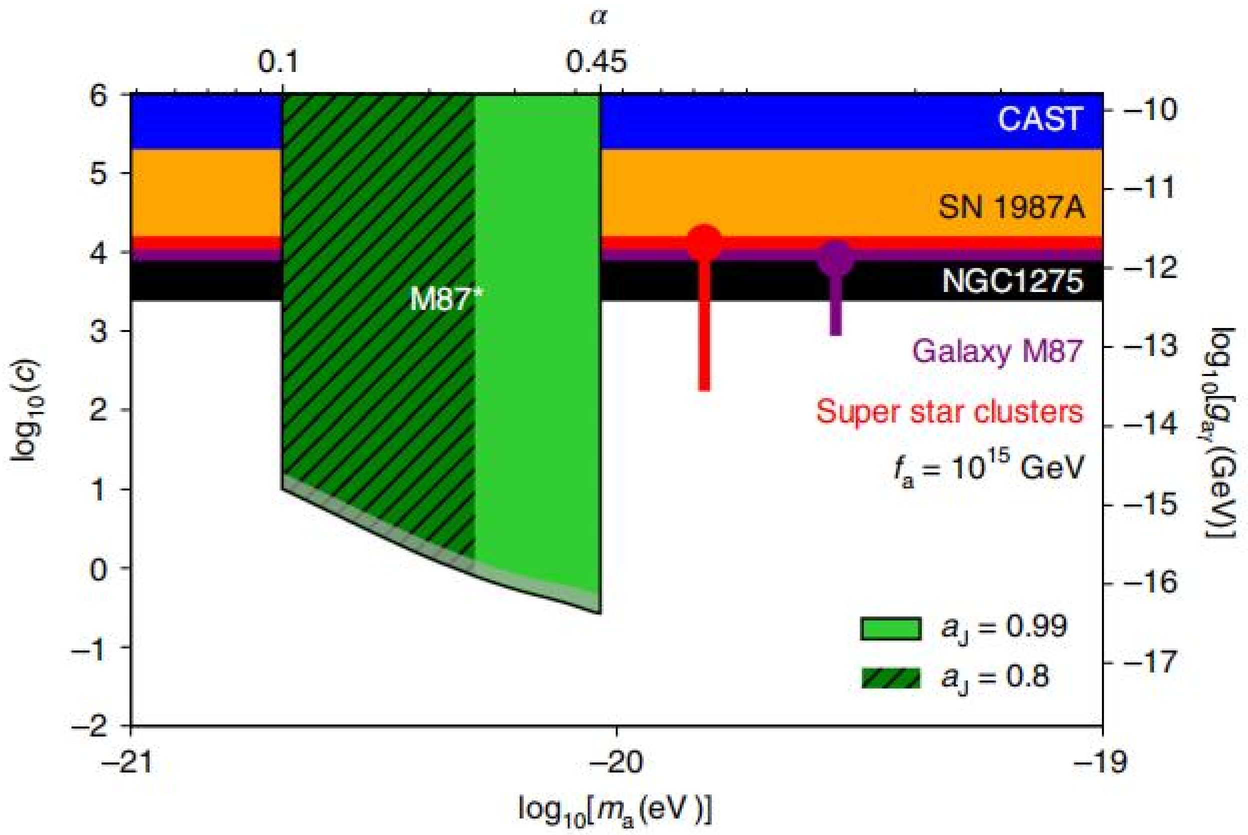
EHT, 2021, ApJL, 910, L12

Search for axions with EHT polarimetric imaging



EHT, 2021, ApJL, 910, L12

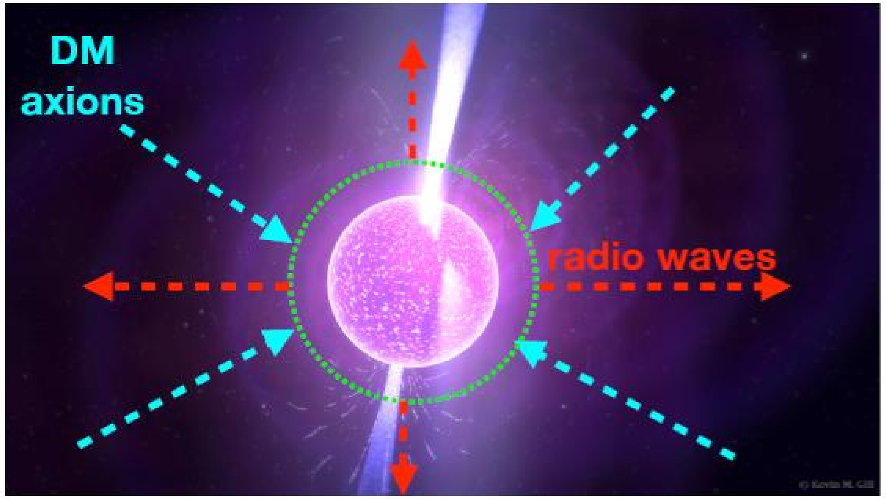
We use differences of two sequential days i.e., (5, 6) and (10, 11), to suppress astrophysical uncertainties



Chen et al., 1905.02213
Chen et al., 2105.04572

Axion-photon conversion in neutron stars

NS with strong B-field and surrounding plasma

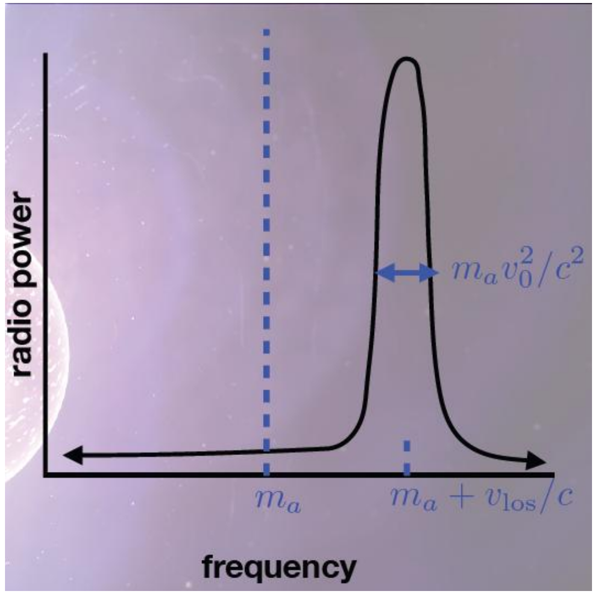


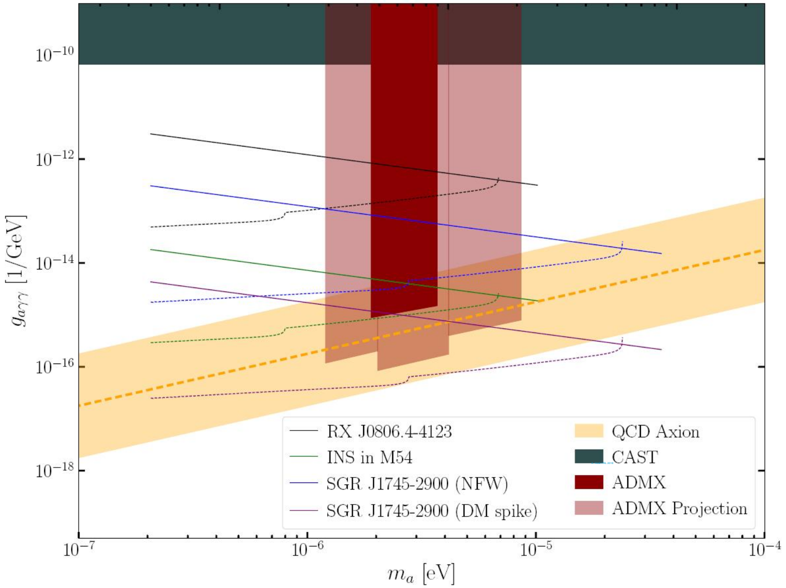
radio waves

radio emission propagates to Earth

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

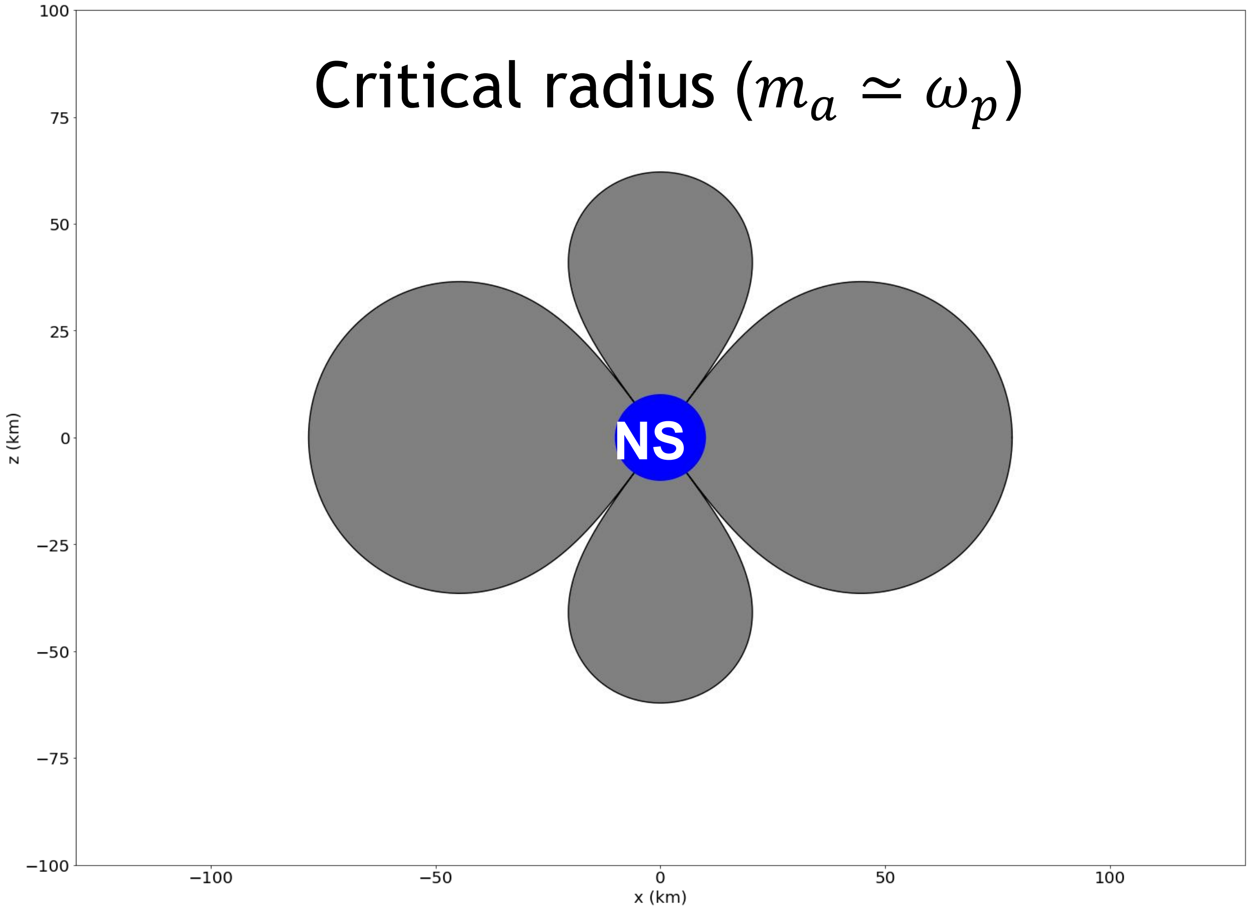
DM axions resonantly convert to radio waves when $m_a = m_\gamma$





- Pshirkov+ JETP 2009; Huang+ PRD 2018; Hook+ PRL 2018
- Narrow line in radio frequency
- Can extend to mass range beyond the cavity experiment

Axion-photon conversion in neutron stars



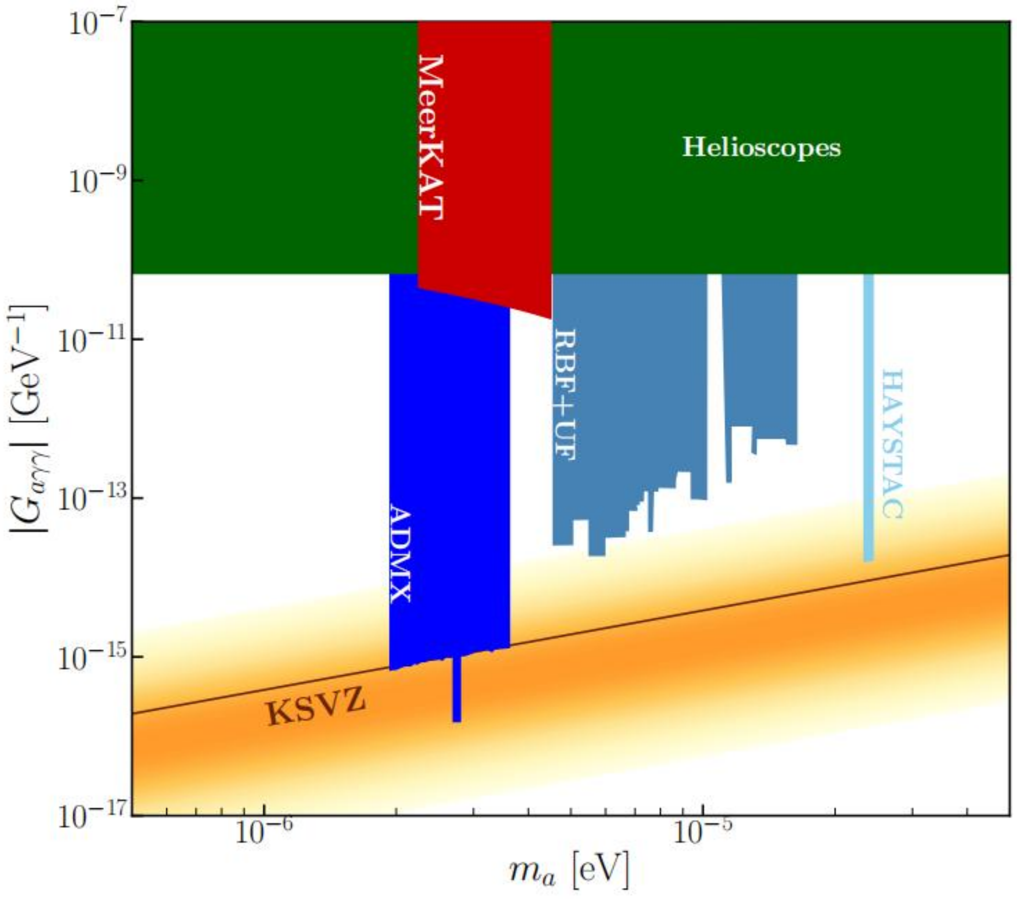
$$\bar{S}_{\nu_i} = \frac{F}{\Delta\nu} = 3.8 \times 10^{-6}\ \mathrm{Jy} \left(\frac{100\,\mathrm{pc}}{d}\right)^2 \left(\frac{16\,\mathrm{kHz}}{\Delta\nu}\right) \times \left(\frac{\mathrm{d}\mathcal{P}/\mathrm{d}\Omega}{5.7 \times 10^9 \mathrm{W}}\right) \int_{\nu_{i,\min}}^{\nu_{i,\max}} \frac{\mathrm{d}\nu}{\sqrt{2\pi}\sigma_0} \mathrm{e}^{-\frac{(\nu - m_\mathrm{a})^2}{2\sigma_0^2}},$$

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\Omega} \simeq 5.7 \times 10^9\ \mathrm{W} \left(\frac{g_{a\gamma\gamma}}{10^{-12}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{r_\mathrm{NS}}{10\,\mathrm{km}}\right)^{5/2} \left(\frac{m_\mathrm{a}}{\mathrm{GHz}}\right)^{4/3} \times \left(\frac{B_0}{10^{14}\,\mathrm{G}}\right)^{5/6} \left(\frac{P}{\mathrm{sec}}\right)^{7/6} \left(\frac{\rho_\mathrm{DM}^\infty}{0.45\,\mathrm{GeV\,cm^{-3}}}\right) \left(\frac{M_\mathrm{NS}}{\mathrm{M}_\odot}\right)^{1/2} \times \left(\frac{200\,\mathrm{km\,s^{-1}}}{v_0}\right) \frac{3\,(\hat{\mathbf{m}} \cdot \hat{\mathbf{r}})^2 + 1}{|3 \cos\theta\, \hat{\mathbf{m}} \cdot \hat{\mathbf{r}} - \cos\theta_\mathrm{m}|^{7/6}}, \quad (3)$$

High B-field, nearby, radio-quiet pulsar located in high DM field is optimal

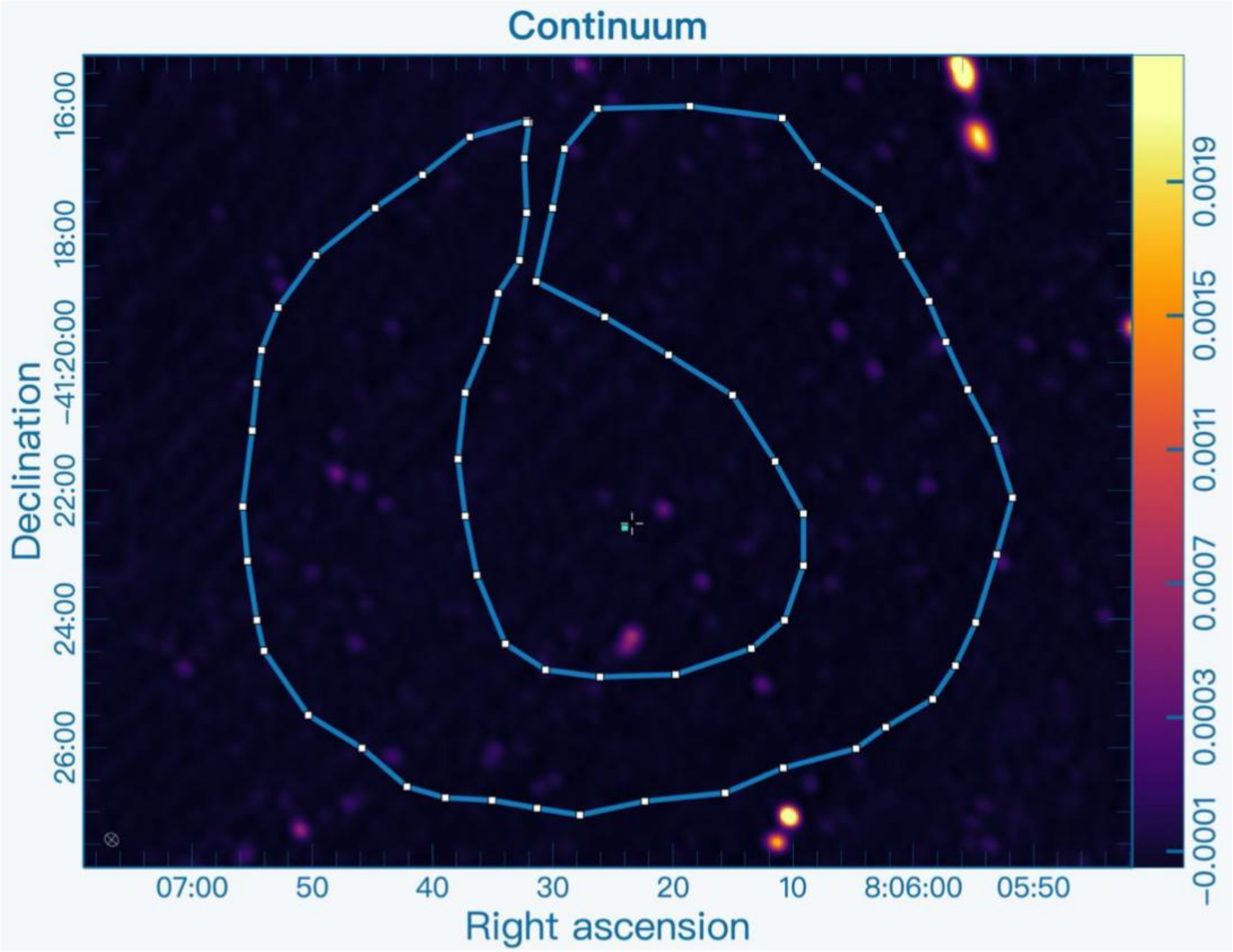
MeerKAT observation of RX J0806.4-4123

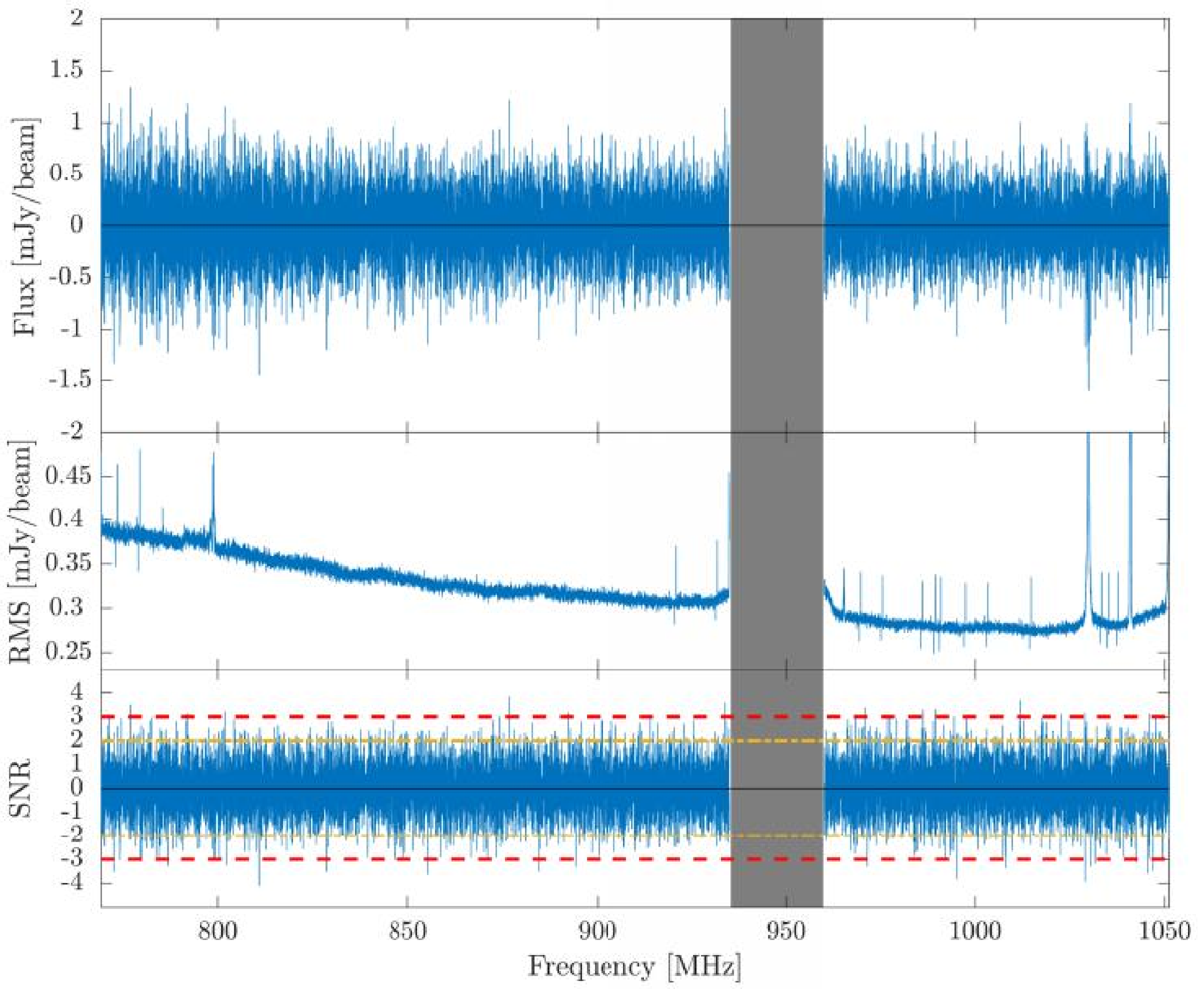
PI: Qiang Yuan (PMO)
Co-I: Yogesh Chandola, Fujun Du, Ran Ding, Nick Houston, Xiaoyuan Huang, Gyula Jozsa, Yin-Zhe Ma



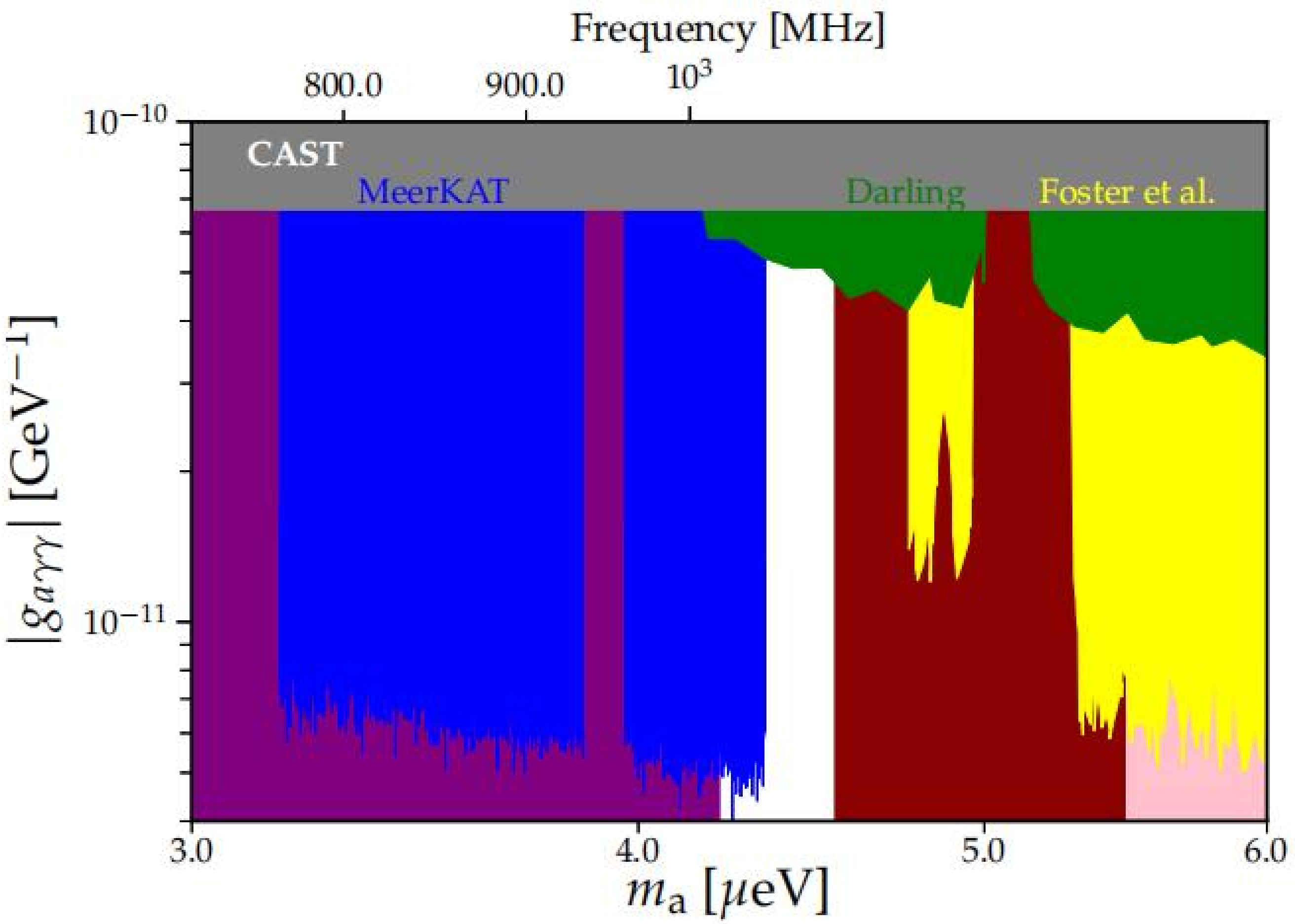
UHF Band MeerKAT
Target: neutron star RX J0806.4-4123
frequency range: 544-1088 MHz
Axion mass range: 2.5-5 μeV
Frequency resolution: 16 kHz
Area observed: 19 arcmin x 14.9 arcmin
Time resolution: 8 seconds

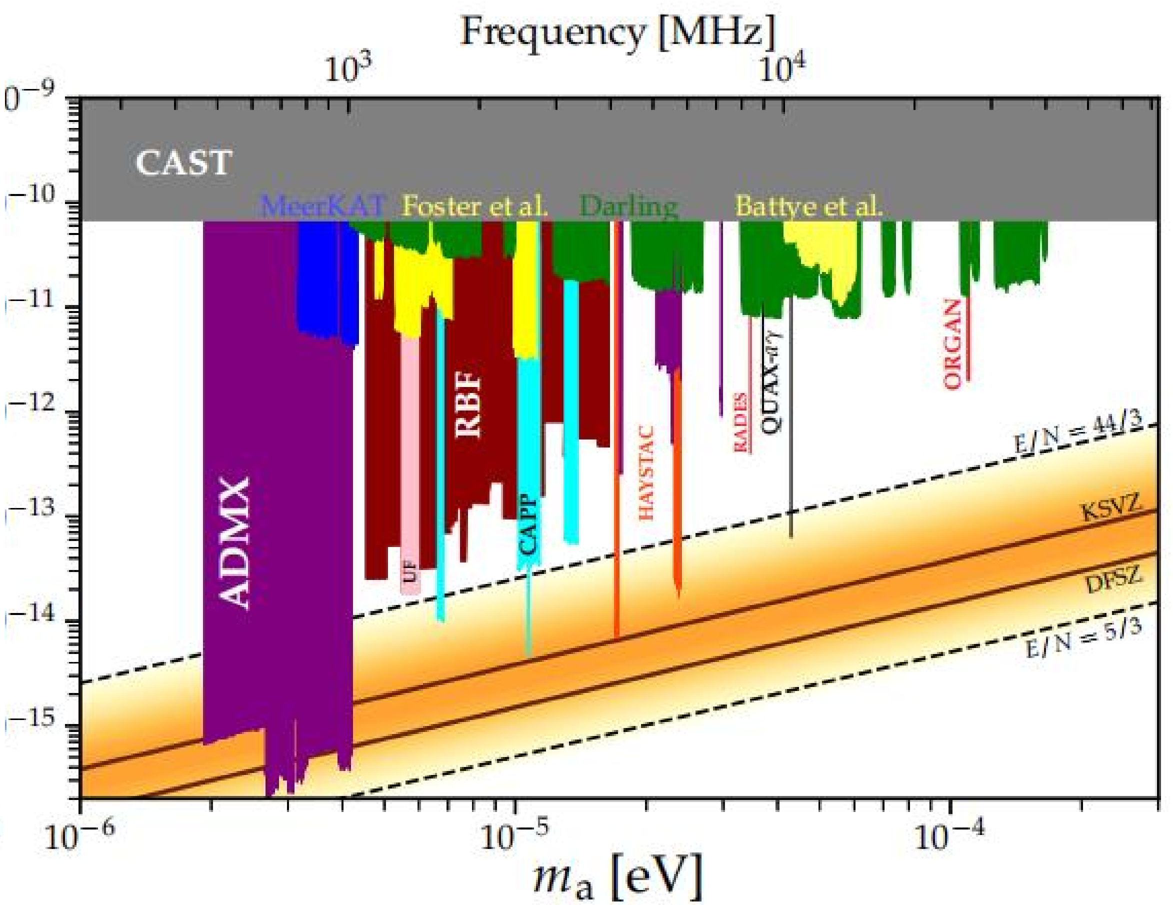
MeerKAT observation of RX J0806.4-4123





MeerKAT observation of RX J0806.4-4123





Summary

- Radio astronomy provides a very powerful tool to probe axions/ALPs in a wide parameter space, via various mechanisms (conversion, birefringence, PTA, etc.)
- Using the high-resolution polarization imaging of radio emission around black holes by the EHT, ALPs in the ultralight mass window can be effectively constrained
- High spectral resolution of isolate, radio-quiet pulsar by UHF band observations of MeerKAT (the SKA pathfinder) probes a mass gap of cavity experiments
- Future observations with better precision and higher sensitivity by e.g., the SKA, will be extremely helpful in studying axions/dark matter

Thank you!