DARK MATTER COMPLEMENTARITY: A CASE STUDY

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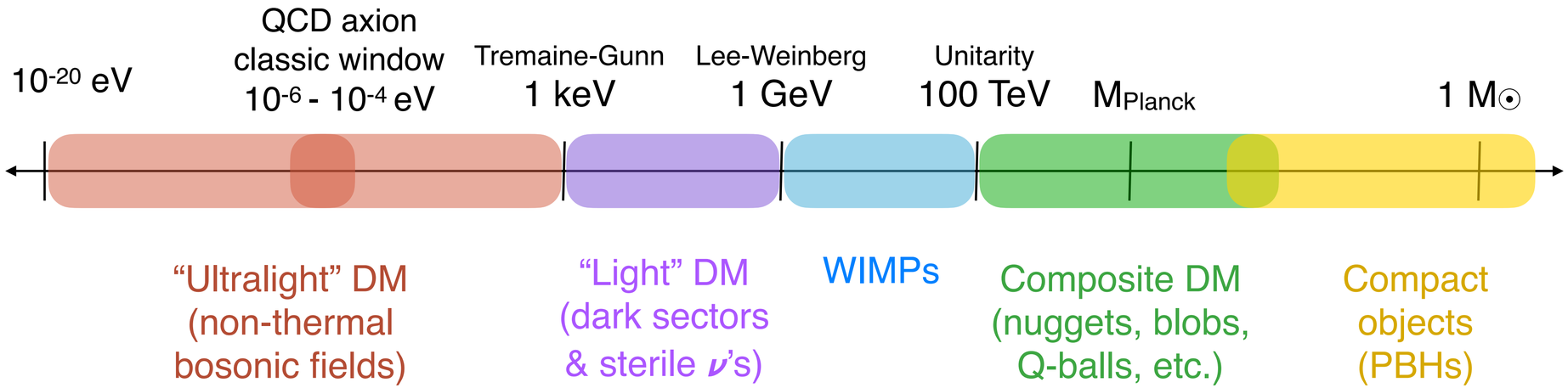
Canada Research Chair in Astrophysics beyond the Standard Model
Xmas 2023 @ IFT

WHAT IS THE DARK MATTER?

DARK MATTER MASS

(not to scale)

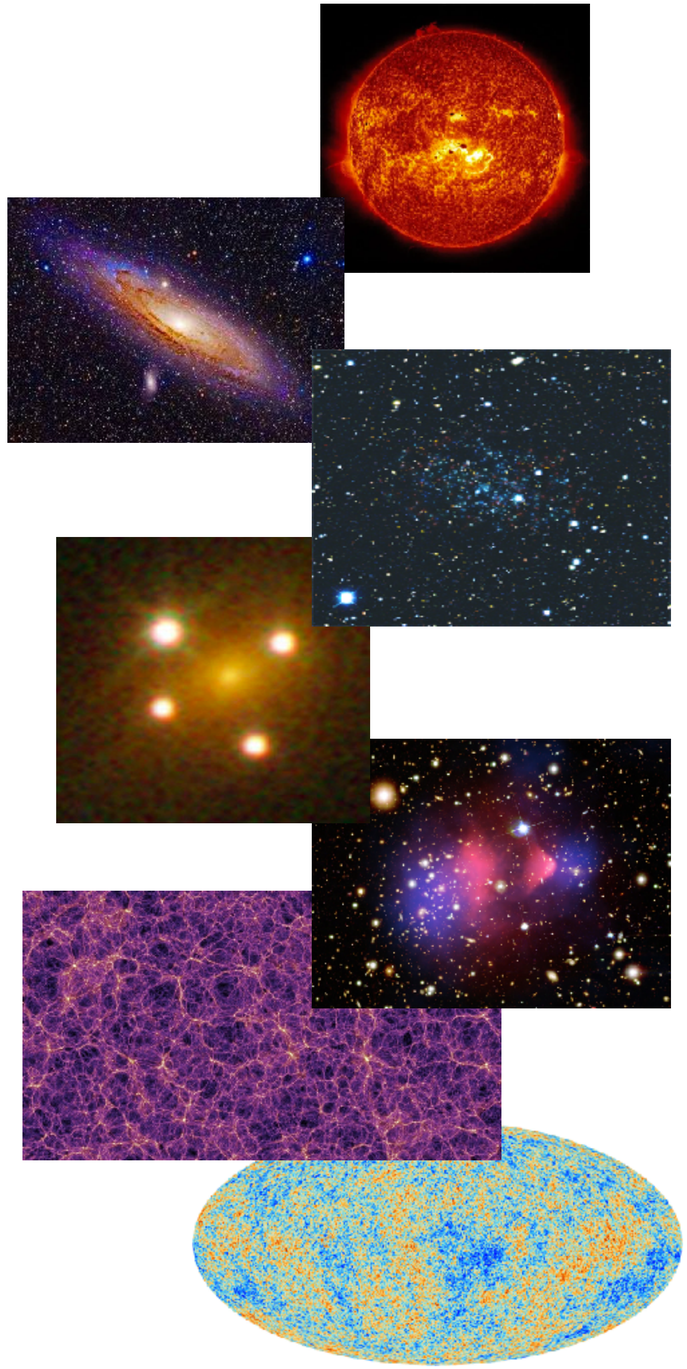


➤ Many possibilities spanning 90+ orders of magnitude!

A DIVERSITY OF THEORIES REQUIRES THAT WE EXPLORE A DIVERSITY OF APPROACHES AND SYSTEMS!

APPROACH/PHILOSOPHY

- Use any/all available astrophysical systems that can tell us about dark matter
- 20 orders of magnitude in length and 18 orders of magnitude in time
- Consider this information in a holistic, self-consistent way (“complementarity” of different probes)



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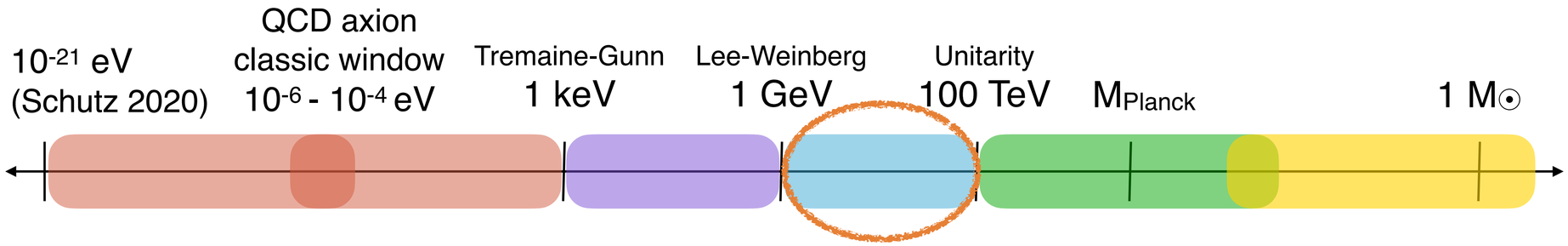


"Ultralight" DM (non-thermal bosonic fields)

"Light" DM (dark sectors & sterile ν's)

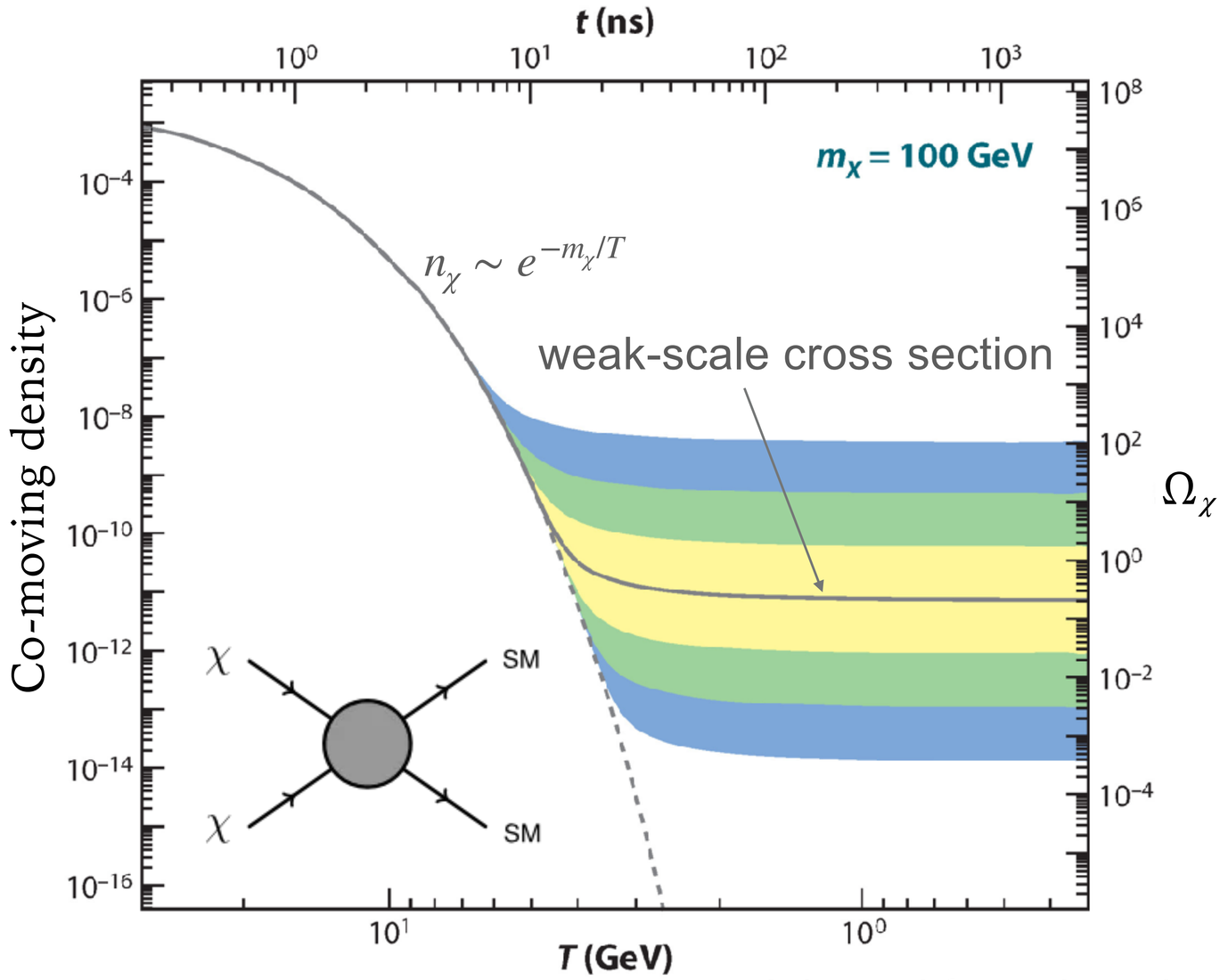
WIMPs

Composite DM (nuggets, blobs, Q-balls, etc.)

Compact objects (PBHs)

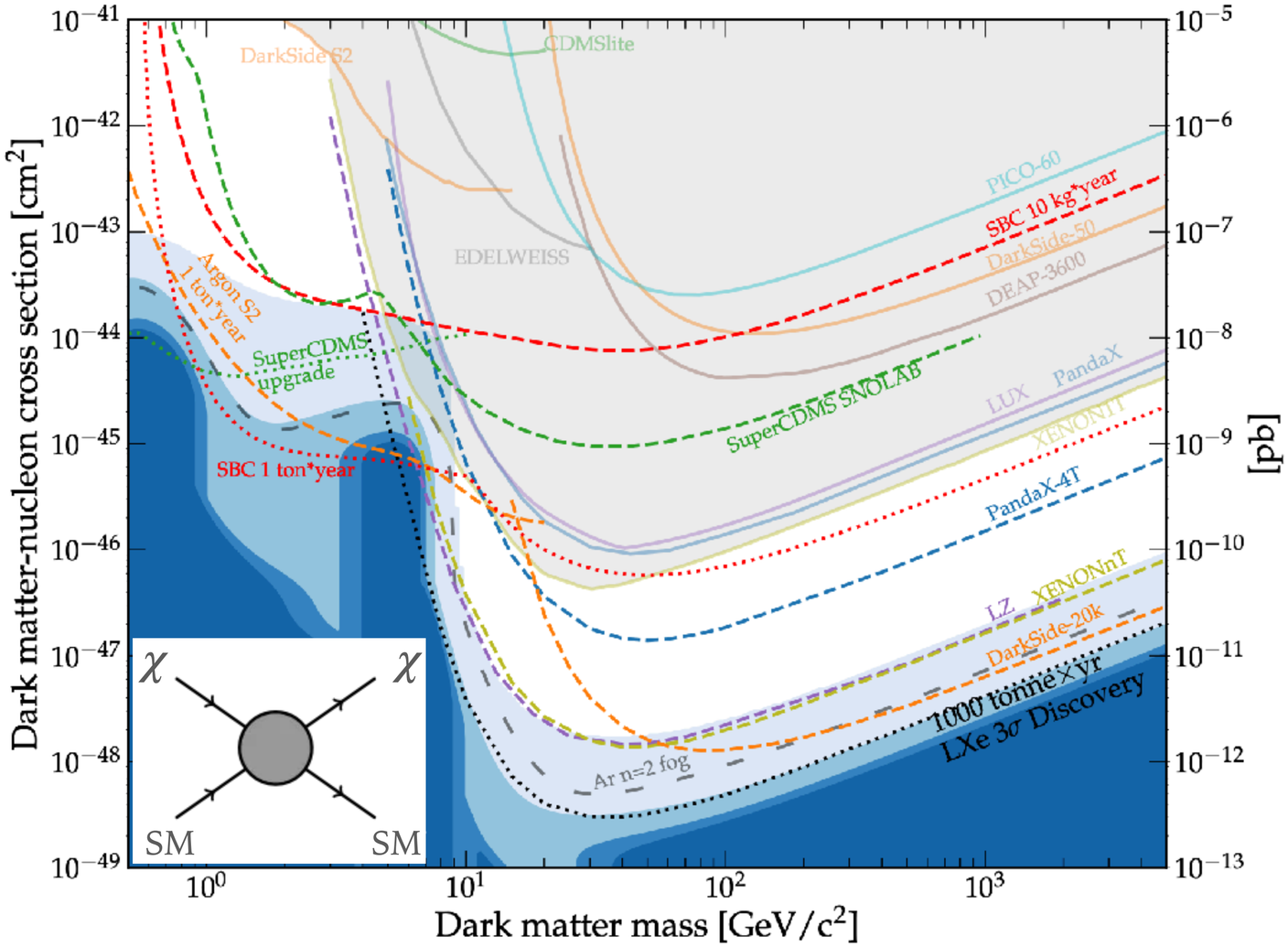
What is the status? (Already a need for complementarity)

THERMAL DARK MATTER CANDIDATE: WIMPS (FREEZE-OUT)



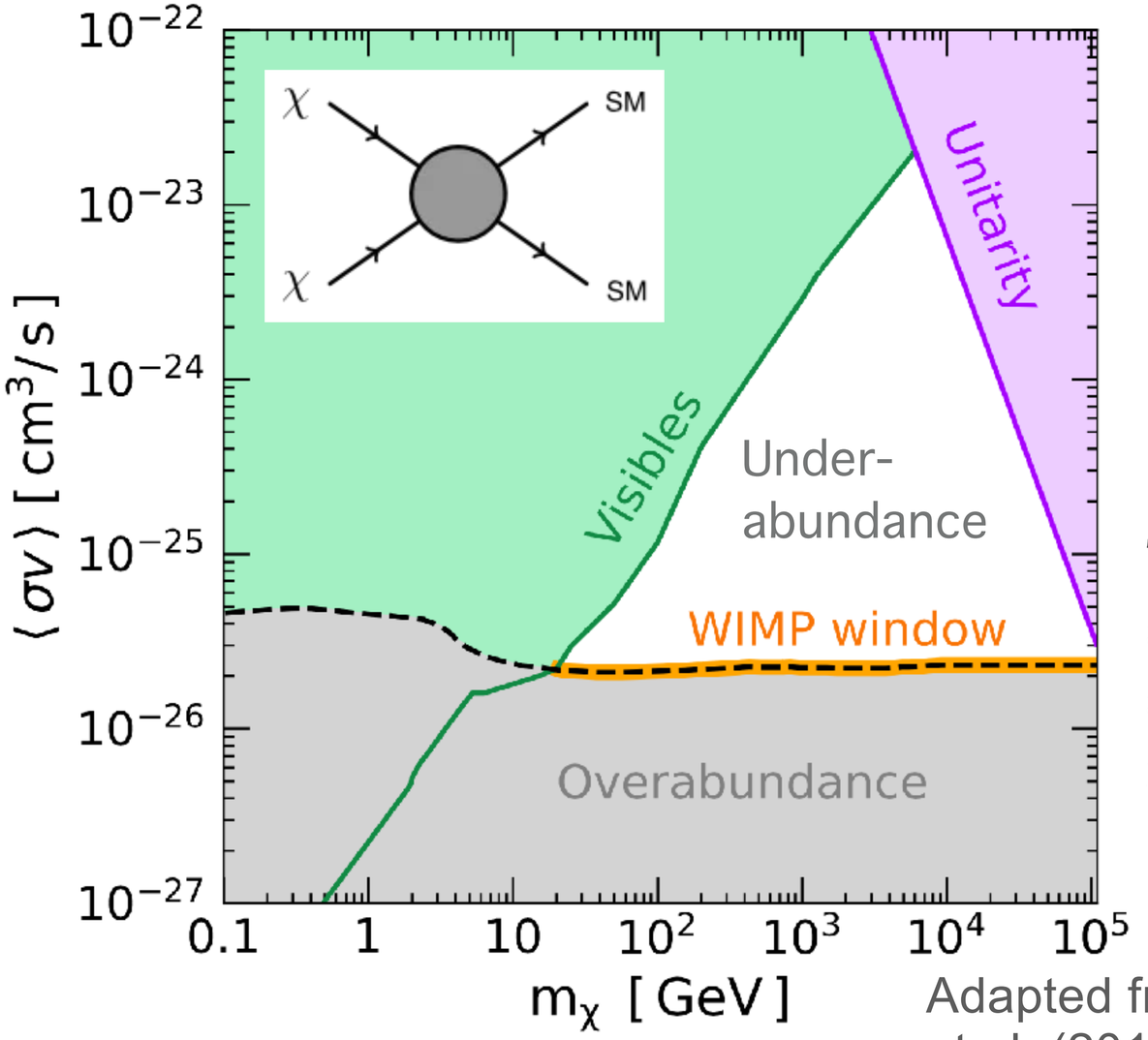
Adapted from Jonathan Feng

WIMP DIRECT DETECTION (MODEL DEPENDENT)



Akerib et al. Snowmass 2021 report

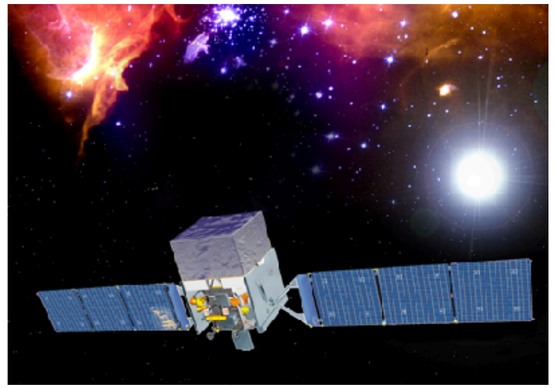
WIMP (THERMAL FREEZE-OUT) INDIRECT DETECTION WINDOW



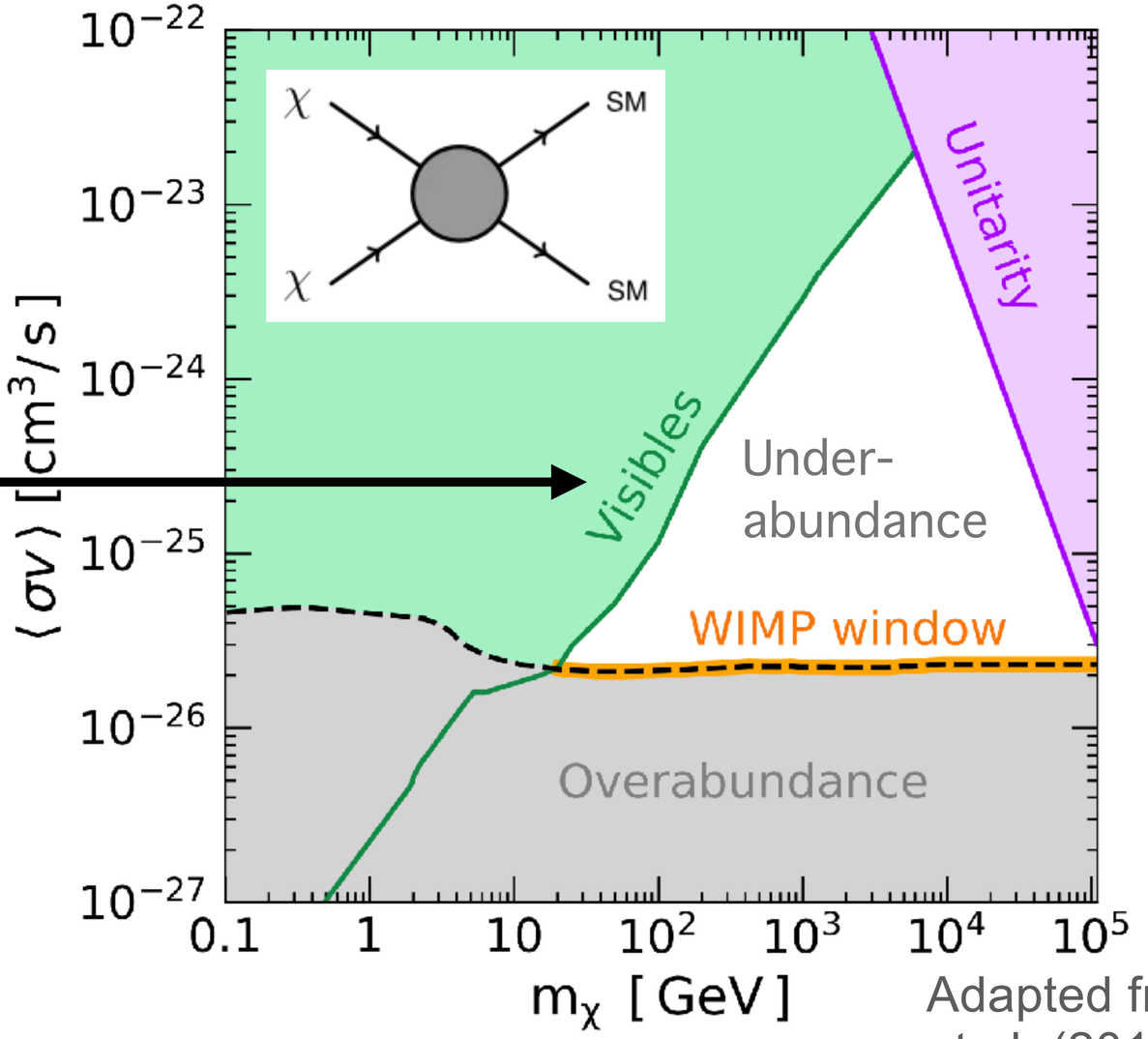
Thermal target assuming s-wave annihilation (velocity independent)

Adapted from Leane et al. (2018)

WIMP (THERMAL FREEZE-OUT) INDIRECT DETECTION WINDOW



Visible byproducts cascade and can be observed in gamma rays with Fermi



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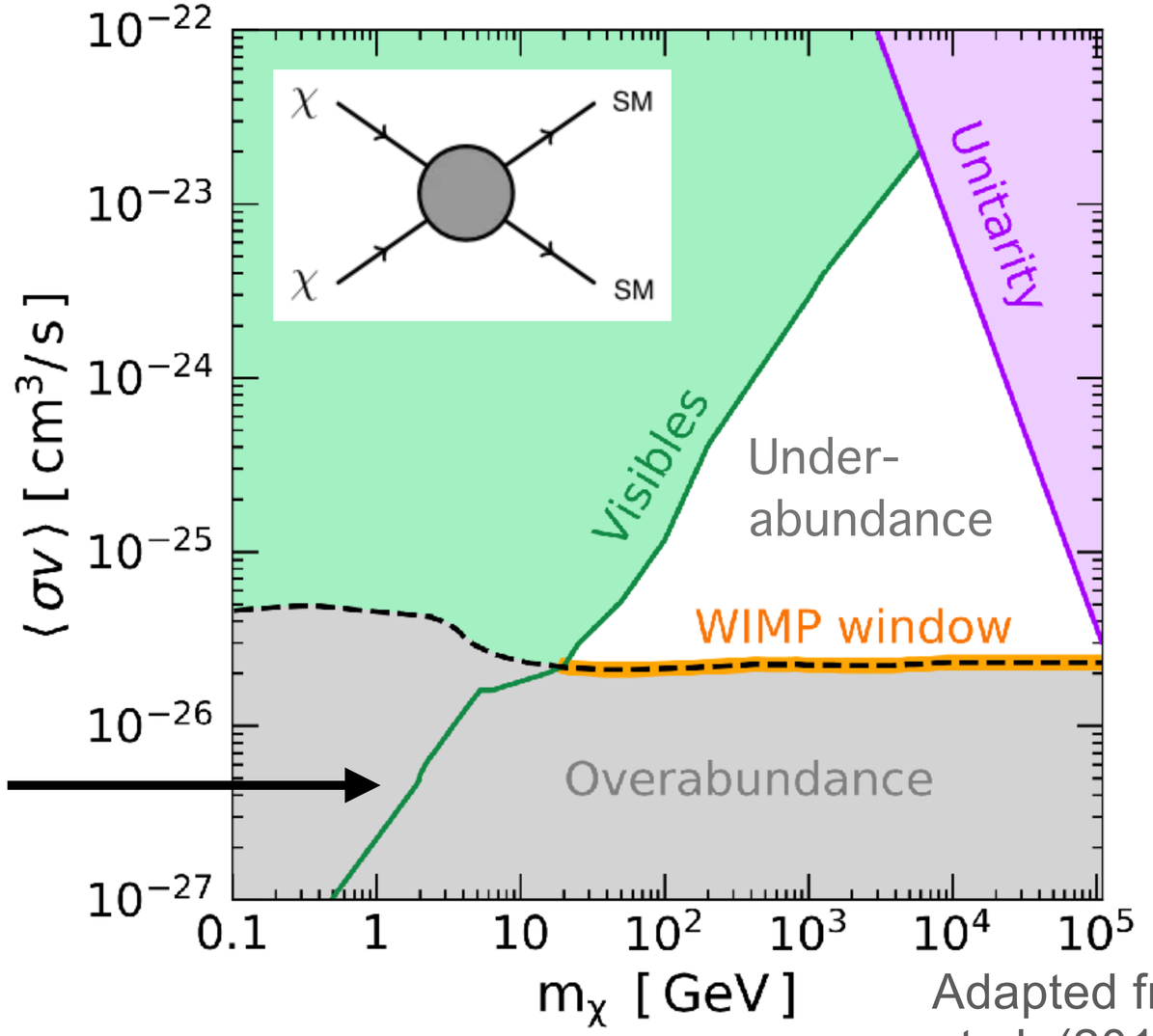
WIMP (THERMAL FREEZE-OUT) INDIRECT DETECTION WINDOW

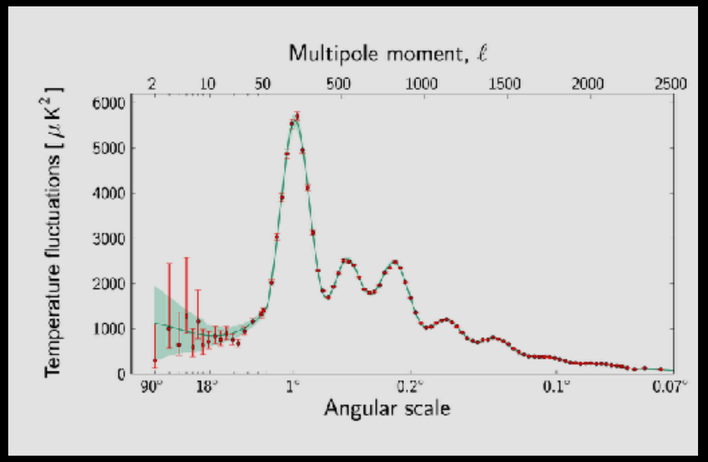
Low-mass bounds are driven by CMB constraint assuming s-wave cross section



Adapted from Leane et al. (2018)

Too hot for atoms to form (plasma)
Not transparent

Cool enough for atoms to exist
Transparent



Us looking far away/back in time

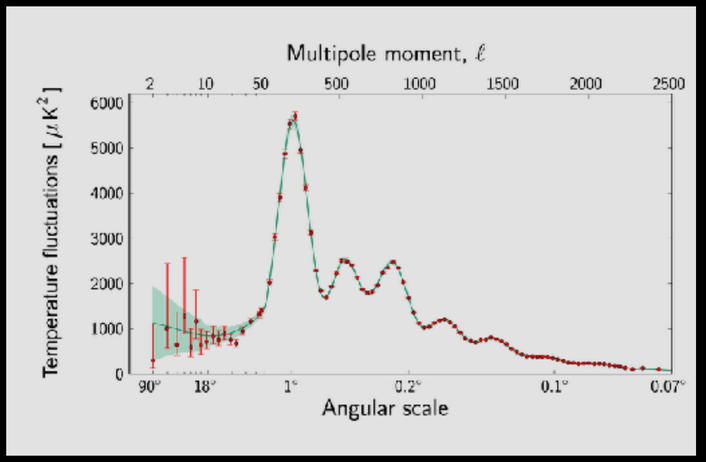
time

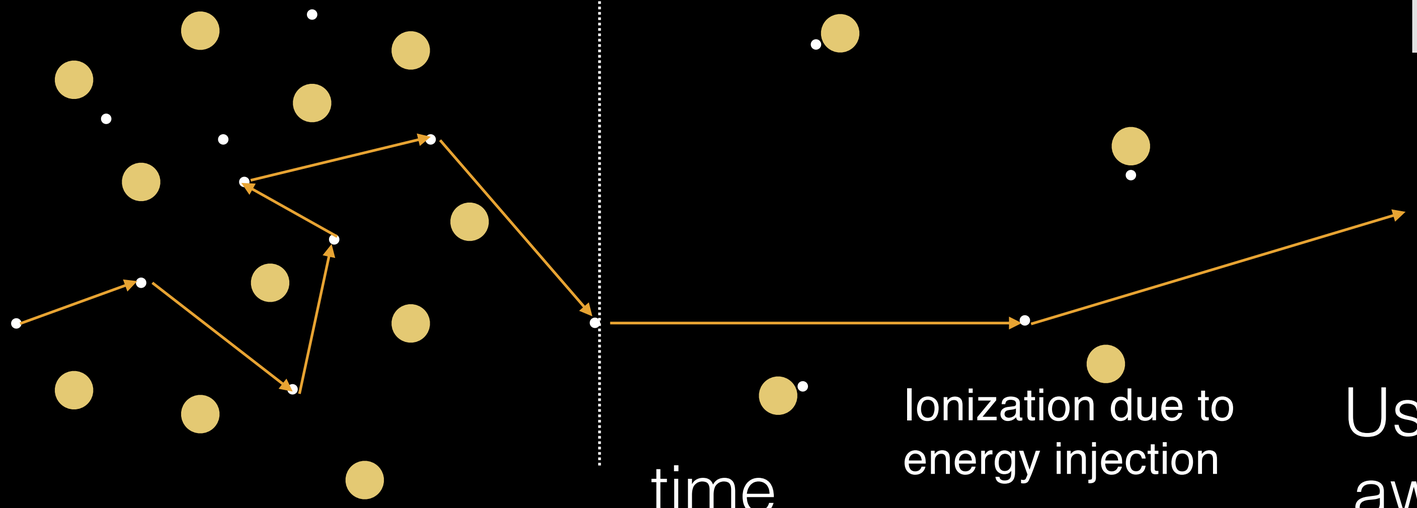
Smaller
Denser
Hotter

Larger
Less dense
Cooler

Too hot for atoms to form (plasma)
Not transparent

Cool enough for atoms to exist
Transparent





Ionization due to energy injection

Us looking far away/back in time

time

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Denser
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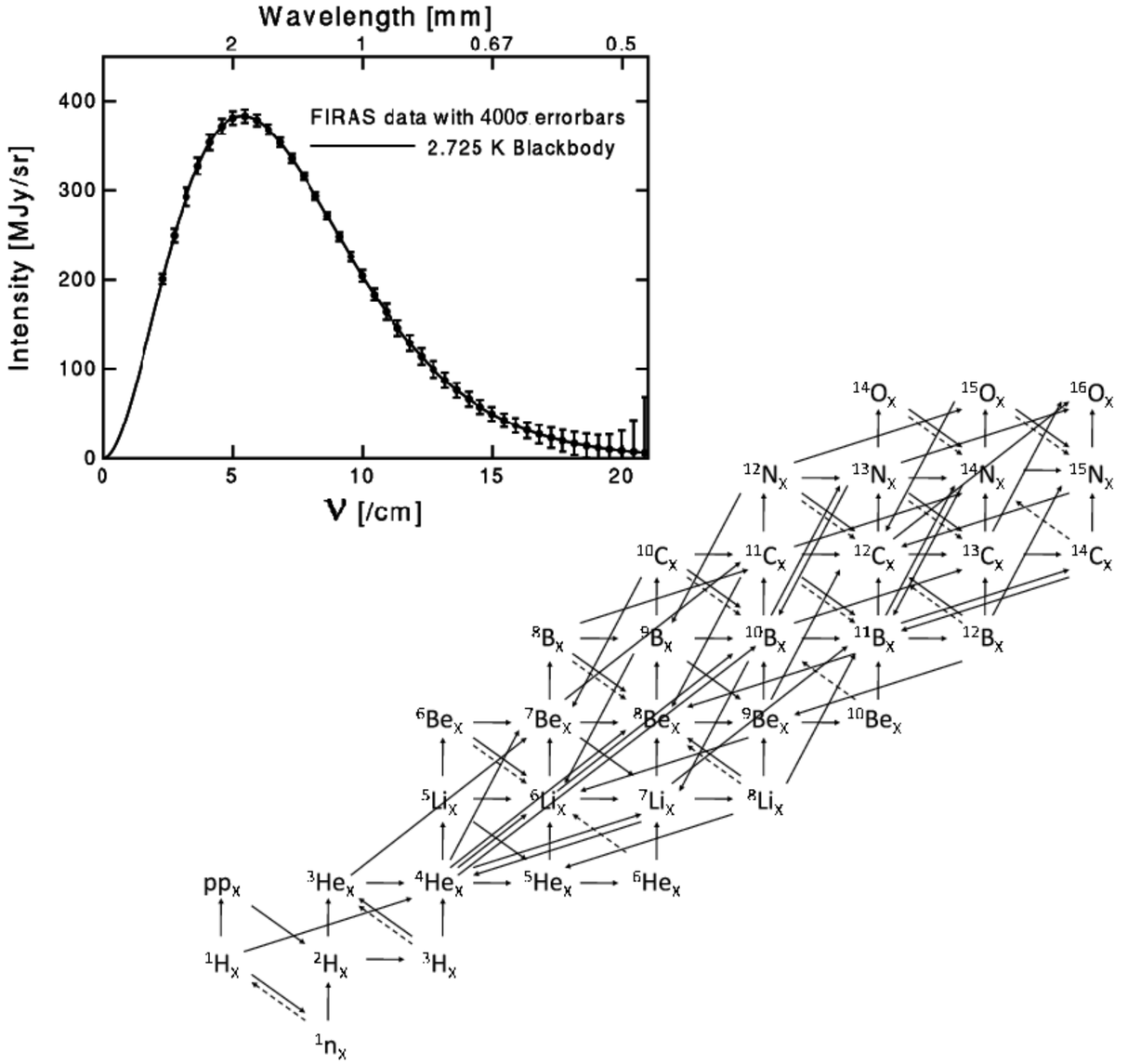
EARLY UNIVERSE IS EXTREMELY SENSITIVE TO ENERGY INJECTION

- If one part per billion of the dark matter annihilates, that would ionize whole universe post-recombination
- Before recombination, energy injection would cause CMB spectrum to deviate from blackbody measured by FIRAS at ppm level
- Big Bang Nucleosynthesis also is very sensitive to energy injection which causes photodissociation of light elements, messes up flow chart of nuclear processes



THE UPSHOT: YOU CAN ESSENTIALLY TREAT THE UNIVERSE AS A CALORIMETER, SO DARK MATTER CAN'T BE A WIMP* BELOW ~10 GEV

*UNLESS ANNIHILATION IS STRONGLY VELOCITY DEPENDENT

LEE-WEINBERG BOUND

- For dark matter masses above mass scale of mediators (~100 GeV if they are electroweak)

$$\sigma \sim \frac{\alpha^2}{m_\chi}$$

- Below mediator mass scale,

$$\sigma \sim \frac{\alpha^2 m_\chi^2}{m_V^4}$$

which saturates perturbative cross section needed for relic dark matter density at ~GeV masses if mediator is W or Z, **new mediator is required for sub-GeV thermal dark matter**!

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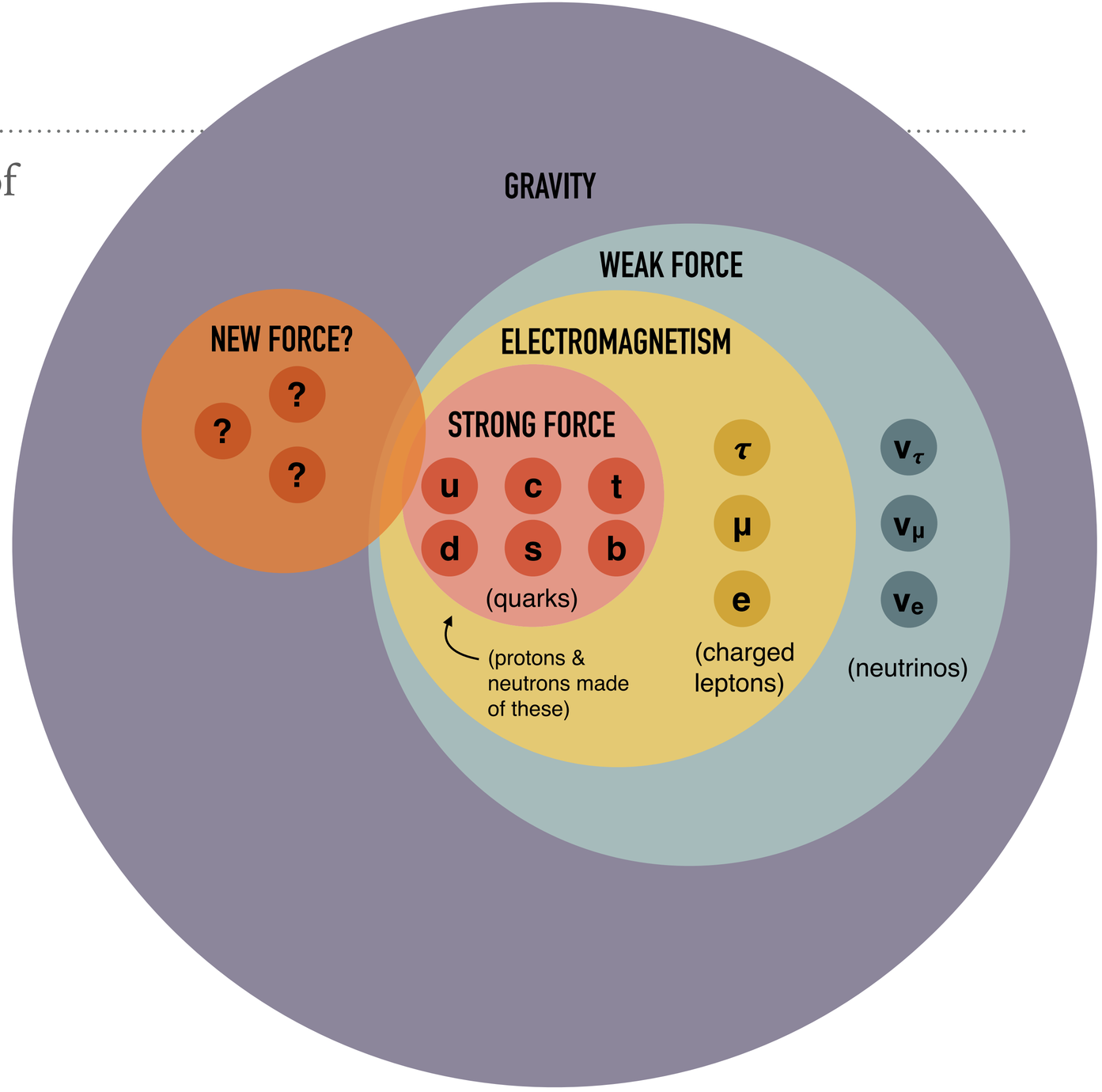
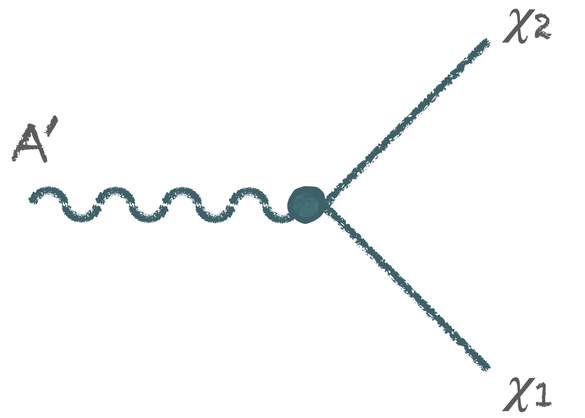


PRESERVING THE SUCCESSES OF FREEZE-OUT AT LOWER DARK MATTER MASSES WITH DARK SECTORS

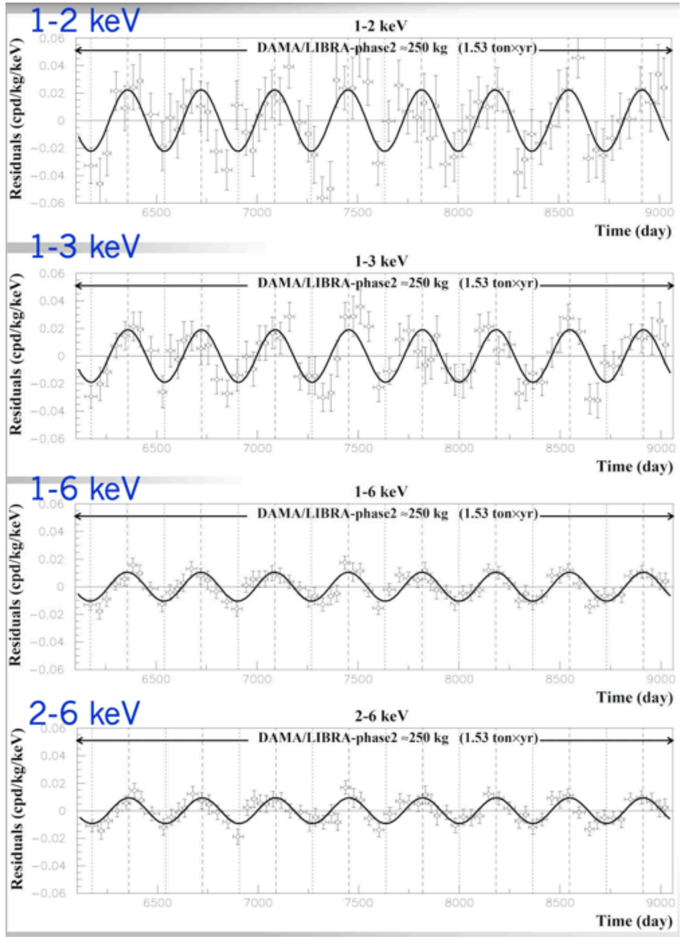
PSEUDO-DIRAC DARK MATTER

- If dark matter is charged under a new gauge group, e.g. dark U(1), with a massive gauge boson (dark photon with mass coming from some symmetry breaking), Dirac dark matter multiplet will naturally split into multiple mass states χ_1 and χ_2 with small Majorana mass splitting $\delta = m_2 - m_1$
- Majorana states don't carry conserved charge and couplings are off-diagonal (i.e. no state appears twice in vertex)
  Arkani-Hamed, Finkbeiner, Slatyer, Weiner "A theory of dark matter" (~2000 citations)

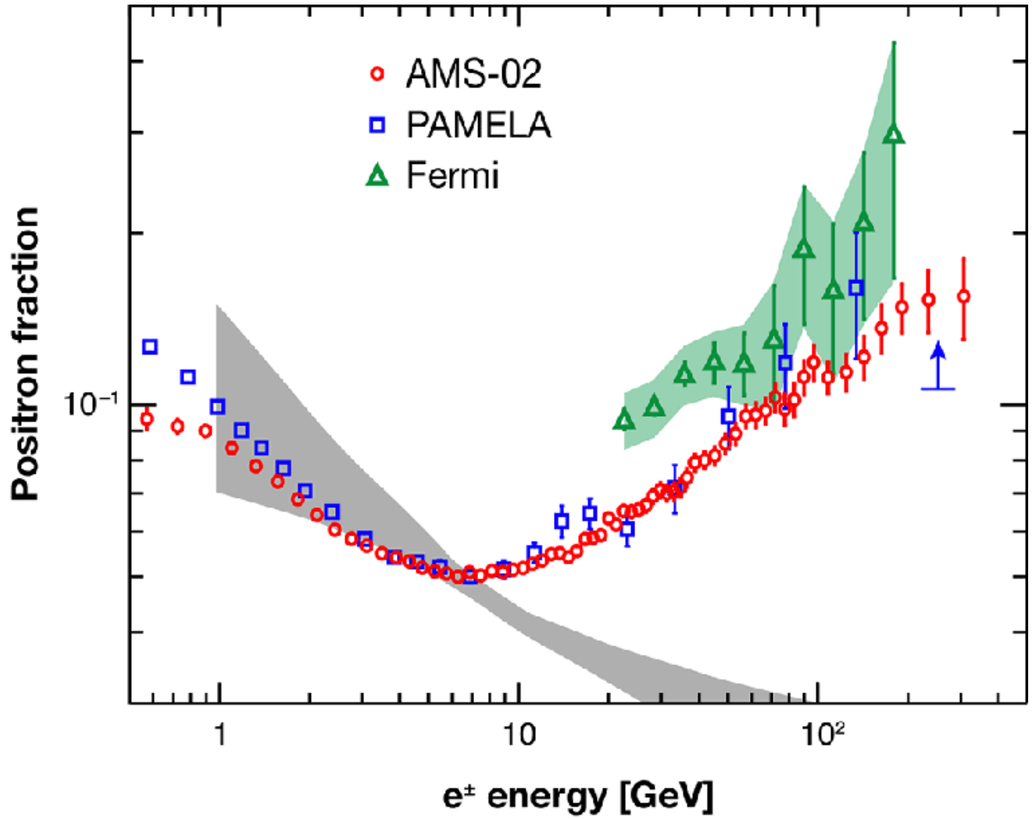
$$\mathscr{L} \supset \frac{\kappa}{2} F'_{\mu\nu} F^{\mu\nu} + i g_\chi A'_\mu \chi_2 \gamma^\mu \chi_1$$



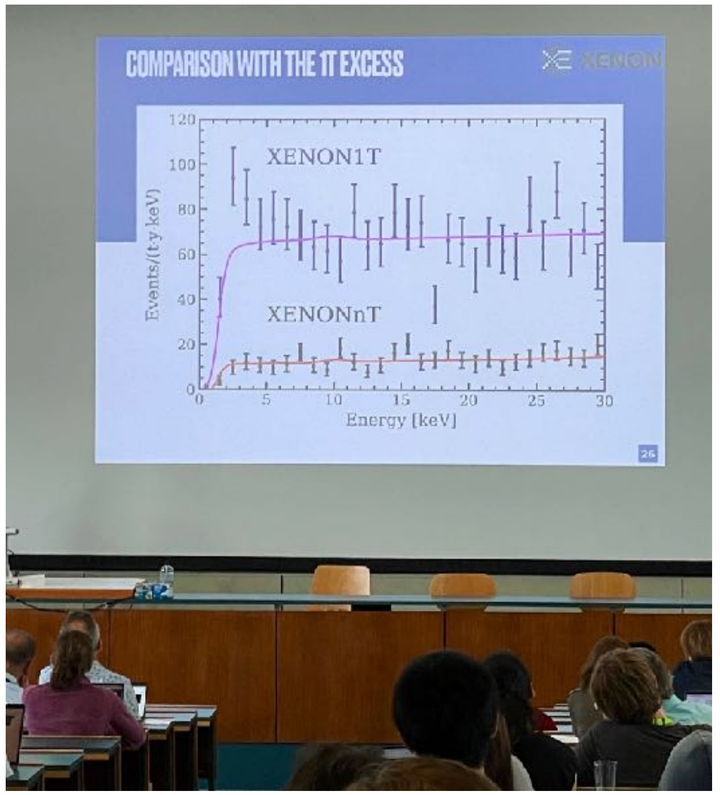
PSEUDO-DIRAC DARK MATTER IS OFTEN INVOKED WHEN THERE ARE ANOMALIES



DAMA/LIBRA annual modulation
e.g. Tucker-Smith & Weiner (2001)
~1000 citations

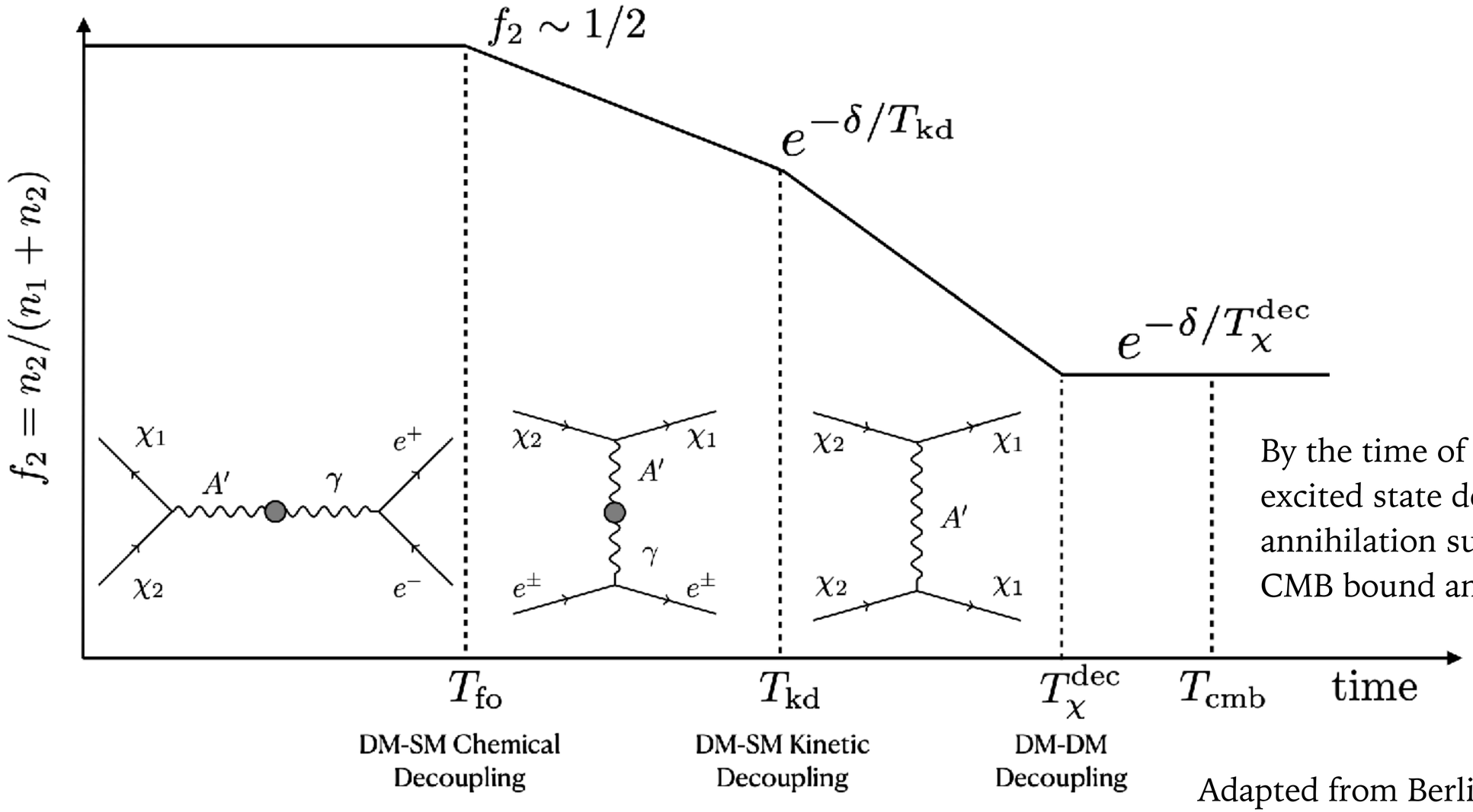


Rising positron fraction at high energies
e.g. Arkani-Hamed et al. (2008)
~2000 citations



XENON1T excess (photo I took at IDM during XENONnT talk)
e.g. Baryakhtar et al. (2020)
An et al. (2020)
~100 citations

FREEZE-OUT OF PSEUDO-DIRAC DARK MATTER



By the time of recombination, excited state depleted so annihilation suppressed— no CMB bound anymore!

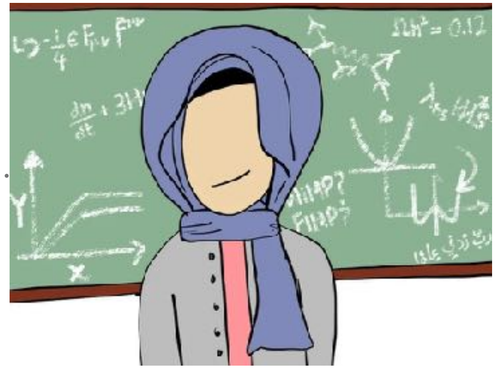
Adapted from Berlin, Krnjaic, Pinetti

HAS THE PARAMETER SPACE FOR THIS WELL-STUDIED MODEL BEEN MAPPED SYSTEMATICALLY?

HAVE OBSERVABLES BEEN TREATED HOLISTICALLY WITH COMPLEMENTARITY IN MIND?

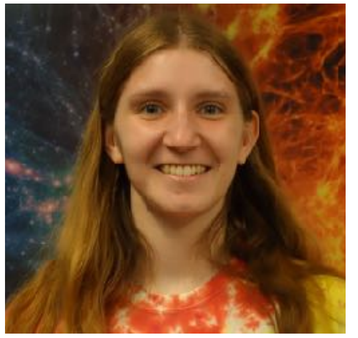
NO! PLAN FOR REST OF TALK

- Discuss a few regions of pseudo-Dirac dark matter parameter space where the thermal history and observables have not been well-characterized:
  - If the mediator is close to twice the dark matter mass, freeze-out is resonant which substantially changes allowed couplings, mass splittings (Brahma, Heeba, **KS** 2308.01960)
  - Dark matter could scatter exothermically/endothermically, altering the structure of small galaxies (O'Neil, Vogelsberger, Heeba, **KS**, et al. MNRAS 2023)
  - If the couplings are very small, freeze-in thermal history is possible and excited state becomes cosmologically metastable, decaying at late times (Heeba, Lin, **KS** PRD 2023)



Dr. Saniya Heeba

Nirmalya Brahma

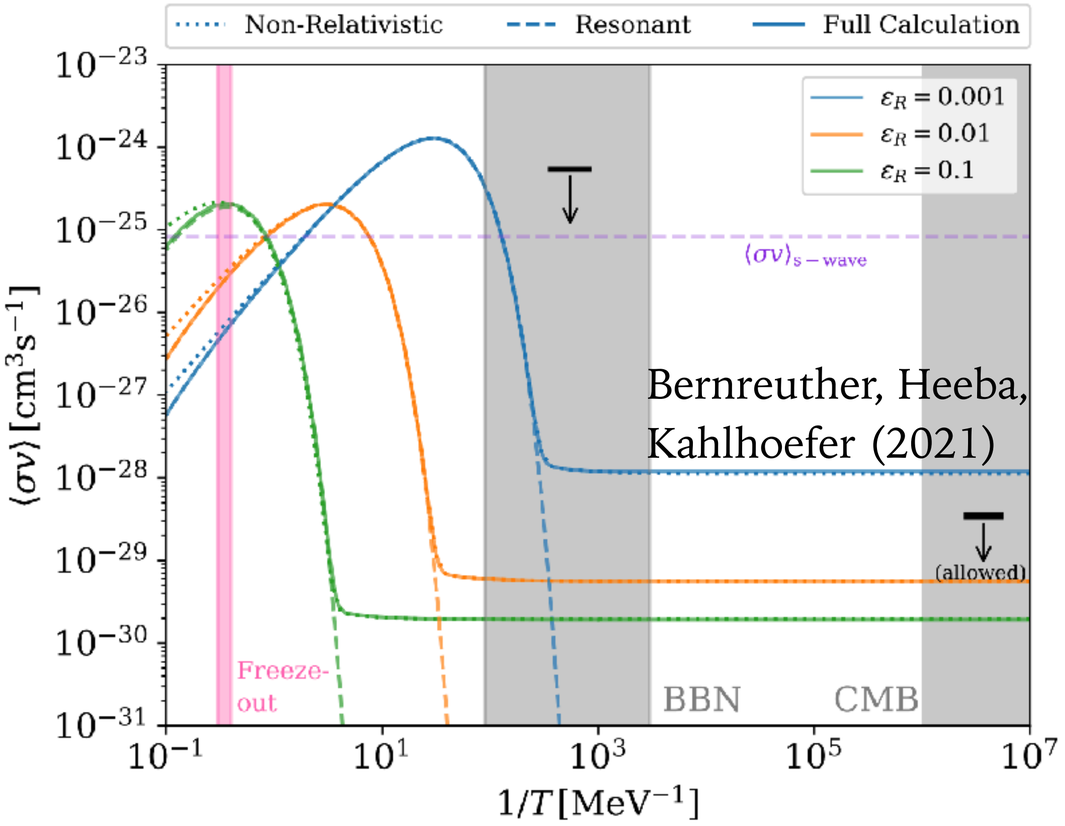


Stephanie O'Neil

RESONANT INELASTIC DARK MATTER

IS IT POSSIBLE TO HAVE SMALL MASS SPLITTINGS CONSISTENT WITH THE CMB?

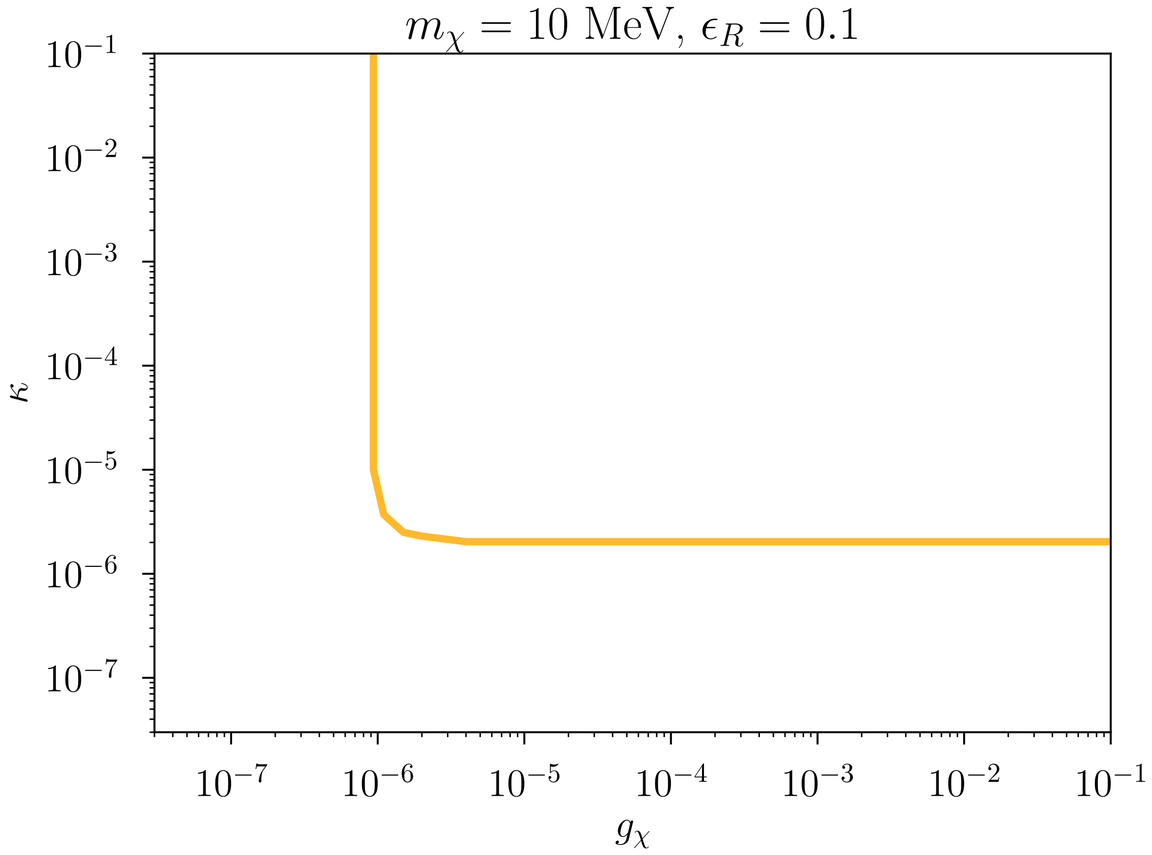
- Usually by the time of recombination, if the mass splitting isn't much bigger than an eV then the excited state won't be very thermally depleted
- If the excited state is around, then small amount of it will annihilate with ground state and mess up the CMB… unless! What if there is a strong velocity dependence to annihilation so it happens a lot during freeze-out but not at late times?
- If mediator is resonant with around twice the mass of the dark matter, a lot of dark matter can be produced on resonance for *very* small couplings so that annihilation is very inefficient off resonance
- But… we can't be too resonant! Otherwise that delays the dark matter annihilation into an era when cosmic calorimetry is relevant

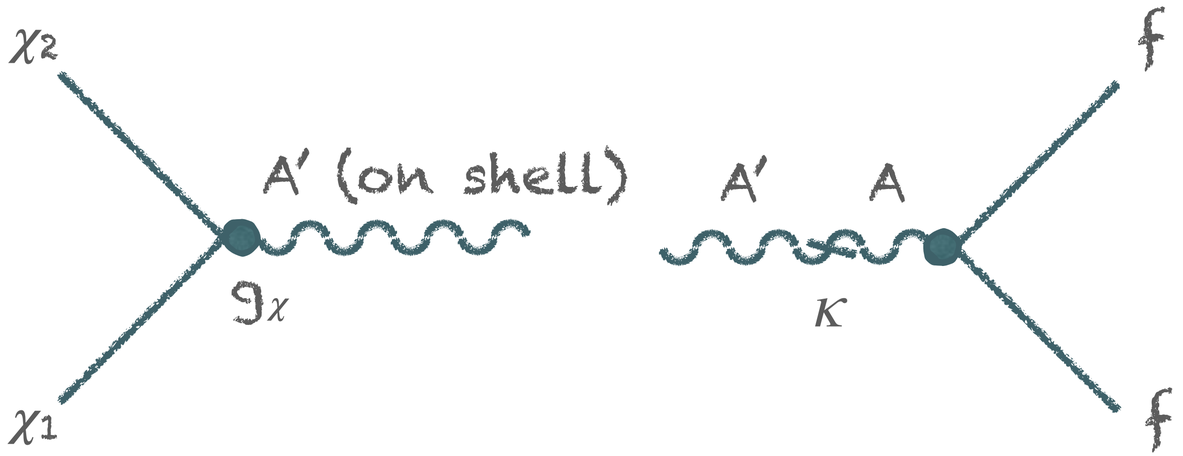


$$\varepsilon_R = \frac{m_{A'}^2 - 4m_\chi^2}{4m_\chi^2} = \frac{m_{A'}^2 - s_{\mathrm{min.}}}{s_{\mathrm{min.}}}$$

Too much fine-tuning is ruled out by cosmology!

PARAMETER SPACE SETTING THE RELIC ABUNDANCE

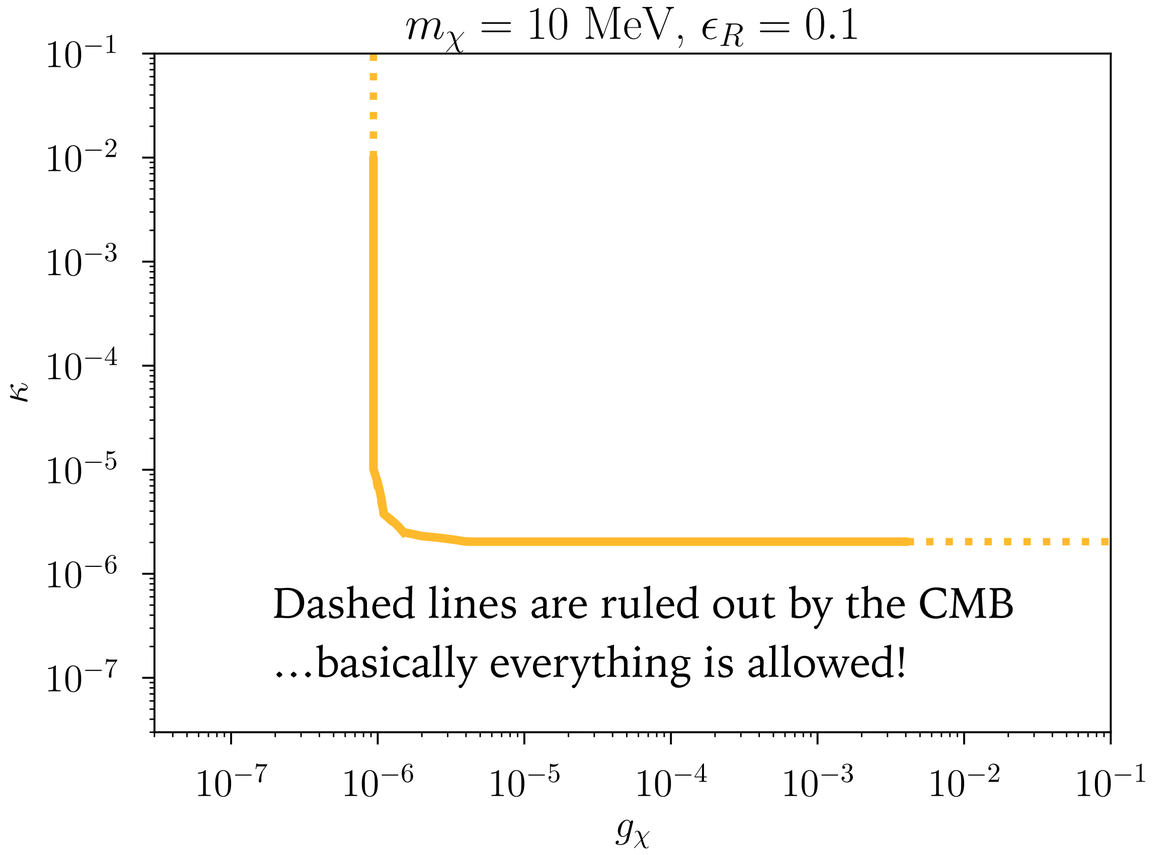


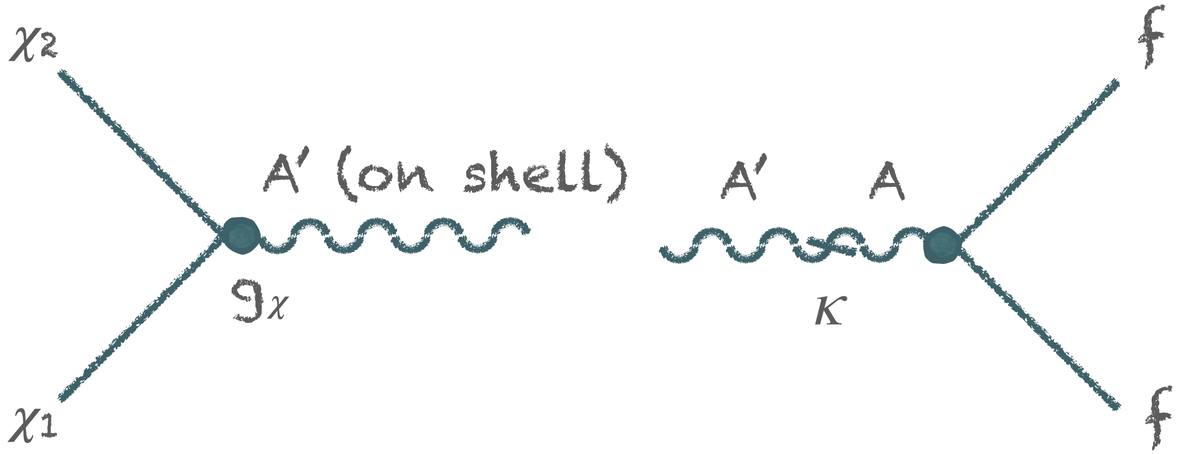


Whichever step is slower controls the rate, so relic abundance only depends on one coupling or the other

Brahma, Heeba, **KS** 2308.01960

PARAMETER SPACE SETTING THE RELIC ABUNDANCE





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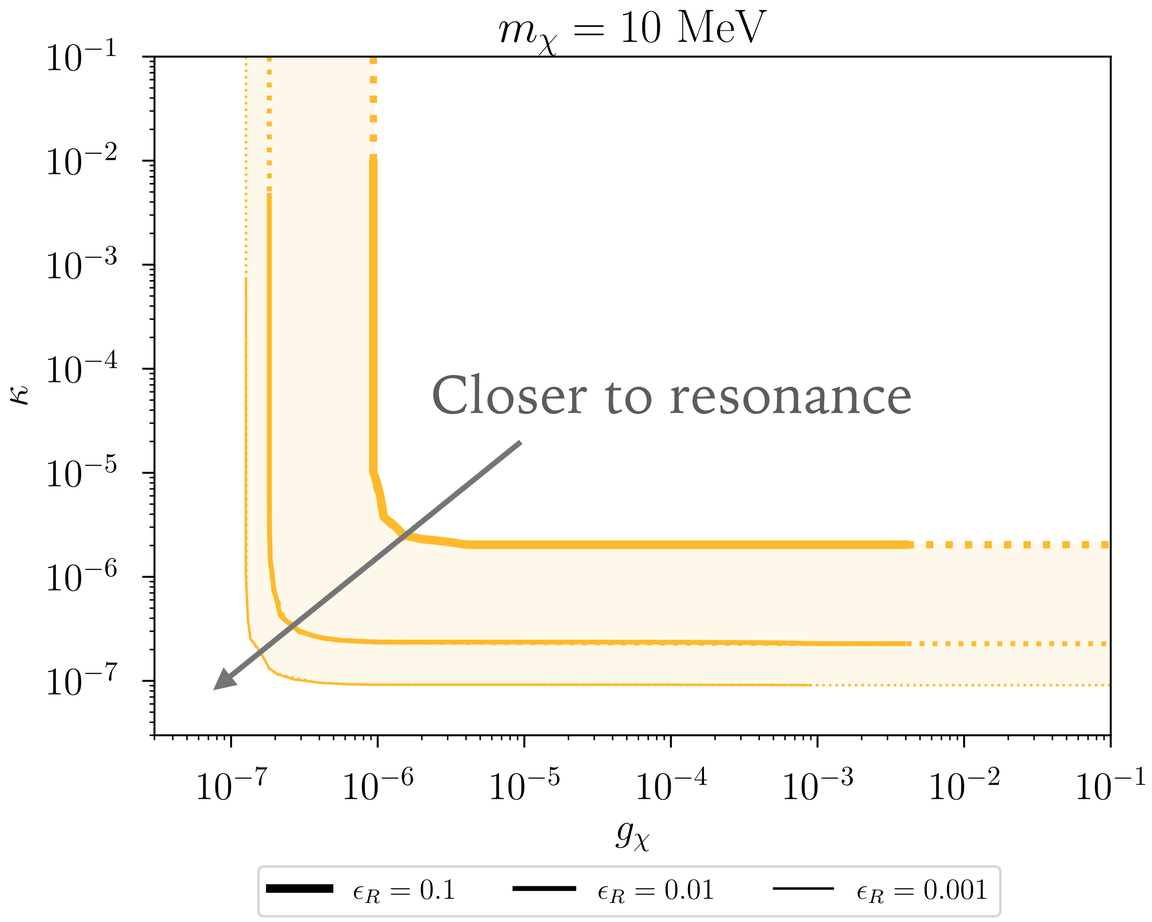

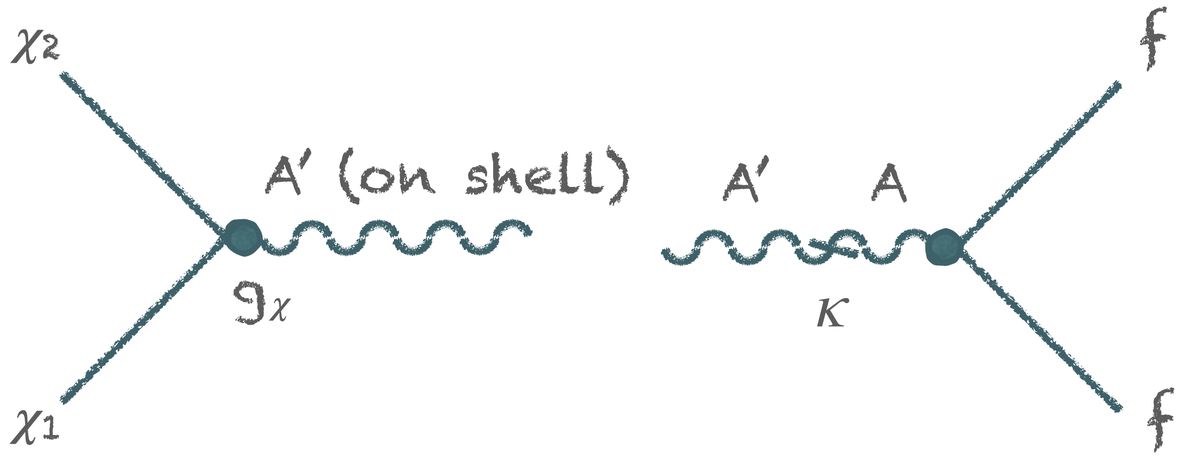

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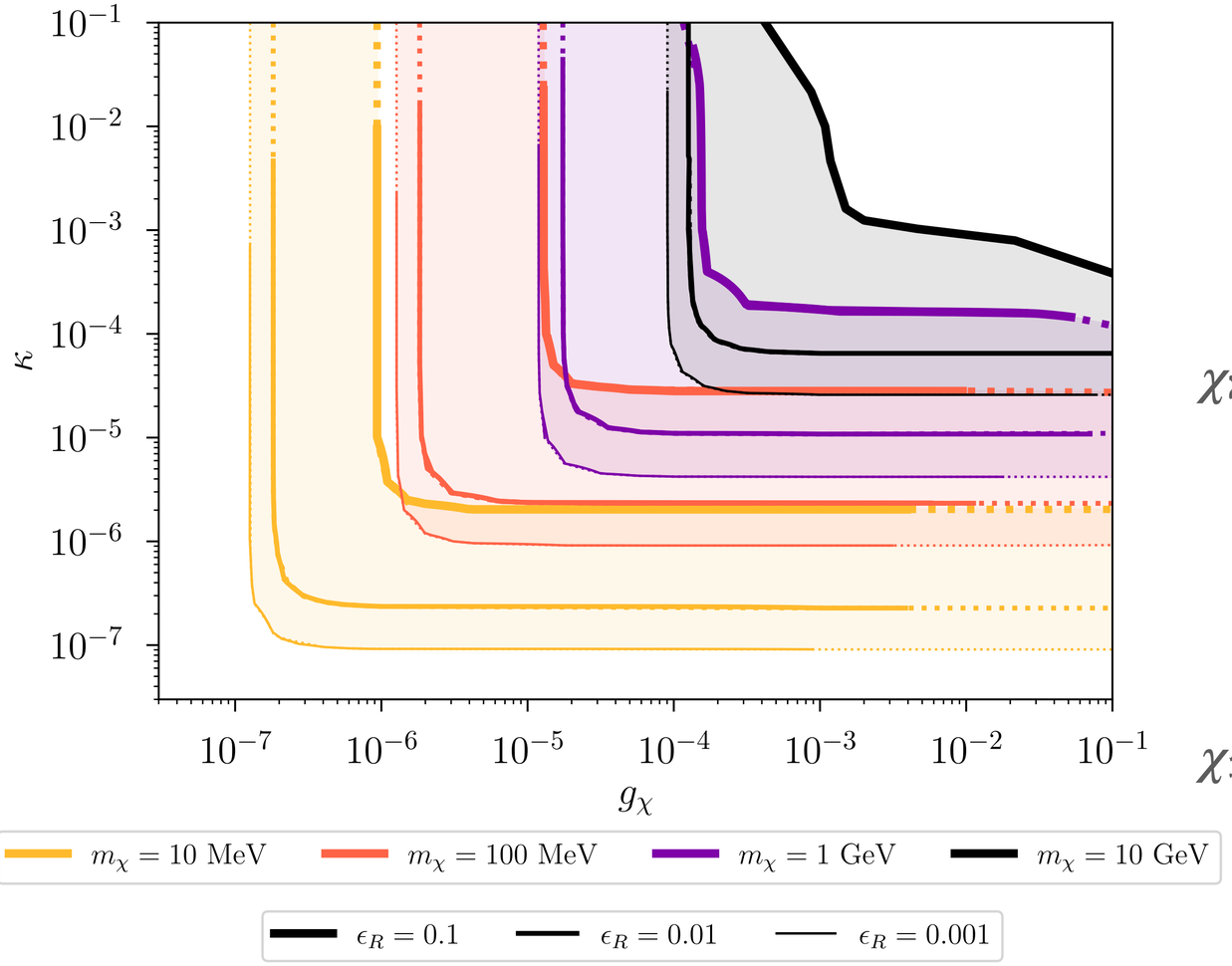

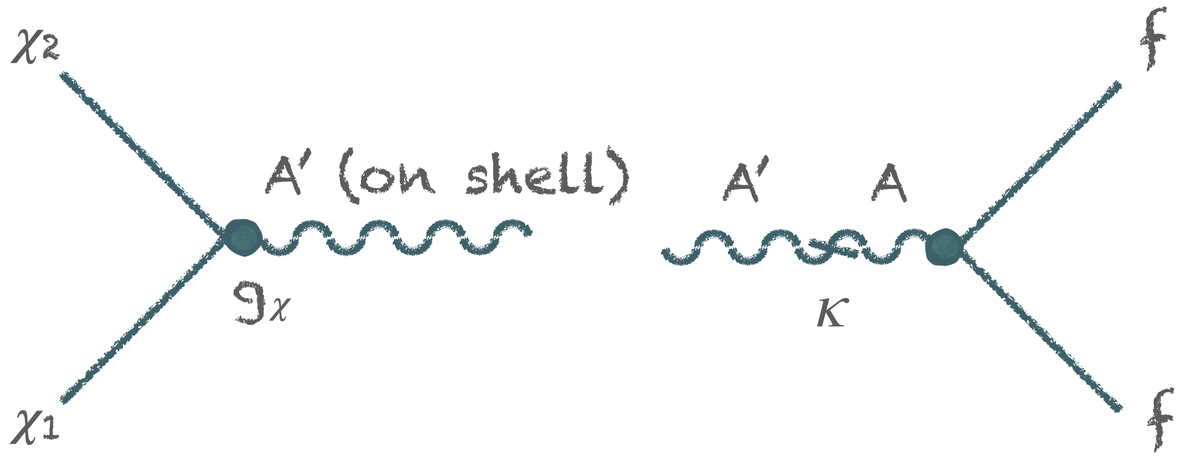

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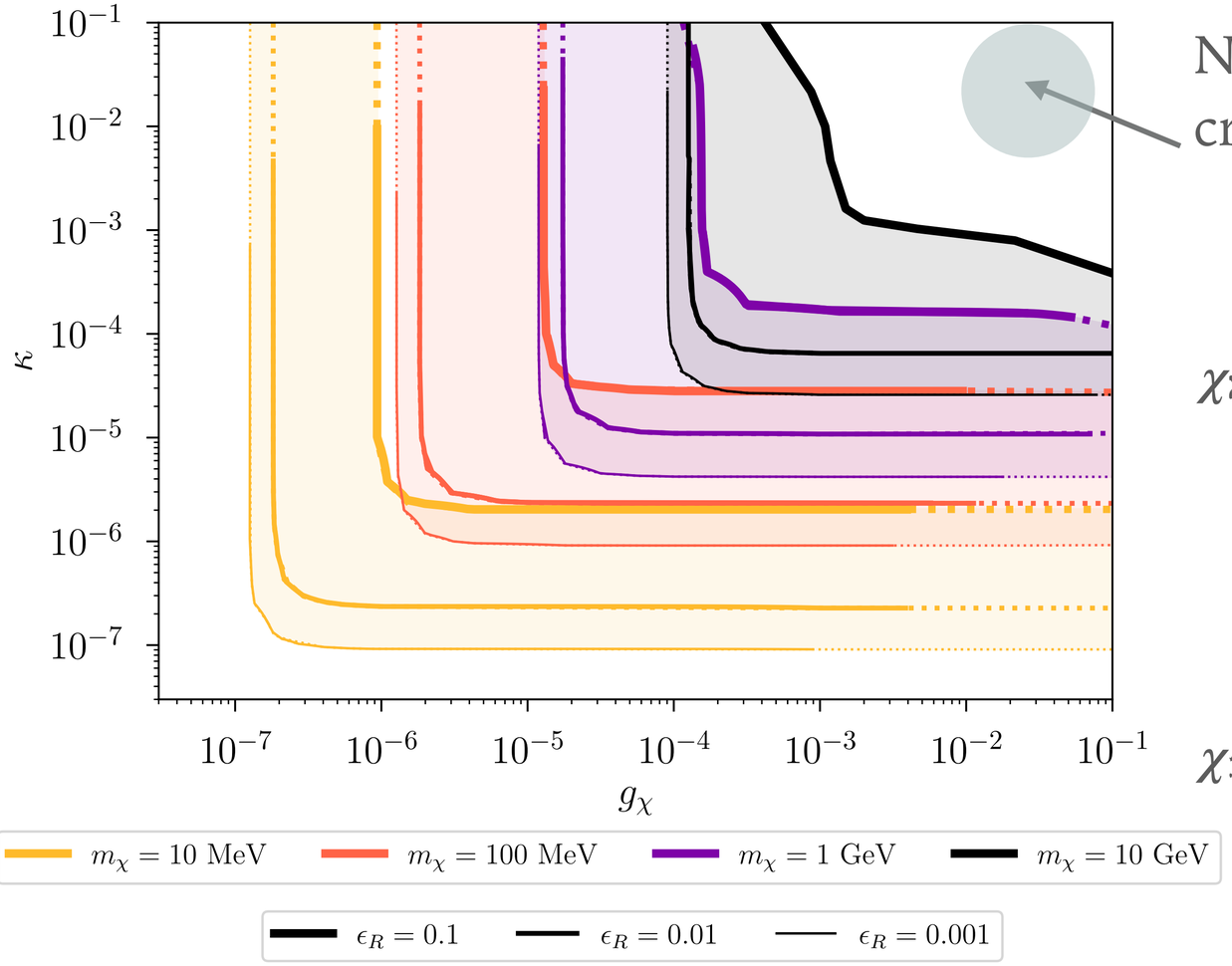
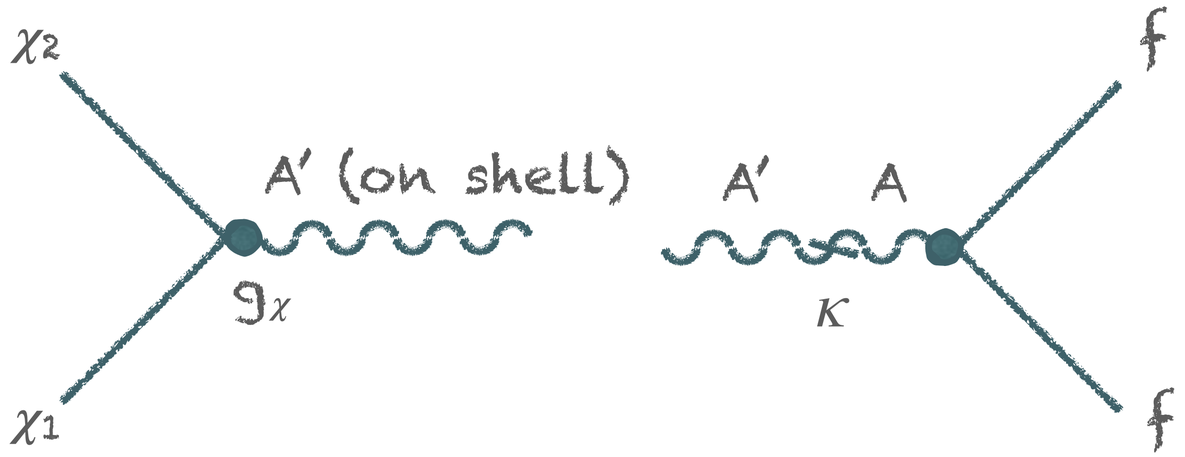


Non-resonant freeze-out cross sections live here



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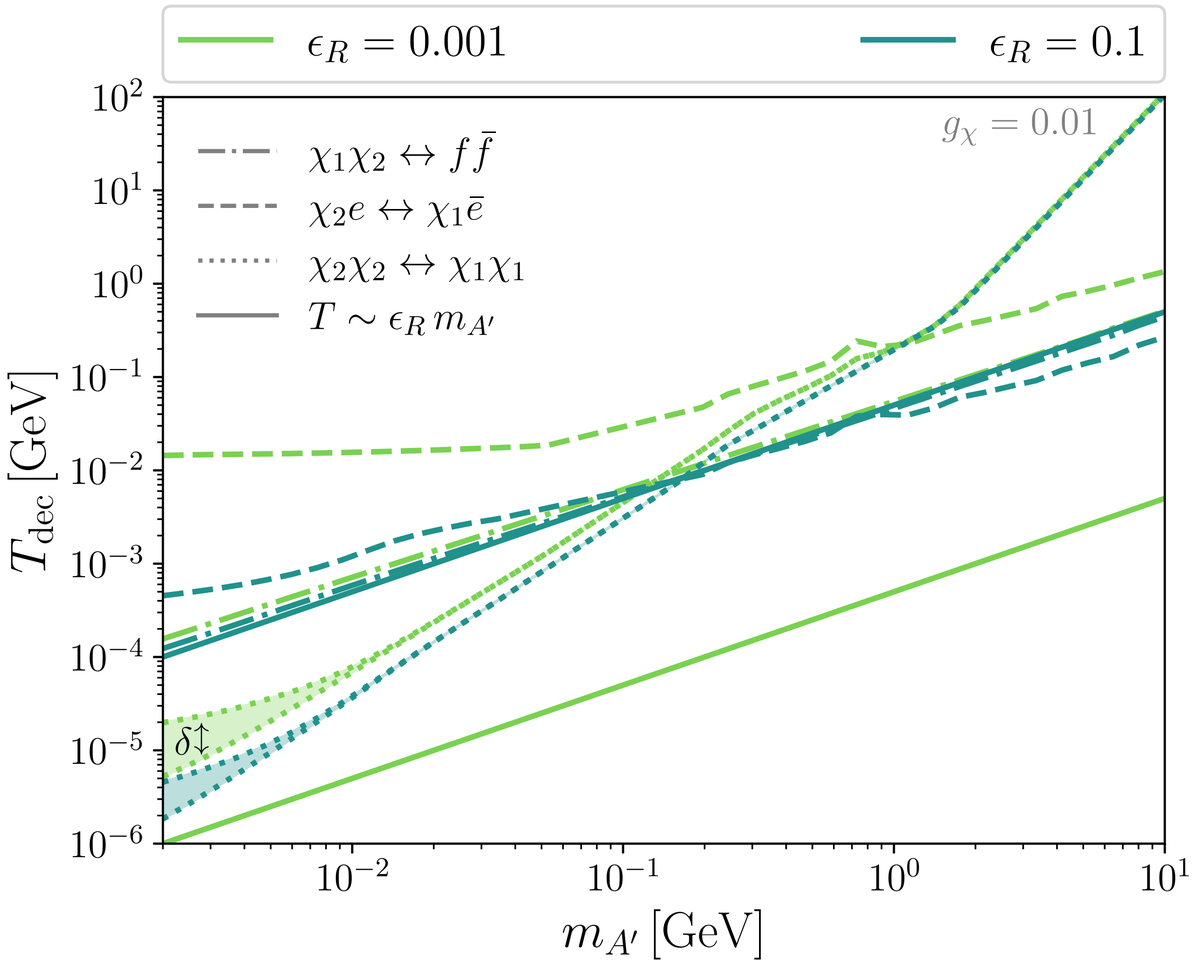
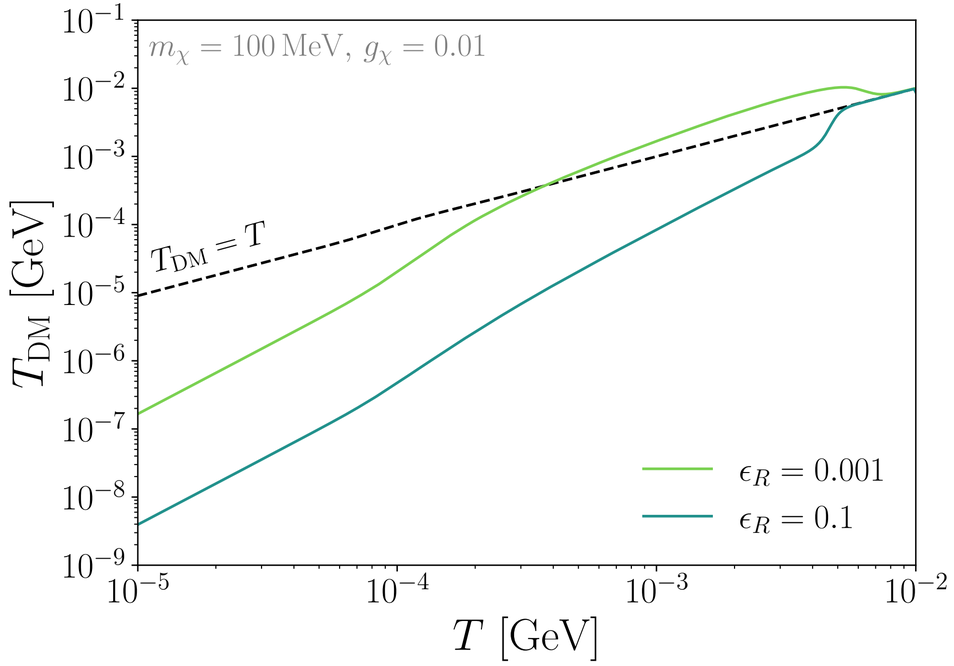
UNUSUAL THERMAL HISTORY FOR RESONANT DARK MATTER



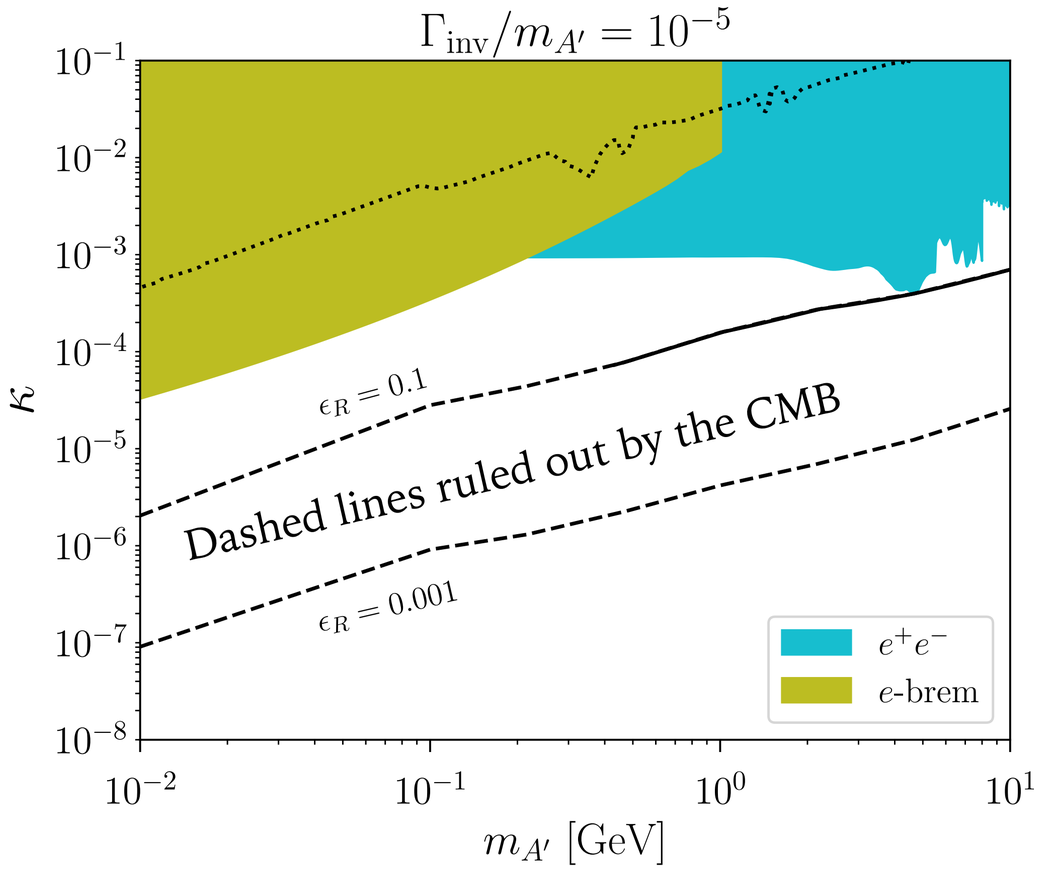
Brahma, Heeba, **KS** 2308.01960

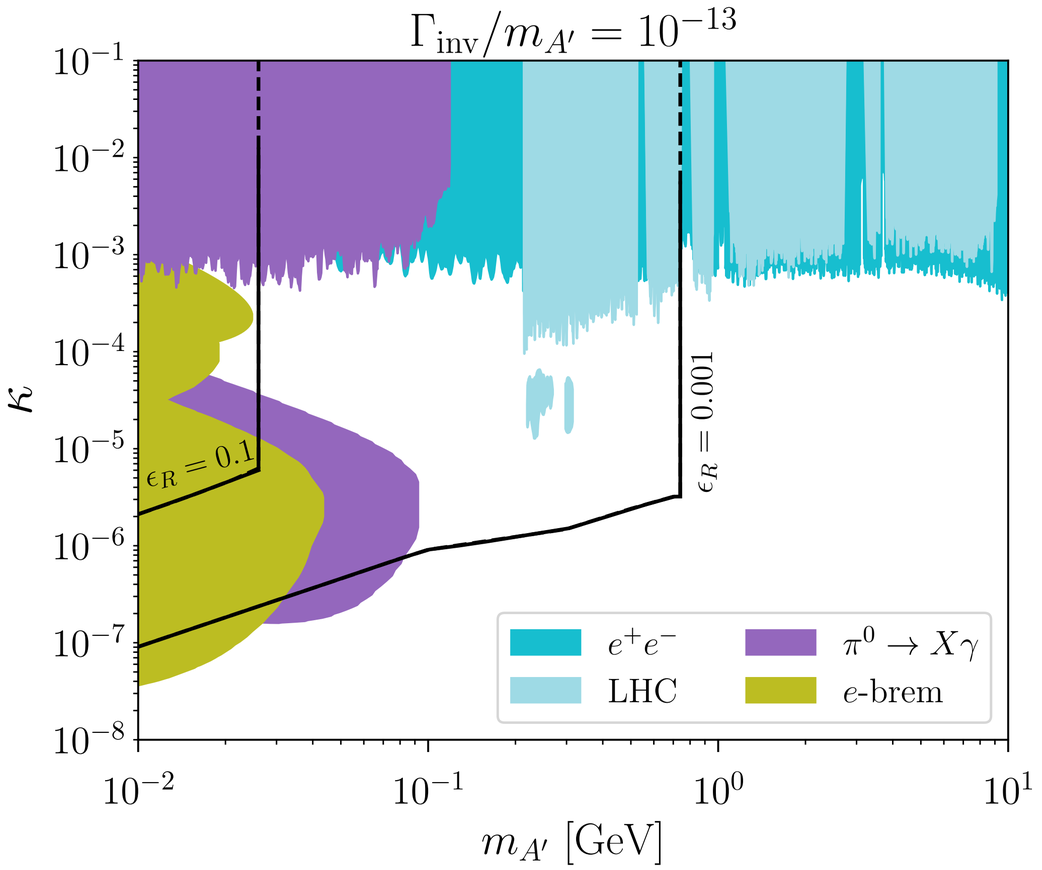


- The couplings can be so tiny that the dark matter kinetically decouples from the SM before it's done annihilating, temperature evolves very differently from SM temperature!
- Have to solve full coupled Boltzmann equations (not just one for dark matter density) to capture full behavior

TERRESTRIAL CONSEQUENCES OF THERMAL HISTORY

Limits computed with DarkCast, Ilten et al. (2018)





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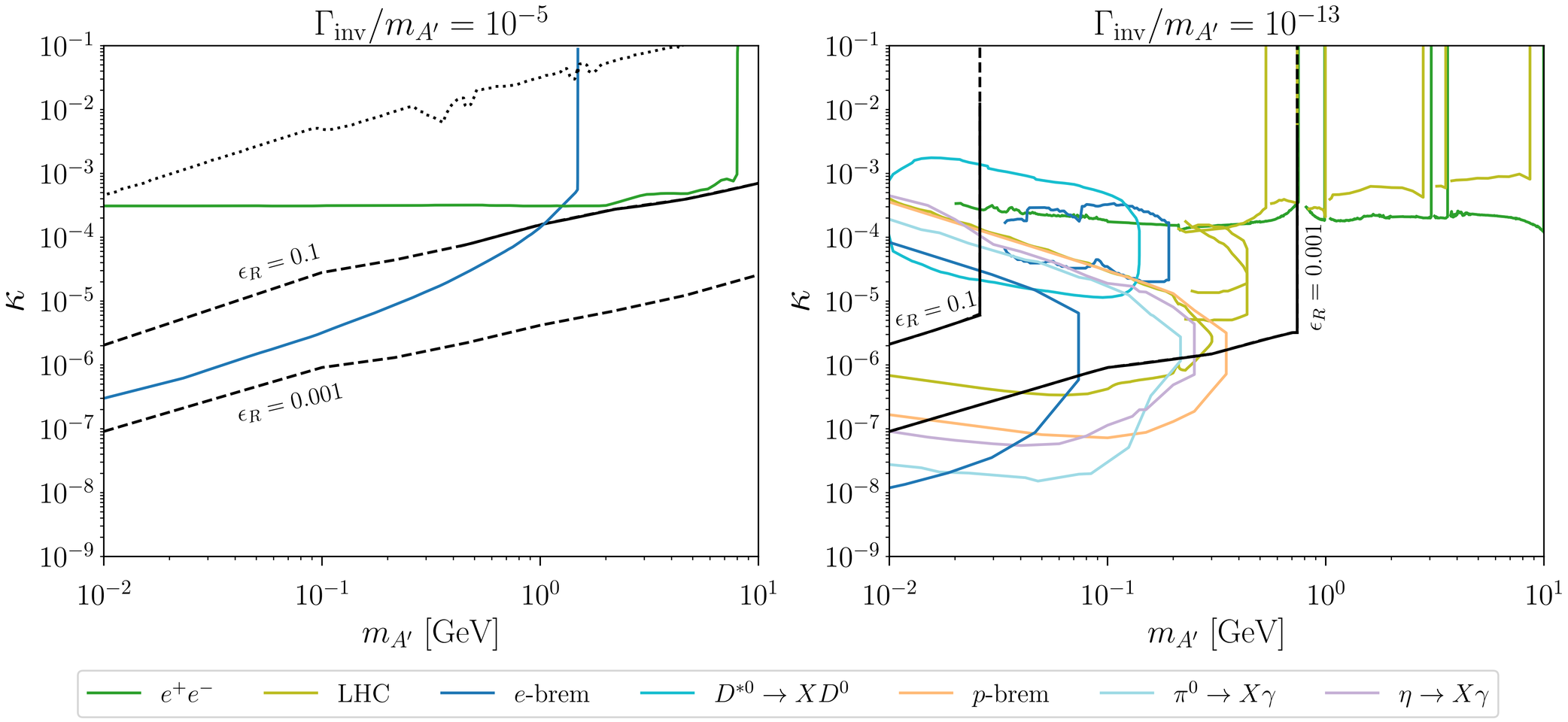

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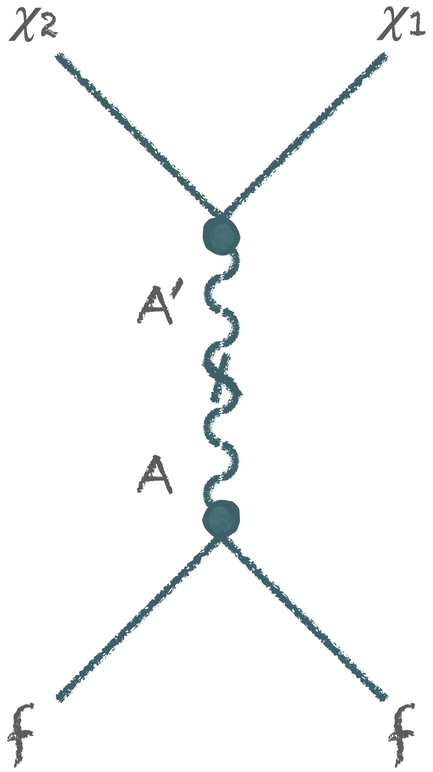
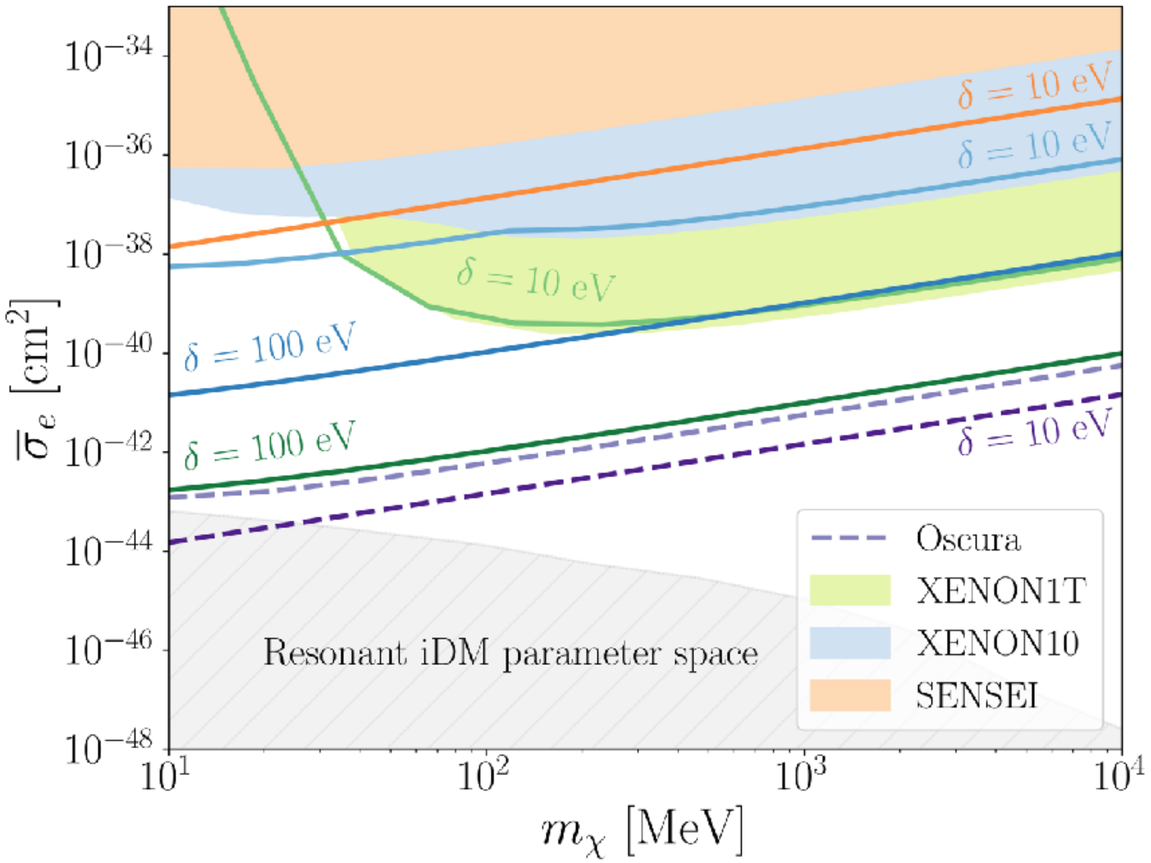
SIGNATURES OF THE COSMOLOGICALLY PRESENT EXCITED STATE



Relic excited state is unique to this case (usually it's very depleted) and can deposit energy differently in direct detection



Brahma, Heeba, **KS** 2308.01960

Reach extends to lower DM masses because mass splitting overcomes Milky Way kinematics… still hard to target due to small couplings but not crazy

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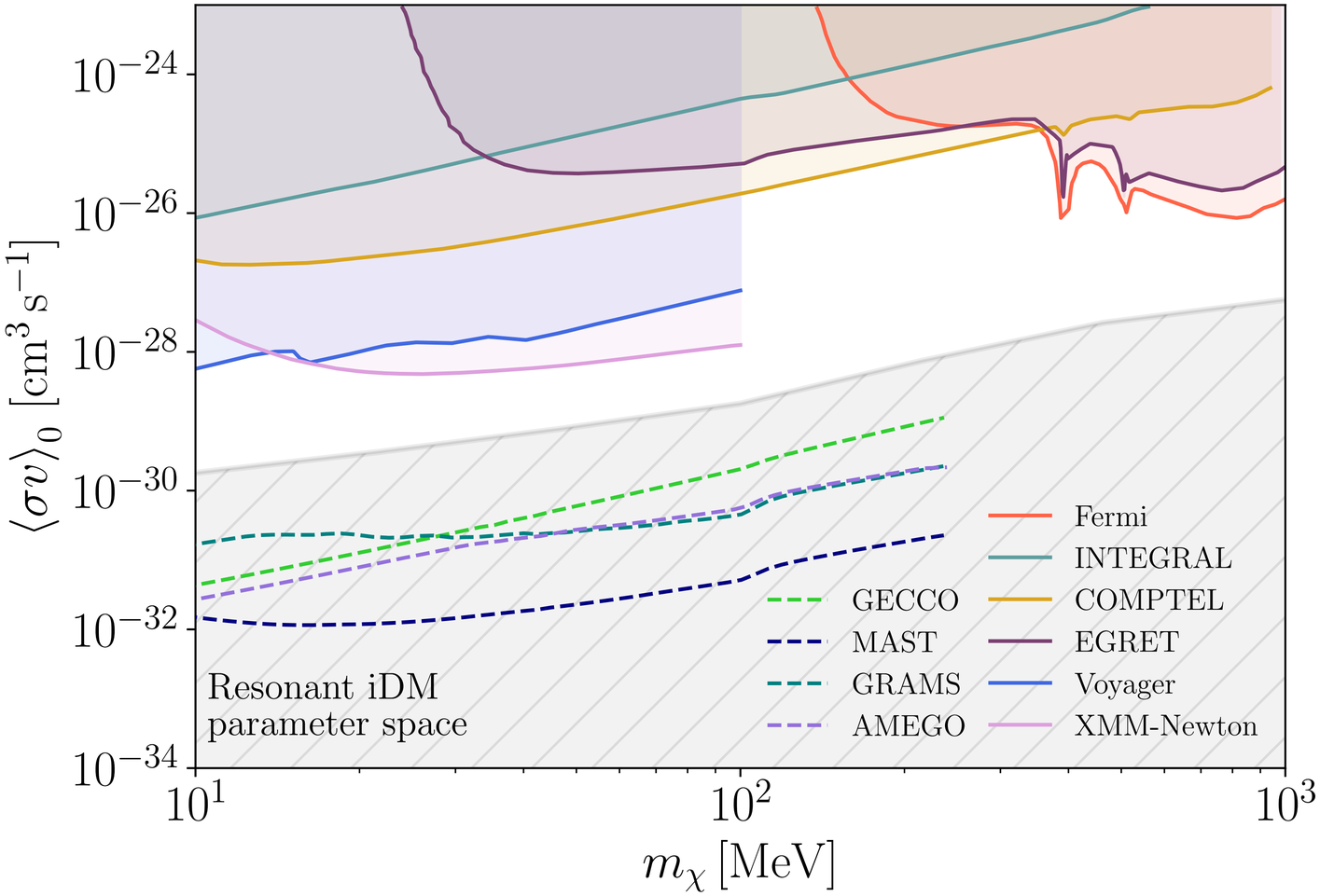
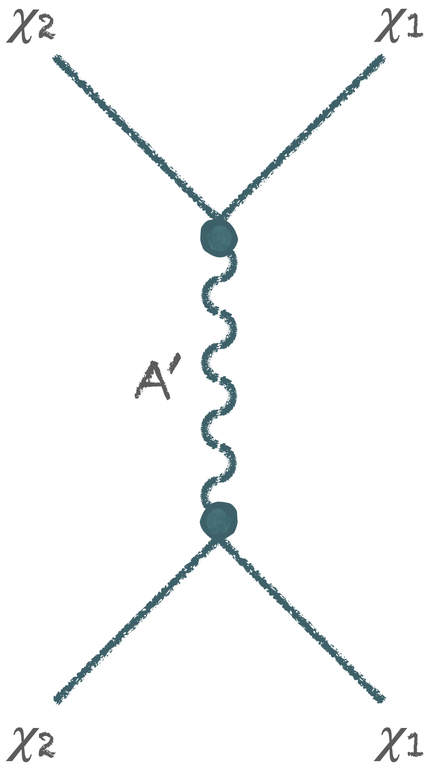


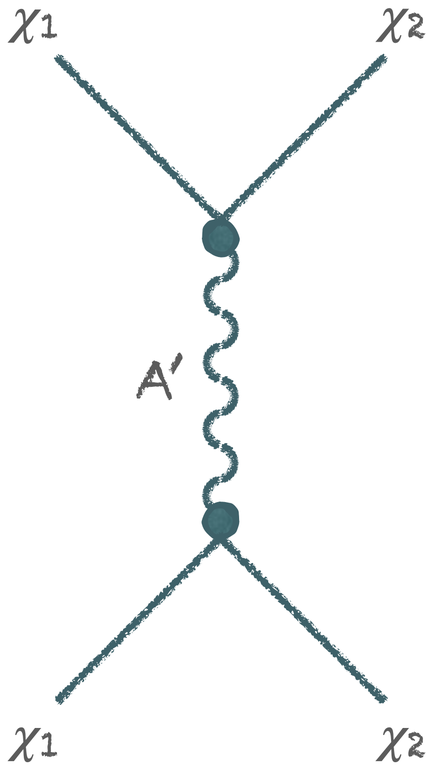
This candidate would have escaped detection in indirect searches so far but not necessarily for much longer!

Brahma, Heeba, **KS** 2308.01960

ASTROPHYSICAL SCATTERING SIGNATURES (SET BY DARK GAUGE COUPLING)



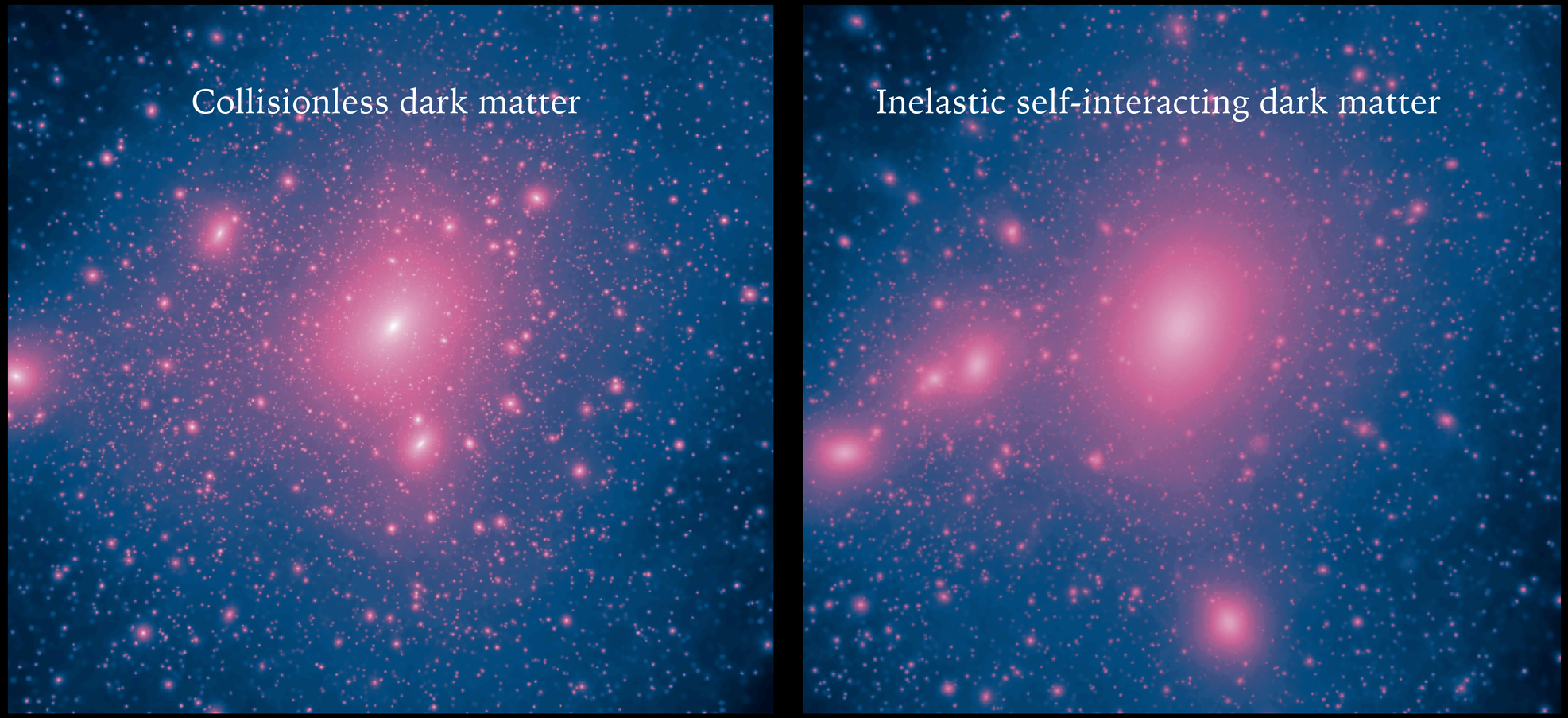
Exothermic scattering



Endothermic scattering

- Relic excited state can be collisionally de-excited and populate the ground state
- Mass splitting could be below kinematic threshold for upscattering in a typical galactic environment, re-populating excited state
- These scattering channels convert between kinetic and mass energy, providing a way to heat and cool dark matter depending on the parameters and astrophysical environment
- Can we get exotic dark matter distributions (very dense clumps, disks, etc) from this kind of energy transfer?

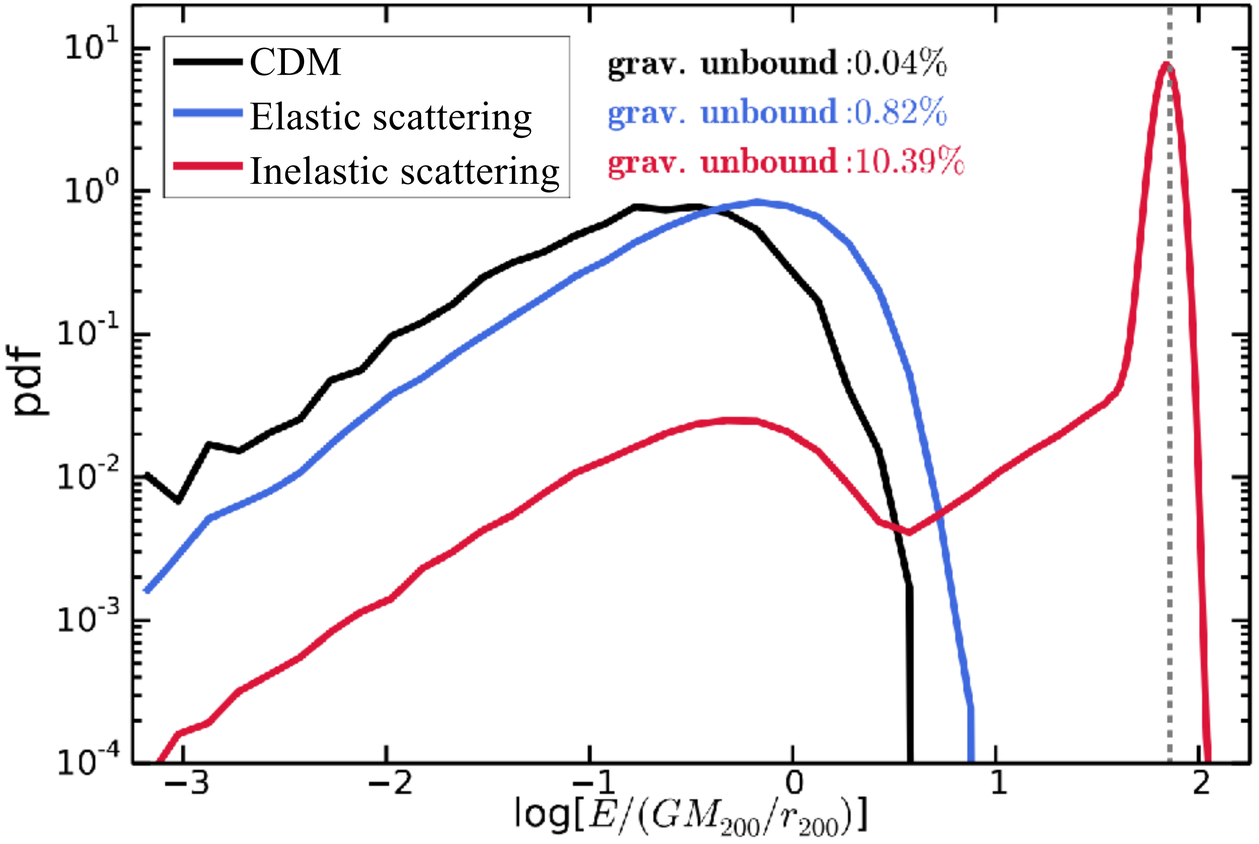
WHAT HAPPENS TO GALAXY HALOS IF ONLY EXOTHERMIC SCATTERING IS POSSIBLE?

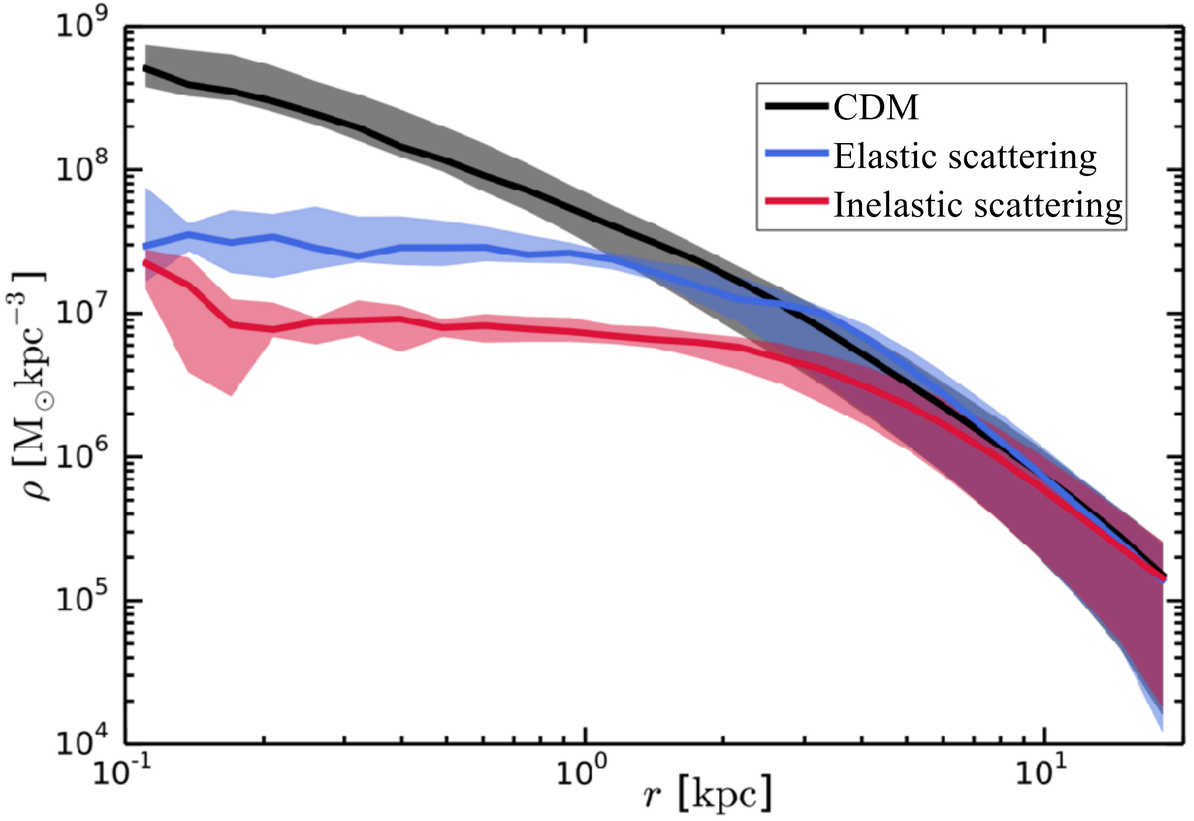


Vogelsberger, Zavala, **KS**, Slatyer MNRAS (2019)

Based on lighter mediator regime where Sommerfeld enhancement is possible, cross sections from **KS** & Slatyer (2015)

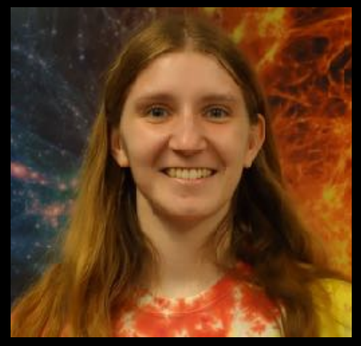
DARK MATTER PARTICLES GET KICKED OUT OF THEIR HALOS, DENSITIES SMEARED

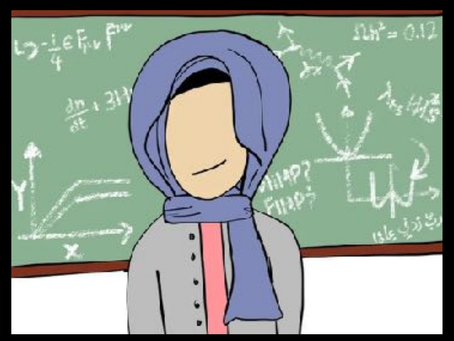




Vogelsberger, Zavala, **KS**, Slatyer MNRAS (2019)

WHAT HAPPENS TO GALAXY HALOS IF YOU ADD BOTH EXO- AND ENDOTHERMIC SCATTERING?



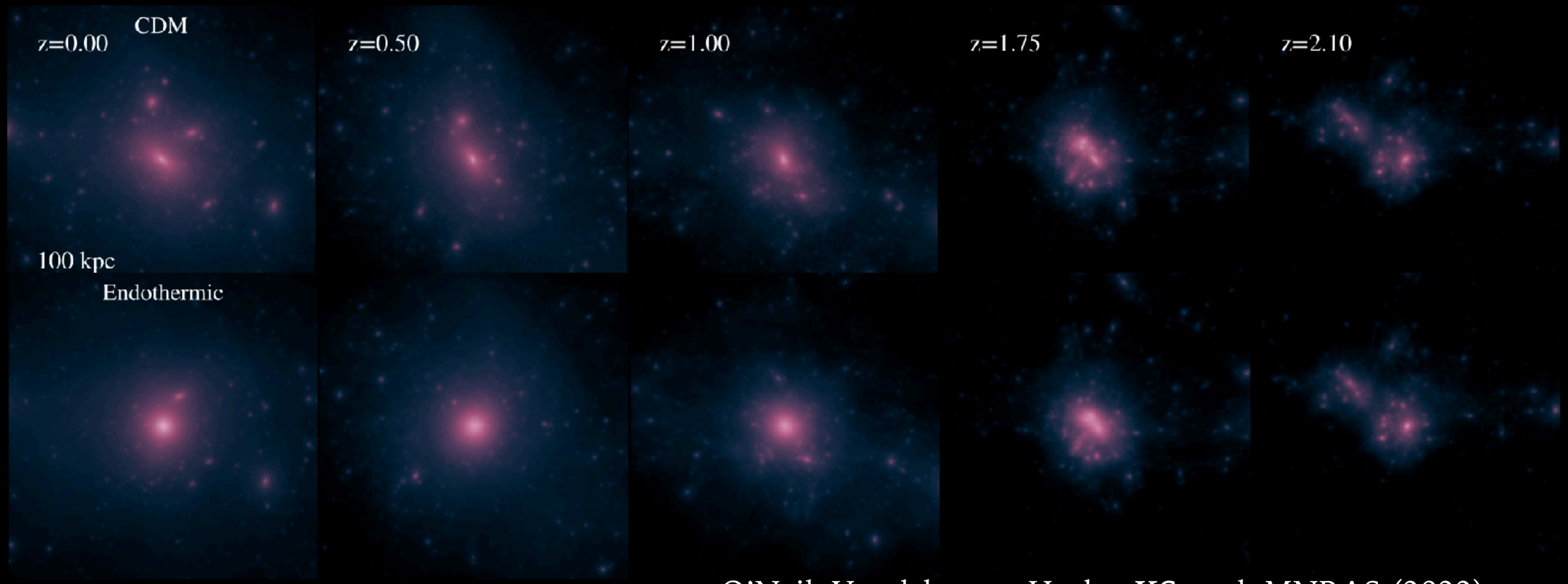


Stephanie O'Neil and Saniya Heeba

O'Neil, Vogelsberger, Heeba, **KS** et al. MNRAS (2022)

Simulations done in the Born regime of scattering

WHAT HAPPENS TO GALAXY HALOS IF YOU ADD ENDOTHERMIC SCATTERING?



O'Neil, Vogelsberger, Heeba, **KS** et al. MNRAS (2022)

. . . MOST OF THE "ACTION" HAPPENS AFTER FORMATION OF HEAVIER HALOS (LATER IN BOTTOM-UP STRUCTURE FORMATION) DUE TO KINETIC BARRIER TO UPSCATTERING!

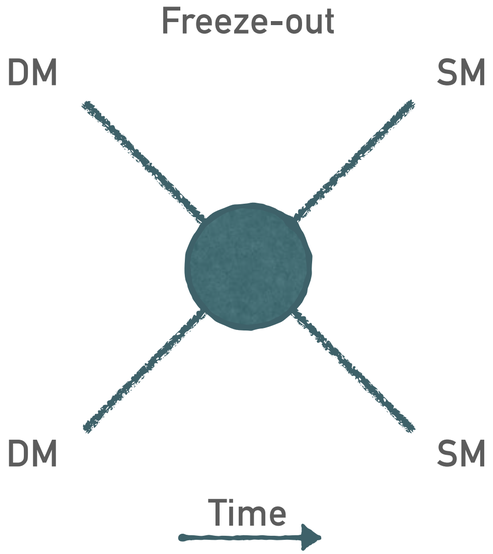
THE UPSHOT: INELASTIC SCATTERING COULD COMPLETELY CHANGE HOW DWARF GALAXIES LOOK

Vogelsberger, Zavala, **KS**, Slatyer MNRAS (2019)
O'Neil, Vogelsberger, Heeba, **KS** et al. MNRAS (2022)

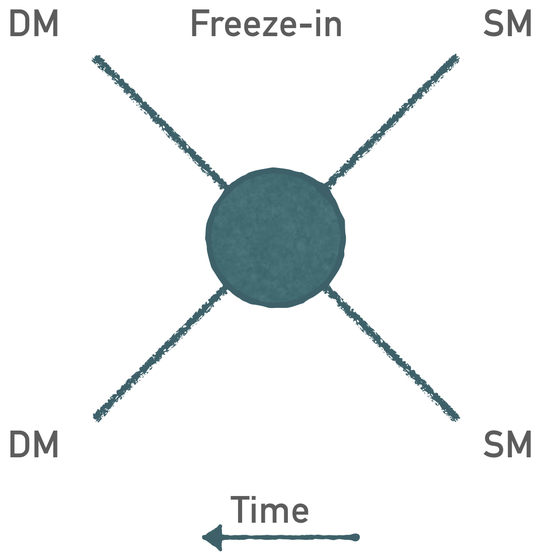
Cartoon by Dr. Saniya Heeba

INELASTIC FREEZE-IN

FREEZE-OUT VS. FREEZE-IN

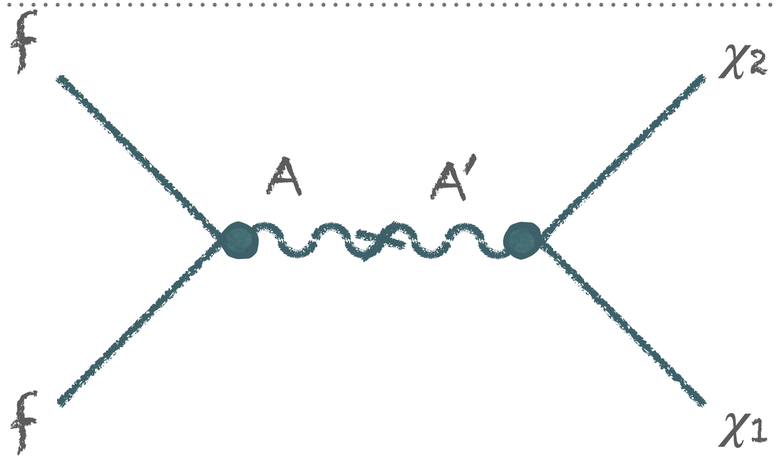


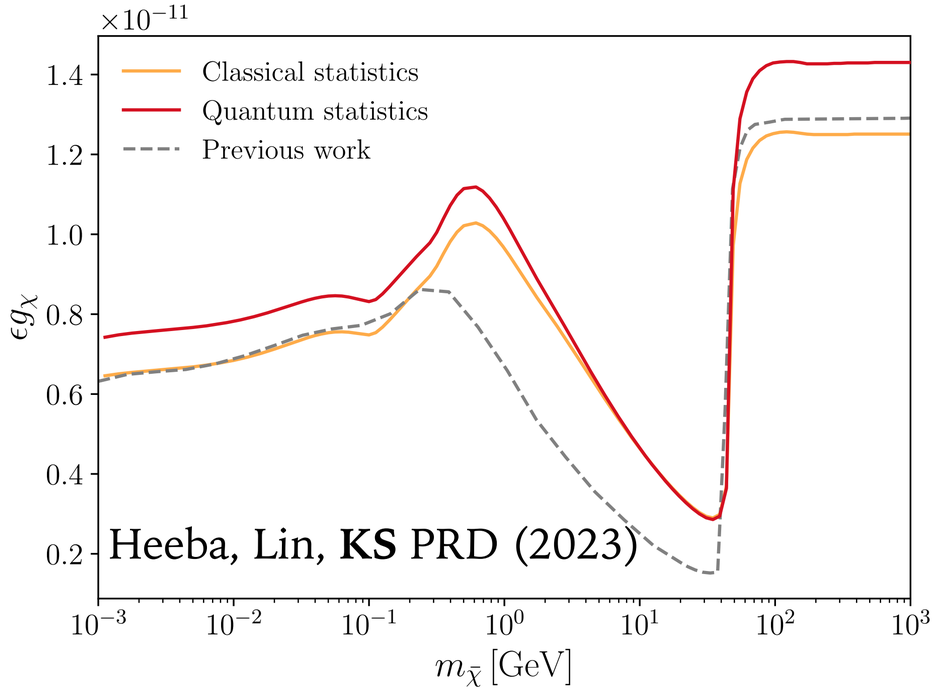
- DM is part of thermal bath, has high thermal initial abundance
- Independent of initial conditions due to thermalization
- DM abundance depleted by DM annihilation to SM
- Relatively large coupling means there are direct and indirect detection observables



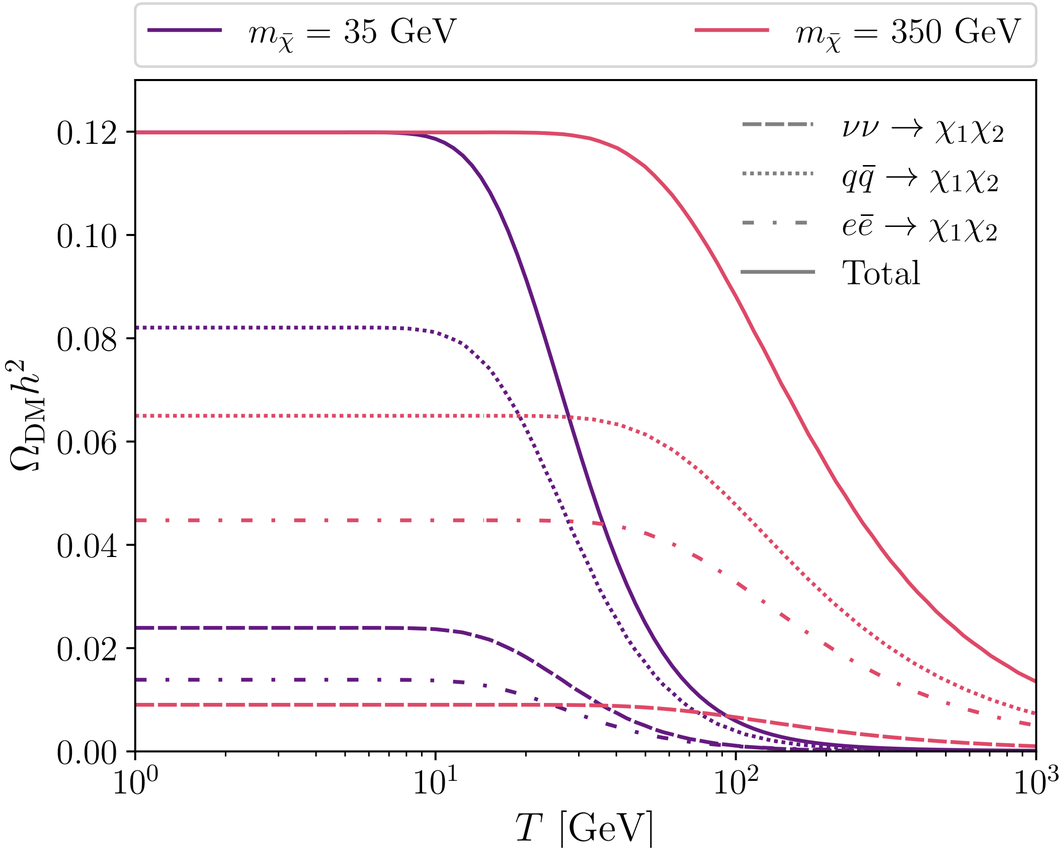
- DM is not in thermal equilibrium with SM, couplings *extremely* tiny
- Independent of initial conditions if IR-dominated process
- DM abundance produced by SM annihilation to DM
- Smallest meaningful DM contact with SM plasma, key benchmark for low-mass direct detection and fixed target

FREEZE-IN OF PSEUDO-DIRAC DARK MATTER

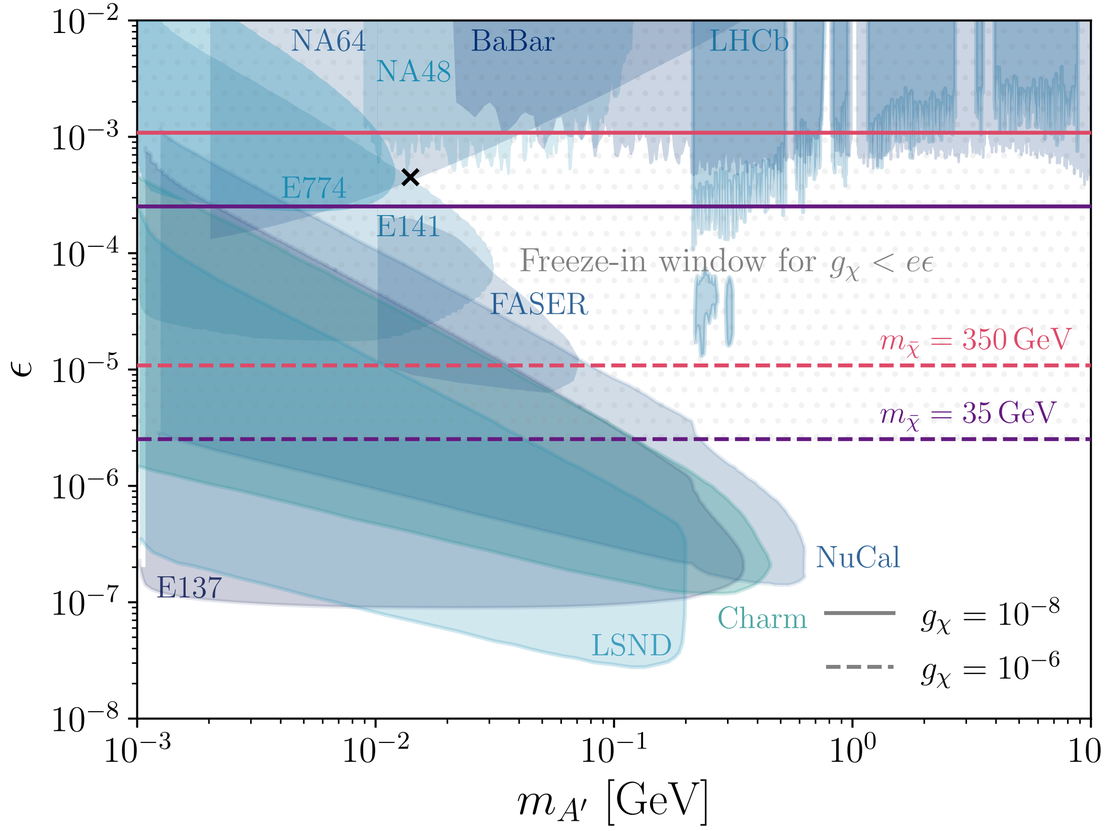


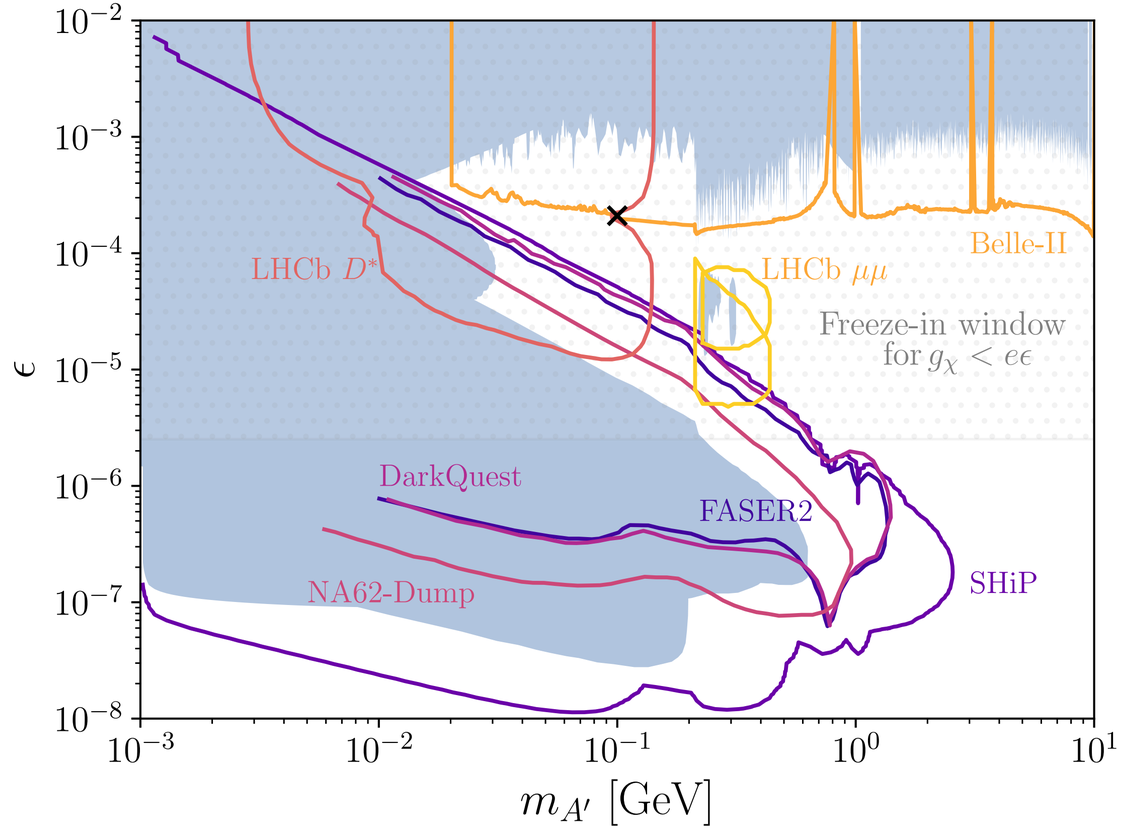


- Ground and excited state are produced symmetrically by fermion-antifermion annihilation with extremely small branching fraction
- Mass splitting is too small to matter kinematically so we (mostly) reproduce light mediator Dirac result



HIGH DEGREE OF COMPLEMENTARITY WITH TERRESTRIAL EXPERIMENT





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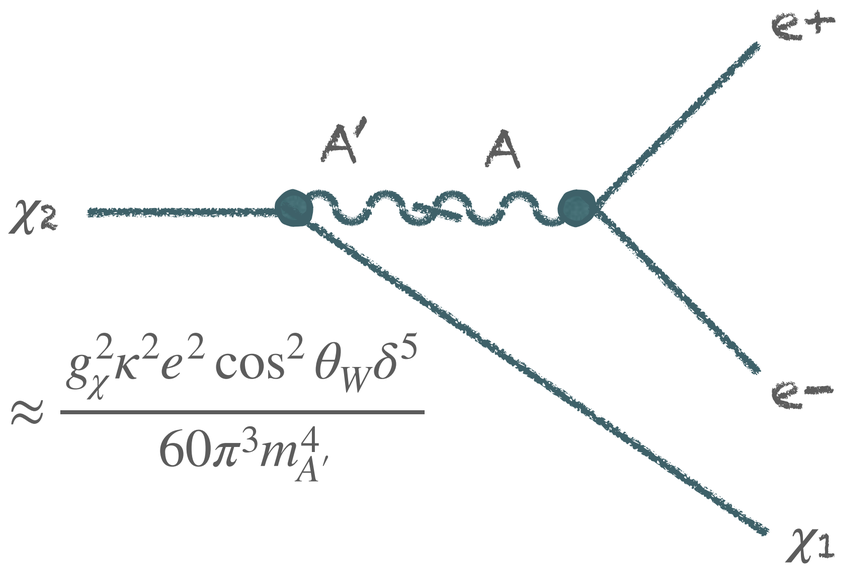
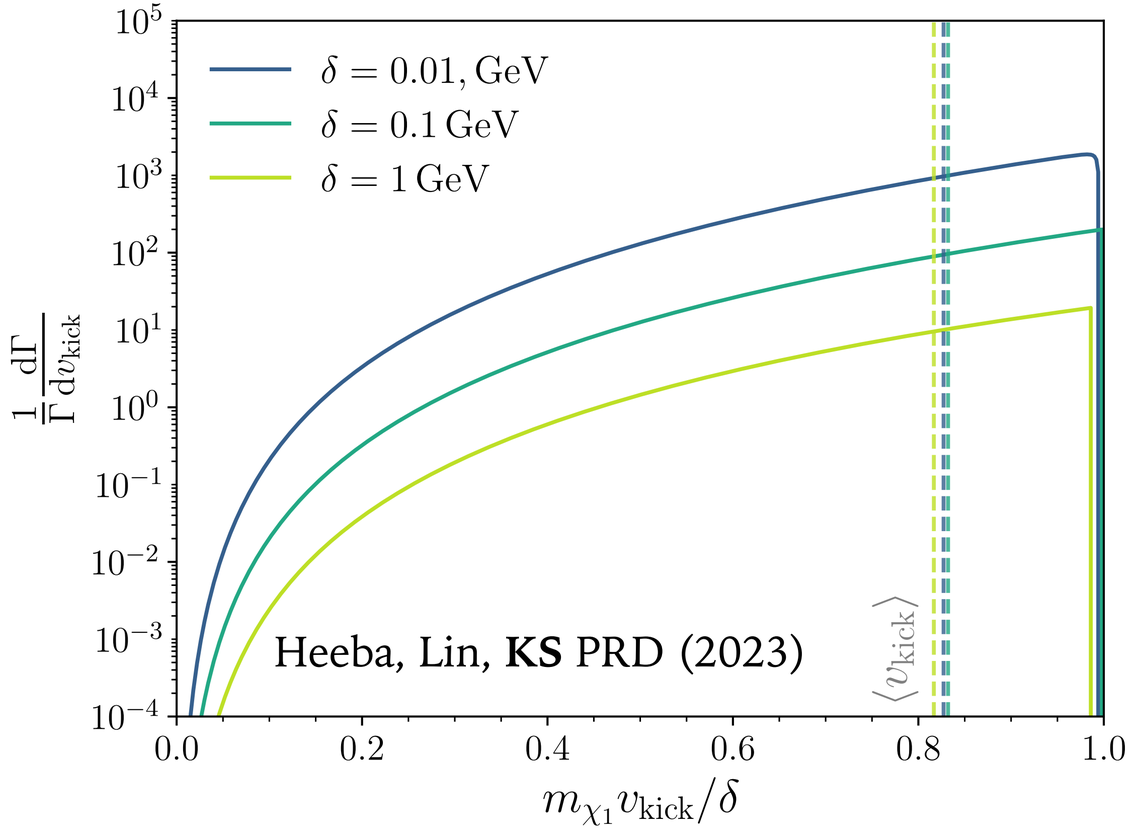
COSMOLOGY OF THE META-STABLE EXCITED STATE



$$\Gamma \approx \frac{g_\chi^2 \kappa^2 e^2 \cos^2\theta_W \delta^5}{60\pi^3 m_{A'}^4}$$

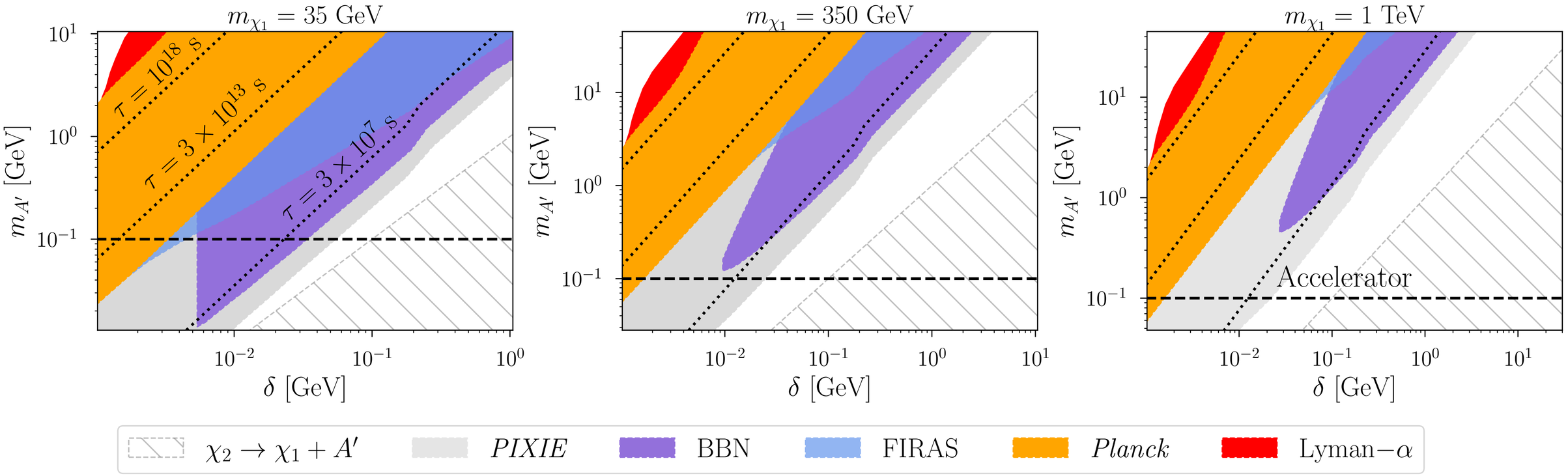
$$\tau \sim 10^7 \text{ seconds} \times \left(\frac{m_{A'}}{1 \text{ GeV}}\right)^4 \left(\frac{100 \text{ MeV}}{\delta}\right)^5$$



- All other processes are extremely suppressed/rare due to small freeze-in couplings and low DM density
- Most of mass splitting energy goes into recoiling electrons, ground state gets a velocity kick, $v_{\rm kick} \sim \delta/m_\chi$
- Decaying dark matter excited states have been of interest due to Hubble tension but lacking self-consistent thermal history!

UNIVERSE AS A CALORIMETER FOR INELASTIC FREEZE-IN

- Electron-positron pairs from three-body decay can inject energy into our cosmic calorimeter! Lots of the parameter space is available and will be tested by future probes (accelerator, PIXIE)



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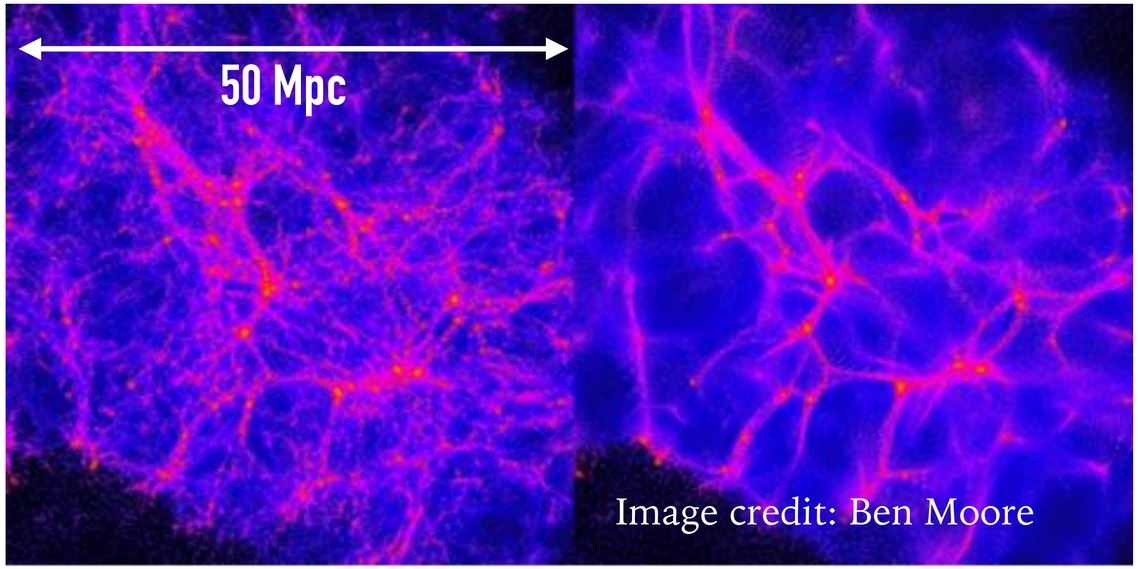
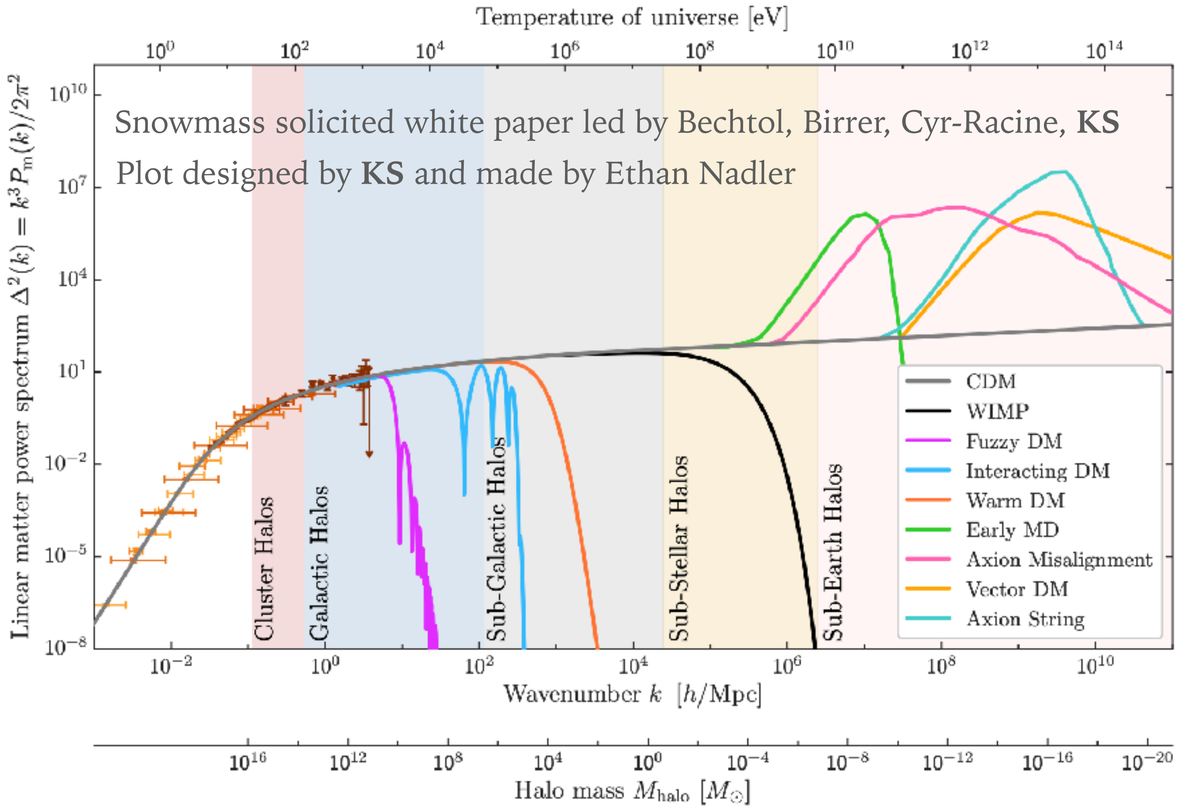
DARK MATTER KICK COULD IMPACT THE FORMATION OF STRUCTURE



← Cooler/Slower Hotter/Faster →

Three-body kick to the ground state particle could affect structure formation!

- Probes of cosmic structure formation on smaller scales provide another observational handle on dark sector



IMPACT OF THE INELASTIC THREE-BODY VELOCITY KICK

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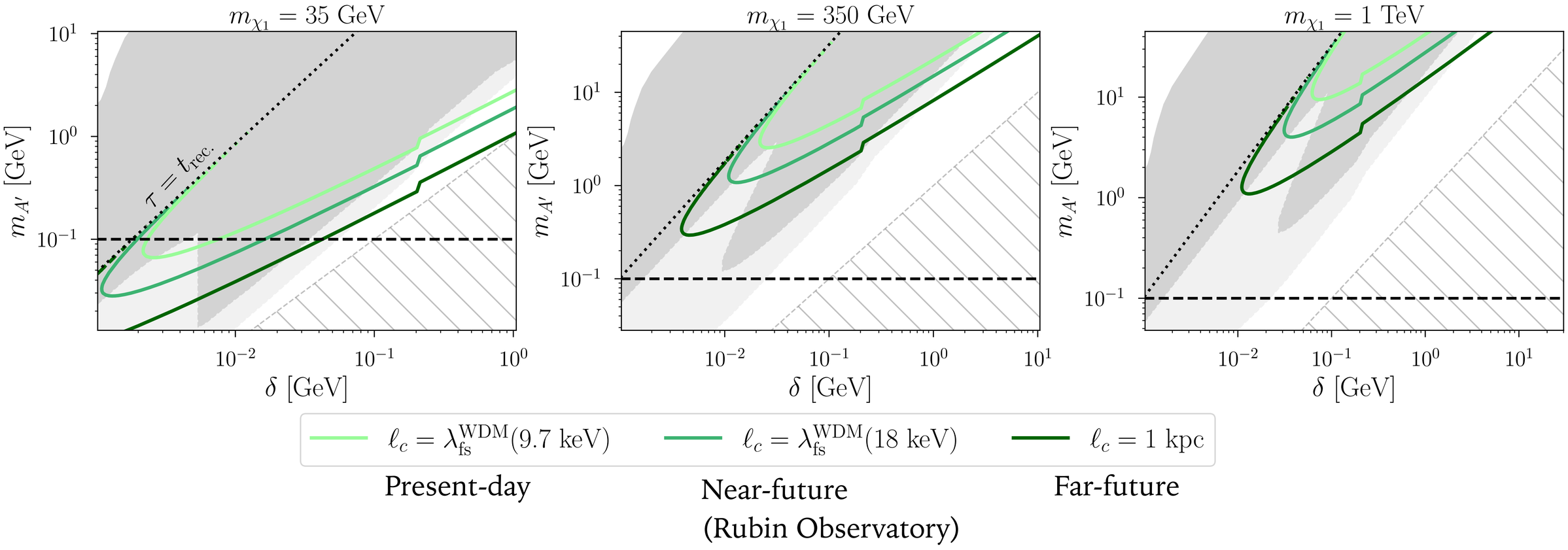
- Dark matter velocity kick from three-body decay can hinder the growth of structure on characteristic length scales… complementary to electron calorimeter signatures!



SUMMARY

- Dark sectors are *incredibly* rich, even very simple, well-explored models have not been completely characterized in terms of thermal history and observables in very testable portions of parameter space
- Self-consistency of model requires complementarity between different types of probes (terrestrial, astrophysical, cosmological) and a holistic view rather than considering observables in isolation will allow us to explore parameter space faster
- It's a big universe, lots of room for creativity!