Dark Matter in Radio Astronomy

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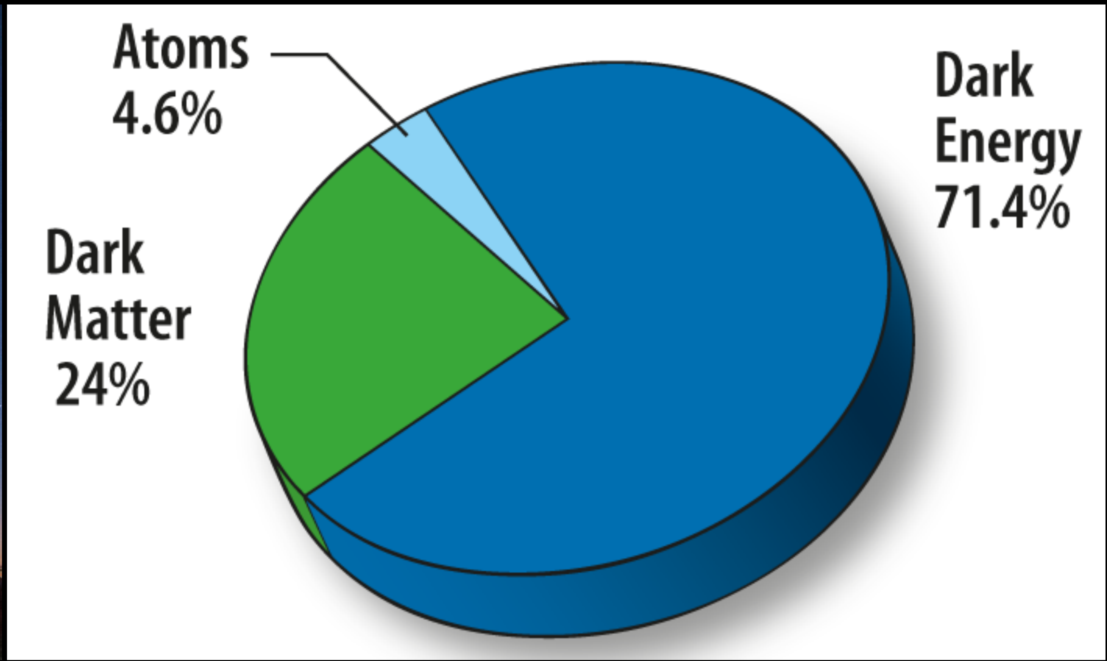
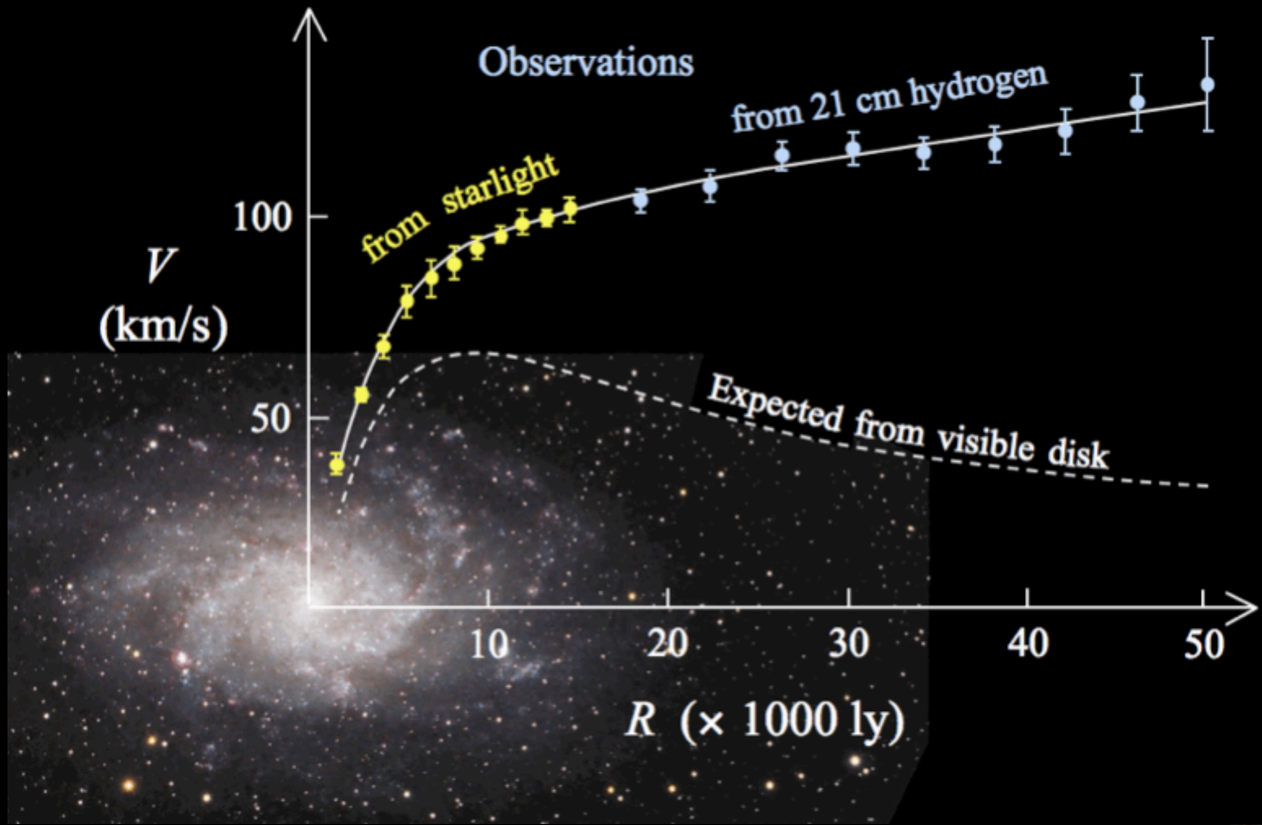
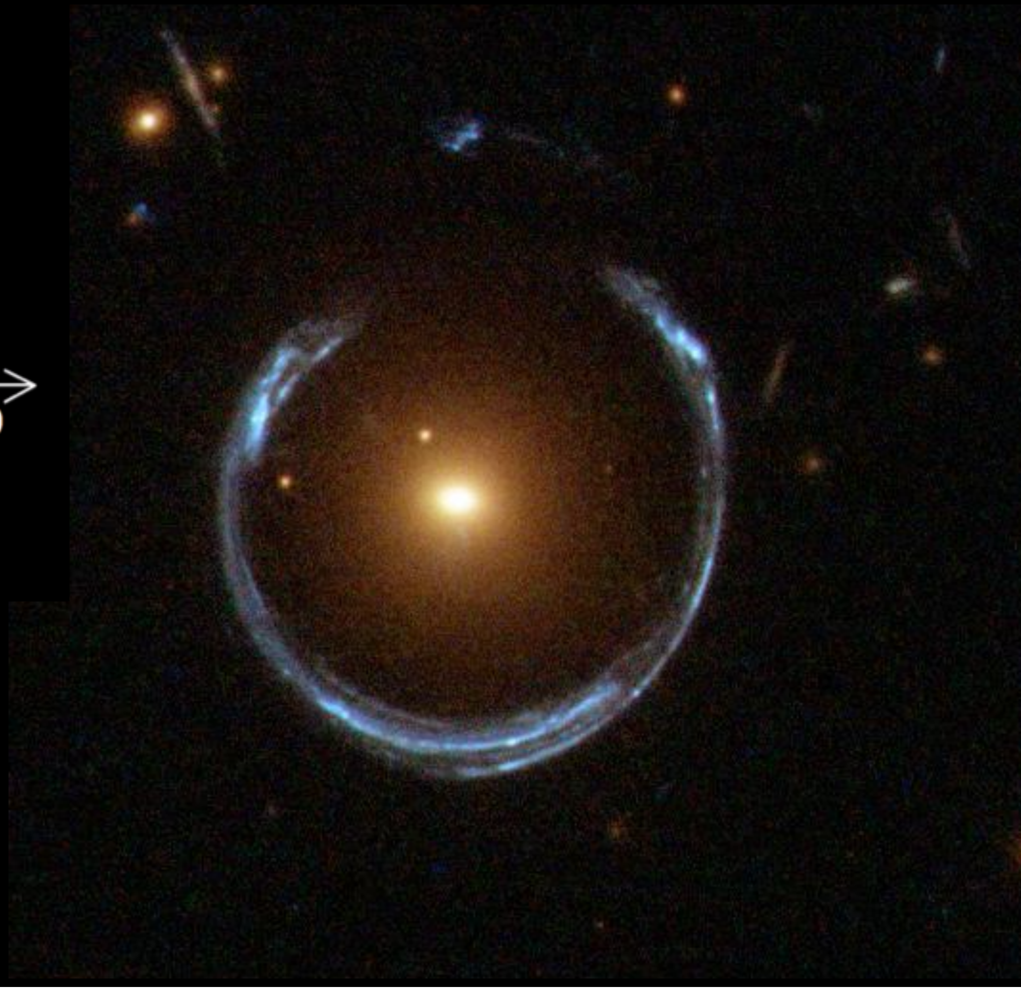
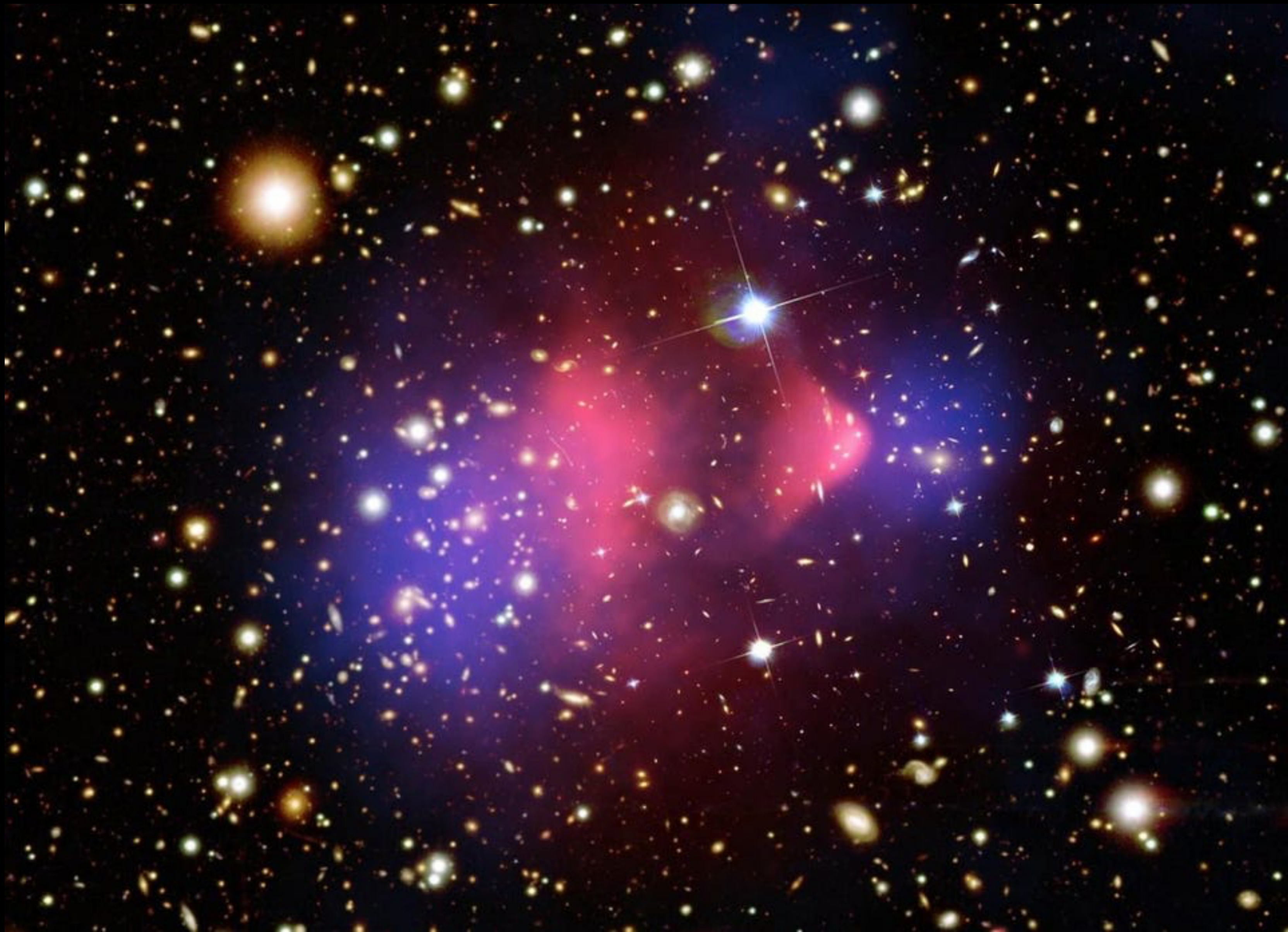


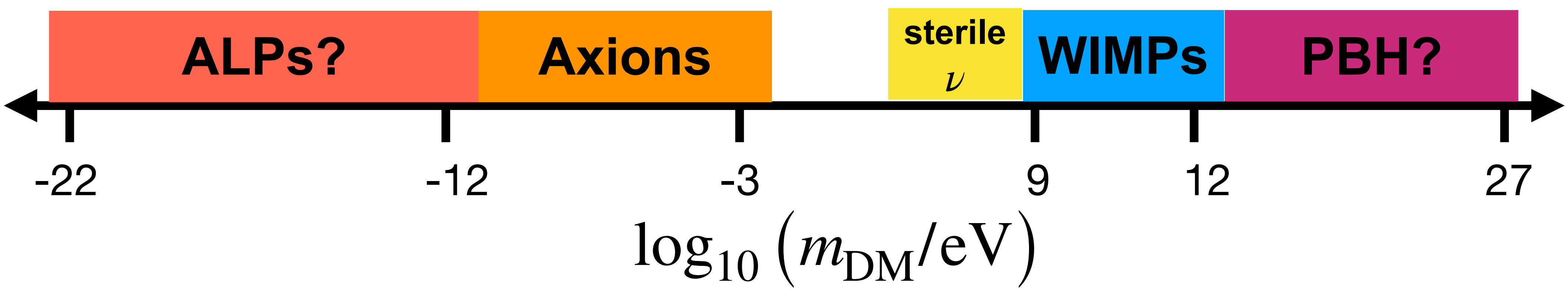
Zhou, Houston, Jozsa, Chen, YZM, Yuan et al., 2022, Phys. Rev. D
Guo, Li, Huang, YZM, Beck et al., 2023, Phys. Rev. D
Cang, YZM, Gao, 2023, Astrophys. J.
Planck Collaboration (including YZM), 2020, Astron. Astrophys.


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!



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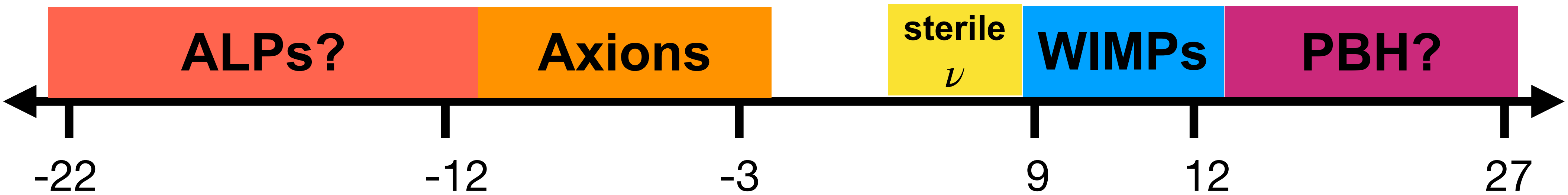
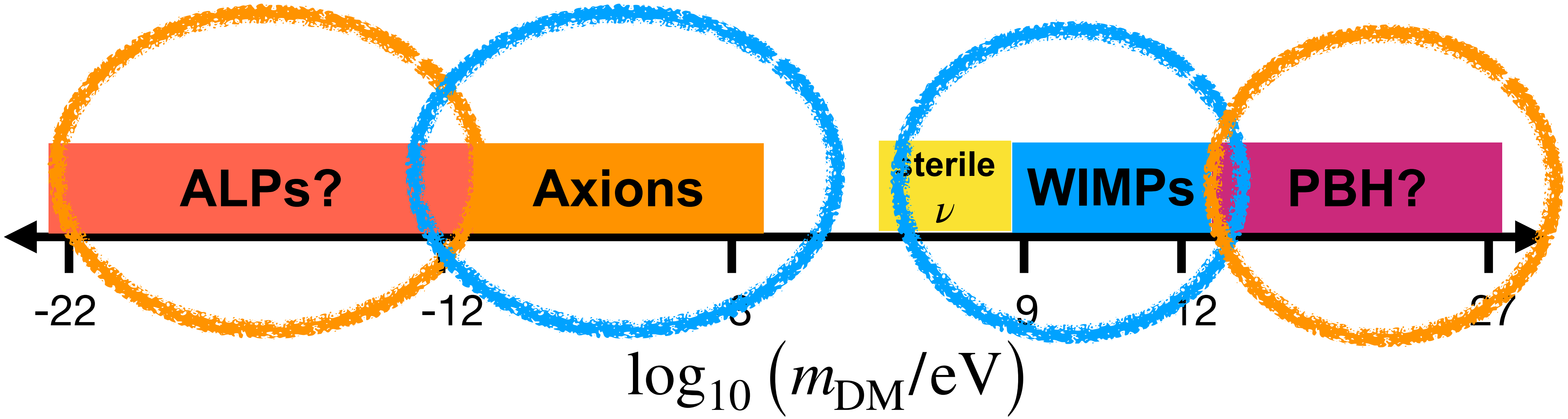


$$\log_{10}\left(m_{\mathrm{DM}}/\mathrm{eV}\right)$$

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

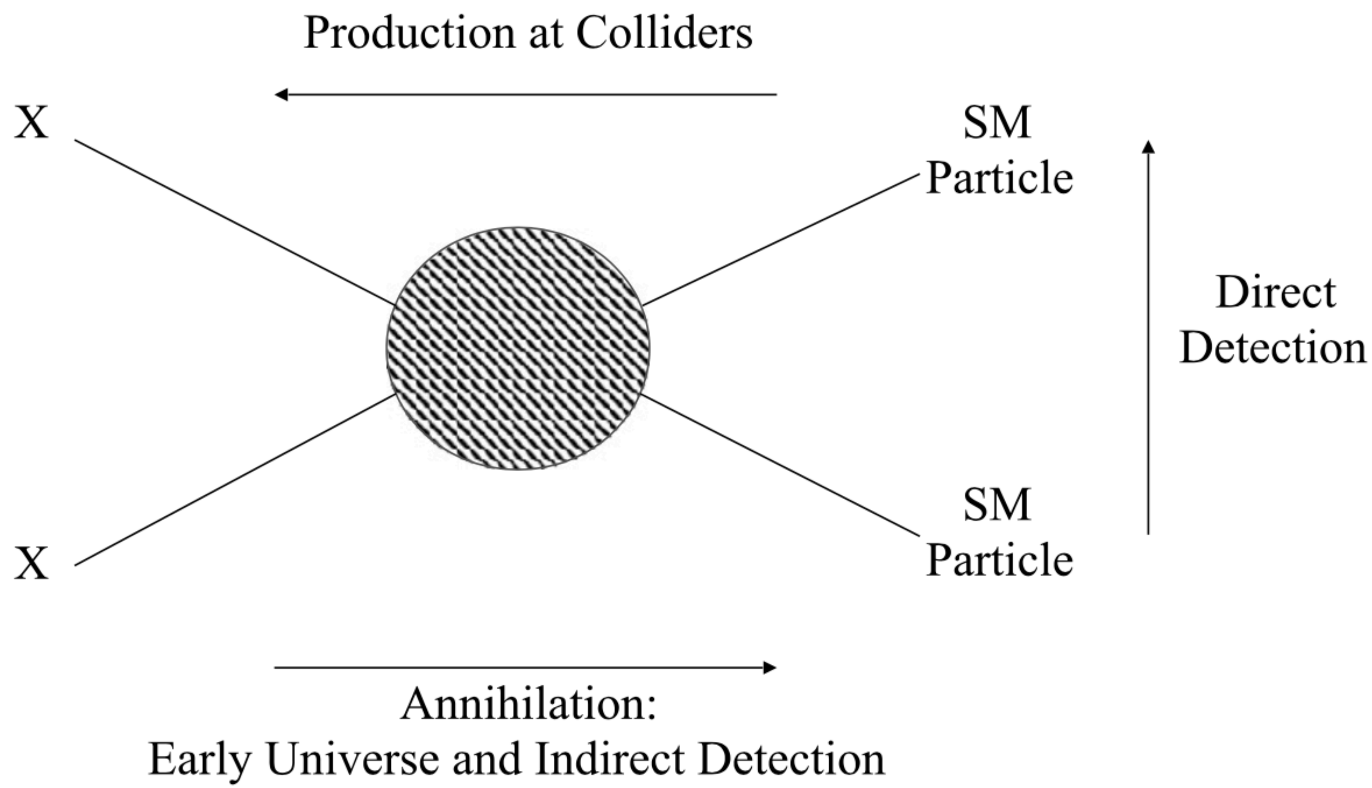
—Nobel Telephone Interview of James Peebles (October 2019)

It is a huge scale to search!



Effects (DM in radio astronomy):

- Produce radio waves that are measurable by radio telescopes
- Produce enough perturbations to change the CMB power spectrum
- Change the timing and polarisation signal of pulsars which are measurable with radio telescopes (wavy dark matter)



Tools:

- Neutron Stars Observations
- Radio Observations of dwarf galaxies
- Pulsar Timing Array
- Cosmic Microwave Background Radiation

- Axions ($m_{\mathrm{a}} \sim \mu\mathrm{eV}$)

  — Direct Observations of Radio Quiet Neutron Star

  Zhou, Houston, Jozsa, Chen, YZM, Yuan et al., 2022, Phys. Rev. D

- WIMP ($m_X \sim 10\,\mathrm{GeV}$)

  —Radio Observations of dwarf galaxies

  Guo, Li, Huang, YZM, Beck et al., 2023, Phys. Rev. D

- Axion-Like Particles ($m_{\mathrm{a}} \sim 10^{-22}\,\mathrm{eV} \ll \mu\mathrm{eV}$):

  —Pulsar Timing Array and Pulsar Polarisation Array

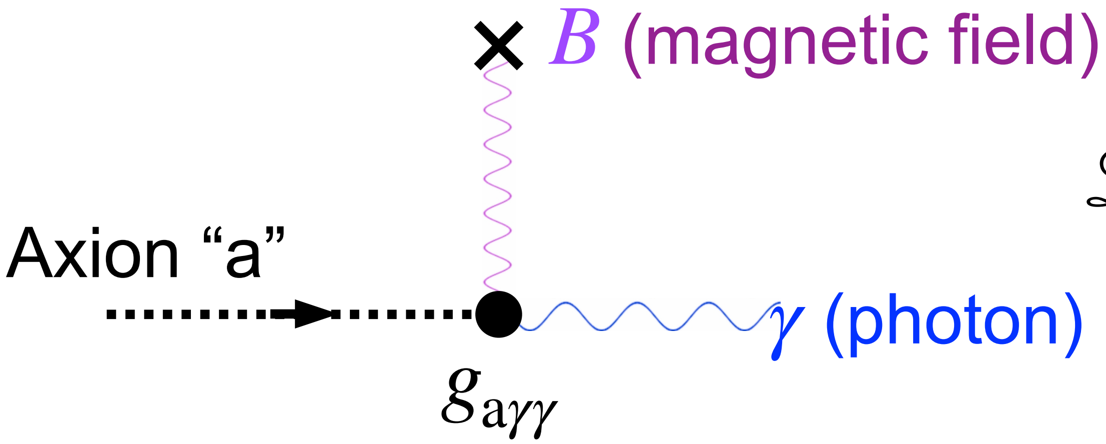
- Primordial Black Holes ($m_X \sim 10^{15}\,\mathrm{eV}$)

  —CMB constraints on relativistic degrees of freedom

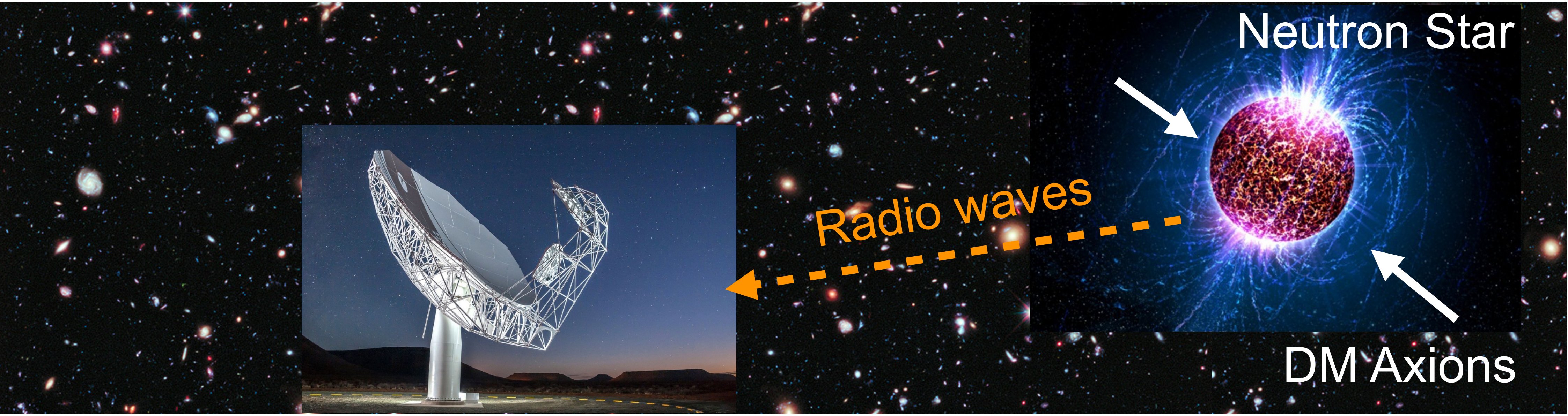
  Cang, YZM, Gao, 2023, ApJ

Peccei & Quinn 1977
Weinberg 1978
Wilcezk 1978
Svrcek & Witten 2006

Converting Axions into photons



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

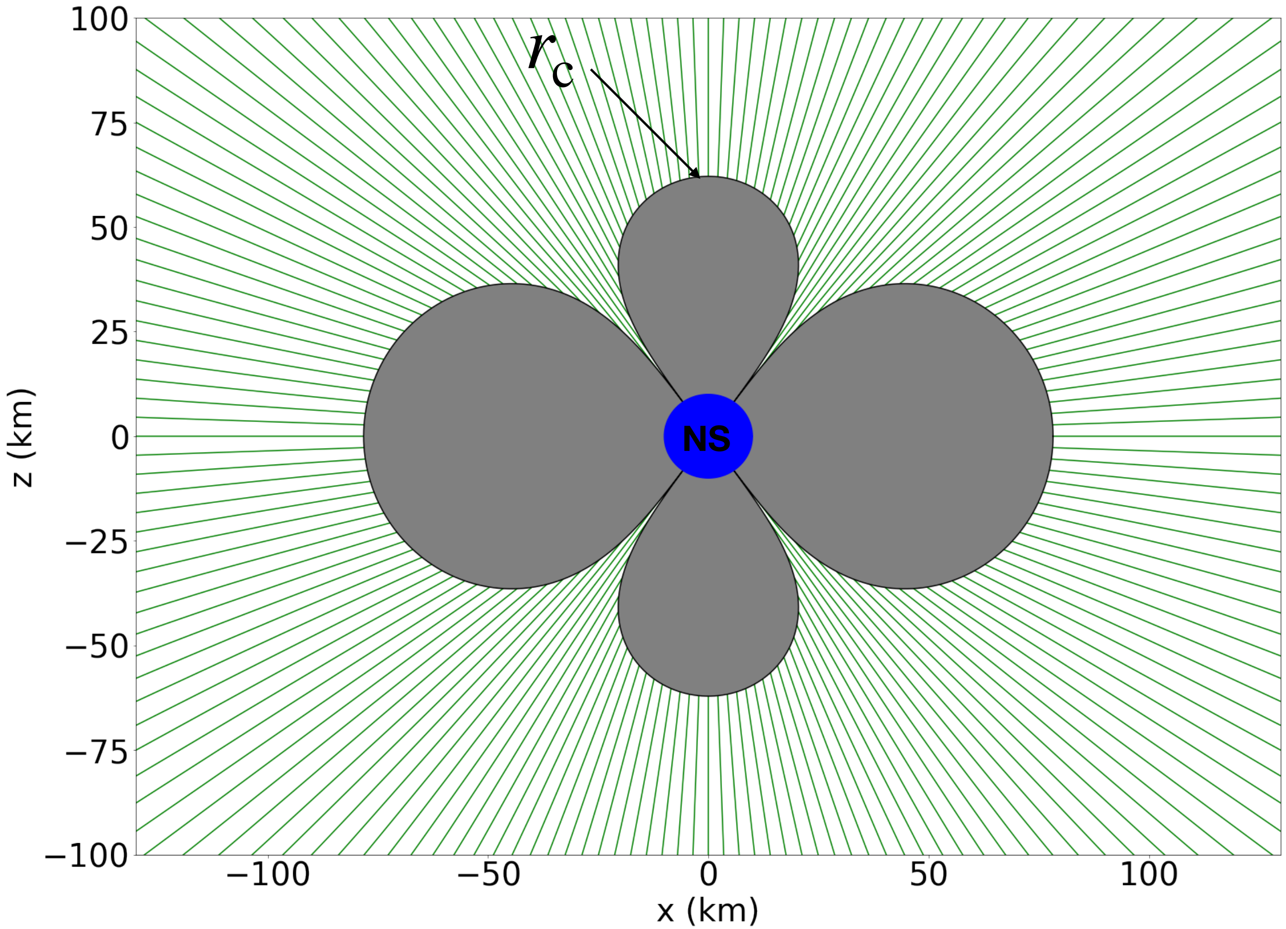


How to calculate this flux?

- **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, with $B_0 \sim 2 \times 10^{13}$ Gauss dipole magnetic field.
- Solve EOMs to find axion/photon oscillation probability, maximised at the critical radius r_c when photon plasma frequency $\simeq$ axion mass
- **Output:** Use geodesic equations to propagate photons from critical surface to Earth, ideally accounting for NS rotation, gravitational and plasma effects
- 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



Putting everything together. **Final Step**

Radiated power:

$$\frac{\mathrm{d}P}{\mathrm{d}\Omega} \simeq 5.7\times 10^{9}\ \mathrm{W}\left(\frac{g_{a\gamma\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right)^{2}\left(\frac{r_{\mathrm{NS}}}{10\ \mathrm{km}}\right)^{5/2}\left(\frac{m_{\mathrm{a}}}{\mathrm{GHz}}\right)^{4/3}\left(\frac{B_0}{10^{14}\ \mathrm{G}}\right)^{5/6}$$

$$\left(\frac{P}{\mathrm{sec}}\right)^{7/6}\left(\frac{\rho_{\mathrm{DM}}^{\infty}}{0.45\ \mathrm{GeV\,cm}^{-3}}\right)\left(\frac{M_{\mathrm{NS}}}{\mathrm{M}_{\odot}}\right)^{1/2}\left(\frac{200\,\mathrm{km\,s}^{-1}}{v_0}\right)\frac{3\,(\hat{\mathbf{m}}\cdot\hat{\mathbf{r}})^{2}+1}{\left|3\cos\theta\,\hat{\mathbf{m}}\cdot\hat{\mathbf{r}}-\cos\theta_{\mathrm{m}}\right|^{7/6}},$$

Average flux density in channel i:

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

(assuming a Gaussian spectrum with width $\sigma_0 = 5\times 10^{-6}\,m_{\mathrm{a}}$)

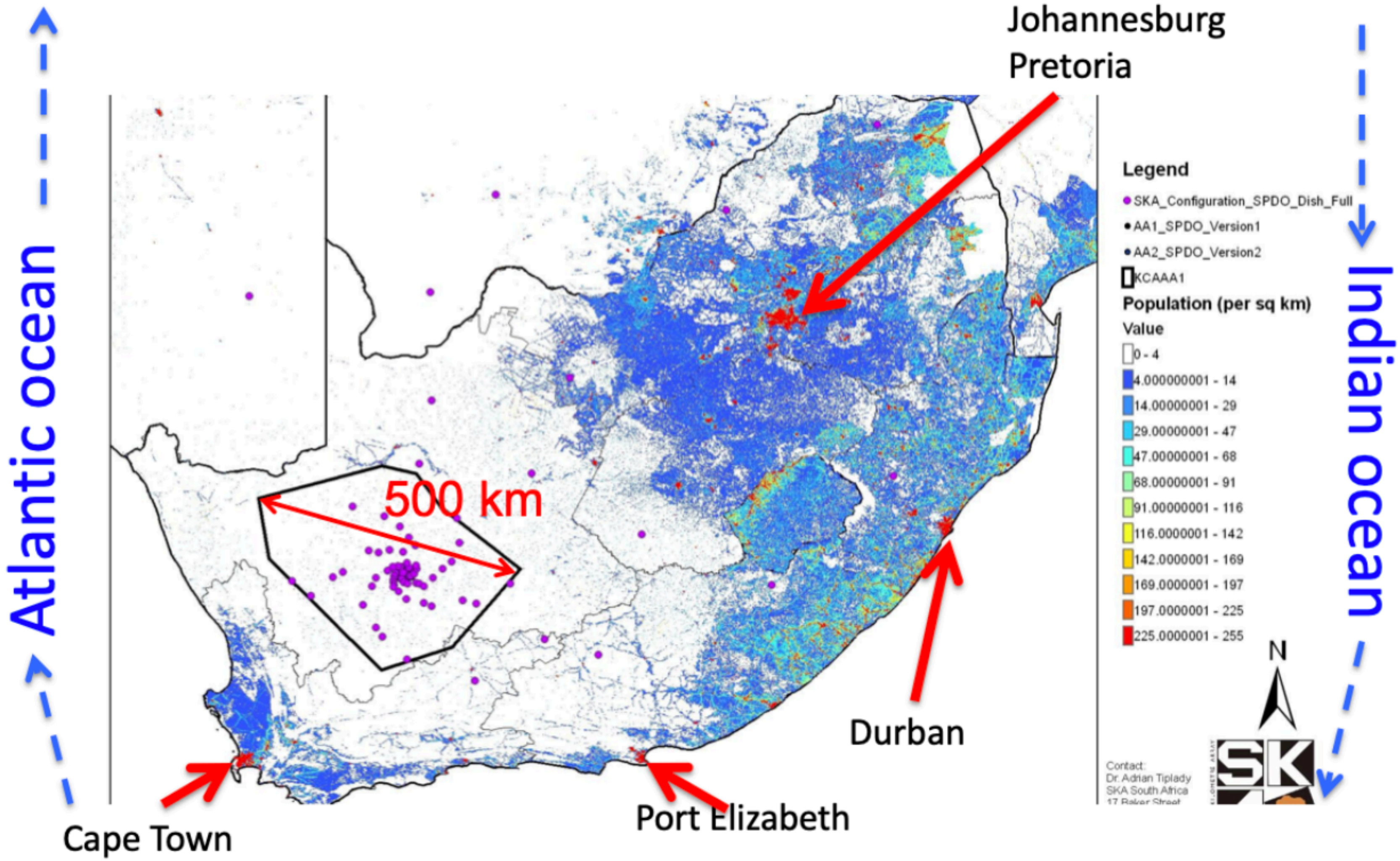
MeerKAT 2020 Open Time call for proposal

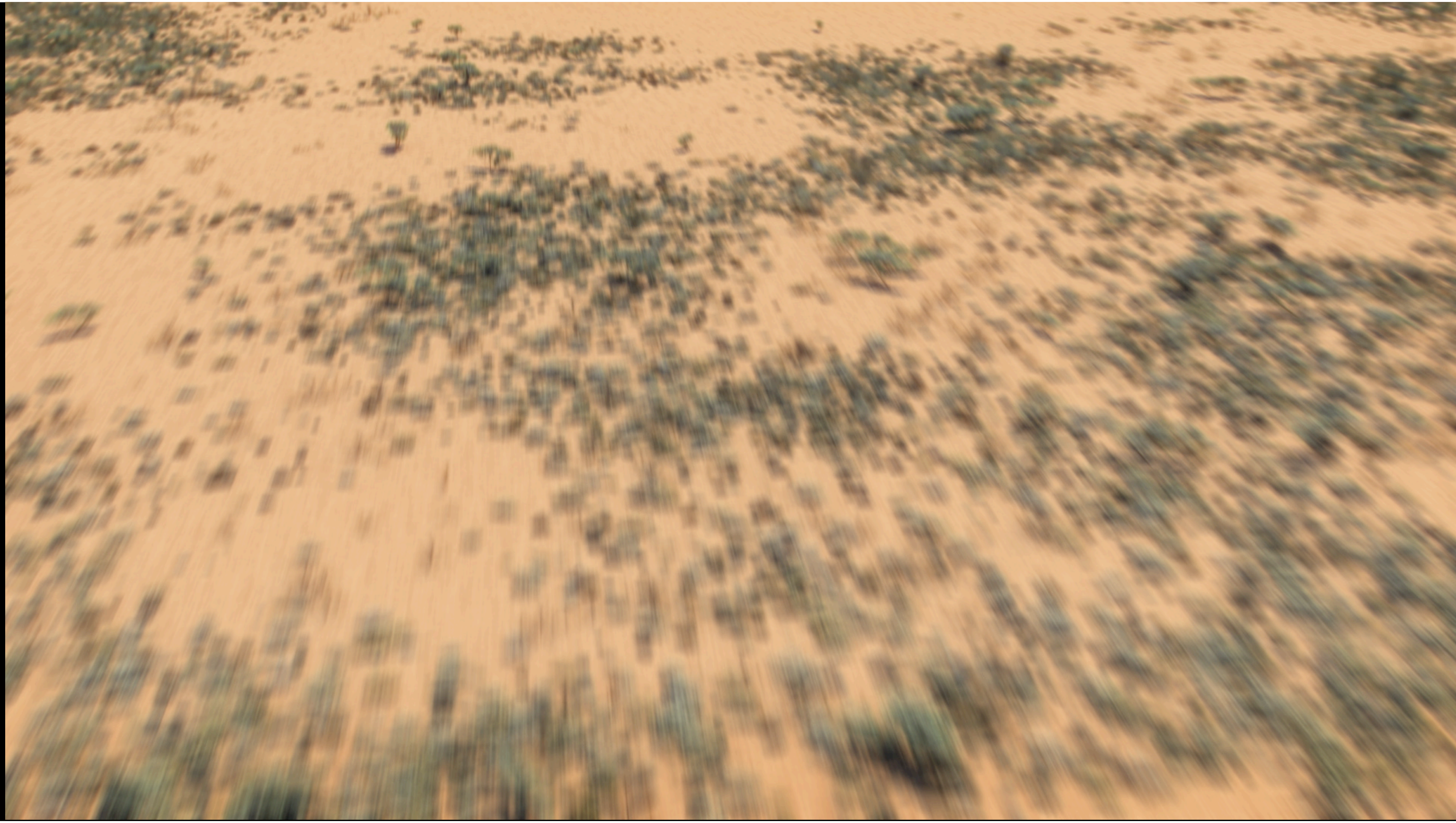
Qiang Yuan (PMO), Yin-Zhe Ma (UKZN)
Yunfan Zhou, Nick Houston (BUT), Chandreyee Sengupta, Xiaoyuan Huang, Fujun Du, Yogesh Chandola (PMO), Ran Ding (AnHui), Gyula Jozsa (SARAO), Hao Chen (UCT)

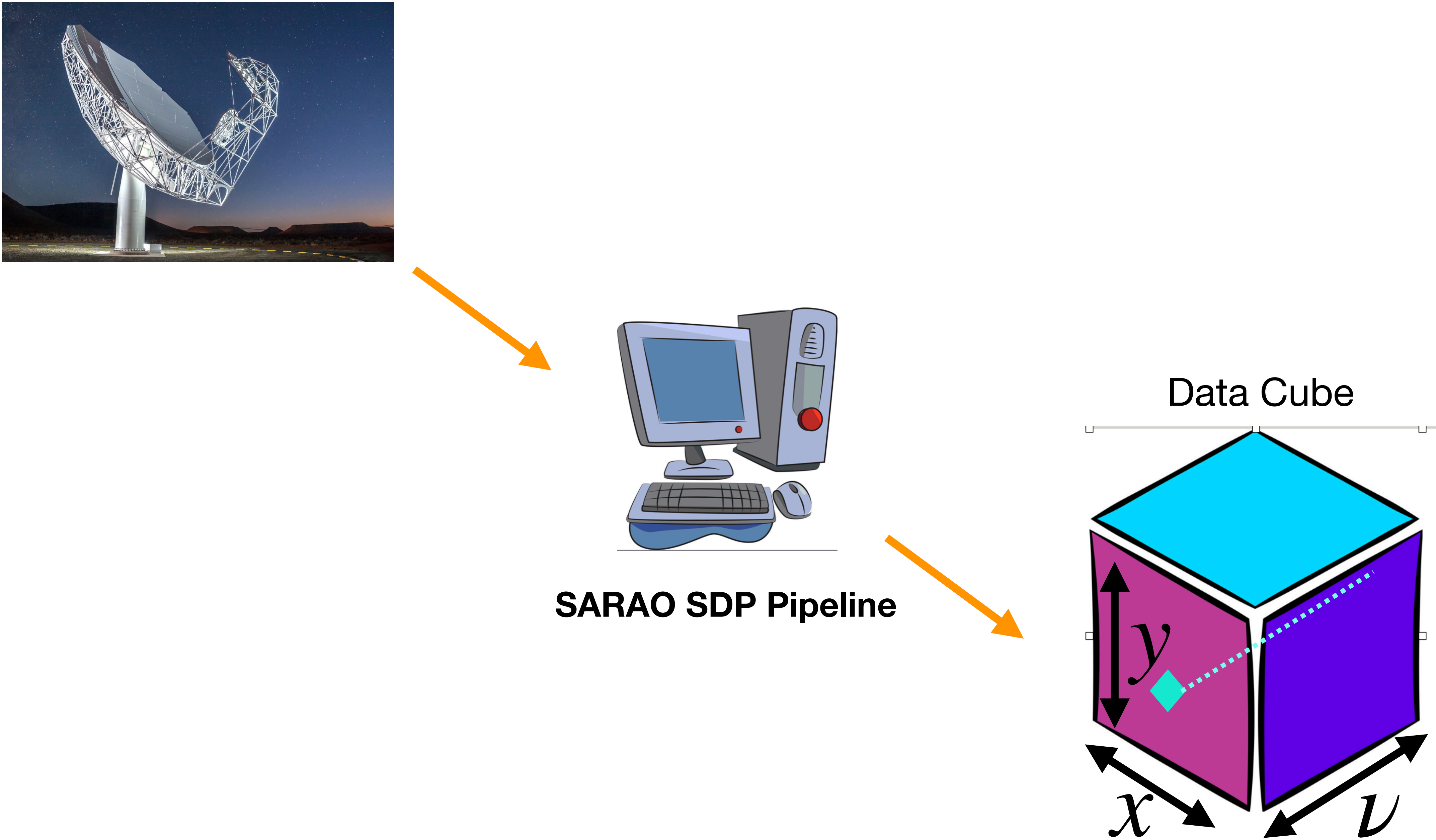
UHF Band MeerKAT
Target: neutron star RX J0806.4-4123
frequency range: 544-1,088 MHz
Axion mass range: 2.5-5 μeV
Frequency resolution: 16 kHz
Area observed: $19\,\mathrm{arcmin} \times 14.9\,\mathrm{arcmin}$
Time resolution: 8 seconds

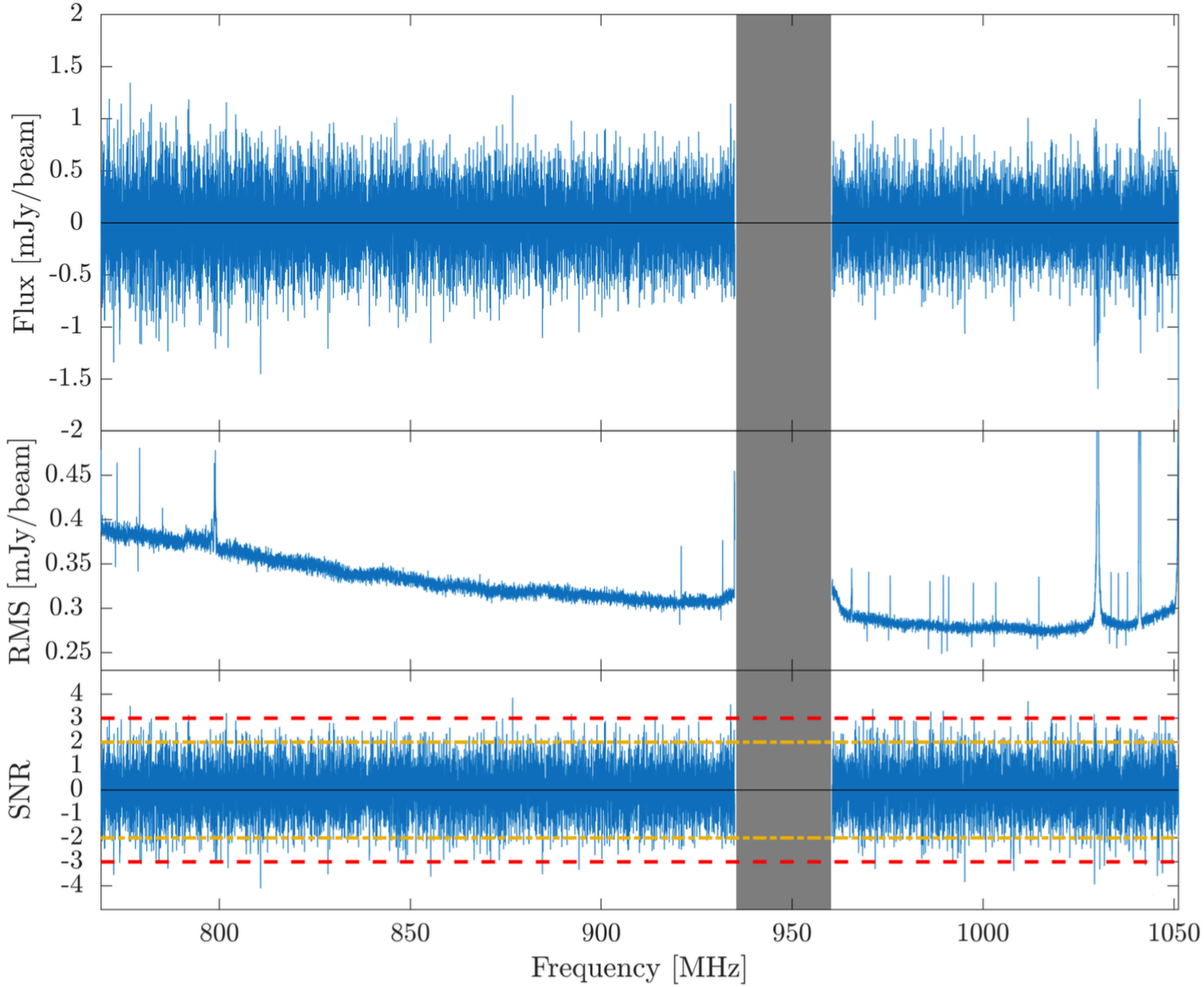
→ Allocated time: 10 hours (Priority A)

The Square Kilometre Array (SKA) in South Africa



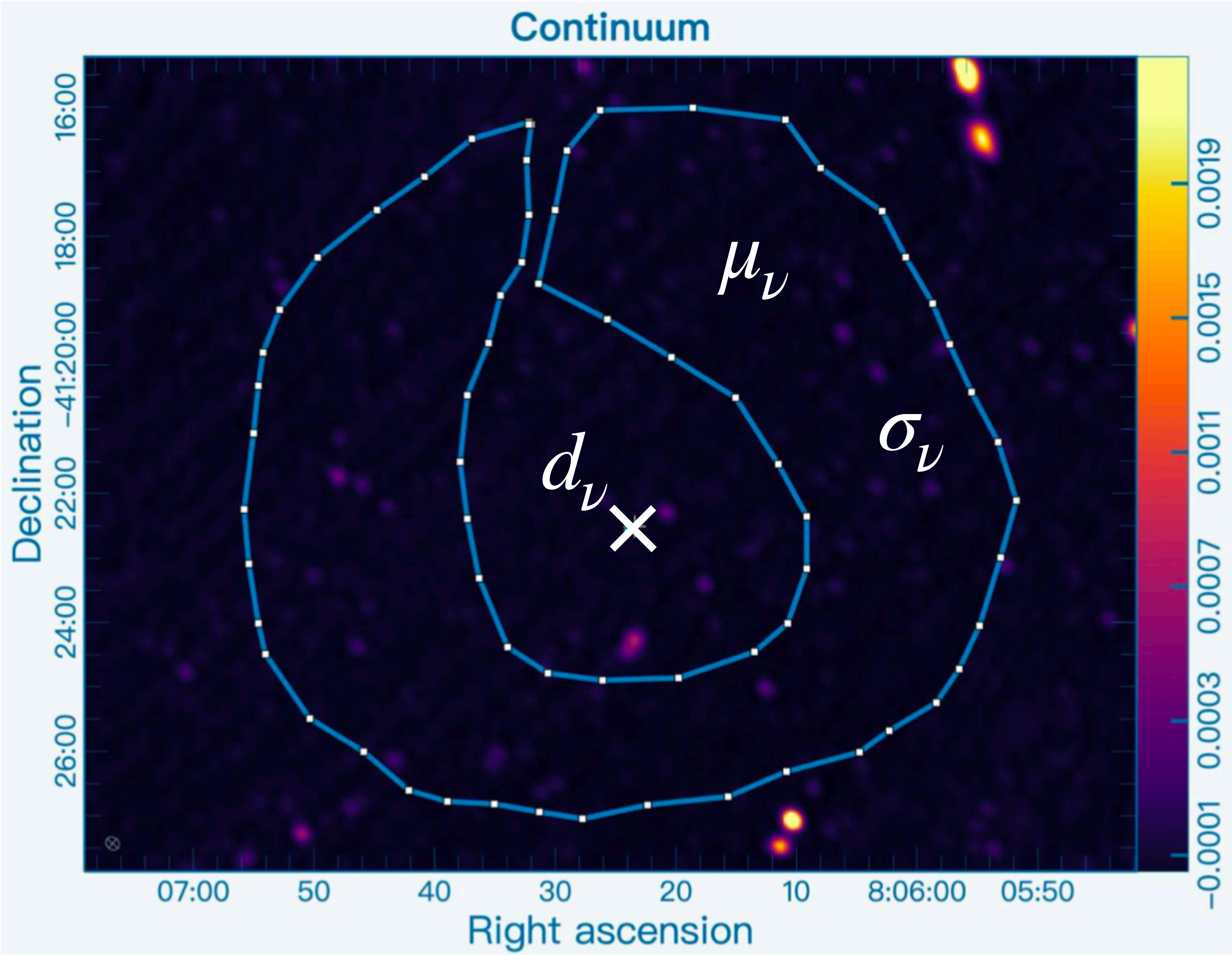



SARAO SDP Pipeline
Data Cube
y
x
ν



Spike feature

Zhou, Houston, Jozsa, Chen, YZM, Yuan et al. 2022, Phys. Rev. D



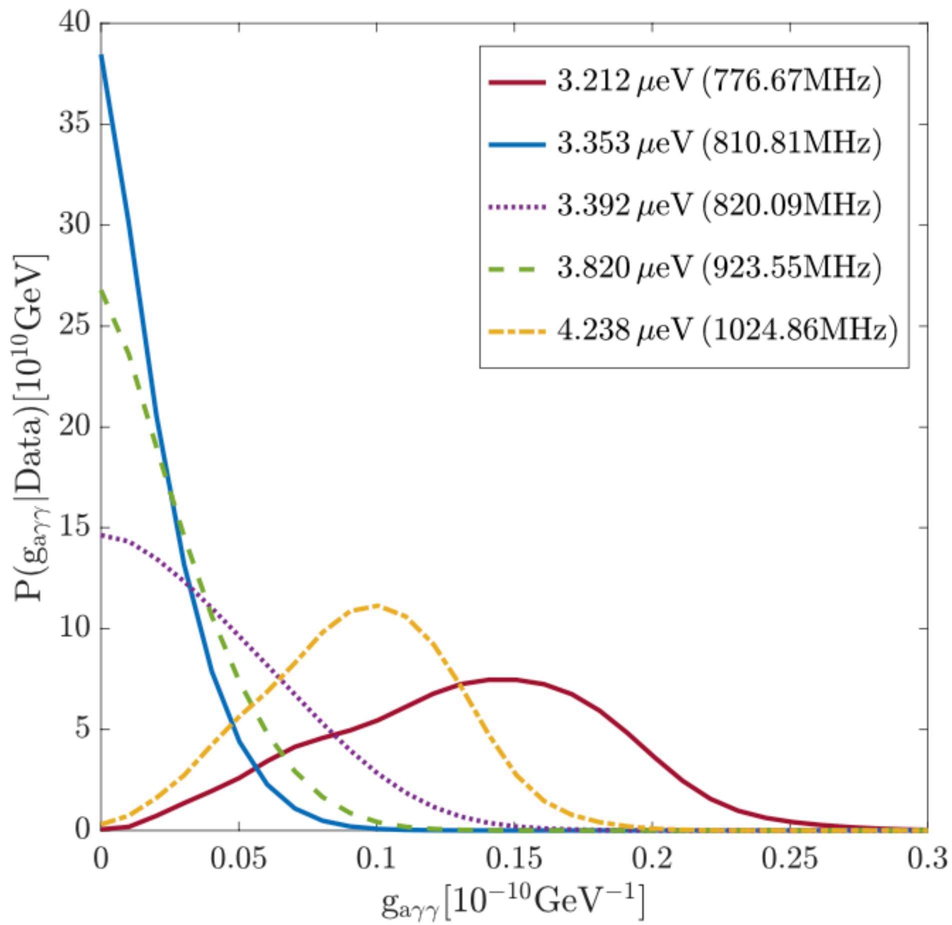
Continuum
Declination
16:00
18:00
−41:20:00
22:00
24:00
26:00
Right ascension
07:00
50
40
30
20
10
8:06:00
05:50
μ_ν
σ_ν
d_ν
0.0019
0.0015
0.0011
0.0007
0.0003
−0.0001

Mapping Data to Theory

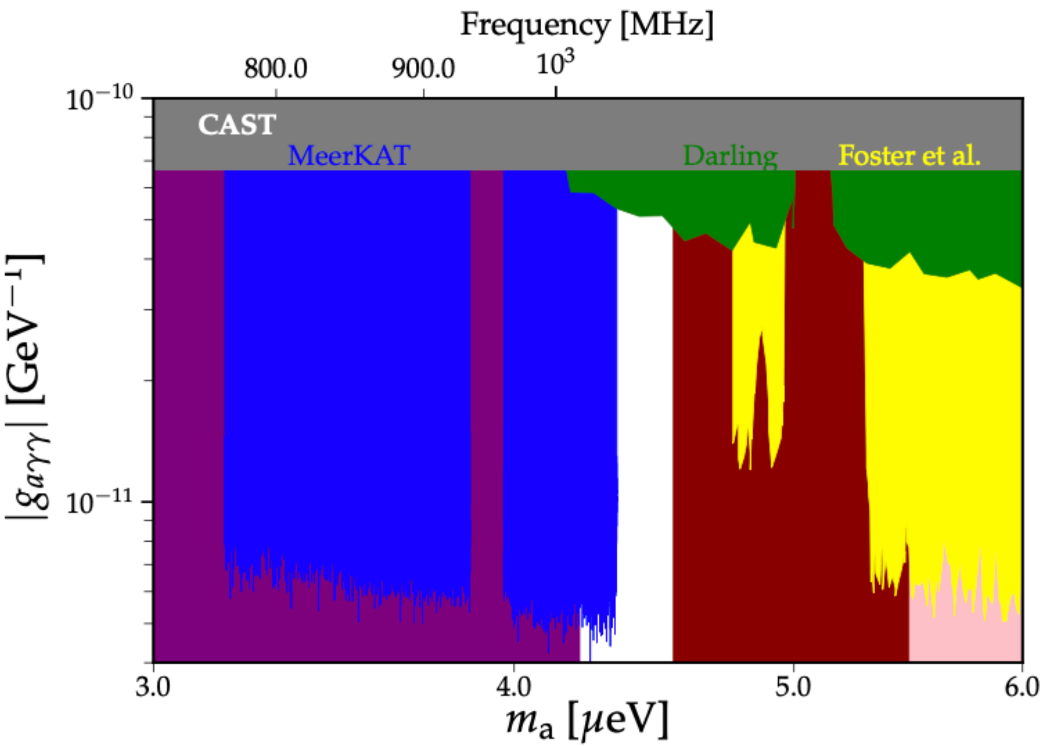
$$F \equiv \int_{\Delta\Omega} \mathrm{d}\Omega\, I(\Omega) p_{a\to\gamma}\,, \quad I(\Omega) = \frac{n_\mathrm{a} v_\mathrm{a}}{4\pi}$$

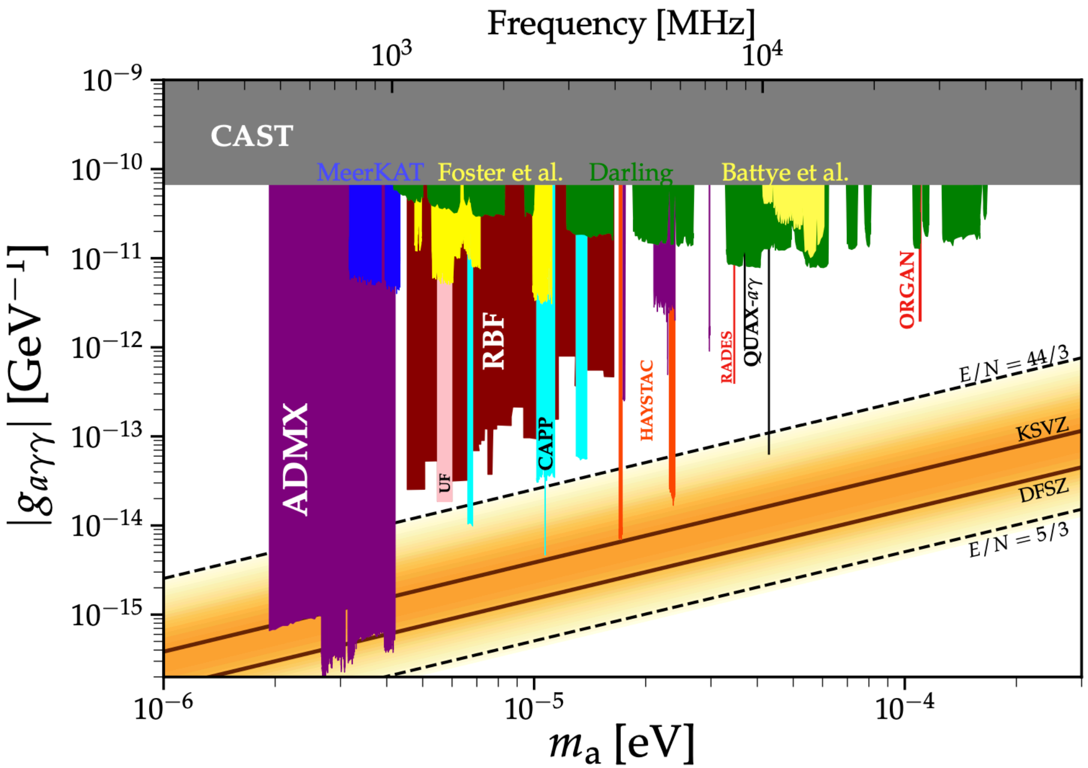
$$S_\nu \;=\; F/\Delta\nu \sim g_{a\gamma\gamma}^2 m_a^{5/3} B_0^{5/3} P^{4/3} \rho_\infty M_\mathrm{NS} v_0^{-1}$$

$$\mathcal{L}\left(m_\mathrm{a}, g_{\mathrm{a}\gamma\gamma}\right) = \prod_{i=1}^{N_\mathrm{ch}} \frac{1}{\sqrt{2\pi}\sigma_{\nu_i}} \exp\left[-\frac{\left(d_{\nu_i} - \mu_{\nu_i} - \bar{S}_{\nu_i}(m_\mathrm{a}, g_{\mathrm{a}\gamma\gamma})\right)^2}{2\sigma_{\nu_i}^2}\right]$$



Zhou, Houston, Jozsa, Chen, YZM, Yuan et al. 2022, Phys. Rev. D





Zhou, Houston, Jozsa, Chen, YZM, Yuan et al. 2022, Phys. Rev. D

$$\chi + \chi \to \gamma + \gamma$$

DM

Synchrotron Radiation

$$\rho_\chi(r) = \rho_0 \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - 1\right)\right]$$

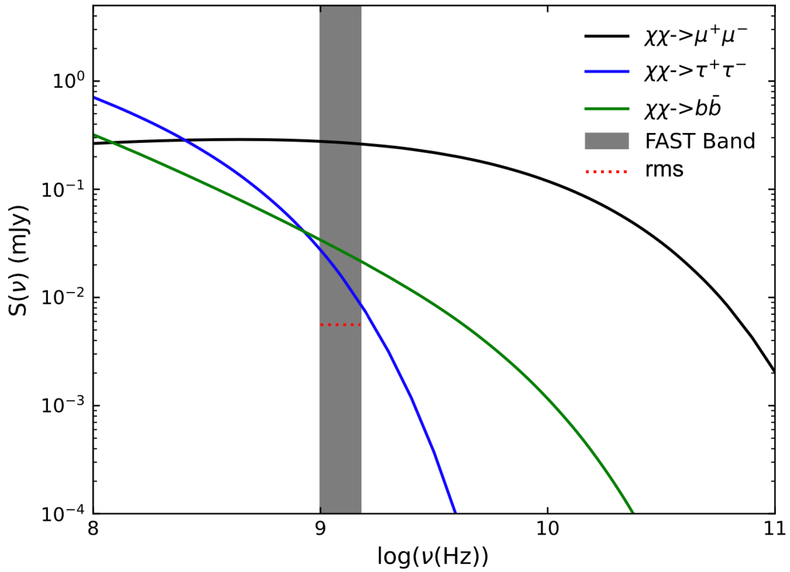
$$\frac{\partial}{\partial t}\frac{\partial n_e}{\partial E} = \nabla \cdot \left[D(E,r)\nabla\left(\frac{\partial n_e}{\partial E}\right)\right] + \frac{\partial}{\partial E}\left[b(E,r)\frac{\partial n_e}{\partial E}\right] + Q(E,r)$$

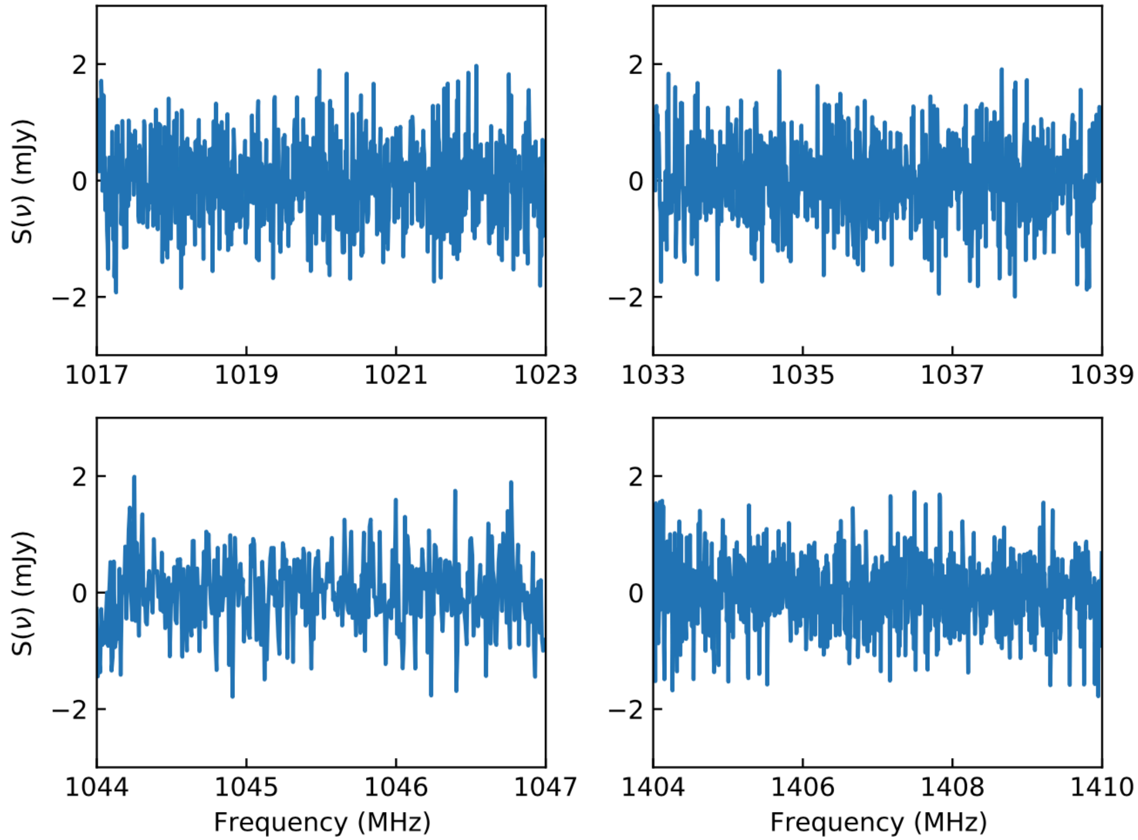
$$S_\nu = 2\int_{\hat{\Omega}} \mathrm{d}\Omega \int_{\mathrm{LoS}} \frac{\mathrm{d}l}{4\pi} \int_{m_e}^{M_\chi} \mathrm{d}E\mathcal{P}_{\mathrm{syn}}(E)\frac{\partial n_e}{\partial E}$$

Guo, Li, Huang, YZM, Beck et al., 2023, Phys. Rev. D

L-Band FAST

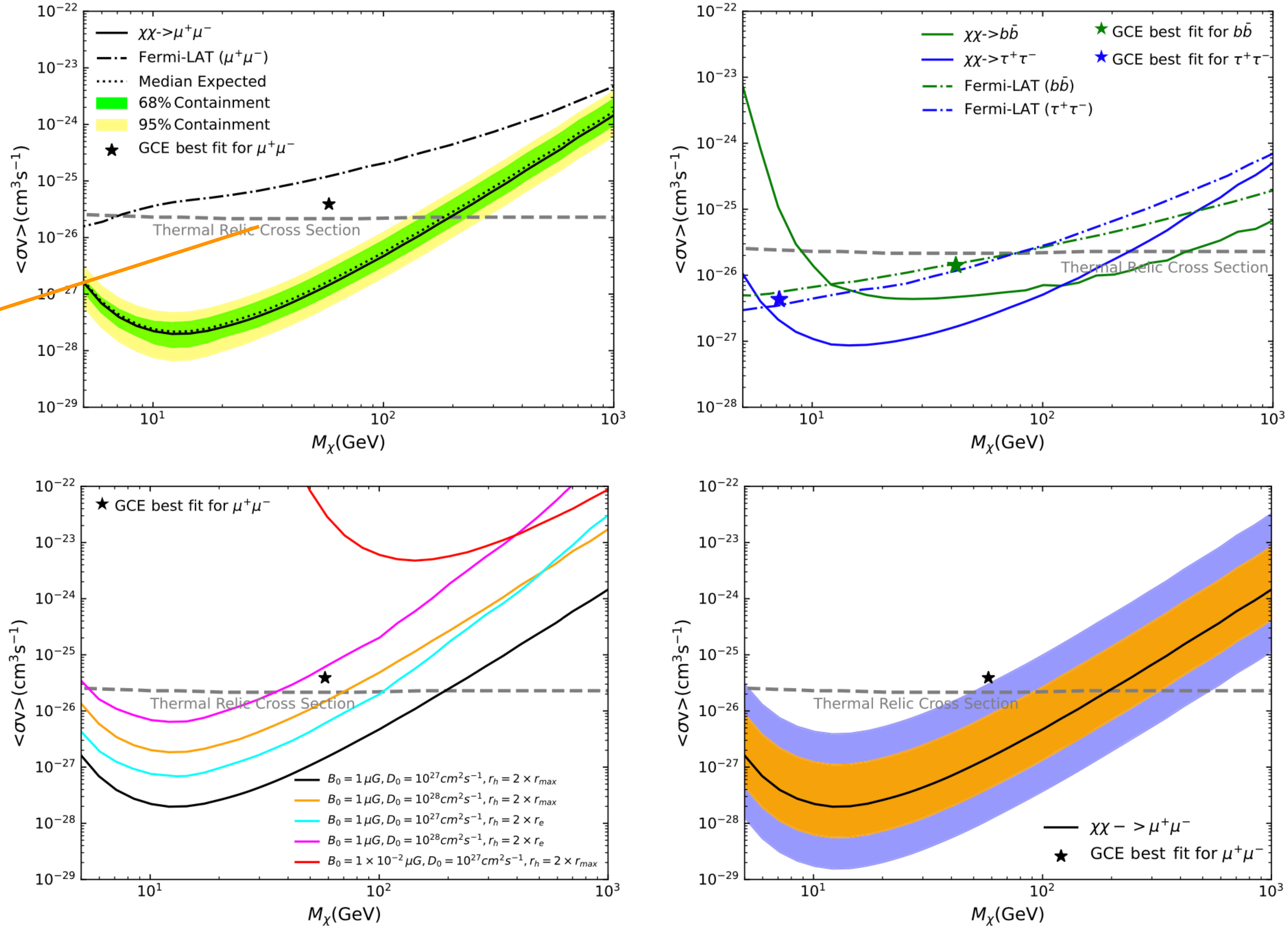
Target: dwarf galaxy Coma Berenices
Frequency: 1000-1500 MHz
Observational Time: 2020-12-14 7am-8:50am
WIMP mass range: $10\,\mathrm{GeV} - 10^3\,\mathrm{GeV}$
Frequency resolution: 7.6 kHz
Beam: 19
Observed both ON & OFF mode





$$\chi^2(M_\chi, \langle\sigma v\rangle) = \sum_i^N \frac{(S_{\mathrm{data},i} - S_{\mathrm{model},i})^2}{\sigma_i^2}$$

Excluded 99% C.L.

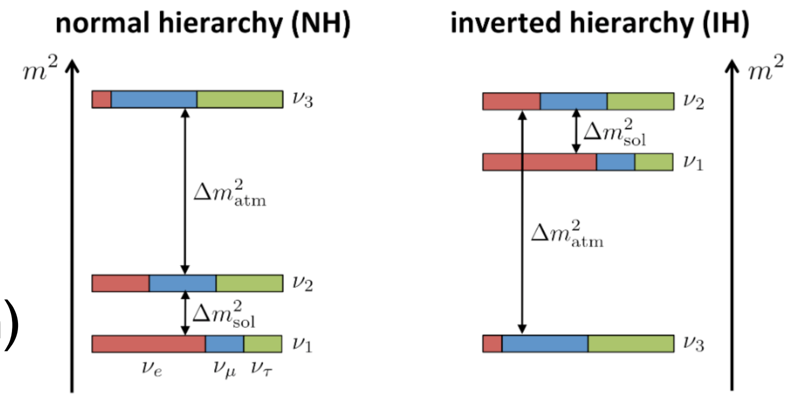


Guo, Li, Huang, YZM, Beck et al., 2023, Phys. Rev. D

Neutrino(-like) sector

Outstanding issues:

- Absolute mass scale
- Mass ordering
- (Dirac/Majorana and CP violation)
- Additional (sterile) neutrinos or relativistic particles



$\sum m_\nu > 0.058\,\mathrm{eV}$ $\sum m_\nu > 0.105\,\mathrm{eV}$

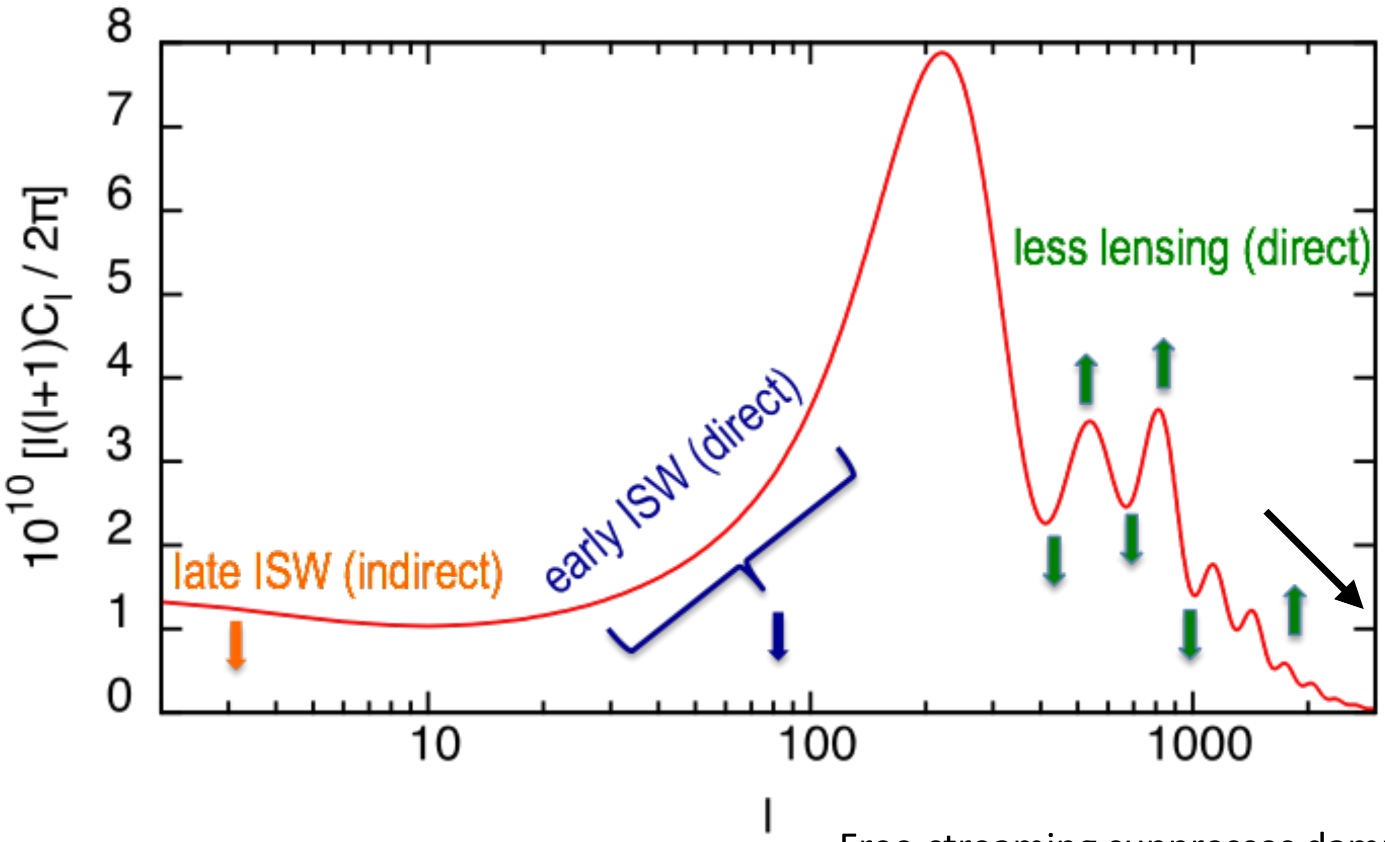
Cosmology → $\sum m_\nu$

Cosmology → $N_{\rm eff}$

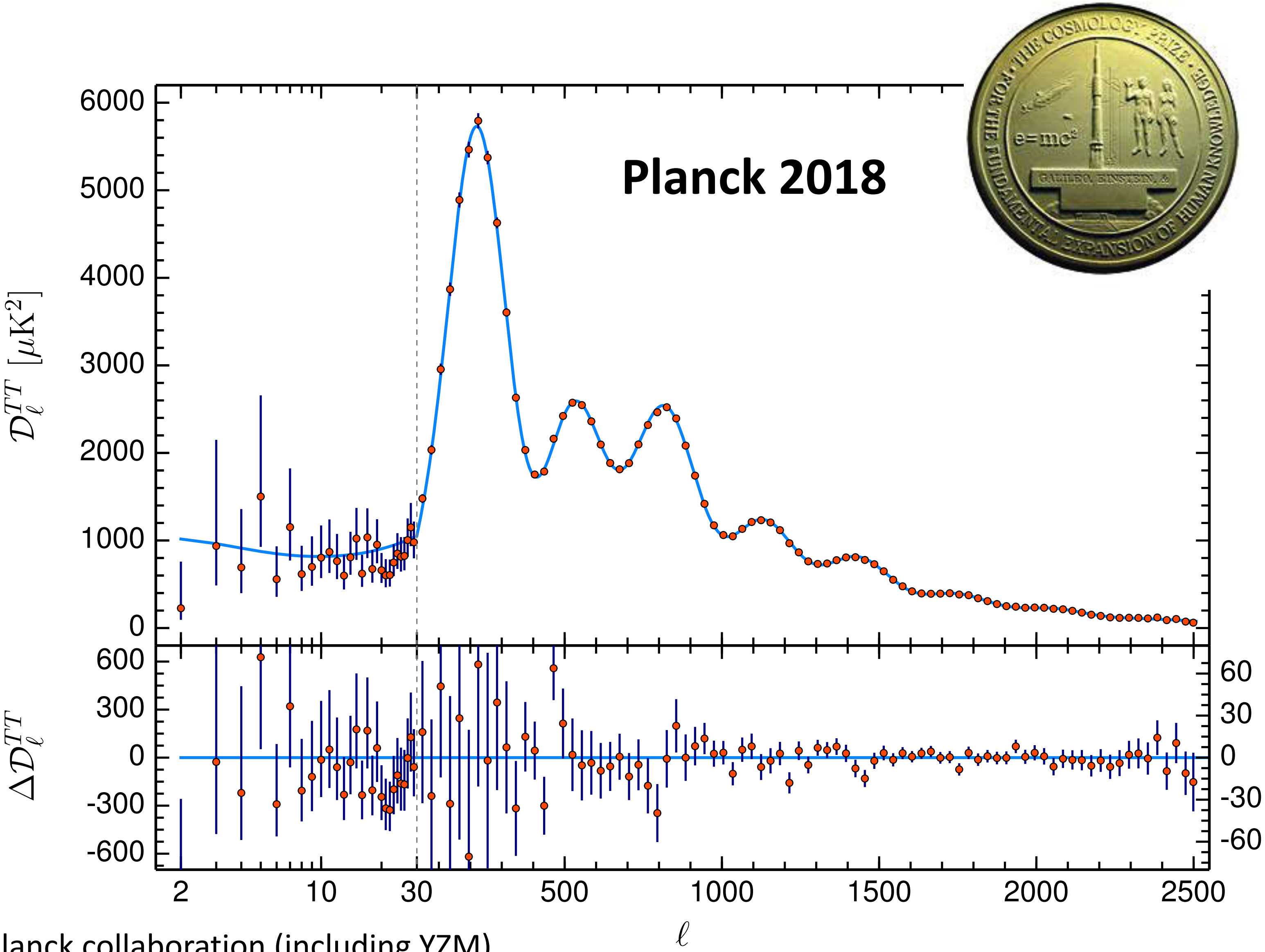
$N_{\rm eff} = 3.046$ in standard model

(see also Aich, YZM, Dai, Xia 2020, PRD)

Neutrino constraints



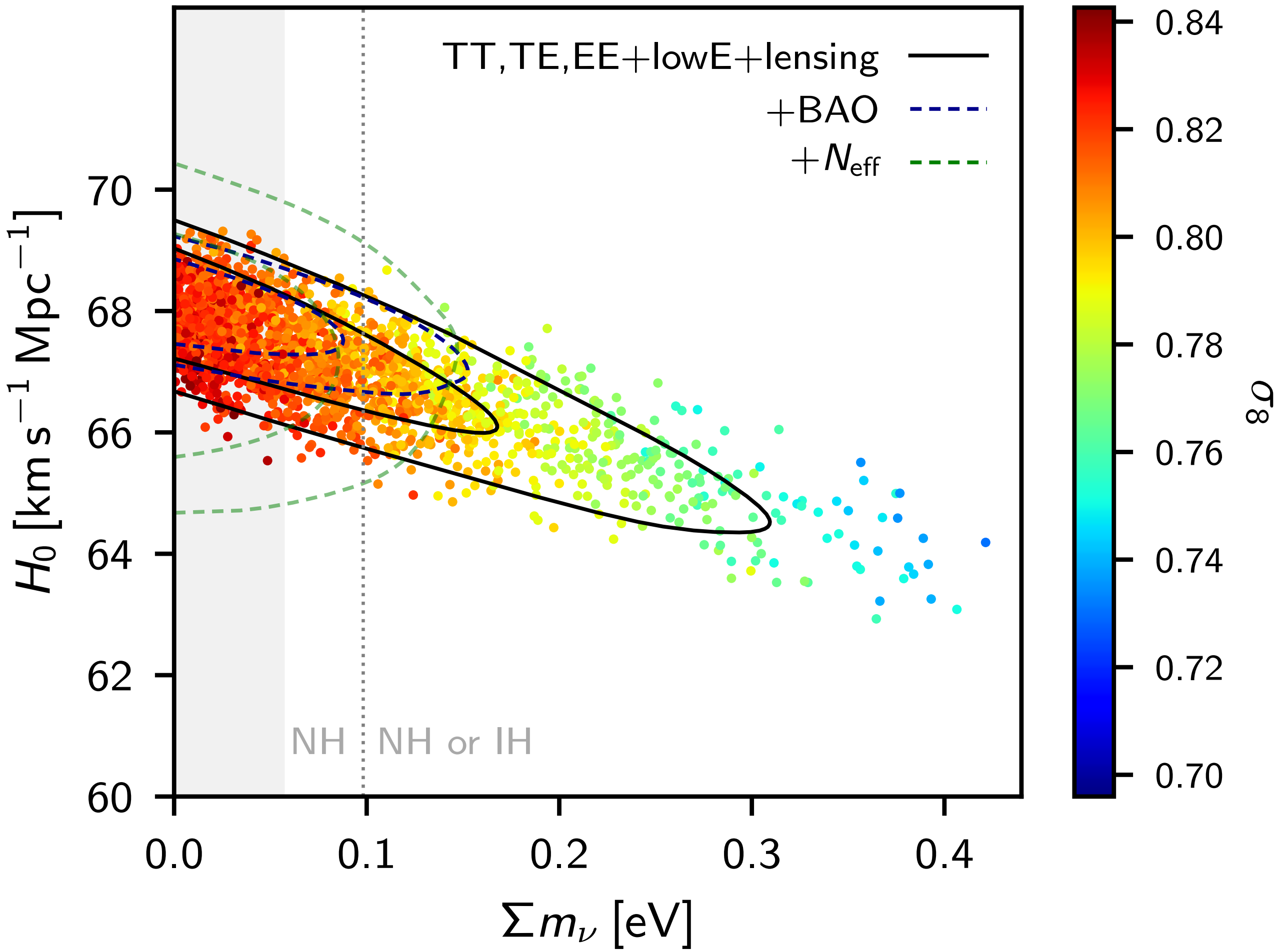
Free-streaming suppresses damping tail



Planck 2018

Planck collaboration (including YZM)

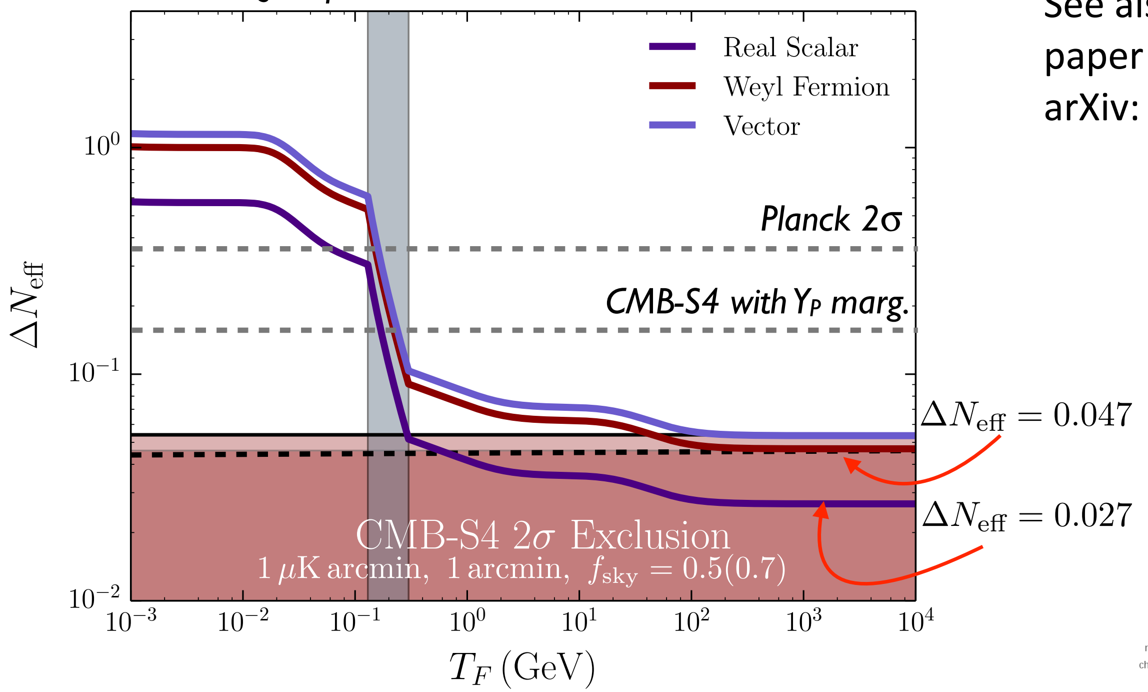
arXiv: 1807.06209, 1807.06205



$$\sum m_\nu < 0.12 \text{ eV} \quad (95\,\%, \textit{Planck} \text{ TT,TE,EE+lowE+lensing+BAO}).$$

Natural targets and CMB limits

QCD phase transition

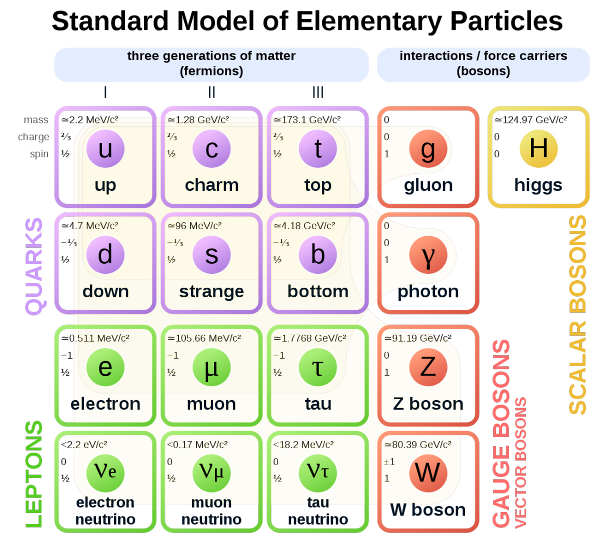


CMB-S4 Science Book

Decoupling temperature

See also Snowmass white paper (including Y.-Z. Ma) arXiv: 2203.08024

$$N_{\rm eff} = 3.046$$ in standard model



Summary:

- Axion decay constant $g_{a\gamma\gamma} < 6 \times 10^{-11}\,[\mathrm{GeV}^{-1}]$ for m_a = 3.1-4.5 $\mu\mathrm{eV}$ from 10-hour MeerKAT time, of observing a radio-quiet pulsar.

- WIMP decaying into leptons can cascade to synchrotron radiation, which can be probed by radio telescope. Using FAST, we placed stringent constraint on DM decaying into $\mu^+\mu^-, \tau^+\tau^-, b\bar{b}$, which excludes GCE best-fitting values at 99% C.L.

- CMB is placing interesting upper limits on neutrino masses, which can lead to the final determination if neutrino mass hierarchy in the next few years.

Summary:

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- WIMP decaying into leptons can cascade to synchrotron radiation, which can be probed by radio telescope. Using FAST, we placed stringent constraint on DM decaying into $\mu^+\mu^-, \tau^+\tau^-, b\bar{b}$, which excludes GCE best-fitting values at 99% C.L.
- The Pulsar Timing Array (PTA) and Polarisation Array (PPA) can be used to detect the axion-like WDM as a common correlated signal. This approach forms a great complementarity with the CMB measurement.
- Primordial black holes induced by small-scale scalar perturbation may not constitute a significant fraction of DM due to the relativistic constraints (N_{eff}).

Back up

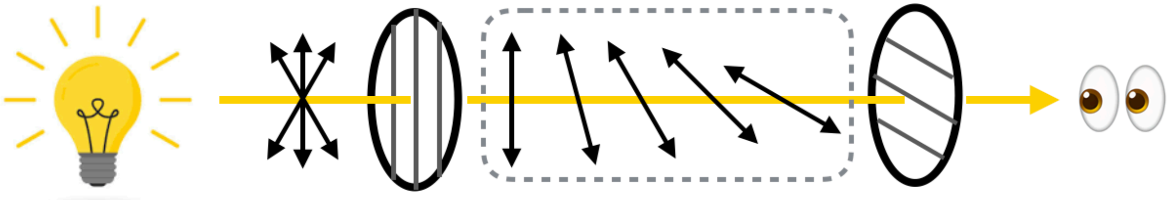
Axion-Like-Particles: Cosmic Birefringence (CB) effect with PTA & PPA

Carroll & Field, 1991, PRD

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

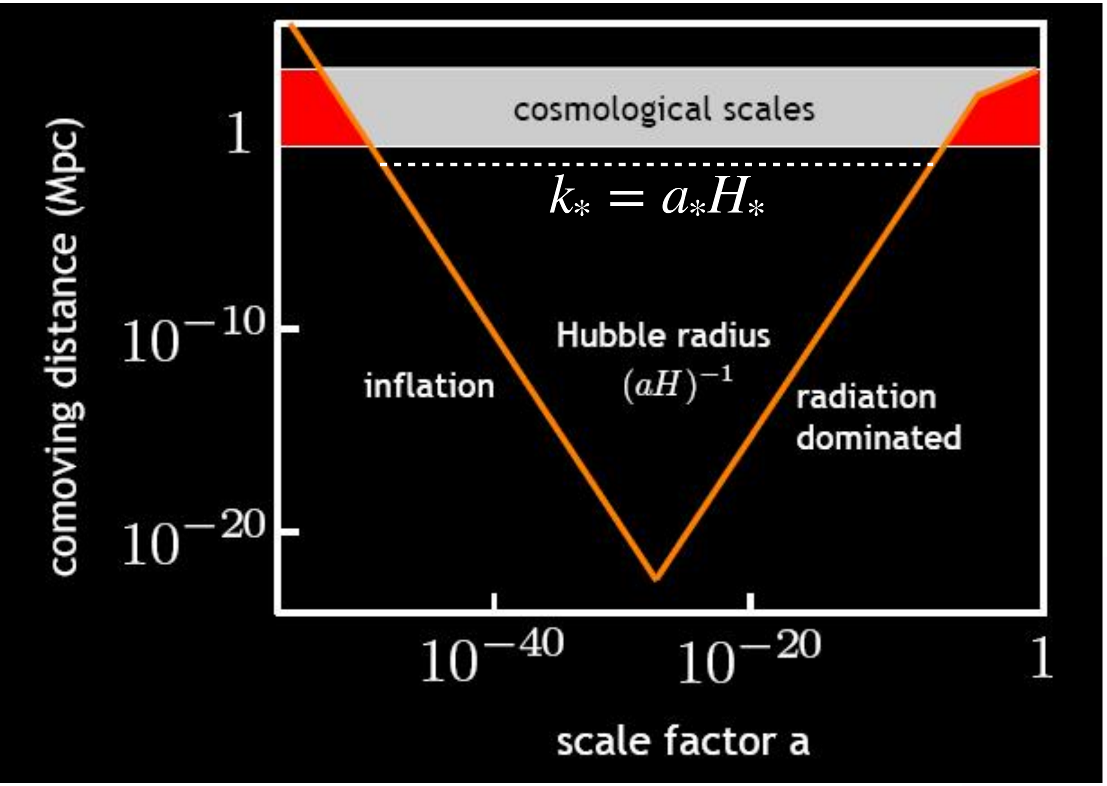
Cherns-Simons coupling

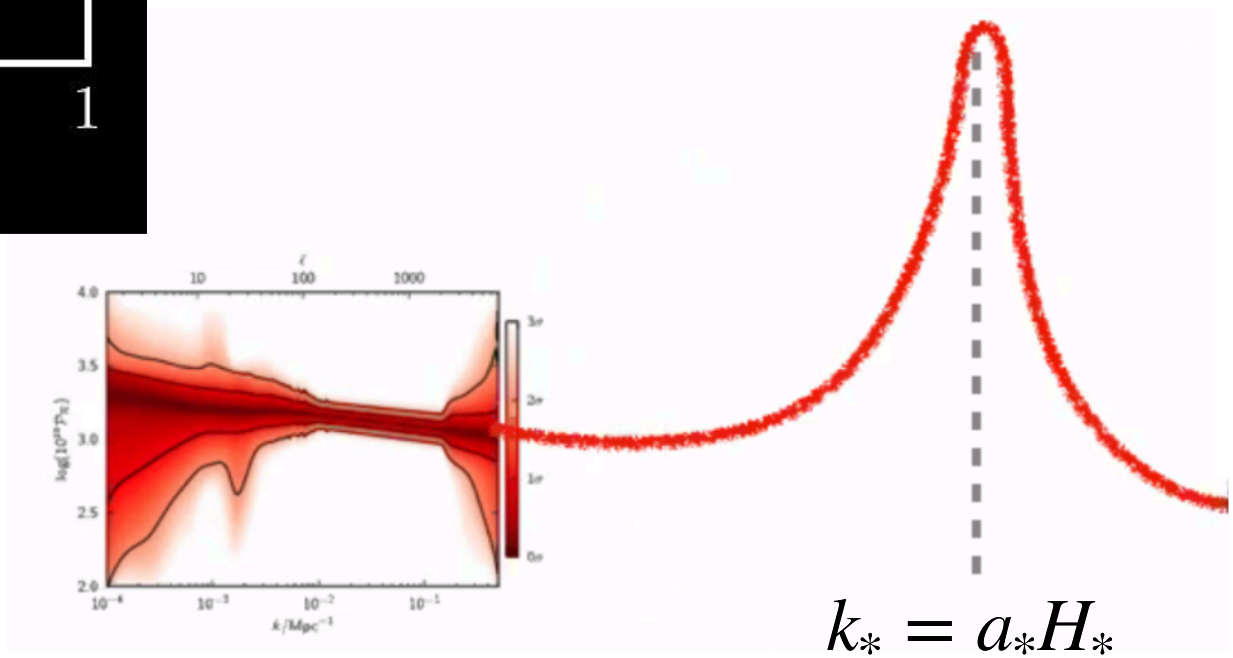
$$\omega_\pm \simeq k \pm g\left(\frac{\partial a}{\partial t} + \nabla a \cdot \frac{\mathbf{k}}{k}\right) \xrightarrow[\text{relativistic}]{\text{non}-} k \pm g\frac{\partial a}{\partial t}$$

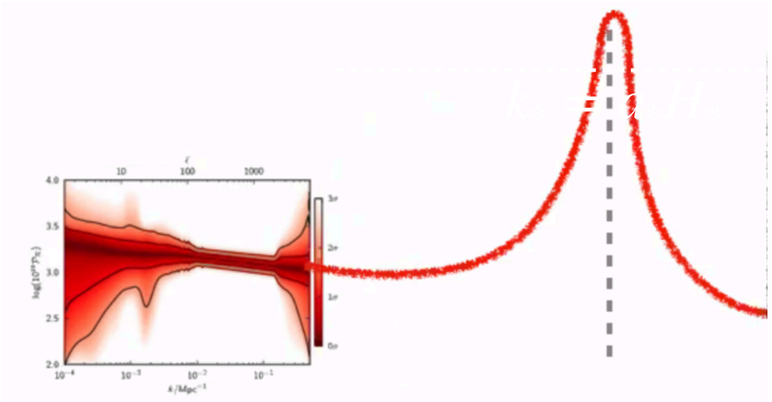


$$\begin{aligned}\Delta\theta &= -g\int_{t_i}^{t_f} \partial_t a(\mathbf{x}, t)\, dt \\ &= \frac{g}{m_a}[\sqrt{\rho_i}\cos(m_a t_i + m_a \mathbf{v}\cdot\mathbf{x_i} + \phi) \\ &\quad -\sqrt{\rho_f}\cos\left(m_a t_f + m_a \mathbf{v}\cdot\mathbf{x_f} + \phi\right)]\end{aligned}$$

Observational signature:
Polarisation angle rotation

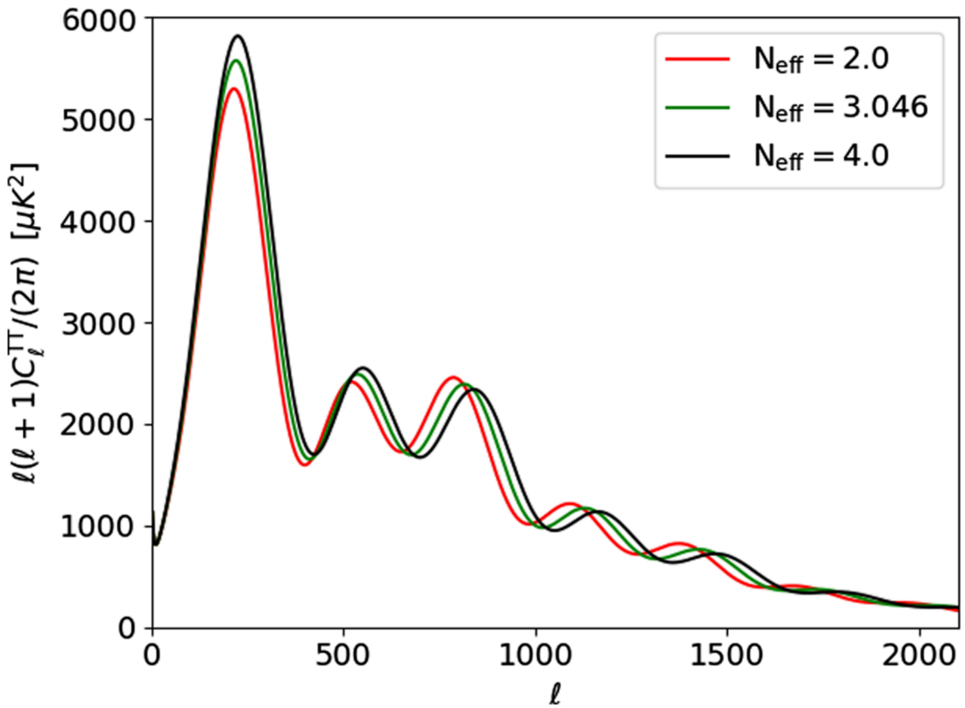

cosmological scales
1
10^{-10}
10^{-20}
comoving distance (Mpc)
$k_* = a_* H_*$
Hubble radius
$(aH)^{-1}$
inflation
radiation
dominated
10^{-40}
10^{-20}
1
scale factor a


$k_* = a_* H_*$



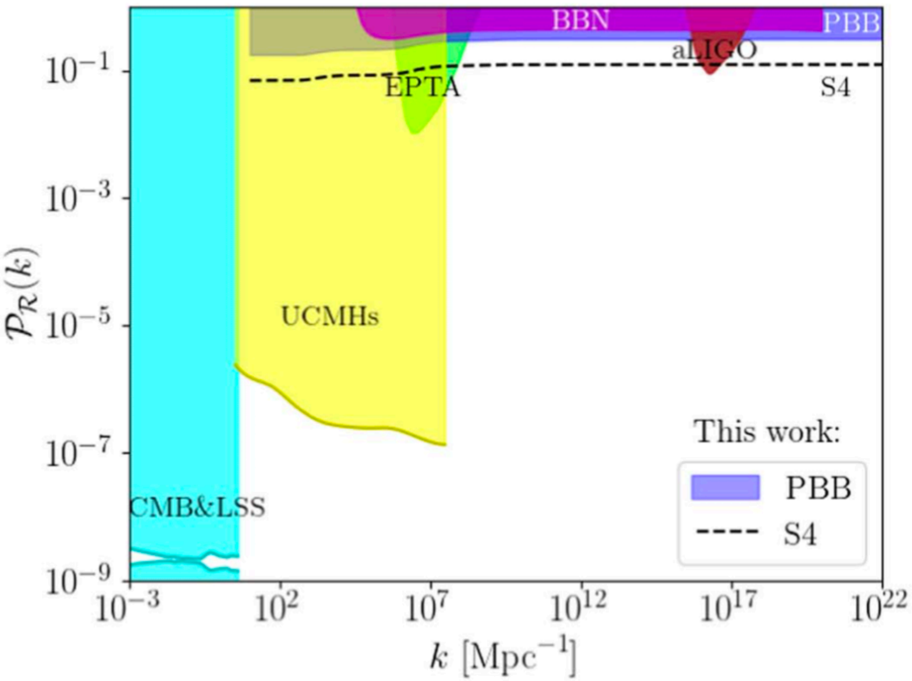
$$P_{\mathscr{R}} \xrightarrow[\text{Gravitational Waves}]{\text{Scalar-Induced}} \Psi = \frac{\mathrm{d}\Omega_{\mathrm{GW}}}{\mathrm{d}\ln k} \sim P_{\mathscr{R}}^2$$

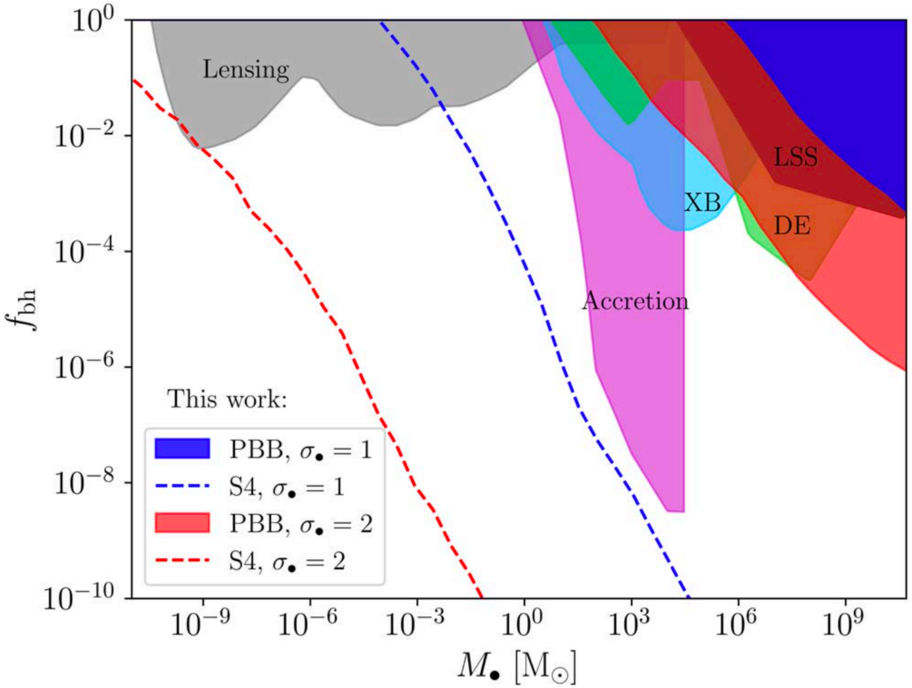
$$C_\ell \xleftarrow{\text{Constrained}} \Delta N_{\mathrm{eff}} = 8.3 \times 10^4\, \Omega_{\mathrm{GW}}$$



- Delaying matter-radiation equality
- Adding anisotropic stress
- Changing sound horizon

Aich, YZM, Dai, Xia, 2020, PRD
Cang, Gao, YZM, 2023, ApJ





- Exclude PBH with peak mass $M_\bullet = [5 \times 10^5, 5 \times 10^{10}]\,\mathrm{M}_\odot$ as the major DM candidates
- Limits on $P_{\mathscr{R}}(k)$ for $k = [10, 10^{22}]\,\mathrm{Mpc}^{-1}$
- Future CMB-S4 can expand the mass range to $[10^{-5}, 5 \times 10^{10}]\,\mathrm{M}_\odot$

Cang, Gao, YZM, 2023, ApJ