Detection of *Light* Particle Dark Matter

Introduction

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QSFP school
7th Sept 2021

Forewords

Overview

1) Evidence for DM, Candidates, Direct Detection basics (sub-GeV)
2) Direct detection in noble liquids
3) DD in semiconductors and other solid-state ideas

Tutorials

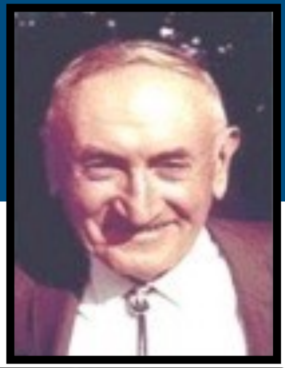
1) after this session
2) hands-on on setting exclusion limits on DM interactions (material provided). Tools available online from XENON-1t

Lecture 1: Useful references and further readings:

- Feebly-Interacting Particles:FIPs 2020 Workshop Report
  https://arxiv.org/abs/2102.12143
- TASI lecture by T. Lin on *dark matter models and direct detection*
  https://arxiv.org/abs/1904.07915
- N. Fornengo's lectures at SoUP 2021
  https://indico.cern.ch/event/871645/timetable/?print=1&view=nicecompact
- J. Monroe's lecture at CHIPP 2019
  https://indico.cern.ch/event/744252/timetable/?print=1&view=indico_weeks_view
- R. Essig et al. *Direct Detection of sub-GeV Dark Matter with Semiconductor Targets*
  https://arxiv.org/abs/1509.01598

We live in a dark universe

Evidence for Dark Matter



Coma Cluster

Rotation curves

Strong/Weak lensing

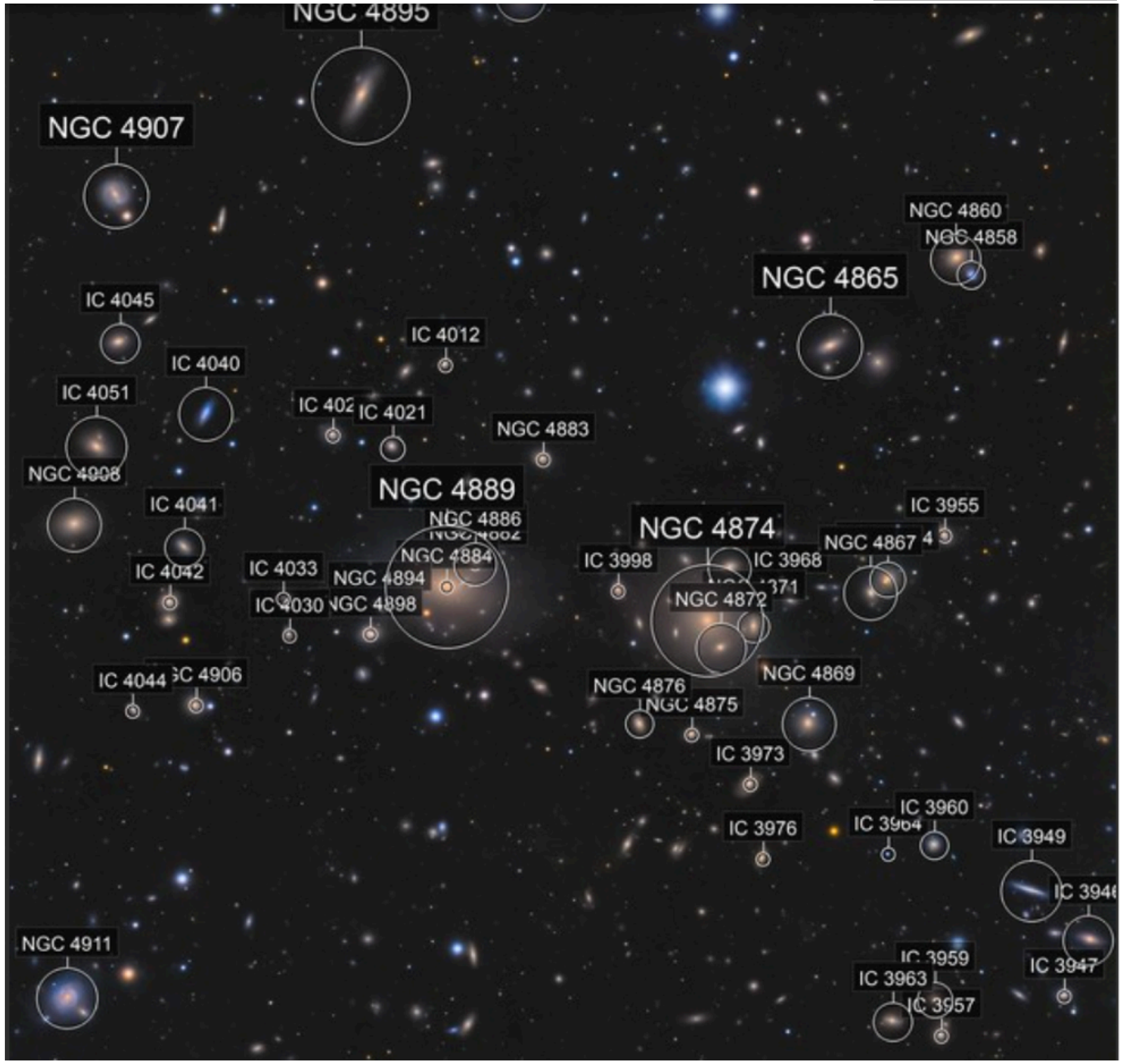
Galaxy Merger

CMB

…

$$2\langle T\rangle = -\langle V_{GPE}\rangle$$

$$\frac{M_{grav}}{M_{lumi}} \sim 10$$



https://www.astrobin.com/411907/0/

—> Tutorial 1

Evidence for Dark Matter

Vera Rubin

Coma Cluster
Rotation curves (10 kpc)
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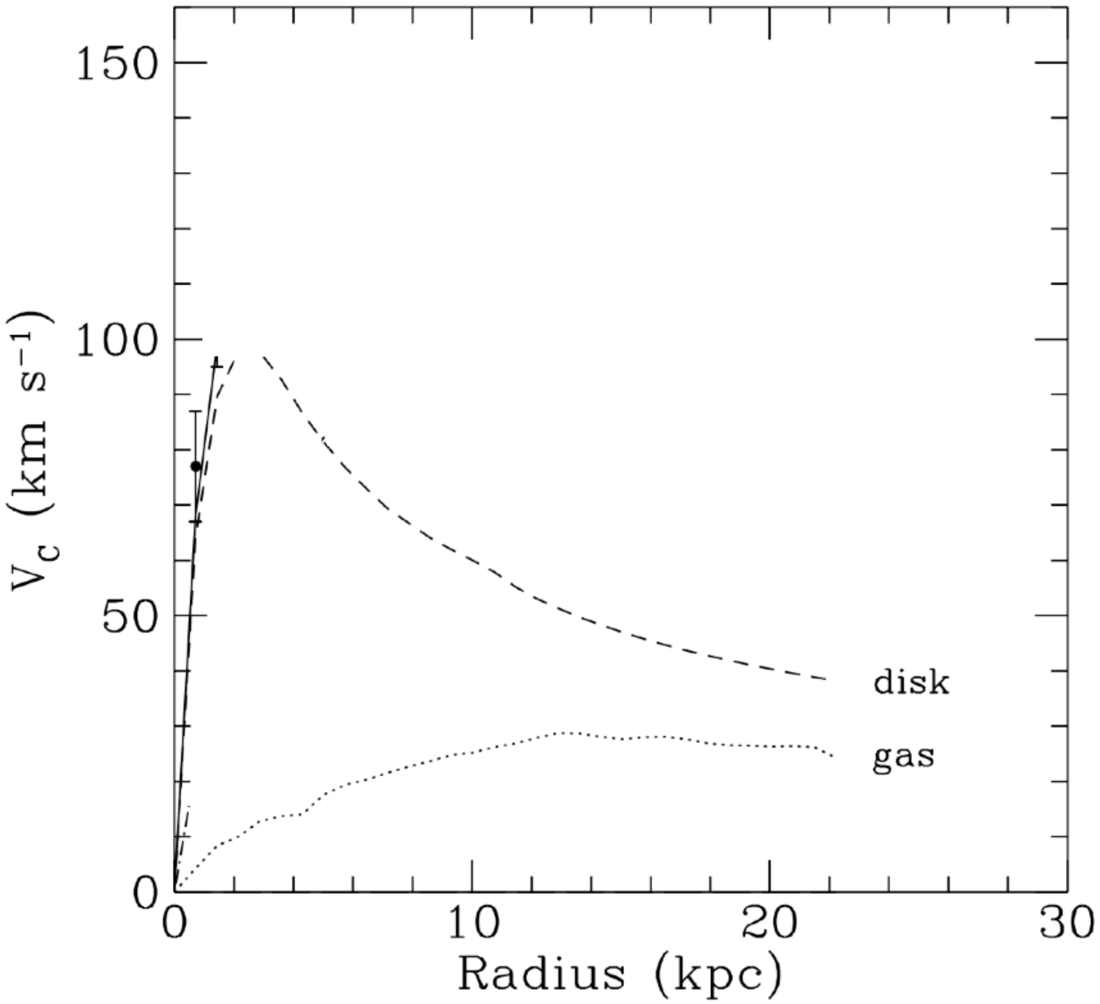

—> Tutorial 1

Evidence for Dark Matter

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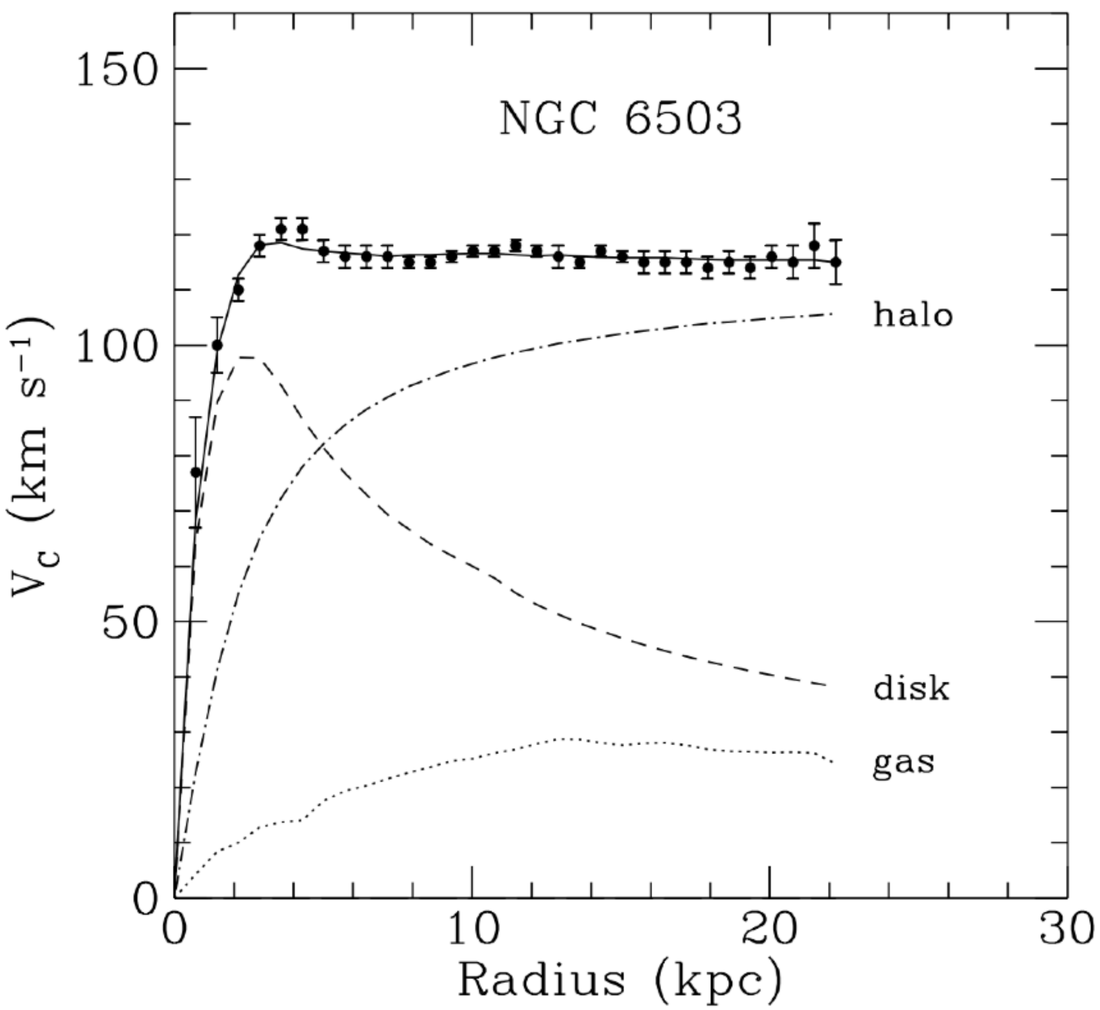
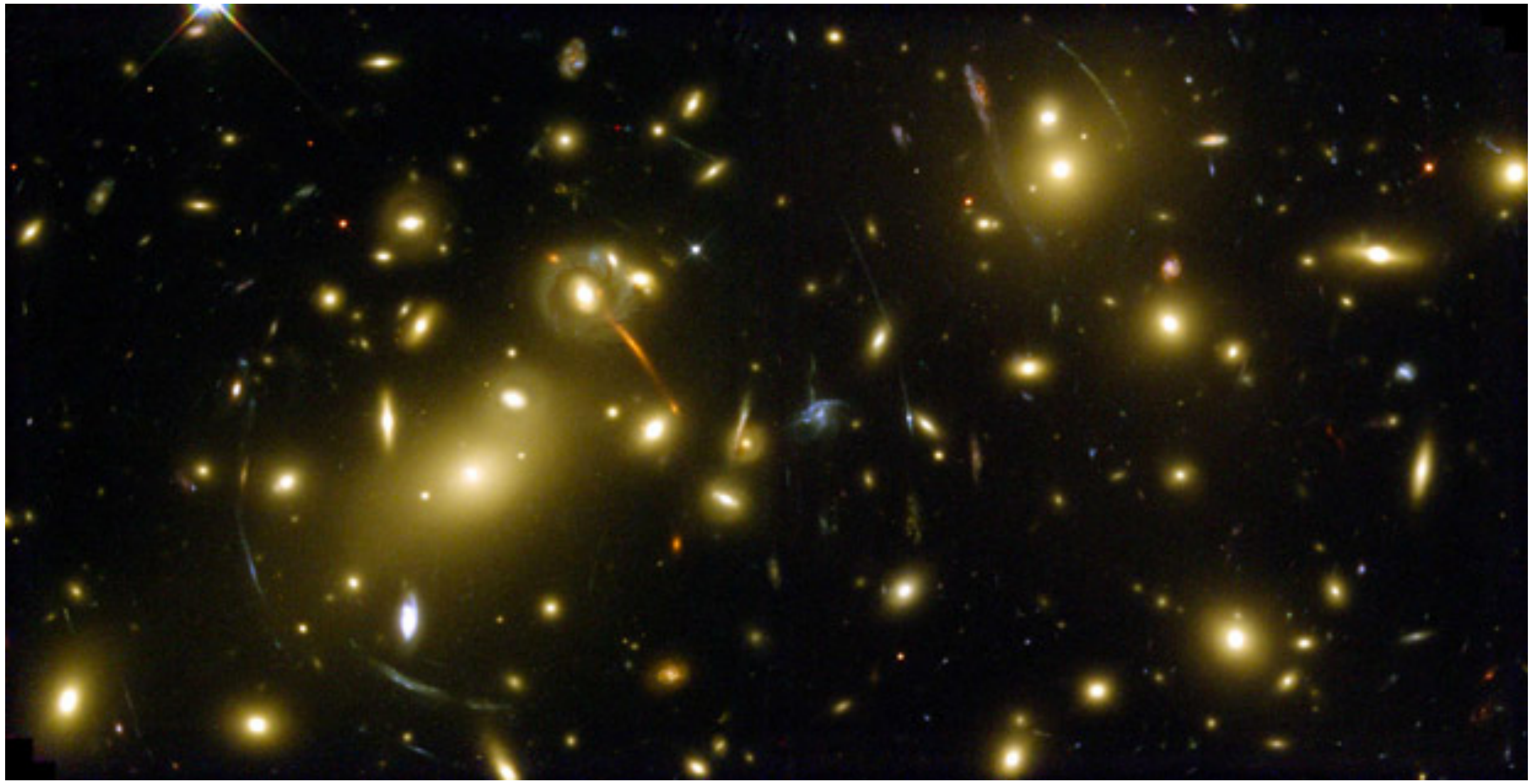


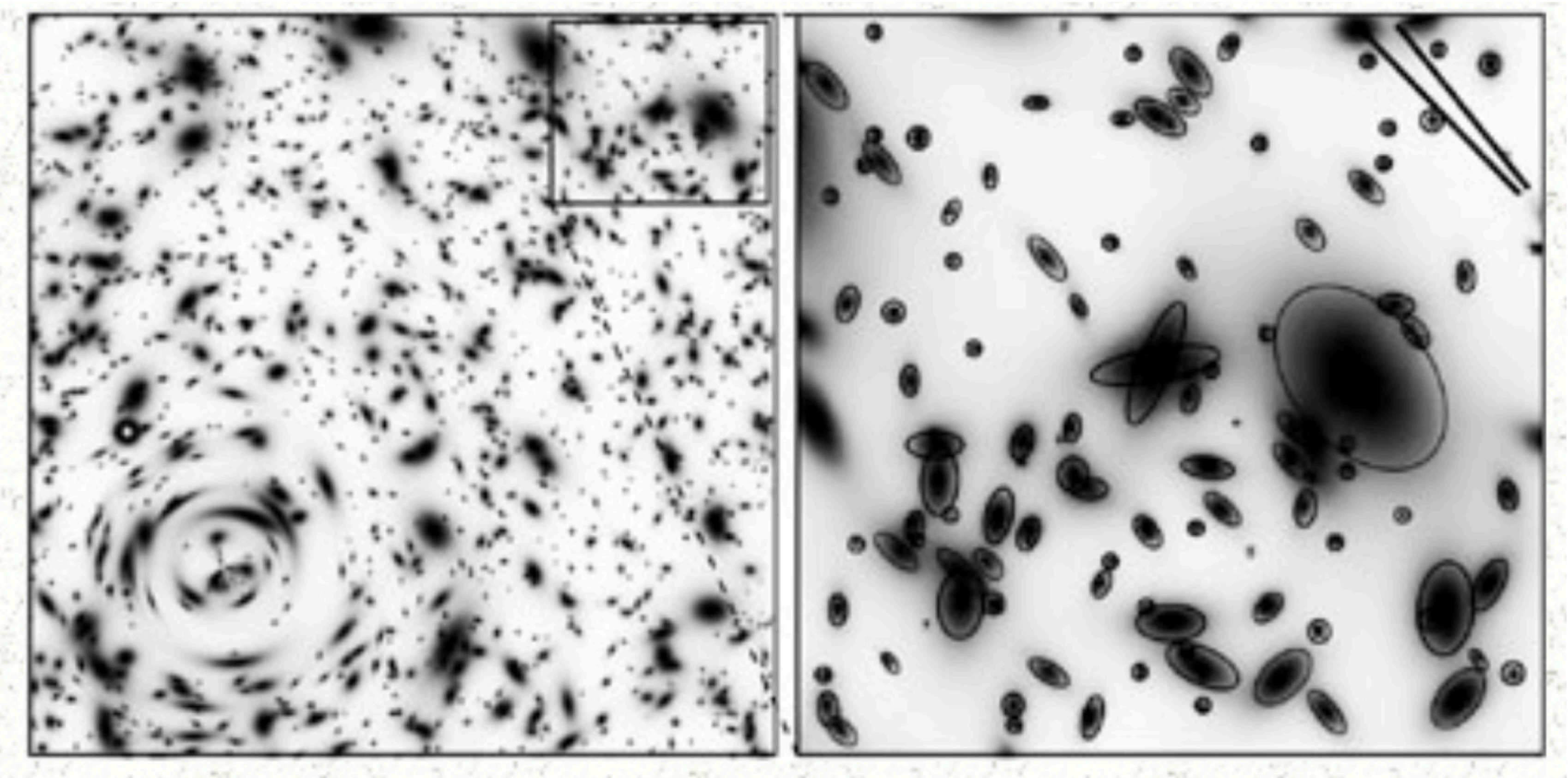
Vera Rubin

https://arxiv.org/pdf/astro-ph/9809214.pdf

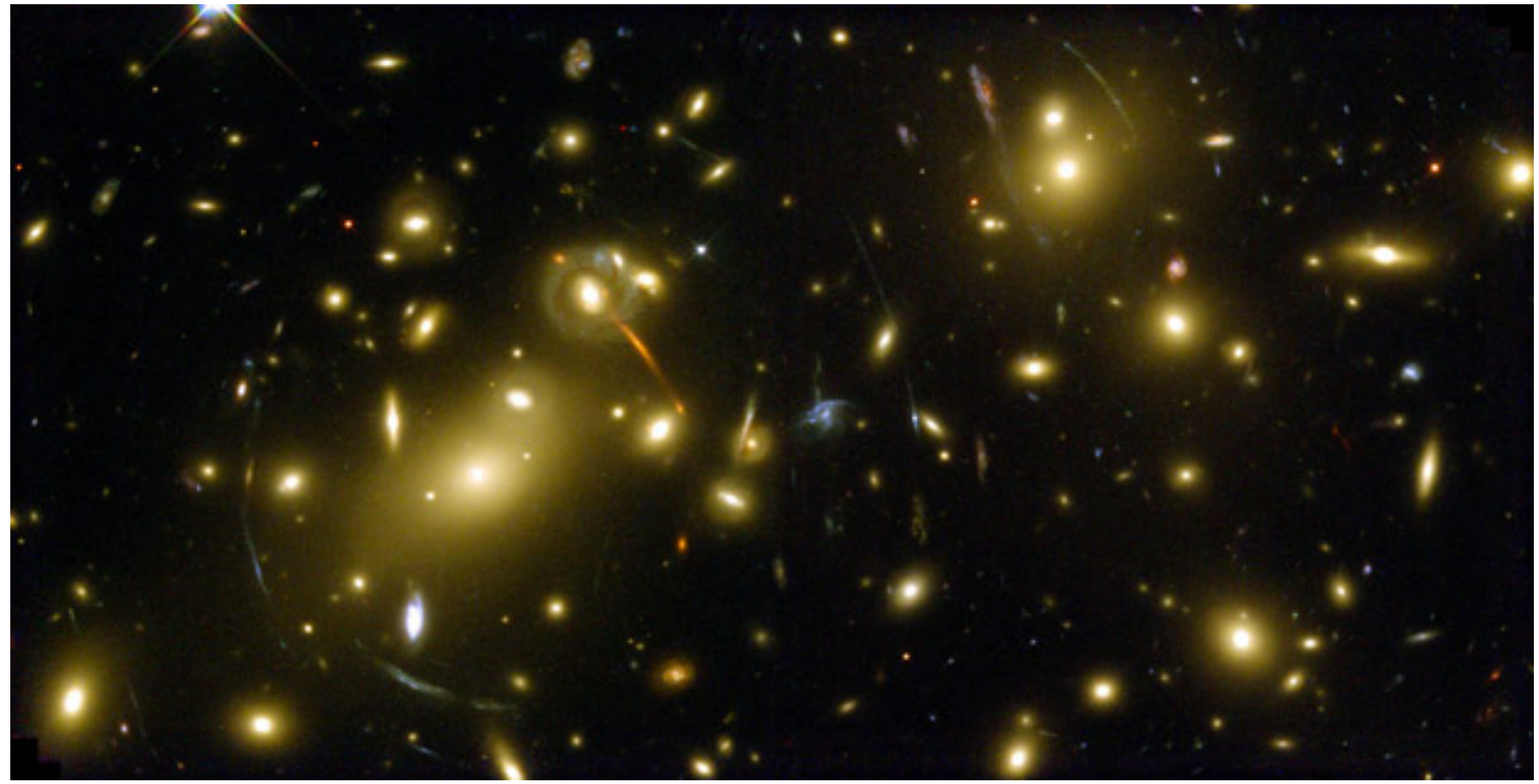
—> Tutorial 1

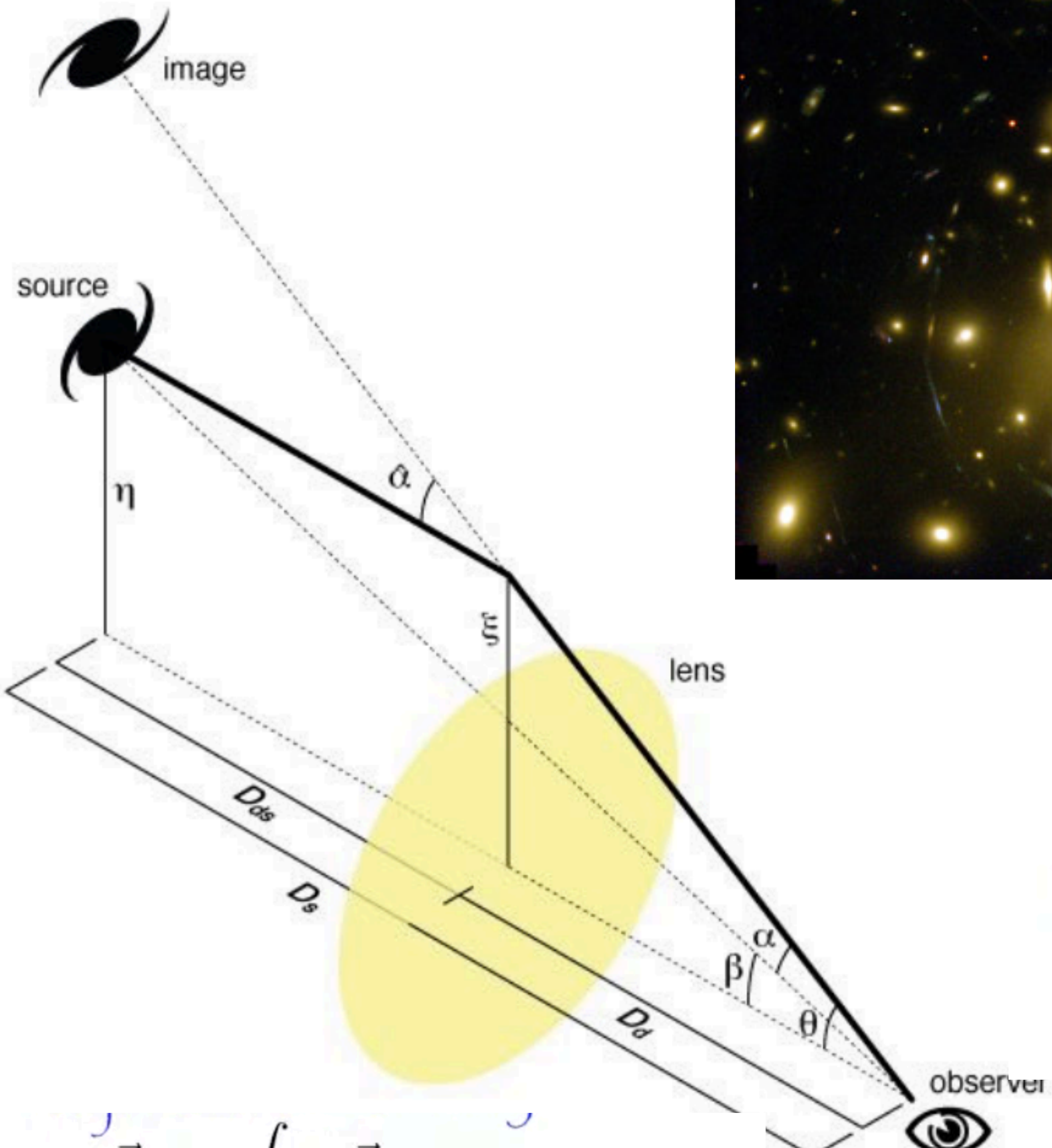
Gravitational lensing





Gravitational lensing





$$\vec{\beta} = \vec{\theta} - \frac{D_{ds}}{D_s}\alpha(D_d\vec{\theta})$$

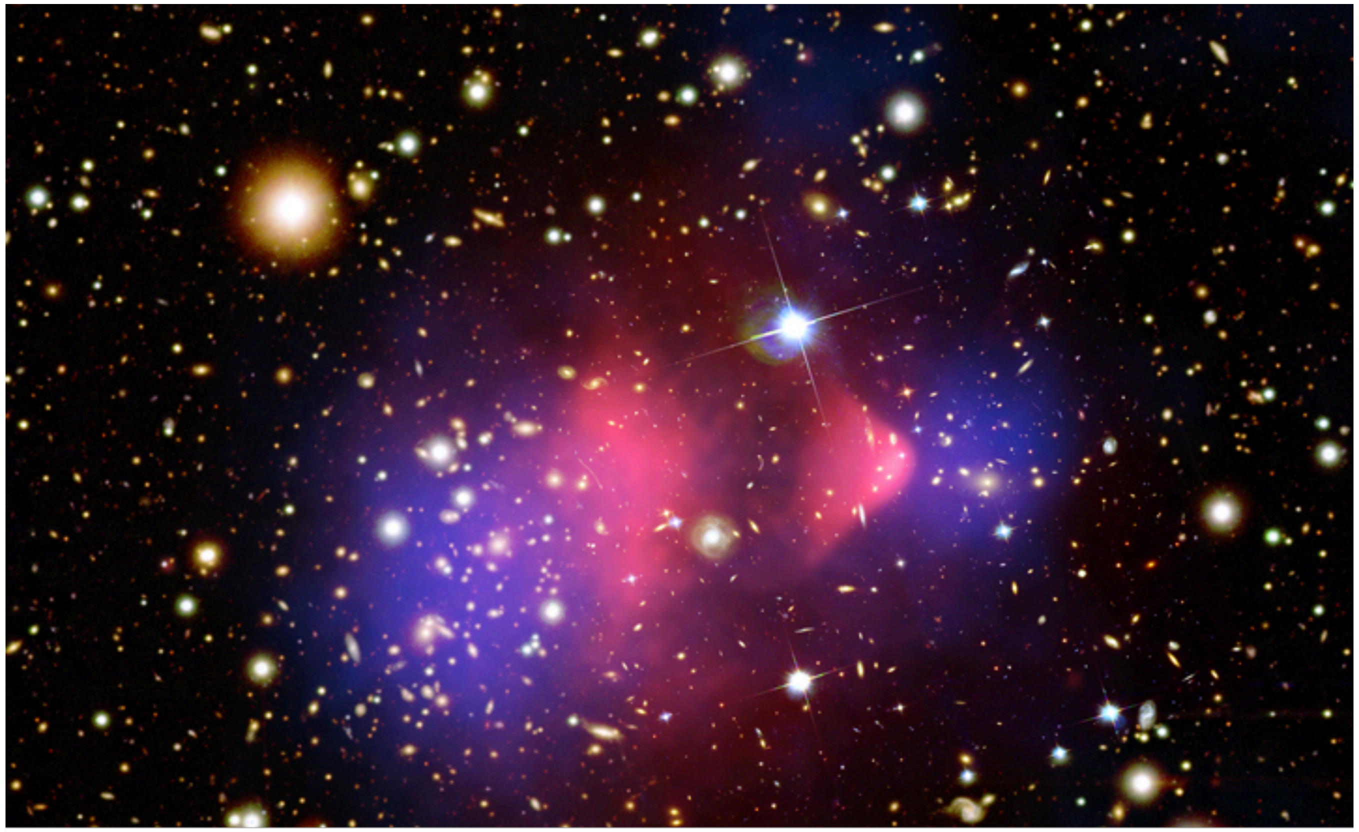
$$\alpha(\vec{\theta}) = 4G\int \frac{(\vec{\xi}-\vec{\xi}')\Sigma(\vec{\xi}')}{|\vec{\xi}-\vec{\xi}'|^2}\, d^2\xi'$$

$$\Sigma(\vec{\xi}') = \int \rho(\vec{\xi}, z)\, dz$$

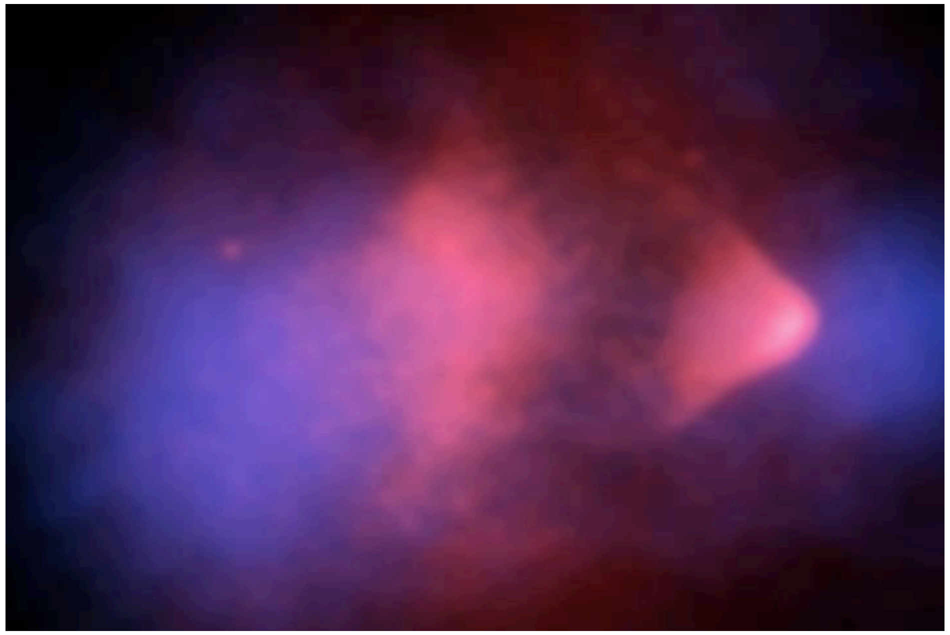
https://arxiv.org/pdf/0908.4157.pdf

Evidence for Dark Matter

Coma Cluster
Rotation curves (10 kpc)
Strong/Weak lensing
Galaxy Merger (Mpc)
CMB
…



Xray gas (Chandra)
Dark Matter



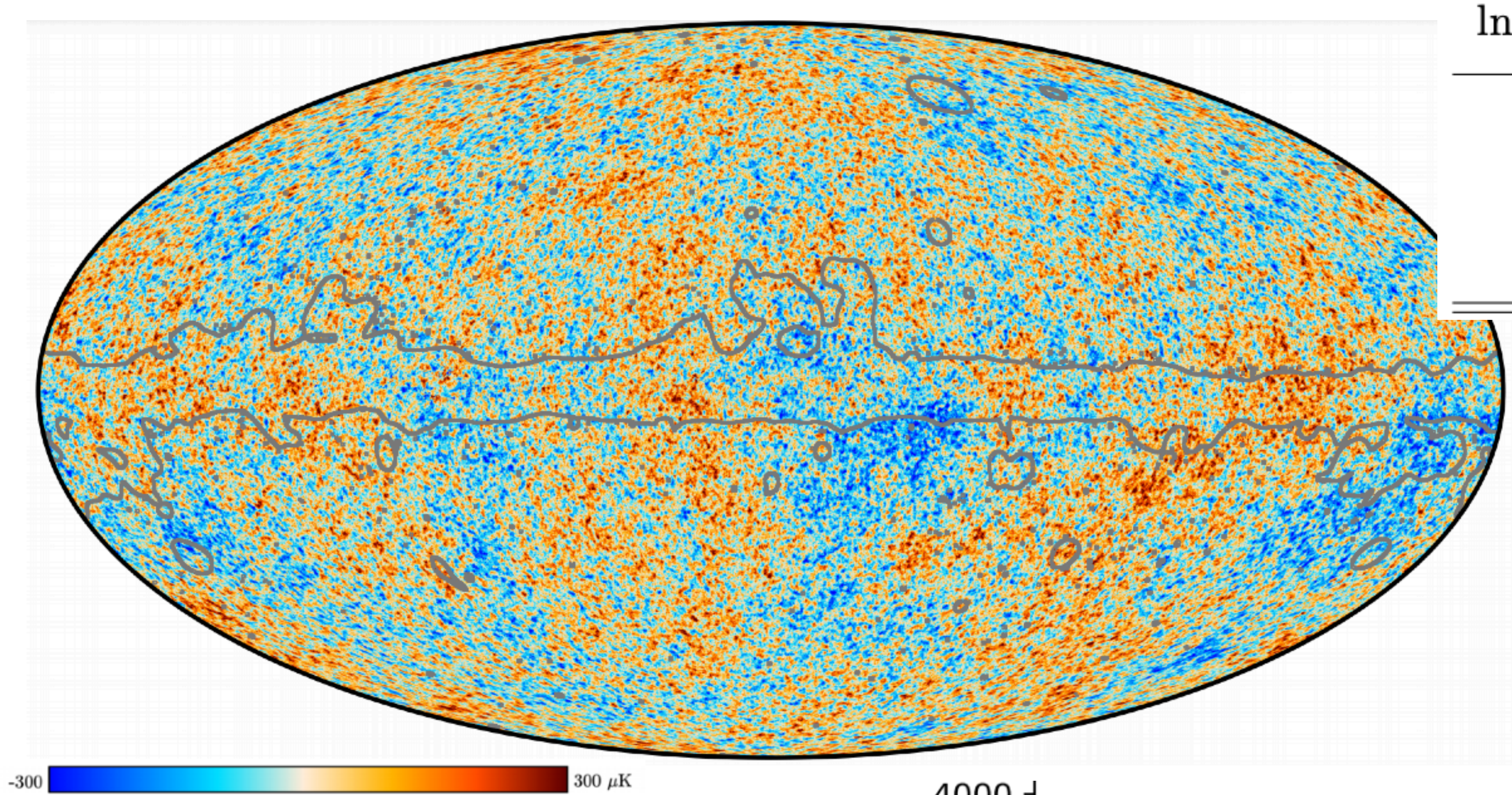
https://www.nasa.gov/vision/universe/starsgalaxies/dark_matter_proven.html

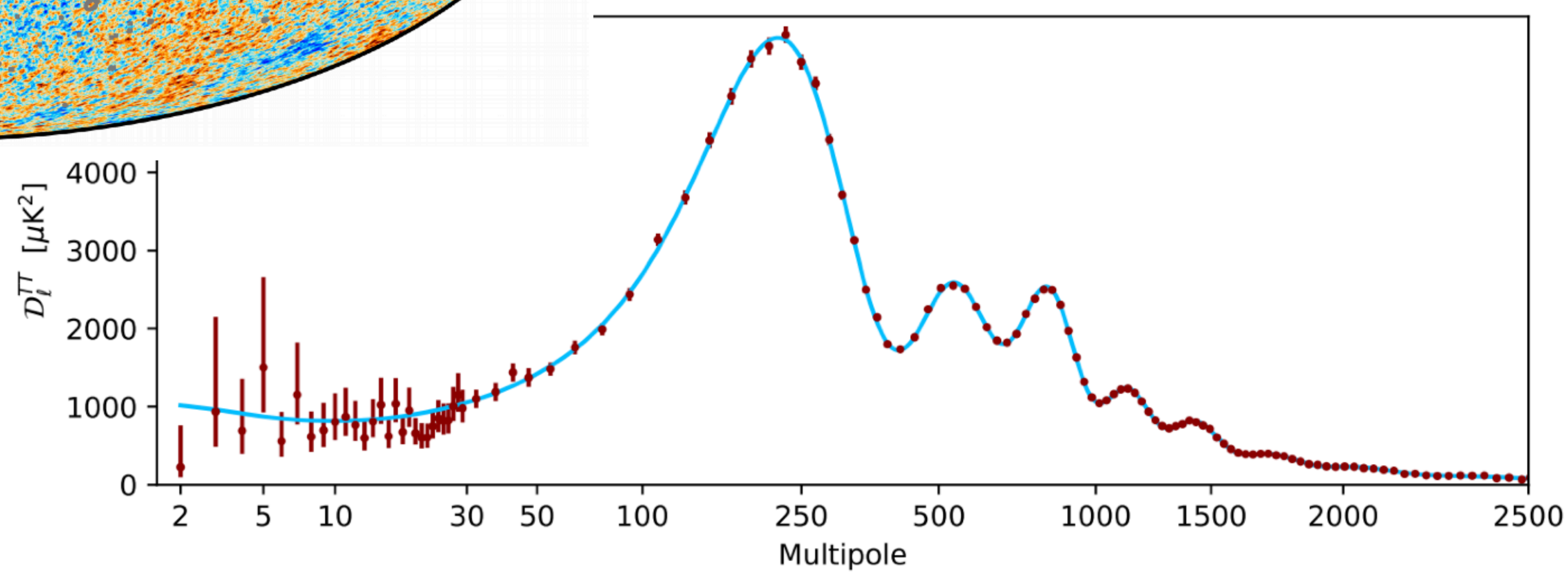
Evidence for Dark Matter

Coma Cluster
Rotation curves (10 kpc)
Strong/Weak lensing
Galaxy Merger (Mpc)
CMB (100 kpc)

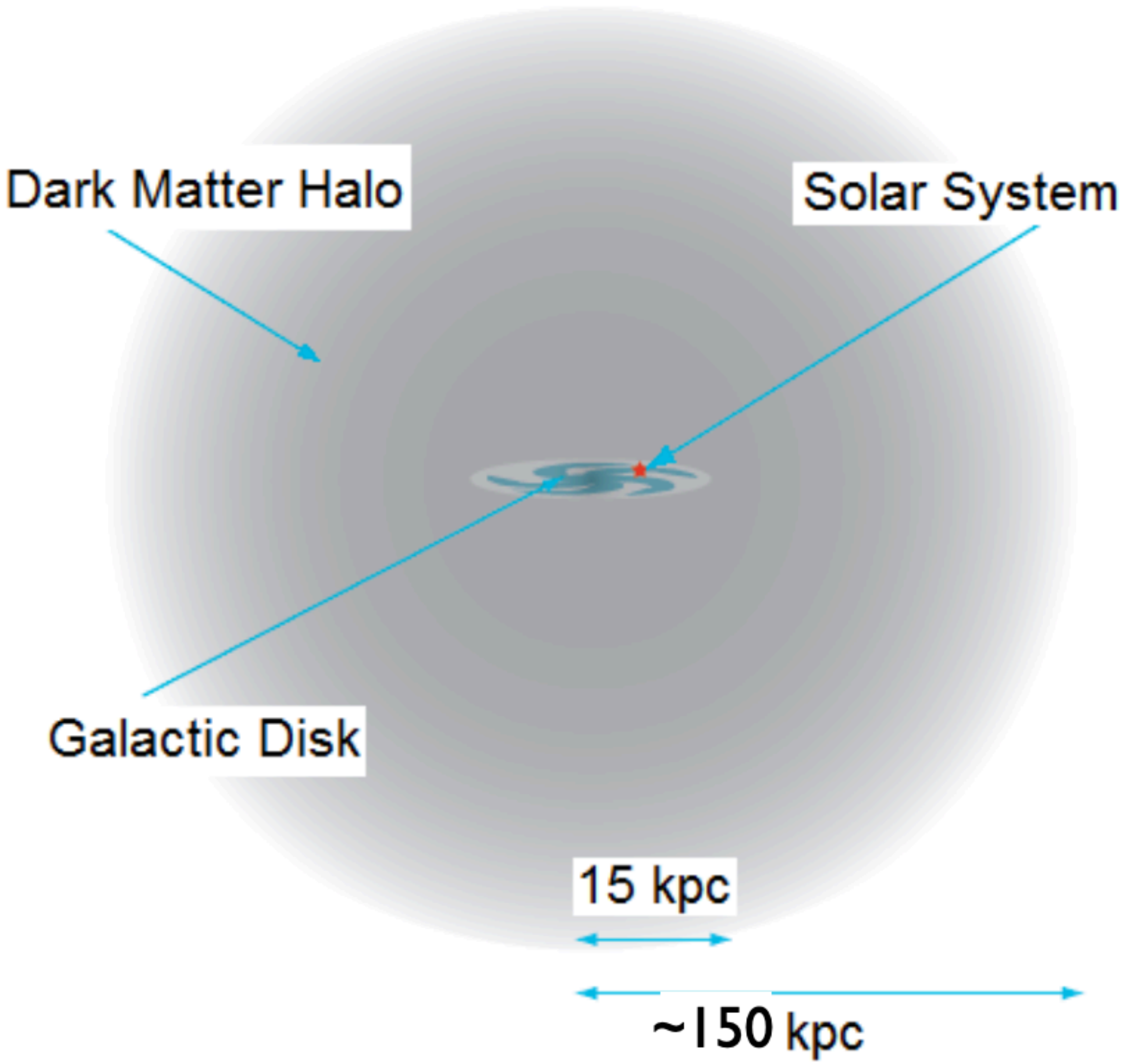
	Planck TT,TE,EE+lowE+lensing	+BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.1193 ± 0.0009
$100\,\theta_{MC}$	1.0409 ± 0.0003	1.0410 ± 0.0003
n_s	0.965 ± 0.004	0.966 ± 0.004
τ	0.054 ± 0.007	0.056 ± 0.007
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.044 ± 0.014	3.047 ± 0.014
h	0.674 ± 0.005	0.677 ± 0.004
σ_8	0.811 ± 0.006	0.810 ± 0.006
Ω_m	0.315 ± 0.007	0.311 ± 0.006
Ω_Λ	0.685 ± 0.007	0.689 ± 0.006

Ω = density parameter





Standard DM Halo model



Dark Matter Properties:

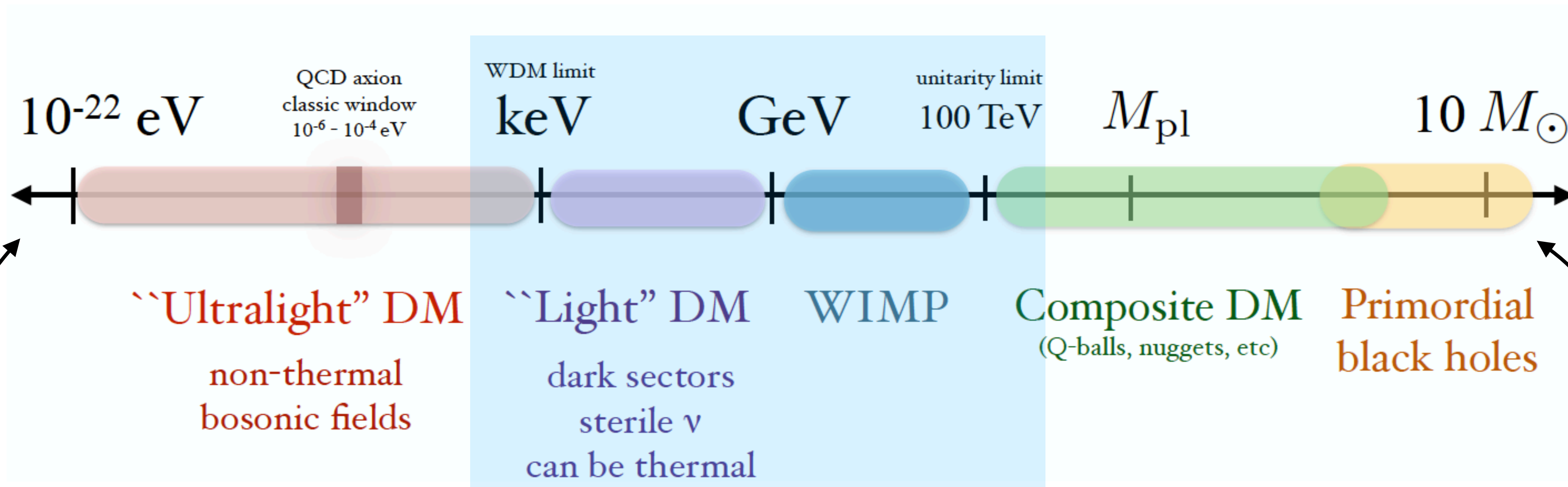
Optically Dark
Interact Gravitationally
Stable
Collision-less
Mass unknown?

$$\rho_0 = 0.3\ GeV/c^2$$

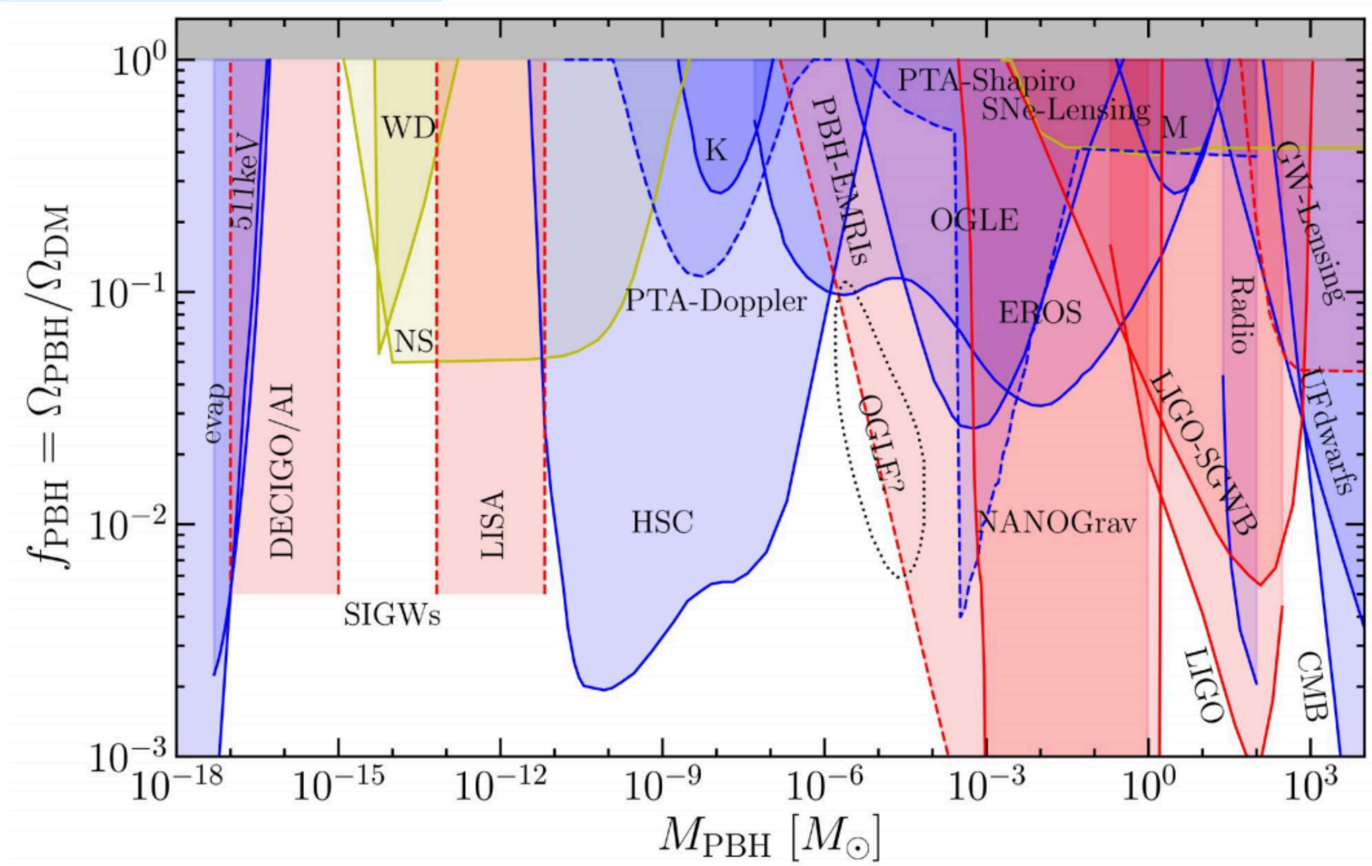
The Solar system is travelling across static halo (DM wind) —> directionality

DM mass parameter space

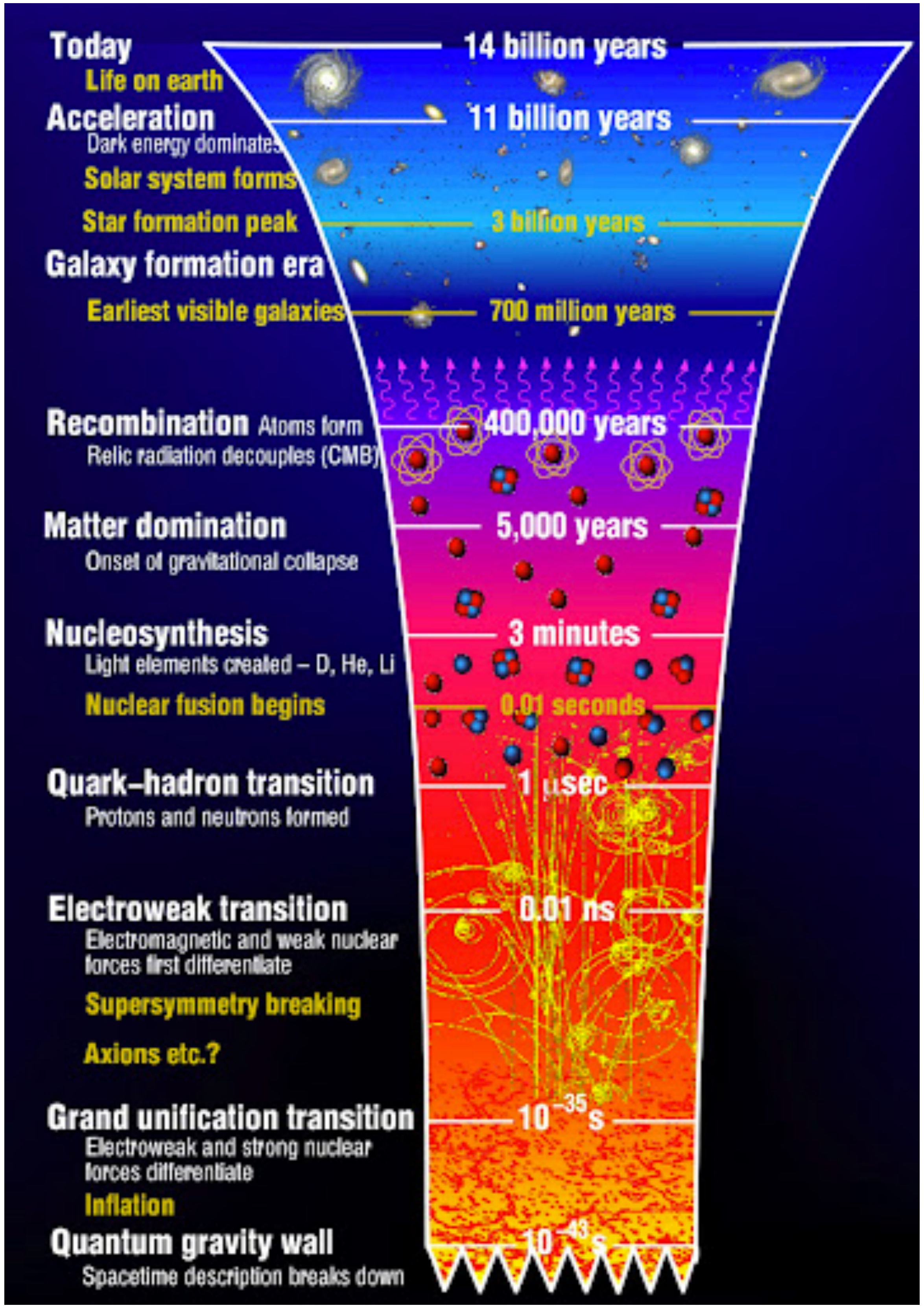
see TASI lecture by T. Lin



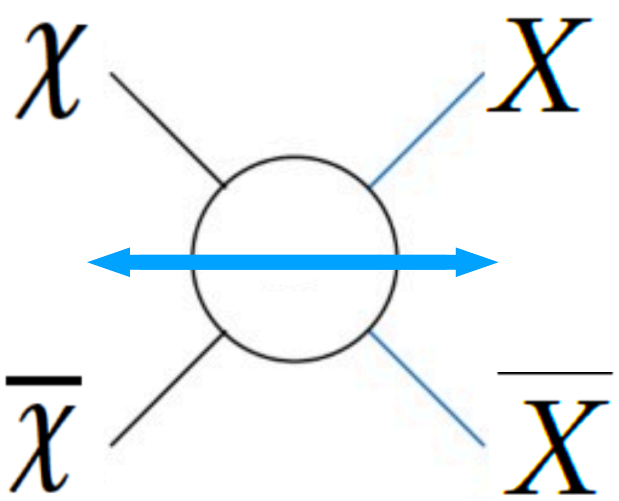
$$\lambda_{\rm dB} = \frac{2\pi}{m_{\rm DM} v} \approx 0.4\ \text{kpc} \left(\frac{10^{-22}\text{eV}}{m_{\rm DM}}\right)$$



A tiny bit of Cosmology



Thermal equilibrium:



Boltzmann equation:

$$\frac{dn}{dt} = -3Hn - \langle \sigma_A v \rangle \left(n^2 - n_{eq}^2 \right)$$

expansion of the Universe

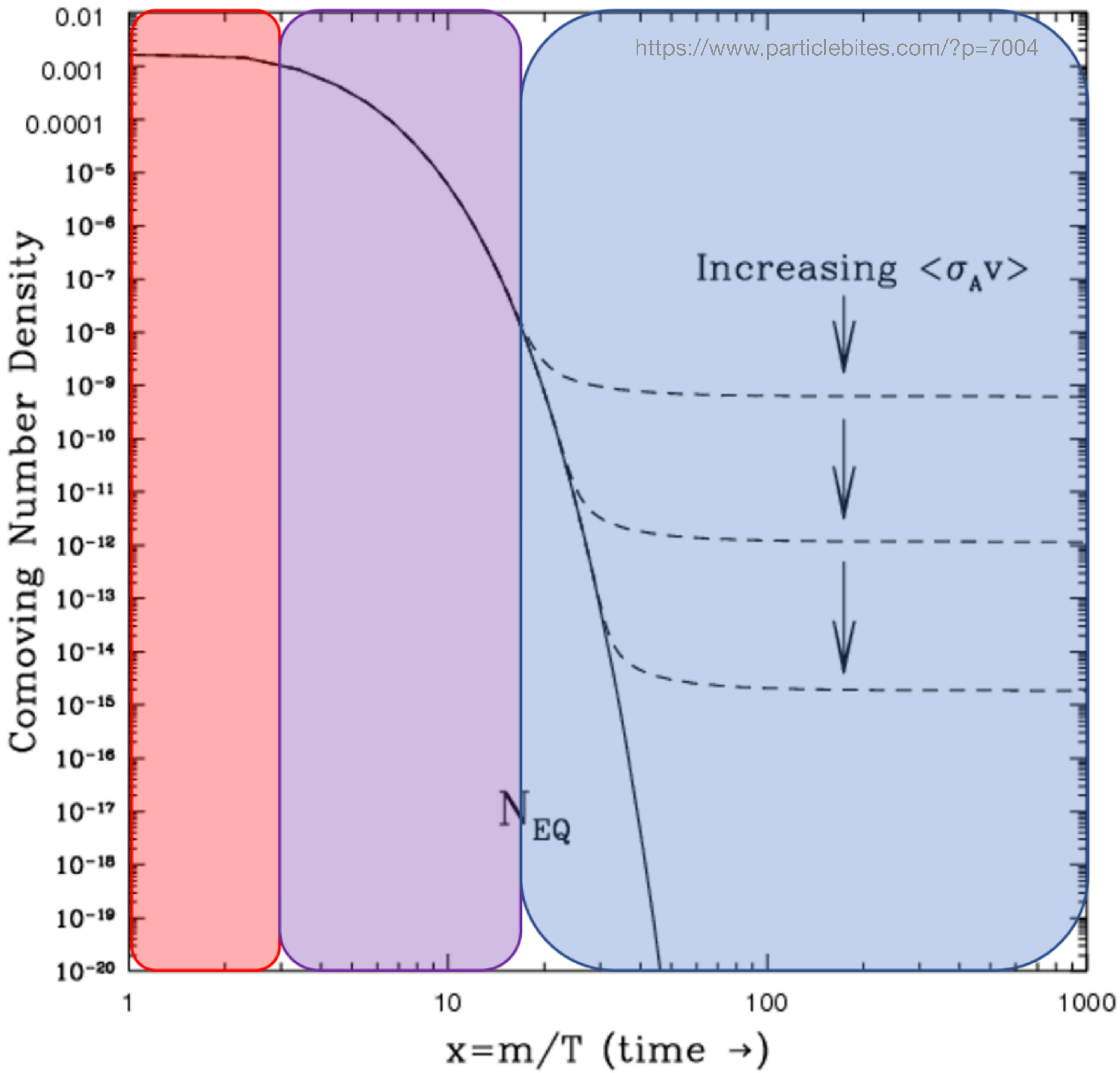
annihilation

production

Thermal Production: Freeze-out

T < m_χ : the production stops

x > ~ 20 : the annihilation is inefficient



$$\frac{dn}{dt} = -3Hn - \langle \sigma_A v \rangle \left(n^2 - n_{eq}^2 \right)$$

$$n_\chi^{eq} \approx g \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi / T}$$

$$\boxed{\Omega h^2 = 8.5 \cdot 10^{-11} \frac{g_\star^{1/2}(x_f)}{g_{\star S}(x_f)} \left(\frac{\mathrm{GeV}^{-2}}{\langle \sigma_{\mathrm{ann}} v \rangle_{\mathrm{int}}} \right)}$$

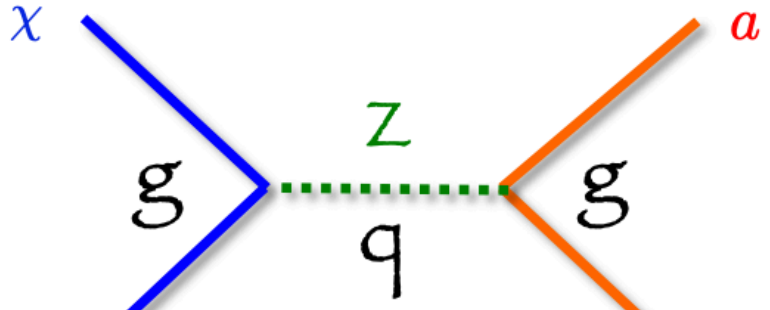
The WIMP miracle:
Ω_χ ~ 0.1 <=> <σv> at the weak scale
for m_χ ~ GeV-TeV

FREEZE-OUT: —> Tutorial 1

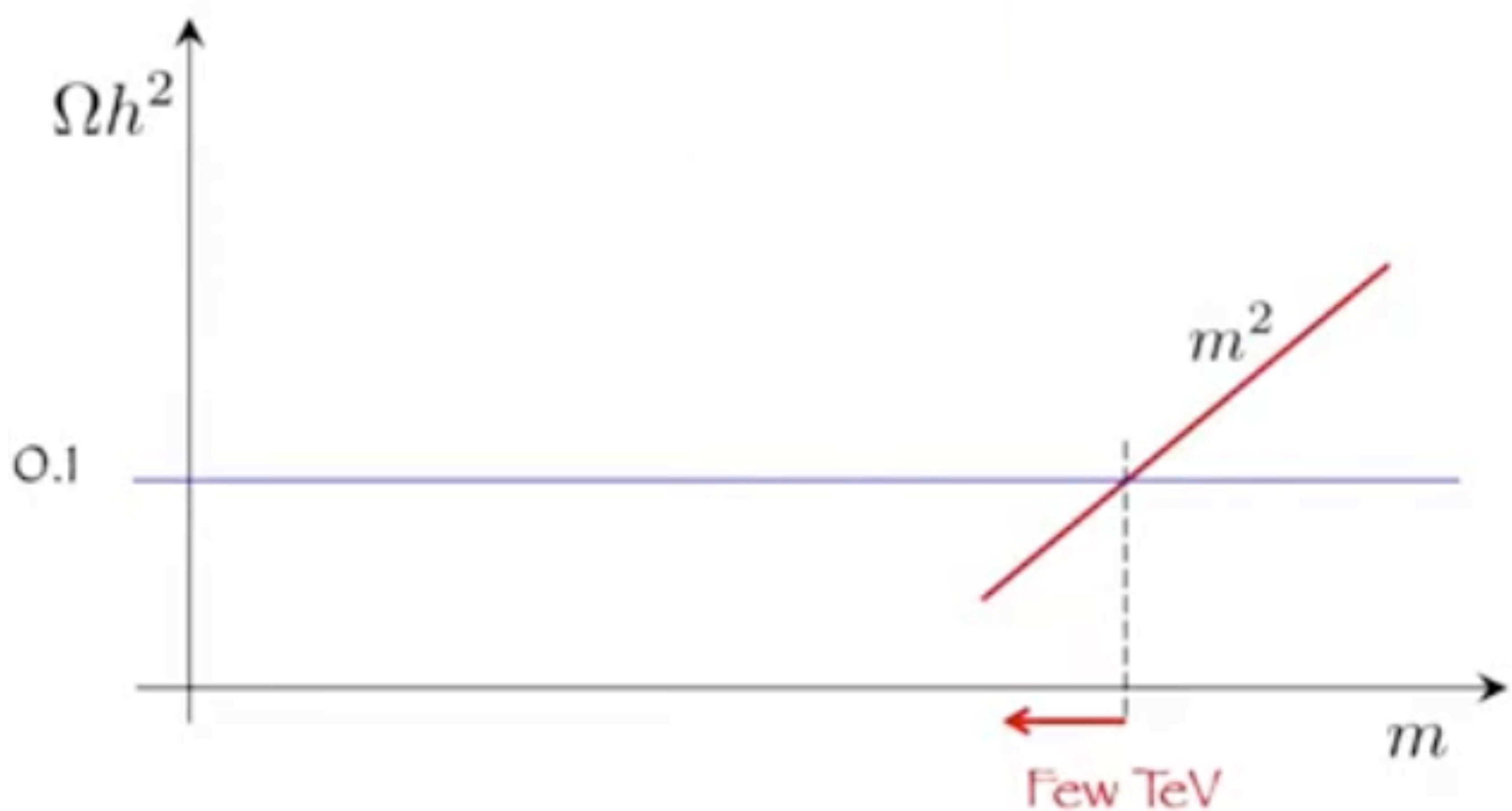
"Natural" limits

$m \gg m_Z$ $\qquad \langle \sigma_{\rm ann} v \rangle \sim \dfrac{g^4}{m_{\rm DM}^2}$

$$\boxed{\Omega h^2 = 8.5 \cdot 10^{-11} \, \frac{g_\star^{1/2}(x_f)}{g_{\star S}(x_f)} \left(\frac{\mathrm{GeV}^{-2}}{\langle \sigma_{\rm ann} v \rangle_{\rm int}} \right)}$$

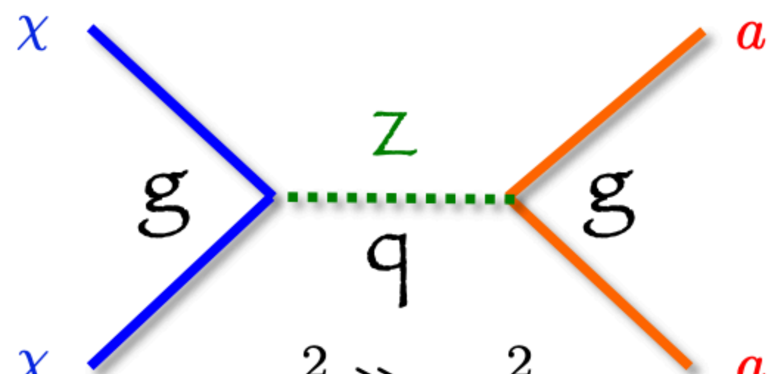


$q^2 \gg m_Z^2$



“Natural” limits

$$m \gg m_Z \qquad \langle \sigma_{\rm ann} v \rangle \sim \frac{g^4}{m_{\rm DM}^2}$$



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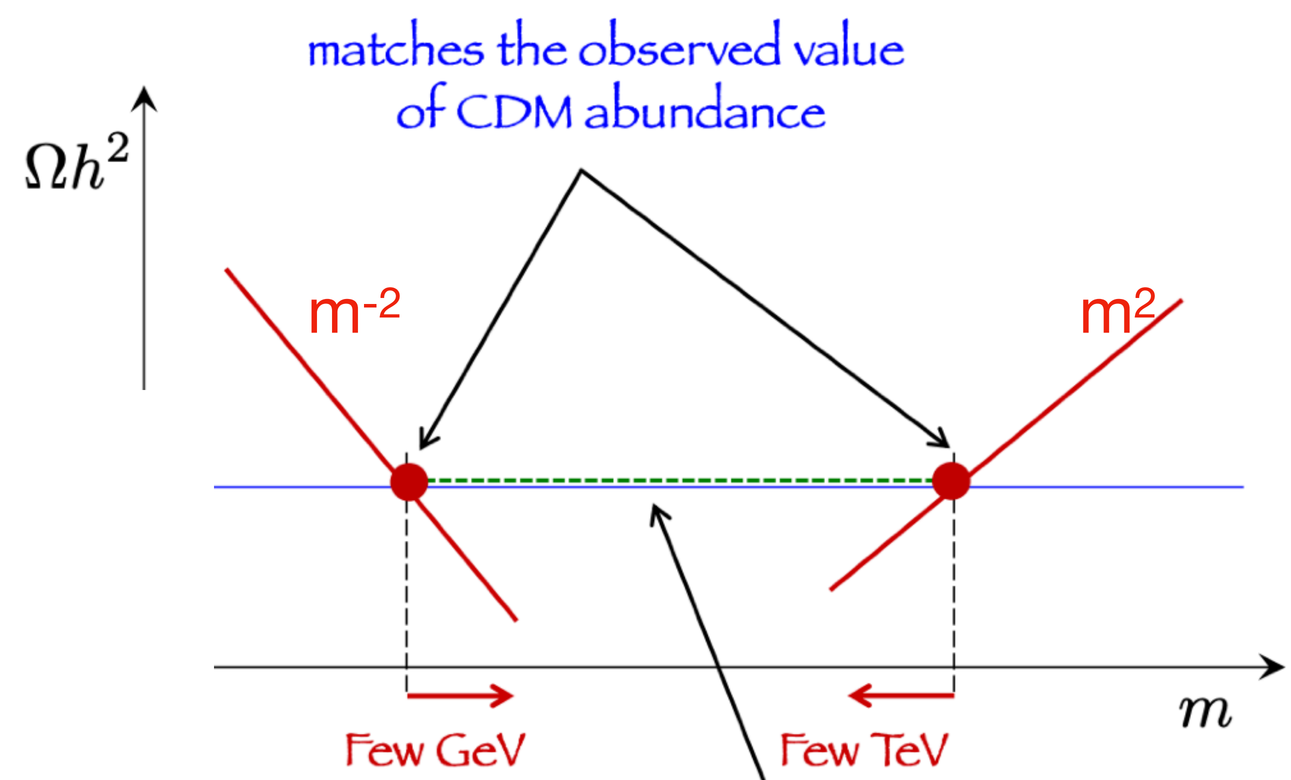
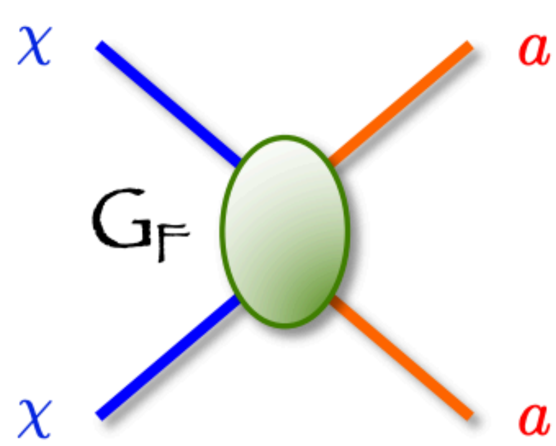


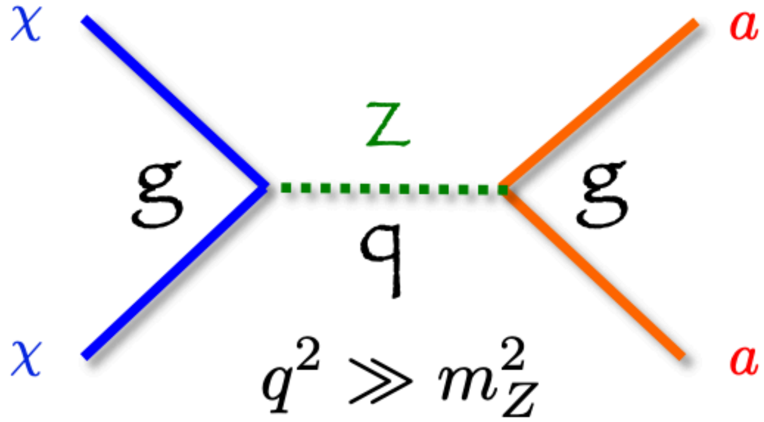
Favourite mass range for **WIMPs**

$$m \ll m_Z \qquad \langle \sigma_{\rm ann} v \rangle \sim G_F^2 m_{\rm DM}^2$$



"Natural" limits

$m \gg m_Z \qquad \langle \sigma_{\rm ann} v \rangle \sim \dfrac{g^4}{m_{\rm DM}^2}$



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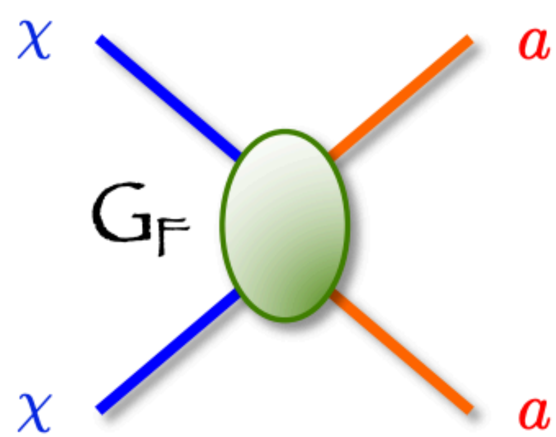
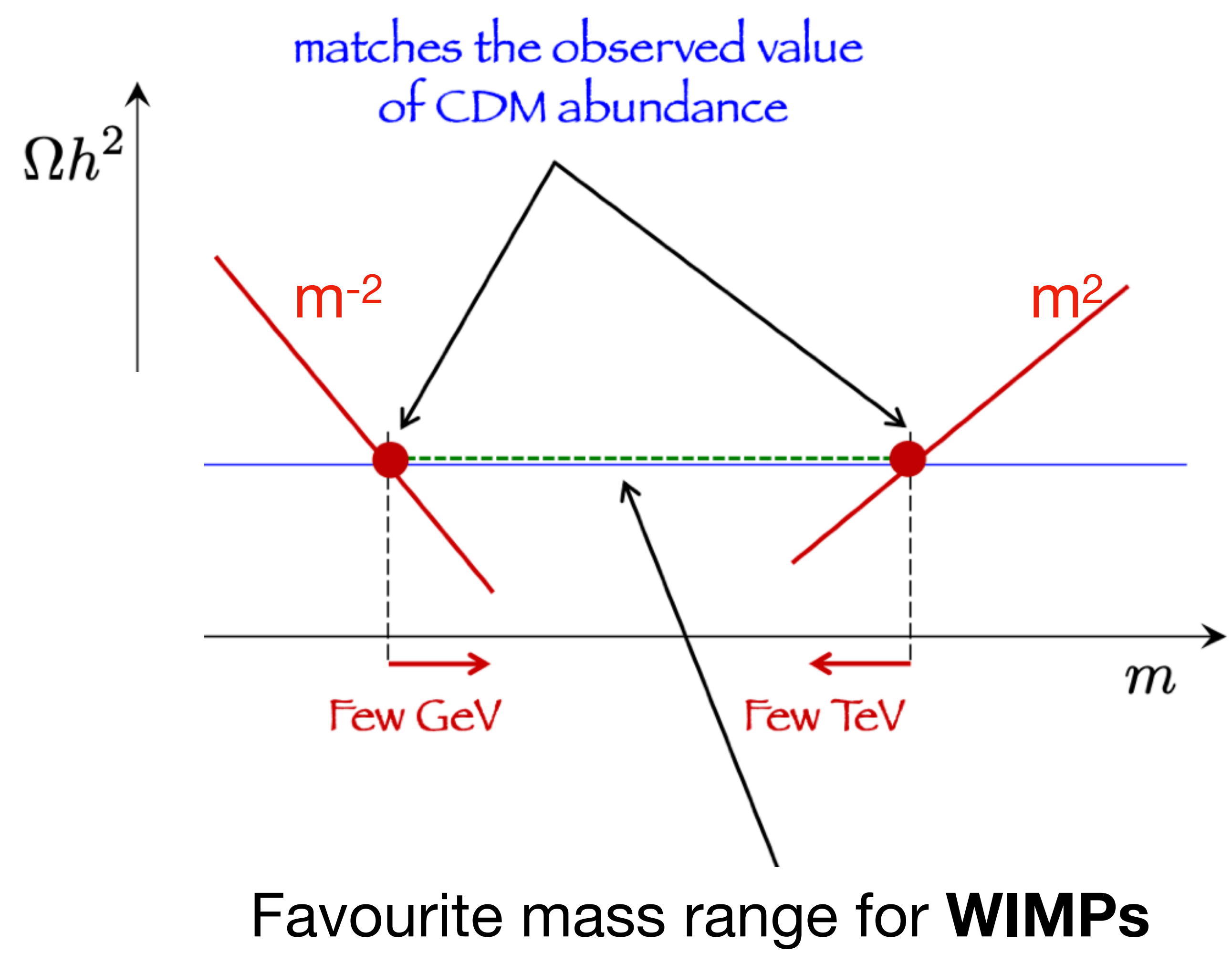


$$\Omega h^2 = 8.5 \cdot 10^{-11} \, \frac{g_\star^{1/2}(x_f)}{g_{\star S}(x_f)} \left(\frac{\mathrm{GeV}^{-2}}{\langle \sigma_{\rm ann} v \rangle_{\rm int}} \right)$$



The WIMP miracle:

$\Omega_\chi \sim 0.1$ <=> <σv> at the weak scale for $m_\chi \sim$ GeV-TeV

Lighter Candidates: need for new mediator(s)

The implication is that for **sub-GeV DM**, new mediators below the weak scale are required

Lighter Candidates: need for new mediator(s)

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- Vector - Dark Photon

kinetic mixing with SM: k or ε

$$\mathcal{L} \supset -\frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}(1-\kappa^2)V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + e(\tilde{A}_\mu + \kappa V_\mu)J^\mu_{\rm EM} + g_\chi V_\mu J^\mu_D$$

- Pseudo-Vector - Axion-like Particles

Not necessarily the QCD axion, coupled to fermions or gauge bosons

$$\frac{\partial_\mu a}{f_a}\bar{f}\gamma^\mu\gamma^5 f \qquad \frac{a}{f_a}F\tilde{F}$$

- Scalar - Dark Higgs

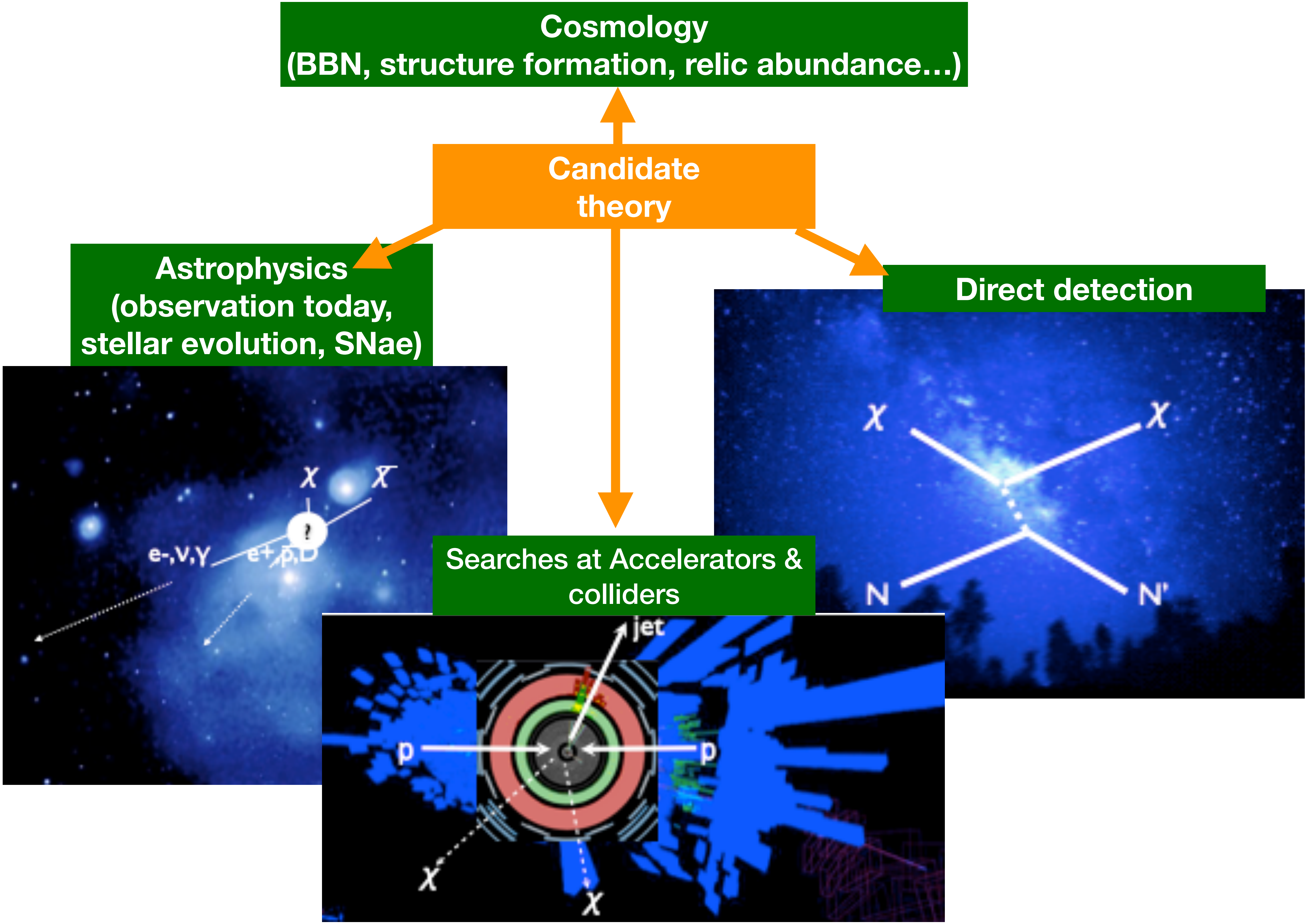
interaction with fermions, proportional to f mass

$$\propto y_f \phi \bar{f} f$$

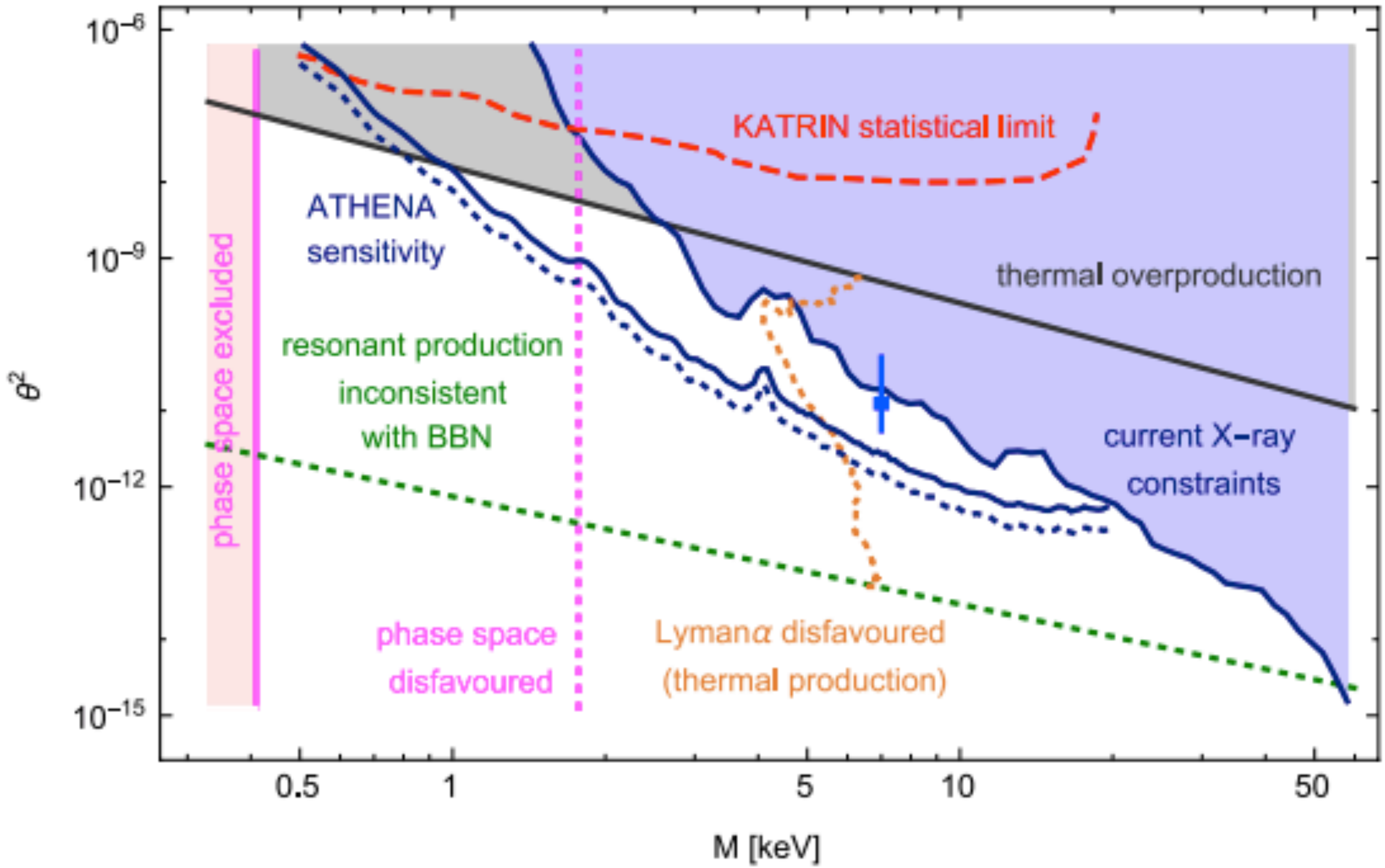
- Spinor - Heavy neutral lepton

sterile neutrino, mixed with SM neutrinos

$$\bar{L}H\nu_s$$

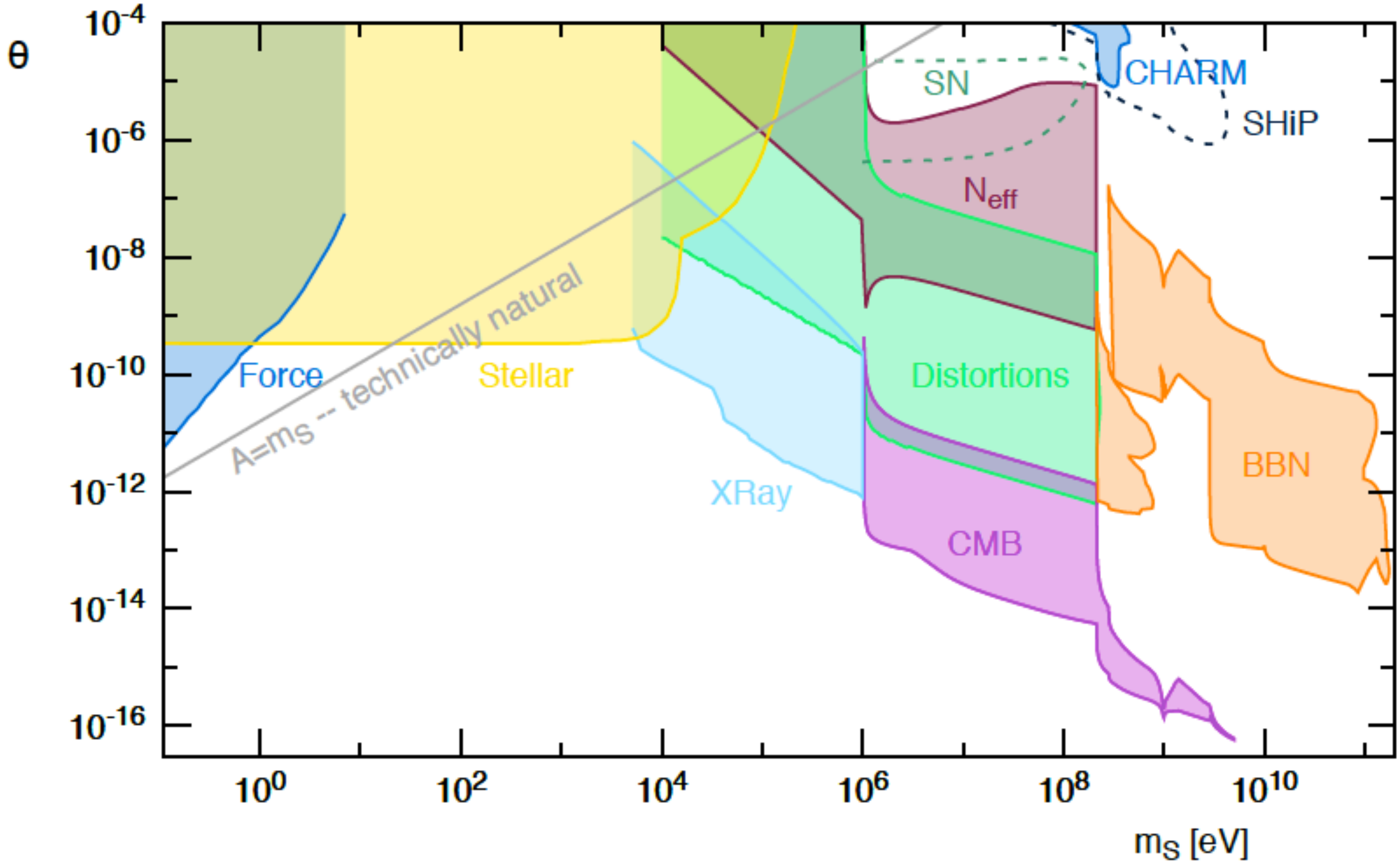

Cosmology
(BBN, structure formation, relic abundance…)
Candidate theory
Astrophysics
(observation today, stellar evolution, SNae)
Direct detection
Searches at Accelerators & colliders
χ
χ̄
e-,ν,γ
e+,p̄,D̄
χ
χ
N
N'
jet
p
p
χ
χ

Sterile Neutrinos as keV DM



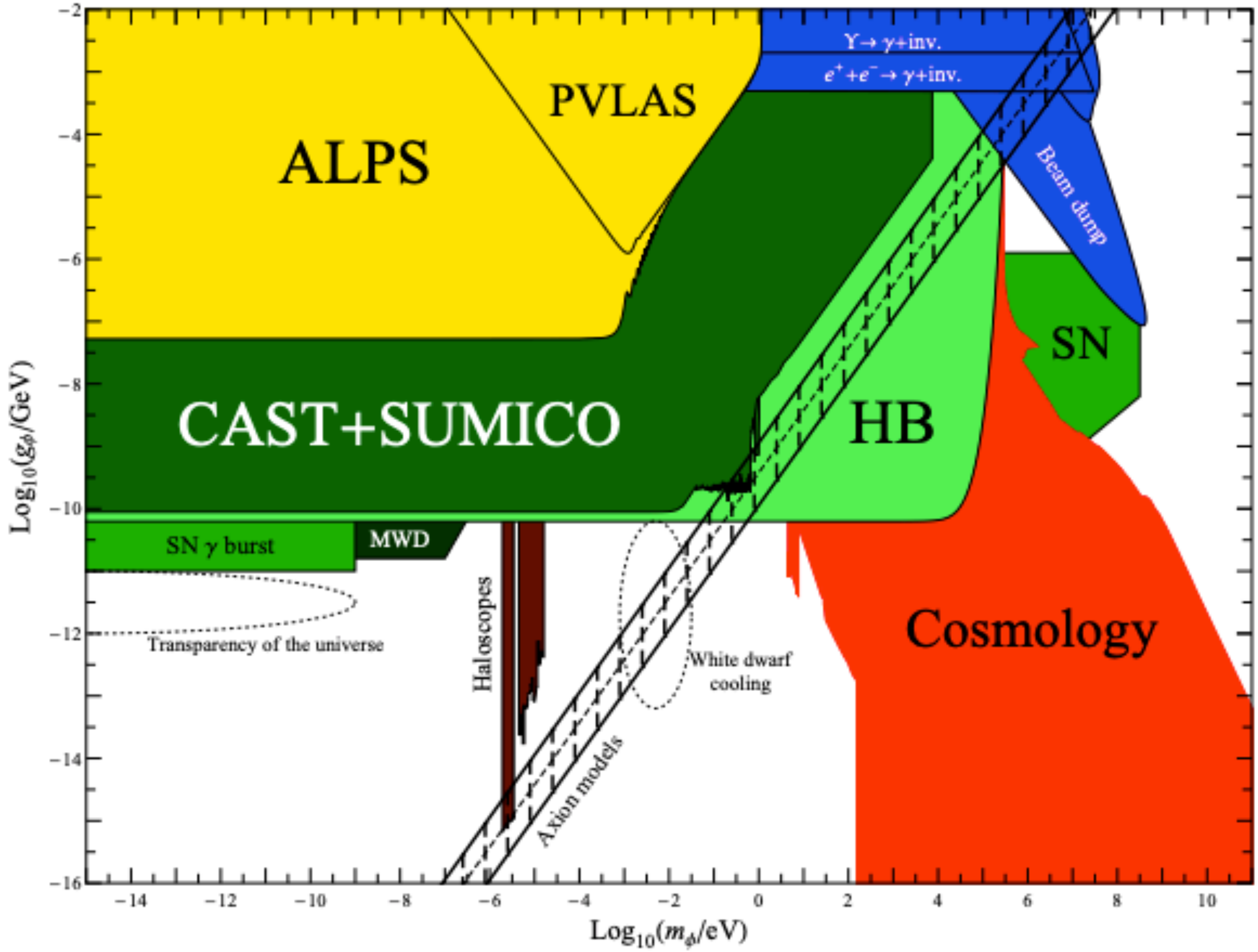
Boyarsky, Drewes, Lasserre, Mertens, Ruchayskiy [1807.07938]

Scalar Portal



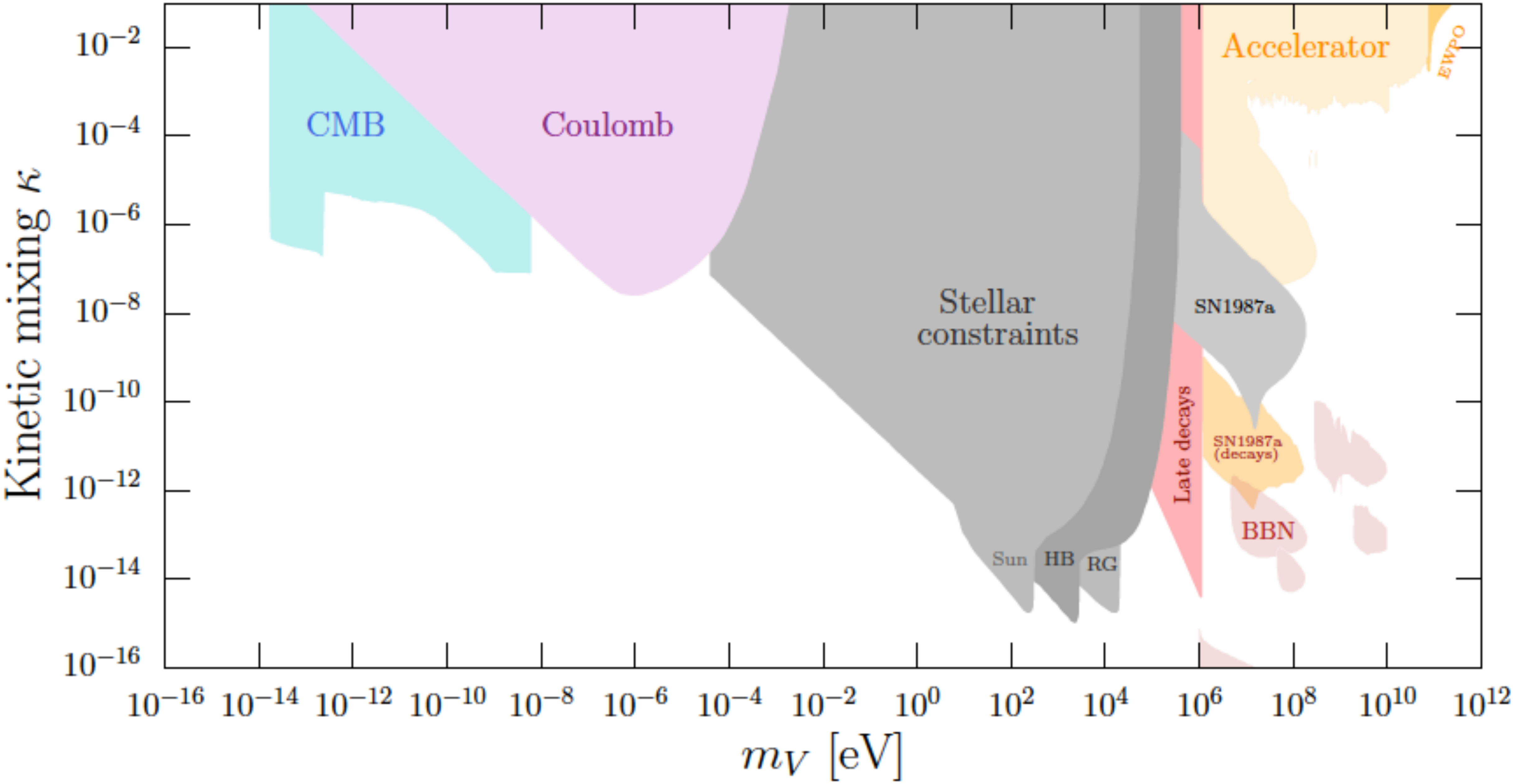
https://arxiv.org/abs/2102.12143

Axion-like particles



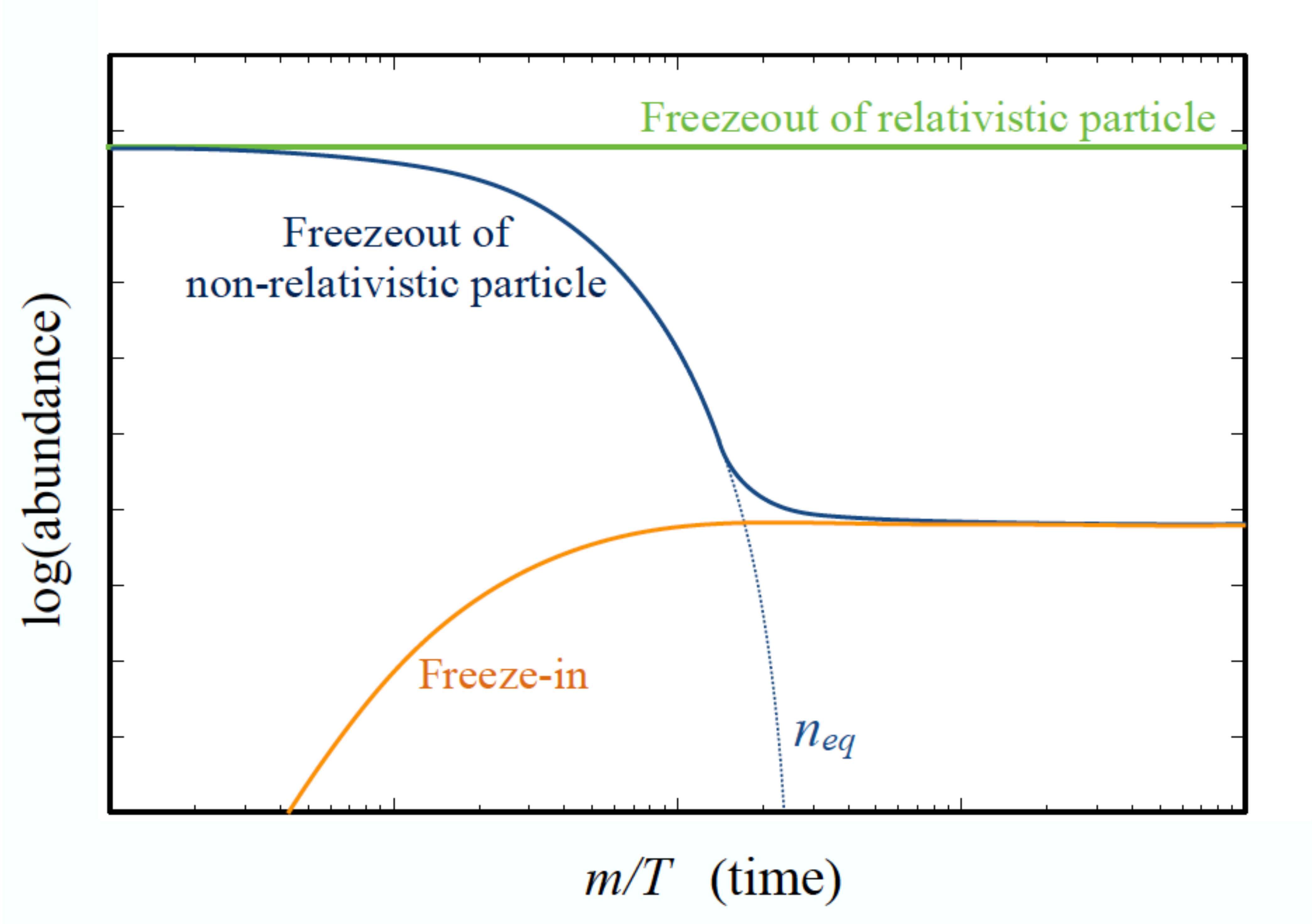
https://arxiv.org/pdf/1210.3196.pdf

Existing Bounds on vector mediator



https://arxiv.org/abs/1904.07915

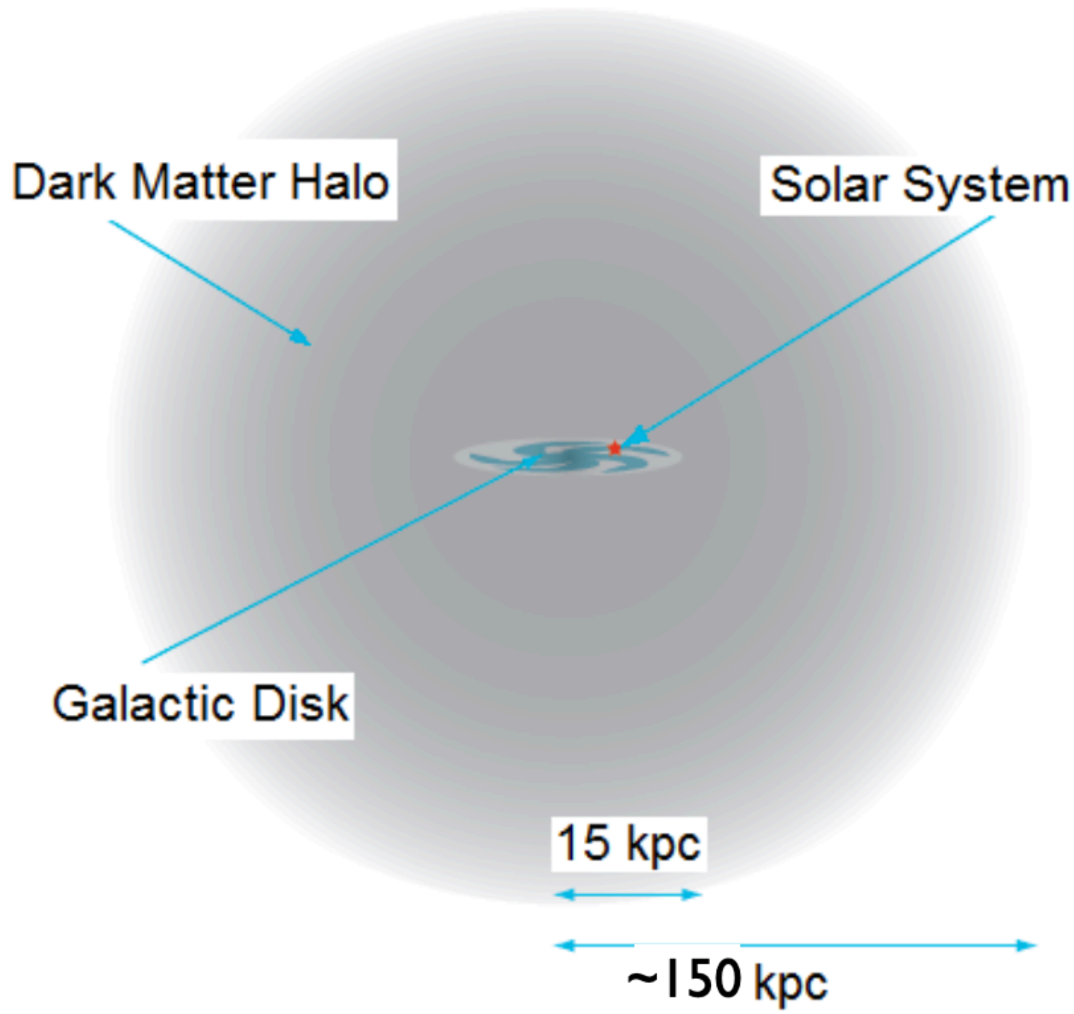
Production Mechanisms - conclusions

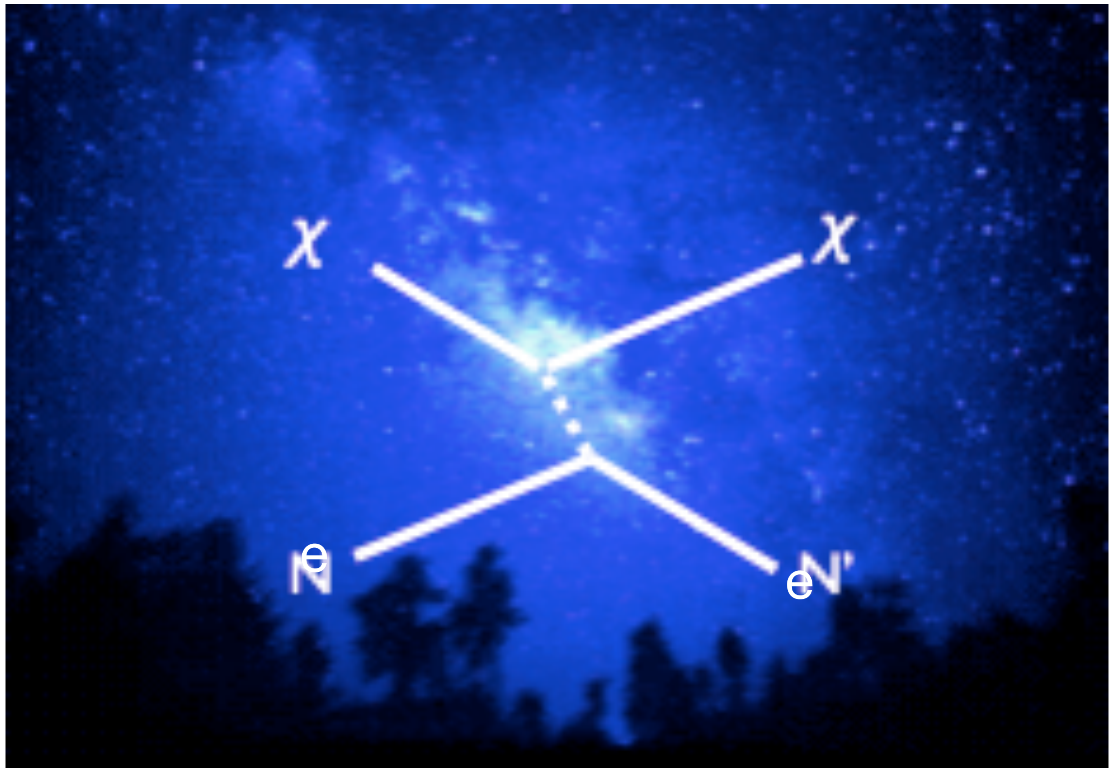


https://arxiv.org/pdf/0911.1120.pdf

DM direct detection

DM direct detection





Lighter the candidate
==> more challenging the detection

DM direct detection

Number of Events = (Flux) x (Cross Section) x (Exposure)

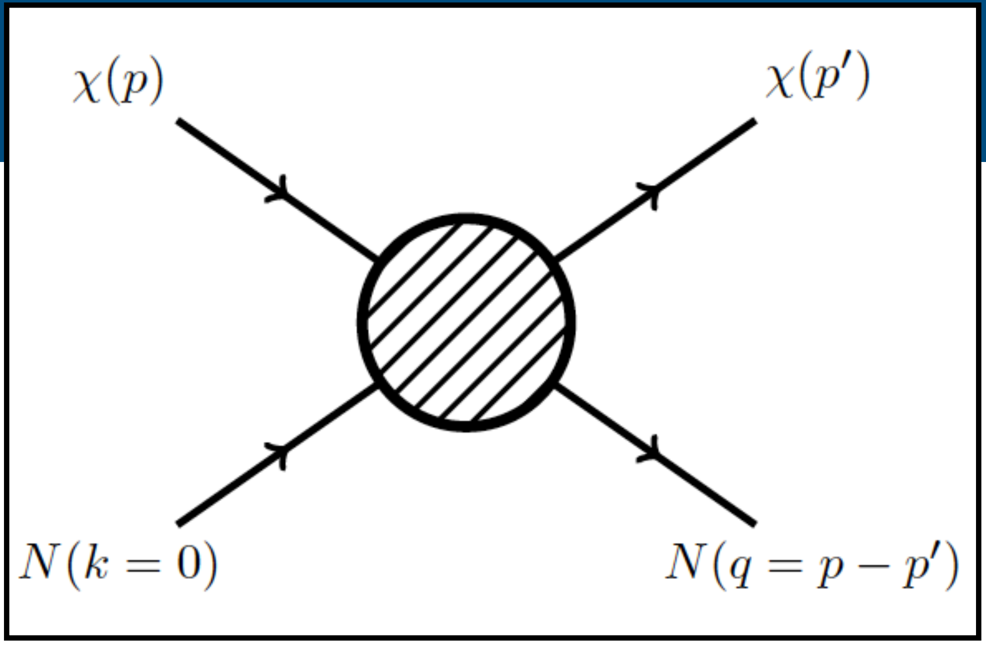
(how much dark matter)

(how likely it is to interact)

(how long you look)

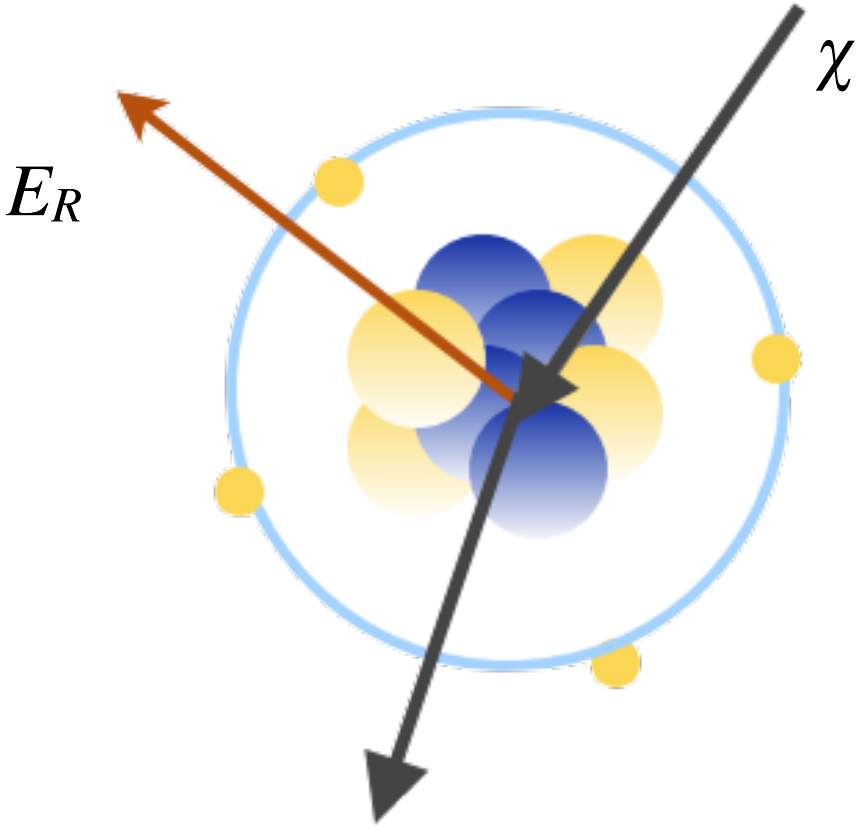
Differential rate

$$\boxed{\frac{dR}{dE_R} = N_T n_\chi \int \frac{d\sigma}{dE_R} v f(\mathbf{v})\, d^3\mathbf{v}}$$

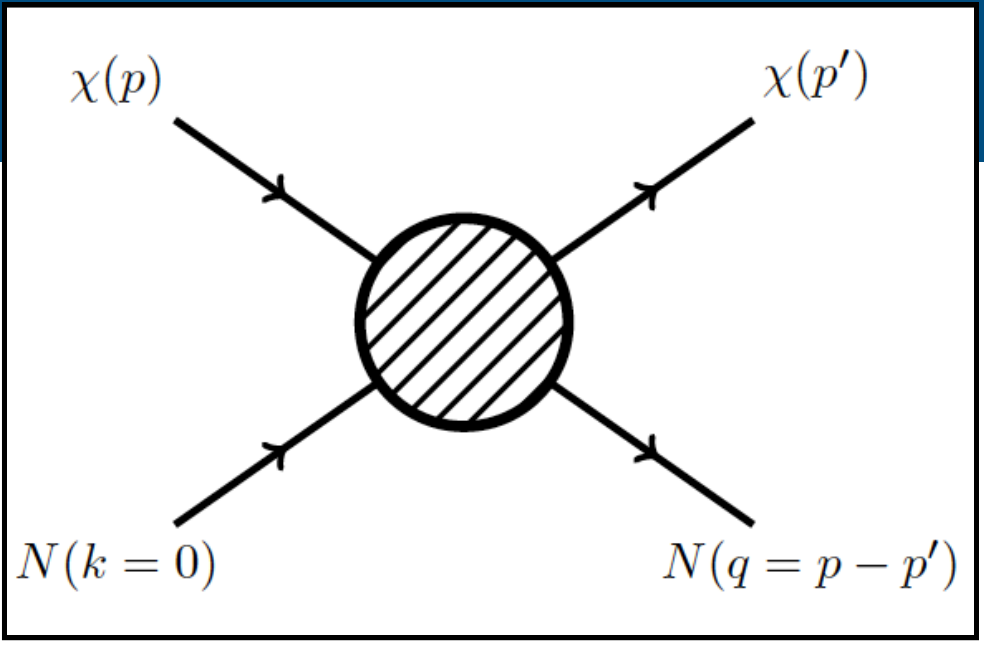


$$E_i = \frac{\mathbf{p}^2}{2m_\chi}, \quad \mathbf{p} = m_\chi \mathbf{v}$$

$$E_f = \frac{(\mathbf{p}-\mathbf{q})^2}{2m_\chi} + \frac{\mathbf{q}^2}{2m_N}$$



Differential rate



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$$E_i = \frac{\mathbf{p}^2}{2m_\chi}, \quad \mathbf{p} = m_\chi \mathbf{v}$$

$$E_f = \frac{(\mathbf{p}-\mathbf{q})^2}{2m_\chi} + \frac{\mathbf{q}^2}{2m_N}$$

$$v_{\min} = \sqrt{m_N E_R / 2\mu_{\chi N}^2}$$

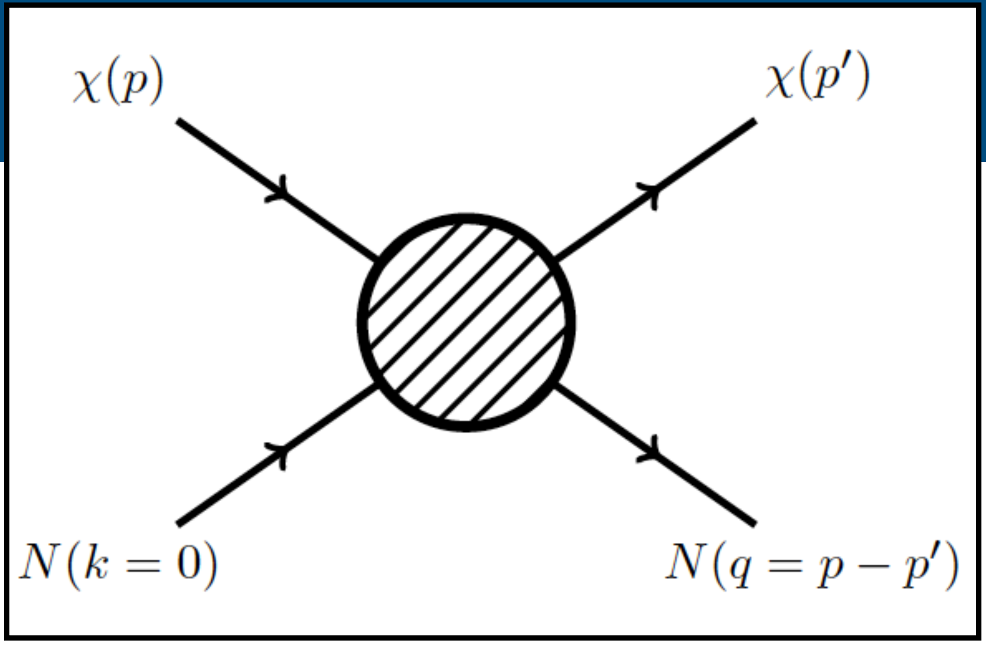
$$|\mathbf{q}|_{\max} = 2\mu_{\chi N}|\mathbf{p}|/m_\chi = 2\mu_{\chi N} v \text{ where } v \sim 10^{-3}.$$

$$\mu_{\chi N} \simeq 10 - 100 \text{ GeV and } |\mathbf{q}|_{\max} \simeq 20 - 200\,\text{MeV}.$$

$$E_R^{\max} = \frac{|\mathbf{q}|^2_{\max}}{2m_N} = \frac{2\mu_{\chi N}^2 v^2}{m_N} \simeq 20 - 200\,\text{keV}.$$

—> Tutorial 1

Cross section calculation



SPIN INDEPENDENT CASE

$$\sigma \quad \propto \quad \mathcal{M} = \langle \mathcal{N}, \chi | \mathcal{L}_{\text{eff}} | \mathcal{N}, \chi \rangle$$

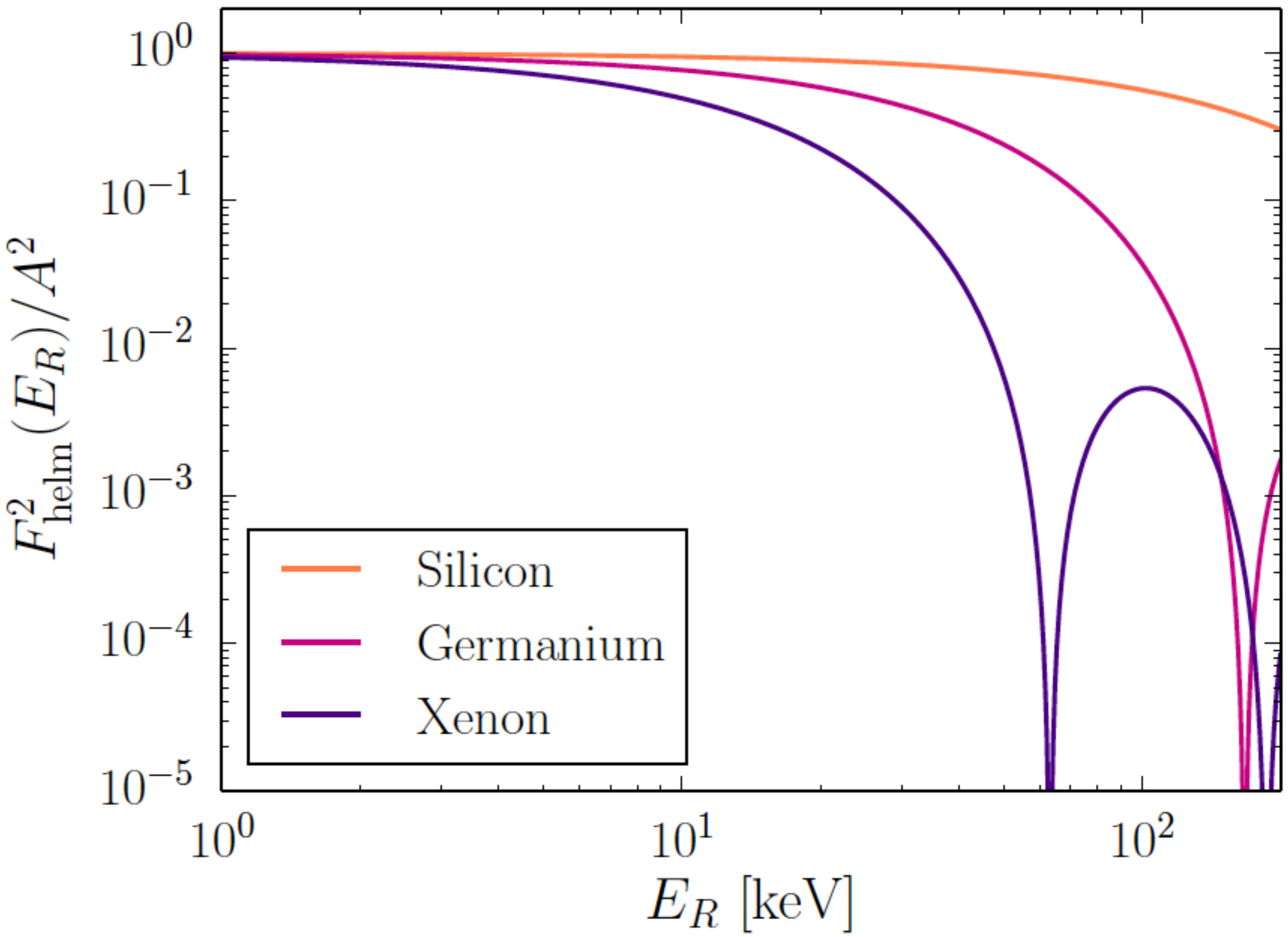
$$\mathcal{O}_1^{\text{NR}} = \mathbb{1}$$

Non-relativistic limit, **coherent** interaction

nuclear response functions describe the q dependence

$$F(qr_n) = 3\frac{j_1(qr_n)}{qr_n} \times \exp\left(-\frac{q^2 s^2}{2}\right)$$

$$\sigma \quad \propto \quad A^2 \left[\sigma^{(\text{nucleon})}_{\text{scalar}}\right] F^2(E_R)$$



WIMP - nucleon

$$\boxed{\frac{dR}{dE_R} = N_T n_\chi \int \frac{d\sigma}{dE_R} v f(\mathbf{v})\, d^3\mathbf{v}}$$

Cross section

Nuclear Form Factor

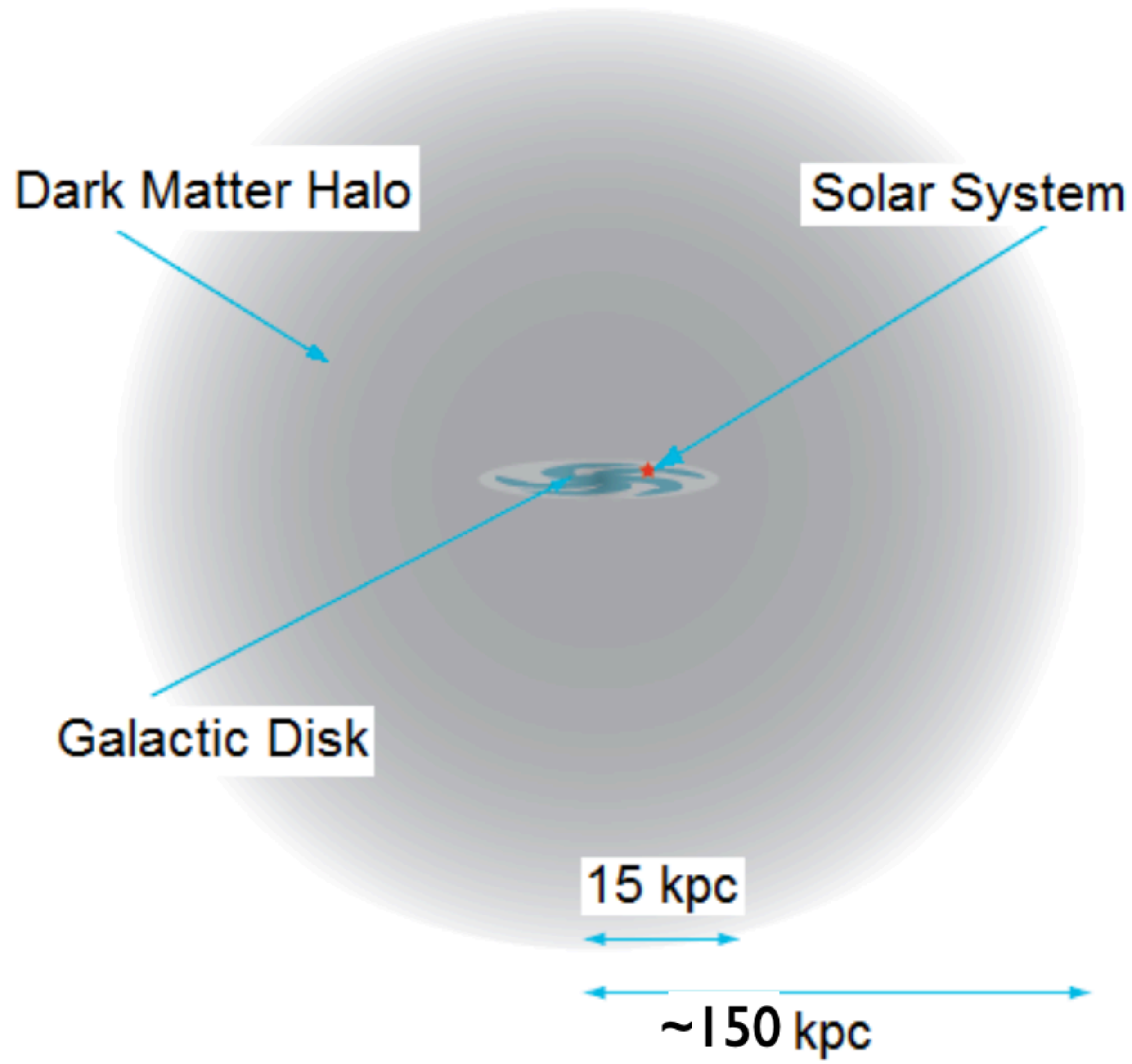
Astrophysics

$$\frac{dR^{NR}}{dE_R} = \boxed{\sigma_n} \boxed{\frac{\rho_\chi}{M_\chi}} \boxed{\frac{m_A}{2\mu_{n\chi}^2}} \boxed{A^2 F_A(q)^2} \boxed{\int_{v_{min}(E_R)}^{v_{esc}} d^3v \frac{f(v, v_E)}{v}}$$

Dark Matter Properties

Target

Standard DM Halo model - velocity distribution

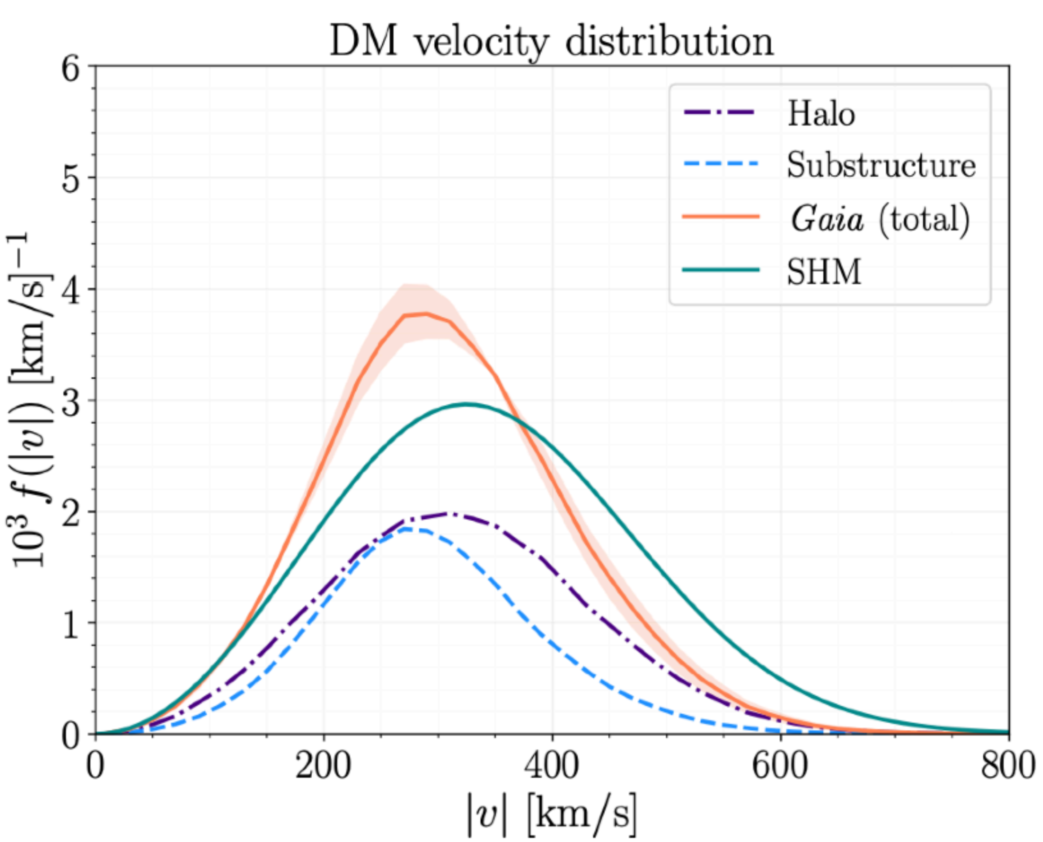


$$\rho_0 = 0.3\ GeV/c^2$$

$$f(\vec{v}) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{|\vec{v}|^2}{2\sigma^2}}$$

$$\sigma = \sqrt{\frac{3}{2}} v_c \quad where \quad v_c = 220\ km/s$$

$v_{esc} \sim 544 - 600$ km/s



Interaction rates

Cross section

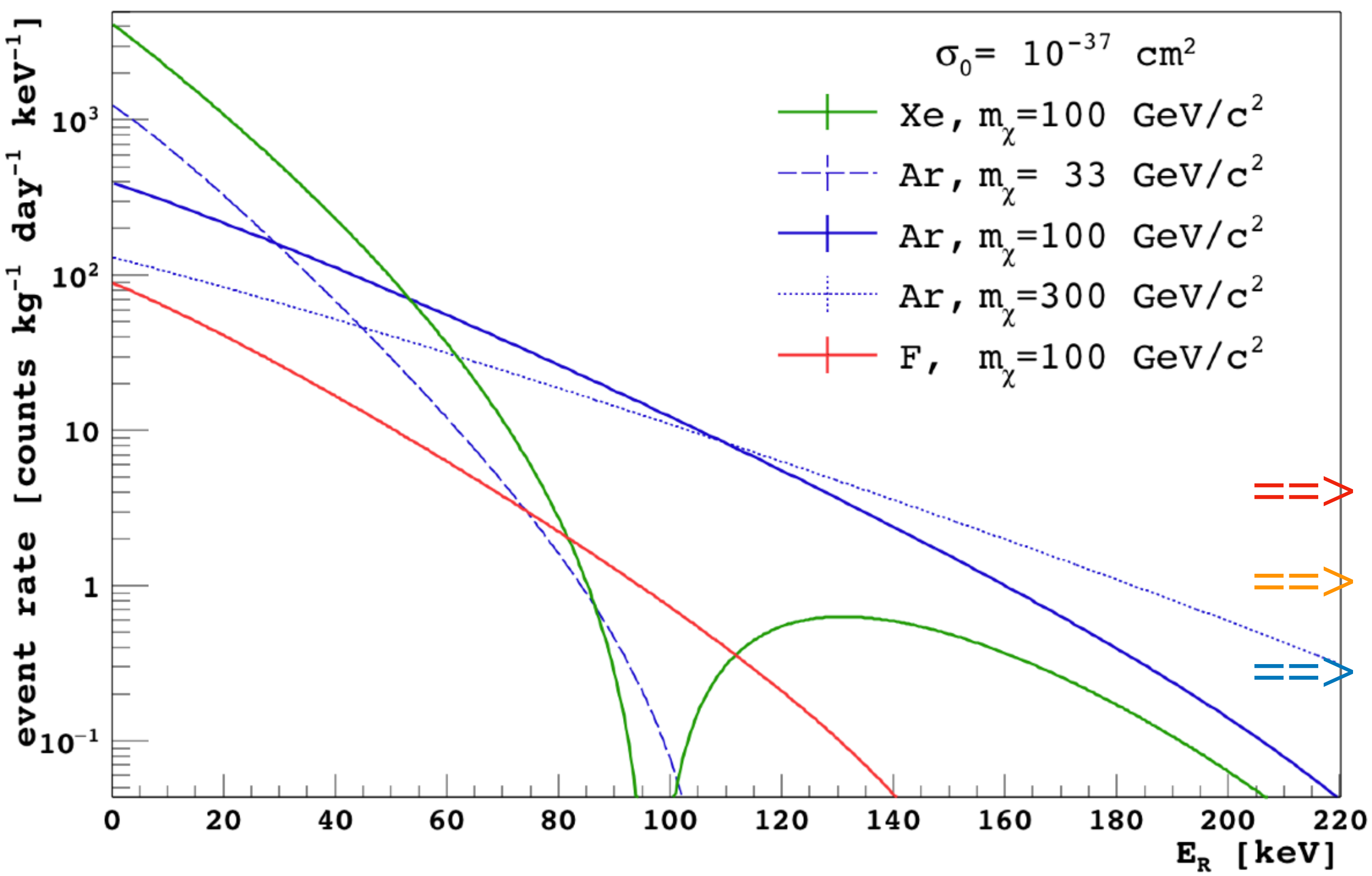
Nuclear Form Factor

Astrophysics

$$\frac{dR^{NR}}{dE_R} = \boxed{\sigma_n} \boxed{\frac{\rho_\chi}{M_\chi}} \boxed{\frac{m_A}{2\mu^2_{n\chi}}} \boxed{A^2 F_A(q)^2} \boxed{\int_{v_{min}(E_R)}^{v_{esc}} d^3v \frac{f(v, v_E)}{v}}$$

Dark Matter Properties

Target



==> event rate scales as A^2

==> large A means lower E_R

==> lower DM mass means lower E_R

WIMP signal prediction

- Interaction rates:

~ 1 ev / t / day at M ~ 100 GeV / σ ~ 10^{-47} cm^2.

- Interaction deposited energies:

~ 100 keV for WIMP mass ~ 100 GeV

~ 1 keV for WIMP mass ~ 10 GeV

~ 0.1 eV for WIMP mass ~ 100 MeV

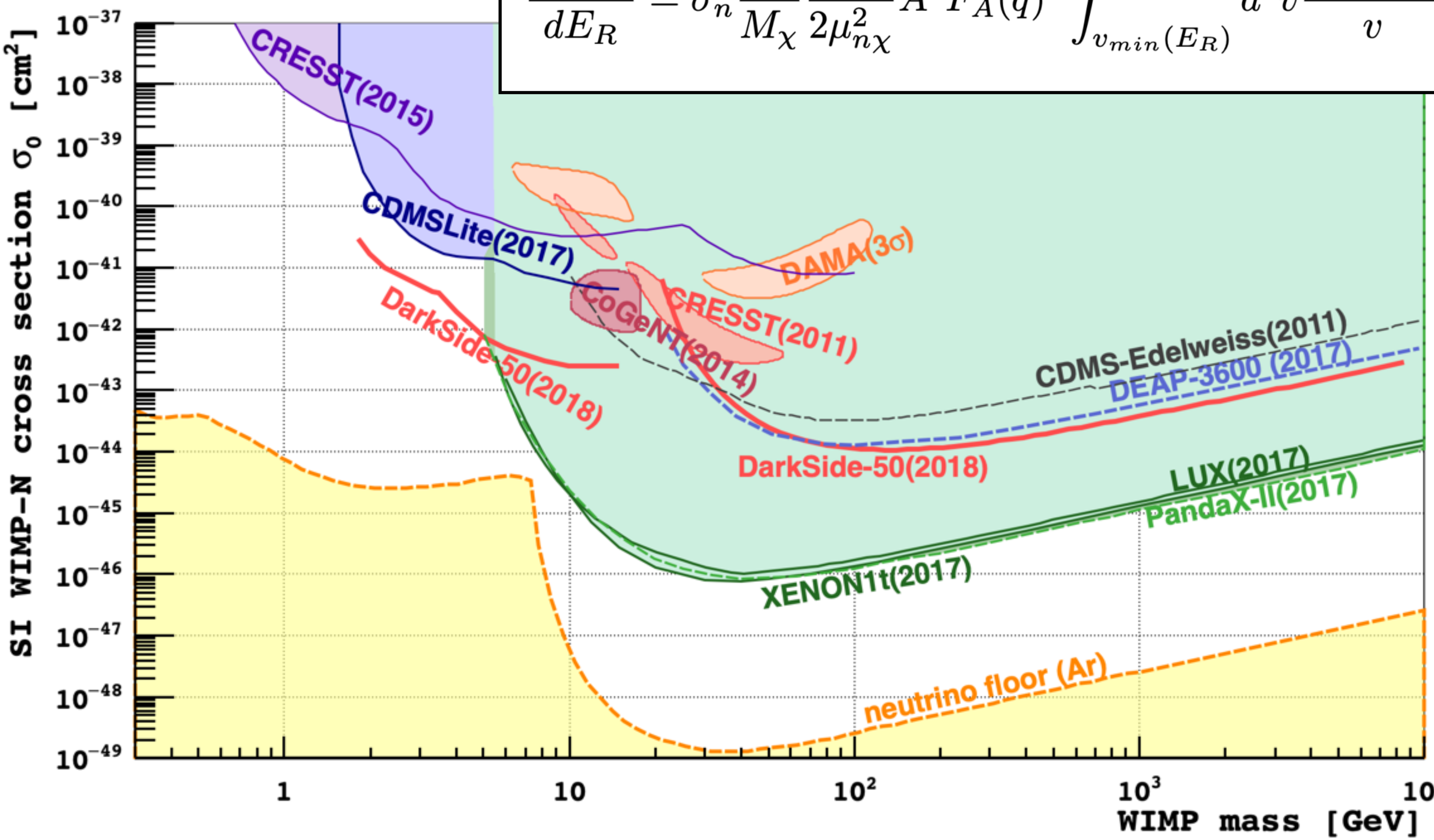
==> event rate scales as A^2

==> large A means lower E_R

==> lower DM mass means lower E_R

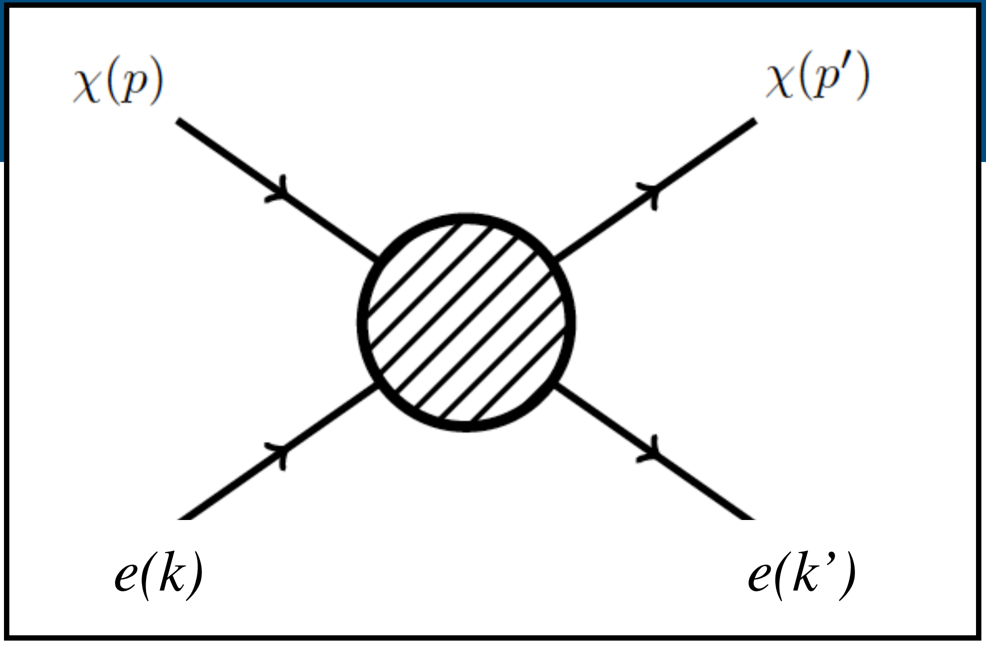
Current exclusion limits

$$\frac{dR^{NR}}{dE_R} = \sigma_n \frac{\rho_\chi}{M_\chi} \frac{m_A}{2\mu_{n\chi}^2} A^2 F_A(q)^2 \int_{v_{min}(E_R)}^{v_{esc}} d^3v \frac{f(v, v_E)}{v}$$



Dark Matter - Electron

$$\boxed{\frac{dR}{d\,\omega} = N_T n_\chi \int \frac{d\sigma}{d\,\omega} v f(\mathbf{v})\, d^3\mathbf{v}}$$



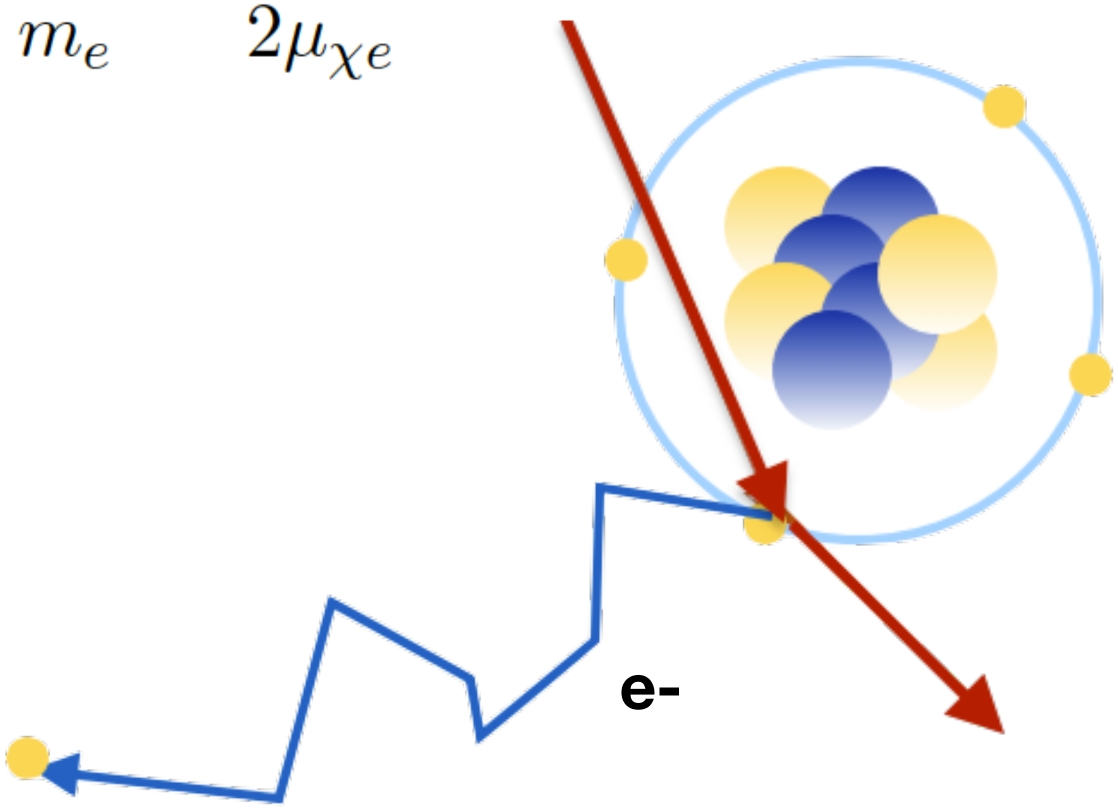
$$\omega = \frac{\mathbf{p}\cdot\mathbf{q}}{m_\chi} - \frac{\mathbf{q}^2}{2m_\chi} = E_e(\mathbf{k}') - E_e(\mathbf{k}),$$

$$k_e \simeq 1/R_{\mathrm{Bohr}} = \alpha m_e$$

$$\frac{\mathbf{p}\cdot\mathbf{q}}{m_\chi} = \frac{\mathbf{k}\cdot\mathbf{q}}{m_e} - \frac{\mathbf{q}^2}{2\mu_{\chi e}}$$

$$v_{e,i} = |\mathbf{k}|/m_e \gg v_{\chi,i} = |\mathbf{p}|/m_\chi$$

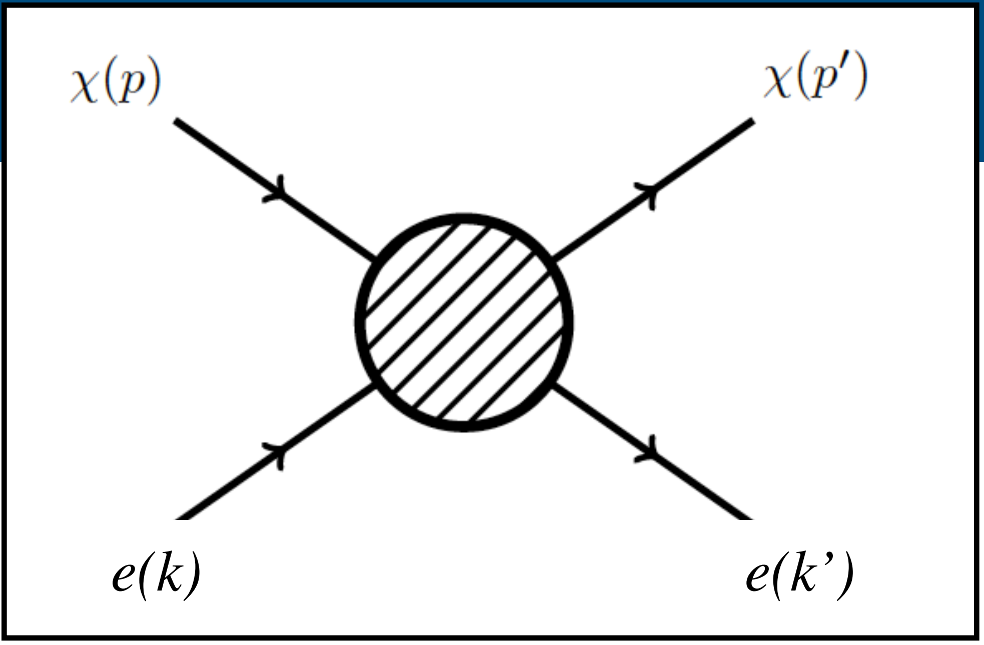
10^{-2} 10^{-3}



—> Tutorial 1

Dark Matter - Electron

$$\boxed{\frac{dR}{d\,\omega} = N_T n_\chi \int \frac{d\sigma}{d\,\omega} v f(\mathbf{v})\, d^3\mathbf{v}}$$



$$\omega = \frac{\mathbf{p}\cdot\mathbf{q}}{m_\chi} - \frac{\mathbf{q}^2}{2m_\chi} = E_e(\mathbf{k}') - E_e(\mathbf{k}),$$

$$k_e \simeq 1/R_{\rm Bohr} = \alpha m_e$$

$$\frac{\mathbf{p}\cdot\mathbf{q}}{m_\chi} = \frac{\mathbf{k}\cdot\mathbf{q}}{m_e} - \frac{\mathbf{q}^2}{2\mu_{\chi e}}$$

$$v_{e,i} = |\mathbf{k}|/m_e \gg v_{\chi,i} = |\mathbf{p}|/m_\chi$$

10^{-2} 10^{-3}

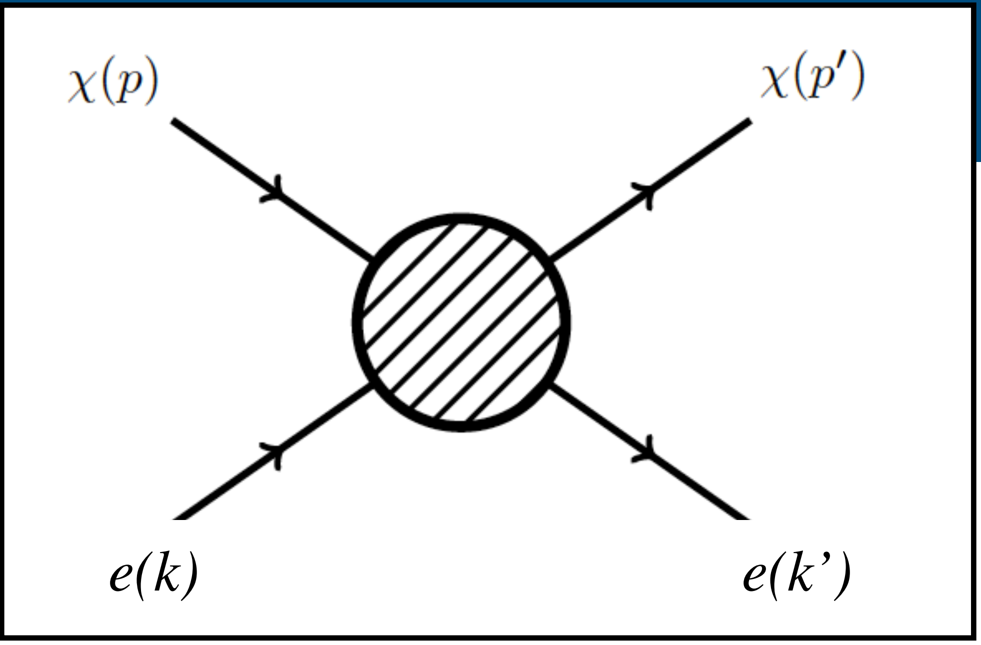
$$|\mathbf{q}| \simeq \mu_{\chi e} v_{e,i}$$

$m_\chi \gtrsim m_e$:

$$|\mathbf{q}| \simeq \mu_{\chi e} v_{e,i} \approx m_e v_{e,i}$$

$$\omega \simeq m_e v_{e,i} v_{\chi,i} \approx \text{few eV}$$

Dark Matter - Electron



$$\boxed{\frac{dR}{d\,\omega} = N_T n_\chi \int \frac{d\sigma}{d\,\omega} v f(\mathbf{v})\, d^3\mathbf{v}}$$

$$\omega = \frac{\mathbf{p}\cdot\mathbf{q}}{m_\chi} - \frac{\mathbf{q}^2}{2m_\chi} = E_e(\mathbf{k}') - E_e(\mathbf{k}),$$

$$\frac{\mathbf{p}\cdot\mathbf{q}}{m_\chi} = \frac{\mathbf{k}\cdot\mathbf{q}}{m_e} - \frac{\mathbf{q}^2}{2\mu_{\chi e}}$$

$$k_e \simeq 1/R_{\mathrm{Bohr}} = \alpha m_e$$

$$v_{e,i} = |\mathbf{k}|/m_e \gg v_{\chi,i} = |\mathbf{p}|/m_\chi$$

$$|\mathbf{q}| \simeq \mu_{\chi e} v_{e,i}$$

$m_\chi \gtrsim m_e$:

$$|\mathbf{q}| \simeq \mu_{\chi e} v_{e,i} \approx m_e v_{e,i}$$

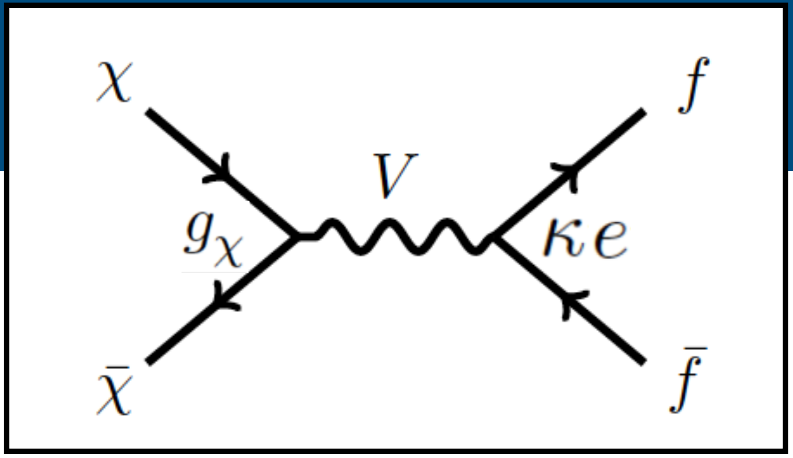
$$\omega \simeq m_e v_{e,i} v_{\chi,i} \approx \text{few eV}$$

$m_\chi \lesssim m_e$:

$$|\mathbf{q}| \simeq \mu_{\chi e} v_{e,i} \approx m_\chi v_{e,i}$$

$$\omega \simeq \frac{1}{2} m_\chi v_{\chi,i}^2$$

Cross section calculation



<u>Free</u> electrons, j initial state

$$(\sigma v)_j = \int \frac{d^3\mathbf{p}'}{(2\pi)^3} \frac{d^3\mathbf{k}'}{(2\pi)^3} (2\pi)\delta(\Delta E_e - \omega) \frac{|\mathcal{M}_{\text{free}}|^2}{16 m_\chi^2 m_e^2} |f_{j\to\mathbf{k}'}(\mathbf{q})|^2$$

$$|\mathcal{M}|^2 = \frac{16 g_\chi^2 \kappa^2 e^2 m_\chi^2 m_e^2}{((q_\mu^2) - m_V^2)^2} \approx \frac{16 g_\chi^2 \kappa^2 e^2 m_\chi^2 m_e^2}{(|\mathbf{q}|^2 + m_V^2)^2}$$

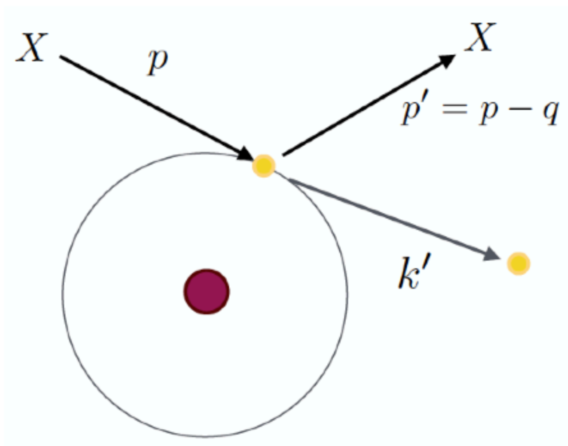
Model <u>dependent</u>,
here assuming generic V boson

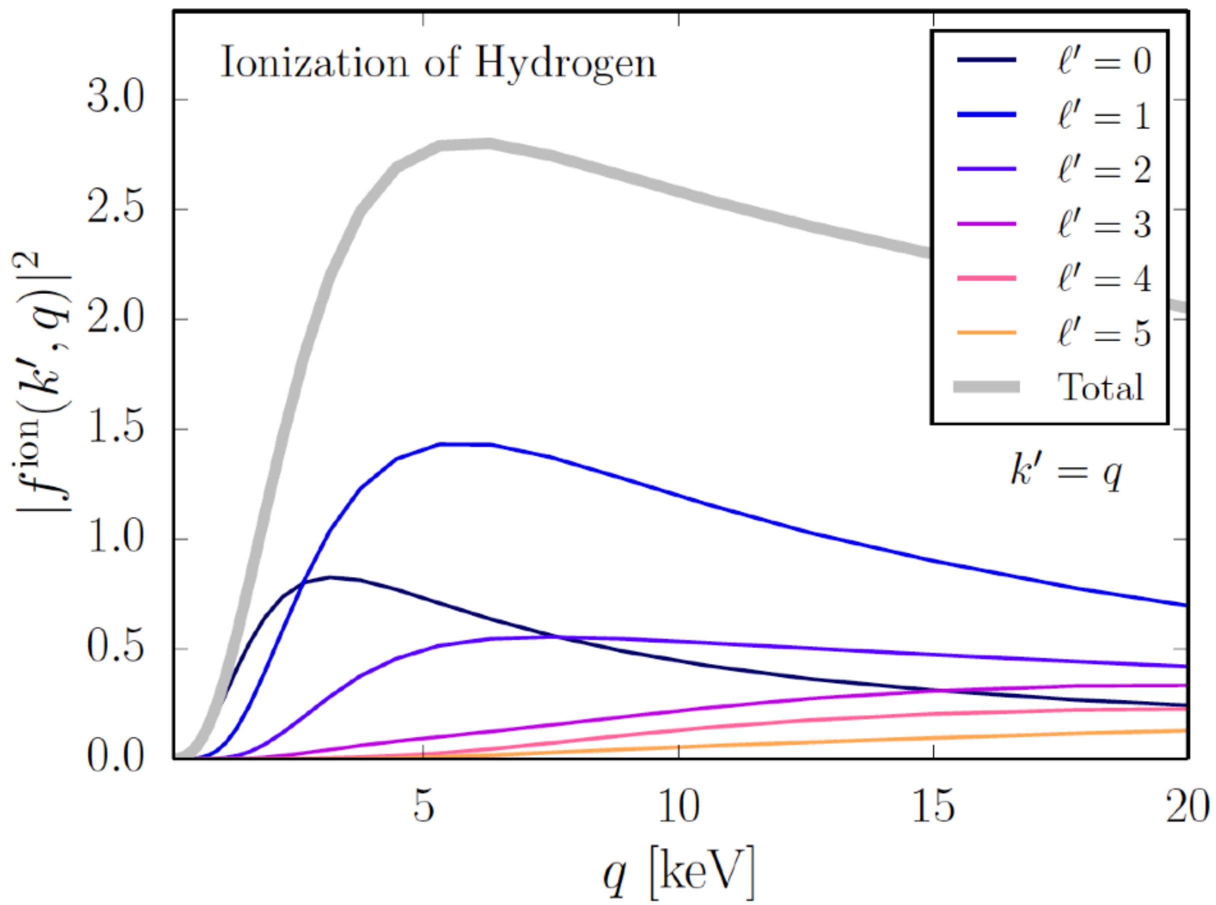
$$\frac{\mu_{\chi e}^2 |\mathcal{M}|^2}{16\pi m_\chi^2 m_e^2} \equiv \bar{\sigma}_e F_{\text{DM}}^2(q), \quad F_{\text{DM}}^2(q) \equiv \left(\frac{(\alpha m_e)^2 + m_V^2}{|\mathbf{q}|^2 + m_V^2} \right)^2$$

Light mediator: $F_{DM}(q) = \frac{\alpha^2 m_e^2}{q^2}$

Heavy mediator: $F_{DM}(q) = 1$

Free electrons —> Atoms





Cross section

Form Factor (interaction)

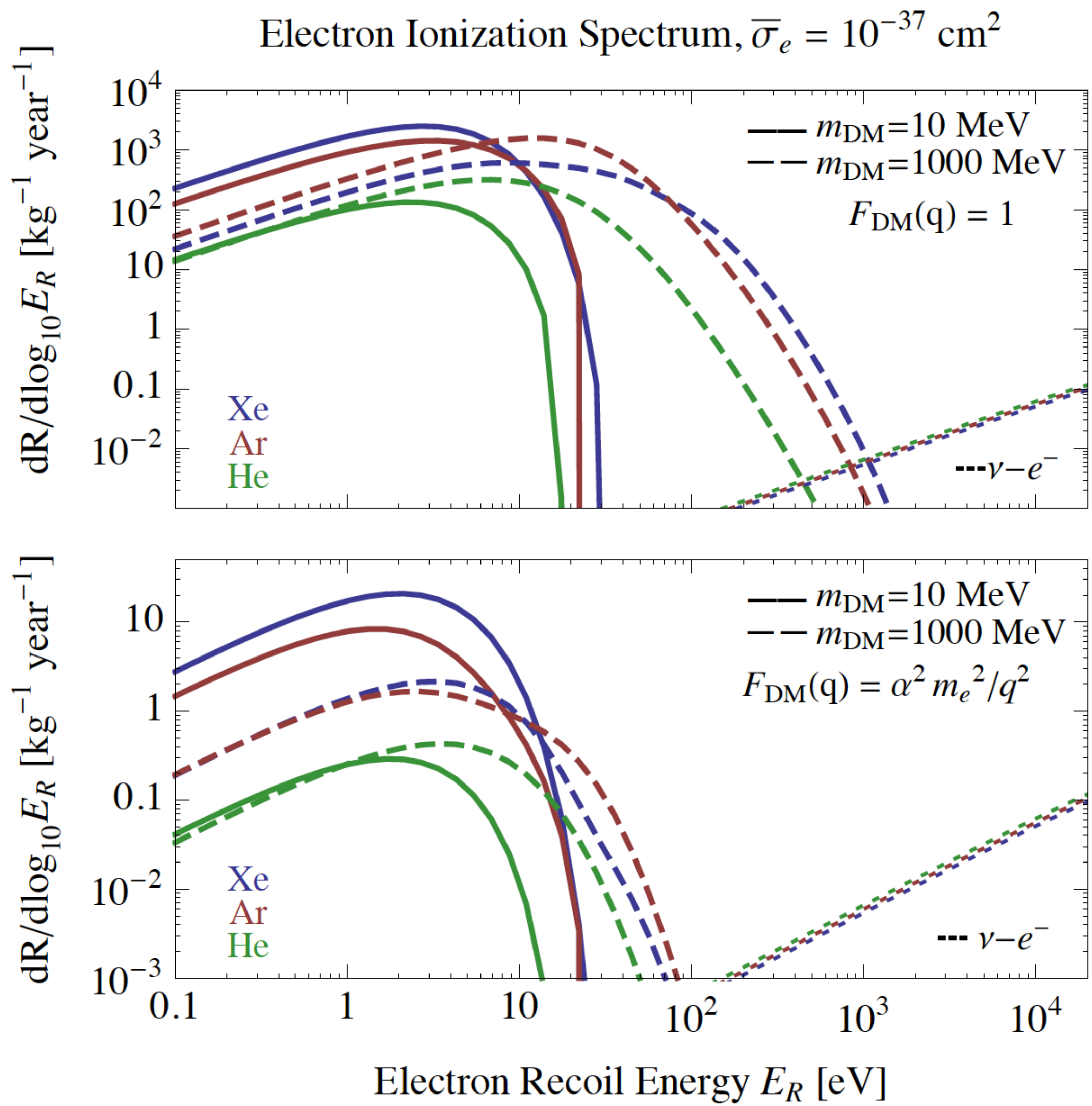
Astrophysics

$$\frac{dR^{ER}}{dE_e} = \boxed{\bar{\sigma}_e} \boxed{\frac{\rho_\chi}{M_\chi}} \frac{1}{8\mu_{e\chi}^2} \int \boxed{q dq |F_{DM}(q)}|^2 \boxed{|f_{n,l}^{ion}(q, E_e)}|^2 \boxed{\eta(v_{min})}$$

Electron wave-functions

Dark Matter Properties

Predicted spectra



DM-interaction signal prediction

WIMP-nucleon

DM -electron

- Interaction rates:

R ~ 1 ev / t / day at M ~ 100 GeV / $\sigma \sim 10^{-47}$ cm^2

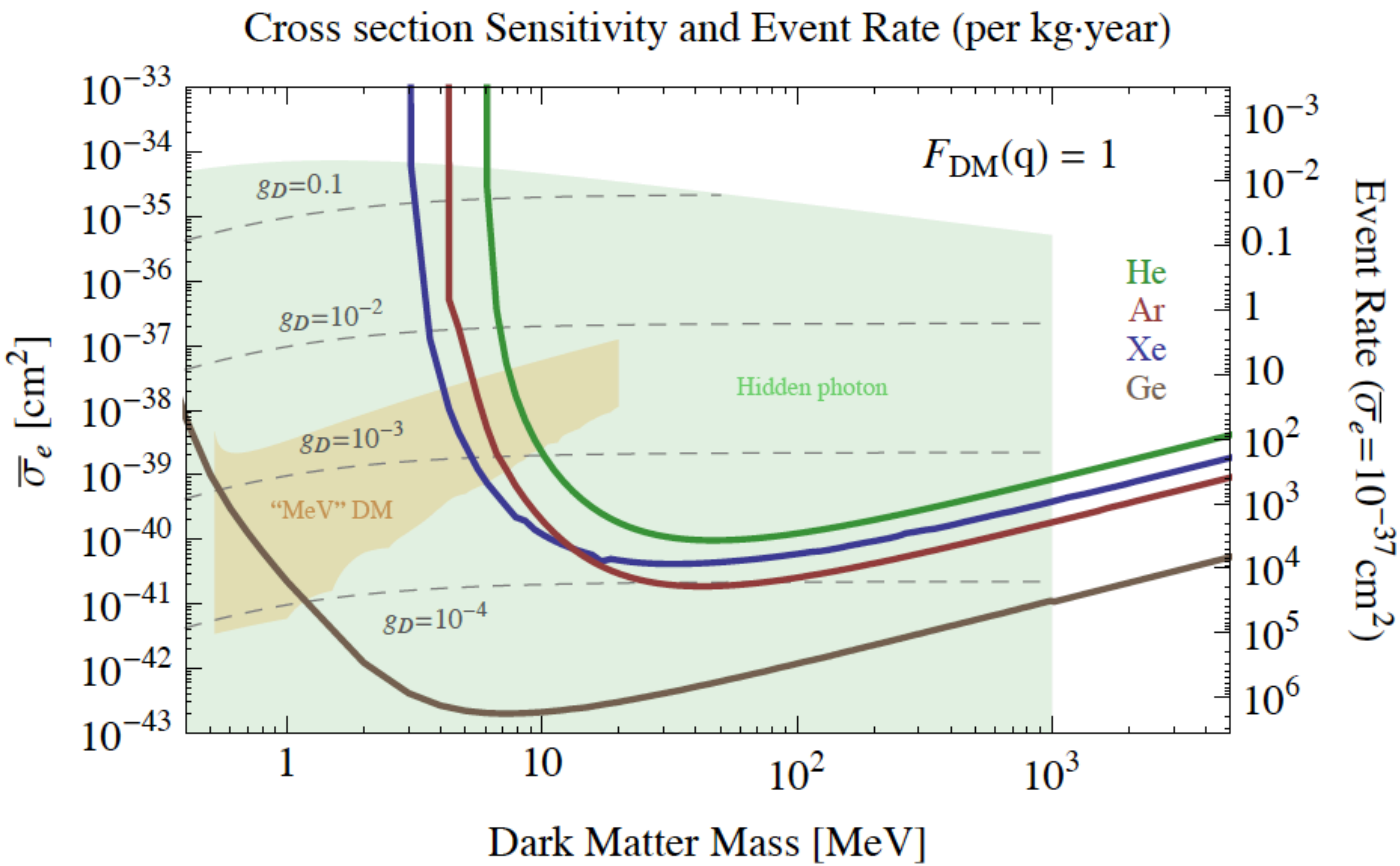
R ~ $N_T\, \rho/m_\chi\, \sigma_e\, v_0$ ~ **50 ev / kg / day**
at m_χ ~ 10 MeV / $\sigma \sim 10^{-37}$ cm^2

- Interaction deposited energies:

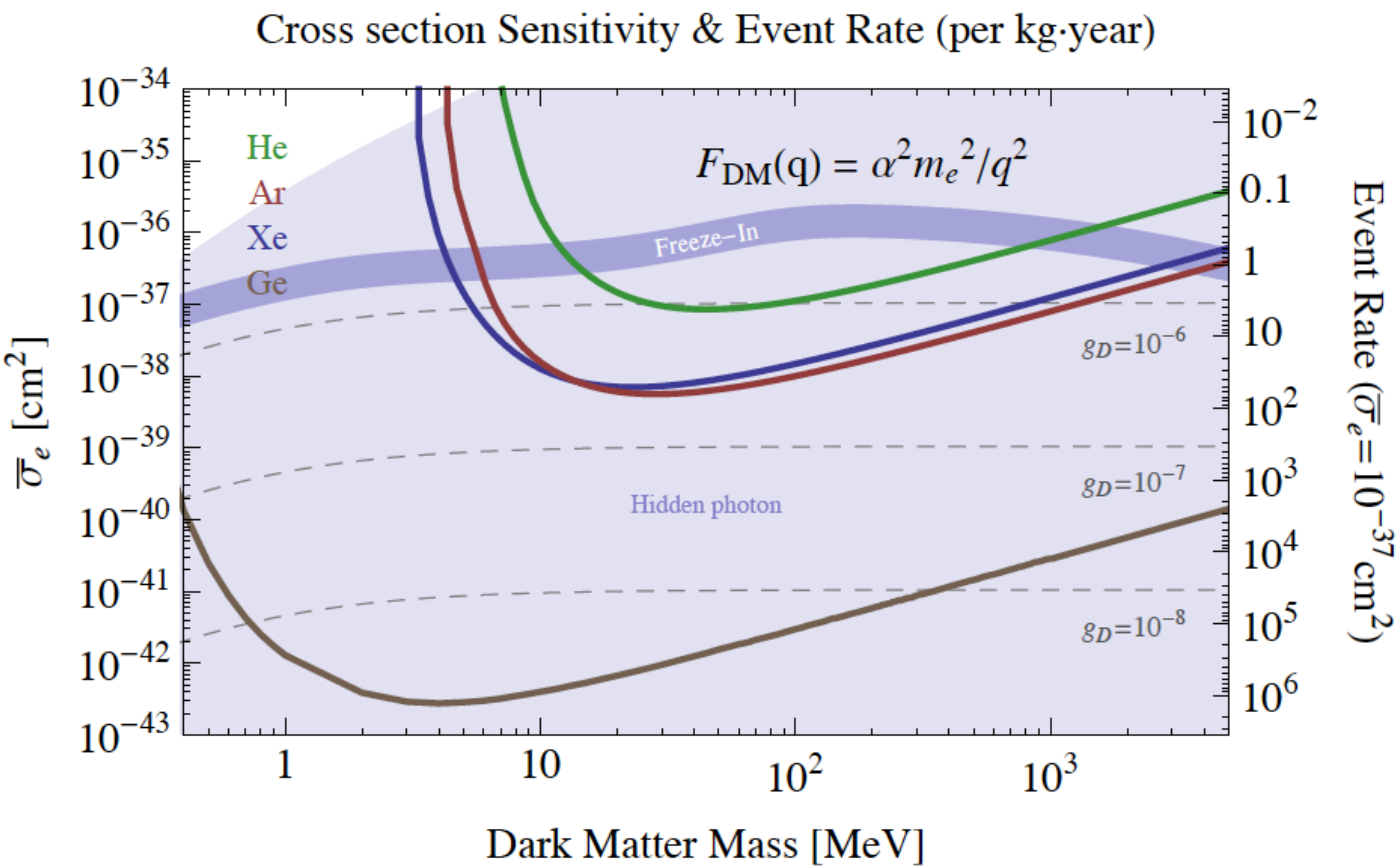
E_R ~ 100 keV for WIMP mass ~ 100 GeV
E_R ~ 1 keV for WIMP mass ~ 10 GeV
E_R ~ 0.1 eV for WIMP mass ~ 100 MeV

E_R ~ 50 eV for m_χ ~ 100 MeV
E_R ~ 10 eV for m_χ ~ 10 MeV

Projected Sensitivity

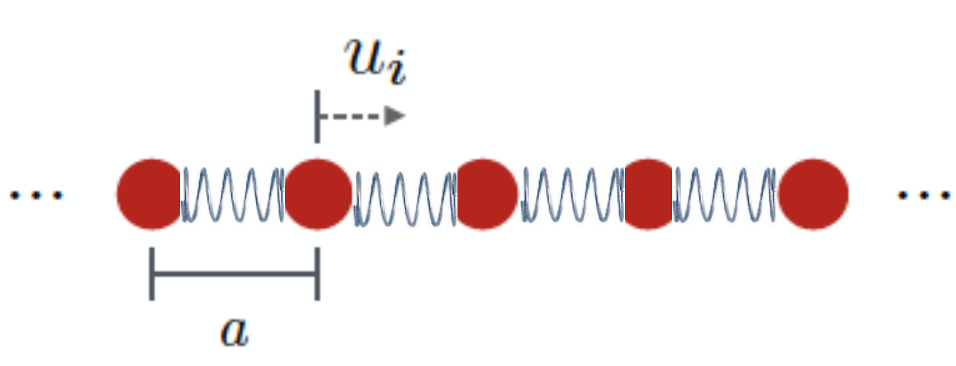


Projected Sensitivity



Phys.Rev. D85 (2012) 076007

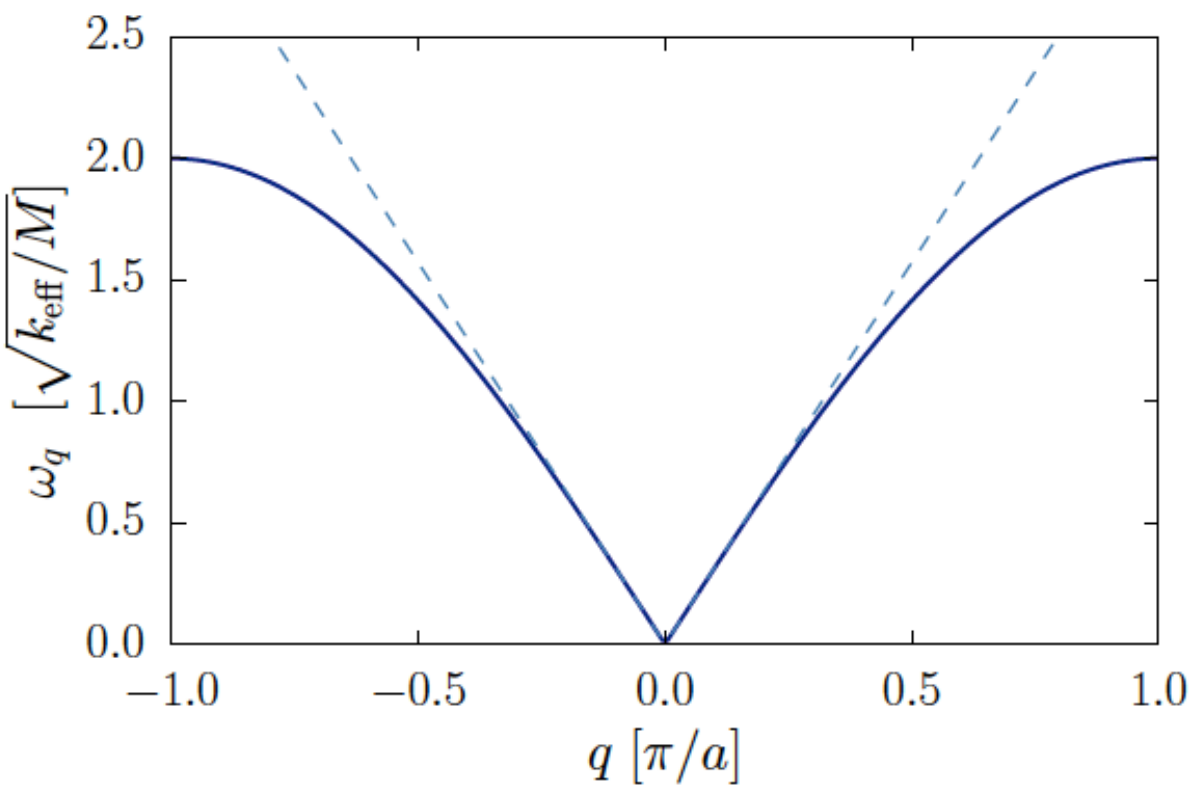
At even lower deposited energies



a = inter-atom distance
~ 10^{-10} m
~ 10^5 eV

u_i : displacement

For ~MeV DM: Edep ~ 0.1 eV => q << 1



q = amplitude of wave vector

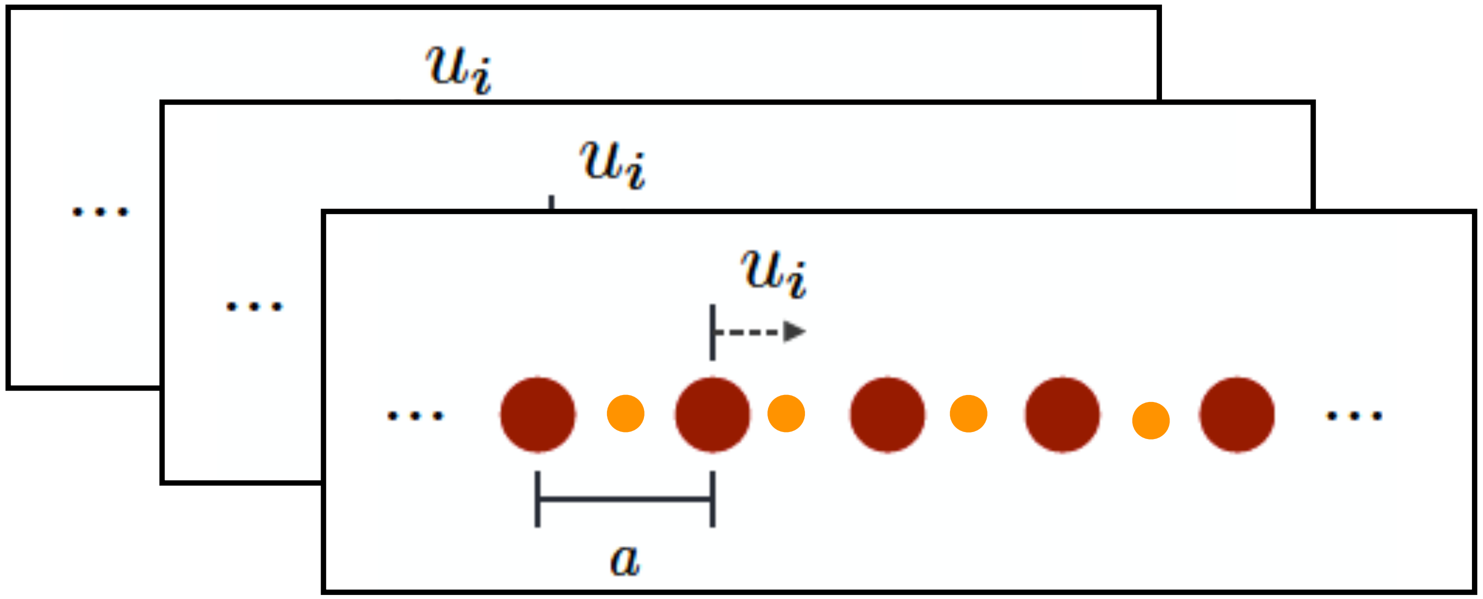
q ~ 0 : low frequency oscillations
q ~ π/a : perfectly out of phase

ω_q : energy of the vibration mode

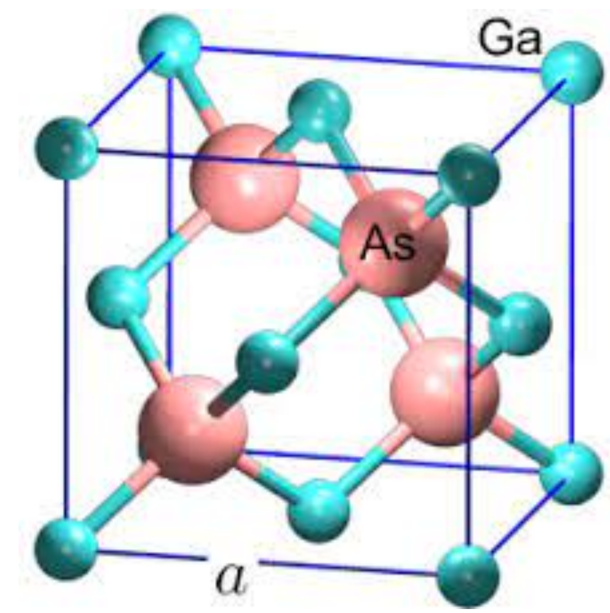
slope: sound speed (10^{-5})

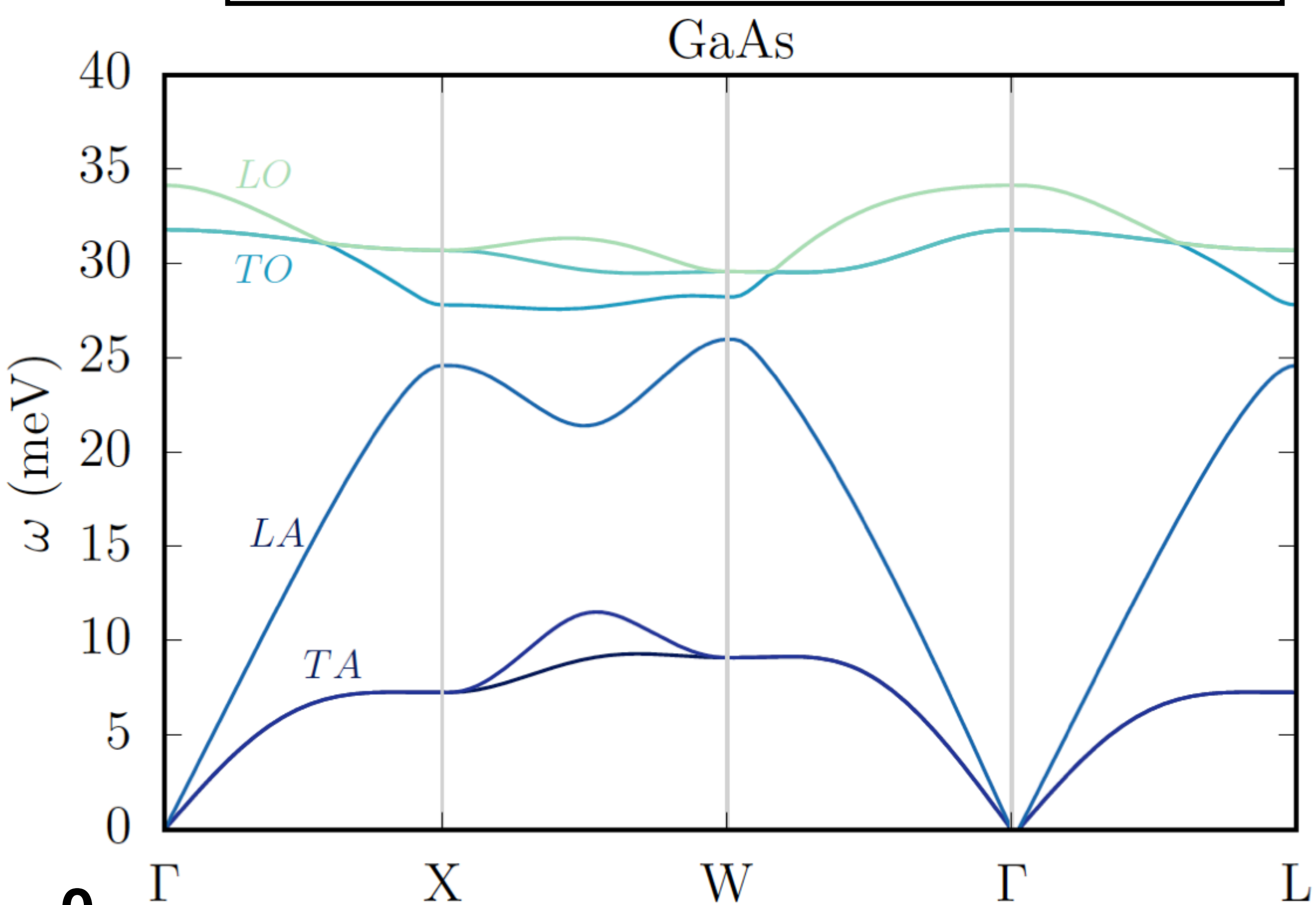
https://arxiv.org/pdf/1712.06598.pdf

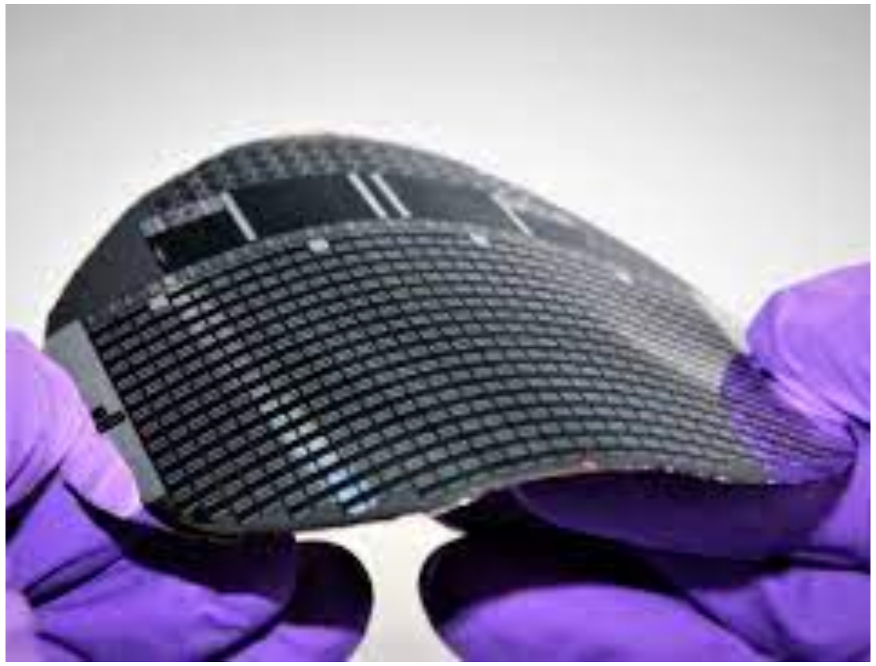
At even lower deposited energies



3D



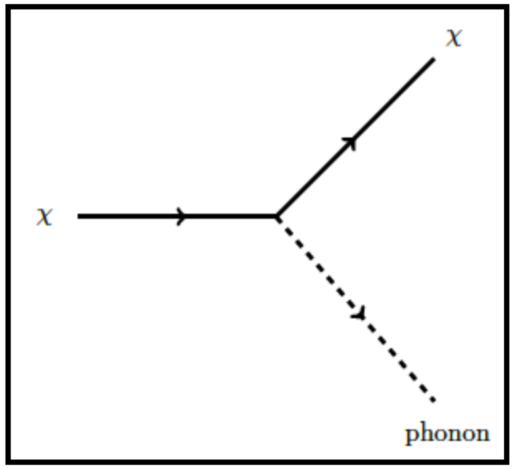


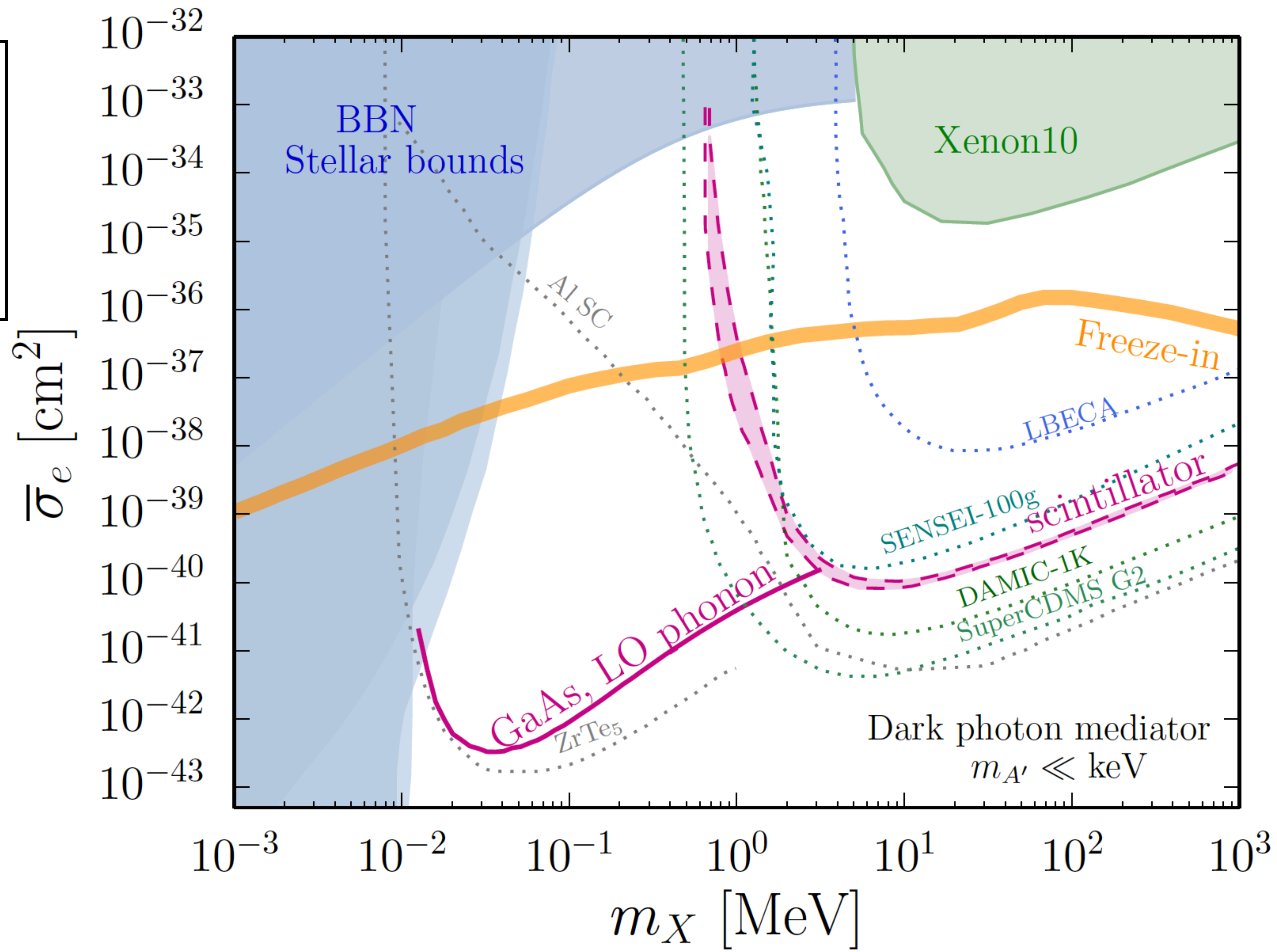


q = 0

https://arxiv.org/pdf/1712.06598.pdf

Projected sensitivity





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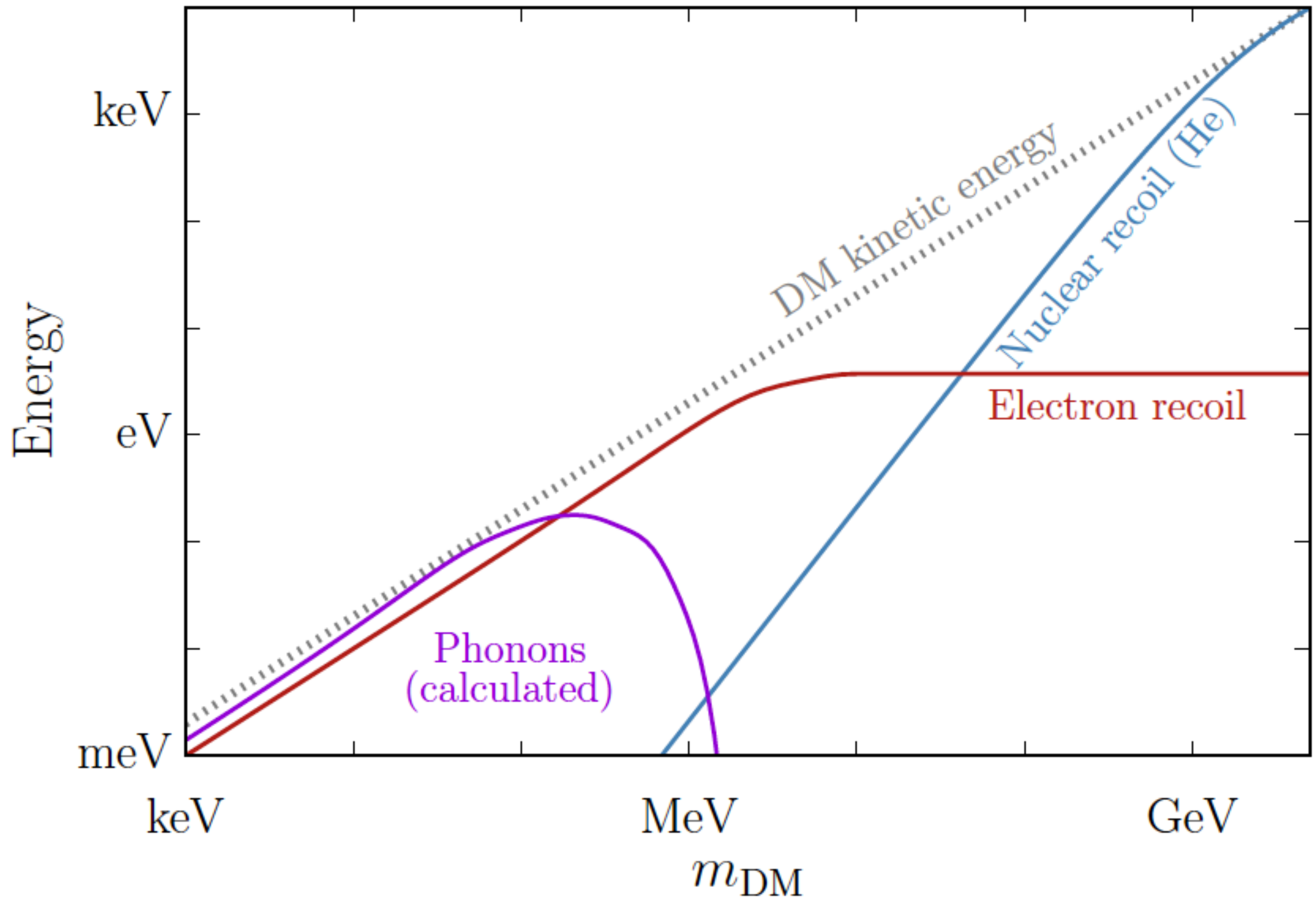
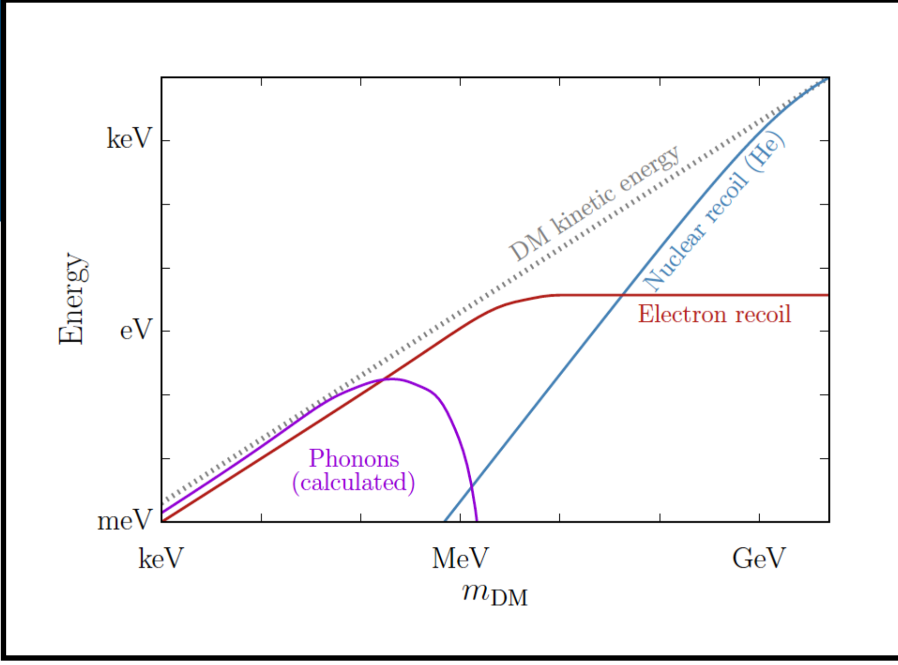
Summary



https://arxiv.org/abs/1904.07915

Detector Technologies

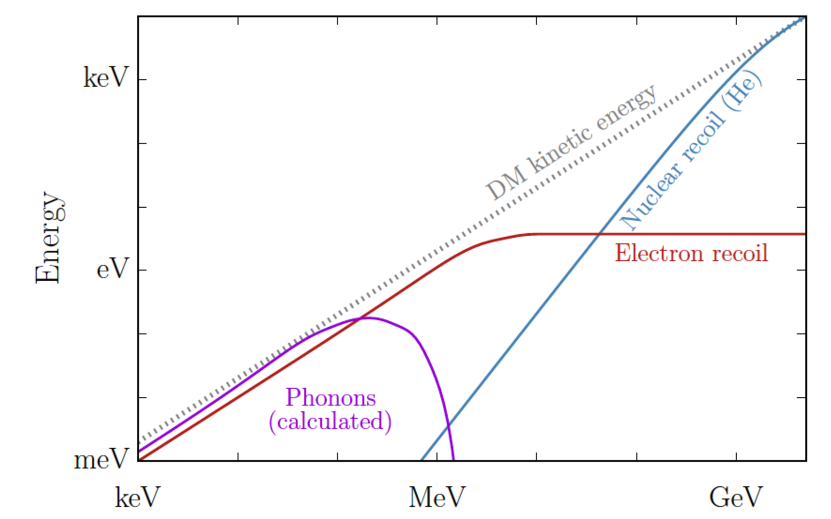


Atomic/Molecular systems (e.g Noble liquids)

~ 10 eV

12 eV for Xe, 15 eV for Ar 23 eV mean ionisation E

Detector Technologies



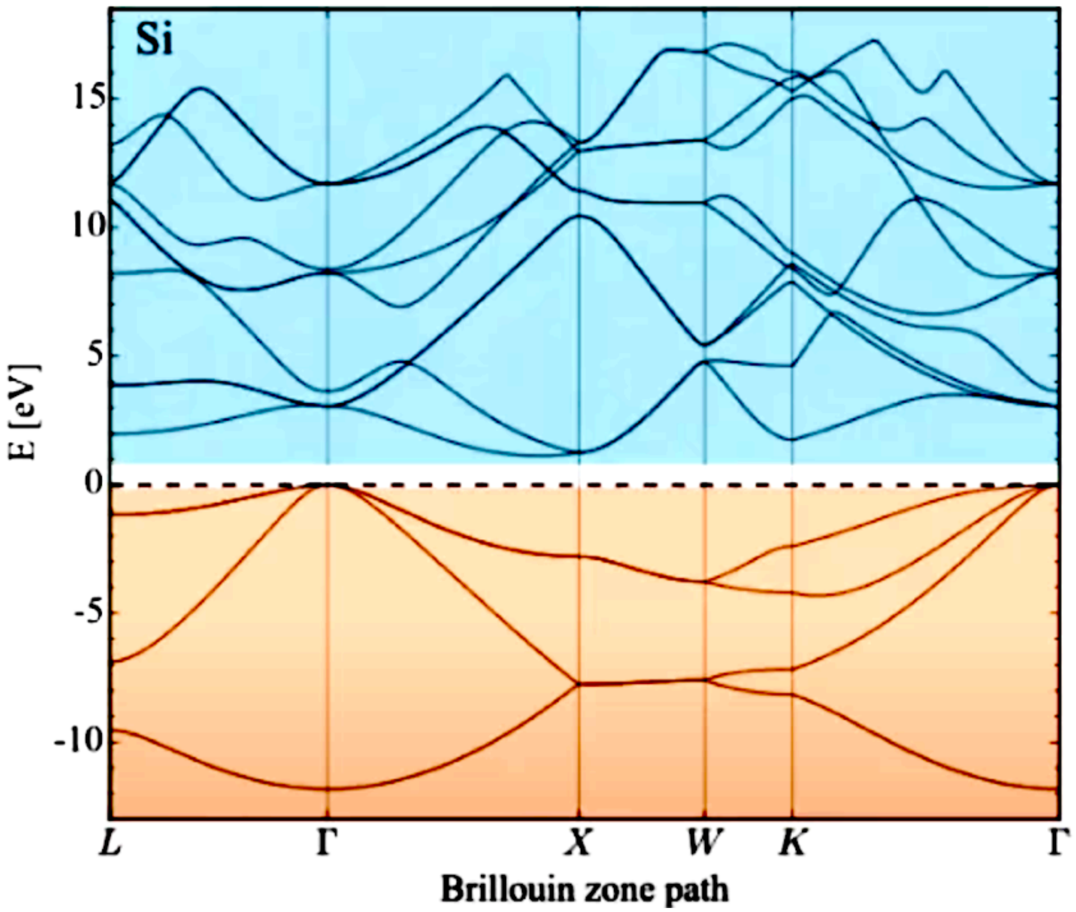
Atomic/Molecular systems (e.g Noble liquids)

~ 10 eV

12 eV for Xe, 15 eV for Ar 23 eV mean ionisation E

Semiconductors ~ 1 eV

$$\left|f_{n,l}^{ion}(q, E_e)\right|^2 \longrightarrow \left|f_{\text{crystal}}(q, E_e)\right|^2$$

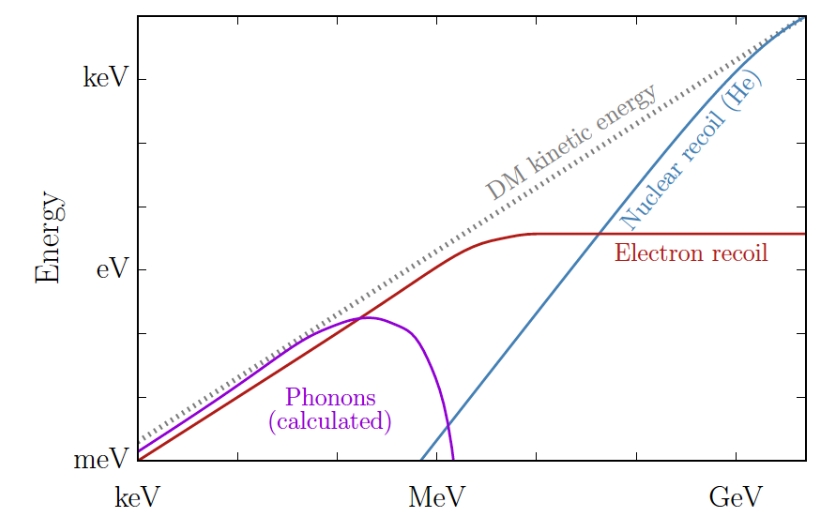


empty conduction band

$$E_{\text{gap}} = \begin{cases} 1.11 \text{ eV} & \text{(silicon)} \\ 0.67 \text{ eV} & \text{(germanium)} \end{cases}$$

filled valence band

Detector Technologies



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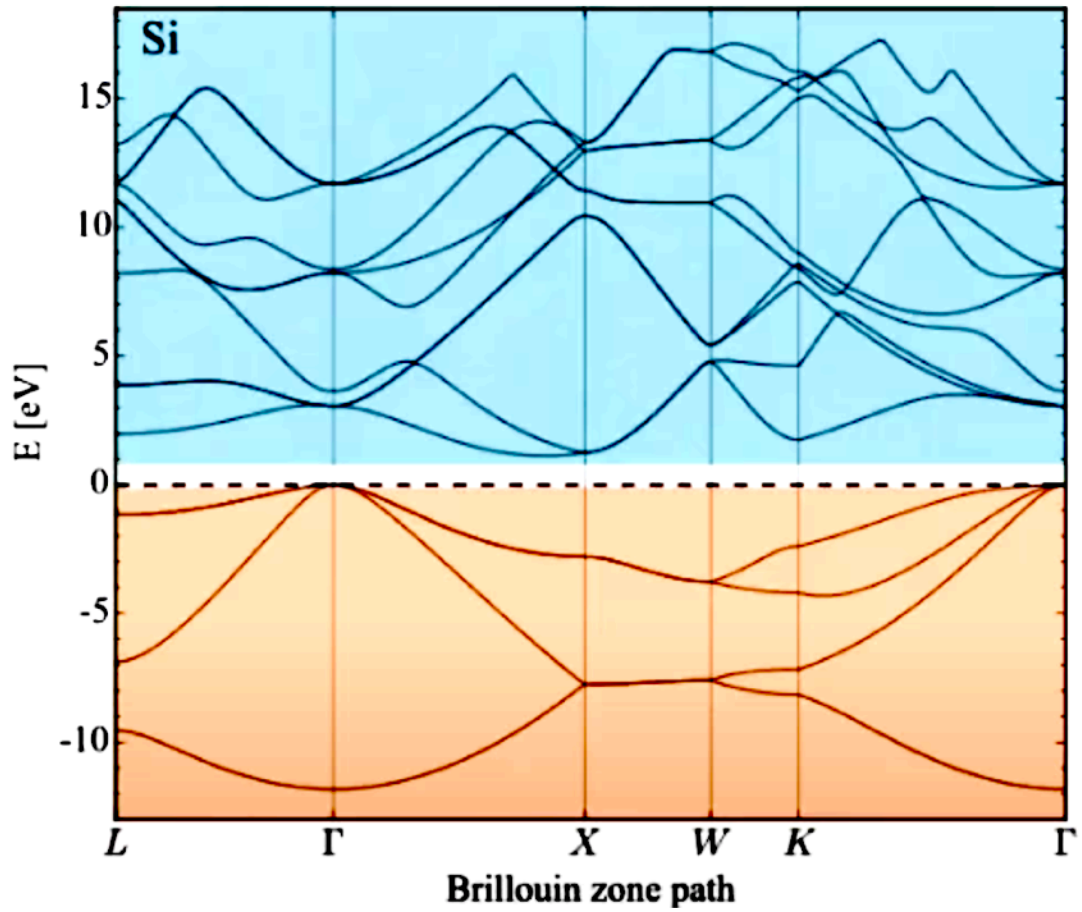

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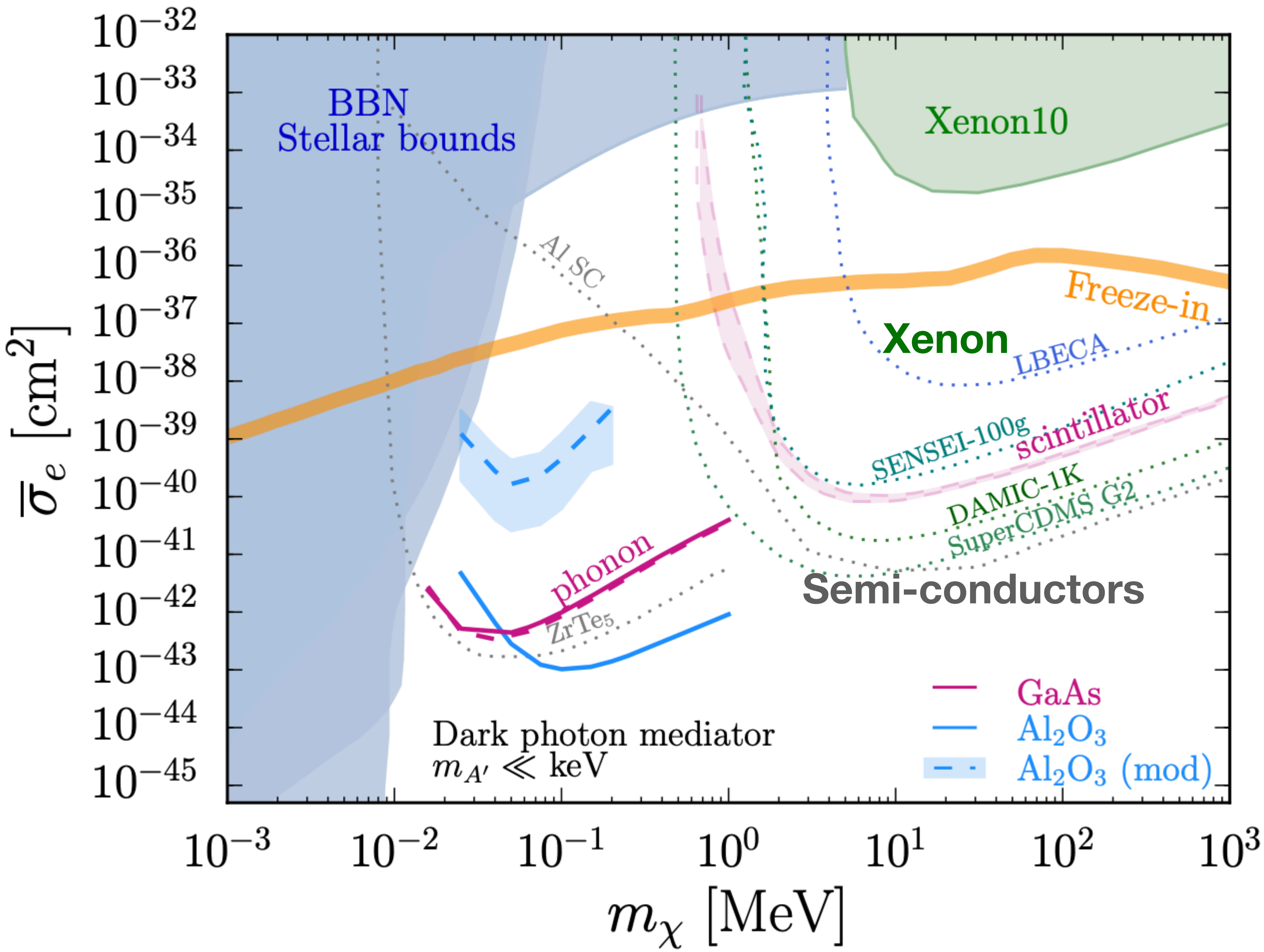
filled valence band

Superconductors, Dirac materials ~ meV

Y. Hochberg, et al Phys. Rev. Lett. 116, 011301 (2016), arXiv:1504.07237 [hep-ph].
Y. Hochberg et al Phys. Rev. D97, 015004 (2018), arXiv:1708.08929 [hep-ph].

Conclusions



https://arxiv.org/pdf/1807.10291.pdf

Extra Slides