Light Dark Matter (0.1GeV-10GeV) and Ultralight bosonic Dark Matter

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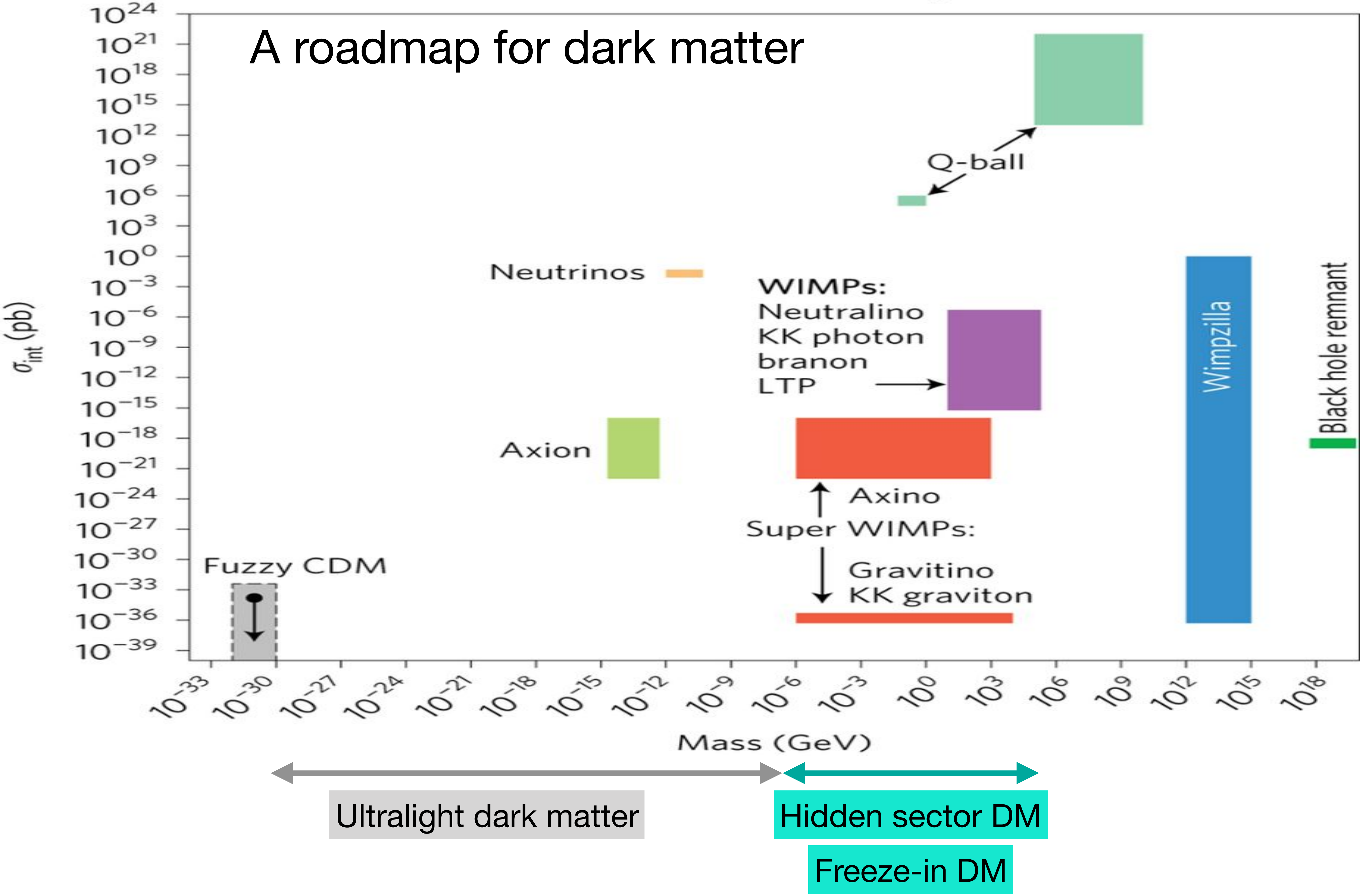
1609.02147, 1705.09455 and 1902.02348

Dark Matter (WIMPs) direct detection @PKU
2019-10-14

Conrad & Reimer

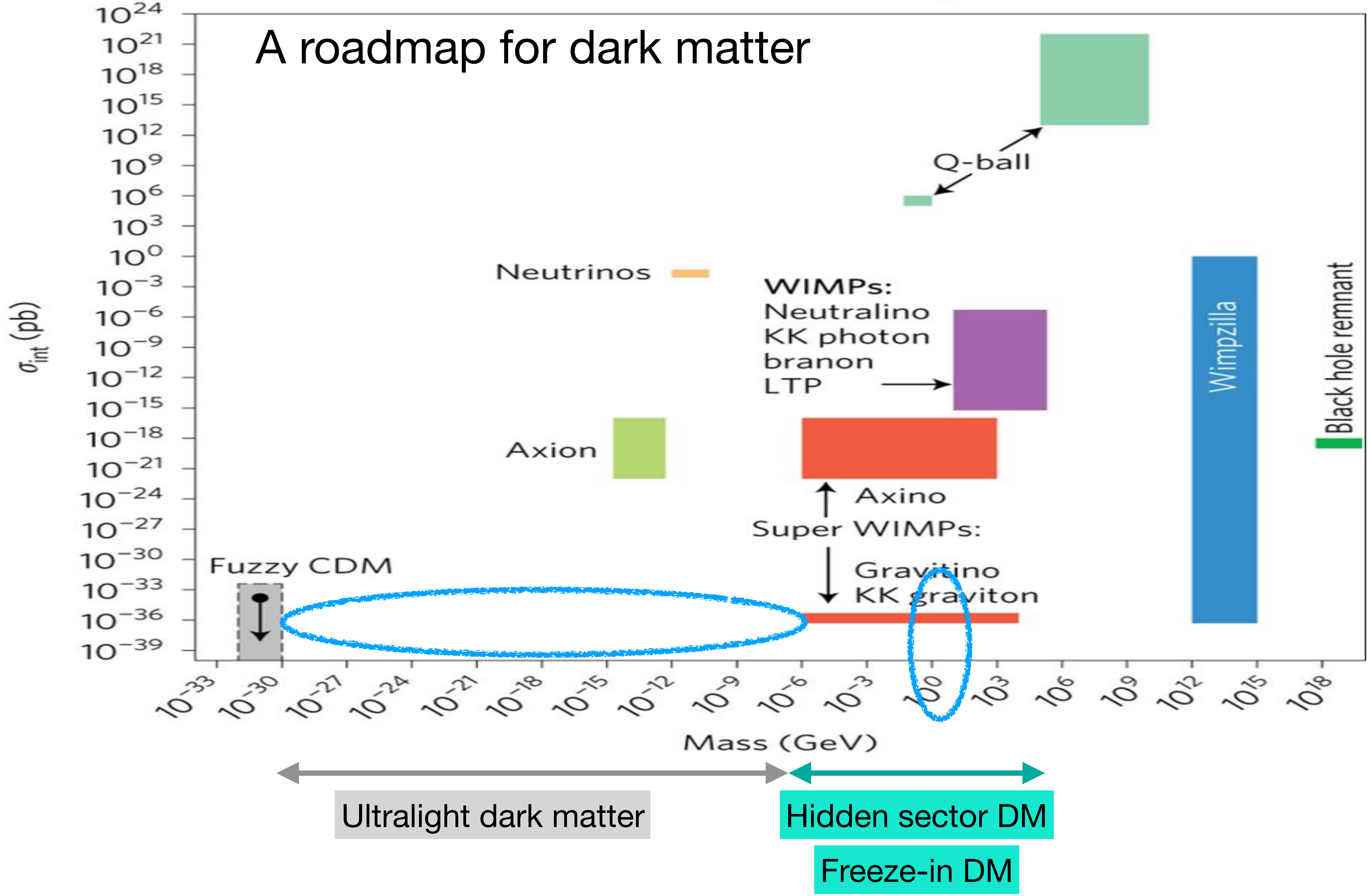
A roadmap for dark matter



Axion-like particle, dark photons, dark scalar, sterile neutrino, etc

A roadmap for dark matter

Conrad & Reimer



Axion-like particle, dark photons, dark scalar, sterile neutrino, etc

Outlines

- A model building issue regarding light DM (0.1-10) GeV
- The small scale problems for ultralight bosonic DM

WIMP: Standard Freeze-out

- Thermal cross-section

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m_W^2} \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

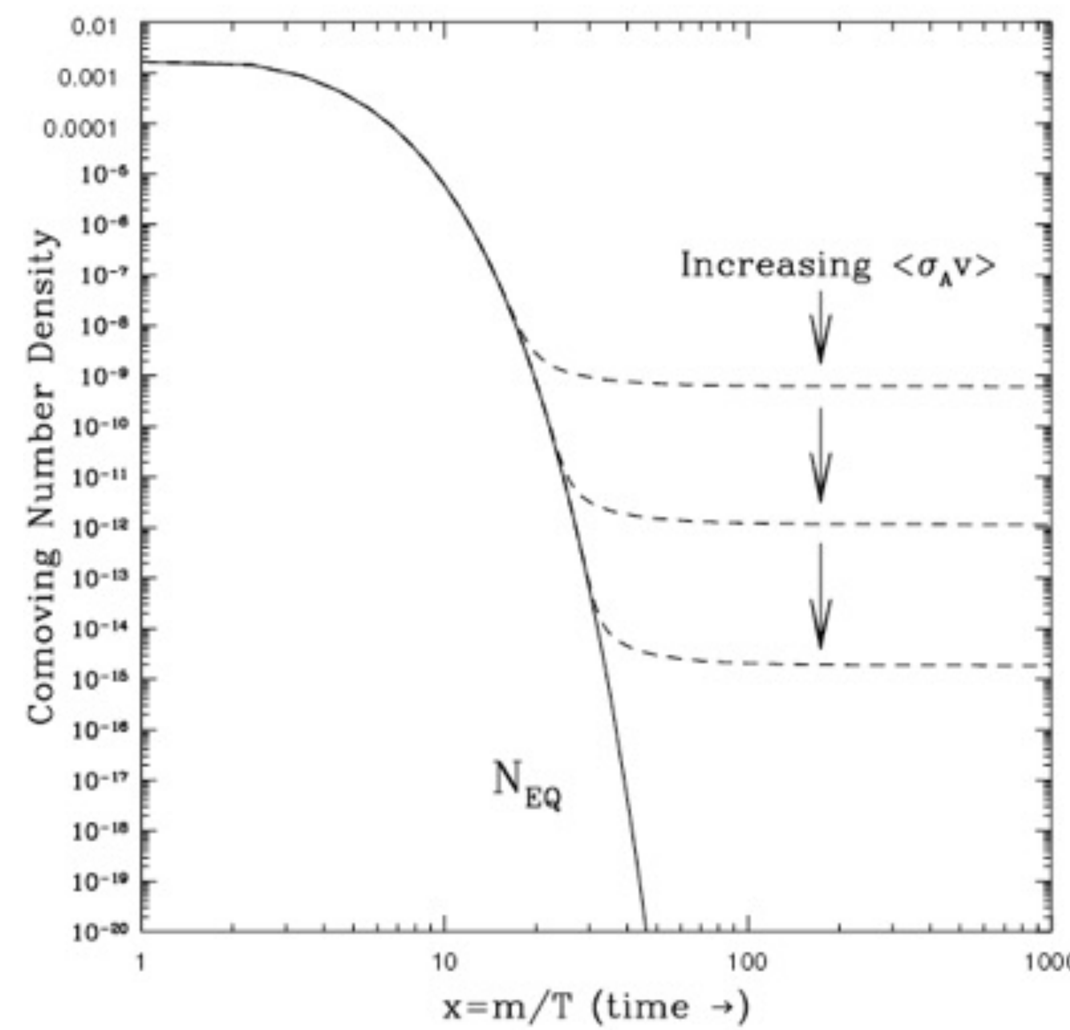
- DM Annihilation cross-section

$$\langle \sigma v \rangle \sim \frac{g^4}{m_{\mathrm{DM}}^2} \Rightarrow g^2 \sim \frac{m_{\mathrm{DM}}}{10\mathrm{TeV}}$$

- Light DM (0.1GeV - 10 GeV)

$$g \in [0.003,\ 0.03]$$

- If no prejudice about g << 1.
- Other heavy particles in the diagram, W/Z/h



Jungman *et al* hep-ph/9506380

Standard Freeze-out

- Light DM (0.1GeV - 10 GeV) looks very normal!
- There are extra motivations for this mass range
  - Asymmetric DM: $n_{DM} \sim n_B$
  - Strongly-Interacting Dark Matter: 3 DM -> 2 DM
- We stay with the simple freeze-out.

Motivation from a special case: Detectable Light Dark Matter (0.1-10) GeV

- Detectable: can have signal in both direct and indirect searches
  - 1. Has sizable coupling to SM fermions
  - 2. Thermal freeze-out
    - DM Annihilation to SM fermions
    - Pressure from CMB constraints for this mass range

Pressure from CMB constraints

- DM annihilation injects extra energy into the primordial plasma, which would delay recombination and thus leave observable imprints in the CMB.

Pressure from CMB constraints

$$DM + DM \rightarrow SM + SM$$

- The rate DM energy density converted into EM energy

$$\frac{d\rho_{DM}}{dt} = m_{DM} n_{DM} n_{DM} \langle \sigma v \rangle \times f_{eff}$$

- f_{eff} : the efficiency with which the energy released in DM annihilation is absorbed by the primordial plasma

Pressure from CMB constraints

- DM DM > SM SM

- The rate DM energy density converted into EM energy

$$\frac{d\rho_{DM}}{dt} = m_{DM} n_{DM} n_{DM} \langle \sigma v \rangle \times f_{eff}$$

- f_{eff} : the efficiency with which the energy released in DM annihilation is absorbed by the primordial plasma

Channel	DM Mass (GeV)	$f_{\rm eff}$	$f_{\rm eff,new}$
Electrons	1	0.85	0.45
$\chi\chi \to e^+e^-$	10	0.77	0.67
	100	0.60	0.46
	700	0.58	0.45
	1000	0.58	0.45
Muons	1	0.30	0.21
$\chi\chi \to \mu^+\mu^-$	10	0.29	0.23
	100	0.23	0.18
	250	0.21	0.16
	1000	0.20	0.16
	1500	0.20	0.16
Taus	200	0.19	0.15
$\chi\chi \to \tau^+\tau^-$	1000	0.19	0.15
W bosons	200	0.26	0.19
$\chi\chi \to W^+W^-$	300	0.25	0.19
	1000	0.24	0.19
Z bosons	200	0.24	0.18
$\chi\chi \to ZZ$	1000	0.23	0.18
Higgs bosons	200	0.30	0.22
$\chi\chi \to h\bar{h}$	1000	0.28	0.22
b quarks	200	0.31	0.23
$\chi\chi \to b\bar{b}$	1000	0.28	0.22
Light quarks	200	0.29	0.22
$\chi\chi \to u\bar{u}, d\bar{d}$ (50% each)	1000	0.28	0.21

1310.3815, Tracy Slatyer et al.

Pressure from CMB constraints

- f_{eff} : the efficiency with which the energy released in DM annihilation is absorbed by the primordial plasma

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$\chi\chi \to \tau^+\tau^-$	1000	0.19	0.15

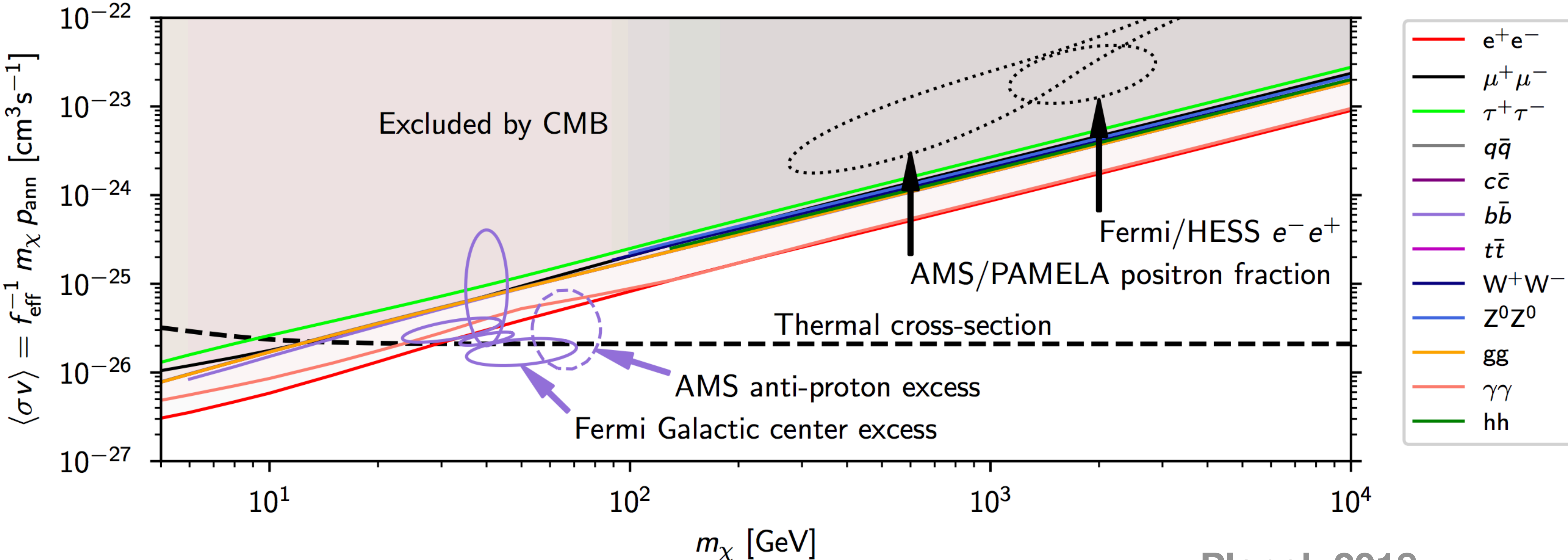
XDM electrons	1	0.85	0.52
$\chi\chi \to \phi\phi$	10	0.81	0.67
followed by	100	0.64	0.49
$\phi \to e^+e^-$	150	0.61	0.47
	1000	0.58	0.45
XDM muons	10	0.30	0.21
$\chi\chi \to \phi\phi$	100	0.24	0.19
followed by	400	0.21	0.17
$\phi \to \mu^+\mu^-$	1000	0.20	0.16
	2500	0.20	0.16
XDM taus	200	0.19	0.15
$\chi\chi \to \phi\phi, \phi \to \tau^+\tau^-$	1000	0.18	0.14
XDM pions	100	0.20	0.16
$\chi\chi \to \phi\phi$	200	0.18	0.14
followed by	1000	0.16	0.13
$\phi \to \pi^+\pi^-$	1500	0.16	0.13
	2500	0.16	0.13

Constrain annihilation to mediator as well

1310.3815, Tracy Slatyer et al.

Pressure from CMB constraints

- DM mass should be larger than ~ 10 GeV



Planck 2018

How to escape CMB constraints?

- 1. Annihilate into neutrinos only!
  - (X) not detectable in direct detection
- 2. P-wave annihilation or no annihilation (asymmetric DM)
  - (X) not detectable in indirect detection

$$\langle \sigma v \rangle = \frac{1}{4m_{DM}^2} \int dPS_2 |\mathbf{M}|^2$$

$$|\mathbf{M}|^2 \approx a + bv^2 + \cdots$$

$$\langle \sigma v \rangle \propto v^2 \approx 10^{-6}$$

Too small for indirect detection!

Escape CMB constraints while being detectable in indirect searches

- How about cross-section linear in v?
  - For CMB, single v is enough $v \approx \sqrt{T_{CMB}/m_{DM}} \approx 10^{-5}$
  - For indirect detection
    - Cluster, v ~ 1000 km/s ~ 3 x 10^{-3}
    - Galaxy, v ~ 220 km/s ~ 1 x 10^{-3}
    - Dwarfs, v ~ 10 km/s ~ 3 x 10^{-5}
  - Detectable in Cluster and Galaxy, not in Dwarfs

Linear dependence in v

- Cross-section linear in v

$$\langle \sigma v \rangle = \frac{1}{4m_{DM}^2} \int dPS_2 \, |\mathbf{M}|^2$$

$$\mathrm{DM} + \mathrm{DM} \to \mathrm{X} + \mathrm{X}$$

- If $m_{MD} = m_X$, then the two-body phase space

$$\int dPS_2 = \frac{1}{8\pi} v$$

- For s-wave annihilation, this gives

$$\langle \sigma v \rangle \approx \frac{1}{2} \sigma_0 v$$

Linear dependence in v

- In practice, not exact degenerate

$$\Delta = m_{\rm DM} - m_{\rm X}$$

$$\langle \sigma v_{\rm rel} \rangle \;\simeq\; \sigma_0 \sqrt{\frac{v_{\rm rel}^2}{4} + \frac{2\Delta}{m_{\rm DM}}}$$

- Model building for $\Delta \ll m_{DM}$
  - Symmetry reason
    - Custodial symmetry: dark SU(2) vector DM $\Delta < 0$
    - Chiral symmetry: dark pion DM $\Delta > 0$
    - Supersymmetry: NMSSM setup 1901.02018

Dark SU(2) gauge boson as DM

- $K_{1,2}$ are DM, K_3 is dark photon mediator

$$\mathcal{L}_{\rm D} = -\frac{1}{4}K^a_{\mu\nu}K^a_{\mu\nu} + (D_\mu\Phi)^\dagger(D_\mu\Phi) - \mu^2\Phi^\dagger\Phi + \frac{\lambda}{2}(\Phi^\dagger\Phi)^2$$

$$\mathcal{L}_{\rm mix} = \frac{1}{\Lambda^2}(\Phi^\dagger T^a\Phi)K^a_{\mu\nu}B_{\mu\nu}$$

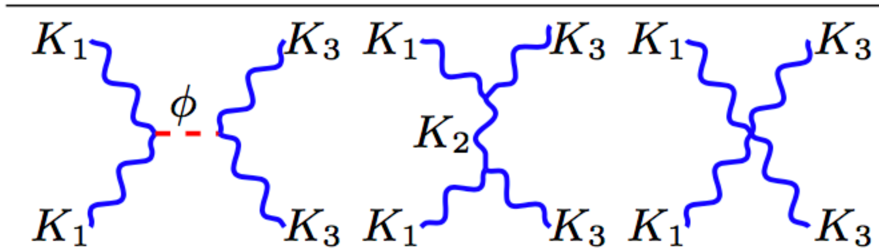
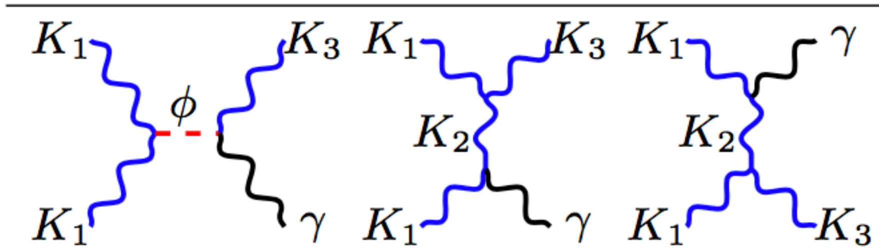
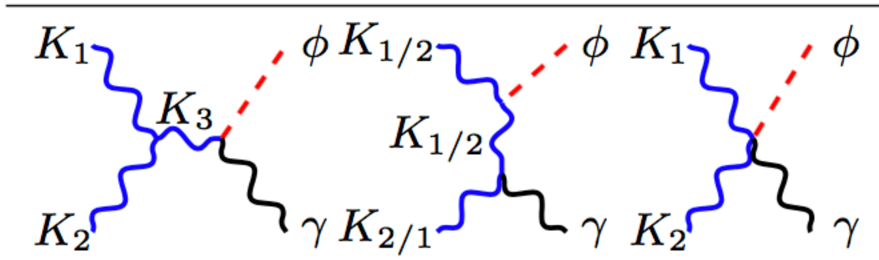
$$\supset \frac{\varepsilon}{2}\left(1+\frac{\phi}{v_d}\right)^2\left[\partial_\mu K^3_\nu - \partial_\nu K^3_\mu + g_d(K^1_\mu K^2_\nu - K^2_\mu K^1_\nu)\right]\frac{1}{\cos\theta_w}B_{\mu\nu}$$

$\varepsilon \equiv -v_d^2\cos\theta_w/(2\Lambda^2)$ $\qquad m_k = \frac{g_d v_d}{2}$

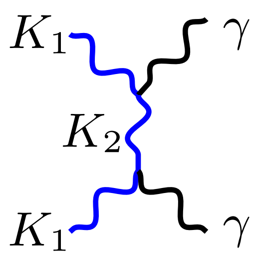
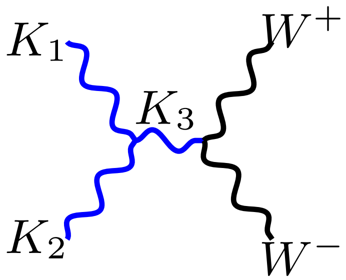
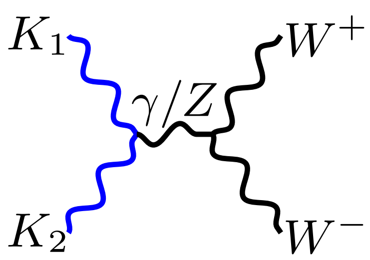
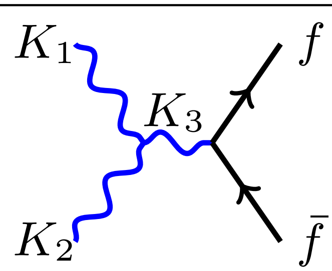
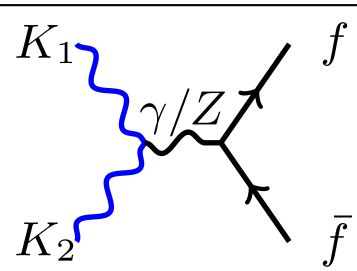
$$\Delta \equiv m_k - m_{K_3} \simeq -\frac{m_k}{2}\frac{\varepsilon^2}{\cos^2\theta_w}\frac{(m_k^2 - \cos^2\theta_w m_{Z,\rm SM}^2)}{m_k^2 - m_{Z,\rm SM}^2}$$

$$\mathcal{L} \supset K_3^\mu\left(\varepsilon\, eJ^\mu_{\rm em} - \varepsilon g\tan\theta_w\frac{m_k^2}{m_k^2 - m_Z^2}J^\mu_Z\right)$$

Dark SU(2) gauge boson as DM

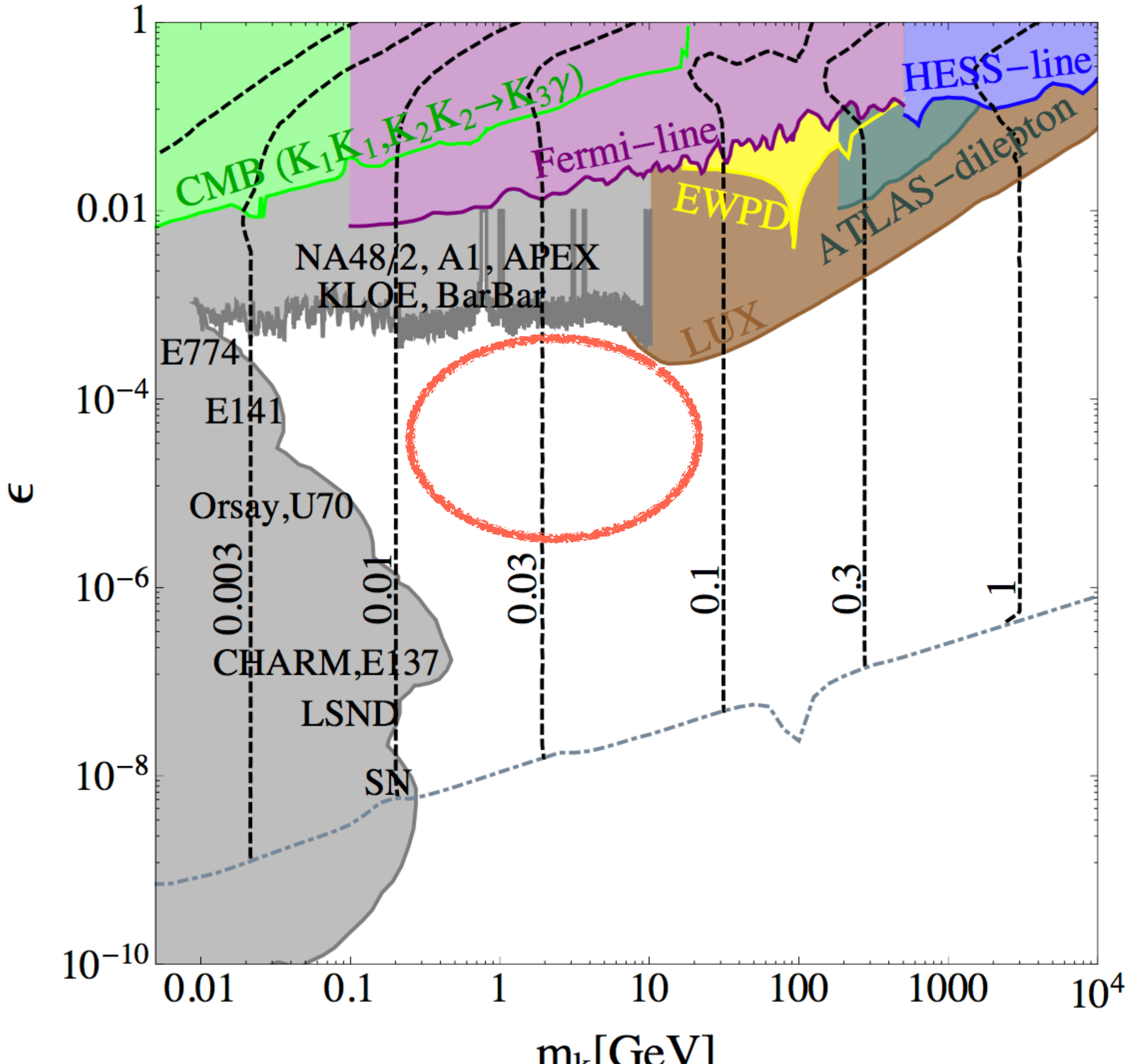
process	$v_{\rm rel}$-dependence	ε-dependence	freeze-out	CMB	Indirect Detection
	$\sqrt{\frac{v_{\rm rel}^2}{4}+\frac{2\Delta}{m_{\rm DM}}}$	1	dominant	negligible	✓
	1	ε^2	subdominant	dominant	✓ (γ line)
	1	ε^2	subdominant (requires $m_\phi < 2m_k$)	dominant (requires $m_\phi < 2m_k$)	✓ (γ line if $m_\phi < 2m_k$)

Dark SU(2) gauge boson as DM

	1	ε^4	negligible	negligible	negligible
 	$v_{\rm rel}^2$	ε^2	subdominant	negligible	negligible
 	$v_{\rm rel}^2$	ε^2	subdominant	negligible	negligible

Dark SU(2) gauge boson as DM

- Viable model waiting for new direct detection exp



Dark pion model

	SU(N)	$U(1)'$
u_d	$\square$	$2/3$
d_d	$\square$	$-1/3$
ϕ	1	2

$$\pi_d^{\pm} = DM$$

$$\pi_d^0 \to A'A'$$

- Chiral Lagrangian

$$\mathcal{L} = \frac{1}{4} f_\pi^2 \,\mathrm{Tr}\left[\partial_\mu U^\dagger \partial^\mu U\right] + \mu \frac{f_\pi^2}{2} \,\mathrm{Tr}\left[U^\dagger M + M^\dagger U\right]$$

$$U = e^{i\sigma^a \pi_d^a}$$

$$\pi_d^a \sigma^a = \begin{pmatrix} \pi_d^0 & \sqrt{2}\pi_d^+ \\ \sqrt{2}\pi_d^- & -\pi_d^0 \end{pmatrix}$$

- Degenerate pion mass

$$m_\pi^2 = \mu(m_{u_d} + m_{d_d}) = 2\mu m_{q_d}$$

Dark pion model

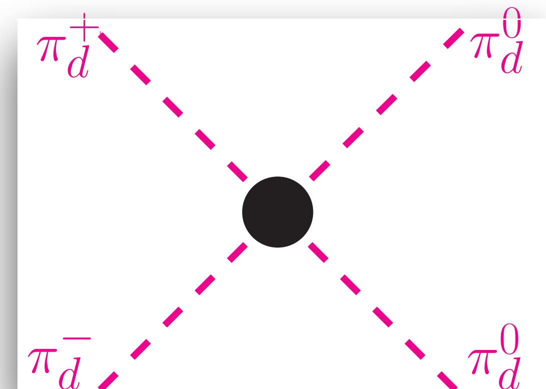
- Mass splitting between DM and π⁰ by U(1)’

$$\Delta \equiv m_{\pi_d^\pm} - m_{\pi_d^0} = g'^2 \frac{f_\pi^2}{2m_\pi} > 0$$

- Interaction with SM through kinetic mixing

$$\mathcal{L} \supset \frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

- Annihilation



$$\sigma v_{\rm rel} = \frac{9}{64\pi} \frac{m_\pi^2}{f_\pi^4} \sqrt{\frac{v_{\rm rel}^2}{4} + \frac{2\Delta}{m_\pi}}$$

Freeze-out

$$\approx 6 \times 10^{-26} {\rm cm^3 s^{-1}} \times \left(\frac{m_\pi / f_\pi^2}{7 \times 10^{-4} {\rm GeV^{-1}}} \right)^2, \quad v_{\rm fo} \sim 0.47$$

CMB

$$\approx 10^{-26} {\rm cm^3 s^{-1}} \times \sqrt{\frac{2\Delta}{m_\pi}}, \qquad v_{\rm CMB} \to 0$$

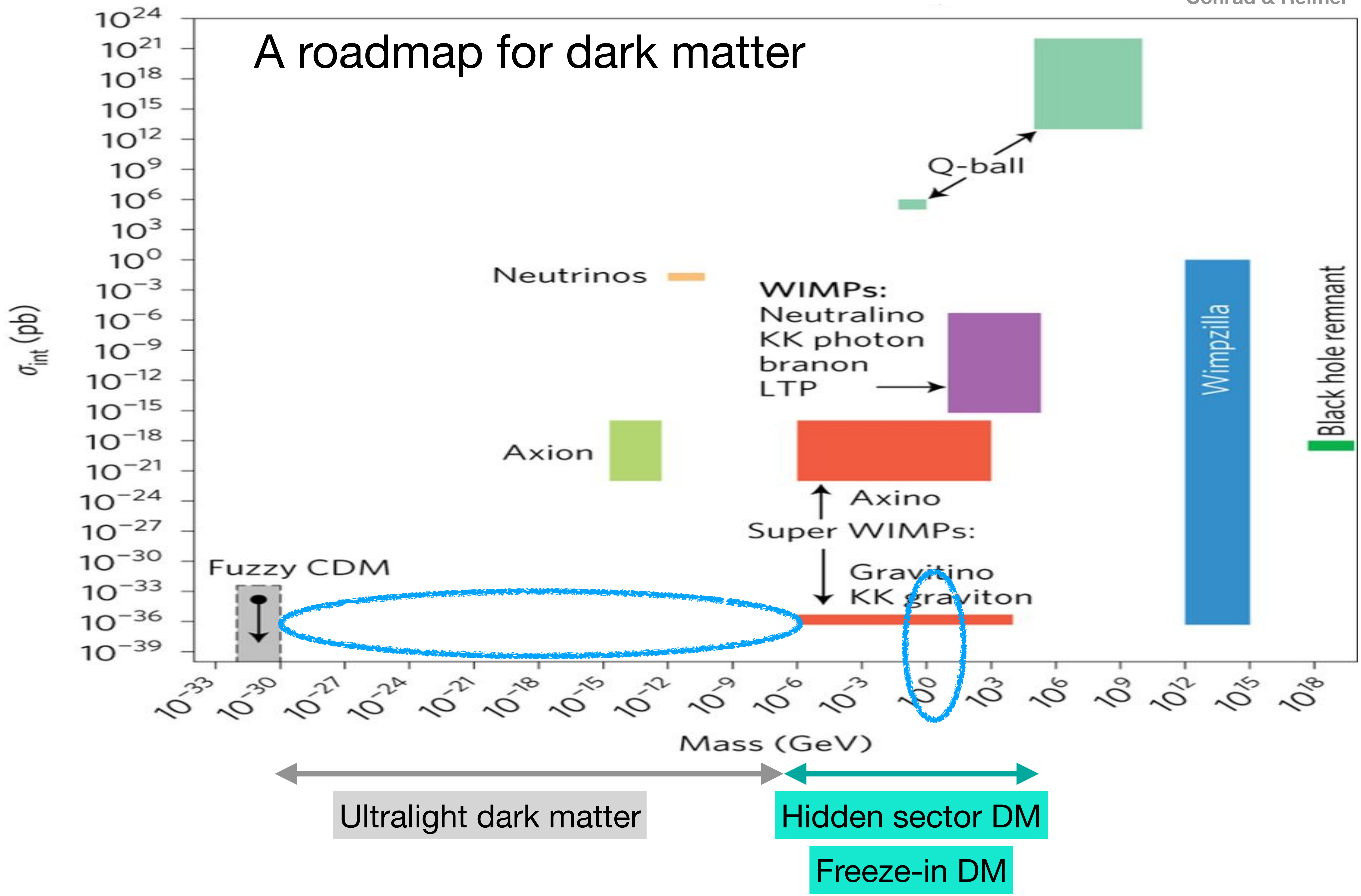
Summary for detectable light DM

- We show two light DM models with direct detection signal, while can have sizable indirect detection

<table>
<tr><td>Model</td><td colspan="2">$SU(2)_d$ dark gauge boson</td><td>dark pion</td></tr>
<tr><td rowspan="2">mass splitting</td><td colspan="2">$\Delta \simeq -\frac{1}{2}\varepsilon^2 m_{\rm DM}$, eq. (10)</td><td>$\Delta \simeq g'^2 f_\pi^2/(2m_\pi)$, eq. (28)</td></tr>
<tr><td>$10^{-7} \lesssim \varepsilon \lesssim 10^{-3}$
$\Delta < 0$ small</td><td>$\varepsilon \gtrsim 10^{-3}$
$\Delta < 0$ large</td><td>$g' \gtrsim 0.05$
$\Delta > 0$</td></tr>
<tr><td>freeze-out</td><td colspan="3">$\sigma v_{\rm rel} \propto v_{\rm rel}$</td></tr>
<tr><td>CMB</td><td>$\sigma v_{\rm rel} \simeq 0$</td><td rowspan="3">$\sigma v_{\rm rel} \simeq 0$</td><td rowspan="2">$\sigma v_{\rm rel} \propto \sqrt{\frac{2\Delta}{m_{\rm DM}}}$</td></tr>
<tr><td>Galaxies</td><td rowspan="2">$\sigma v_{\rm rel} \propto v_{\rm rel}$</td></tr>
<tr><td>Clusters</td><td>$\sigma v_{\rm rel} \propto \mathbf{BF} \times \sqrt{\frac{2\Delta}{m_{\rm DM}}}$</td></tr>
</table>

Conrad & Reimer

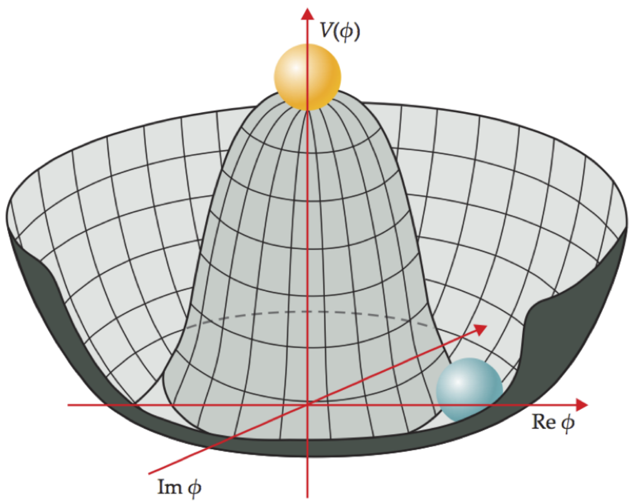
A roadmap for dark matter



Axion-like particle, dark photons, dark scalar, sterile neutrino, etc

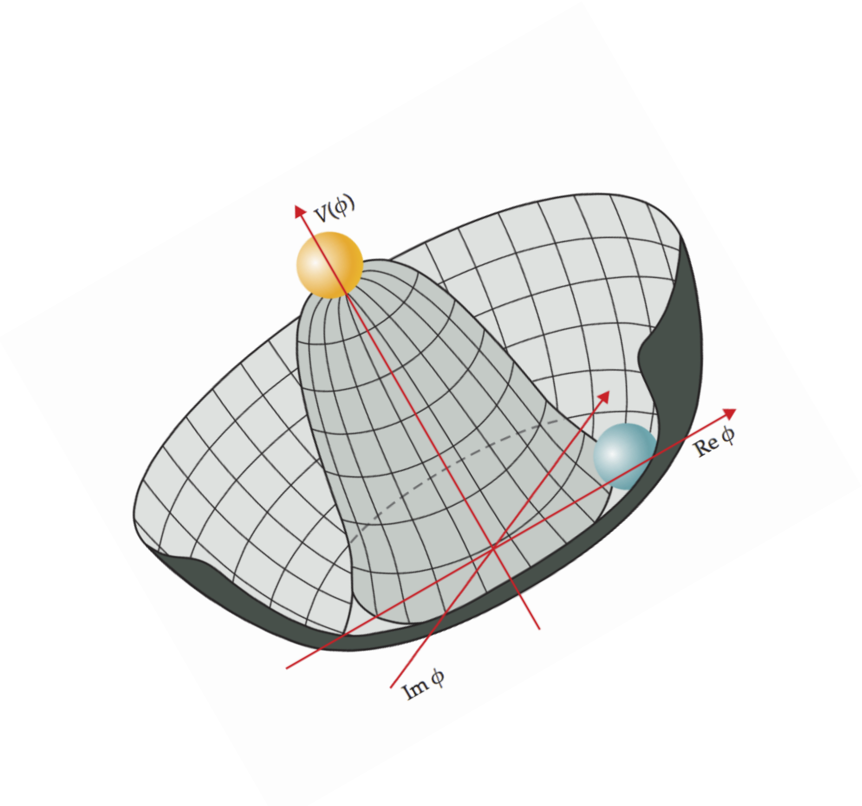
The axion in the cosmology

- Global U(1)$_{PQ}$ symmetry
  - Spontaneous broken leads to massless goldstone (Axion)



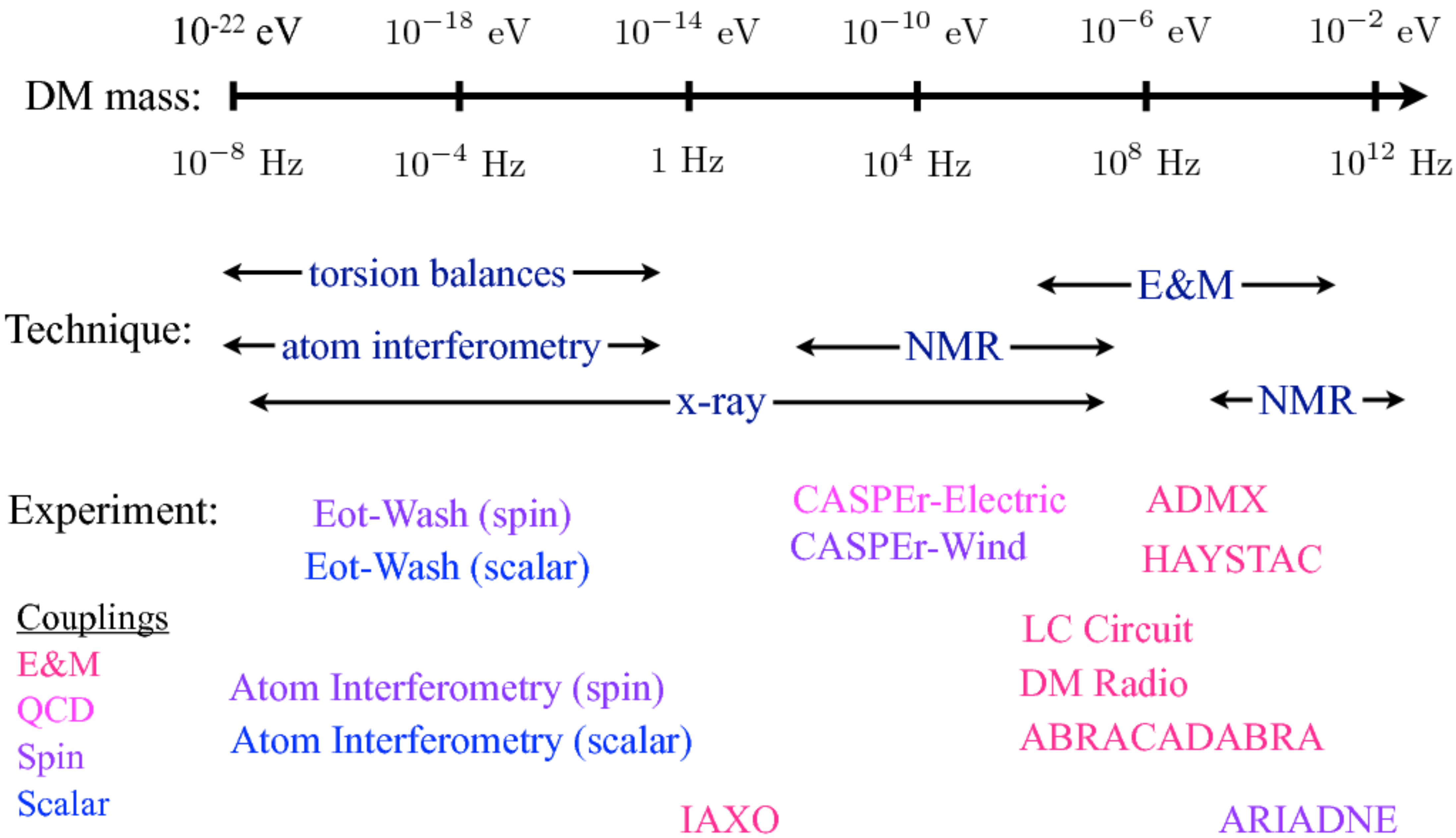
- At QCD scale~400MeV,
  - Potential from Chiral Lagrangian explicitly broke the symmetry leads to massive axion
  - Energy stored in coherent oscillation of axion field
  - When mass ~ Hubble, becoming cold dark matter

  The misalignment production



- Ultralight dark matter candidates also include other bosonic particles: scalars, Axion-like particle (ALP), dark photon

The ultralight dark matter searches



The ultralight dark matter searches

DM mass: 10^{-22} eV, 10^{-18} eV, 10^{-14} eV, 10^{-10} eV, 10^{-6} eV, 10^{-2} eV

10^{-8} Hz, 10^{-4} Hz, 1 Hz, 10^{4} Hz, 10^{8} Hz, 10^{12} Hz

Technique:

- ← torsion balances →
- ← atom interferometry →
- ← x-ray →
- ← NMR →
- ← E&M →
- ← NMR →

Experiment:

Eot-Wash (spin)

Eot-Wash (scalar)

CASPEr-Electric

CASPEr-Wind

ADMX

HAYSTAC

LC Circuit

DM Radio

ABRACADABRA

Atom Interferometry (spin)

Atom Interferometry (scalar)

IAXO

ARIADNE

Couplings

E&M

QCD

Spin

Scalar

$\frac{a}{\Lambda}F\tilde{F}$

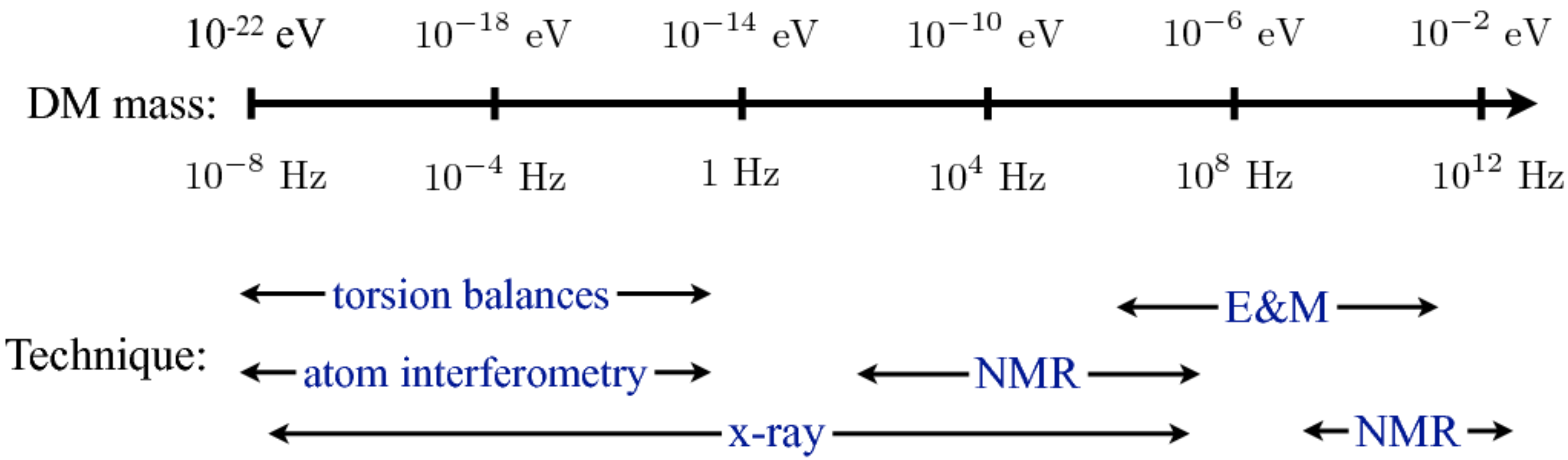
$\frac{a}{\Lambda}G\tilde{G}$

$\frac{\partial_\mu a}{\Lambda}\bar{N}\gamma^\mu\gamma_5 N$

$\frac{S}{\Lambda}FF$

Vector case: U(1)’ , $U(1)_{B-L}$, $U(1)_{Lmu-Ltau}$ etc

The ultralight dark matter searches



Experiment:

Eot-Wash (spin)
Eot-Wash (scalar)
CASPEr-Electric
CASPEr-Wind
ADMX
HAYSTAC
LC Circuit
DM Radio
ABRACADABRA
Atom Interferometry (spin)
Atom Interferometry (scalar)
IAXO
ARIADNE

Couplings
E&M
QCD
Spin
Scalar

$\frac{a}{\Lambda}F\tilde{F}$

$\frac{a}{\Lambda}G\tilde{G}$

$\frac{\partial_\mu a}{\Lambda}\bar{N}\gamma^\mu\gamma_5 N$ $\quad \frac{S}{\Lambda}FF$

Vector case: U(1)' , $U(1)_{B-L}$, $U(1)_{Lmu-Ltau}$ etc

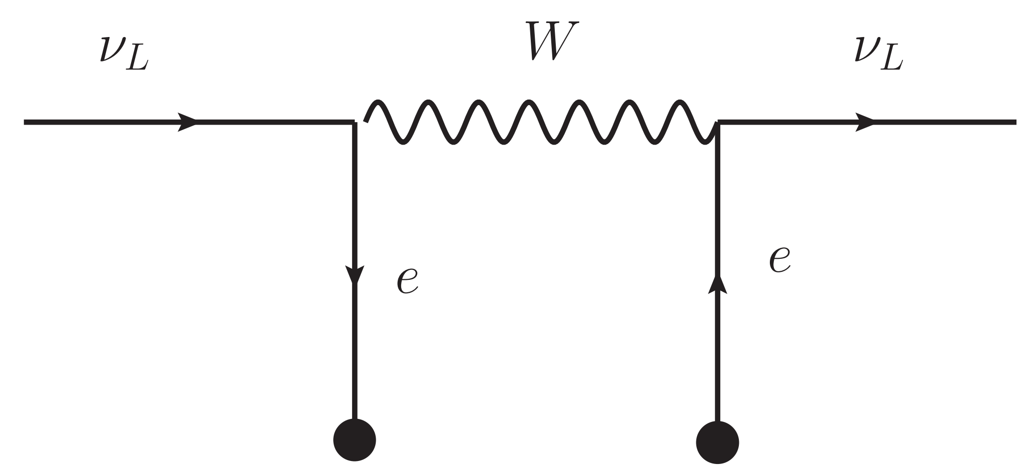
- Coupling with neutrinos?

A. Berlin; G. Krnjaic, P. Machado, L. Necib; V. Brdar, J. Kopp, JL, X.P. Wang; …….

Neutrino oscillation in a dark matter medium

- The Mikheyev–Smirnov–Wolfenstein effect

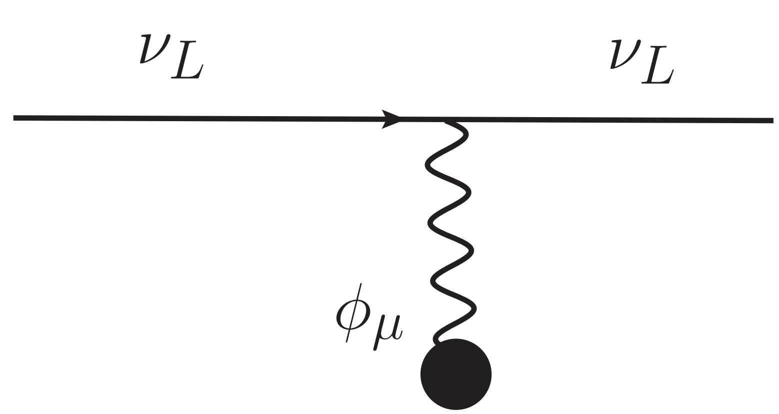
  (similar as light travel in the water)

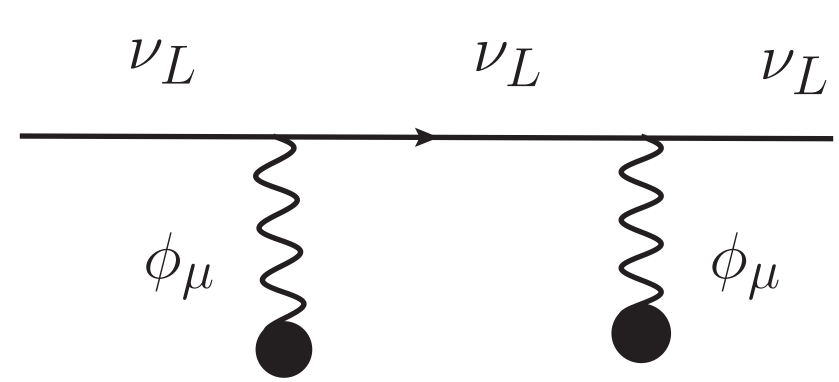


- Vector dark matter model, U(1)$_{\text{mu-tau}}$ dark photon

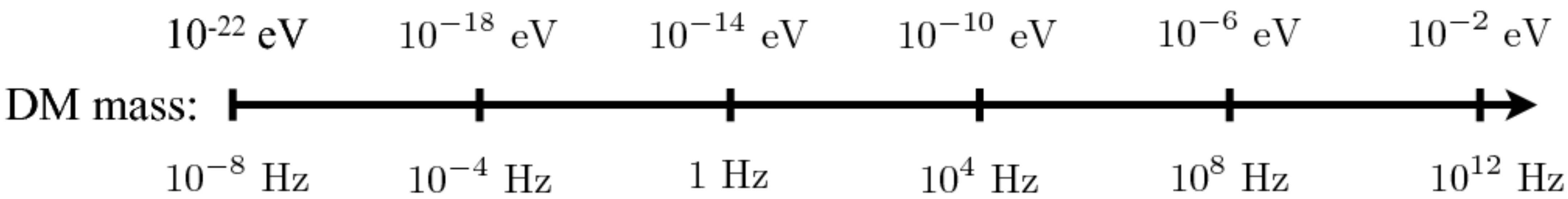
$$\mathcal{L}_{vector} = \bar{\nu}_L^{\alpha} i\gamma^{\mu}\partial_{\mu}\nu_L^{\alpha} - \frac{1}{2}m_{\nu}^{\alpha\beta}\overline{(\nu_L^c)^{\alpha}}\nu_L^{\beta} + \boxed{gQ^{\alpha\beta}\phi^{\mu}\bar{\nu}_L^{\alpha}\gamma_{\mu}\nu_L^{\beta}}$$

- Similar MSW effect for neutrinos from dark matter medium



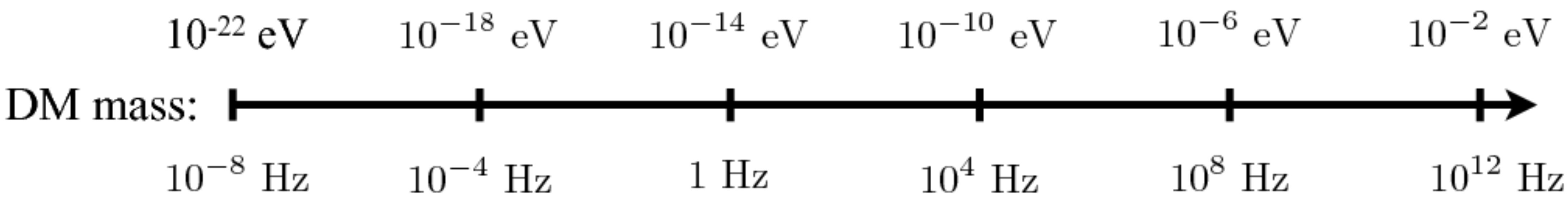


Cold Dark Matter: the small-scale problems



- The small-scale problems for CDM
    - Core-cusp
    - Missing satellite
    - Too big to fail

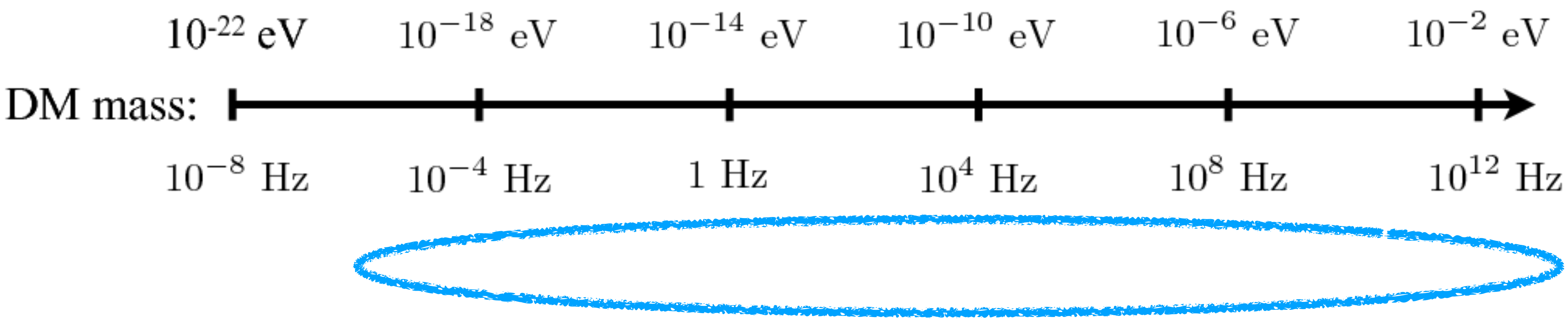
Cold Dark Matter: the small-scale challenges



- The possible solutions
  - Better understanding of baryonic physics
  - Fuzzy dark matter: de Broglie wavelength ~ kpc scale
  - Self-interacting dark matter (SIDM): self-interaction kinematically thermalize the inner halo
    - Difficult for ultralight dark matter

$$\Lambda_{\mathrm{QCD}}^4 \left(\frac{a}{f_a}\right)^4 = \frac{m_a^2}{f_a^2} a^4 \qquad \frac{\alpha'^2}{\Lambda^4}(F\,.\,F)^2$$

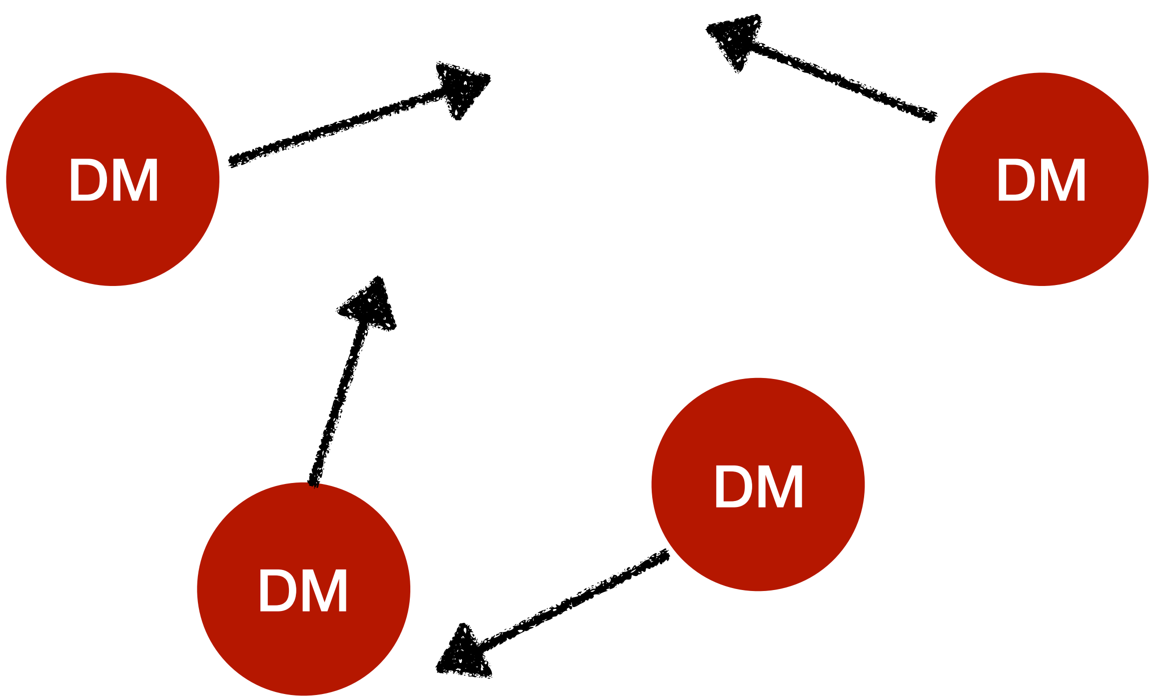
Cold Dark Matter: the small-scale challenges



- For mass > 10^{-21} eV ultralight bosonic DM
  - The small-scale problems is not solved
  - A solution from Co-Interacting DM scenario

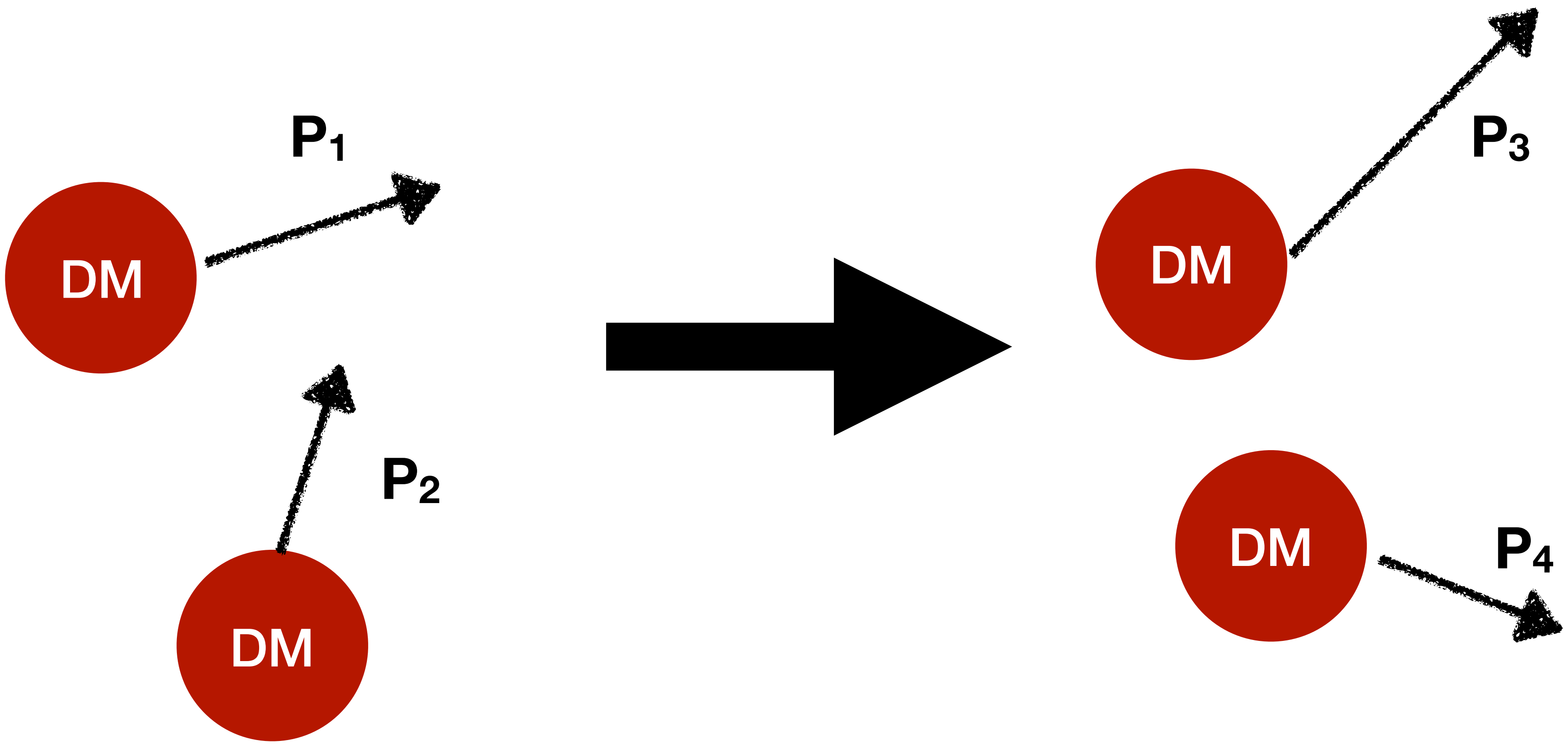
Self-Interacting DM v.s. Co-Interacting DM

- SIDM picture:
  self-collisions can cause heat (kinetic energy) transfer



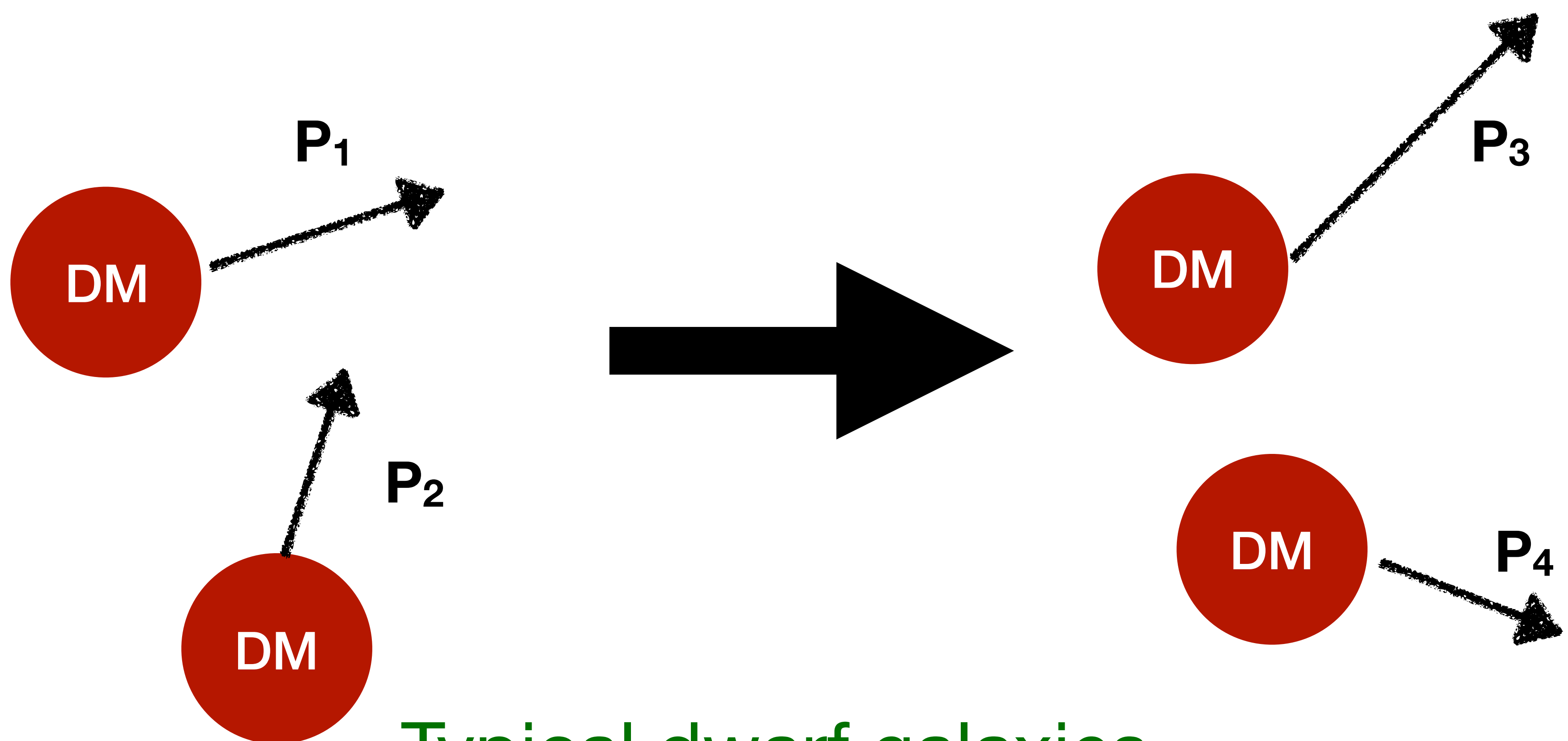
SIDM v.s. Co-Interacting DM

- SIDM picture:
  self-collisions can cause heat (kinetic energy) transfer



SIDM v.s. Co-Interacting DM

- SIDM picture:
  self-collisions can cause heat (kinetic energy) transfer



Typical dwarf galaxies

$$\rho_{\rm DM} \sim 0.1 {\rm M_\odot/pc^3}, v_{\rm rel} \sim 50 {\rm km/s}$$

Solution from SIDM

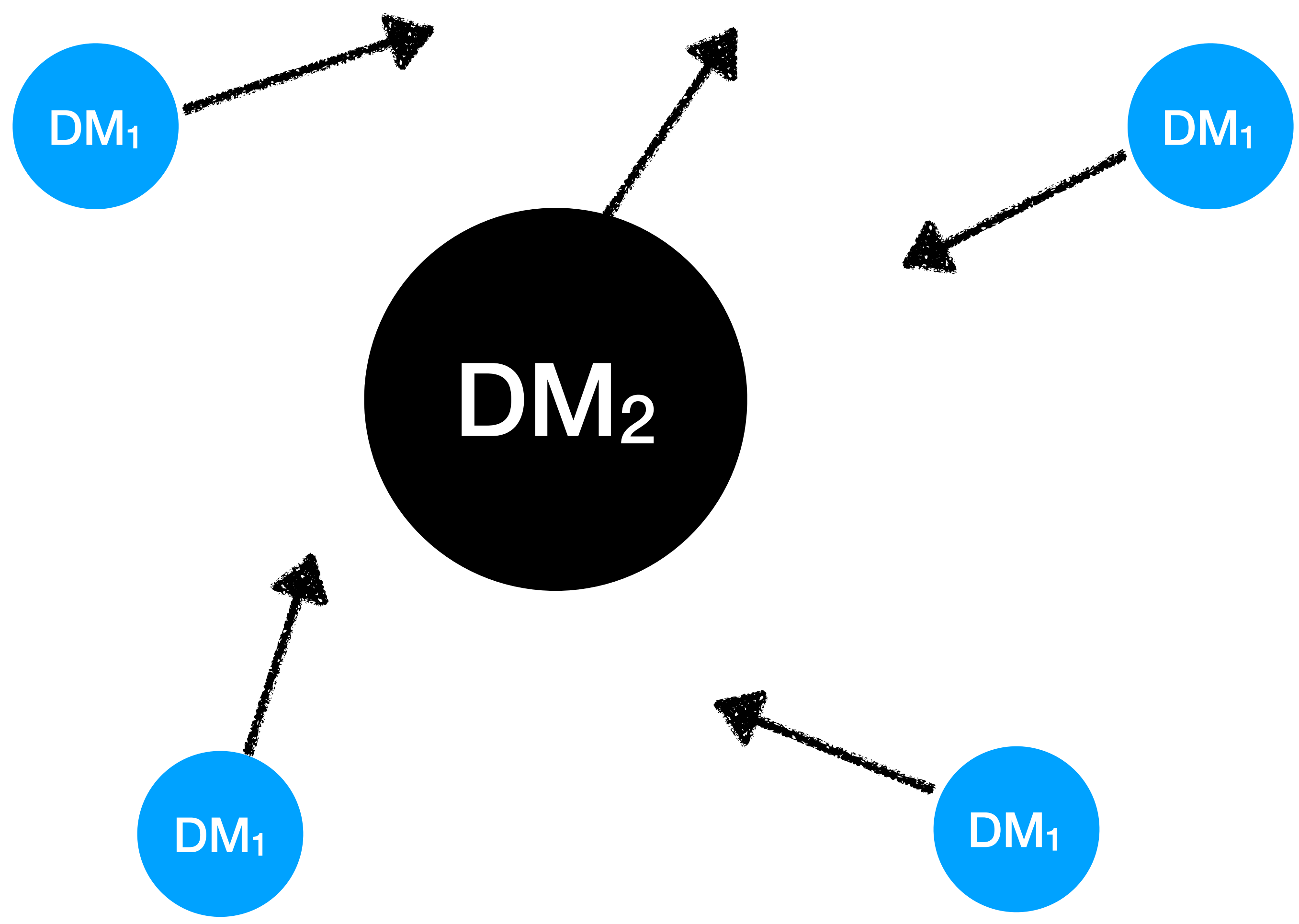
$$\frac{\sigma}{m} \sim \frac{\rm cm^2}{\rm g}$$

$$R = \sigma v_{\rm rel} \rho_{\rm DM}/m \sim 0.1 {\rm Gyr^{-1}}$$

For individual DM_1 , one collision per 10 Gyr is enough.
Due to equal mass, one collision is **effective**.

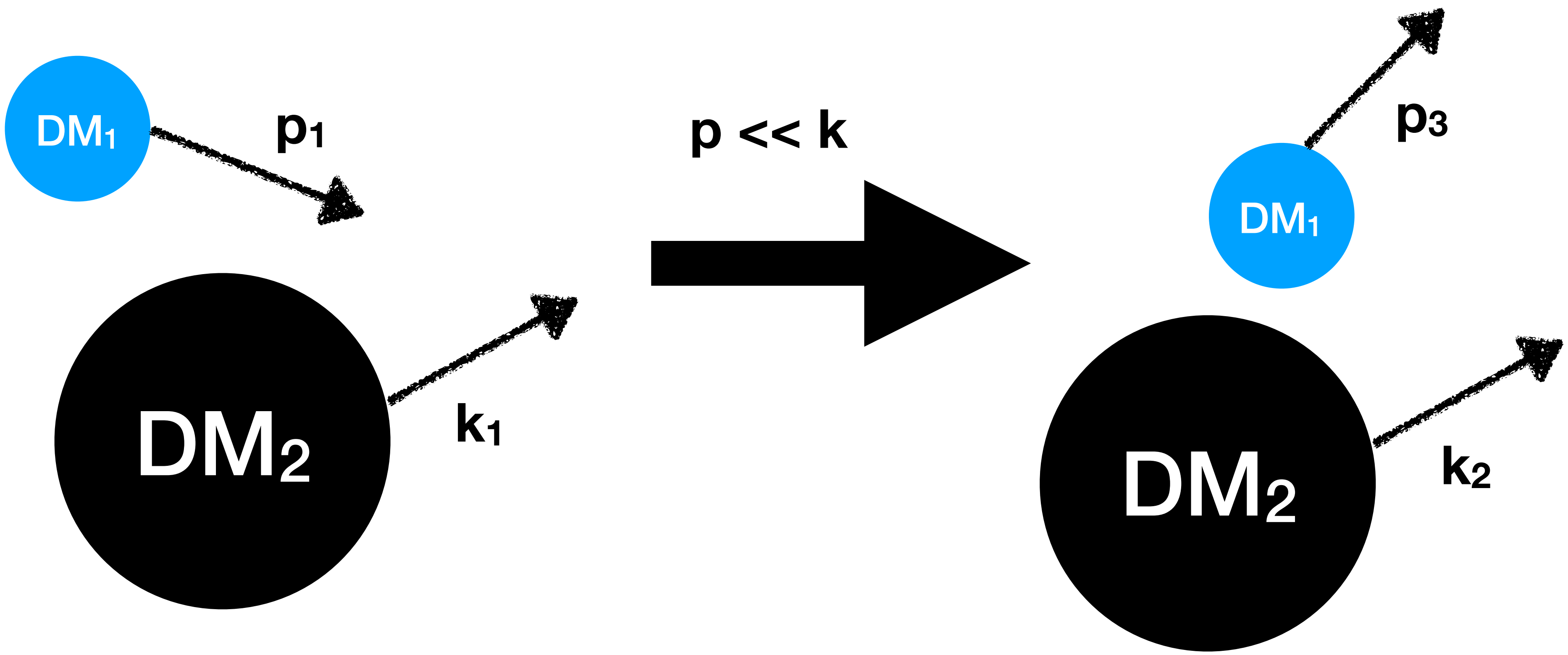
SIDM v.s. Co-Interacting DM

- Co-IDM picture:
  1. two DM component DM_1 and DM_2 (two WIMPs example)
  2. **$m_1 << m_2$**, relic density fraction **$f_1 >> f_2$**
  3. **1-2 interaction cross-section** >> 1-1 and 2-2 interactions



SIDM v.s. Co-Interacting DM

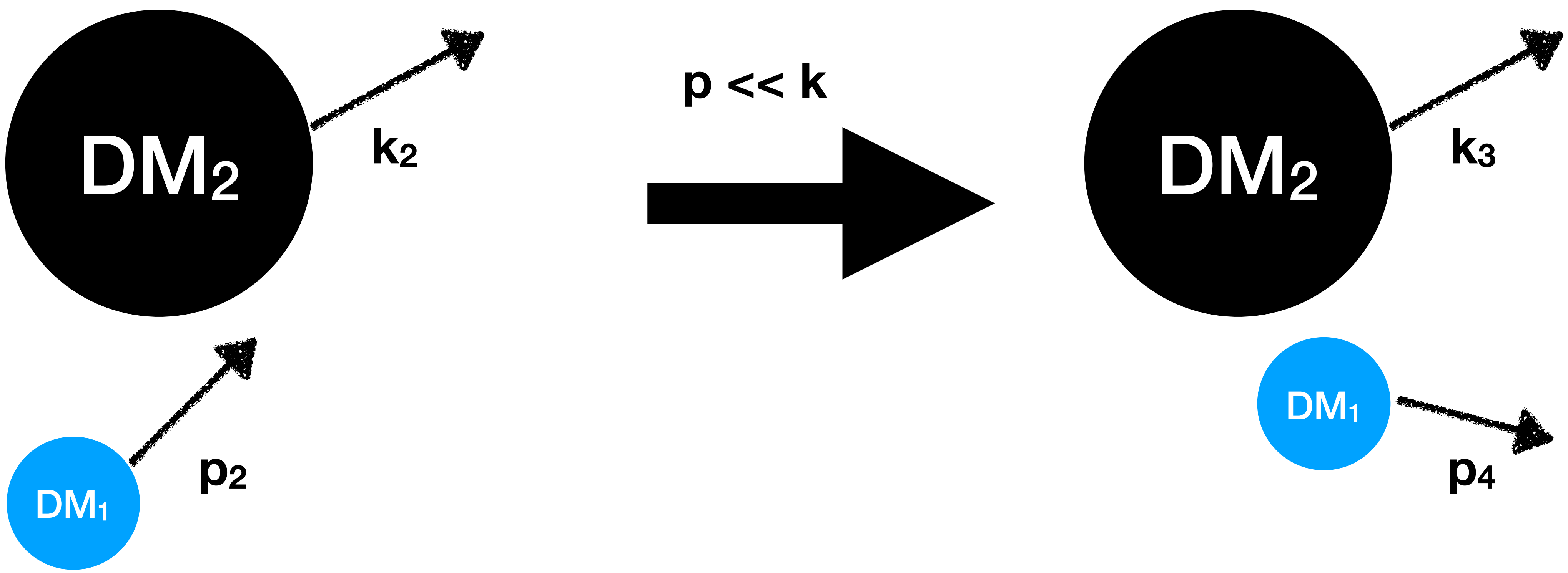
- Co-IDM picture:
  DM_1 kinetic energy can be transferred through collision with DM_2



- Both DM_1 and DM_2 have similar initial velocity dispersion from gravitational falling

SIDM v.s. Co-Interacting DM

- Co-IDM picture:
  DM_1 kinetic energy can be transferred through collision with DM_2

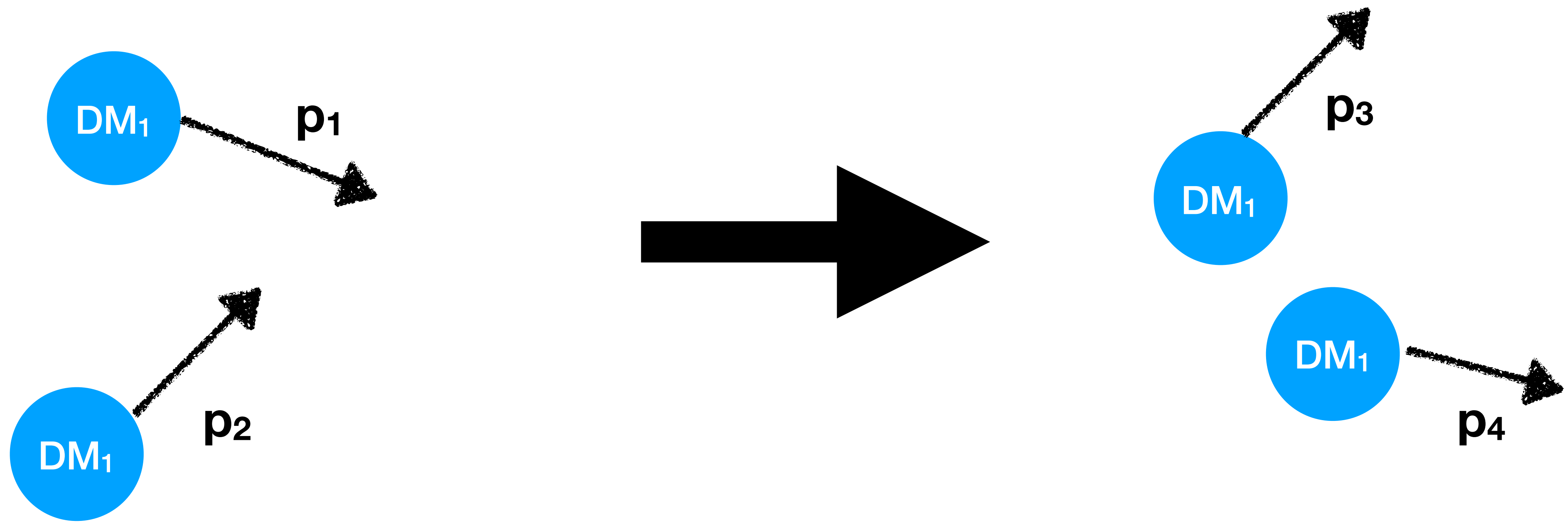


- After the first collision, another DM_1 collides with DM_2

- $m_1 << m_2$: DM_1 significantly change momentum by one collision, while DM_2 needs $(m_2/m_1)^2$ times of scattering (the random walk penalty)

SIDM v.s. Co-Interacting DM

- Co-IDM picture:
  DM_1 kinetic energy transferred between different DM_1

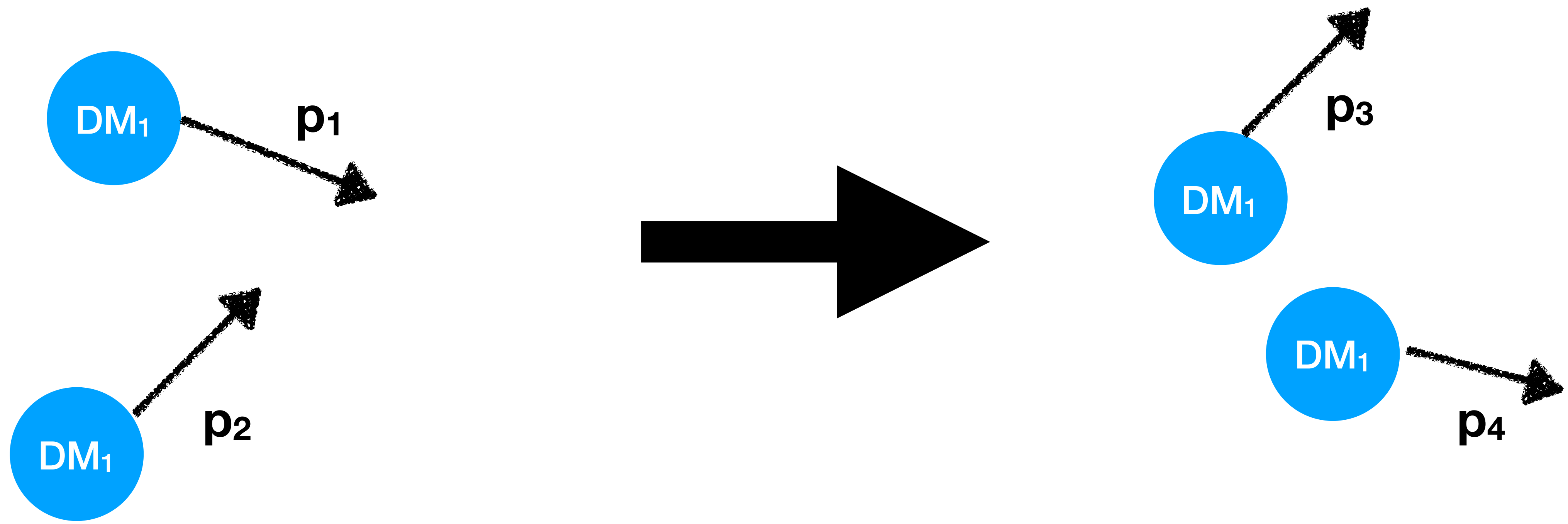


- Neglecting DM_2 momentum/energy changes (small f_2 = small total kinetic energy)

- **The Net effect**: DM_1 particles has kinetic energy transfer between themselves

SIDM v.s. Co-Interacting DM

- Co-IDM picture:
  DM_1 kinetic energy transferred between different DM_1



Typical dwarf galaxies

$$\rho_{\rm DM} \sim 0.1 {\rm M}_\odot/{\rm pc}^3, v_{\rm rel} \sim 50 {\rm km/s}$$

Solution from Co-Interaction DM

$$R_1 = (\sigma_{12} v_{\rm rel}) \rho_{{\rm DM}_2}/m_2$$
$$= f_2 (\sigma_{12} v_{\rm rel}) \rho_{\rm DM}/m_2 \sim 0.1 {\rm Gyr}^{-1}$$

1. For each DM_1, one collision with DM_2 per 10 Gyr is enough.
2. Due to small mass, one collision for DM_1 is **effective**.
3. For each DM_2, it has many collisions with DM_1 per 10 Gyr, but its momentum change is suppressed by random walk factors.

Co-Interacting dark matter

- Example model: two component DM
  - ultralight bosonic A' and dark fermion ψ with U(1) interaction

$$\mathscr{L} \supset g'\bar{\psi}\gamma_\mu \psi A'^{\mu}$$

Co-Interacting dark matter

- Example model: two component DM, A' and dark fermion ψ with U(1) interaction

$$\mathscr{L} \supset g' \bar{\psi} \gamma_\mu \psi A'^\mu$$

- Novelty:
  1. A' (DM_1) dominant component, m_1 << eV, ultralight
  2. ψ (DM_2) dark fermion subdominant, m_2 ~ weak scale

- Unusual features:
  1. A' has large occupation number
  2. two components has huge mass difference

- Other assumptions:
  1. similar initial velocity dispersion $v_0 \sim 10^{-3}$
  2. $f_1 + f_2 = 1$

A' and ψ scattering

$$\psi(k_1) + A'(p_1) \to \psi(k_2) + A'(p_2)$$

- Boltzmann equation

$$\left(\partial_t + v_i \partial_{x_i} + \dot{v}_i \partial_{v_i}\right) \mathcal{N}(\mathbf{x}, \mathbf{p}, \mathbf{t}) = \mathcal{C}(\mathbf{x}, \mathbf{p}, \mathbf{t})$$

Recall normally it is

$$\mathcal{N}_1 \mathcal{N}_2 \left(1 \pm \mathcal{N}_3\right)\left(1 \pm \mathcal{N}_4\right) - \mathcal{N}_3 \mathcal{N}_4 \left(1 \pm \mathcal{N}_1\right)\left(1 \pm \mathcal{N}_2\right) \approx \left(\mathcal{N}_1 \mathcal{N}_2 - \mathcal{N}_3 \mathcal{N}_4\right)$$

Collisional kernels in the limit of large occupation number $\mathcal{N}^{A'} \gg 1$

$$C_\psi \simeq \sum_{spin} \int \frac{d^3\mathbf{p_1} d^3\mathbf{k_2}}{(2\pi)^5 8 m_{A'}^2 m_\psi^2} |\mathbf{M}\left(\mathbf{k_1}, \mathbf{p_1}, \mathbf{k_2}, \mathbf{p_2}\right)|^2 \times \delta(E_{k_1} + E_{p_1} - E_{k_2} - E_{p_2}) \underline{\mathcal{N}_{p_1}^{A'} \mathcal{N}_{p_2}^{A'} \left(\mathcal{N}_{k_2}^{\psi} - \mathcal{N}_{k_1}^{\psi}\right)}$$

$$C_{A'} \simeq \sum_{spin} \int \frac{d^3\mathbf{k_1} d^3\mathbf{k_2}}{(2\pi)^5 8 m_{A'}^2 m_\psi^2} |\mathbf{M}\left(\mathbf{k_1}, \mathbf{p_1}, \mathbf{k_2}, \mathbf{p_2}\right)|^2 \times \delta(E_{k_1} + E_{p_1} - E_{k_2} - E_{p_2}) \underline{\mathcal{N}_{p_1}^{A'} \mathcal{N}_{p_2}^{A'} \left(\mathcal{N}_{k_2}^{\psi} - \mathcal{N}_{k_1}^{\psi}\right)}$$

Novel features

$$\psi(k_1) + A'(p_1) \to \psi(k_2) + A'(p_2)$$

1. Large occupation number of A'

$$\langle \mathcal{N}^{A'} \rangle \sim \frac{\rho_{A'}/m_{A'}}{m_{A'}^3 v_0^3} \sim 3 \times 10^{76} \times \left(\frac{\rho_{A'}}{0.1 \mathrm{M}_\odot/\mathrm{pc}^3} \right) \left(\frac{m_{A'}}{10^{-18}\mathrm{eV}} \right)^{-4} \left(\frac{v_0}{10^{-3}} \right)^{-3}$$

2. Suppression from the forward-backward scattering cancellation

$$p \ll k \to \left(\mathcal{N}^{\psi}_{k_2} - \mathcal{N}^{\psi}_{k_1} \right) \sim \mathcal{N}^{\psi} \times \frac{m_{A'}}{m_\psi}$$

3. Random walk suppression from multiple scattering for ψ

$$\Gamma_\psi \equiv \frac{C_\psi}{\mathcal{N}_\psi}, \quad \Gamma_\psi^{\mathrm{eff}} \simeq \Gamma_\psi \frac{m_{A'}^2}{m_\psi^2}$$

"effective" = collision rate with significant momentum change

A' and ψ effective scattering rate

$$\psi(k_1) + A'(p_1) \to \psi(k_2) + A'(p_2)$$

- A' dominates relic abundance

$$\Gamma_{A'}^{\rm eff} \simeq \Gamma_{A'} \equiv \frac{C_{A'}}{\mathcal{N}_{A'}} \simeq n_\psi \langle \sigma v \rangle_{\psi A'} \langle \mathcal{N}^{A'} \rangle \left(\frac{m_{A'}}{m_\psi} \right)$$

Small A' mass

Final state Bose enhancement

Forward-backward cancellation

Scattering cross-section

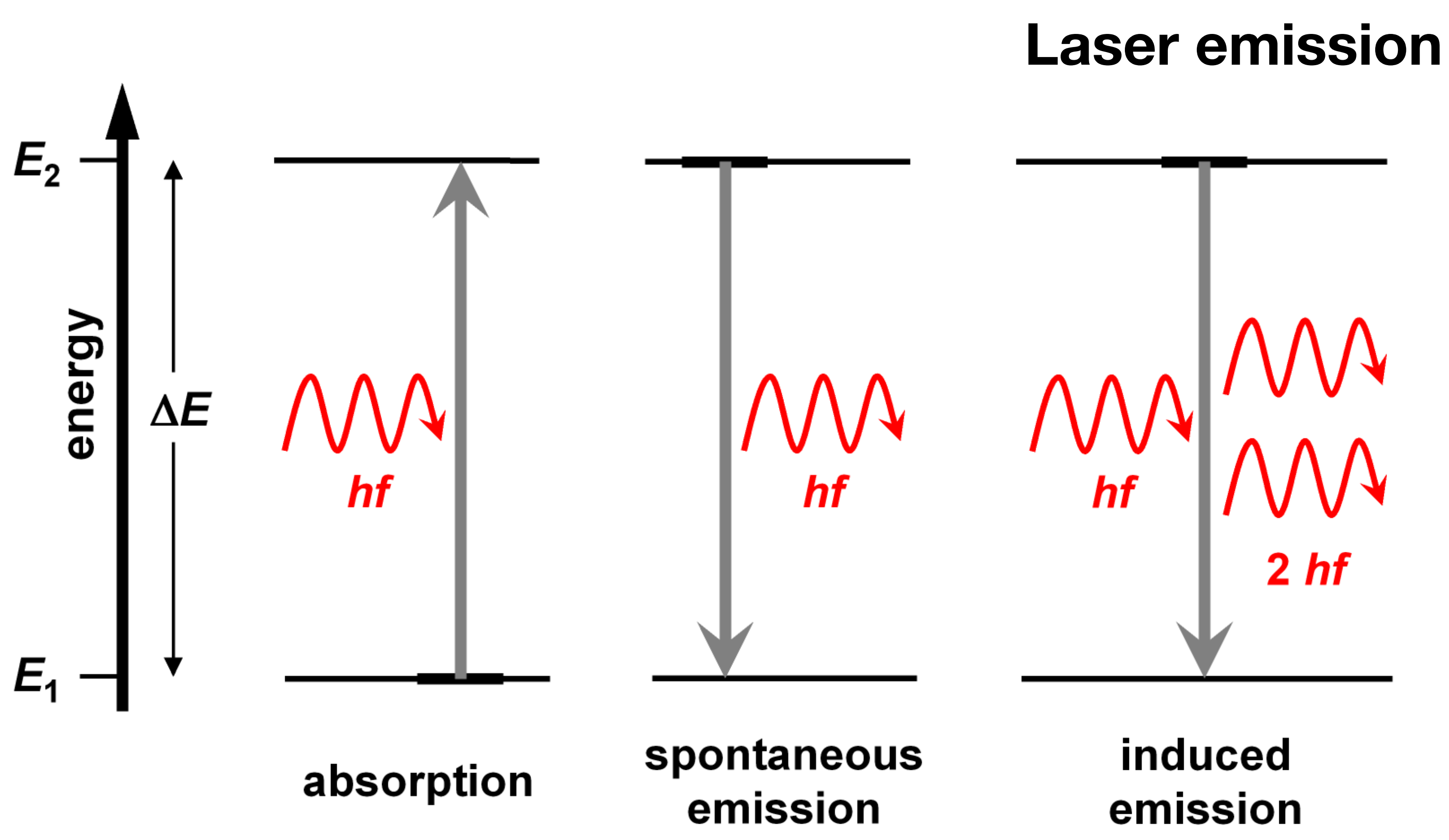
$$\langle \sigma v \rangle_{\psi A'} \simeq \frac{g'^4 v_{\rm rel}}{4\pi m_\psi^2}$$

The dark atom laser emission

$$\psi(k_1) + A'(p_1) \to \psi^* \to \psi(k_2) + A'(p_2)$$

- A' dominates relic abundance

$$\Gamma_{A'}^{\rm eff} \simeq \Gamma_{A'} \equiv \frac{C_{A'}}{\mathcal{N}_{A'}} \simeq n_\psi \langle \sigma v \rangle_{\psi A'} \langle \mathcal{N}^{A'} \rangle \left(\frac{m_{A'}}{m_\psi} \right)$$



The dark atom laser emission

$$\psi(k_1) + A'(p_1) \rightarrow \psi^* \rightarrow \psi(k_2) + A'(p_2)$$

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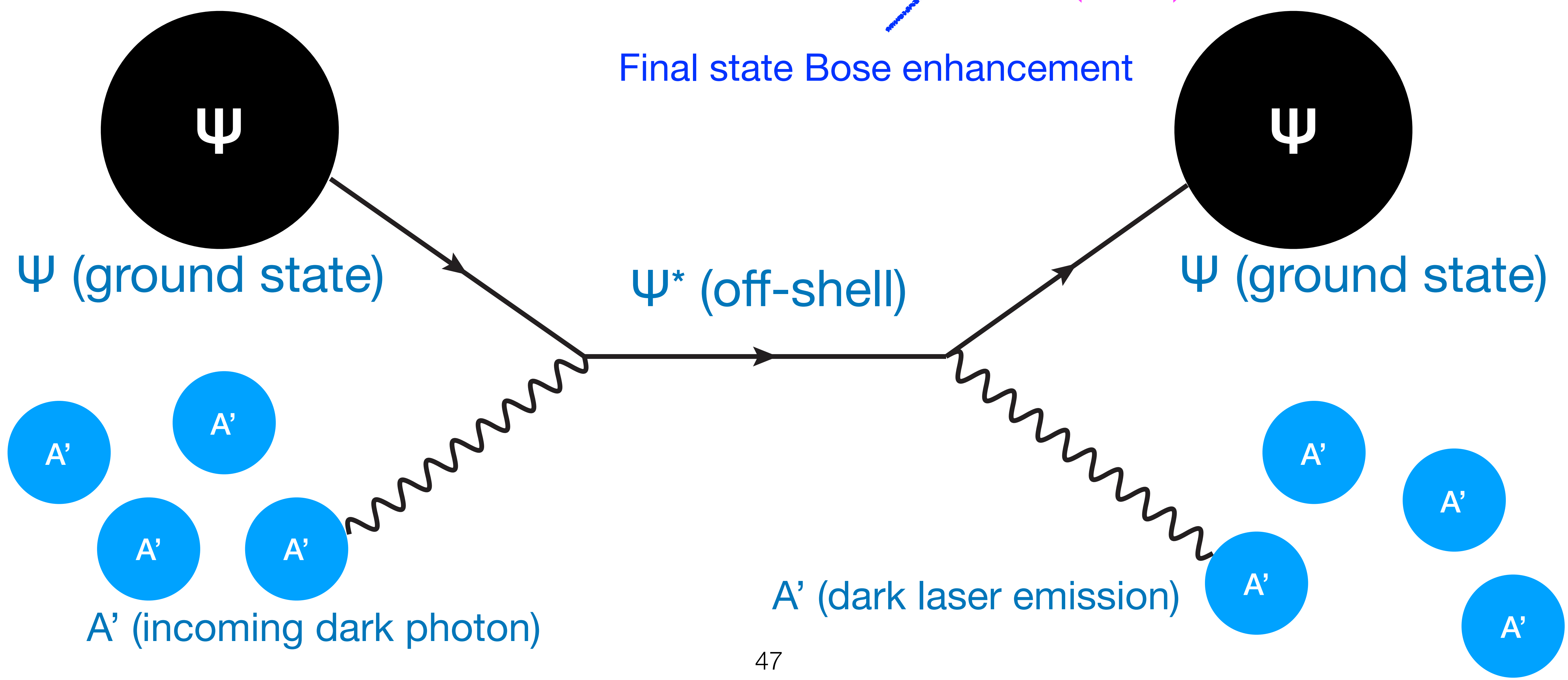
Forward-backward cancellation

$$\Gamma^{\rm eff}_{A'} \simeq \Gamma_{A'} \equiv \frac{C_{A'}}{\mathcal{N}_{A'}} \simeq n_\psi \langle \sigma v \rangle_{\psi A'} \langle \mathcal{N}^{A'} \rangle \left(\frac{m_{A'}}{m_\psi} \right)$$

Final state Bose enhancement

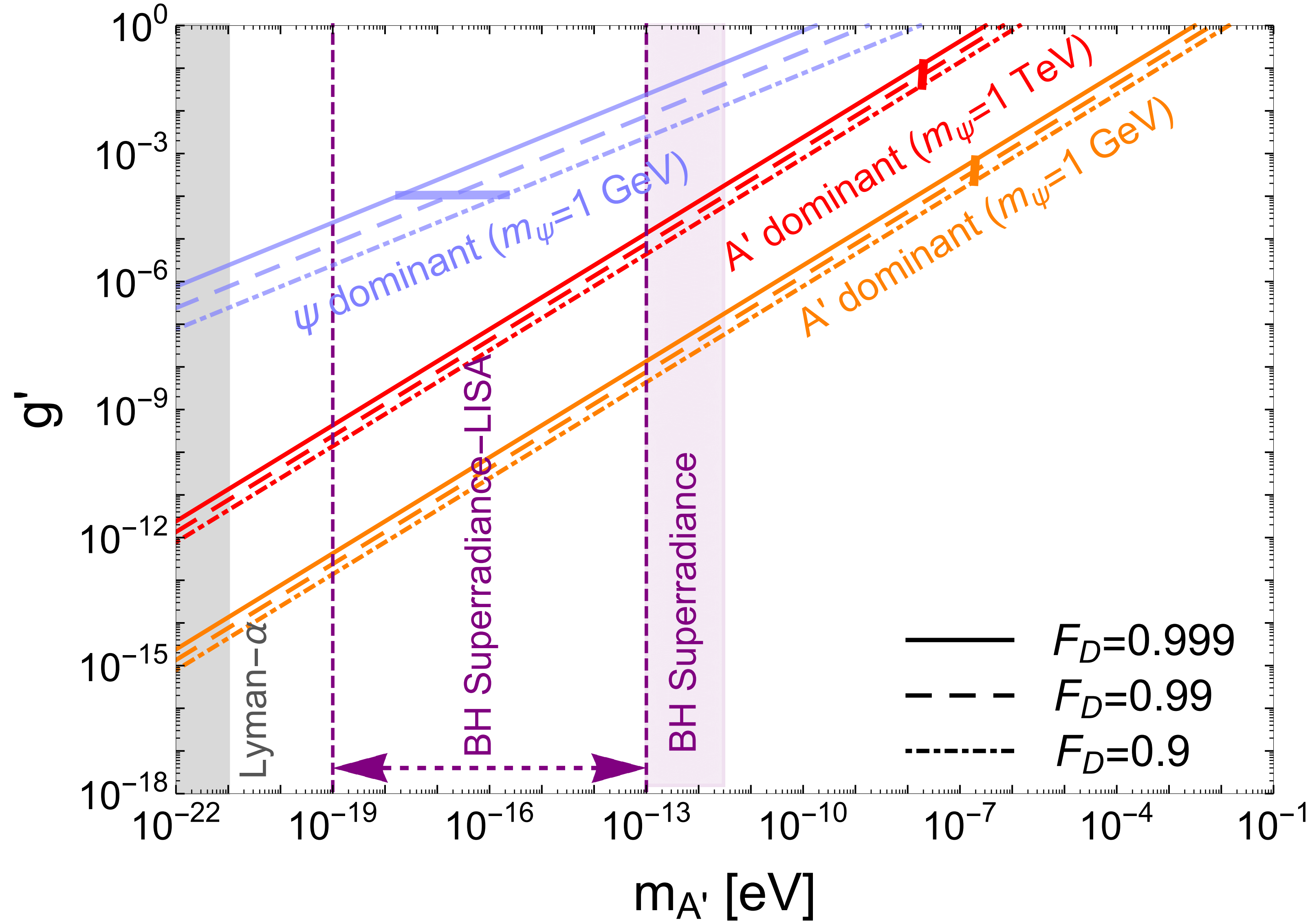


A’ and ψ effective scattering rate

$$\psi(k_1) + A'(p_1) \to \psi(k_2) + A'(p_2)$$

- In typical dwarf galaxies

$$\Gamma^{\rm eff}_{A'} \approx 0.14{\rm Gyr}^{-1}\frac{F_\psi}{0.05}\left(\frac{g'}{10^{-12}}\right)^4\left(\frac{m_{A'}}{10^{-18}{\rm eV}}\right)^{-3}\left(\frac{m_\psi}{1{\rm GeV}}\right)^{-4}\times\left(\frac{v_{\rm rel}}{10{\rm km/s}}\right)\left(\frac{v_0}{10{\rm km/s}}\right)^{-3}\left(\frac{\rho_{\rm DM}}{0.1{\rm M_\odot/pc^3}}\right)^2$$



Summary

- For light DM (0.1-1)GeV to be detectable in both direct and indirect exp, model building is necessary.
- For ultralight bosonic DM, small scale problems can be solved .
    - e.g. dark atom laser emission

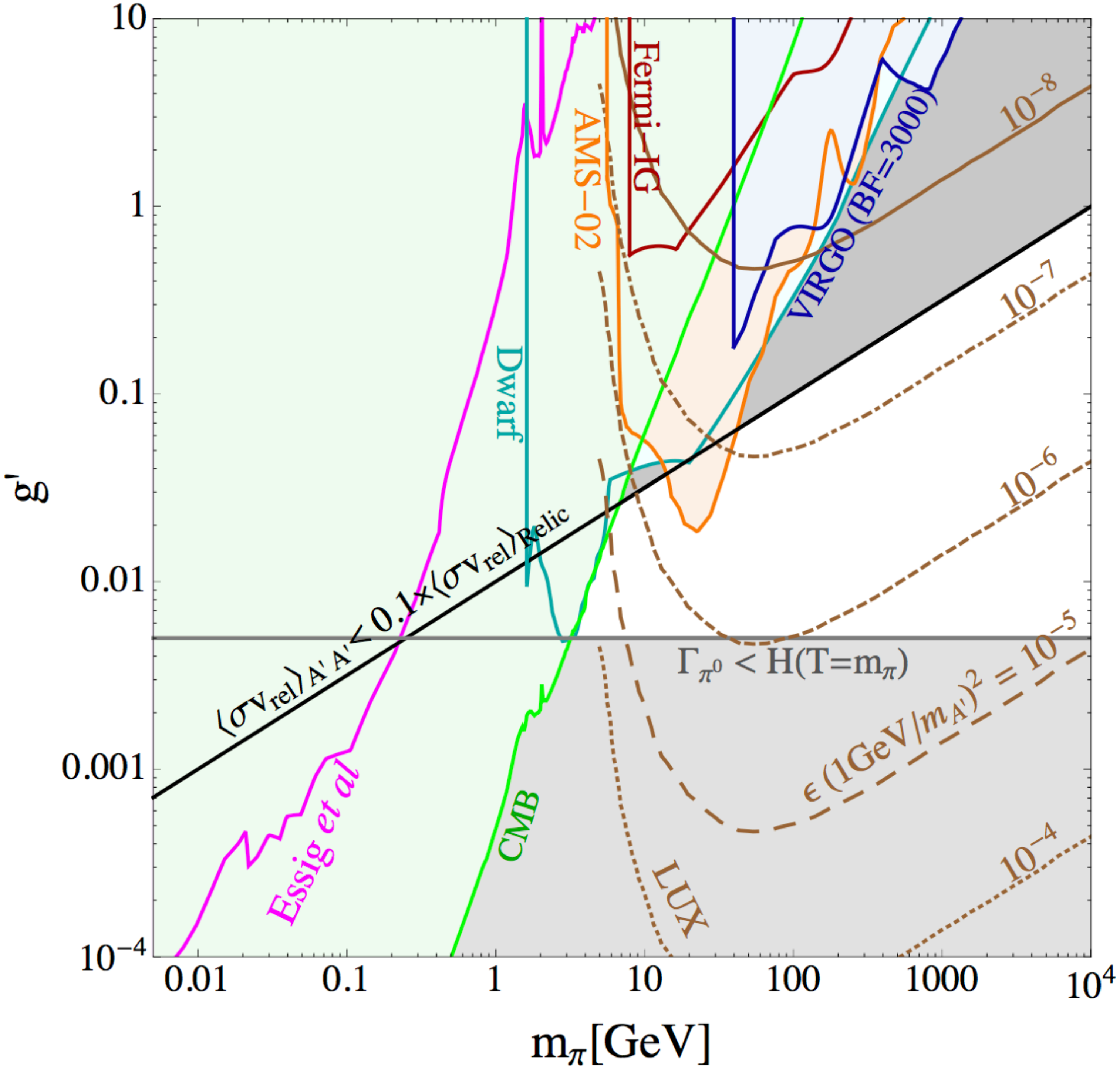
$$\psi(k_1) + A'(p_1) \to \psi^* \to \psi(k_2) + A'(p_2)$$

Thank you!

Thank you!

Backup slides

Dark pion model



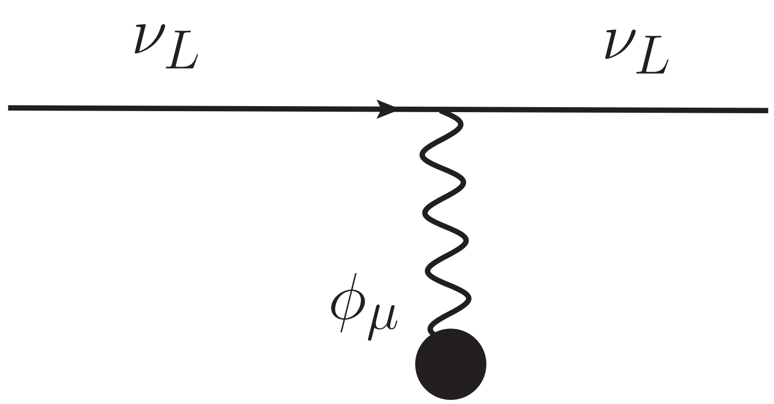
Neutrino oscillation in a dark matter medium

$$V_{\text{eff}} = -\frac{1}{2E_\nu}\left(2(p_\nu \cdot \phi) g Q + g^2 Q^2 \phi^2\right)$$

$$\phi_\mu = \xi_\mu \phi_0 \cos(m_\phi t)$$

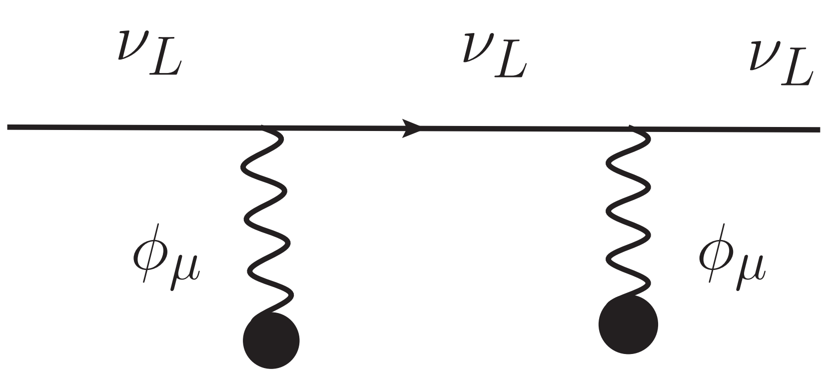
$$Q_{\mu-\tau} = 0, 1, -1$$

- Linear term (Classic = Quantum forward scattering):
  - Only for fully polarized vector DM



Full Hamiltonian

- Quadratic term (Classic = Quantum forward scattering): $H = V_{\text{vac}} + V_{\text{MSW}} + V_{\text{eff}}$
  - both fully polarized or unpolarized



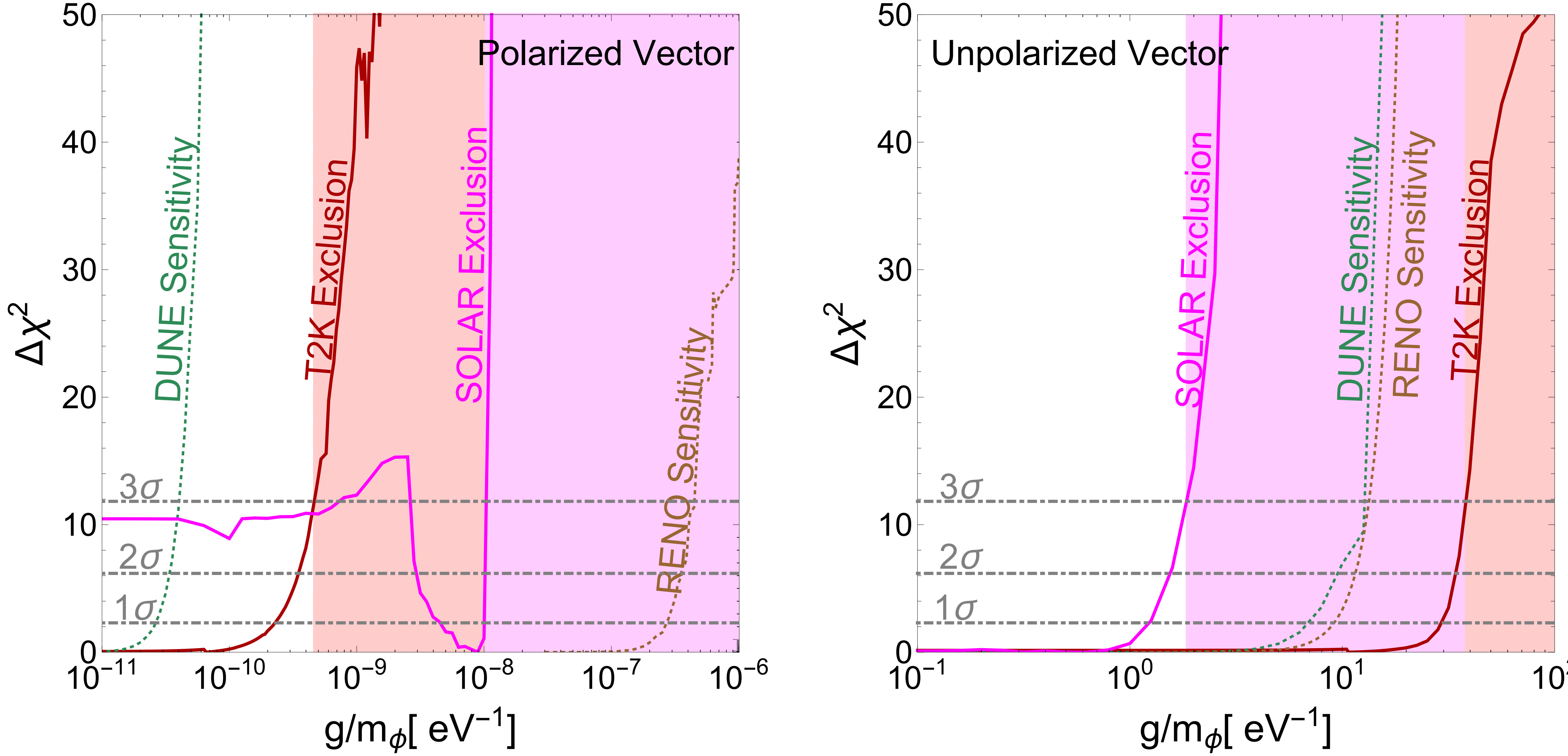
Solving Schrödinger equation

$$H_{\beta\alpha}|\alpha\rangle = i\partial_t|\beta\rangle$$

$$P_{\alpha\beta}(t) = |\langle\alpha(t)|\beta(0)\rangle|^2$$

Neutrino oscillation constraint on DM interaction

$$V_{\rm eff} = -\frac{1}{2E_\nu}\left(2(p_\nu\cdot\phi)gQ + g^2Q^2\phi^2\right)$$



- Constraint on coupling $g/m_{DM} < 10^{-9}$ (10^{0}) eV^{-1}

A' and ψ effective scattering rate

$$\psi(k_1) + A'(p_1) \to \psi(k_2) + A'(p_2)$$

- A' dominates relic abundance

$$\Gamma_{A'}^{\rm eff} \simeq \Gamma_{A'} \equiv \frac{C_{A'}}{\mathcal{N}_{A'}} \simeq n_\psi \langle \sigma v \rangle_{\psi A'} \langle \mathcal{N}^{A'} \rangle \left(\frac{m_{A'}}{m_\psi} \right)$$

Small A' mass

Final state Bose enhancement

Forward-backward cancellation

Scattering cross-section

$$\langle \sigma v \rangle_{\psi A'} \simeq \frac{g'^4 v_{\rm rel}}{4\pi m_\psi^2}$$

- Rate for ψ

$$\Gamma_\psi^{\rm eff} \simeq n_{A'} \langle \sigma v \rangle_{\psi A'} \langle \mathcal{N}^{A'} \rangle \frac{m_{A'}}{m_\psi} \frac{m_{A'}^2}{m_\psi^2}$$

Large ψ mass
Random walk factor

$$\Gamma_\psi^{\rm eff} \ll \Gamma_{A'}^{\rm eff}$$