GRAPPA

GRavitation AstroParticle Physics Amsterdam

Novel approaches in the Search for Dark Matter

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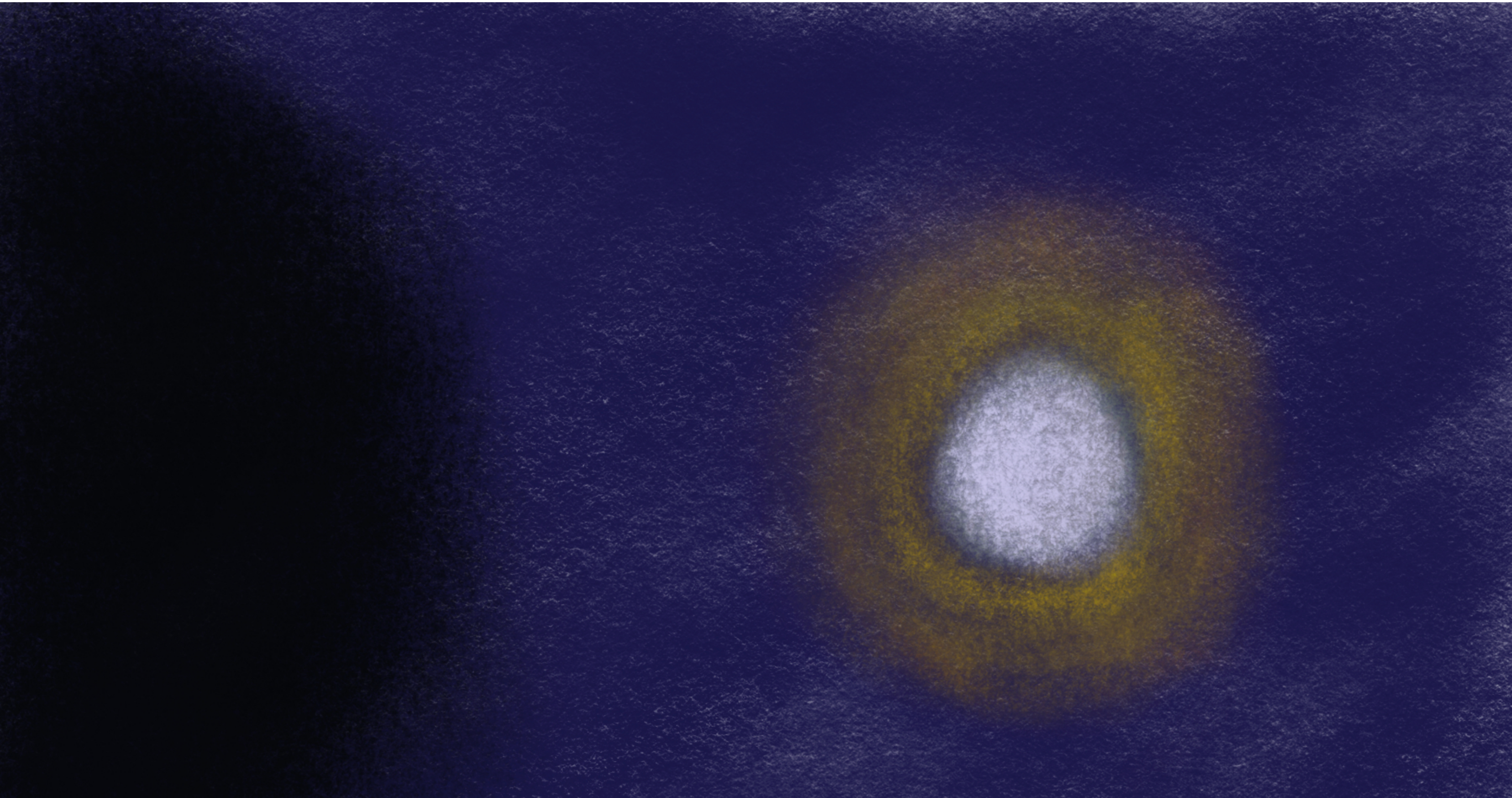
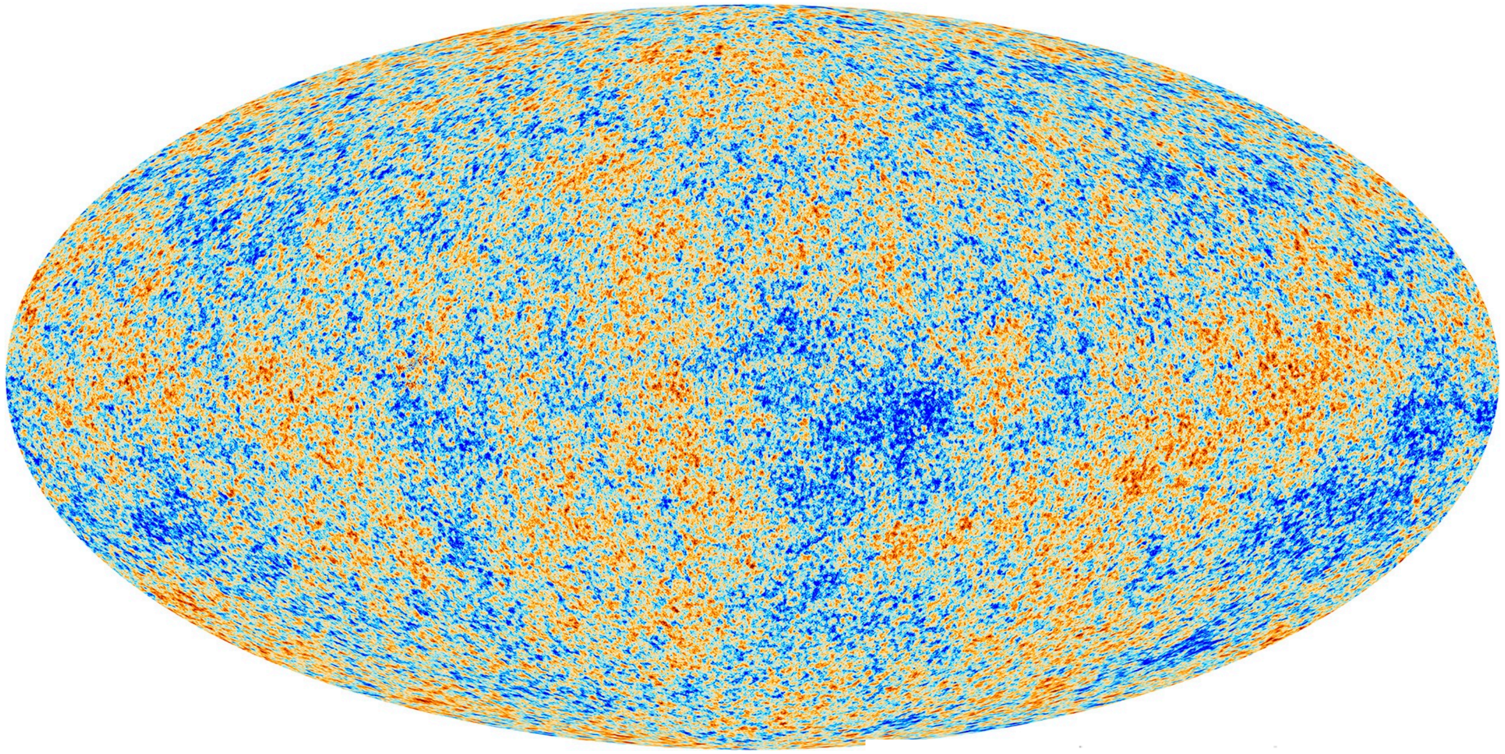
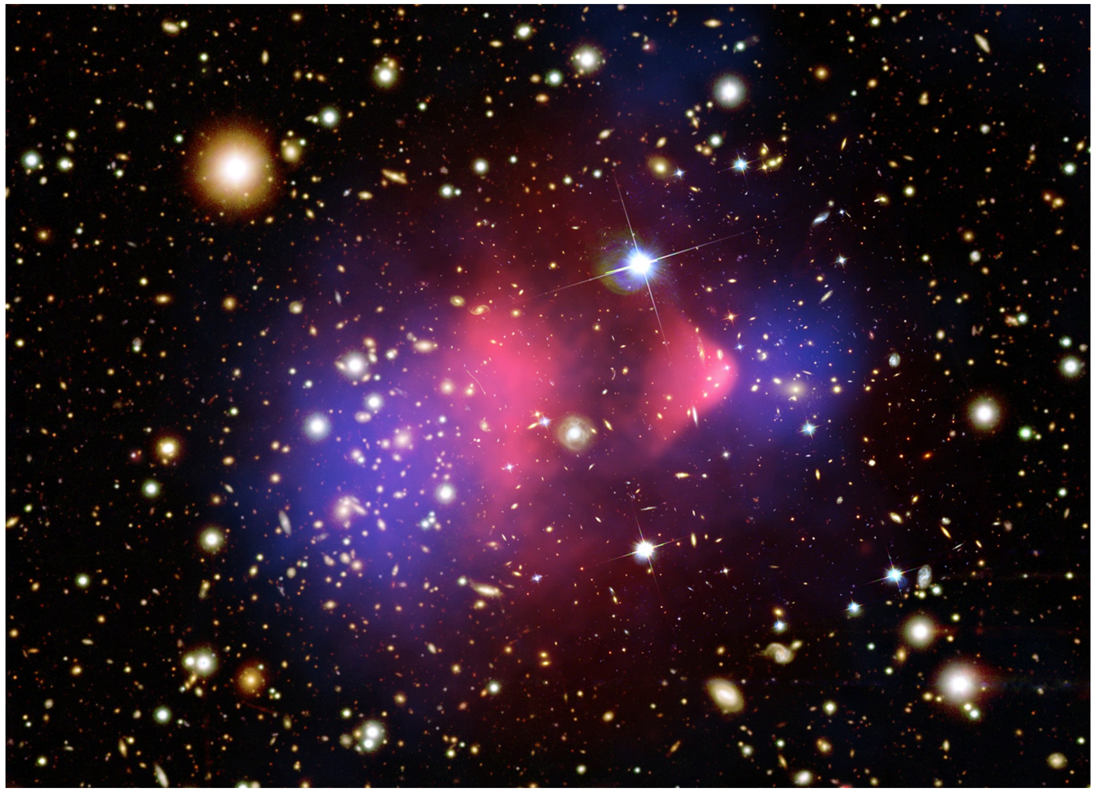
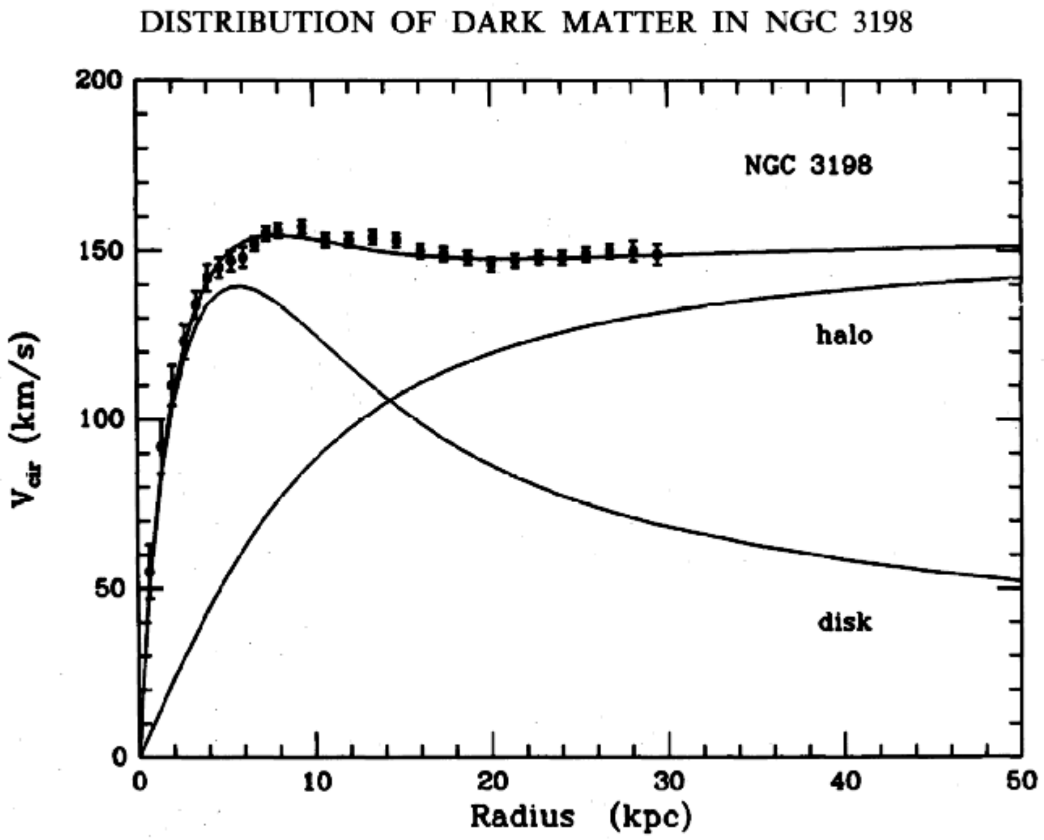


Cold Dark Matter Basics

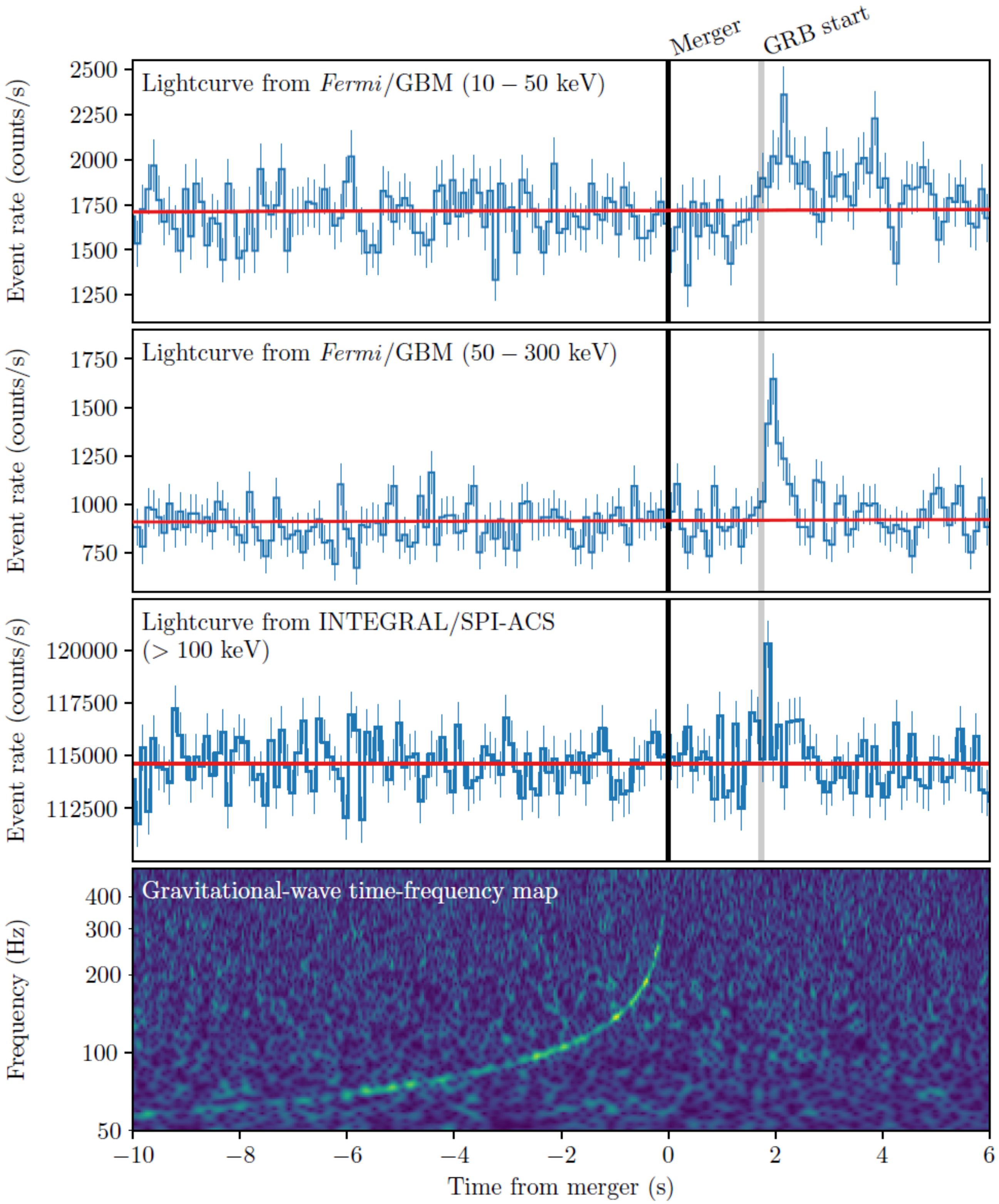






Dark Matter Basics - Modifications of Gravity

- Modifications to gravity can account for all of the DM without violating any physical principles, but all require additional degrees of freedom (dof)
- Not all dof created equal - dof's that were invoked to solve fundamental issues in particle physics deserve a special place in the space of theories
- Modified Gravity theories cannot account for all the observations that require DM - specifically cosmological cold DM.



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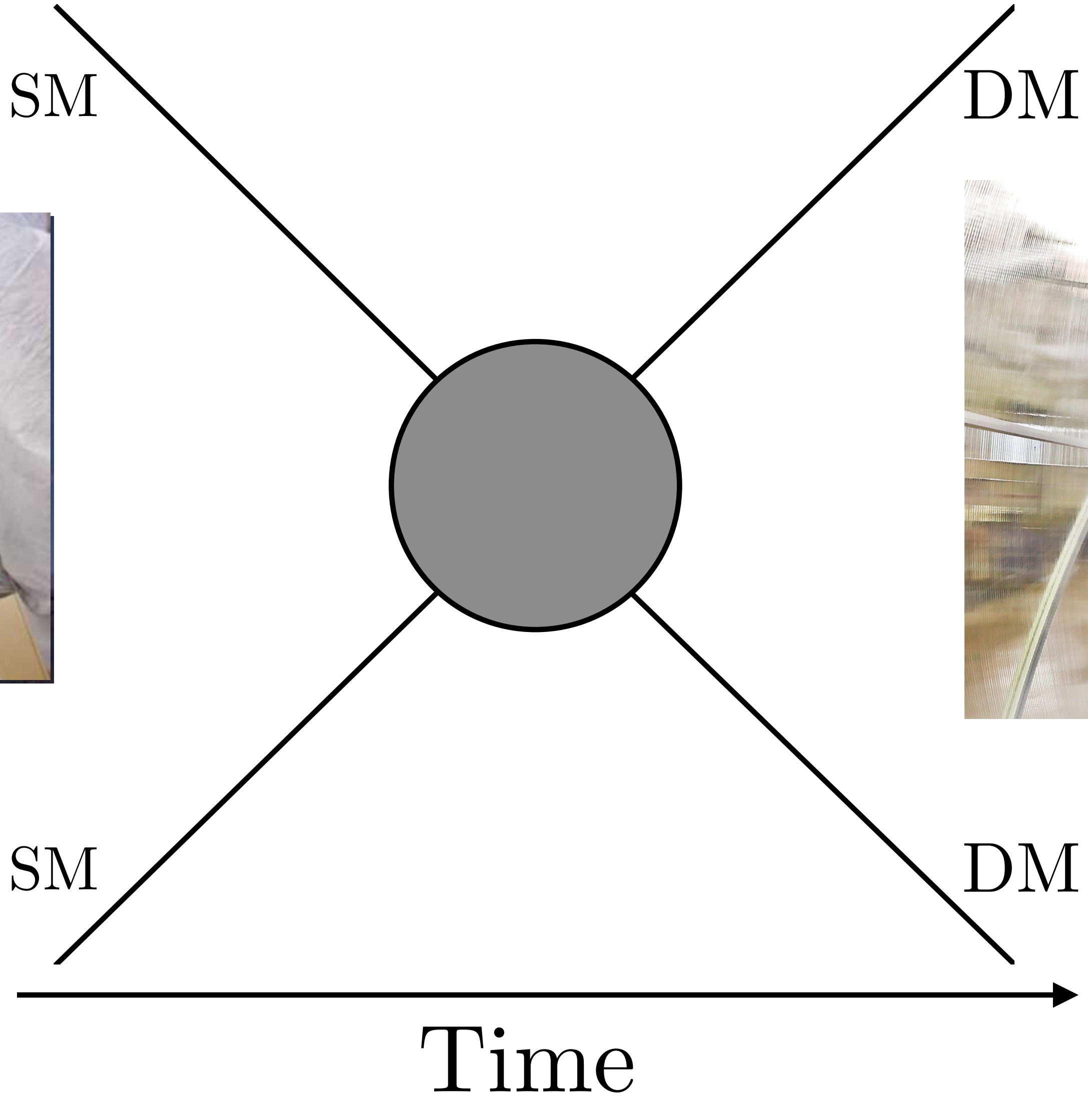
Current Search Strategies



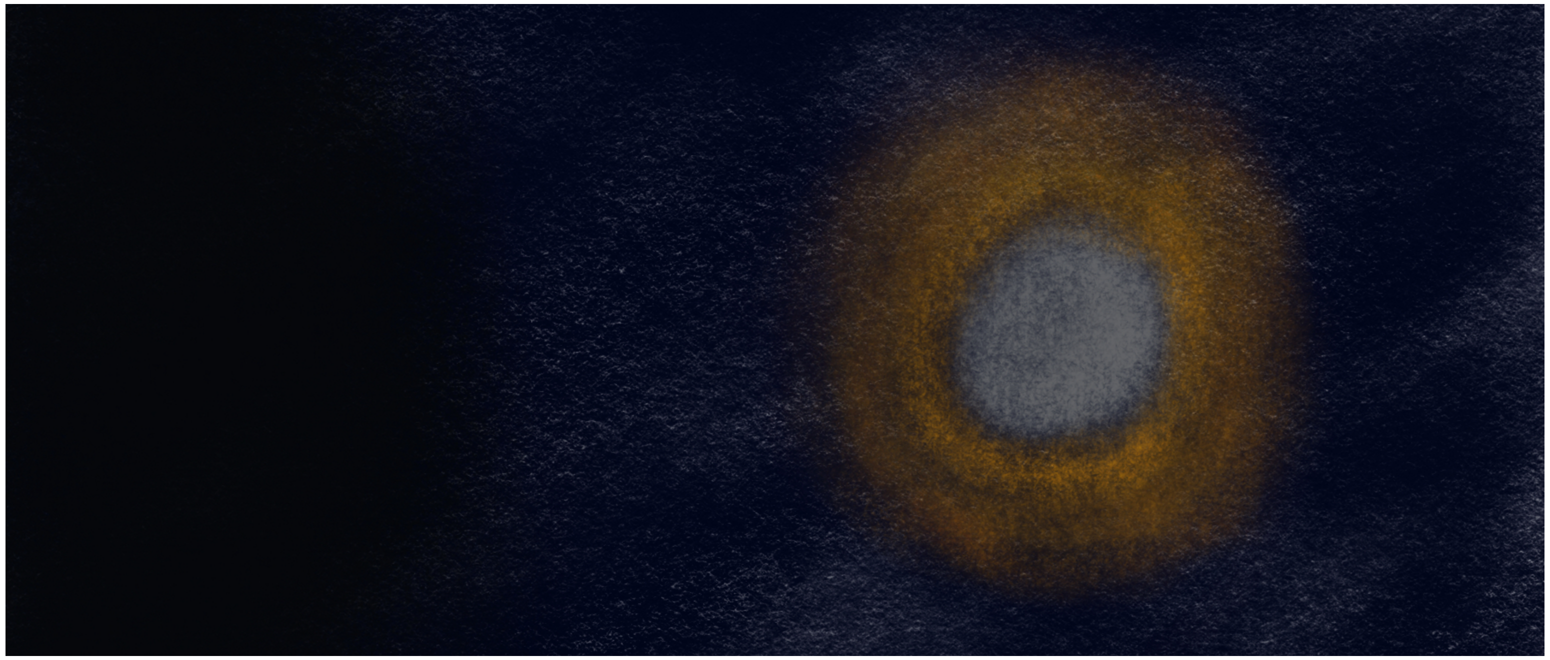
[illegible] Detection:

- Signals always plagued by systematic errors in the background,
- [illegible] frontier
- [illegible] with next gen telescopes - CTA

How to Proceed in the Search for Dark Matter

Need approaches to find the particle nature of DM

- How can we use next generation gravitational wave and radio telescopes to find DM?



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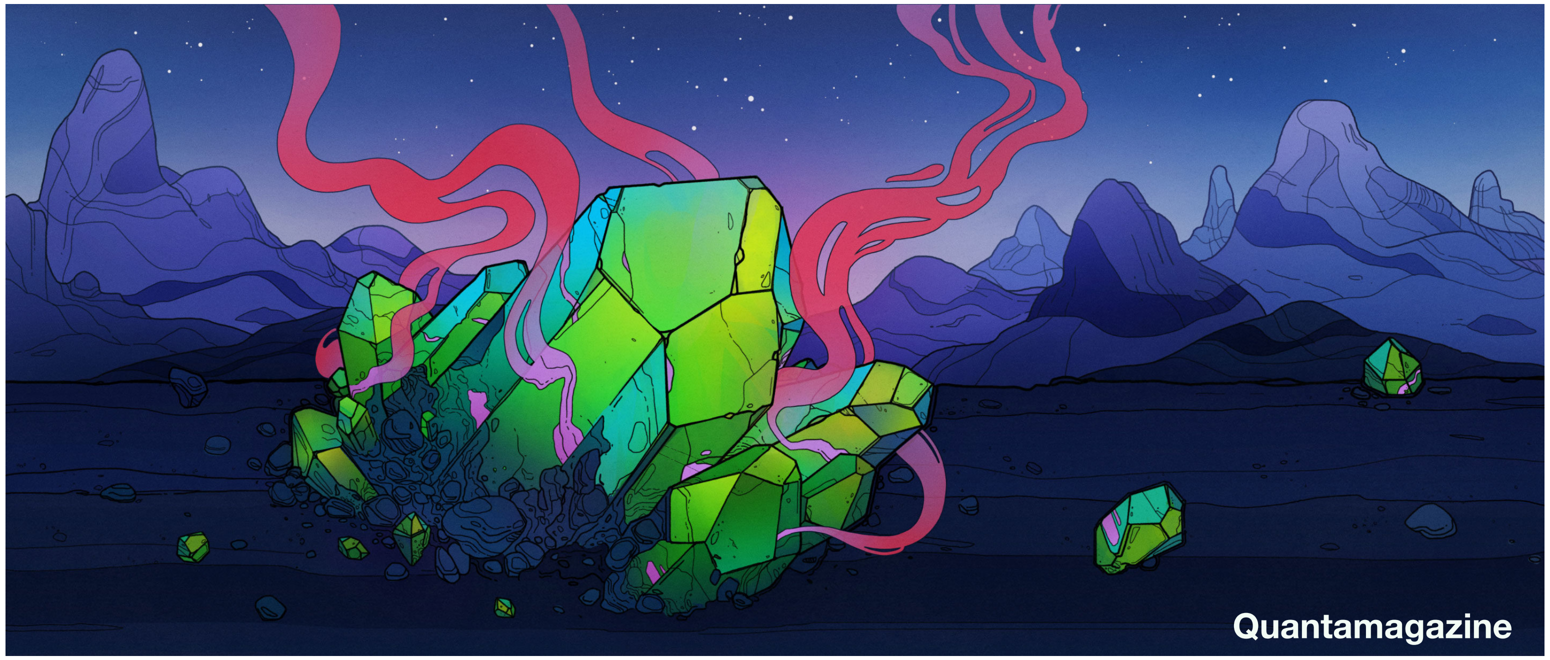
- What can ancient minerals buried deep underground tell us about DM?



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Multi-Messenger Signal of Axion Dark Matter

Strong-CP Problem and the QCD axion

- The standard model displays charge parity (CP) violation through the weak interaction
- The strong interaction also admits a CP violating term in its Lagrangian

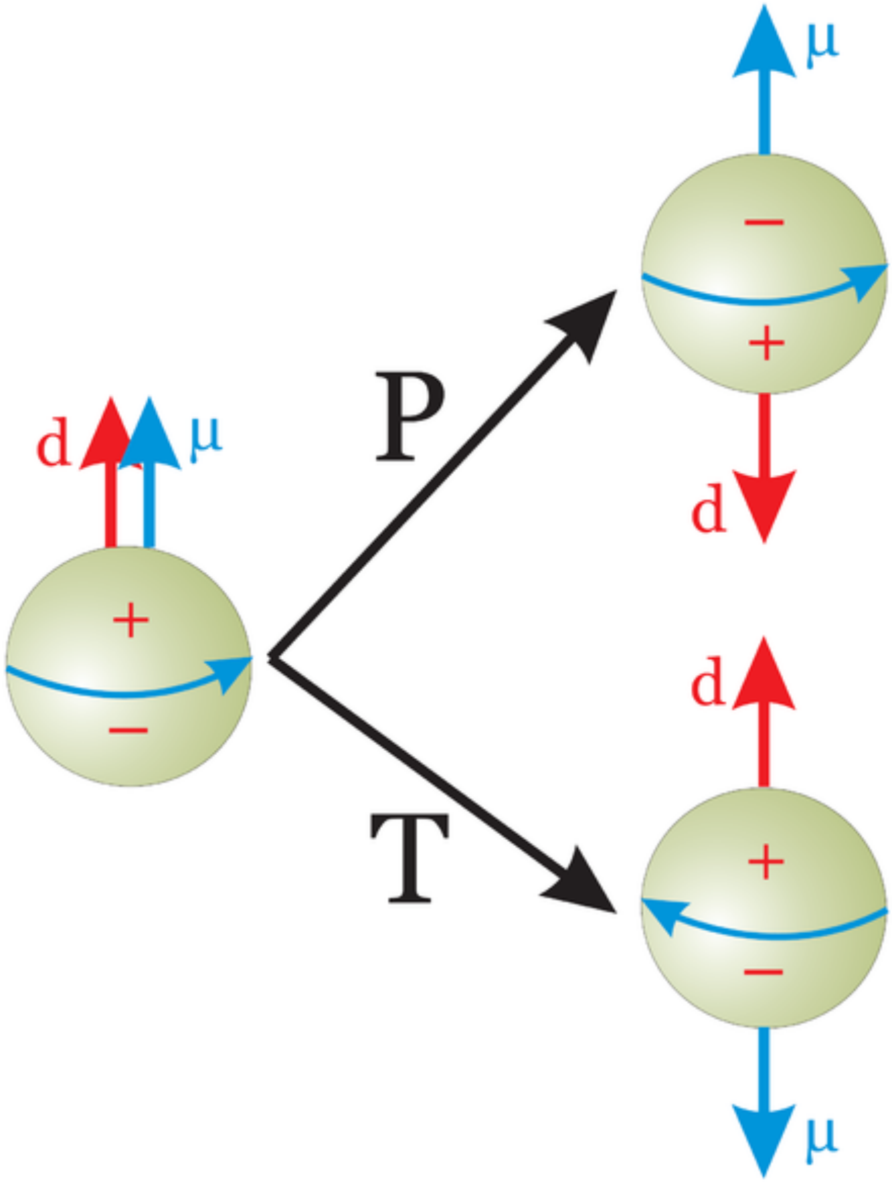
$$\mathcal{L} = -\frac{g_s^2\theta}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- No evidence of CP violation has ever been observed in QCD; this would manifest as a neutron electric dipole

$$|\theta| < 10^{-10} \qquad |\theta| \neq \mathcal{O}(1)$$

- Promoting theta to a field allows the CP-violating term to dynamically reach zero
- Goldstones theorem then produces a boson, the axion

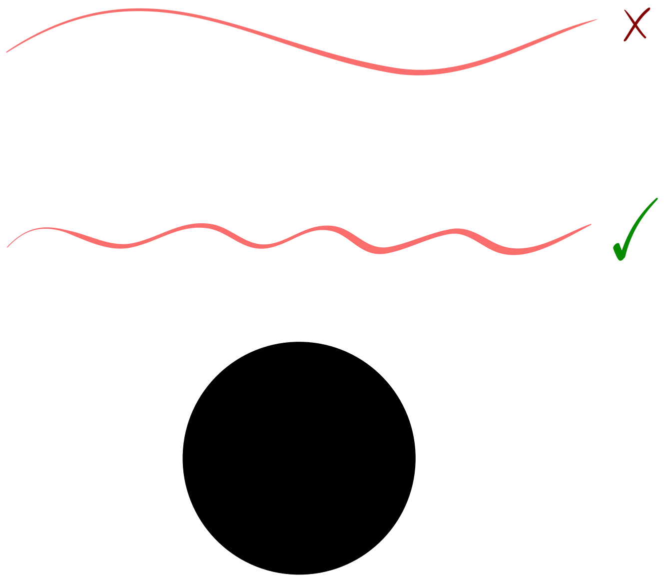
$$\boxed{\theta \rightarrow \bar{\theta}}$$



Axion Dark Matter

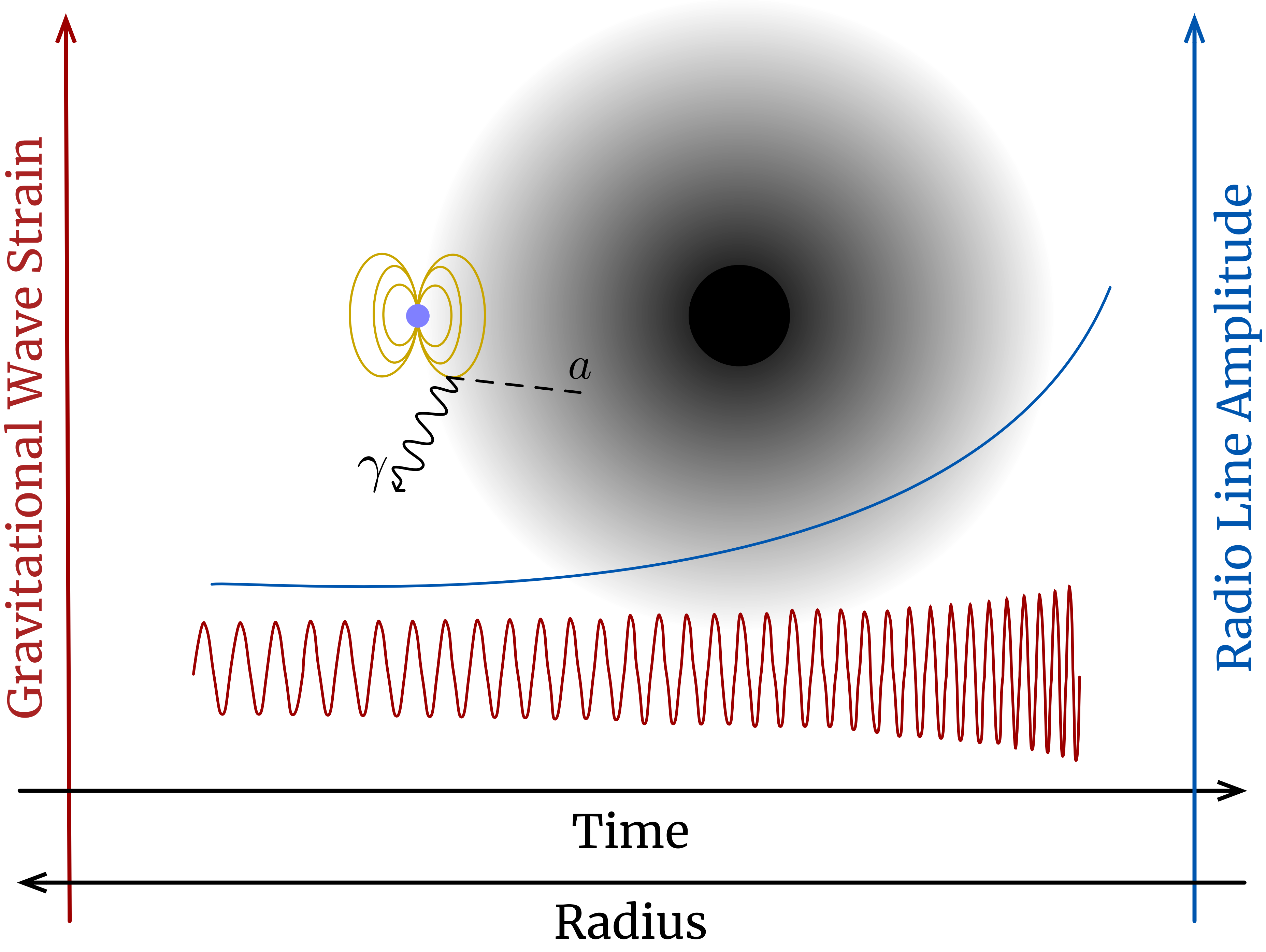
- The same QCD axion particle can make up all of the DM
- Behaves like matter, inherits all the successes of CDM Cosmology
- Axion like particles (ALPS) are generic predictions from various other extensions to the standard model - compactifications of higher dimensional string theories generically produce spin-0 particles
- Can be considered as particles in astrophysical settings; Compton wavelength is relatively small

$$\lambda = \frac{h}{mc}$$

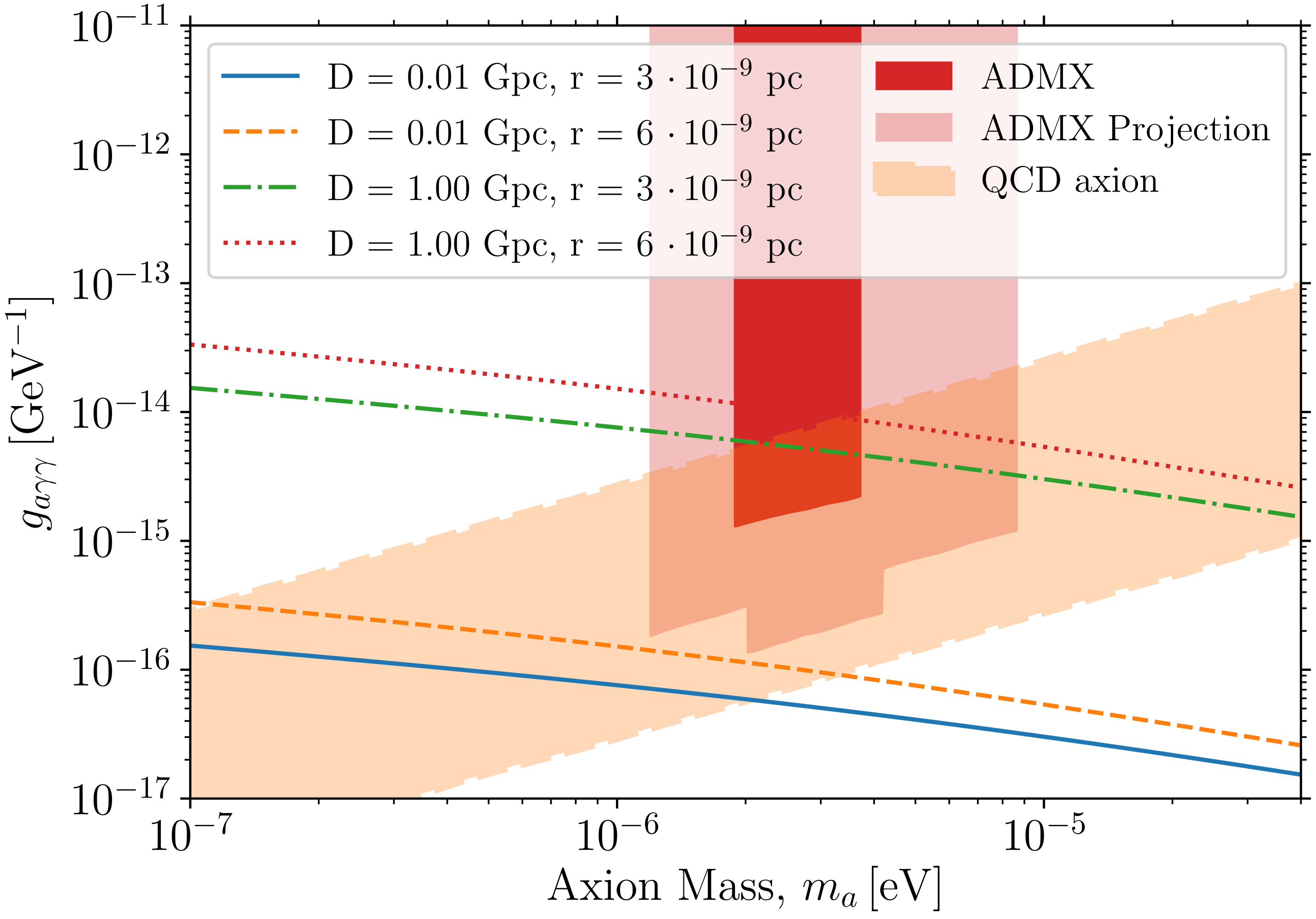


$$m > 10^{-7}\mathrm{eV}$$

Multi-Messenger Signal



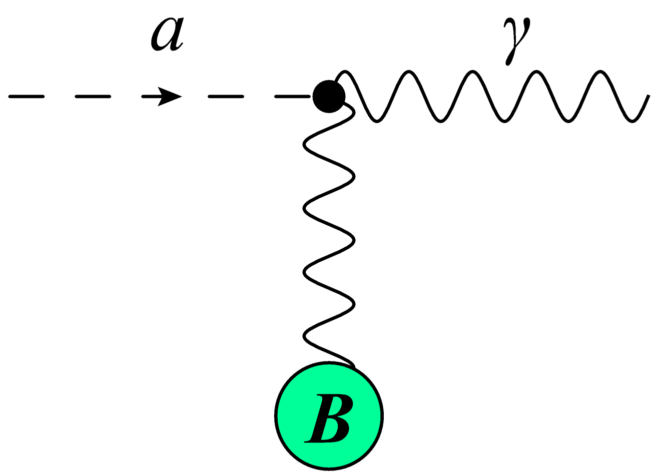
Quick View of the Final Result



- Can probe the QCD axion and axion like particles (ALPs) through their coupling to photons

- Requires the density to be high enough/ system to be close by

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$



Intermediate Black Holes

- Intermediate mass BHs are the least constrained mass window, between 10^3 and 10^5 solar masses
- They have not been detected by GWs but their existence observed in the centres of galaxies
- The are thought to be quite abundant in star clusters such as globular clusters
- They can form through multiple channels:
  1. Merging of many stellar mass BHs
  2. Merger and consequent collapse of massive stars

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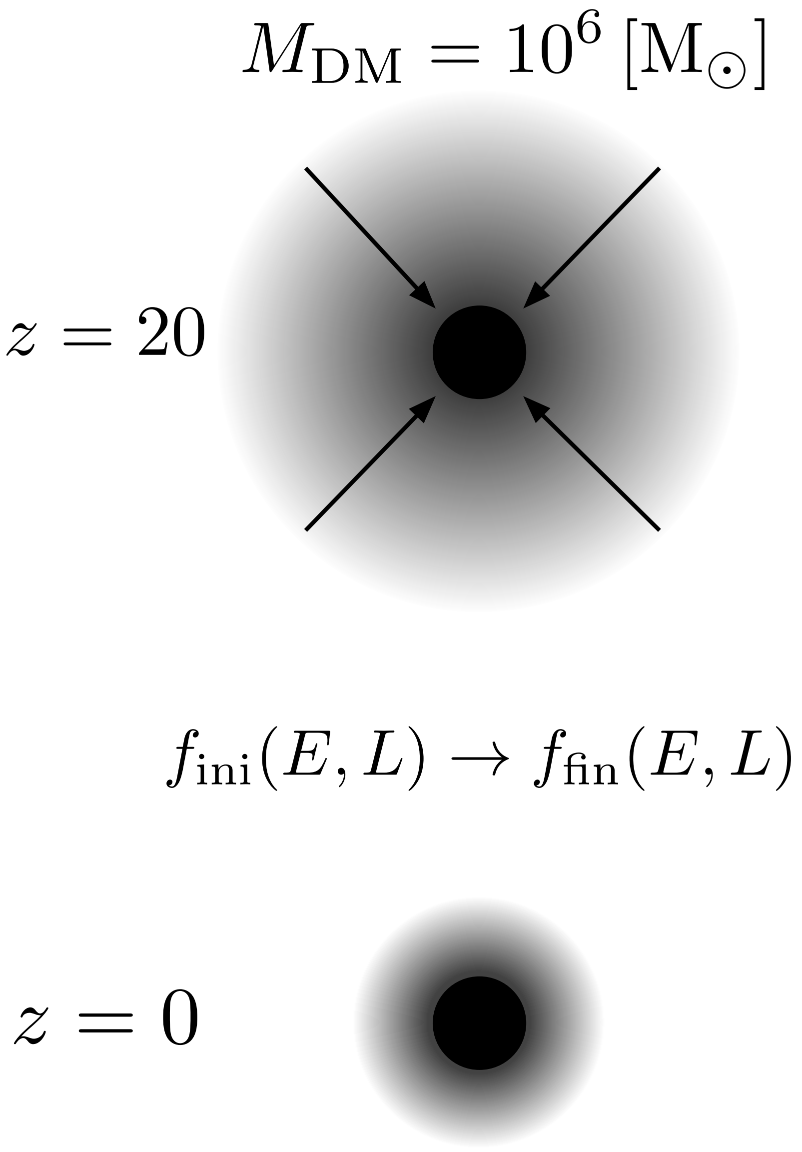
DM Halo and Formation of a Mini-Spike

- These IMBHs can be born in mini-halos of 10^6 solar masses
- Assume that the growth of the central BH is adiabatic i.e.
- Depends on the initial profile of the DM halo
- Can be disrupted by baryons i.e. IMBH has to be left alone for a long time



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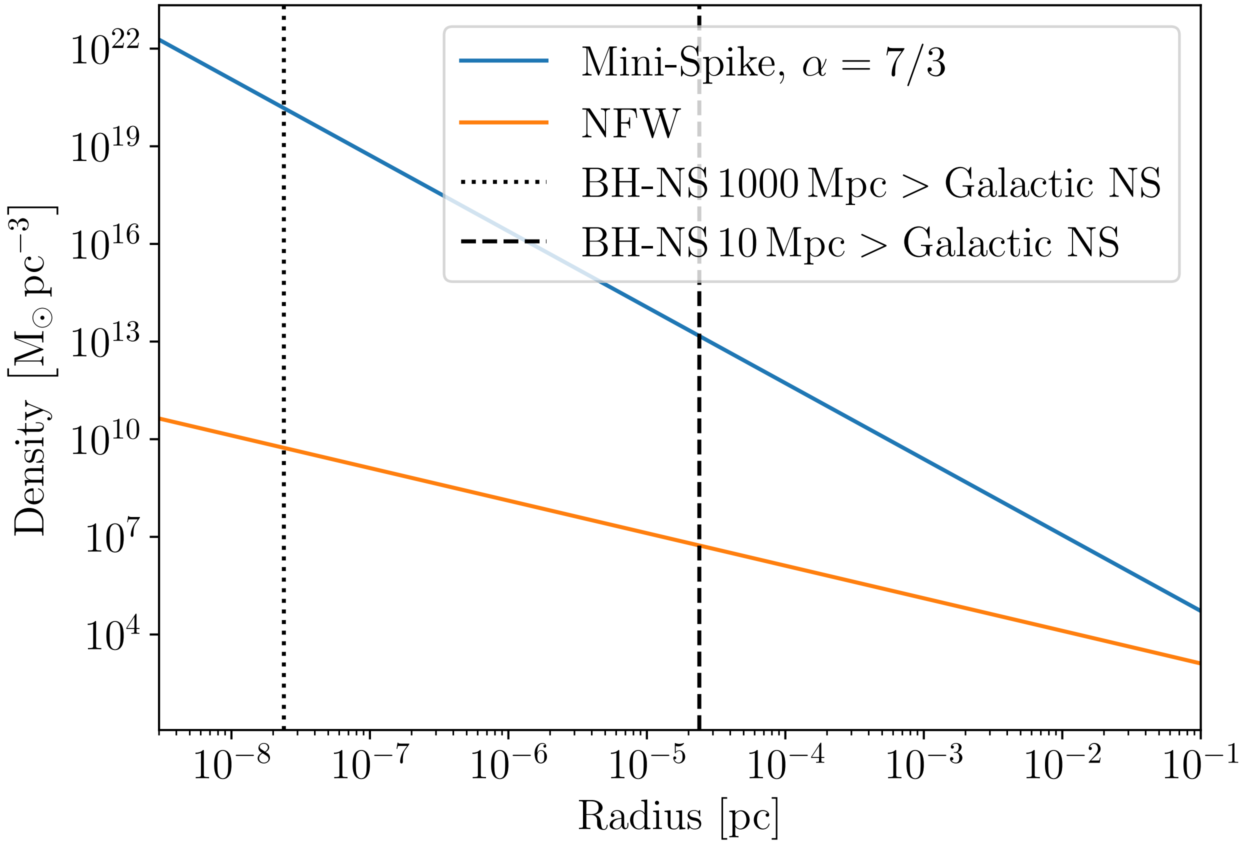
Structure of the Mini-Spike

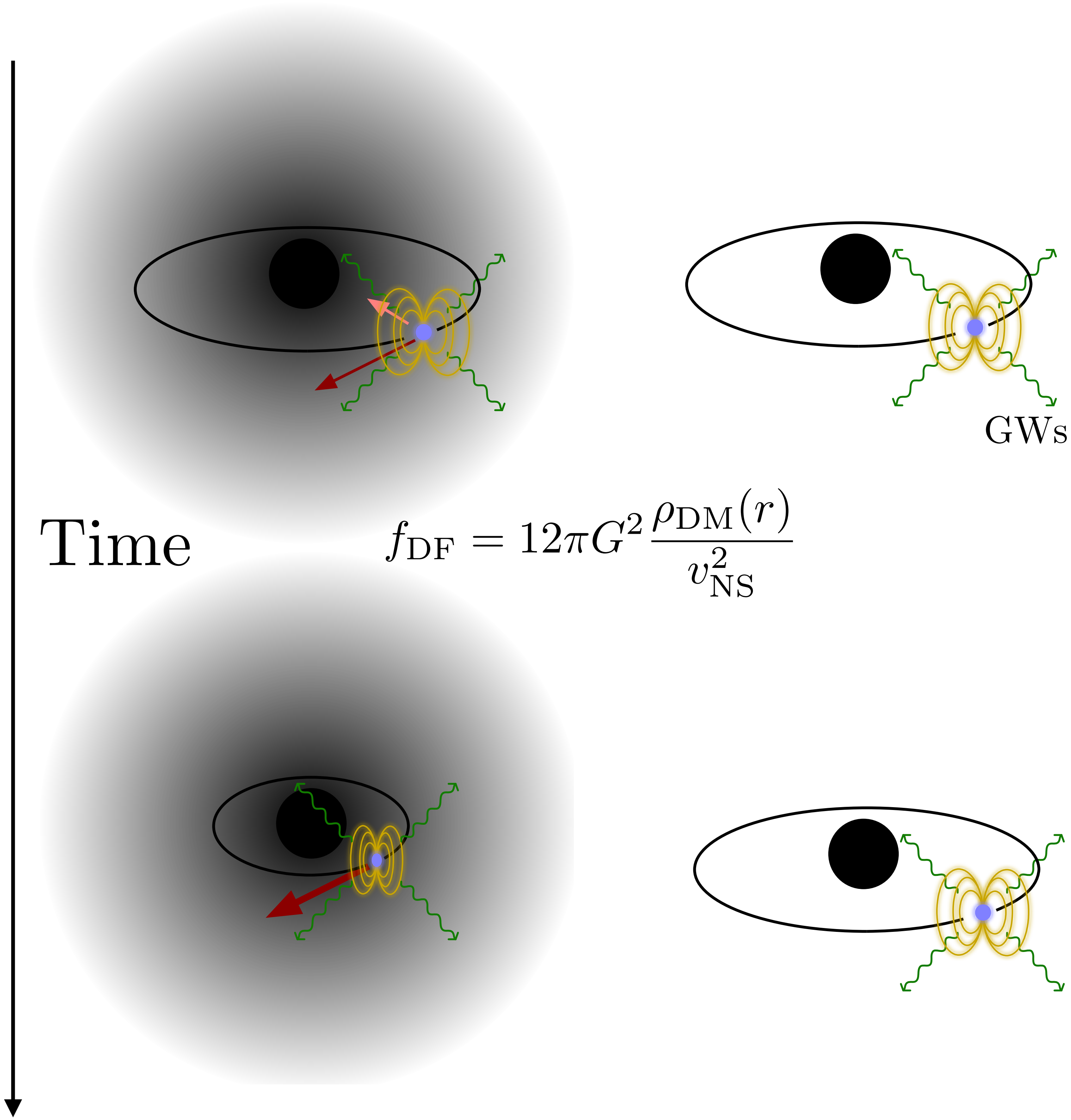


- Final structure of the spike is assumed to be a power law
- Power law depends on the initial density profile, NFW produces a slope of 7/3 therefore we take this as the baseline scenario
- Density is extremely enhanced towards innermost stable orbit (ISCO)

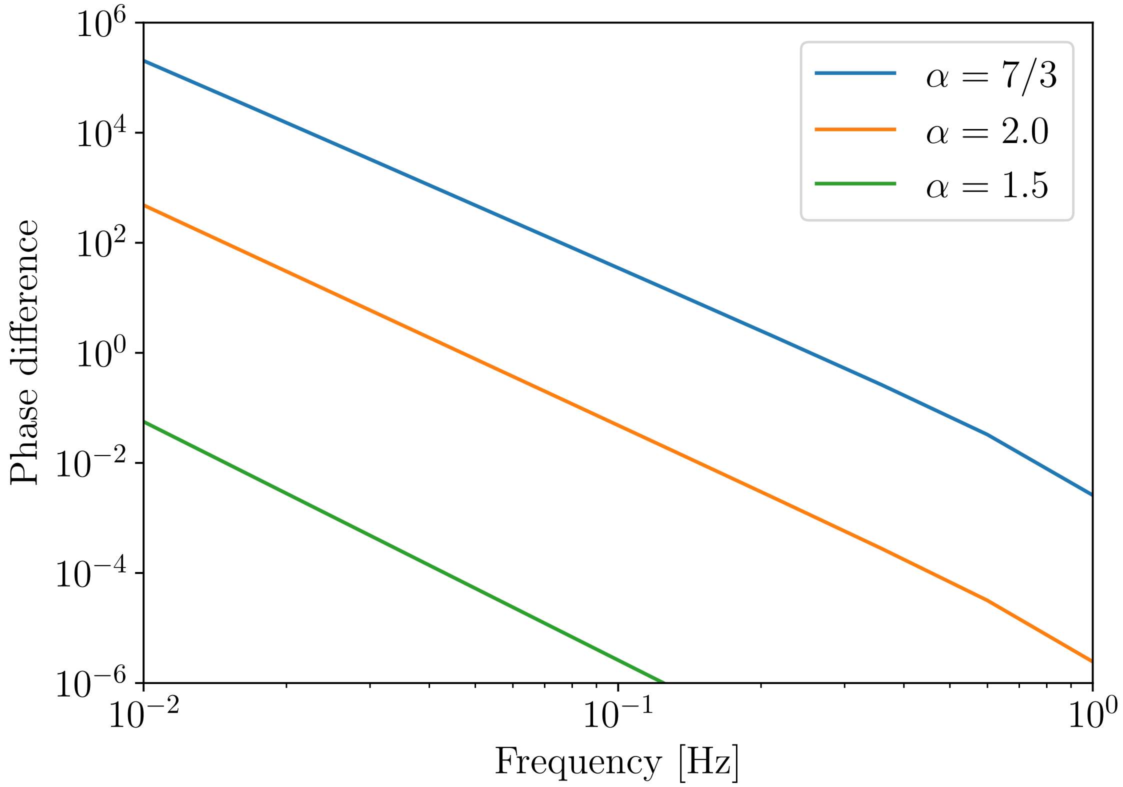
$$\rho_{\mathrm{sp}} = \rho_{\mathrm{sp}}^{0}\left(\frac{r_{\mathrm{sp}}}{r}\right)^{\alpha}$$

$$M(< r_{\mathrm{h}}) = 4\pi \int_{0}^{0.2 r_{\mathrm{sp}}} \rho_{\mathrm{DM}} r^{2} dr = 2M_{\mathrm{BH}}$$

Gravitational Wave Signal - Dynamical Friction



$$f_{\mathrm{DF}} = 12\pi G^2 \frac{\rho_{\mathrm{DM}}(r)}{v_{\mathrm{NS}}^2}$$



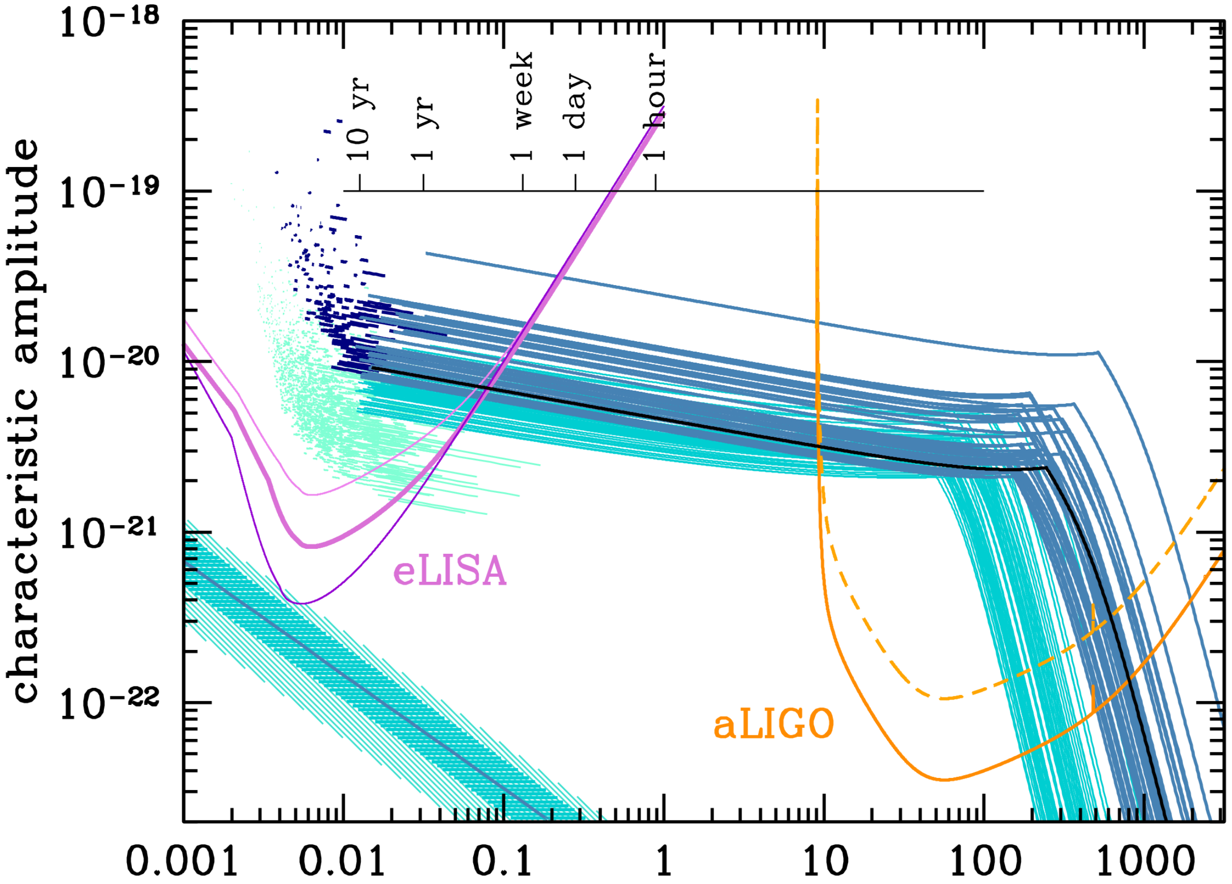
- The presence of the DM cloud causes energy loss through dynamical friction
- Inspiral takes less time than vacuum inspiral

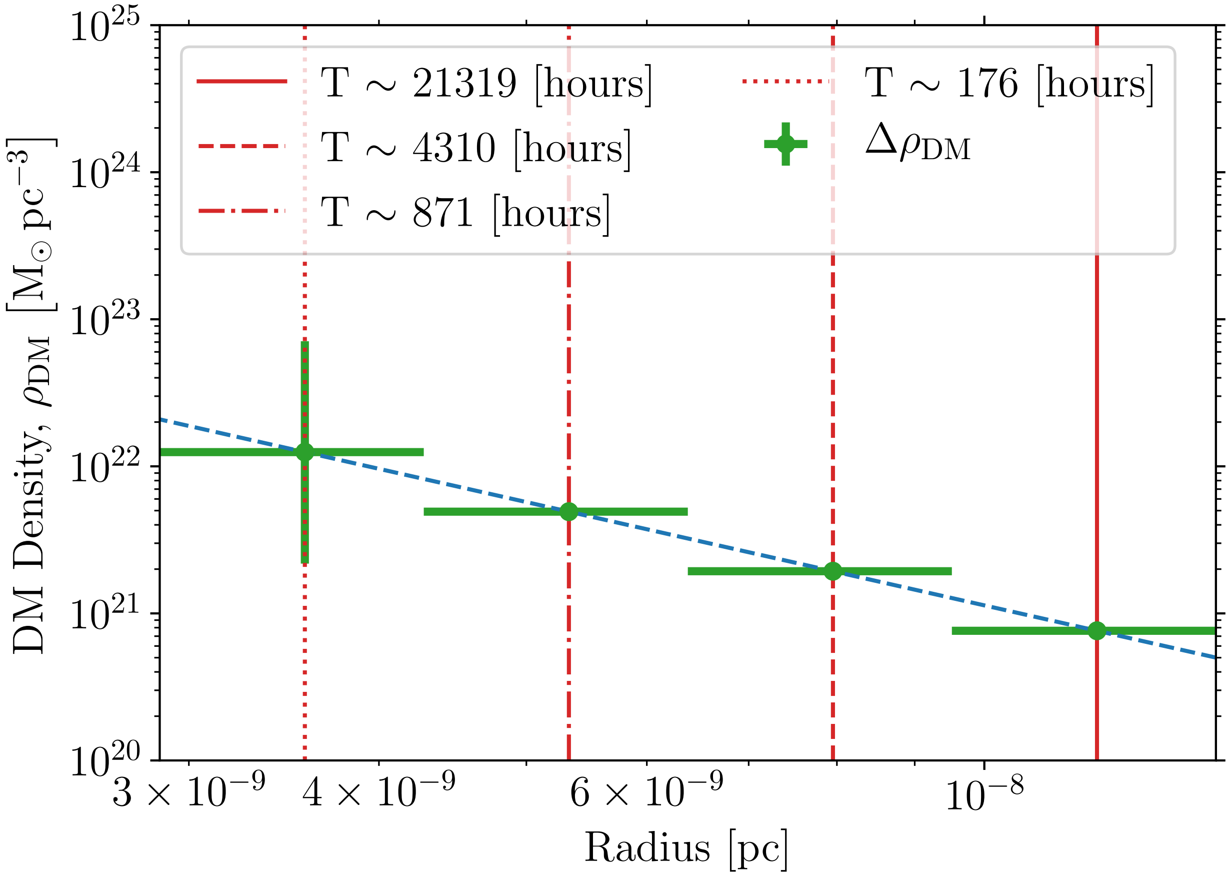
Rates and Lisa Sensitivity

- Uncertainty in IMBH formation channels make merger rate calculations extremely uncertain
- Lisa will see these objects for 5 years prior to merger

$$\mathcal{R} \sim 3 - 10\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

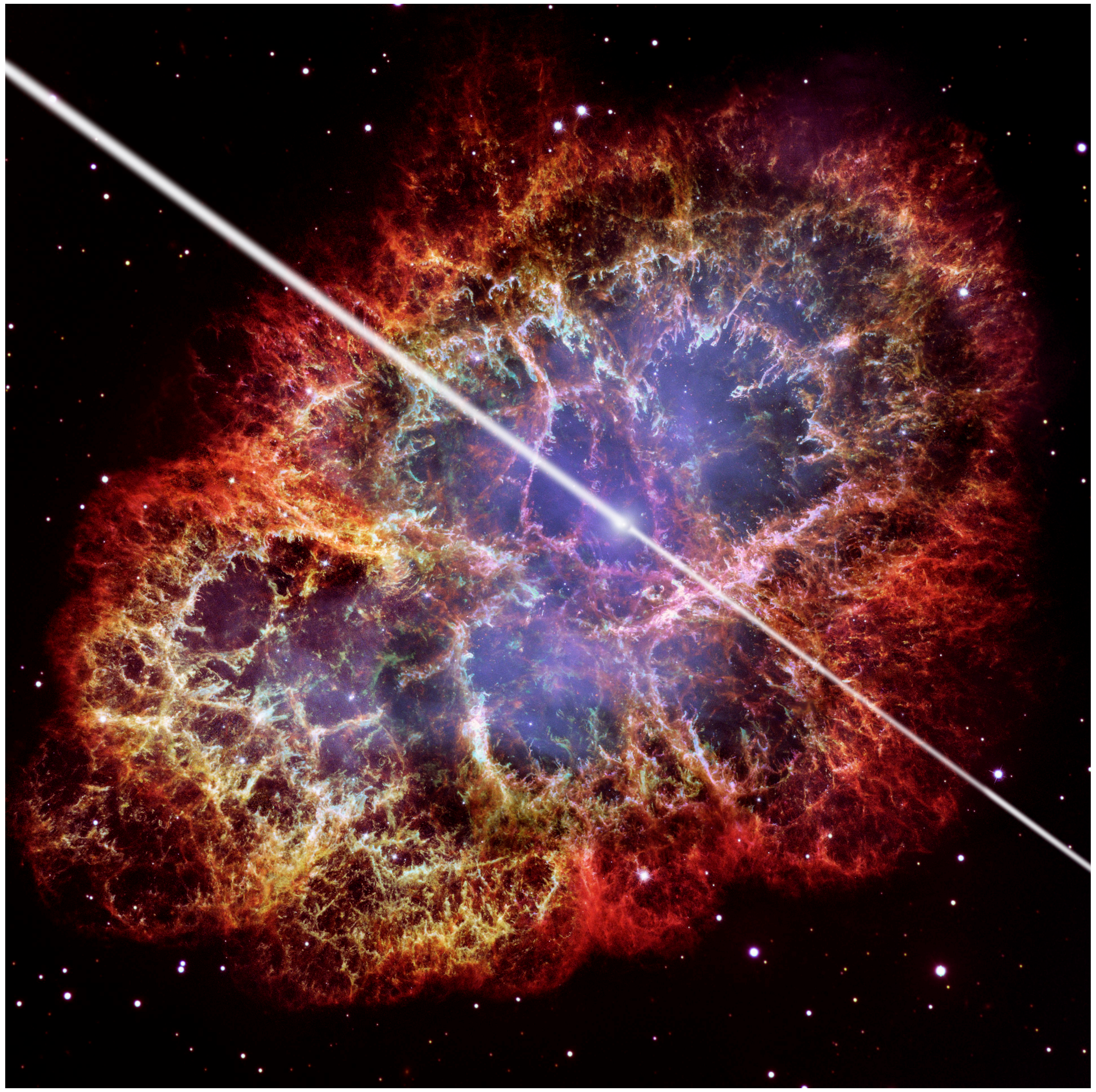
Rates for IMBH mergers with stellar mass objects





Neutron Stars

- Young pulsars have extremely high magnetic fields
- They are formed at the end of a stars lifetime
- They are surrounded by a dense plasma
- They are highly abundant in stellar clusters, therefore will be the dominant merging stellar mass object to IMBHs



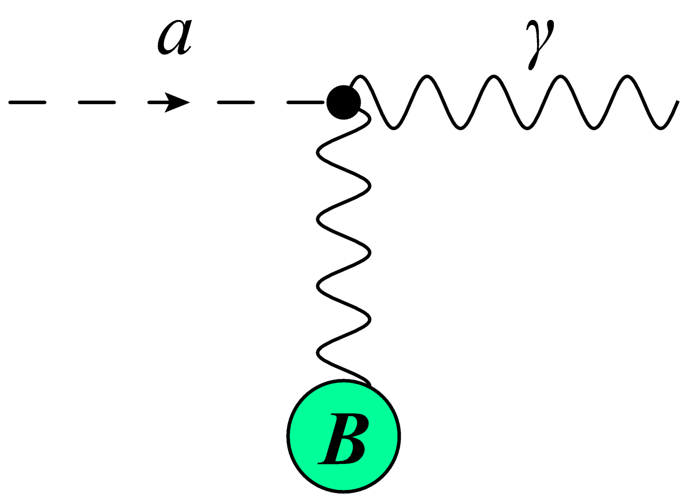
$$B_{\text{young}} \sim 10^{10} - 10^{14}\,[\mathrm{G}]$$

$$P_{\text{young}} \sim 10\,[\mathrm{s}]$$

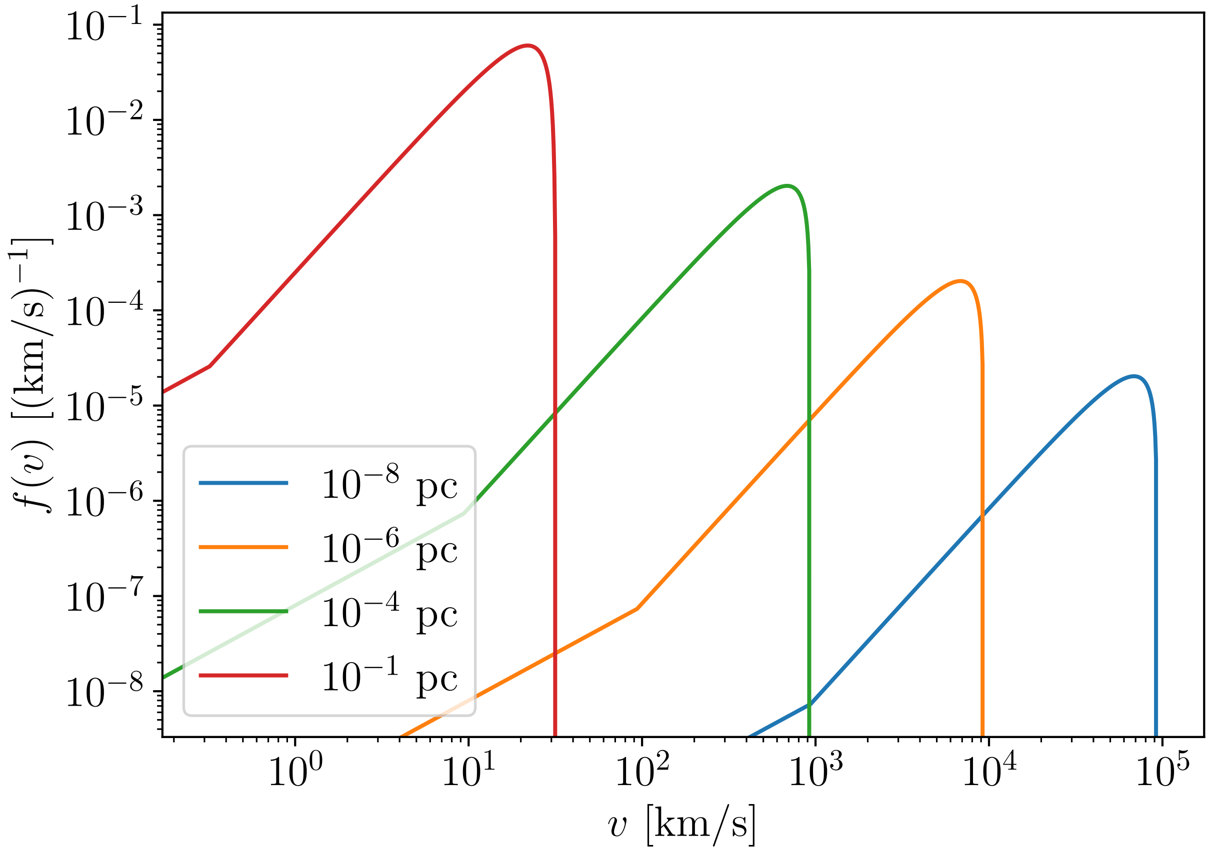
Axion-Photon Conversion

$$\frac{d\mathcal{P}}{d\Omega} \sim 2 \times p_{a\gamma}\rho_{\mathrm{DM}}(r_c)v_c r_c^2$$

$$p_{a\gamma} = \frac{g_{a\gamma\gamma}^2 B(r_c)^2 L_{\mathrm{conv}}^2}{2v_c}$$



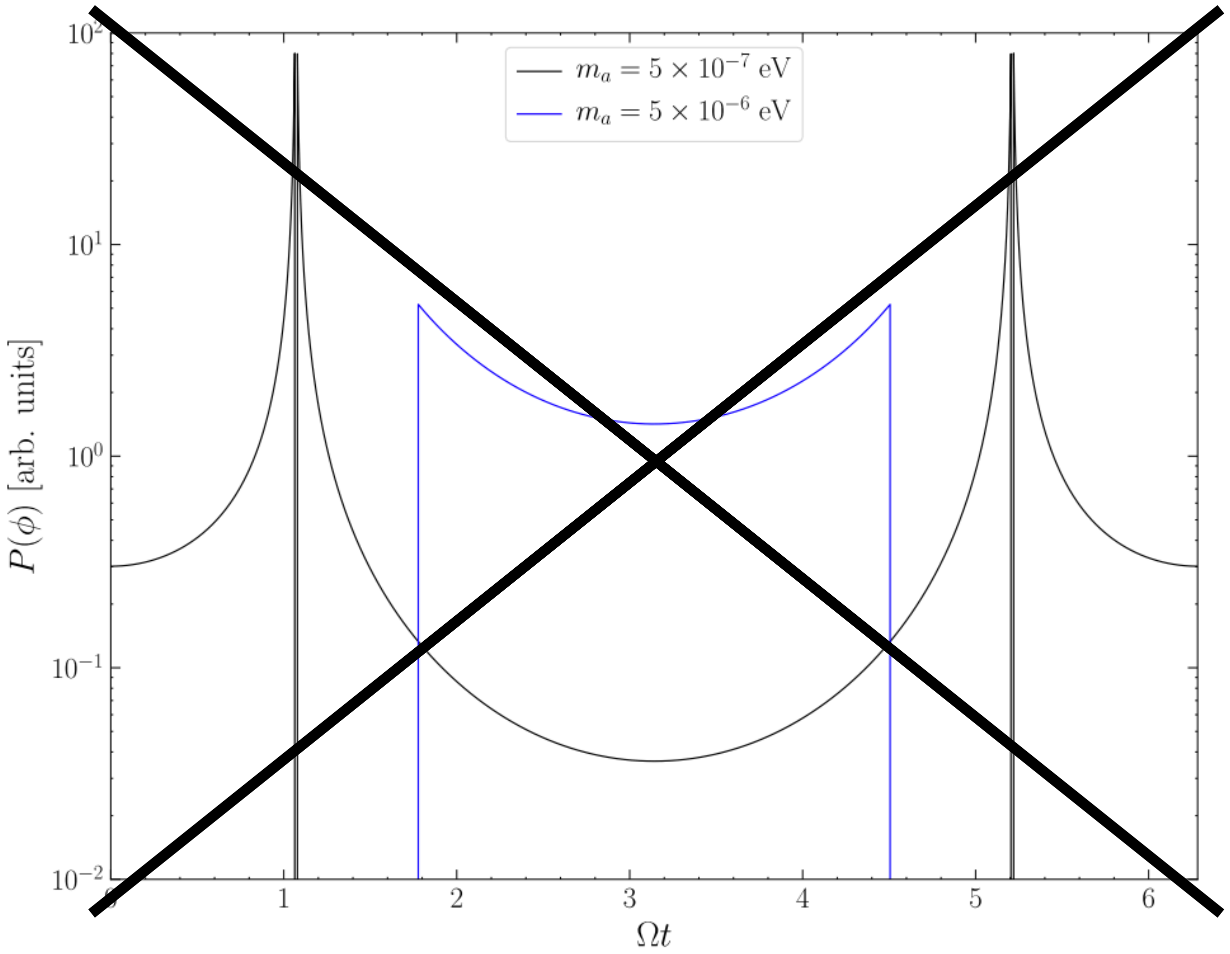
- The finite electron density in the plasma gives the photon an effective mass
- Signal is dependent on the velocity distribution of the DM
- Velocity distribution calculated using Eddington's formula

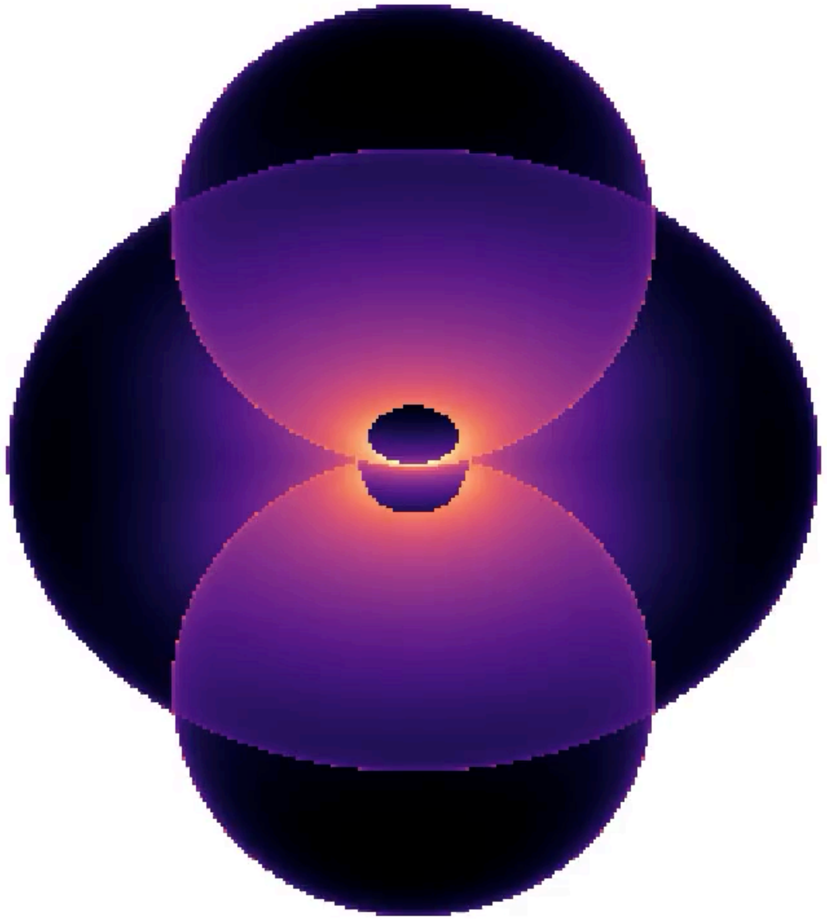


$$\mathcal{E} = \Psi(r) - \frac{1}{2}v^2$$

$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\left[\int_0^{\mathcal{E}} \frac{\mathrm{d}\Psi}{\sqrt{\mathcal{E}-\Psi}}\frac{\mathrm{d}^2\rho}{\mathrm{d}\Psi^2} + \frac{1}{\sqrt{\mathcal{E}}}\left(\frac{\mathrm{d}\rho}{\mathrm{d}\Psi}\right)_{\Psi=0}\right]$$

Radio Signal





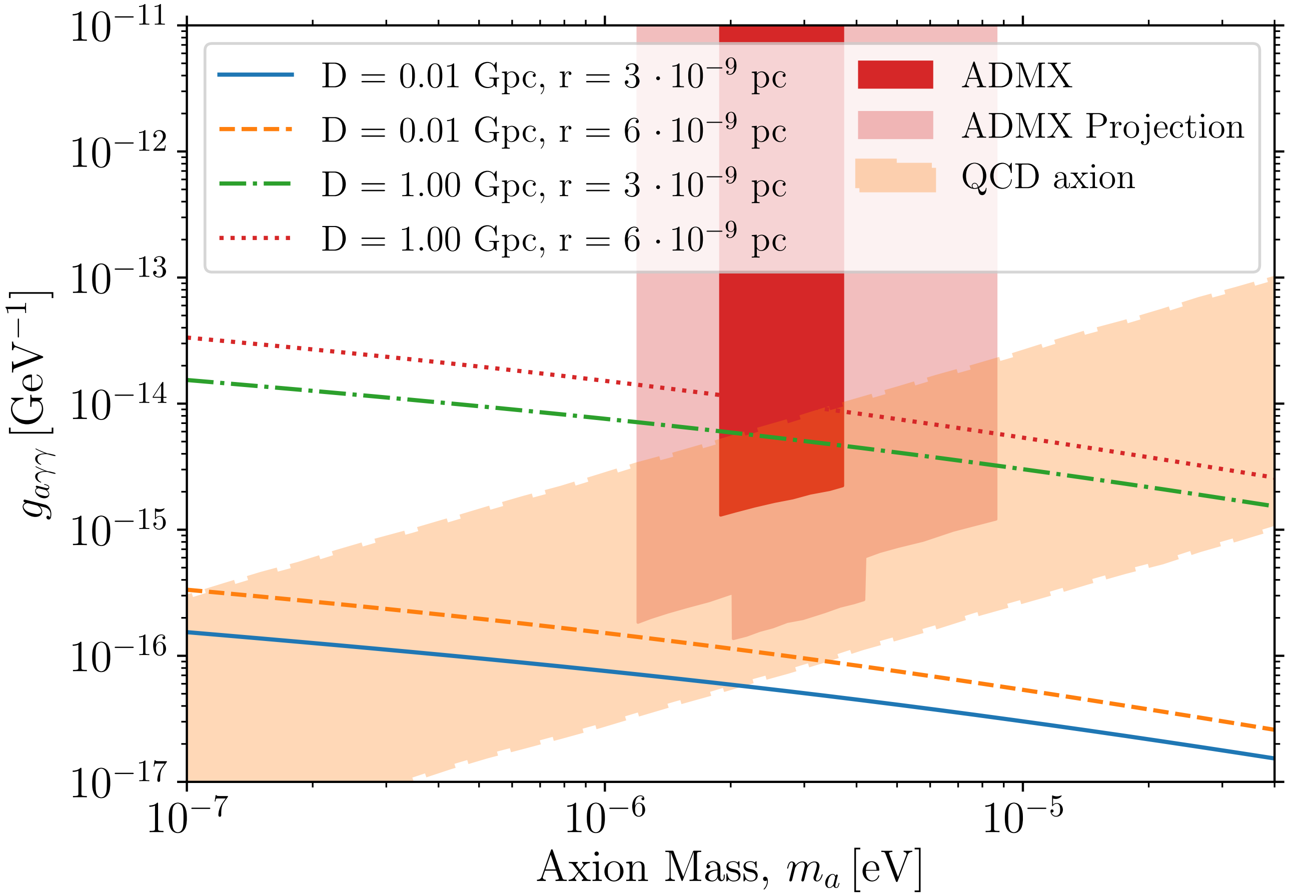
- By assuming that not only radial trajectories contribute to the final signal, time variations due to rotation of NS are averaged out

- Probably cannot observe Doppler shift from rotation around the BH, since the velocity of the

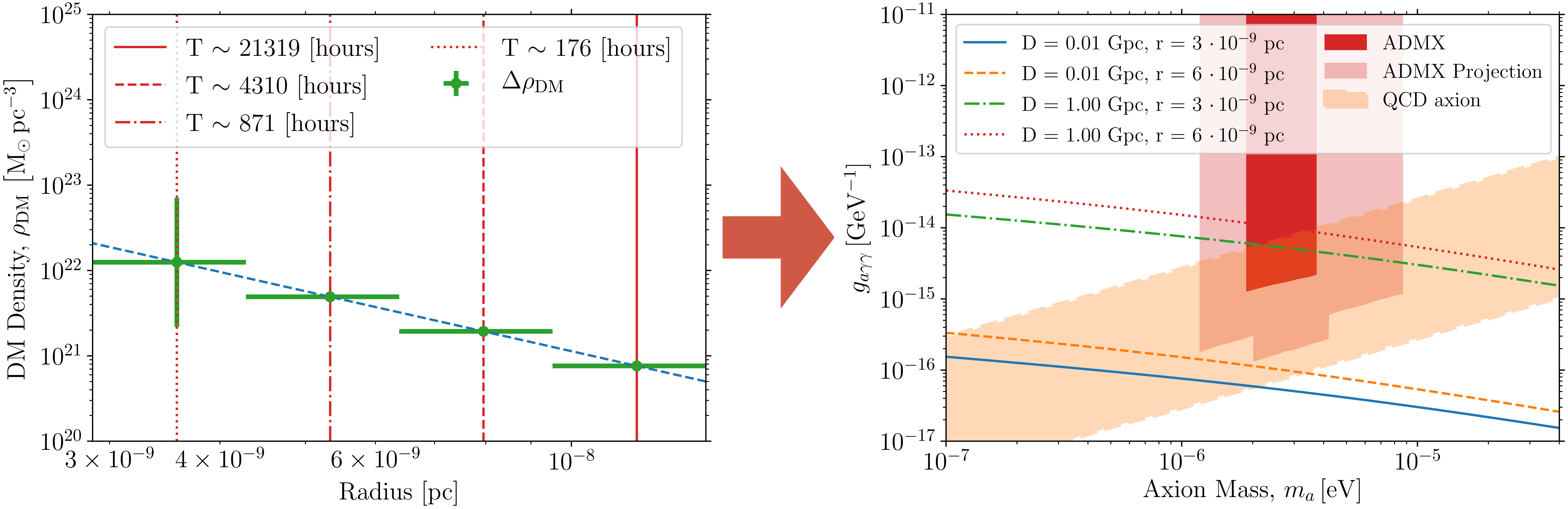
Square Kilometre Array Sensitivity

$$S_{\mathrm{min}} = \frac{\mathrm{SEFD}}{\sqrt{2B_a T_{\mathrm{obs}}}}$$

- Not much time variation, therefore easy to use signal to noise calculation
- Assumed 100 hours observation
- Bandwidth of the signal is set by the velocity distribution of the DM



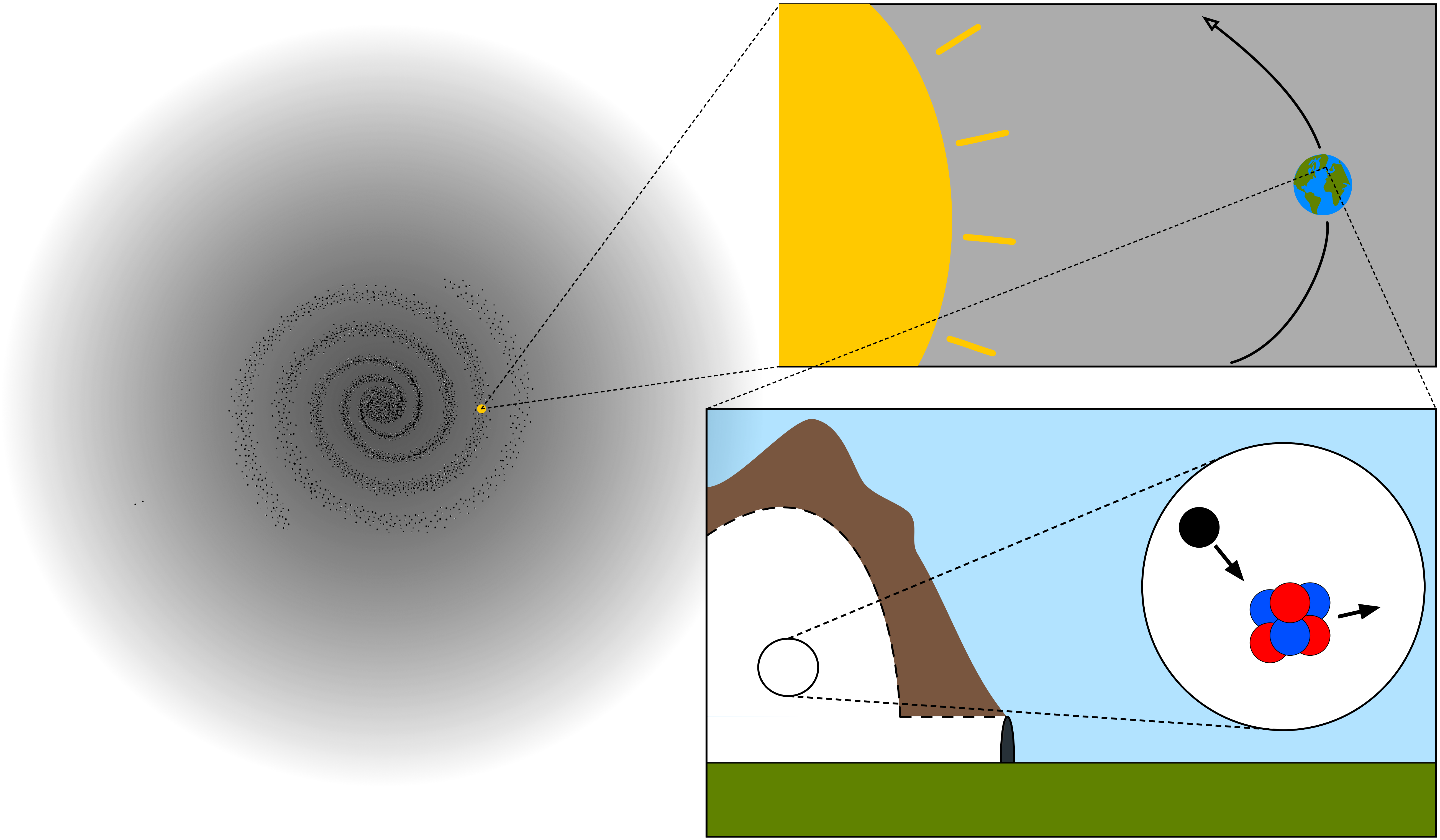
Final Constraints



- Depending on the distance to the source and characteristics of the NS, this system can provide a multi messenger signal of QCD axion DM
- Difficult to set robust limits due to the uncertainty in the NS properties, magnetic field etc.
- If many are found, utilising NS population properties will allow for a more robust constraint

Paleo Detectors: Using Ancient Minerals to Search for Dark Matter

How to Search for Dark Matter on Earth



Dark Matter and Direct Detection Experiments

- I will assume the Dark Matter is a Weakly Interacting Massive Particle (WIMP) and only consider spin independent interactions.
- Basic premise of Direct Detection Experiments is to detect any prompt emission from a WIMP-nucleon scattering event.
- Built underground to prevent muon background from Cosmic Rays interacting with the atmosphere.

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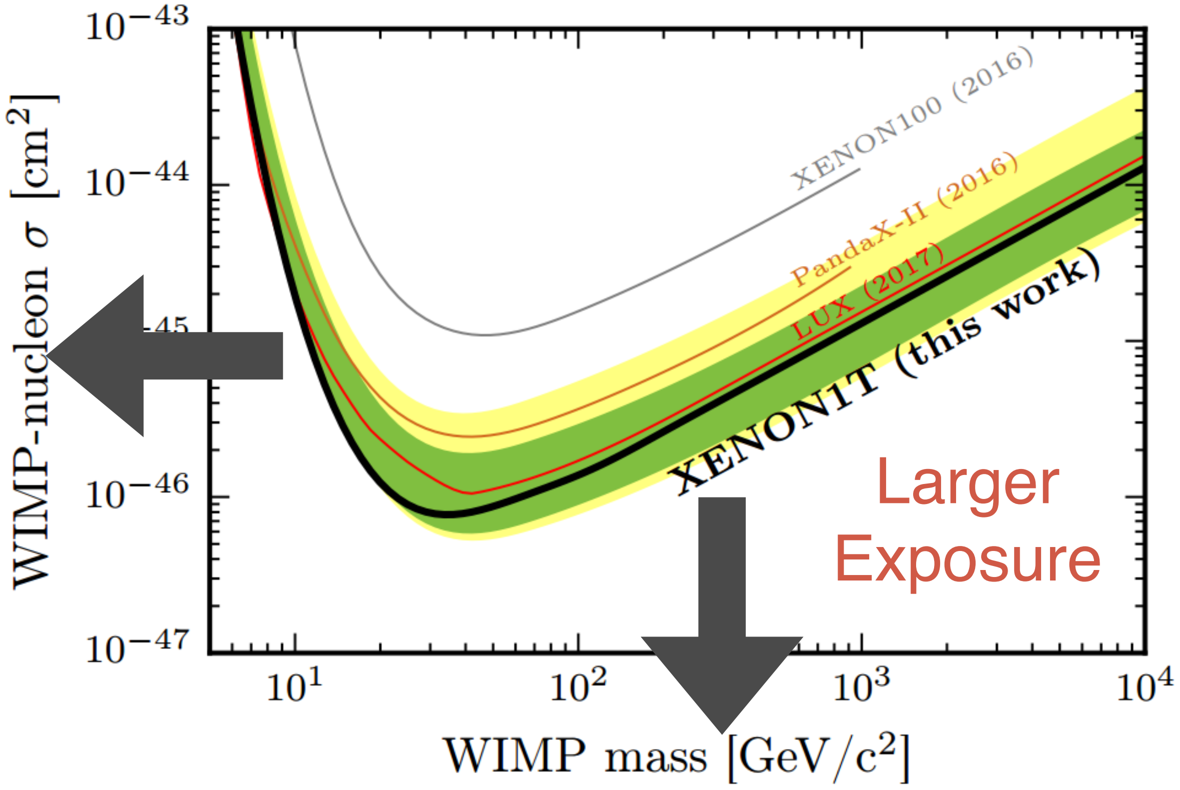
Lower Energy Threshold

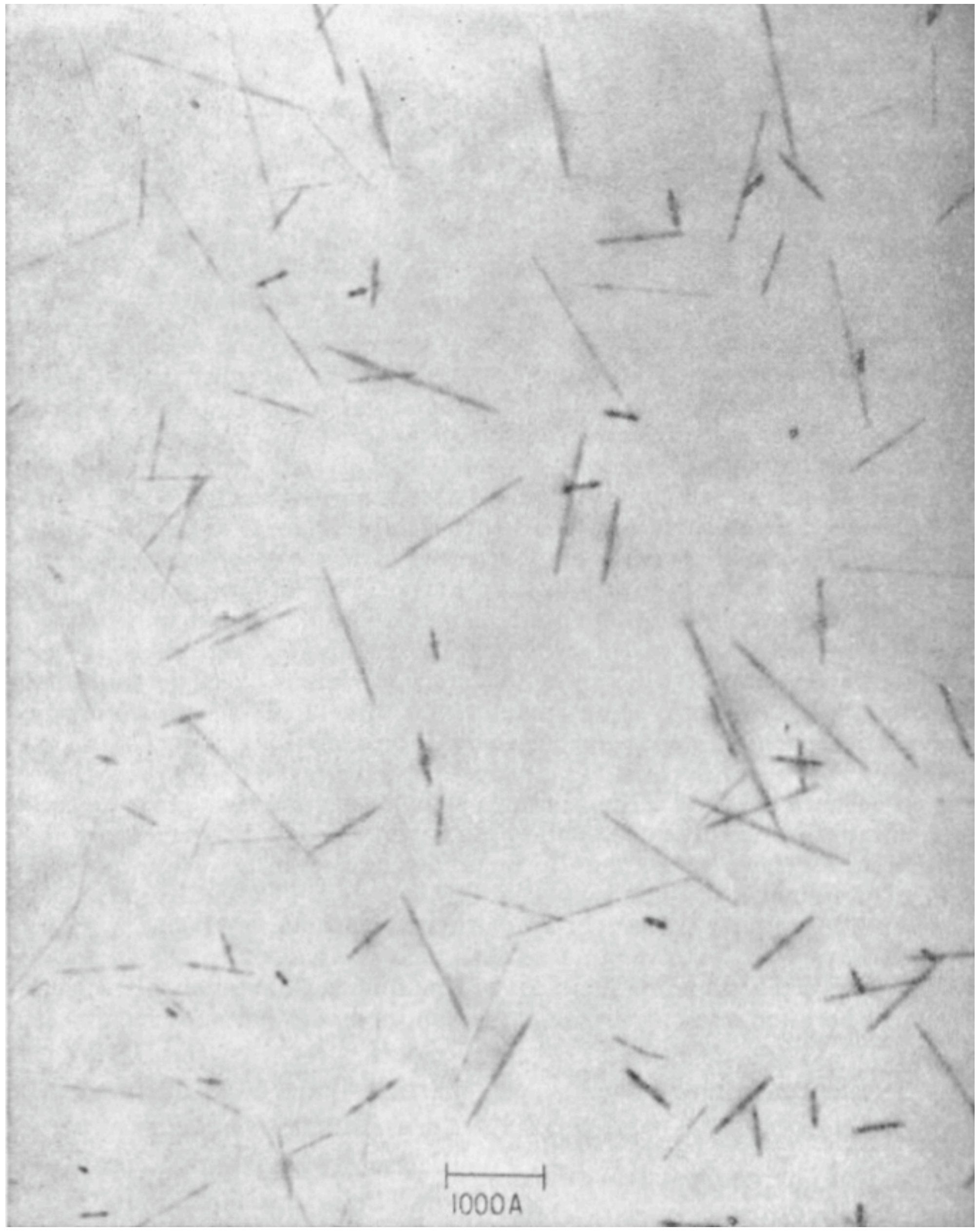


Larger Exposure

$$\boxed{\text{Recoil Rate} \propto \text{Target Mass} \times \text{Observation Time}}$$

Paleo-Detectors

- Paleo-detectors are minerals from far below the Earths surface (5-10 km). This is necessary to shield the mineral from cosmic ray backgrounds.
- Instead of phonons, charge, and light, paleo-detectors look for permanent damage track features in the structure of the mineral.



↓ Smaller Targets

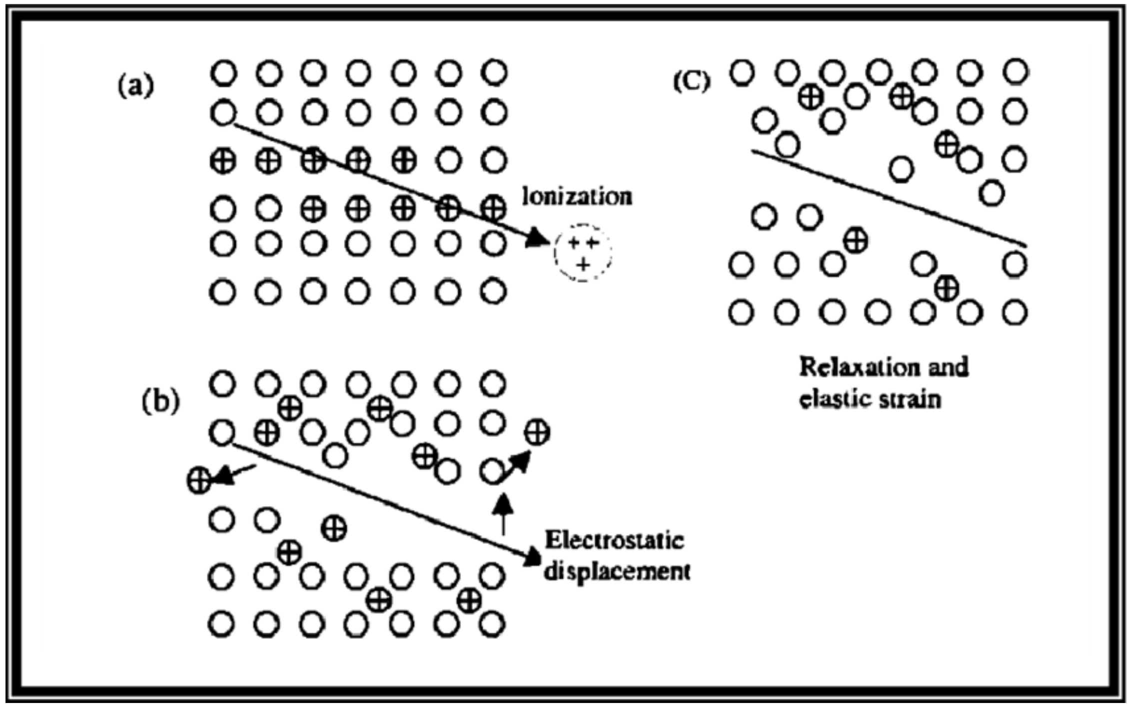
↑ Huge Exposure

$$\boxed{\text{Recoil Rate} \propto \text{Target Mass} \times \text{Observation Time}}$$

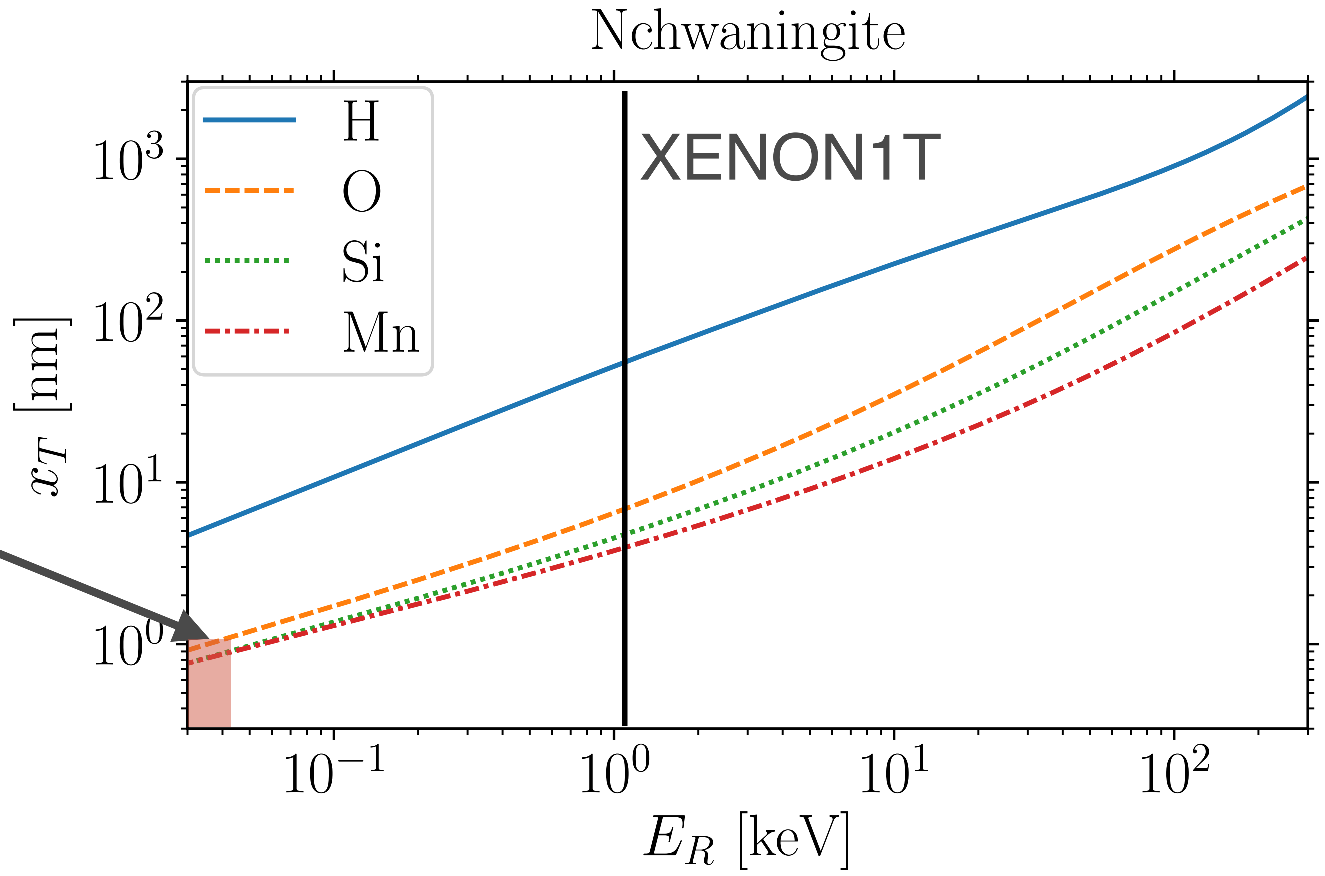
Paleo-Detector Basics

- Damage tracks are caused by recoiling nuclei depositing energy through multiple scatters. The detailed mechanism is unknown.

- Annealing timescales are extremely long compared to the age of the mineral.



High track length resolution allows us to probe low energy recoils - We are therefore sensitive to lighter dark matter



Backgrounds

- Unlike Xenon1T we have many backgrounds…

- Neutrinos from the Sun, Supernovae, and produced in the atmosphere all contribute to our background.

- We also have to contend with natural radioactivity, most importantly Uranium-238 which contributes multiple background components.

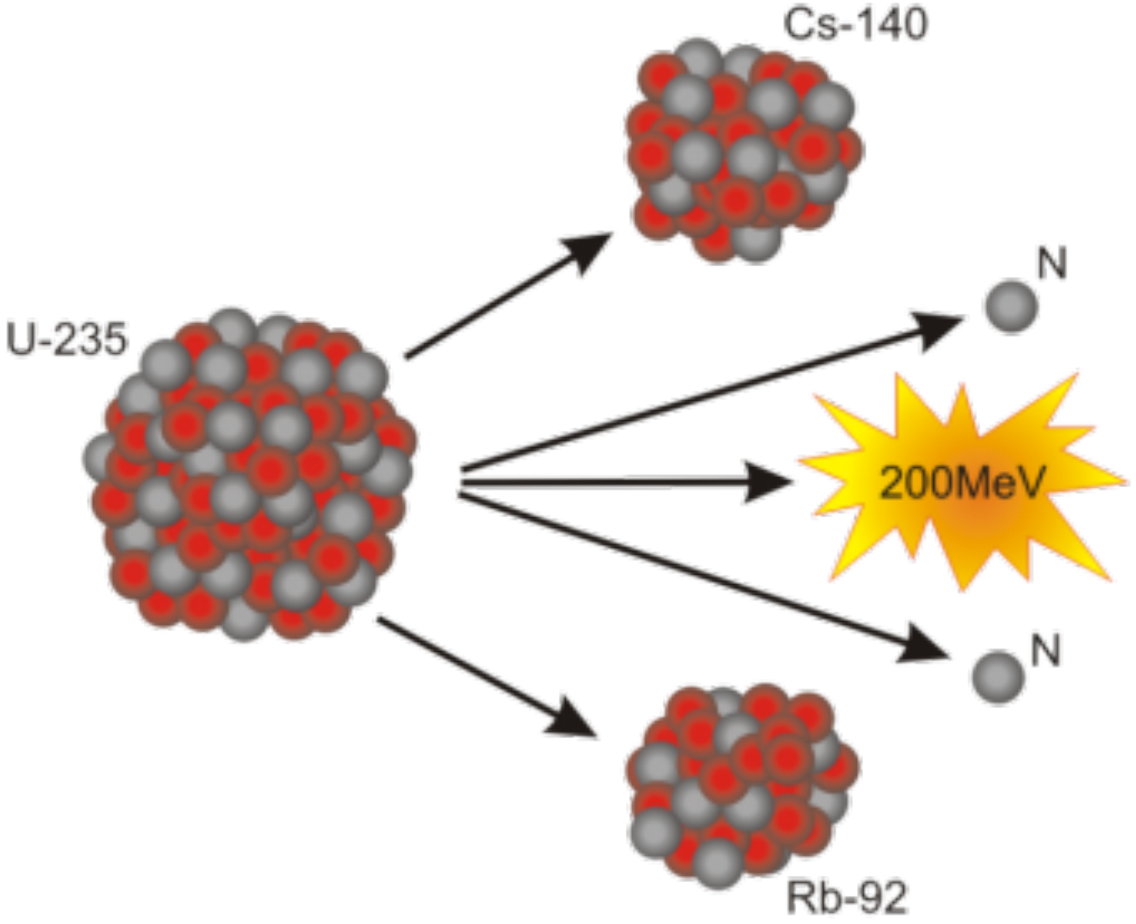
    A. Uranium-238 that has gone through a single alpha decay.

    B. Neutron emission from spontaneous fission of the Uranium-238.

- We mitigate these by using minerals which contain hydrogen and are formed with extremely low abundances of Uranium-238.

$$\boxed{{}^{238}\mathrm{U} \xrightarrow{\alpha} {}^{234}\mathrm{Th}} \xrightarrow{\beta^-} {}^{234\mathrm{m}}\mathrm{Pa} \xrightarrow{\beta^-} {}^{234}\mathrm{U} \xrightarrow{\alpha} {}^{230}\mathrm{Th}$$

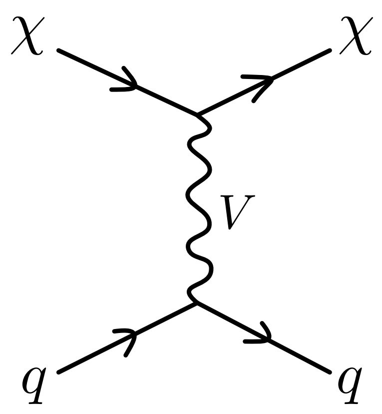
$$\xrightarrow{\alpha} {}^{226}\mathrm{Ra} \xrightarrow{\alpha} {}^{222}\mathrm{Rn} \xrightarrow{\alpha} \ldots \longrightarrow {}^{206}\mathrm{Pb}$$



$$\text{Uranium-238 Concentration} \sim 0.01\,\text{ppb}$$

Dark Matter Signal

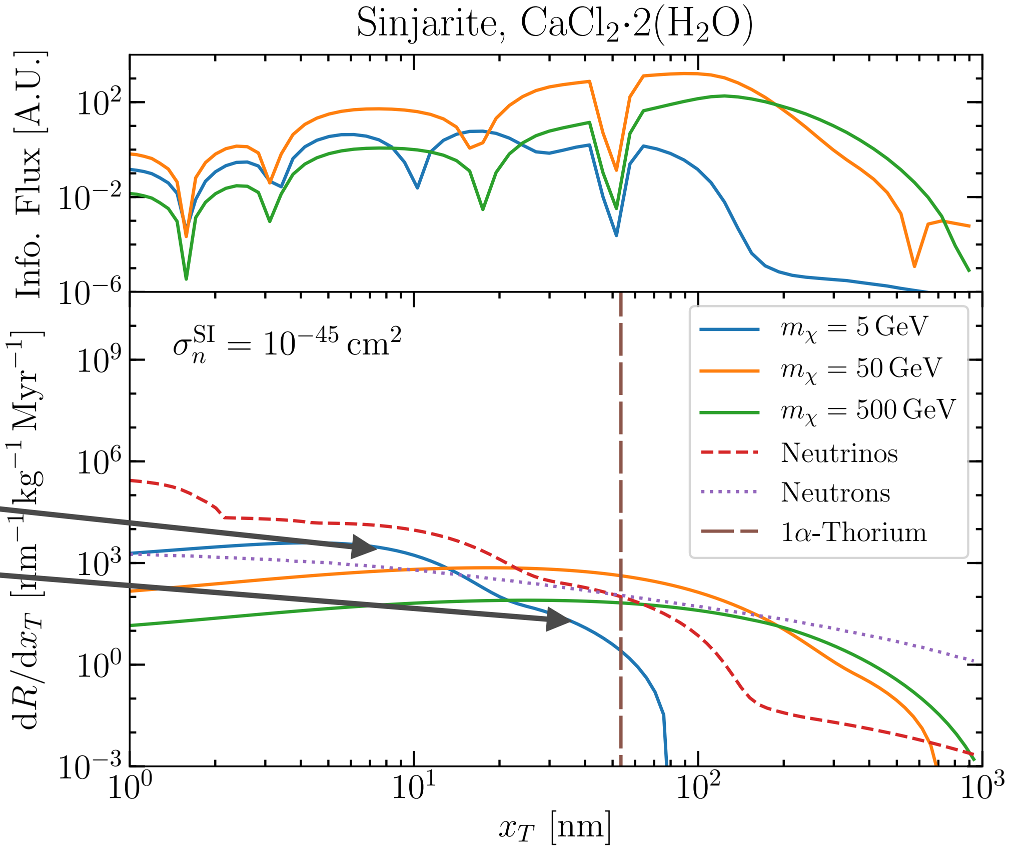
- Signal is proportional to the interaction strength.
- We utilise the different shapes of the backgrounds from a dark matter signal.
- Hydrogen effectively slows fast neutrons, mitigating the background further



$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_N m_\chi} \int_{v_{\min}}^{\infty} v f(\mathbf{v}) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \mathrm{d}^3\mathbf{v}$$

$$+$$

$$\frac{\mathrm{d}R}{\mathrm{d}x_T} = \sum_i^{\text{nuclei}} \xi_i \frac{\mathrm{d}R_i}{\mathrm{d}E_R} \left(\frac{\mathrm{d}E_R}{\mathrm{d}x_T}\right)_i$$



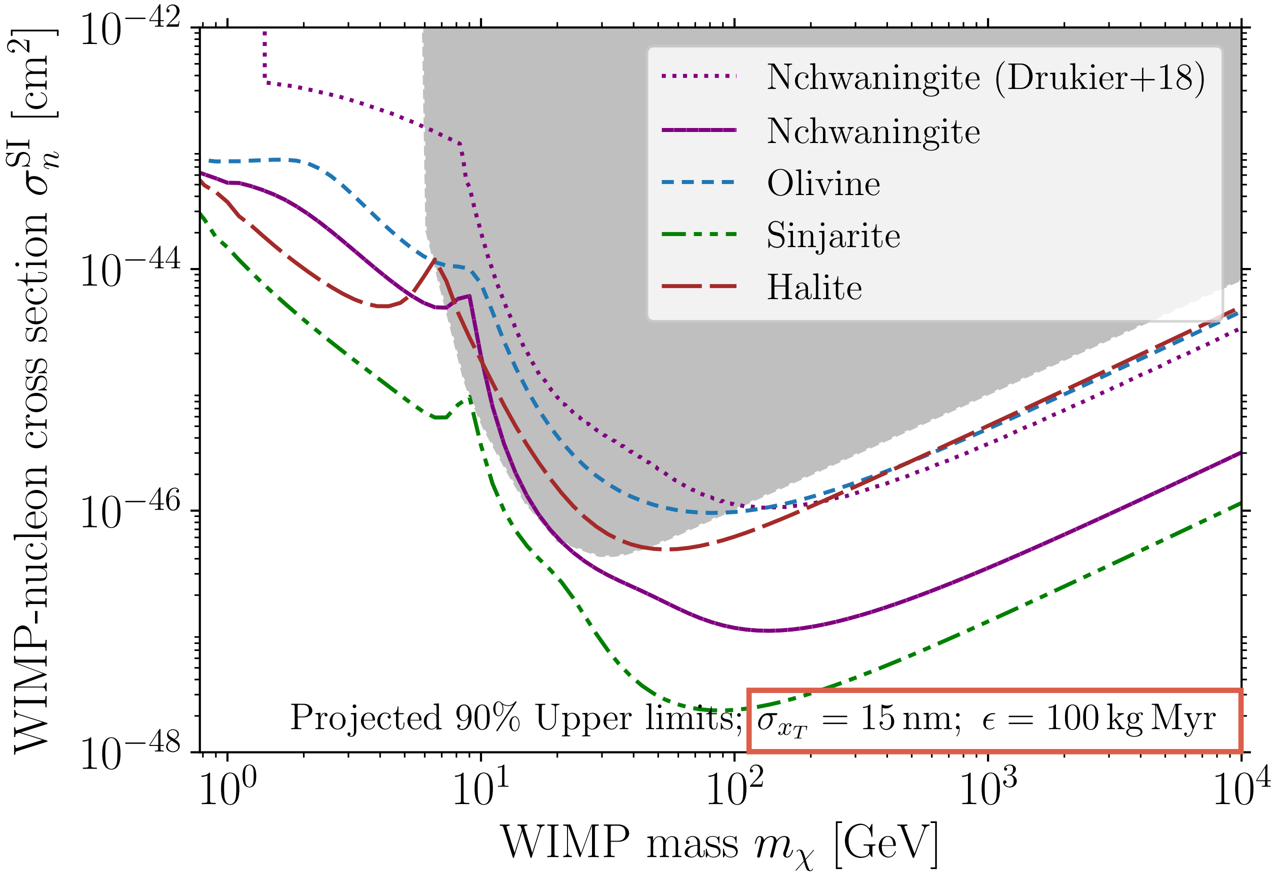
Bumps from different nuclei in mineral

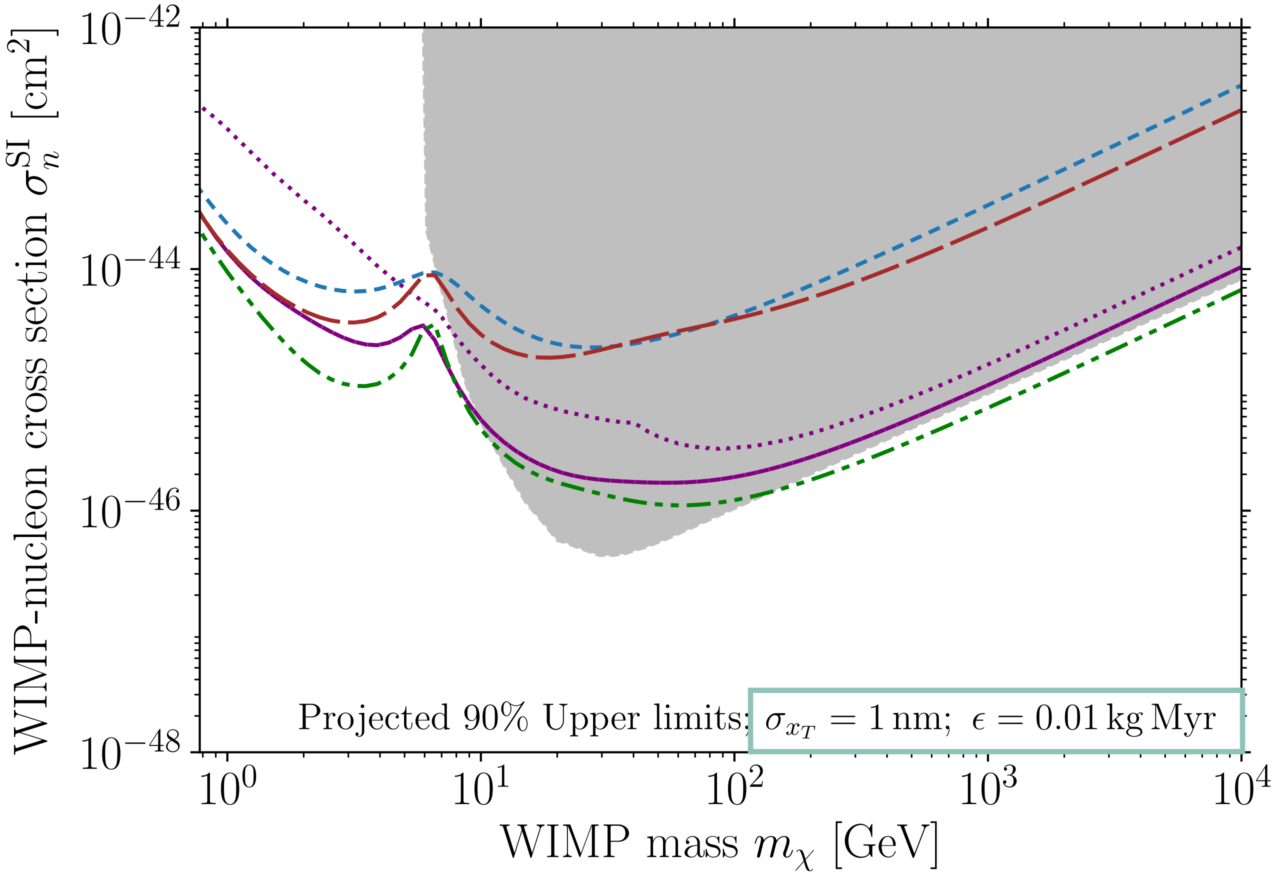
🟥 - Density of DM, DM mass, and nucleon mass

🟩 - Velocity distribution of DM in the galaxy

🟧 - Interaction strength as a function of energy

Sensitivity to Dark Matter Signal



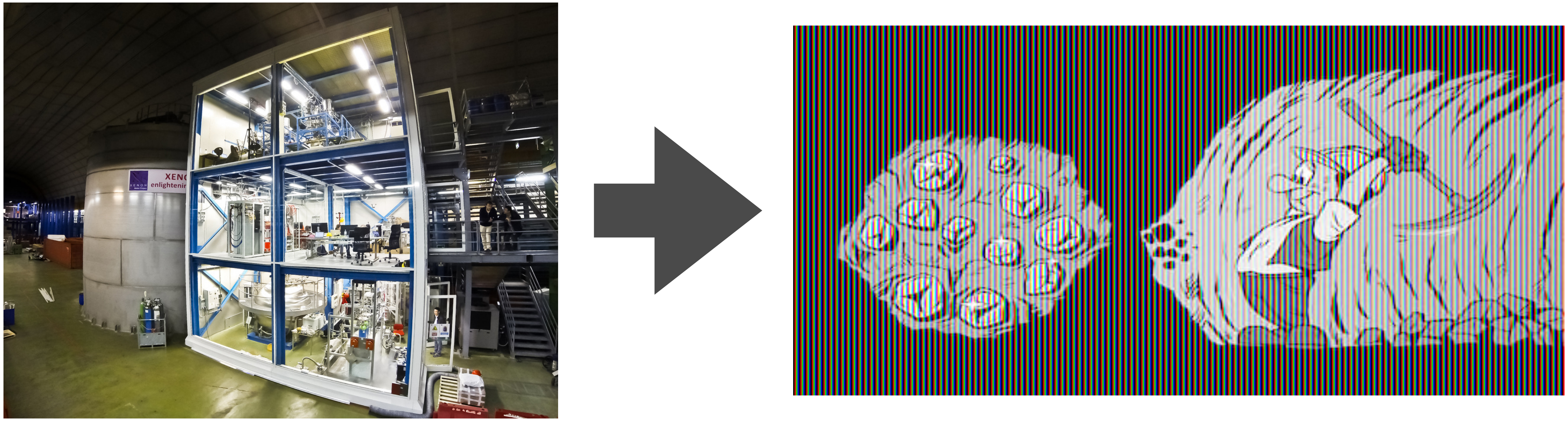


Using the faster scanning method we can can probe WIMP DM well below current experimental limits > 1 GeV

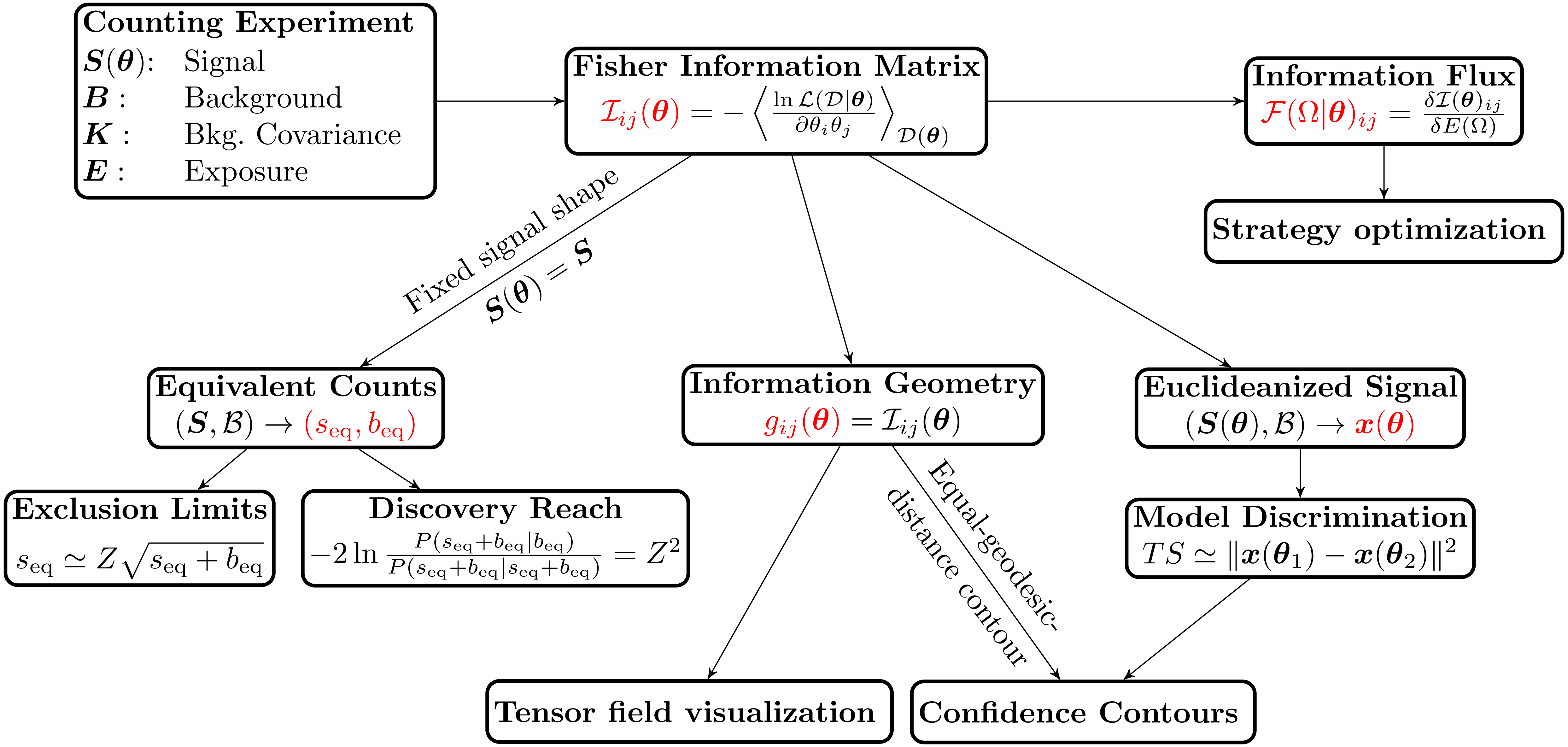
More precision allows us to probe lighter DM masses

Next Steps

- Paleo-detectors could be the most sensitive dark matter direct detection experiments to date.
- We are currently beginning the experimental program to make these detectors a reality.
- Have funding for initial feasibility studies:
    - Understanding track formation.
    - Natural abundances of Uranium-238.
- The background can also be thought of as a signal, we are investigating the possibility of using paleo-detectors as long-lived neutrino detectors.



Swordfish - Analysis Tool



Counting Experiment

$\boldsymbol{S}(\boldsymbol{\theta})$: Signal

$\boldsymbol{B}$: Background

$\boldsymbol{K}$: Bkg. Covariance

$\boldsymbol{E}$: Exposure

Fisher Information Matrix

$$\mathcal{I}_{ij}(\boldsymbol{\theta}) = -\left\langle \frac{\ln \mathcal{L}(\mathcal{D}|\boldsymbol{\theta})}{\partial\theta_i\theta_j} \right\rangle_{\mathcal{D}(\boldsymbol{\theta})}$$

Information Flux

$$\mathcal{F}(\Omega|\boldsymbol{\theta})_{ij} = \frac{\delta\mathcal{I}(\boldsymbol{\theta})_{ij}}{\delta E(\Omega)}$$

Strategy optimization

Fixed signal shape

$\mathbf{S}(\boldsymbol{\theta}) = \mathbf{S}$

Equivalent Counts

$$(\boldsymbol{S}, \mathcal{B}) \to (s_{\rm eq}, b_{\rm eq})$$

Information Geometry

$$g_{ij}(\boldsymbol{\theta}) = \mathcal{I}_{ij}(\boldsymbol{\theta})$$

Euclideanized Signal

$$(\boldsymbol{S}(\boldsymbol{\theta}), \mathcal{B}) \to \boldsymbol{x}(\boldsymbol{\theta})$$

Exclusion Limits

$$s_{\rm eq} \simeq Z\sqrt{s_{\rm eq} + b_{\rm eq}}$$

Discovery Reach

$$-2\ln\frac{P(s_{\rm eq}+b_{\rm eq}|b_{\rm eq})}{P(s_{\rm eq}+b_{\rm eq}|s_{\rm eq}+b_{\rm eq})} = Z^2$$

Equal-geodesic-distance contour

Model Discrimination

$$TS \simeq \|\boldsymbol{x}(\boldsymbol{\theta}_1) - \boldsymbol{x}(\boldsymbol{\theta}_2)\|^2$$

Tensor field visualization

Confidence Contours

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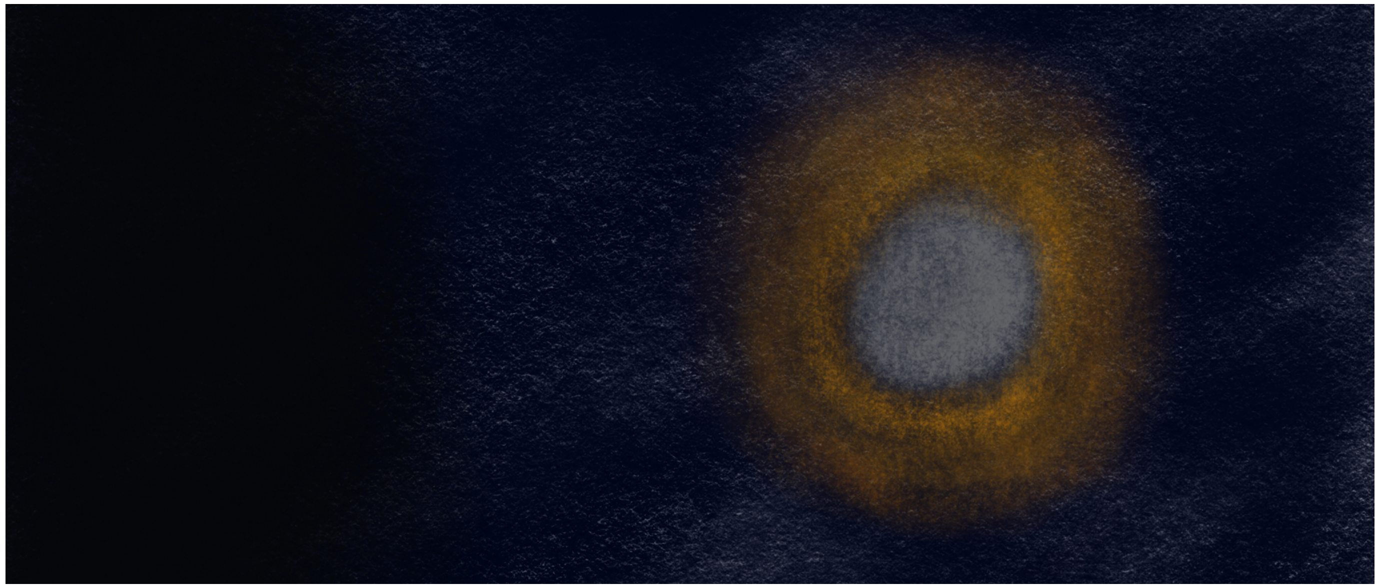
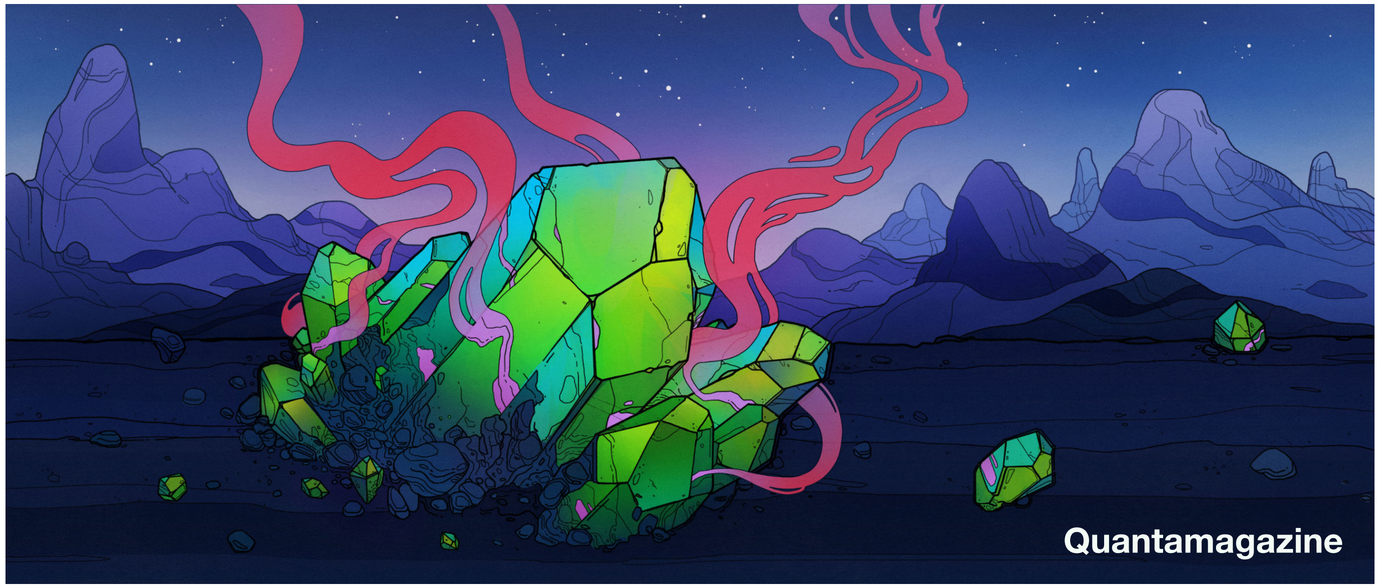
https://github.com/cweniger/swordfish

Conclusions

- The time is right to think hard about new directions in the search for dark matter
- Utilising the guaranteed next generation of detectors is a good start
- Can we go further? What kind of new observables are there?





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