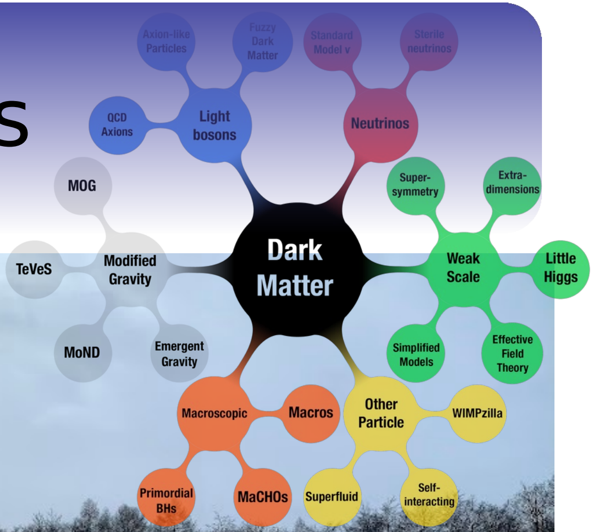
Radio searches of ALPs



Aritra Basu
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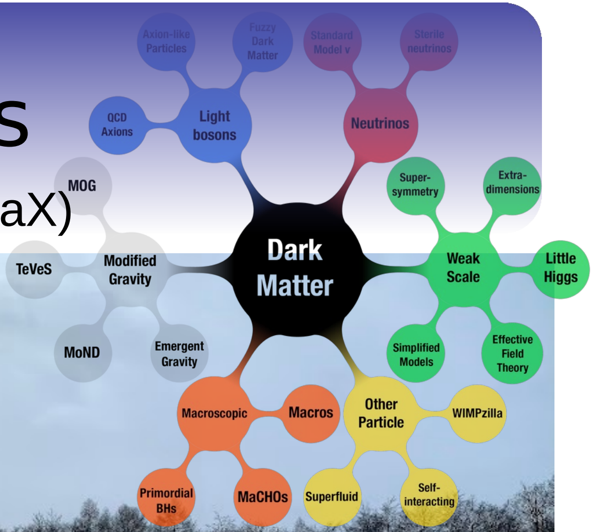
Thüringer Landessternwarte
Tautenburg

15th June 2024, Barolo Astroparticle Meeting, Barolo

Radio searches of ALPs

– LOFAR2.0 Dark Matter eXperiment (LoDMaX)



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Thanks to:
Dominik J. Schwarz, Martin Vollmann, Marco Regis, Yuko Urakawa, Lovorka Gajović, Shivani Deshmukh, Marcus Brüggen, Volker Heesen, Matthias Hoeft, Simona Vegetti, Ahmed Ayad, Jamie McDonald

15th June 2024, Barolo Astroparticle Meeting, Barolo

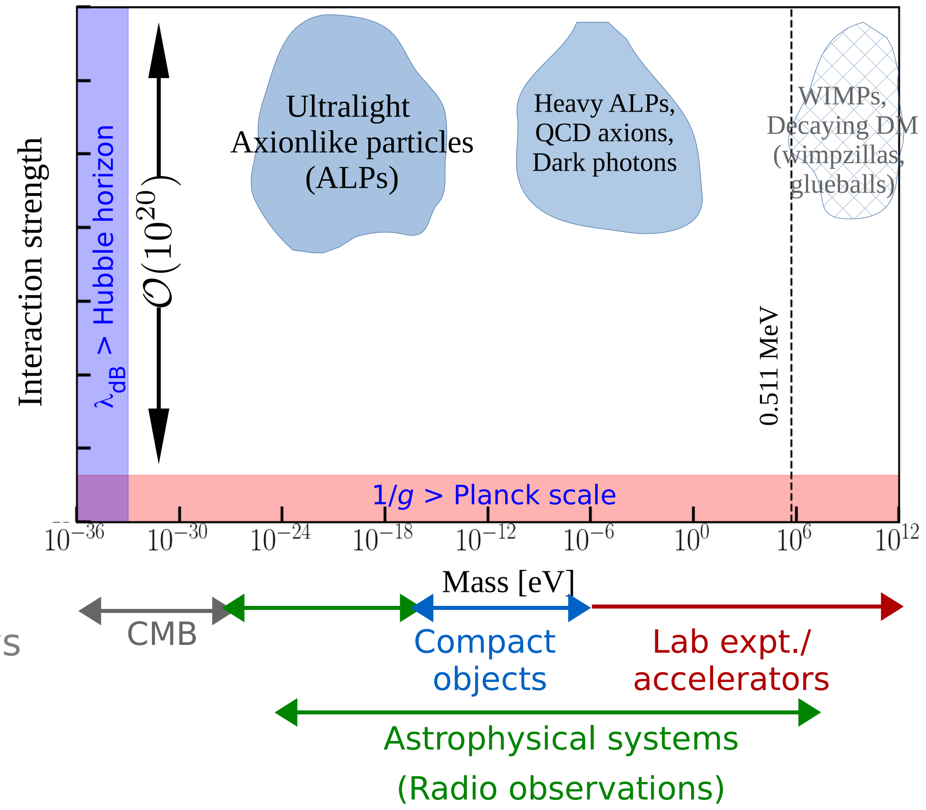
Today's talk

– Telescopes and the type of data
  – Capabilities and scope
  – Types of signal we can look for

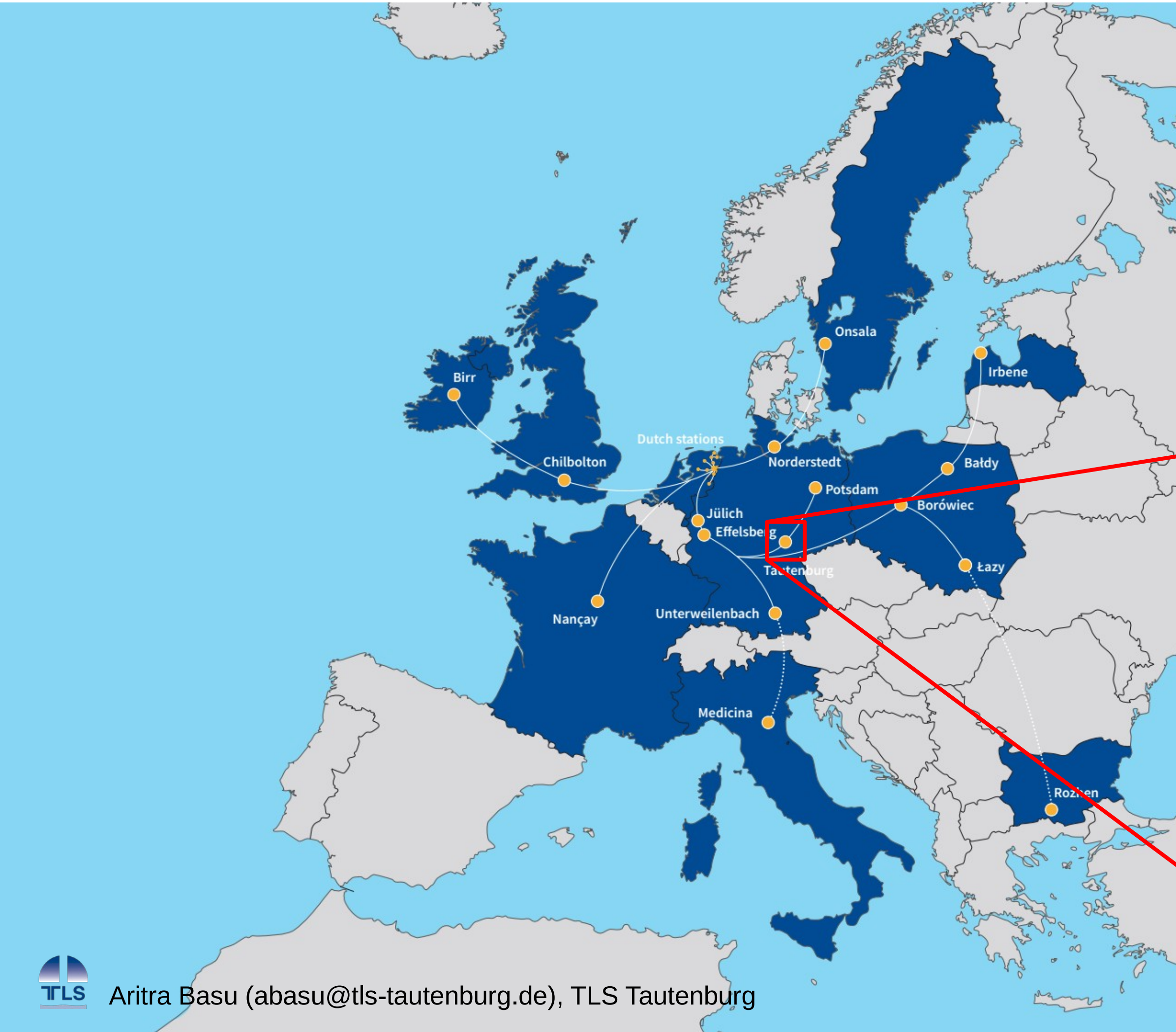
– Searching for ultralight axionlike particles
  – Spectropolarimetry of strong gravitational lenses
  – Differential birefringence from polarization surveys

– Spectral line and time domain
  – Possibilities with current telescope capabilities

[based on the works of Jamie McDonald, Samuel Witte, Elisa Todarello, Marco Regis, Marco Taoso]



Our instruments — LOFAR [ERIC]



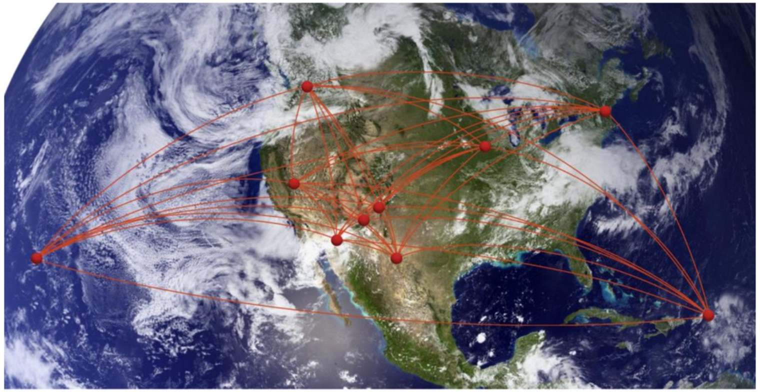
Low Band Antenna
(LBA; 10–80 MHz)

High Band Antenna
(HBA; 110–240 MHz)

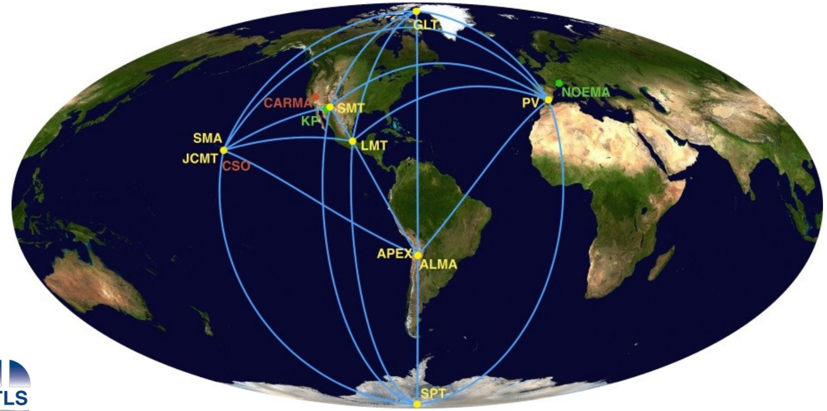
Our instruments — VLA, MeerKAT, VLBA (SKA, ngVLA, DSA2000)

Karl G. Jansky
Very Large Array
(Socorro, Mew Mexico, USA)

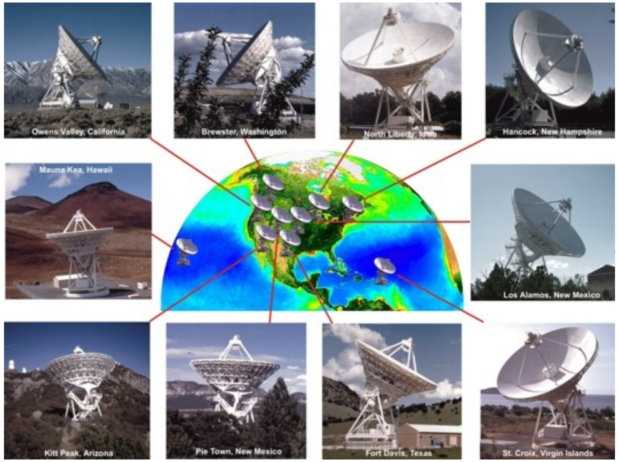
The MeerKAT
(Karoo desert, South Africa)



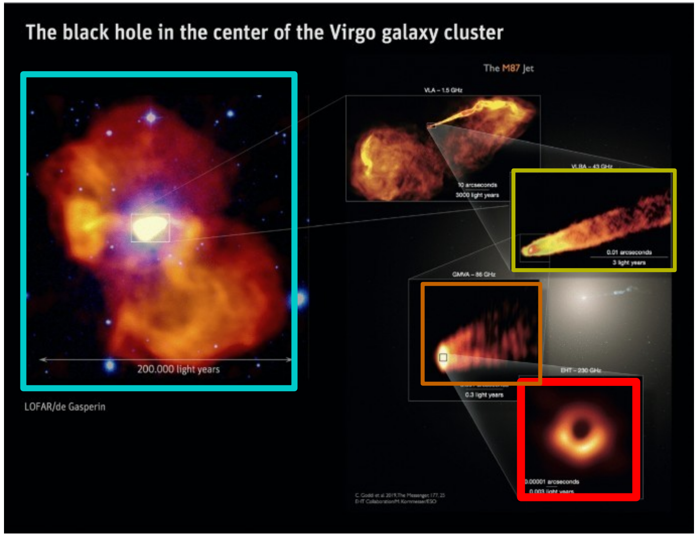
Very Long Baseline Array
(Continental US)



Event Horizon Telescope
(Planet Earth)

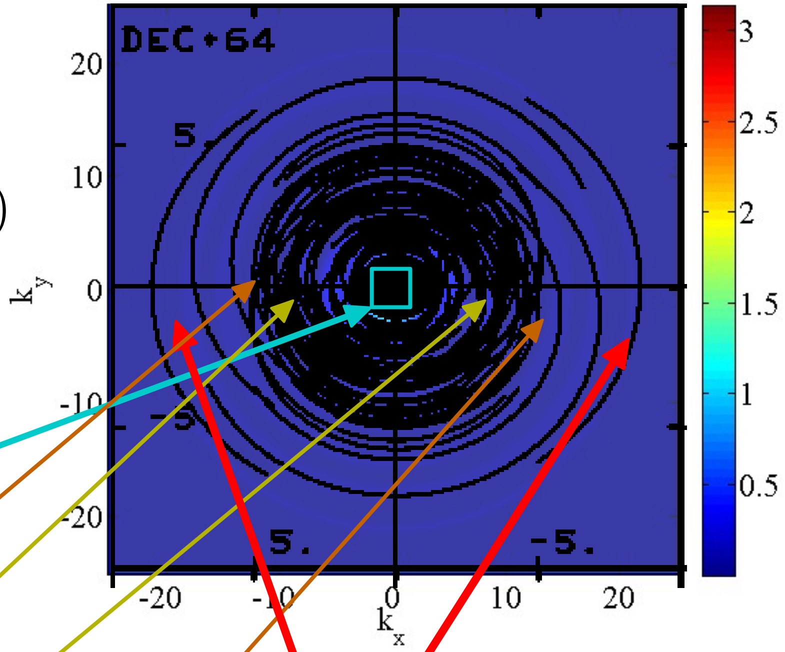


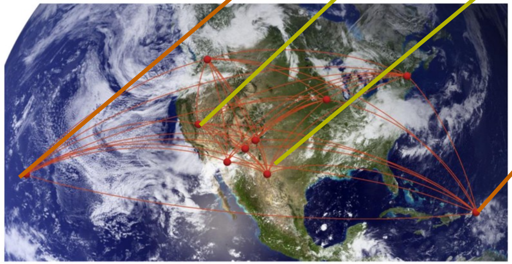
Fourier modes of the sky

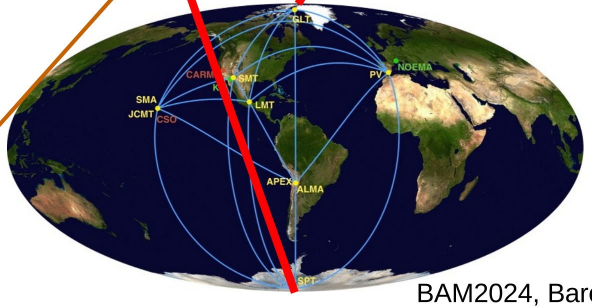


$$\mathcal{FT}(\text{sky}) \rightarrow V(u, v)$$

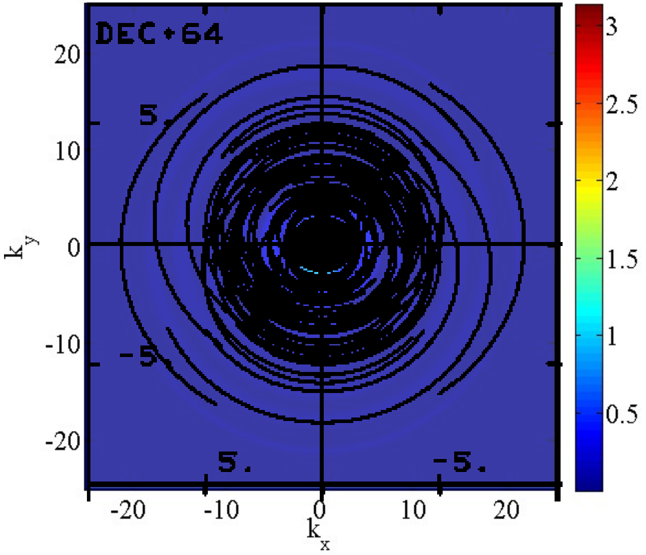
Visibilities







Visibilities: Least level of data we start with



Correlated visibilities (for astronomers)

$$^{N}C_2 \text{ values averaged over 1 to 10 s}$$

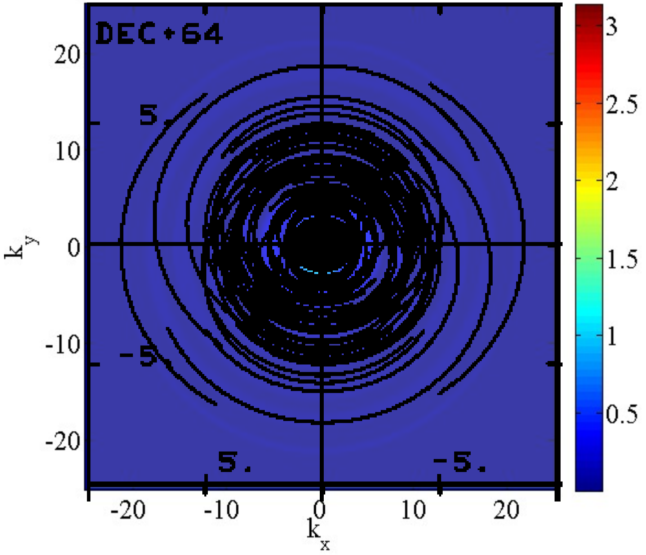
↓

$$\text{Frequency channels} : 2^{10}\text{–}2^{16}$$
$$\times$$
$$\text{Stokes parameters} : 4$$

Raw digitized data: 150–400 GBps ⇒ 0.5–3 GBps

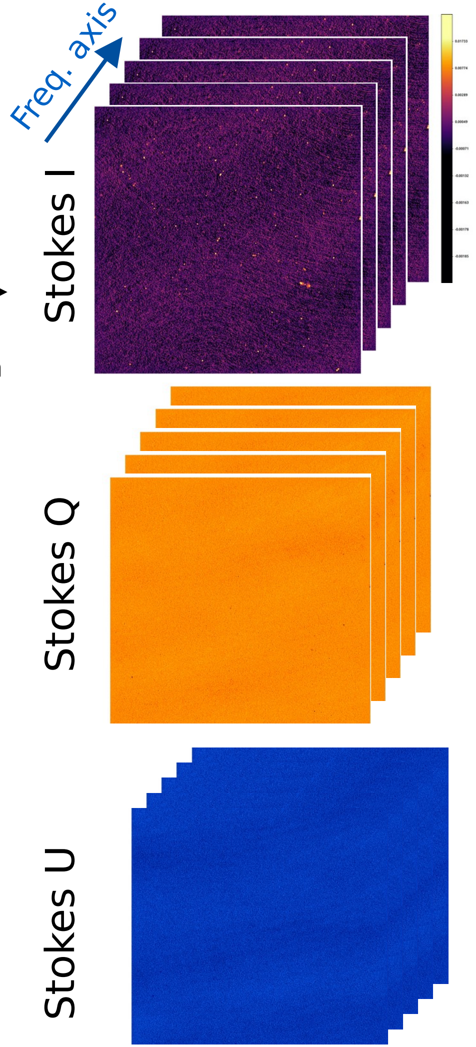
Raw data → 2 to 10 PB per 8 h observation (not stored at all)
(all processed by a “correlator” in real time)

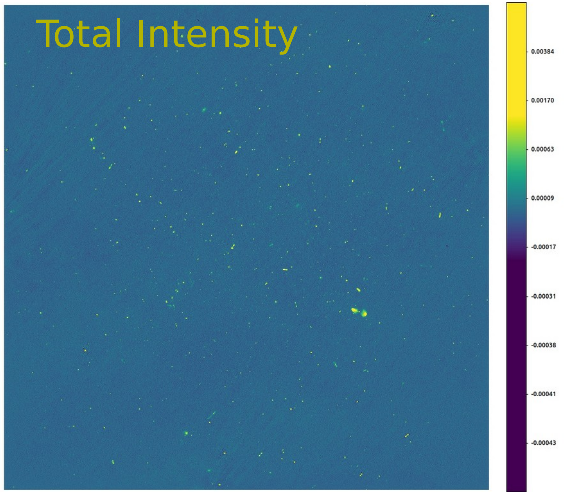
Visibilities → High level data products

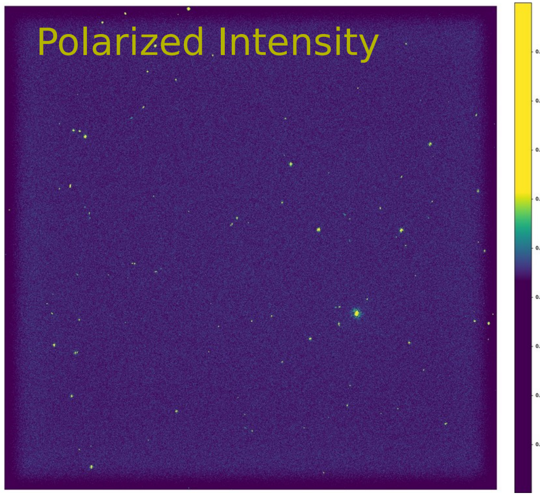


Data editing,
Calibration

Imaging
(inv. Fourier transform
+ deconvolution)







Correlated visibilities (for astronomers)

$^{N}C_2$ values averaged over 1 to 10 s

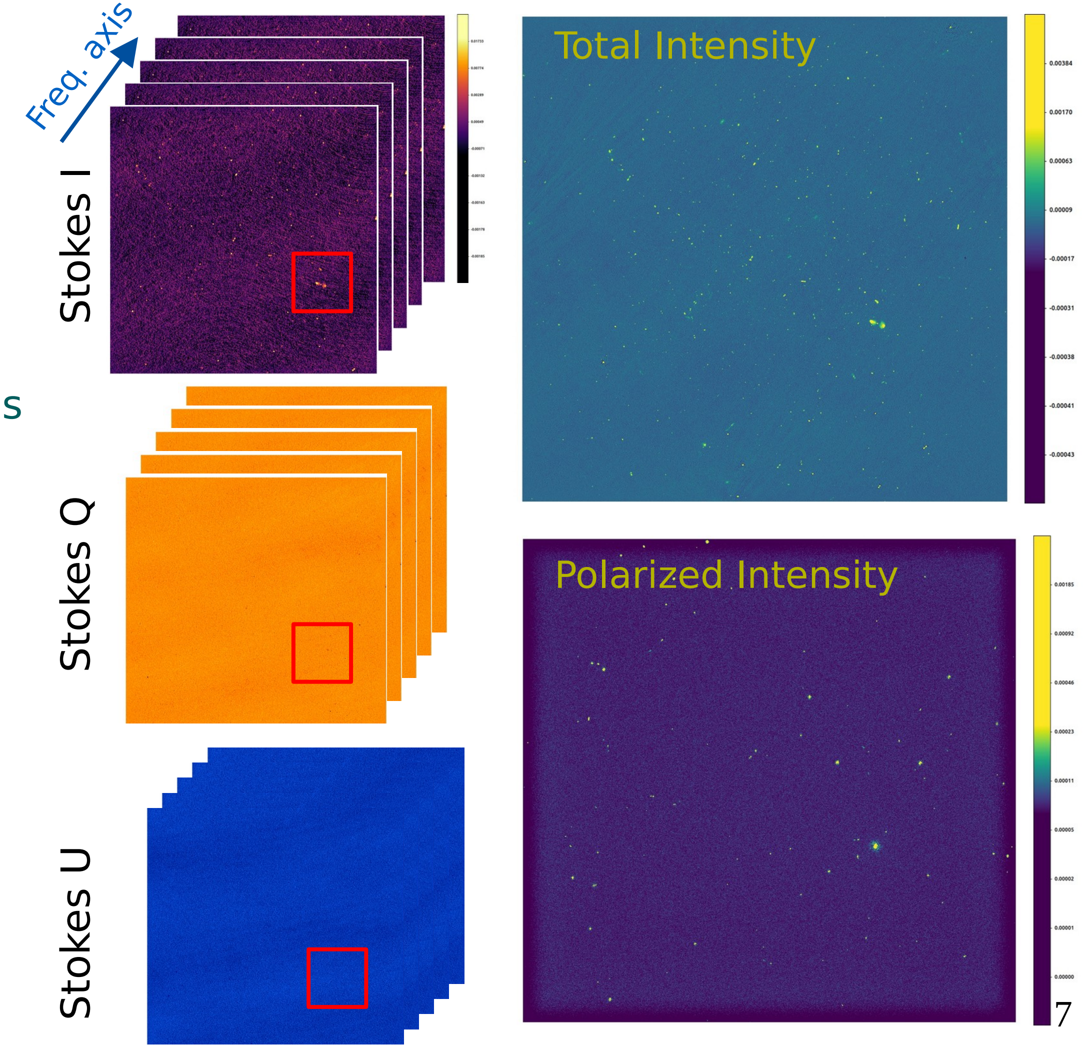
↓

Frequency channels : 2^{10}–2^{16}

×

Stokes parameters : 4

Images: DM searches



Standard observations and data analysis methods

$$\text{Imaging} \approx 10\,\text{s} \quad [\text{Practically 30 min}]$$

$$\text{Spectral resolution} : \Delta\nu/\nu \approx 10^{-4}\text{–}10^{-2}$$

Effects of ALP—photon coupling

Birefringence

Parity violation gives rise to dispersion relations in light propagation

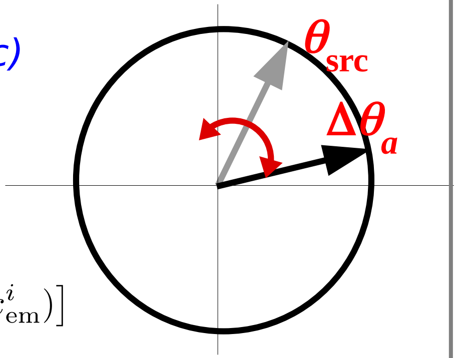
$$\omega_{\pm} \simeq k \pm \frac{1}{2} g_{a\gamma} \partial_0 a$$

Left- and right-circular polarization travel at different speeds in ALP field

→ *Birefringence (achromatic)*

$$\Delta \theta_{\rm a} = \frac{1}{2} \int_{t_{\rm em}}^{t_{\rm obs}} \Delta \omega \, d t$$

$$= \frac{1}{2} g_{a\gamma} \left[a(t_{\rm obs}, x^i_{\rm obs}) - a(t_{\rm em}, x^i_{\rm em}) \right]$$



Smoking gun: $\Delta\theta_{\rm a}$ oscillates with time

Effects of ALP—photon coupling

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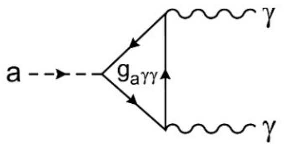
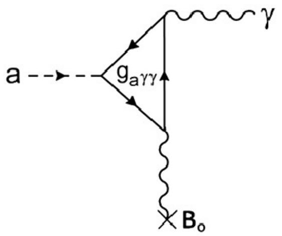
Smoking gun: $\Delta\theta_a$ oscillates with time

Axion—photon interconversion



Decay into photons

(Primakoff effect)



Conversion in the presence of magnetic fields

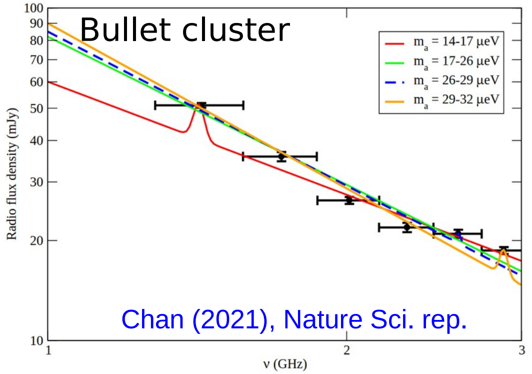
(Stimulated decay)

$$\nu_0 = \frac{m_a}{4\,\pi\,\hbar}$$

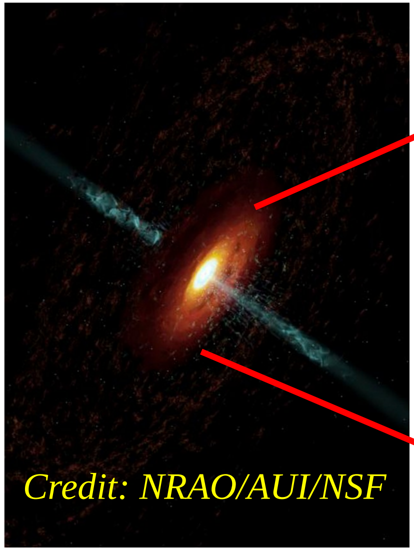
0.1–1 GHz ⇒ 1–10 μeV

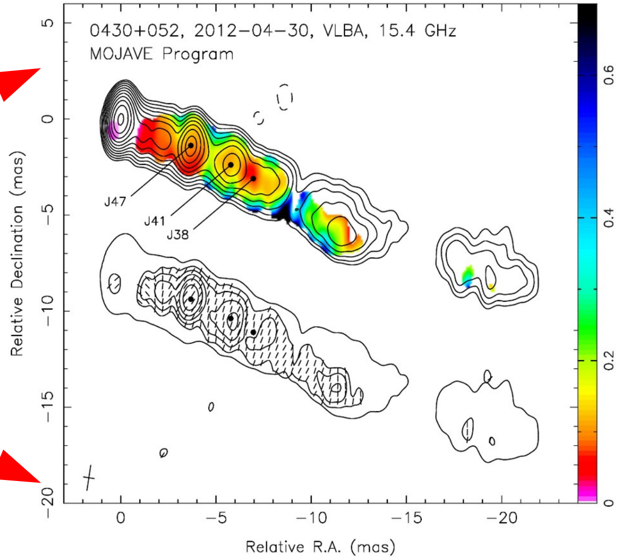
$$\frac{\Delta\nu}{\nu_0} = \frac{\sigma_{\rm DM}}{c} \approx \mathcal{O}(10^{-3})$$

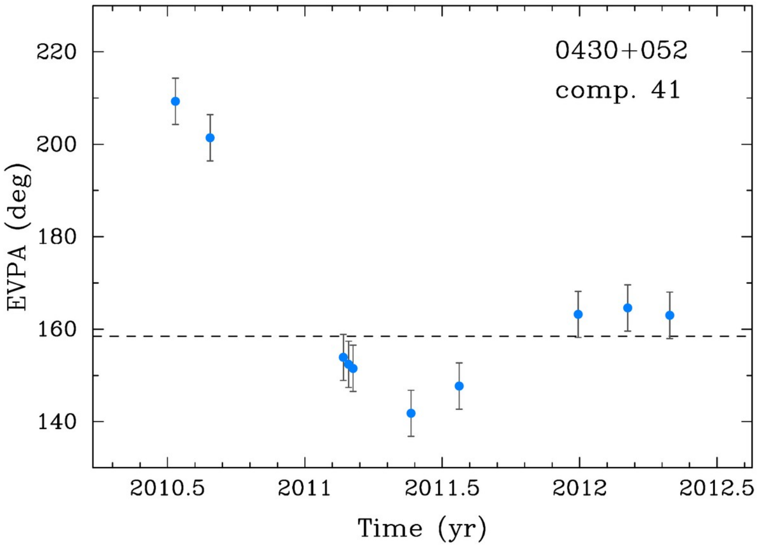
Δν ~ 0.1–1 MHz



Birefringence: Parsec-scale jets





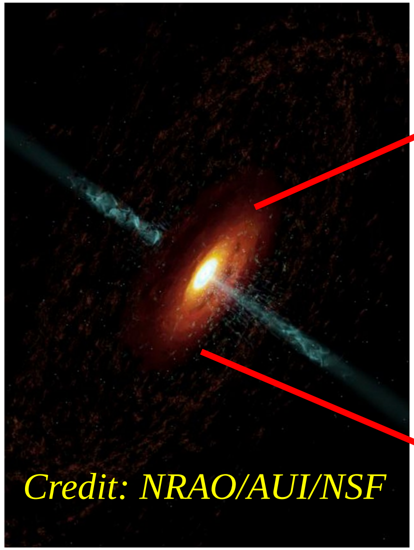


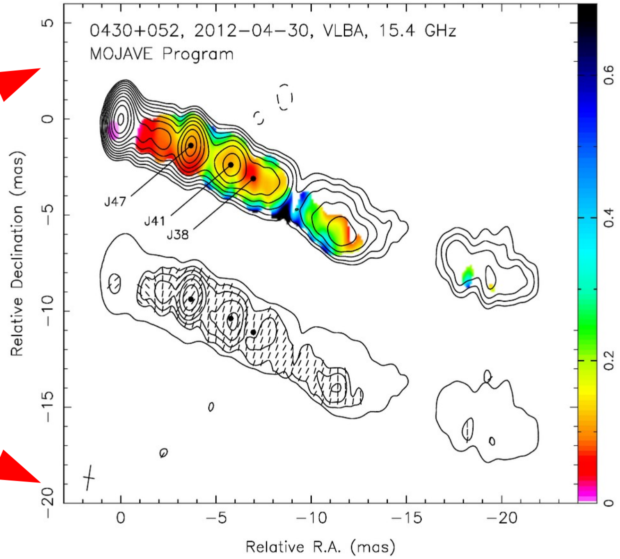
$$\Delta\theta_a = 5^\circ \sin\left(2\pi\frac{t}{T}+\delta\right)\left(\frac{\rho_{\rm DM}}{20\,{\rm GeV\,cm^{-3}}}\right)^{1/2}\left(\frac{g_{a\gamma}}{10^{-12}\,{\rm GeV^{-1}}}\right)\left(\frac{m_a}{10^{-22}\,{\rm eV}}\right)^{-1}$$

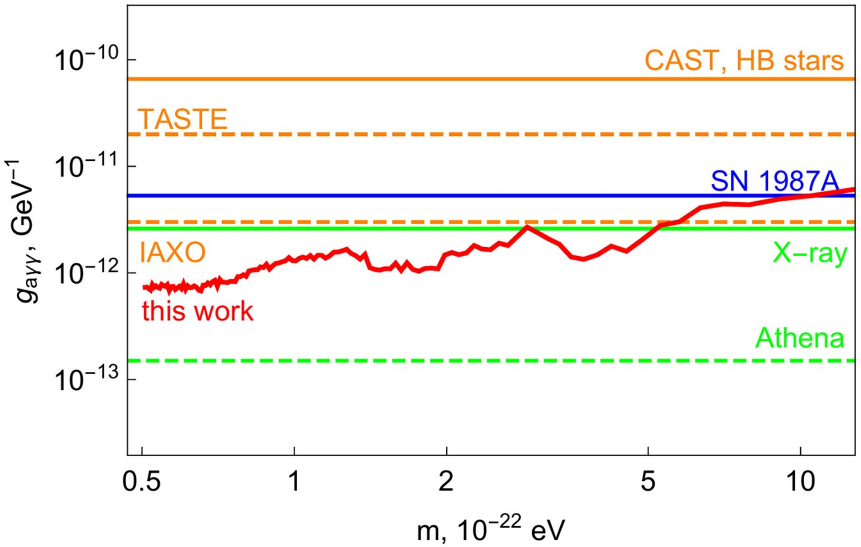
Ivanov et al. (2019) JCAP

Search for synchronous changes in polarization angle of multiple clumps.

Birefringence: Parsec-scale jets







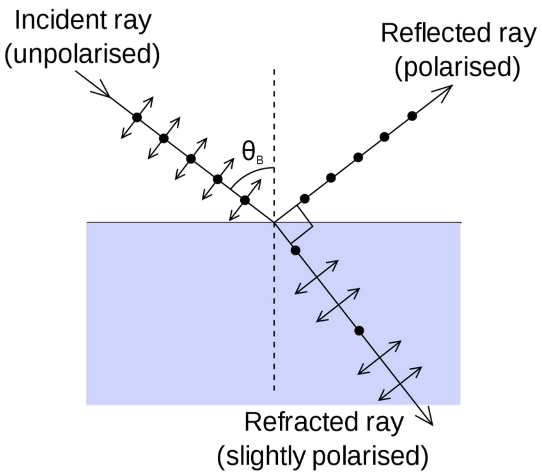
$$\Delta\theta_a = 5^\circ \sin\left(2\pi\frac{t}{T} + \delta\right)\left(\frac{\rho_{\rm DM}}{20\,{\rm GeV\,cm^{-3}}}\right)^{1/2}\left(\frac{g_{a\gamma}}{10^{-12}\,{\rm GeV^{-1}}}\right)\left(\frac{m_a}{10^{-22}\,{\rm eV}}\right)^{-1}$$

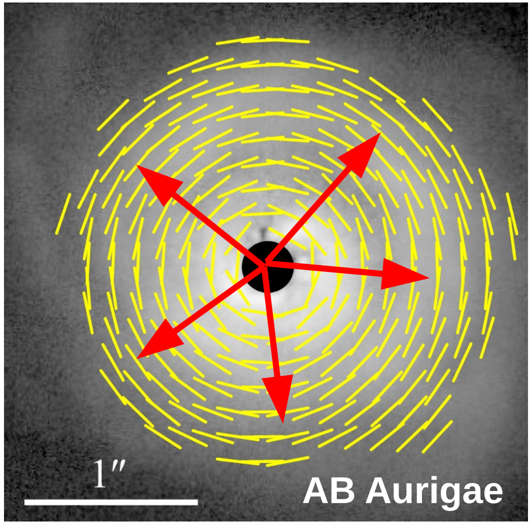
Ivanov et al. (2019) JCAP

Search for synchronous changes in polarization angle of multiple clumps.

Non-detection limited by angle calibration, astrophysics & instrument stability

Birefringence: Protoplanetary discs





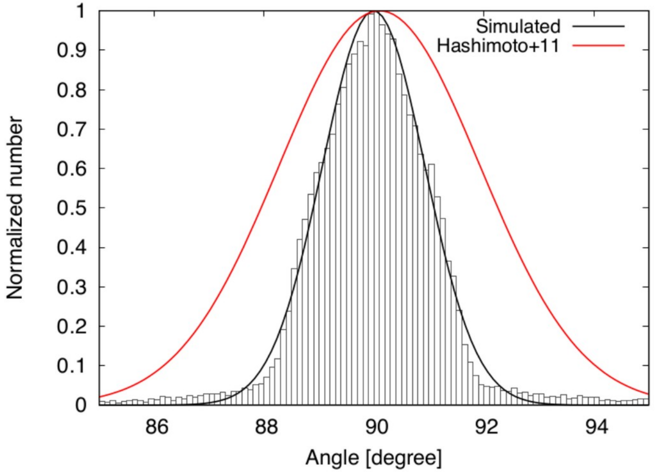
Hashimoto et al. (2011) ApJ

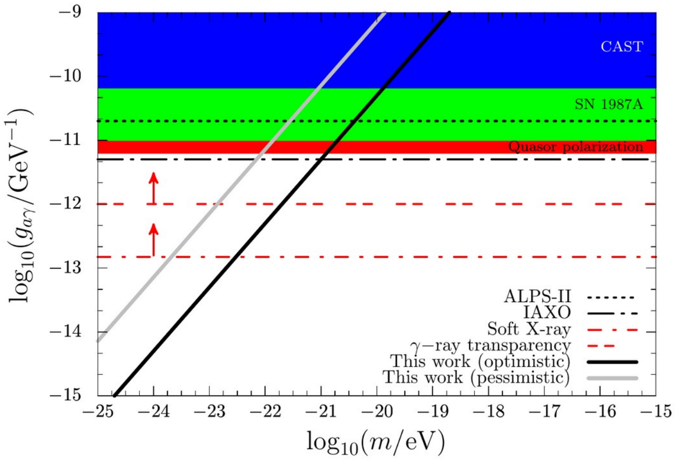
Scattering induces polarization in the perpendicular direction.

For thin disks, photon path is along the radial vector

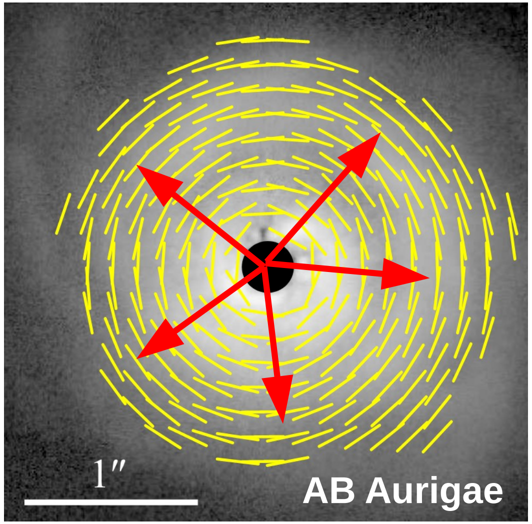
⇒ Polarization perpendicular [tangential to disk]

Birefringence: Protoplanetary discs





Fujita et al. (2019) PRL



Hashimoto et al. (2011) ApJ

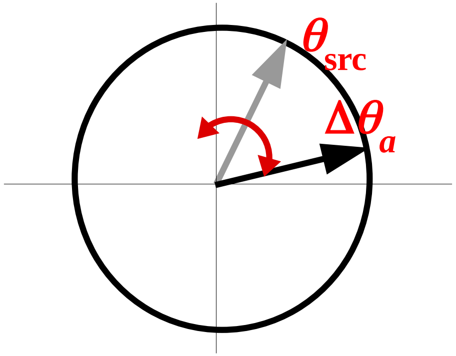
For thin disks, photon path is along the radial vector

⇒ Polarization perpendicular [tangential to disk]

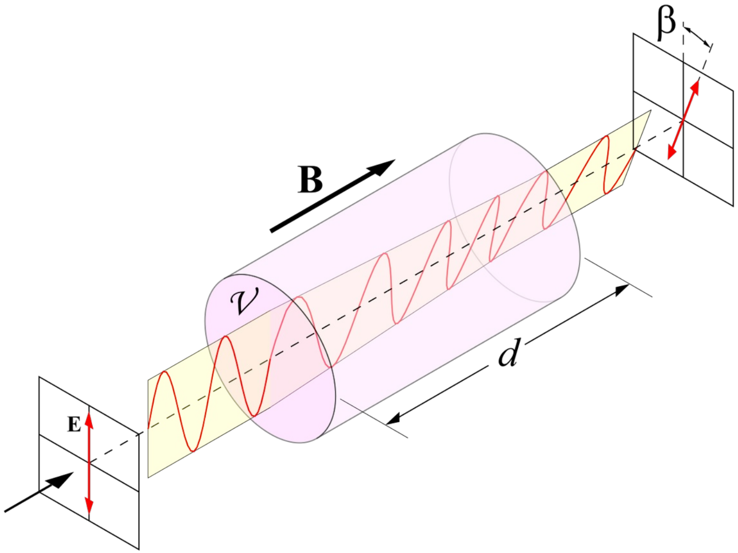
Non-detection limited by angle calibration and astrophysics.

Typical systematics in birefringence

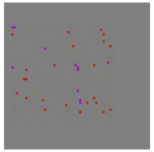
→ *Birefringence (achromatic)*



$$\theta_{\rm obs}(t) = \underline{\Delta\theta_a(t)} + [\theta_{\rm src}(t) + {\rm RM}(t)\,(c/\nu)^2] + \delta\theta_{\rm cal}(t)$$



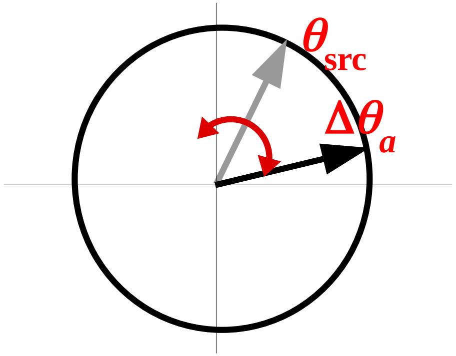
$$\mathrm{RM} = C \int n_{\rm e}\, B_{\|}\, \mathrm{d}l$$



Smoking gun: $\Delta\theta_{\rm a}$ oscillates with time

Typical systematics in birefringence

→ *Birefringence (achromatic)*



Smoking gun: $\Delta\theta_a$ oscillates with time

$$\theta_{\rm obs}(t) = \underline{\Delta\theta_a(t)} + [\theta_{\rm src}(t) + {\rm RM}(t)\,(c/\nu)^2] + \delta\theta_{\rm cal}(t)$$

$[\theta_{\rm src}(t) + {\rm RM}(t)\,(c/\nu)^2]$ ⟶ Assume a source model

External contributions (dust in CMB)

$\delta\theta_{\rm cal}(t)$ ⟶ Requires instrumental stability [days to years]

Polarizer alignment (CMB measurements)

Daily effect: Day/Night

Seasonal effect: Summer/Winter

Solar effects: Solar cycle (11 year)

Birefringence: Strong gravitational lensing

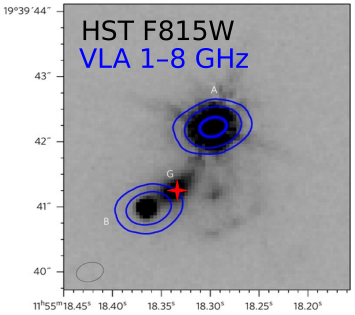
Image A

Image B

Basu et al. (2021), PRL

Schwarz, Goswami & Basu (2021), PRD.

CLASS B1152+199



Mao, w/ Basu, et al., (2017), Nature astron.

$$\left.\begin{aligned}\theta_{0,\mathrm{A}} &= \theta_{\mathrm{qso}} + \Delta\,\theta_{\mathrm{a,A}} + \delta\,\theta_{\mathrm{cal}} \\ \theta_{0,\mathrm{B}} &= \theta_{\mathrm{qso}} + \Delta\,\theta_{\mathrm{a,B}} + \delta\,\theta_{\mathrm{cal}}\end{aligned}\right\} \quad \Delta\theta_{\mathrm{A,B}} = \Delta\theta_{\mathrm{a,lens}} + \text{statistical noise}$$

$$\Delta\,\theta_{\mathrm{a,lens}} = \frac{\rho_{\mathrm{a}}^{1/2} g_{\mathrm{a}\gamma}}{m_{\mathrm{a}}} \sin\left[\frac{m_{\mathrm{a}}\Delta t}{2}\right] \sin\left(m_{\mathrm{a}} t_{\mathrm{em}} + \delta_{\mathrm{em}} - \pi/2\right)$$

Birefringence: Strong gravitational lensing

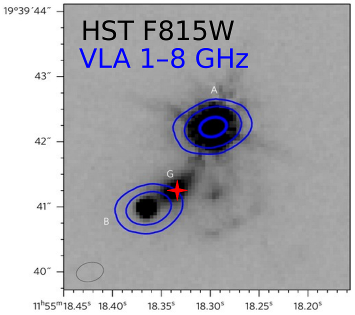
Image A

Basu et al. (2021), PRL

Schwarz, Goswami & Basu (2021), PRD.

Image B

CLASS B1152+199



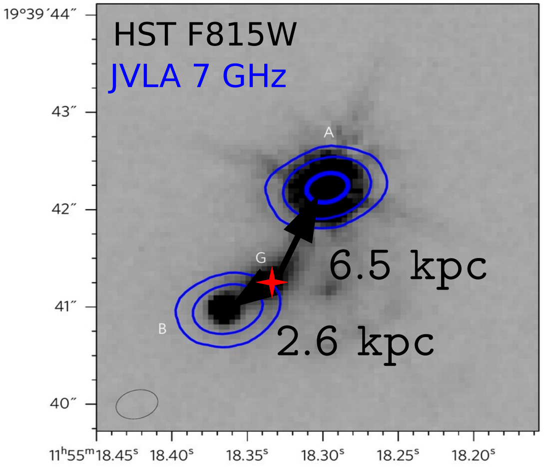
Mao, w/ Basu, et al., (2017), Nature astron.

Spectropolarimetry at cm-wavelengths is needed to remove electromagnetic *(chromatic) birefringence* induced by Faraday rotation.

$$\Delta\theta_{\mathrm{Faraday}} \propto \mathrm{RM}\,\lambda^2 \;\rightarrow\; 0 \text{ at } \lambda = 0$$

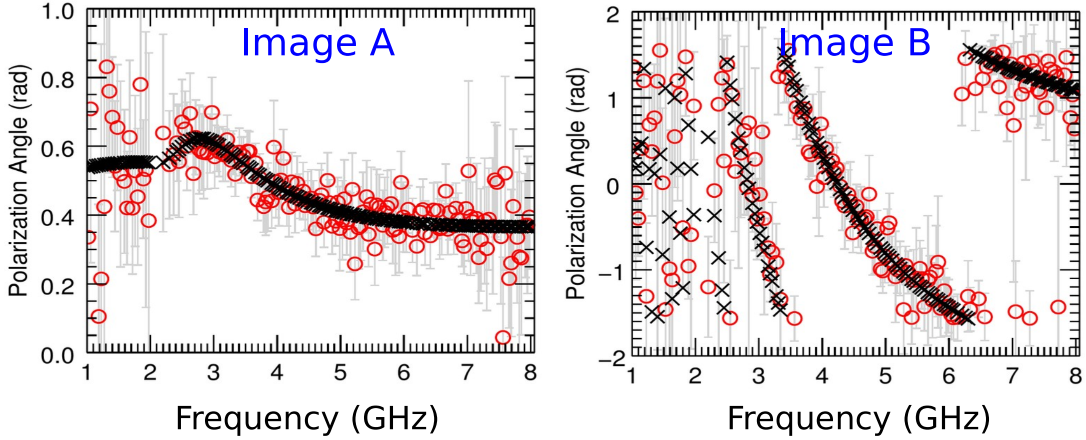
Constrain from CLASS B1152+199

CLASS B1152+199

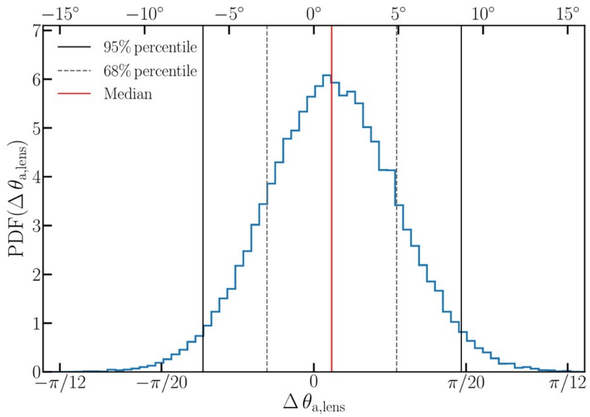


Mao, w/ Basu et al., (2017) Nature Astron.

Karl G. Jansky Very Large Array
(Polarization obs.: 1–8 GHz)

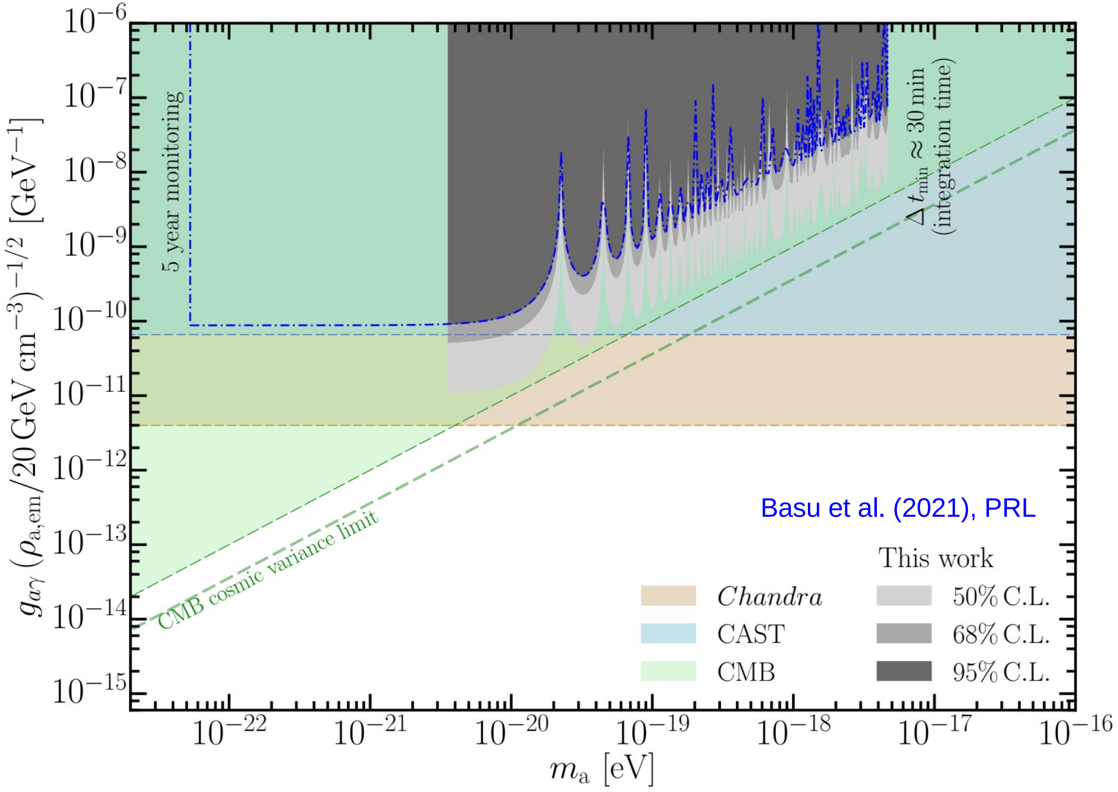


$$\Delta\theta_{a,\mathrm{lens}} = 1.04^{\circ}{}^{+7.67}_{-5.59} \qquad |\Delta\theta_{a,\mathrm{lens}}| \leq 8.71^{\circ}$$



Basu et al. (2021), PRL

Constrain from CLASS B1152+199



Constrain from a single lens system

→ Comparable to CAST

CERN Axion Solar Telescope

Robust constraints: free of calibration systematics and astrophysical assumptions

Strong gravitational lensing: towards statistical sample

Preliminary

Constrain from a (small) sample of lensed system

→ Already improved over CAST

Currently being followed up through multi-epoch broadband VLA+VLBA campaign (PI: Basu)

→ 100 hr of simultaneous observations

Deshmukh, Basu, Schwarz et al. (in prep.)

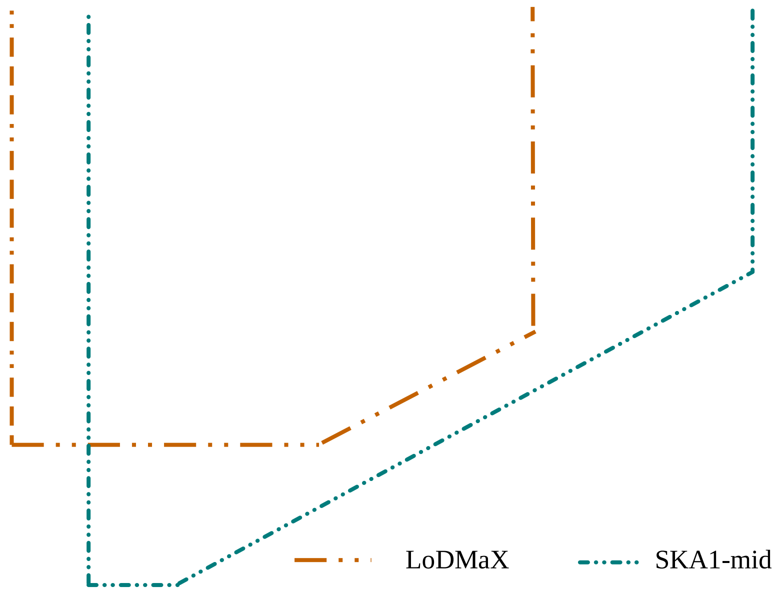
Kovaćs, Mao, w/ Basu, et al. (in prep.)

$$\Delta\theta_{a,\mathrm{lens}} = 1.07^{\circ}{}^{+3.97}_{-1.86} \quad |\Delta\theta_{a,\mathrm{lens}}| \leq 2.5^{\circ}$$

Robust constraints: free of calibration systematics and astrophysical assumptions

Extension to a sample

Strong gravitational lensing: towards statistical sample



Constrain from a (small) sample of lensed system

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Deshmukh, Basu, Schwarz et al. (in prep.)

Kovaćs, Mao, w/ Basu, et al. (in prep.)

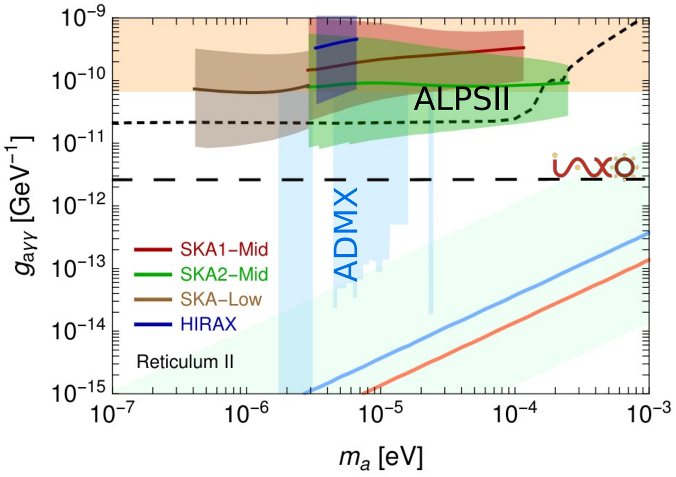
Expected: $|\Delta\theta_{a,\mathrm{lens}}| \ll 0.1^\circ$

Robust constraints: free of calibration systematics and astrophysical assumptions

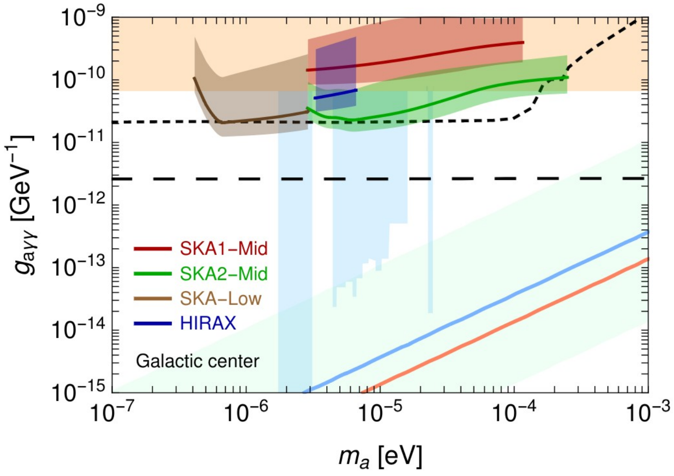
Extension to a sample

DM-rich systems: Stimulated decay

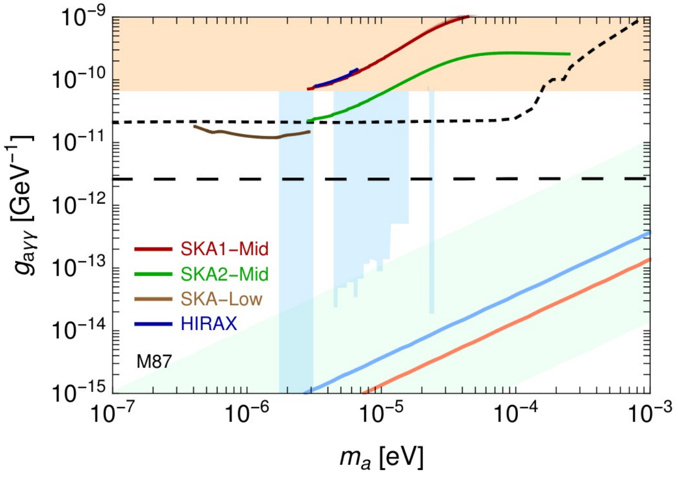
Dwarf Spheroidal galaxies



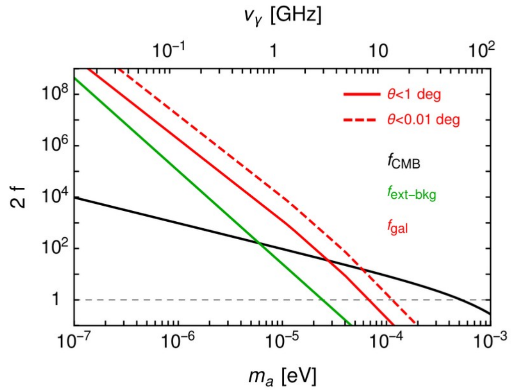
Galactic center



M87



Caputo et al. (2019), JCAP



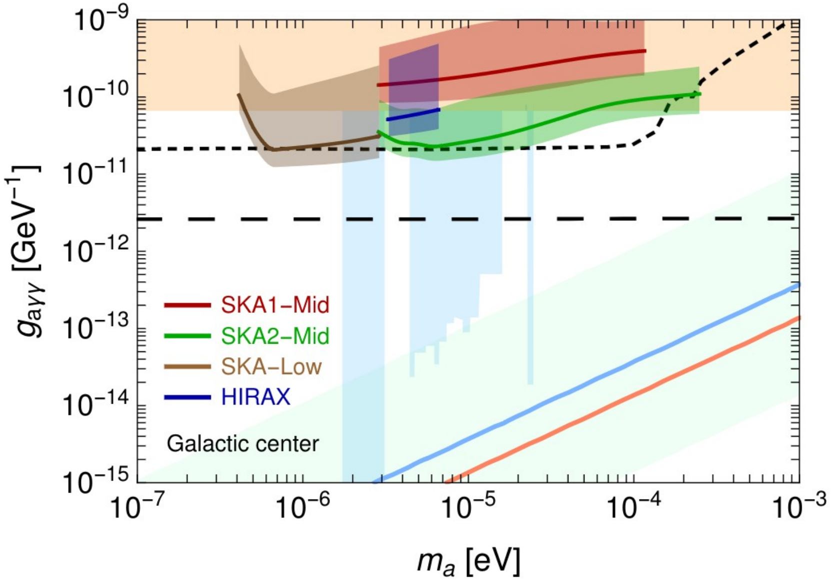
In a photon bath, axions decays into two photons

$$\nu_0 = \frac{m_a}{4\,\pi\,\hbar}$$

Elisa's talk on Wednesday

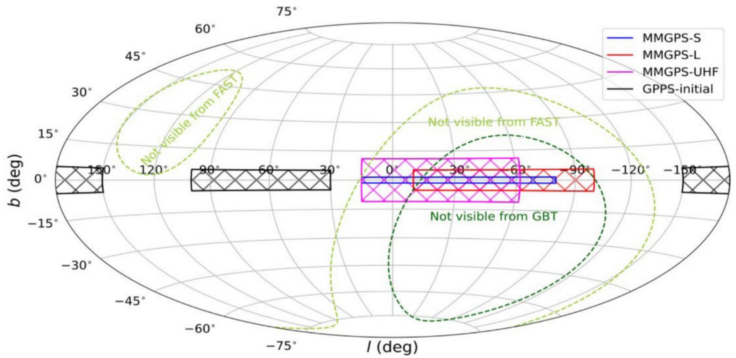
Galactic center: recent future

Galactic center



The MPIfR MeerKAT Galactic Plane Survey (MMGPS)

[PI: Michael Kramer; Project scientist: Basu]

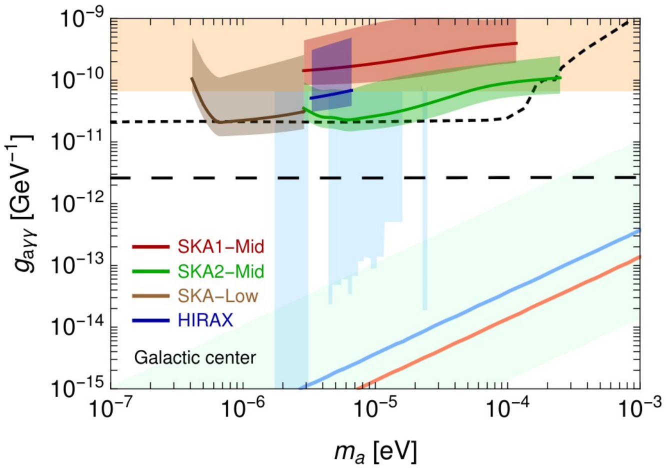


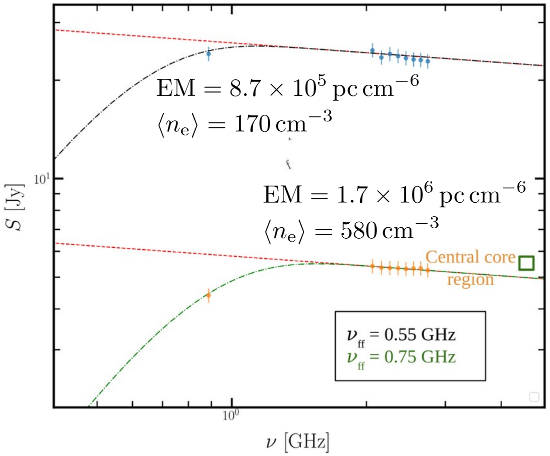
Padmanabh et al. (2023), MNRAS

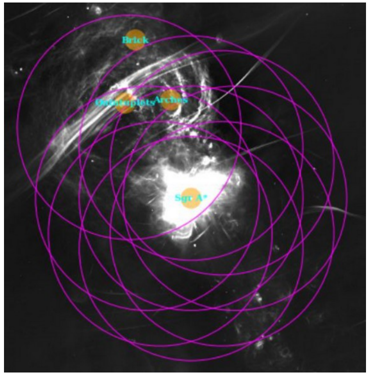
3000 hr survey of the Galactic plane covering ~600 MHz to 2.8 GHz

Galactic center: recent future

Galactic center







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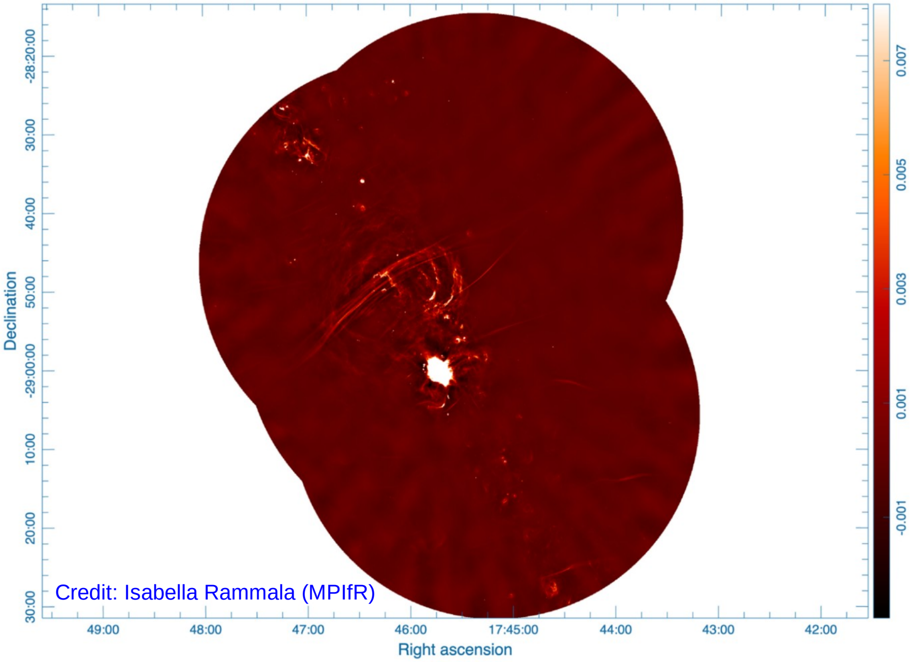
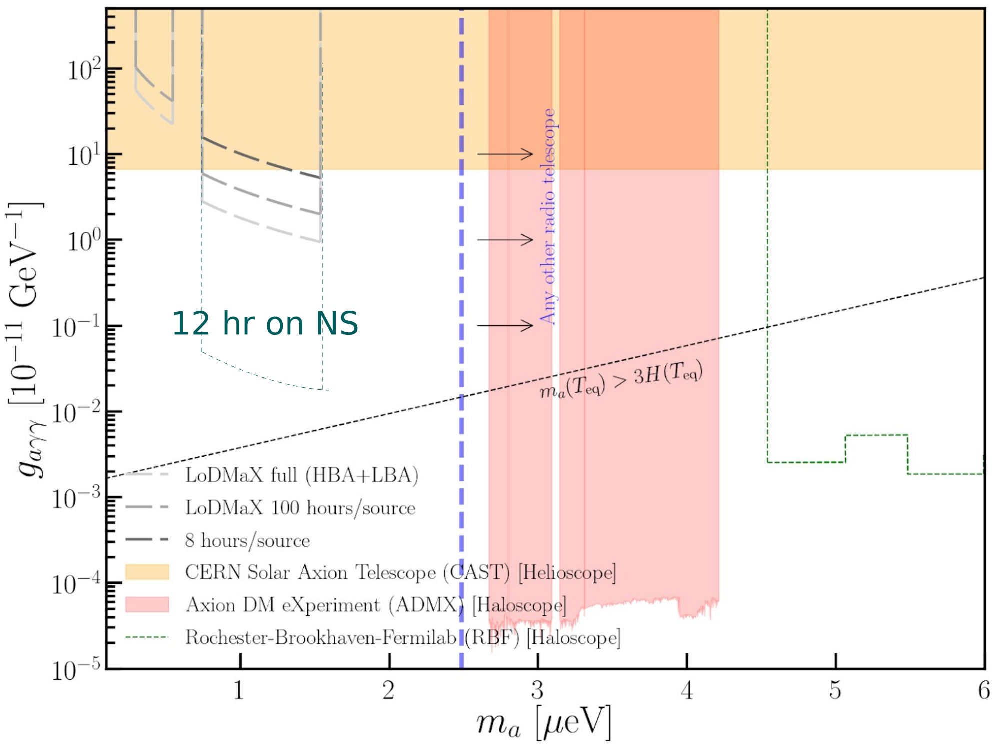


- 200 hr dedicated to GC (1.9–3.5 GHz)
- ~5–10 arcsec resolution (0.2 to 40 pc physical scale)
- 32k channels ⇒ $\Delta\nu/\nu \sim 3 \times 10^{-5}$

DM-rich systems: Stimulated decay at low frequencies



LOFAR2.0 can probe lower mass regime

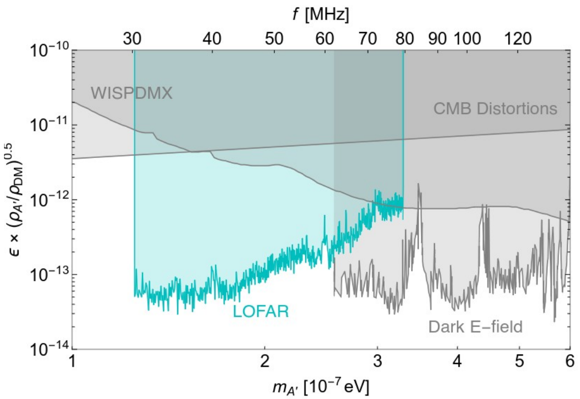
→ Inaccessible to other radio telescopes and lab-experiments

Frequency : 40 to 170 MHz

m_a : 0.5 to 1.5 μeV

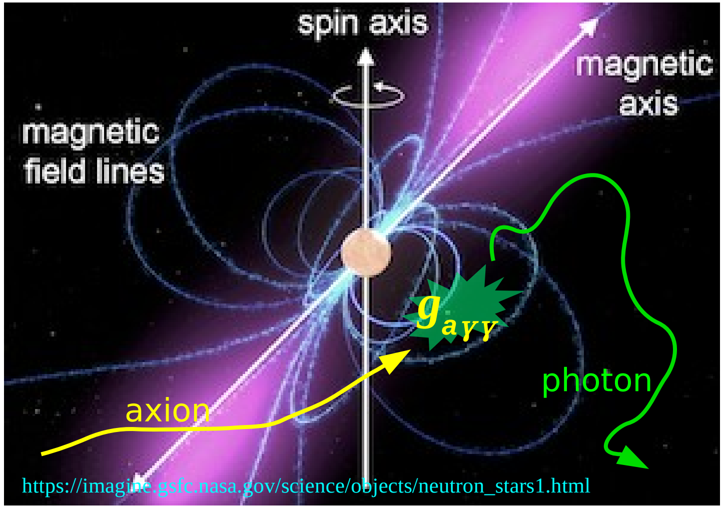
Targets: dwarf Spheroidals,
Red (dead) ellipticals,
(Super) Relaxed galaxy clusters,
Isolated neutron stars, …

Solar observations!



An et al. (2024), Nature Com.

Strong magnetic fields: axion to photon conversion



$$\mathcal{L} \to g_{a\gamma\gamma}\, a\, E \cdot B$$

$$p_{a\to\gamma} \sim g_{a\gamma\gamma}^2\, B^2\, L^2$$ Probability of (resonant) conversion

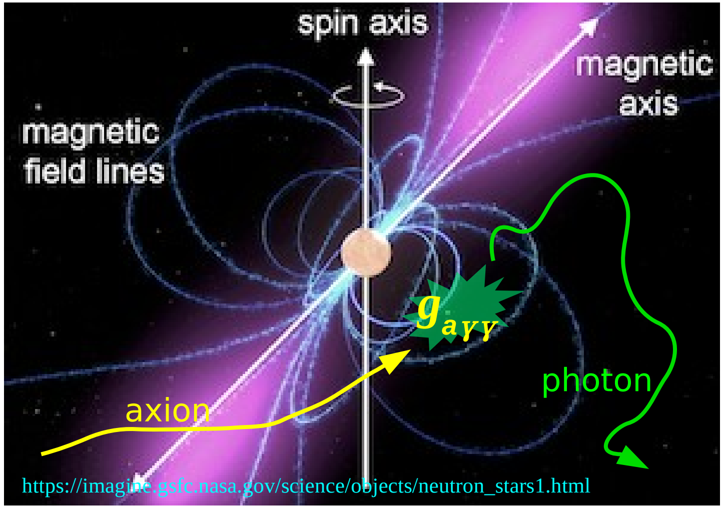
$$m_a = \omega_p = \mathcal{O}(10\,\mu\mathrm{eV})$$ [QCD axions]

Strong-B ~ 10^{14} G

Jamie & Sam's talks on Wednesday

Small coherence L ~ 10–100 km

Strong magnetic fields: axion to photon conversion



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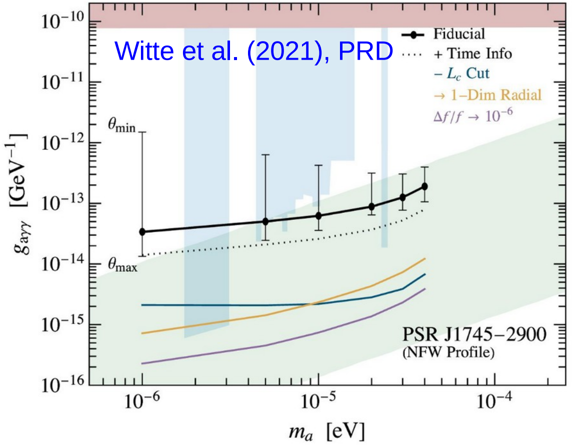
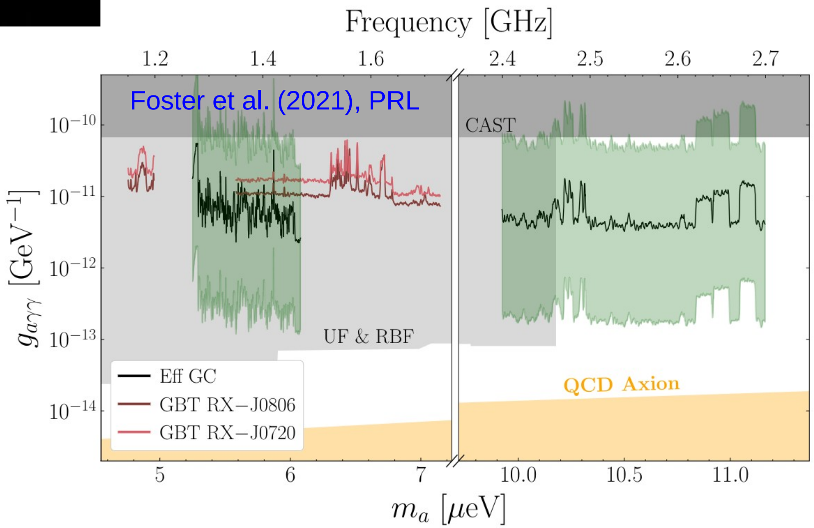
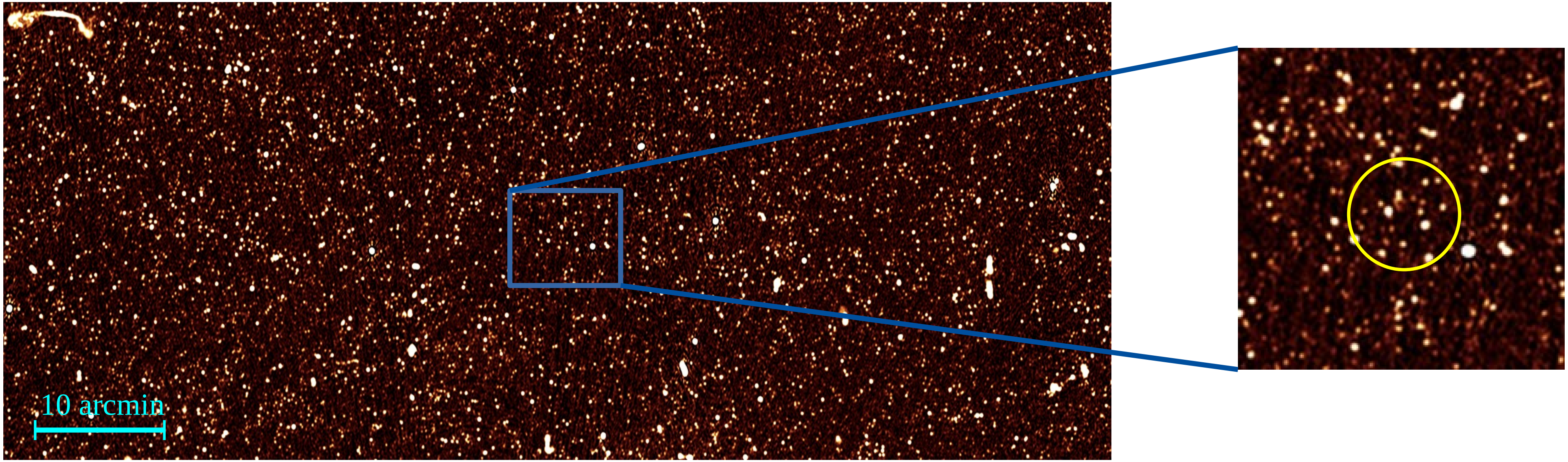




Also see:
Hook et al. (2018), PRL
Battye et al. (2021), JHEP
Battye et al. (2023), PRD

Neutron stars: Single dish *vs.* Interferometers

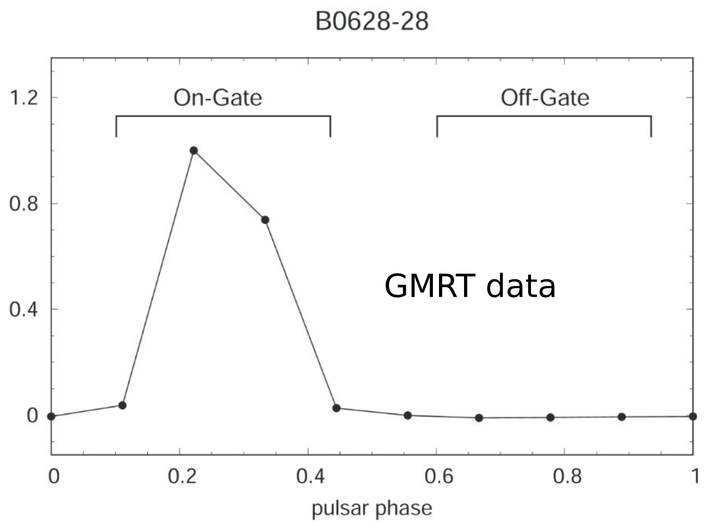


Heywood et al. (2022), MNRAS

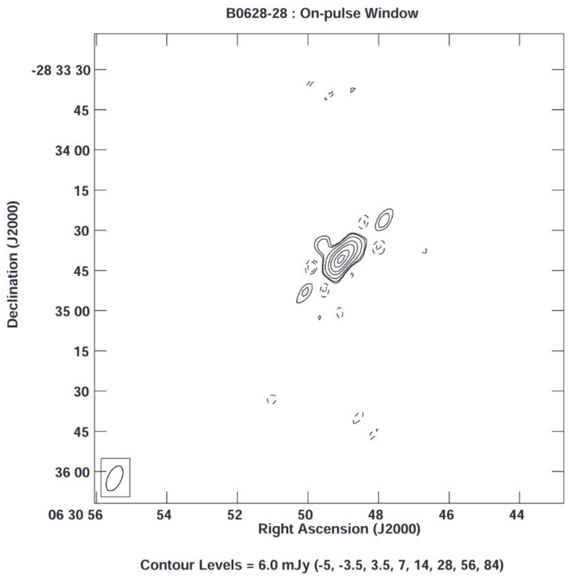
Typical FoV of single dishes has many sources in them!

- Challenging flux level (zero level offset)
- Contaminating sources (confusion limited)
- Spurious signal from recombination lines

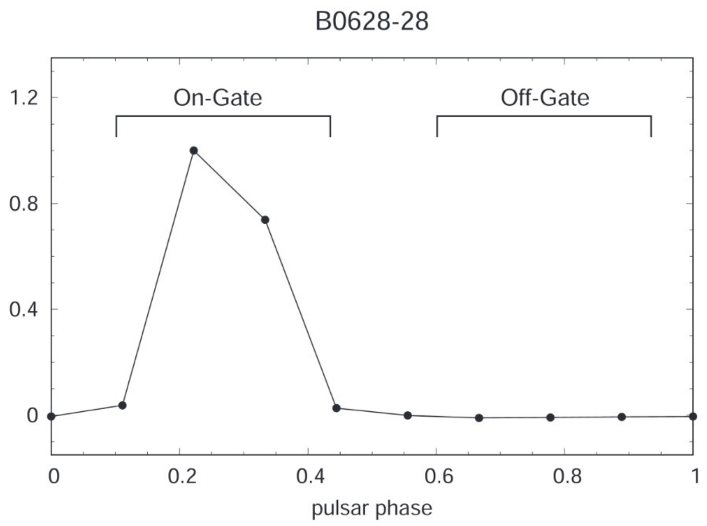
Neutron stars: direct imaging

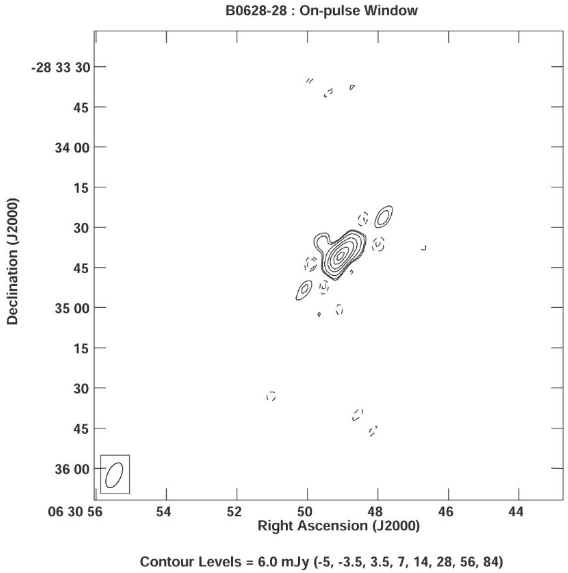


Basu R., Mitra & Melikidze (2020), ApJ



Neutron stars: direct imaging





Basu R., Mitra & Melikidze (2020), ApJ

Correlate data offline

→ Make images at μs—ms
→ confident signal from NS

Correlated visibilities (for astronomers)

$^{N}C_2$ values averaged over 1 to 10 s

↓

Frequency channels : 2^{10}–2^{16}
×
Stokes parameters : 4

} 1–20 TB per 8 h obs

Raw digitized data: 150–400 GBps ⇒ 0.5–3 GBps

Raw data → 2 to 10 PB per 8 h observation (not stored at all)
(all processed by a "correlator" in real time)

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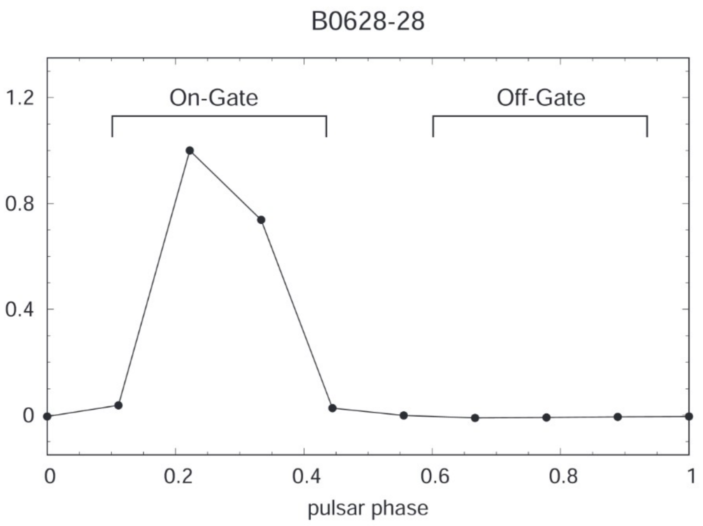

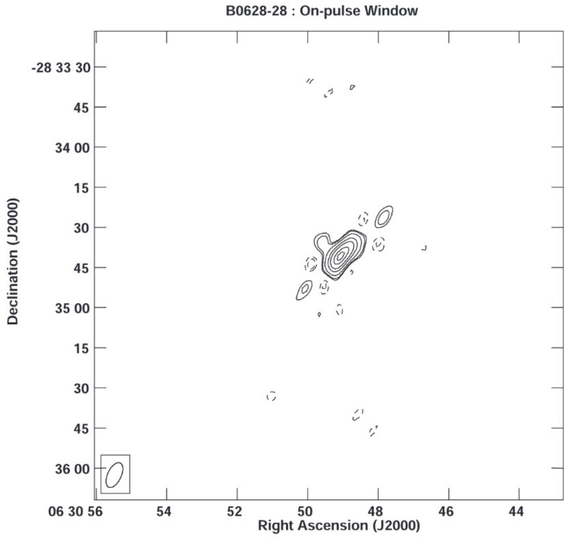

Basu R., Mitra & Melikidze (2020), ApJ

Correlate data offline

→ Make images at μs—ms
→ confident signal from NS

Doable with MMGPS, but....
800 TB per hour!!!

Correlated visibilities (for astronomers)

${}^{N}C_2$ values averaged over 1 to 10 s

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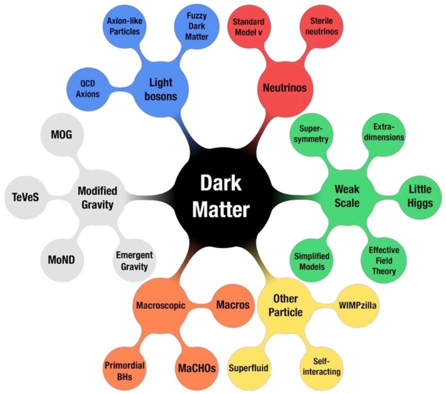
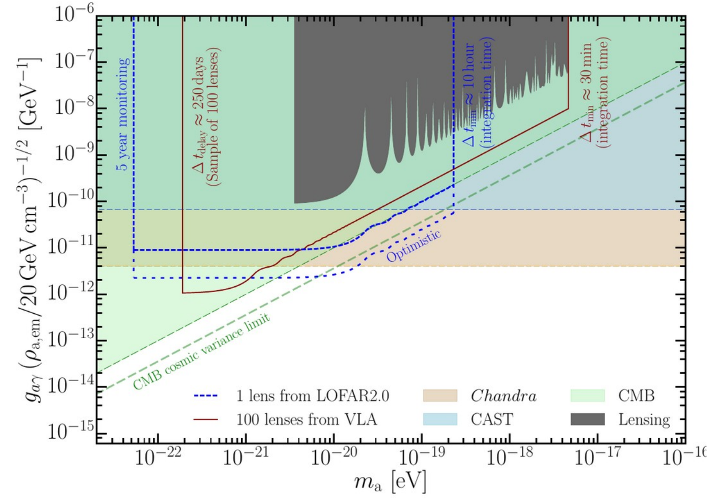
DM searches at radio frequencies



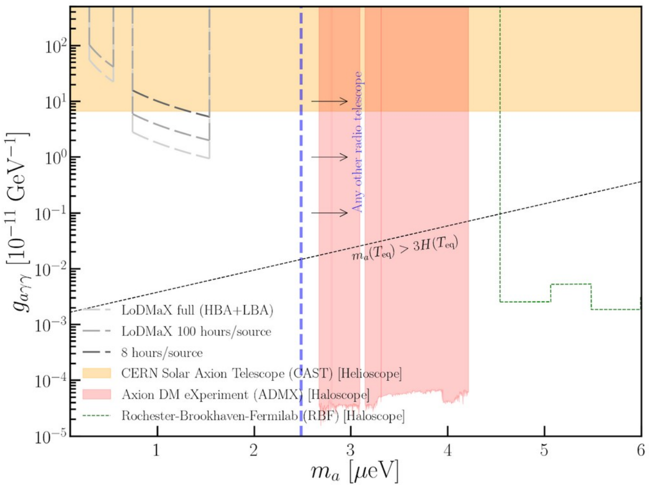
- Radio astronomy can play a crucial role in expanding DM searches
  - Often probes complementary parameter space w.r.t on-going lab-experiments
  - *Requires dedicated community effort to make DM searches mainstream astrophysics*
- Almost all observational techniques can be exploited
  - Polarimetry: ALP birefringence [strong lenses, compact objects, black holes]
  - Deep continuum imaging: WIMPs, wimpzillas, neutralino [dSphs, ellipticals, relaxed clusters]
  - Spectral line: Primakoff effect, Sterile neutrinos, dark photons [neutron stars, dSphs, ellipticals]
  - Timing: Ultralight ALPs, cosmic strings [pulsar timing arrays]
- Explore new theoretical ideas and astrophysical systems
  - *SKA precursors: ASKAP and MeerKAT are already providing exciting data*
  - Harness the synergy between radio astronomy and particle physics!
  - Characteristics of the signal → Setup optimal/dedicated observations

LOFAR2.0 Dark Matter eXperiment (LoDMaX)



Polarimetry

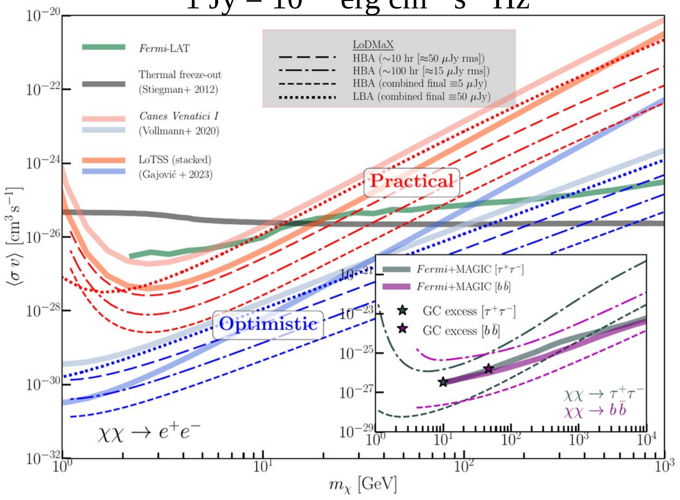
Ultralight ALPs



Spectral line

QCD axions
Heavy ALPs
Dark photons

$1\ \mathrm{Jy} = 10^{-23}\ \mathrm{erg\ cm^{-2}\ s^{-1}\ Hz^{-1}}$



Deep continuum

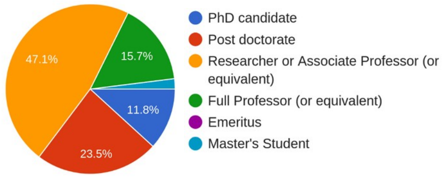
WIMP annihilation
(e^+e^-, $\tau^+\tau^-$, *bb*)
Decaying DM
– wimpzillas, glueballs

A LOFAR2.0 large programme for up to 6000 hr has been submitted to hunt for DM

To join the LoDMaX team – contact: Dominik J. Schwarz and me

dschwarz@physik.uni-bielefeld.de; abasu@tls-tautenburg.de

Currently, 80 members from 15 countries



https://sites.google.com/view/lodmax/home