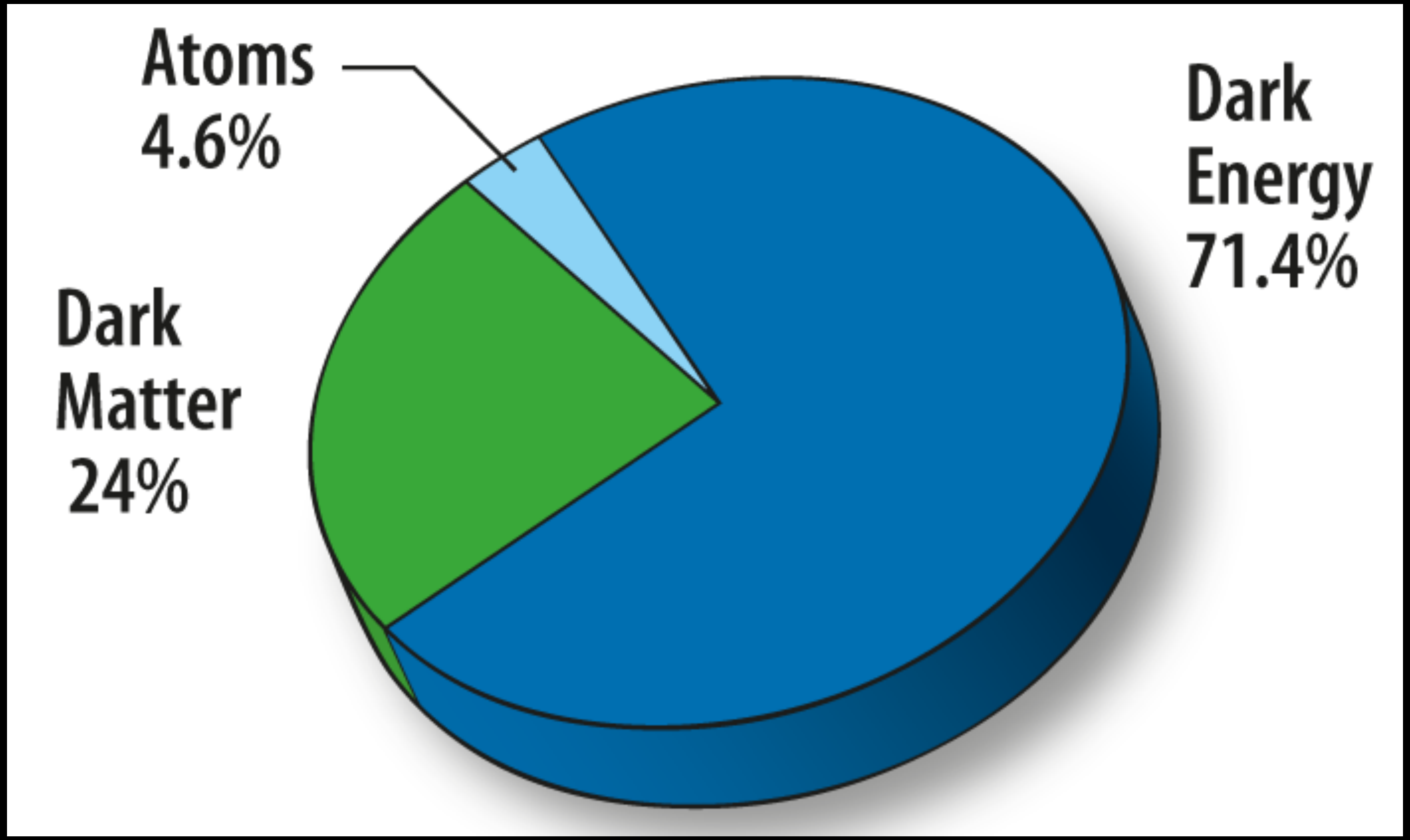
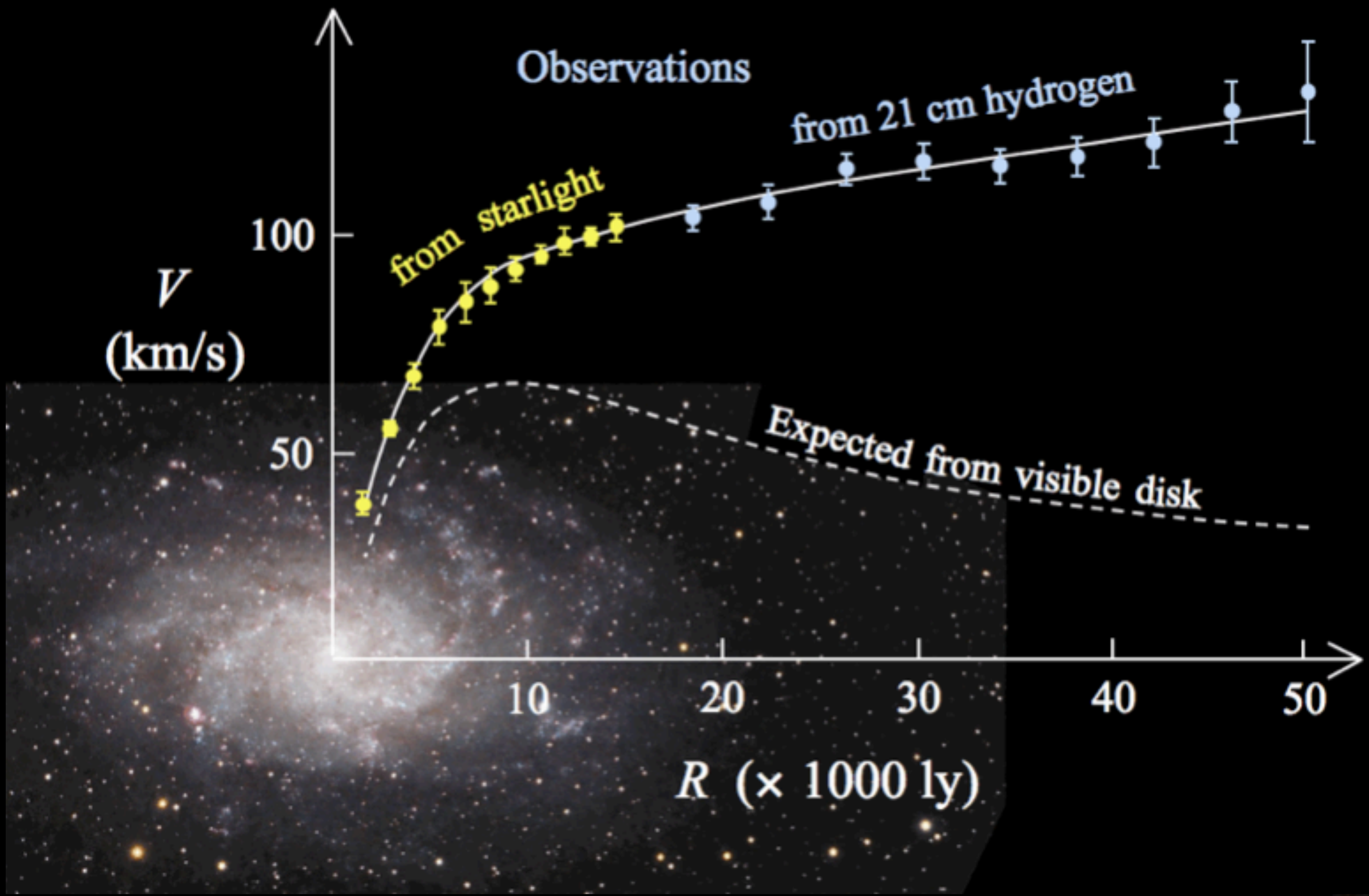
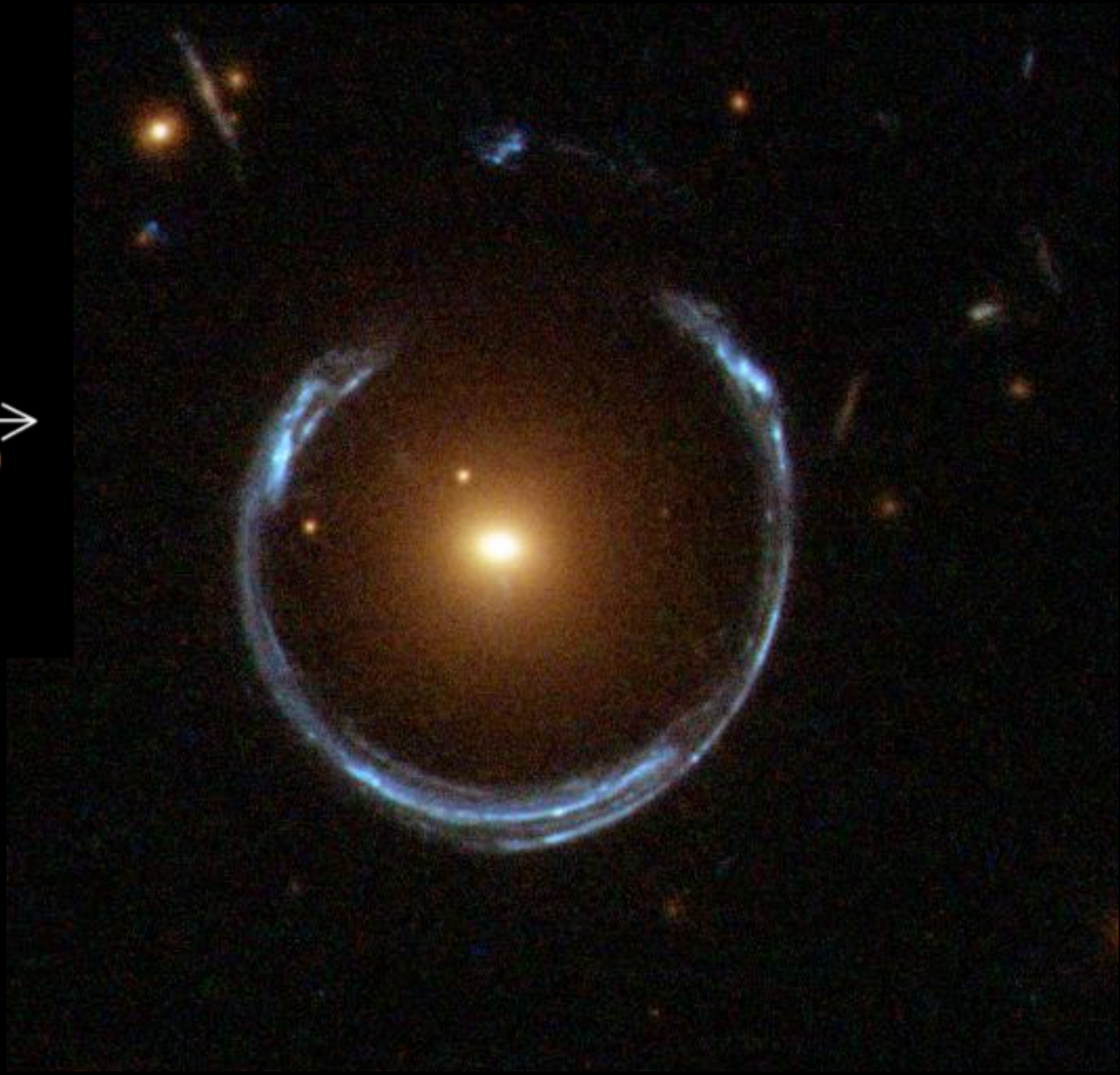
Searching for Axion dark matter with the MeerKAT radio telescope

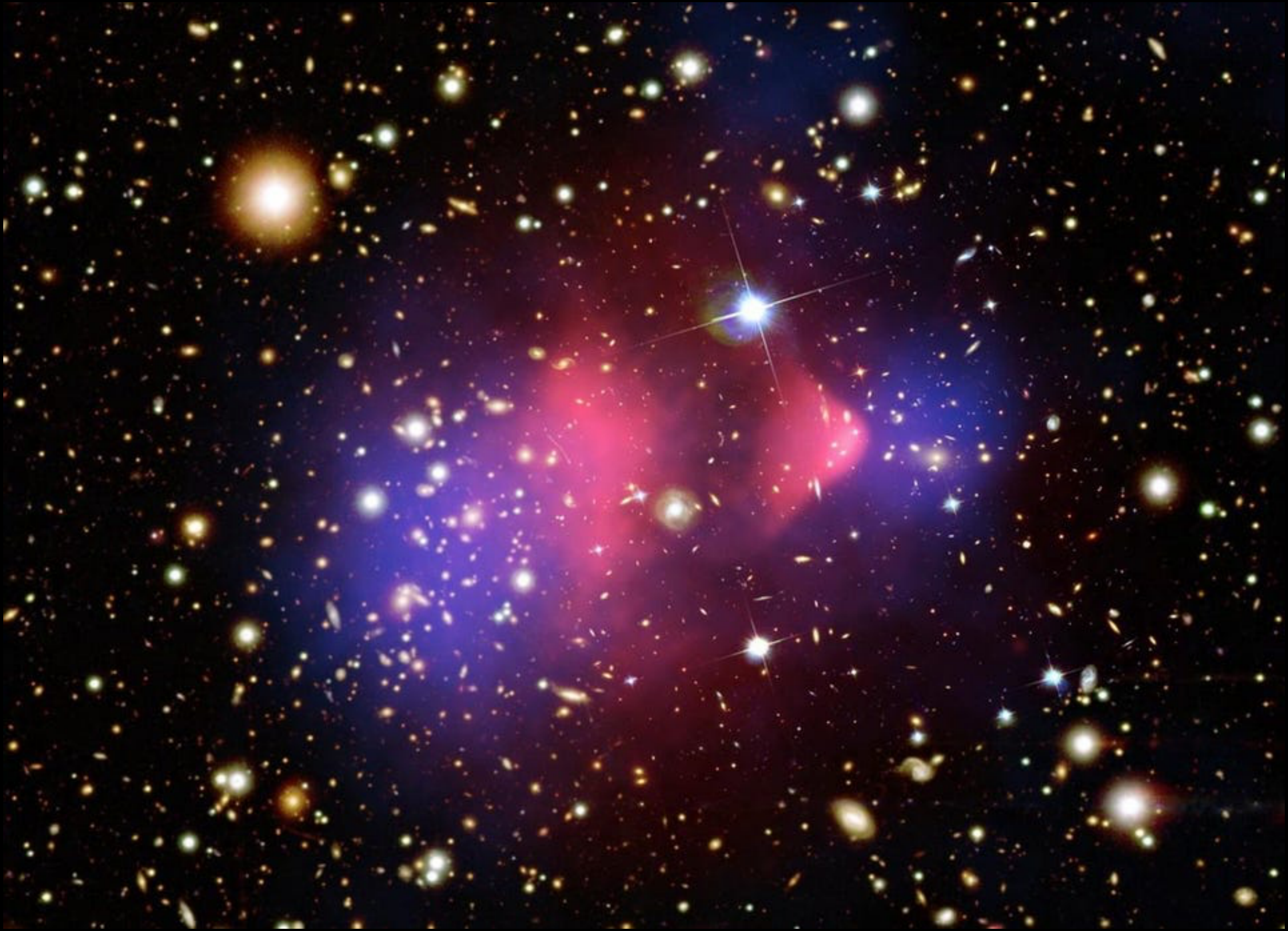
Dr. Nick Houston
Beijing University of Technology
On behalf of the MeerKAT-Axion collaboration:

Qiang Yuan (PMO), Yin-Zhe Ma (UKZN/PMO)
Yunfan Zhou, Xiaoyuan Huang, Fujun Du, Yogesh Chandola, Chandreyee Sengupta (PMO),
Nick Houston, Ran Ding (Anhui U.), Gyula Jozsa (SARAO/MPIfRA), Hao Chen (UCT)

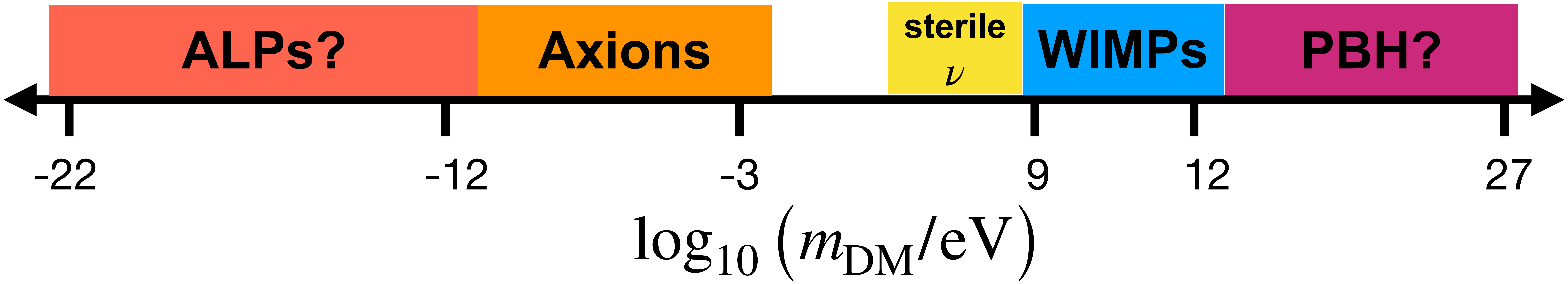



Observations
from 21 cm hydrogen
from starlight
100
V
(km/s)
50
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)

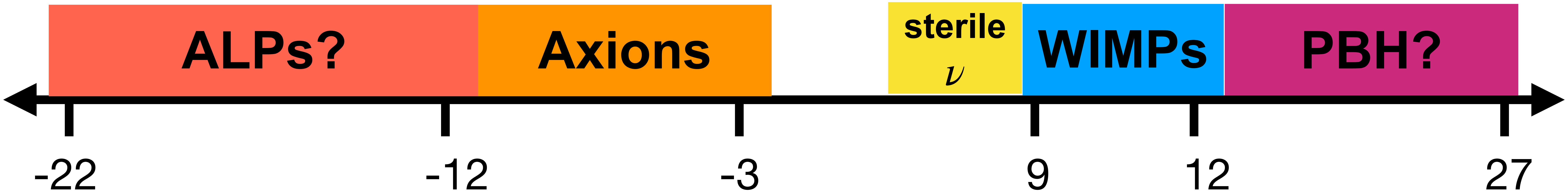




It is a huge scale to search!



It is a huge scale to search!

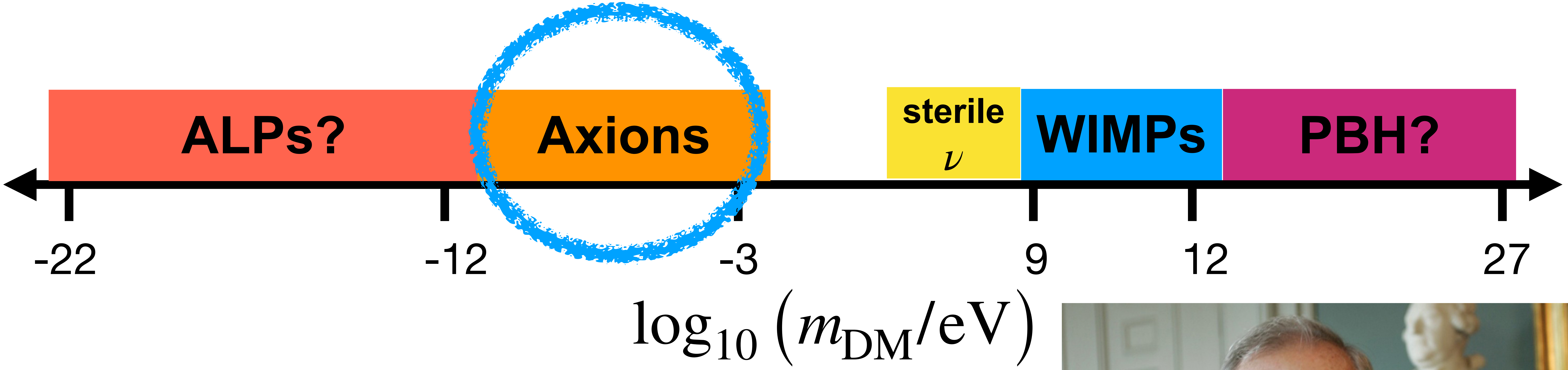


$$\log_{10}\left(m_{\rm DM}/{\rm eV}\right)$$

You don’t know where to look, so you have to work hard and look everywhere.

—Nobel Telephone Interview of James Peebles (October 2019)

It is a huge scale to search!

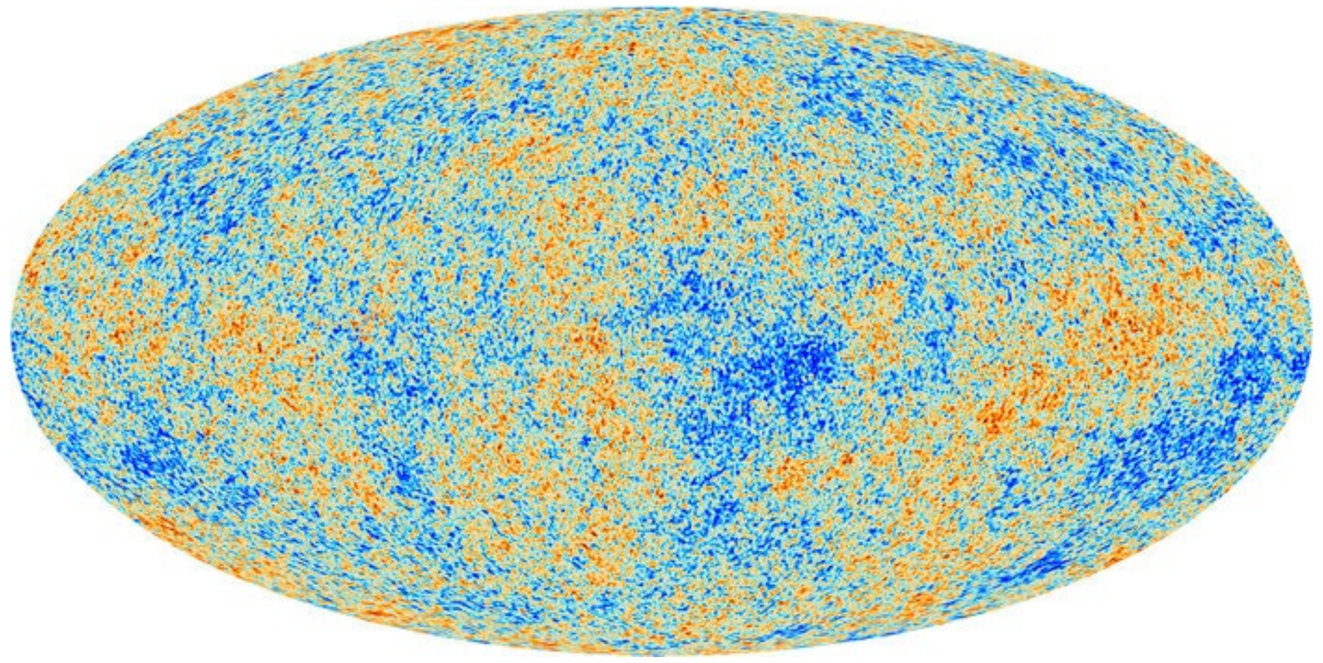


You don't know where to look, so you have to work hard and look everywhere.

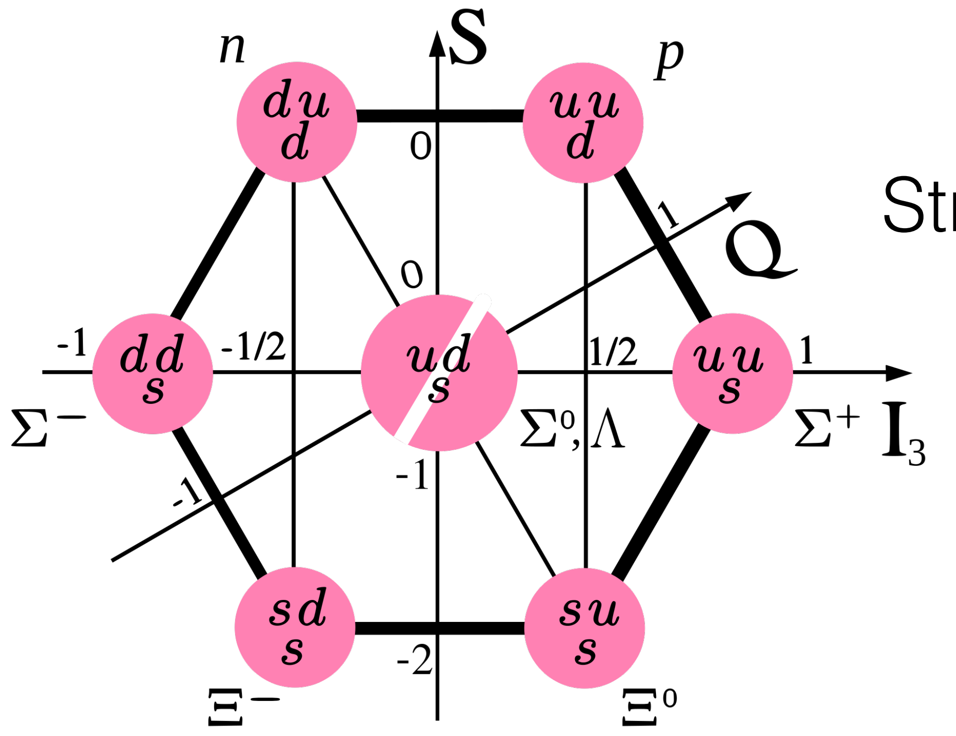
—Nobel Telephone Interview of James Peebles (October 2019)

Axions are light (sub-eV) pseudo-Goldstone bosons, characterised broadly by their mass and an overall scale (their decay constant)

They arise both as a minimal extension of the Standard Model, to solve the Strong CP problem, whilst also being a generic prediction of the exotic physics of string and M theory

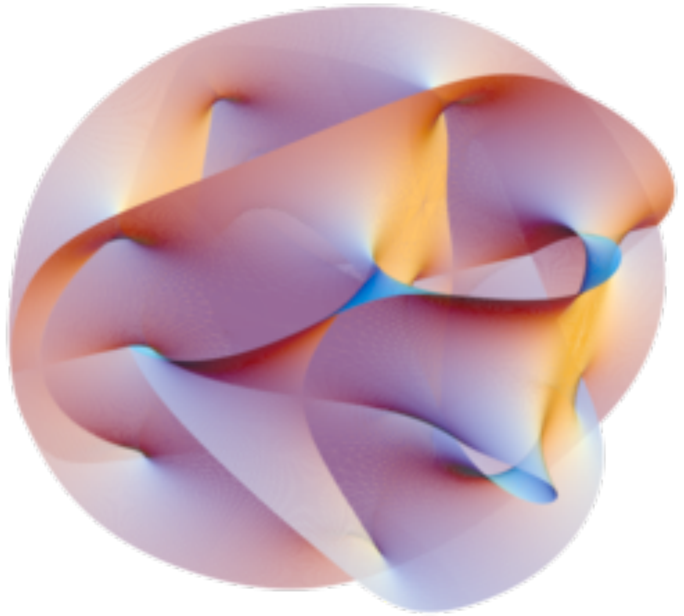


(Planck 2015)

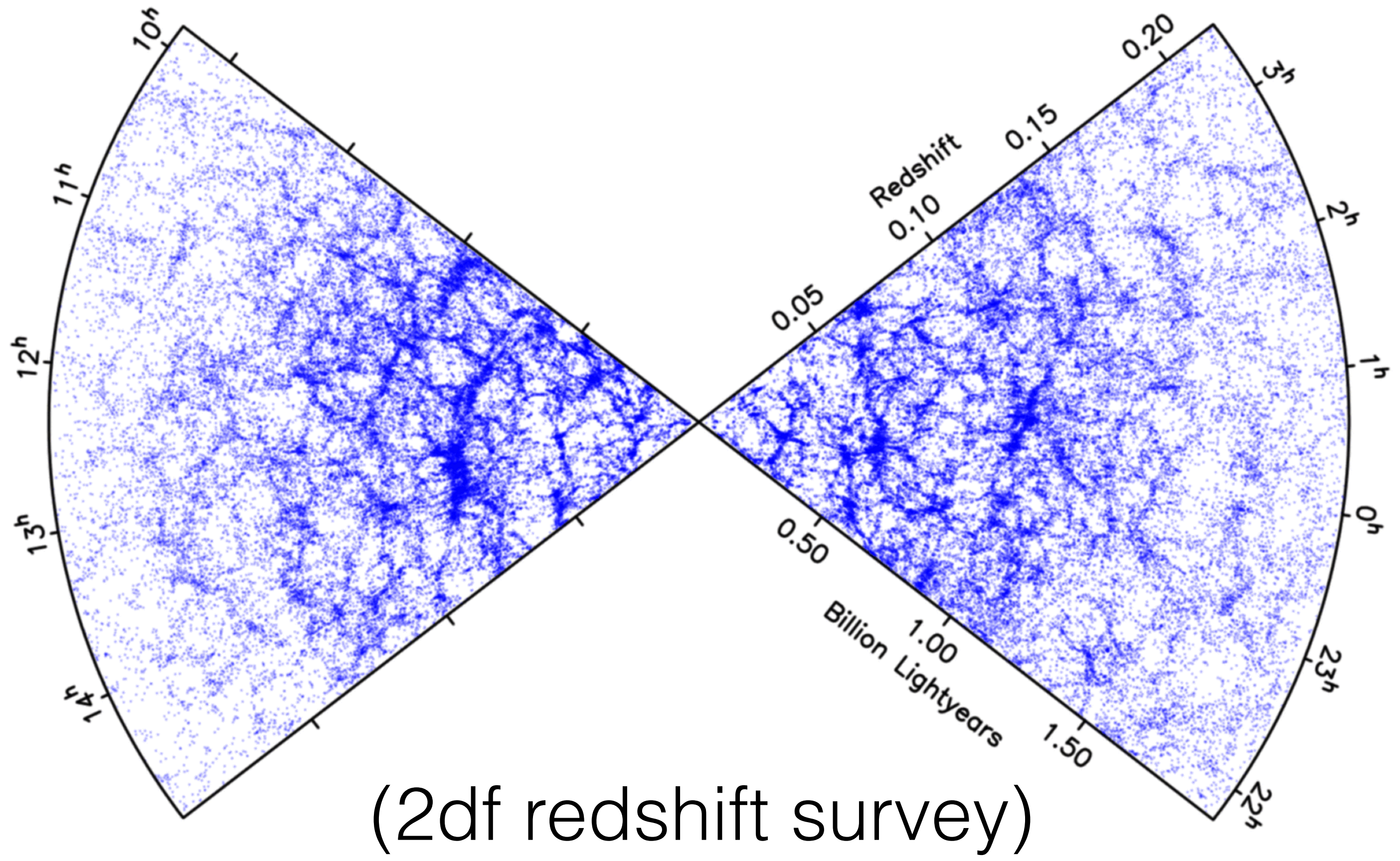


Strong CP problem

Compactifications

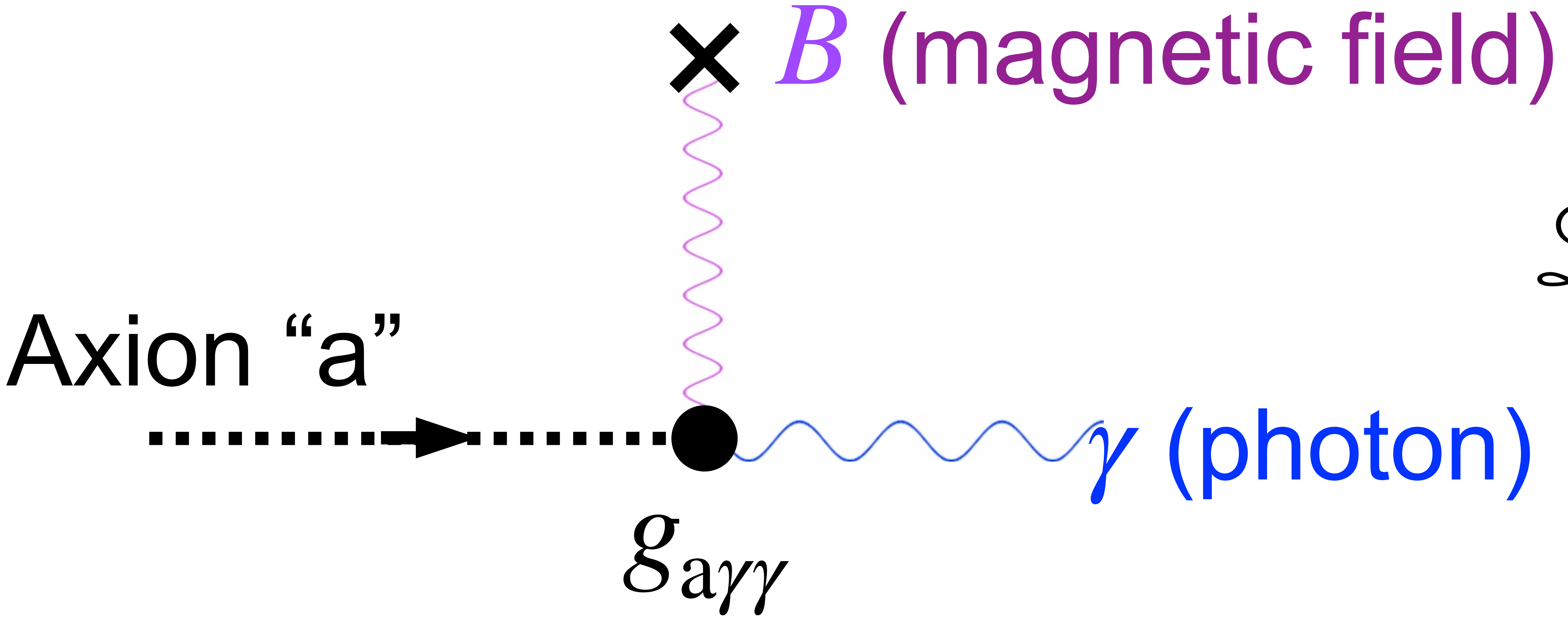


In turn they can affect:
early Universe cosmology, inflation,
big bang nucleosynthesis, CMB formation,
dark matter, dark energy, stellar evolution,
galaxy formation, large scale structure…



(2df redshift survey)

Converting Axions into photons



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

How to calculate this flux?

- **Input:** Standard dark matter density, velocity distribution. From Liouville's theorem

$$\rho_{\rm DM}^{r_c} = \rho_{\rm DM}^{\infty} \frac{2}{\sqrt{\pi}} \frac{1}{v_0} \sqrt{\frac{2GM_{\rm NS}}{r_c}} + \cdots$$

- **Conversion:** Use a GJ model for the NS magnetosphere:

$$B_z = \frac{B_0}{2} \left(\frac{r_0}{r}\right)^3 \left[3 \cos\theta \, \hat{\mathbf{m}} \cdot \hat{\mathbf{r}} - \cos\theta_m\right] \qquad \hat{\mathbf{m}} \cdot \hat{\mathbf{r}} = \cos\theta_m \cos\theta + \sin\theta_m \sin\theta \cos(\Omega t)$$

- Solve EOMs to find axion/photon oscillation probability

$$\left[-i\frac{d}{dr} + \frac{1}{2k}\begin{pmatrix} m_a^2 - \xi\,\omega_p^2 & \Delta_B \\ \Delta_B & 0 \end{pmatrix}\right]\begin{pmatrix} \tilde{A}_{\parallel} \\ \tilde{a} \end{pmatrix} = 0\,, \quad \xi = \frac{\sin^2\tilde{\theta}}{1 - \frac{\omega_p^2}{\omega^2}\cos^2\tilde{\theta}}\,, \quad \Delta_B = B g_{a\gamma\gamma} m_a \frac{\xi}{\sin\tilde{\theta}}\,,$$

- **Output:** Use geodesic equations to propagate photons to Earth, ideally accounting for time dependence, gravitational, plasma effects etc

- First explored in Pshirkov et al, *J.Exp.Theor.Phys.* 108 (2009), arxiv: 0711.1264. However this was mostly ignored until Hook et al, Phys.Rev.Lett. 121 (2018), arxiv: 1804.03145. Since then $\mathcal{O}(20)$ theory/observational papers

MeerKAT 2020 Open Time call for proposal

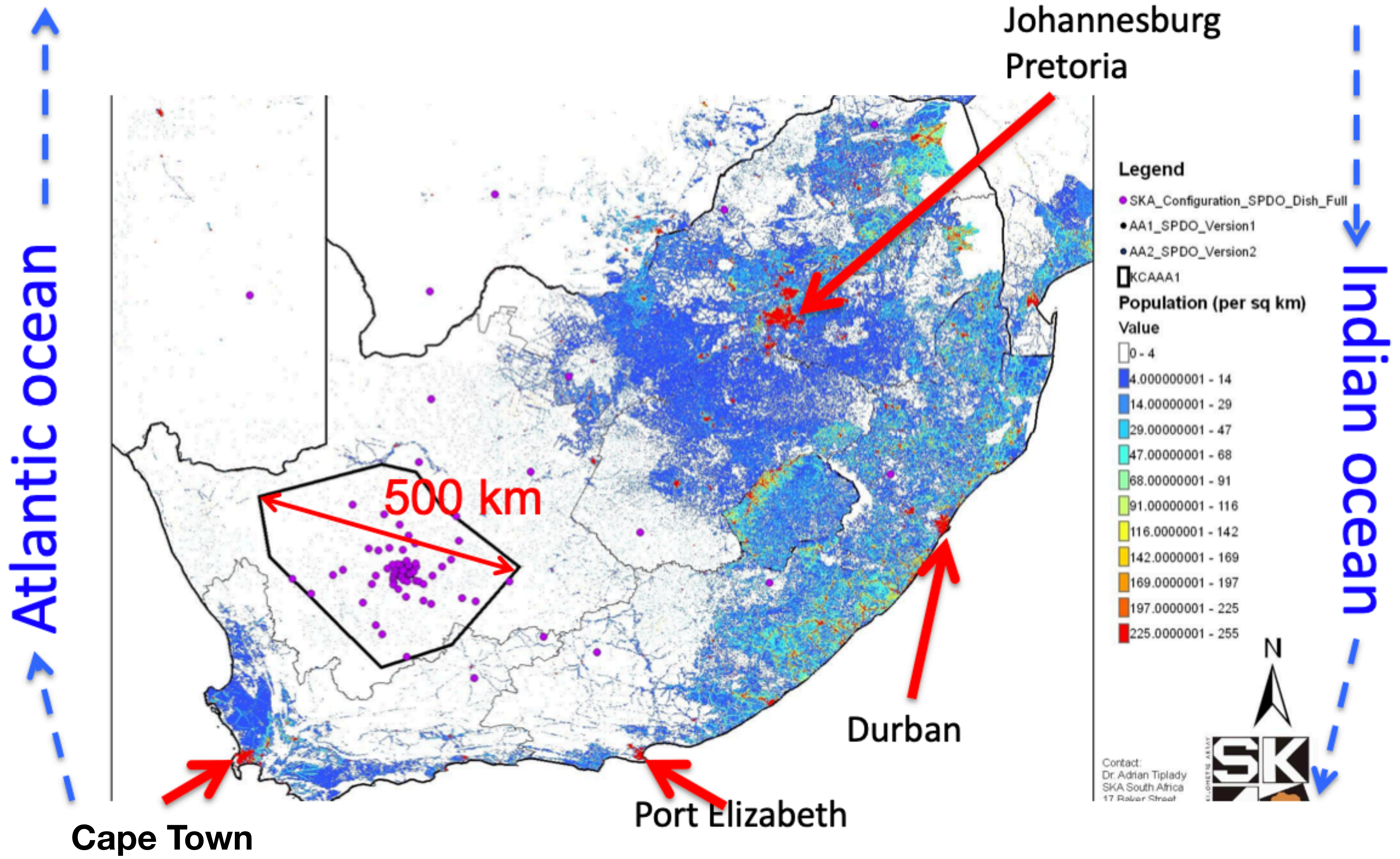
Qiang Yuan (PMO), Yin-Zhe Ma (UKZN/PMO)
Nick Houston (BJUT), Yunfan Zhou, Chandreyee Sengupta, Xiaoyuan Huang, Fujun Du, Yogesh Chandola (PMO), Ran Ding (Anhui U.), Gyula Jozsa (SARAO/MPIfRA), Hao Chen (UCT)

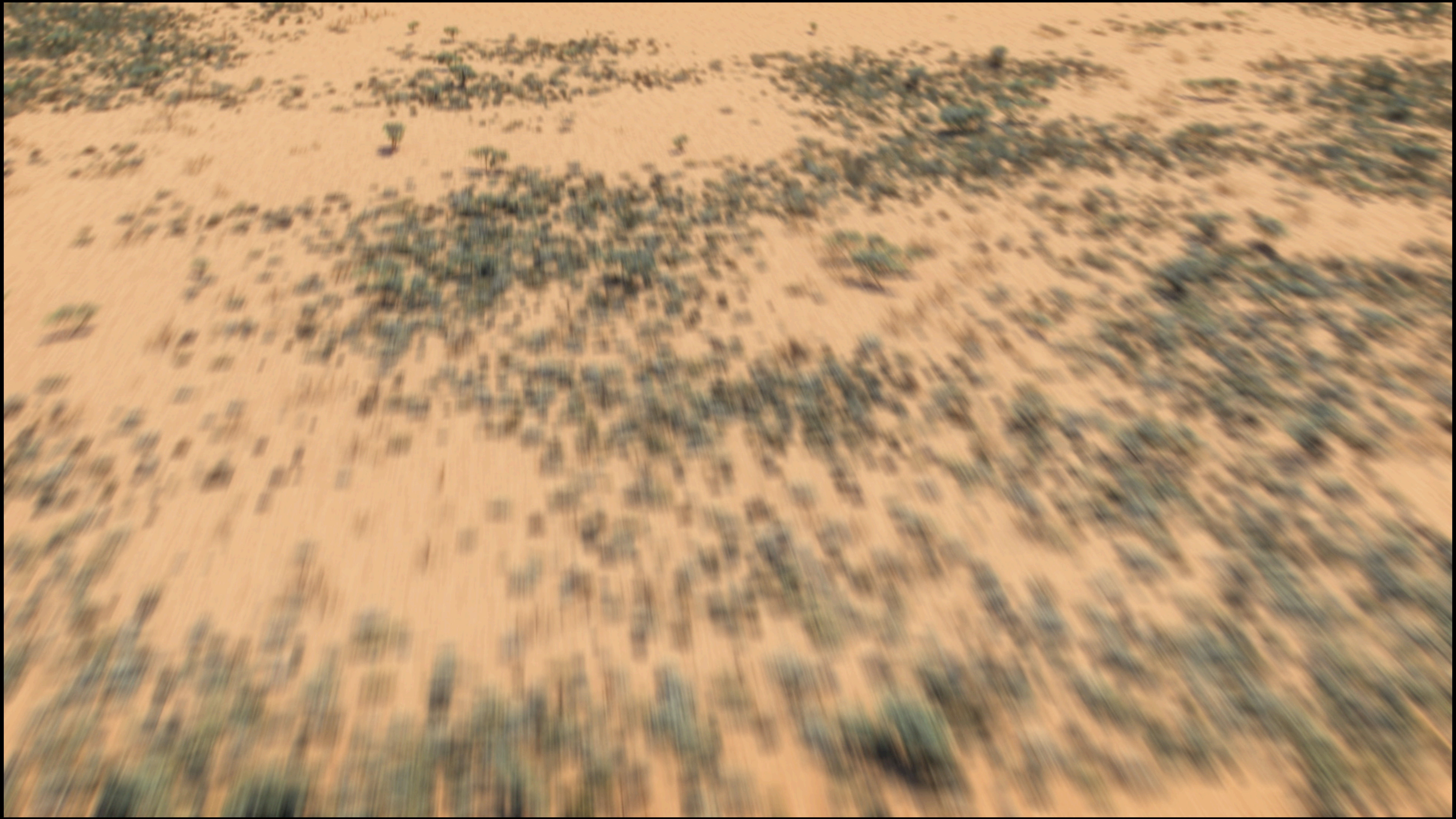
UHF Band MeerKAT

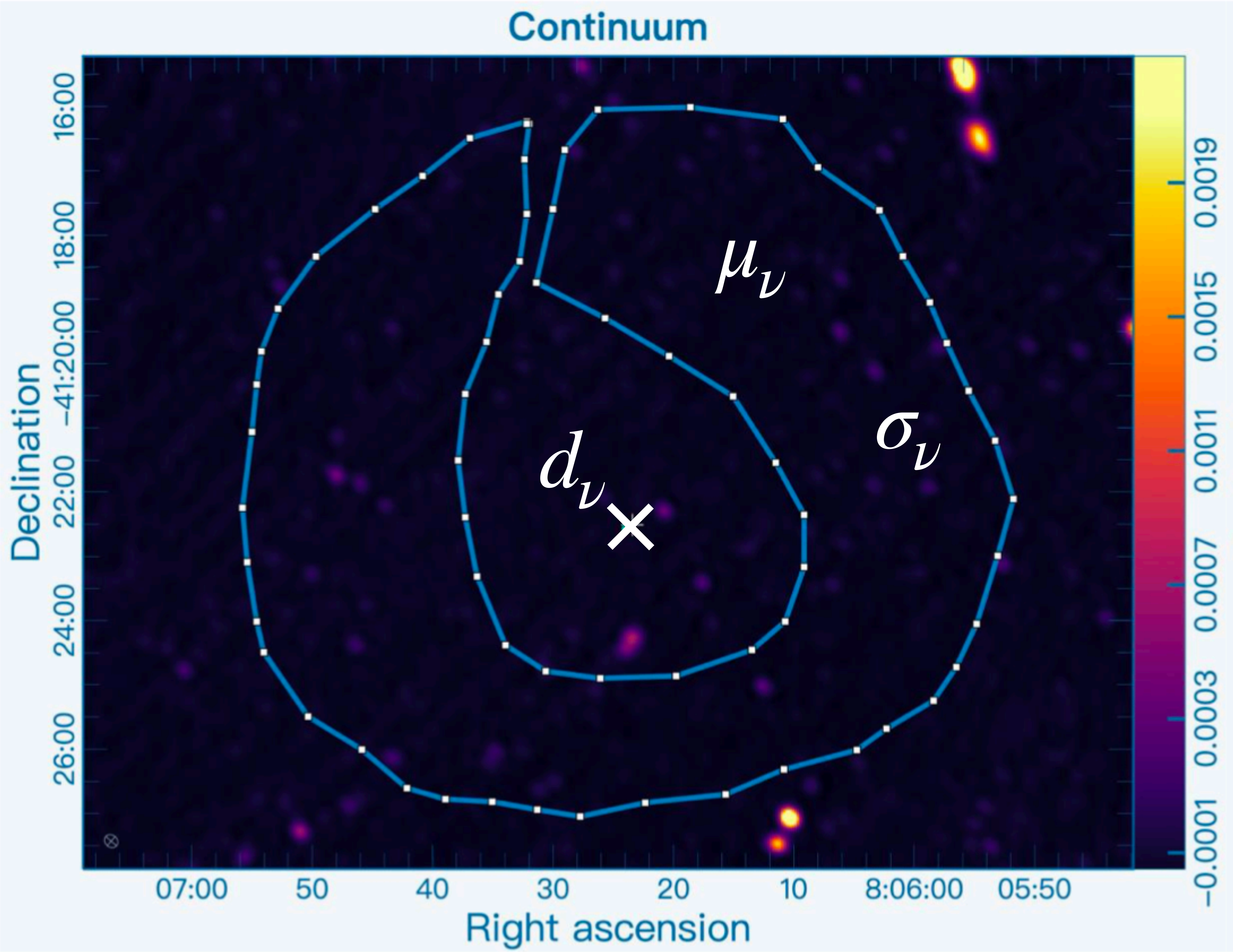
Target: neutron star RX J0806.4-4123
frequency range: 544-1,088 MHz
Axion mass range: 2.5-5 $\mu\mathrm{eV}$
Frequency resolution: 16 kHz
Area observed: $19\,\mathrm{arcmin} \times 14.9\,\mathrm{arcmin}$
Time resolution: 8 seconds

→ Allocated time: 10 hours (Priority A)

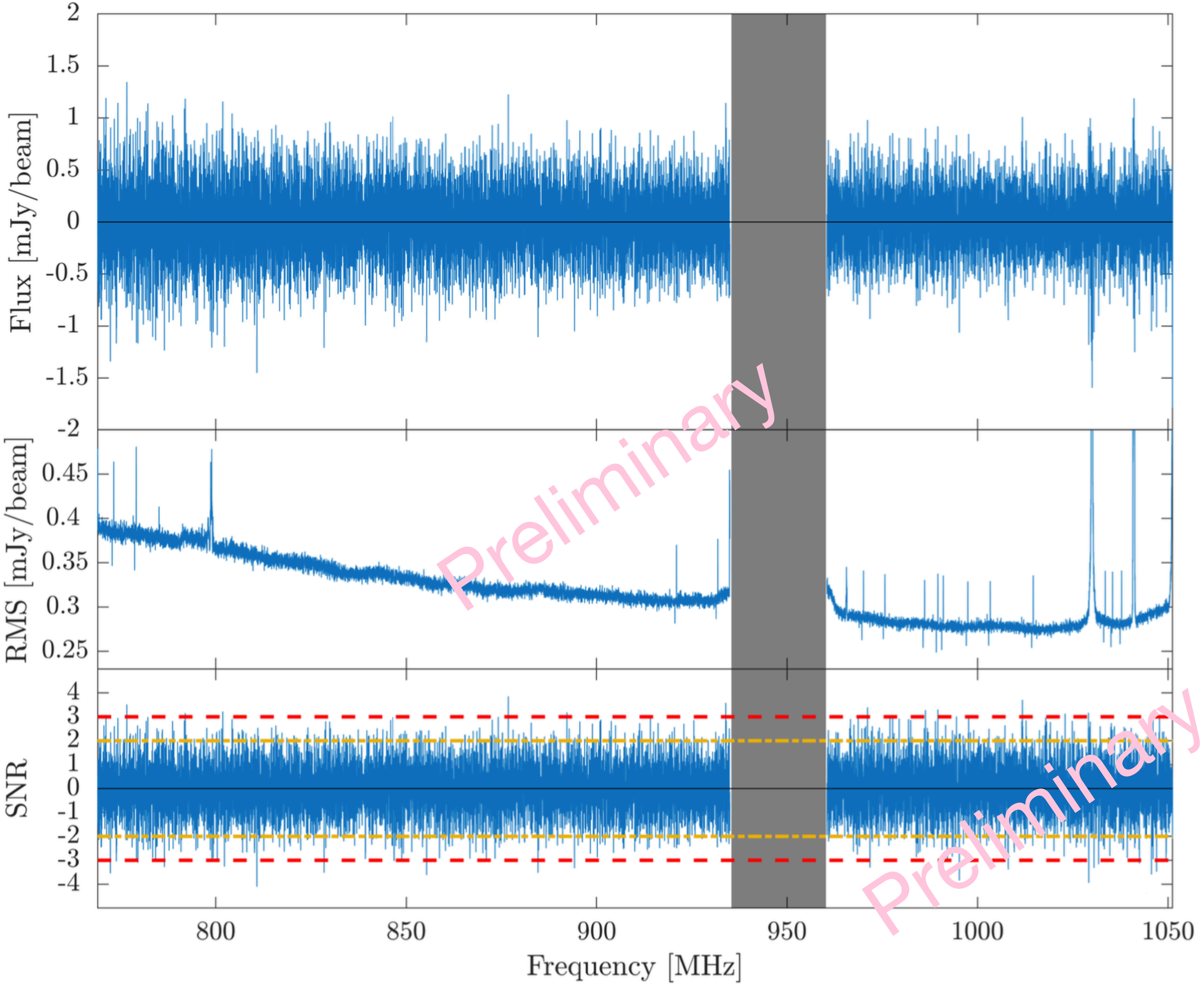
The Square Kilometre Array (SKA) in South Africa







Continuum
Declination
16:00
18:00
−41:20:00
22:00
24:00
26:00
Right ascension
07:00
50
40
30
20
10
8:06:00
05:50
−0.0001
0.0003
0.0007
0.0011
0.0015
0.0019
μ_ν
σ_ν
d_ν



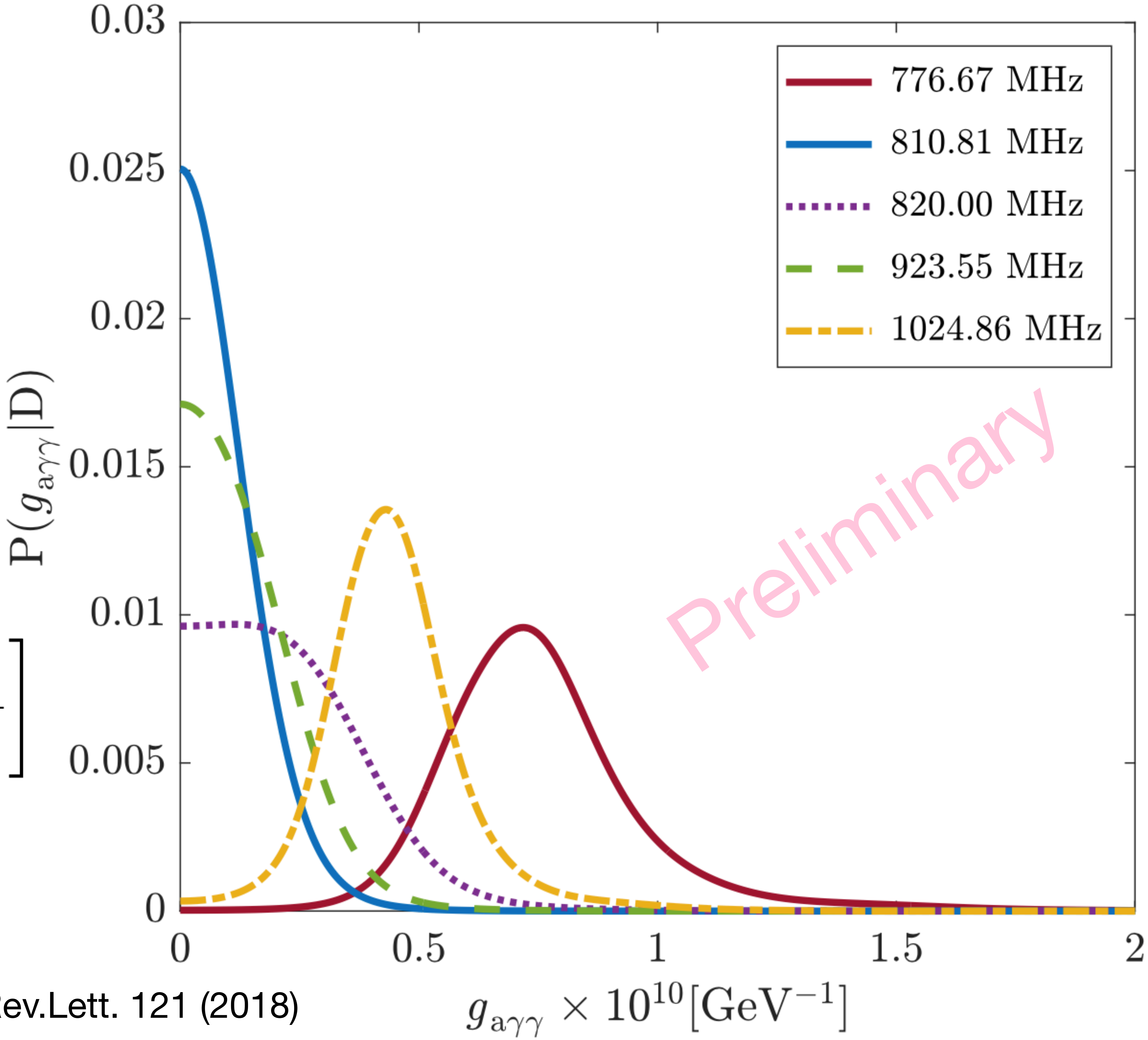
Flux [mJy/beam]
RMS [mJy/beam]
SNR
Frequency [MHz]
Preliminary
Preliminary

Mapping Data to Theory

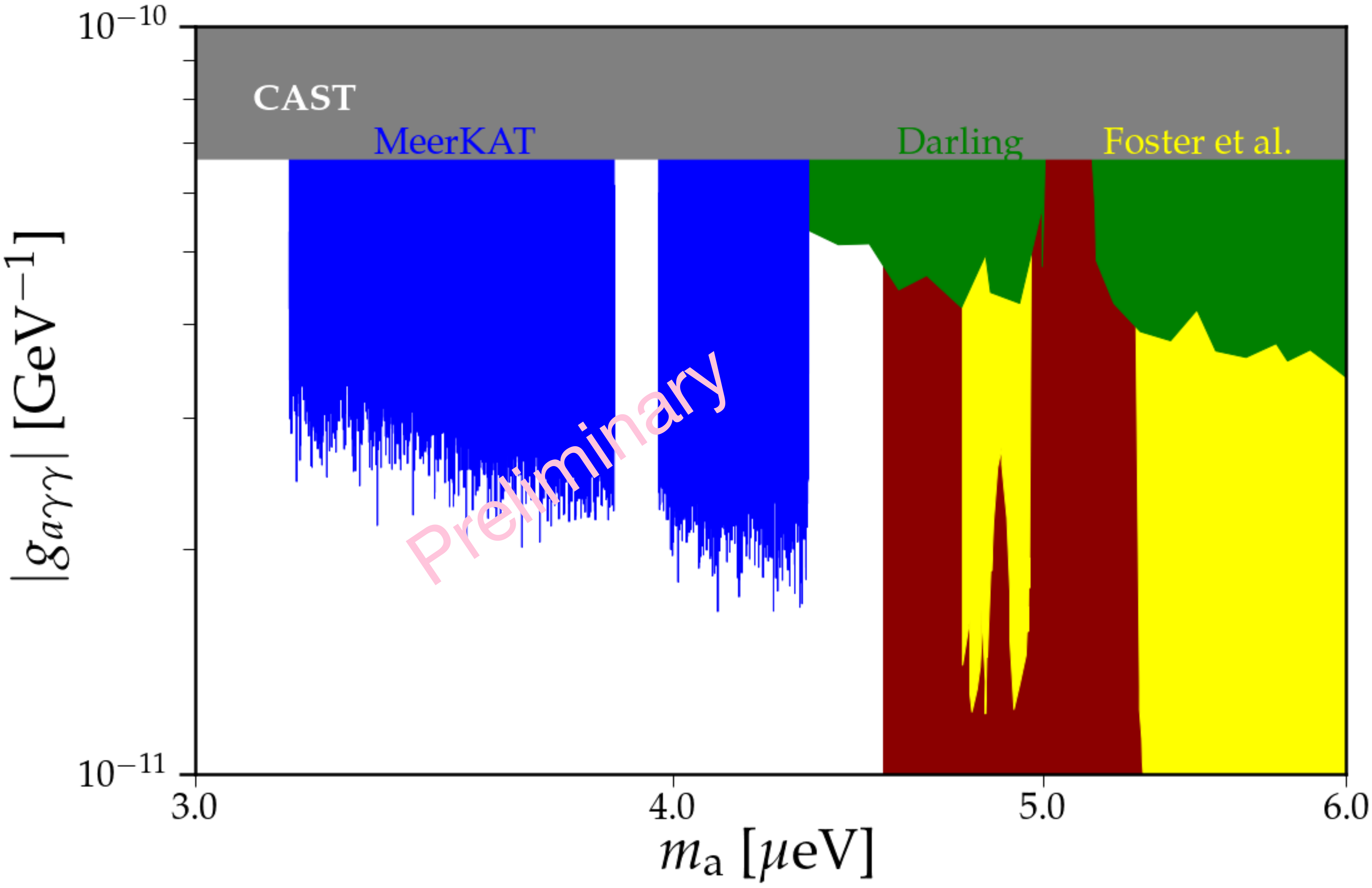
$$F \equiv \int_{\Delta\Omega} \mathrm{d}\Omega\, I(\Omega) p_{a\to\gamma}\,, \quad I(\Omega) = \frac{n_\mathrm{a} v_\mathrm{a}}{4\pi}$$

$$S_\nu \;=\; F/\Delta\nu \sim g_{a\gamma\gamma}^2 m_a^{5/3} B_0^{5/3} P^{4/3} \rho_\infty M_\mathrm{NS} v_0^{-1}$$

$$\mathcal{L}_i\left(\mathbf{d}|S_{\nu_i}\right) = \frac{1}{\sqrt{2\pi\sigma_{\nu_i}^2}} \exp\left[-\frac{\left(d_{\nu_i} - \mu_{\nu_i} - S_{\nu_i}\right)^2}{2\sigma_{\nu_i}^2}\right]$$



Following here the theoretical analysis of Hook et al, Phys.Rev.Lett. 121 (2018)



CAST
MeerKAT
Darling
Foster et al.
Preliminary
10^{-10}
10^{-11}
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
3.0
4.0
5.0
6.0
m_a [μeV]

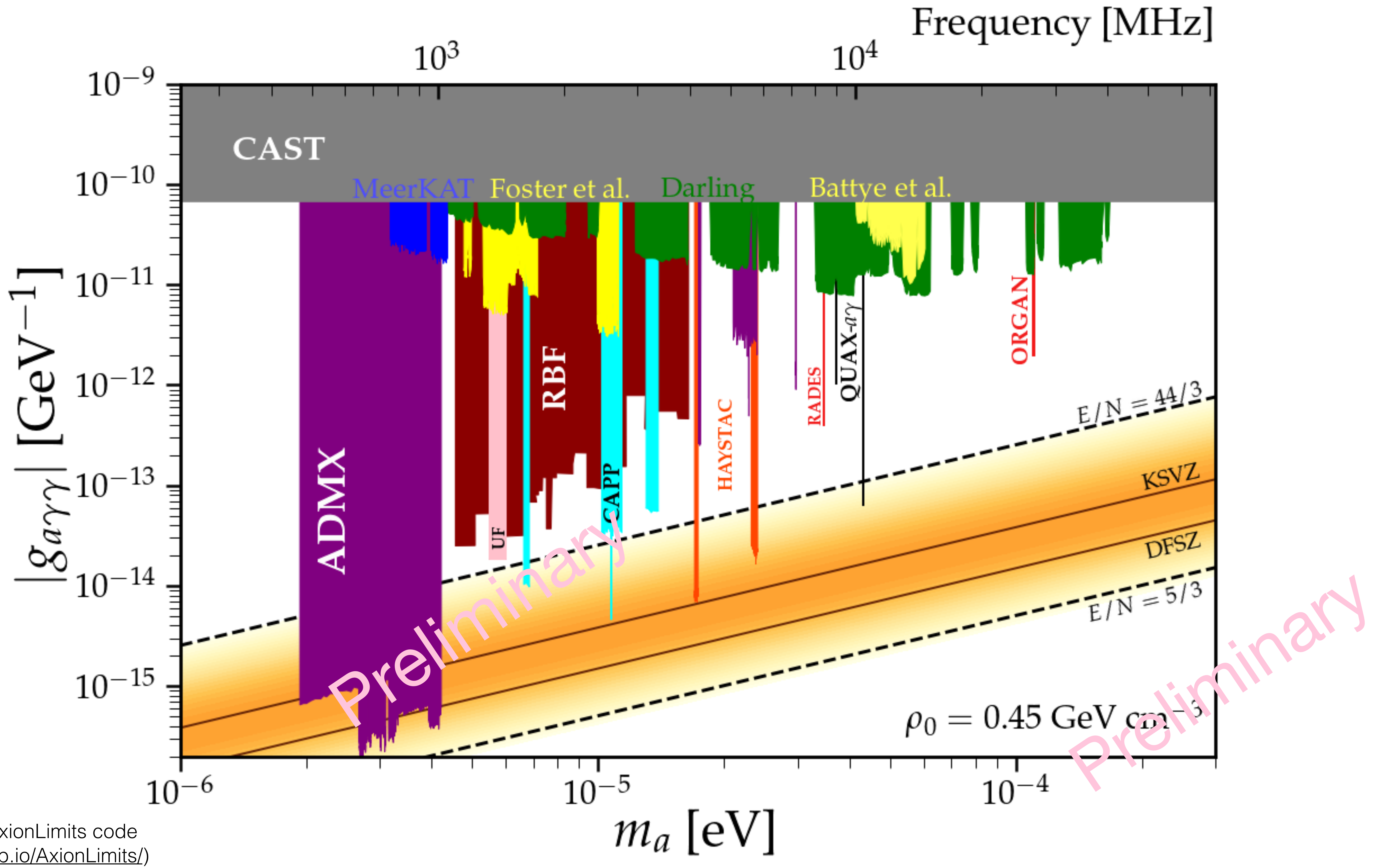


Figure made using AxionLimits code
(https://cajohare.github.io/AxionLimits/)

Summary:

- For 10-hours MeerKAT observations, we obtained the axion decay constant upper limit $g_{a\gamma\gamma} < 4.6 \times 10^{-11}\,[\mathrm{GeV}^{-1}]$, over 769-1051 MHz, corresponding to the mass range of 3.1-4.5 $\mu\mathrm{eV}$.

Outlook (future experiment)

- Better frequency resolution
- Broader frequency range
- More isolated neutron stars/exotic candidate with strong magnetic field.