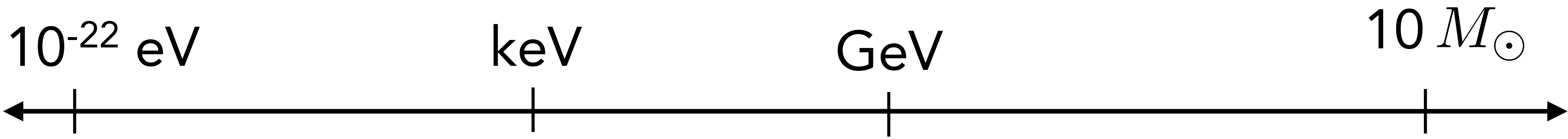
Light and ultralight dark matter: theory and detection

Tongyan Lin
UCSD

CIPANP 2018

Mass scale of dark matter



There are well-defined targets (lampposts) testable with current or planned searches, over an enormous mass range.

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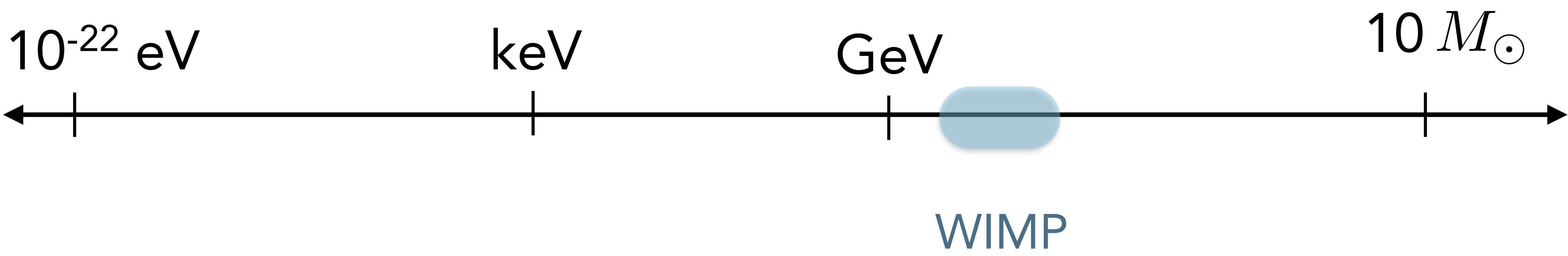

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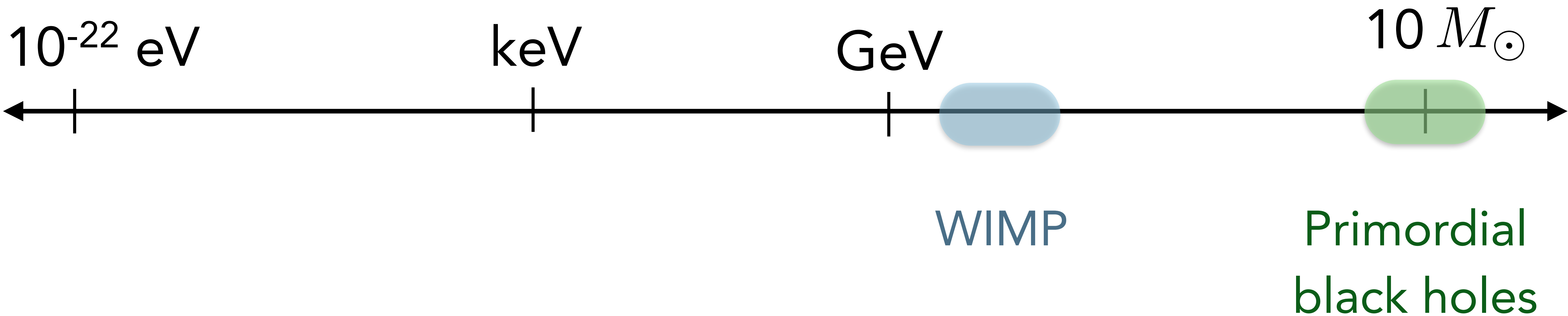

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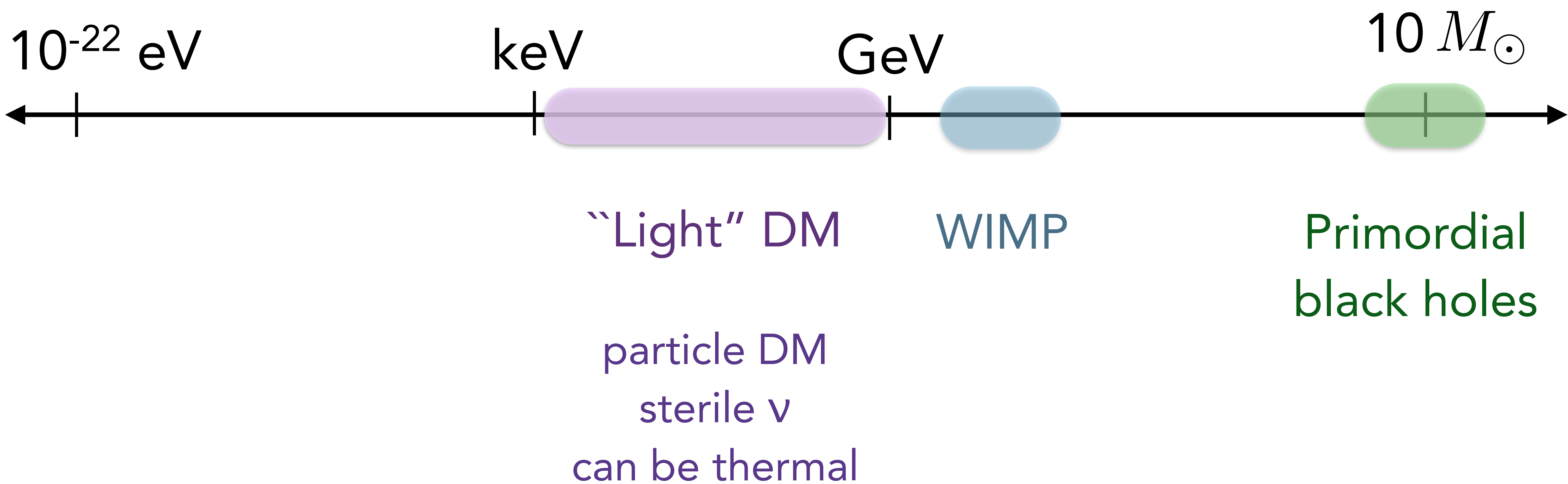

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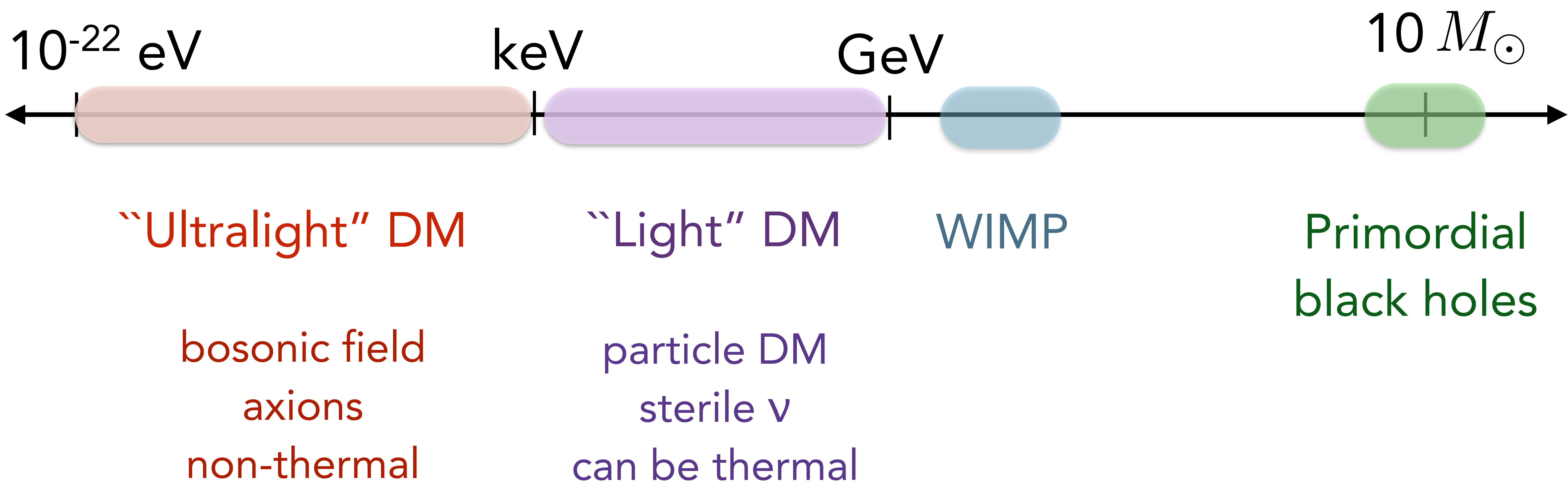

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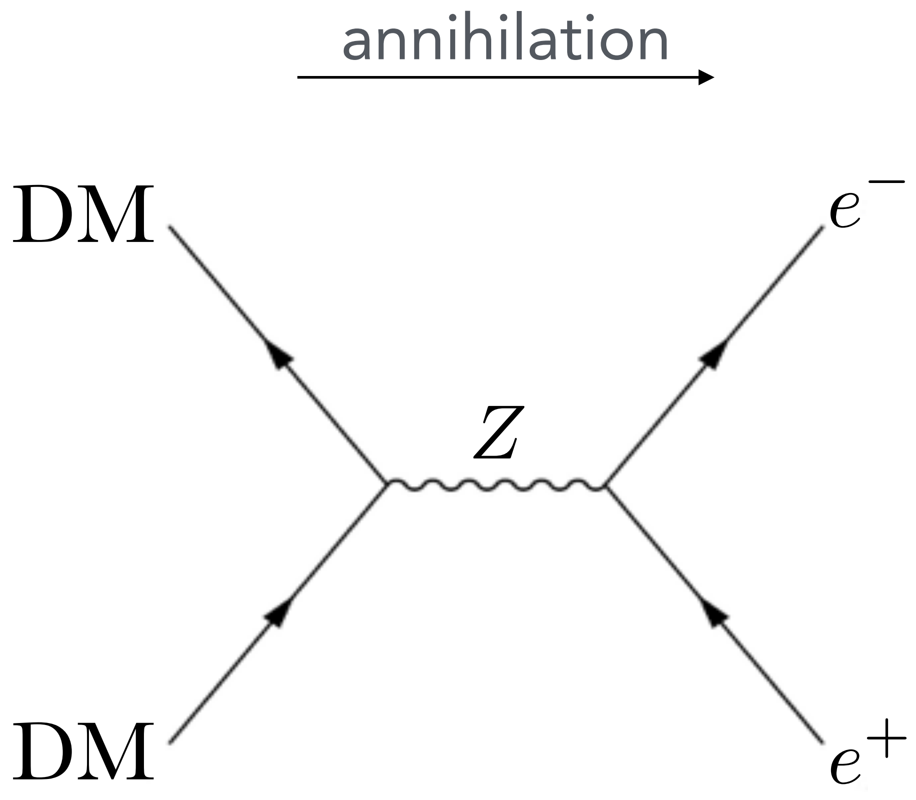
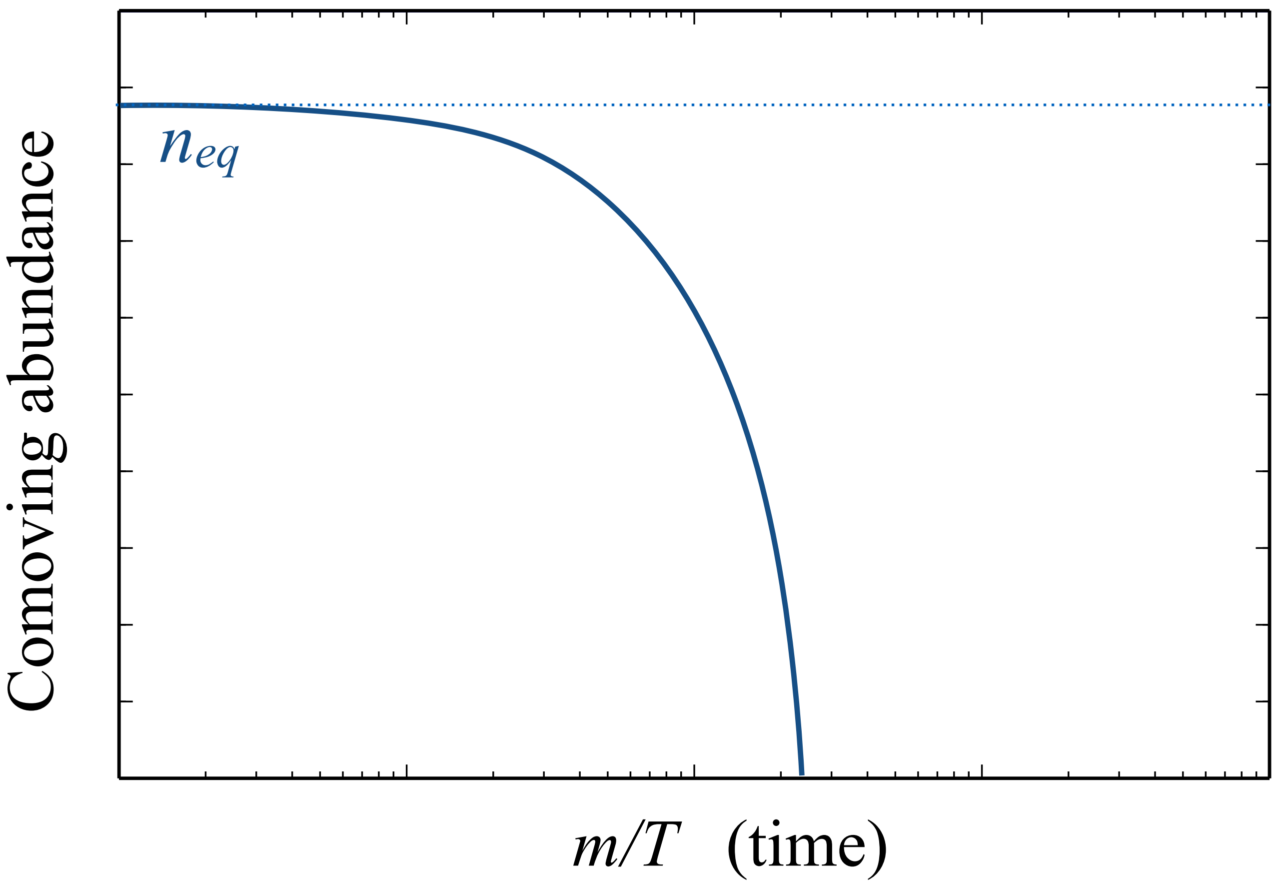
``Light” DM

(M = keV-GeV)

WIMP dark matter





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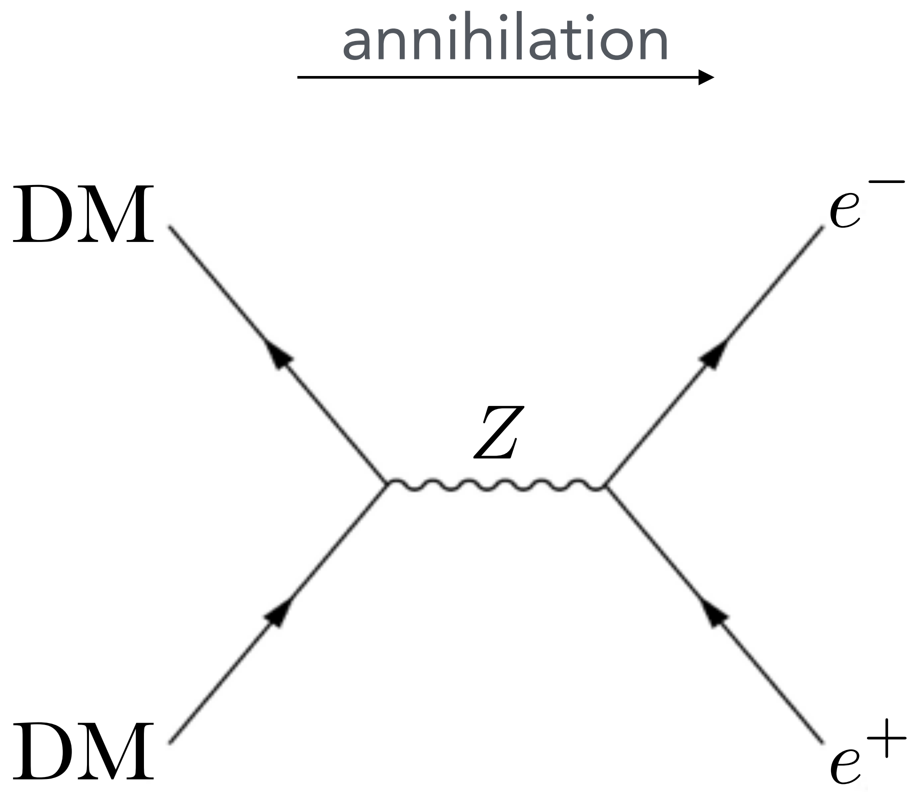
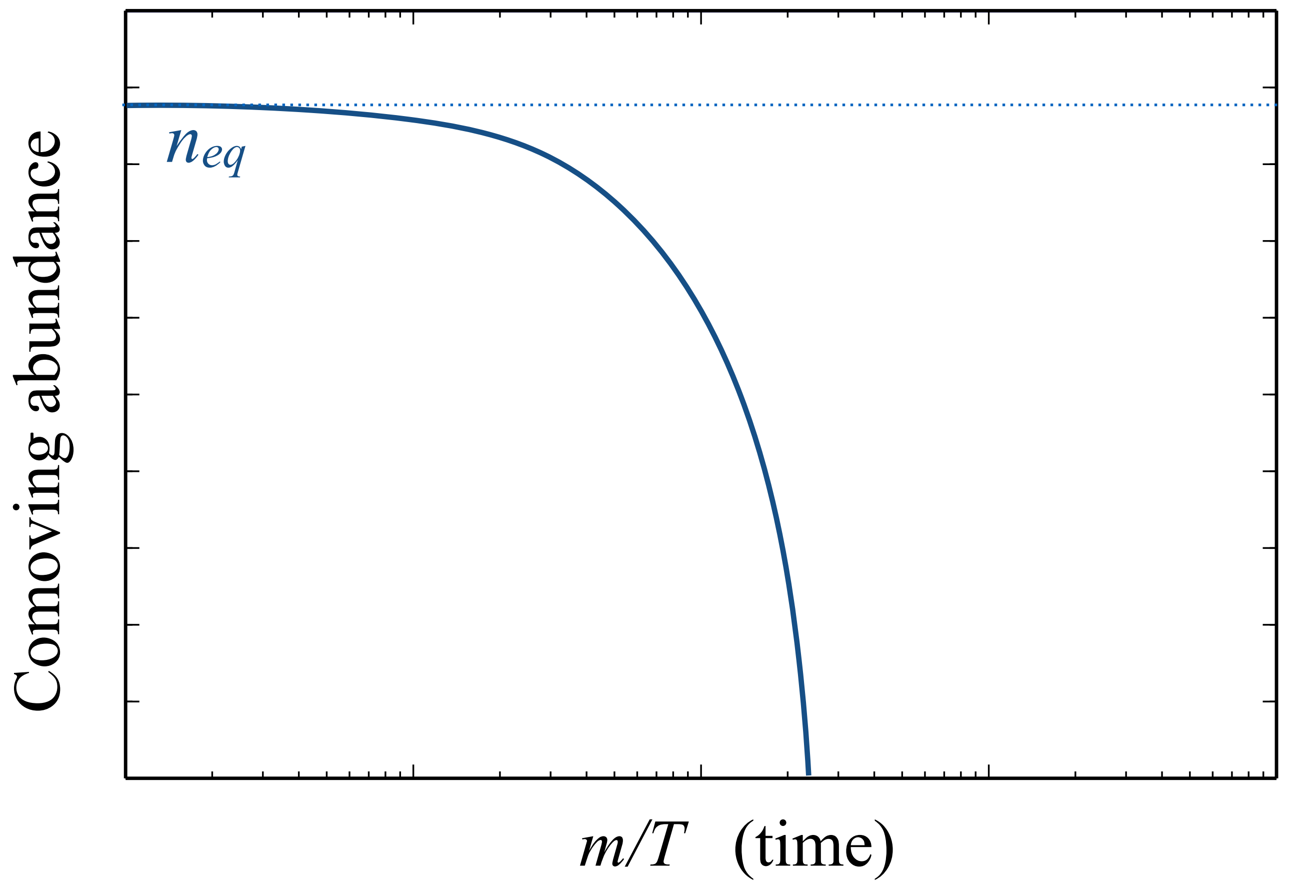




Thermal Freeze-out

Number density ``frozen" when expansion > annihilation.

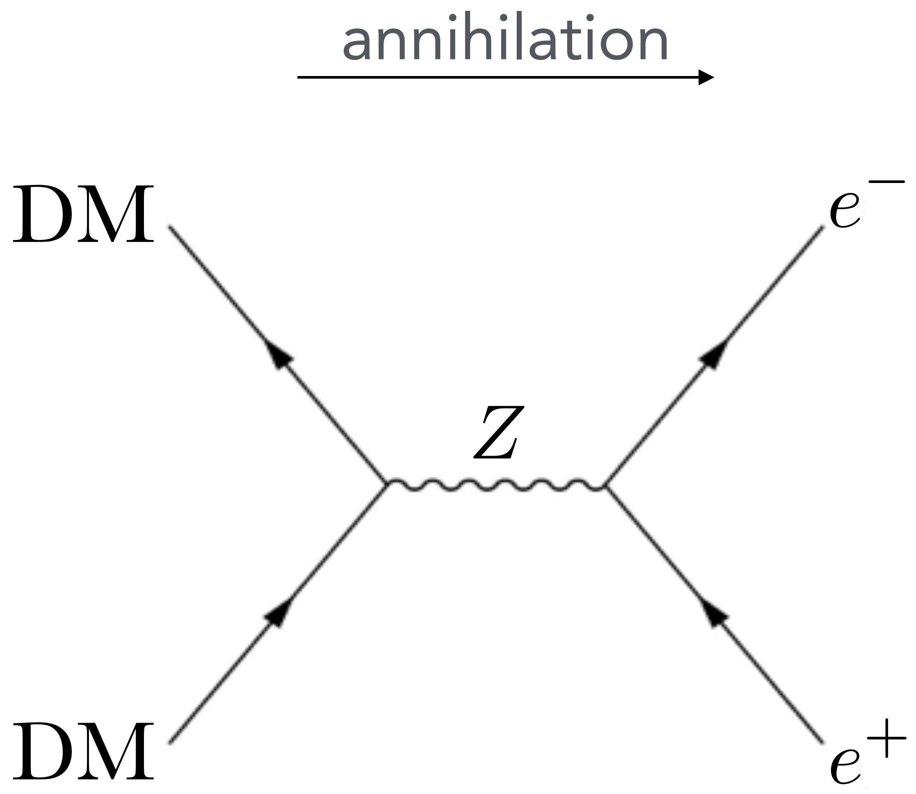
$$\Gamma = n \langle \sigma v \rangle$$

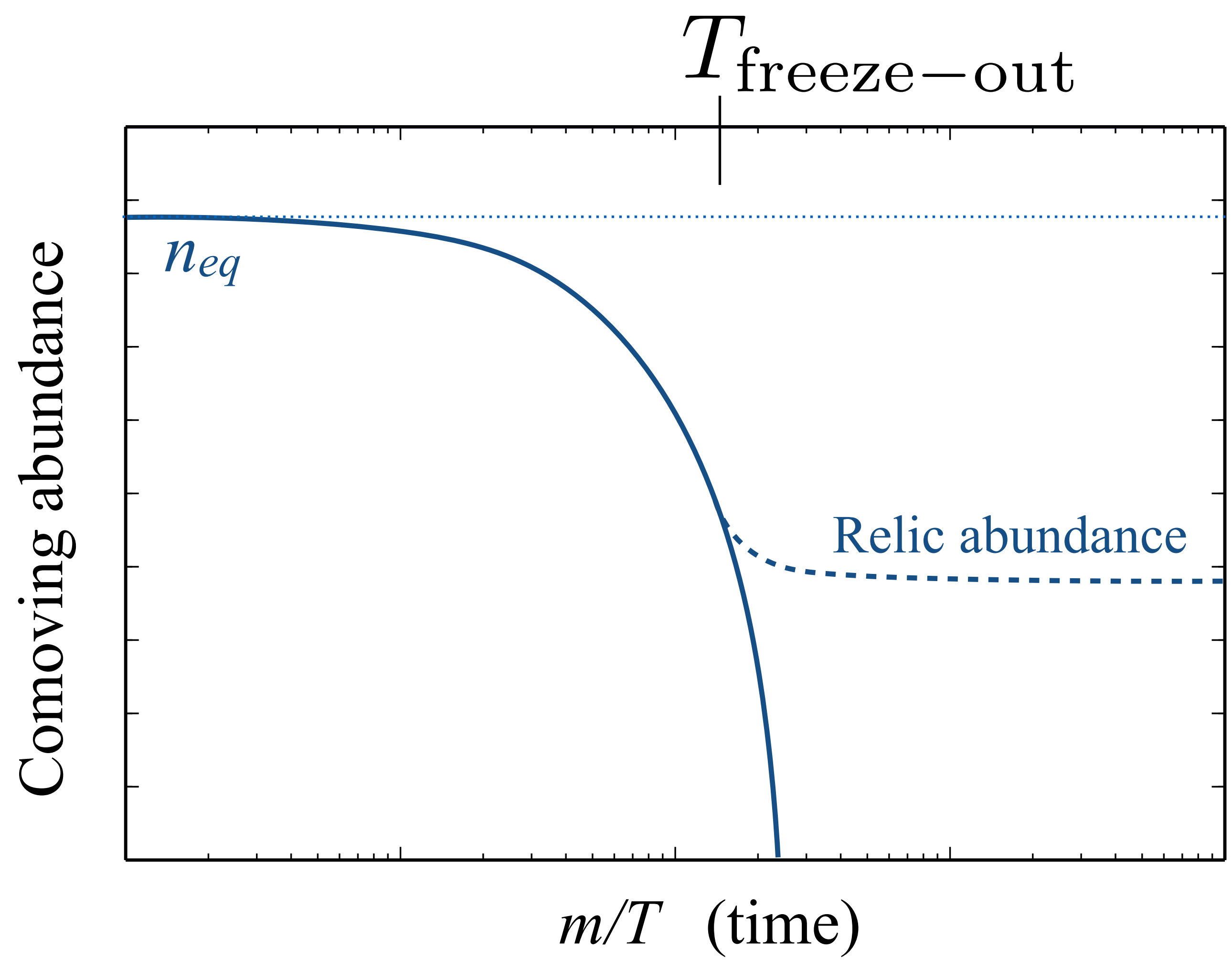
Rate of expansion of universe

Early universe thermodynamics

Particle physics: rate of annihilation

WIMP dark matter





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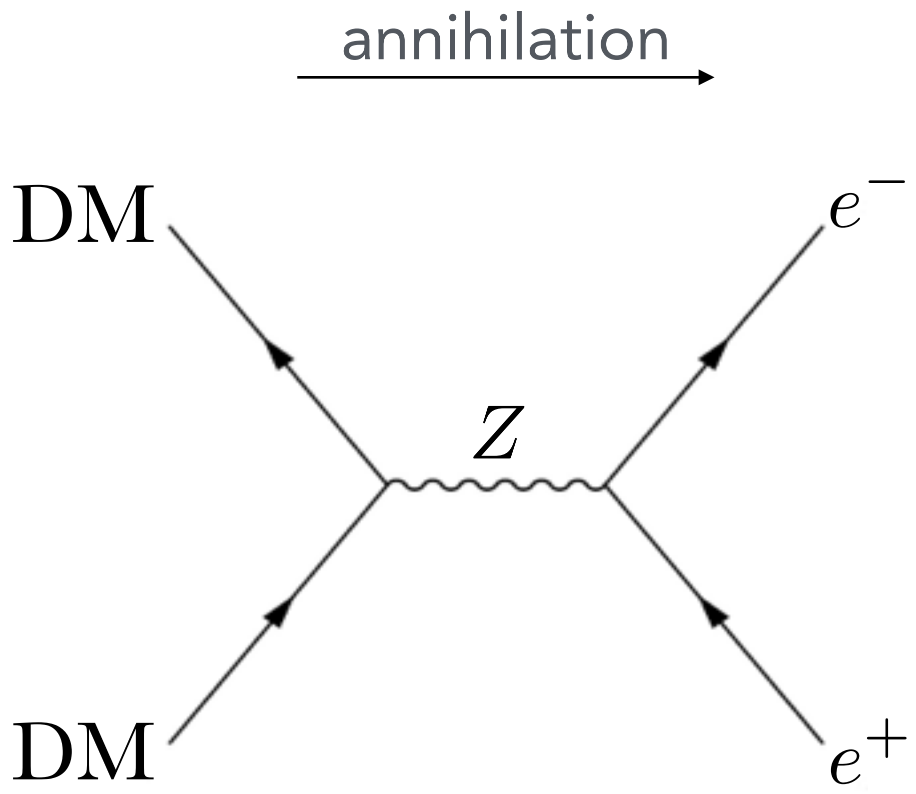
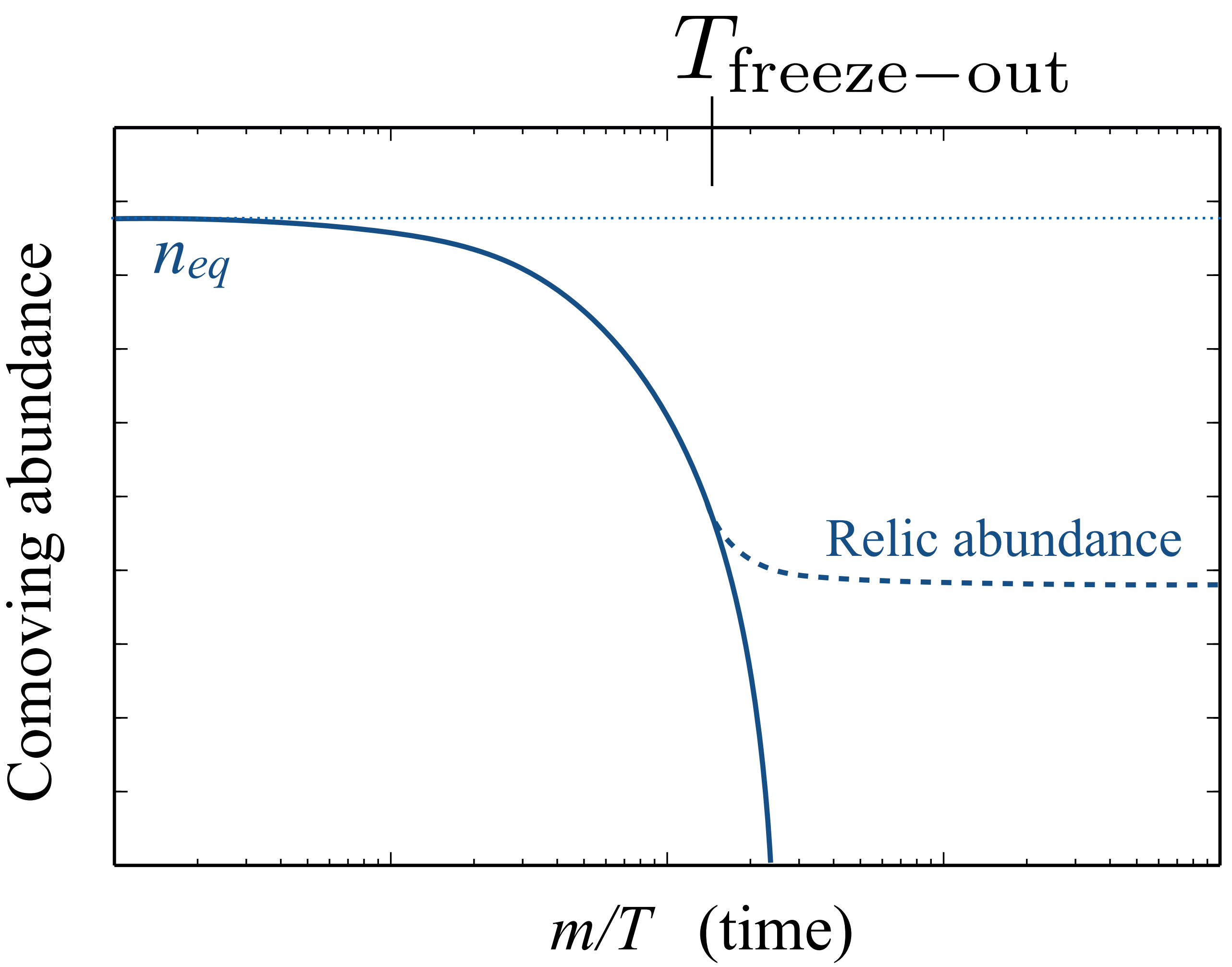


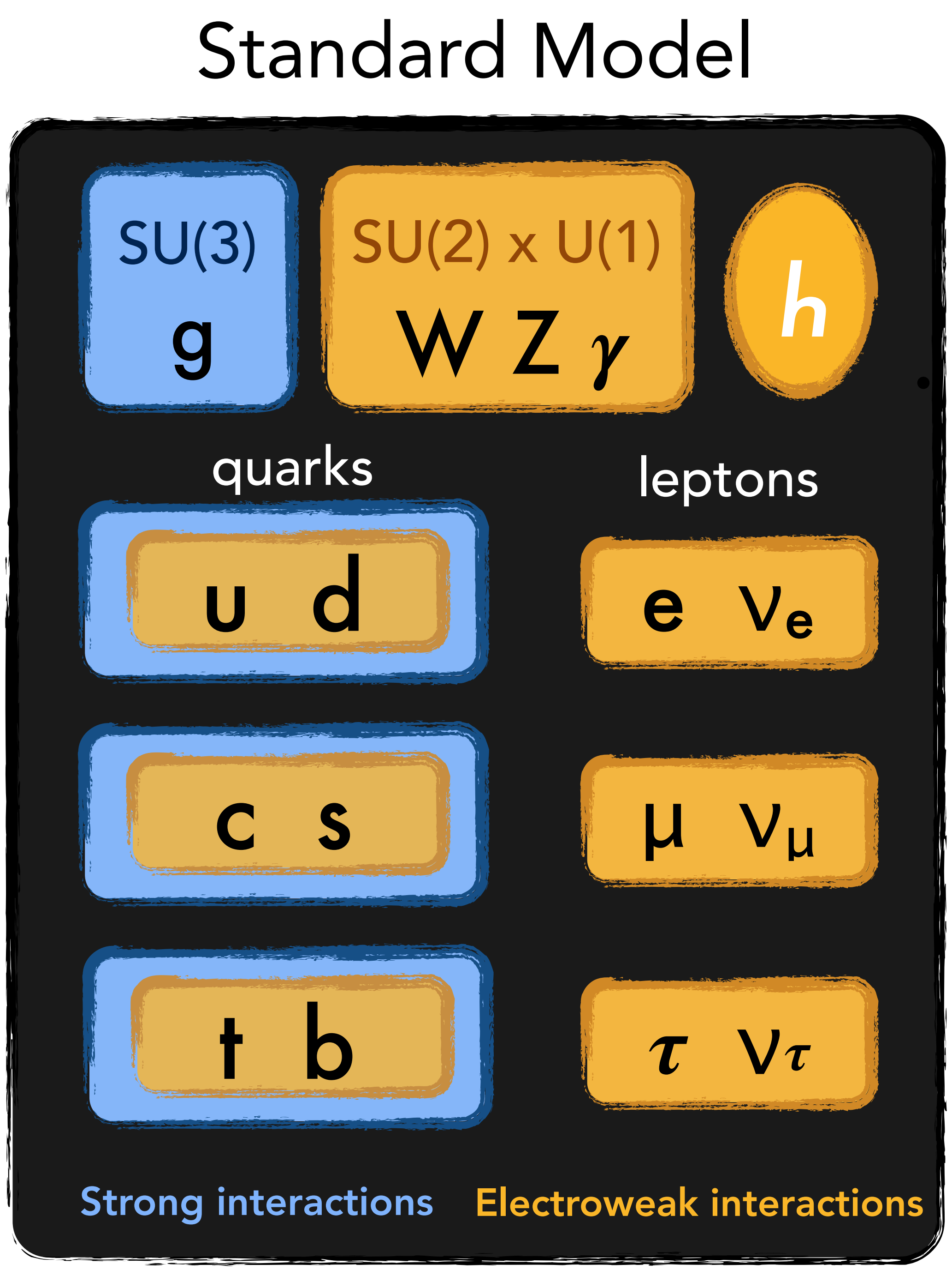


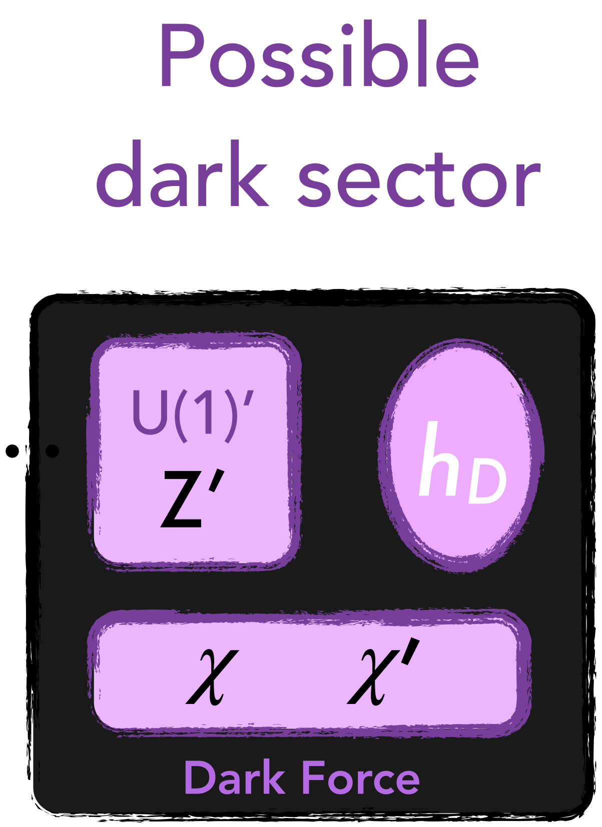
$$\langle \sigma v \rangle \sim \frac{\alpha_W^2}{\mathrm{TeV}^2} \longrightarrow \Omega h^2 \sim 0.1$$

Favored DM mass range of 10 GeV - 10 TeV

May be tied to new physics at the weak scale

Dark sectors





Theory landscape includes dark gauge forces, flavor, higgs, inelastic DM, etc.

Light dark matter

Heuristic arguments pointing towards weak scale change with the presence of new mass scales and interactions

Processes depleting the dark matter number density:

Light dark matter

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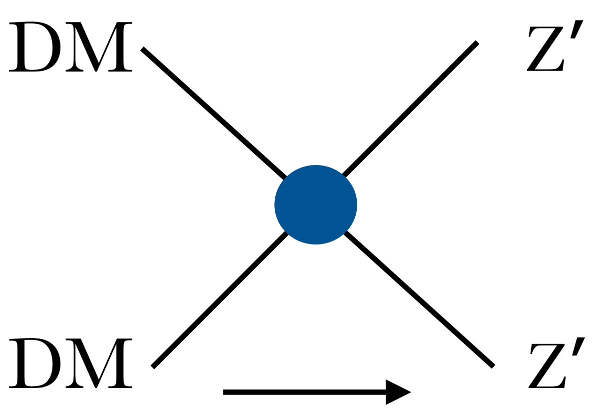
Processes depleting the dark matter number density:

annihilation to light mediators



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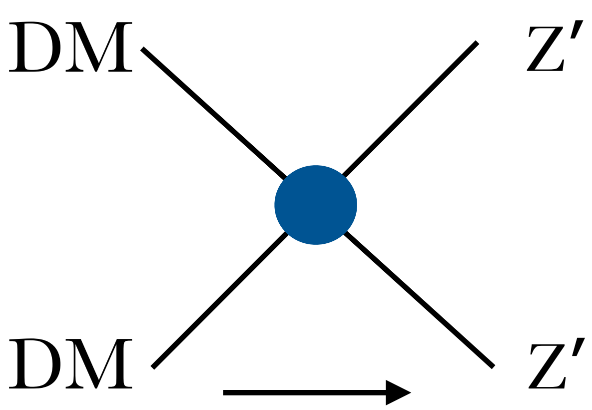

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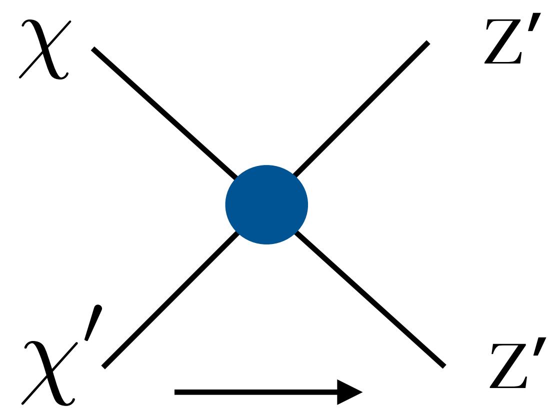
co-annihilation and co-scattering



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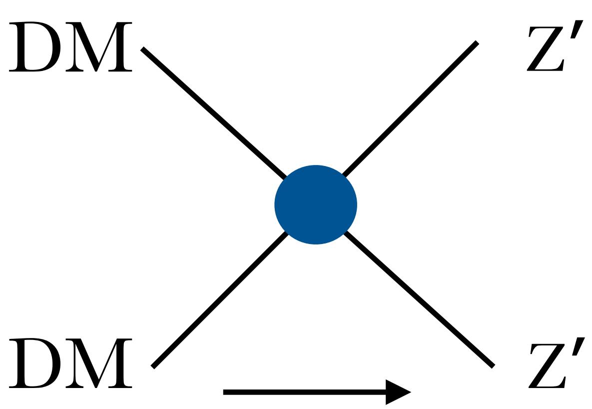

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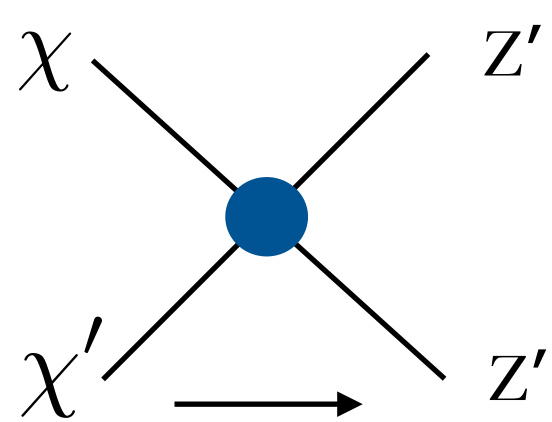

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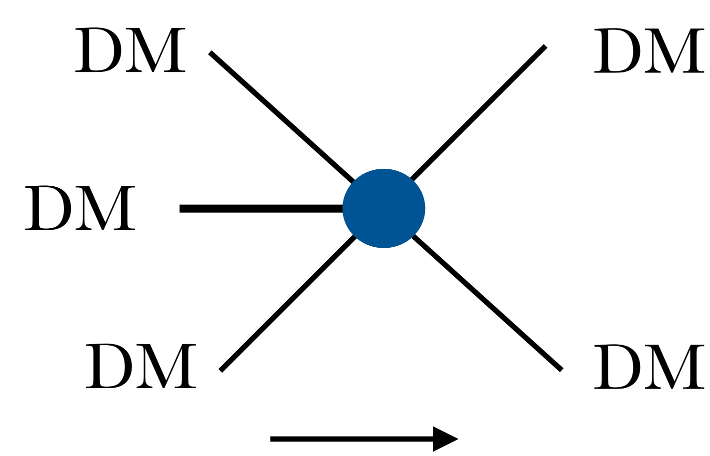
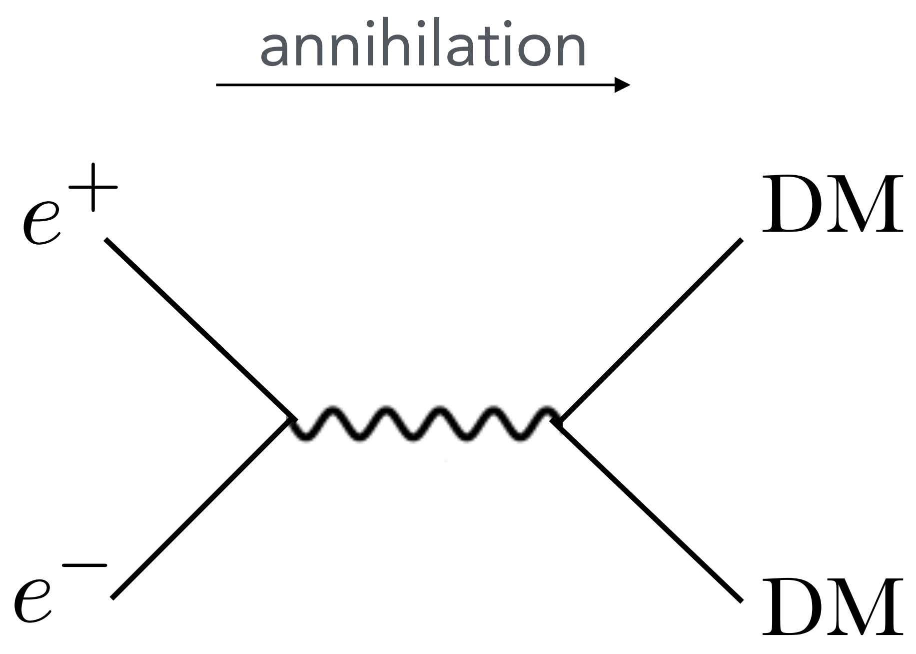
3 to 2 annihilation



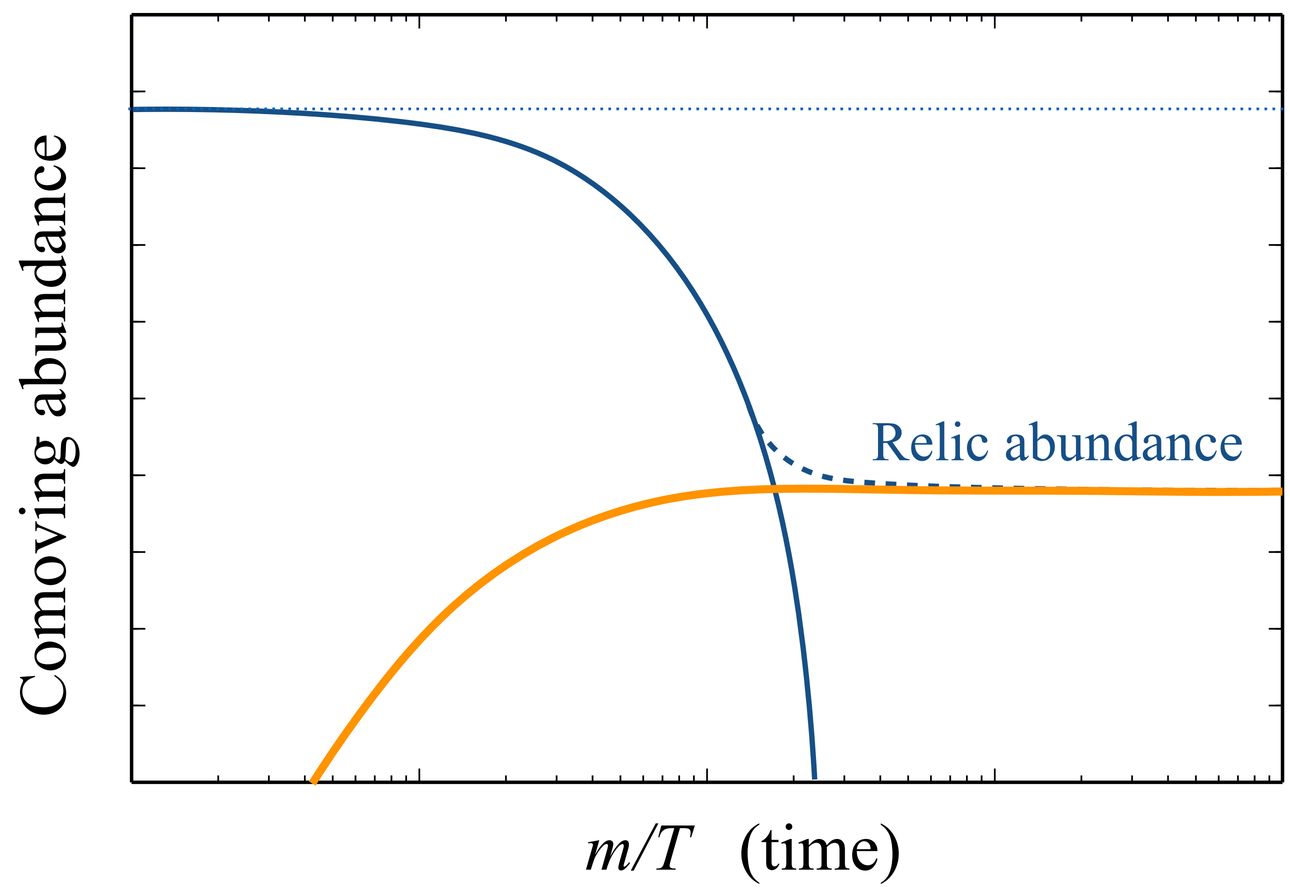
e.g. Carlson et al. 1992
Hochberg et al. 2014, 2015
Kuflik et al. 2015
Farina et al. 2016

Freeze-in

Evolution of DM abundance may also be modified



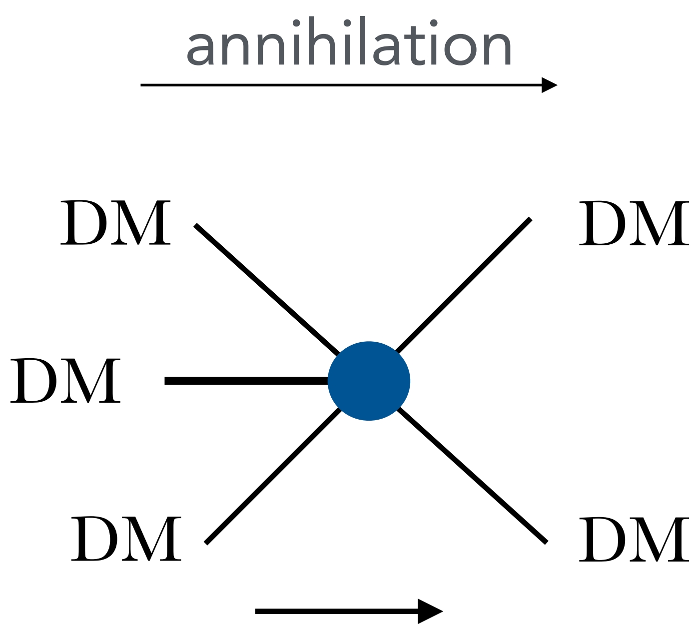
See also: sterile neutrino

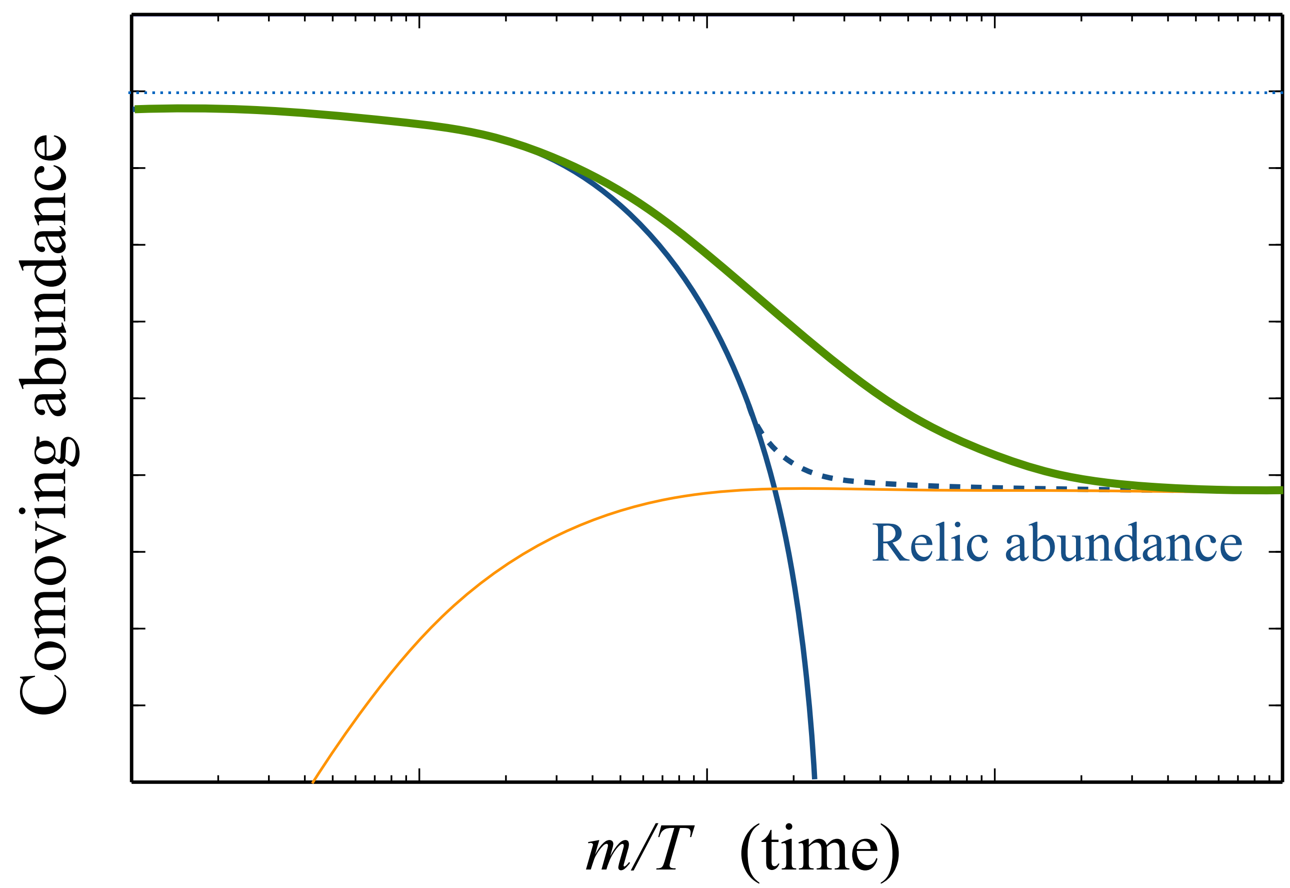


Dark matter *only* populated by out-of-equilibrium annihilations of SM into dark sector

Dodelson and Widrow 1993
Hall et al. 2009
Chu, Hambye, Tytgat 2011
Essig, Mardon, Volansky 2011
Bernal et al. 2017 (review)

Cannibal DM





Number changing processes in dark sector can also heat up dark sector thermal bath

Carlson et al. 1992
Bernal et al. 2015
Kuflik et al. 2015
Pappadopulo, Ruderman, Trevisan 2016
Farina et al. 2016

Light dark matter

1. Thermal relic benchmarks for masses down to ~**keV** (warm DM)

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2. Excess entropy in the dark sector is deposited back into the Standard Model thermal bath

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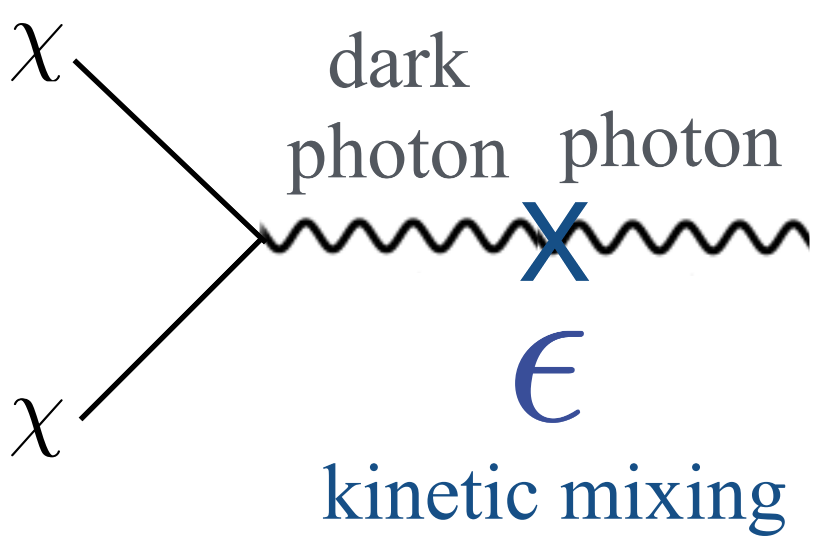
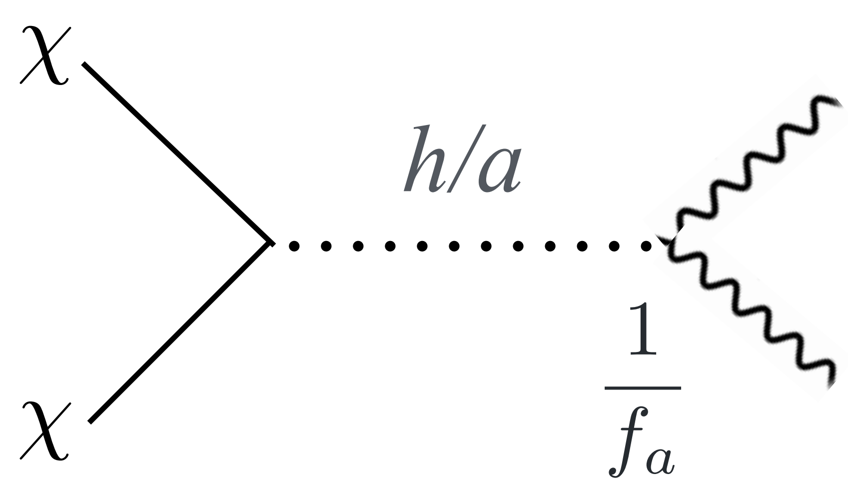
Portals to the Standard Model

vector portal



Higgs or axion portal



+ neutrino portal

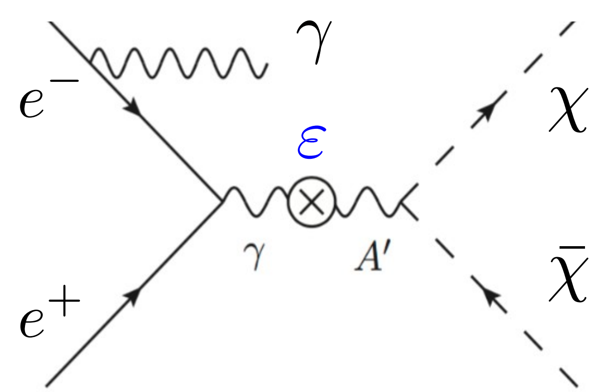
Searches for light DM

Varied new phenomenology in the presence of low-mass dark sectors; See many talks in DM & Cosmic Physics sessions

Searches for light DM

Accelerators

e+e- colliders
fixed target



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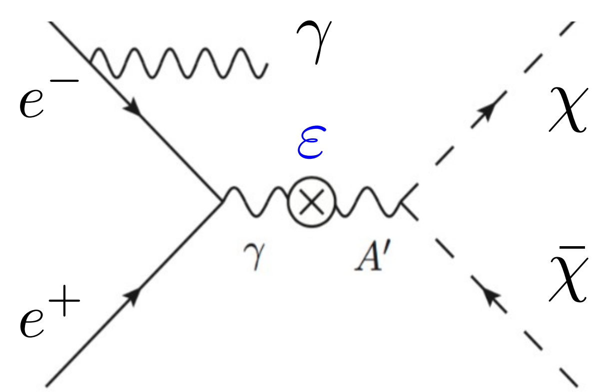

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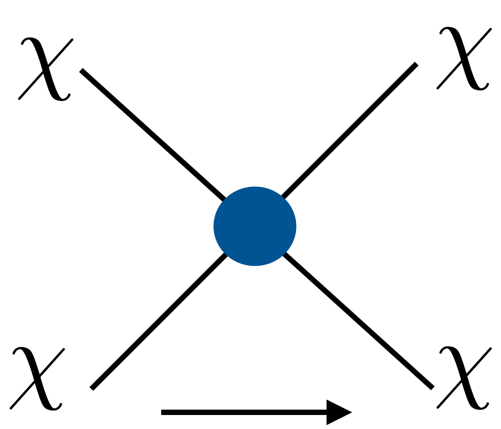
Astrophysics and Cosmology



self interactions
stellar production
DM annihilation
baryon drag/cooling

Searches for light DM

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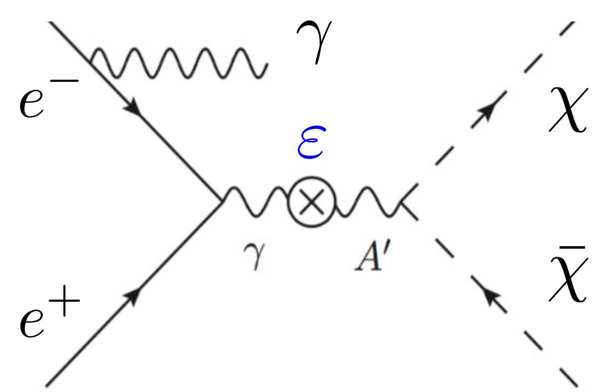

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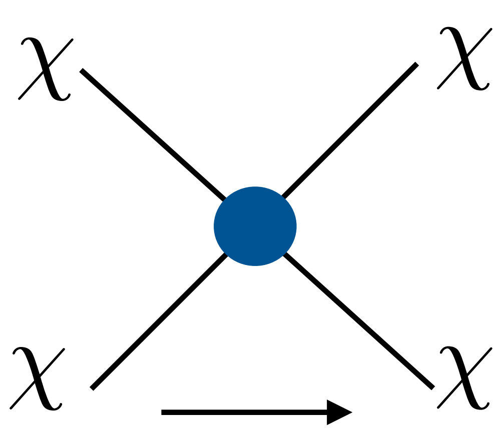

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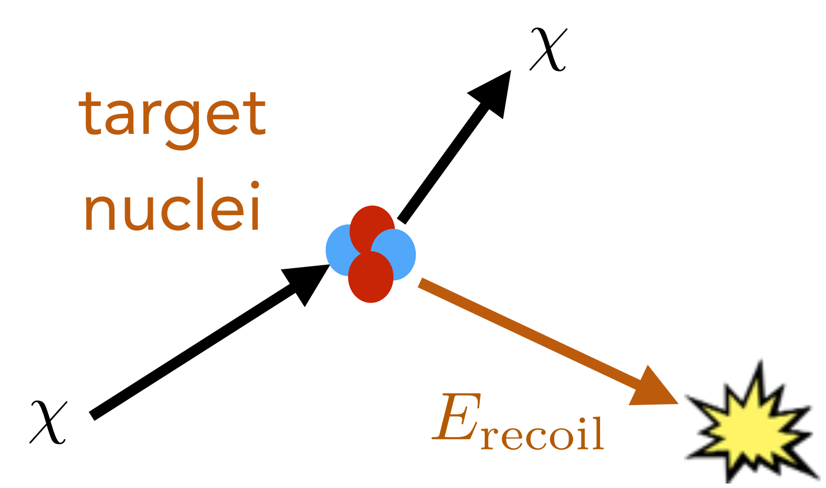
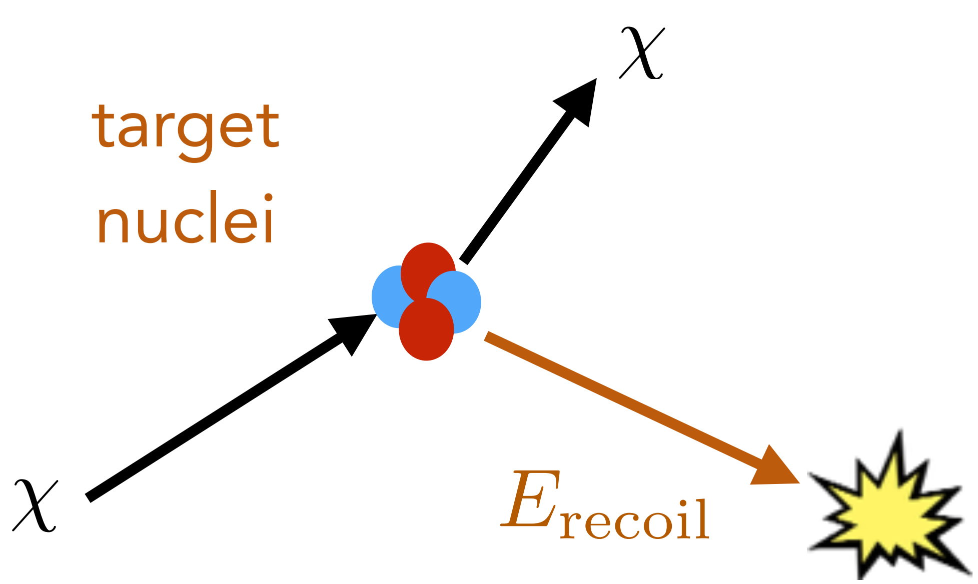
Direct detection

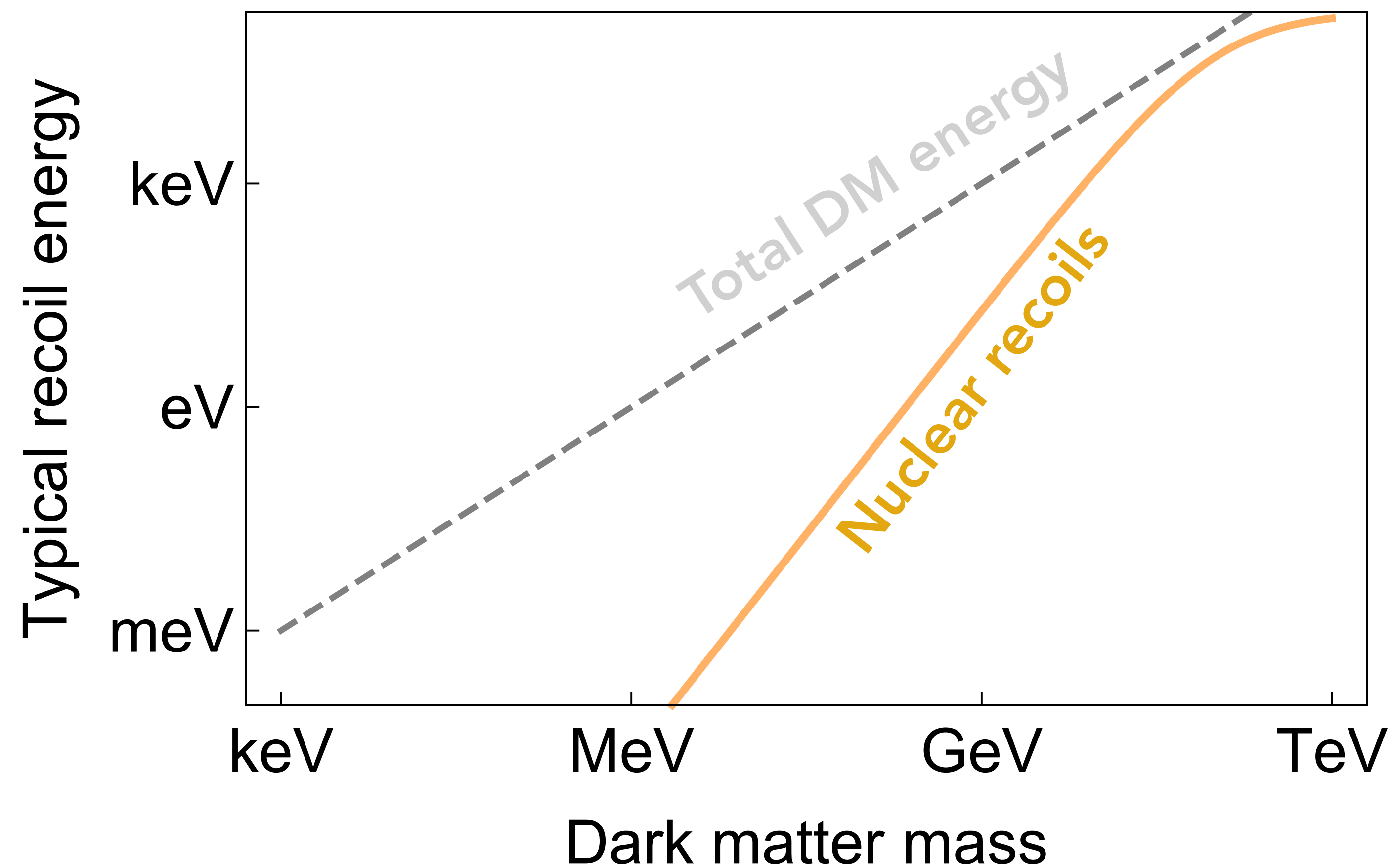


Direct detection of light DM



Heat, ionization, light
from recoiling nucleus

$$E_R \sim \frac{\mu_{\chi N}^2 v^2}{m_N} \sim 1 - 100\,\mathrm{keV}$$



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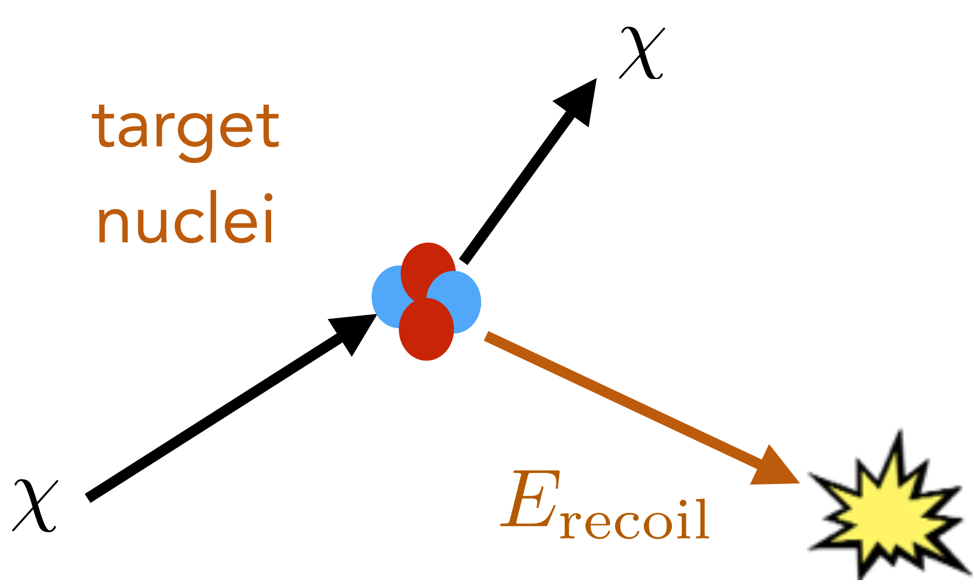

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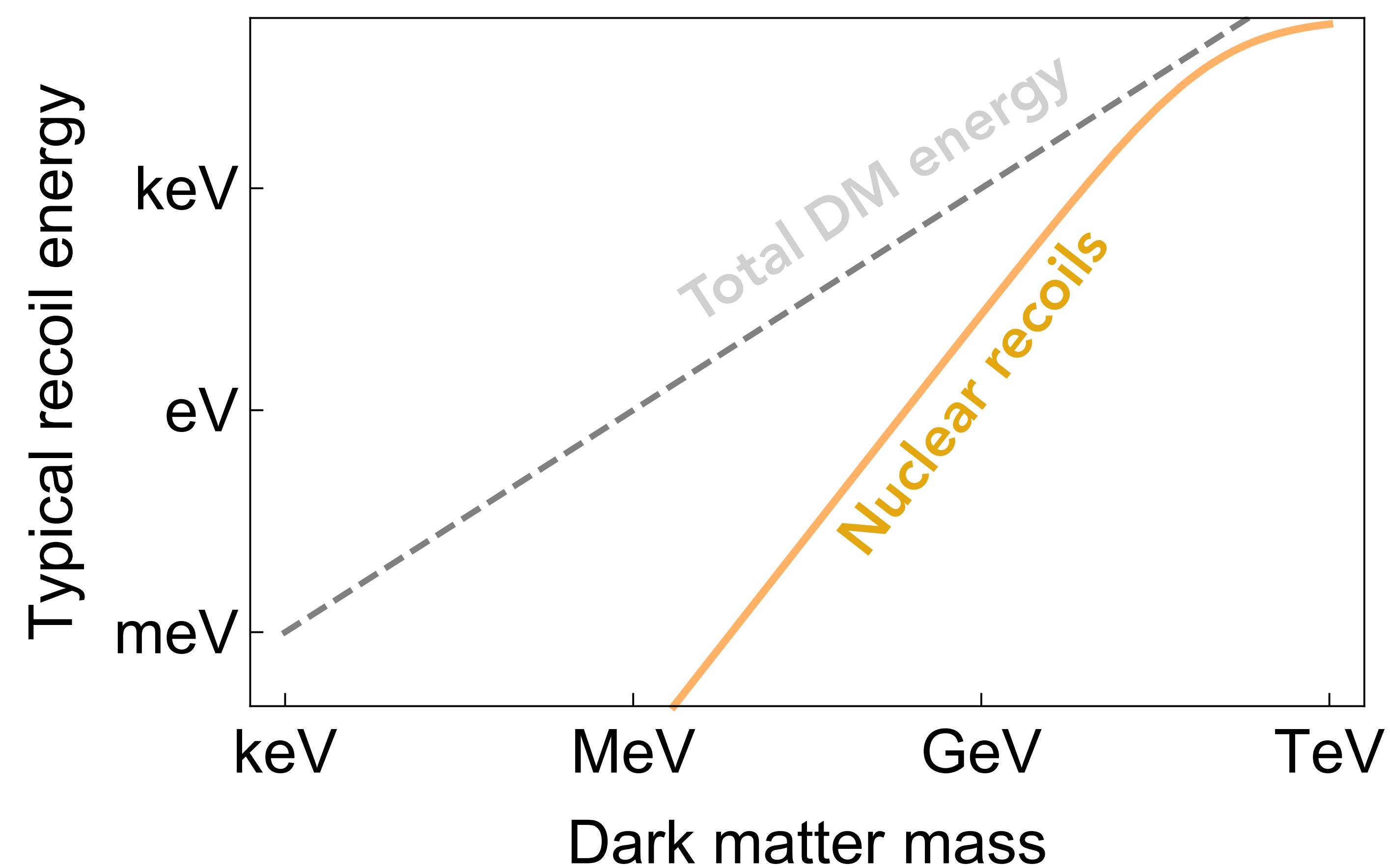


Goal: access total DM energy, obtain sensitivity to ~**meV** recoils for **keV** DM scattering.

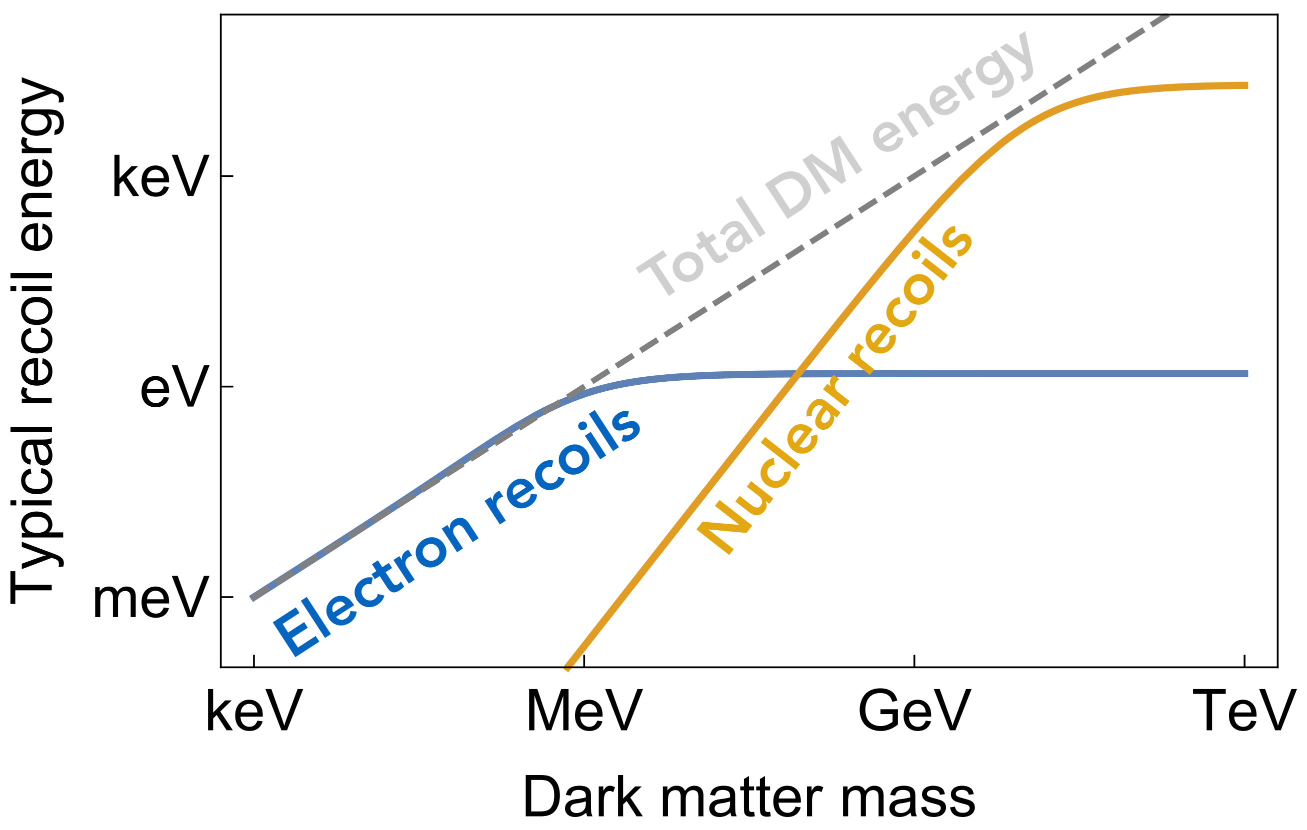
DM-electron interactions

Light DM can more effectively deposit energy into electrons

Typical electron $v \sim 10^{-3}$

Threshold limited by electron band gap of material

Electron recoils



DM-electron interactions

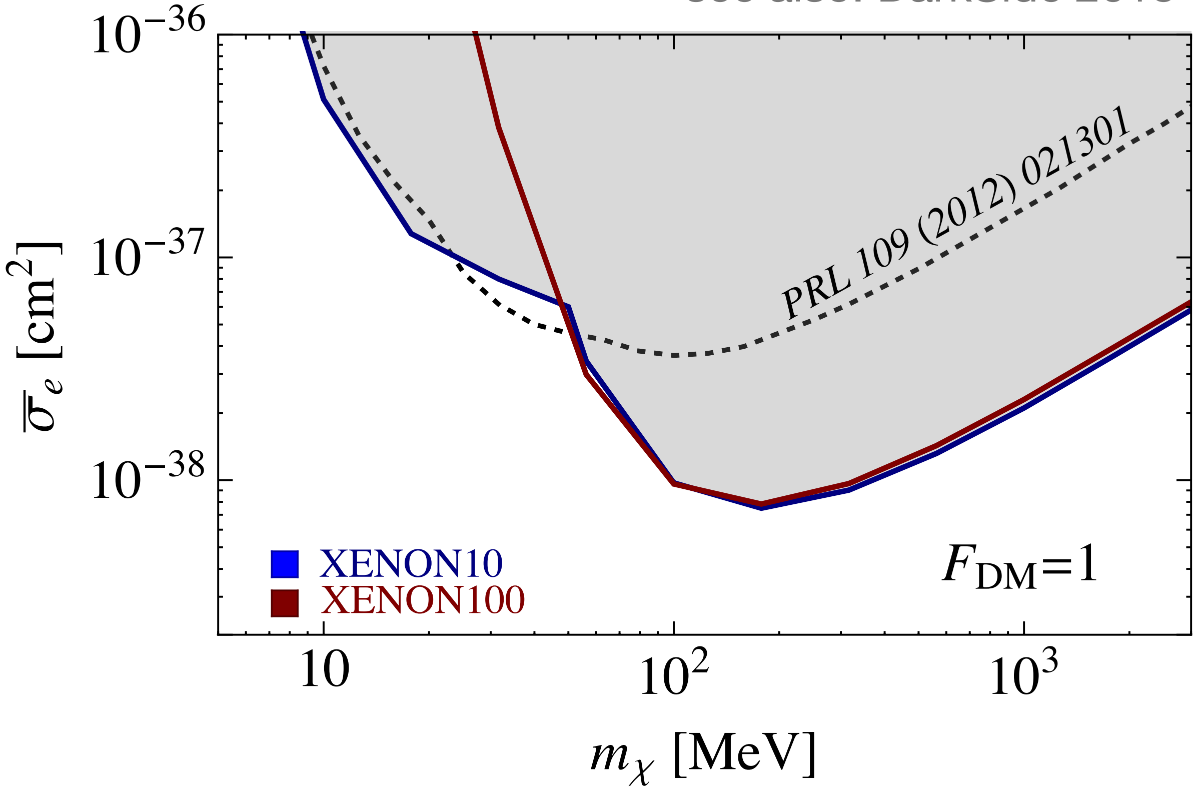
- Ionization in atoms with

$$E_{th} \gtrsim 12 \text{ eV}$$

- Excitations in semiconductors with

$$E_{th} \gtrsim \text{eV}$$

Essig, Volansky, Yu 2017
see also: DarkSide 2018

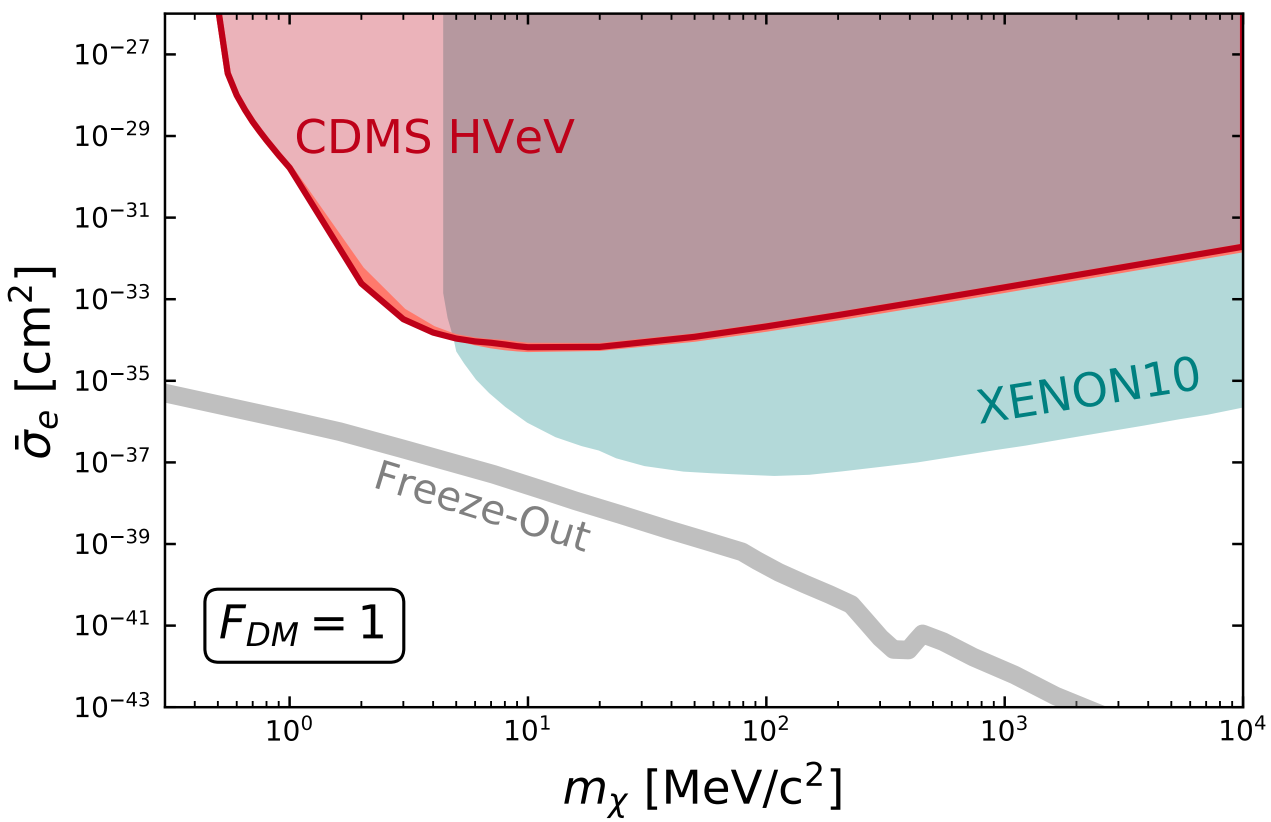


- Superconductors and Dirac materials have also been proposed, with threshold as low as $E_{th} \gtrsim \text{meV}$

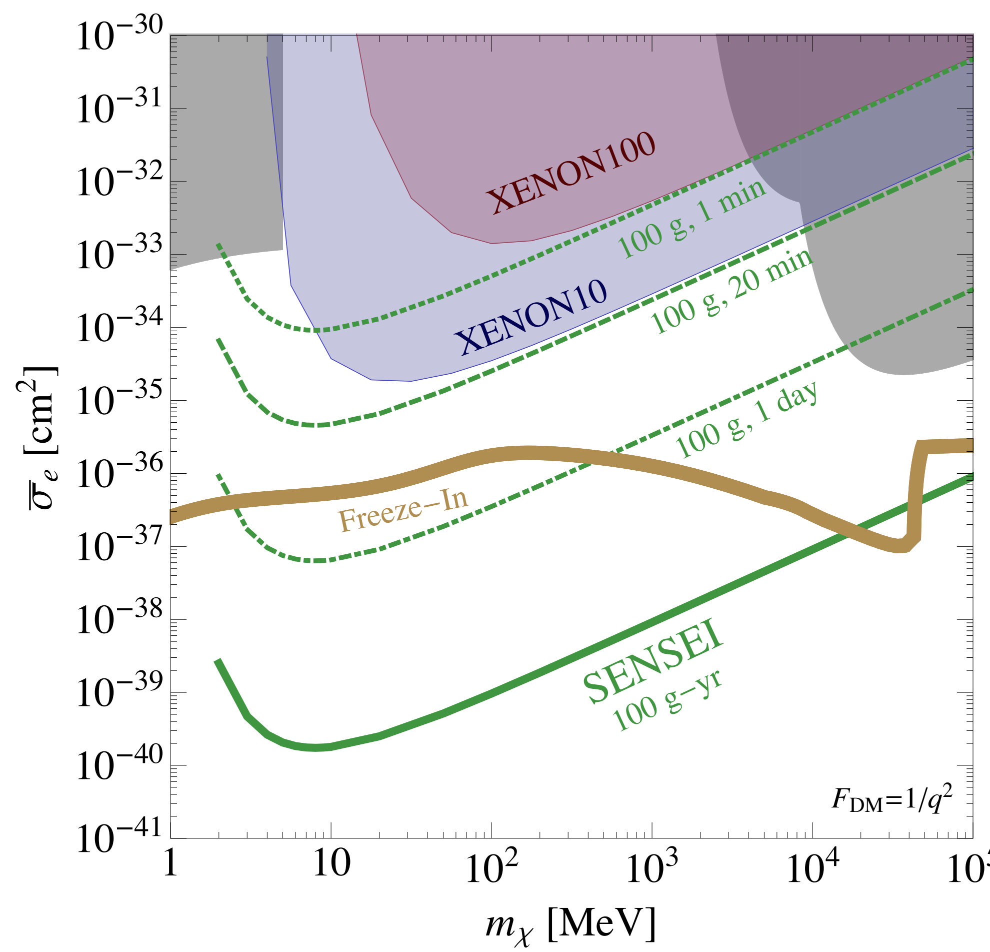
Hochberg et al. 2015; Hochberg et al. 2017
Hochberg, TL, Zurek 2016a

DM-electron interactions

Results and projections for semiconductor targets
with single electron (~eV) sensitivity



see SuperCDMS talk (F. Ponce)



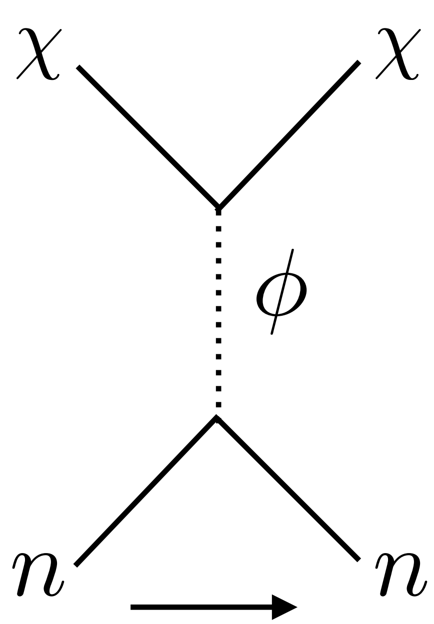
see SENSEI talk (G. Moroni)

Promising progress towards thermal relic benchmarks!

Essig et al., 1509.01598,
Essig, Volansky, Yu 2017

DM-nucleus interactions

DM-nucleon scattering



For low mass dark matter, the possible momentum transfer is

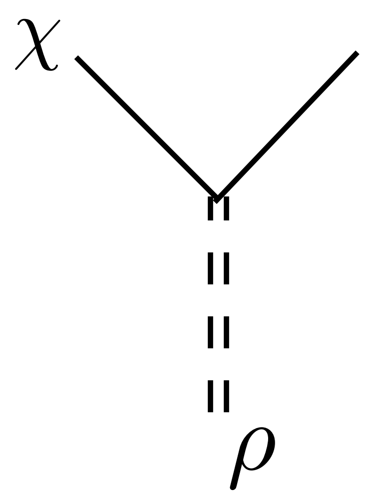
$$Q \sim m_\chi v \sim 1/\text{Angstrom}$$

$$\text{for } m_X = \text{MeV}$$

At these scales, DM no longer scatters off of single atoms — the relevant degree of freedom is a phonon

DM-phonon interactions

DM-phonon scattering



Quasiparticle

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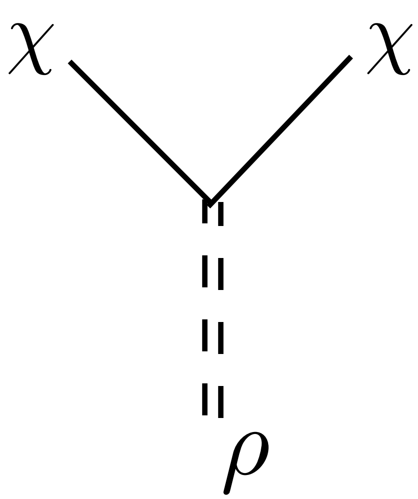

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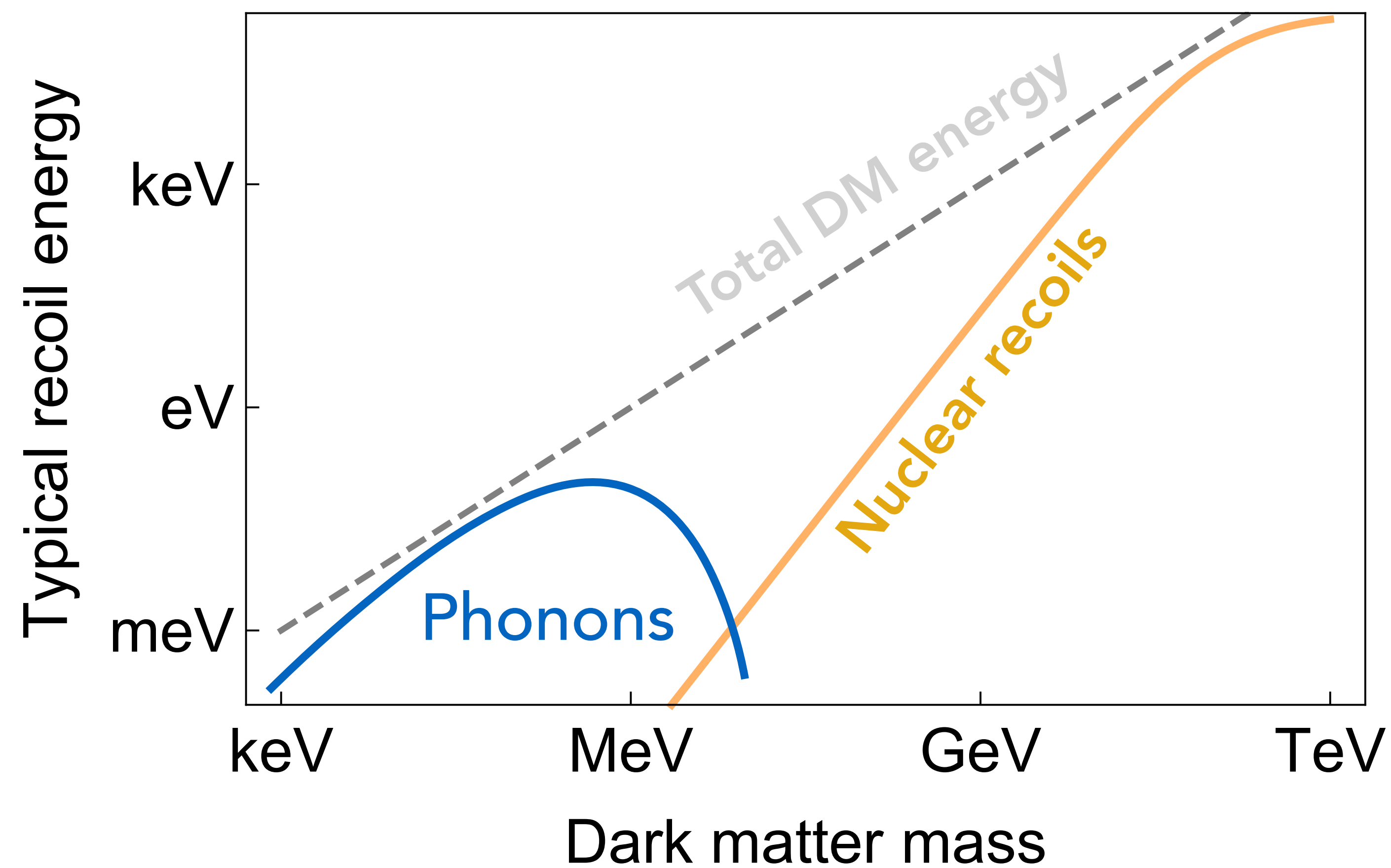
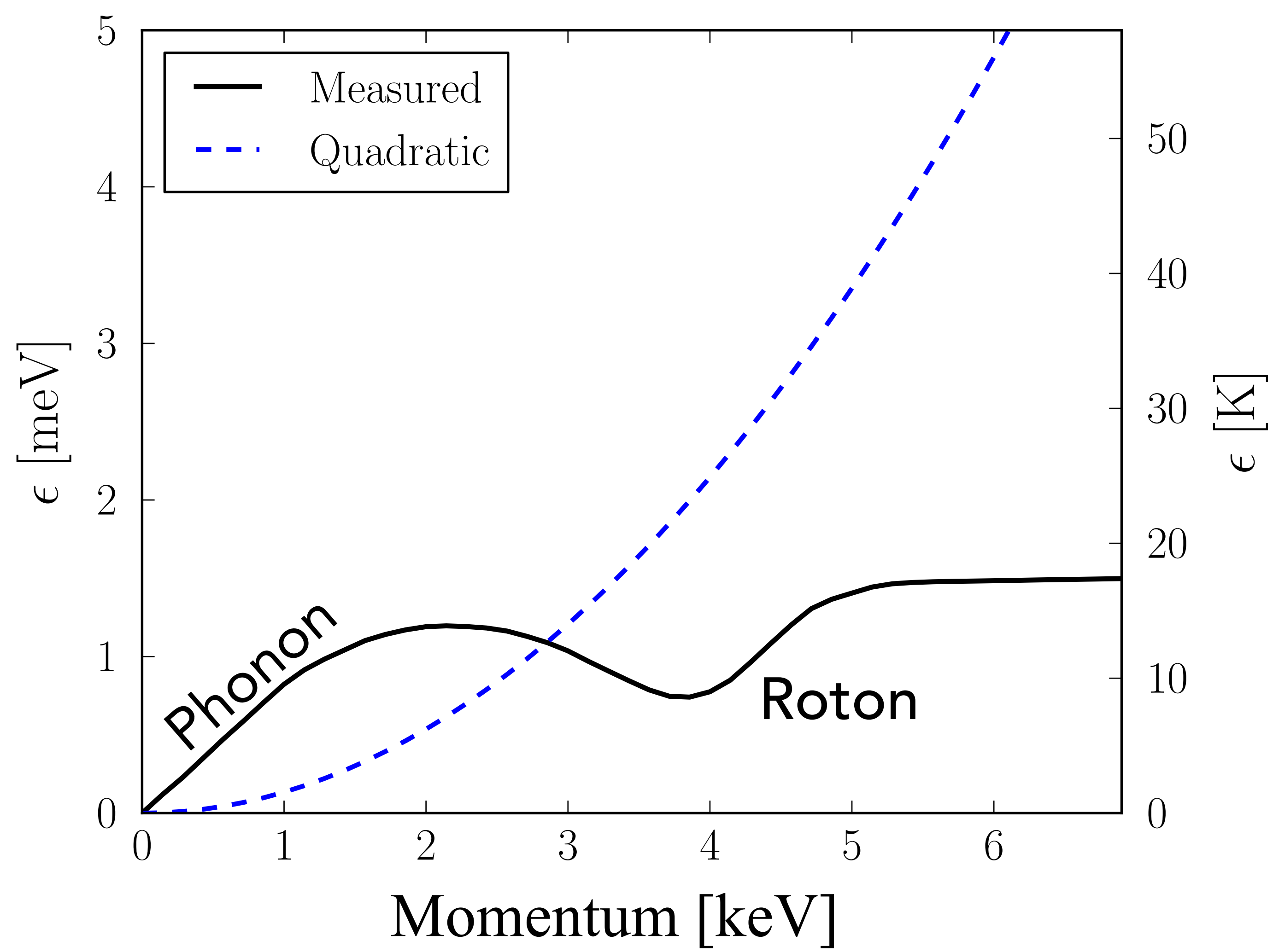


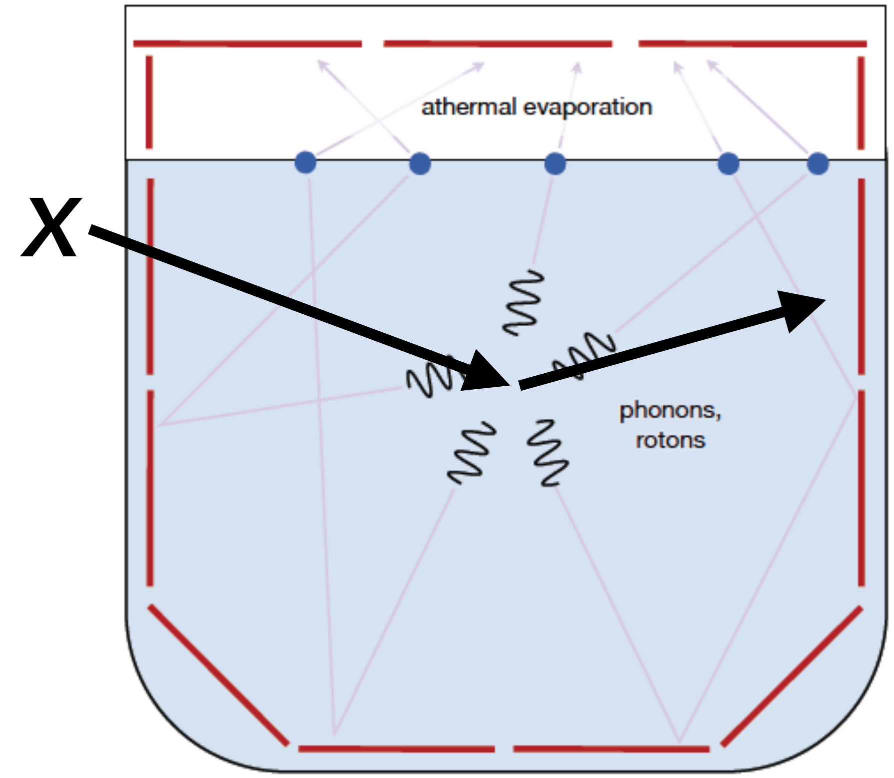
DM scattering into **single** or **few** phonons has different kinematics

Superfluid helium

Long-lived quasiparticle excitations

Possible ~meV thresholds





See Dan McKinsey's talk

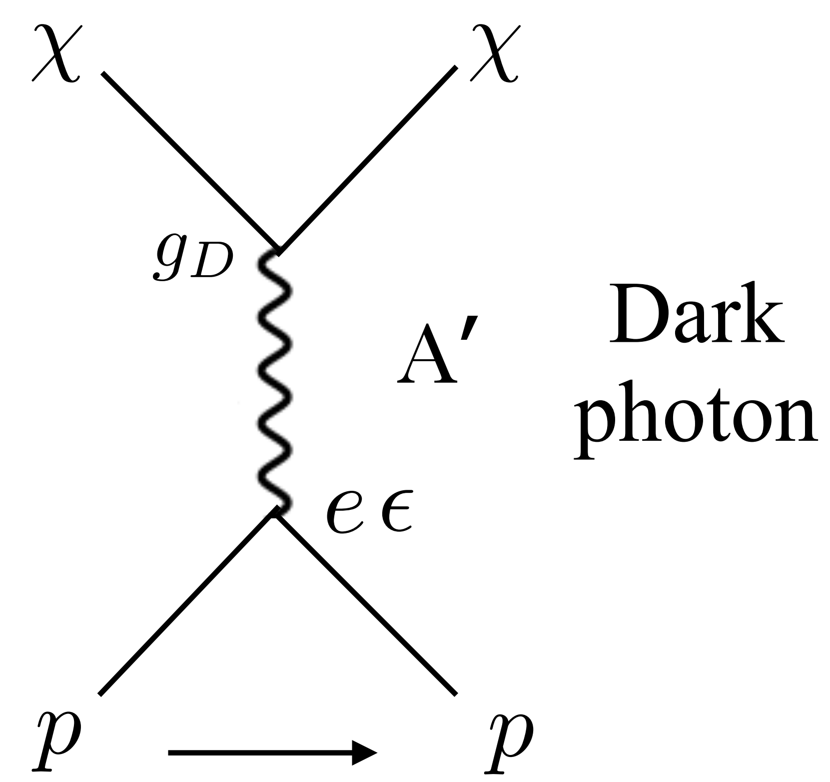
Schutz and Zurek 2016
Knapen, **TL**, Zurek 2016

Polar materials

Polar materials contain *gapped optical phonons*

Advantages:

- Commonly used materials such as GaAs and sapphire
- Optical phonons analogous to oscillating electric dipoles: dark photon interactions
- Kinematics suited for sub-GeV DM
- Potential directionality



Kinetically mixed dark photon A'

$$\epsilon e A'_\mu J^\mu_{\rm EM}$$

Knapen, TL, Pyle, Zurek 2017
+ work in progress with S. Griffin

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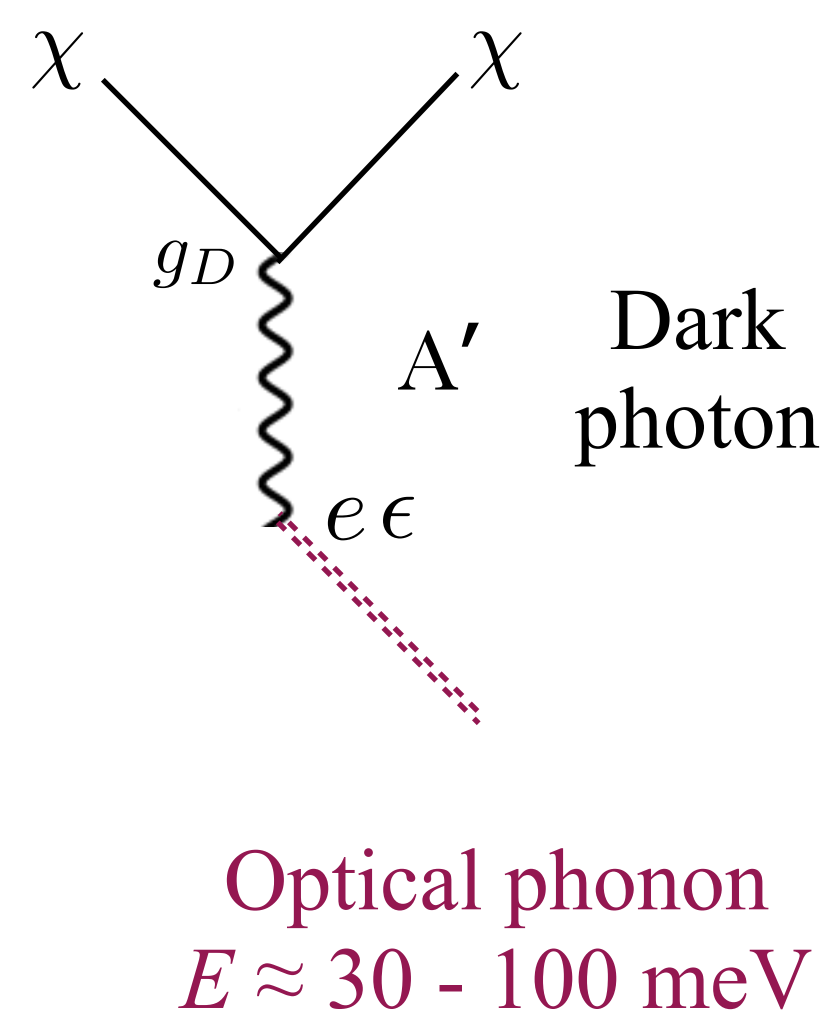

Knapen, TL, Pyle, Zurek 2017
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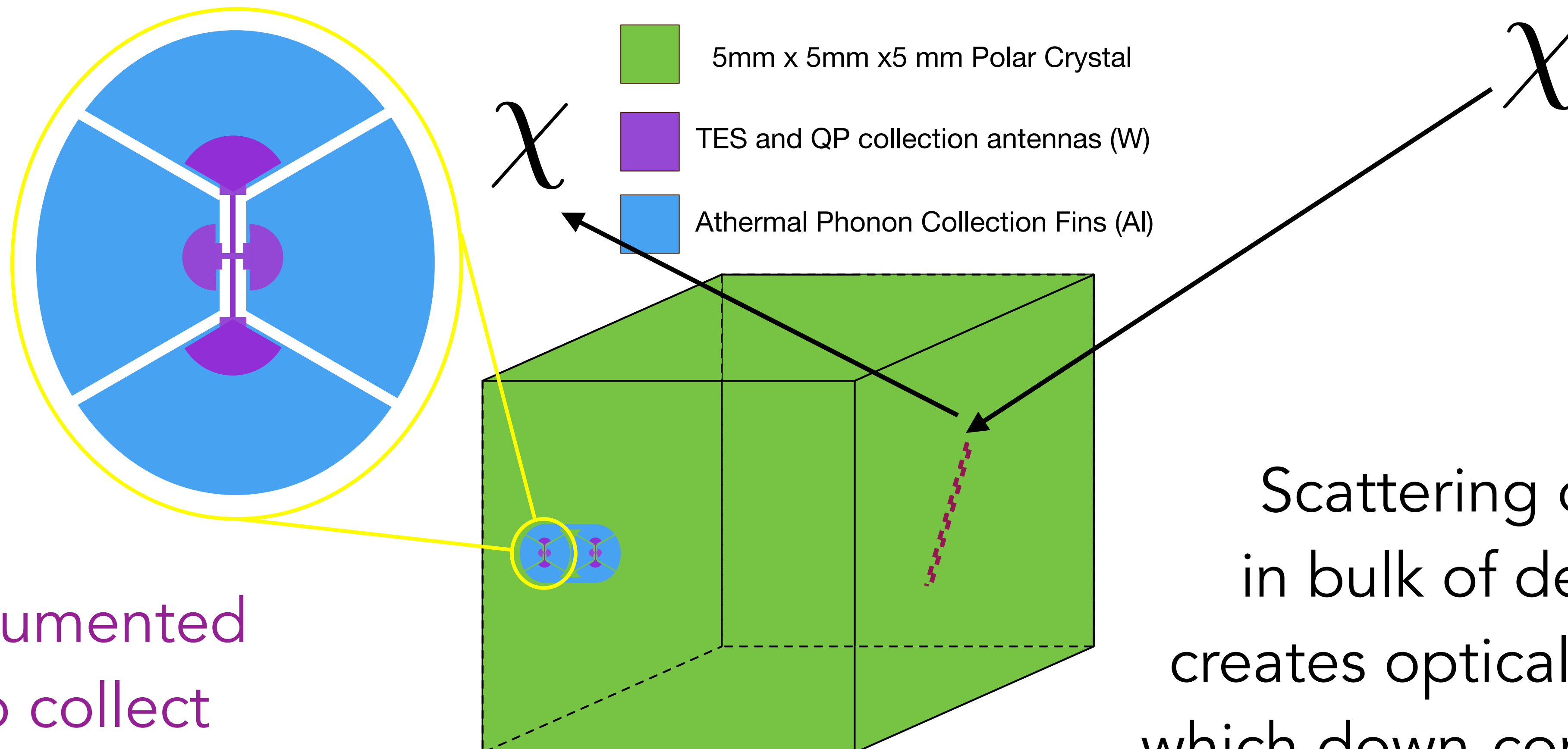
Detector concept

TES with E_{th} ~ 10 meV

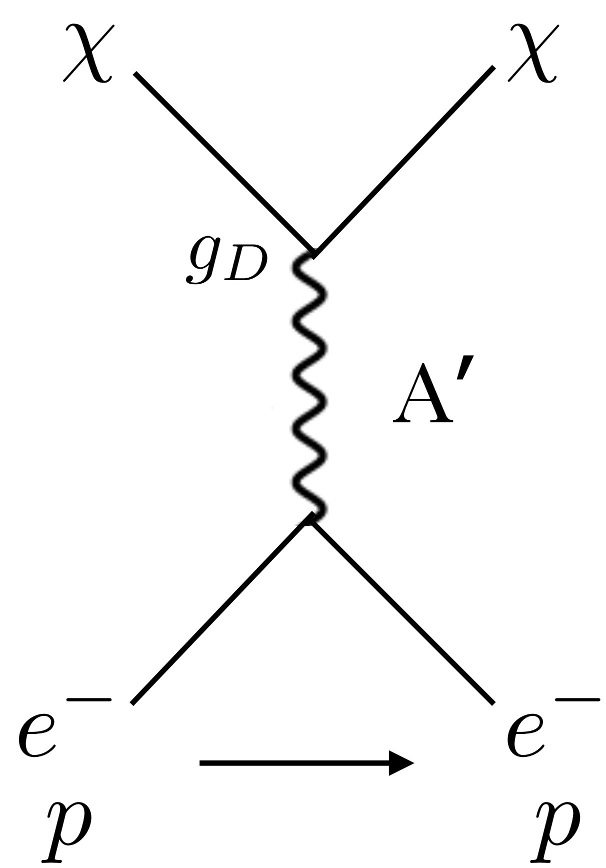


Surface instrumented with TES to collect deposited energy

~gram of target material

Scattering of DM in bulk of detector creates optical phonon, which down-converts into many athermal phonons

Dark photon interactions



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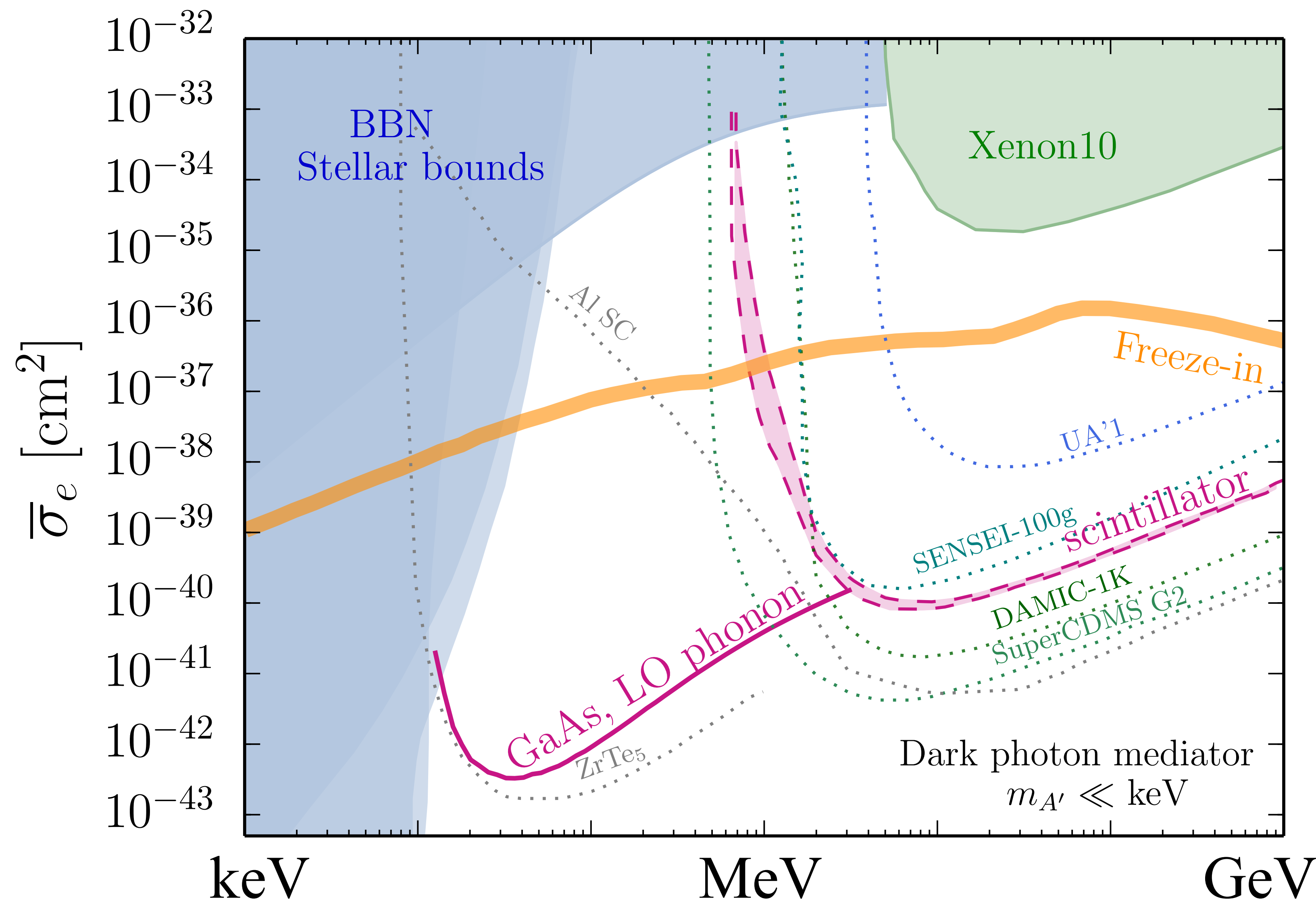


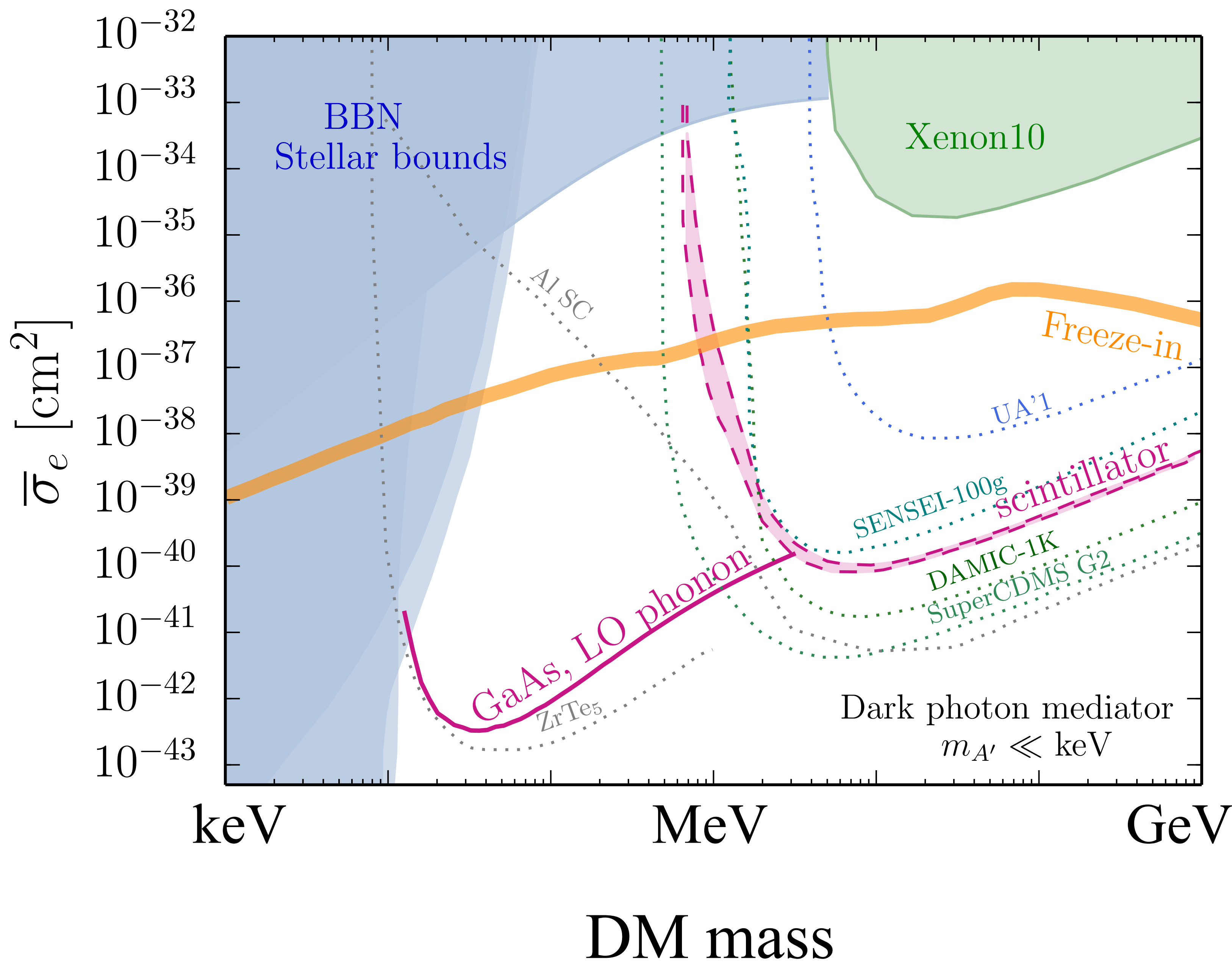
DM mass

Cosmic Visions 2017;
Essig, Volansky, Yu 2017
Vogel and Redondo 2014
Derenzo et al. 2016

all projections assume kg-yr exposure

Dark photon interactions

- DM sensitivity from optical phonon production in GaAs
- Polar materials can probe interesting new parameter space even with gram-scale target
- Pure GaAs/sapphire crystals readily available



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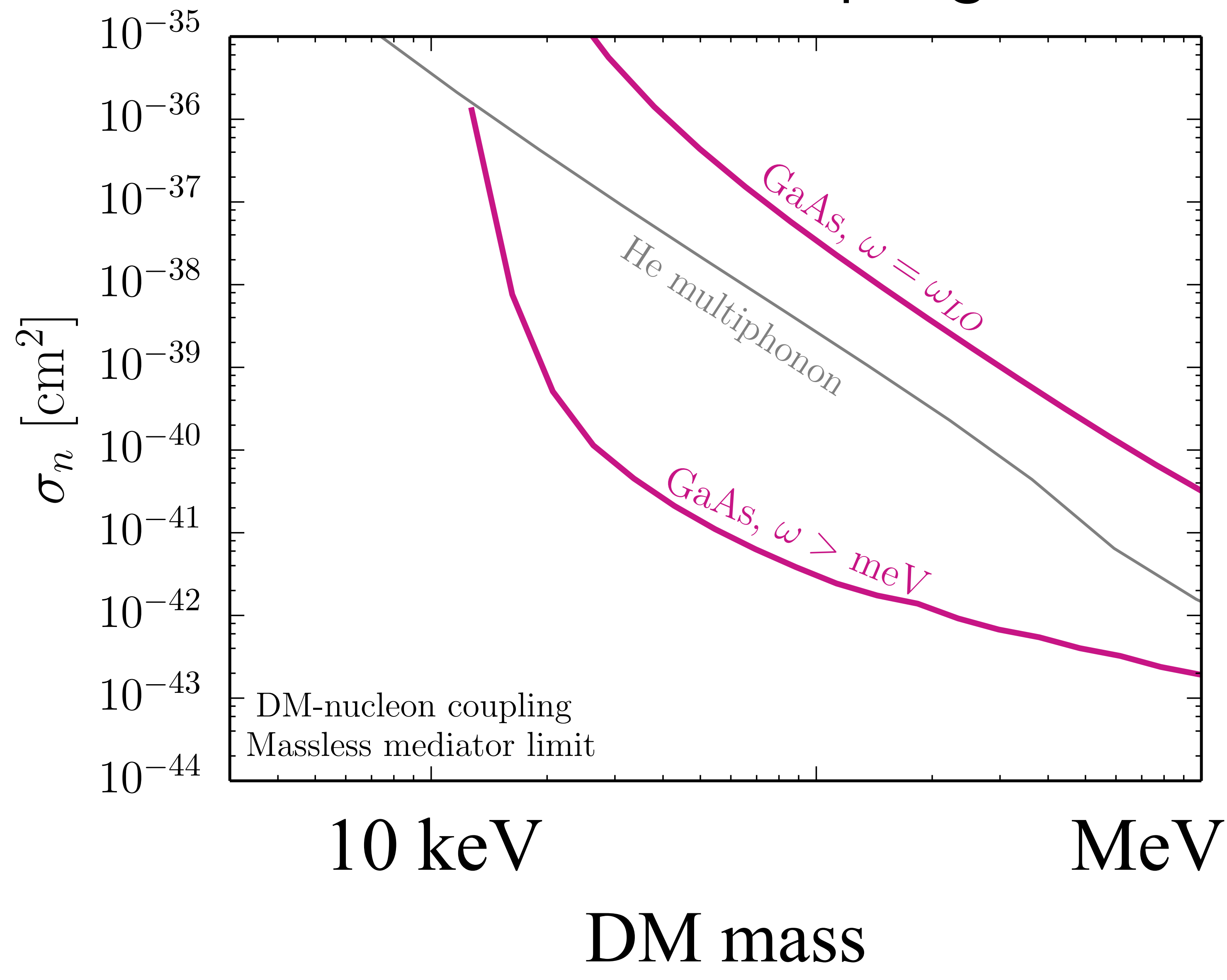
DM-nucleon scattering

Single phonon production can be used for sub-MeV DM-nucleon scattering, competitive with multi-phonons in superfluid He

Nucleon coupling



Knapen, TL, Zurek 2017

``Ultralight” DM

(M < keV)

Ultralight bosonic dark matter

- Candidates:
  - Dark photon
  - Pseudoscalar (axion)
  - Scalar

} appear in UV completions of Standard Model

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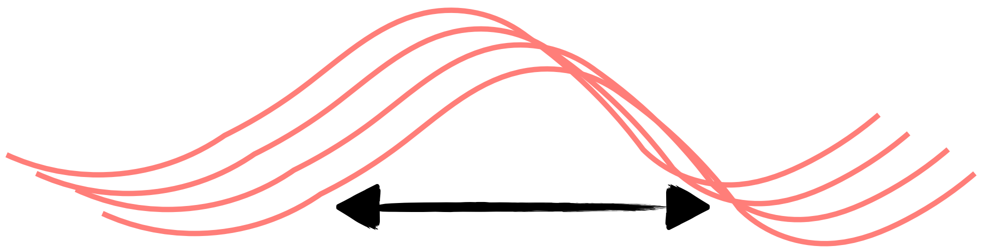
Occupation number is high:

$$\frac{\rho_{\rm DM}}{m_{\rm DM}} \gg \lambda_{\rm dB}^{-3}$$



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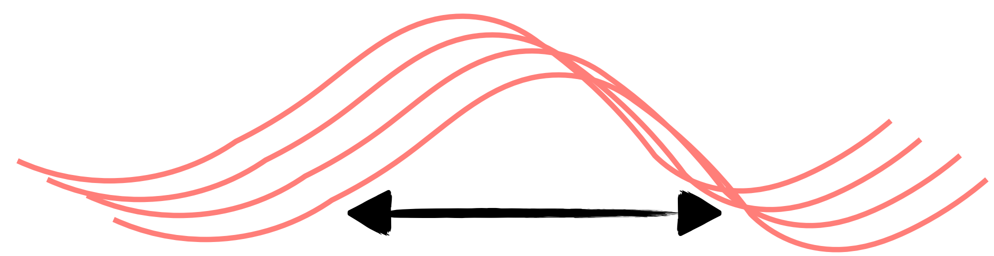
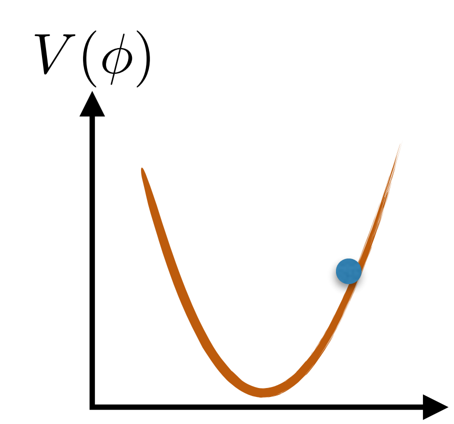


$$\lambda_{\rm de\,Broglie} = \frac{2\pi}{m_{\rm DM} v}$$

- Non-thermal relic abundance

$$\rho_{\rm DM} = \frac{1}{2} m_{\rm DM}^2 \phi_0^2$$

ϕ_0 — field amplitude today



Vector dark matter

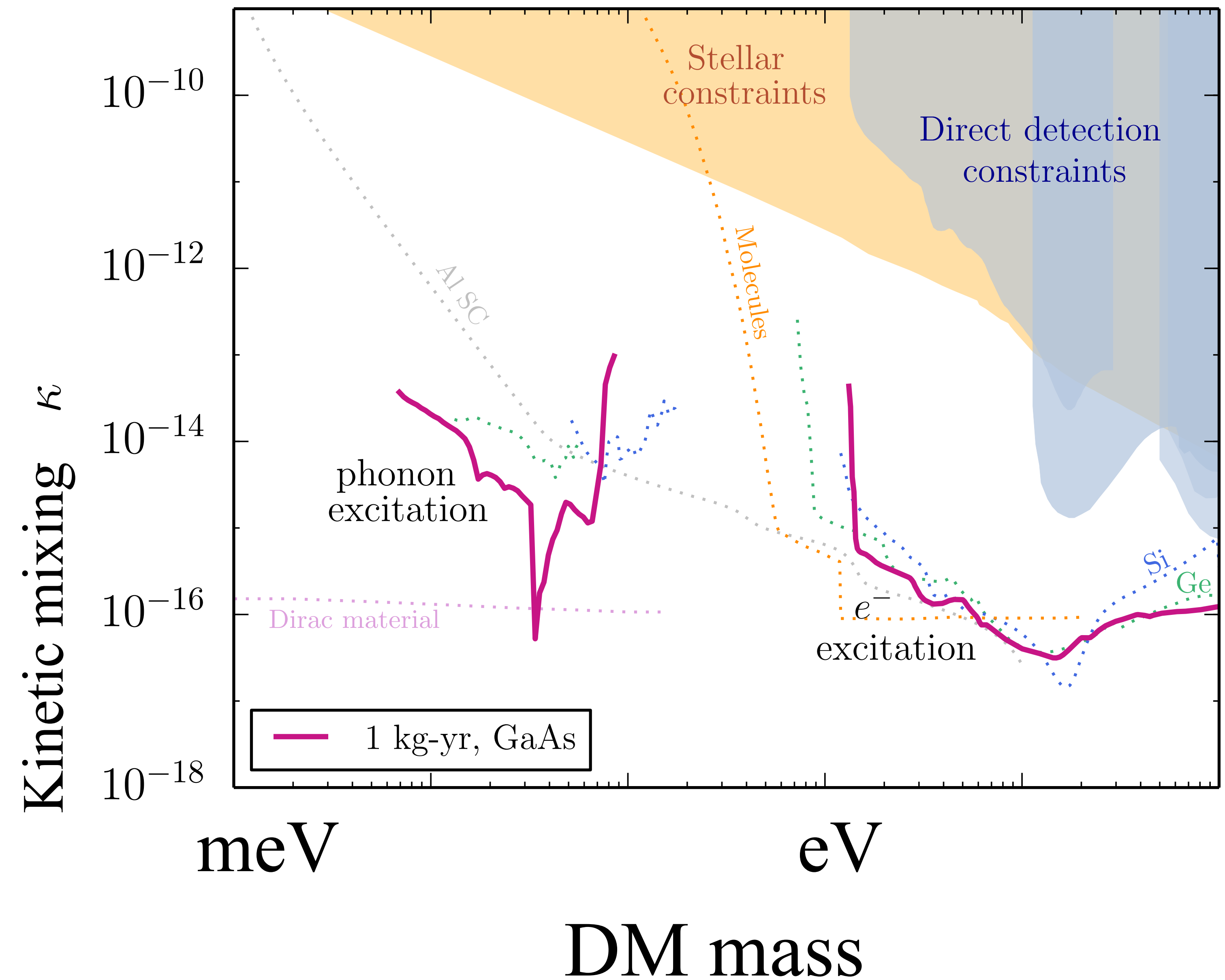
For massive vectors, correct relic abundance can be achieved via inflationary production:

$$m_V \approx 10^{-5}\ \text{eV} \times \left(\frac{10^{14}\ \text{GeV}}{H_{inf}}\right)^4$$

Hubble scale of inflation

Graham, Mardon, Rajendran 2015

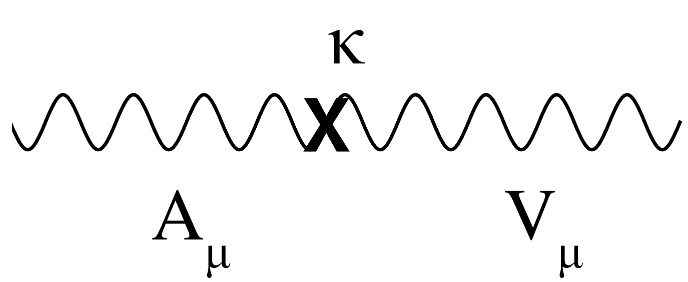
Kinetically mixed dark photon

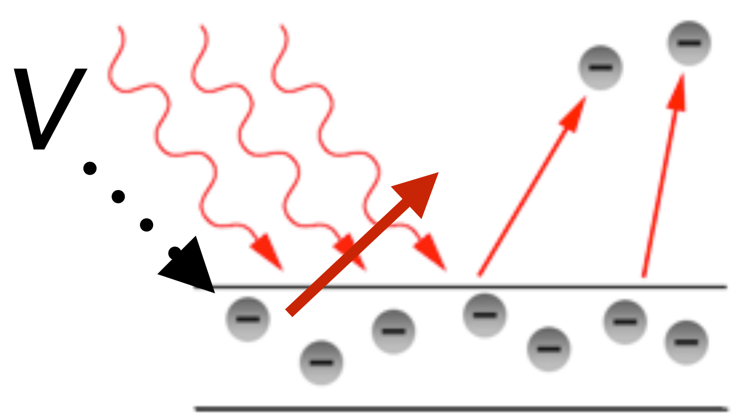


An, Pospelov, Pradler 2013, 2014
Hochberg, TL, Zurek 2017; Bloch et al. 2016
Knapen, TL, Pyle, Zurek 2017
DAMIC: Chavarria et al. 2017

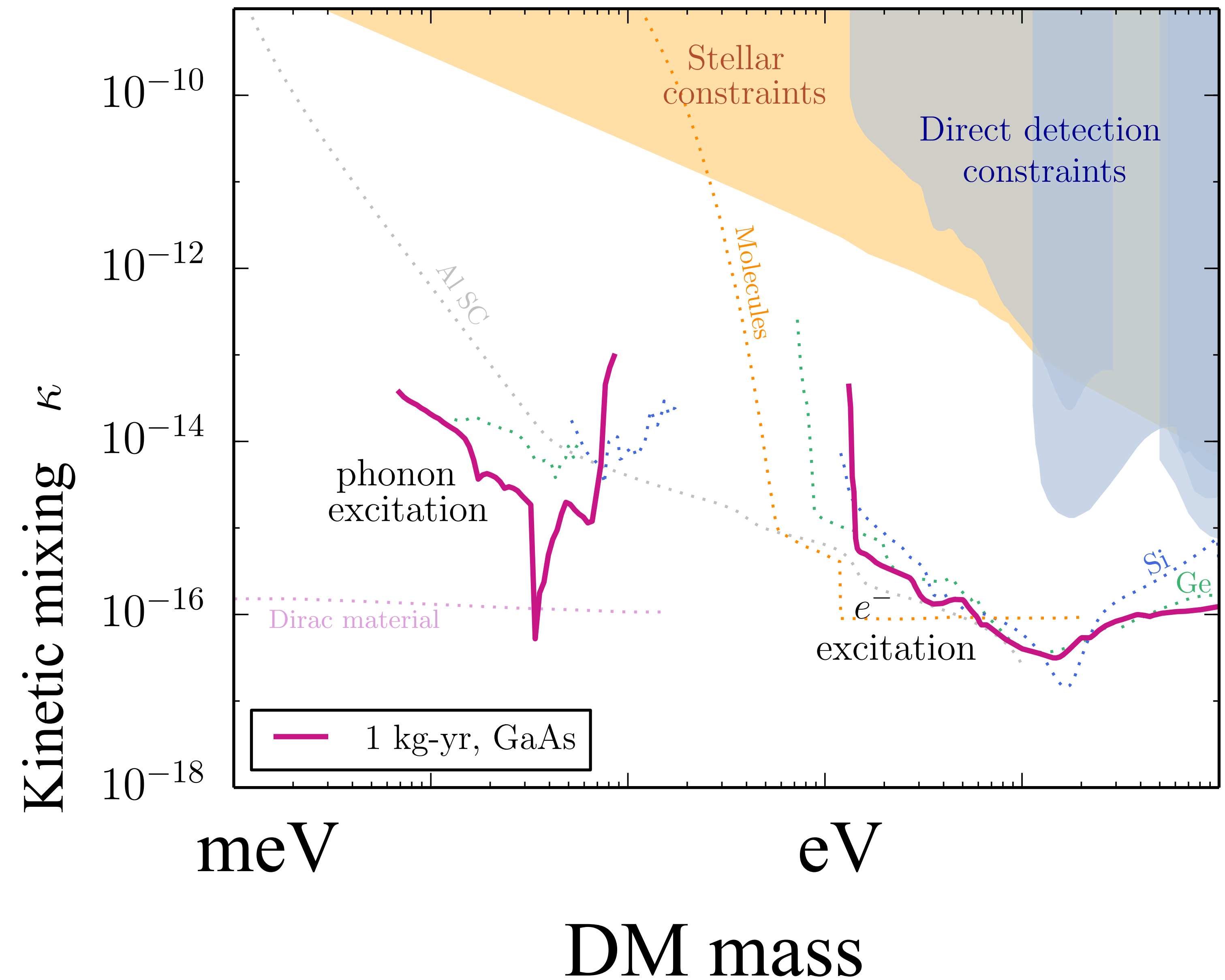
Vector dark matter

Direct detection experiments with sensitivity to meV or eV excitations can also probe bosonic DM





Kinetically mixed dark photon



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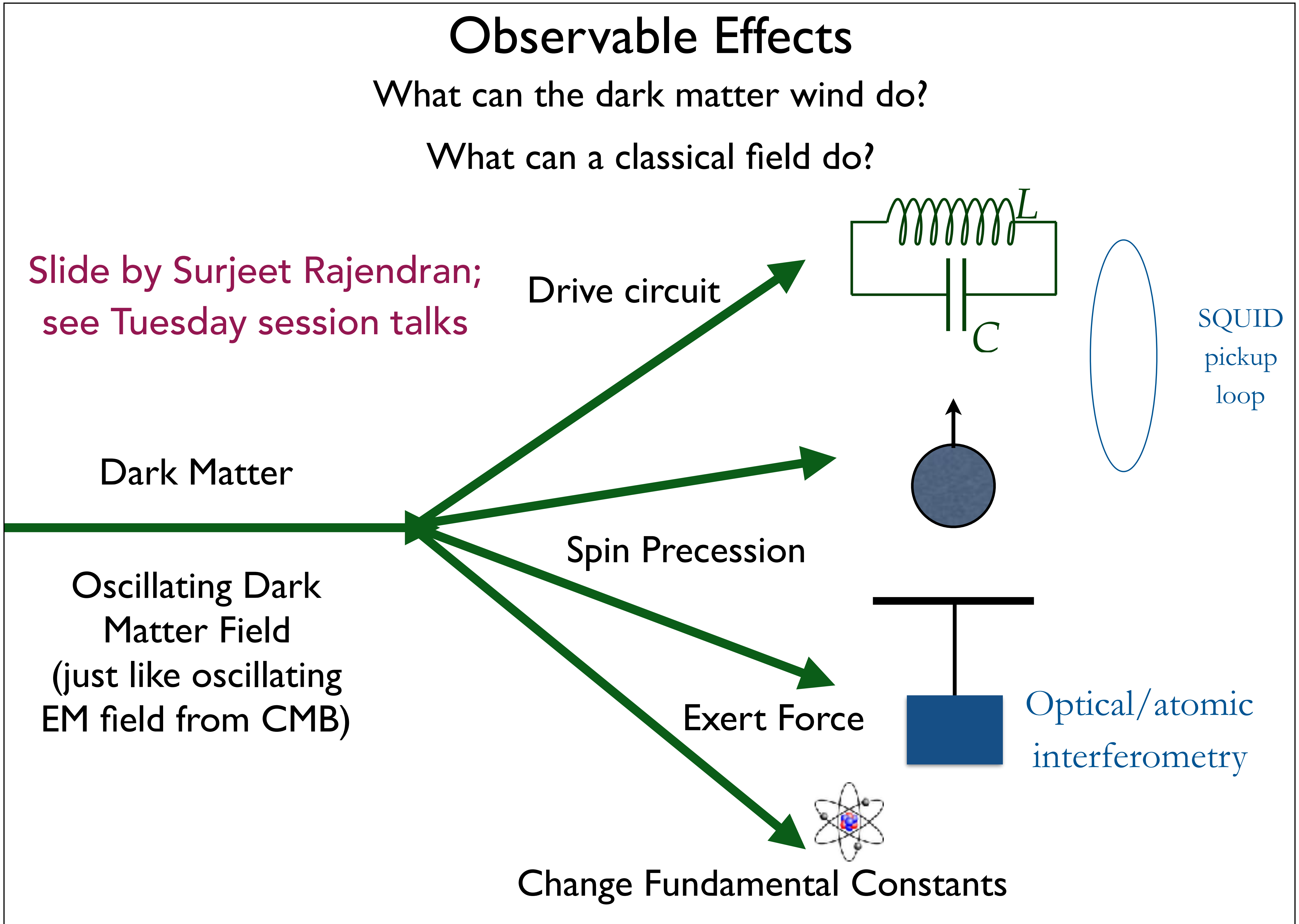
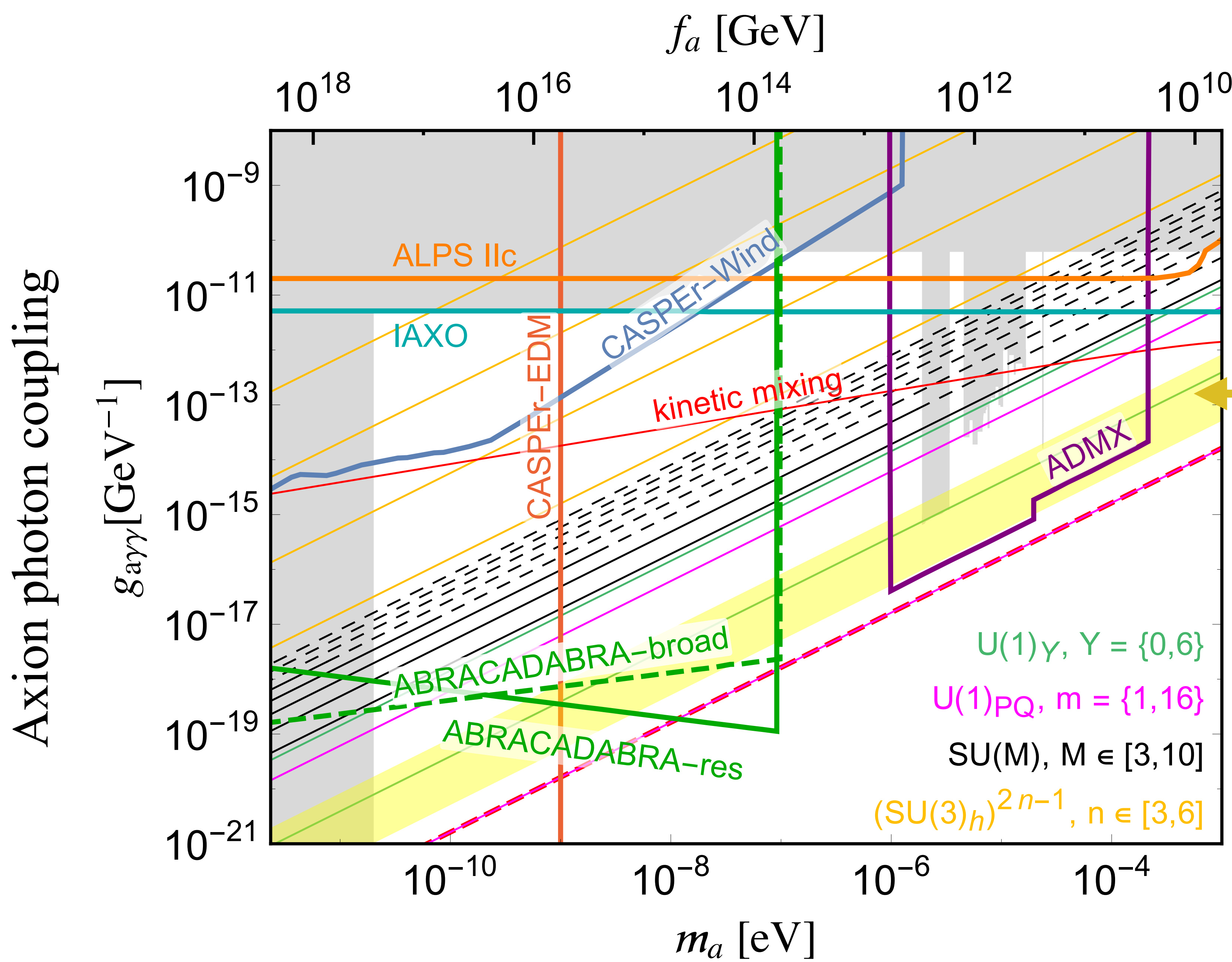
Getting down to 10^{-22} eV



Axions

Recent work has explored theory possibilities for axion beyond the usual "QCD axion" line



usual window for QCD axion

other models

Figure from Agrawal, Fan, Reece, and Wang 2018
see also: Agrawal and Howe 2017

Conclusions

- New directions explore many orders of magnitude in DM mass, generalizing WIMP and axion to a much broader theory landscape and phenomenology.
- Only scratched the surface in methods for detection.
- Exciting times in the search for low mass DM!

Thanks!