A (partial) theory summary: WIMPs, sub-GeV & axions

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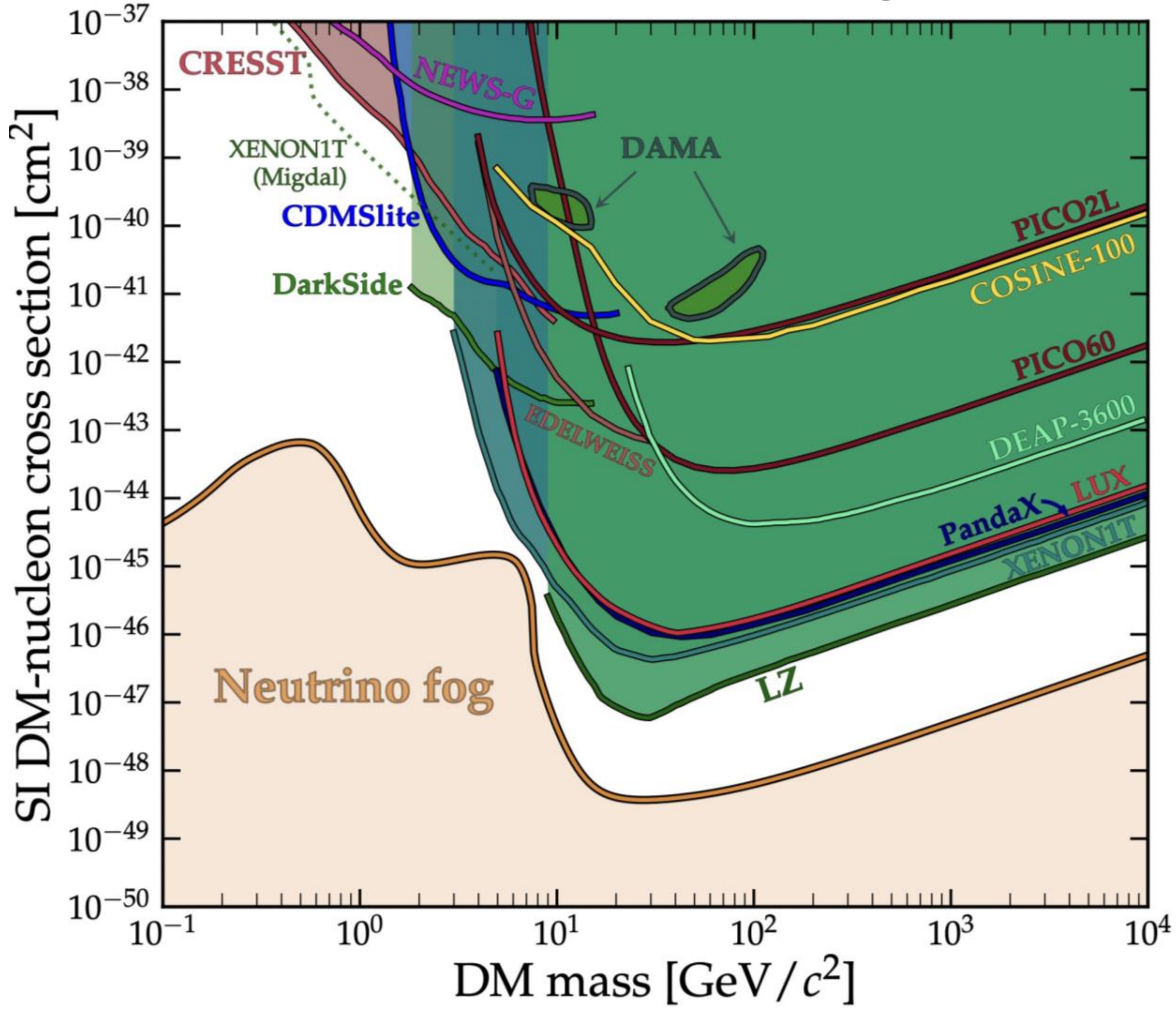
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

THE UNIVERSITY OF MELBOURNE

WIMPs – where do we stand?

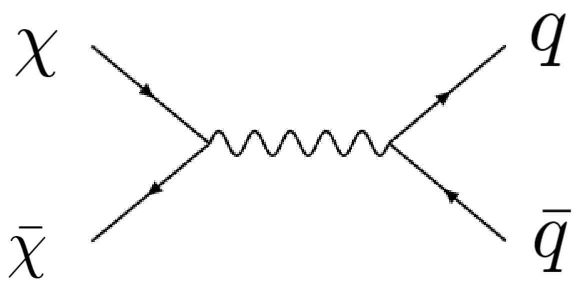
Figure: C. O'Hare

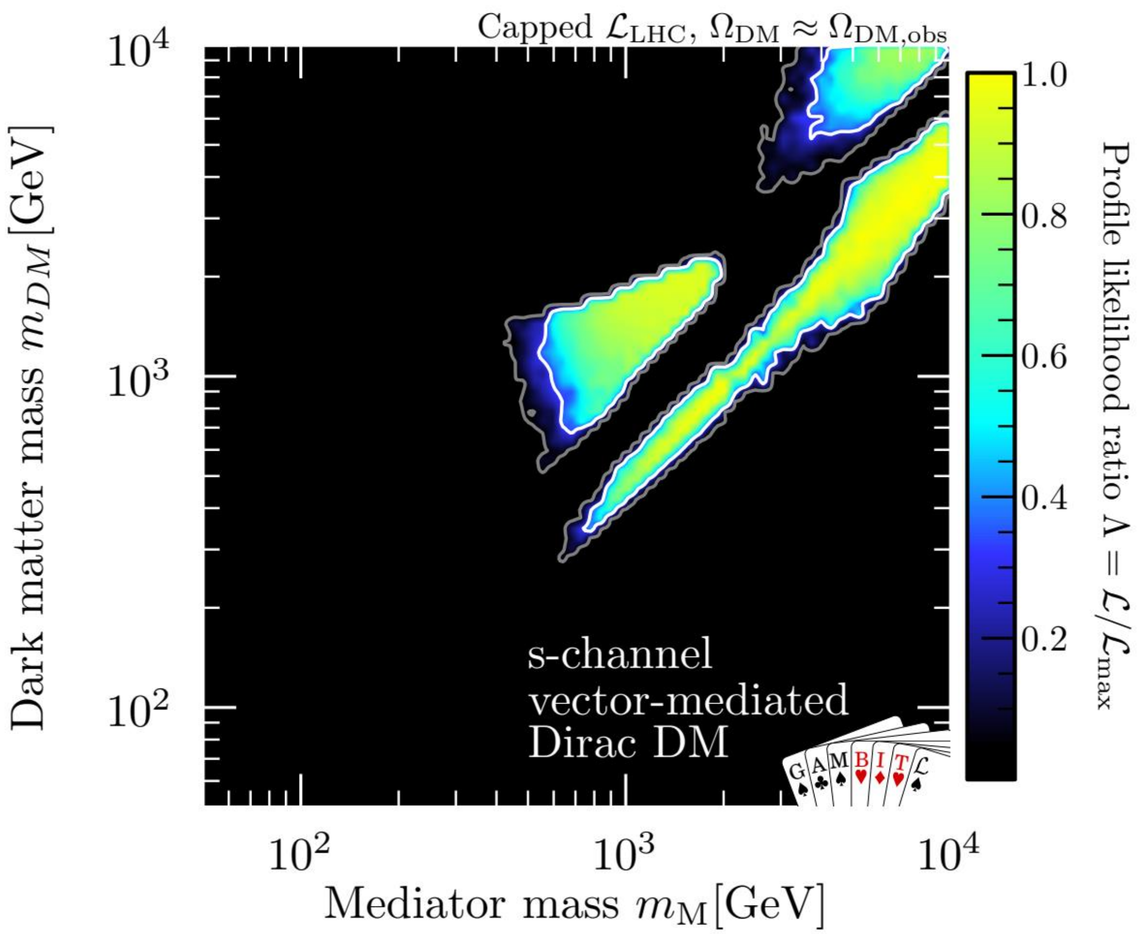


WIMP simplified models

White (UoA) & GAMBIT collaboration
Eur.Phys.J.C (2023)

Dirac fermion DM + vector mediator





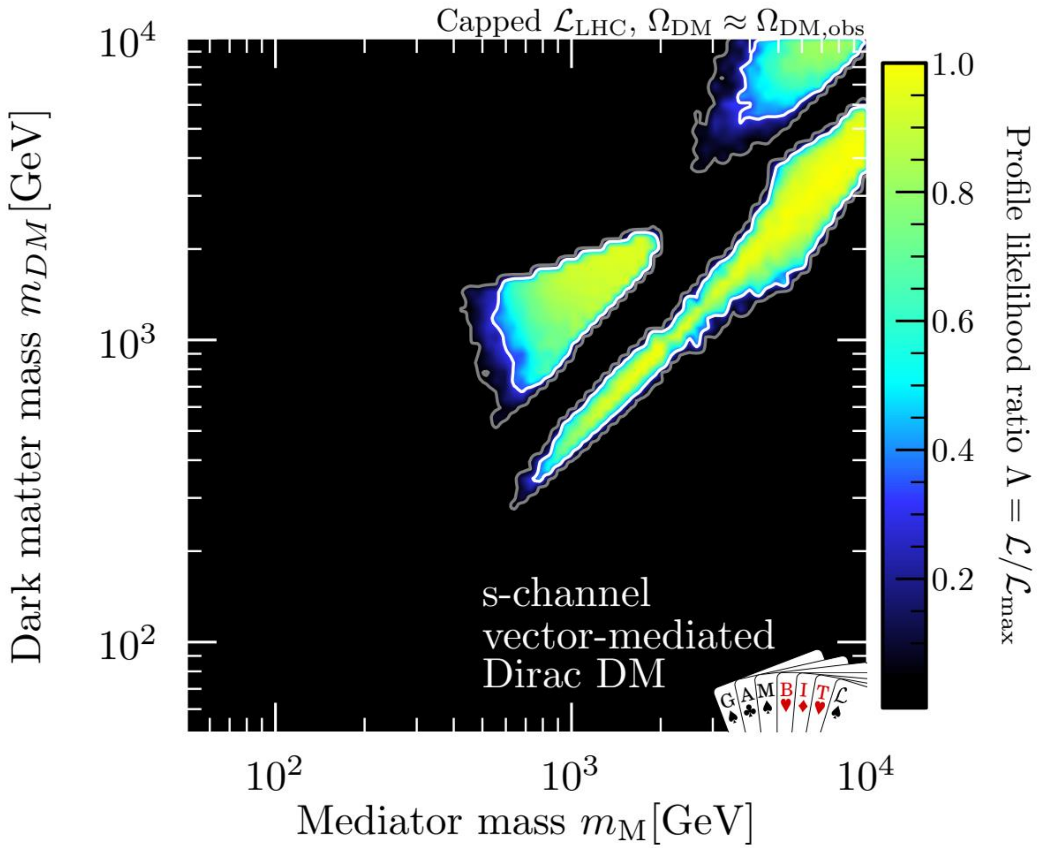
Included in likelihood

- Relic density
- Direct detection
- Indirect detection (Fermi)
- LHC searches: monojet, dijet

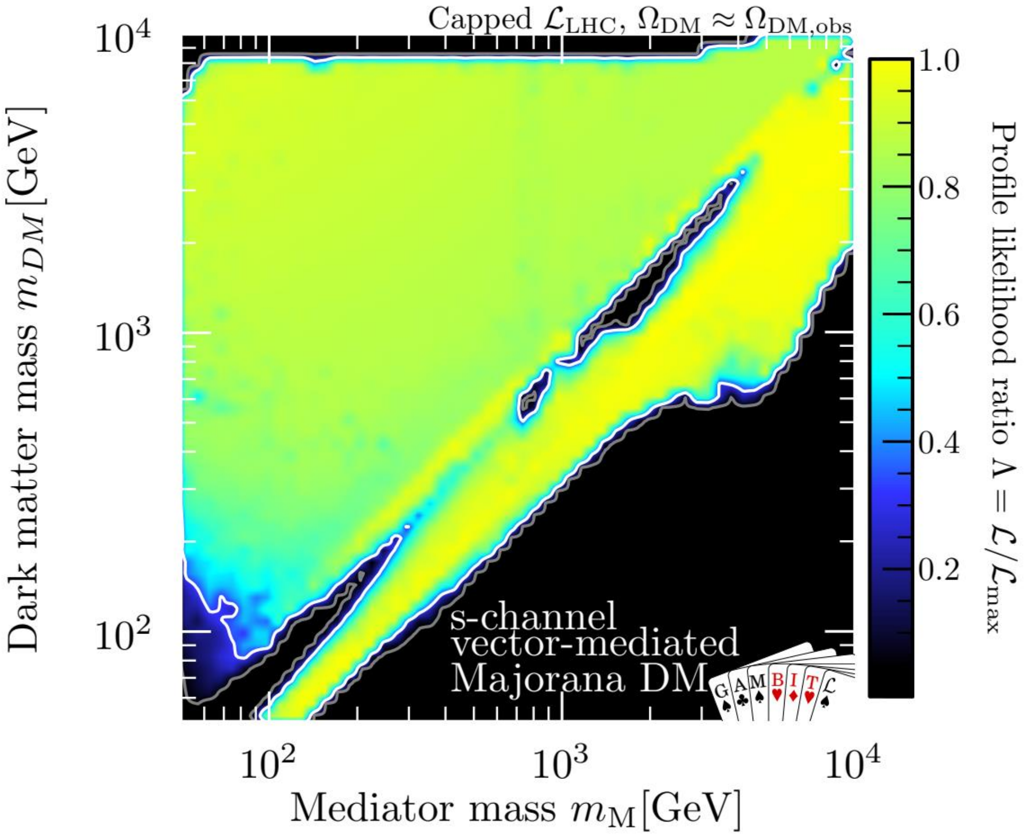
WIMP simplified models

White (UoA) & GAMBIT collaboration
Eur.Phys.J.C (2023)

Dirac fermion DM

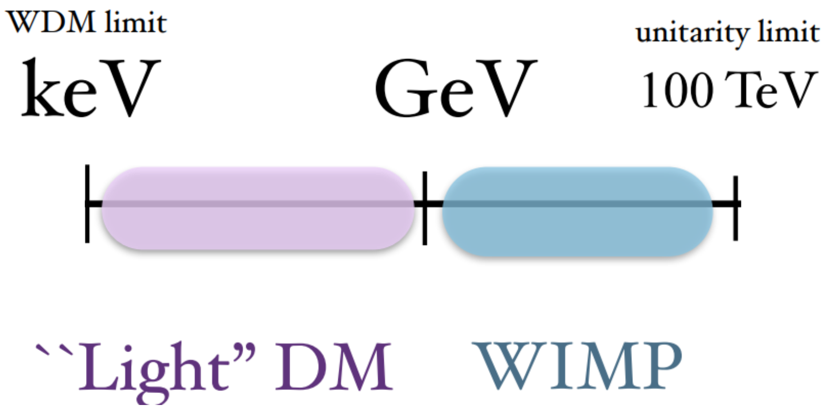


Majorana fermion DM



Direct detection cross-section
is velocity suppressed

Sub-GeV dark matter

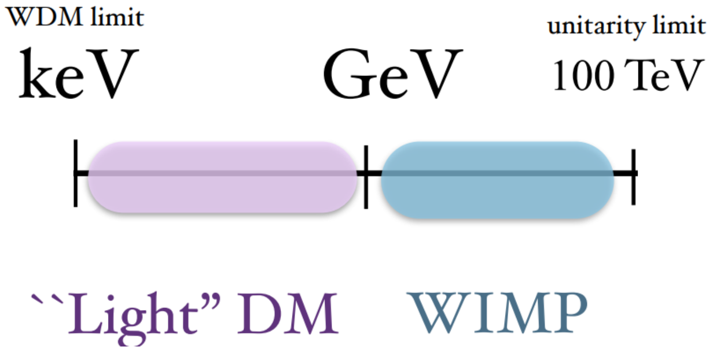


- DM can be produced thermally for masses $\gtrsim$ keV
- Models commonly feature light mediators
- Dark sectors that interact very weakly with SM (e.g. freeze-in DM)

Sub-GeV dark matter

How to probe sub-GeV dark matter?

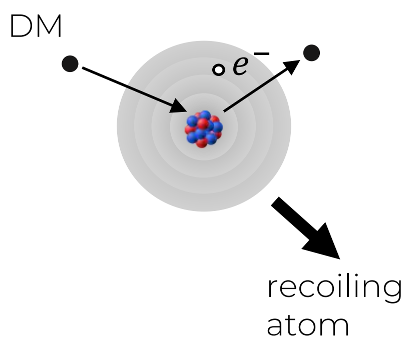
- CMB, BBN → see talks by Céline Bœhm & Josh Wood
- Indirect detection (annihilation or decay)
- Low-threshold direct detection experiments
- Migdal effect
- Boosted dark matter
- DM capture/annihilation in compact objects
- DM production in beam dump experiments
- …



Migdal effect

See Alex Ritter's talk

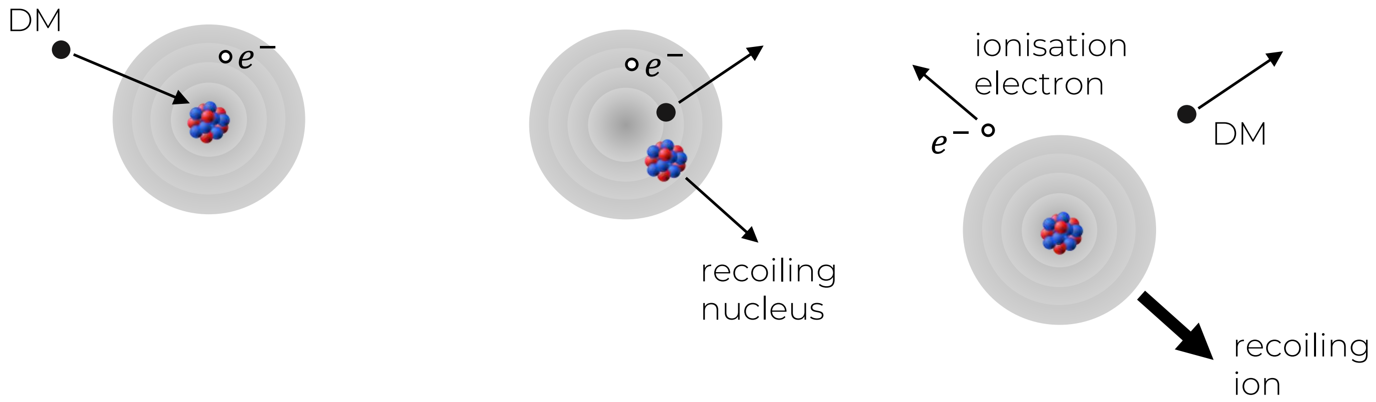
Elastic scattering



$$E_{NR}^{\max} = 0.1\,\mathrm{keV}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

Low-energy recoil
(sub-threshold)

Migdal (inelastic)



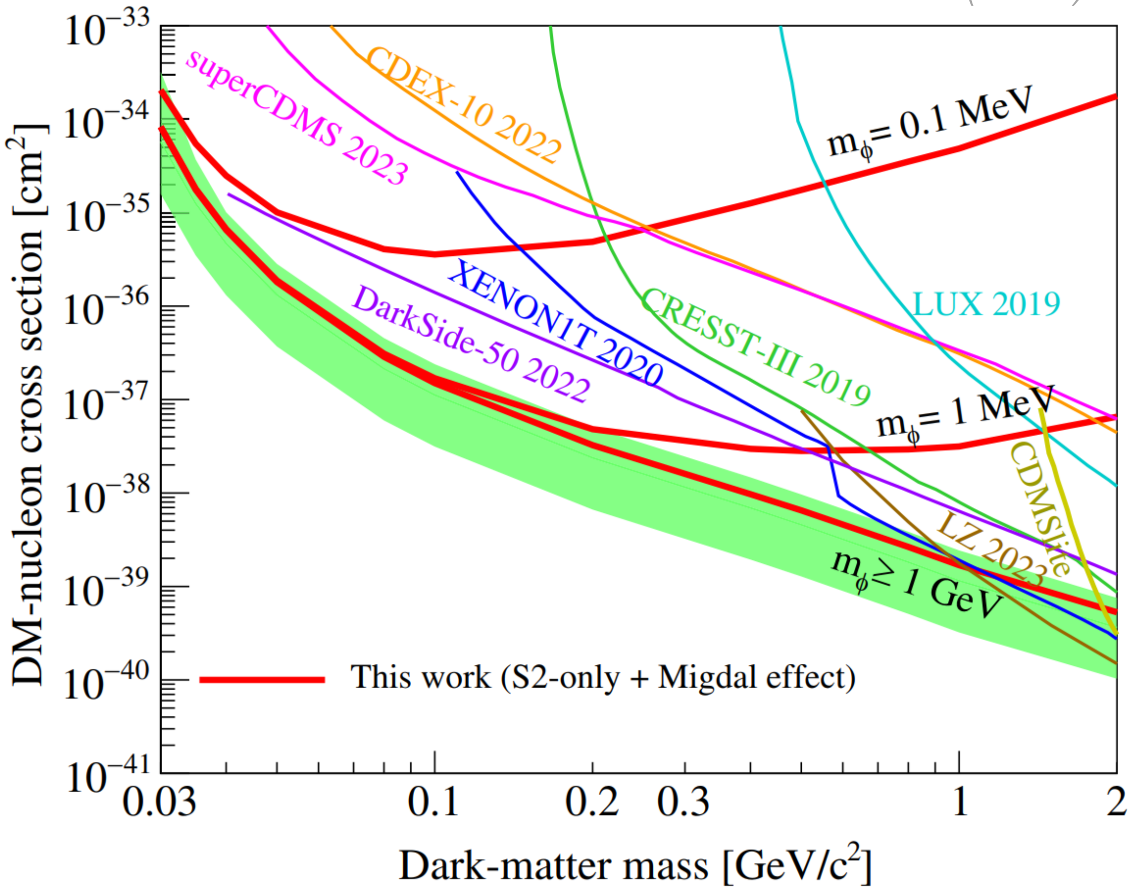
$$\omega_{\max} = \frac{1}{2} m_\chi v_\chi^2 \sim 3\,\mathrm{keV}\left(\frac{m_\chi}{\mathrm{GeV}}\right)$$

Higher energy
electronic signal

Migdal effect

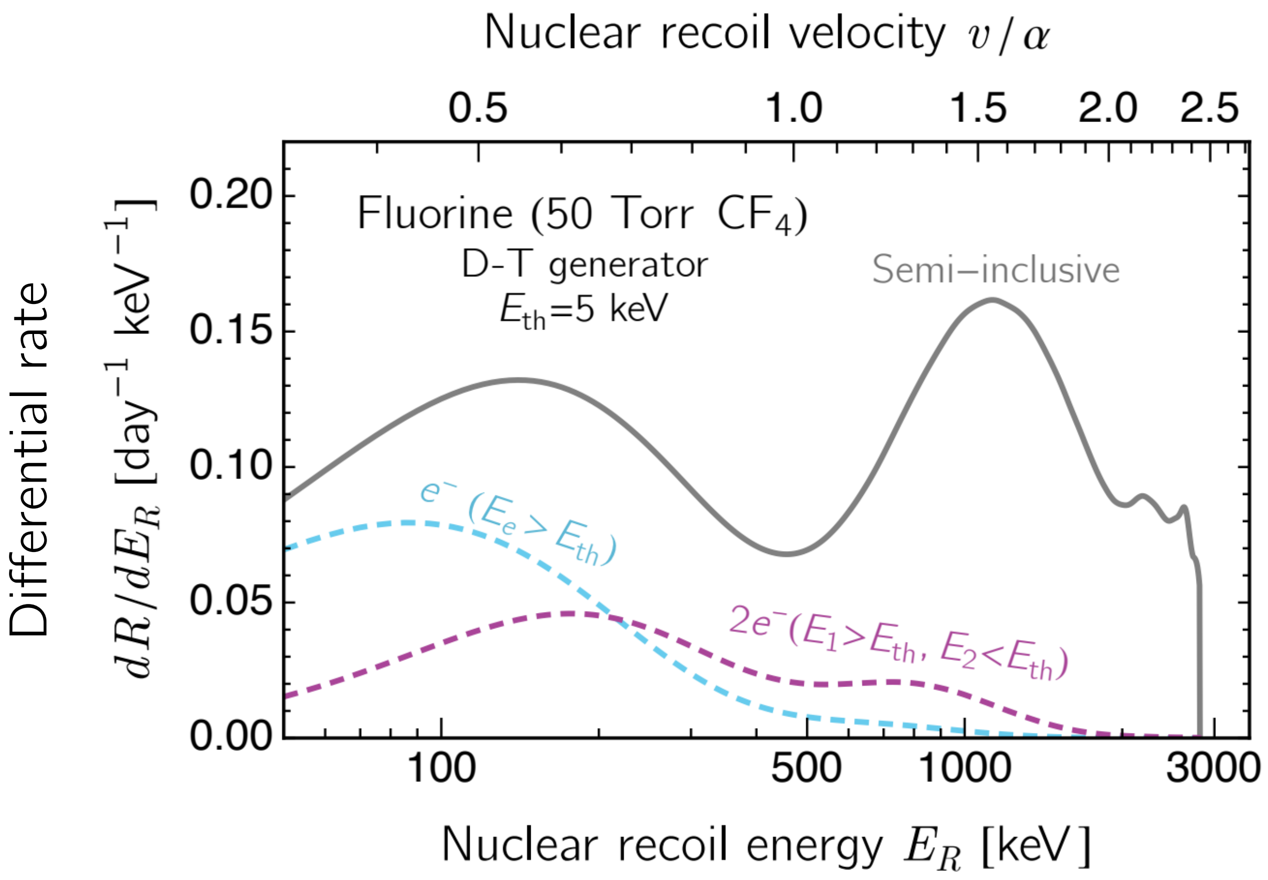
Provides world-leading direct detection limit for masses below 1 GeV

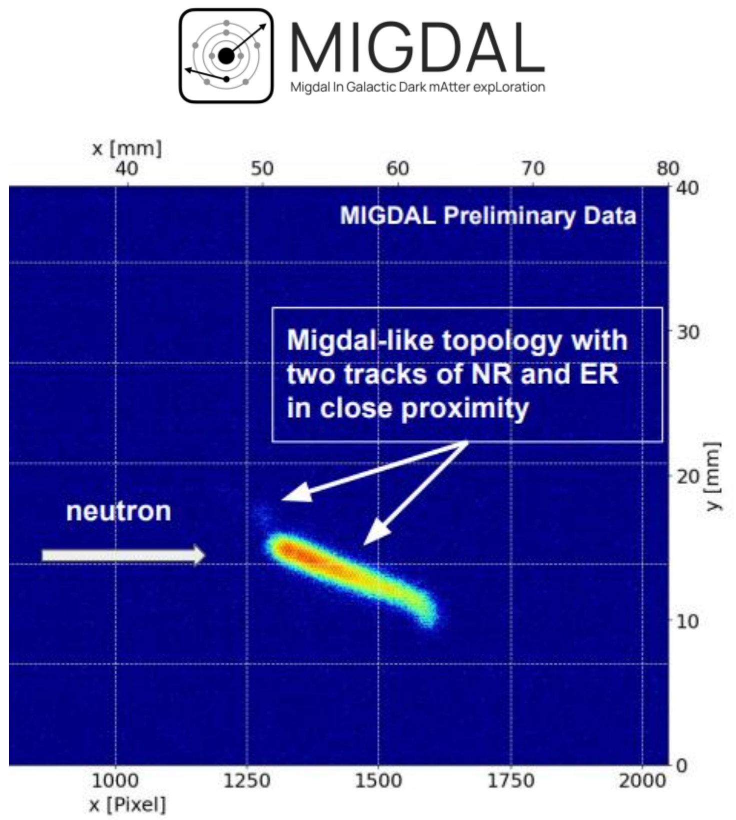
PandaX-4T (2023)



Migdal effect – precision theory

PC (UoM), Dolan (UoM), McCabe, Quiney
Phys. Rev. D 2023



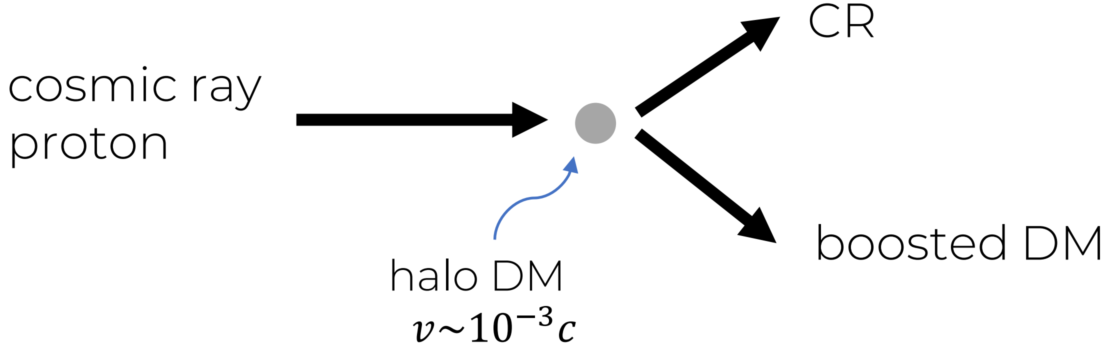


Ongoing neutron scattering experiments to validate theory

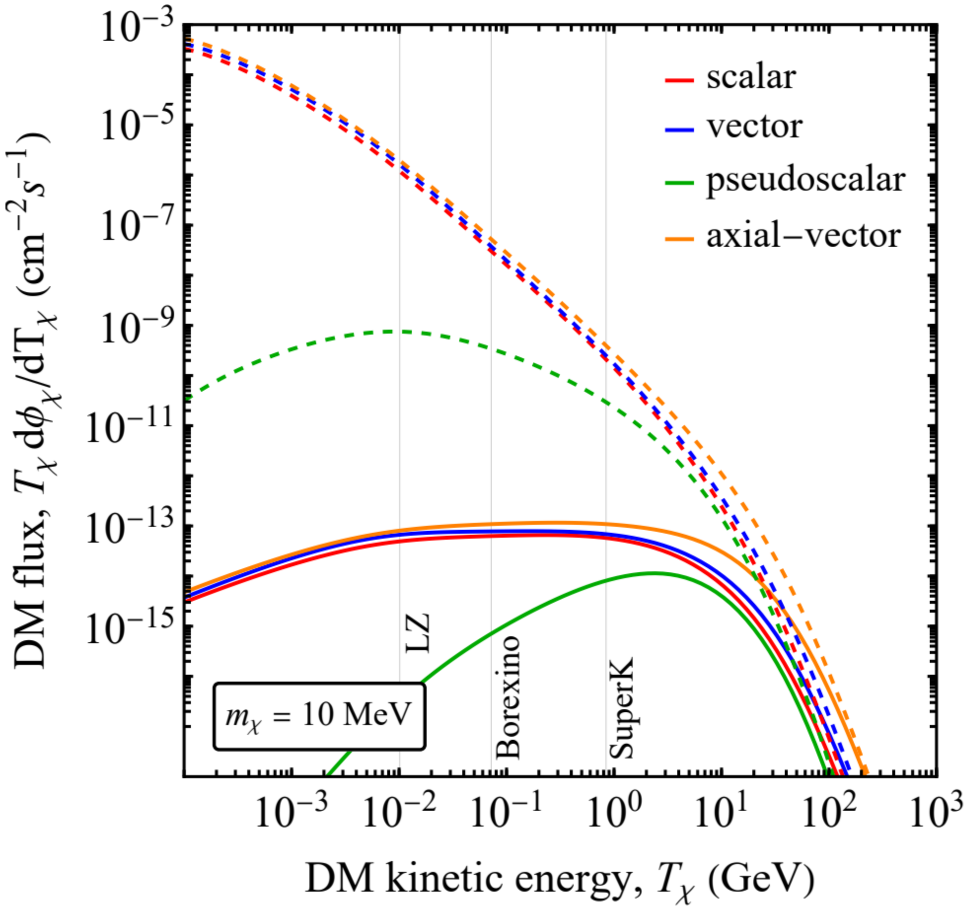
Cosmic ray upscattered DM

Halo DM can be boosted by scattering with cosmic rays

Bringmann & Pospelov '18



Bell, Newstead, Shaukat Ali (2023)

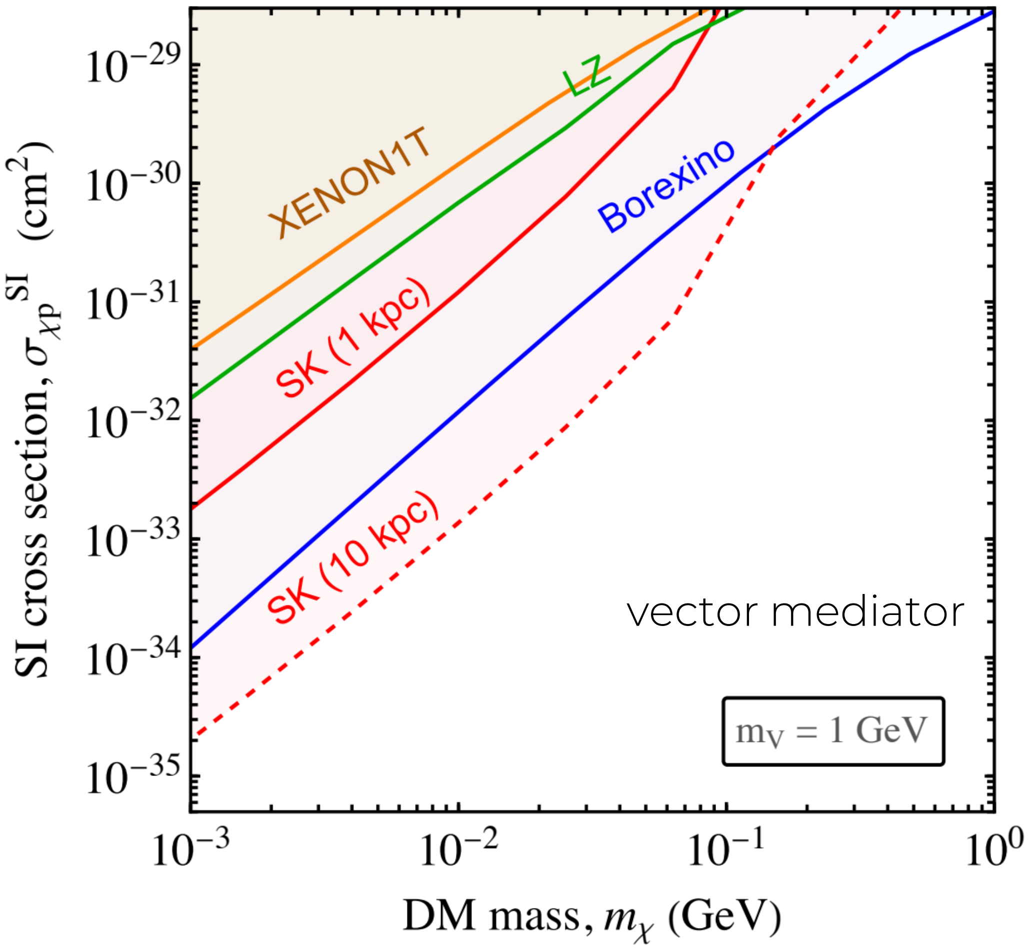


Flux of relativistic DM for direct detection experiments

Cosmic ray upscattered DM

- DM-SM interaction appears *twice* *(CR upscattering & detection)*
- Only sensitive to large cross-sections → light mediators
- Constraints from both direct detection & neutrino experiments

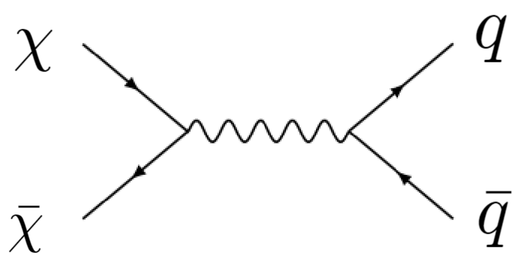
Bell, Newstead, Shaukat Ali (UoM) '23



Cosmic ray upscattered DM

Bell, Newstead, Shaukat Ali (UoM)
2309.11003

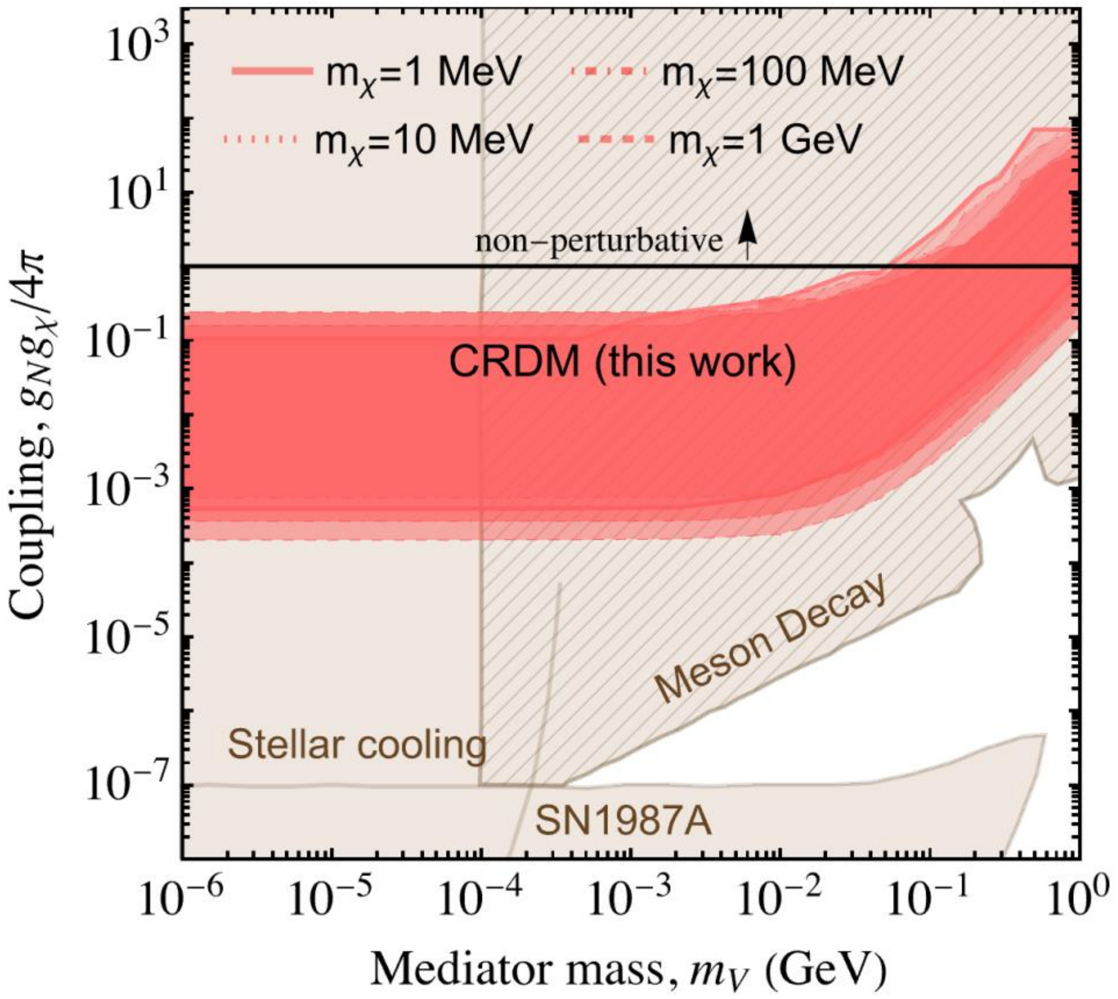
- *But,* mediator is also constrained by meson decays, stellar cooling



→ *Mediator constraints generally stronger than CRDM bounds*

See Iman Shaukat Ali's ECR workshop talk

vector mediator

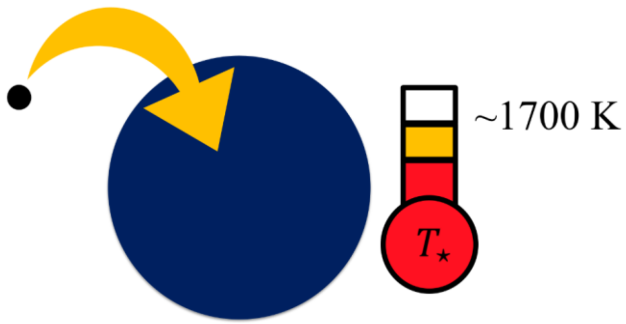


Neutron Star Heating

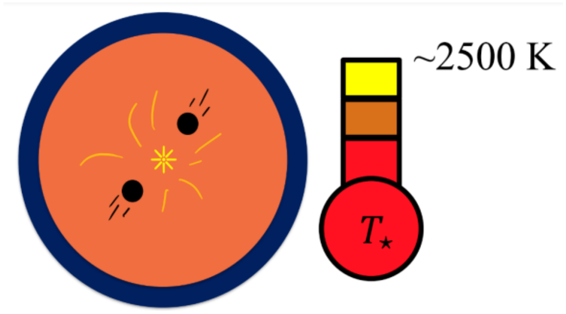
Baryakhtar et. al. '17

Neutron stars *efficiently capture* dark matter due to their high density

DM capture & kinetic heating



DM Annihilation



Isolated neutron stars expected to cool to 1000K after ~10Myr

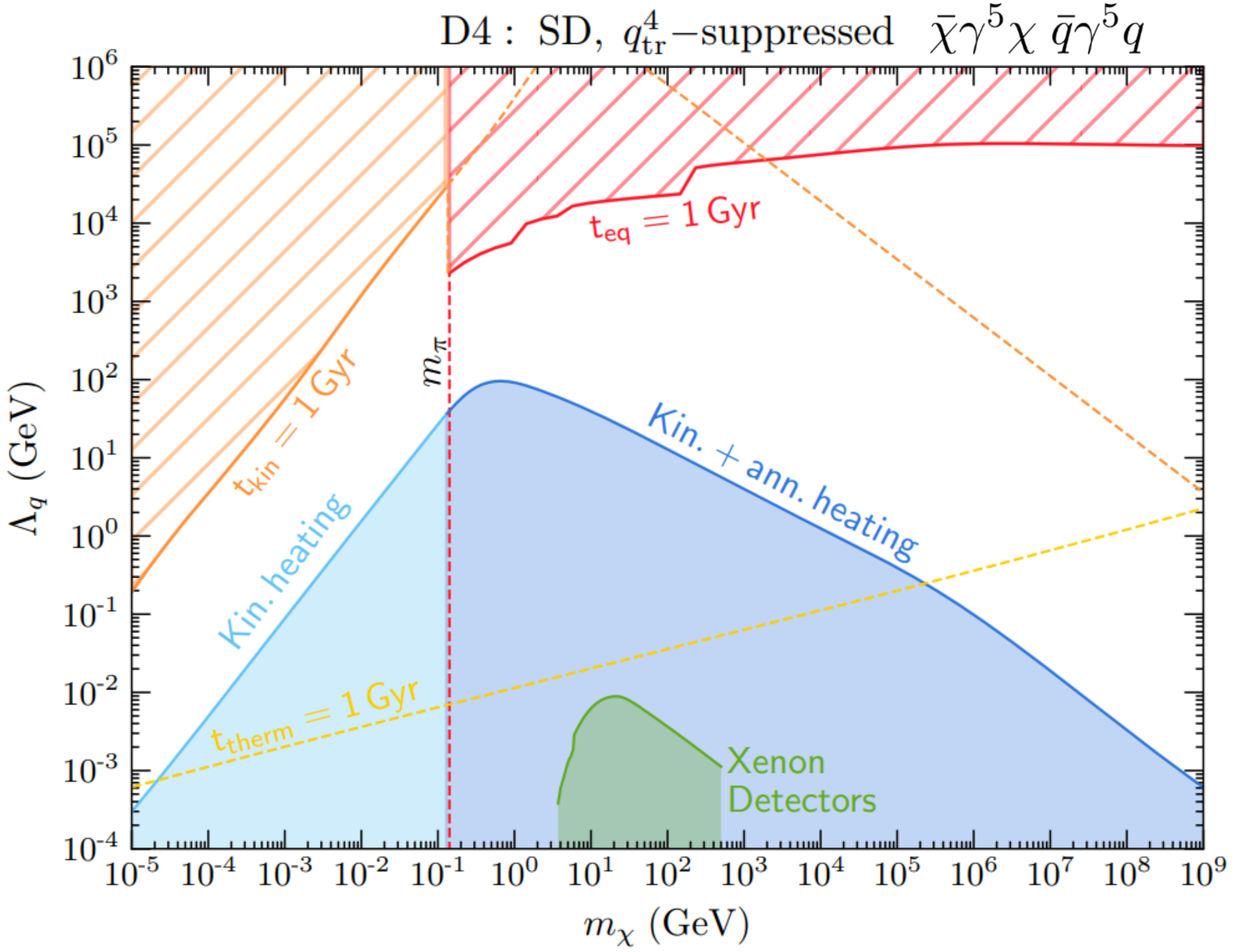
Coolest known neutron star has temperature 4×10^4 K

NS heating (projected sensitivity)

Bell (UoM), Busoni (ANU), Virgato (UoM)+ (in progress)

Bell (UoM), Busoni (ANU), Thomas (UoA), Virgato (UoM)+ JCAP (2021)

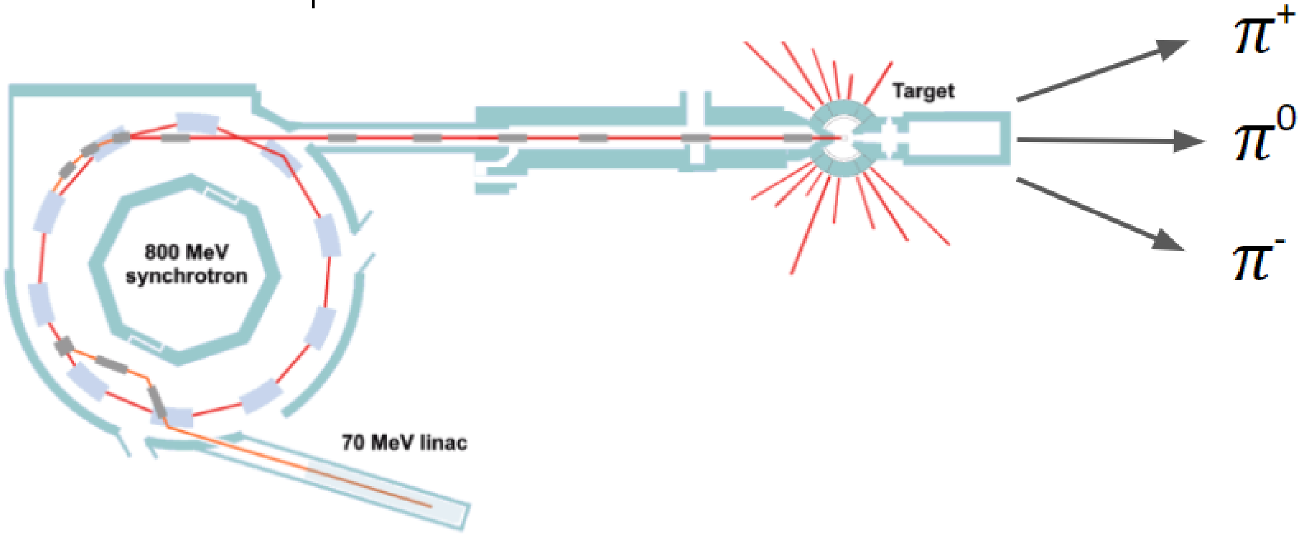
- Observation of old, cold NS would constrain DM interactions
- Sensitivity to velocity/momentum suppressed interactions



★ See Michael Virgato's Poster

Producing DM at beam dumps

Dark sector particles can be produced in beam dumps
and detected with neutrino detectors



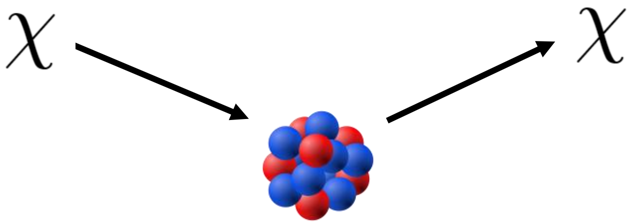
Production of dark photon

$$\pi^- + p \rightarrow n + A'$$
$$\pi^0 \rightarrow \gamma + A'$$

Dark photon
decays into DM

$$A' \rightarrow \chi\bar{\chi}$$

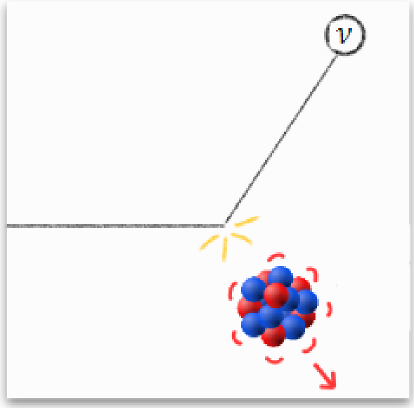
(Relativistic) DM scatters
in detector



Detecting DM with beam dumps

Newstead (UoM)+
Phys. Rev. Lett. (2023)

Elastic scattering - CEvNS (~keV):

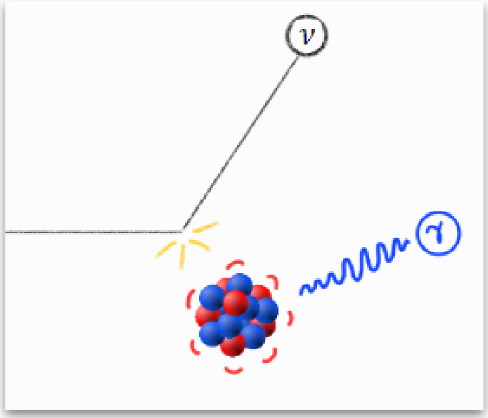


$$E_{R,\max} = \frac{2E_\nu^2}{m_T + 2E_\nu^2}$$

$$\sigma(^{12}\mathrm{C}) \approx 1.3 \times 10^{-40}\mathrm{cm}^2$$

Pro: large σ
Con: hard to detect, larger backgrounds

NC inelastic scattering deexcitation (~MeV):



$$\omega_{\max} \approx E_\nu \left(1 - \frac{E_\nu^2}{2m_T^2}\right)$$

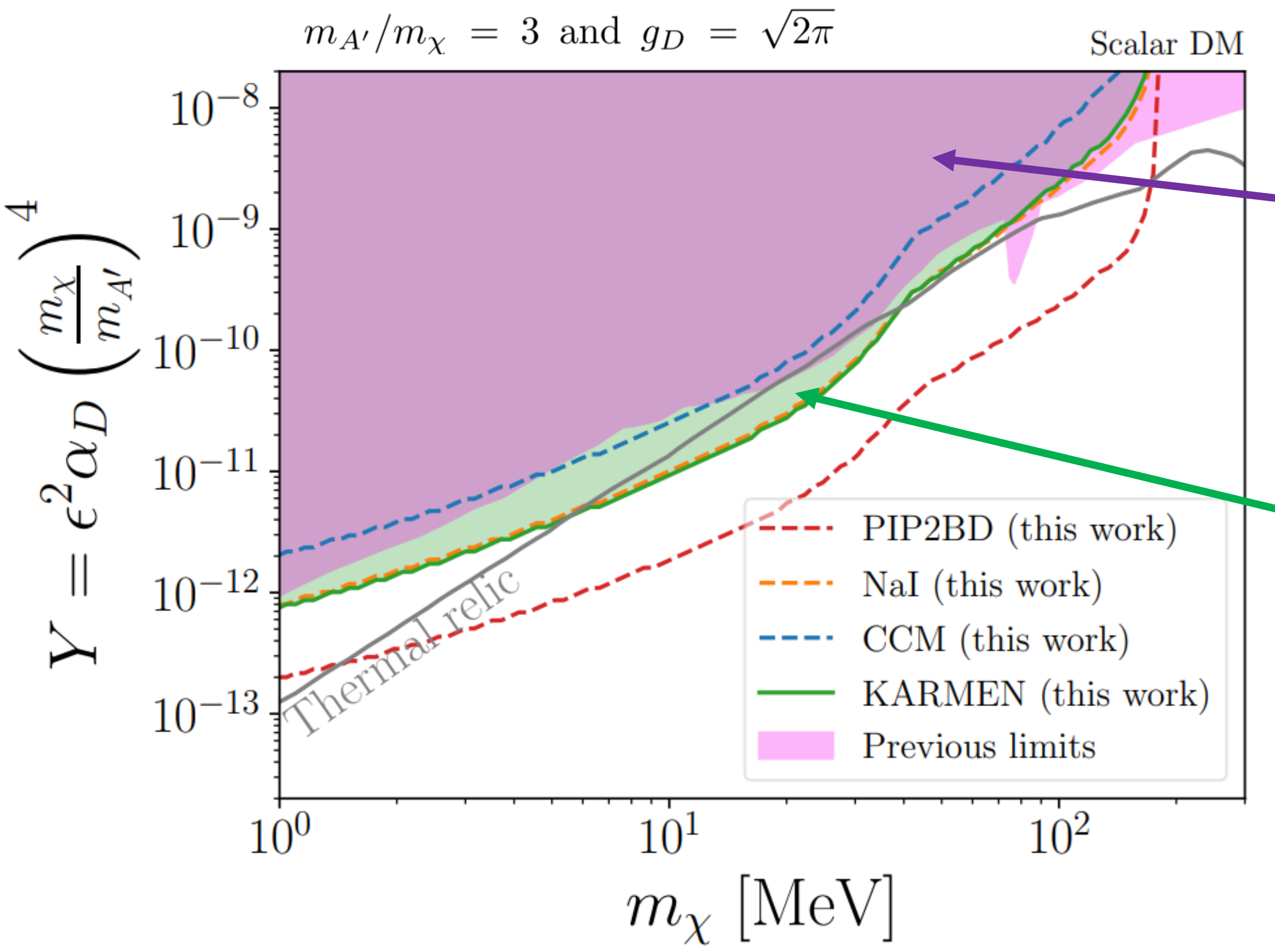
$$\sigma(^{12}\mathrm{C}(15.1\mathrm{MeV})) \approx 10^{-41}\mathrm{cm}^2$$

Pro: easier to detect, line search lower bg
Con: smaller σ, larger theoretical uncertainties

Slide credit: J. Newstead

Detecting DM with beam dumps

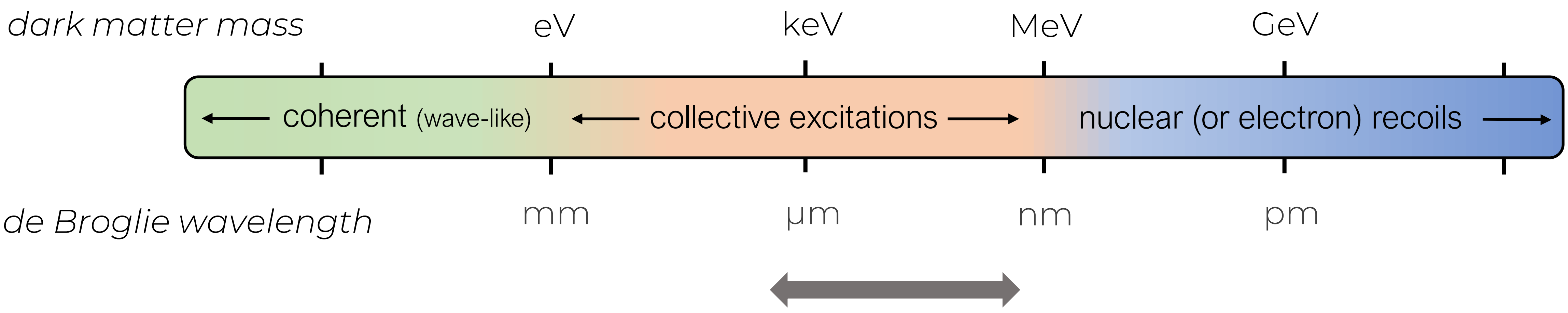
Newstead (UoM)+
Phys. Rev. Lett. (2023)



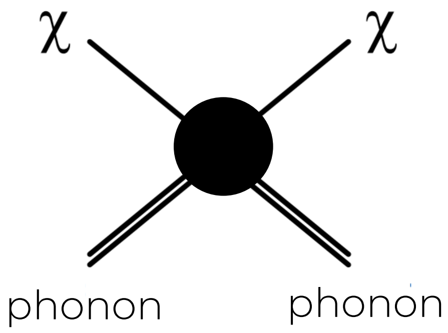
Existing limits from Coherent, LSND, MiniBoone

Improved limit using inelastic channel

Sub-MeV direct detection: collective excitations



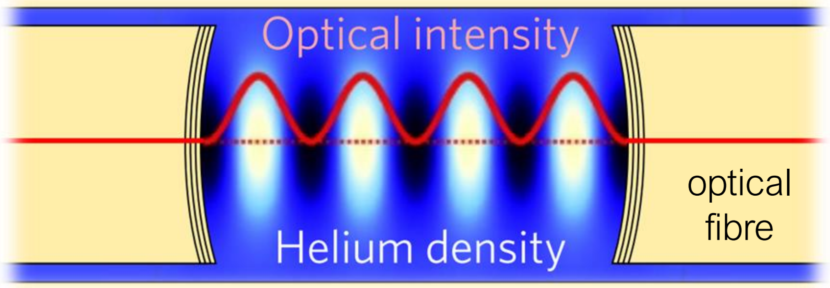
Sub-MeV mass DM interacts directly with collective excitations (*e.g. phonons*)



Superfluid Optomechanics

Superfluid optomechanical cavities are *single phonon detectors*

Figure: Kashkanova+ '16



superfluid ^{4}He filled optical cavity

Coupling between acoustic (density) modes and optical modes

converts ~μeV phonons into ~eV photons

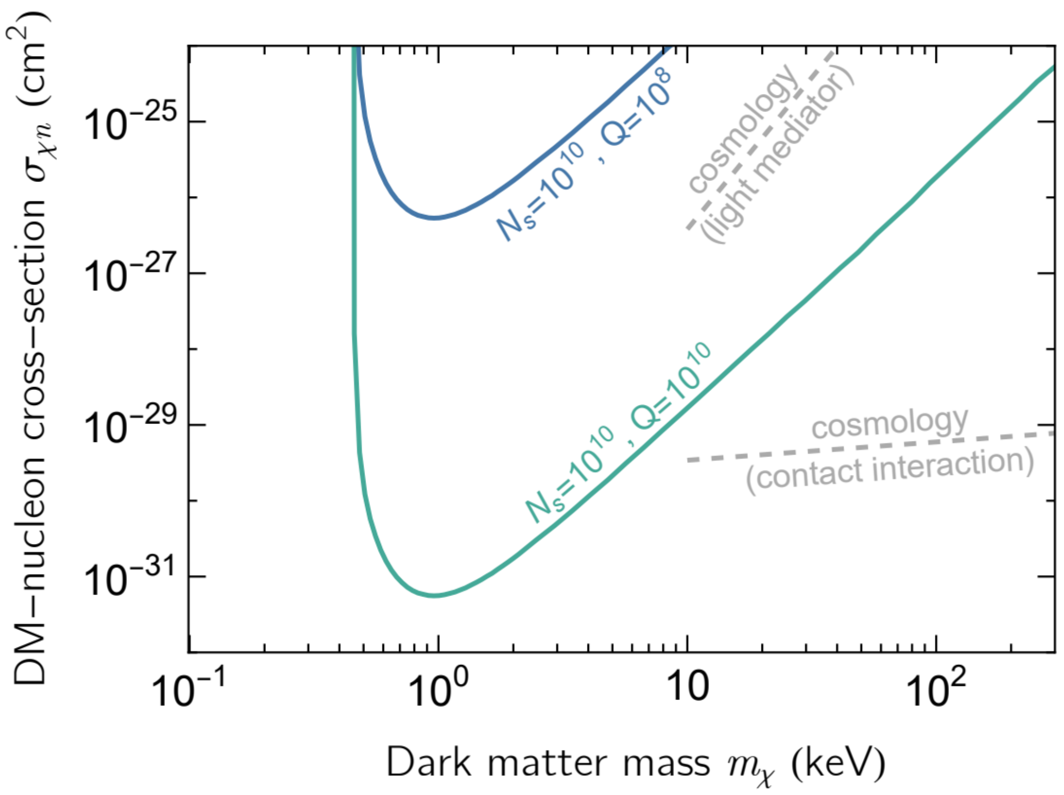
Optomechanical systems have demonstrated μeV phonon counting (e.g. Patil et. al. '22)

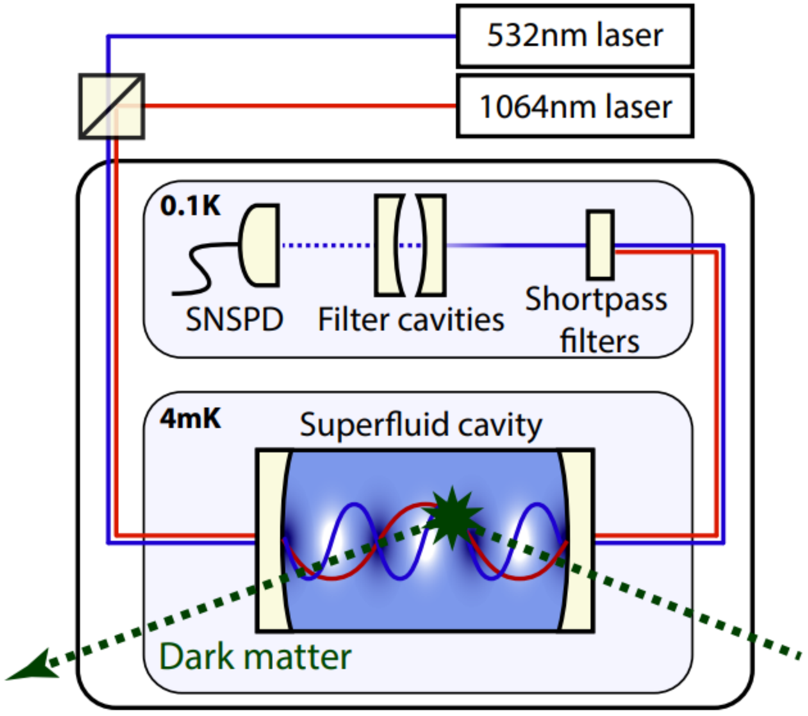
Optomechanical Dark Matter Instrument (ODIN)

PC (UoM), Dolan (UoM), Goryachev (UWA)+
arXiv:2306.09726

Proposal for direct detection of keV-scale dark matter

Projected sensitivity





Axion DM

Goldstone boson of spontaneously broken $U(1)_{PQ}$

Production of DM axions depends on when PQ symmetry broken:

Pre-inflationary PQ breaking

- Same initial field value everywhere
- "Misalignment" production mechanism

Post-inflationary PQ breaking

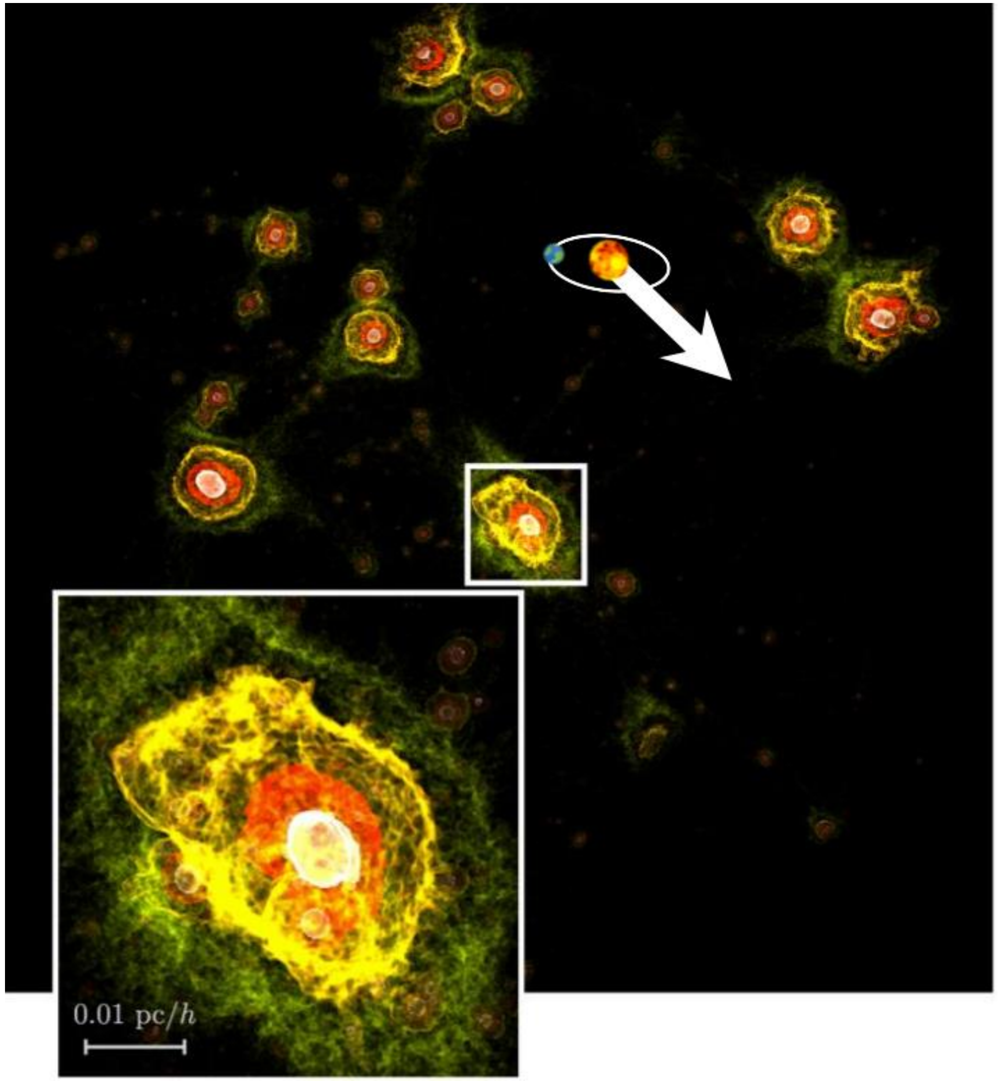
- Field takes on different values in different patches
- Axions produced from decay of topological defects (strings, domain-walls)

$$10^{-5}\,\text{eV} \lesssim m_a \lesssim 10^{-3}\,\text{eV}$$

Axion miniclusters

(post-inflationary PQ breaking)

O'Hare (UoS)+ *Phys. Rev. D* (2023)



- Gravitationally bound clumps of axions with similar mass to asteroids and radii ~AU
- Contain ~75% of axions before galaxy formation

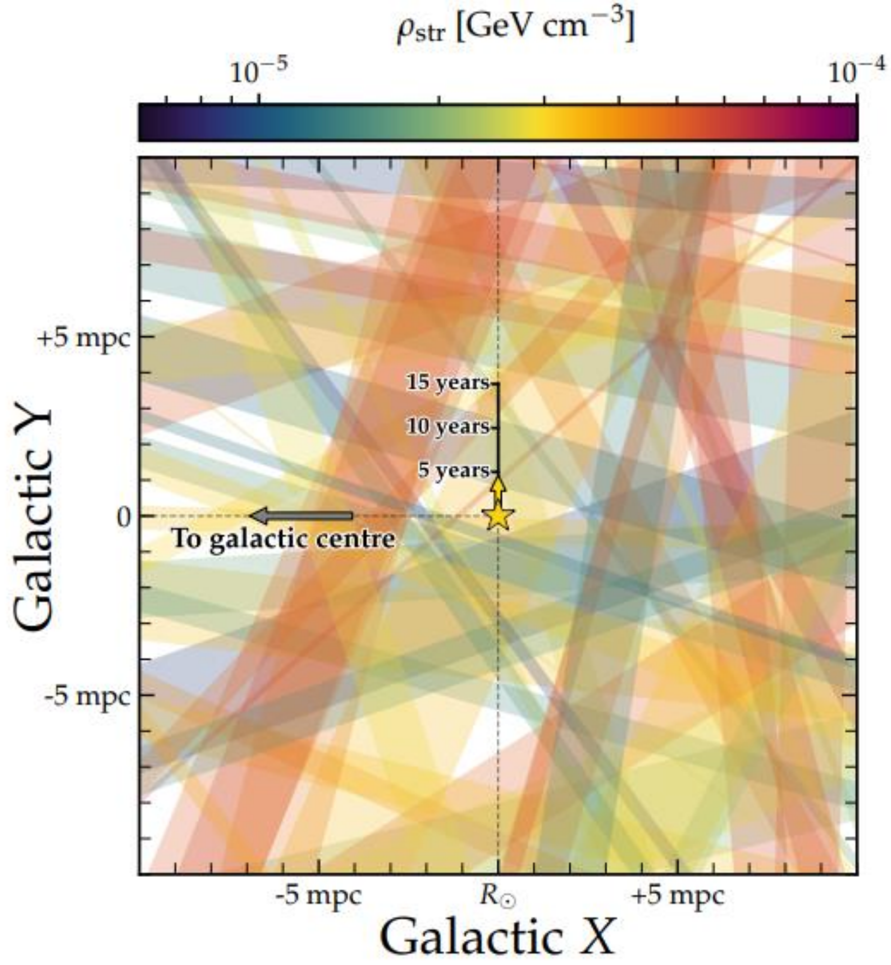
Do these survive until today or are they tidally disrupted?

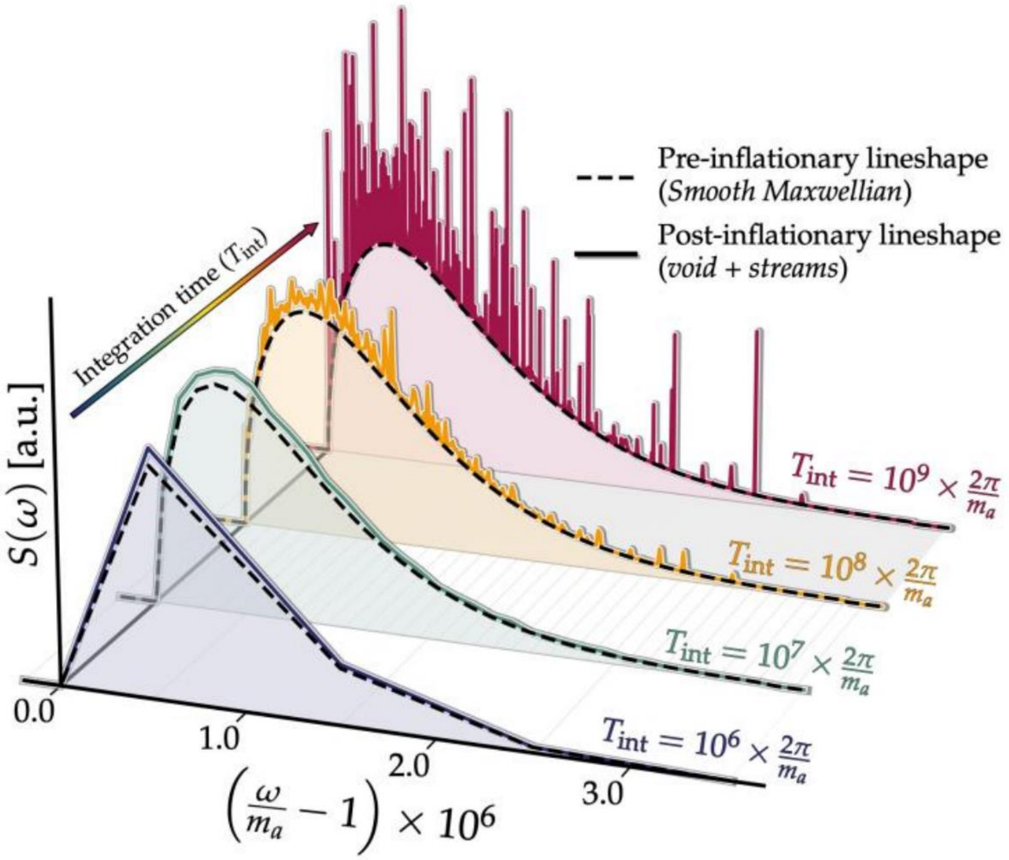
Significant implications for haloscopes

Tidal disruption & streams

O'Hare (UoS)+ (2023)

Local DM distribution is sum of hundreds of streams: $\frac{1}{\rho_{\rm DM}}\sum_{i=1}^{N_{\rm str}}\rho^i_{\rm str} = 81 \pm 6\%$





DFSZ axions & domain walls

PC, Dolan, Hayat, Thamm, Volkas (UoM)
arXiv:2310.16348

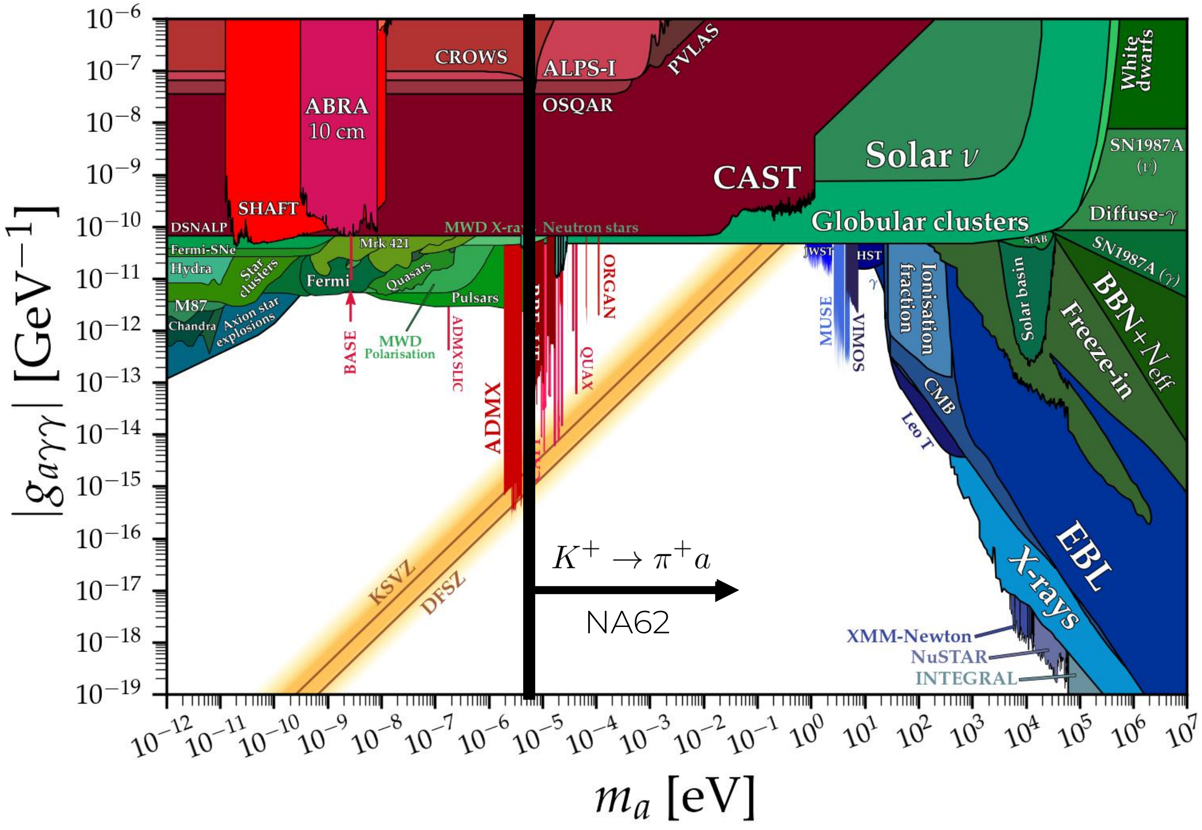
Benchmark DFSZ model has stable domain walls

- Excludes post-inflationary scenario in minimal model

Can be solved if PQ charges of quarks are *flavour-dependent*

Leads to flavour violation, e.g. $K^+ \to \pi^+ a$

$$f_a > 8.3 \times 10^{11} |C^V_{sd}| \,\mathrm{GeV}$$



★ See Maaz Hayat's poster

Summary

Very diverse range of theory activity within the Centre, from axions to WIMPs and beyond…

- Nuclear structure for DM – *talk by Raghda Abdel Khaleq*
- Migdal effect & H-doping – *talk by Alex Ritter*
- BBN bounds on light DM – *talk by Josh Wood*
- Dark photons – *talk by Nicholas Hunt-Smith*
- Stellar constraints – *talk by Fred Hiskens*