LOW ENERGY AVENUES FOR SUB-MEV DARK MATTER SEARCHES

Angelo Esposito

SAPIENZA UNIVERSITÀ DI ROMA

INFN Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali di Frascati, Sept. 18th 2024

OUTLINE

OUTLINE

- Searching for light dark matter:
    - challenges and opportunities
    - intro to spontaneously broken spacetime symmetries

OUTLINE

- Searching for light dark matter:
  - challenges and opportunities
  - intro to spontaneously broken spacetime symmetries
- Ideas for sub-MeV dark matter detection:
  - superfluid He-4
  - anti-ferromagnets

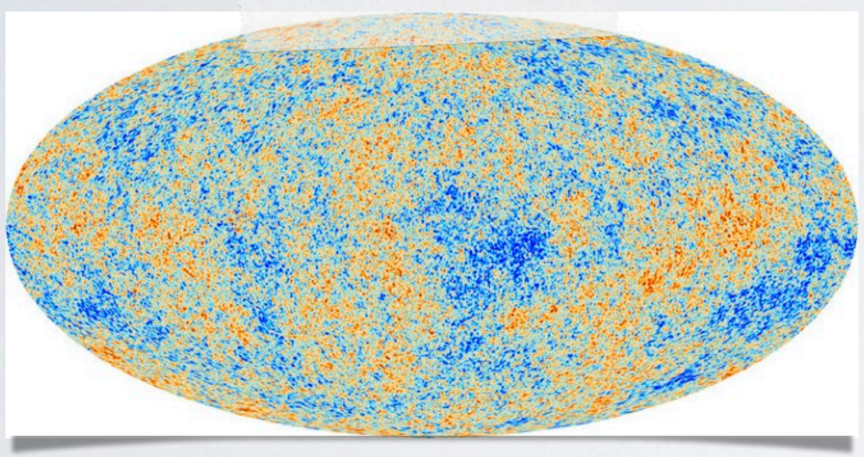
OUTLINE

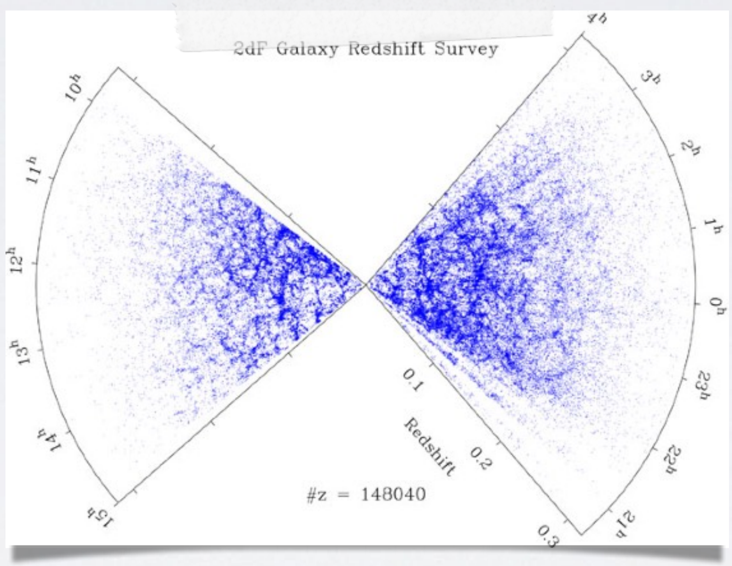
- Searching for light dark matter:
  - challenges and opportunities
  - intro to spontaneously broken spacetime symmetries
- Ideas for sub-MeV dark matter detection:
  - superfluid He-4
  - anti-ferromagnets
- Outlook

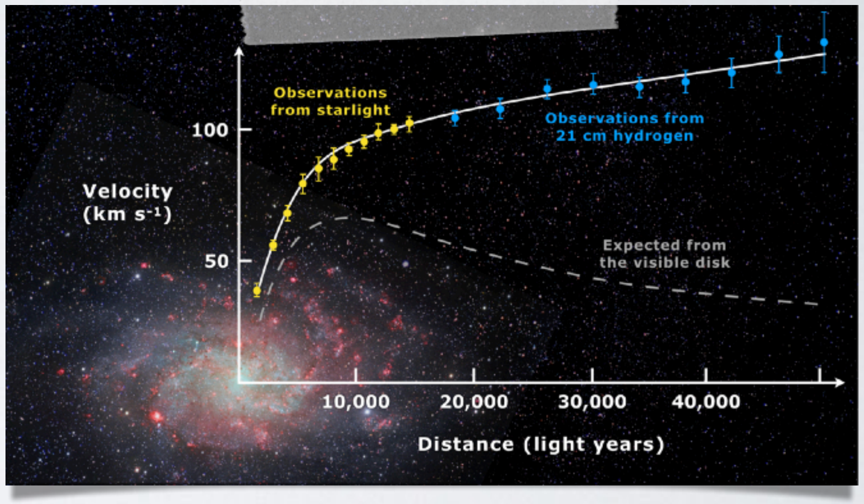
SUB-MEV DARK MATTER

SUB-MEV DARK MATTER

- Most of the matter ($\sim 80\,\%$) that interacts gravitationally is dark

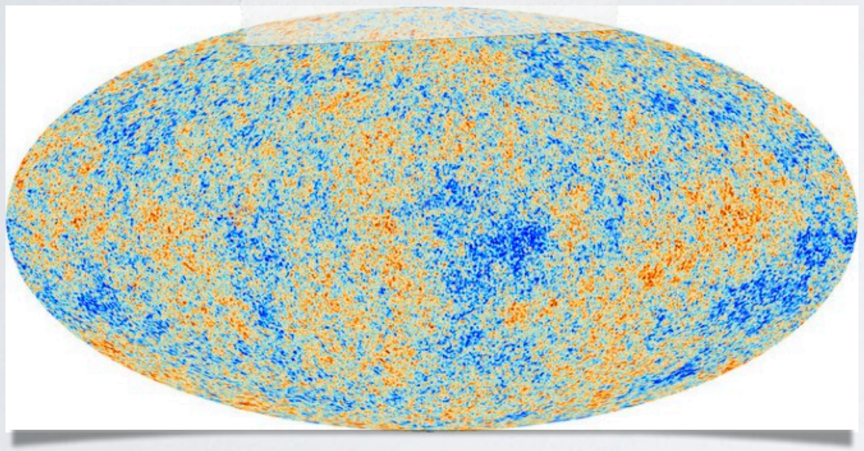


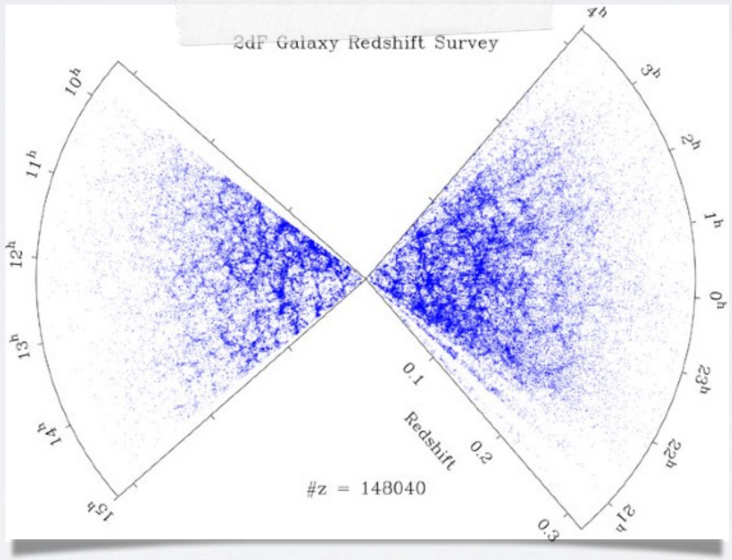


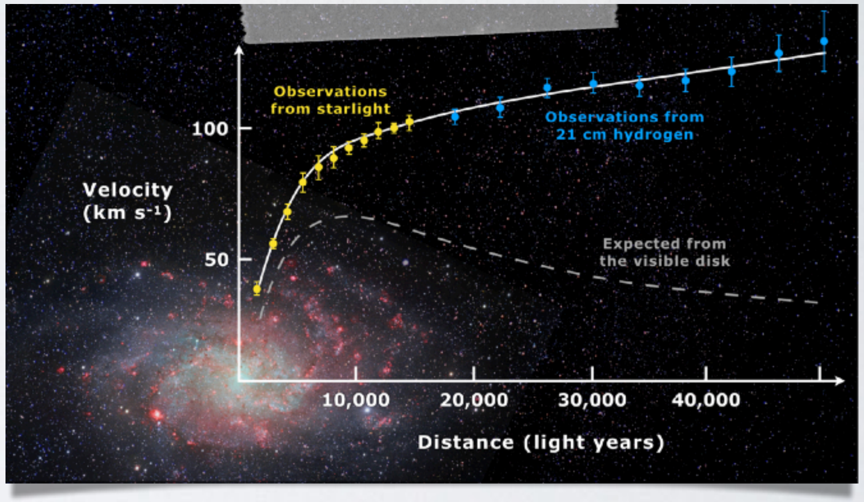


SUB-MEV DARK MATTER

- Most of the matter ($\sim 80\,\%$) that interacts gravitationally is dark



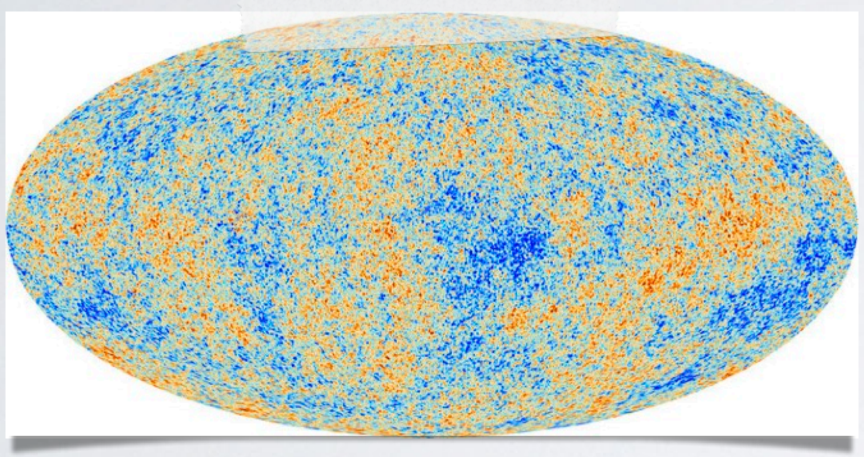


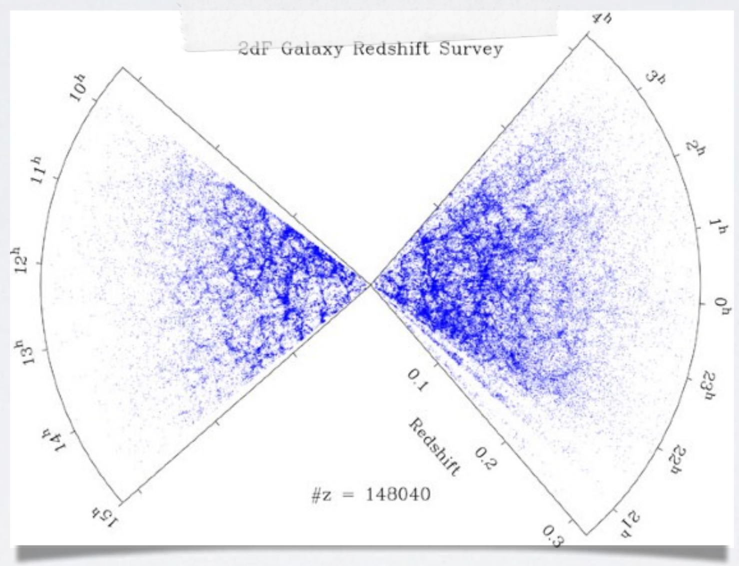


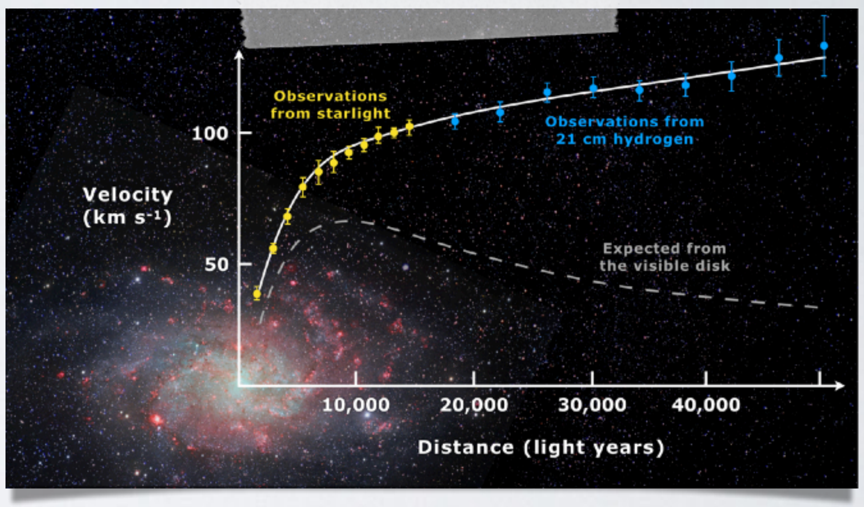
- One of the strongest evidences for physics beyond the Standard Model

SUB-MEV DARK MATTER

- Most of the matter ($\sim 80\,\%$) that interacts gravitationally is dark





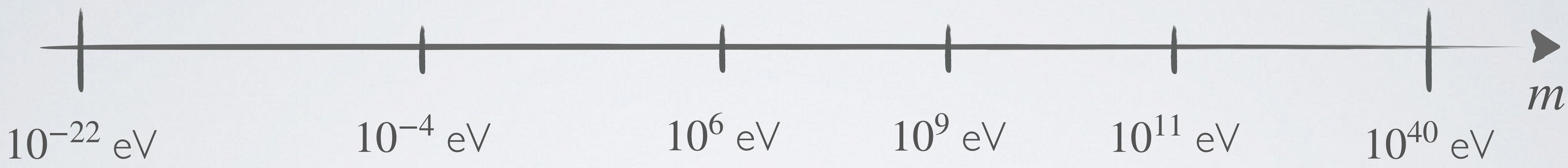


- One of the strongest evidences for physics beyond the Standard Model

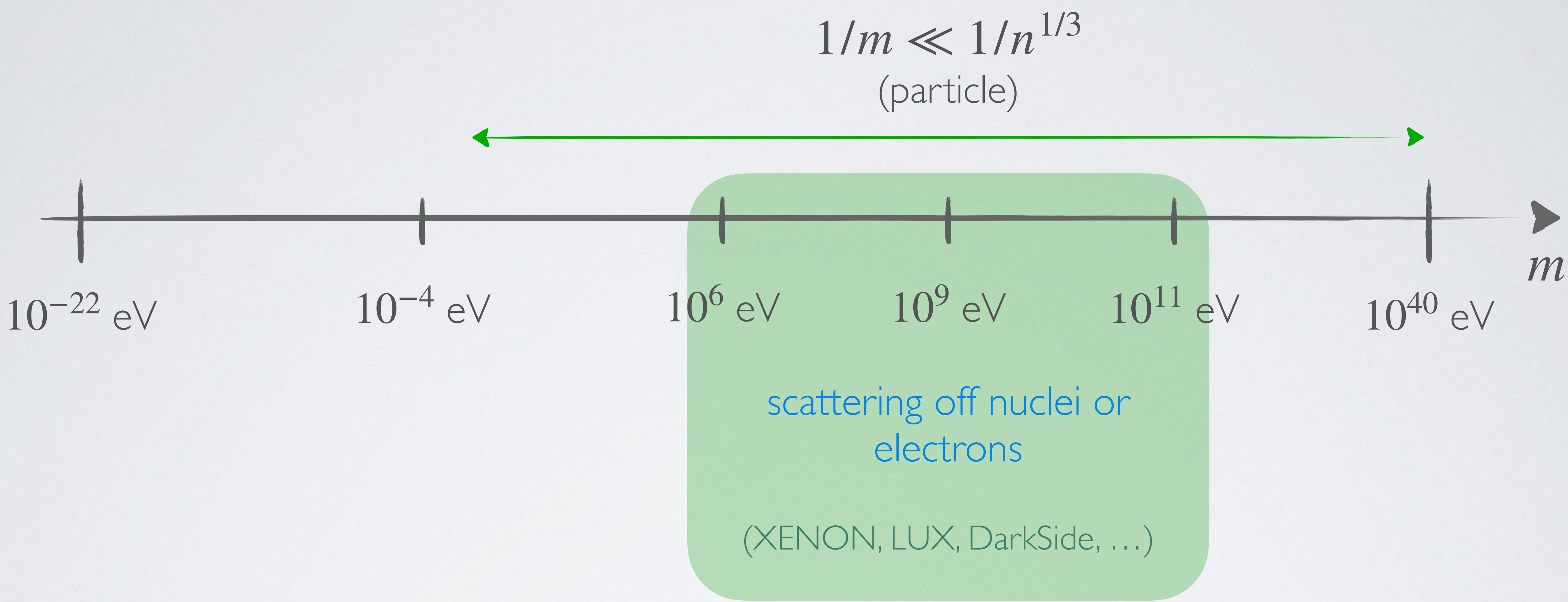
- However… huge possible mass range → detection techniques vary widely depending on the dark matter mass

SUB-MEV DARK MATTER

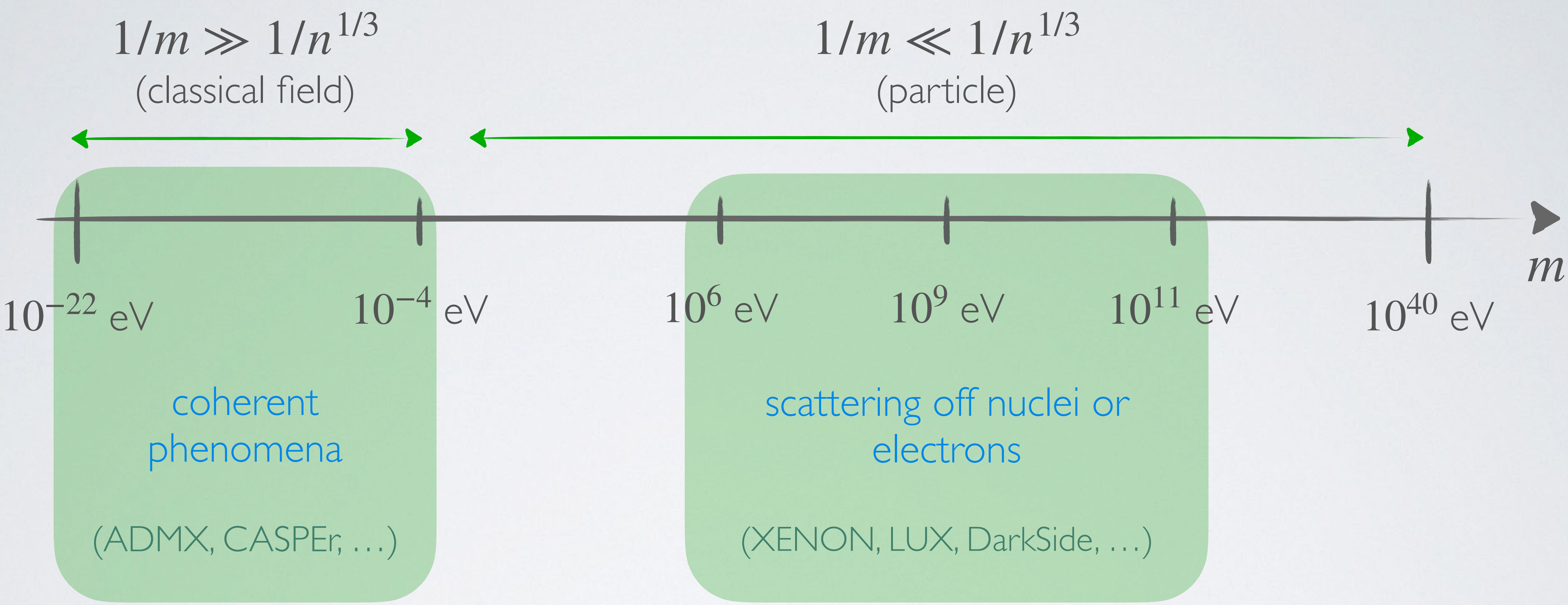
SUB-MEV DARK MATTER



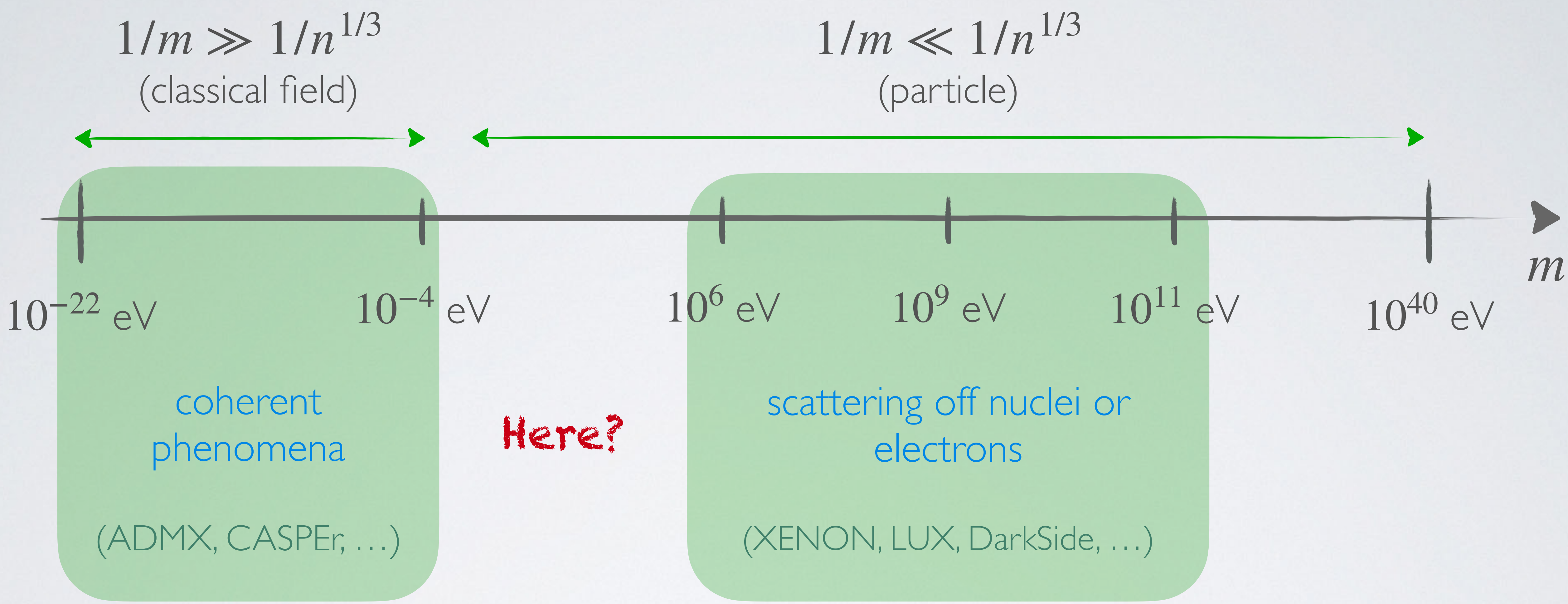
SUB-MEV DARK MATTER



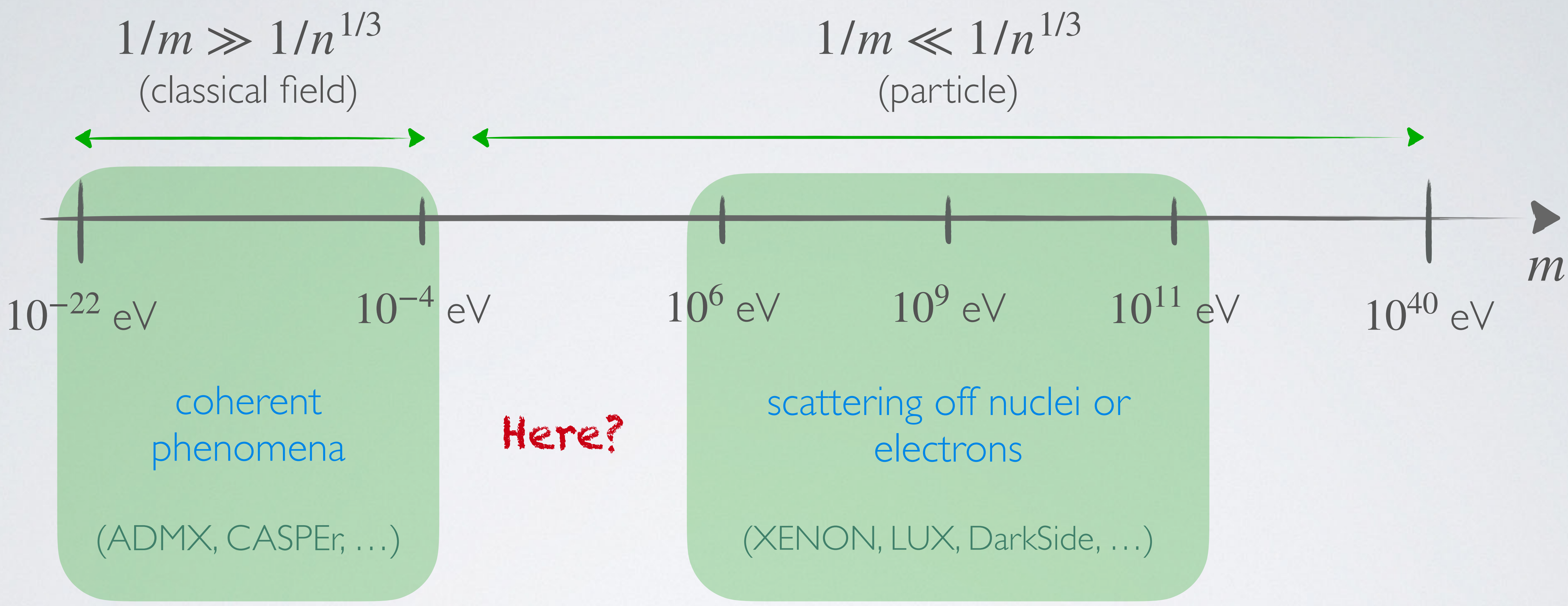
SUB-MEV DARK MATTER



SUB-MEV DARK MATTER

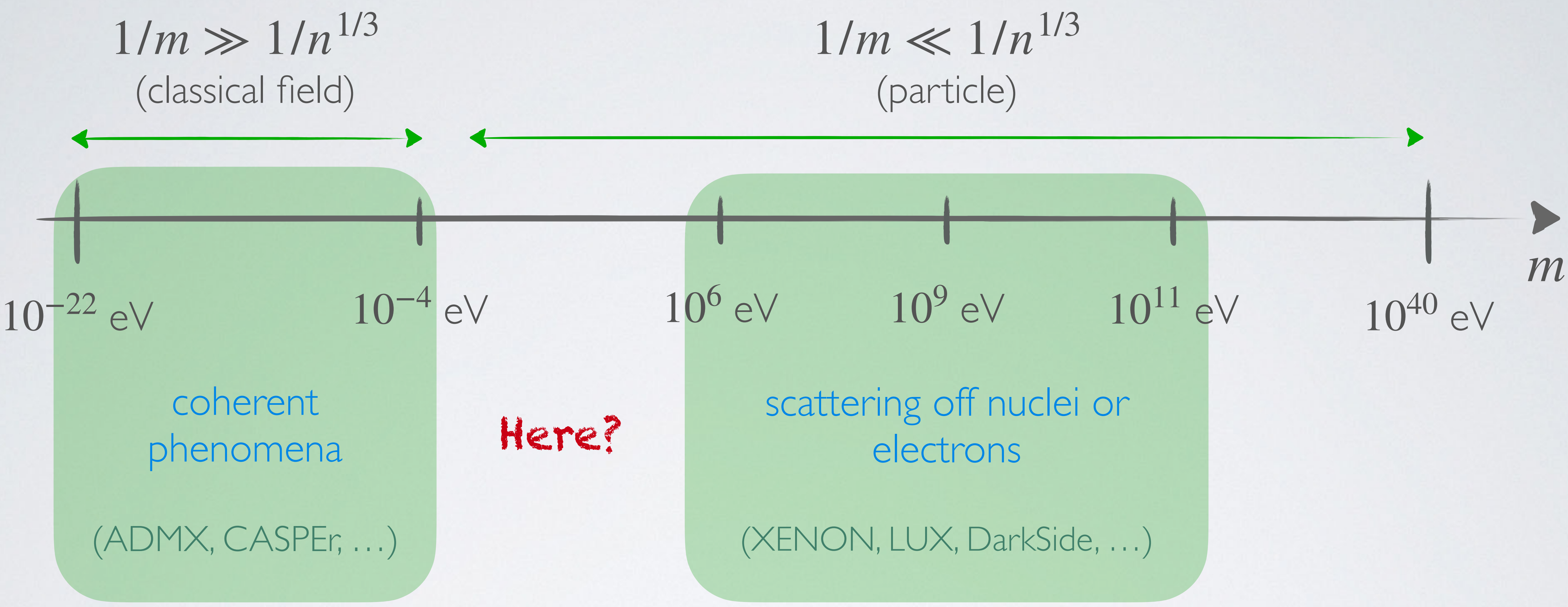


SUB-MEV DARK MATTER



- Dark matter is a particle but too light for elastic recoil

SUB-MEV DARK MATTER



- Dark matter is a particle but too light for elastic recoil
- Need new materials and/or observables

SUB-MEV DARK MATTER

SUB-MEV DARK MATTER

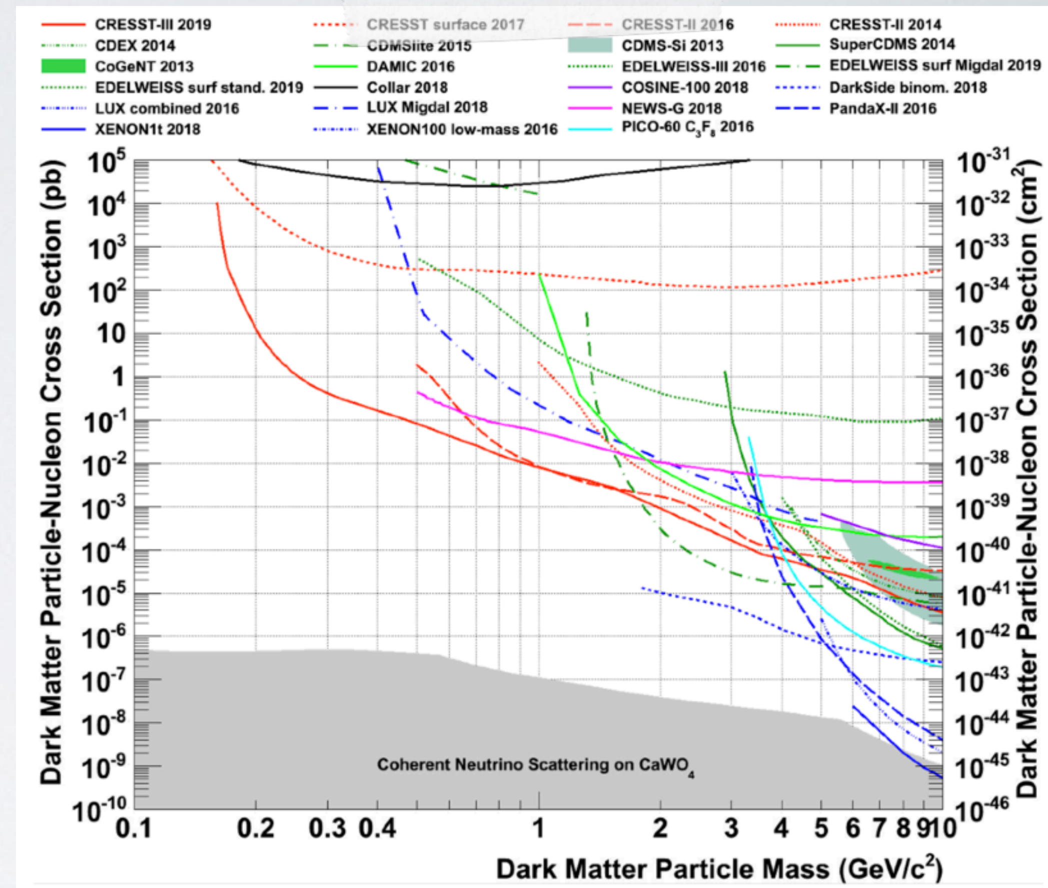
- For an elastic scattering

$$E_{\mathrm{T}} = \frac{m_\chi/m_{\mathrm{T}}}{(1+m_\chi/m_{\mathrm{T}})^2} E_\chi \gtrsim E_{\mathrm{threshold}}$$

SUB-MEV DARK MATTER

- For an elastic scattering

$$E_{\mathrm{T}} = \frac{m_\chi/m_{\mathrm{T}}}{(1+m_\chi/m_{\mathrm{T}})^2} E_\chi \gtrsim E_{\mathrm{threshold}}$$



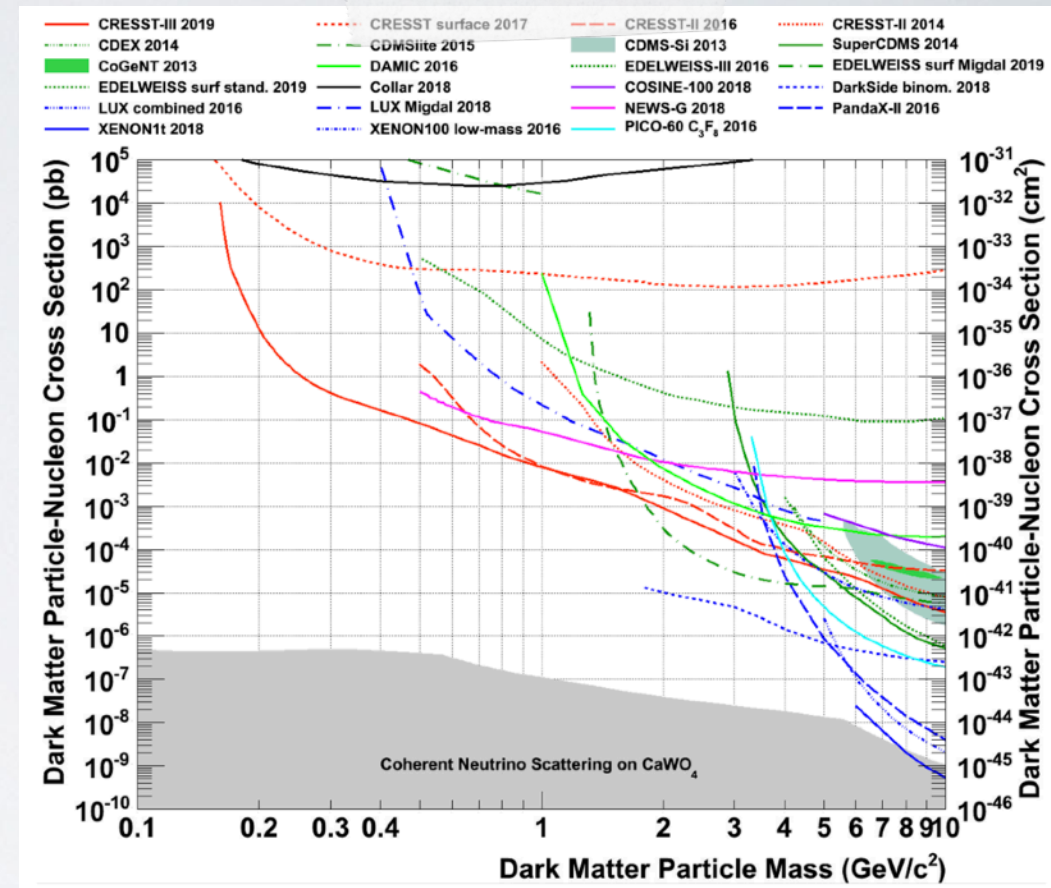
[CRESST — PRD 2019, 1904.00498]

- For $m_\chi \lesssim 1$ MeV elastic scattering off nuclei or electrons is very inefficient

SUB-MEV DARK MATTER

- For an elastic scattering

$$E_{\mathrm{T}} = \frac{m_\chi / m_{\mathrm{T}}}{(1 + m_\chi / m_{\mathrm{T}})^2} E_\chi \gtrsim E_{\mathrm{threshold}}$$



[CRESST — PRD 2019, 1904.00498]

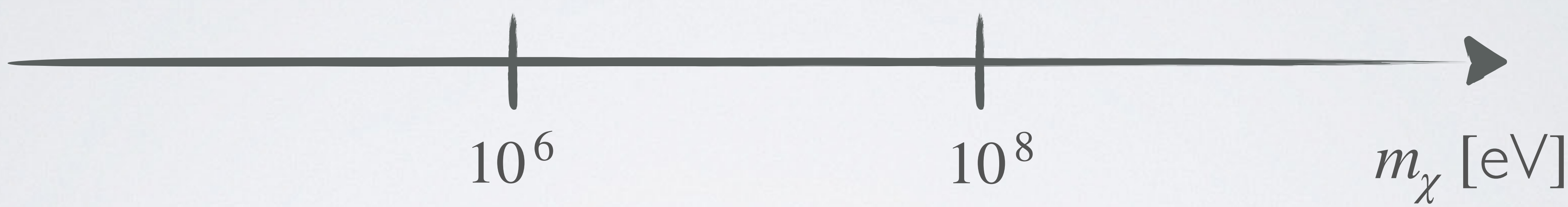
- For $m_\chi \lesssim 1$ MeV elastic scattering off nuclei or electrons is very inefficient

- To evade this we must look into inelastic processes → one possibility are collective excitations

NASTY STUFF

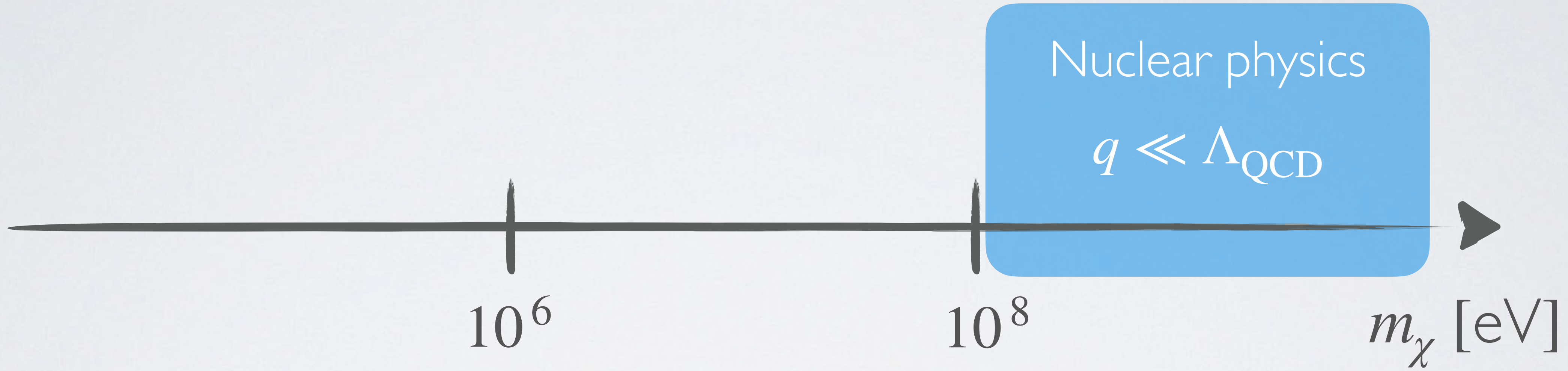
NASTY STUFF

- For light dark matter one needs to delve into condensed matter



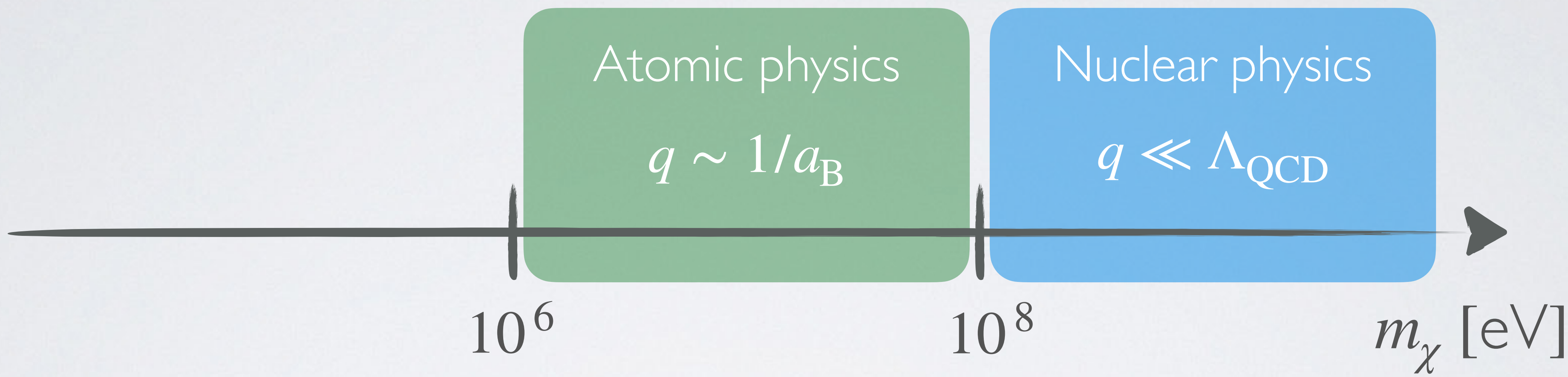
NASTY STUFF

- For light dark matter one needs to delve into condensed matter



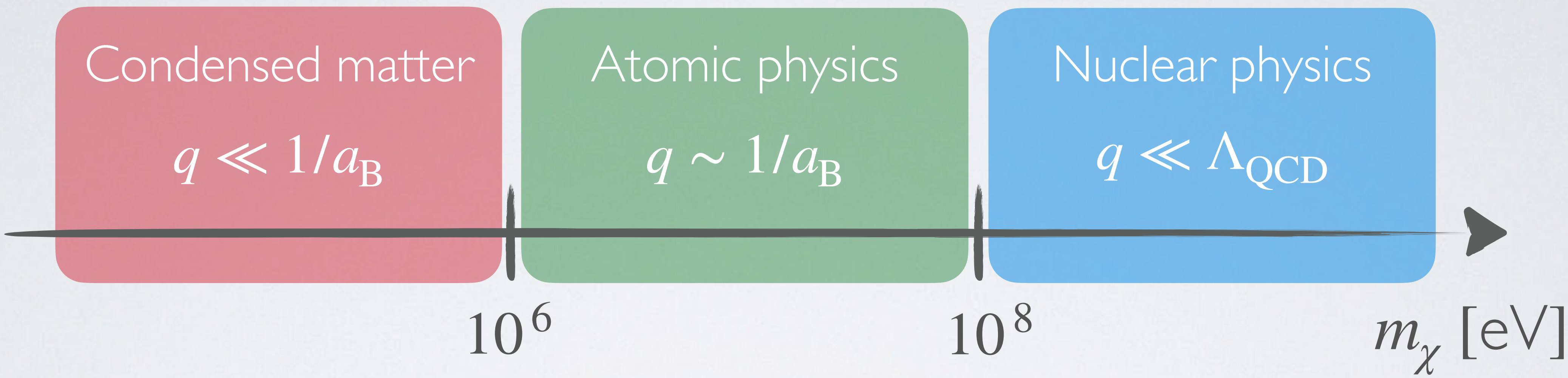
NASTY STUFF

- For light dark matter one needs to delve into condensed matter



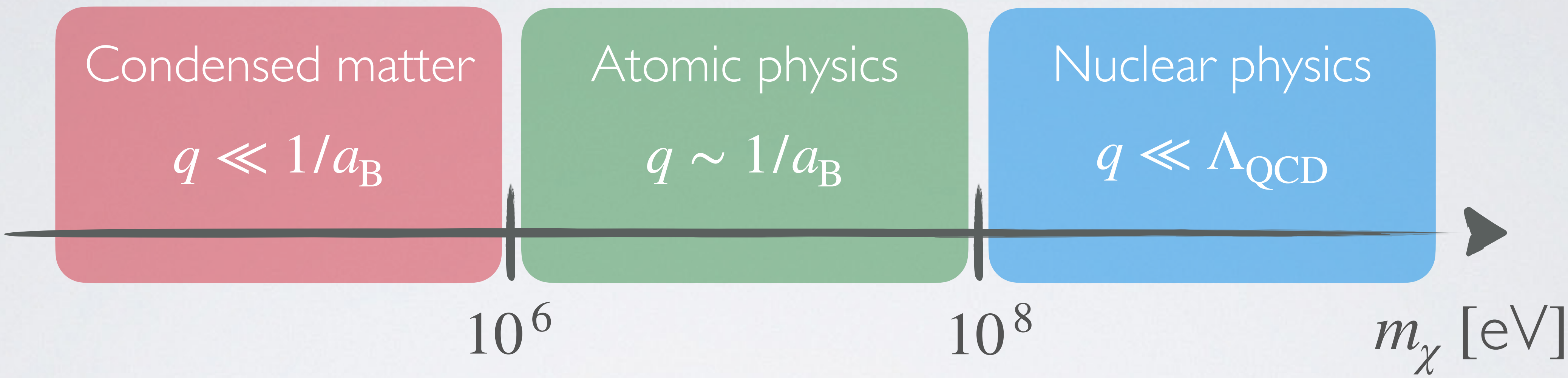
NASTY STUFF

- For light dark matter one needs to delve into condensed matter



NASTY STUFF

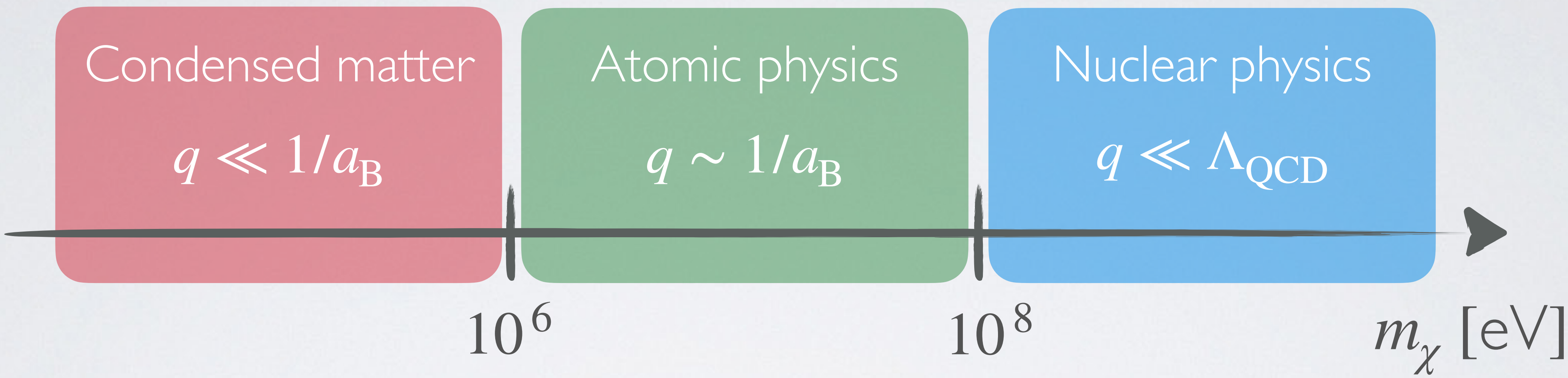
- For light dark matter one needs to delve into condensed matter



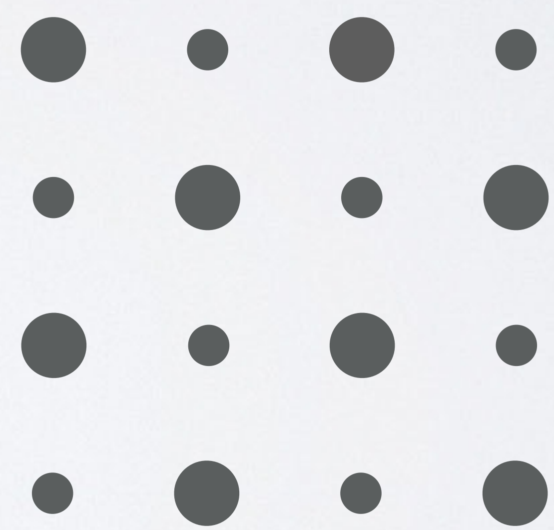
- Must account for the complicated many-body physics (correlations, strong coupling, …)

NASTY STUFF

- For light dark matter one needs to delve into condensed matter

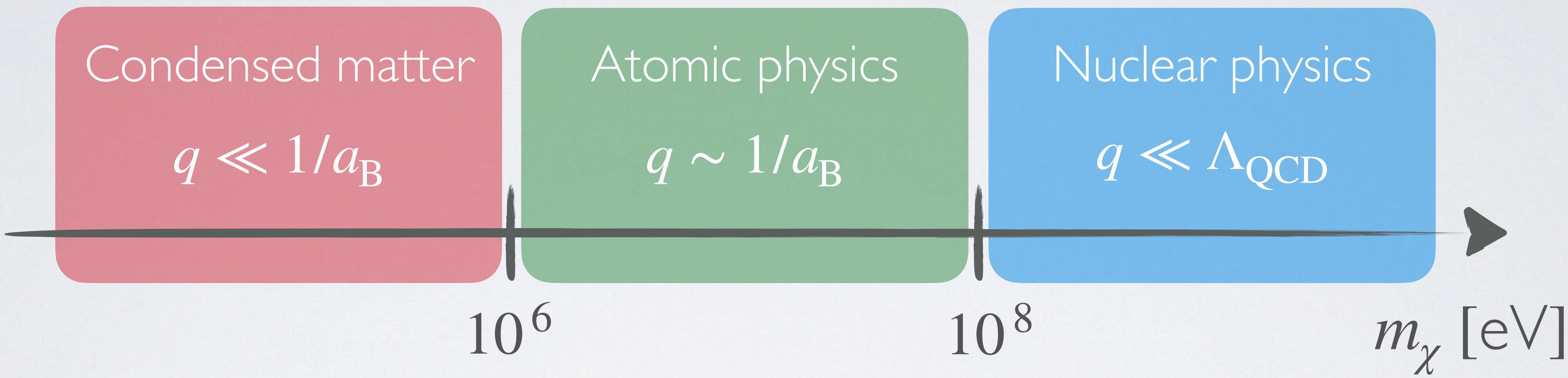


- Must account for the complicated many-body physics (correlations, strong coupling, …)

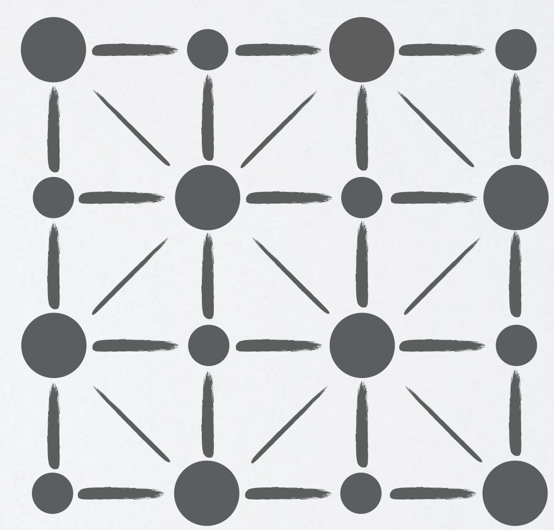


NASTY STUFF

- For light dark matter one needs to delve into condensed matter

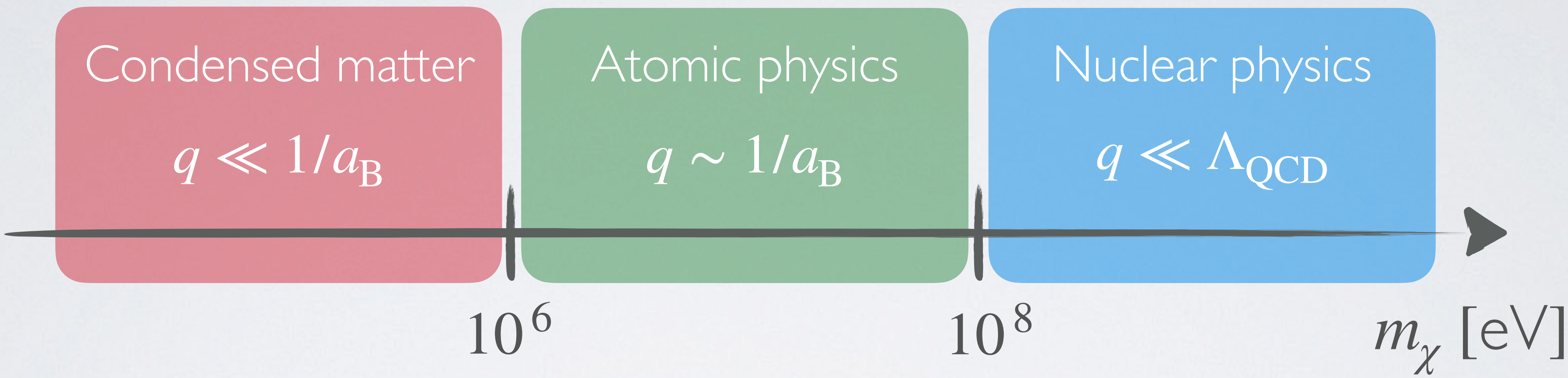


- Must account for the complicated many-body physics (correlations, strong coupling, …)

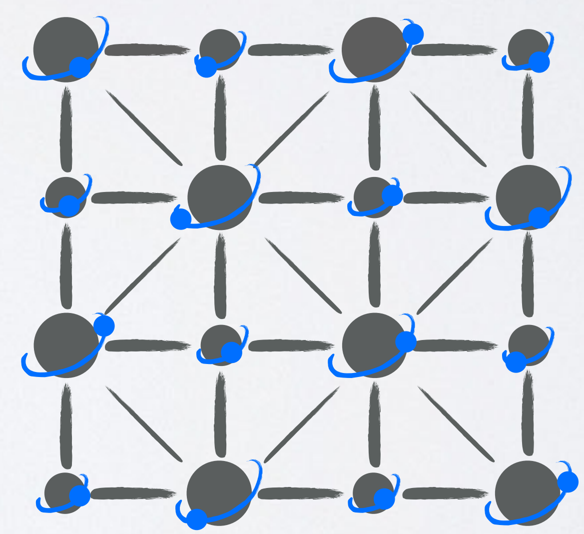


NASTY STUFF

- For light dark matter one needs to delve into condensed matter

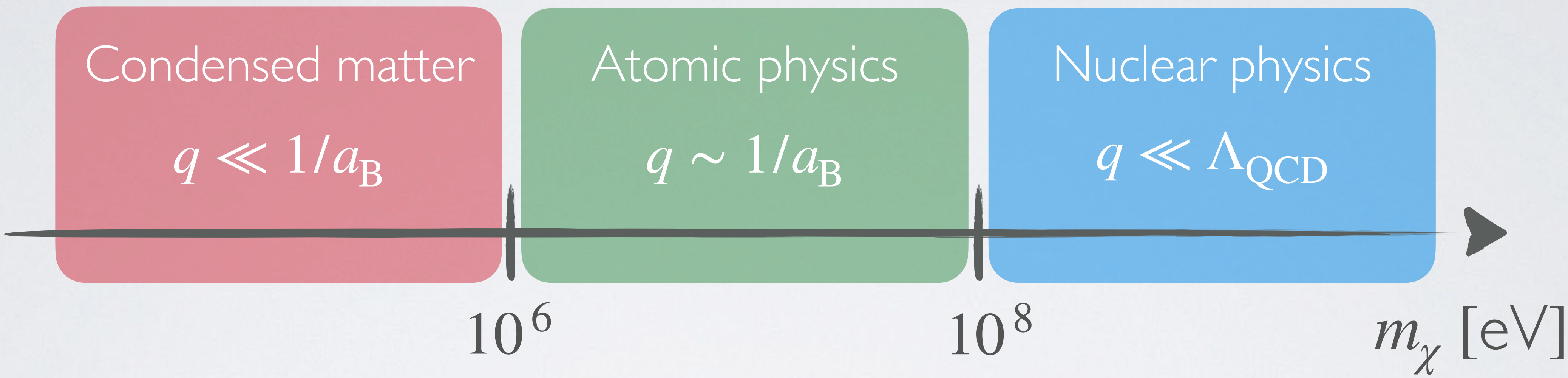


- Must account for the complicated many-body physics (correlations, strong coupling, …)

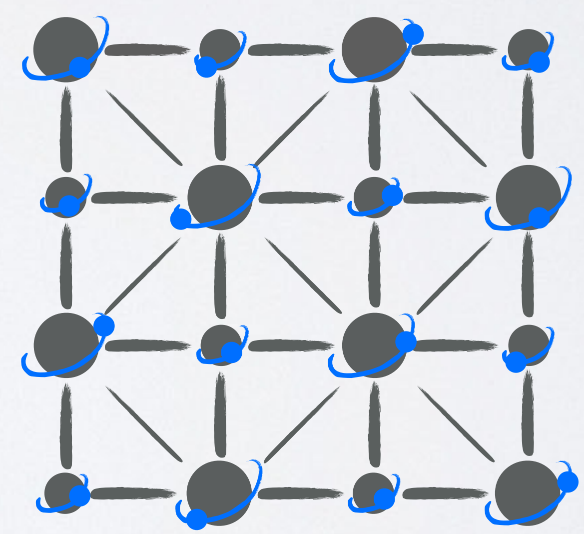


NASTY STUFF

- For light dark matter one needs to delve into condensed matter



- Must account for the complicated many-body physics (correlations, strong coupling, …)



- Need theoretical tools that allow to solve or bypass these problems

COLLECTIVE MODES IN HEP

COLLECTIVE MODES IN HEP

- All phases of matter spontaneously break spacetime and (maybe) internal symmetries

COLLECTIVE MODES IN HEP

- All phases of matter spontaneously break spacetime and (maybe) internal symmetries

Goldstone's theorem

Spontaneous symm. breaking $\longleftrightarrow$ existence of soft modes

COLLECTIVE MODES IN HEP

- All phases of matter spontaneously break spacetime and (maybe) internal symmetries

Goldstone's theorem

Spontaneous symm. breaking $\longleftrightarrow$ existence of soft modes

- At low energies the system can be described by an EFT for Goldstones, systematically organized in a derivative expansion

$$\mathscr{L}_{\mathrm{EFT}}[\pi, \partial] \sim \sum_{n,m} g_{n,m} \partial^n \pi^m$$

COLLECTIVE MODES IN HEP

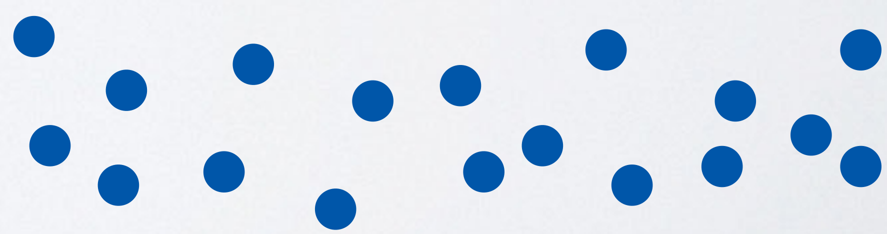
- All phases of matter spontaneously break spacetime and (maybe) internal symmetries

Goldstone's theorem

Spontaneous symm. breaking $\longleftrightarrow$ existence of soft modes

- At low energies the system can be described by an EFT for Goldstones, systematically organized in a derivative expansion

$$\mathscr{L}_{\text{EFT}}[\pi, \partial] \sim \sum_{n,m} g_{n,m} \partial^n \pi^m$$



COLLECTIVE MODES IN HEP

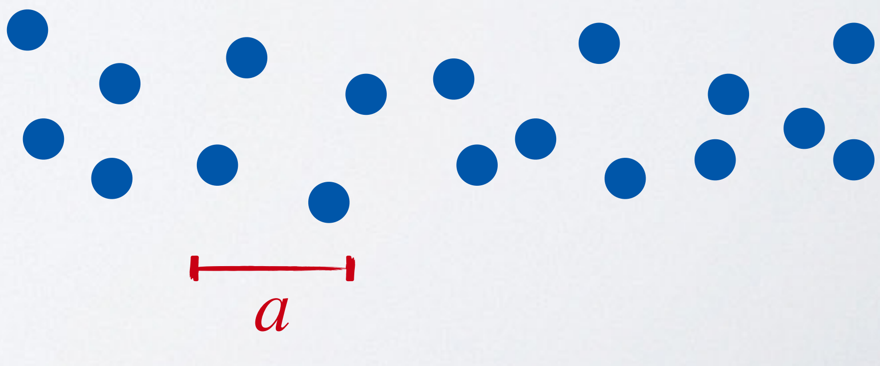
- All phases of matter spontaneously break spacetime and (maybe) internal symmetries

Goldstone's theorem

Spontaneous symm. breaking $\longleftrightarrow$ existence of soft modes

- At low energies the system can be described by an EFT for Goldstones, systematically organized in a derivative expansion

$$\mathscr{L}_{\text{EFT}}[\pi, \partial] \sim \sum_{n,m} g_{n,m} \partial^n \pi^m$$



COLLECTIVE MODES IN HEP

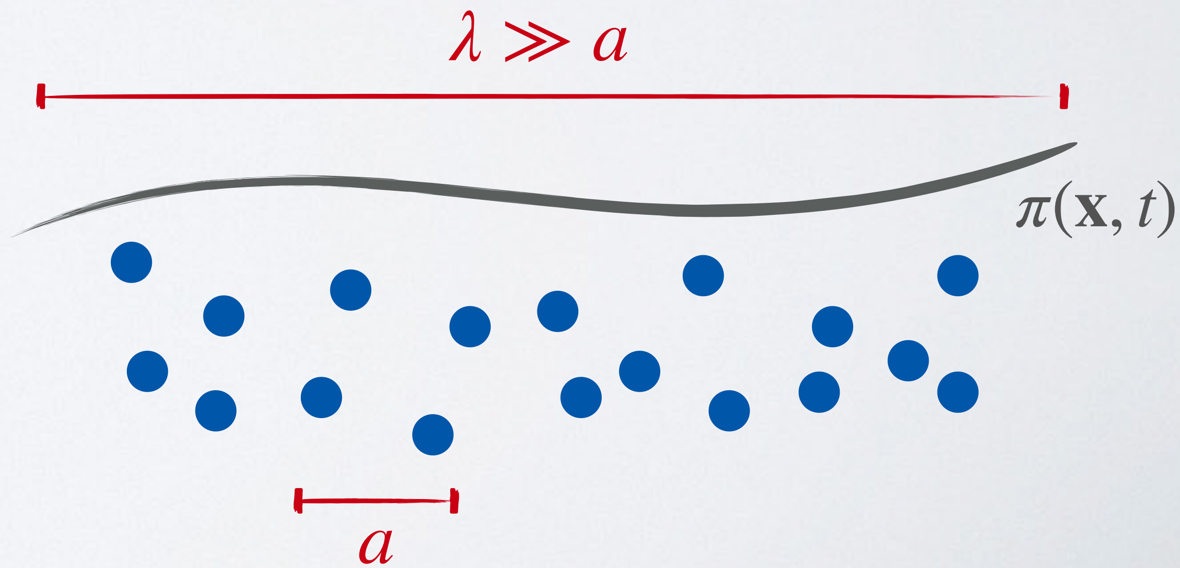
- All phases of matter spontaneously break spacetime and (maybe) internal symmetries

Goldstone's theorem

Spontaneous symm. breaking $\longleftrightarrow$ existence of soft modes

- At low energies the system can be described by an EFT for Goldstones, systematically organized in a derivative expansion

$$\mathscr{L}_{\rm EFT}[\pi, \partial] \sim \sum_{n,m} g_{n,m} \partial^n \pi^m$$



COLLECTIVE MODES IN HEP

- All phases of matter spontaneously break spacetime and (maybe) internal symmetries

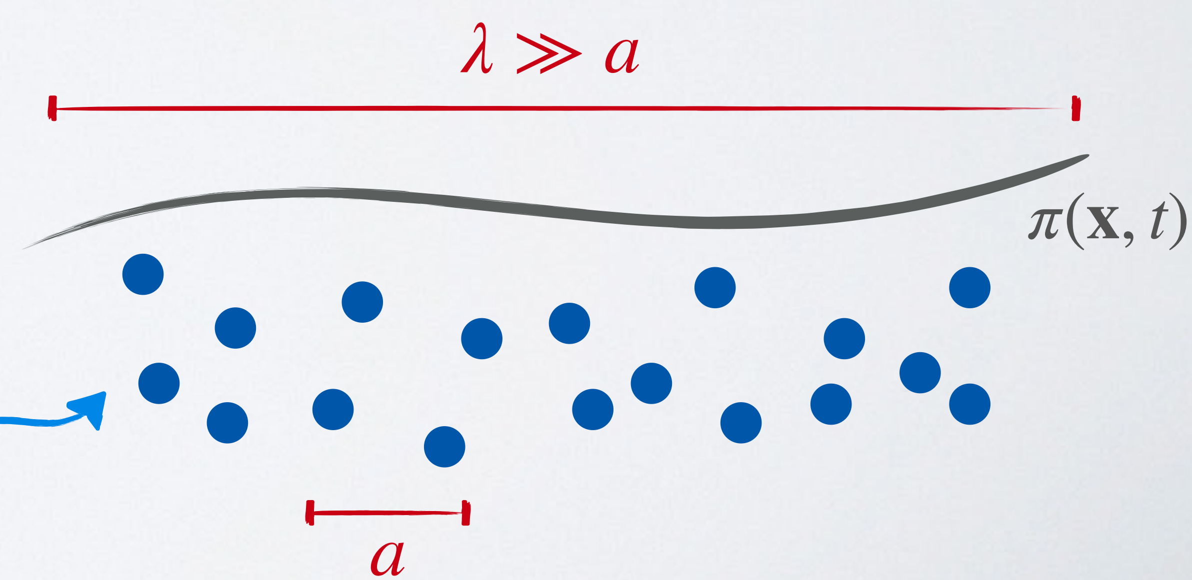
Goldstone's theorem

Spontaneous symm. breaking $\longleftrightarrow$ existence of soft modes

- At low energies the system can be described by an EFT for Goldstones, systematically organized in a derivative expansion

$$\mathscr{L}_{\text{EFT}}[\pi, \partial] \sim \sum_{n,m} g_{n,m} \partial^n \pi^m$$

complicated microscopic physics encoded here



COLLECTIVE MODES IN HEP

COLLECTIVE MODES IN HEP

- Goldstone's theorem for spontaneously broken spacetime symmetries is less constraining

COLLECTIVE MODES IN HEP

- Goldstone's theorem for spontaneously broken spacetime symmetries is less constraining

Unbroken spacetime symm.	Broken spacetime symm.
$\text{num}(\pi) = \text{dim}(G/H)$	$\text{num}(\pi) \leq \text{dim}(G/H)$
$\omega(\mathbf{q}) = \|\mathbf{q}\|$	$\omega(\mathbf{q}) \neq \|\mathbf{q}\|$
Manifest Poincaré invariance	Non-manifest Poincaré invariance

COLLECTIVE MODES IN HEP

- Goldstone's theorem for spontaneously broken spacetime symmetries is less constraining

Unbroken spacetime symm.	Broken spacetime symm.
num(π) = dim(G/H)	num(π) $\leq$ dim(G/H)
$\omega(\mathbf{q}) = \lvert\mathbf{q}\rvert$	$\omega(\mathbf{q}) \neq \lvert\mathbf{q}\rvert$
Manifest Poincaré invariance	Non-manifest Poincaré invariance

- Simple example: string in 2D

COLLECTIVE MODES IN HEP

- Goldstone's theorem for spontaneously broken spacetime symmetries is less constraining

Unbroken spacetime symm.	Broken spacetime symm.
$\text{num}(\pi) = \dim(G/H)$	$\text{num}(\pi) \leq \dim(G/H)$
$\omega(\mathbf{q}) = \lvert \mathbf{q} \rvert$	$\omega(\mathbf{q}) \neq \lvert \mathbf{q} \rvert$
Manifest Poincaré invariance	Non-manifest Poincaré invariance

- Simple example: string in 2D

COLLECTIVE MODES IN HEP

- Goldstone's theorem for spontaneously broken spacetime symmetries is less constraining

Unbroken spacetime symm.	Broken spacetime symm.
$\text{num}(\pi) = \text{dim}(G/H)$	$\text{num}(\pi) \leq \text{dim}(G/H)$
$\omega(\mathbf{q}) = \lvert\mathbf{q}\rvert$	$\omega(\mathbf{q}) \neq \lvert\mathbf{q}\rvert$
Manifest Poincaré invariance	Non-manifest Poincaré invariance

- Simple example: string in 2D

3 broken generators:

$K_\perp, P_\perp, J$

COLLECTIVE MODES IN HEP

- Goldstone's theorem for spontaneously broken spacetime symmetries is less constraining

Unbroken spacetime symm.	Broken spacetime symm.
num(π) = dim(G/H)	num$(\pi) \leq$ dim(G/H)
$\omega(\mathbf{q}) = \lvert\mathbf{q}\rvert$	$\omega(\mathbf{q}) \neq \lvert\mathbf{q}\rvert$
Manifest Poincaré invariance	Non-manifest Poincaré invariance

- Simple example: string in 2D

3 broken generators:

$K_\perp, P_\perp, J$

COLLECTIVE MODES IN HEP

- Goldstone's theorem for spontaneously broken spacetime symmetries is less constraining

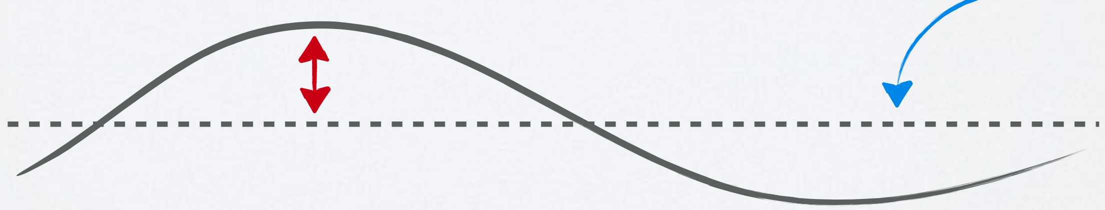
Unbroken spacetime symm.	Broken spacetime symm.
$\text{num}(\pi) = \dim(G/H)$	$\text{num}(\pi) \leq \dim(G/H)$
$\omega(\mathbf{q}) = \lvert\mathbf{q}\rvert$	$\omega(\mathbf{q}) \neq \lvert\mathbf{q}\rvert$
Manifest Poincaré invariance	Non-manifest Poincaré invariance

- Simple example: string in 2D

only one Goldstone:

$$\omega(\mathbf{q}) = c_s \lvert\mathbf{q}\rvert$$

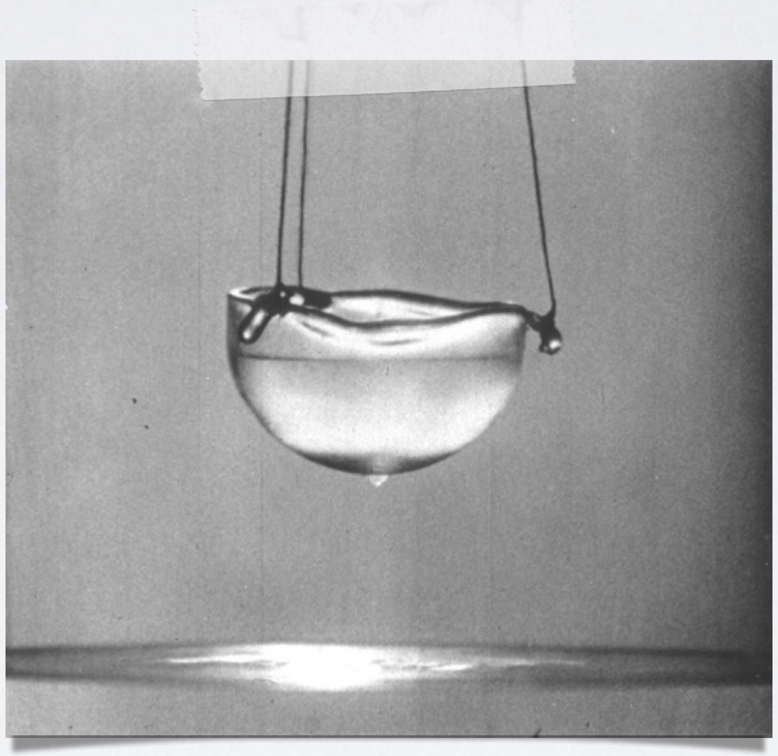
$\delta x_\perp(x_{\parallel}, t)$



3 broken generators:

$K_\perp, P_\perp, J$

Superfluid ^{4}He



[w/ Acanforta, Caputo, Geoffray, Piccinini, Polosa, Rossi, Sun]

SUPERFLUID ^{4}He

SUPERFLUID ^{4}He

- Superfluid ^{4}He is an interesting target to probe dark matter with *spin-independent* interactions

SUPERFLUID ^{4}He

- Superfluid ^{4}He is an interesting target to probe dark matter with *spin-independent* interactions

    1. $E_{\text{ionization}} \simeq 25$ eV $\rightarrow$ low electronic background

SUPERFLUID ^{4}He

- Superfluid ^{4}He is an interesting target to probe dark matter with *spin-independent* interactions

  1. $E_{\text{ionization}} \simeq 25$ eV $\rightarrow$ low electronic background
  2. High radiopurity

SUPERFLUID ^{4}He

- Superfluid ^{4}He is an interesting target to probe dark matter with *spin-independent* interactions

  1. $E_{\text{ionization}} \simeq 25$ eV $\longrightarrow$ low electronic background
  2. High radiopurity
  3. Multi-phonon processes allow to probe down to $m_\chi \sim \mathcal{O}(\text{keV})$

SUPERFLUID ^{4}He

- Superfluid ^{4}He is an interesting target to probe dark matter with *spin-independent* interactions

  1. $E_{\rm ionization} \simeq 25$ eV $\longrightarrow$ low electronic background
  2. High radiopurity
  3. Multi-phonon processes allow to probe down to $m_\chi \sim \mathcal{O}(\text{keV})$

- Idea: look for events where the dark matter produces more than one phonon

[Guo, McKinsey – PRD 2013, 1302.0534; Schutz, Zurek – PRL 2016, 1604.08206; Knapen, Lin, Zurek – PRD 2017, 1611.06228; Acanfora, **AE**, Polosa – EPJC 2019, 1902.02361; Caputo, **AE**, Polosa – PRD 2019, 1907.10635; Baym et al. – PRD 2021, 2005.08824; Caputo, **AE**, Piccini, Polosa, Rossi – PRD 2021, 2012.01432; Matchev et al. – JHEP 2022, 2108.07275; You et al. – 2208.14474]

SUPERFLUID ^{4}He

- Superfluid ^{4}He is an interesting target to probe dark matter with *spin-independent* interactions
    1. $E_{\text{ionization}} \simeq 25$ eV $\longrightarrow$ low electronic background
    2. High radiopurity
    3. Multi-phonon processes allow to probe down to $m_\chi \sim \mathcal{O}(\text{keV})$

- Idea: look for events where the dark matter produces more than one phonon

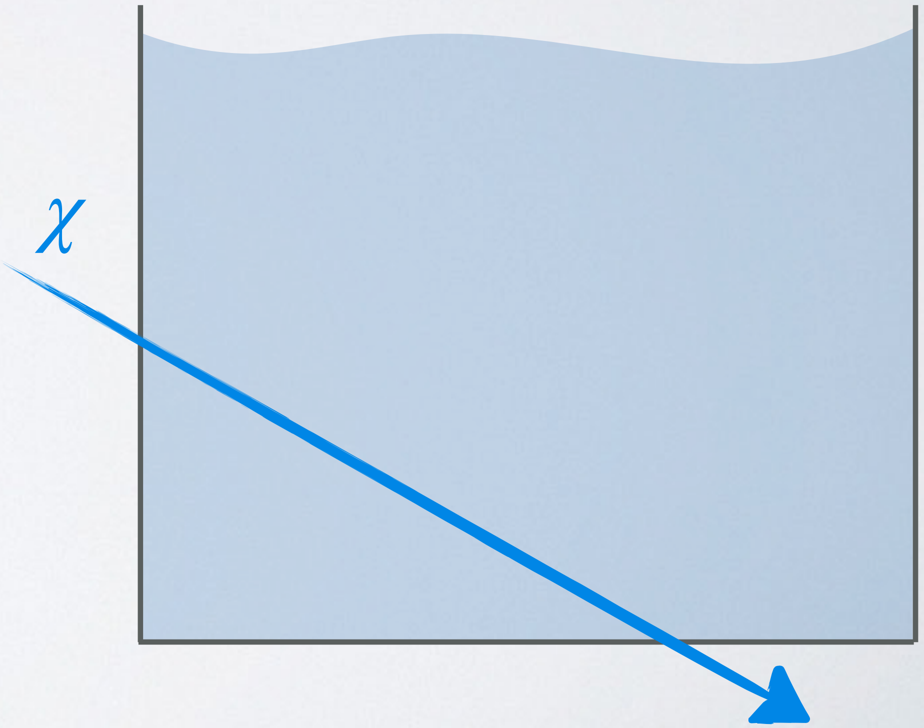
[Guo, McKinsey — PRD 2013, 1302.0534; Schutz, Zurek — PRL 2016, 1604.08206; Knapen, Lin, Zurek — PRD 2017, 1611.06228; Acanfora, **AE**, Polosa — EPJC 2019, 1902.02361; Caputo, **AE**, Polosa — PRD 2019, 1907.10635; Baym et al. — PRD 2021, 2005.08824; Caputo, **AE**, Piccini, Polosa, Rossi — PRD 2021, 2012.01432; Matchev et al. — JHEP 2022, 2108.07275; You et al. — 2208.14474]

SUPERFLUID ^{4}He

- Superfluid ^{4}He is an interesting target to probe dark matter with *spin-independent* interactions

    1. $E_{\text{ionization}} \simeq 25$ eV $\longrightarrow$ low electronic background
    2. High radiopurity
    3. Multi-phonon processes allow to probe down to $m_\chi \sim \mathcal{O}(\text{keV})$

- Idea: look for events where the dark matter produces more than one phonon



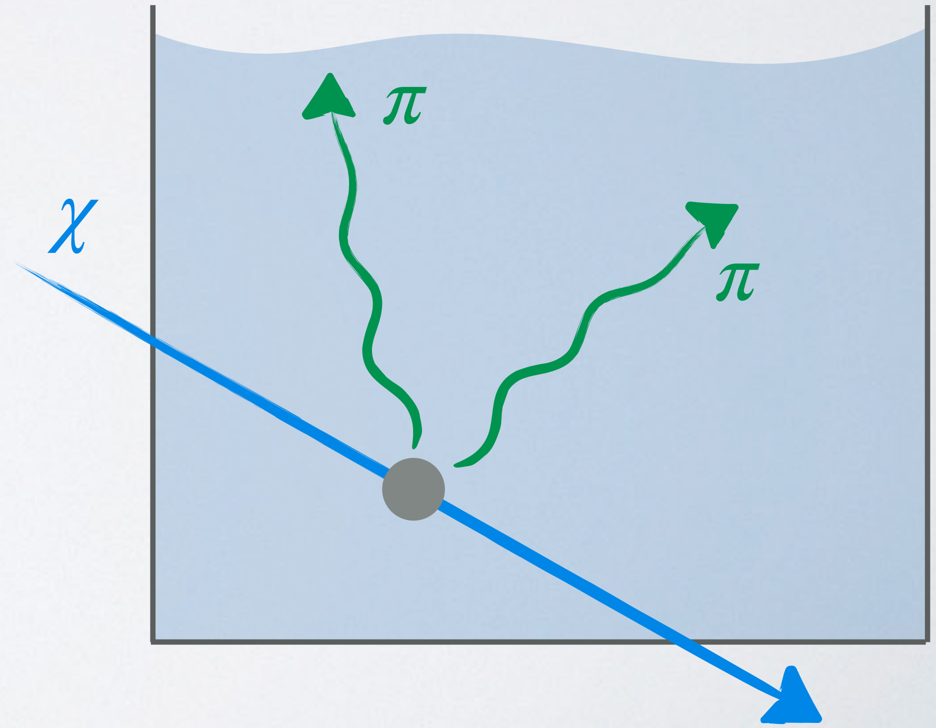
[Guo, McKinsey — PRD 2013, 1302.0534; Schutz, Zurek — PRL 2016, 1604.08206; Knapen, Lin, Zurek — PRD 2017, 1611.06228; Acanfora, **AE**, Polosa — EPJC 2019, 1902.02361; Caputo, **AE**, Polosa — PRD 2019, 1907.10635; Baym et al. — PRD 2021, 2005.08824; Caputo, **AE**, Piccini, Polosa, Rossi — PRD 2021, 2012.01432; Matchev et al. — JHEP 2022, 2108.07275; You et al. — 2208.14474]

SUPERFLUID ^{4}He

- Superfluid ^{4}He is an interesting target to probe dark matter with *spin-independent* interactions

 1. $E_{\text{ionization}} \simeq 25$ eV $\longrightarrow$ low electronic background
 2. High radiopurity
 3. Multi-phonon processes allow to probe down to $m_\chi \sim \mathcal{O}(\text{keV})$

- Idea: look for events where the dark matter produces more than one phonon



[Guo, McKinsey – PRD 2013, 1302.0534; Schutz, Zurek – PRL 2016, 1604.08206; Knapen, Lin, Zurek – PRD 2017, 1611.06228; Acanfora, **AE**, Polosa – EPJC 2019, 1902.02361; Caputo, **AE**, Polosa – PRD 2019, 1907.10635; Baym et al. – PRD 2021, 2005.08824; Caputo, **AE**, Piccini, Polosa, Rossi – PRD 2021, 2012.01432; Matchev et al. – JHEP 2022, 2108.07275; You et al. – 2208.14474]

SUPERFLUIDS IN A NUTSHELL

SUPERFLUIDS IN A NUTSHELL

- Intuitive example: gas of weakly repulsive bosons

SUPERFLUIDS IN A NUTSHELL

- Intuitive example: gas of weakly repulsive bosons
- At $T = 0$ all bosons are in the $\mathbf{k} = 0$ state $\rightarrow$ system described by a single collective wave function

SUPERFLUIDS IN A NUTSHELL

- Intuitive example: gas of weakly repulsive bosons
- At $T = 0$ all bosons are in the $\mathbf{k} = \mathbf{0}$ state $\quad\longrightarrow\quad$ system described by a single collective wave function

$$\Psi(x) = \sqrt{n(x)}\, e^{i\psi(x)}$$

SUPERFLUIDS IN A NUTSHELL

- Intuitive example: gas of weakly repulsive bosons

- At $T = 0$ all bosons are in the $\mathbf{k} = \mathbf{0}$ state $\longrightarrow$ system described by a single collective wave function

$$\Psi(x) = \sqrt{n(x)}\, e^{i\psi(x)}$$

- Repulsion generates density waves with $\omega = c_s q$ $\longrightarrow$ below a critical velocity, the superfluid is inviscid (no dissipation)

SUPERFLUIDS IN A NUTSHELL

- Intuitive example: gas of weakly repulsive bosons

- At $T = 0$ all bosons are in the $\mathbf{k} = 0$ state $\quad\rightarrow\quad$ system described by a single collective wave function

$$\Psi(x) = \sqrt{n(x)}\, e^{i\psi(x)}$$

- Repulsion generates density waves with $\omega = c_s q$ $\quad\rightarrow\quad$ below a critical velocity, the superfluid is inviscid (no dissipation)

$$\rho(\omega) = \frac{dN}{d\omega} \propto q^2 \frac{dq}{d\omega} \xrightarrow{q \to 0} 0$$

SUPERFLUIDS IN A NUTSHELL

- Intuitive example: gas of weakly repulsive bosons
- At $T = 0$ all bosons are in the $\mathbf{k} = 0$ state → system described by a single collective wave function

$$\Psi(x) = \sqrt{n(x)}\, e^{i\psi(x)}$$

- Repulsion generates density waves with $\omega = c_s q$ → below a critical velocity, the superfluid is inviscid (no dissipation)

$$\rho(\omega) = \frac{dN}{d\omega} \propto q^2 \frac{dq}{d\omega} \xrightarrow{q \to 0} 0$$

- Not enough modes to lose energy/momentum into

THE COND-MAT WAY

THE COND-MAT WAY

- ^{4}He is microscopically strongly coupled $\longrightarrow$ multi-phonon emission rate is hard to compute

THE COND-MAT WAY

- ^{4}He is microscopically strongly coupled $\longrightarrow$ multi-phonon emission rate is hard to compute

standard way

THE COND-MAT WAY

- ^{4}He is microscopically strongly coupled → multi-phonon emission rate is hard to compute

<u>*standard way*</u>

strongly coupled atomic Hamiltonian

THE COND-MAT WAY

- ^{4}He is microscopically strongly coupled → multi-phonon emission rate is hard to compute

<u>*standard way*</u>

strongly coupled atomic Hamiltonian

↓

clever ansatz for the condensate w.f.

THE COND-MAT WAY

- ^{4}He is microscopically strongly coupled $\longrightarrow$ multi-phonon emission rate is hard to compute

<u>*standard way*</u>

strongly coupled atomic Hamiltonian

$\downarrow$

clever ansatz for the condensate w.f.

$\downarrow$

extrapolation of the structure factor

$$\frac{d\Gamma}{d\omega\, dq} = \frac{\rho_{\rm He}\, \sigma_{\chi n}\, q}{2m_\chi\, m_{\rm He}\, p_i} S(q,\omega)$$

THE COND-MAT WAY

- ^{4}He is microscopically strongly coupled $\longrightarrow$ multi-phonon emission rate is hard to compute

standard way

strongly coupled atomic Hamiltonian

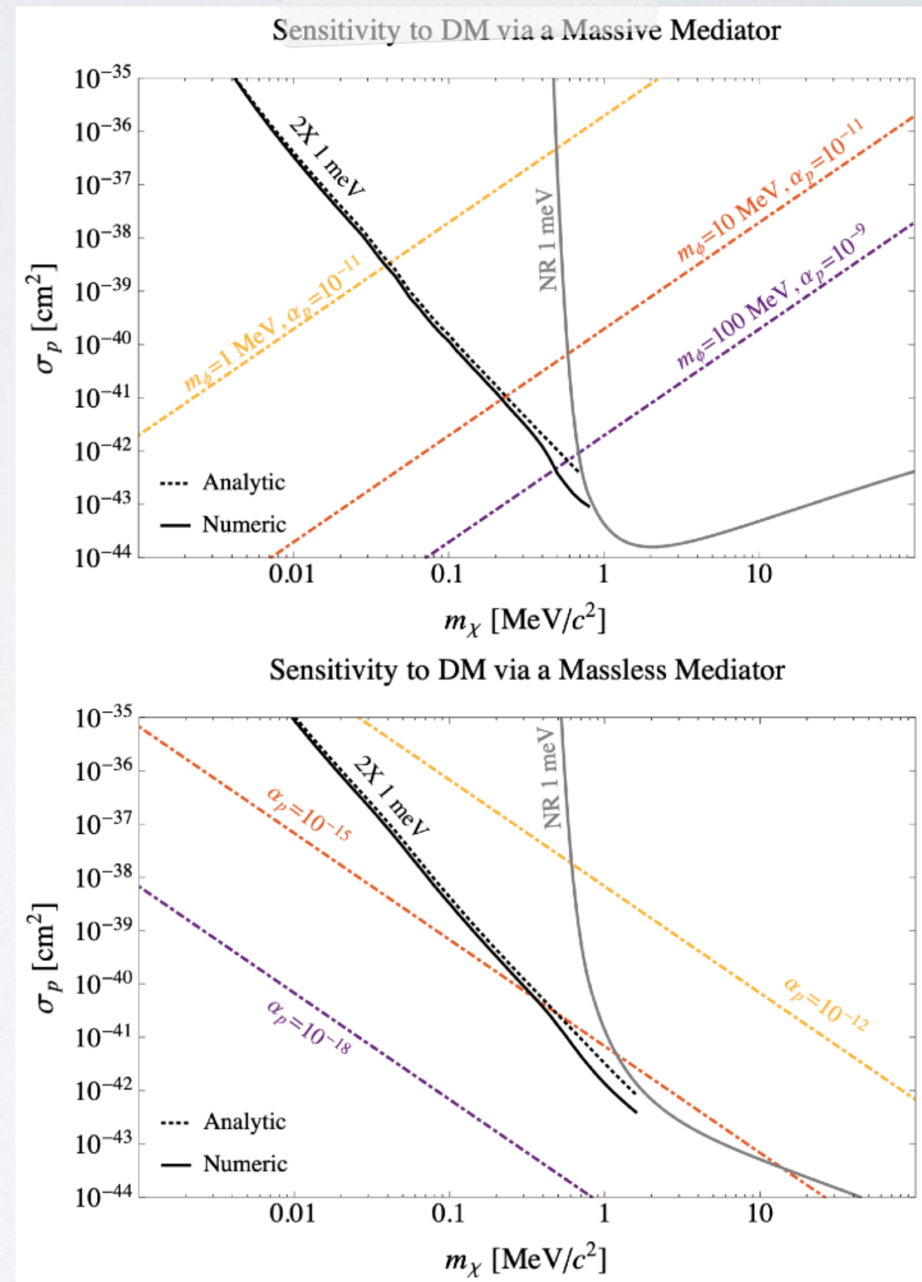
$\downarrow$

clever ansatz for the condensate w.f.

$\downarrow$

extrapolation of the structure factor

$$\frac{d\Gamma}{d\omega\, dq} = \frac{\rho_{\text{He}}\, \sigma_{\chi n}\, q}{2 m_\chi\, m_{\text{He}}\, p_i}\, S(q,\omega)$$



[Schutz, Zurek – PRL 2016, 1604.08206; Knapen, Lin, Zurek – PRD 2017, 1611.06228; Baym et al. – PRD 2021, 2005.08824]

THE HEP WAY

THE HEP WAY

- Alternatively, the symmetry breaking pattern of a superfluid:

THE HEP WAY

- Alternatively, the symmetry breaking pattern of a superfluid:

$$\mathbf{K}\,,\, H\,,\, \mathbf{P}\,,\, \mathbf{J}\,,\, Q$$

THE HEP WAY

- Alternatively, the symmetry breaking pattern of a superfluid:

$$\cancel{\mathbf{K}}\,,\ \cancel{H}\,,\ \mathbf{P}\,,\ \mathbf{J}\,,\ \cancel{Q} \qquad \longrightarrow \qquad \mathbf{P}\,,\ \mathbf{J}\,,\ \bar{H} = H - \mu Q$$

THE HEP WAY

- Alternatively, the symmetry breaking pattern of a superfluid:

$$\cancel{\mathbf{K}}, \cancel{H}, \mathbf{P}, \mathbf{J}, \cancel{Q} \quad \longrightarrow \quad \mathbf{P}, \mathbf{J}, \bar{H} = H - \mu Q$$

- Realized by a real scalar field

$$\psi(x) \xrightarrow{Q} \psi(x) + a \qquad \langle \psi(x) \rangle = \mu t \qquad \psi(x) = \mu t + \pi(x)$$

[see, e.g., Son — hep-th/0204199; Nicolis, Piazza — JHEP 2012, 1112.5174]

THE HEP WAY

- Alternatively, the symmetry breaking pattern of a superfluid:

$$\cancel{\mathbf{K}}\,,\,\cancel{H}\,,\,\mathbf{P}\,,\,\mathbf{J}\,,\,\cancel{Q} \quad \longrightarrow \quad \mathbf{P}\,,\,\mathbf{J}\,,\,\bar{H} = H - \mu Q$$

- Realized by a real scalar field

$$\psi(x) \xrightarrow{Q} \psi(x) + a \qquad \langle \psi(x) \rangle = \mu t \qquad \psi(x) = \mu t + \pi(x)$$

[see, e.g., Son — hep-th/0204199; Nicolis, Piazza — JHEP 2012, 1112.5174]

- Gapless phonon = Goldstone $\longrightarrow$ low energy EFT:

THE HEP WAY

- Alternatively, the symmetry breaking pattern of a superfluid:

$$\cancel{\mathbf{K}}\,,\,\cancel{H}\,,\,\mathbf{P}\,,\,\mathbf{J}\,,\,\cancel{Q} \quad\longrightarrow\quad \mathbf{P}\,,\,\mathbf{J}\,,\,\bar{H}=H-\mu Q$$

- Realized by a real scalar field

$$\psi(x) \xrightarrow{Q} \psi(x)+a \qquad\qquad \langle\psi(x)\rangle = \mu t \qquad\qquad \psi(x) = \mu t + \pi(x)$$

[see, e.g., Son — hep-th/0204199; Nicolis, Piazza — JHEP 2012, 1112.5174]

- Gapless phonon = Goldstone $\longrightarrow$ low energy EFT:

$$\mathscr{L}_{\text{EFT}} = P\left(\sqrt{\partial_\mu\psi\partial^\mu\psi}\right)$$

THE HEP WAY

- Alternatively, the symmetry breaking pattern of a superfluid:

$$\cancel{\mathbf{K}}\,,\,\cancel{H}\,,\,\mathbf{P}\,,\,\mathbf{J}\,,\,\cancel{Q} \quad \longrightarrow \quad \mathbf{P}\,,\,\mathbf{J}\,,\,\bar{H} = H - \mu Q$$

- Realized by a real scalar field

$$\psi(x) \xrightarrow{Q} \psi(x) + a \qquad \langle \psi(x) \rangle = \mu t \qquad \psi(x) = \mu t + \pi(x)$$

[see, e.g., Son — hep-th/0204199; Nicolis, Piazza — JHEP 2012, 1112.5174]

- Gapless phonon = Goldstone $\longrightarrow$ low energy EFT:

$$\mathscr{L}_{\text{EFT}} = P\left(\sqrt{\partial_\mu \psi \partial^\mu \psi}\right)$$

$$\sim \dot{\pi}^2 - c_s^2 \left(\nabla \pi\right)^2 + \lambda \dot{\pi} \left(\nabla \pi\right)^2 + \lambda' \dot{\pi}^3 + \dots$$

[see, e.g., Acanfora, **AE**, Polosa — EPJC 2019, 1902.02361]

THE HEP WAY

- Alternatively, the symmetry breaking pattern of a superfluid:

$$\cancel{\mathbf{K}}, \cancel{H}, \mathbf{P}, \mathbf{J}, \cancel{Q} \quad \longrightarrow \quad \mathbf{P}, \mathbf{J}, \bar{H} = H - \mu Q$$

- Realized by a real scalar field

$$\psi(x) \xrightarrow{Q} \psi(x) + a \qquad \langle \psi(x) \rangle = \mu t \qquad \psi(x) = \mu t + \pi(x)$$

[see, e.g., Son — hep-th/0204199; Nicolis, Piazza — JHEP 2012, 1112.5174]

- Gapless phonon = Goldstone $\longrightarrow$ low energy EFT:

$$\mathscr{L}_{\text{EFT}} = P\left(\sqrt{\partial_\mu \psi \partial^\mu \psi}\right)$$

$$\sim \dot{\pi}^2 - c_s^2(\nabla \pi)^2 + \lambda \dot{\pi}(\nabla \pi)^2 + \lambda' \dot{\pi}^3 + \ldots$$

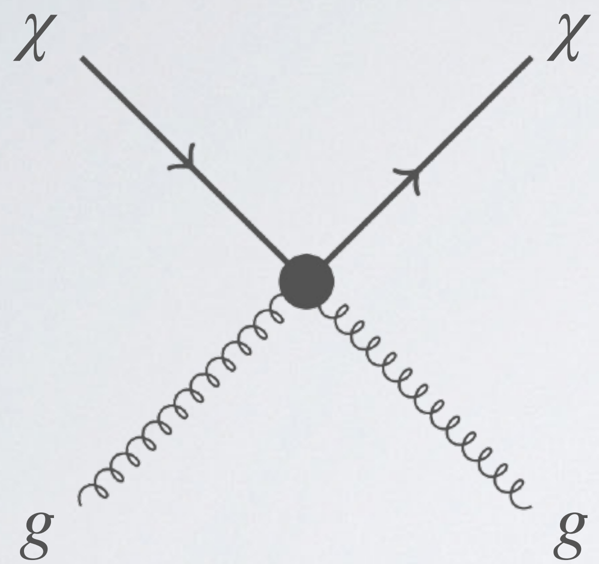
effective coefficients are given by the equation of state: $P \equiv P(\mu)$

[see, e.g., Acanfora, **AE**, Polosa — EPJC 2019, 1902.02361]

DM-PHONON INTERACTION

DM-PHONON INTERACTION

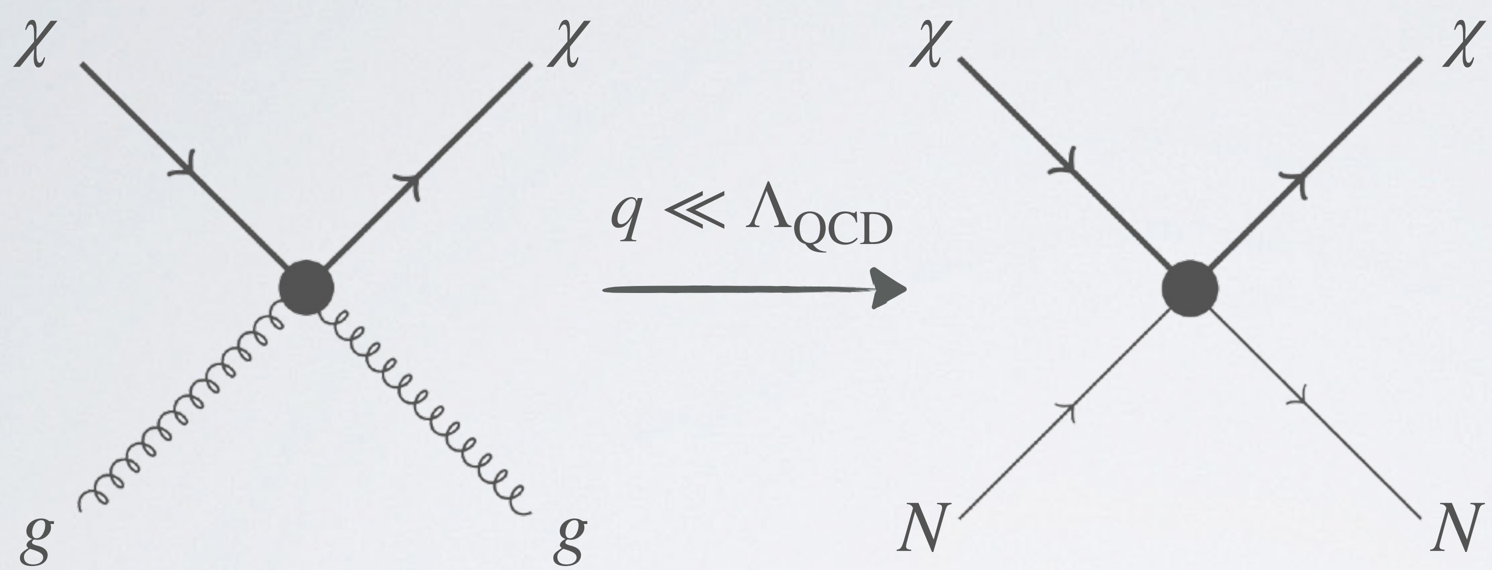
- At low energies, dark matter couples to the *number density field*



$$\mathscr{L}_{\rm int} \sim |\chi|^2 \, \mathrm{tr}\, G_{\mu\nu} G^{\mu\nu}$$

DM-PHONON INTERACTION

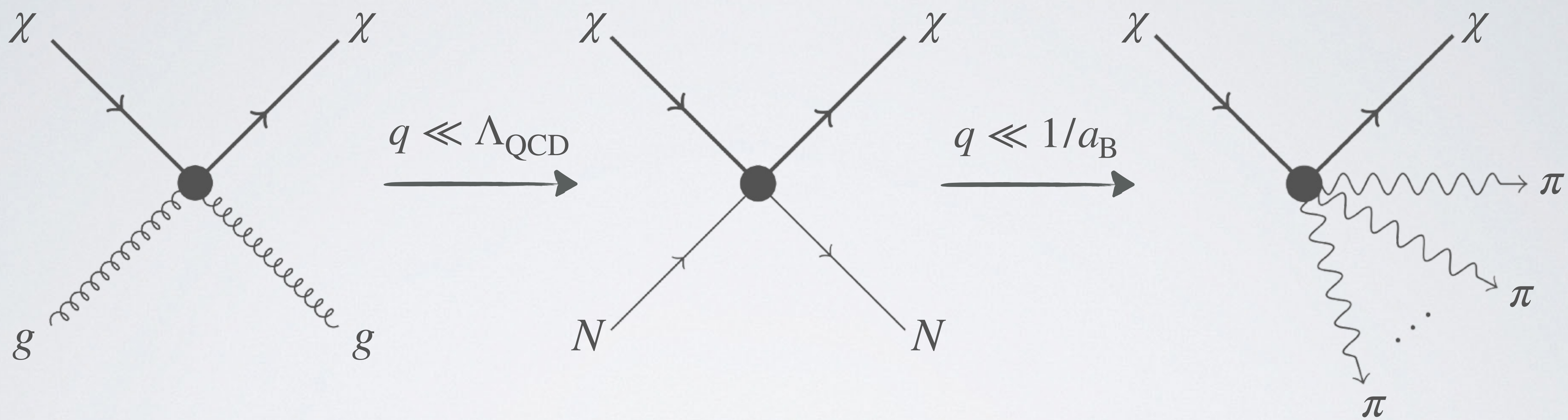
- At low energies, dark matter couples to the *number density field*



$\mathscr{L}_{\rm int} \sim |\chi|^2 \,{\rm tr}\, G_{\mu\nu}G^{\mu\nu}$ $\qquad$ $\mathscr{L}_{\rm int} \sim |\chi|^2 \bar{N}N$

DM-PHONON INTERACTION

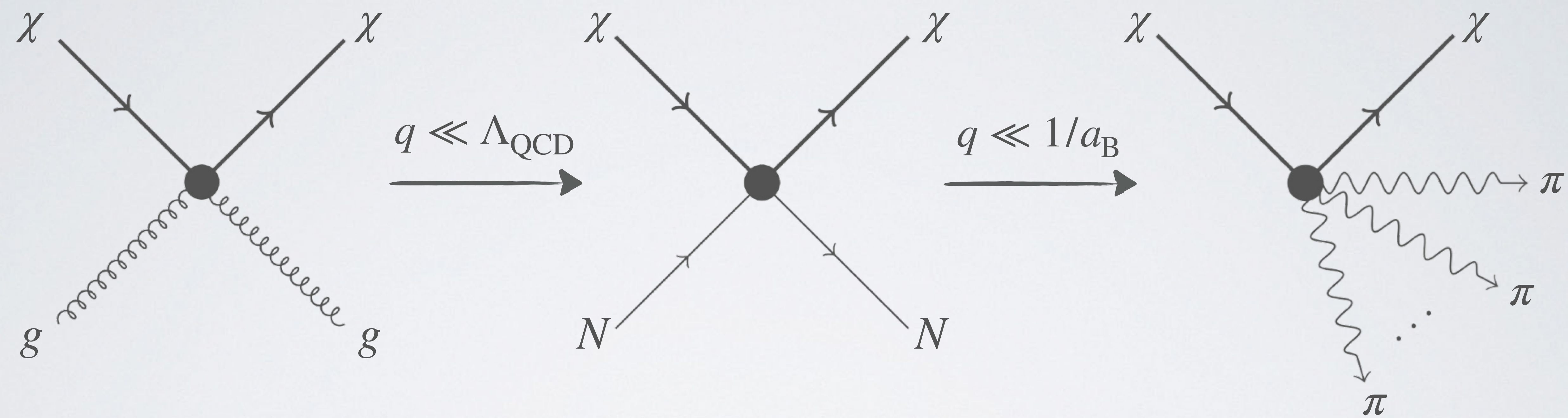
- At low energies, dark matter couples to the *number density field*



$\mathscr{L}_{\rm int} \sim |\chi|^2\, {\rm tr}\, G_{\mu\nu}G^{\mu\nu}$ $\qquad$ $\mathscr{L}_{\rm int} \sim |\chi|^2\, \bar{N}N$ $\qquad$ $\mathscr{L}_{\rm int} \sim |\chi|^2\, n(\pi)$

DM-PHONON INTERACTION

- At low energies, dark matter couples to the *number density field*



$\mathscr{L}_{\rm int} \sim |\chi|^2 \, {\rm tr}\, G_{\mu\nu}G^{\mu\nu}$ $\mathscr{L}_{\rm int} \sim |\chi|^2 \bar{N}N$ $\mathscr{L}_{\rm int} \sim |\chi|^2 n(\pi)$

- Obtain from the $U(1)$ Noether current within the EFT

$$\mathscr{L}_{\rm int} = G_\chi m_\chi |\chi|^2 J^0 \sim |\chi|^2 \left(g\dot{\pi} + g'\dot{\pi}^2 + g''(\nabla\pi)^2 + \dots \right)$$

[see, e.g., Acanfora, **AE**, Polosa — EPJC 2019, 1902.02361]

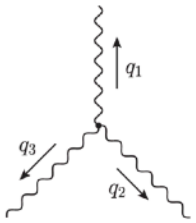
IDEAL REACH

IDEAL REACH

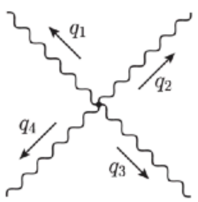
- We can now use standard QFT methods to compute event rates

IDEAL REACH

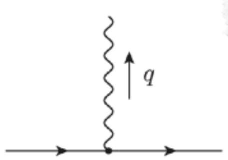
- We can now use standard QFT methods to compute event rates



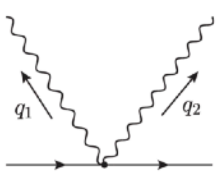
$$= g_1\big(\omega_1\, \boldsymbol{q}_2\cdot\boldsymbol{q}_3 + \omega_2\, \boldsymbol{q}_1\cdot\boldsymbol{q}_3 + \omega_3\, \boldsymbol{q}_1\cdot\boldsymbol{q}_2\big) + g_2\, \omega_1\, \omega_2\, \omega_3\,,$$



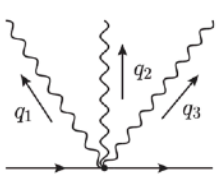
$$\begin{aligned} = i\lambda_1\big(&\boldsymbol{q}_1\cdot\boldsymbol{q}_2\, \boldsymbol{q}_3\cdot\boldsymbol{q}_4 + \boldsymbol{q}_1\cdot\boldsymbol{q}_3\, \boldsymbol{q}_2\cdot\boldsymbol{q}_4 \\ &+ \boldsymbol{q}_1\cdot\boldsymbol{q}_4\, \boldsymbol{q}_2\cdot\boldsymbol{q}_3\big) \\ + i\lambda_2\big(&\omega_1\,\omega_2\, \boldsymbol{q}_3\cdot\boldsymbol{q}_4 + \omega_1\,\omega_3\, \boldsymbol{q}_2\cdot\boldsymbol{q}_4 \\ &+ \omega_1\,\omega_4\, \boldsymbol{q}_2\cdot\boldsymbol{q}_3 + \omega_2\,\omega_3\, \boldsymbol{q}_1\cdot\boldsymbol{q}_4 \\ &+ \omega_2\,\omega_4\, \boldsymbol{q}_1\cdot\boldsymbol{q}_3 + \omega_3\,\omega_4\, \boldsymbol{q}_1\cdot\boldsymbol{q}_2\big) \\ + i\lambda_3\,& \omega_1\,\omega_2\,\omega_3\,\omega_4\,, \end{aligned}$$



$$= G_\chi m_\chi \alpha\, \omega\,,$$



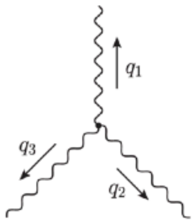
$$= i G_\chi m_\chi \big(\beta_1 \boldsymbol{q}_1\cdot\boldsymbol{q}_2 + \beta_2 \omega_1\, \omega_2\big)\,,$$



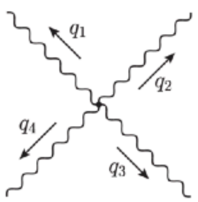
$$= G_\chi m_\chi \big[\gamma_1\big(\omega_1\, \boldsymbol{q}_2\cdot\boldsymbol{q}_3 + \omega_2\, \boldsymbol{q}_1\cdot\boldsymbol{q}_3 + \omega_3\, \boldsymbol{q}_1\cdot\boldsymbol{q}_2\big) + \gamma_2\, \omega_1\, \omega_2\, \omega_3\big]\,.$$

IDEAL REACH

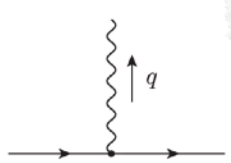
- We can now use standard QFT methods to compute event rates



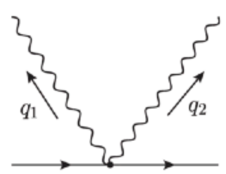
$$= g_1\left(\omega_1\, \boldsymbol{q}_2\cdot\boldsymbol{q}_3 + \omega_2\, \boldsymbol{q}_1\cdot\boldsymbol{q}_3 + \omega_3\, \boldsymbol{q}_1\cdot\boldsymbol{q}_2\right) + g_2\, \omega_1\, \omega_2\, \omega_3\,,$$



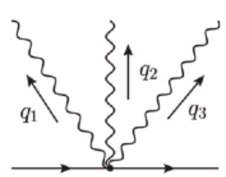
$$\begin{aligned} &= i\lambda_1\big(\boldsymbol{q}_1\cdot\boldsymbol{q}_2\,\boldsymbol{q}_3\cdot\boldsymbol{q}_4 + \boldsymbol{q}_1\cdot\boldsymbol{q}_3\,\boldsymbol{q}_2\cdot\boldsymbol{q}_4 \\ &\quad + \boldsymbol{q}_1\cdot\boldsymbol{q}_4\,\boldsymbol{q}_2\cdot\boldsymbol{q}_3\big) \\ &\quad + i\lambda_2\big(\omega_1\,\omega_2\,\boldsymbol{q}_3\cdot\boldsymbol{q}_4 + \omega_1\,\omega_3\,\boldsymbol{q}_2\cdot\boldsymbol{q}_4 \\ &\qquad + \omega_1\,\omega_4\,\boldsymbol{q}_2\cdot\boldsymbol{q}_3 + \omega_2\,\omega_3\,\boldsymbol{q}_1\cdot\boldsymbol{q}_4 \\ &\qquad + \omega_2\,\omega_4\,\boldsymbol{q}_1\cdot\boldsymbol{q}_3 + \omega_3\,\omega_4\,\boldsymbol{q}_1\cdot\boldsymbol{q}_2\big) \\ &\quad + i\lambda_3\,\omega_1\,\omega_2\,\omega_3\,\omega_4\,, \end{aligned}$$



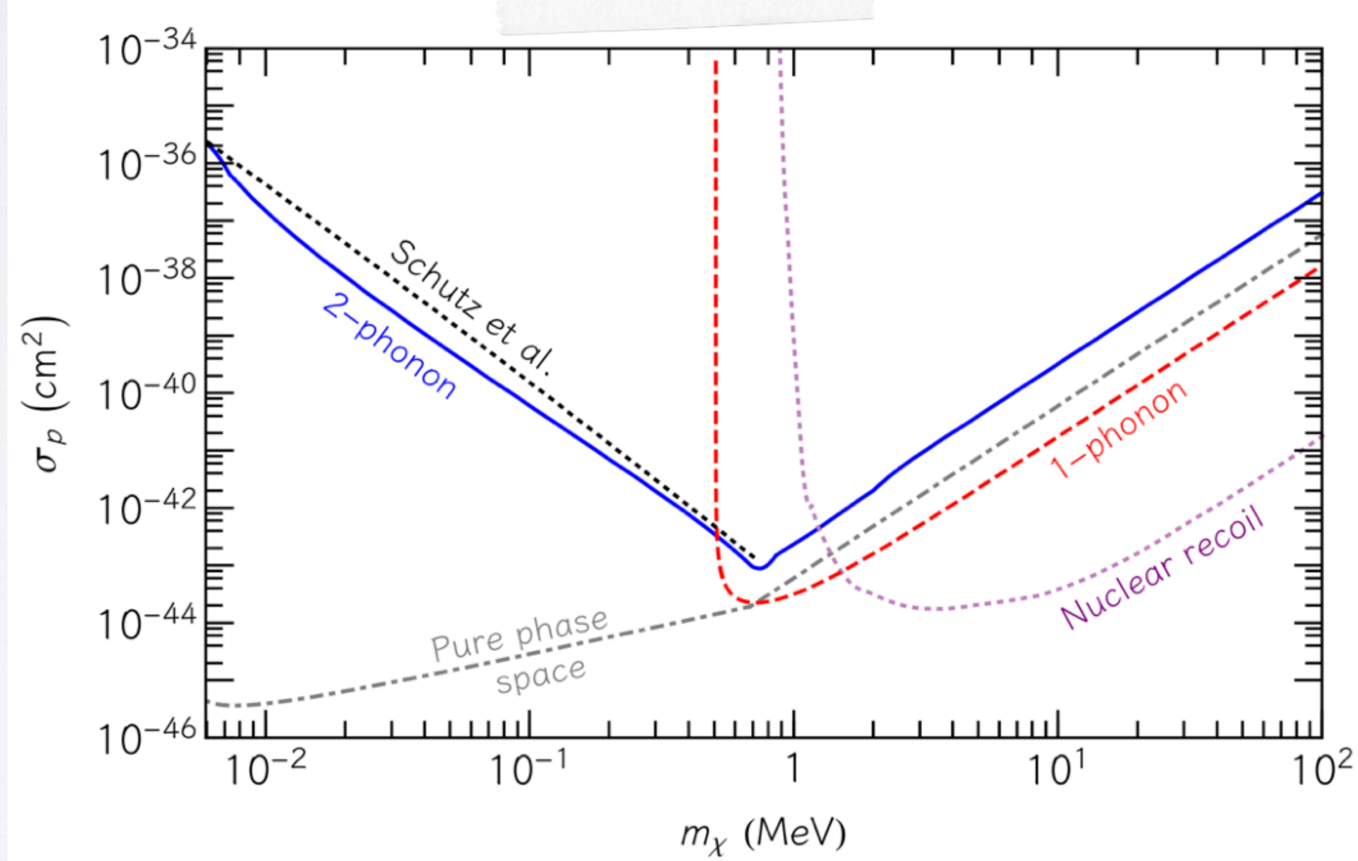
$$= G_\chi m_\chi \alpha\, \omega\,,$$



$$= iG_\chi m_\chi\left(\beta_1 \boldsymbol{q}_1\cdot\boldsymbol{q}_2 + \beta_2 \omega_1\,\omega_2\right)\,,$$



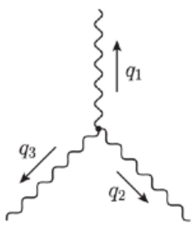
$$= G_\chi m_\chi\left[\gamma_1\left(\omega_1\,\boldsymbol{q}_2\cdot\boldsymbol{q}_3 + \omega_2\,\boldsymbol{q}_1\cdot\boldsymbol{q}_3 + \omega_3\,\boldsymbol{q}_1\cdot\boldsymbol{q}_2\right) + \gamma_2\,\omega_1\,\omega_2\,\omega_3\right].$$



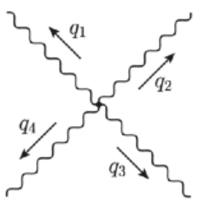
[Acanfora, **AE**, Polosa — EPJC 2019, 1902.02361;
Caputo, **AE**, Polosa — PRD 2019, 1907.10635]

IDEAL REACH

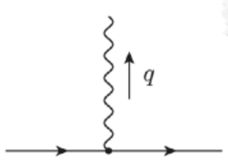
- We can now use standard QFT methods to compute event rates



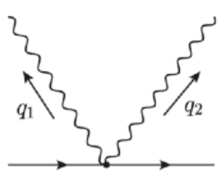
$$= g_1 \left(\omega_1 \, \boldsymbol{q}_2 \cdot \boldsymbol{q}_3 + \omega_2 \, \boldsymbol{q}_1 \cdot \boldsymbol{q}_3 + \omega_3 \, \boldsymbol{q}_1 \cdot \boldsymbol{q}_2 \right) + g_2 \, \omega_1 \, \omega_2 \, \omega_3 \,,$$



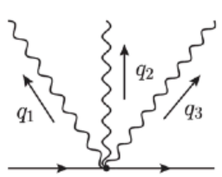
$$= i\lambda_1 \left(\boldsymbol{q}_1 \cdot \boldsymbol{q}_2 \, \boldsymbol{q}_3 \cdot \boldsymbol{q}_4 + \boldsymbol{q}_1 \cdot \boldsymbol{q}_3 \, \boldsymbol{q}_2 \cdot \boldsymbol{q}_4 + \boldsymbol{q}_1 \cdot \boldsymbol{q}_4 \, \boldsymbol{q}_2 \cdot \boldsymbol{q}_3 \right) + i\lambda_2 \left(\omega_1 \, \omega_2 \, \boldsymbol{q}_3 \cdot \boldsymbol{q}_4 + \omega_1 \, \omega_3 \, \boldsymbol{q}_2 \cdot \boldsymbol{q}_4 + \omega_1 \, \omega_4 \, \boldsymbol{q}_2 \cdot \boldsymbol{q}_3 + \omega_2 \, \omega_3 \, \boldsymbol{q}_1 \cdot \boldsymbol{q}_4 + \omega_2 \, \omega_4 \, \boldsymbol{q}_1 \cdot \boldsymbol{q}_3 + \omega_3 \, \omega_4 \, \boldsymbol{q}_1 \cdot \boldsymbol{q}_2 \right) + i\lambda_3 \, \omega_1 \, \omega_2 \, \omega_3 \, \omega_4 \,,$$



$$= G_\chi m_\chi \alpha \, \omega \,,$$

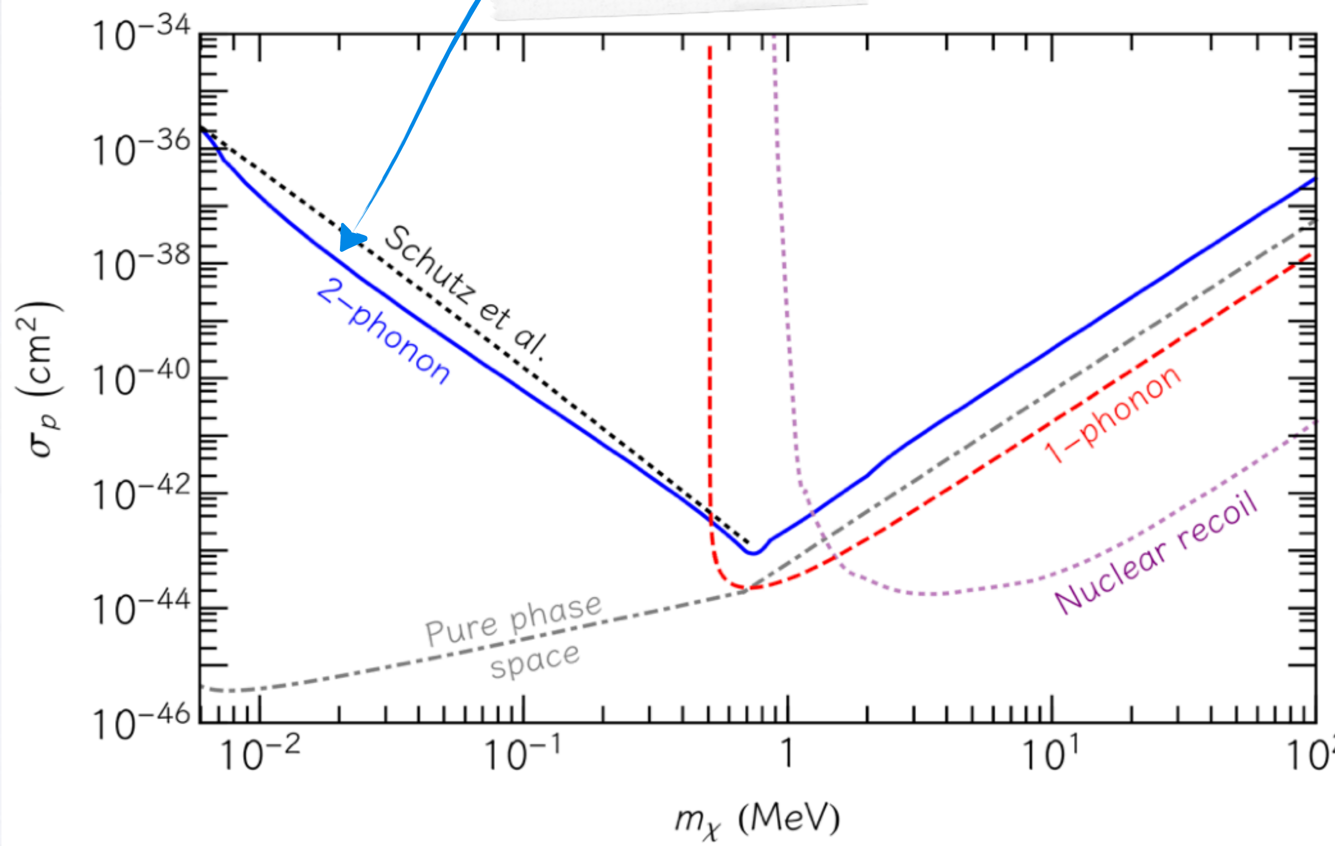


$$= i G_\chi m_\chi \left(\beta_1 \boldsymbol{q}_1 \cdot \boldsymbol{q}_2 + \beta_2 \omega_1 \, \omega_2 \right) ,$$



$$= G_\chi m_\chi \left[\gamma_1 \left(\omega_1 \, \boldsymbol{q}_2 \cdot \boldsymbol{q}_3 + \omega_2 \, \boldsymbol{q}_1 \cdot \boldsymbol{q}_3 + \omega_3 \, \boldsymbol{q}_1 \cdot \boldsymbol{q}_2 \right) + \gamma_2 \, \omega_1 \, \omega_2 \, \omega_3 \right] .$$

revise results obtained with traditional methods



[Acanfora, **AE**, Polosa — EPJC 2019, 1902.02361; Caputo, **AE**, Polosa — PRD 2019, 1907.10635]

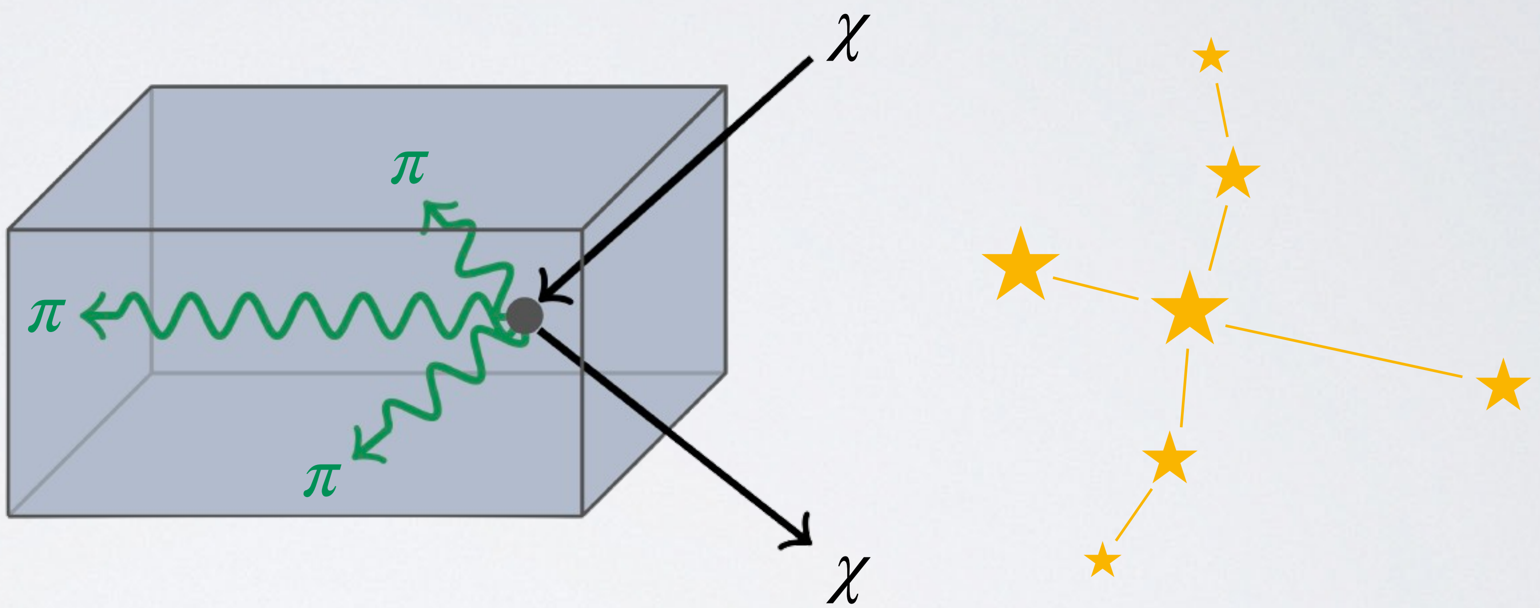
DIRECTIONALITY

DIRECTIONALITY

- EFT allows to also study more complicated signals

DIRECTIONALITY

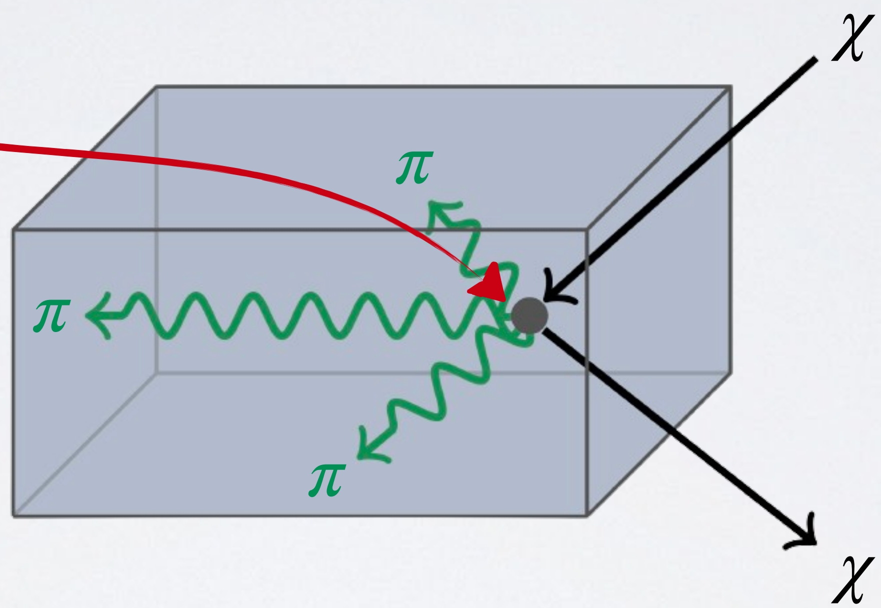
- EFT allows to also study more complicated signals

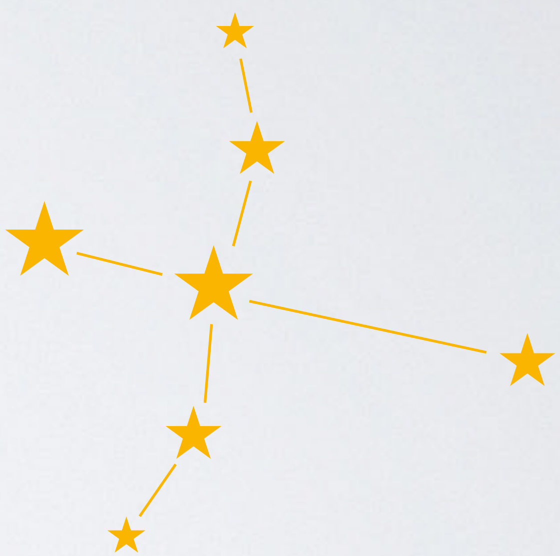


DIRECTIONALITY

- EFT allows to also study more complicated signals

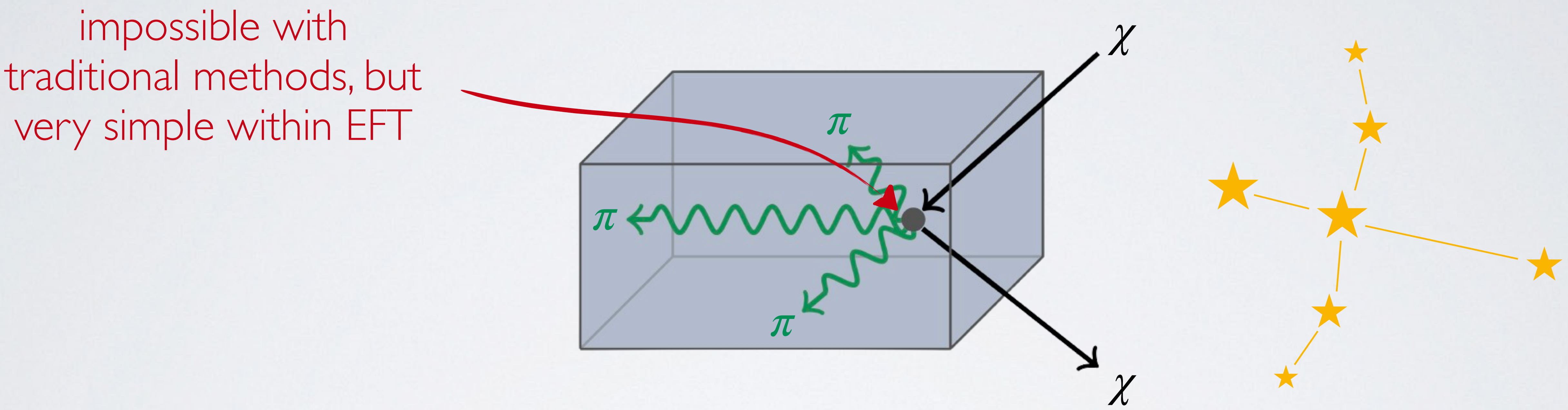
impossible with traditional methods, but very simple within EFT





DIRECTIONALITY

- EFT allows to also study more complicated signals



- If not completely suppressed, this configuration would provide a coincident, direction signal → optimal for background rejection

DIRECTIONALITY

DIRECTIONALITY

- We compute the complicated 4-body, non-Lorentz invariant phase space using Monte Carlo techniques again borrowed from particle physics

DIRECTIONALITY

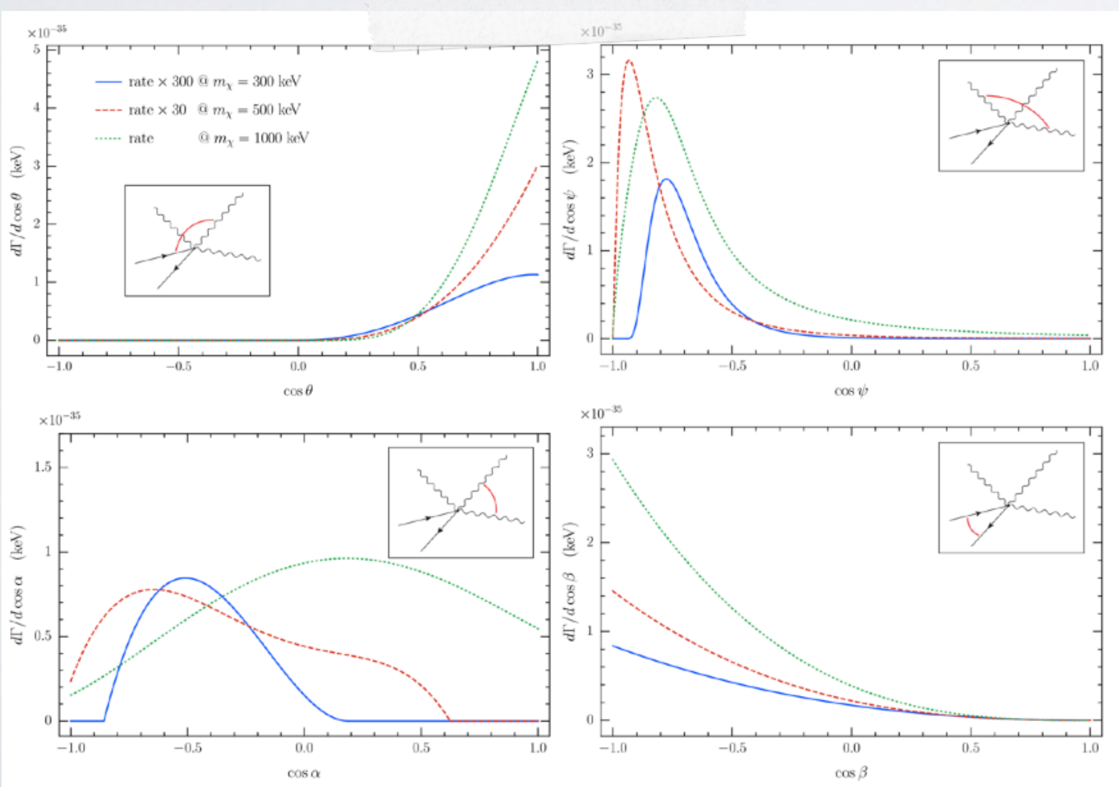
- We compute the complicated 4-body, non-Lorentz invariant phase space using Monte Carlo techniques again borrowed from particle physics

$$d\Phi_4 \sim d^3p_f \prod_{i=1}^{3} d^3q_i \; \delta\left(\frac{p_i^2}{2m_\chi} - \frac{p_f^2}{2m_\chi} - c_s|\mathbf{q}_1| - c_s|\mathbf{q}_2| - c_s|\mathbf{q}_3|\right) \delta^{(3)}\left(\mathbf{p}_i - \mathbf{p}_f - \mathbf{q}_1 - \mathbf{q}_2 - \mathbf{q}_3\right)$$

DIRECTIONALITY

- We compute the complicated 4-body, non-Lorentz invariant phase space using Monte Carlo techniques again borrowed from particle physics

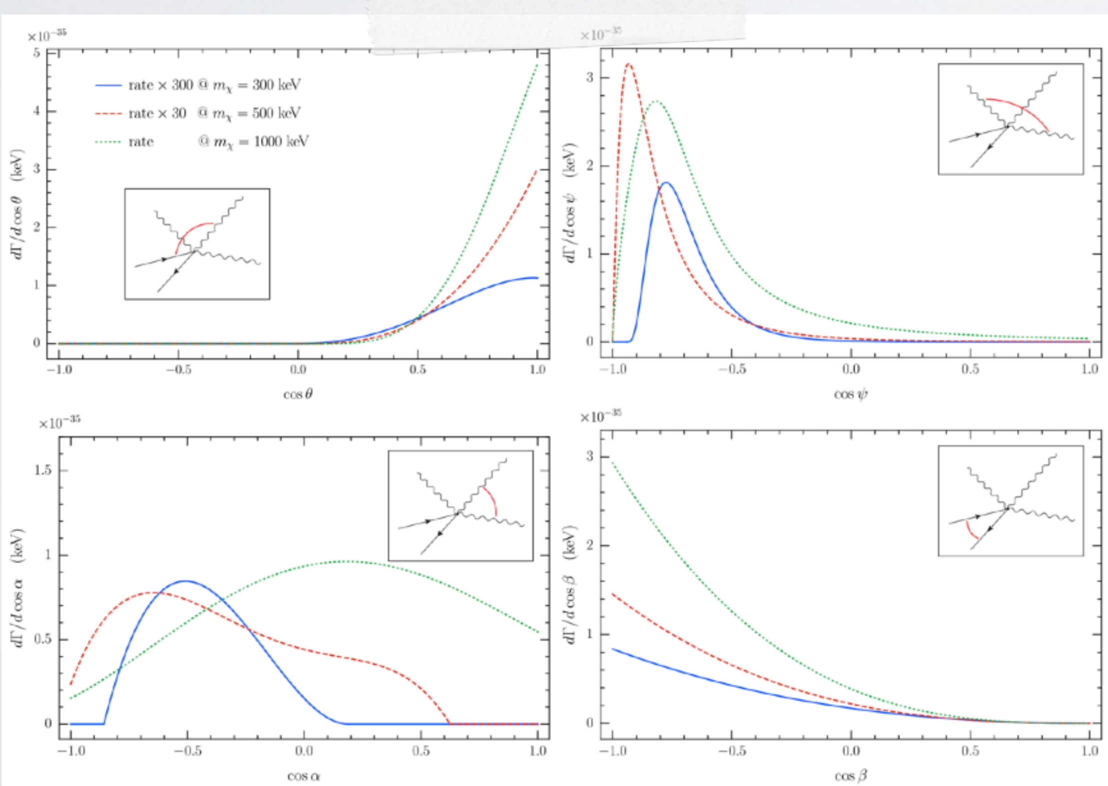
$$d\Phi_4 \sim d^3p_f \prod_{i=1}^{3} d^3q_i \, \delta\left(\frac{p_i^2}{2m_\chi} - \frac{p_f^2}{2m_\chi} - c_s|\mathbf{q}_1| - c_s|\mathbf{q}_2| - c_s|\mathbf{q}_3|\right) \delta^{(3)}(\mathbf{p}_i - \mathbf{p}_f - \mathbf{q}_1 - \mathbf{q}_2 - \mathbf{q}_3)$$

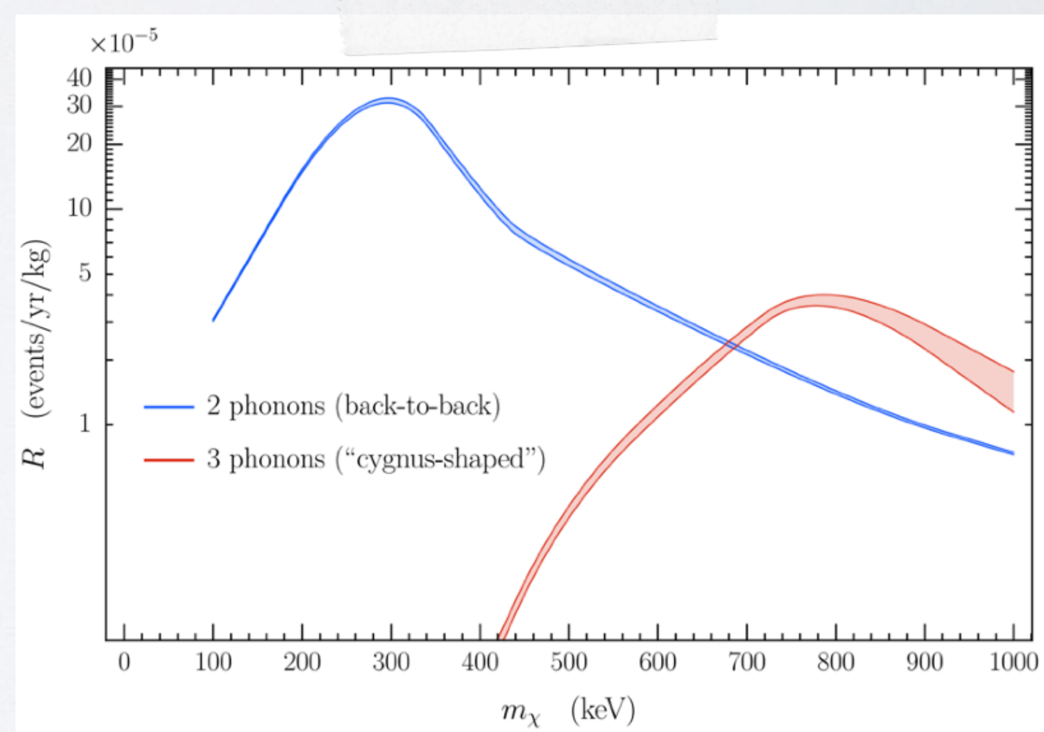


DIRECTIONALITY

- We compute the complicated 4-body, non-Lorentz invariant phase space using Monte Carlo techniques again borrowed from particle physics

$$d\Phi_4 \sim d^3p_f \prod_{i=1}^{3} d^3q_i \, \delta\left(\frac{p_i^2}{2m_\chi} - \frac{p_f^2}{2m_\chi} - c_s|\mathbf{q}_1| - c_s|\mathbf{q}_2| - c_s|\mathbf{q}_3|\right) \delta^{(3)}(\mathbf{p}_i - \mathbf{p}_f - \mathbf{q}_1 - \mathbf{q}_2 - \mathbf{q}_3)$$





[Caputo, **AE**, Piccini, Polosa, Rossi – PRD 2021, 2012.01432]

R&D

R&D

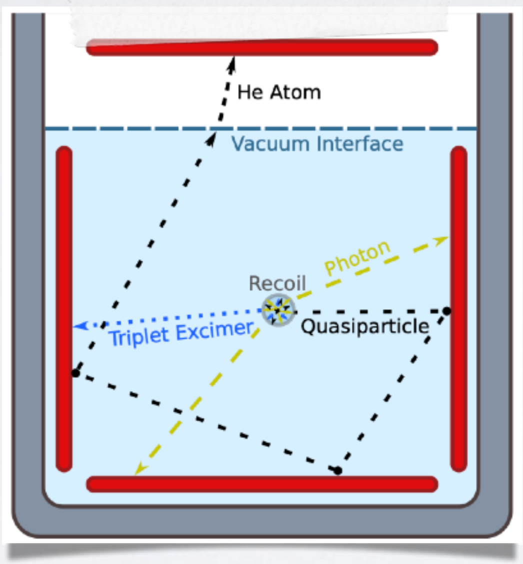
- We still have a long way, but R&D efforts are already going on:

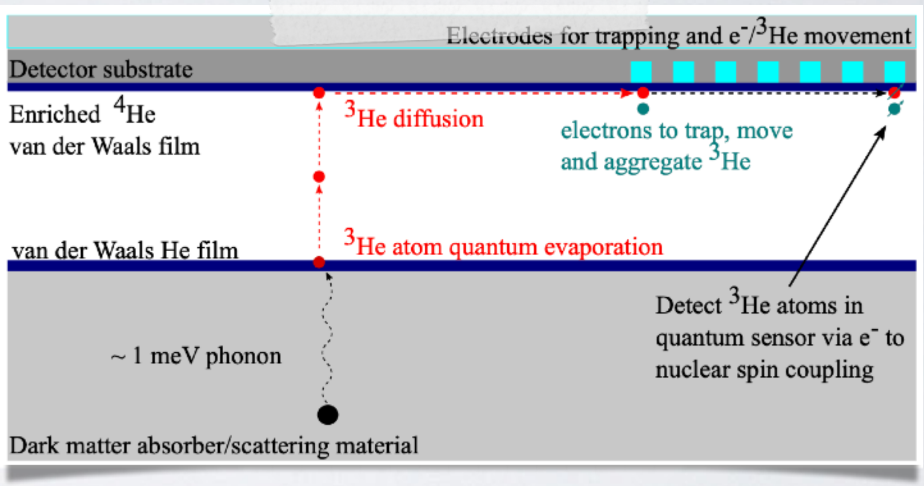
R&D

- We still have a long way, but R&D efforts are already going on:

A. *HeRALD*

[Guo, McKinsey — 1322.0534; Hertel et al. — 1810.06283; TESSERACT — SnowMass; Maris, Seidel, Stein — 1706.00117; Lyon et al. — 2201.00738]



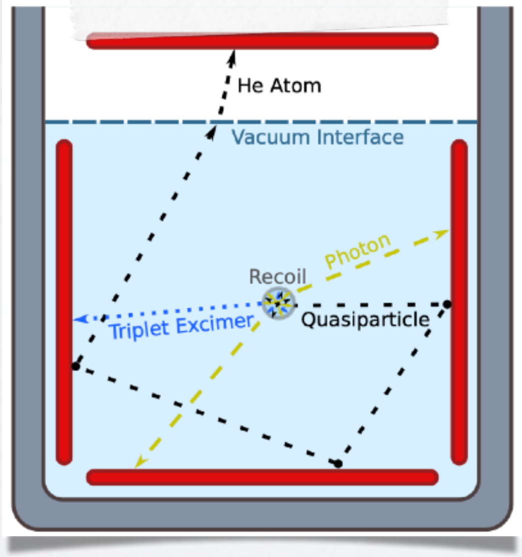


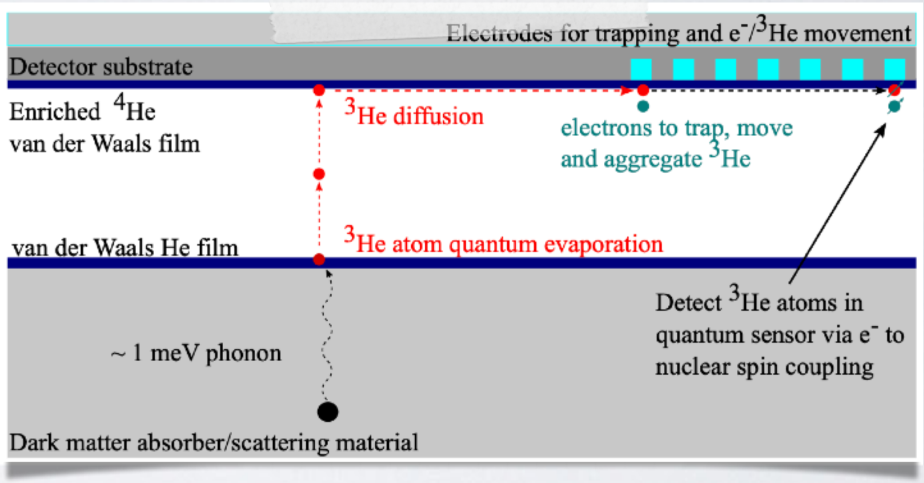
R&D

- We still have a long way, but R&D efforts are already going on:

A. *HeRALD*

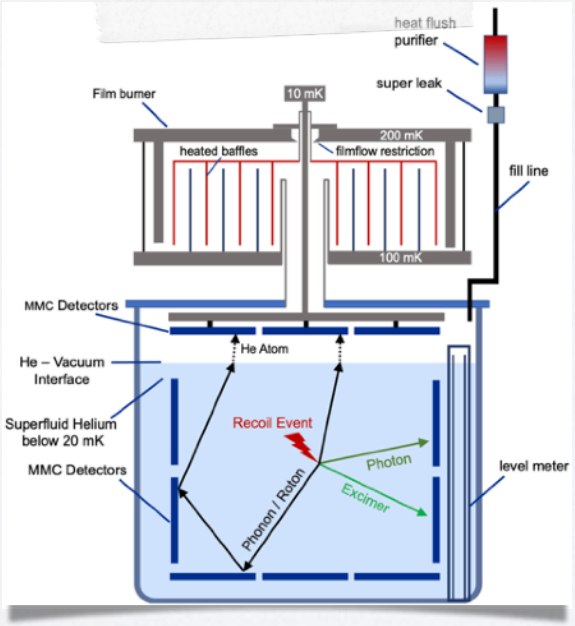
[Guo, McKinsey — 1322.0534; Hertel et al. — 1810.06283; TESSERACT — SnowMass; Maris, Seidel, Stein — 1706.00117; Lyon et al. — 2201.00738]





B. *DELight*

[Krosigk et al. — 2209.10950]

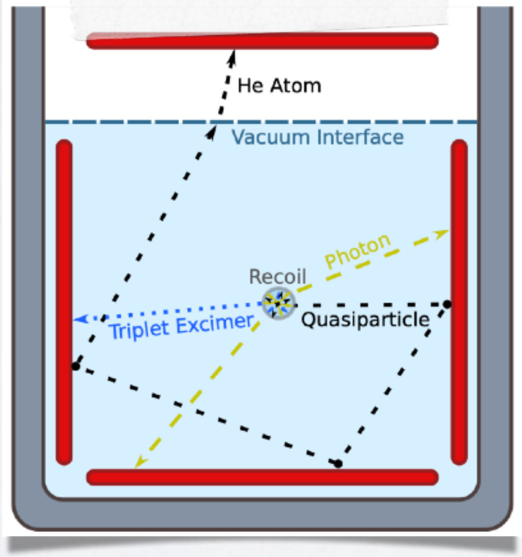


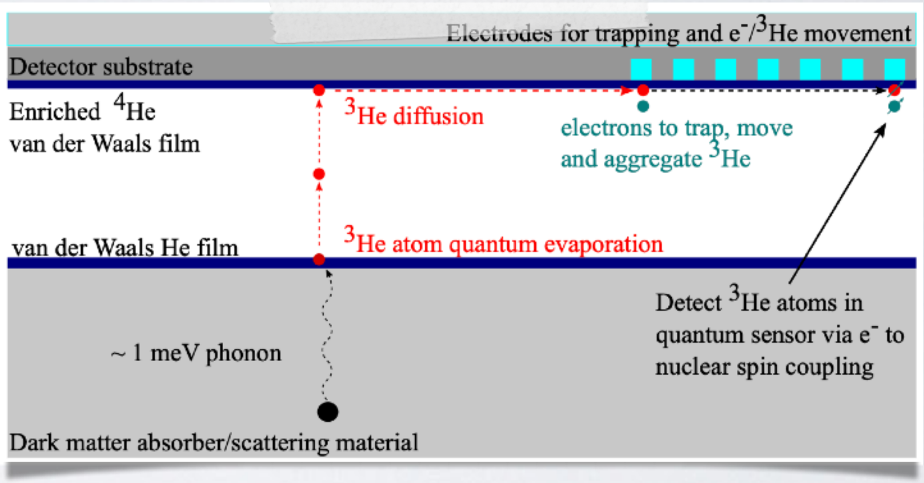
R&D

- We still have a long way, but R&D efforts are already going on:

A. *HeRALD*

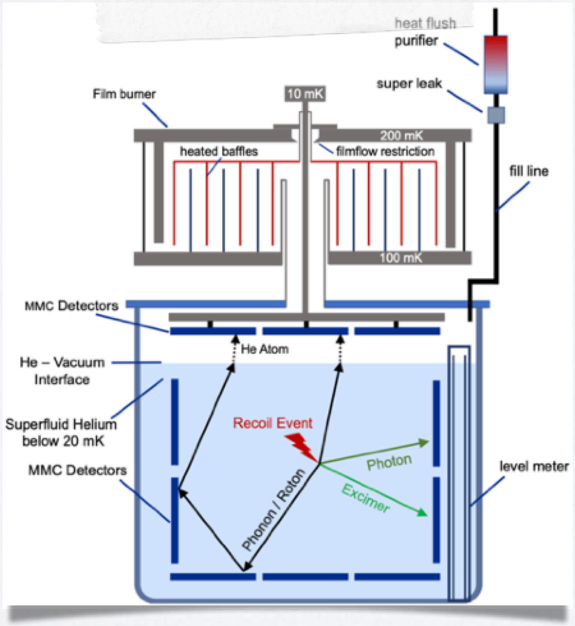
[Guo, McKinsey — 1322.0534; Hertel et al. — 1810.06283; TESSERACT — SnowMass; Maris, Seidel, Stein — 1706.00117; Lyon et al. — 2201.00738]





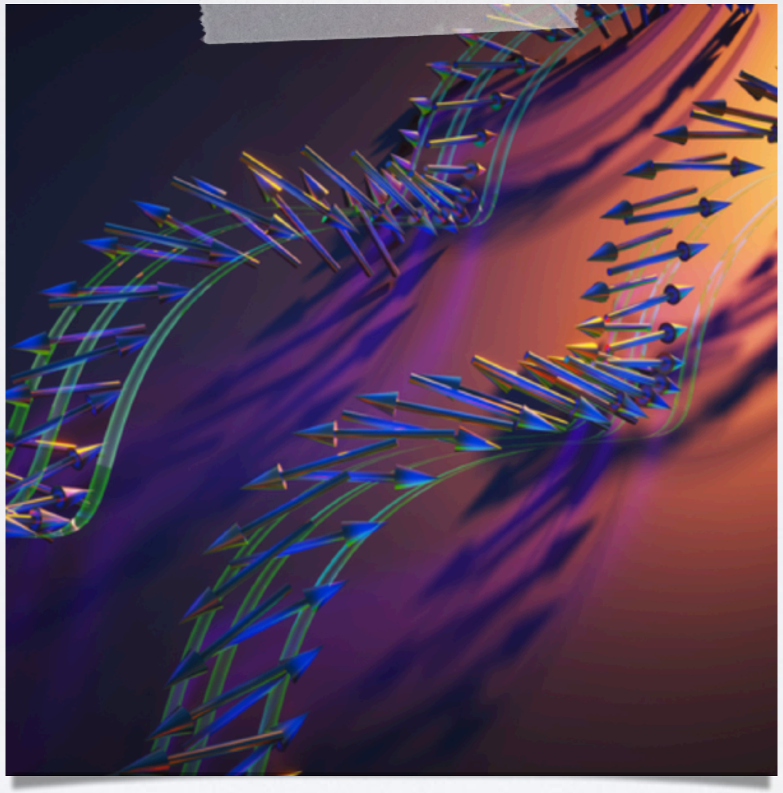
B. *DELight*

[Krosigk et al. — 2209.10950]



Getting there!

Anti-ferromagnets



[w/ Catinari, Pavaskar]

(ANTI-)FERROMAGNETS

(ANTI-)FERROMAGNETS

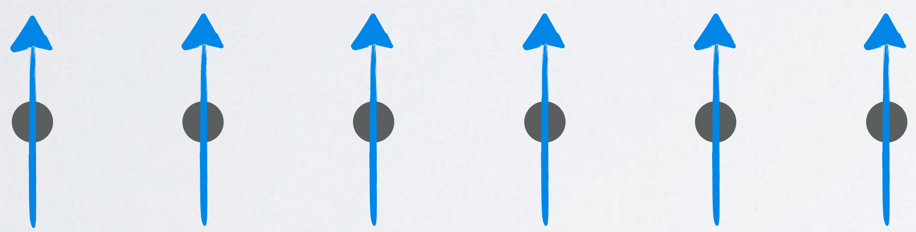
- How about dark matter with spin-*dependent* interactions?

(ANTI-)FERROMAGNETS

- How about dark matter with spin-*dependent* interactions?
- A possibility is to look for the interaction between dark matter and spin-ordered systems

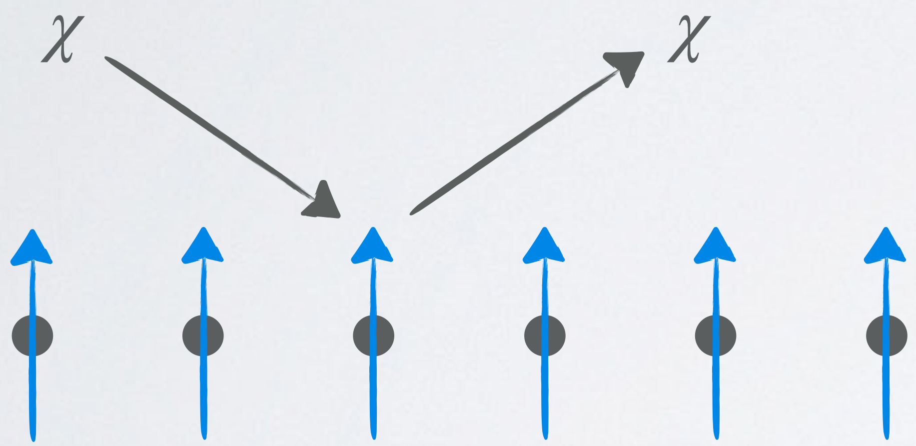
(ANTI-)FERROMAGNETS

- How about dark matter with spin-*dependent* interactions?
- A possibility is to look for the interaction between dark matter and spin-ordered systems



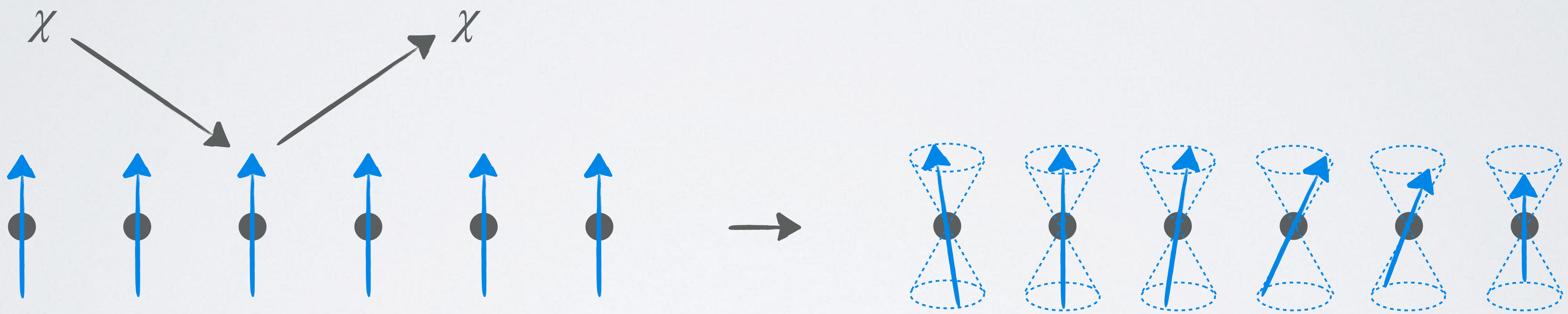
(ANTI-)FERROMAGNETS

- How about dark matter with spin-*dependent* interactions?
- A possibility is to look for the interaction between dark matter and spin-ordered systems



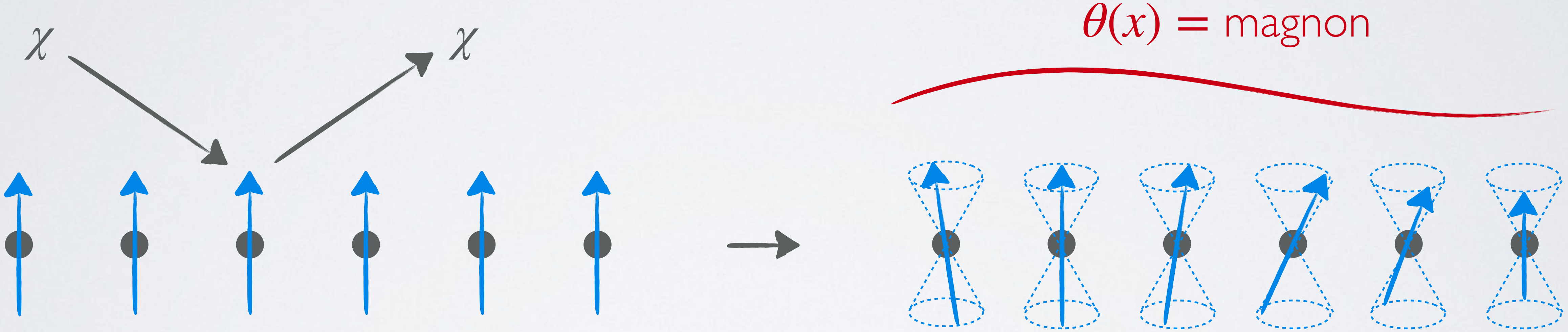
(ANTI-)FERROMAGNETS

- How about dark matter with spin-*dependent* interactions?
- A possibility is to look for the interaction between dark matter and spin-ordered systems



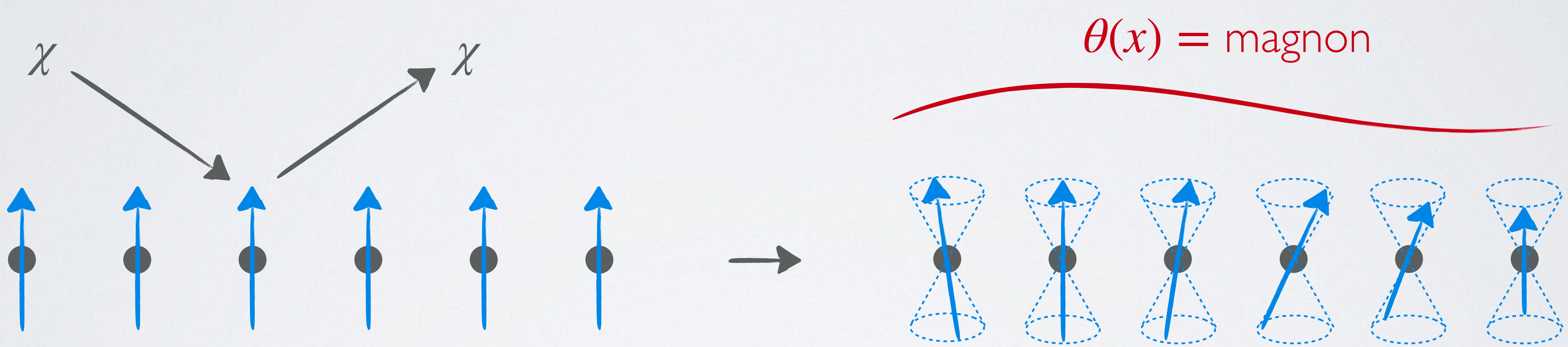
(ANTI-)FERROMAGNETS

- How about dark matter with spin-*dependent* interactions?
- A possibility is to look for the interaction between dark matter and spin-ordered systems



(ANTI-)FERROMAGNETS

- How about dark matter with spin-*dependent* interactions?
- A possibility is to look for the interaction between dark matter and spin-ordered systems



- Ways to detect few magnons have already been proposed and under development (TES, MKID, quantum sensors)

[Trickle, Zhang, Zurek — PRL 2020, 1905.13744; Lachance-Quirion et al. — Science Advances 2017; Lachance-Quirion et al. — Science 2020]

DM-SPIN INTERACTION

DM-SPIN INTERACTION

- At low energies dark matter couples to *spin density field*

DM-SPIN INTERACTION

- At low energies dark matter couples to *spin density field*
- Two benchmark models:

$$\mathscr{L}_{\text{m.d.}} \sim V_{\mu\nu}\,\bar{\chi}\sigma^{\mu\nu}\chi + V_\mu\,\bar{e}\gamma^\mu e$$

[e.g., Sigurdson et al. — PRD 2004, astro-ph/0406355; Chang, Weiner, Yavin — PRD 2010, 1007.4200]

$$\mathscr{L}_{\text{p.m.}} \sim \phi\,\bar{\chi}\chi + \phi\,\bar{e}i\gamma^5 e$$

[e.g., Banks, Fortin, Thomas — 1007.5515; Bagnasco, Dine, Thomas — PLB 1994, hep-ph/9310290]

DM-SPIN INTERACTION

- At low energies dark matter couples to *spin density field*
- Two benchmark models:

$$\mathscr{L}_{\text{m.d.}} \sim V_{\mu\nu}\,\bar{\chi}\sigma^{\mu\nu}\chi + V_{\mu}\,\bar{e}\gamma^{\mu}e$$

[e.g., Sigurdson et al. — PRD 2004, astro-ph/0406355; Chang, Weiner, Yavin — PRD 2010, 1007.4200]

$$\mathscr{L}_{\text{p.m.}} \sim \phi\,\bar{\chi}\chi + \phi\,\bar{e}i\gamma^{5}e$$

[e.g., Banks, Fortin, Thomas — 1007.5515; Bagnasco, Dine, Thomas — PLB 1994, hep-ph/9310290]

- For a non-relativistic system, at low energies:

$$\mathscr{L}_{\text{m.d.}} \xrightarrow{\text{NR}} \chi^{\dagger}\sigma^{i}\chi\left(\delta^{ij} - \nabla^{-2}\nabla^{i}\nabla^{j}\right)\left(e^{\dagger}\frac{\sigma^{i}}{2}e\right) \xrightarrow{\text{IR}} \chi^{\dagger}\sigma^{i}\chi\left(\delta^{ij} - \nabla^{-2}\nabla^{i}\nabla^{j}\right)\, s_{i}$$

$$\mathscr{L}_{\text{p.m.}} \xrightarrow{\text{NR}} \chi^{\dagger}\chi\,\nabla^{-2}\nabla_{i}\left(e^{\dagger}\frac{\sigma^{i}}{2}e\right) \xrightarrow{\text{IR}} \chi^{\dagger}\chi\,\nabla^{-2}\nabla_{i}\, s^{i}$$

DM-SPIN INTERACTION

- At low energies dark matter couples to *spin density field*
- Two benchmark models:

$$\mathscr{L}_{\text{m.d.}} \sim V_{\mu\nu}\,\bar{\chi}\sigma^{\mu\nu}\chi + V_\mu\,\bar{e}\gamma^\mu e$$

[e.g., Sigurdson et al. — PRD 2004, astro-ph/0406355; Chang, Weiner, Yavin — PRD 2010, 1007.4200]

$$\mathscr{L}_{\text{p.m.}} \sim \phi\,\bar{\chi}\chi + \phi\,\bar{e}i\gamma^5 e$$

[e.g., Banks, Fortin, Thomas — 1007.5515; Bagnasco, Dine, Thomas — PLB 1994, hep-ph/9310290]

- For a non-relativistic system, at low energies:

$$\mathscr{L}_{\text{m.d.}} \xrightarrow{\text{NR}} \chi^\dagger\sigma^i\chi\left(\delta^{ij} - \nabla^{-2}\nabla^i\nabla^j\right)\left(e^\dagger\frac{\sigma^i}{2}e\right) \xrightarrow{\text{IR}} \chi^\dagger\sigma^i\chi\left(\delta^{ij} - \nabla^{-2}\nabla^i\nabla^j\right)s_i$$

$$\mathscr{L}_{\text{p.m.}} \xrightarrow{\text{NR}} \chi^\dagger\chi\nabla^{-2}\nabla_i\left(e^\dagger\frac{\sigma^i}{2}e\right) \xrightarrow{\text{IR}} \chi^\dagger\chi\nabla^{-2}\nabla_i s^i$$

spin density

FERROMAGNETS

FERROMAGNETS

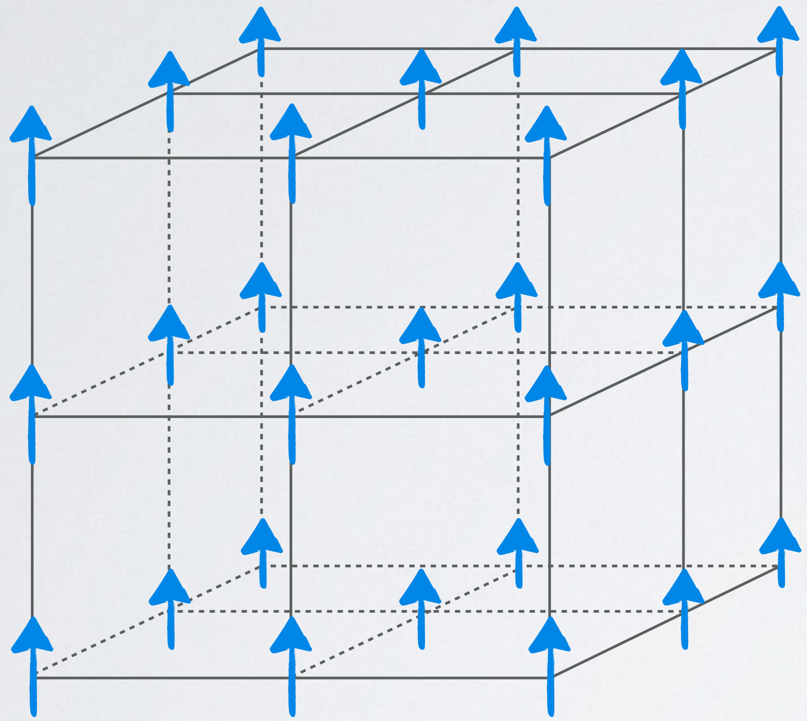
- First proposed to use ferromagnets

[Trickle, Zhang, Zurek — PRL 2020, 1905.13744; Mitridate et al. — PRD 2020, 2005.10256; Chigus, Moroi, Nakayama — PRD 2020, 2001.10666; Trickle, Zhang, Zurek — PRD 2022, 2009.13534]

FERROMAGNETS

- First proposed to use ferromagnets

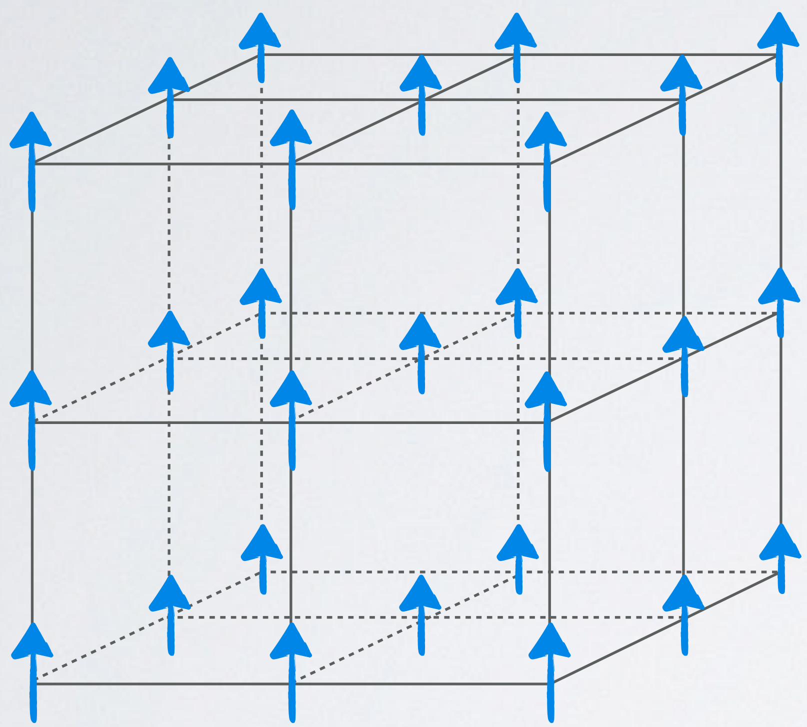
[Trickle, Zhang, Zurek — PRL 2020, 1905.13744; Mitridate et al. — PRD 2020, 2005.10256; Chigus, Moroi, Nakayama — PRD 2020, 2001.10666; Trickle, Zhang, Zurek — PRD 2022, 2009.13534]

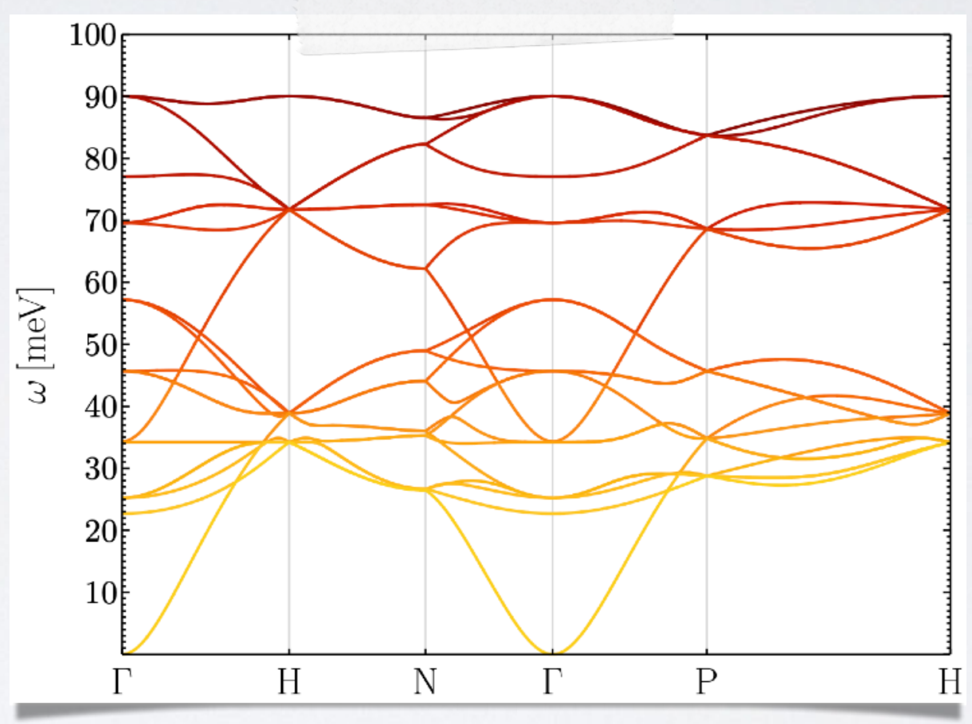


FERROMAGNETS

- First proposed to use ferromagnets

[Trickle, Zhang, Zurek — PRL 2020, 1905.13744; Mitridate et al. — PRD 2020, 2005.10256; Chigus, Moroi, Nakayama — PRD 2020, 2001.10666; Trickle, Zhang, Zurek — PRD 2022, 2009.13534]

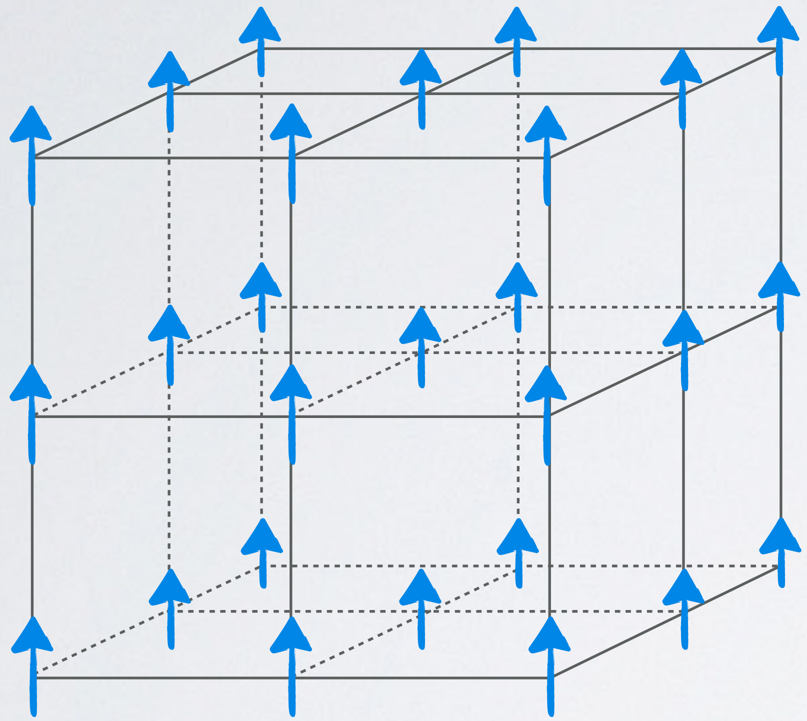


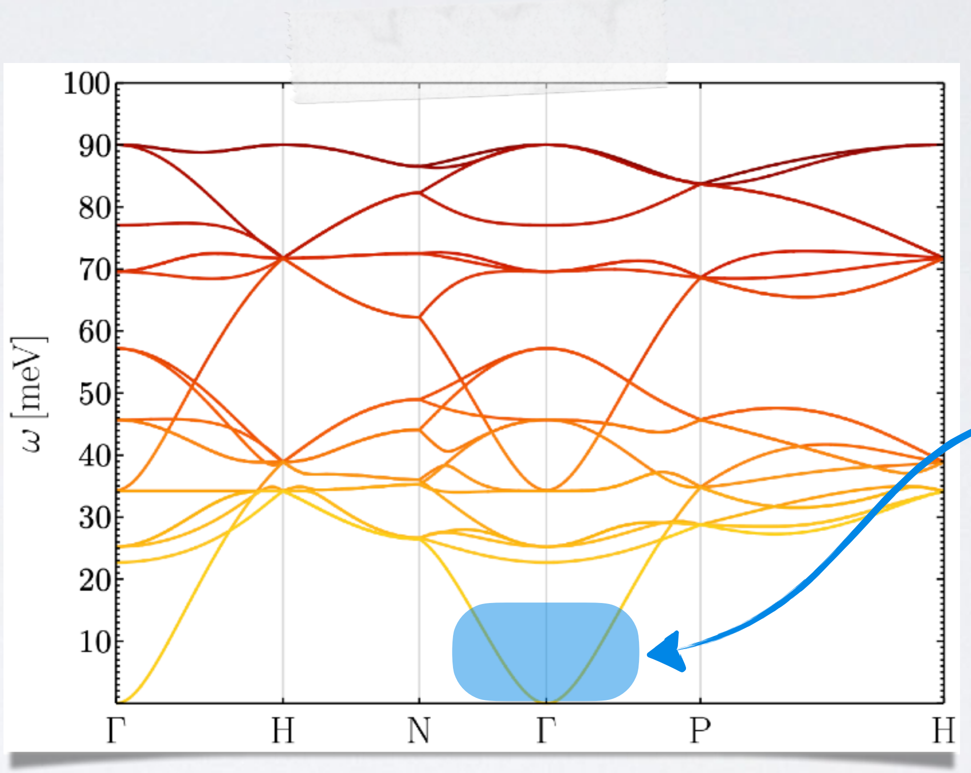


FERROMAGNETS

- First proposed to use ferromagnets

[Trickle, Zhang, Zurek — PRL 2020, 1905.13744; Mitridate et al. — PRD 2020, 2005.10256; Chigus, Moroi, Nakayama — PRD 2020, 2001.10666; Trickle, Zhang, Zurek — PRD 2022, 2009.13534]





for $m_\chi \lesssim 10$ MeV only

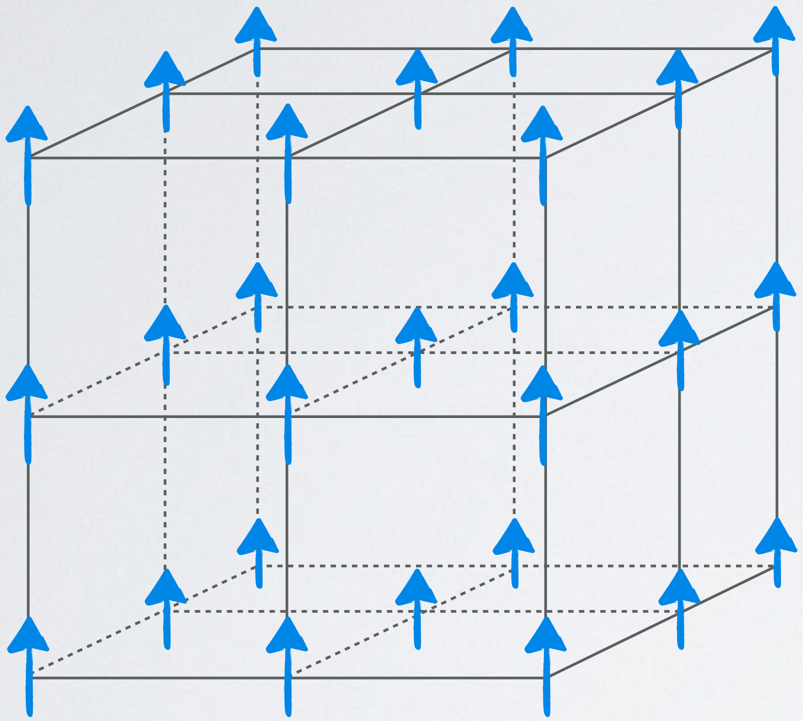
gapless magnons

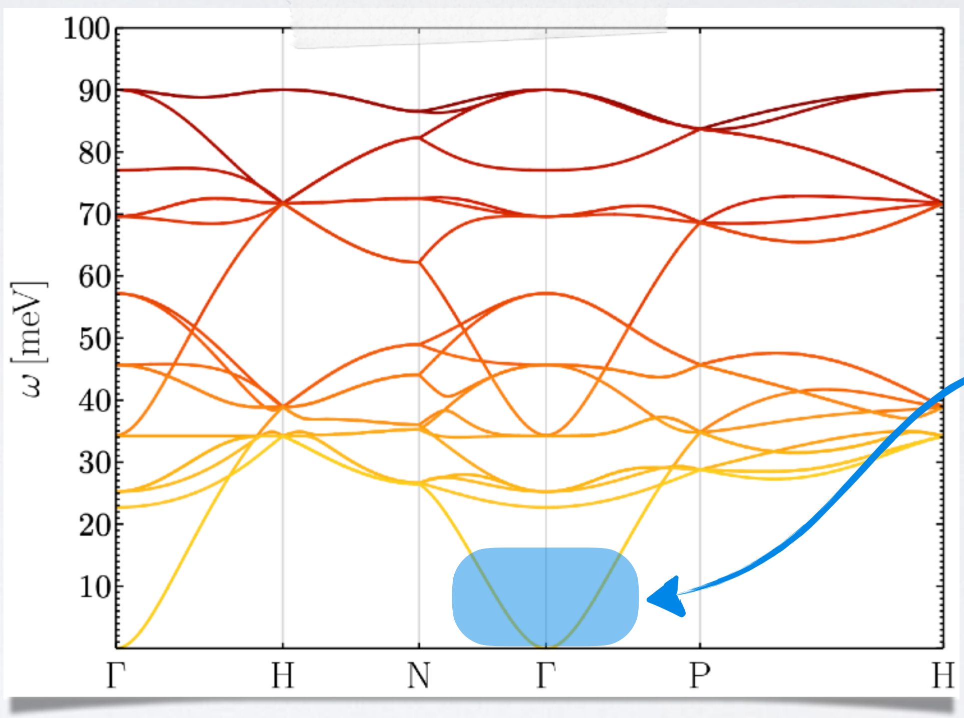
$\omega(q) = q^2/(2m_\theta)$

FERROMAGNETS

- First proposed to use ferromagnets

[Trickle, Zhang, Zurek — PRL 2020, 1905.13744; Mitridate et al. — PRD 2020, 2005.10256; Chigus, Moroi, Nakayama — PRD 2020, 2001.10666; Trickle, Zhang, Zurek — PRD 2022, 2009.13534]





for $m_\chi \lesssim 10$ MeV only

gapless magnons

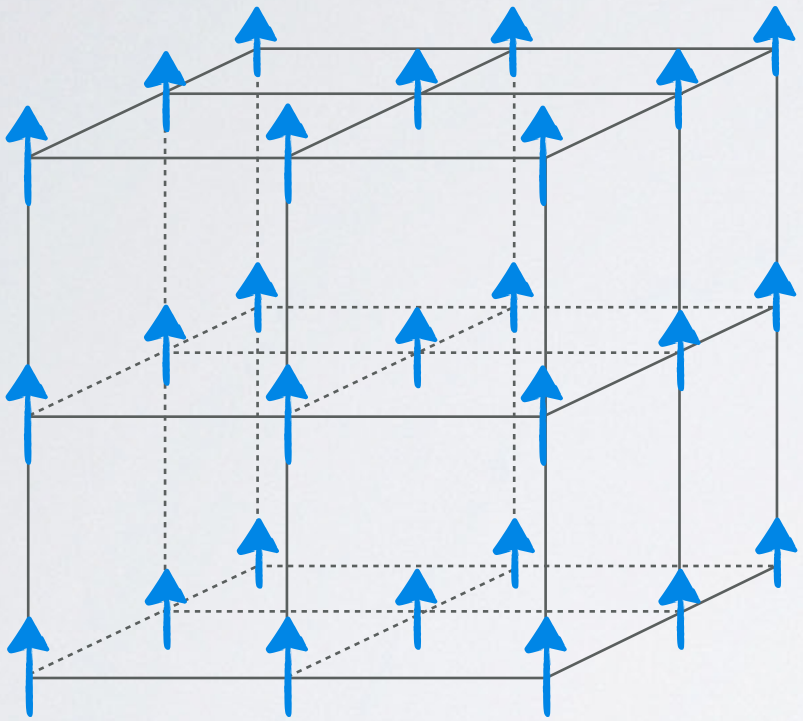
$\omega(q) = q^2/(2m_\theta)$

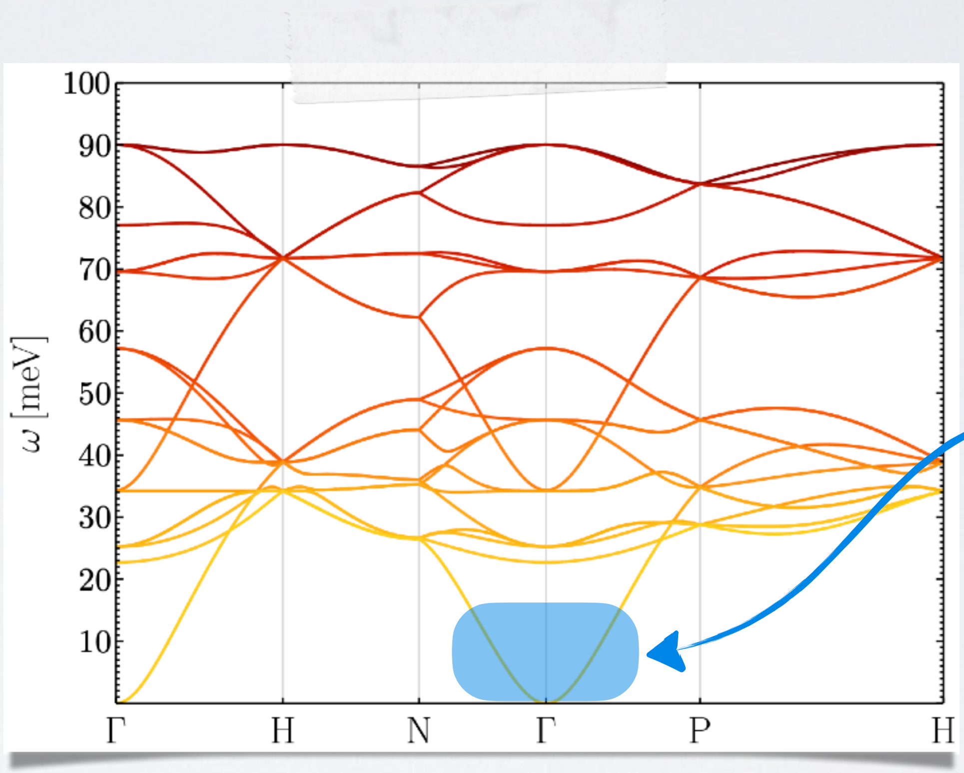
- Conservation of magnetization → only one magnon emitted

FERROMAGNETS

- First proposed to use ferromagnets

[Trickle, Zhang, Zurek — PRL 2020, 1905.13744; Mitridate et al. — PRD 2020, 2005.10256; Chigus, Moroi, Nakayama — PRD 2020, 2001.10666; Trickle, Zhang, Zurek — PRD 2022, 2009.13534]





for $m_\chi \lesssim 10$ MeV only

gapless magnons

$\omega(q) = q^2/(2m_\theta)$

- Conservation of magnetization → only one magnon emitted

$$\omega_{\max} = E_\chi \frac{4\, m_\theta/m_\chi}{(1 + m_\theta/m_\chi)^2}$$ with $m_\theta \sim 1$ MeV → inefficient for $m_\chi \lesssim 1$ MeV

FERROMAGNETS

FERROMAGNETS

- Compute the magnon emission rate

FERROMAGNETS

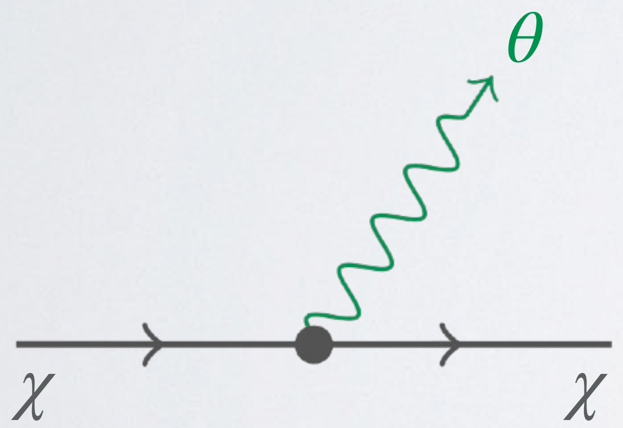
- Compute the magnon emission rate
- Traditional approach: quantize the Heisenberg model

$$H = \frac{1}{2} \sum_{\ell,\ell'}^{N} \sum_{j,j'}^{n} J_{\ell\ell' jj'} \mathbf{S}_{\ell j} \cdot \mathbf{S}_{\ell' j'} \to \sum_{\nu=1}^{n} \sum_{\mathbf{q} \in 1\mathrm{BZ}} \omega_{\nu,\mathbf{q}} b^{\dagger}_{\nu,\mathbf{q}} b_{\nu,\mathbf{q}}$$

FERROMAGNETS

- Compute the magnon emission rate
- Traditional approach: quantize the Heisenberg model

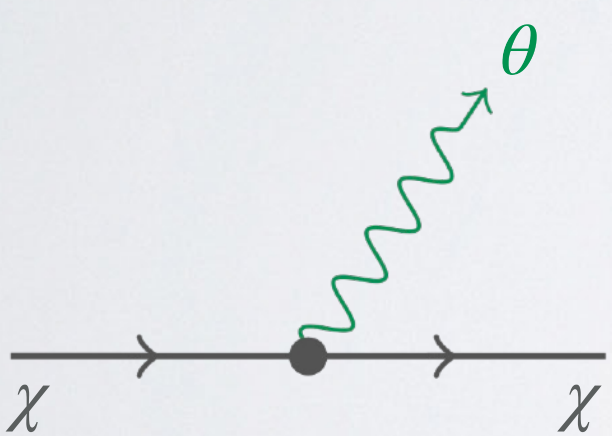
$$H = \frac{1}{2}\sum_{\ell,\ell'}^{N}\sum_{j,j'}^{n} J_{\ell\ell' jj'}\mathbf{S}_{\ell j}\cdot\mathbf{S}_{\ell' j'} \to \sum_{\nu=1}^{n}\sum_{\mathbf{q}\in 1\mathrm{BZ}} \omega_{\nu,\mathbf{q}} b^\dagger_{\nu,\mathbf{q}} b_{\nu,\mathbf{q}}$$

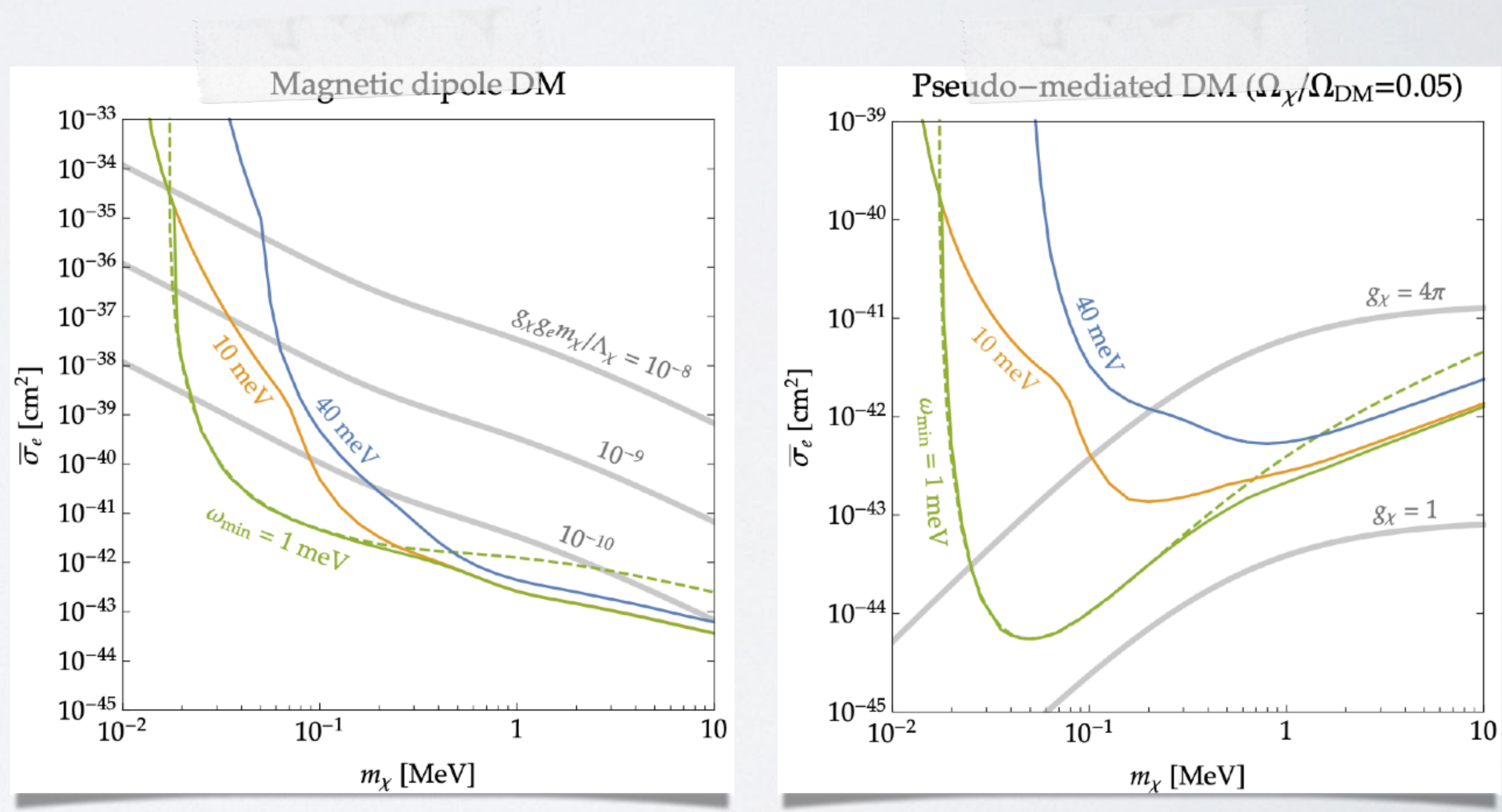


FERROMAGNETS

- Compute the magnon emission rate
- Traditional approach: quantize the Heisenberg model

$$H = \frac{1}{2}\sum_{\ell,\ell'}^{N}\sum_{j,j'}^{n} J_{\ell\ell' jj'}\,\mathbf{S}_{\ell j}\cdot\mathbf{S}_{\ell' j'} \to \sum_{\nu=1}^{n}\sum_{\mathbf{q}\in 1\mathrm{BZ}} \omega_{\nu,\mathbf{q}} b^\dagger_{\nu,\mathbf{q}} b_{\nu,\mathbf{q}}$$





[Trickle, Zhang, Zurek — PRL 2020, 1905.13744]

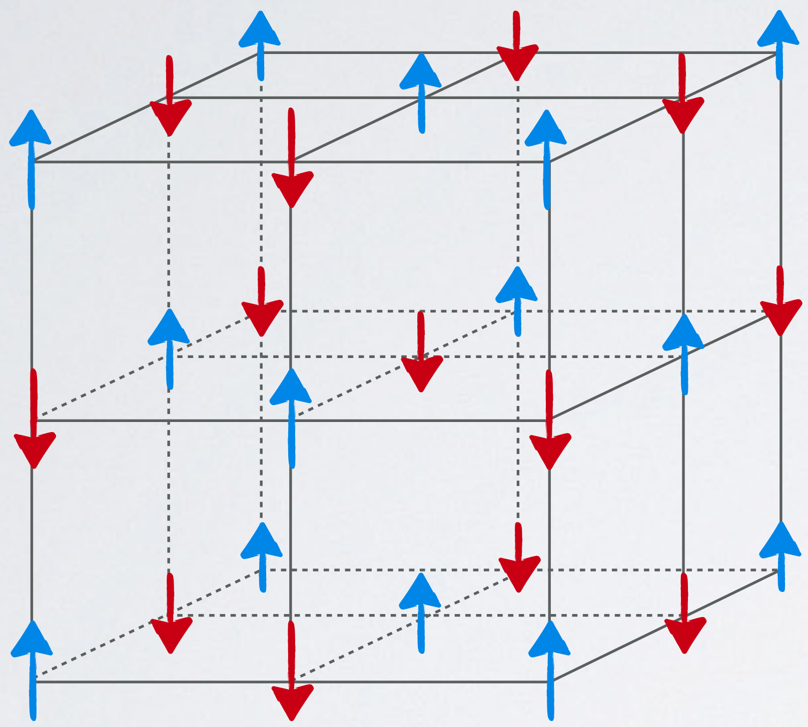
ANTI-FERROMAGNETS

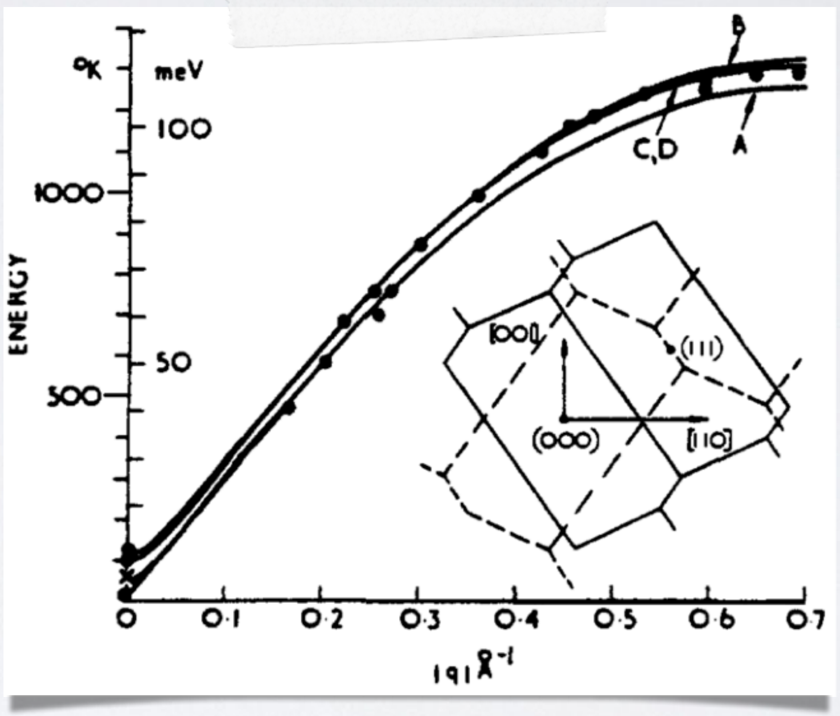
ANTI-FERROMAGNETS

- A better class of materials turns out to be *anti*-ferromagnets

ANTI-FERROMAGNETS

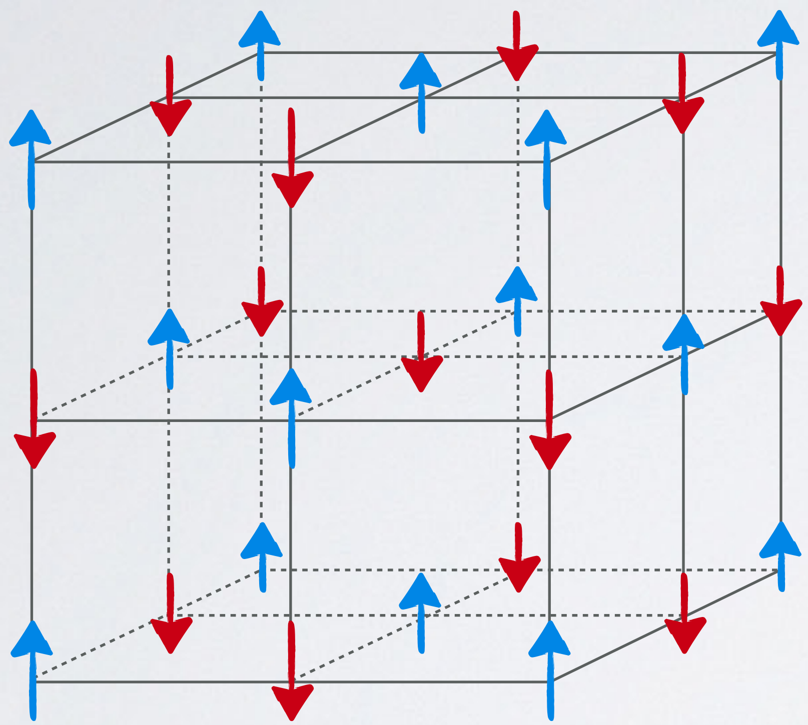
- A better class of materials turns out to be *anti*-ferromagnets

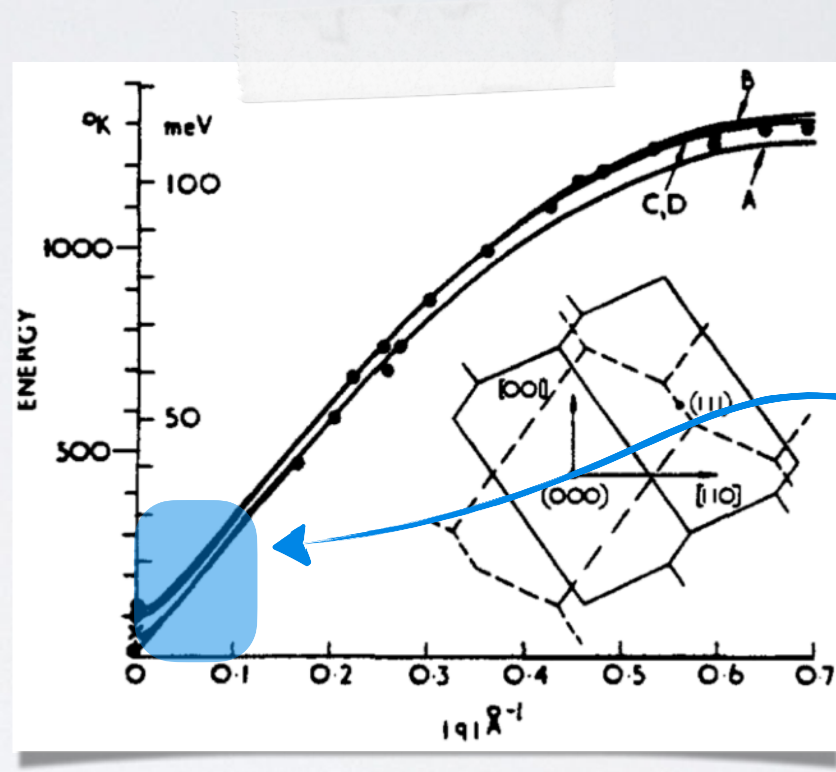




ANTI-FERROMAGNETS

- A better class of materials turns out to be *anti*-ferromagnets



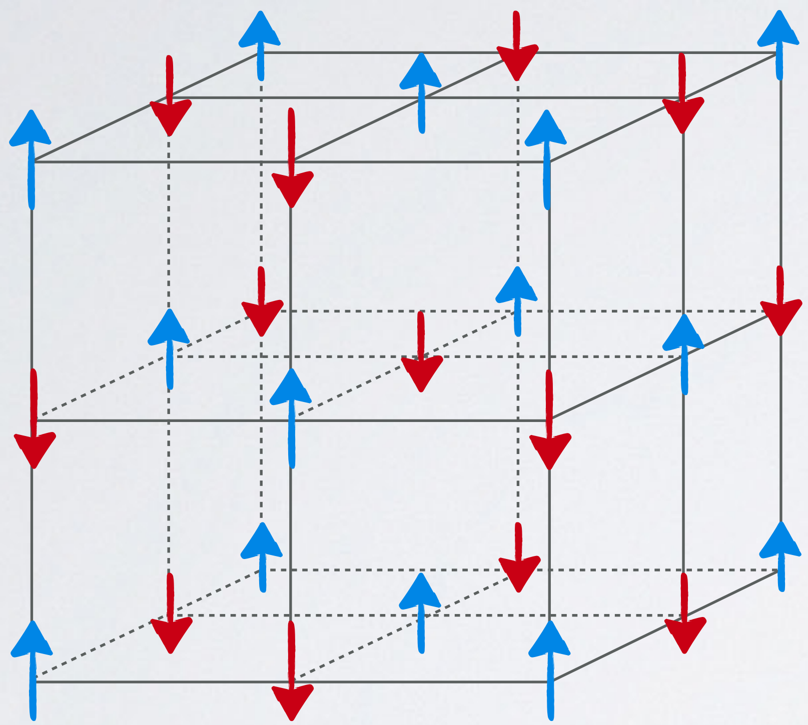


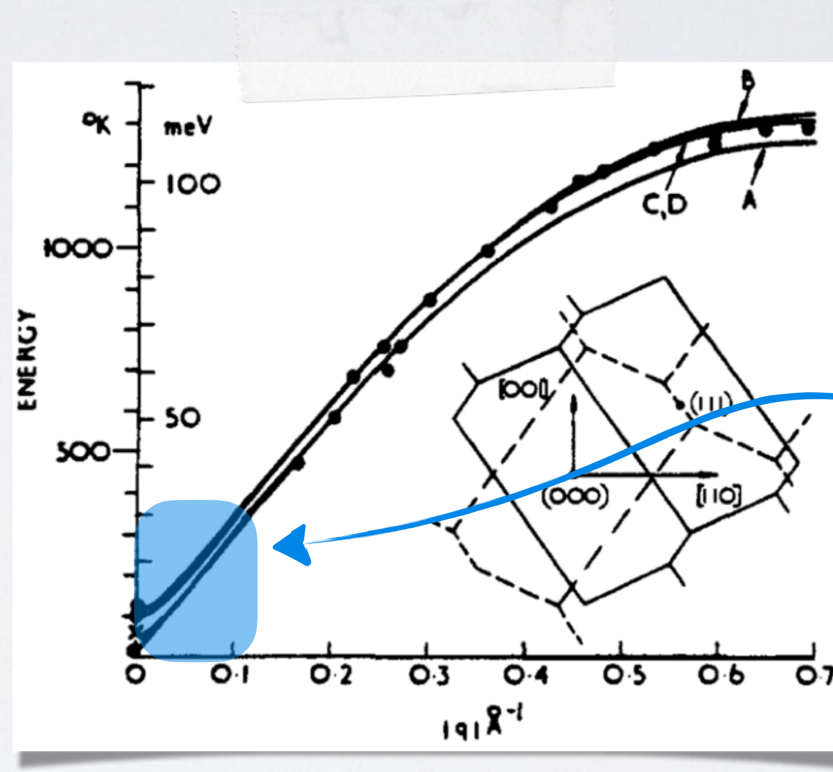
gapless magnons have

$$\omega(q) = v_\theta \, q$$

ANTI-FERROMAGNETS

- A better class of materials turns out to be *anti*-ferromagnets





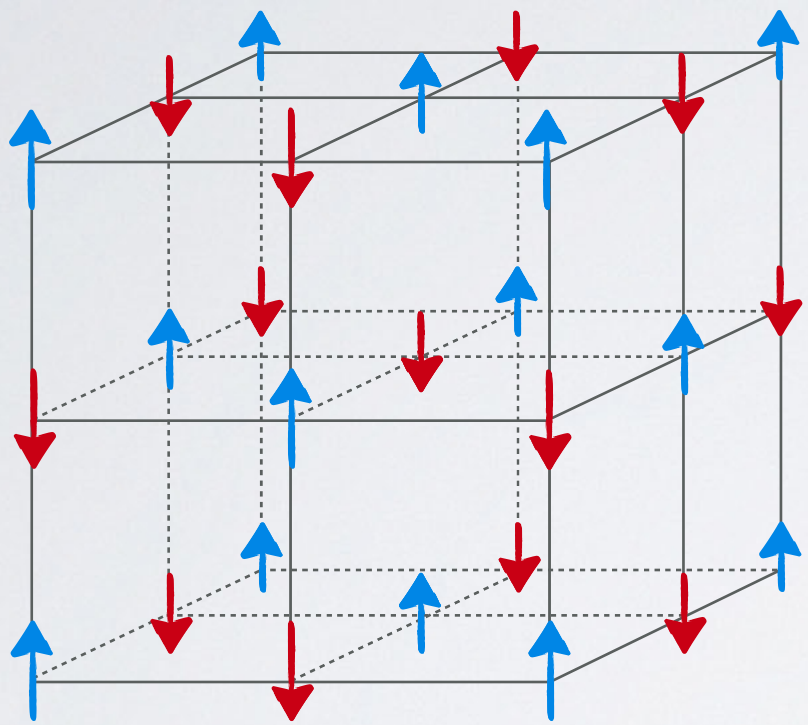
gapless magnons have

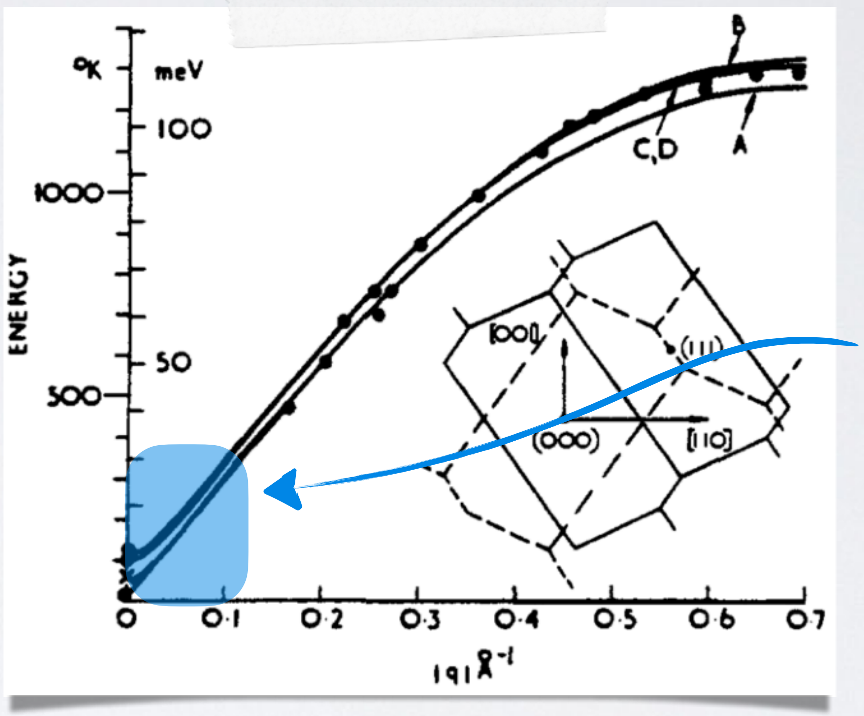
$$\omega(q) = v_\theta\, q$$

- For single-magnon emission: $\omega_{\max} = 4\,E_\chi\,(v_\theta/v_\chi)\left[1-(v_\theta/v_\chi)\right]$

ANTI-FERROMAGNETS

- A better class of materials turns out to be *anti*-ferromagnets





gapless magnons have
$$\omega(q) = v_\theta \, q$$

- For single-magnon emission: $\omega_{\max} = 4\,E_\chi \left(v_\theta / v_\chi\right) \left[1 - \left(v_\theta / v_\chi\right)\right]$

- Nickel-oxide has $v_\theta \sim v_\chi$ → very efficient at absorbing dark matter energy [**AE**, Pavaskar — PRD (2023), 2210.13516]

ANTI-FERROMAGNETS

ANTI-FERROMAGNETS

- Magnons in anti-ferromagnets have two polarizations, analogous to particle and anti-particle in a relativistic theory

ANTI-FERROMAGNETS

- Magnons in anti-ferromagnets have two polarizations, analogous to particle and anti-particle in a relativistic theory

- Dark matter couples to spin density $\rightarrow$ an object with "charge" 0 or 1

ANTI-FERROMAGNETS

- Magnons in anti-ferromagnets have two polarizations, analogous to particle and anti-particle in a relativistic theory

- Dark matter couples to spin density $\rightarrow$ an object with "charge" 0 or 1

- Contrary to ferromagnets, in anti-ferromagnets you can always emit magnon and anti-magnon pairs and compensate for the charge

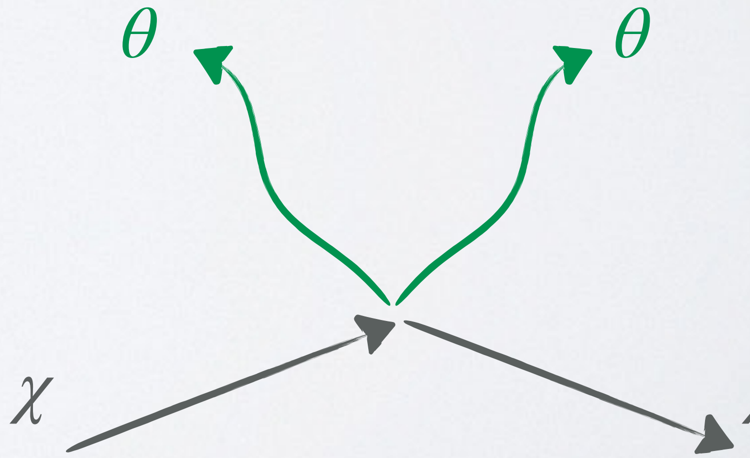
ANTI-FERROMAGNETS

- Magnons in anti-ferromagnets have two polarizations, analogous to particle and anti-particle in a relativistic theory

- Dark matter couples to spin density $\longrightarrow$ an object with "charge" 0 or 1

- Contrary to ferromagnets, in anti-ferromagnets you can always emit magnon and anti-magnon pairs and compensate for the charge

- Multi-magnon emission process evade the kinematical constraints and get down to $m_\chi \sim \mathcal{O}(\text{keV})$



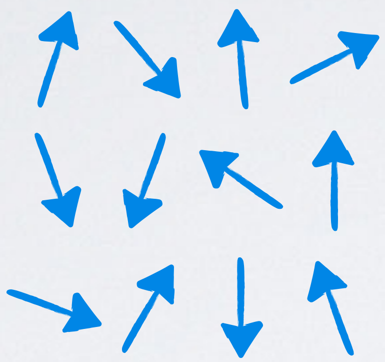
MAGNONS

MAGNONS

- Anti-ferromagnets spontaneously break internal spin symmetry

MAGNONS

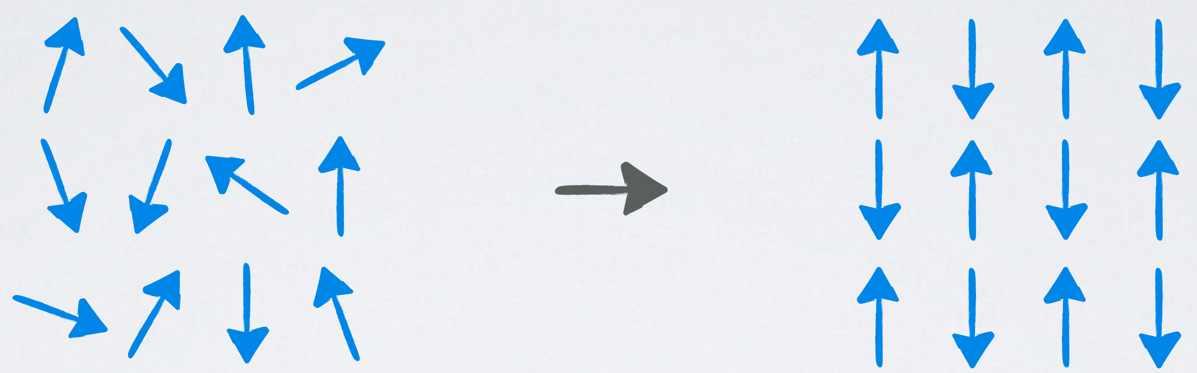
- Anti-ferromagnets spontaneously break internal spin symmetry



$SO(3)$

MAGNONS

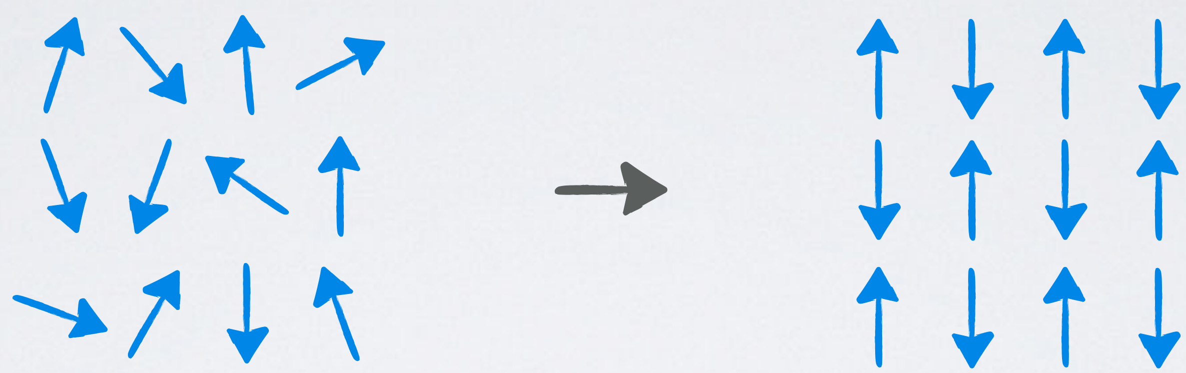
- Anti-ferromagnets spontaneously break internal spin symmetry



$SO(3) \rightarrow SO(2)$

MAGNONS

- Anti-ferromagnets spontaneously break internal spin symmetry



$SO(3)$ $\rightarrow$ $SO(2)$

Gapless magnon = Goldstone

MAGNONS

- Anti-ferromagnets spontaneously break internal spin symmetry

Gapless magnon = Goldstone

- At low energies/momenta magnons can be described by an EFT, invariant under the full symmetry group

MAGNONS

- Anti-ferromagnets spontaneously break internal spin symmetry

Gapless magnon = Goldstone

- At low energies/momenta magnons can be described by an EFT, invariant under the full symmetry group

- Let's build it!

MAGNONS

MAGNONS

- Very similar to the non-linear σ-model:

MAGNONS

- Very similar to the non-linear $\boldsymbol{\sigma}$-model:

$$\mathbf{n}(x) = e^{i\left[\theta^1(x)\, J_1 + \theta^2(x)\, J_2\right]} \cdot \hat{\mathbf{z}} \xrightarrow{SO(3)} R \cdot \mathbf{n}(x)$$

magnon fields, $\theta^a(x) \sim \varepsilon^a\, a_k + \varepsilon^{a*}\, a_k^\dagger$

MAGNONS

- Very similar to the non-linear $\boldsymbol{\sigma}$-model:

$$\mathbf{n}(x) = e^{i\left[\theta^1(x)\,J_1 + \theta^2(x)\,J_2\right]} \cdot \hat{\mathbf{z}} \xrightarrow{SO(3)} R \cdot \mathbf{n}(x)$$

magnon fields, $\theta^a(x) \sim \varepsilon^a\, a_k + \varepsilon^{a*}\, a_k^\dagger$

- At lowest order in the derivative expansion, the most general invariant Lagrangian (density) is

MAGNONS

- Very similar to the non-linear $\boldsymbol{\sigma}$-model:

$$\mathbf{n}(x) = e^{i\left[\theta^1(x)\,J_1 + \theta^2(x)\,J_2\right]} \cdot \hat{\mathbf{z}} \xrightarrow{SO(3)} R \cdot \mathbf{n}(x)$$

magnon fields, $\theta^a(x) \sim \varepsilon^a\, a_k + \varepsilon^{a*}\, a_k^\dagger$

- At lowest order in the derivative expansion, the most general invariant Lagrangian (density) is

$$\mathscr{L} = c_1 \dot{\mathbf{n}}^2 - c_2 \left(\nabla_i \mathbf{n}\right)^2$$

MAGNONS

- Very similar to the non-linear $\boldsymbol{\sigma}$-model:

$$\mathbf{n}(x) = e^{i\left[\theta^1(x)\, J_1 + \theta^2(x)\, J_2\right]} \cdot \hat{\mathbf{z}} \xrightarrow{SO(3)} R \cdot \mathbf{n}(x)$$

magnon fields, $\theta^a(x) \sim \varepsilon^a\, a_k + \varepsilon^{a*}\, a_k^\dagger$

- At lowest order in the derivative expansion, the most general invariant Lagrangian (density) is

$$\mathscr{L} = c_1 \dot{\mathbf{n}}^2 - c_2 \left(\nabla_i \mathbf{n}\right)^2$$

$$= c_1 (\dot{\theta}^a)^2 - c_2 (\vec{\nabla}\theta^a)^2 + \dots$$

MAGNONS

- Very similar to the non-linear σ-model:

$$\mathbf{n}(x) = e^{i\left[\theta^1(x)\,J_1 + \theta^2(x)\,J_2\right]} \cdot \hat{\mathbf{z}} \xrightarrow{SO(3)} R \cdot \mathbf{n}(x)$$

magnon fields, $\theta^a(x) \sim \varepsilon^a\, a_k + \varepsilon^{a*}\, a_k^\dagger$

- At lowest order in the derivative expansion, the most general invariant Lagrangian (density) is

$$\mathscr{L} = c_1 \dot{\mathbf{n}}^2 - c_2 \left(\nabla_i \mathbf{n}\right)^2$$

$$= c_1 (\dot{\theta}^a)^2 - c_2 (\vec{\nabla}\theta^a)^2 + \dots$$

can be extracted from dispersion relation + neutron scattering data

$v_\theta = c_2/c_1$

$\sigma_n \propto c_1$

[Pavaskar, Penco, Rothstein – SciPost Phys. (2022), 2112.13873; **AE**, Pavaskar – PRD (2023), 2210.13516]

MAGNONS

MAGNONS

- Recall that the dark matter interacts via spin density, $\mathbf{s}(x)$

MAGNONS

- Recall that the dark matter interacts via spin density, $\mathbf{s}(x)$
- Easily computed as $SO(3)$ Noether current in the EFT:

MAGNONS

- Recall that the dark matter interacts via spin density, $\mathbf{s}(x)$
- Easily computed as $SO(3)$ Noether current in the EFT:

$$s_i = c_1 \, (\mathbf{n} \times \dot{\mathbf{n}})_i = c_1 \left[\delta_{ia} \, \dot{\theta}^a + \delta_{i3} \, \epsilon_{ab} \, \theta^a \, \dot{\theta}^b + \ldots \right]$$

[**AE**, Pavaskar – PRD (2023), 2210.13516]

MAGNONS

- Recall that the dark matter interacts via spin density, $\mathbf{s}(x)$
- Easily computed as $SO(3)$ Noether current in the EFT:

$$s_i = c_1\,(\mathbf{n}\times\dot{\mathbf{n}})_i = c_1\left[\delta_{ia}\,\dot{\theta}^a + \delta_{i3}\,\epsilon_{ab}\,\theta^a\,\dot{\theta}^b + \dots\right]$$

[**AE**, Pavaskar – PRD (2023), 2210.13516]

one-magnon emission

MAGNONS

- Recall that the dark matter interacts via spin density, $\mathbf{s}(x)$
- Easily computed as $SO(3)$ Noether current in the EFT:

$$s_i = c_1 \,(\mathbf{n} \times \dot{\mathbf{n}})_i = c_1 \left[\delta_{ia}\,\dot{\theta}^a + \delta_{i3}\,\epsilon_{ab}\,\theta^a\,\dot{\theta}^b + \dots\right]$$

[**AE**, Pavaskar — PRD (2023), 2210.13516]

one-magnon emission

two-magnons emission

MAGNONS

- Recall that the dark matter interacts via spin density, $\mathbf{s}(x)$
- Easily computed as $SO(3)$ Noether current in the EFT:

$$s_i = c_1 \, (\mathbf{n} \times \dot{\mathbf{n}})_i = c_1 \left[\delta_{ia} \, \dot{\theta}^a + \delta_{i3} \, \epsilon_{ab} \, \theta^a \, \dot{\theta}^b + \ldots \right]$$

[**AE**, Pavaskar — PRD (2023), 2210.13516]

one-magnon emission

two-magnons emission

- Structure completely dictated by symmetry → just need c_1

MAGNONS

- Recall that the dark matter interacts via spin density, $\mathbf{s}(x)$
- Easily computed as $SO(3)$ Noether current in the EFT:

$$s_i = c_1\,(\mathbf{n}\times\dot{\mathbf{n}})_i = c_1\left[\delta_{ia}\,\dot\theta^a + \delta_{i3}\,\epsilon_{ab}\,\theta^a\,\dot\theta^b + \dots\right]$$

[**AE**, Pavaskar — PRD (2023), 2210.13516]

one-magnon emission

two-magnons emission

- Structure completely dictated by symmetry → just need c_1
- This allows to bypass difficulties in the standard treatment (failure of the Holsten-Primakoff approach) [Dyson — Phys. Rev. 1956]

IDEAL REACH

IDEAL REACH

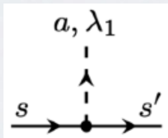
- Just like before, use standard QFT methods to compute event rates

[**AE**, Pavaskar — PRD (2023), 2210.13516]

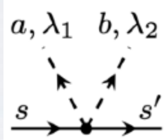
IDEAL REACH

- Just like before, use standard QFT methods to compute event rates

[**AE**, Pavaskar — PRD (2023), 2210.13516]



$$= -\frac{g_\chi g_e \sqrt{c_1}}{m_e}\omega \times \begin{cases} \frac{4}{\Lambda_\chi} P_{ia}(\boldsymbol{q})\sigma^i & \text{m.d.} \\ q^a/q^2 & \text{p.m.} \end{cases},$$

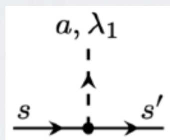


$$= \frac{g_\chi g_e}{m_e}(\omega_1 - \omega_2)\epsilon_{ab} \times \begin{cases} \frac{4}{\Lambda_\chi} P_{iz}(\boldsymbol{q})\sigma^i & \text{m.d.} \\ q^z/q^2 & \text{p.m.} \end{cases}$$

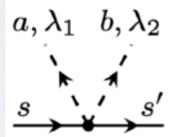
IDEAL REACH

- Just like before, use standard QFT methods to compute event rates

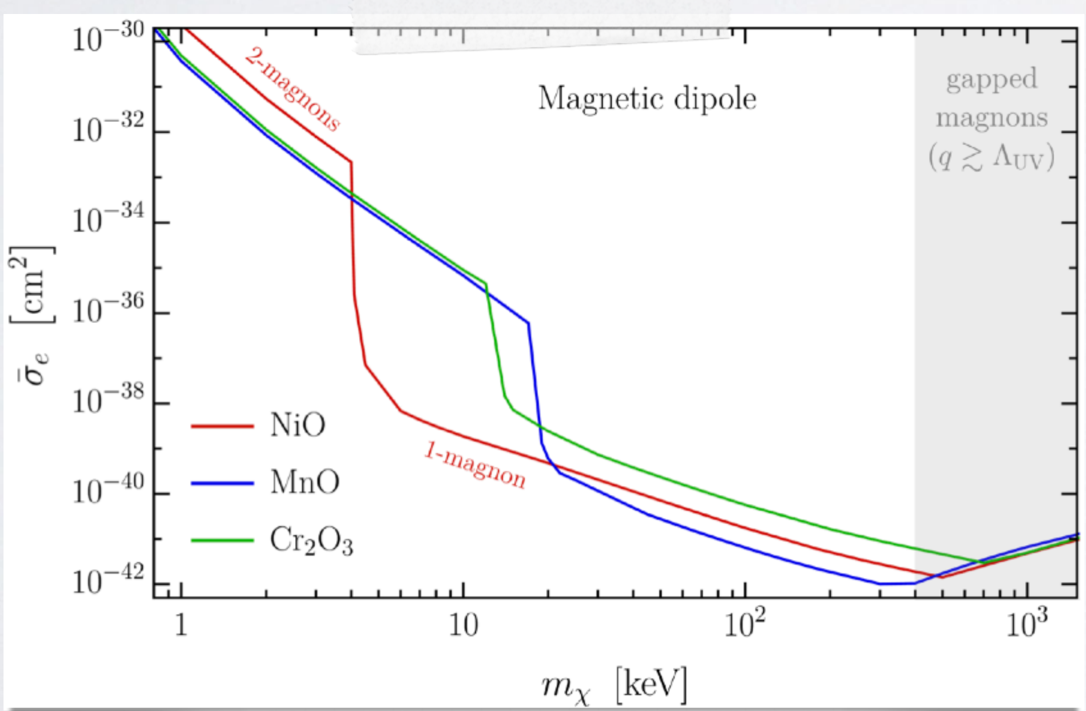
[**AE**, Pavaskar — PRD (2023), 2210.13516]

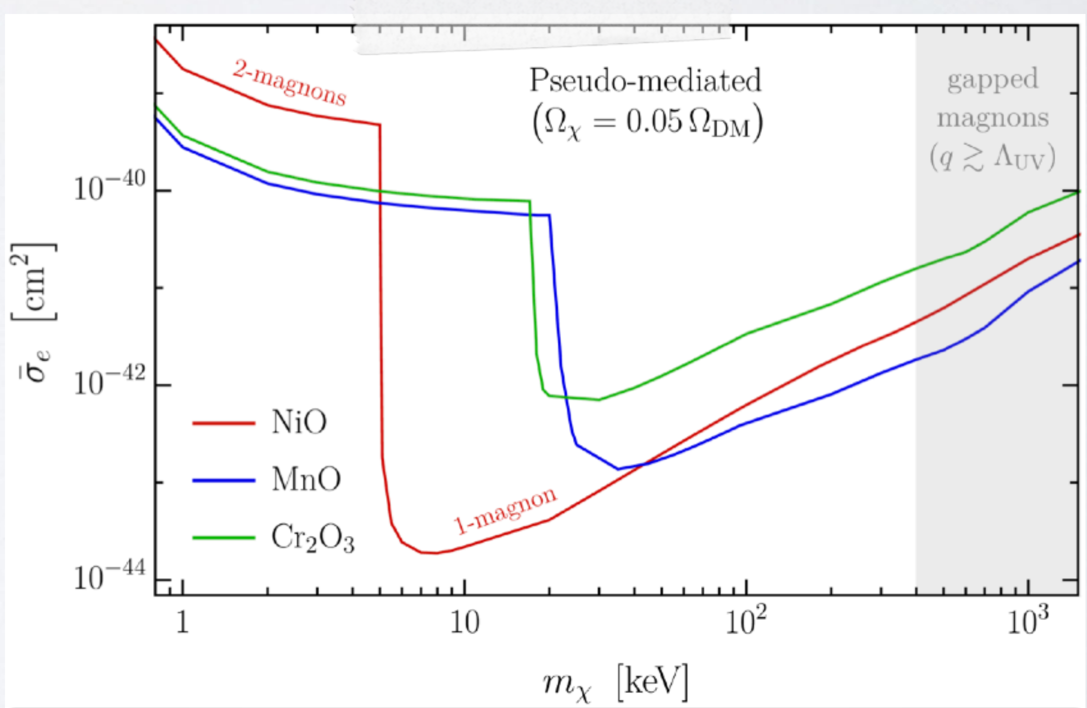


$$= -\frac{g_\chi g_e \sqrt{c_1}}{m_e}\,\omega \times \begin{cases} \frac{4}{\Lambda_\chi} P_{ia}(\boldsymbol{q})\sigma^i & \text{m.d.} \\ q^a/q^2 & \text{p.m.} \end{cases},$$



$$= \frac{g_\chi g_e}{m_e}(\omega_1 - \omega_2)\epsilon_{ab} \times \begin{cases} \frac{4}{\Lambda_\chi} P_{iz}(\boldsymbol{q})\sigma^i & \text{m.d.} \\ q^z/q^2 & \text{p.m.} \end{cases}$$

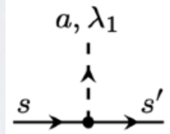




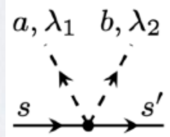
IDEAL REACH

- Just like before, use standard QFT methods to compute event rates

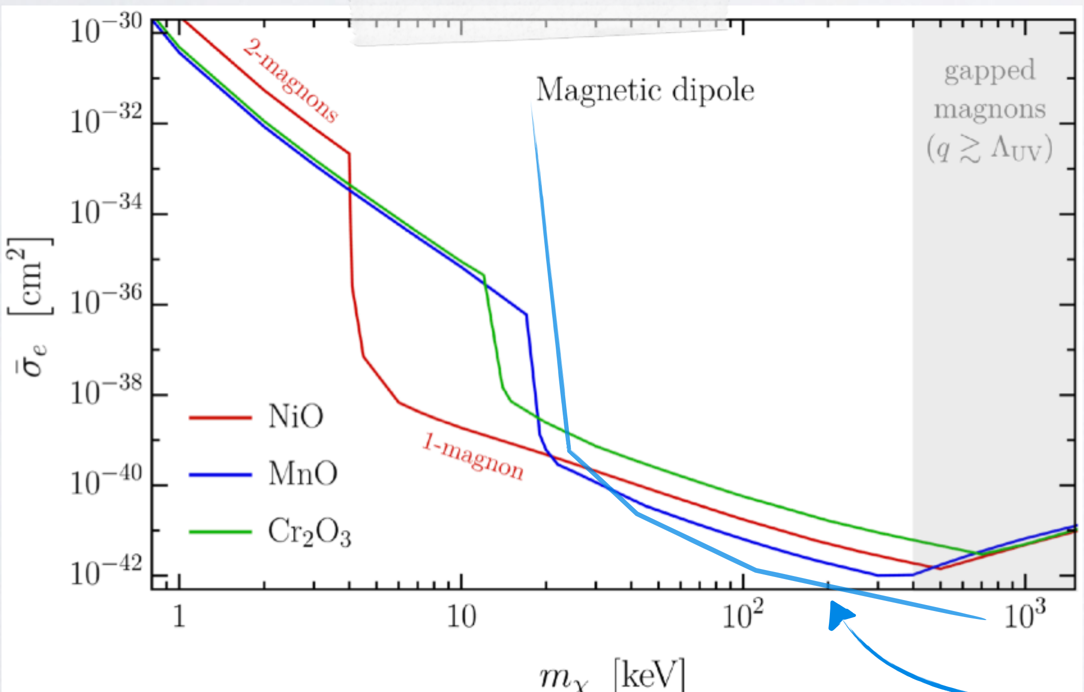
[**AE**, Pavaskar – PRD (2023), 2210.13516]

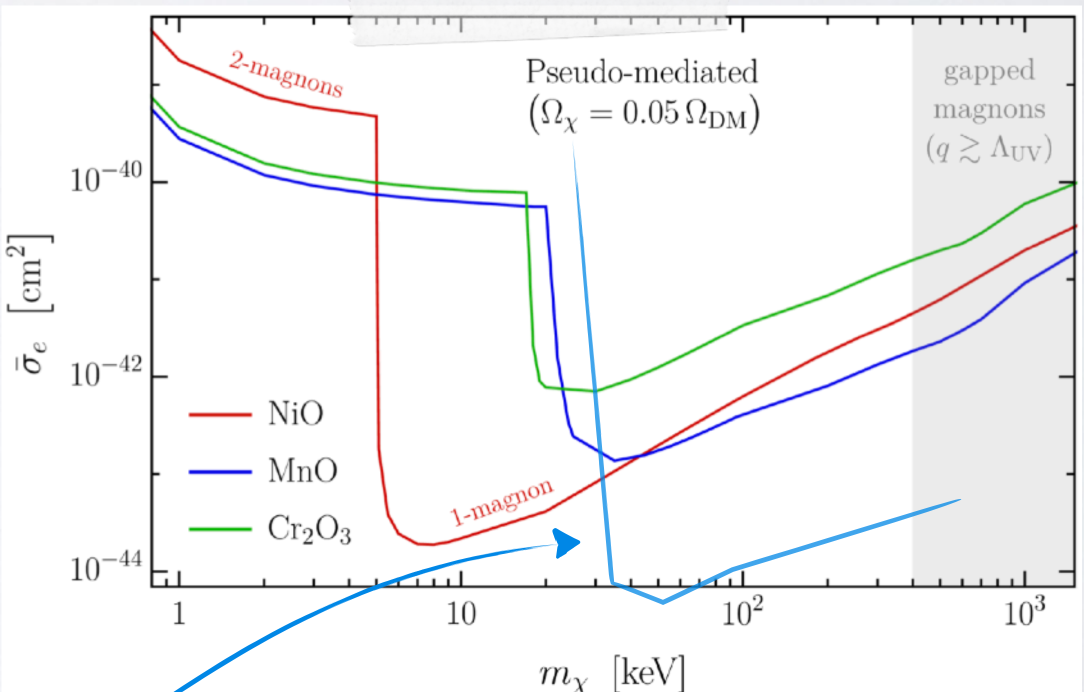


$$= -\frac{g_\chi g_e \sqrt{c_1}}{m_e}\omega \times \begin{cases} \frac{4}{\Lambda_\chi} P_{ia}(\boldsymbol{q})\sigma^i & \text{m.d.} \\ q^a/q^2 & \text{p.m.} \end{cases},$$



$$= \frac{g_\chi g_e}{m_e}(\omega_1 - \omega_2)\epsilon_{ab} \times \begin{cases} \frac{4}{\Lambda_\chi} P_{iz}(\boldsymbol{q})\sigma^i & \text{m.d.} \\ q^z/q^2 & \text{p.m.} \end{cases}$$





ferromagnets

QCD AXION: A SNEAK PEAK

QCD AXION: A SNEAK PEAK

- The very same setup can be used to look for QCD axion dark matter, coupling to electrons

QCD AXION: A SNEAK PEAK

- The very same setup can be used to look for QCD axion dark matter, coupling to electrons

- The axion can be absorbed by the antiferromagnet:

QCD AXION: A SNEAK PEAK

- The very same setup can be used to look for QCD axion dark matter, coupling to electrons

- The axion can be absorbed by the antiferromagnet:

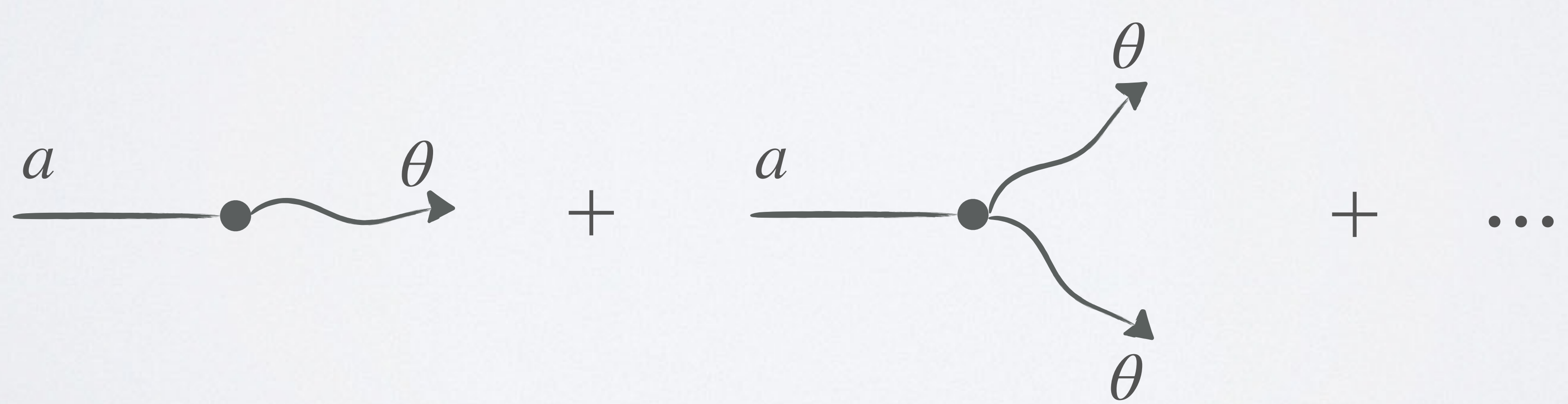
$$\mathscr{L} = \frac{g_{aee}}{2m_e}\partial_\mu a \, \bar{e}\gamma^\mu\gamma^5 e \xrightarrow{\text{NR}} \frac{g_{aee}}{m_e}\vec{\nabla} a \cdot \left(e^\dagger \frac{\vec{\sigma}}{2} e \right) \xrightarrow{\text{IR}} \frac{g_{aee}}{m_e}\vec{\nabla} a \cdot \vec{s}$$

QCD AXION: A SNEAK PEAK

- The very same setup can be used to look for QCD axion dark matter, coupling to electrons

- The axion can be absorbed by the antiferromagnet:

$$\mathscr{L} = \frac{g_{aee}}{2m_e}\partial_\mu a\, \bar{e}\gamma^\mu\gamma^5 e \xrightarrow{\text{NR}} \frac{g_{aee}}{m_e}\vec{\nabla} a \cdot \left(e^\dagger \frac{\vec{\sigma}}{2} e \right) \xrightarrow{\text{IR}} \frac{g_{aee}}{m_e}\vec{\nabla} a \cdot \vec{s}$$



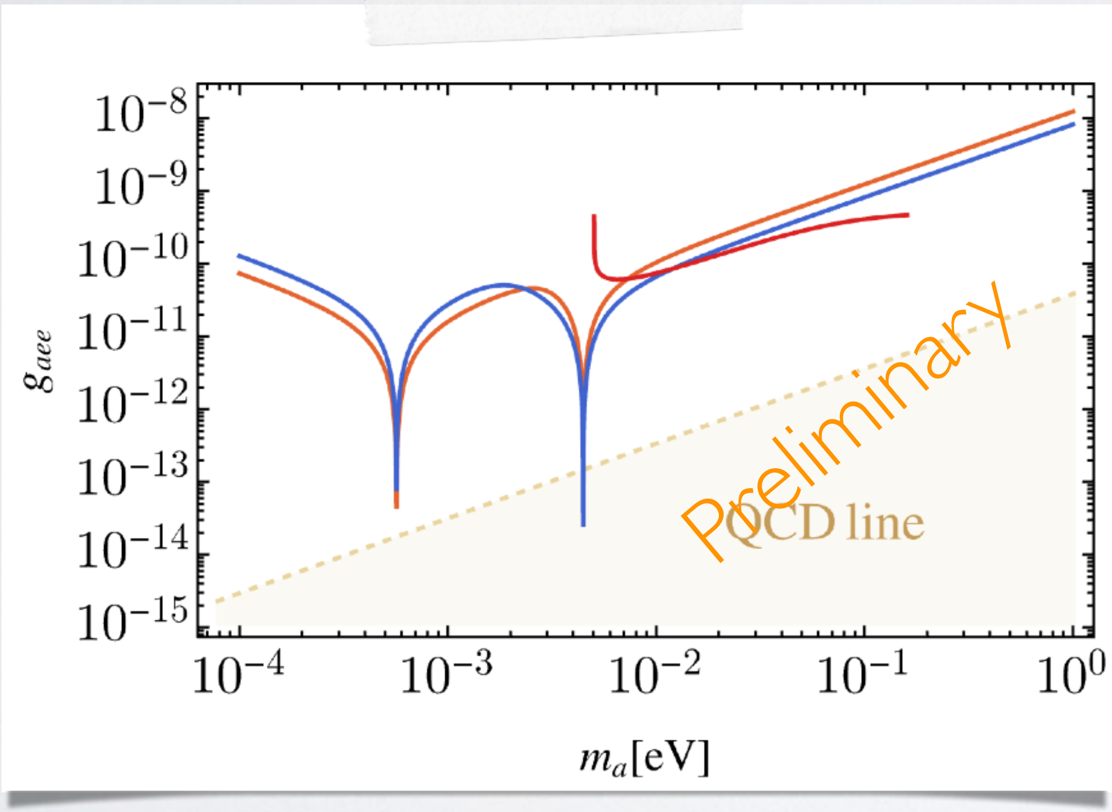
QCD AXION: A SNEAK PEAK

QCD AXION: A SNEAK PEAK

- Once one accounts for more details of the structure of NiO, the projection curves are very promising:

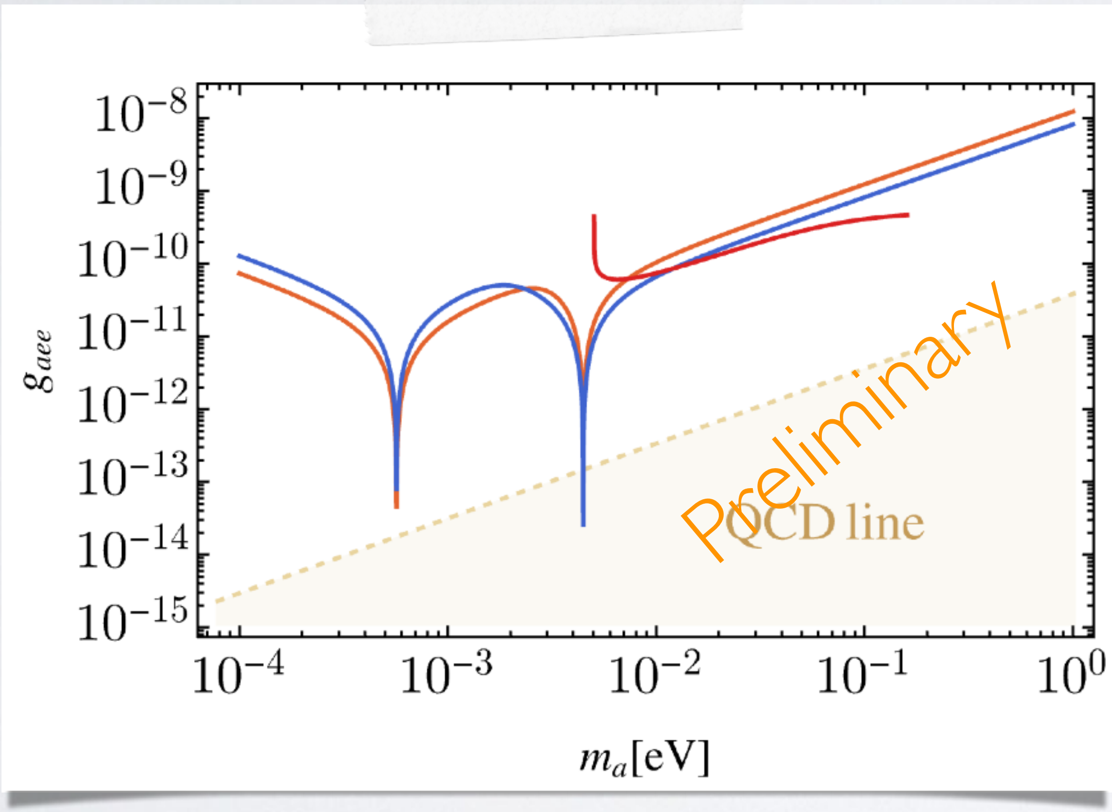
QCD AXION: A SNEAK PEAK

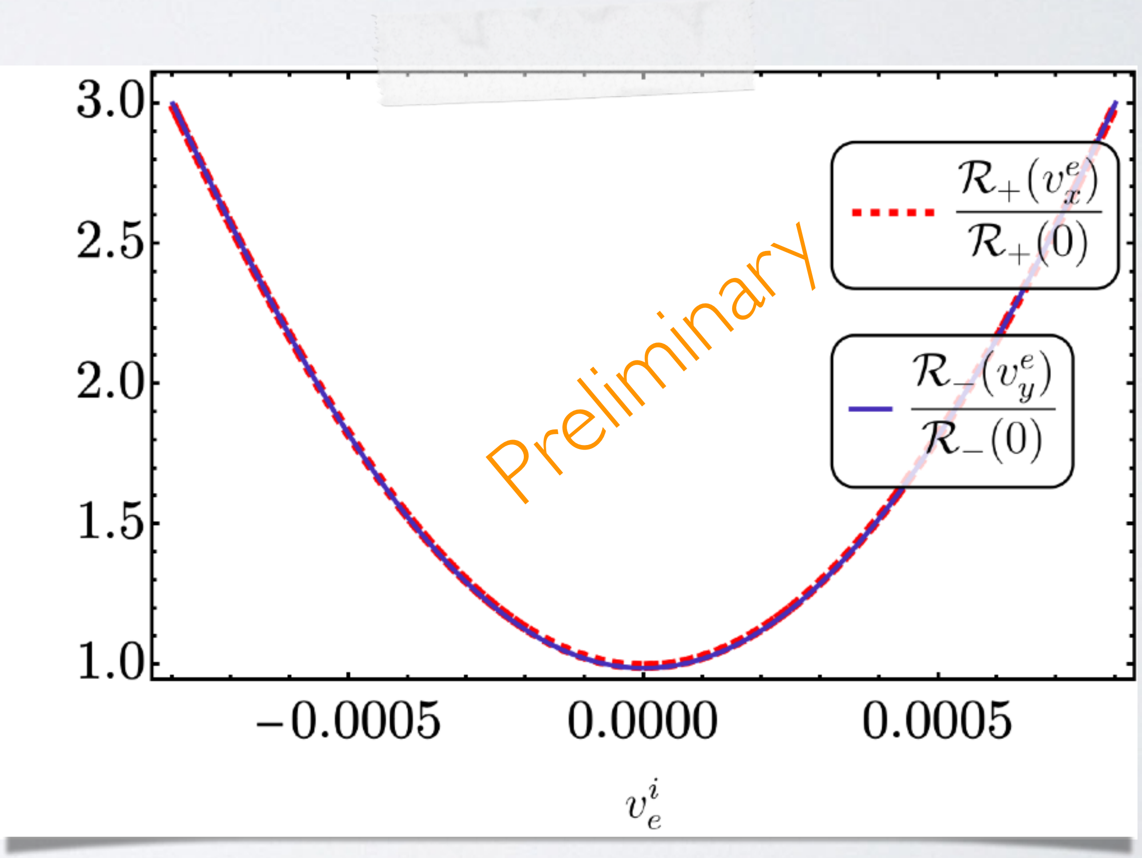
- Once one accounts for more details of the structure of NiO, the projection curves are very promising:



QCD AXION: A SNEAK PEAK

- Once one accounts for more details of the structure of NiO, the projection curves are very promising:





- With almost 300 % directionality

OUTLOOK

OUTLOOK

- The search for sub-MeV dark matter requires new ideas

OUTLOOK

- The search for sub-MeV dark matter requires new ideas
- One must delve in the condensed matter world

OUTLOOK

- The search for sub-MeV dark matter requires new ideas
- One must delve in the condensed matter world
- Very active field with plenty of exciting ideas

OUTLOOK

- The search for sub-MeV dark matter requires new ideas
- One must delve in the condensed matter world
- Very active field with plenty of exciting ideas
- Plethora of condensed matter phenomena can be an asset… but we must find a way of efficiently incorporating it in the particle physics language

OUTLOOK

- The search for sub-MeV dark matter requires new ideas
- One must delve in the condensed matter world
- Very active field with plenty of exciting ideas
- Plethora of condensed matter phenomena can be an asset… but we must find a way of efficiently incorporating it in the particle physics language
- A lot of work left to do!

OUTLOOK

- The search for sub-MeV dark matter requires new ideas
- One must delve in the condensed matter world
- Very active field with plenty of exciting ideas
- Plethora of condensed matter phenomena can be an asset… but we must find a way of efficiently incorporating it in the particle physics language
- A lot of work left to do!

Thank you for the attention!