DARK SECTORS

Katelin Schutz, McGill University
IPP 50th Anniversary Symposium
May 29th 2022

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(A UNIVERSE OF) DARK SECTORS*

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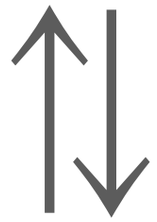
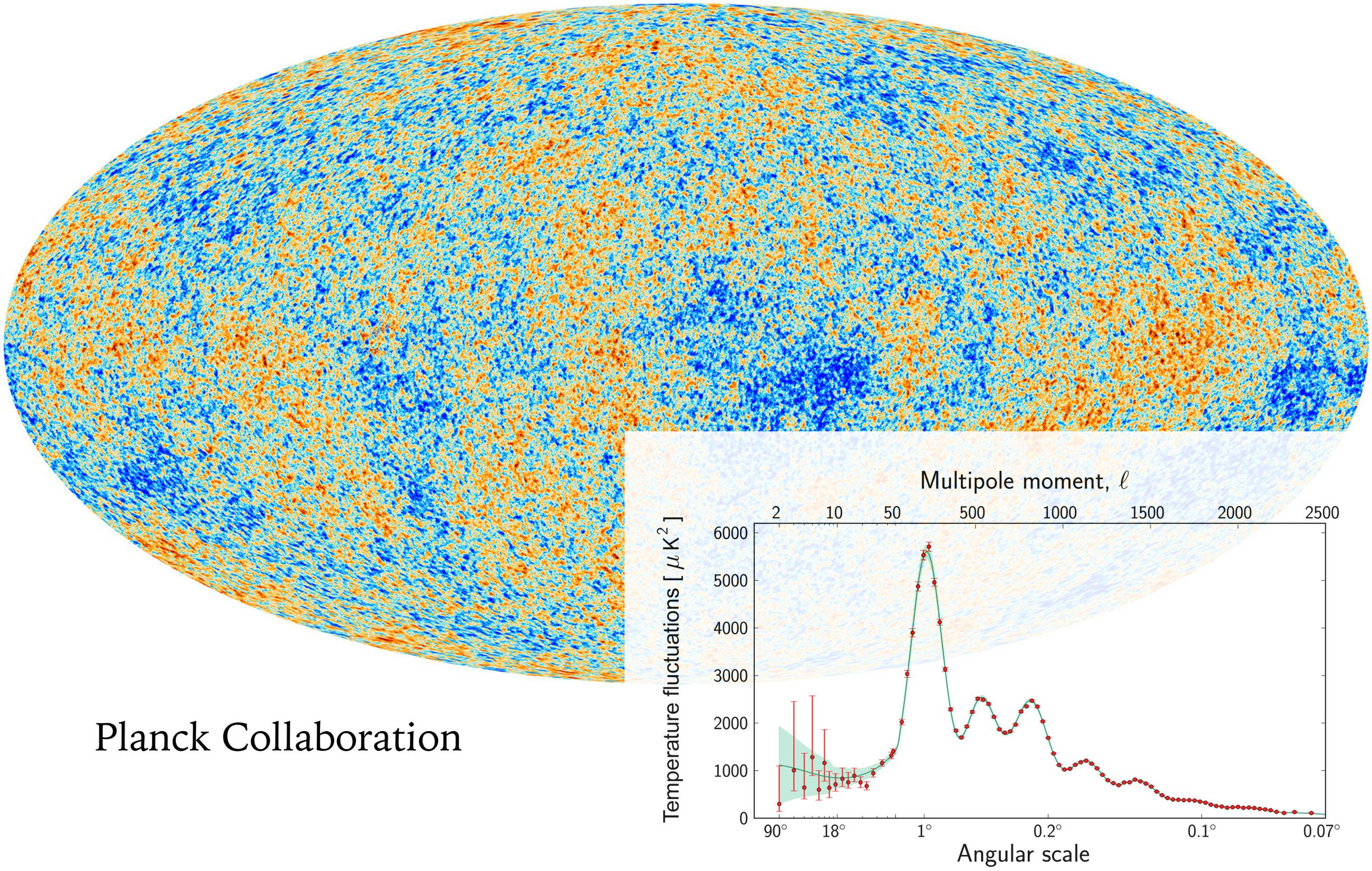
EXISTENCE OF DARK MATTER

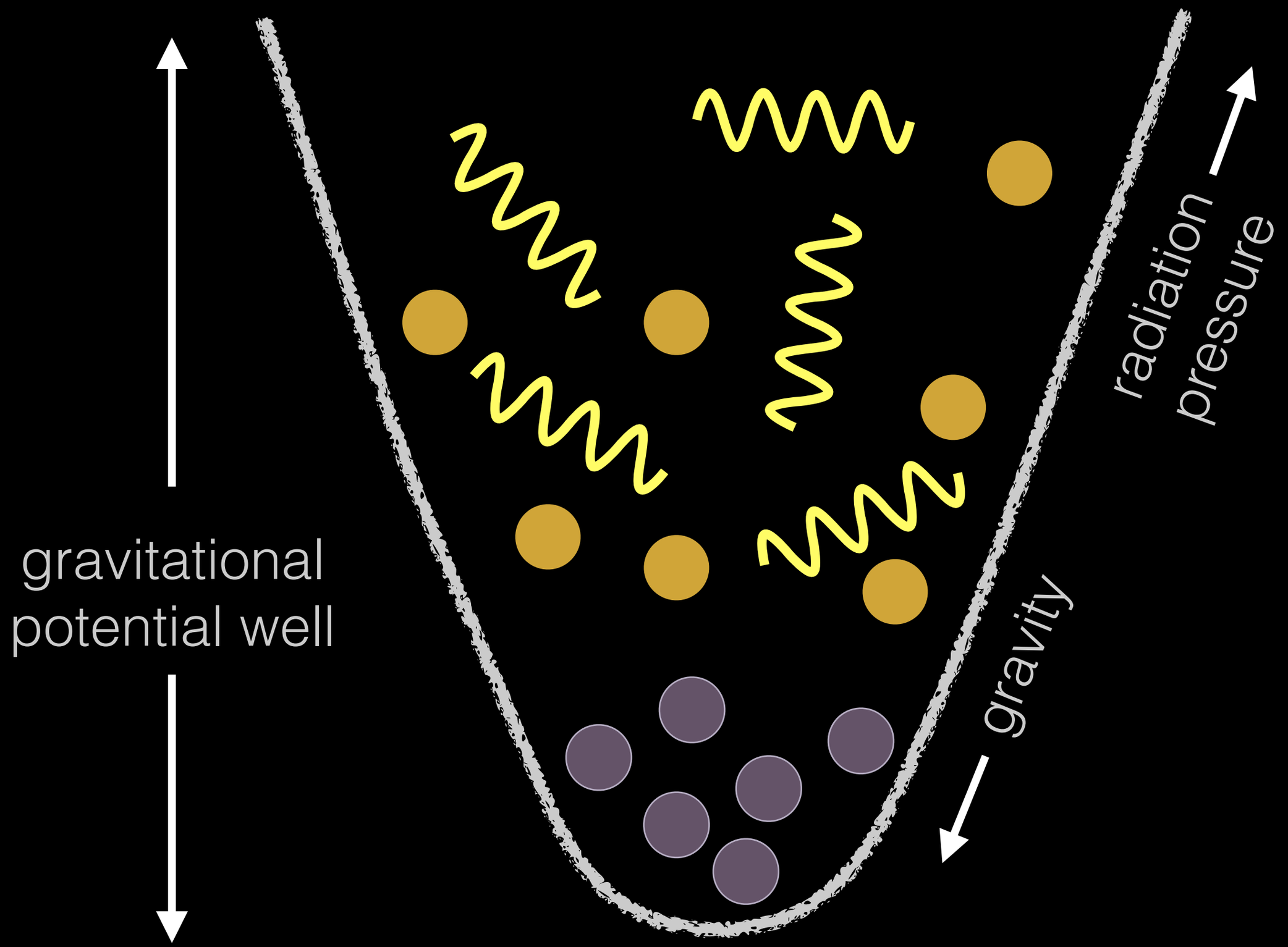


NEED FOR NEW MATTER CONTENT

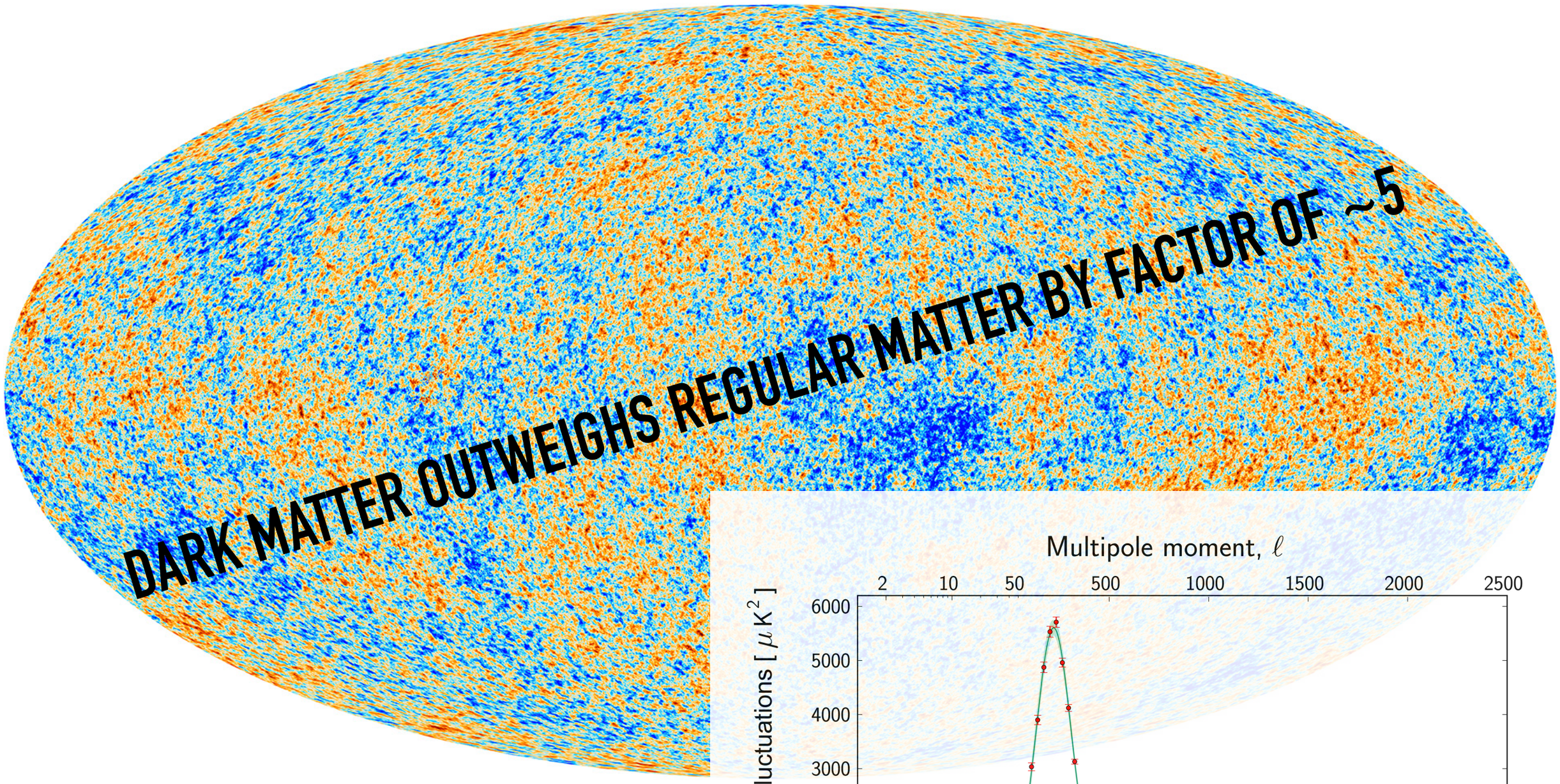
CMB & CMB LENSING



Planck Collaboration


gravitational
potential well
radiation
pressure
gravity

CMB & CMB LENSING



Planck Collaboration

SO WHAT'S THE DARK MATTER MADE OF?

GRAVITY

WEAK FORCE

ELECTROMAGNETISM

STRONG FORCE

u c t

d s b

(quarks)

(protons & neutrons made of these)

τ

μ

e

(charged leptons)

ν_τ

ν_μ

ν_e

(neutrinos)

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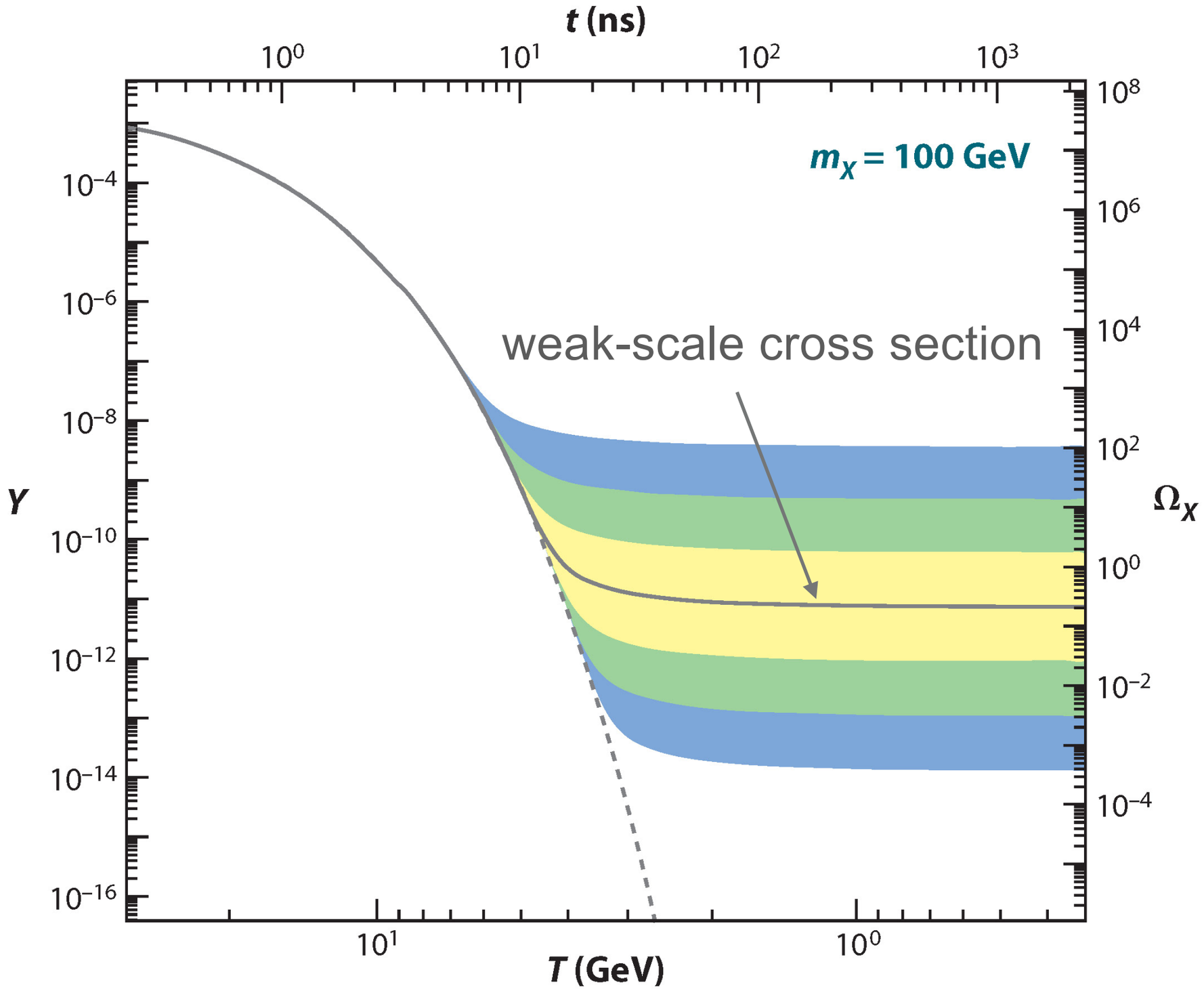
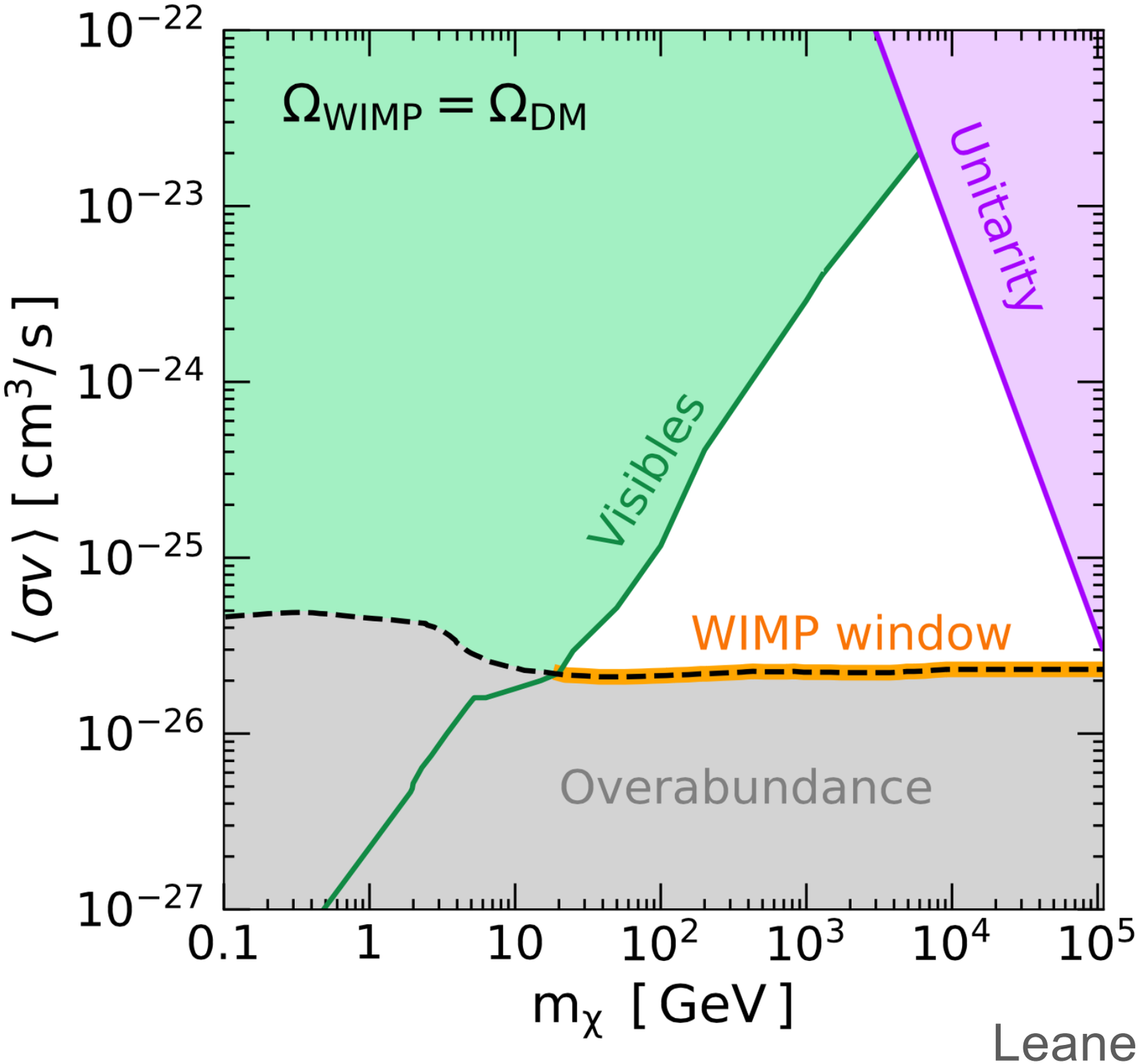
WIMPS AS DARK MATTER

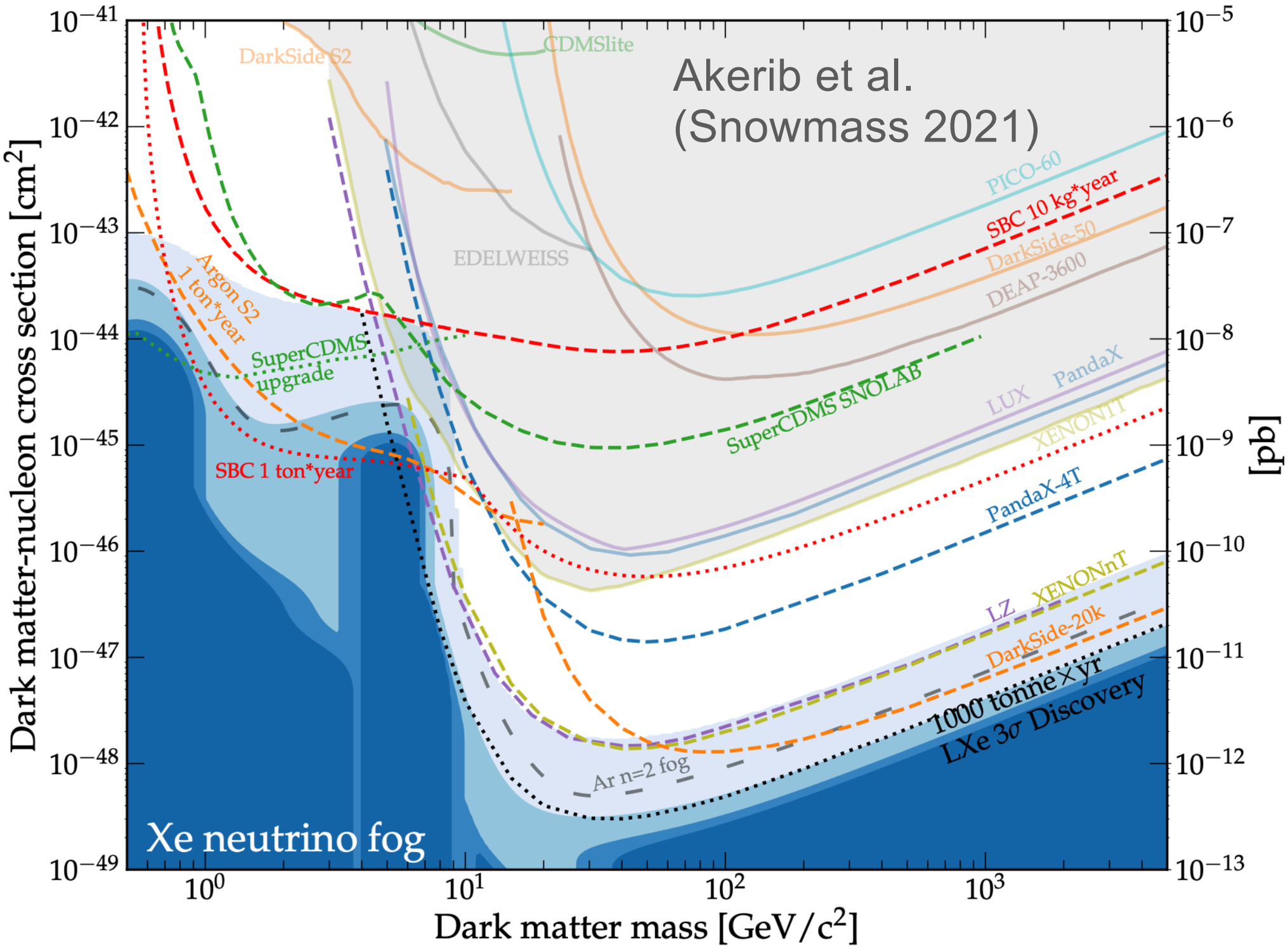


WIMP INDIRECT DETECTION WINDOW (SAME PROCESS AS FREEZE-OUT)



Leane et al. (2018)

WIMP DIRECT DETECTION (MODEL DEPENDENT)



BENEFITS OF WIMPS AS DARK MATTER

- ☑ New physics was expected at weak scale
- ☑ Simple (not many new particles)
- ☑ Relic abundance independent of initial conditions as long as DM is in the bath
- ☑ Fine with early universe observables (BBN and N_{eff})
- ☑ Relevant couplings can be experimentally probed

. . . BUT WE STILL HAVEN'T FOUND WIMPS

REVISITING WIMP ASSUMPTIONS

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?

Dark matter that does not couple directly to SM

GRAVITY

WEAK FORCE

NEW FORCE?

?

ELECTROMAGNETISM

STRONG FORCE

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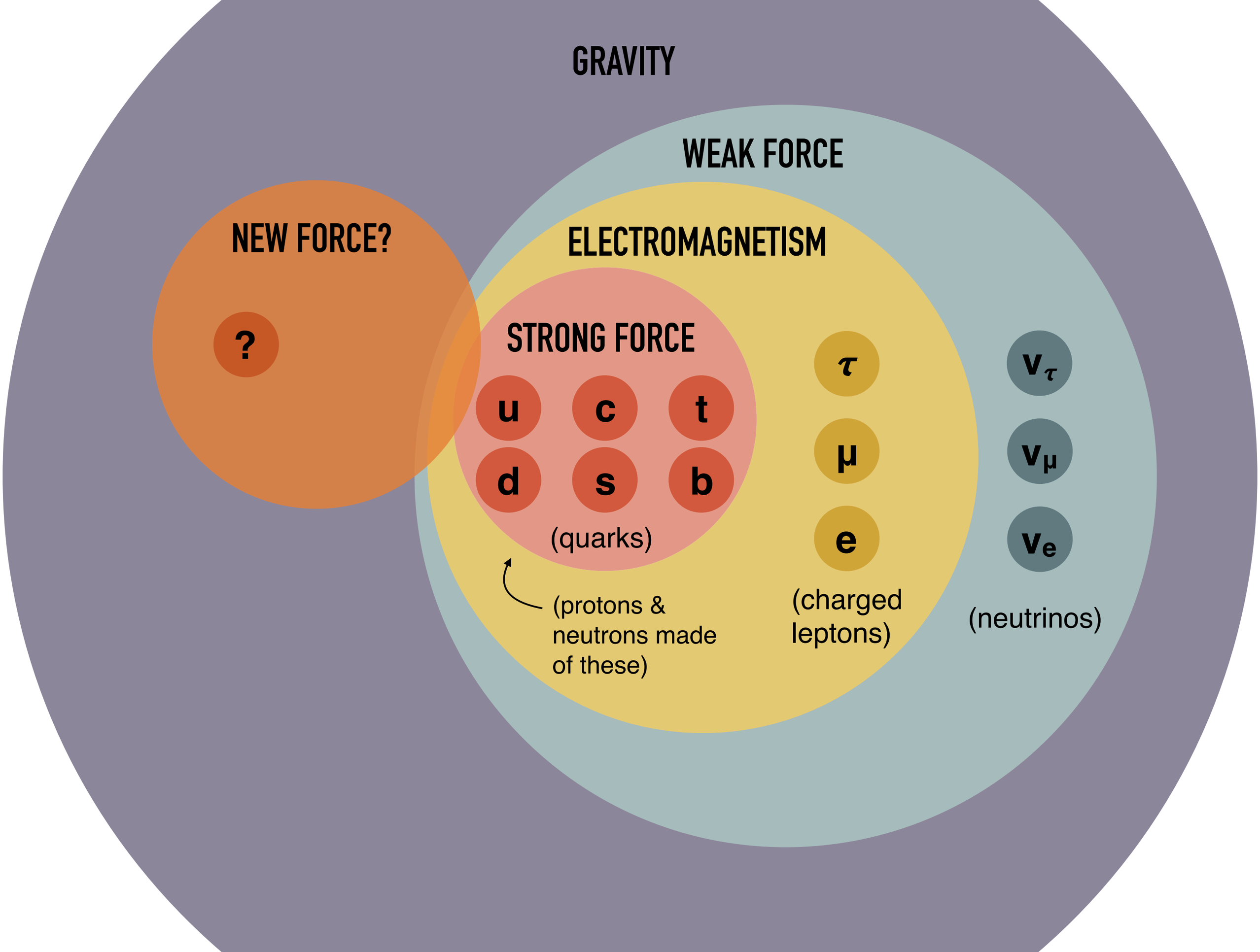
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(protons & neutrons made of these)

τ μ e

(charged leptons)

ν_τ ν_μ ν_e

(neutrinos)

- DM stabilized by new charge
- Finite list of relevant (renormalizable or super-renormalizable) interactions
  - Vector portals (kinetic mixing, B-L, etc.)
  - Higgs portals (including singlet)
  - Neutrino portal
  - Maybe pseudoscalar/axion (dimension 5)

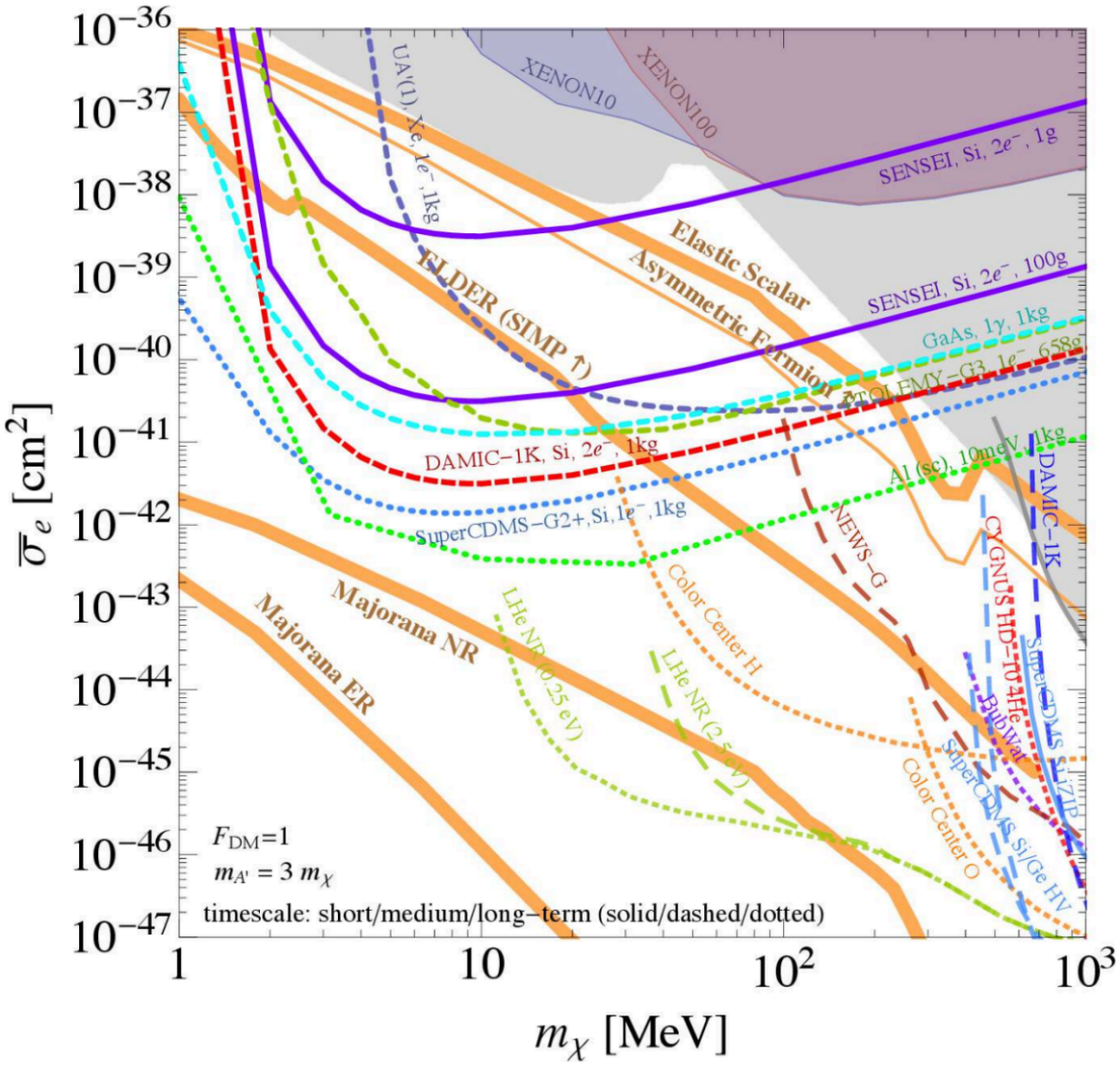
A FEW PLANS OF ATTACK FOR DARK SECTORS

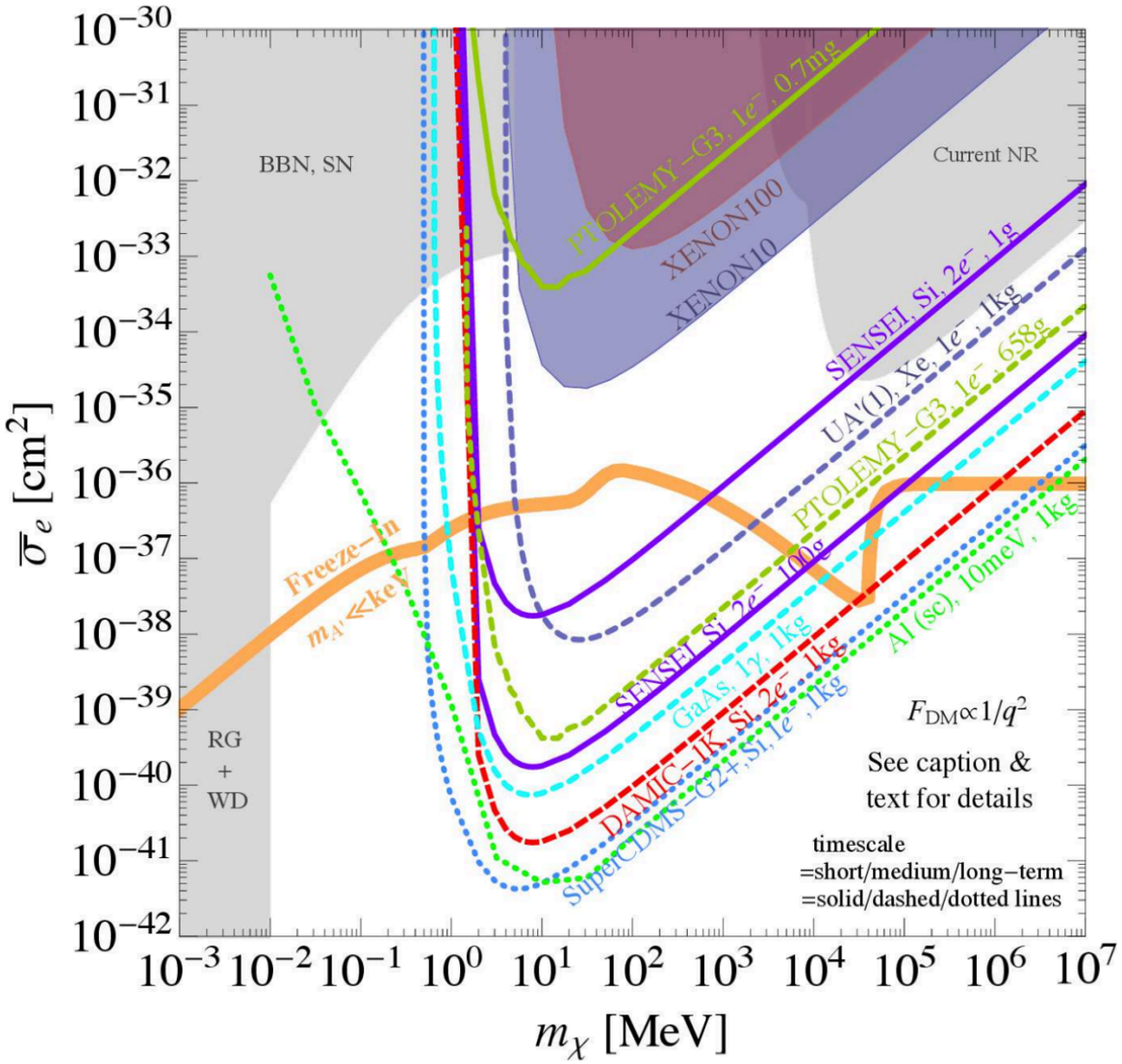
- ☑ Dark matter in a dark sector is often sub-GeV (unlike WIMPs due to e.g. Lee-Weinberg bound) extend the search to lower masses in direct detection
- ☑ Look for mediators/new forces in accelerators/fixed target experiments and astrophysical environments
- ☑ Consider simple, alternative thermal histories beyond WIMP-inspired freeze-out and characterize observable consequences in cosmology

. . . PLUS MANY OTHER APPROACHES

A CASE STUDY

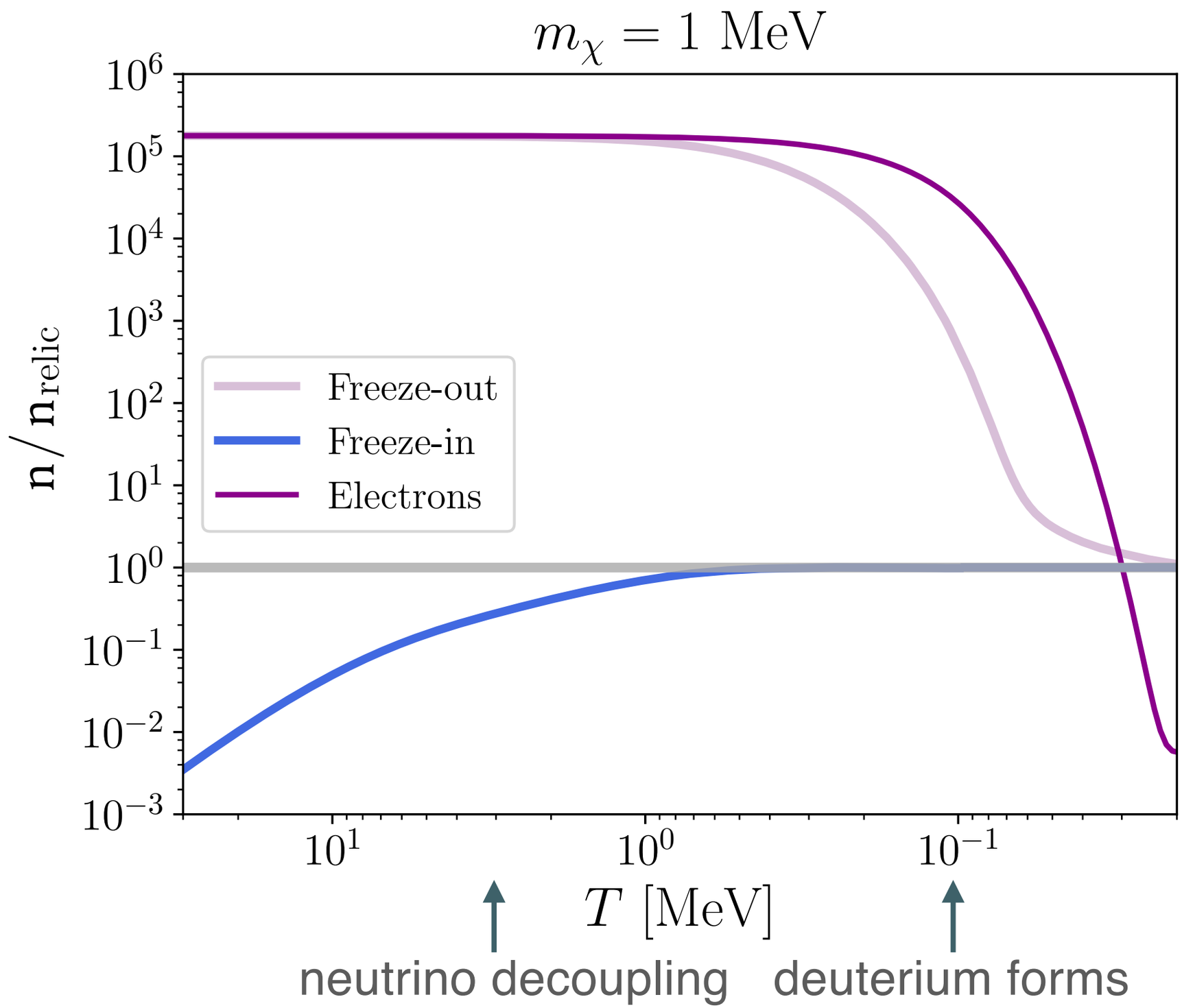
NEW-ISH SUB-GEV DIRECT DETECTION IDEAS



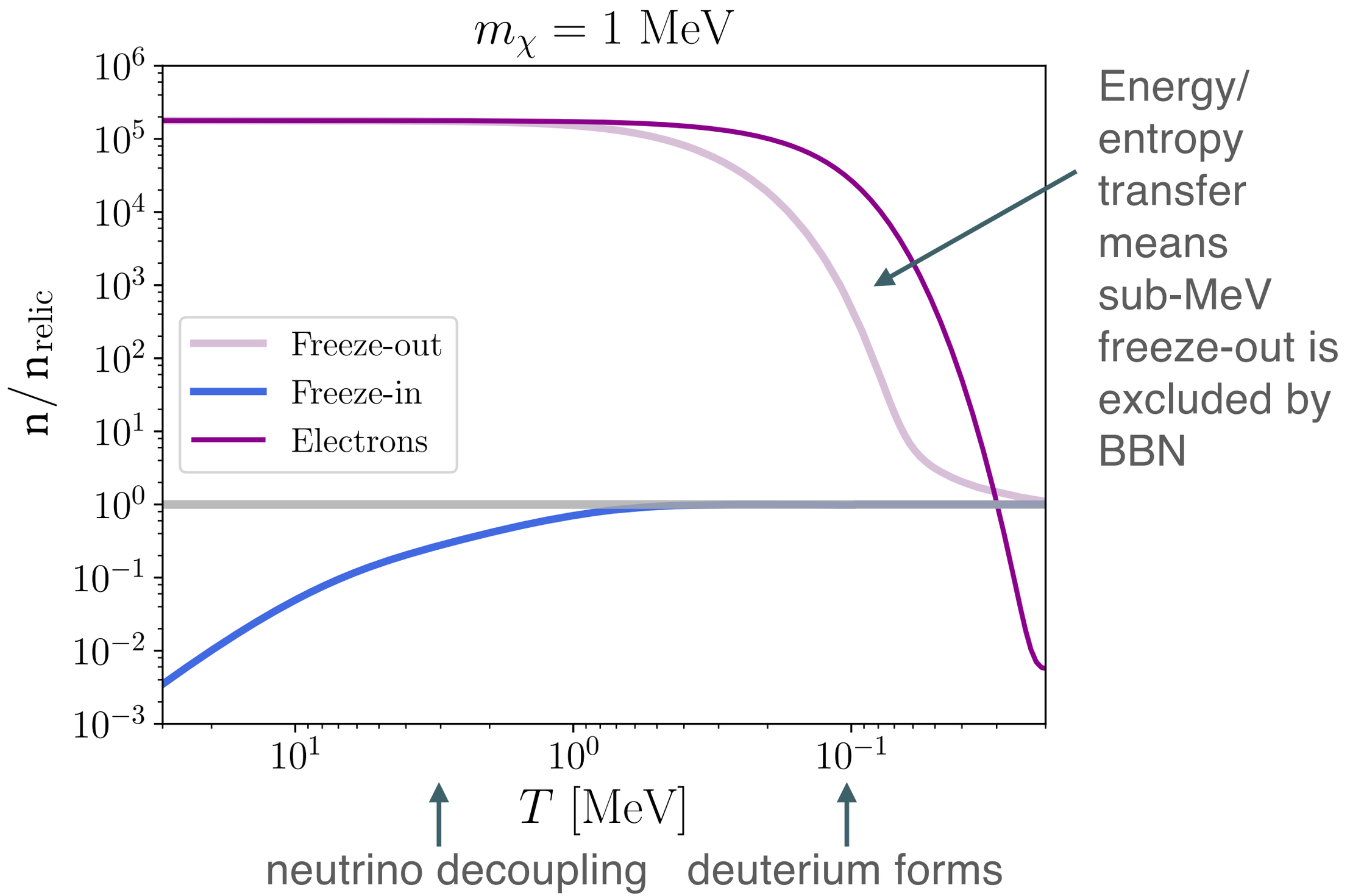


See e.g. dark sectors community report, cosmic visions report, etc.

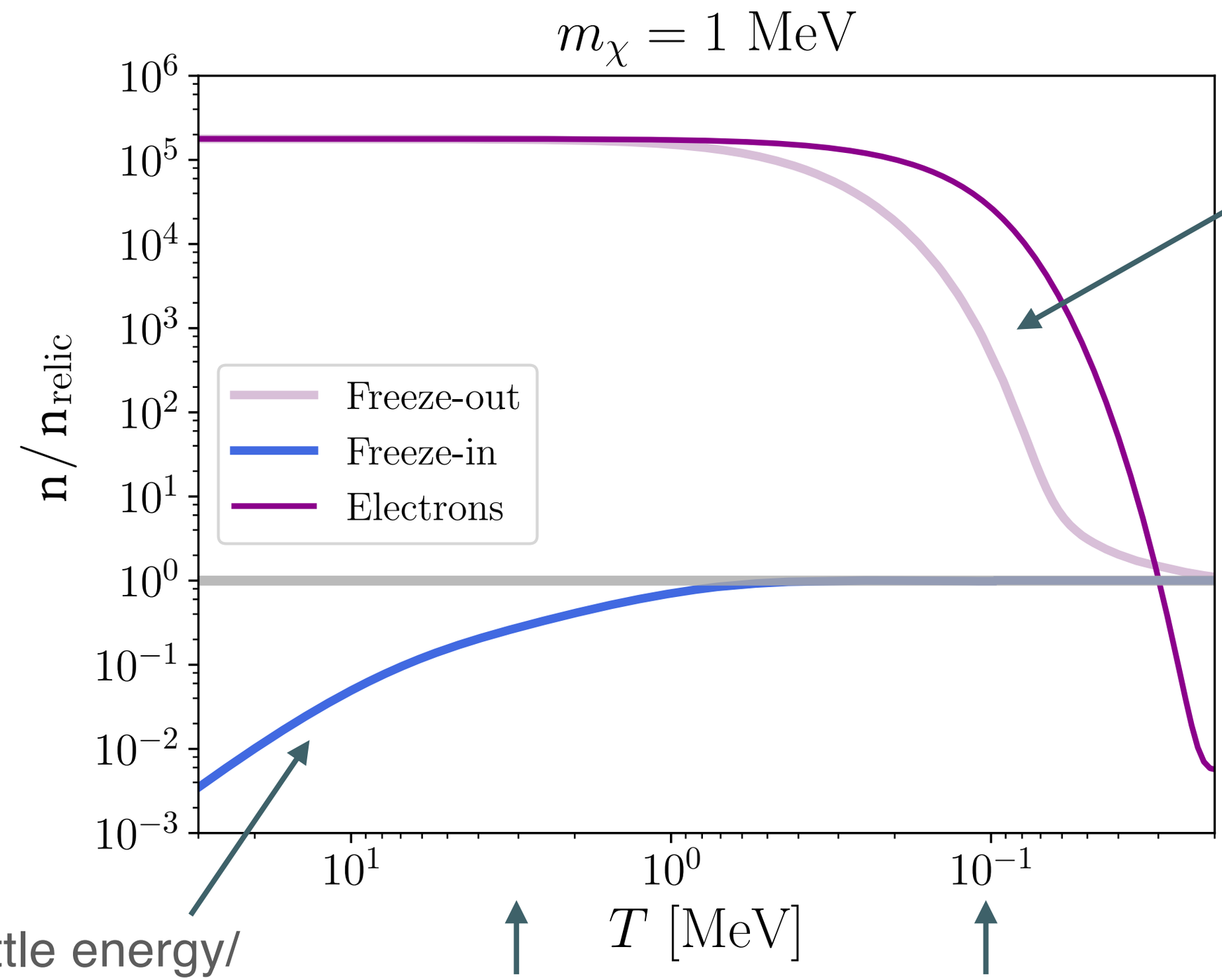
MAKING SUB-MEV DARK MATTER FROM A THERMAL PROCESS



MAKING SUB-MEV DARK MATTER FROM A THERMAL PROCESS



MAKING SUB-MEV DARK MATTER FROM A THERMAL PROCESS

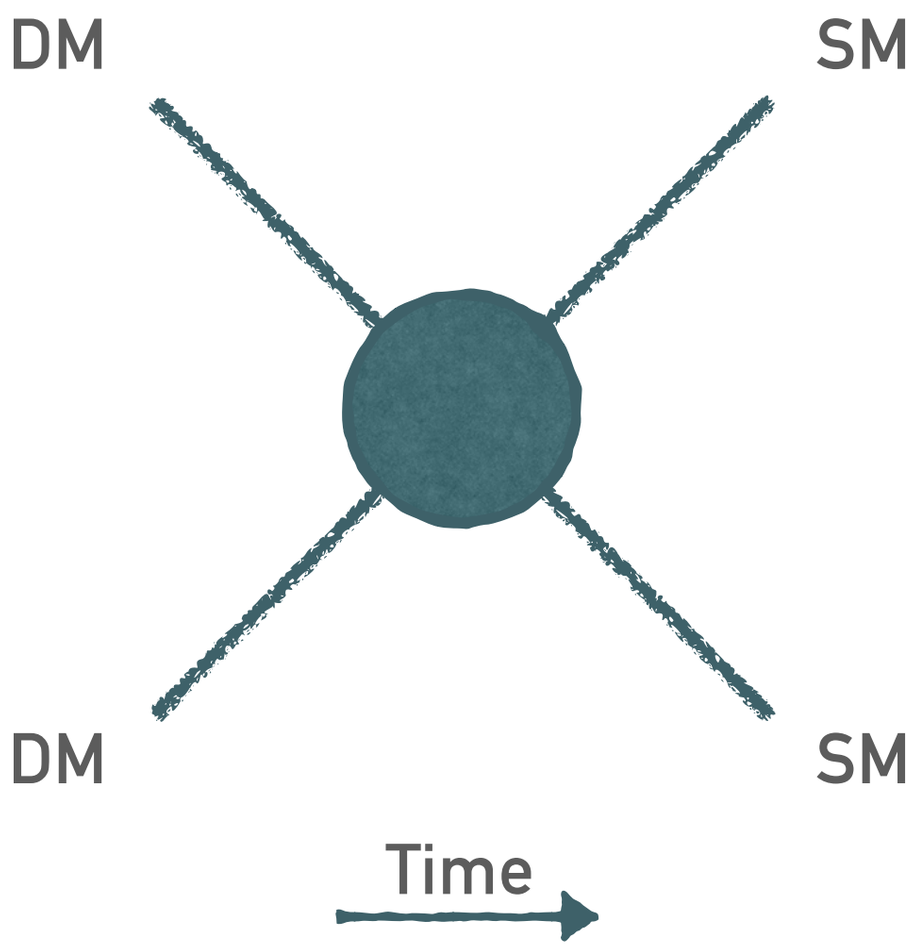


Energy/ entropy transfer means sub-MeV freeze-out is excluded by BBN

Very little energy/ entropy means no BBN issue

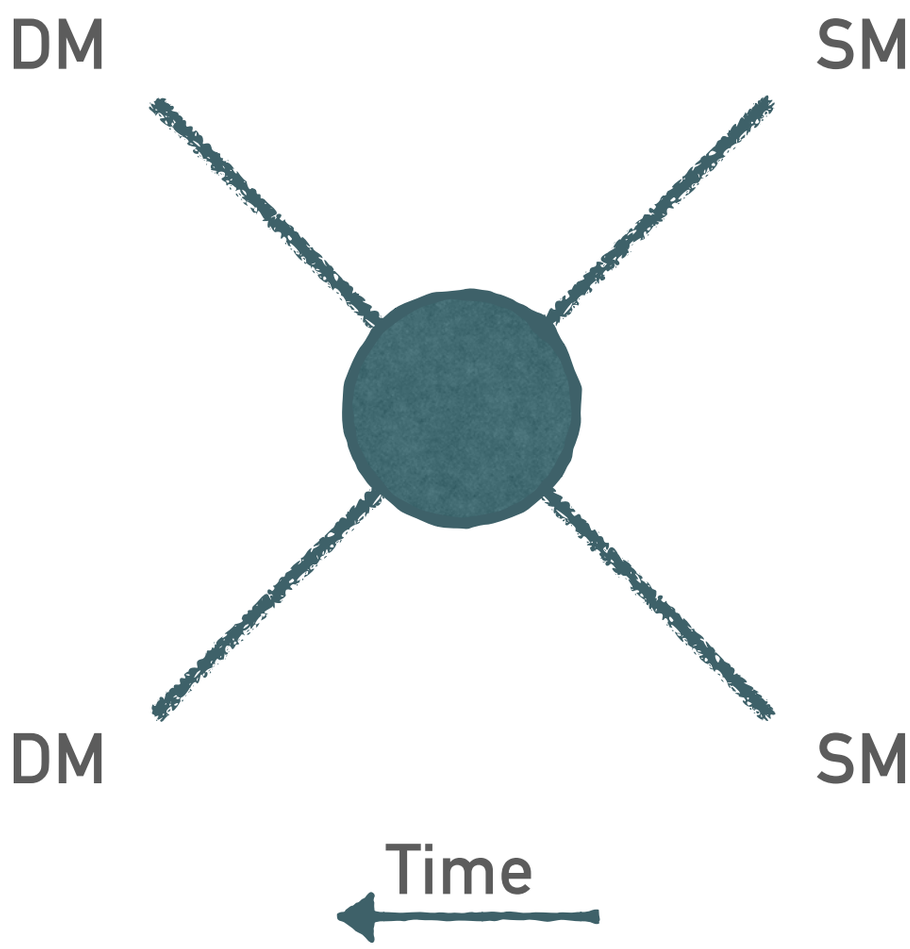
neutrino decoupling

deuterium forms



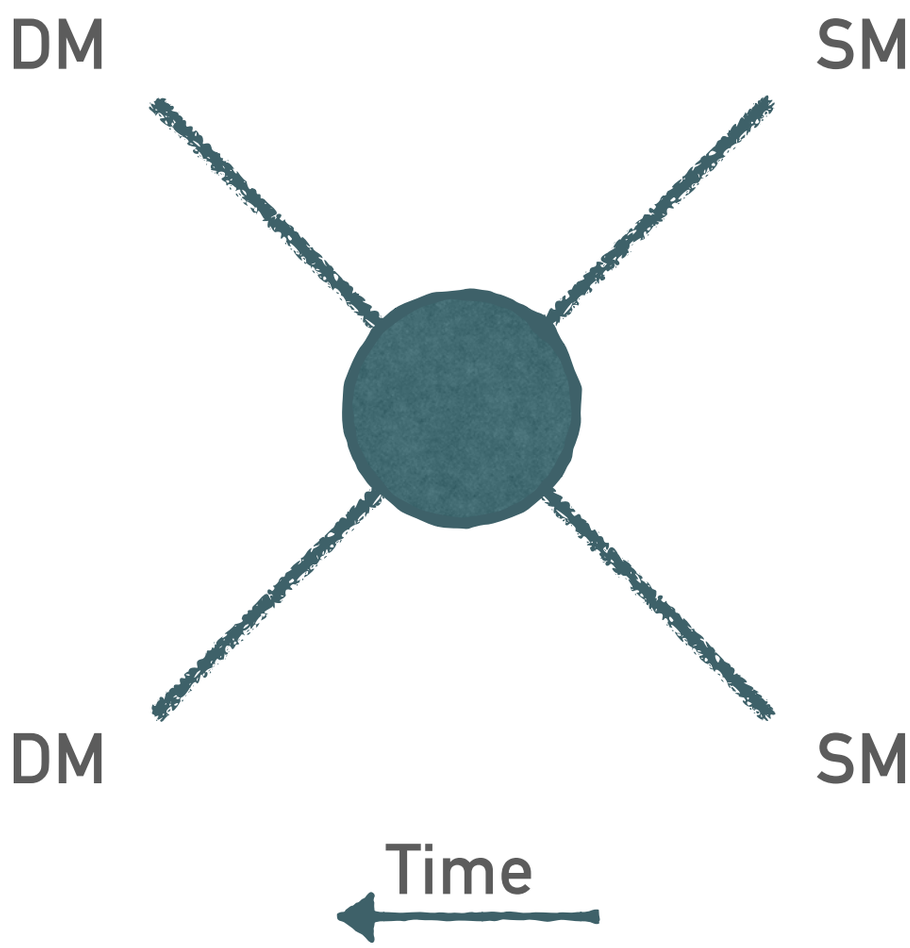
Thermal freeze-out

- ☑ Relic abundance is independent of initial conditions of reheating after inflation (as long as DM is in the bath)
- ☑ Fine with BBN and N_{eff} (above masses of a few MeV)
- ☑ Relevant couplings can be experimentally probed



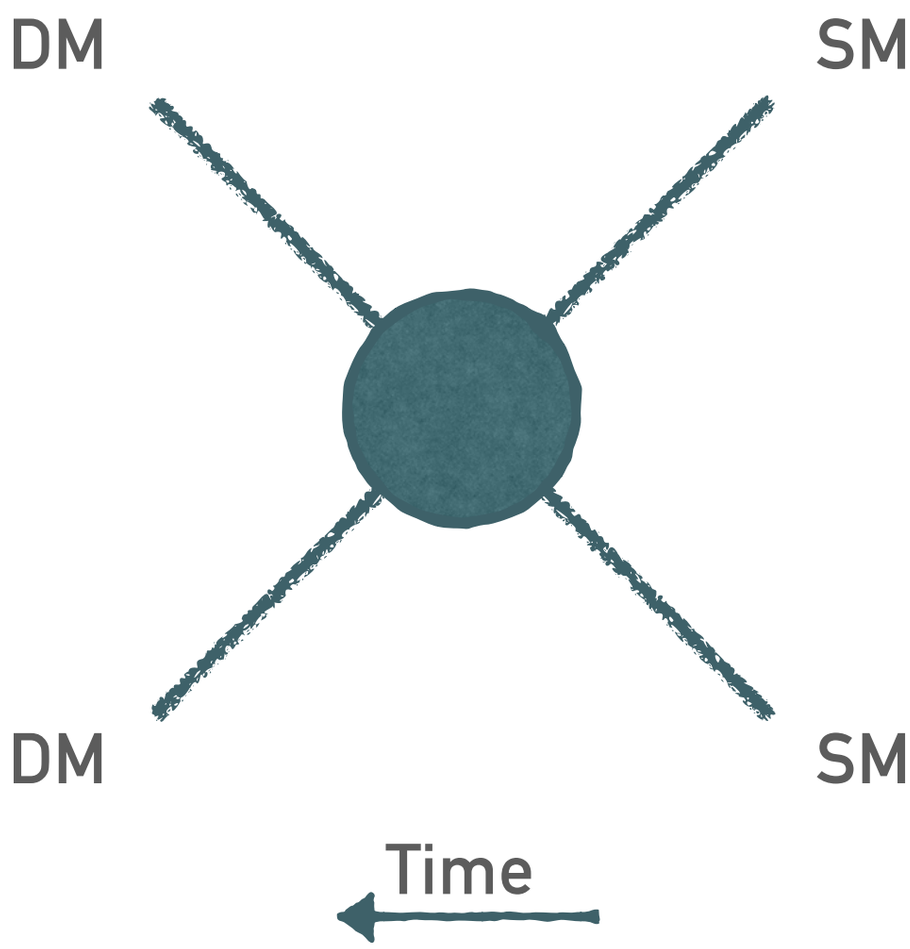
Thermal freeze-in

☑ Fine with BBN and N_{eff} (above masses of a few keV)



Thermal freeze-in

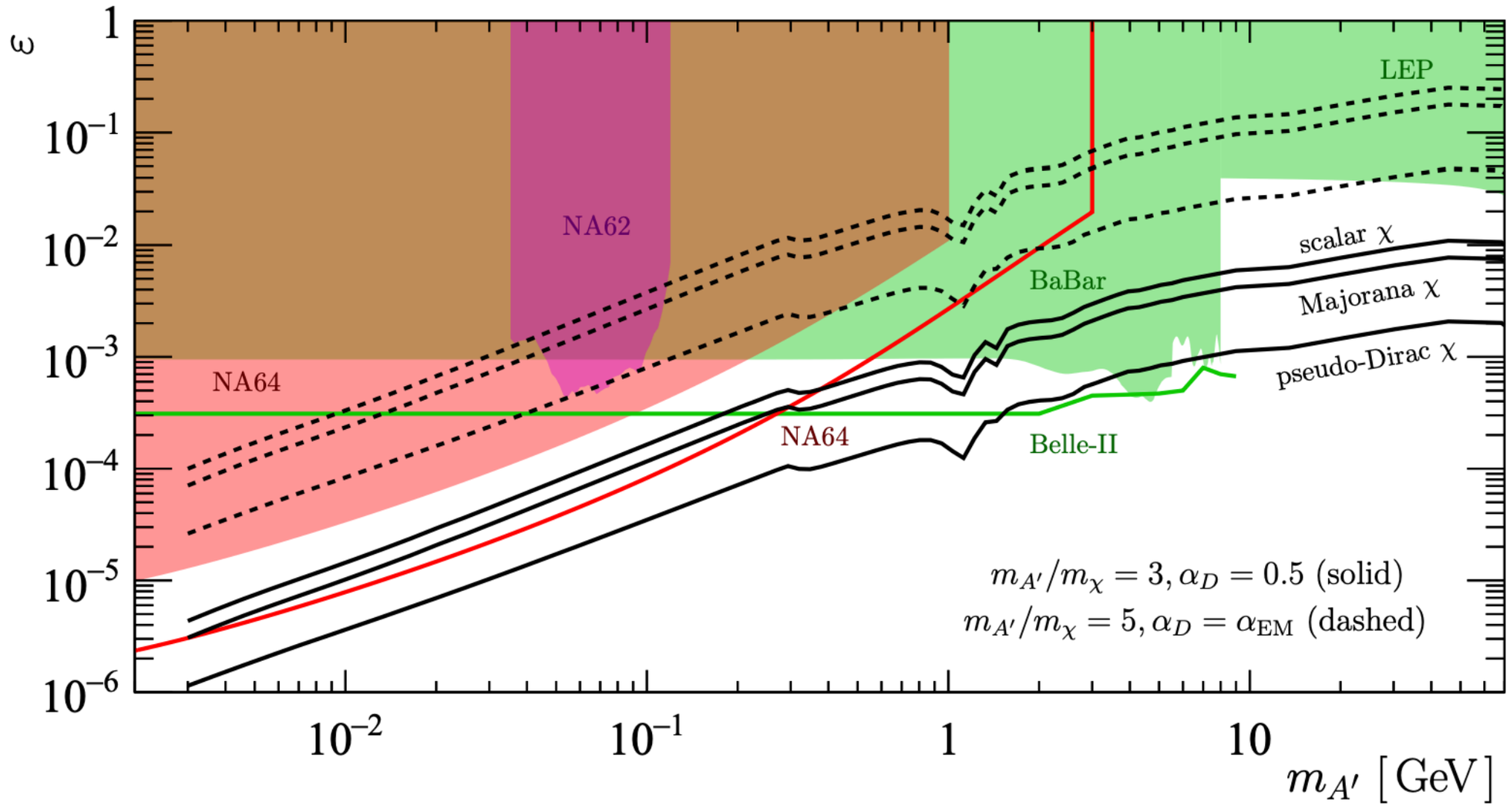
- [x] Fine with BBN and N_{eff} (above masses of a few keV)
- [ ] Not sensitive to initial conditions?



Thermal freeze-in

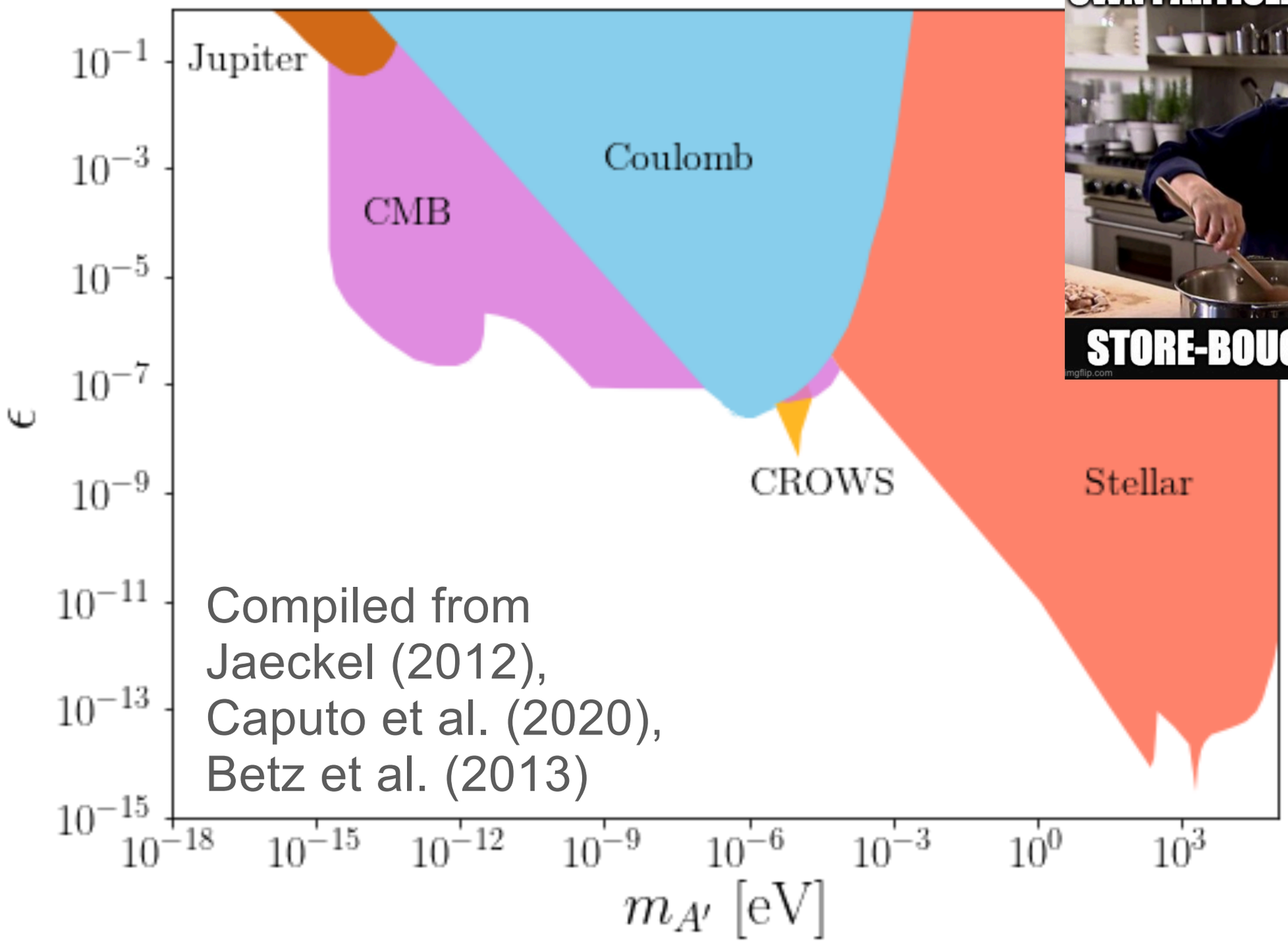
- [x] Fine with BBN and N_{eff} (above masses of a few keV)
- [ ] Not sensitive to initial conditions? Yes! If most of dark matter is made at low temperatures, implies light mediator

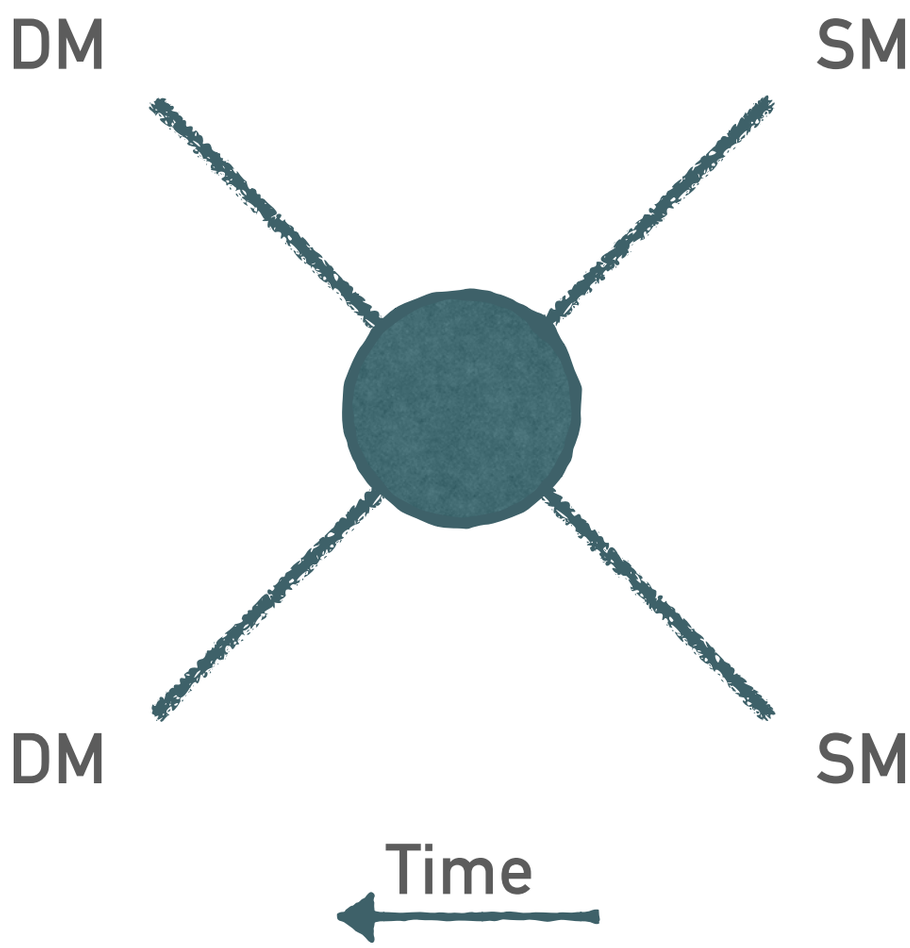
EVERYBODY'S FAVORITE MEDIATOR (DARK PHOTON)



e.g. Graham, Hearty, Williams (2021)

EVEN LIGHTER DARK PHOTONS DECOUPLE IN LOW-MASS LIMIT!

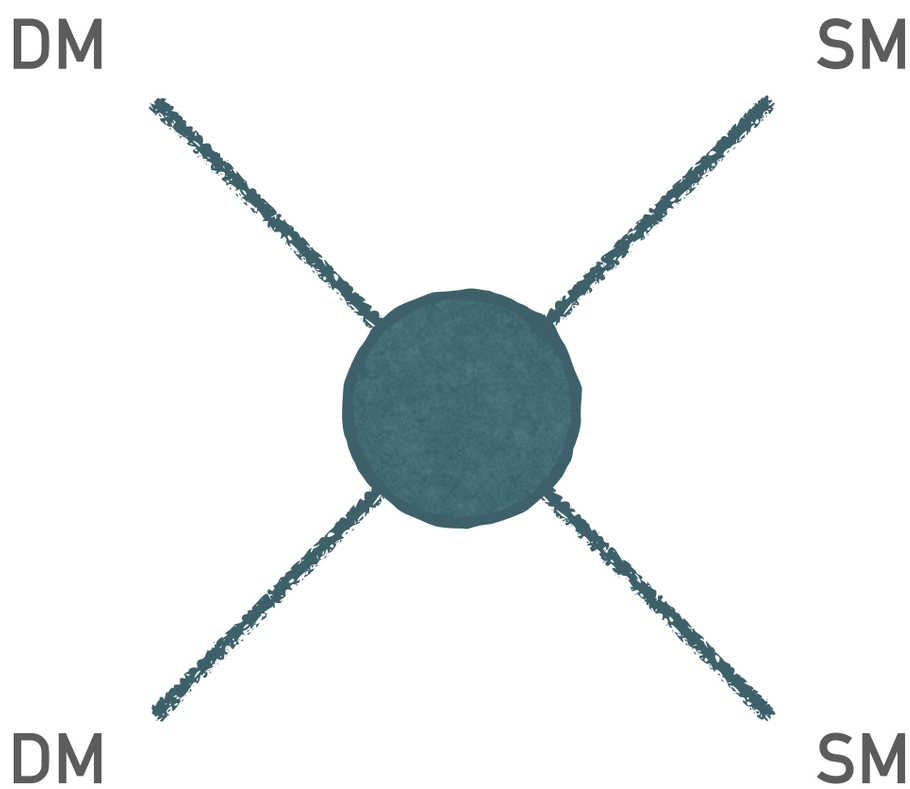




Thermal freeze-in

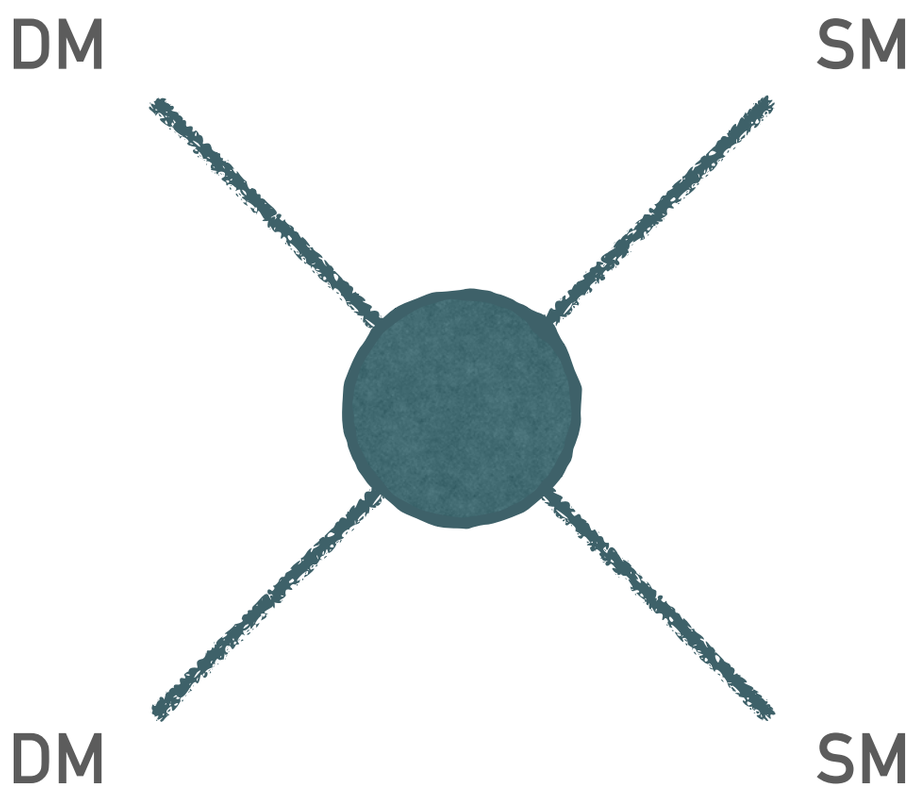
☑ Fine with BBN and N_{eff} (above masses of a few keV)

☑ Not sensitive to initial conditions thanks to light mediator



Thermal freeze-in

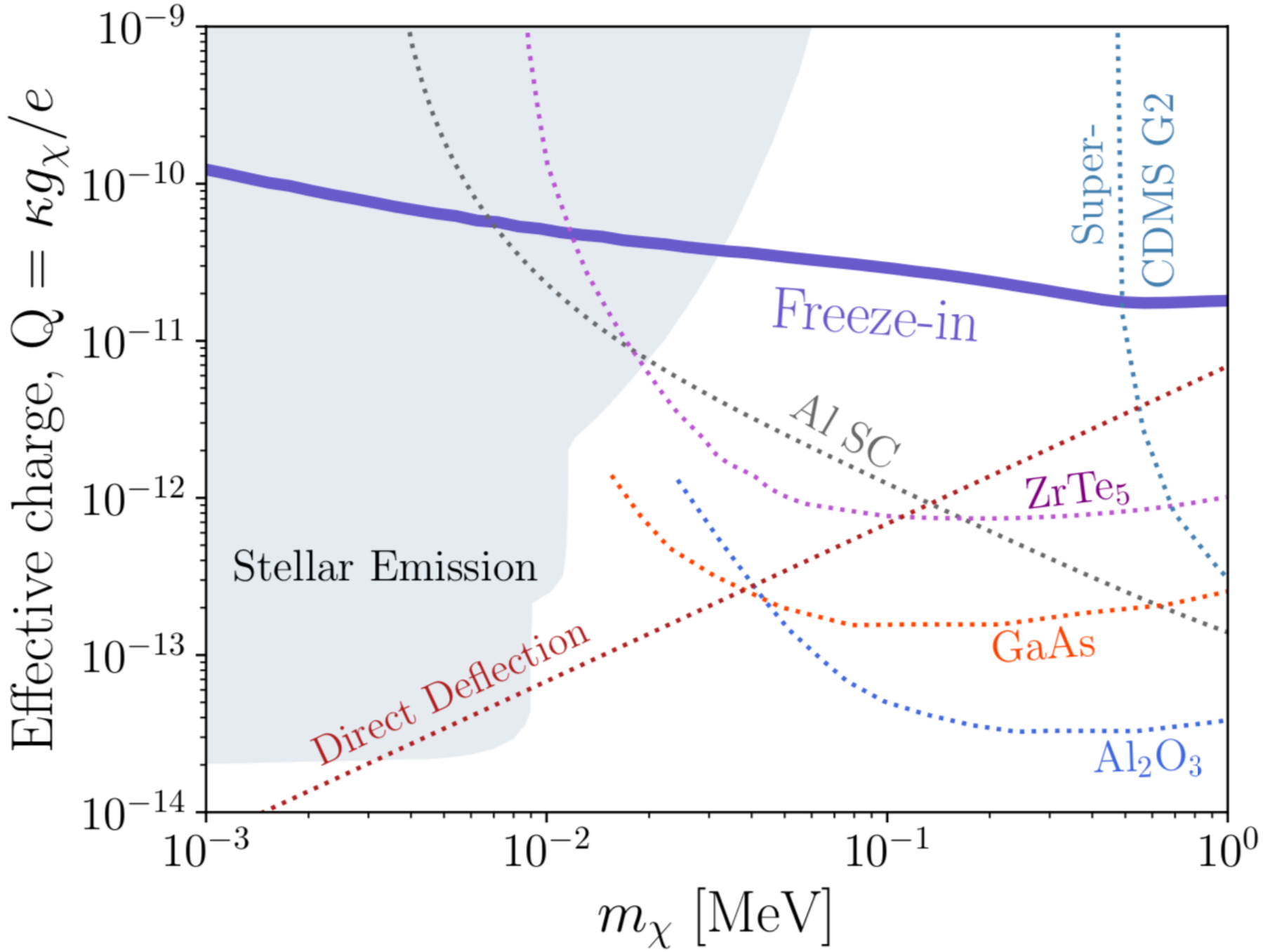
- [x] Fine with BBN and N_{eff} (above masses of a few keV)
- [x] Not sensitive to initial conditions thanks to light mediator
- [ ] Can we search for this if the couplings are so small that this particle is never thermal?



Thermal freeze-in

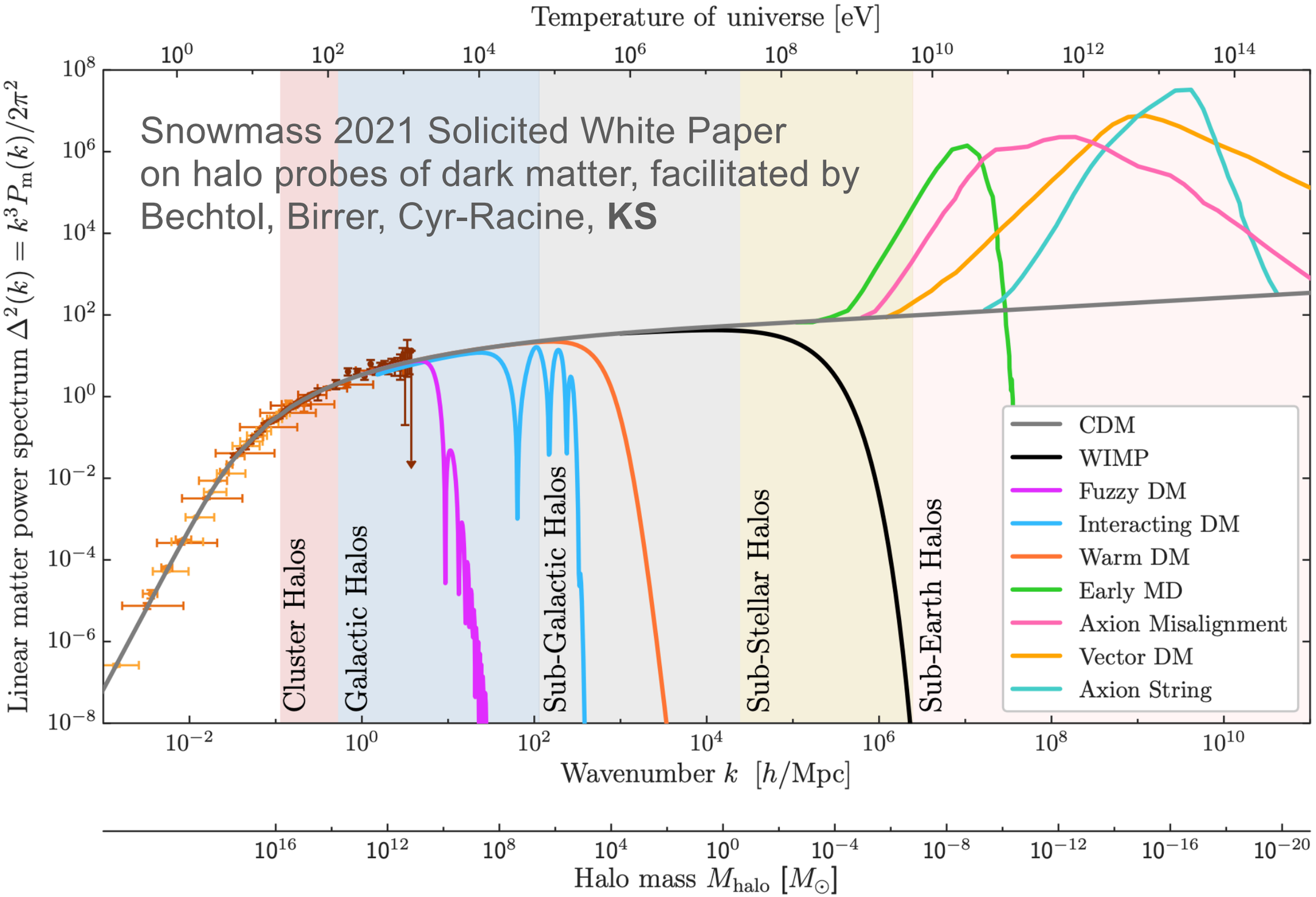
- [x] Fine with BBN and N_{eff} (above masses of a few keV)
- [x] Not sensitive to initial conditions thanks to light mediator
- [ ] Can we search for this if the couplings are so small that this particle is never thermal? Yes, in the lab, thanks to light mediator!

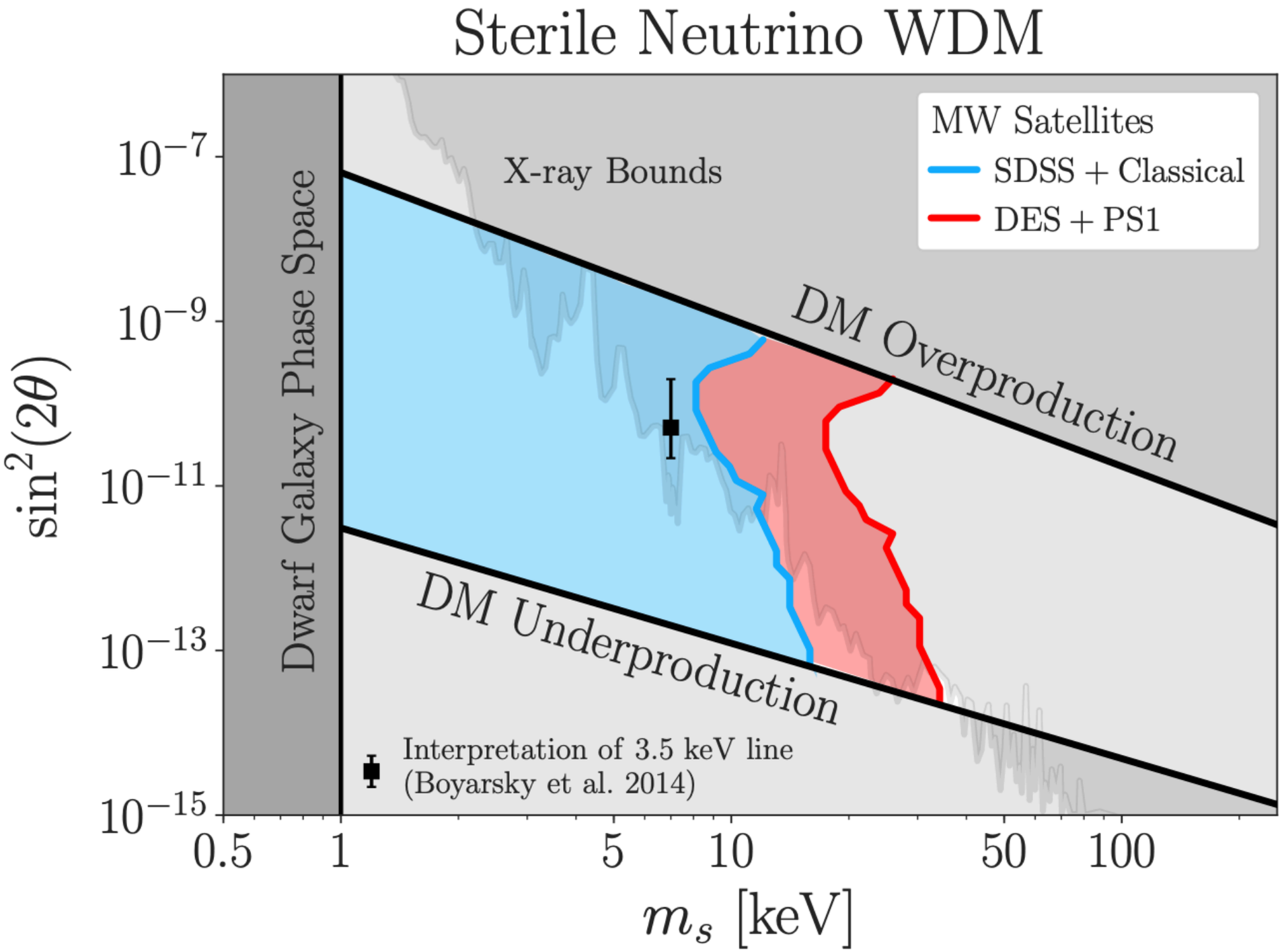
PROPOSED DIRECT DETECTION SENSITIVITY TO FREEZE-IN TARGET



Dvorkin, Lin, **KS** (PRD 2019)

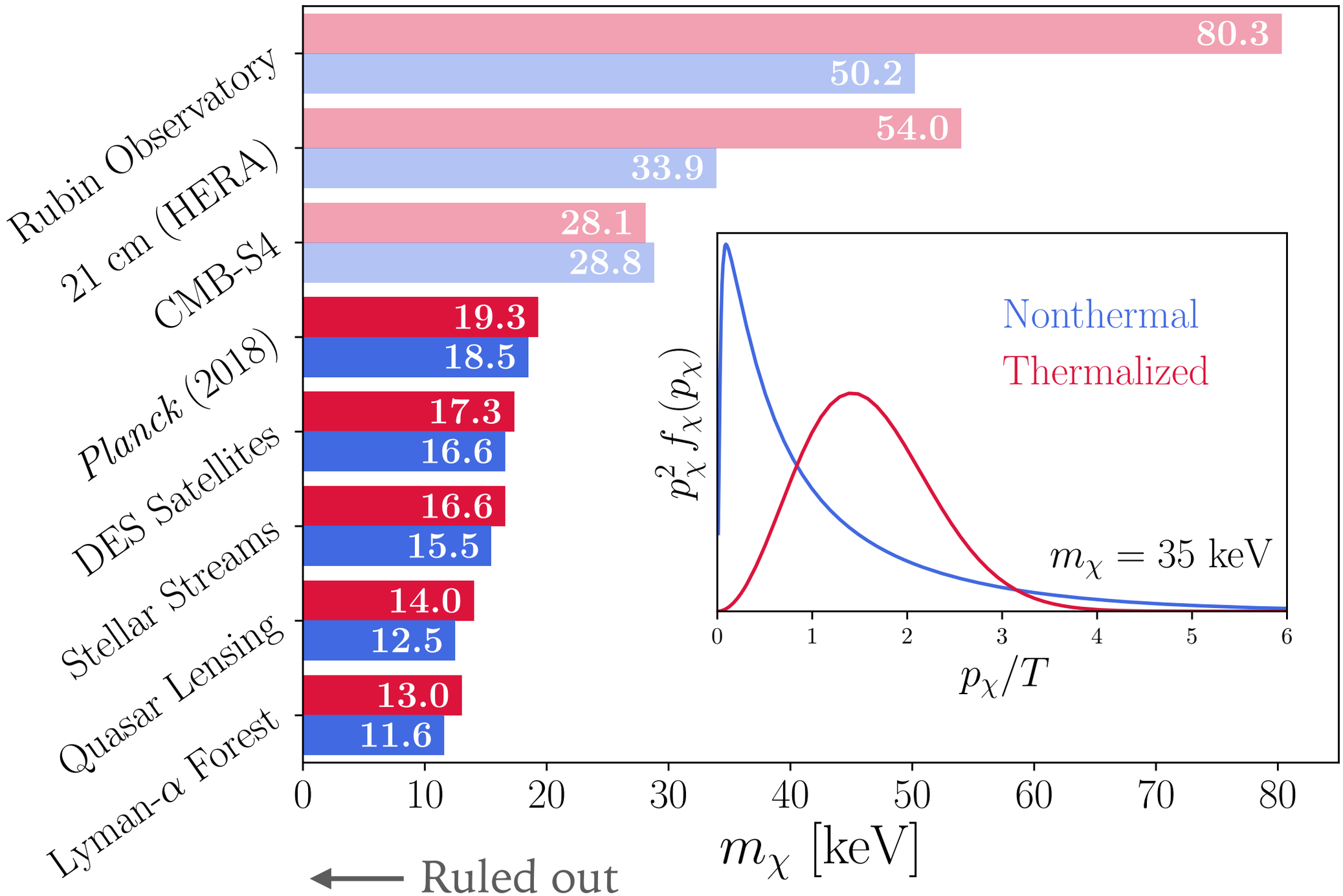
ANOTHER WAY TO TEST DARK MATTER PRODUCTION MECHANISM





DES collaboration (Nadler et al. 2020)

COSMOLOGICAL CONSTRAINTS/PROJECTIONS ON FREEZE-IN TARGET



Dvorkin, Lin, **KS** (PRL 2021)

Lesson learned: adding dark sector doesn’t necessarily make dark matter less detectable, it can make it ***more*** detectable in a wider range of places

ANOTHER QUICK EXAMPLE

GRAVITY

WEAK FORCE

NEW FORCE?

?

ELECTROMAGNETISM

STRONG FORCE

u c t

d s b

(quarks)

(protons & neutrons made of these)

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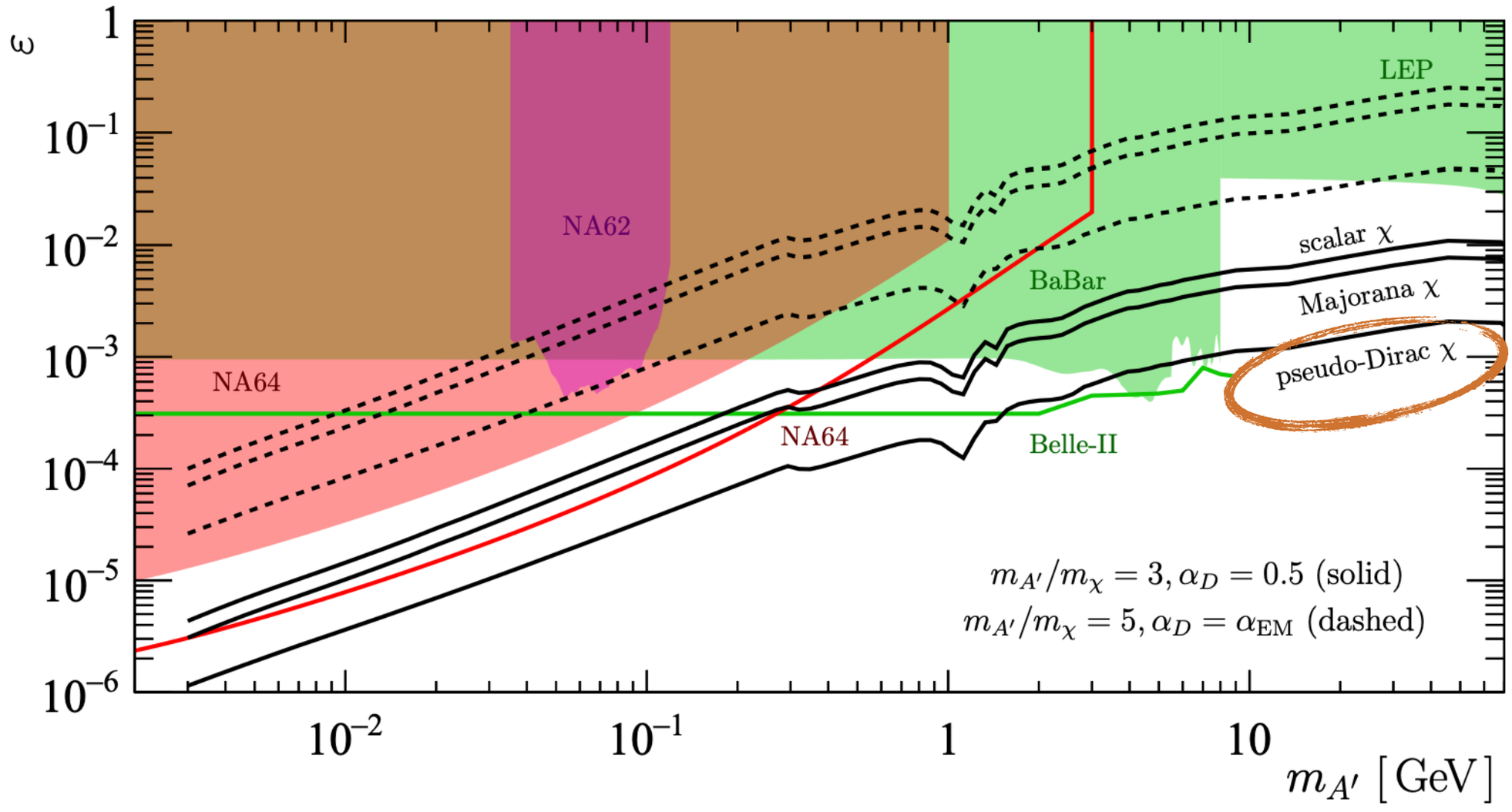
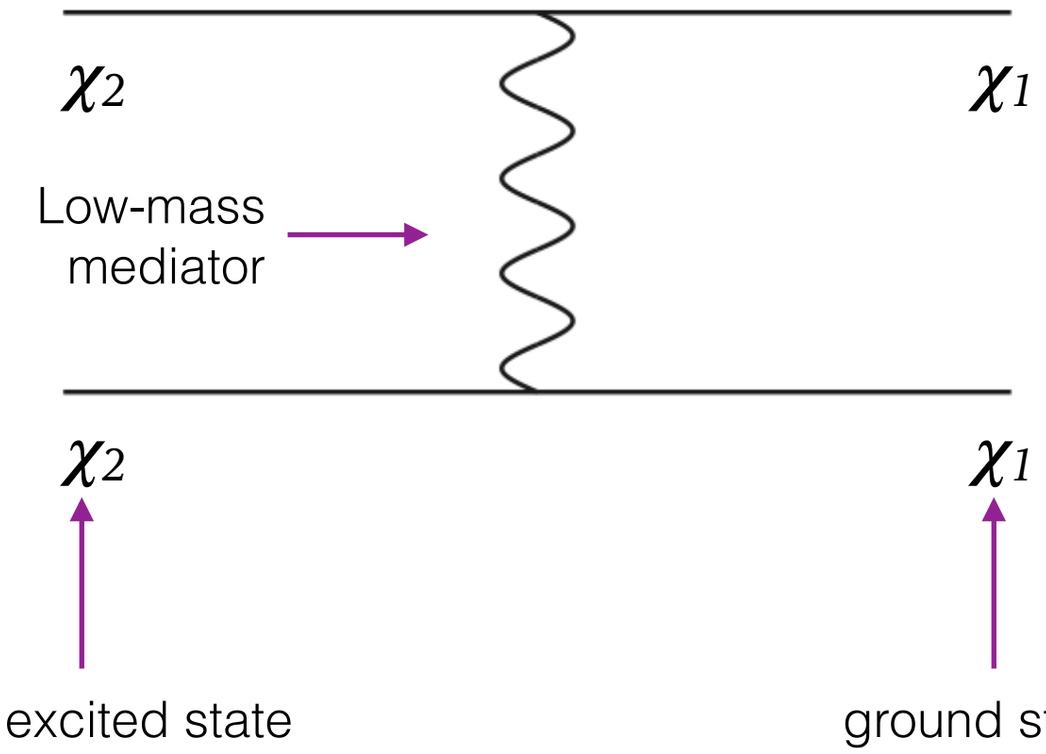


Analogous model but decouple DM from the SM

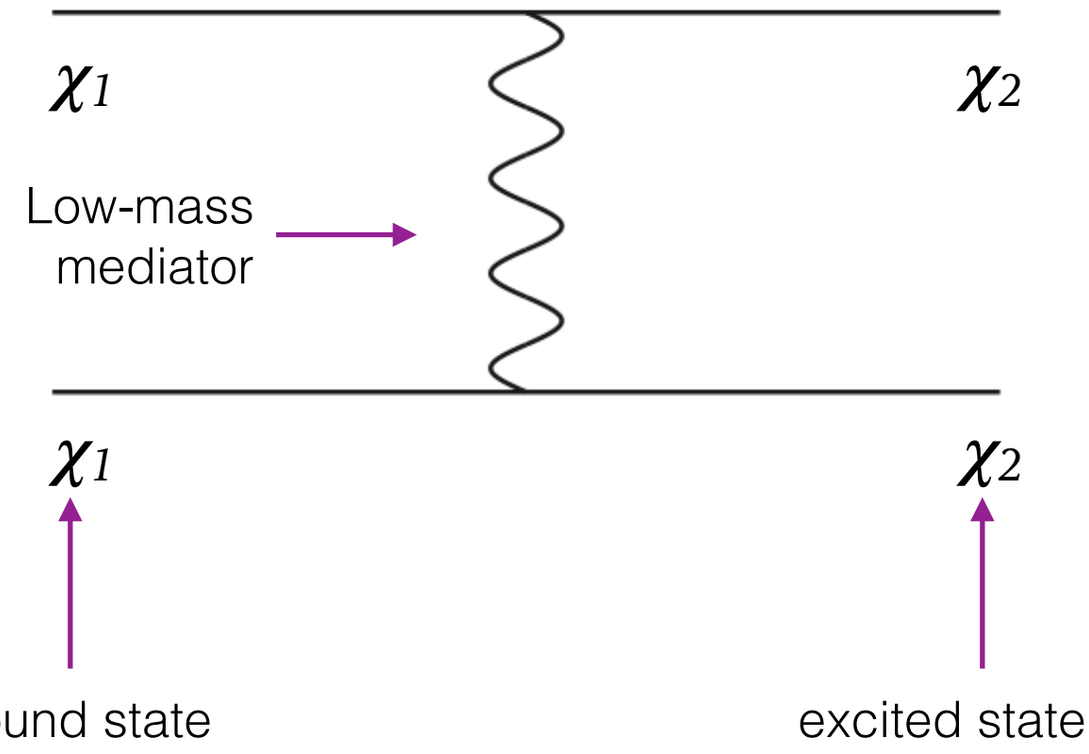
e.g. Graham, Hearty, Williams (2021)

CONVERTING BETWEEN MASS AND KINETIC ENERGY

Exothermic Scattering



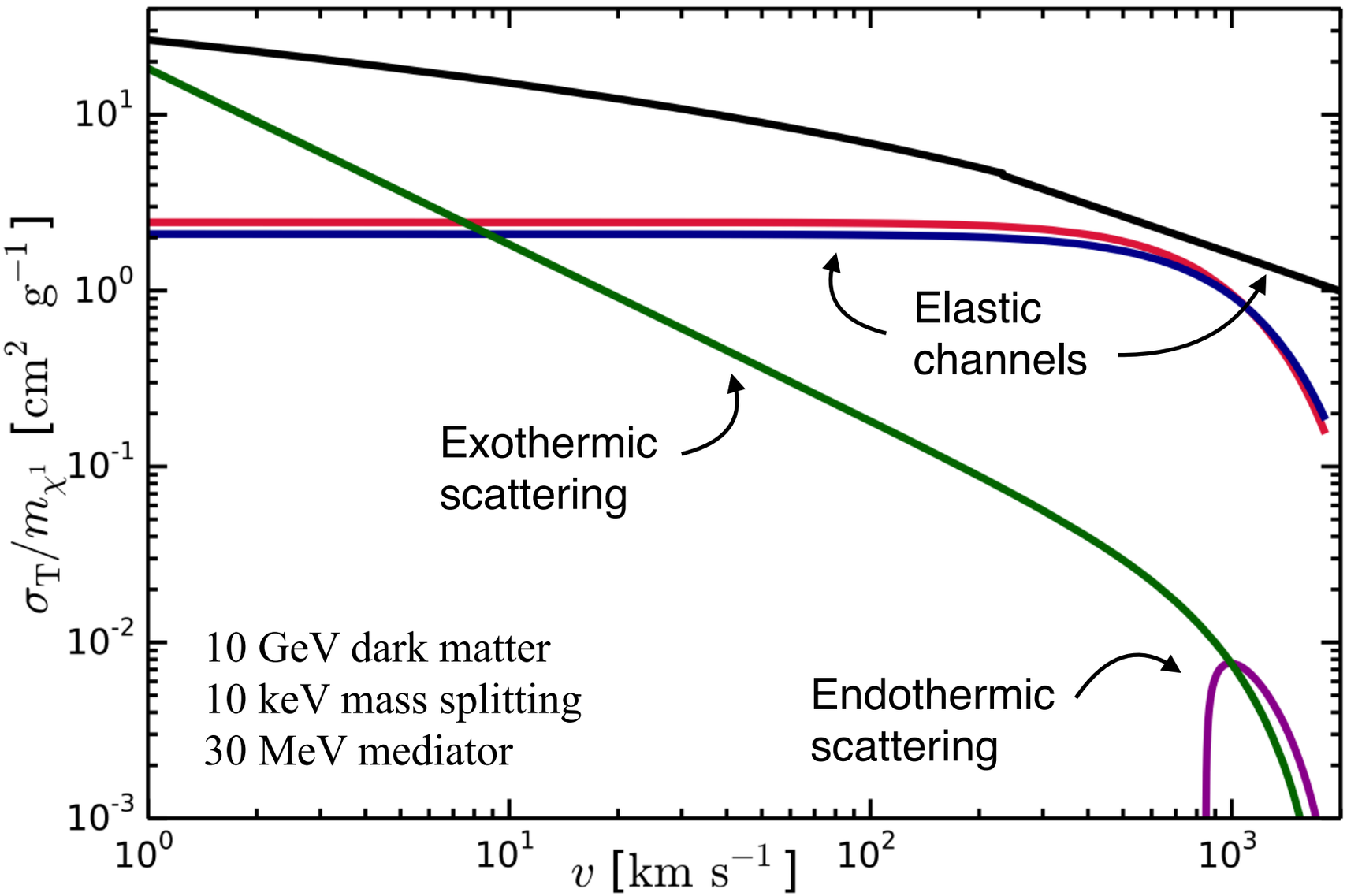
Endothermic Scattering



Naturally velocity-dependent scattering

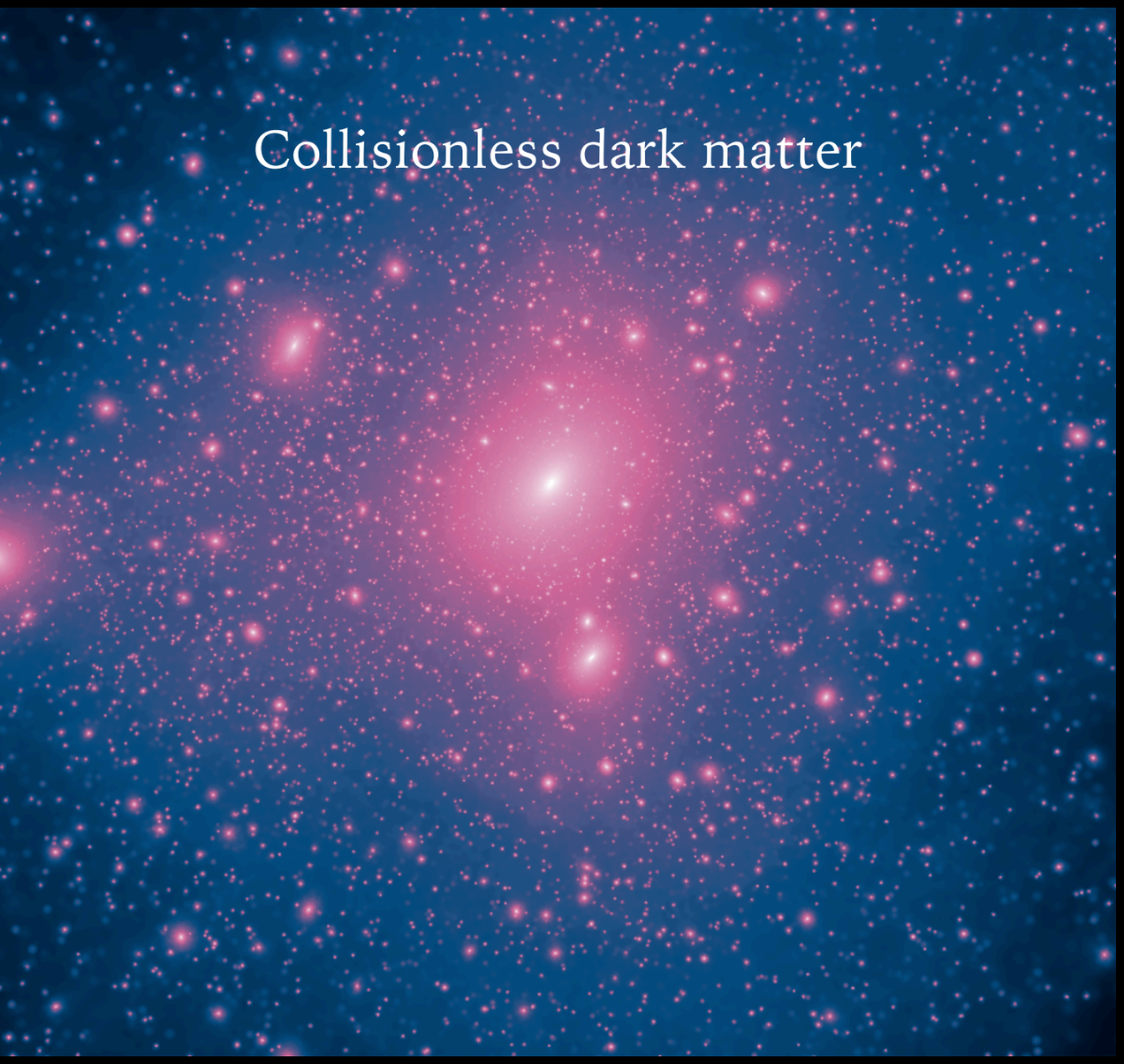
KS & Slatyer JCAP (2015)

EXOTHERMIC SCATTERING CAN BE EFFICIENT AT LOW VELOCITIES



KS & Slatyer JCAP (2015)

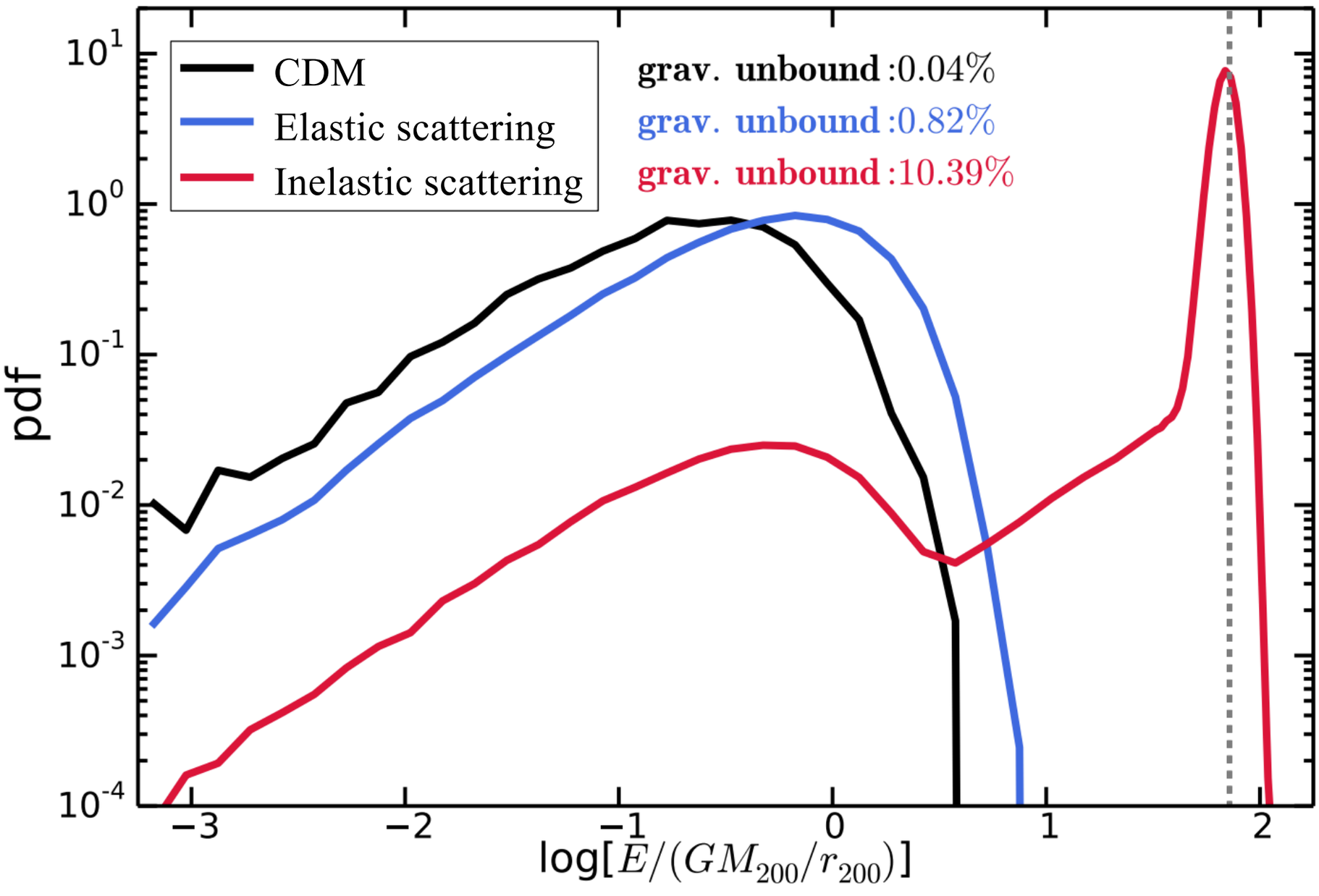
WHAT HAPPENS TO DWARF GALAXIES IF YOU ADD INELASTIC SCATTERING?



Vogelsberger, Zavala, **KS**, Slatyer MNRAS (2019)
also work in progress with Stephanie O'Neil, Saniya Heeba

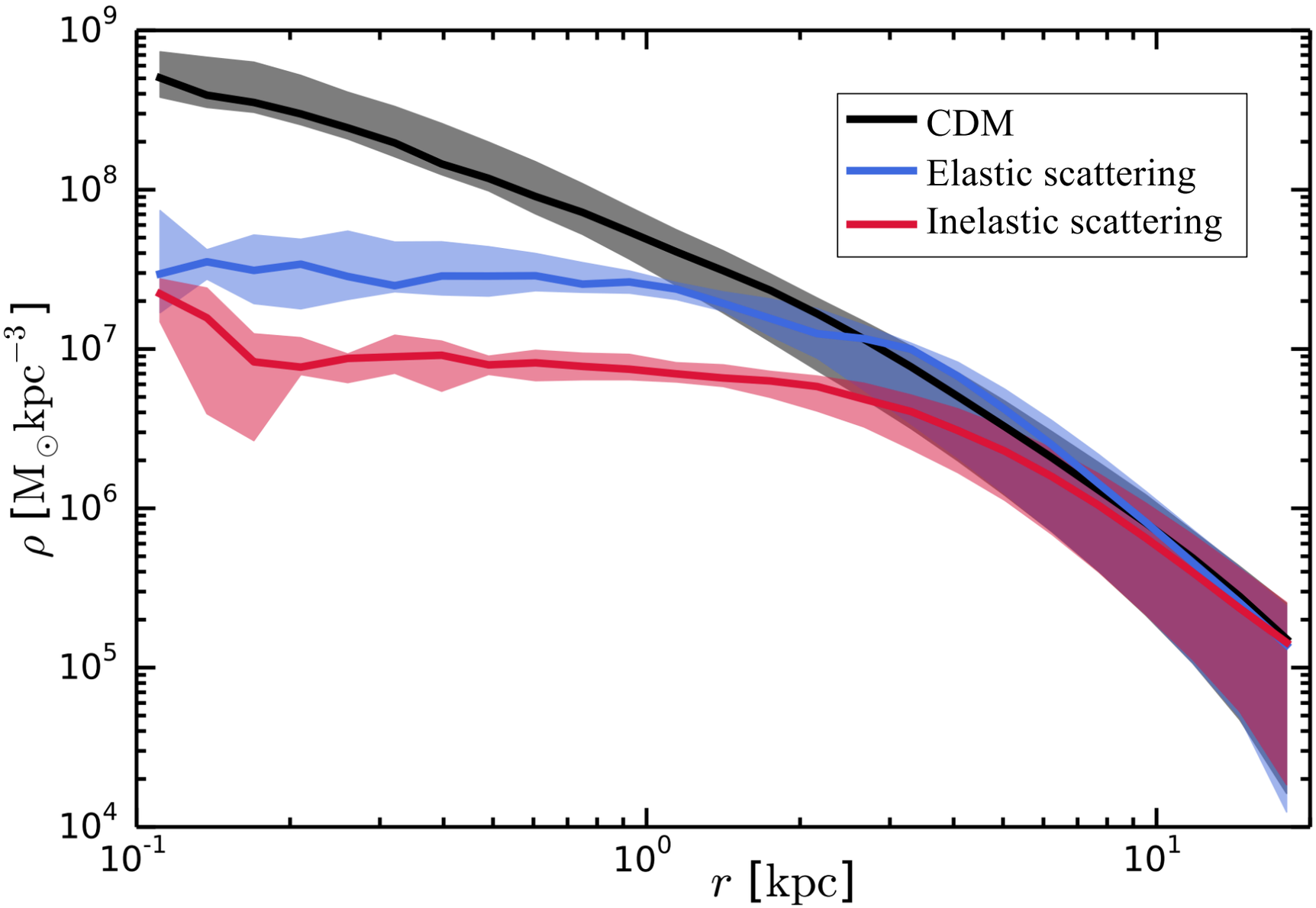
DARK MATTER PARTICLES GET KICKED OUT OF THEIR HALOS

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



DENSITY PROFILES GET SMEARED OUT

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



SERIOUS IMPLICATIONS FOR DWARF GALAXIES

Lesson learned: in some cases, astrophysics might be essential for understanding dark sectors (is this particle physics, astronomy, or just good science?)

DARK SECTORS BEYOND WHAT I'VE DISCUSSED

- More complicated thermal histories involving more complicated dark sectors (SIMPs, ELDERs, KINDERs, cannibal DM, forbidden DM, co-annihilation/scattering, "Pandemic DM", etc etc etc) with unique cosmologies as well as an accompanying need for mediator & direct detection searches
- Dark sectors invoked to explain anomalies (see talk by McKeen), can be independent of DM
- Dark sectors involved in generating baryon asymmetry
- Dark sector solutions to little hierarchy problem (i.e. twin Higgs and variations, some of which have mediators)
- Lots more!

The diversity of dark sectors demands a diversity of approaches and observables, including terrestrial experiments and the “poor man’s particle accelerator” aka the Universe

SUMMARY

- We can *confidently* infer from astrophysical observations that there is matter that interacts with gravity and does not behave like regular matter
- Now trying to understand if this is a new particle with its own associated forces, other auxiliary particles, etc.
- Dark sectors motivate new searches at colliders and new approaches to direct detection
- It's a big Universe! Lots of complementarity between probes and room for creativity in exploring the dark sector