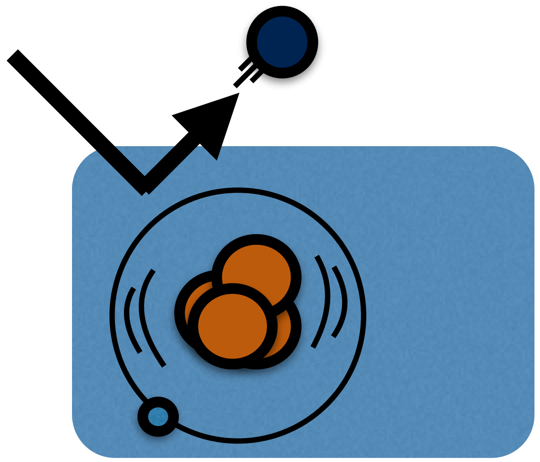
Superfluid Effective Field Theory for Dark Matter Direct Detection

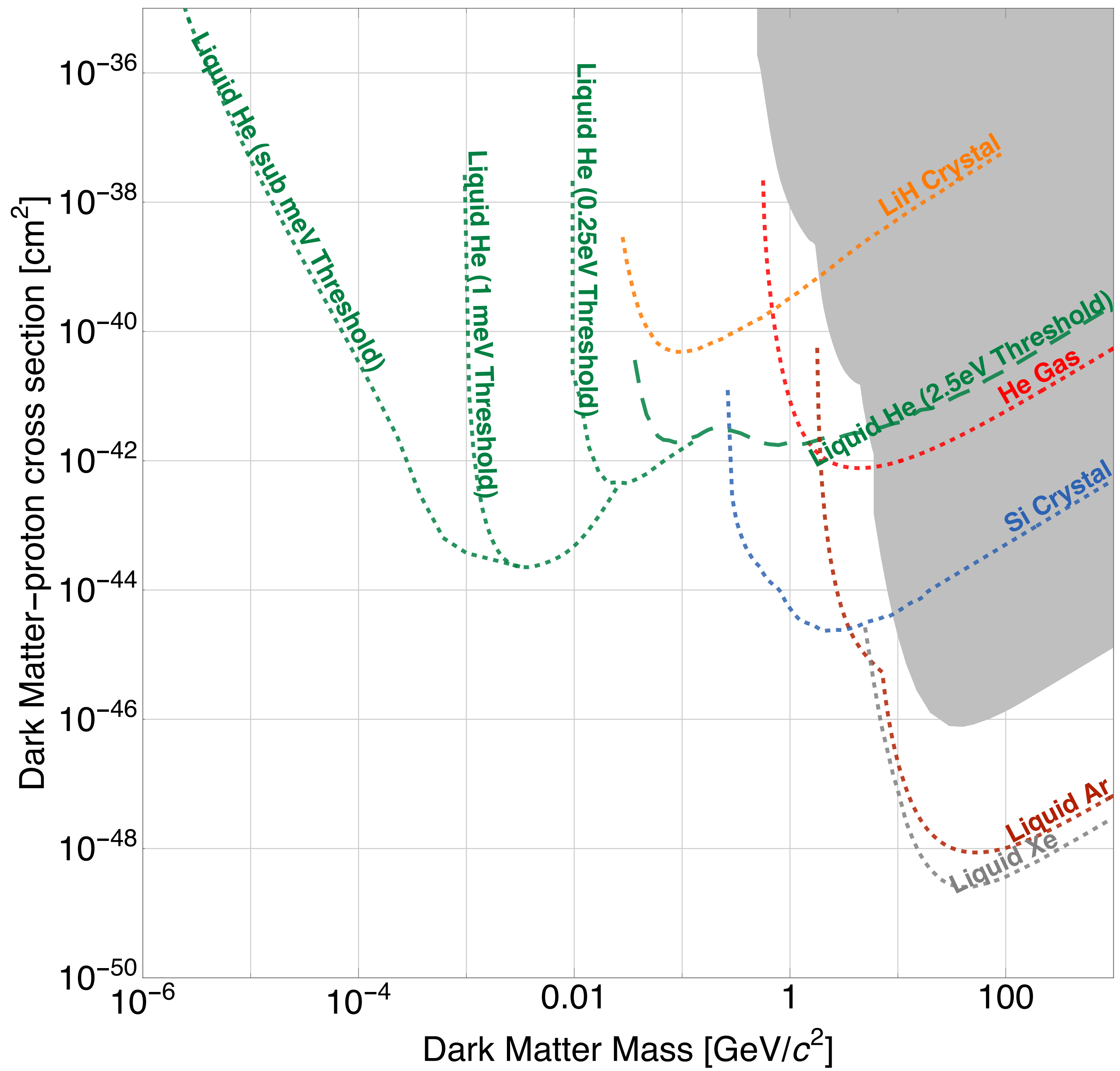
Wei Xue

June 9, 2022
CERN-CKC workshop

UF UNIVERSITY of FLORIDA

Dark matter direct detection





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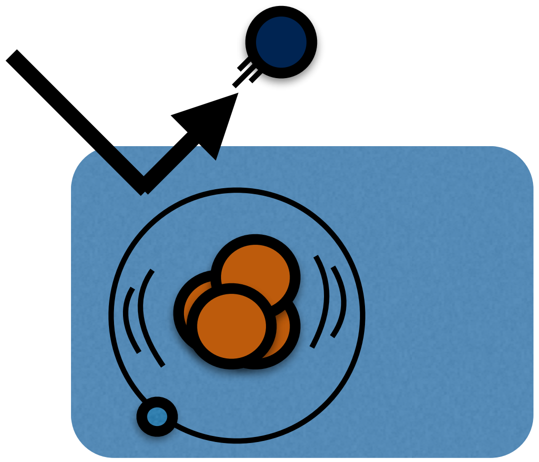
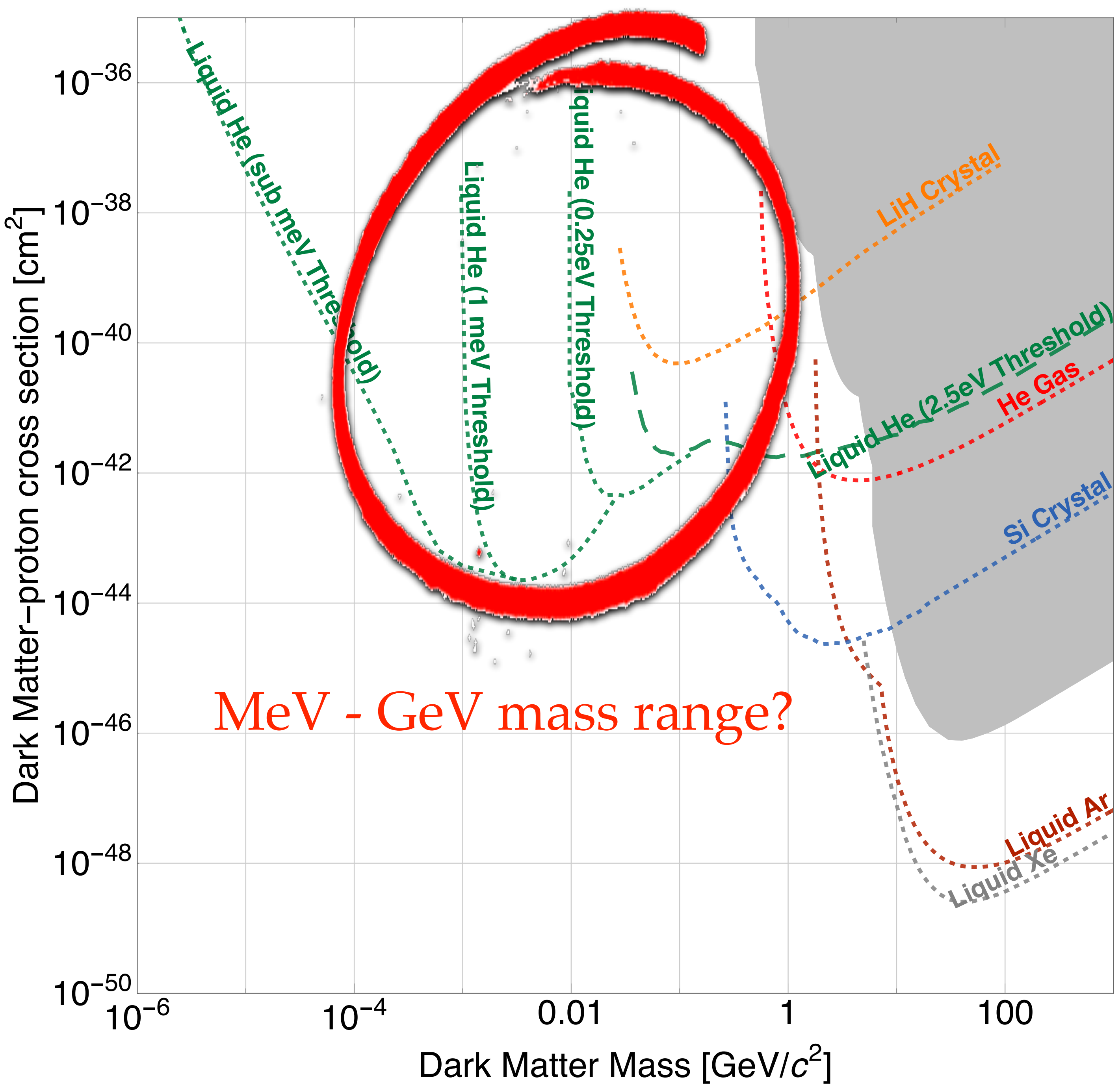




Plan

- theoretical framework to understand
  the quasi-particle production and thermalization

arXiv: 2108.07275

- simulation
  to know the momentum spectrum, flux, thermalization

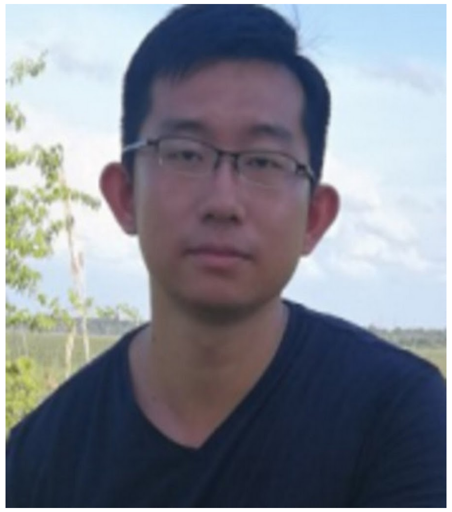
- a prototype experiment at University of Florida

Collaboration

Yoonseok Lee

Tarek Saab

Konstantin Matchev



Yining You

Jordan Smolinsky

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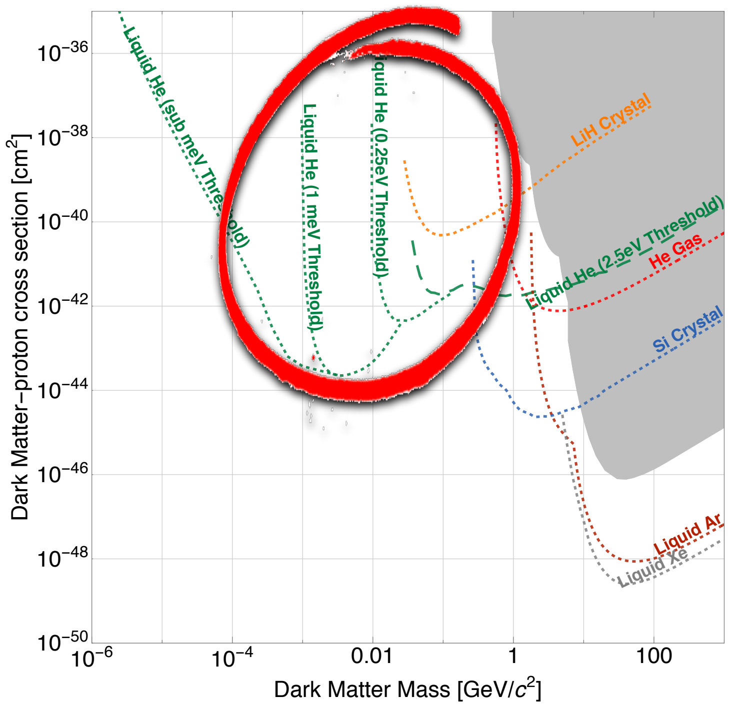
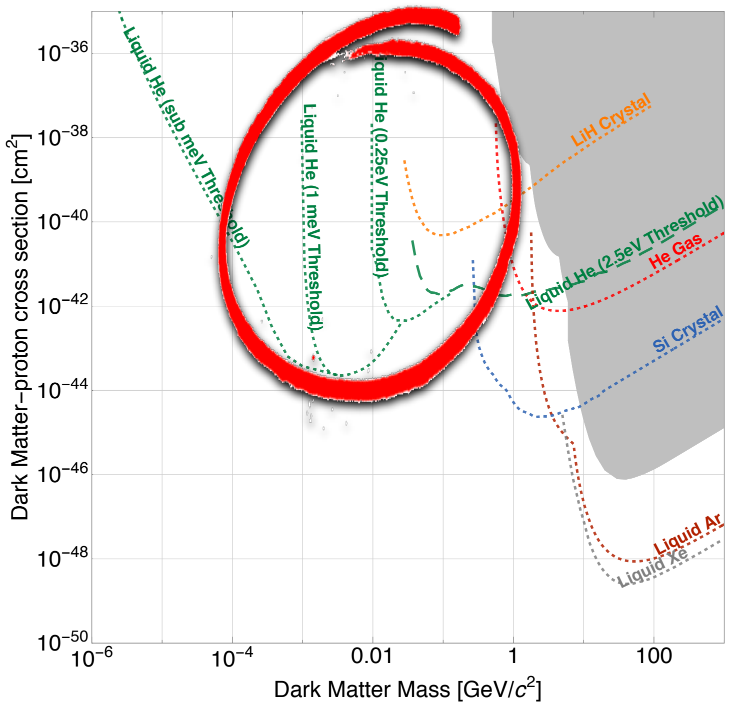
Why ^{4}He superfluid?



Why ^{4}He superfluid?

- Helium as the second lightest element an excellent target material for detecting light particles



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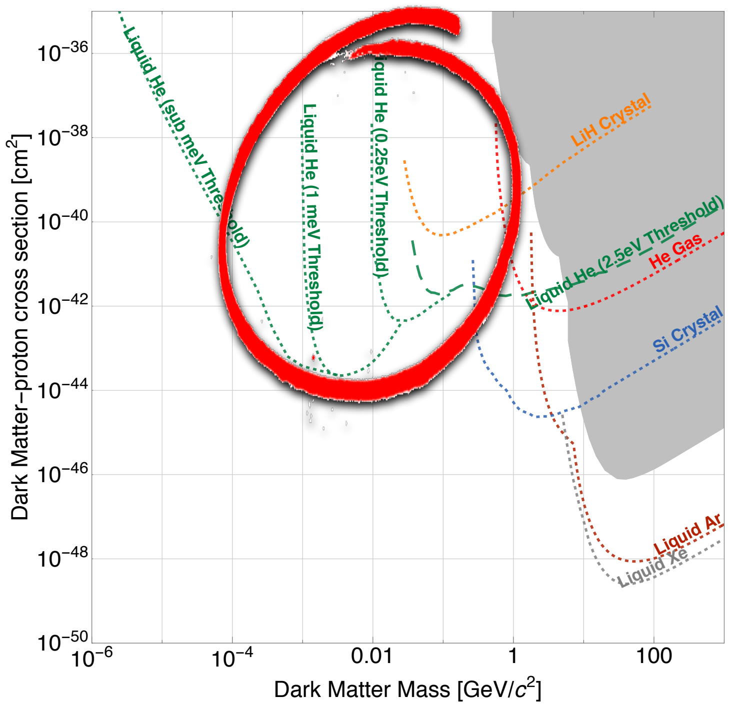

- Helium as the second lightest element an excellent target material for detecting light particles

- superfluid Helium will be cooled to ~0.1 K the system behaves as a vacuum sensitive to tiny perturbations

Previous studies and challenges on superfluid direct detection

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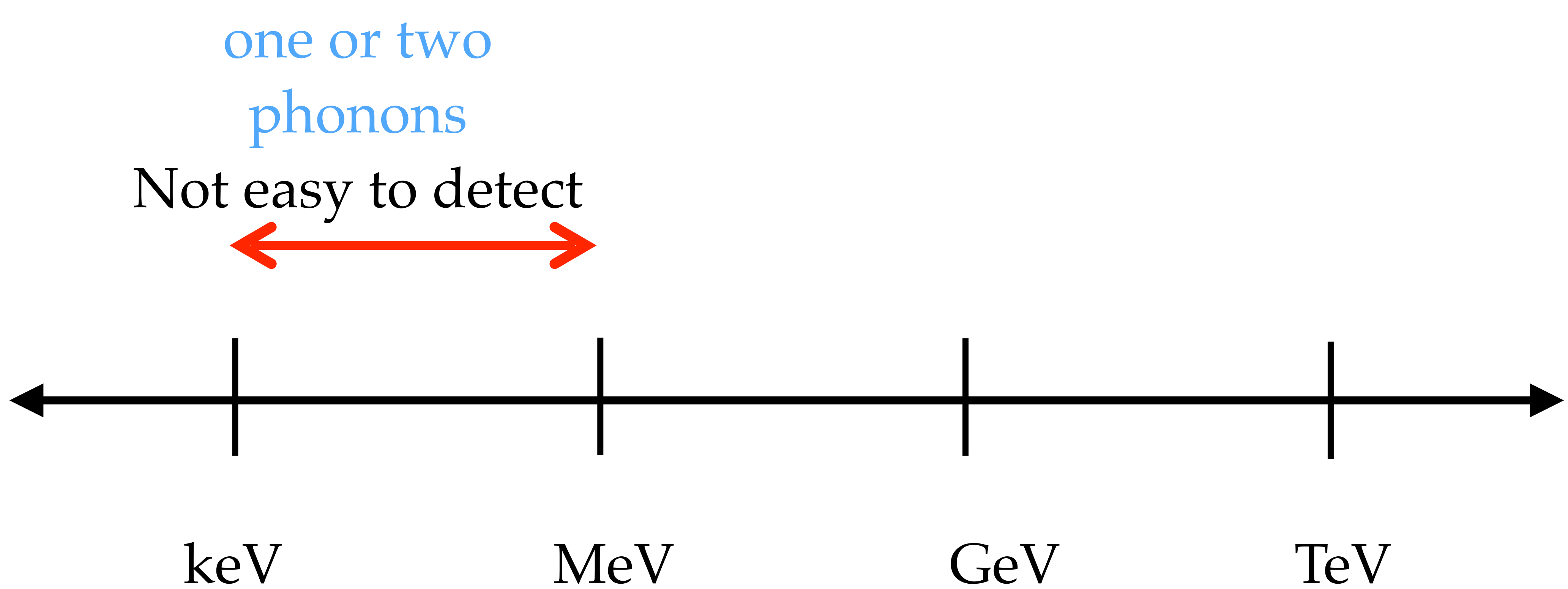

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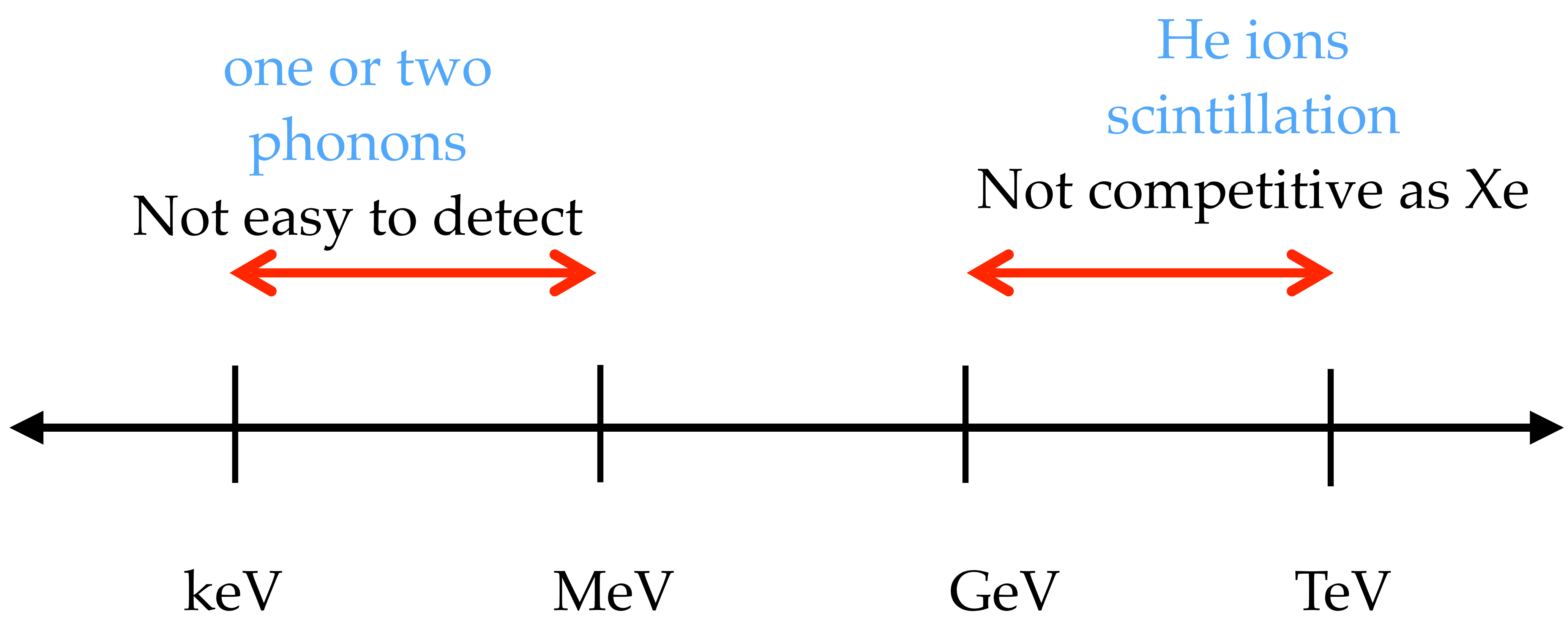

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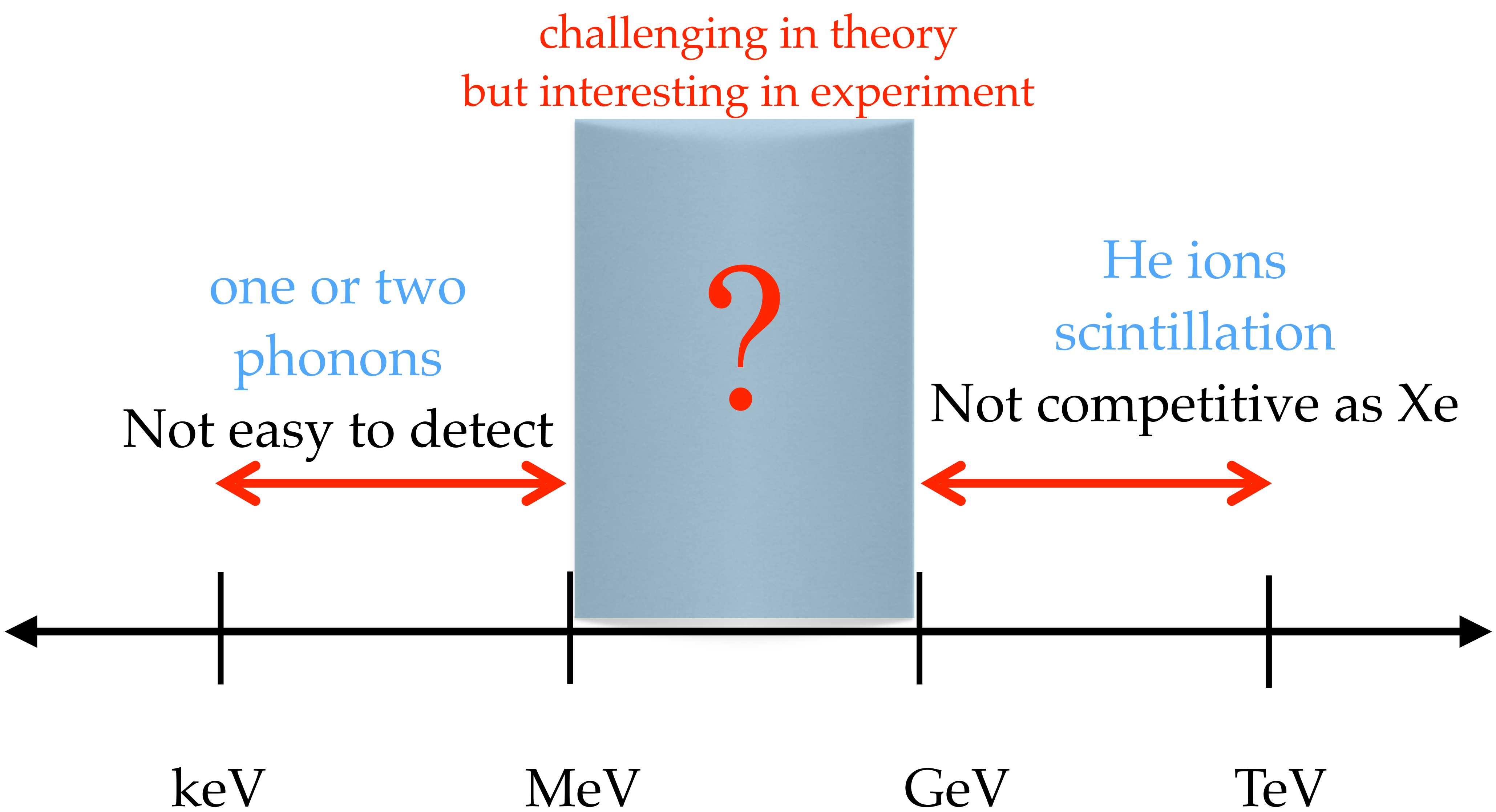

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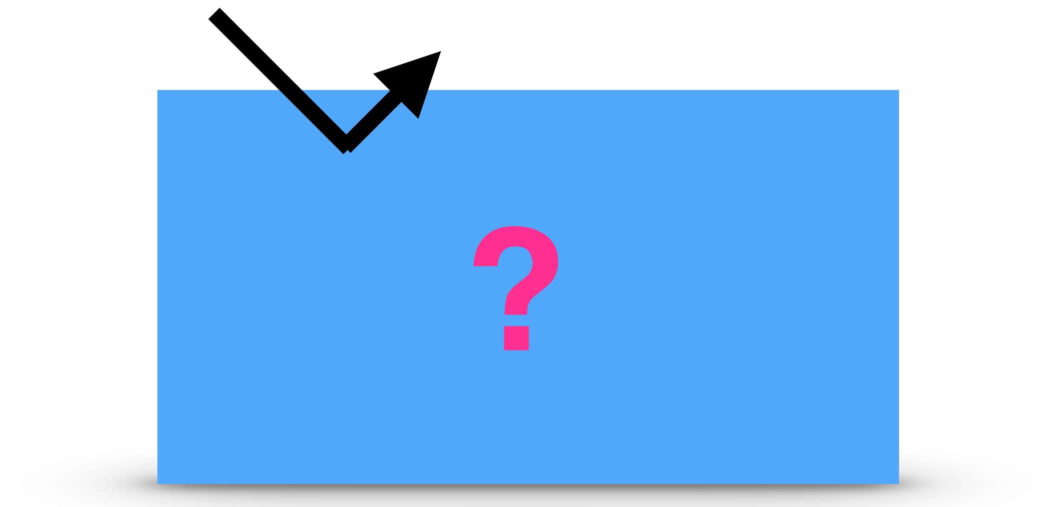
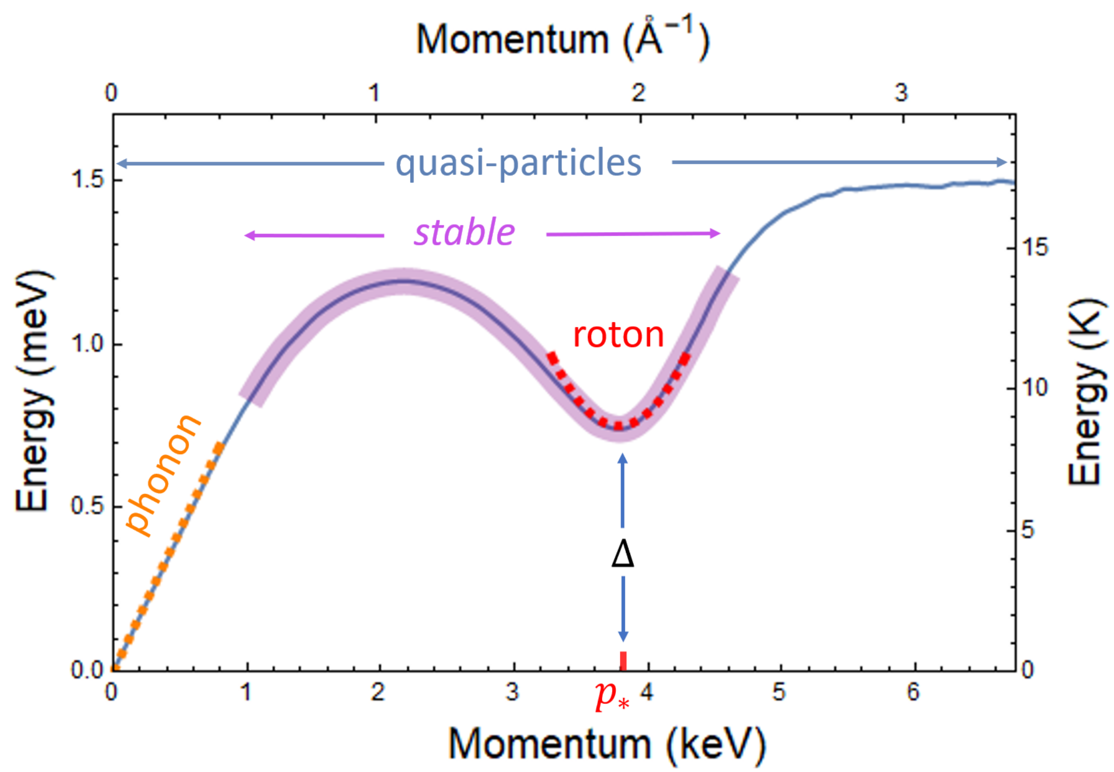
Challenges and motivations

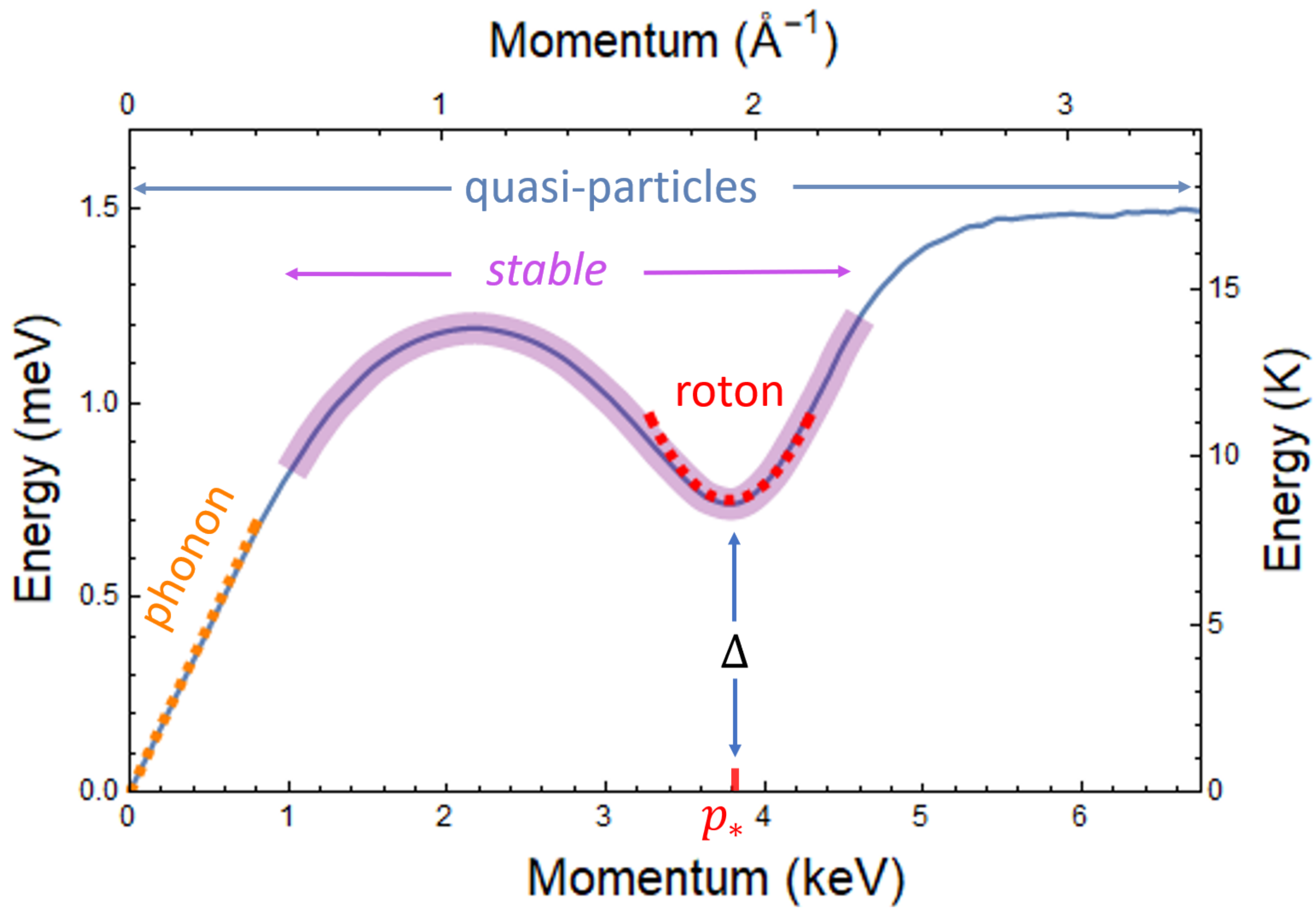
- What happens when a test particle (dark matter or neutron) scatters with the helium superfluid?



- The perturbative theory of superfluid break down ~ keV ?
(inverse of the helium spacing)

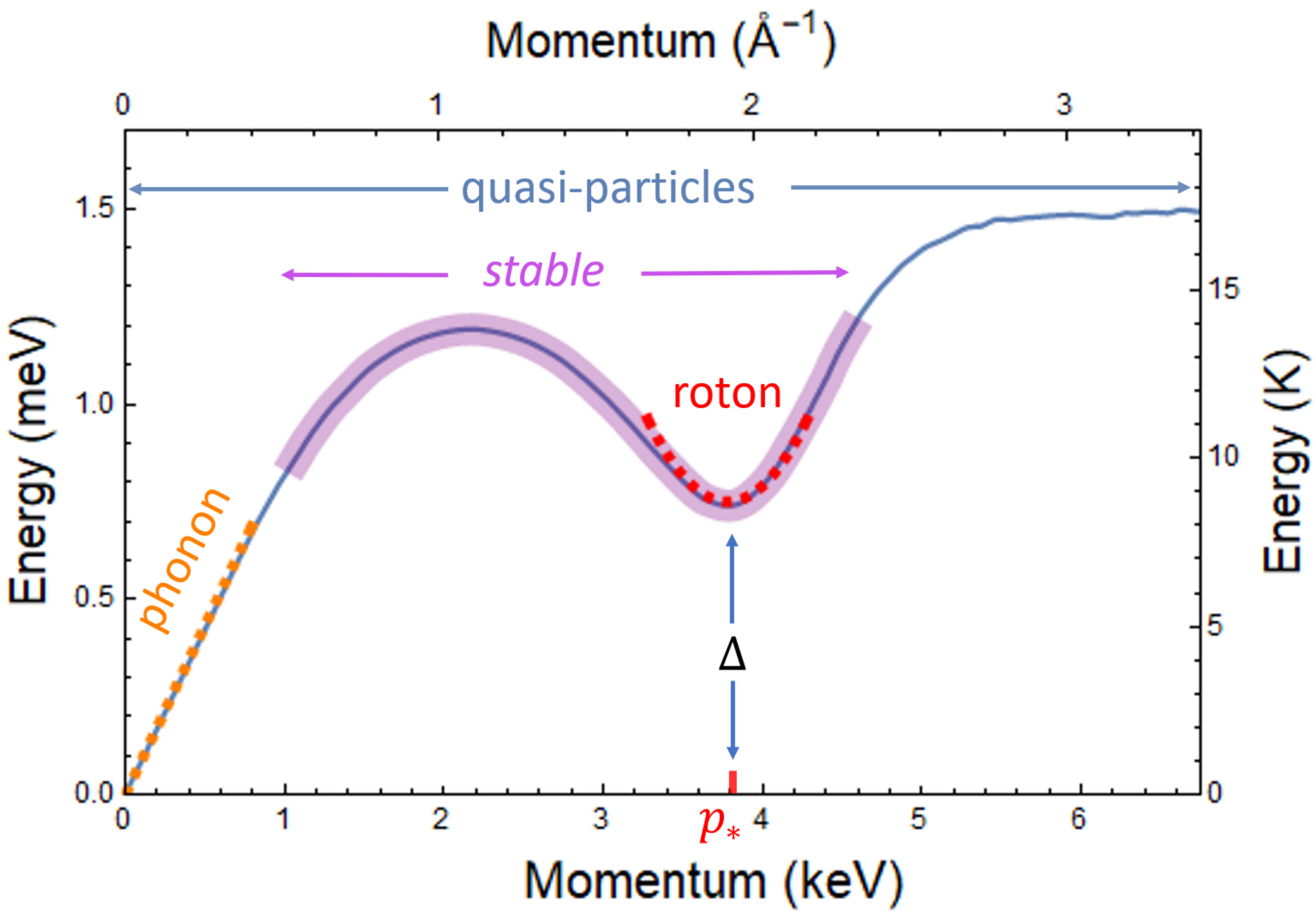


Quasi-particles



Quasi-particles

- atomic spacing ~ keV^{-1}



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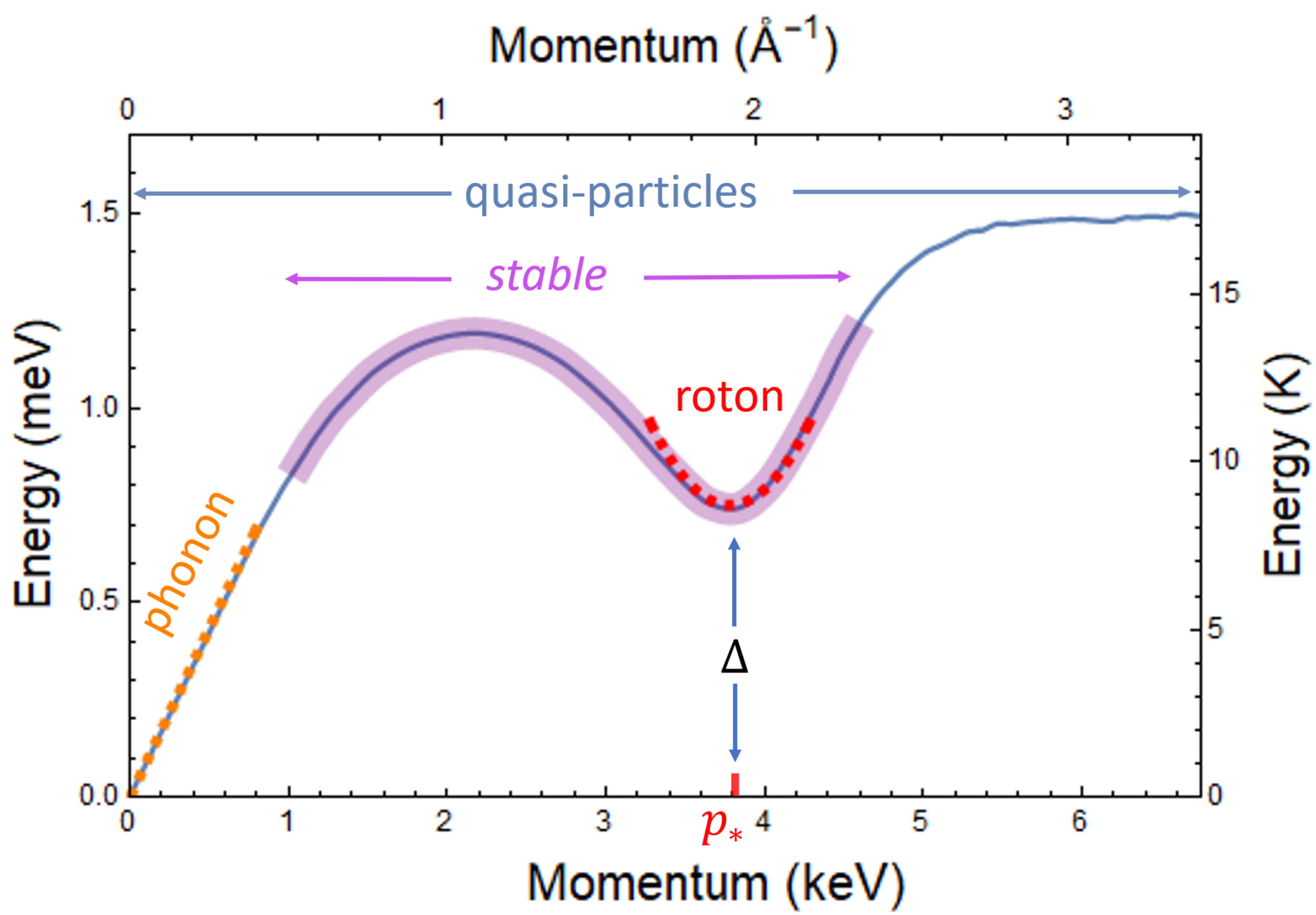
- atomic spacing ~ keV^{-1}

- phonon $E \simeq c_s k$

  sound speed $c_s \sim 10^{-6}$



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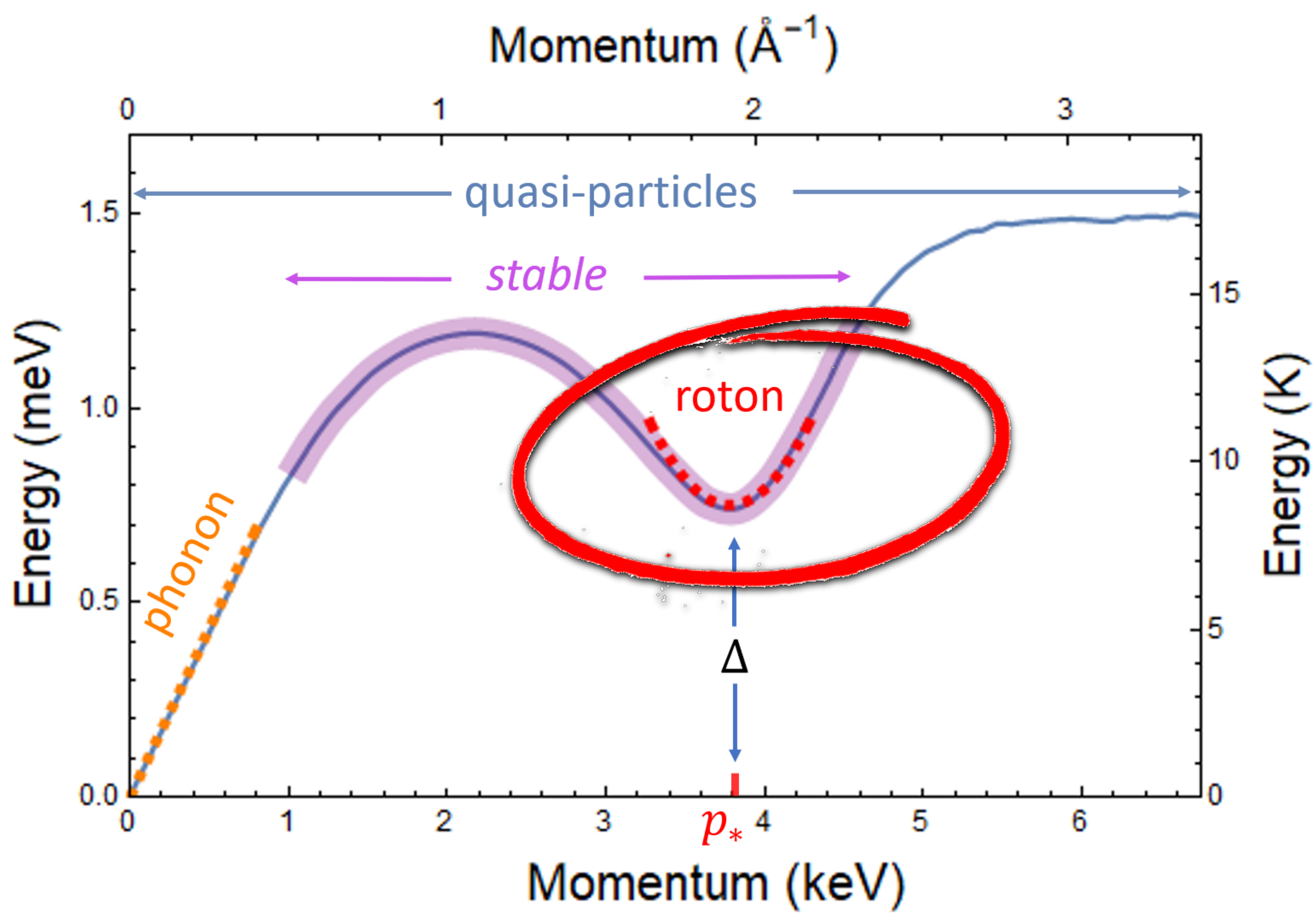
- roton $E_r \simeq \Delta + \dfrac{(p - p_*)^2}{2m_*}$



de Broglie wavelength

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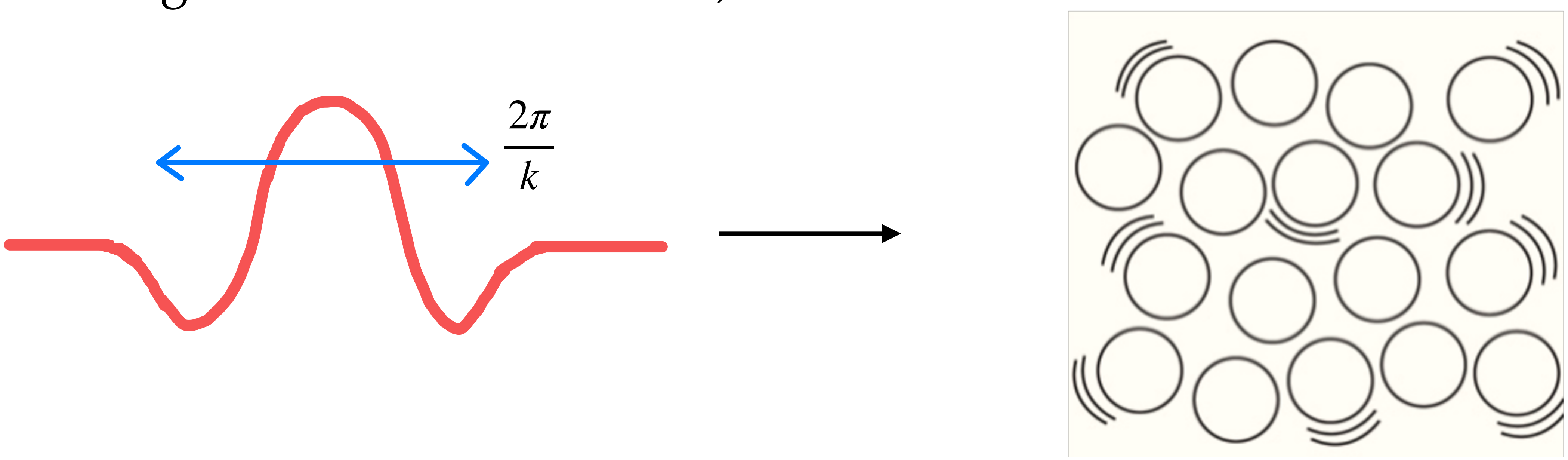

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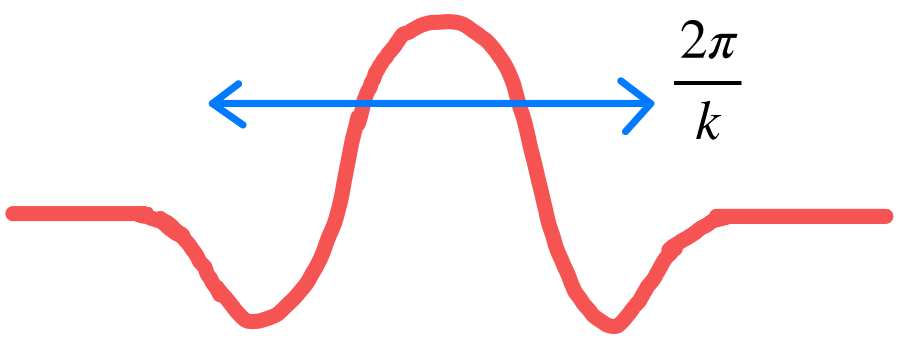
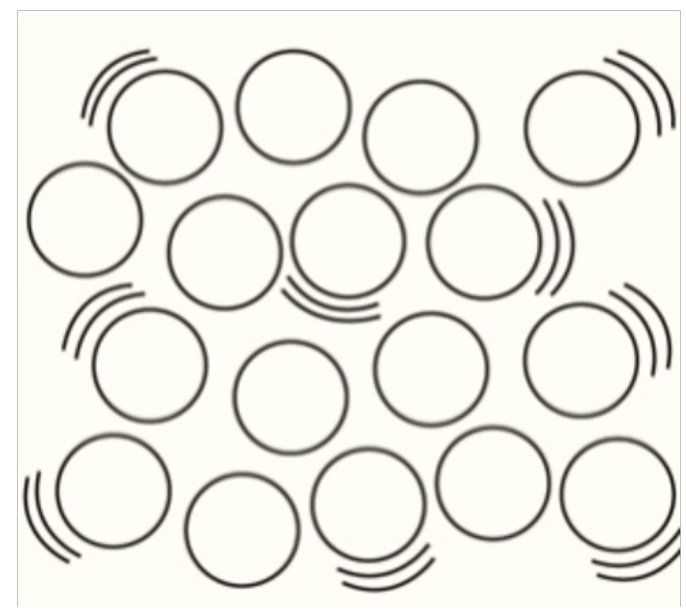
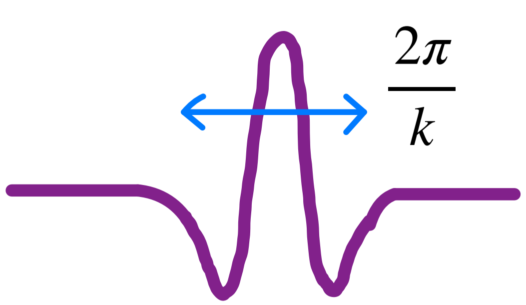
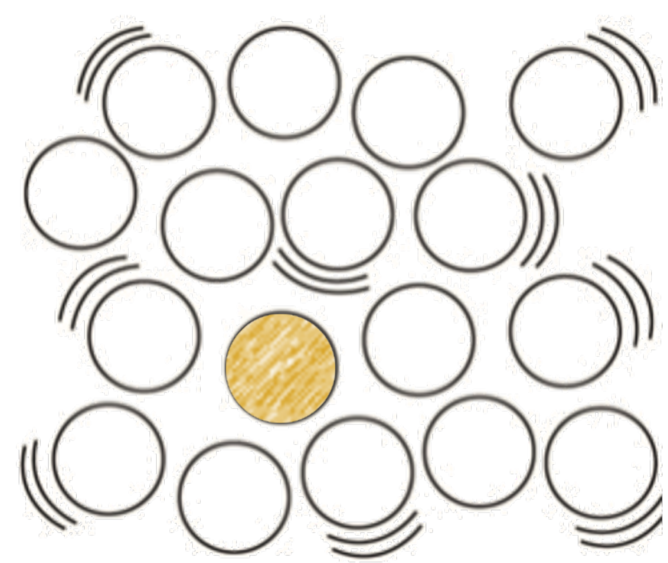


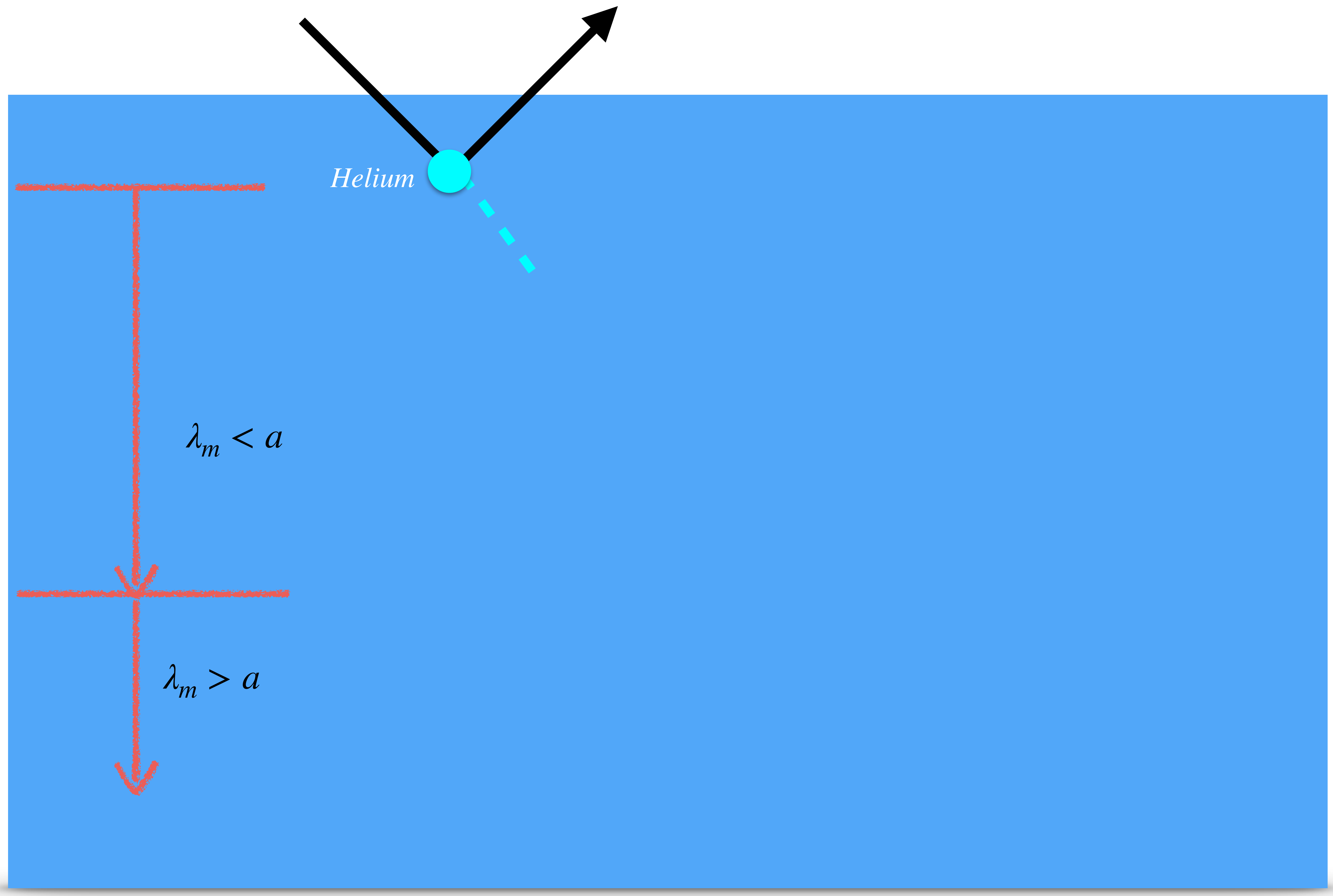


- incoming particle de Broglie wavelength $\ll \lambda_a$
  e.g. MeV-GeV dark matter





What happens after a MeV-GeV dark matter scattering?



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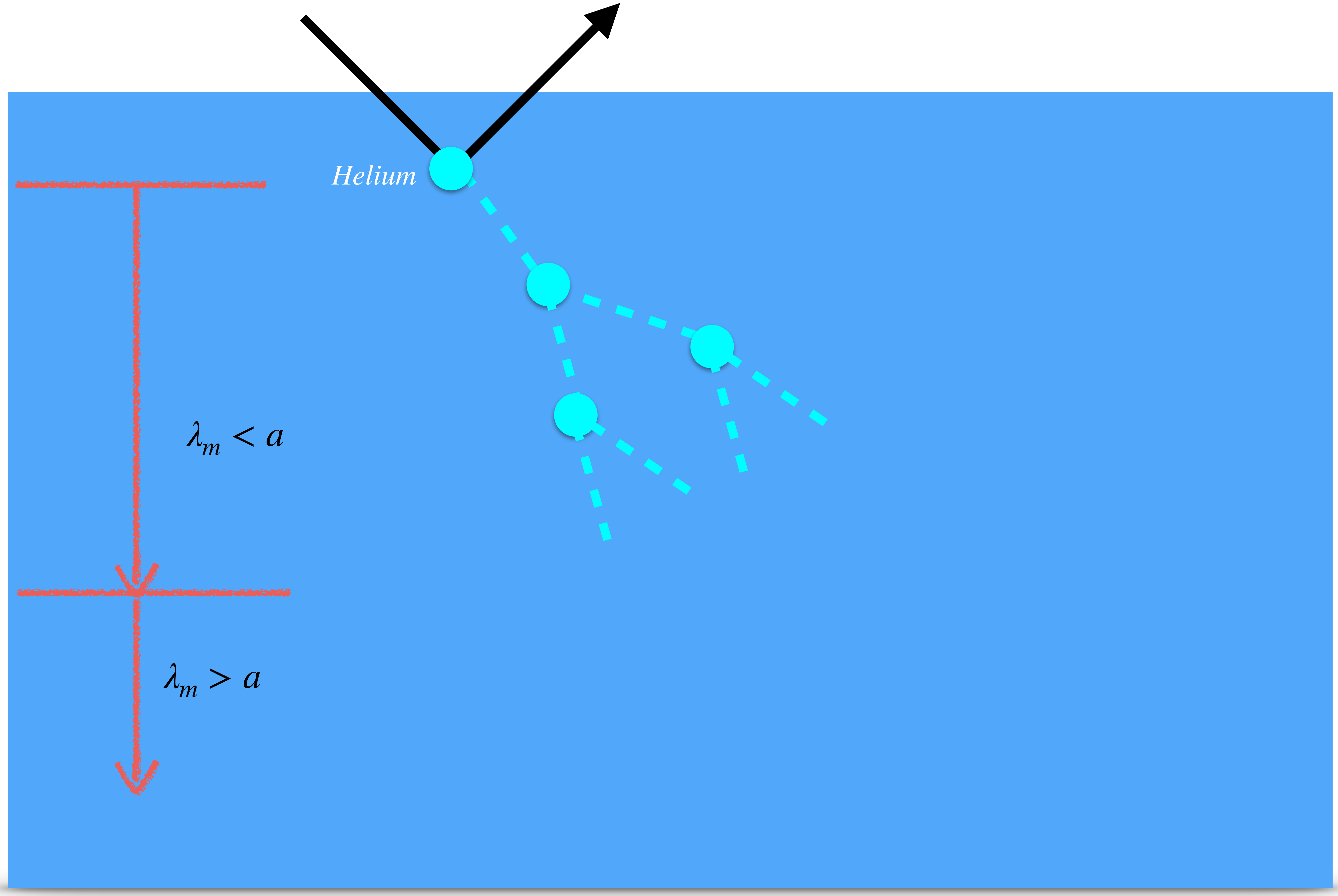

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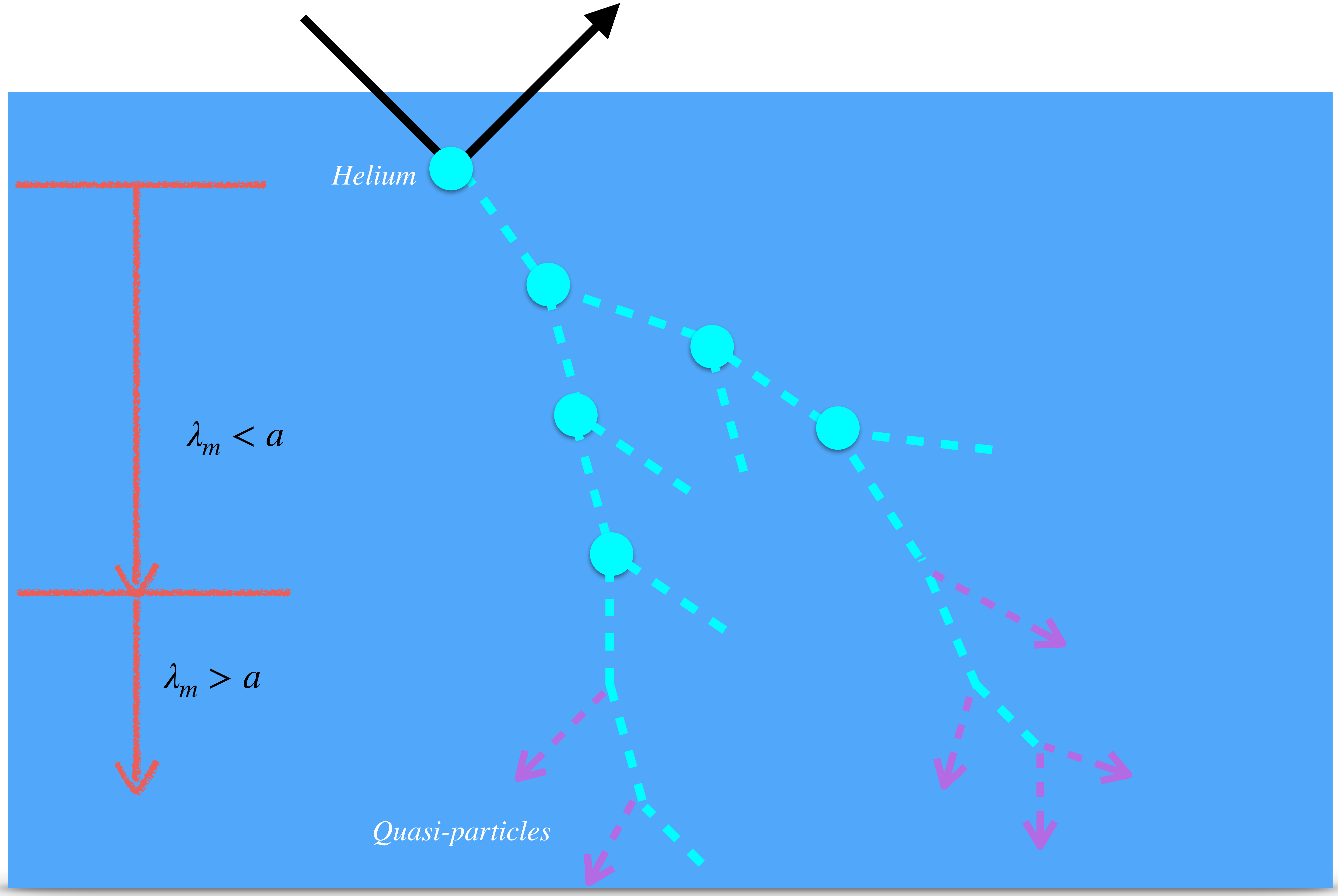
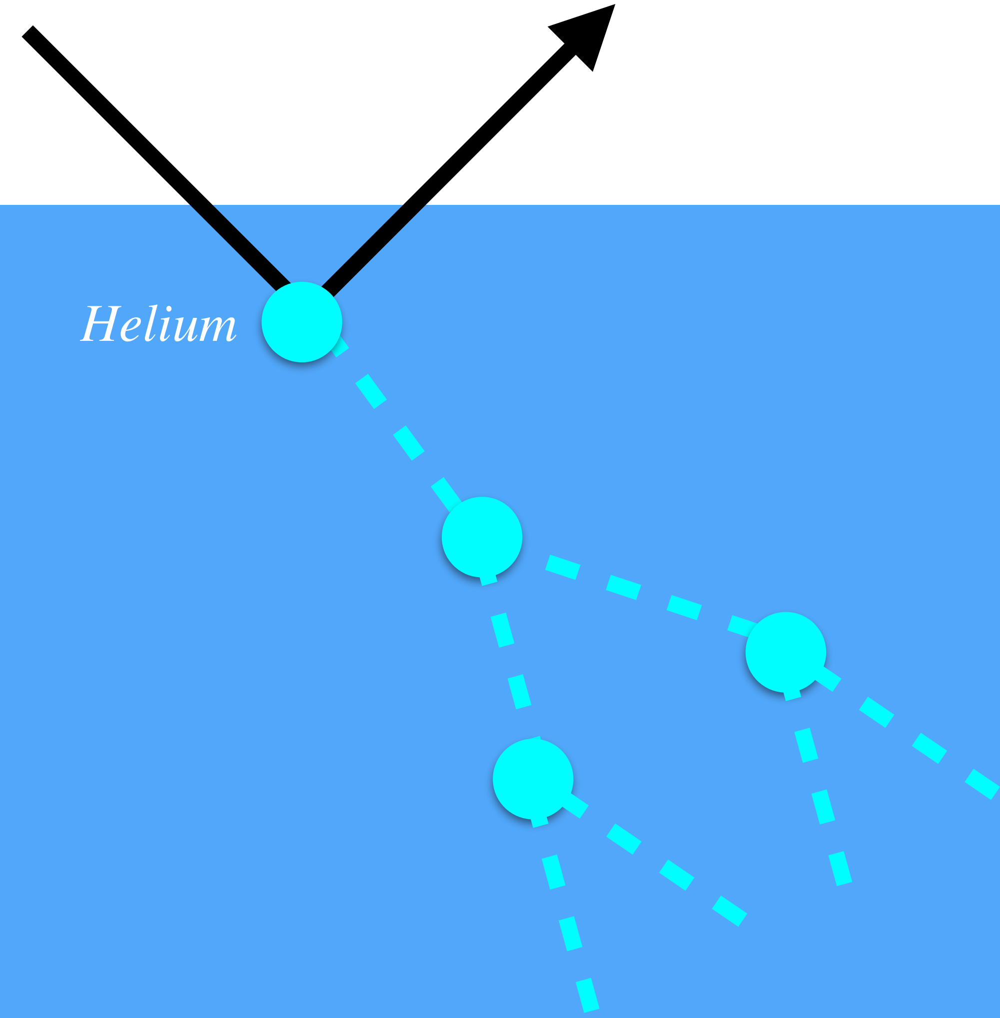
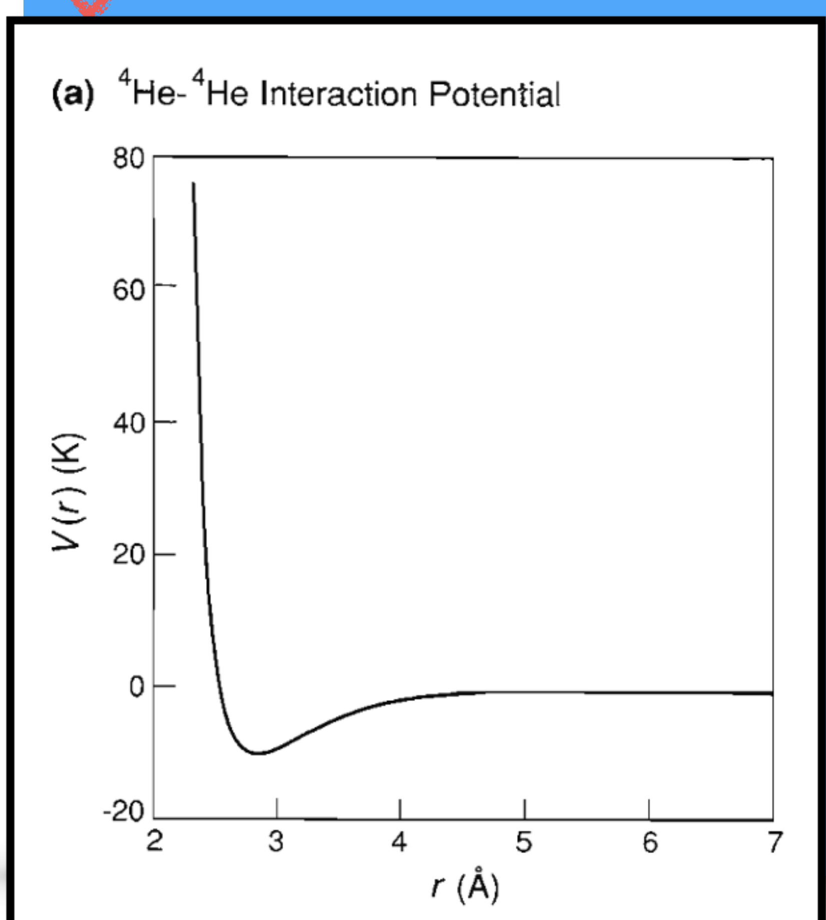


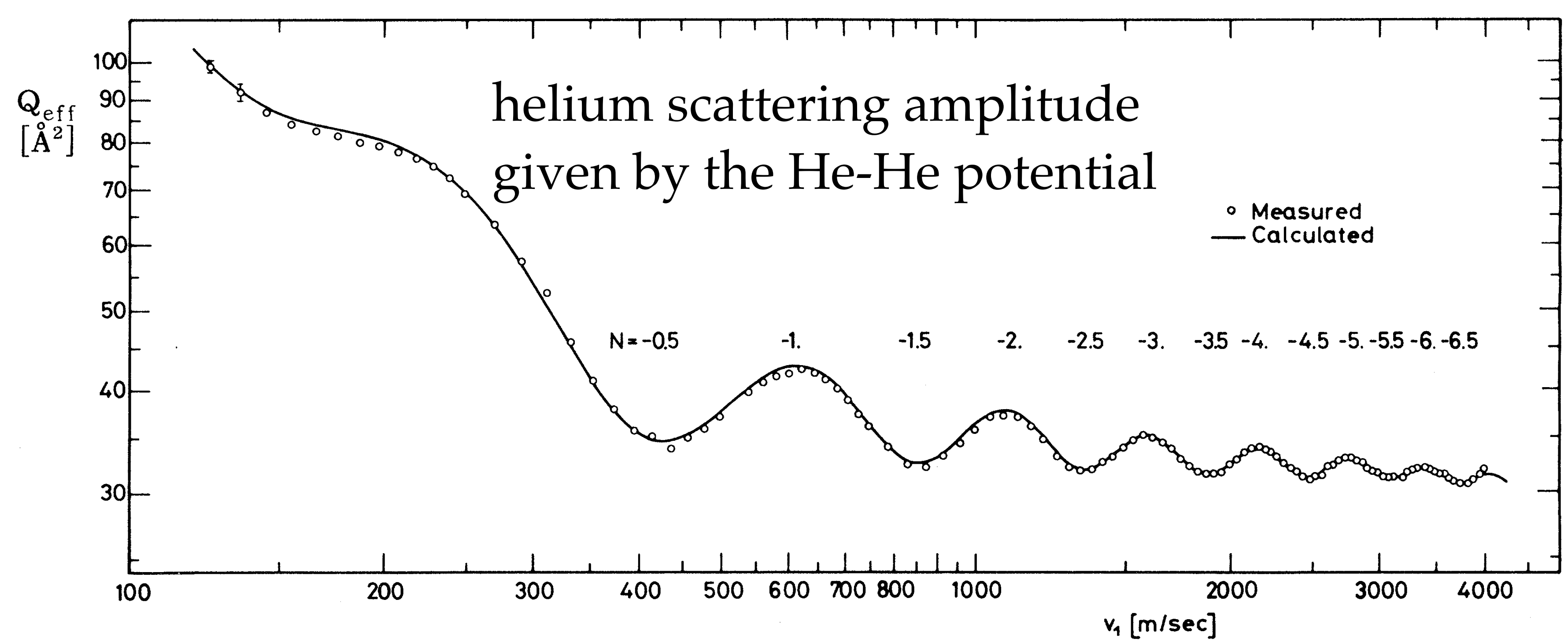
$\lambda_m < a$

$\chi + \text{He} \rightarrow \chi + \text{He}$

$\text{He} + \text{He} \rightarrow \text{He} + \text{He}$







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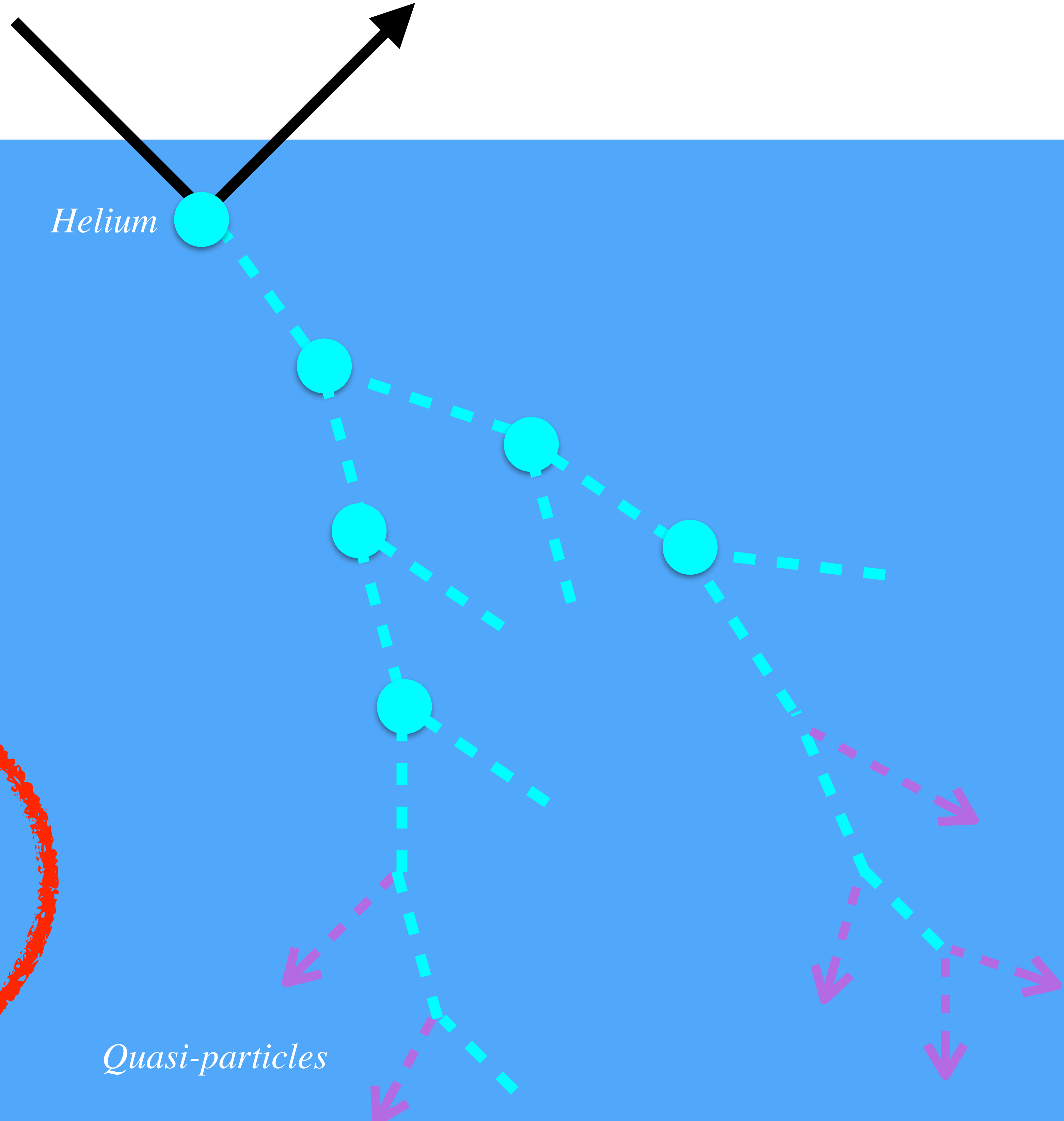
$\lambda_m > a$

$\mathrm{He} \rightarrow \mathrm{He} + \varphi$

$\varphi_1 \rightarrow \varphi_2 + \varphi_3$

$\varphi_1 + \varphi_2 \rightarrow \varphi_3 + \varphi_4$



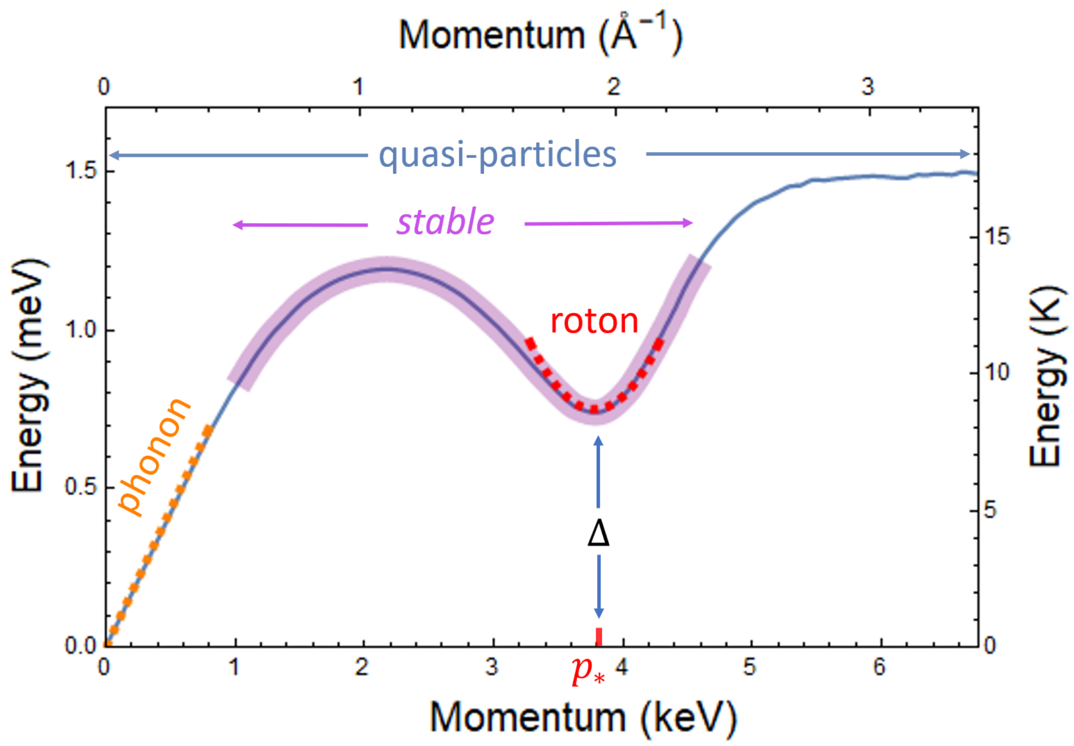
- relevant d.o.f

  phonon π [0 , keV] massless goldstone mode

  roton φ_r ~ keV

  quasi-particles φ (0, 10 keV)

  high momentum helium Φ_{He} (>> keV)



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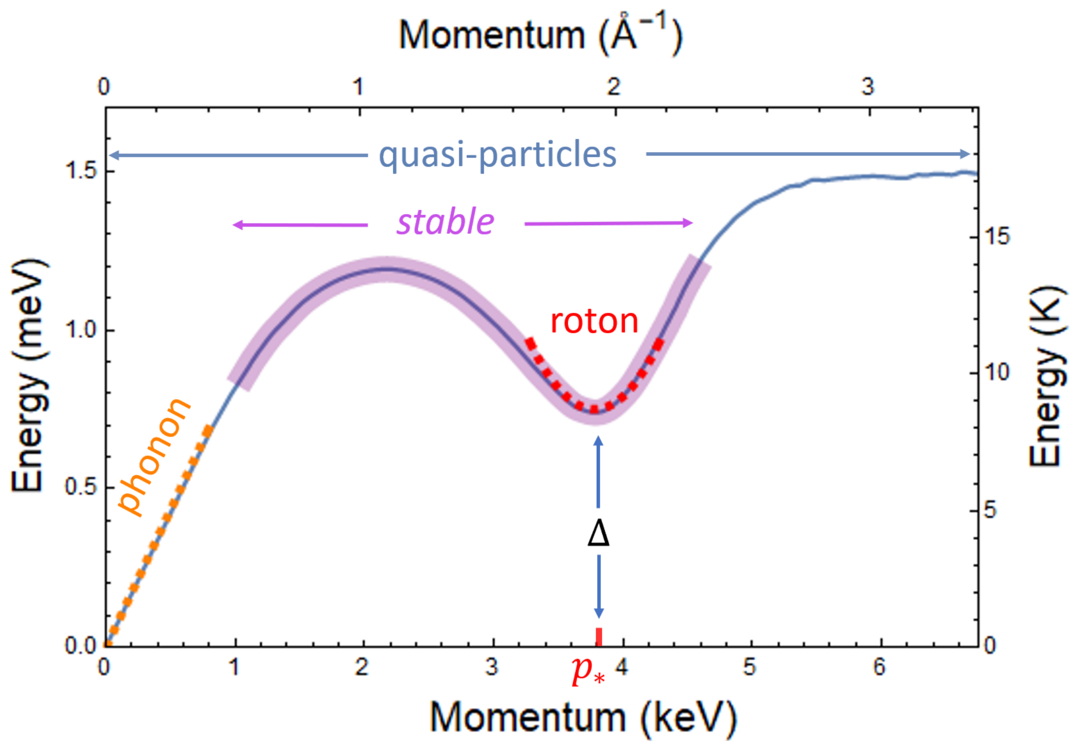

- cutoff Λ ~ keV

  atomic spacing ~ $(\text{keV})^{-1}$

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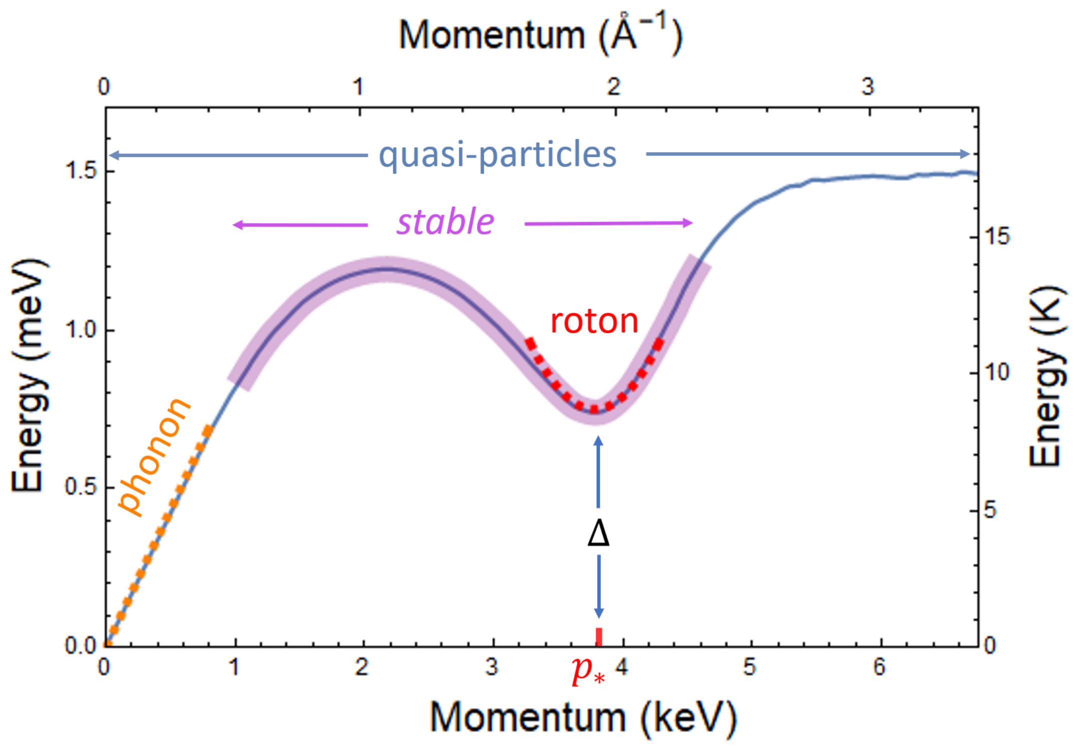

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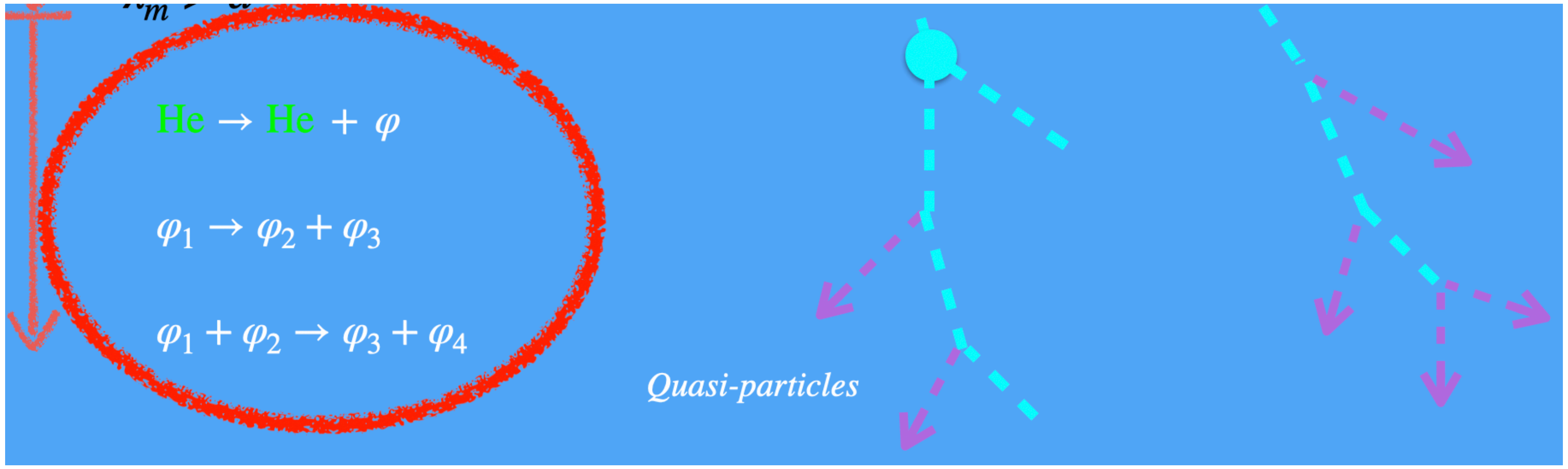
- processes

  quasi-particle Helium interactions to study quasi-particle production

  quasi-particle self interactions to understand thermalization

Why it is challenging?



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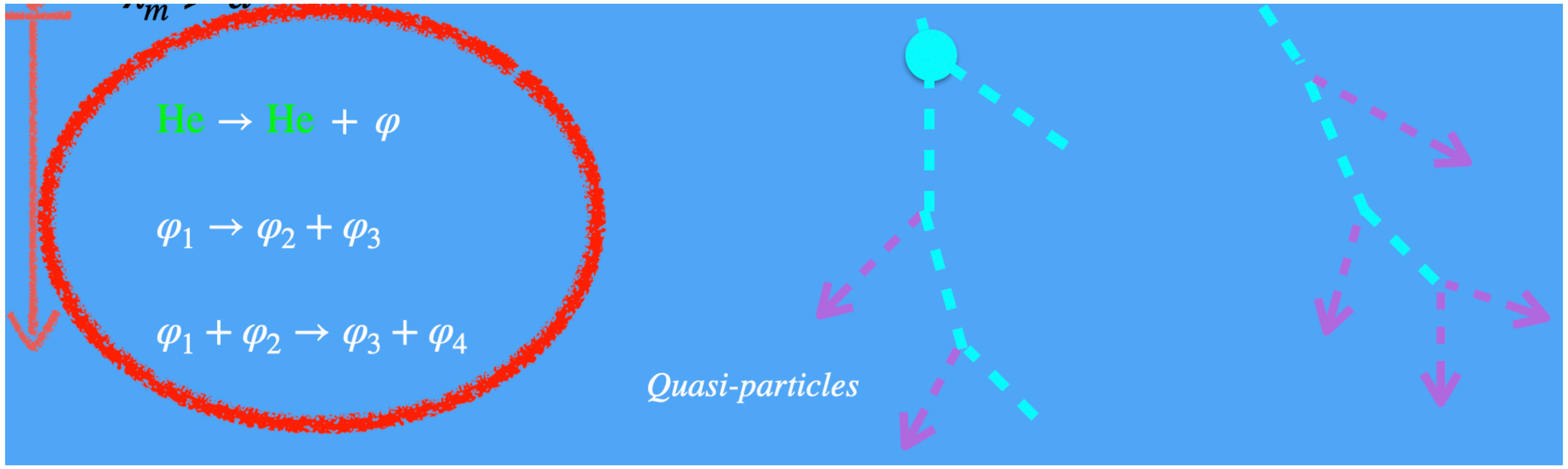
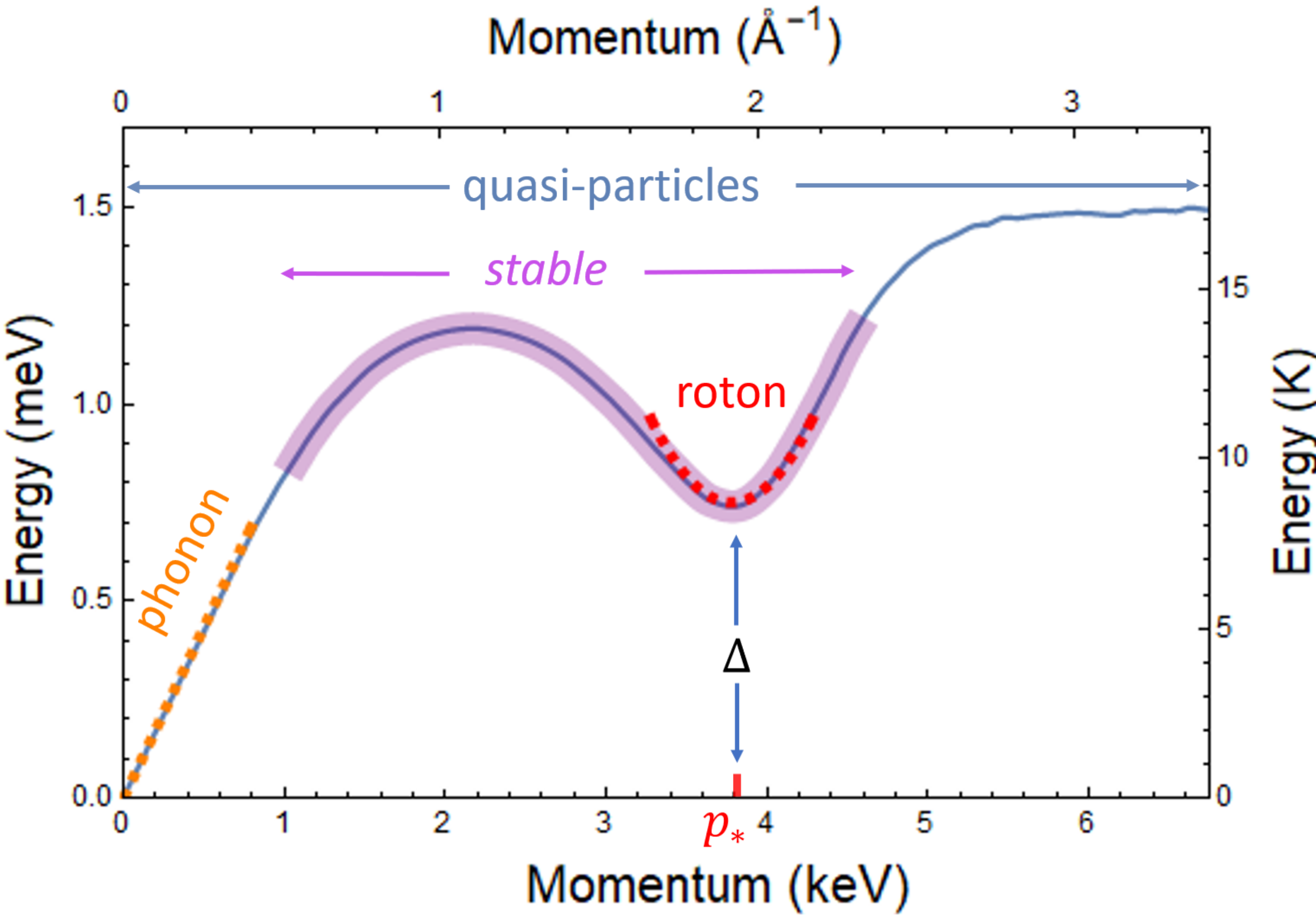


- inverse atomic spacing $\Lambda_{cut} \sim$ keV
- rotons, quasi-particles and heliums momentum $p \gtrsim \Lambda_{cut}$

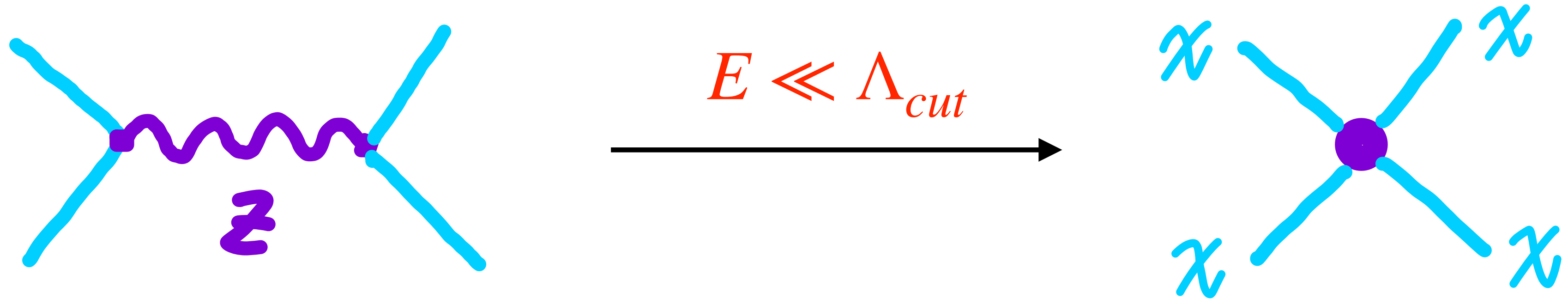


Effective field theory

Effective field theory

- find the relevant degrees of freedom and symmetry

- four-fermion interactions



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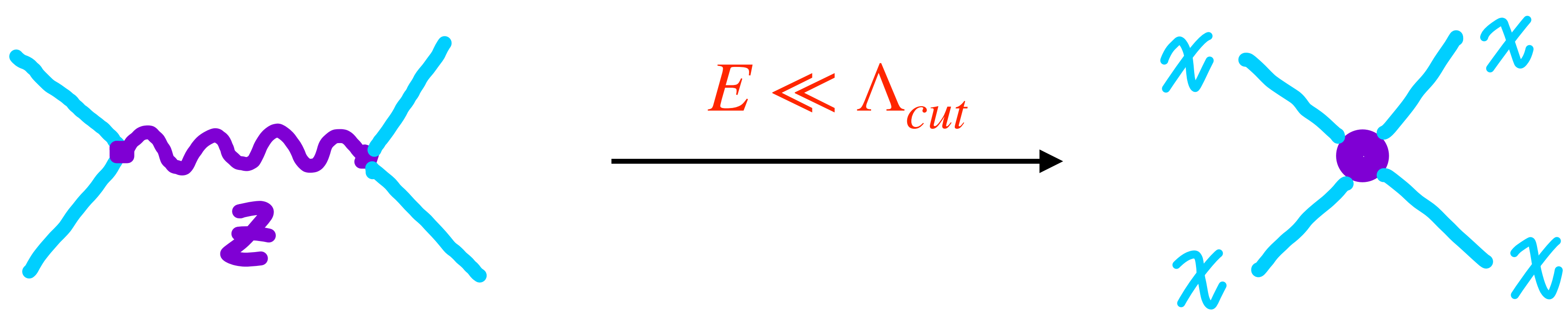
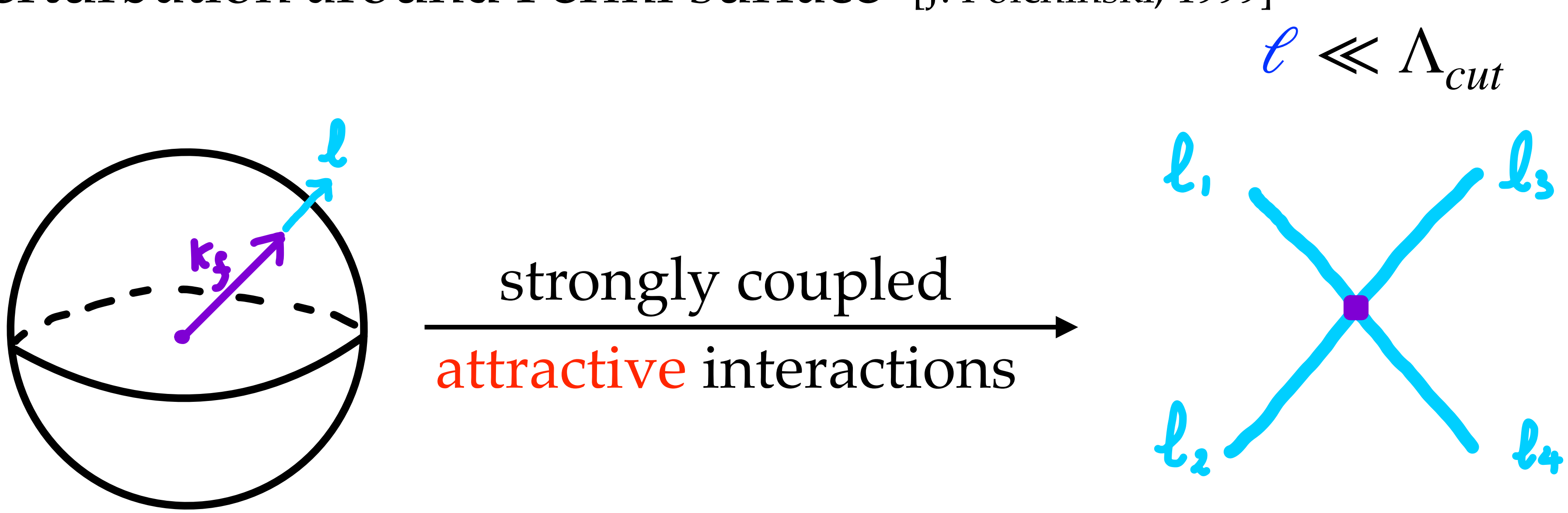


- BCS theory

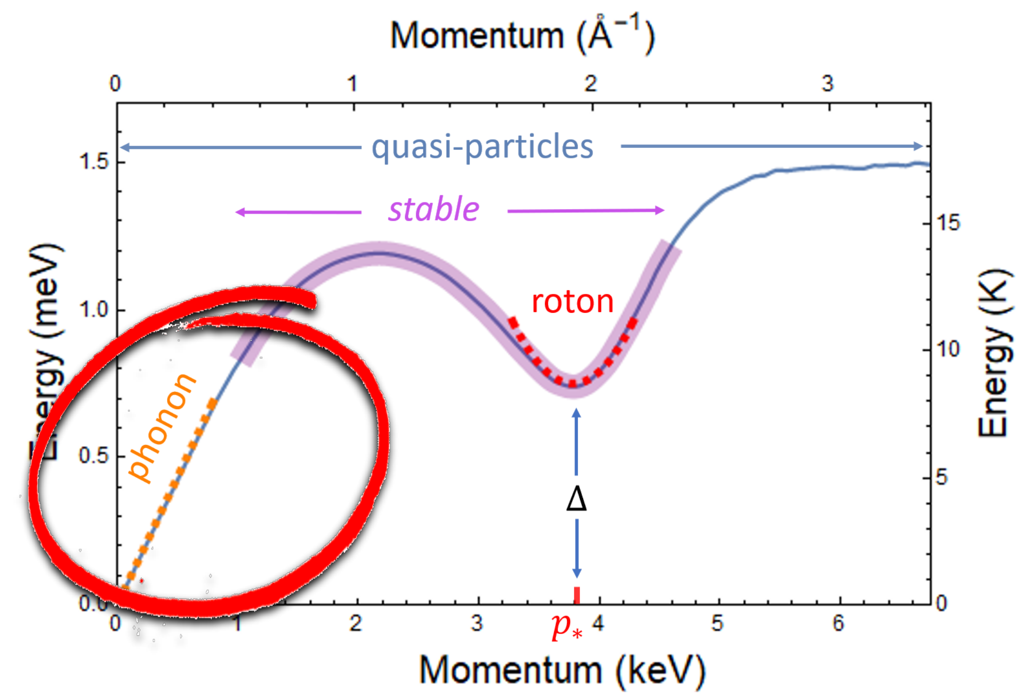
  perturbation around Fermi surface [J. Polchinski, 1999]



Phonons $\pi\,(p \ll \Lambda(\sim \text{keV})\,)$

at low energy, phonons are the relevant d.o.f

with shift symmetry + ``Galilei'' symmetry



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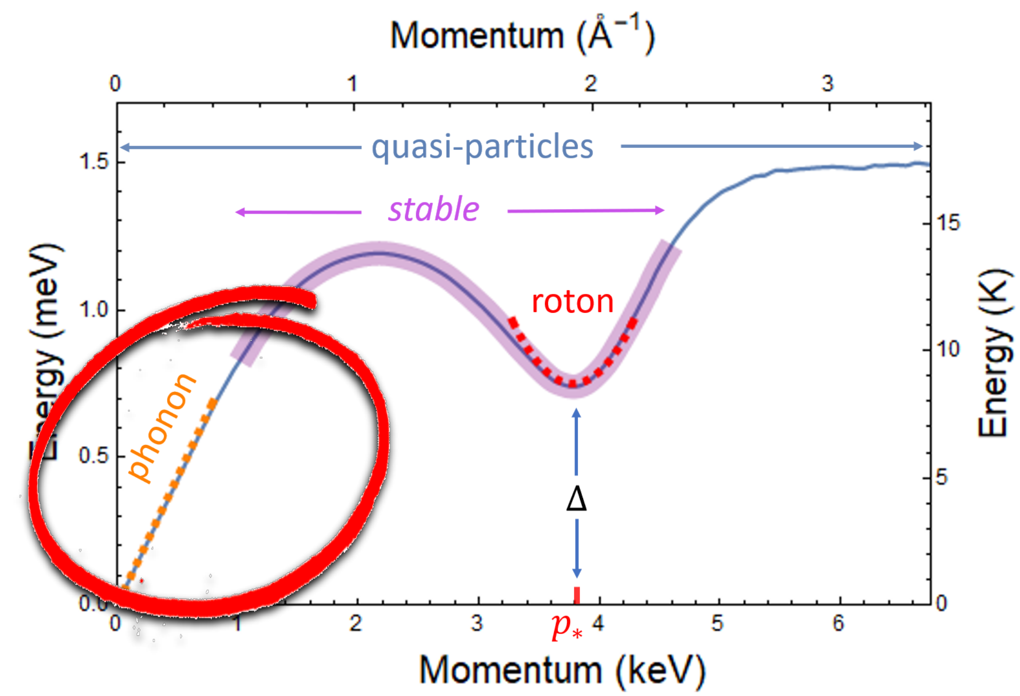

- **Similar to** chiral perturbation theory (pions)

  Effective quantum action method [D. Son, 2002]

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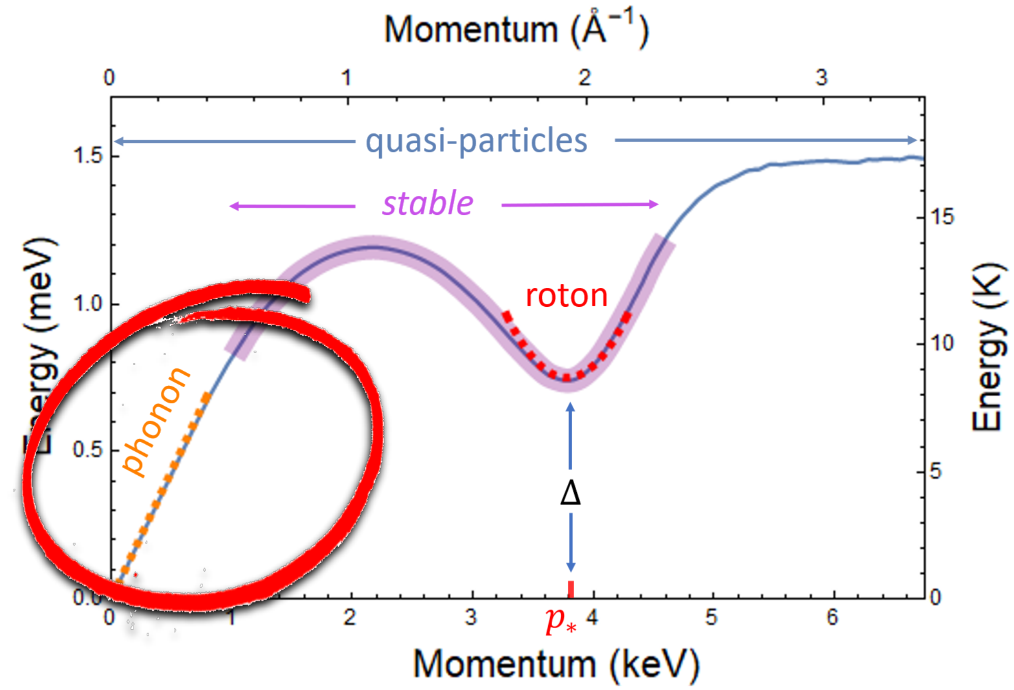


- **Similar to** chiral perturbation theory (pions)

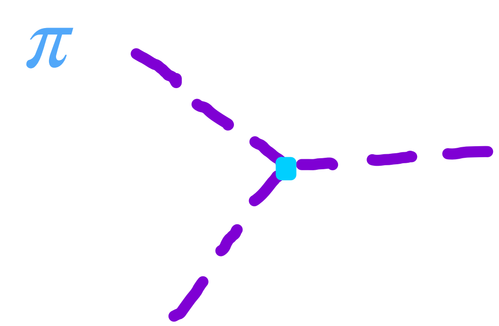
  Effective quantum action method [D. Son, 2002]

- or Power counting method

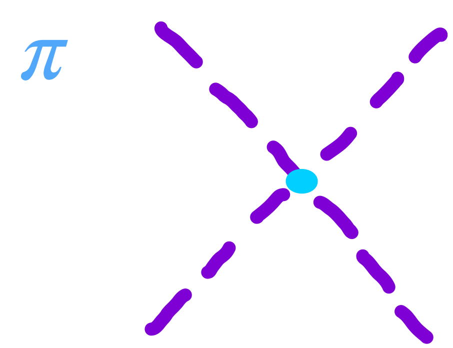
$$[p]=1\,,\quad [t]=-1\,,[x]=-1\,,\quad [\pi]=1$$

phonon interactions

$$\mathscr{L}_{\rm ph} = -\frac{c_s^{3/2}}{2\Lambda^2}\,\dot{\pi}\,\partial_i\pi\,\partial_i\pi + \frac{g_3\,c_s^{-1/2}}{6\,\Lambda^2}\,\dot{\pi}^3 + \mathcal{O}(\pi^4)$$



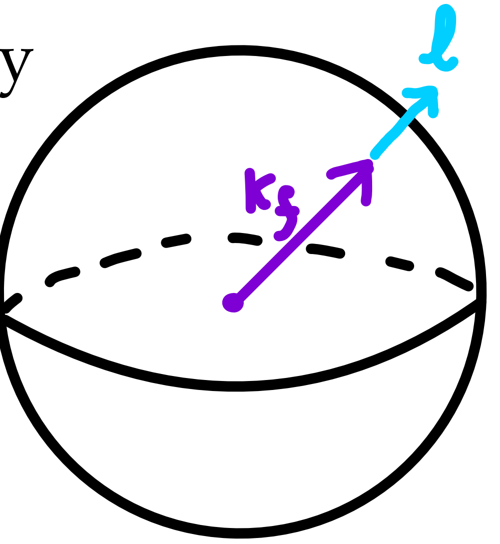
$\sim \frac{1}{\Lambda^2}p^3$



$\sim \frac{1}{\Lambda^4}p^4$

Roton effective field theory

BCS theory



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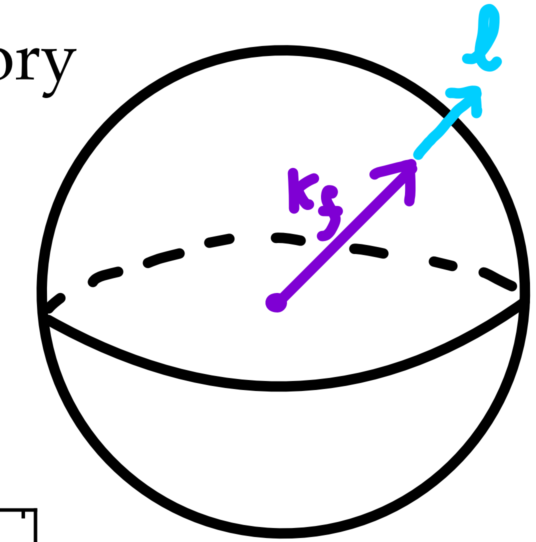

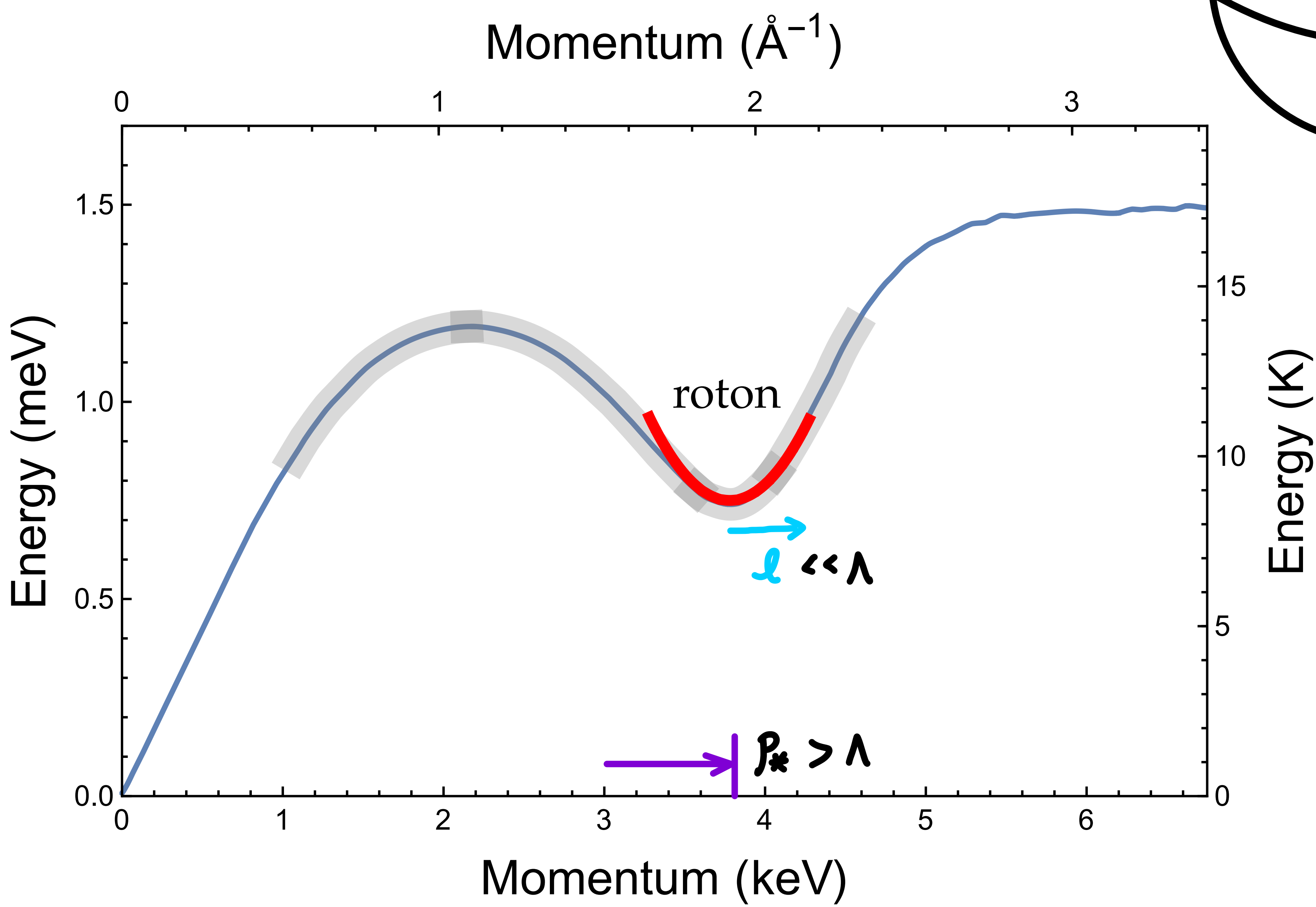

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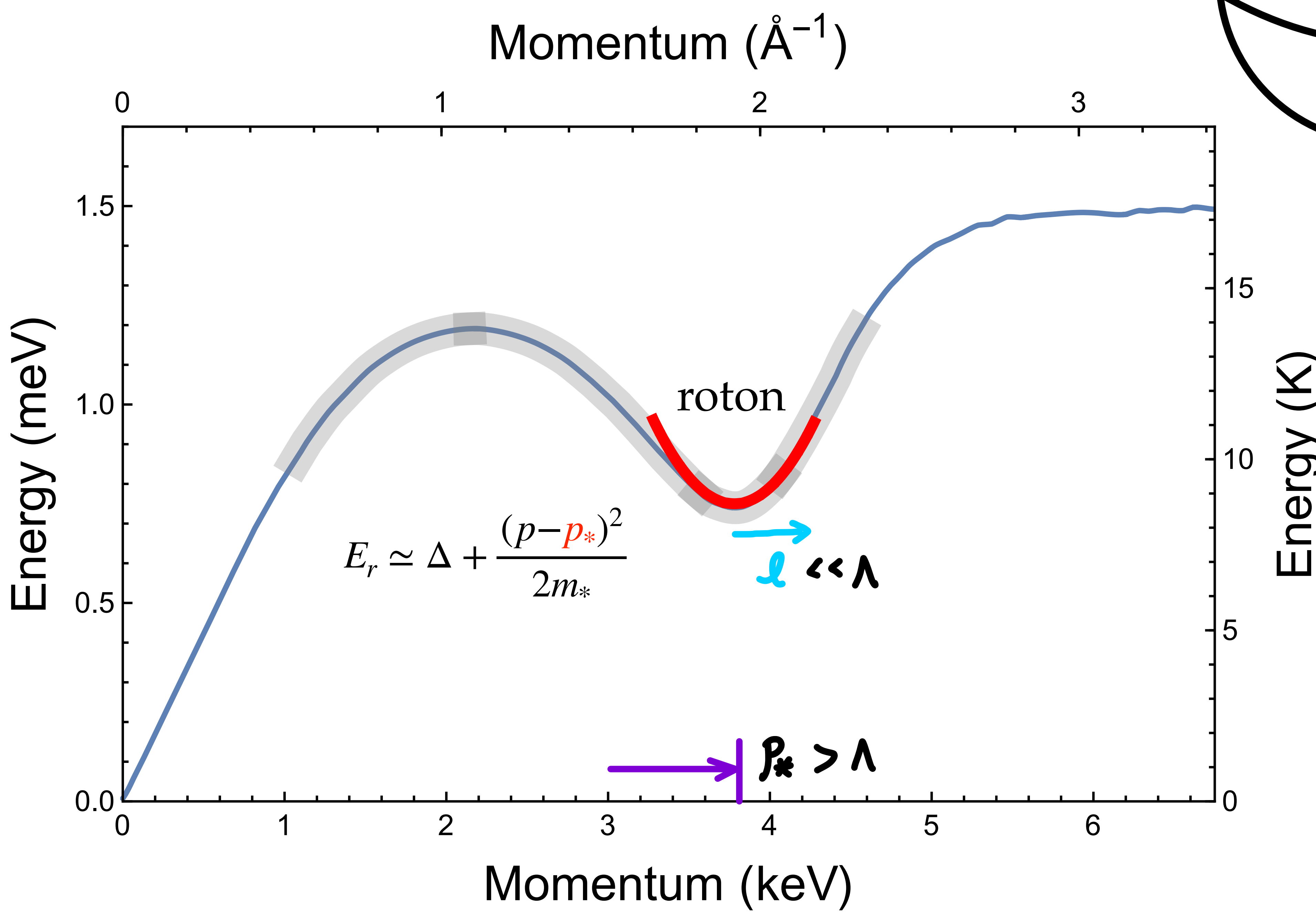

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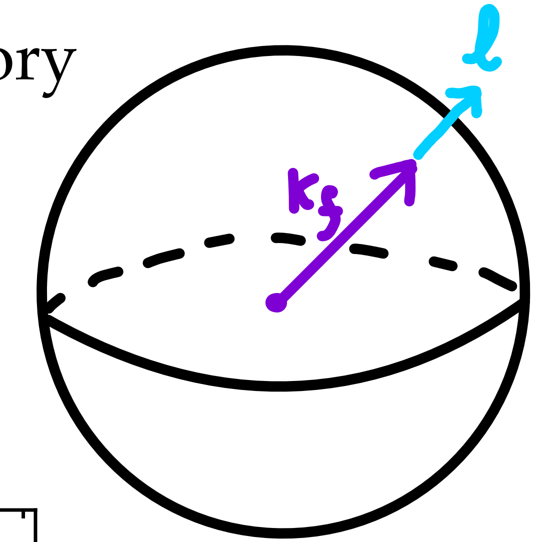

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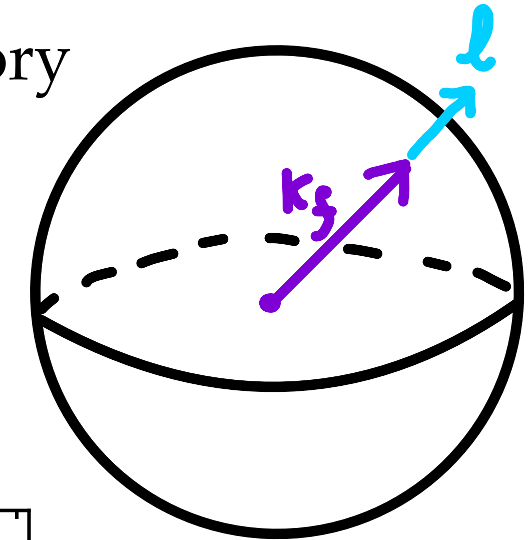
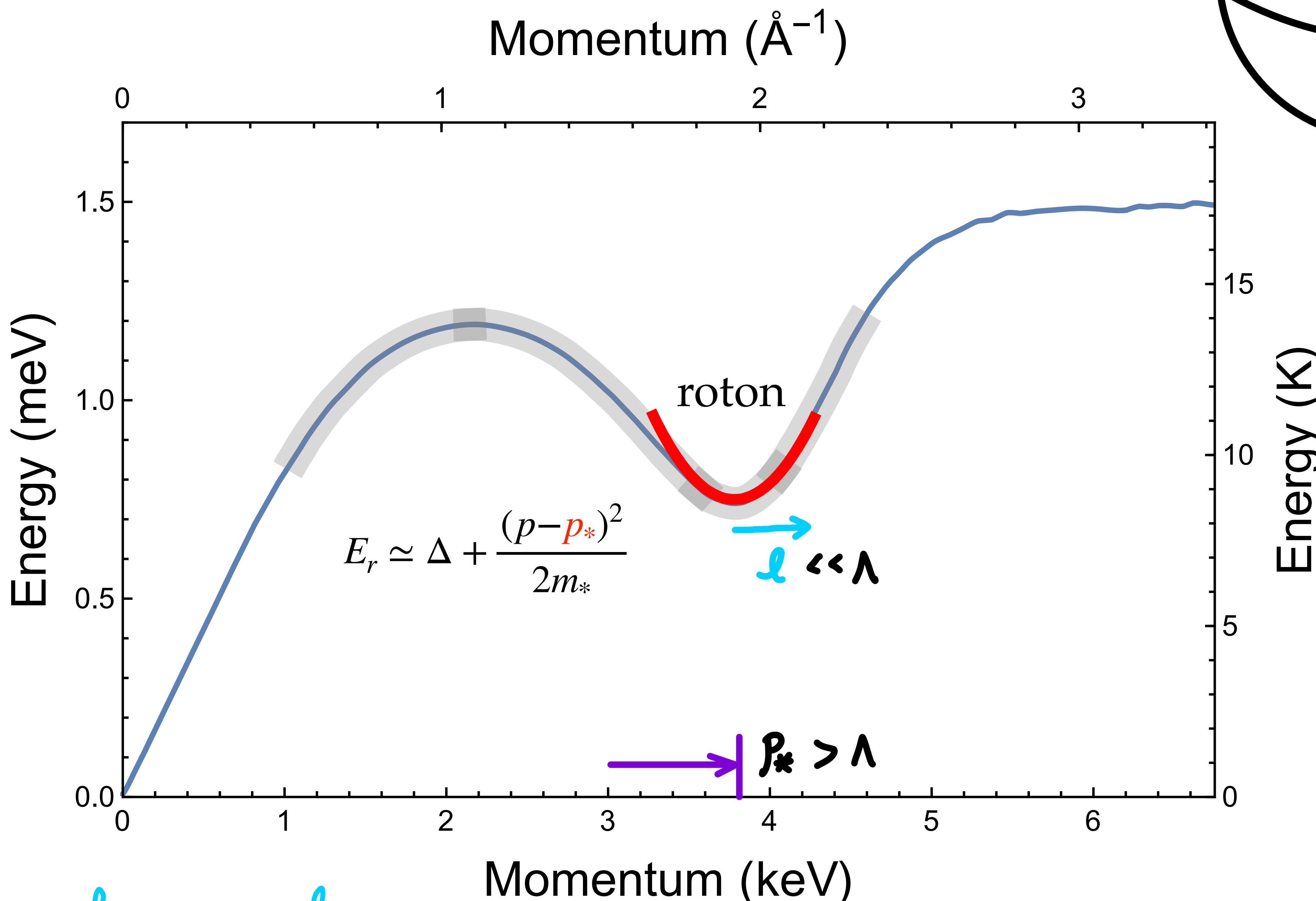
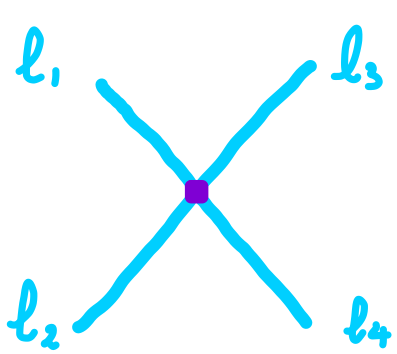
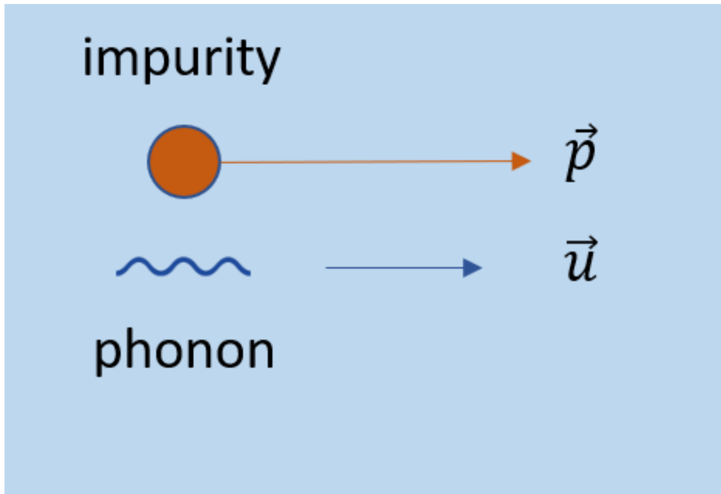




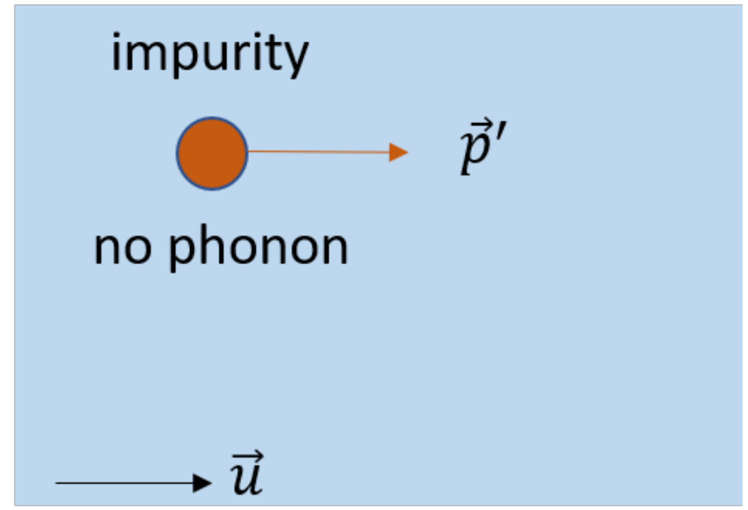


$\lambda_r \simeq 0.93$ consistent with data

Roton and phonon interactions



Lab frame



Boosted frame

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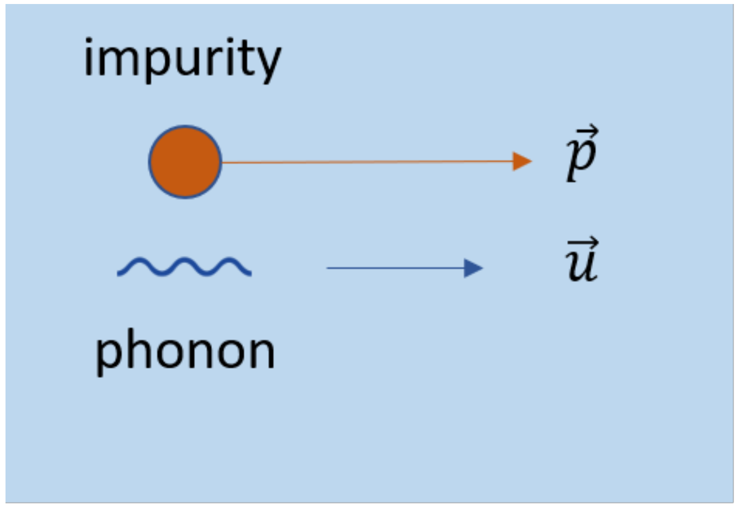

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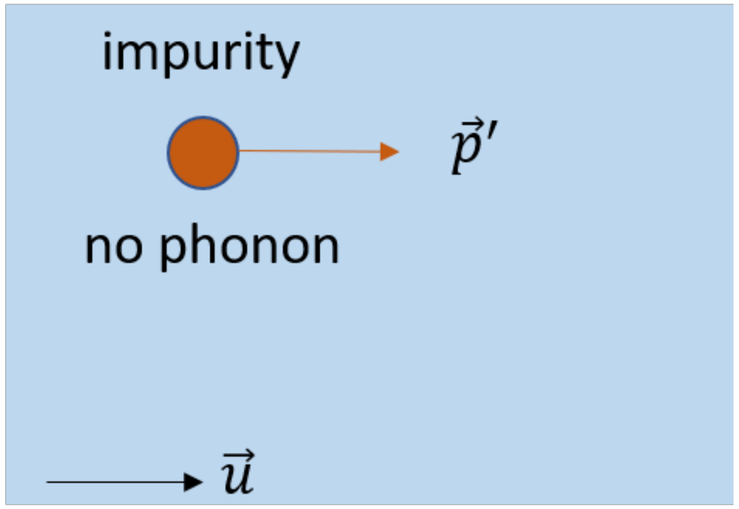
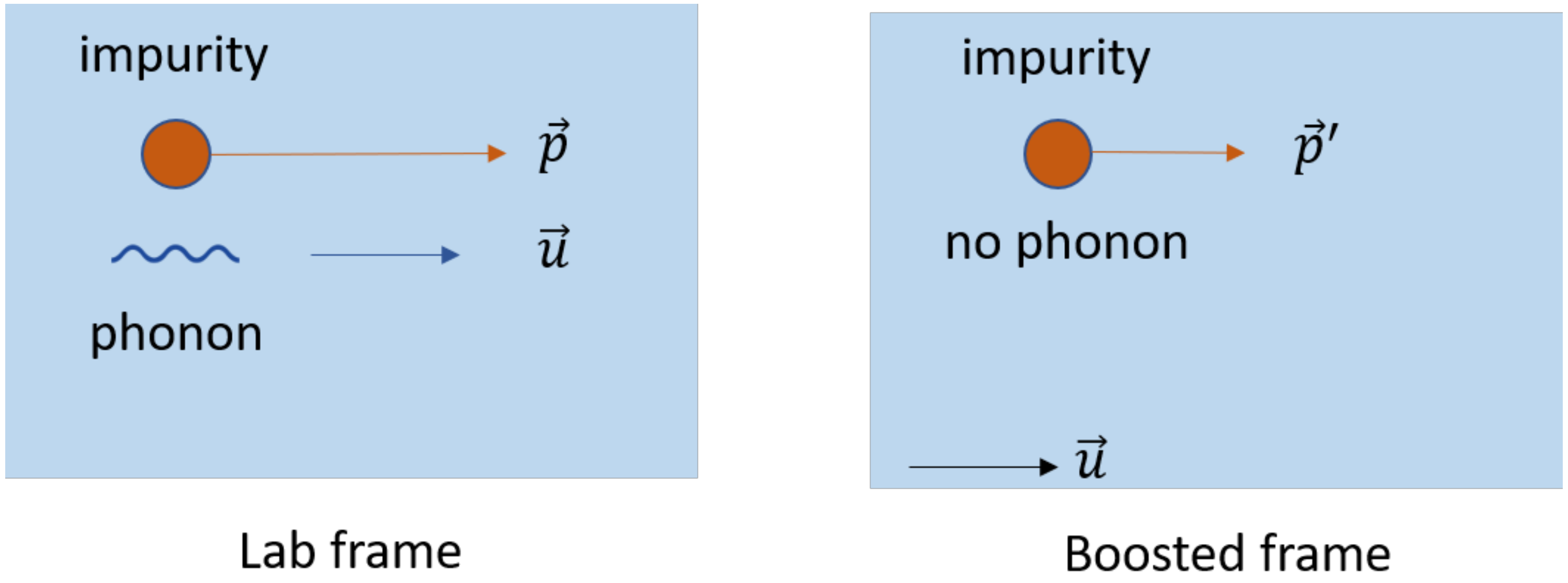


Boosted frame

- roton (as impurity) and phonon interactions

$$V_{\text{ph-r}} = \epsilon_{boost} - \epsilon_{lab} + \boldsymbol{p} \cdot \boldsymbol{u}$$

Roton and phonon interactions



- roton (as impurity) and phonon interactions

$$V_{\text{ph-r}} = \epsilon_{boost} - \epsilon_{lab} + \boldsymbol{p} \cdot \boldsymbol{u}$$

- This method can be applied to dark matter, quasiparticles, etc.

Helium atom Φ_{He} $(p \gg \mathrm{keV})$

- U(1) symmetry $\Phi_{\mathrm{He}} \rightarrow e^{i\alpha}\Phi_{\mathrm{He}}$

    effective field theory breaks down? $p \gg \Lambda$

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- U(1) symmetry $\Phi_{\rm He} \to e^{i\alpha}\Phi_{\rm He}$

  effective field theory breaks down? $p \gg \Lambda$

- **Similar to** Heavy quark effective theory

  $\mathbf{p} = m_Q\mathbf{v}+\mathbf{k}$, $\Lambda/m_Q \ll 1$

Helium atom $\Phi_{\rm He}$ ($p \gg$ keV)

- U(1) symmetry $\Phi_{\rm He} \to e^{i\alpha}\Phi_{\rm He}$

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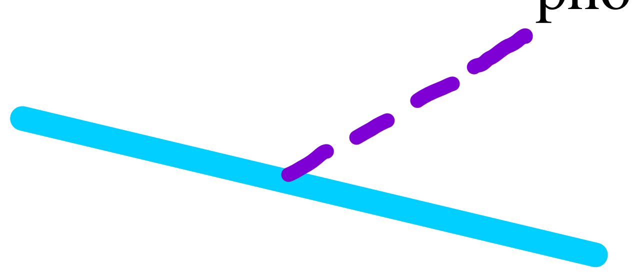
$$\mathbf{p} = m_Q \mathbf{v} + \mathbf{k} \quad , \quad \Lambda/m_Q \ll 1$$

- Helium currents $J^0_{\rm He}$, $J^i_{\rm He}$

$$J^0_{\rm He} = \Phi^\dagger\Phi, \quad J^i_{\rm He} = v^i \Phi^\dagger\Phi$$

  Phonon currents J^0, J^i

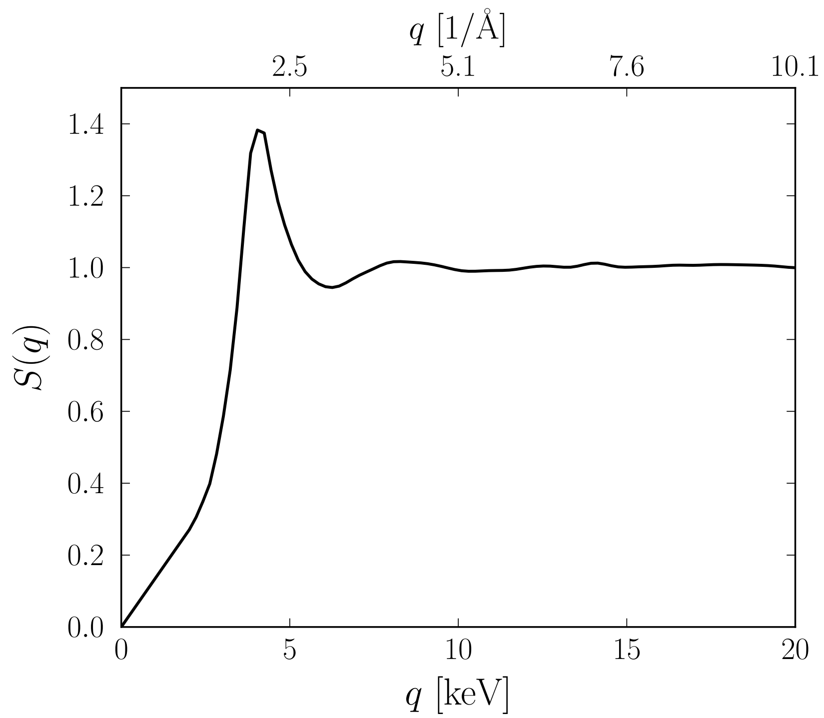
$$J^0 = (\sqrt{\rho}/m_{\rm He}c_s)\,\dot{\pi} + \cdots,$$



$$\mathscr{L}_{JJ} = \lambda_1 \frac{1}{m_{\rm He}\Lambda} J^0 J^0_{\rm He} + \lambda_2 \frac{m_{\rm He}}{\Lambda^3} J^i J^i_{\rm He}$$

He → He + **quasi-particle** from measurement

- dynamical (static) structure function $S(\mathbf{q}, \omega)$ is directly measured in neutron scattering experiments



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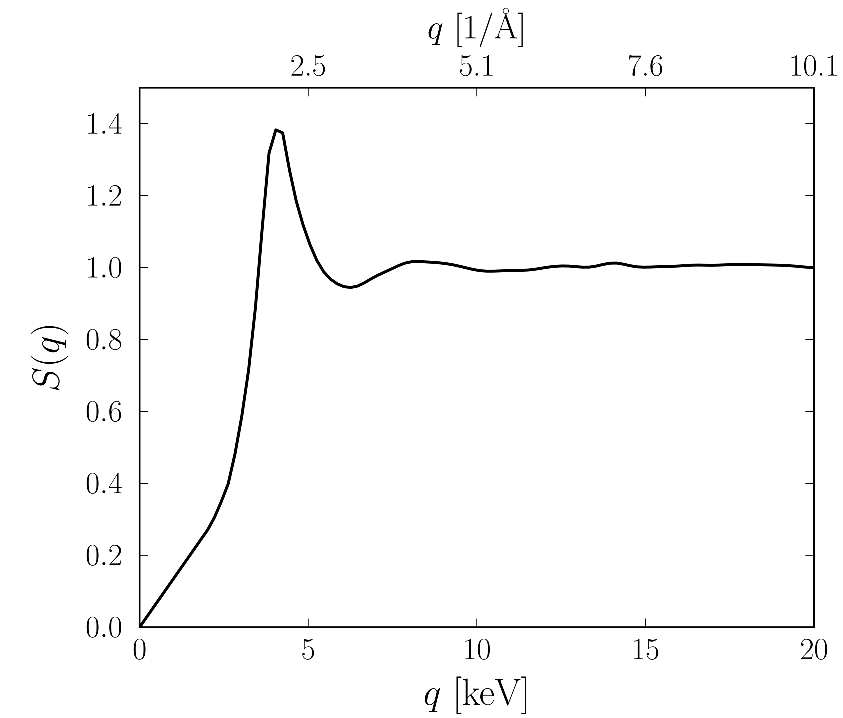

$\Longrightarrow$ HEP language, $S(q) = |\langle vac | j_0 | \varphi \rangle|^2$

Current conservation, we can know $|\langle vac | j_i | \varphi \rangle|^2$

He → He + quasi-particle from measurement

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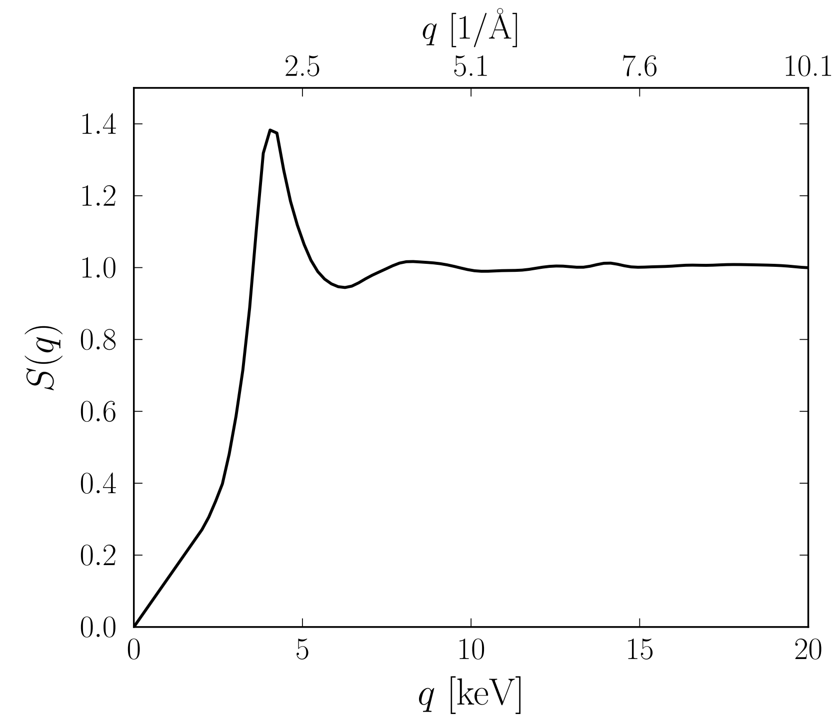


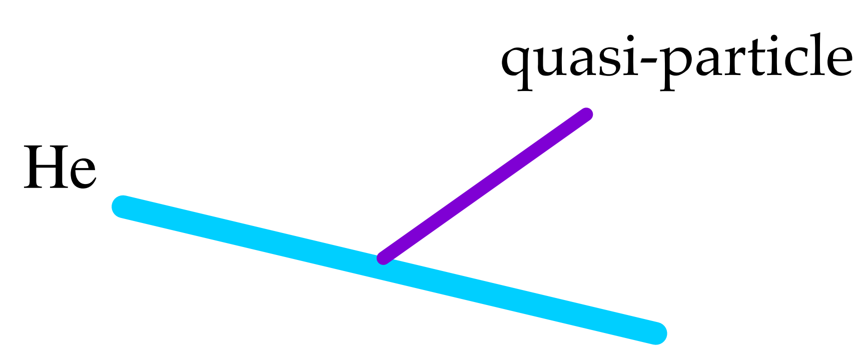
$\Longrightarrow$ HEP language, $S(q) = |\langle vac | j_0 | \varphi \rangle|^2$

Current conservation, we can know $|\langle vac | j_i | \varphi \rangle|^2$

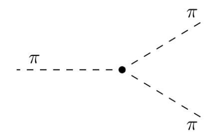
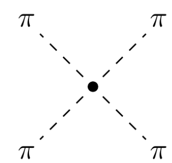
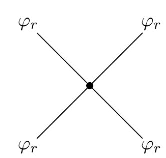
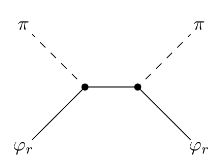
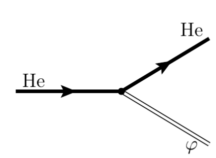
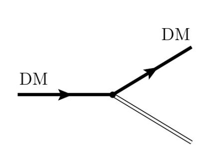
- Helium decay to a quasi-particle,

$$\mathscr{L}_{JJ} = \lambda_1 \frac{1}{m_{\rm He}\Lambda} J^0 J^0_{\rm He} + \lambda_2 \frac{m_{\rm He}}{\Lambda^3} J^i J^i_{\rm He}$$

amplitude $\mathscr{M} \propto \lambda_1 J^0_{\rm He} \langle vac | J^0 | \varphi \rangle + \lambda_1 J^i_{\rm He} \langle vac | J^i | \varphi \rangle$

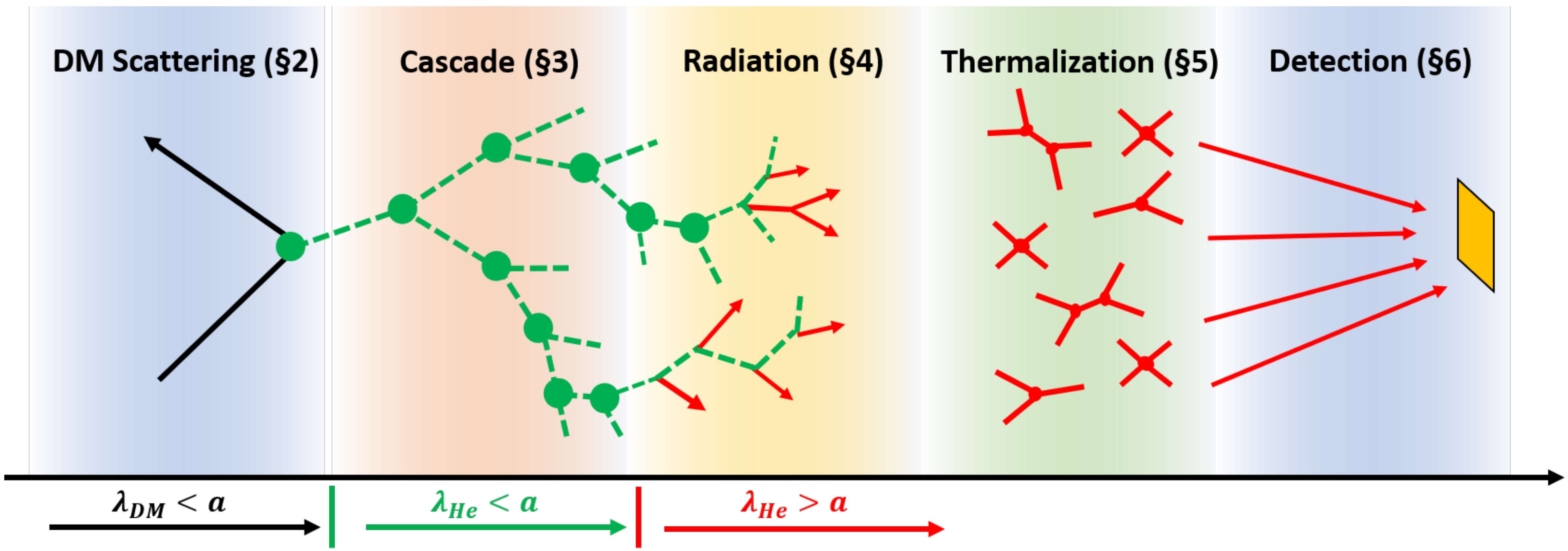


Rate summary

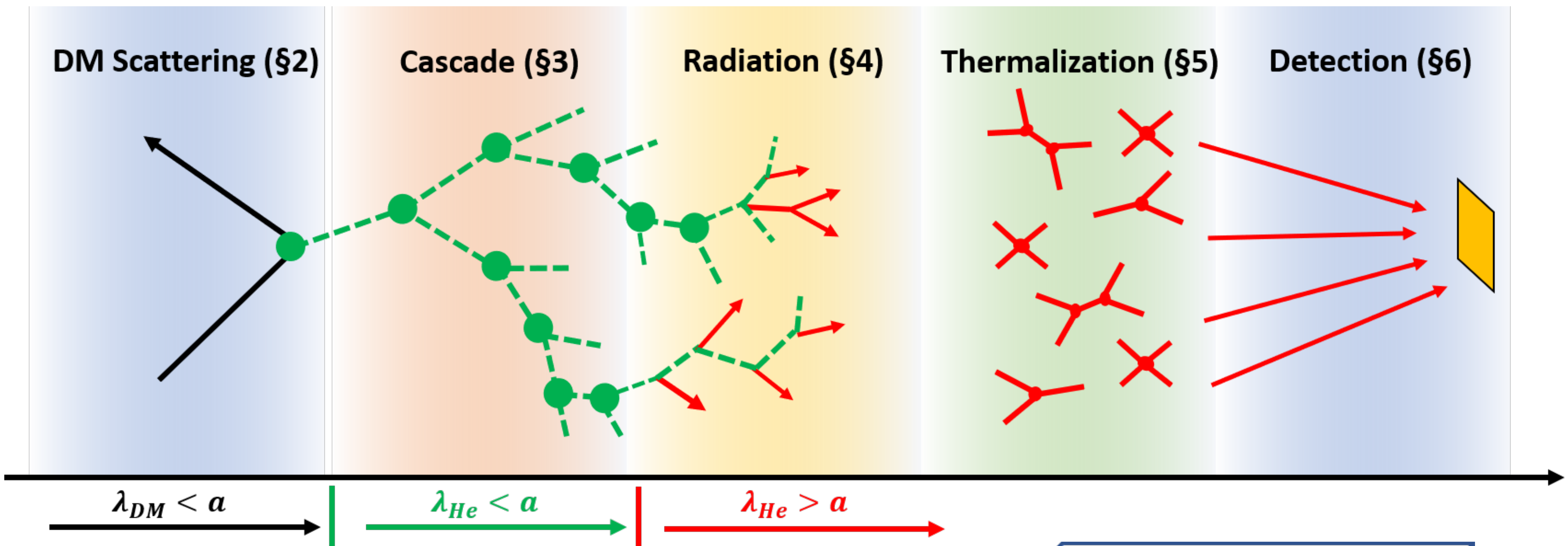
Process	Diagram	Result
Phonon decay $\pi \to \pi + \pi$		$\Gamma = \frac{(u+1)^2 c_s p^5}{120\pi\Lambda^4}$
Phonon self-scattering $\pi + \pi \to \pi + \pi$		$\langle \sigma \Delta v \rangle_\theta \simeq \frac{(2u+2)^2 c_s p_1^4}{96^2 \gamma \pi \Lambda^6}$
Roton self-scattering $\varphi_r + \varphi_r \to \varphi_r + \varphi_r$		$\sigma = \frac{2\lambda_r^2}{\lvert \boldsymbol{v}_1 - \boldsymbol{v}_2 \rvert \cos\frac{\theta}{2} m_* p_*}$
Roton-phonon scattering $\pi + \varphi_r \to \pi + \varphi_r$		$\langle \sigma \rangle_\Omega = \frac{1}{4\pi}\left[\frac{1}{25\Lambda^8}\frac{p_*^4 k^4}{m_*^2 c_s^2} + \frac{2432 + 45\pi^2}{11520\Lambda^8} p_*^2 k^4 + \frac{2y_4}{9\Lambda^7}\frac{p_*^2 k^4}{m_* c_s} + \frac{y_4^2}{\Lambda^6} k^4\right].$
Helium emits quasiparticles $\mathrm{He} \to \mathrm{He} + \varphi$		$\Gamma_m = \frac{2\pi\rho}{m_{\mathrm{He}}} \int \frac{d^3k}{(2\pi)^3} \left(\frac{\lambda_1}{m_{\mathrm{He}}\Lambda} + \frac{\lambda_2 m_{\mathrm{He}}}{\Lambda^3} \frac{\boldsymbol{v}_{\mathrm{He}} \cdot \boldsymbol{k}\omega}{k^2}\right)^2 S(\boldsymbol{k}, \omega)$ Single emission: $S(\boldsymbol{k}, \omega) \to S(k)\delta(E_i - E_f - \omega)$
DM emits quasiparticles $\mathrm{DM} \to \mathrm{DM} + \varphi$		$\Gamma_s = \frac{\rho}{2\pi m_{\mathrm{He}} v_{\mathrm{DM}}} \left(\frac{\lambda}{m_\sigma^2}\right)^2 \int k\, S(k)\, dk$ $\Gamma_m = \frac{2\pi\rho}{m_{\mathrm{He}}} \left(\frac{\lambda}{m_\sigma^2}\right)^2 \int \frac{d^3k}{(2\pi)^3} S(\boldsymbol{k}, \omega)$

arXiv: 2108.07275

Thermalization and Detection



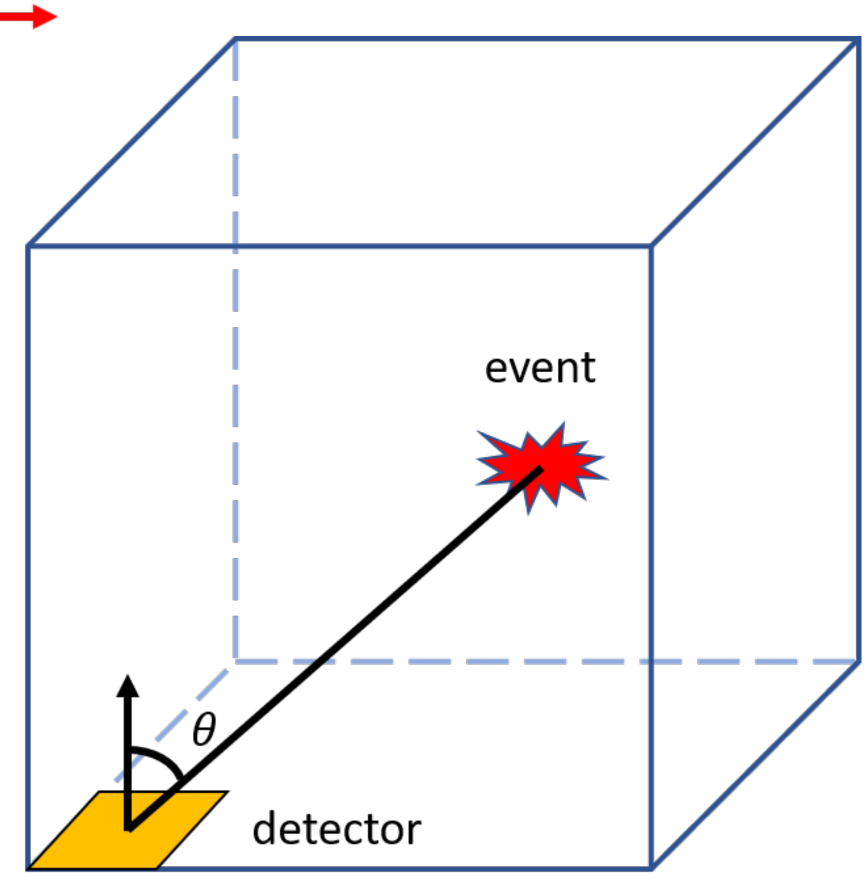
Thermalization and Detection



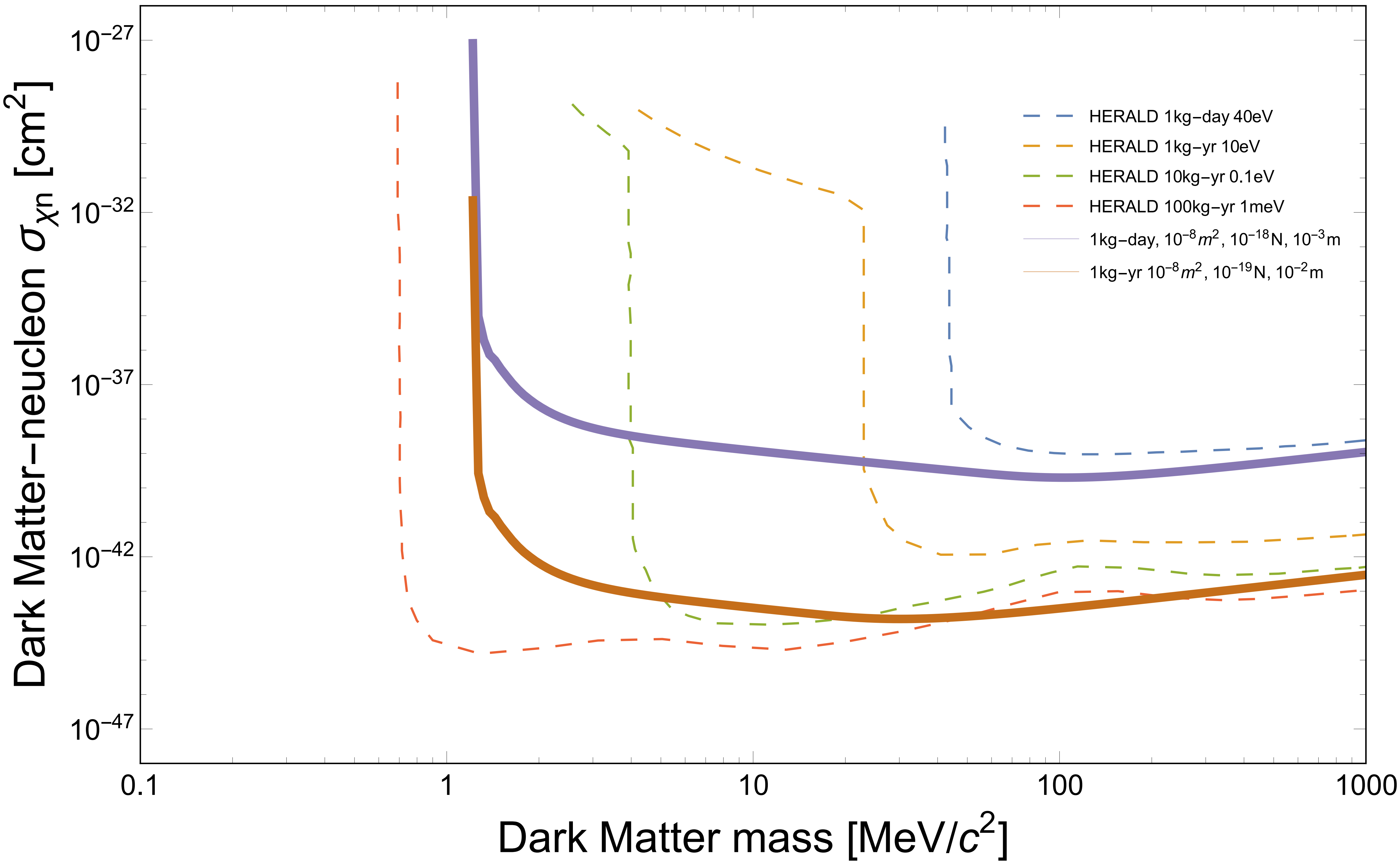
- Nano-mechanical Resonator Detector

  dimension $(10 \sim 100)\,\mu m \times (10 \sim 100)\,\mu m$

  force sensitivity $10^{-18}\,\mathrm{N} \sim 10^{-21}\,\mathrm{N}$



Reach Plots

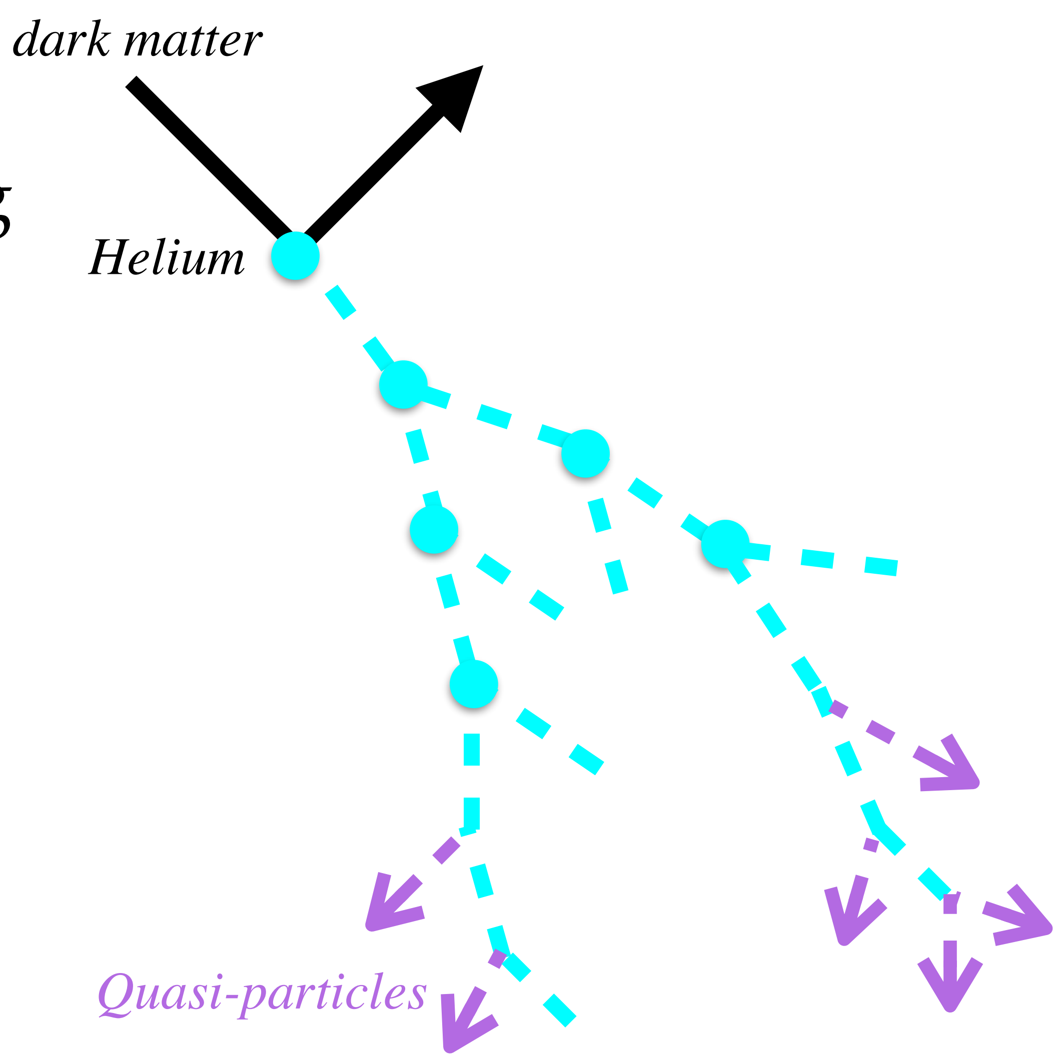


Dark Matter–neucleon $\sigma_{\chi n}$ [cm^2]
10^{-27}
10^{-32}
10^{-37}
10^{-42}
10^{-47}
0.1
1
10
100
1000
Dark Matter mass [MeV/c^2]
HERALD 1kg–day 40eV
HERALD 1kg–yr 10eV
HERALD 10kg–yr 0.1eV
HERALD 100kg–yr 1meV
1kg–day, $10^{-8}m^2$, 10^{-18}N, 10^{-3}m
1kg–yr $10^{-8}m^2$, 10^{-19}N, 10^{-2}m

Summary and future works

- MeV - GeV dark matter
  theoretically and experimentally interesting

- effective field theory
  quasi-particle interactions



Summary and future works

- MeV - GeV dark matter
  theoretically and experimentally interesting
- effective field theory
  quasi-particle interactions
- to do
  simulations
  experiment at UF