Probing the pi-axiverse with astrophysics

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DARK MATTER

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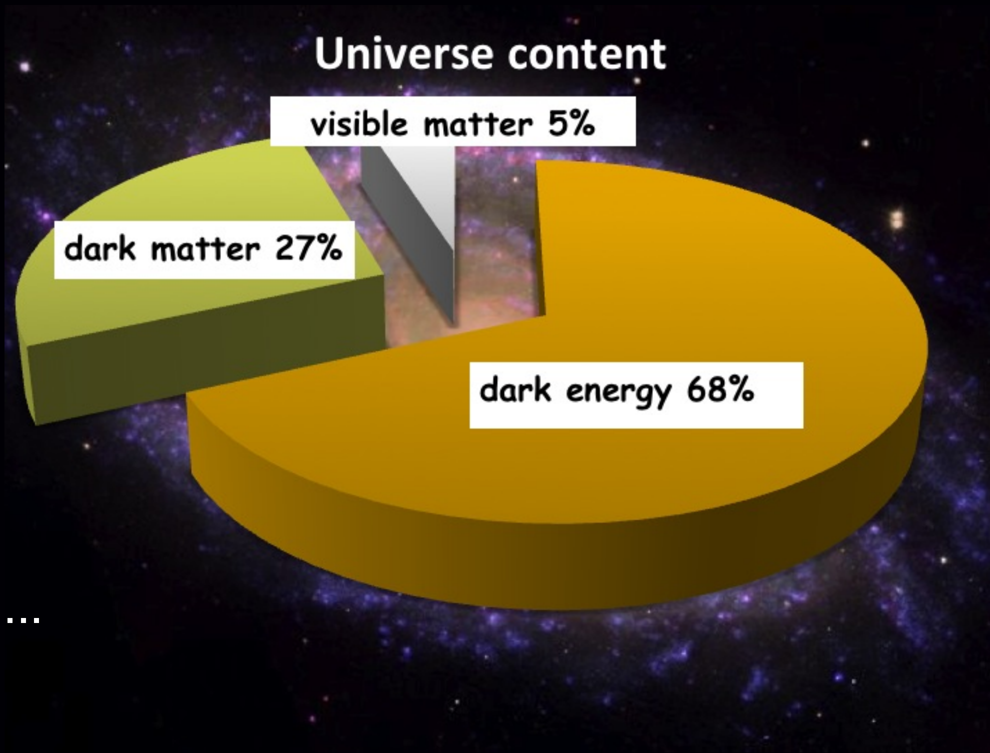
Talk outline

- Why dark matter matters
- What the @#$! is an axion?
- The pi-axiverse
- Axion star mergers
- Observability
- Conclusion

What do we know about dark matter?

- It's important
- It's massive
- It's probably a particle
- Electrically neutral



That's not much to go on....

What the @#$! is an axion?

This is an axion! Dark matter solved!?

Not so fast....

Axion is an american detergent
Needed to “clean up” the Standard Model

Why?

Neutrons have no electric dipole moment
SM lagrangian says they could have one
Parameter that controls this cannot be predicted

$$\mathscr{L} \propto \theta \, \tilde{G}_{\mu\nu} \, G^{\mu\nu}$$

- A problem if you want “naturalness”
- Theorists don’t like fitting parameters....
- So they add a new symmetry that cancels theta out
- This symmetry adds a new particle: the axion

Relax Lagrangians don't bite

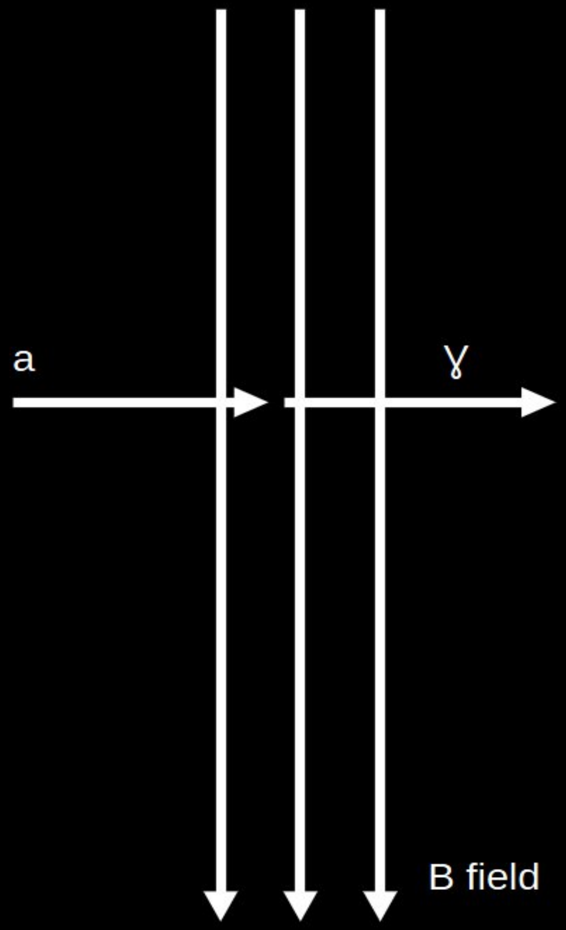
ussually....just tell it you *really* like theory

$$\mathscr{L} \propto (\theta - a\lambda)\tilde{G}_{\mu\nu} G^{\mu\nu}$$

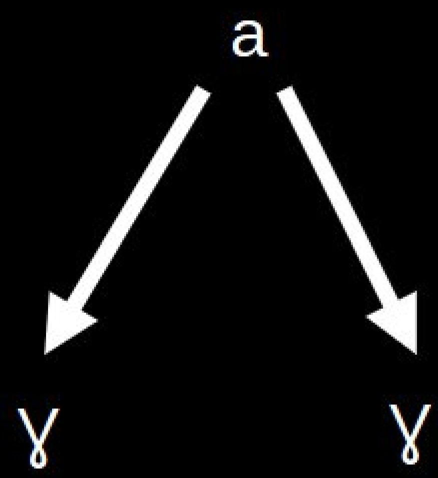
- New Lagrangian part must have axions couple to gluons
- Gluons couple to quarks
- Quarks are charged -> couple to photons
- Thus, axions couple to photons!
- Here is where things get weird

Axions are weird

Magnetic conversion to photons!



Plain old decay (very slow)



Photons at frequencies given by energy of axion

The pi-axiverse

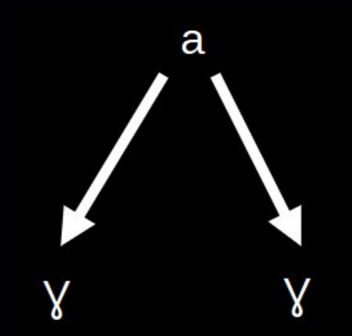
- Axions arise often in stringy theories (extra symmetries)
- Is there another way to get them?

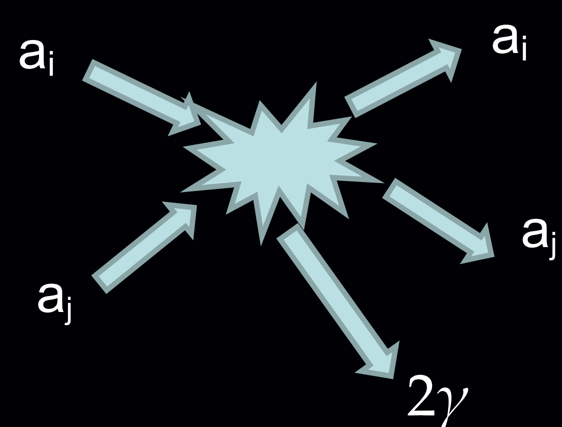
- Enter the pi-axiverse
- Dark matter sector has the same symmetries as the SM
- SU(3) X SU(2) X U(1)
- Dark quarks, photons, etc!

- SM - dark link is via photon mixing
- Dark matter relics are pions and kaons of dark SU(3)
- Ensured by very tiny dark quark masses

The pi-axiverse

- We are left with the following interactions





$$\mathcal{L}^{(1)}_{\rm int} = \frac{\lambda_1}{2F_\pi}\varepsilon^2(\pi^0)F_{\mu\nu}\tilde{F}^{\mu\nu},$$

$$\mathcal{L}^{(4)}_{\rm int} = \frac{\lambda_4}{2\Lambda_4^2}\varepsilon^2(\pi_i)(\pi_j)F_{\mu\nu}F^{\mu\nu}.$$

- The first is a normal axion-like term (magnetic conversion too)
- The second is an intra-species pi-axion interaction
- A dilaton-like coupling mediated by dark photon
- See arxiv: 2304.11176

Parametric resonance

- We have multiple coupled oscillators (pi-axions, photons)
- They are damped and driven
- This results in equations of motion for photon modes

$$0 = \Big(1 + P(t)\Big)\Big(A''_\pm + k^2 A_\pm\Big) + B(t)A'_\pm + \Big(C_\pm(t)k + D(t)\Big)A_\pm,$$

- Where each term is horrific, e.g.

$$P(t) = \frac{4\lambda_3}{\Lambda_3^2}\varepsilon^2 \sum_{i,j}^{N_\pm} \pi^c_{i,0}\pi^c_{j,0}\cos(\theta_i - \theta_j)\cos\varphi_i(t)\cos\varphi_j(t) + \frac{2\lambda_4}{\Lambda_4^2}\varepsilon^2\Big[2\sum_{i,j}^{N_0^c}\pi^c_{i,0}\pi^c_{j,0}\cos(\theta_i - \theta_j) + \sum_{i,j}^{N_0^r}\pi^r_{i,0}\pi^r_{j,0} + 4\sum_{i=1}^{N_0^r}\sum_{j=1}^{N_0^c}\pi^r_{i,0}\pi^c_{j,0}\cos\theta_j\Big]\cos\varphi_i(t)\cos\varphi_j(t)$$

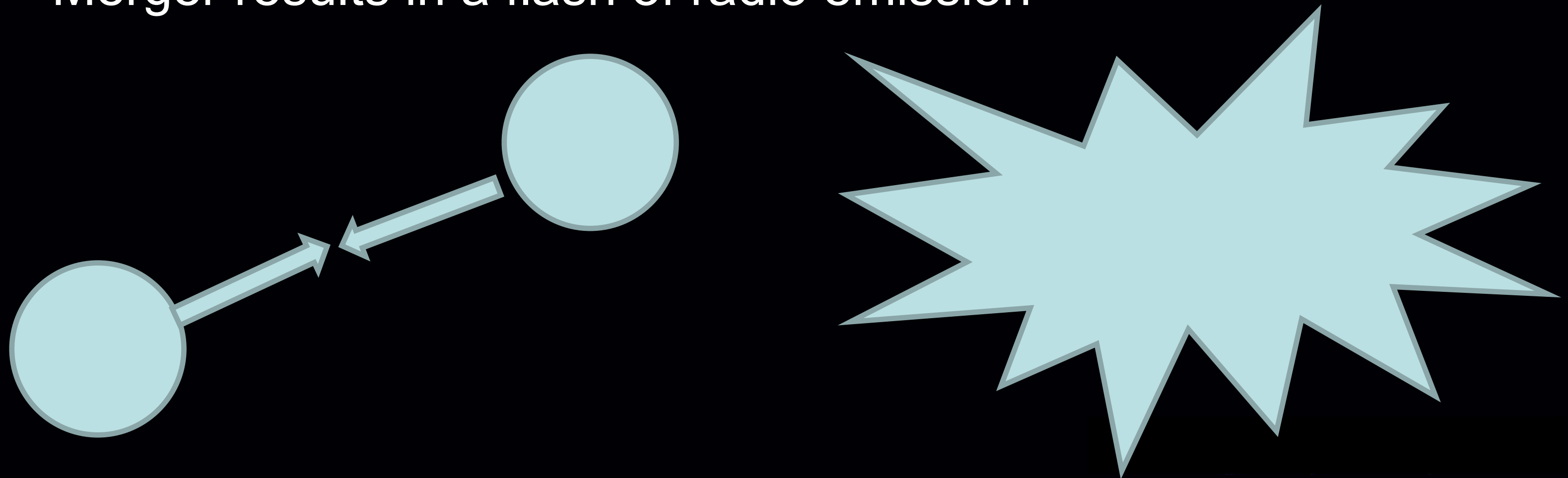
- We solve this numerically, of course

Merging axion stars

- Axion clumps can be stable (star)
- Typically requires $g_a F_a > 0.3$ (most models ~10^{-3})
- Our dilaton interaction mostly obviates this

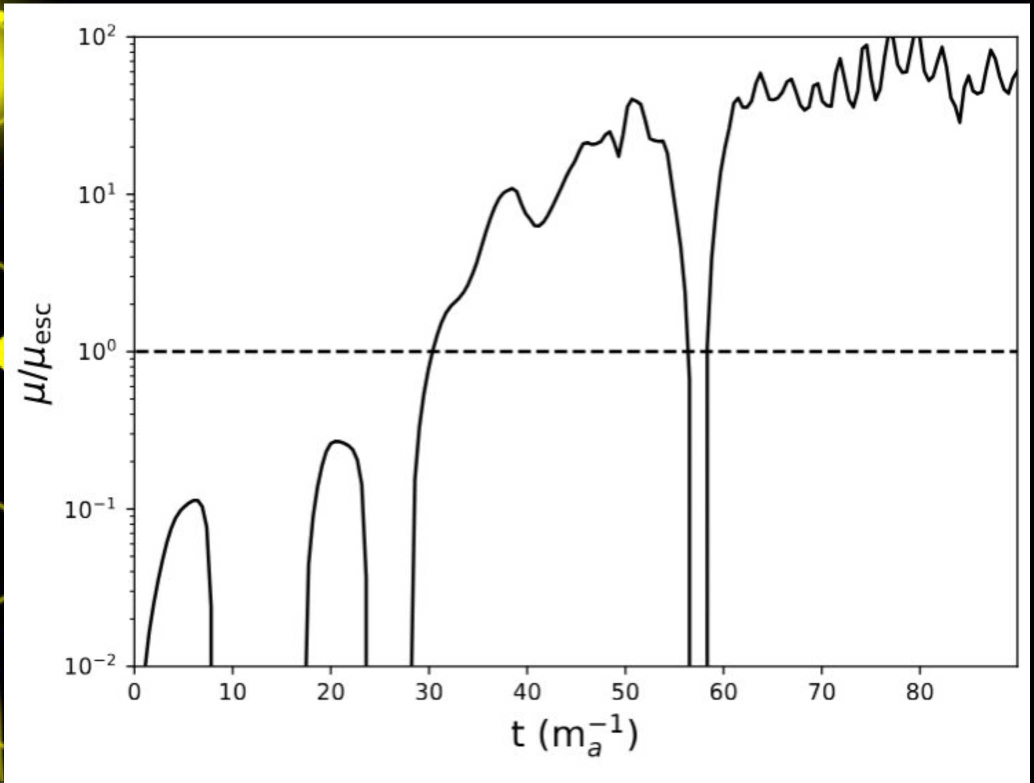
- If a star is too large then it enters resonant decay
- This limits size

- Merging stable stars will exceed this size
- Some excess pi-axions are turned into photons
- Merger results in a flash of radio emission



Our procedure

- Homogeneous density numerical simulations
- Determine maximum stable size
- Translate to spatially varying clump
- Predict observables from mergers
- About 0.2 total mass radiated (Hertzberg 2020)



Example:
exponential growth rate compared to photon escape rate.

Time at which we exceed 1 allows parametric resonance

Observability

- Scan a parameter space for pi-axions
- Mass, couplings, density, initial phase angles between species
- Determine merger flux
- Treat like an FRB (dispersed in time)
- Find density requirement for observation within Milky-Way

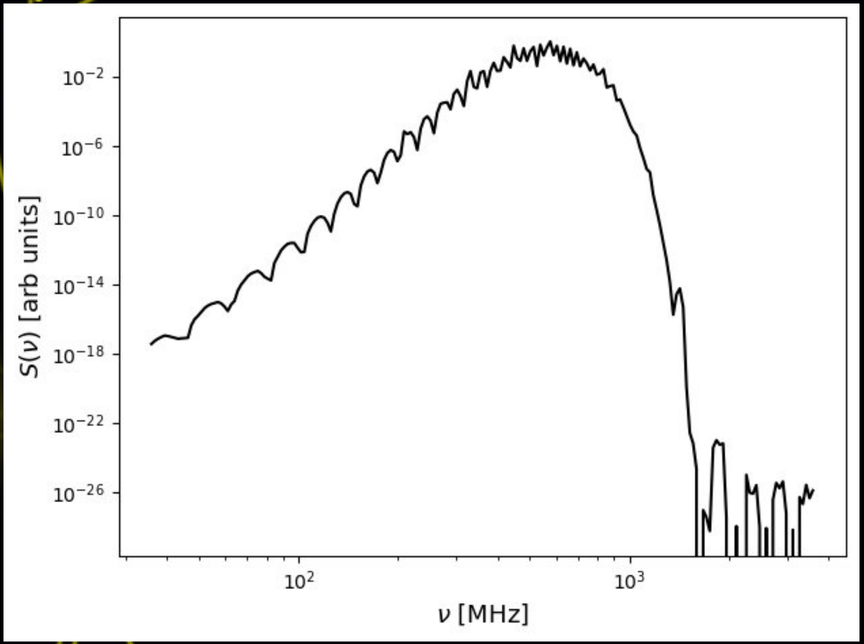
MeerKAT

- Flux ~ 10 μJy
- 550 MHz - 1.7 GHz

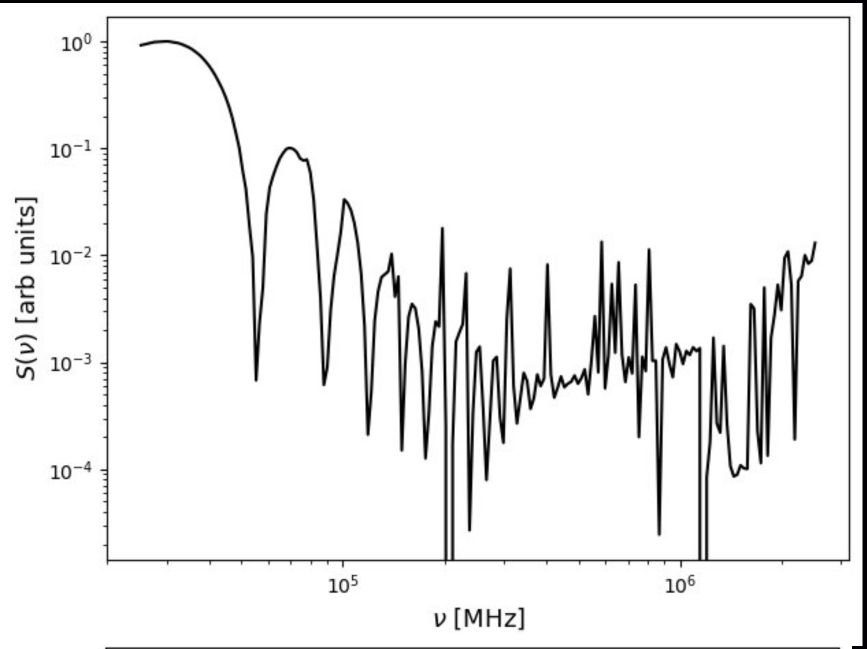
SKA/ngVLA

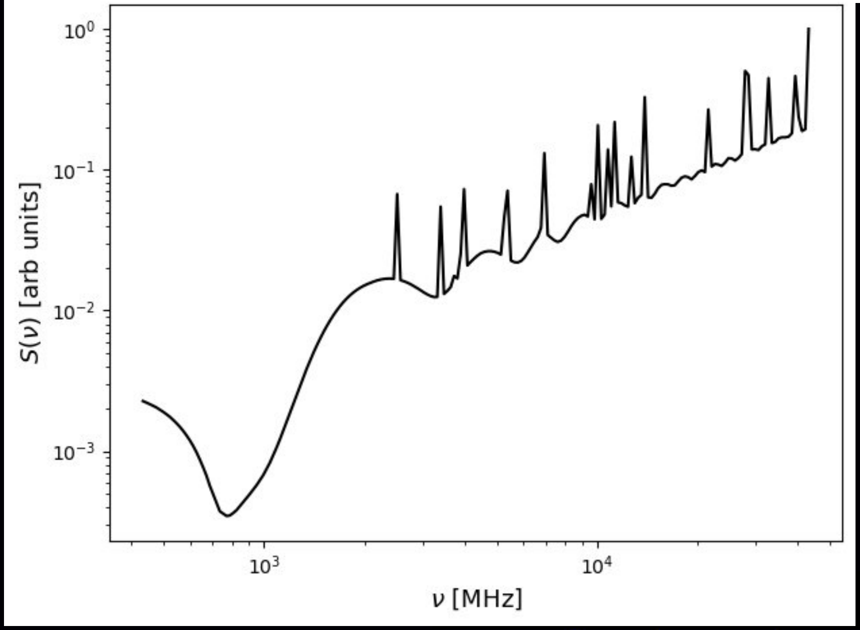
- Flux ~ 1 μJy
- 50 MHz - 50 GHz

Frequency spectra

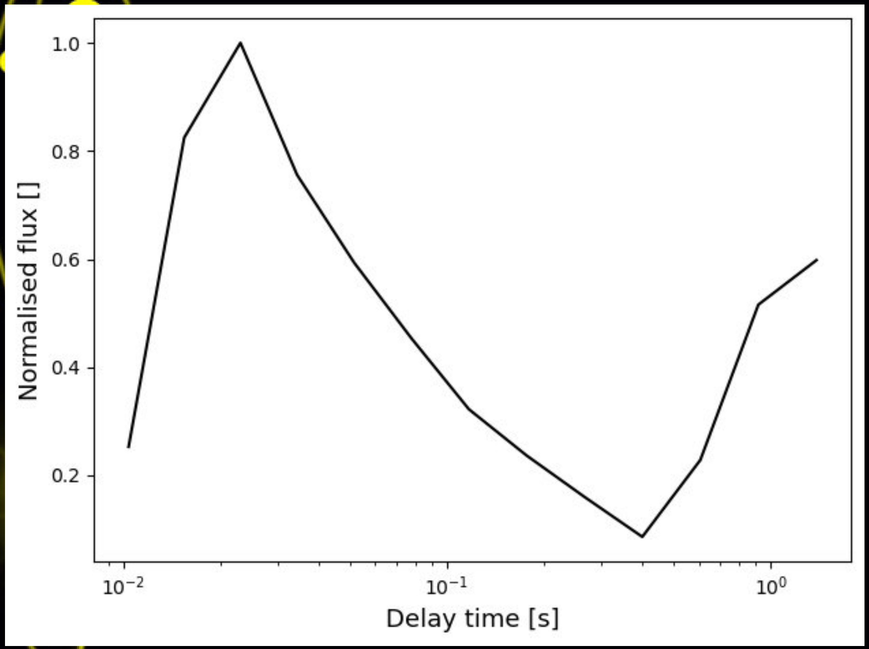


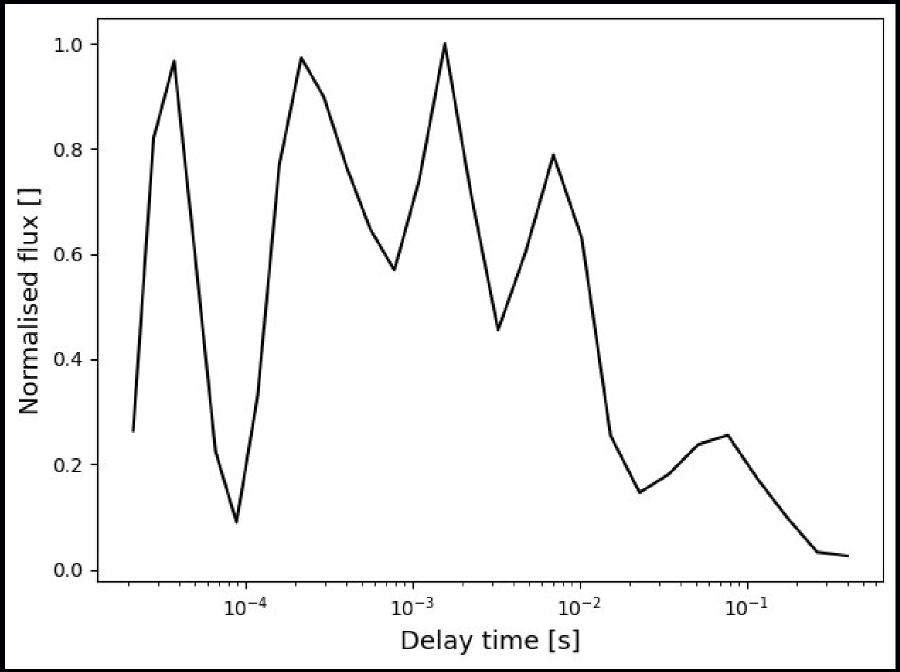
- Very diverse spectra!
- Depend on couplings and initial field phases
- A gift of the “horrific” equations earlier



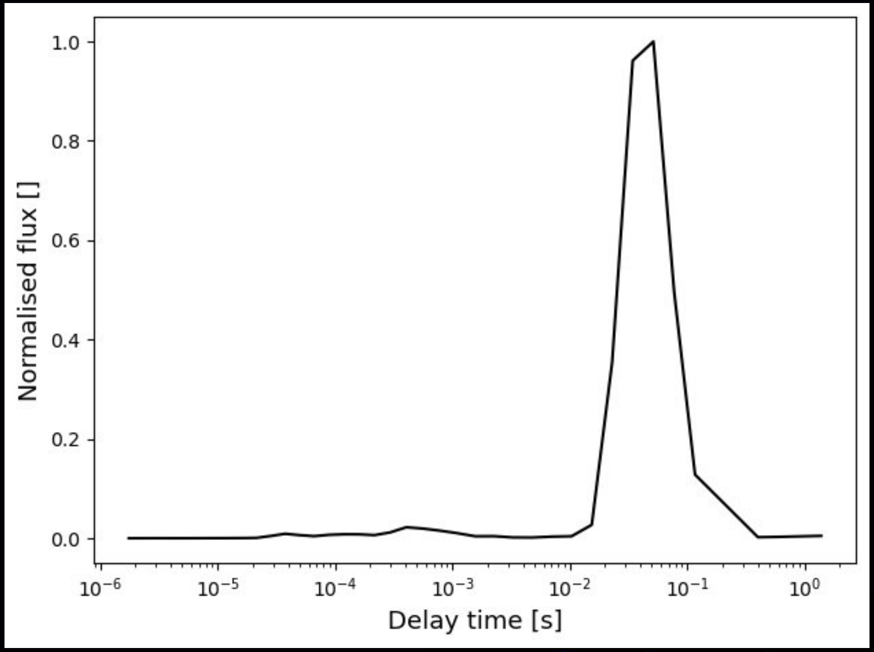


Time delay



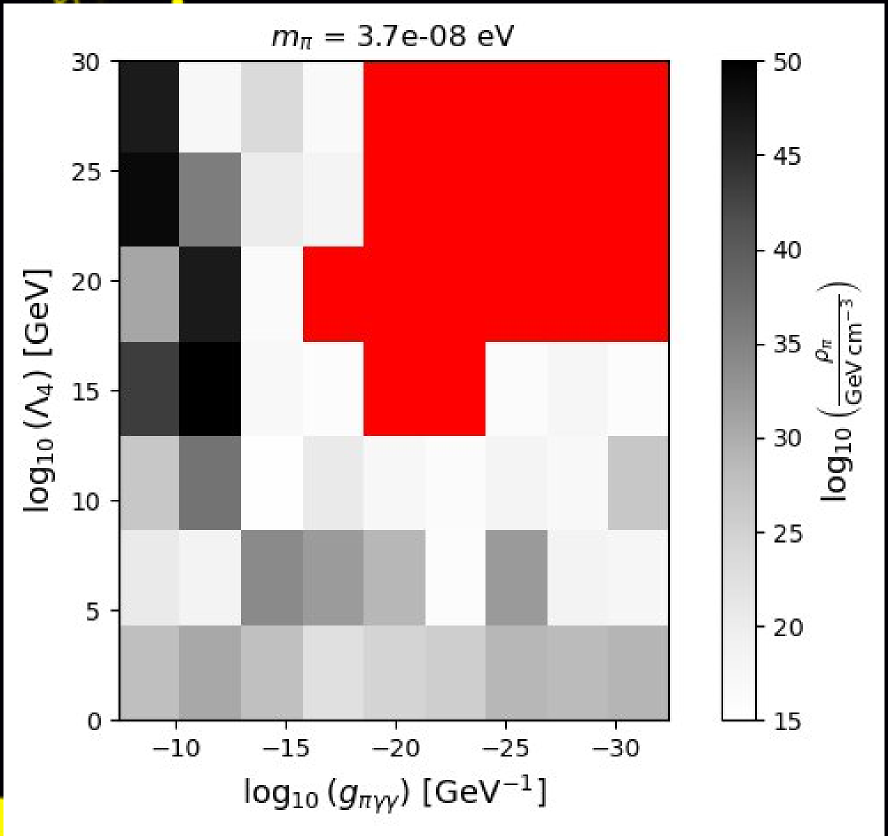


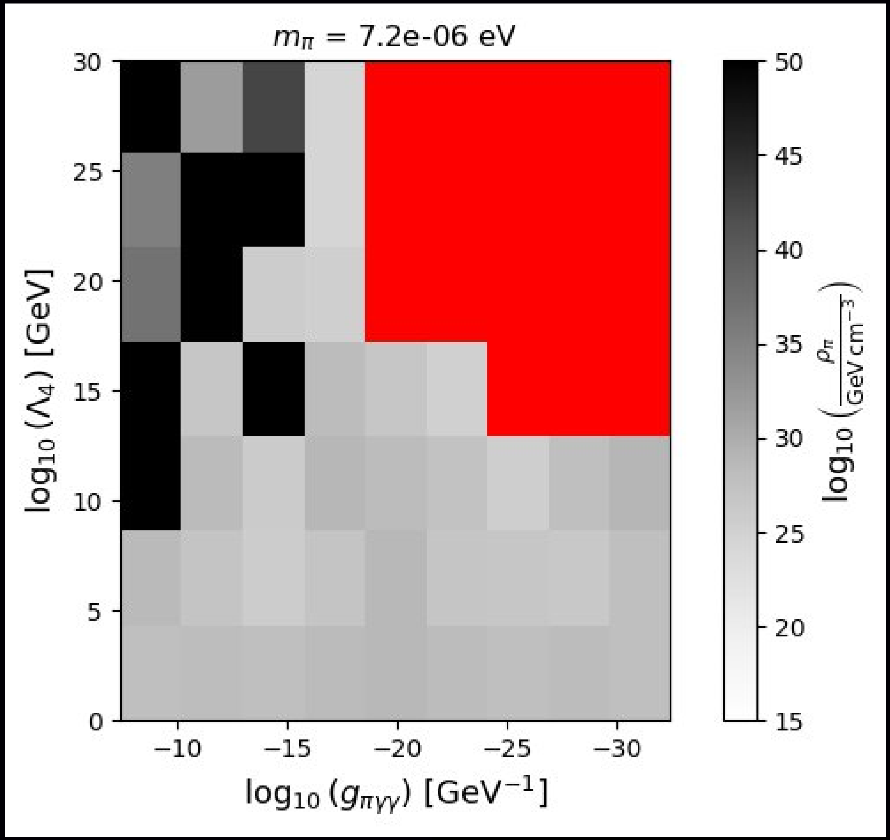
- Diverse delay spectra
- Some FRB-like
- Others very different



Detectability (MeerKAT)

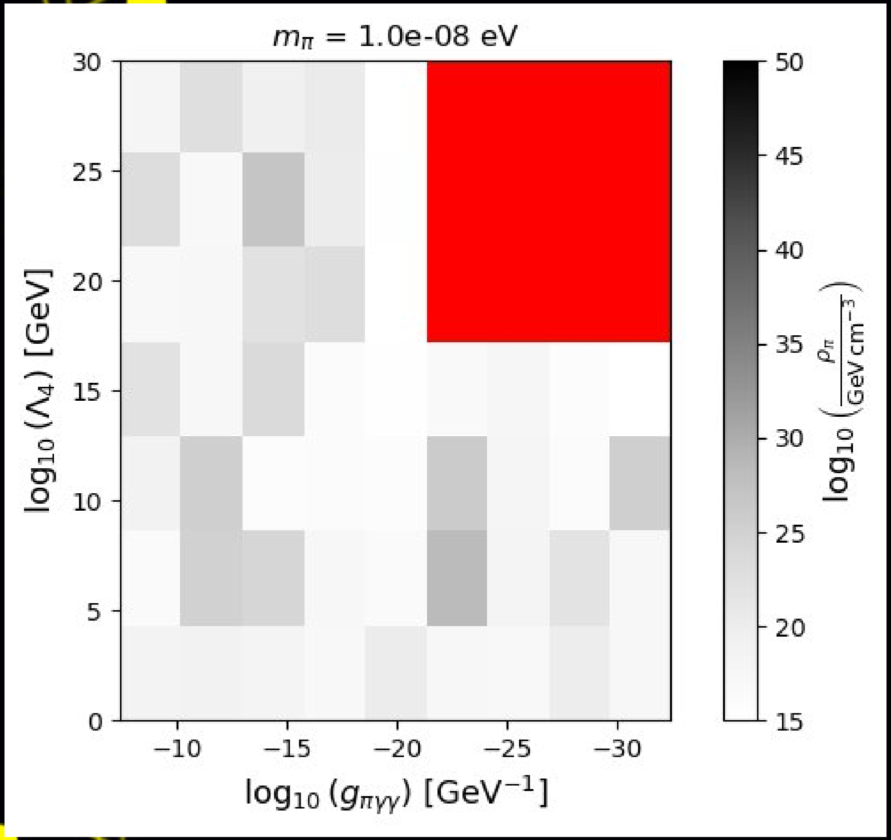
- Mass range much larger than mono-axion theories
- Requires ρ at most 10^7 times solar density
- Can probe very weak couplings

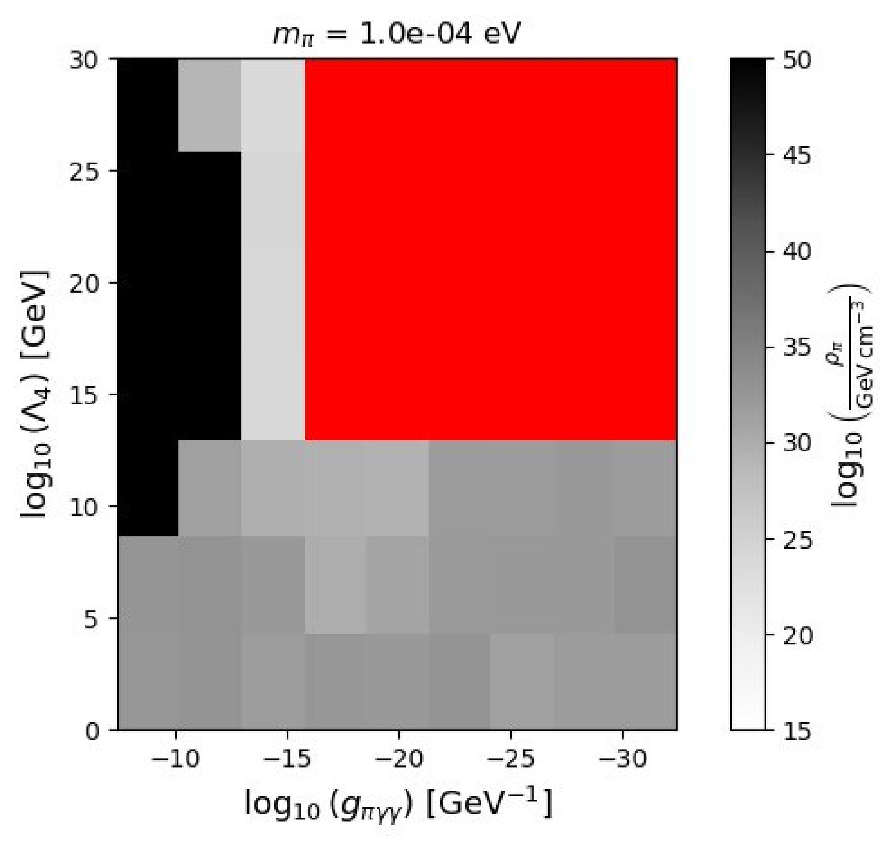




Detectability (SKA)

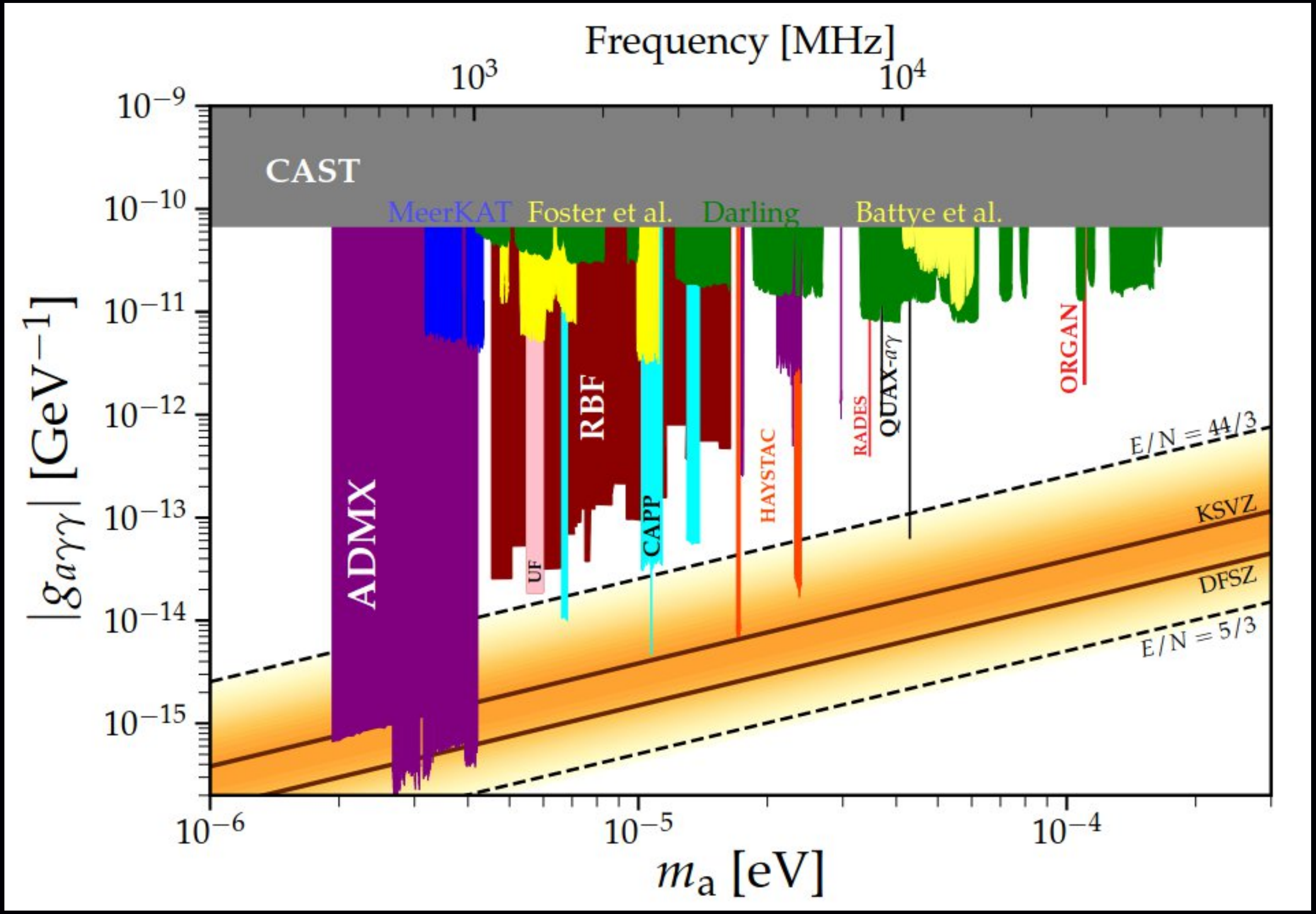
- Expanded mass range
- Allows very low densities for detection





Existing limits

- Current limits on axion couplings



- We can probe our model down to at least ~ 10^{-15} GeV^{-1}
- With quite modest axion star densities

Conclusions

- Alternative way to produce axions (dark copy of SM)
- Pi-axions are neutral mesons in dark sector
- Rich phenomenology with multi-axion model
- Stable axion star mergers are highly detectable
- Can be very distinct from FRBs
- MeerKAT studies should be viable