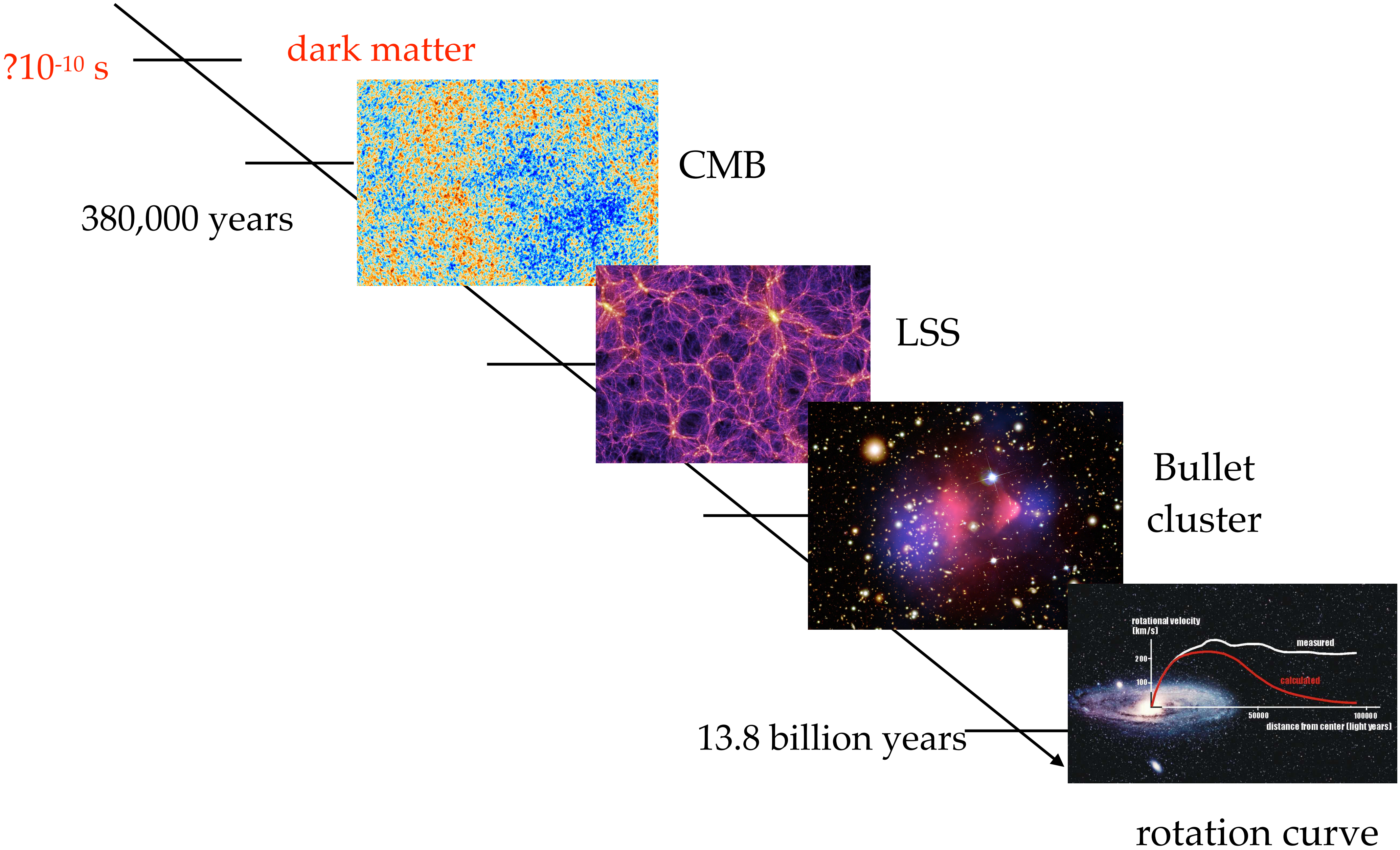
Beyond the WIMP Paradigm

Wei Xue

Copernicus Seminar
April 12, 2022

UF UNIVERSITY of FLORIDA



dark matter
?10^{-10} s
CMB
380,000 years
LSS
Bullet
cluster
rotational velocity
[km/s]
measured
200
100
calculated
50000
100000
distance from center [light years]
13.8 billion years
rotation curve

Fermi National Accelerator Laboratory

FERMILAB-Pub-77/41-THY
May 1977

Cosmological Lower Bound on Heavy Neutrino Masses

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AND

STEVEN WEINBERG**
Stanford University, Physics Department, Stanford, California 94305

ABSTRACT

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29}g/cm^3, the lepton mass would have to be greater than a lower bound of the order of 2 GeV.

**On leave 1976-7 from Harvard University.

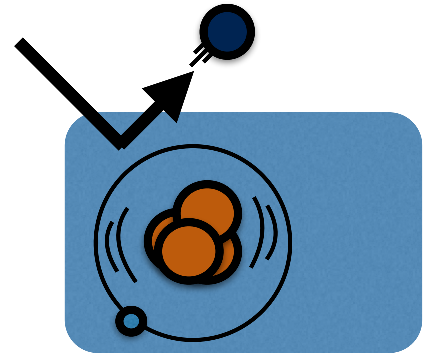
*Operated by Universities Research Association Inc. under contract with the Energy Research and Development Administration

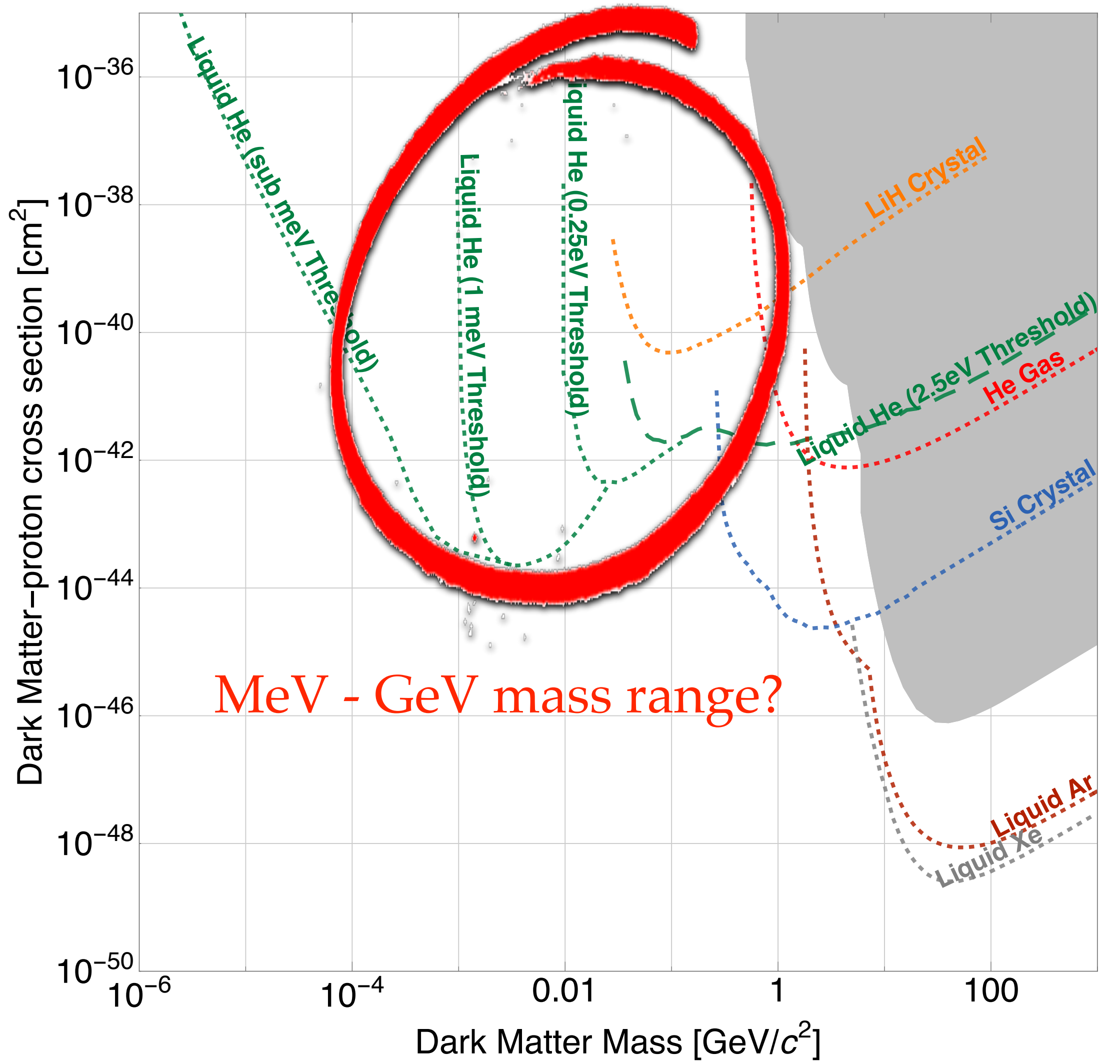
e

Ben Lee (1935 — June 1977)

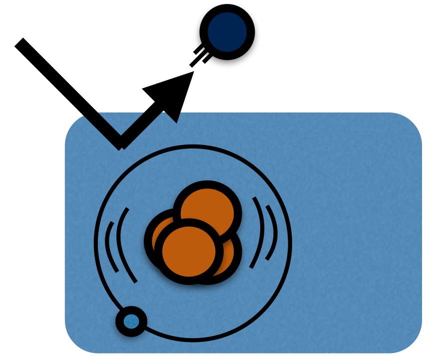
Steven Weinberg (1933— July 2021)

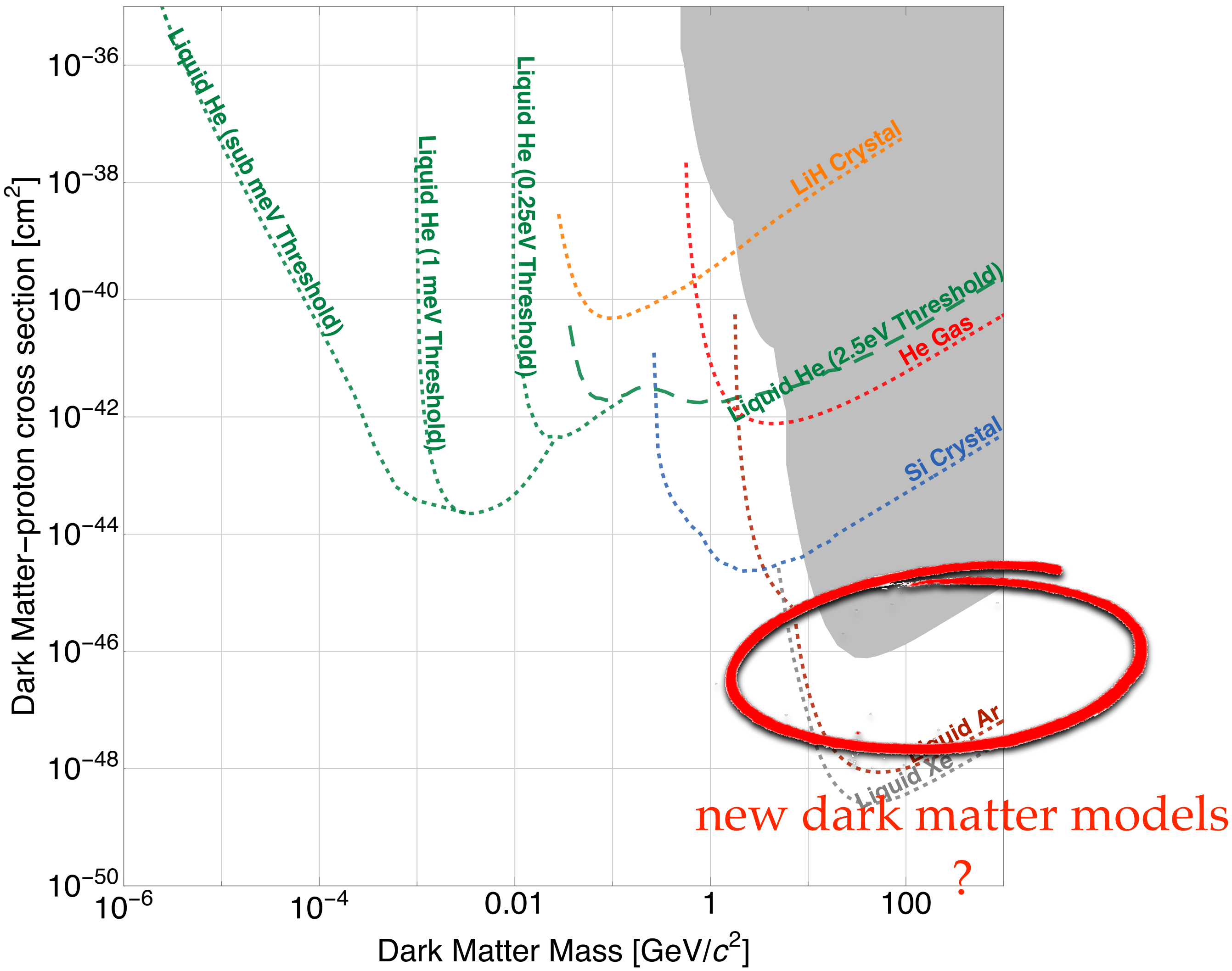
Dark matter direct detection





Dark matter direct detection





Outline

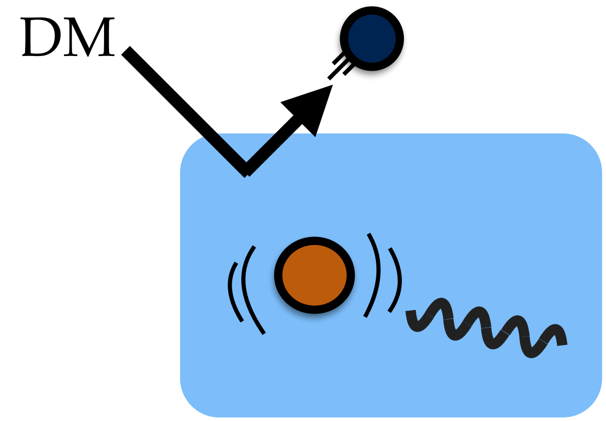
- New experiment
  Superfluid He4 dark matter detector

arXiv: 2108.07275
JHEP
Konstantin Matchev, Jordan Smolinsky and Yining You

- New paradigm
  Continuum dark matter

arXiv: 2105.07035 & 2105.14023
PRD & PRL
Csaba Csaki, Sungwoo Hong, Gowri Kurup, Seung Lee, and Maxim Perelstein

- Summary and outlook

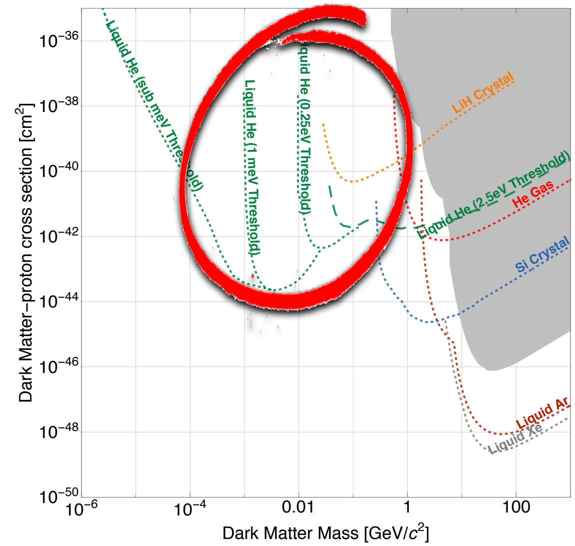


Dark Matter Detection with Superfluid

Matchev, Smolinsky, You and **WX**
JHEP

future work + Saab and Lee

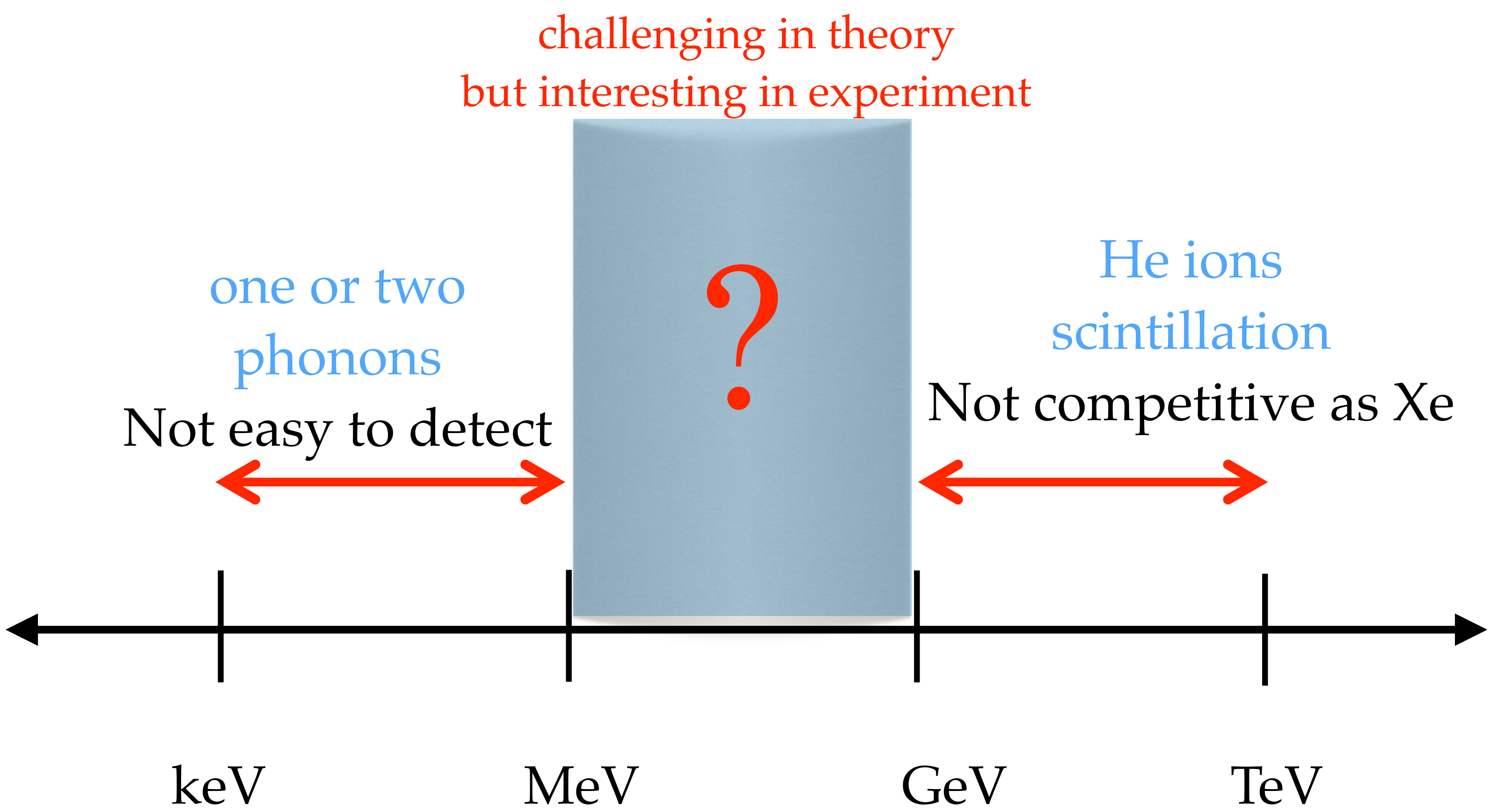
Why ^{4}He superfluid?



- 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



Schutz and Zurek (2016)
Knapen, Lin and Zurek (2016)
Acanfora, Esposito and Polosa (2019)
…

Guo and McKinsey (2013)
Ito and Seidel (2013)
Bandler, Lanou, Maris, More, Porter, Seide (1992)
H. J. Maris, G. M. Seidel and D. Stein (2017)
…

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

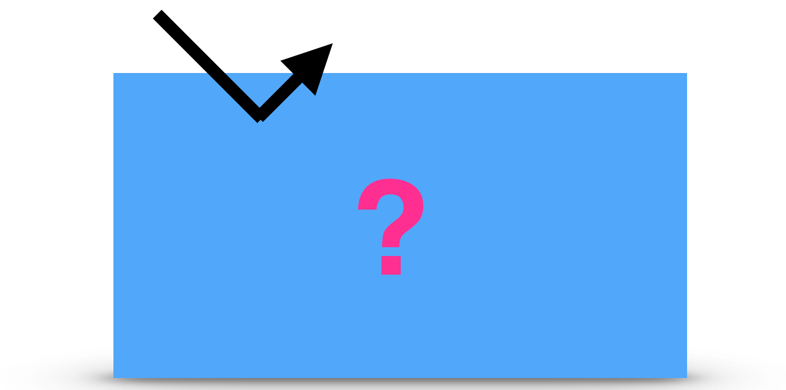
Konstantin Matchev

Yining You

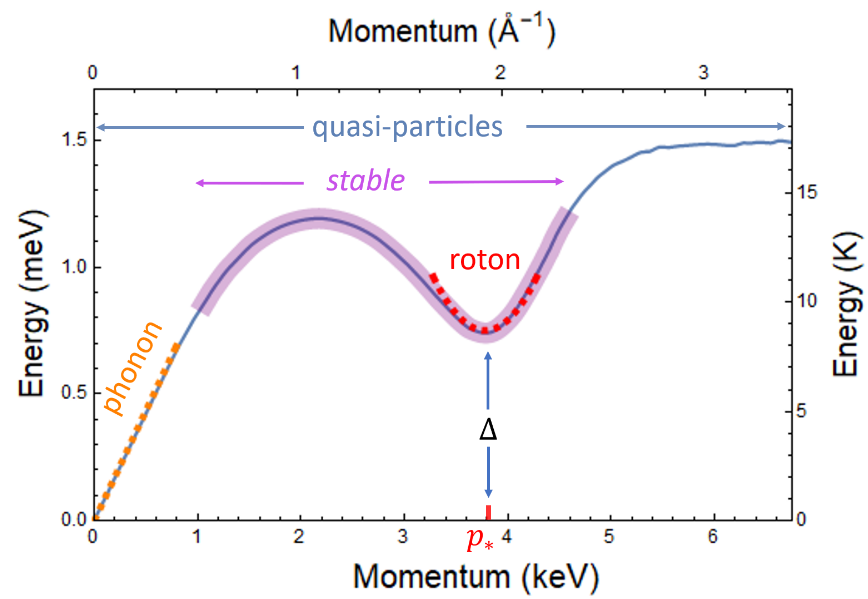
Jordan Smolinsky

Challenges and motivations

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



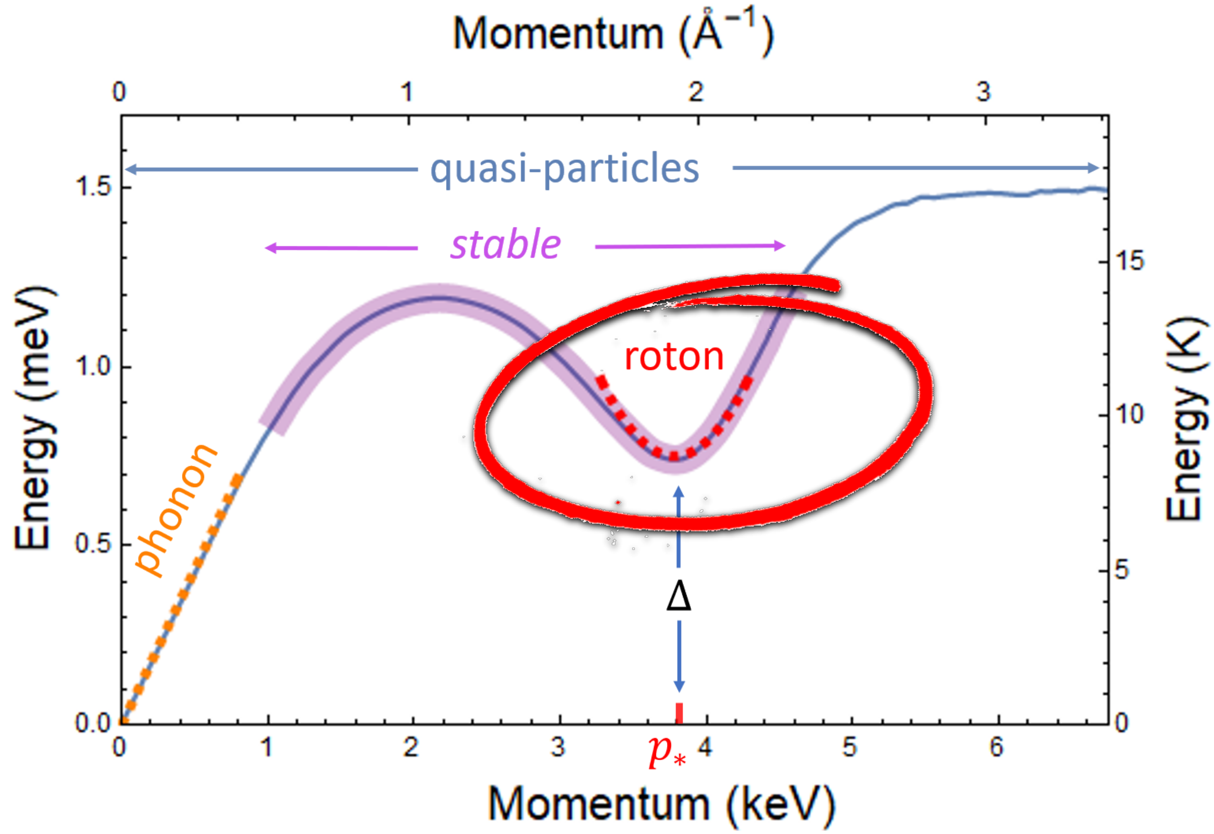
- The perturbative theory of superfluid break down ~ keV ?
  (inverse of the helium spacing)



Quasi-particles

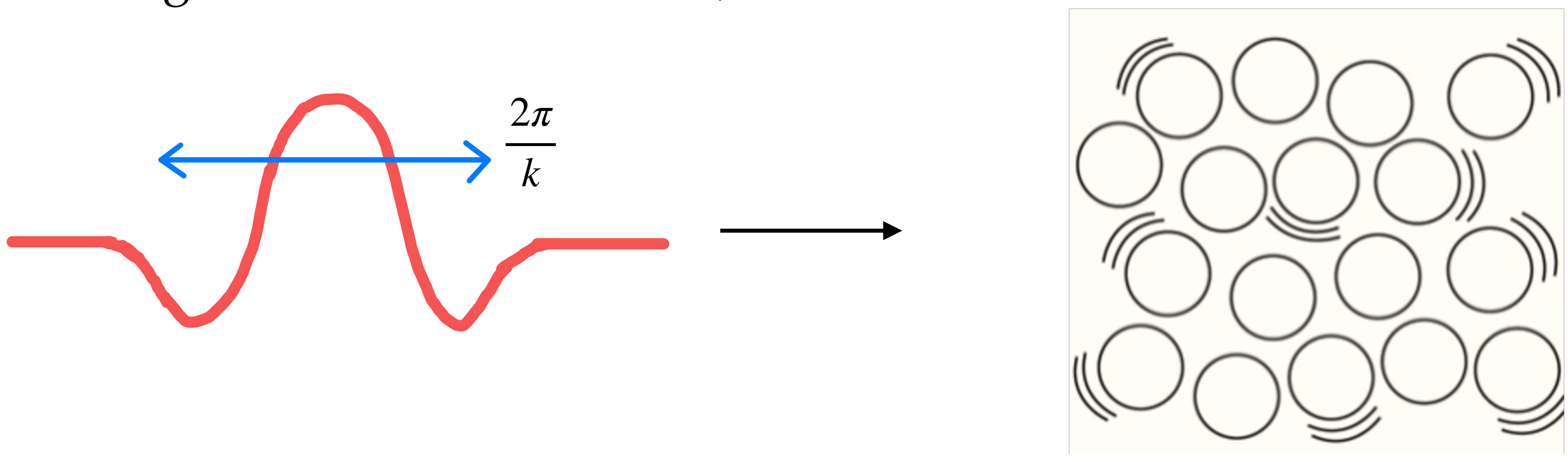
- atomic spacing ~ keV^{-1}
- phonon $E \simeq c_s k$

  sound speed $c_s \sim 10^{-6}$
- roton $E_r \simeq \Delta + \dfrac{(p - p_*)^2}{2m_*}$

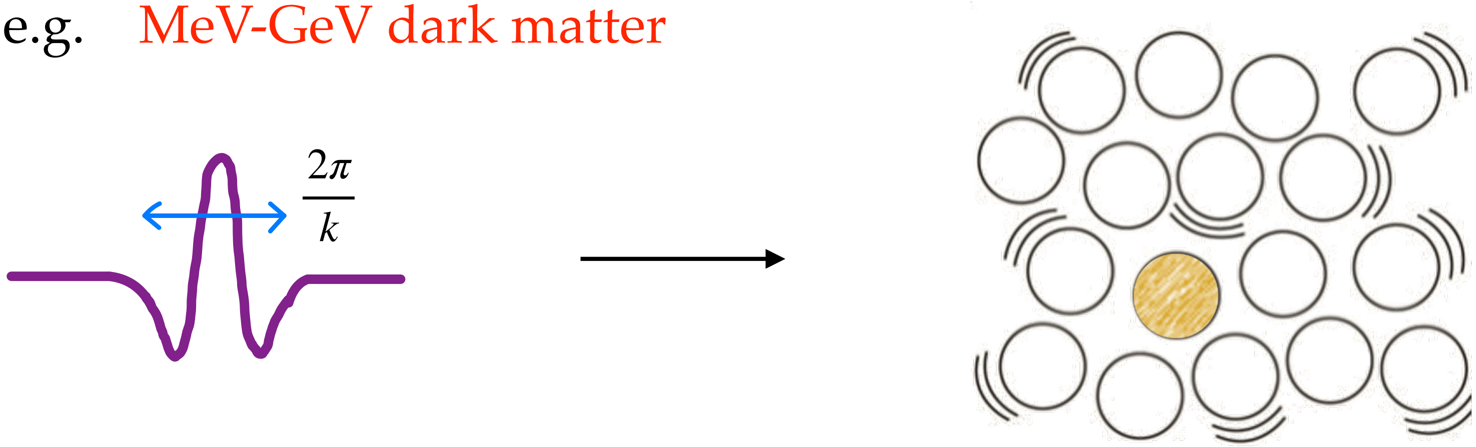


de Broglie wavelength

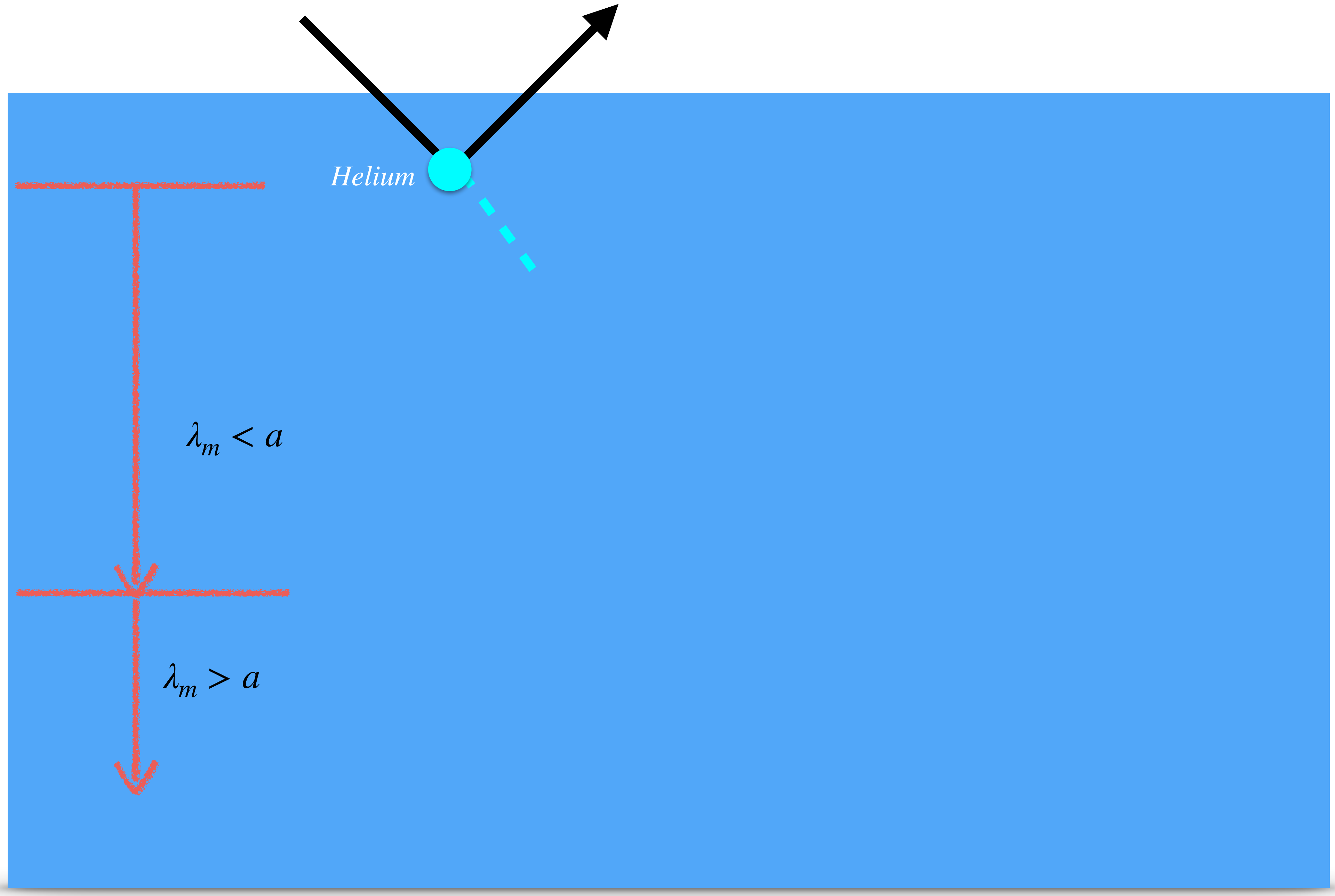
- atomic spacing $\lambda_a \sim$ keV^{-1}
- incoming particle de Broglie wavelength $\gtrsim \lambda_a$
  e.g. sub-MeV dark matter, v~ 10^{-3} c



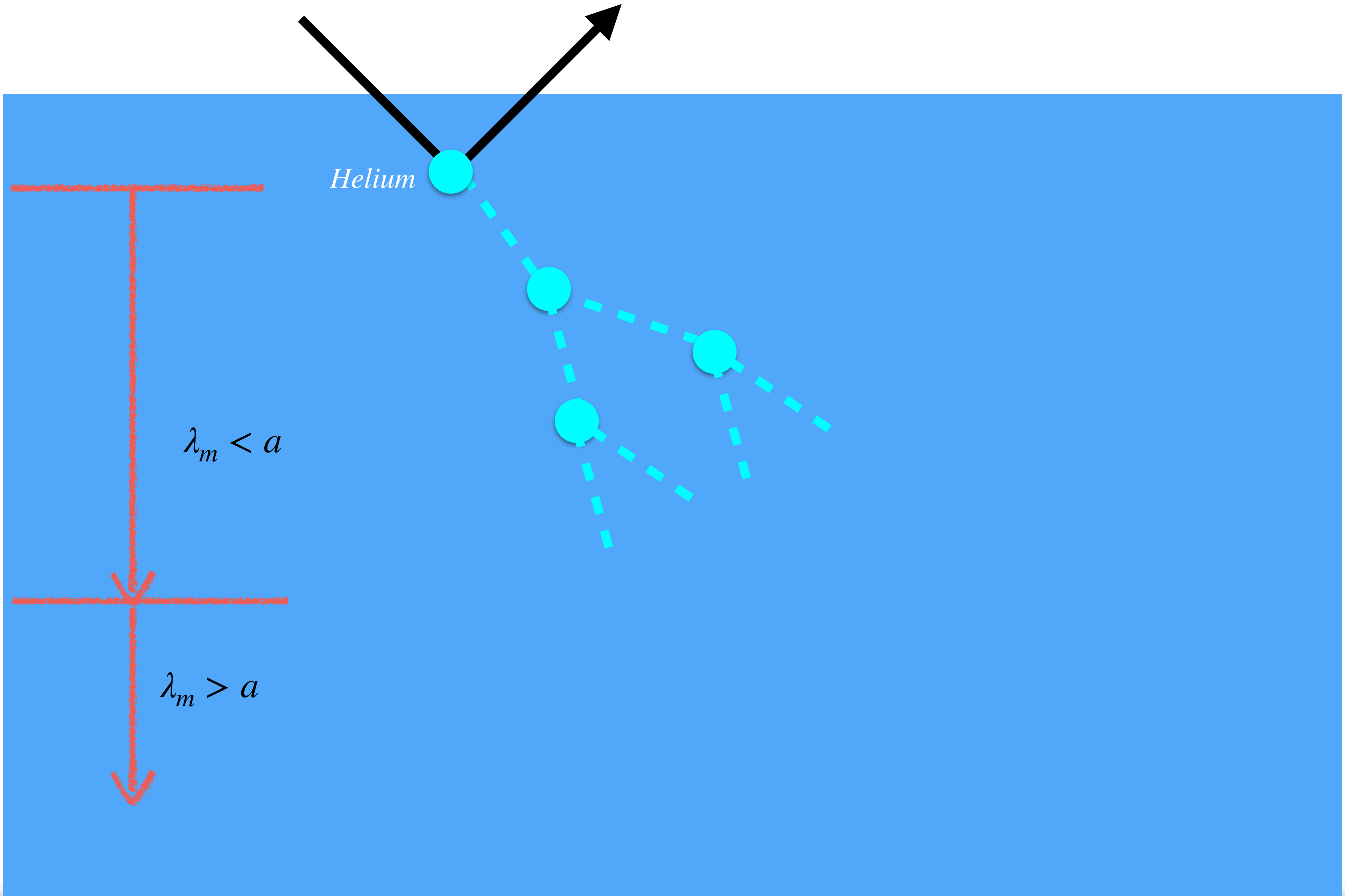
- incoming particle de Broglie wavelength $\ll \lambda_a$
  e.g. MeV-GeV dark matter



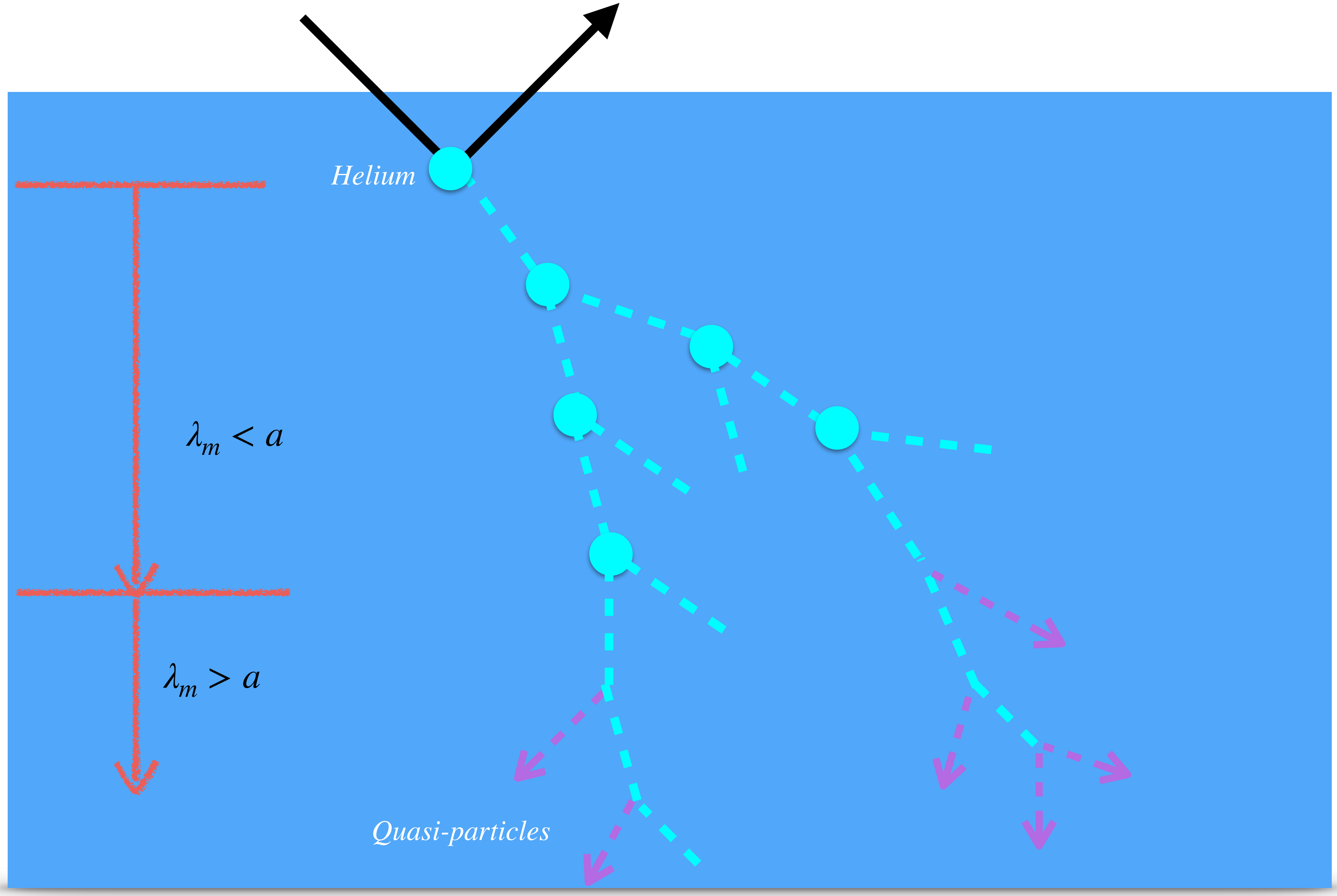
What happens after a MeV-GeV dark matter scattering?

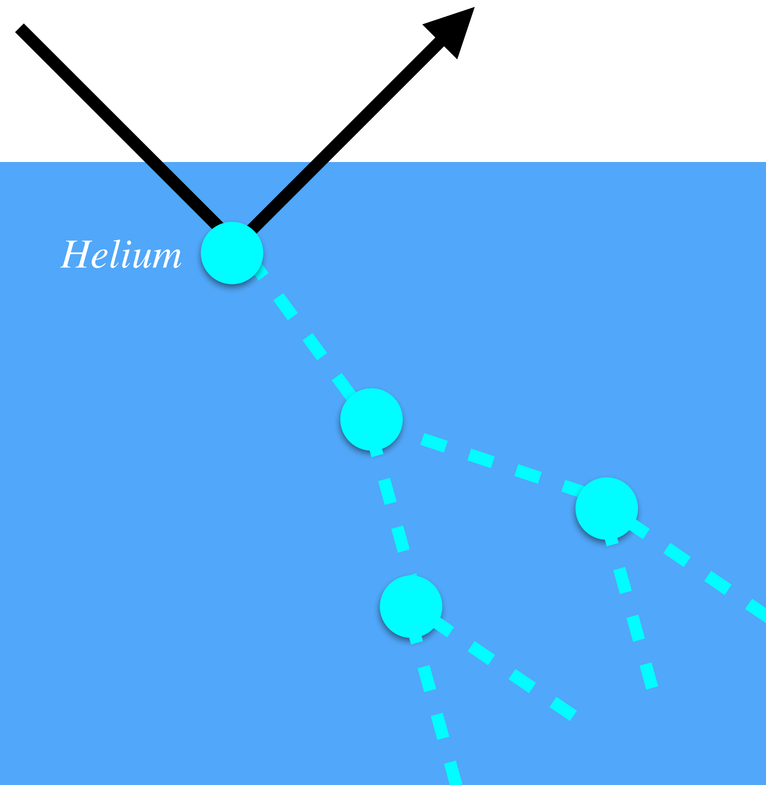


What happens after a MeV-GeV dark matter scattering?



What happens after a MeV-GeV dark matter scattering?

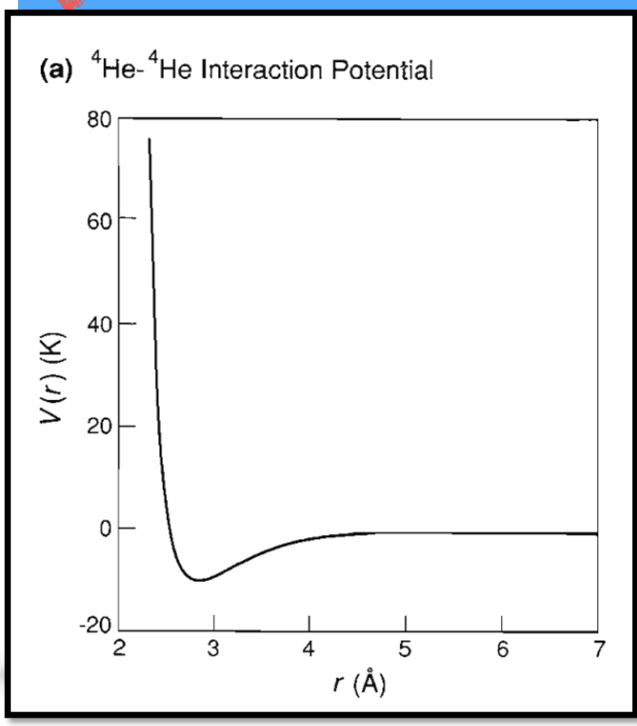




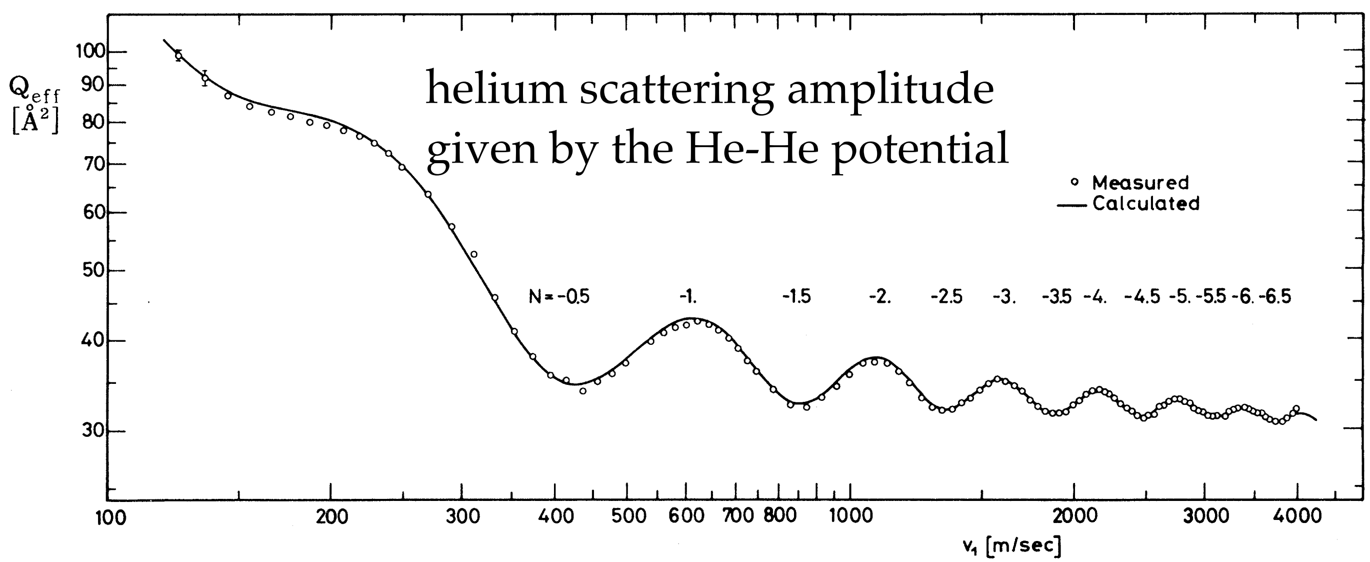
$\lambda_m < a$

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

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



helium scattering amplitude given by the He-He potential



$\lambda_m < a$

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

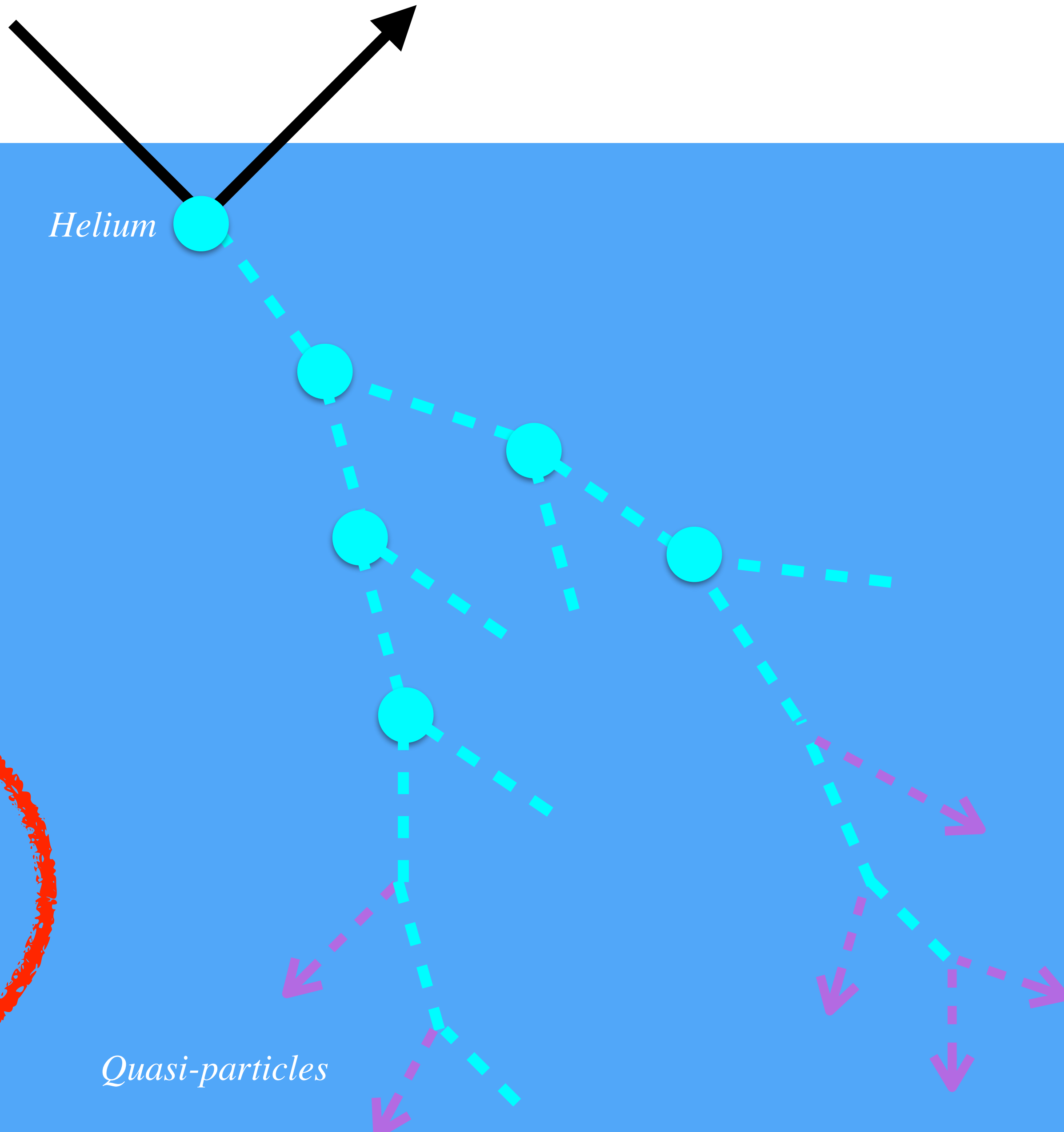
$\mathrm{He} + \mathrm{He} \rightarrow \mathrm{He} + \mathrm{He}$

$\lambda_m > a$

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

$\varphi_1 \rightarrow \varphi_2 + \varphi_3$

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



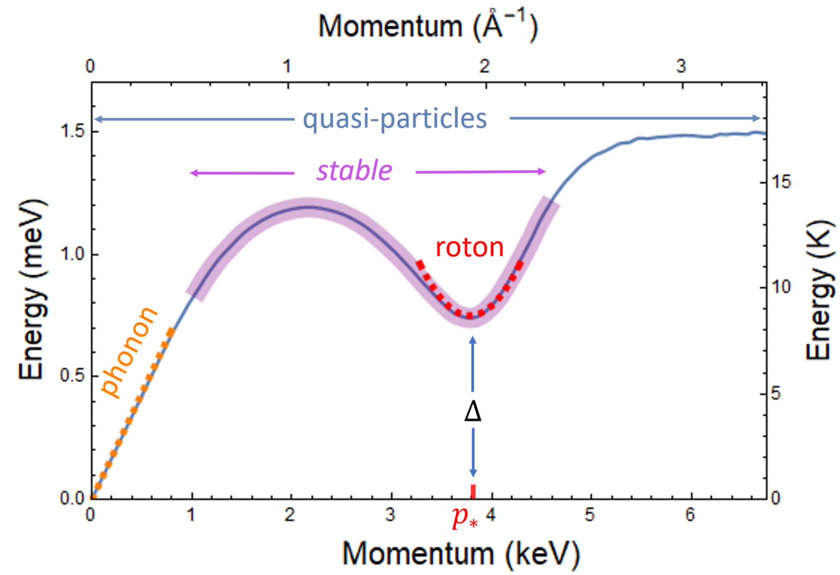
- relevant d.o.f

  phonon π [0 , keV] massless goldstone mode

  roton φ_r ~ keV

  quasi-particles φ (0, 10 keV)

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



- cutoff Λ ~ keV

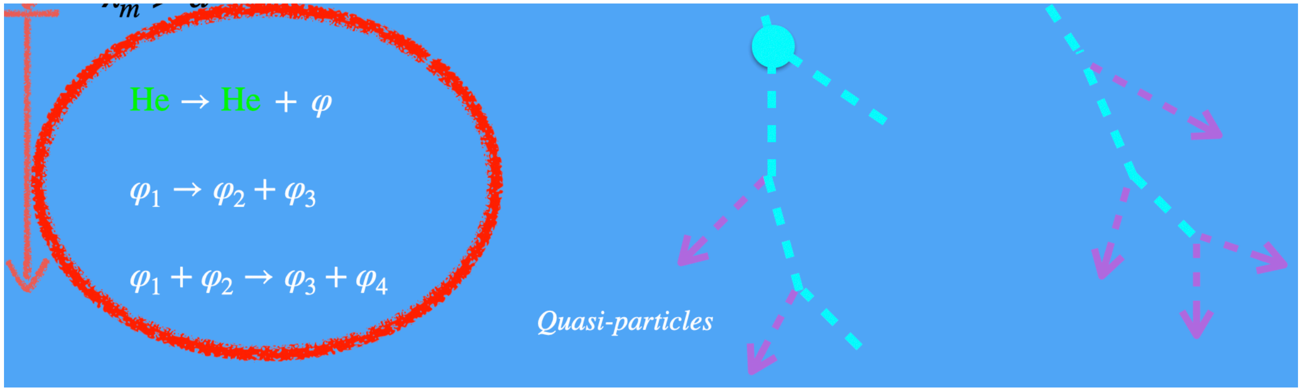
  atomic spacing ~ $(\mathrm{keV})^{-1}$

- processes

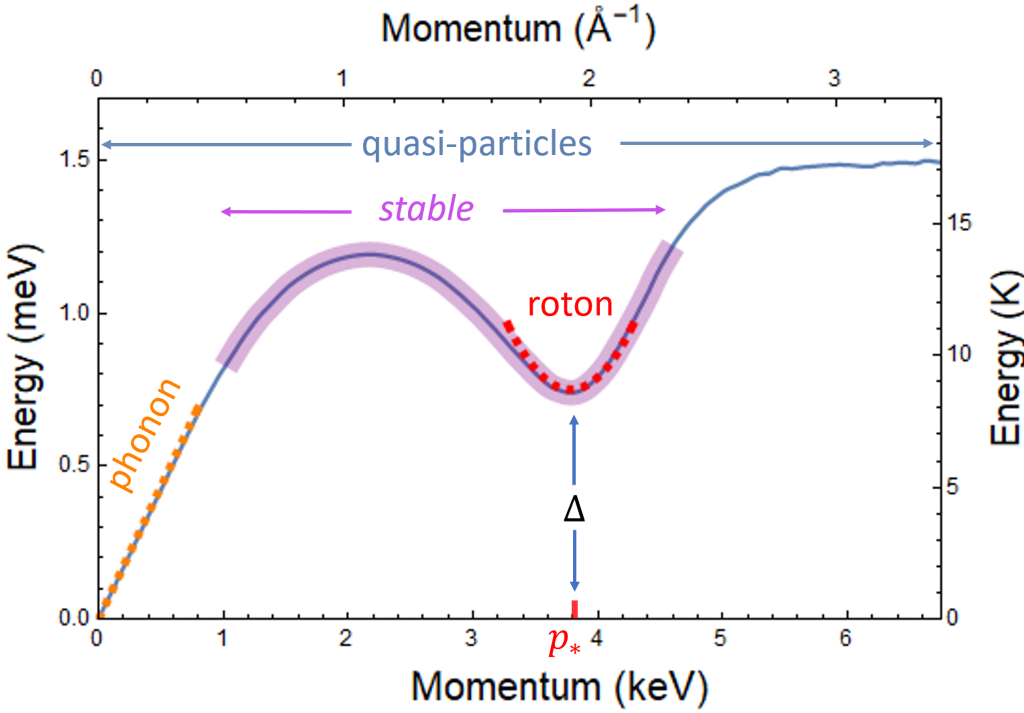
  quasi-particle Helium interactions to study quasi-particle production

  quasi-particle self interactions to understand thermalization

Why it is challenging?



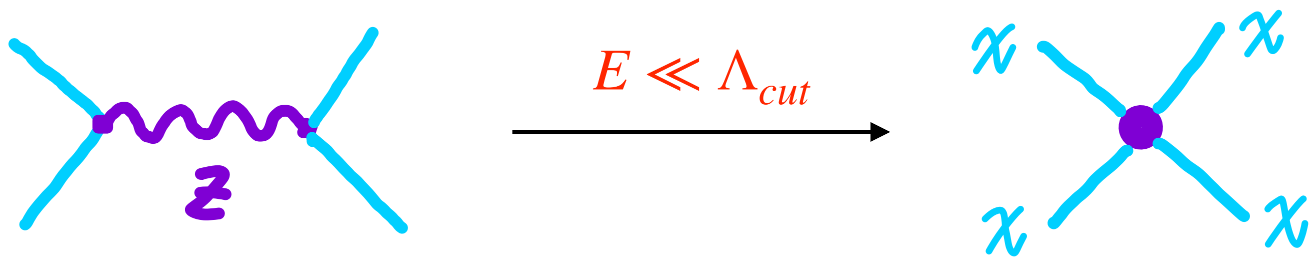
- inverse atomic spacing $\Lambda_{cut} \sim \mathrm{keV}$
- rotons, quasi-particles and heliums momentum $p \gtrsim \Lambda_{cut}$



Effective field theory

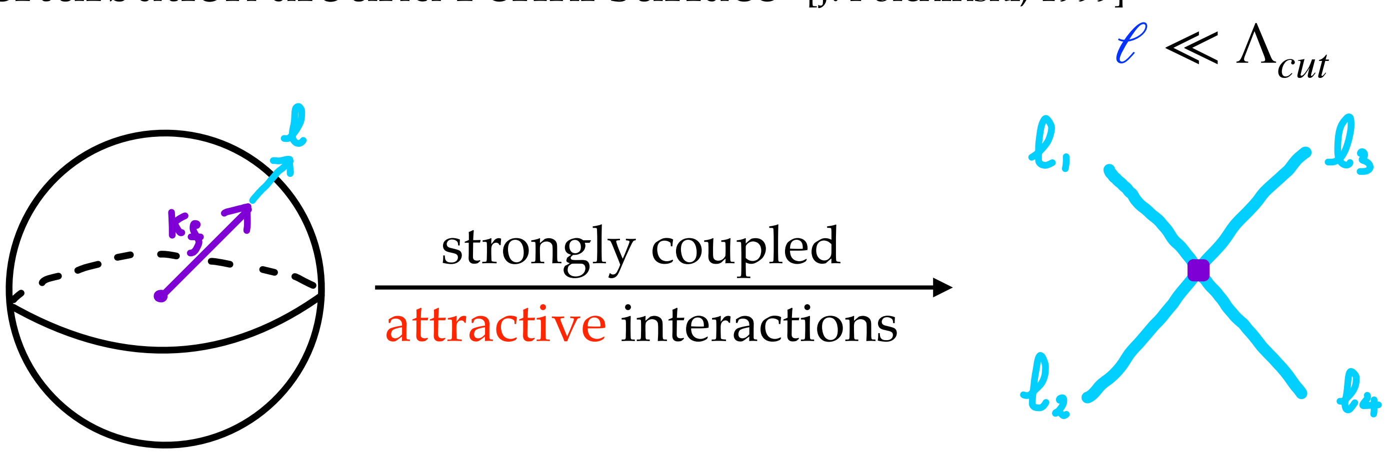
- find the relevant degrees of freedom and symmetry

- four-fermion interactions



- BCS theory

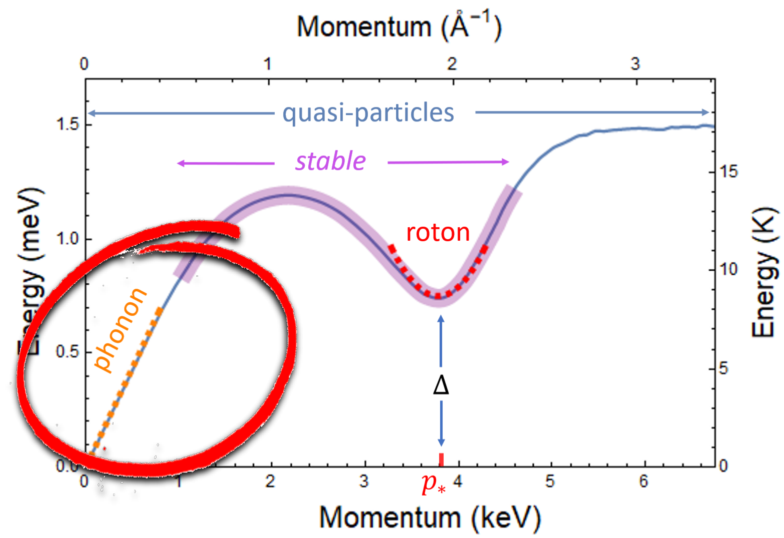
  perturbation around Fermi surface [J. Polchinski, 1999]



Phonons π (p $\ll \Lambda(\sim$ keV))

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

with shift symmetry + ``Galilei" symmetry



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

Effective quantum action method [D. Son, 2002]

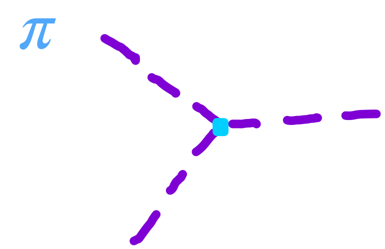
- or Power counting method

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

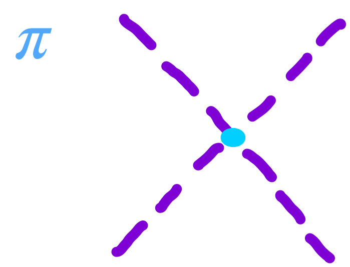
phonon interactions

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

$$+\mathcal{O}(\pi^4)$$



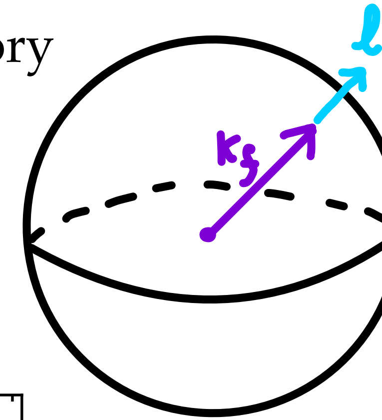
$$\sim \frac{1}{\Lambda^2}p^3$$

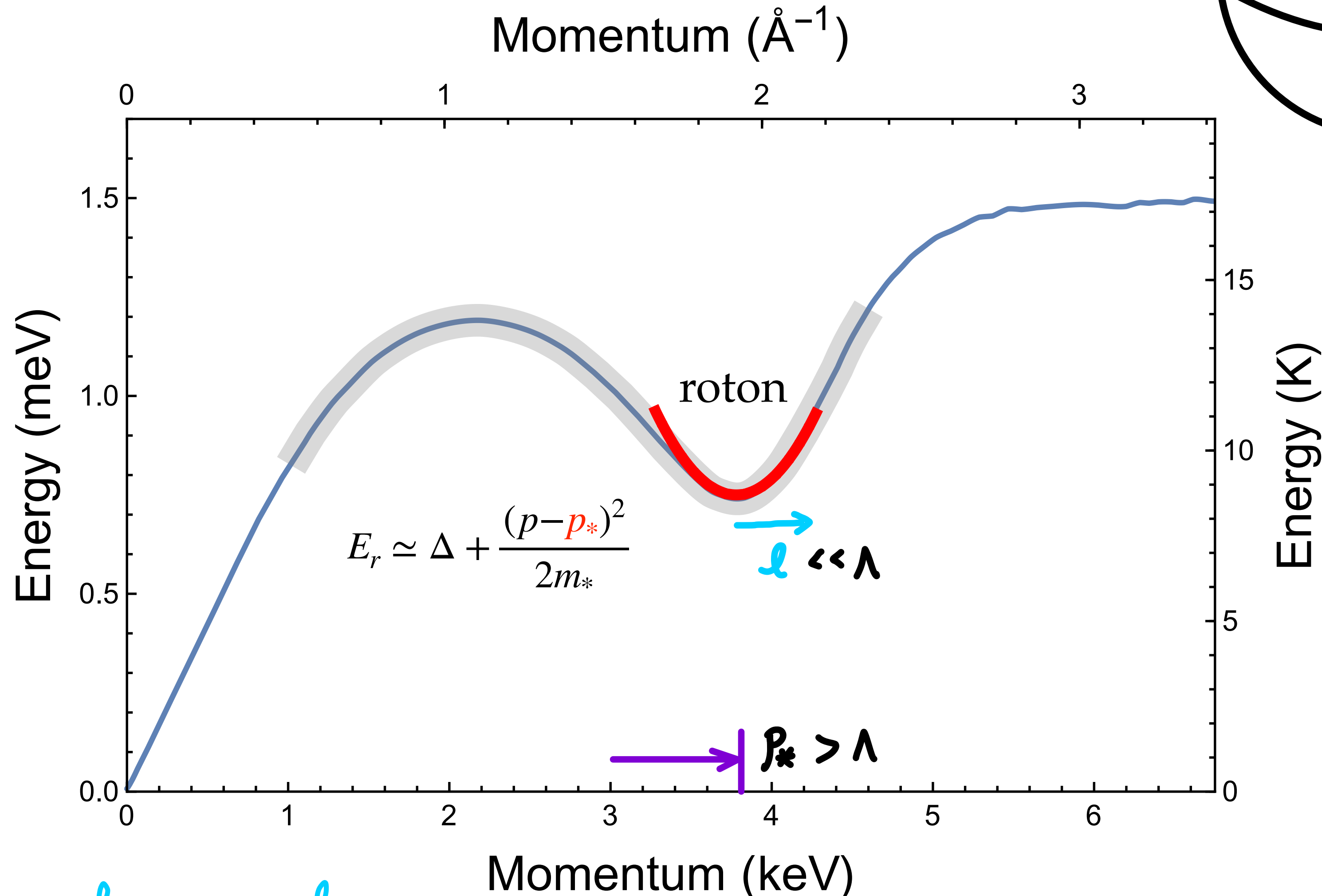


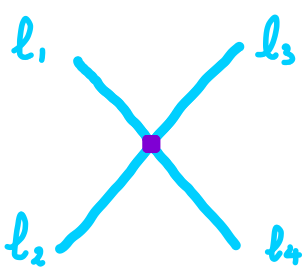
$$\sim \frac{1}{\Lambda^4}p^4$$

Roton effective field theory

BCS theory

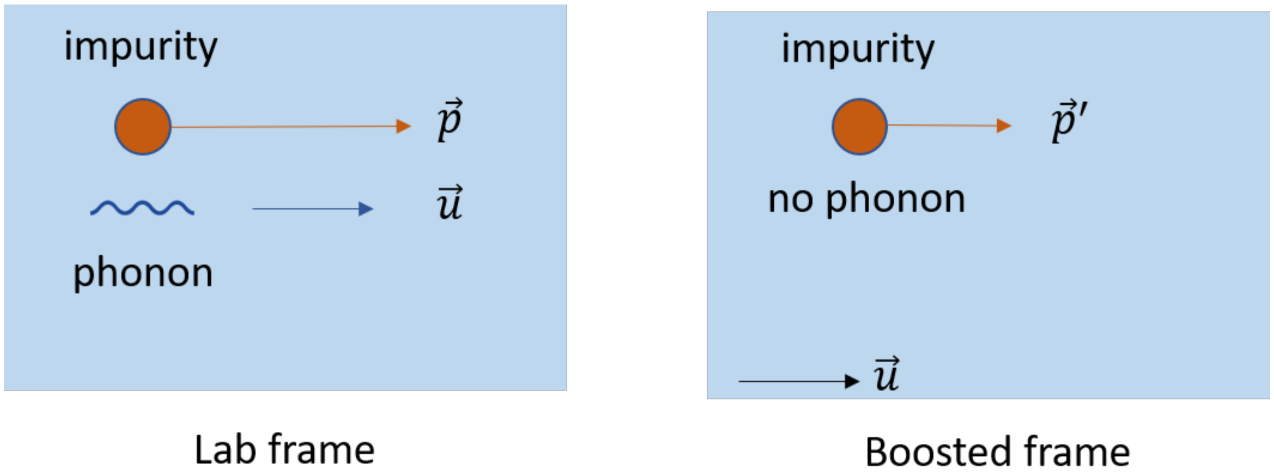






$\lambda_r \simeq 0.93$ consistent with data

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

- 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

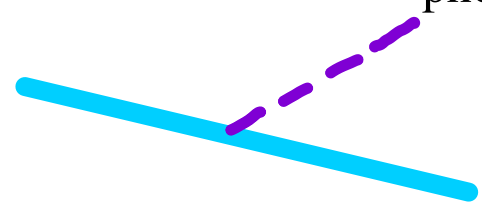
$$\mathbf{p} = m_Q\mathbf{v} + \mathbf{k} \quad , \quad \Lambda/m_Q \ll 1$$

- 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

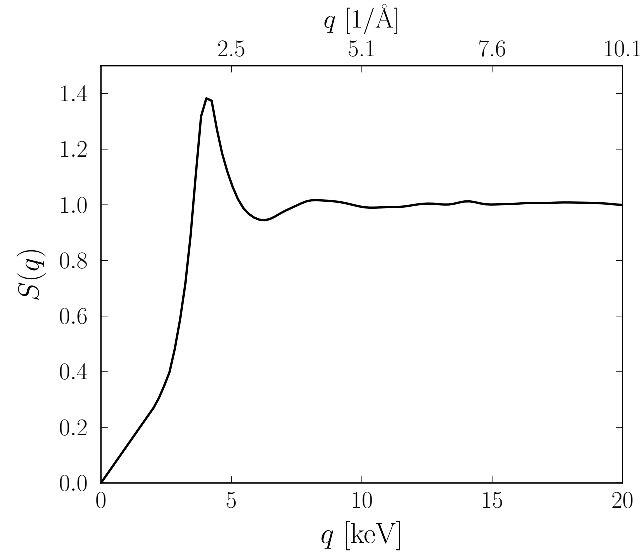
$$J^0 = \frac{\sqrt{\rho}}{m_{\rm He}c_s}\dot{\pi} + \cdots,$$



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

He → He + quasi-particle from measurement

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



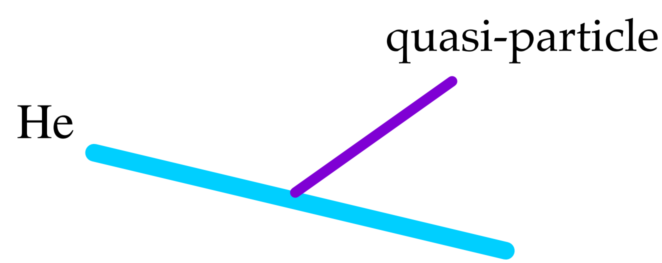
$\Longrightarrow$ HEP language, $S(q) = |\langle vac | j_0 | \varphi \rangle|^2$

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

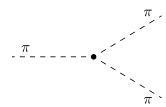
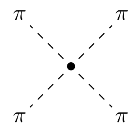
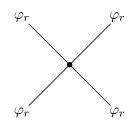
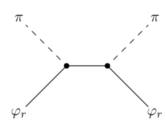
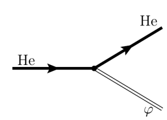
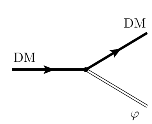
- Helium decay to a quasi-particle,

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

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

arXiv: 2108.07275

Summary and future works

- MeV - GeV dark matter

  theoretically and experimentally interesting

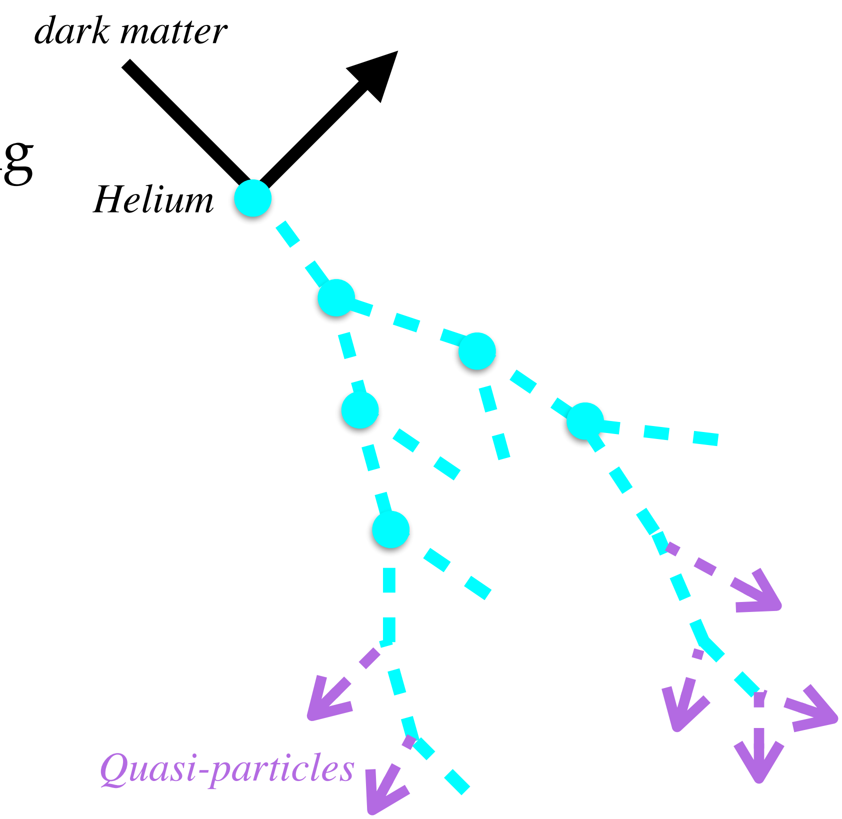
- effective field theory

  quasi-particle interactions

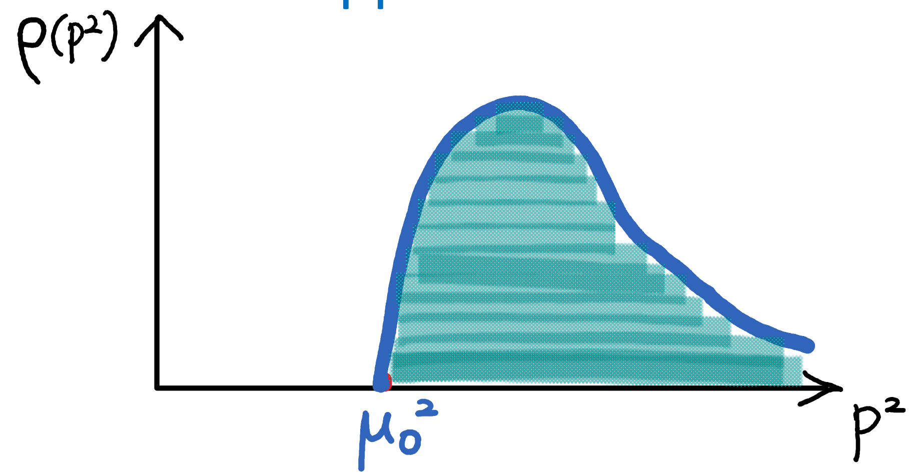
- to do

  simulations

  experiment at UF



<Gapped Continuum>

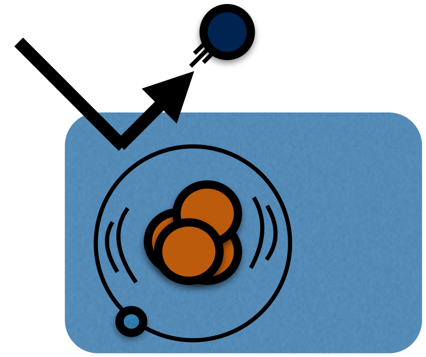


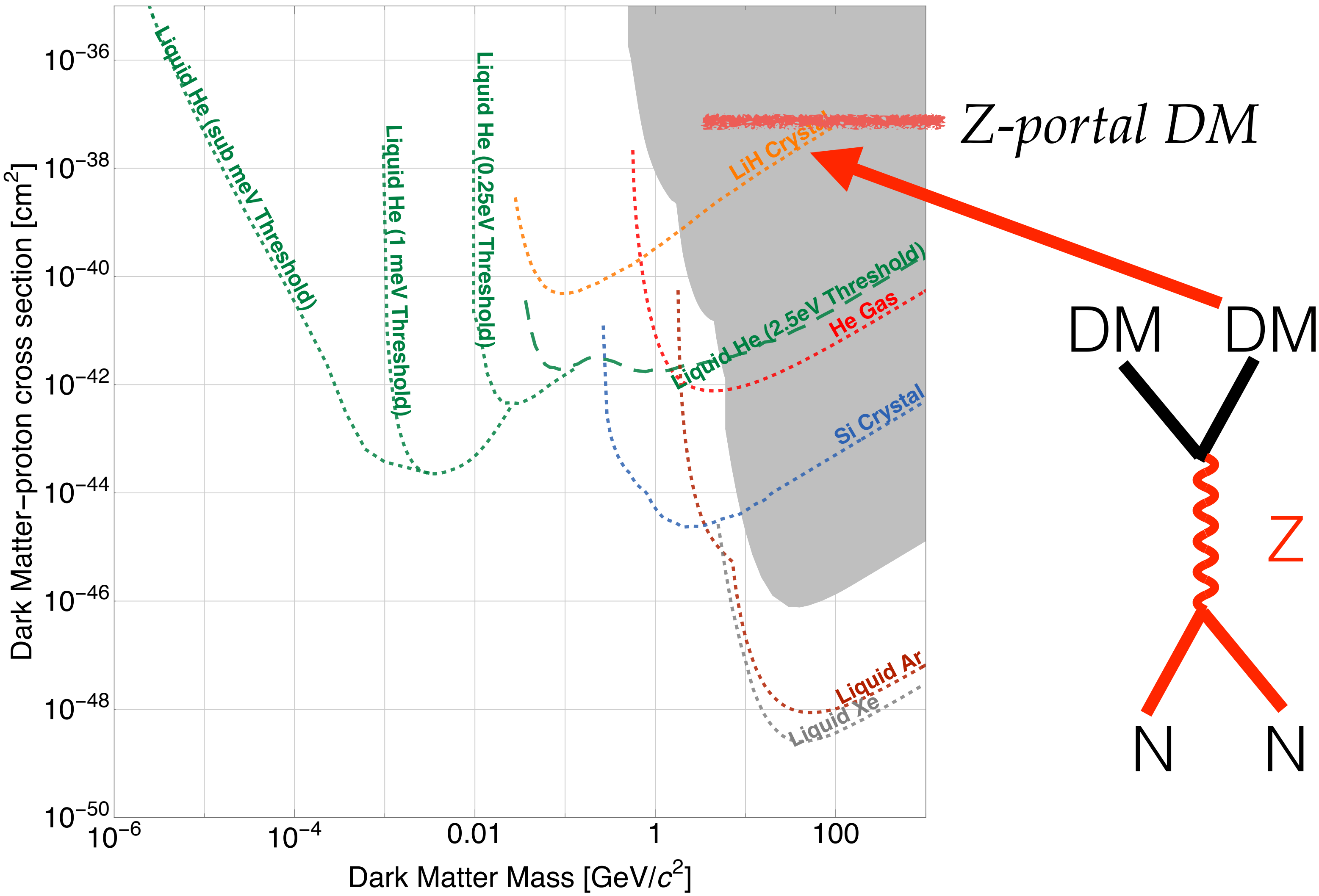
New Dark Matter Paradigm

[arXiv: 2105.07035 & 2105.14023]

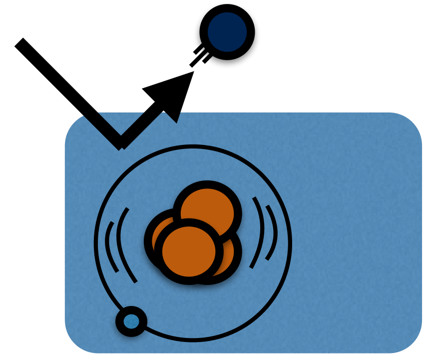
With Csaki, Hong, Kurup, Lee, and Perelstein

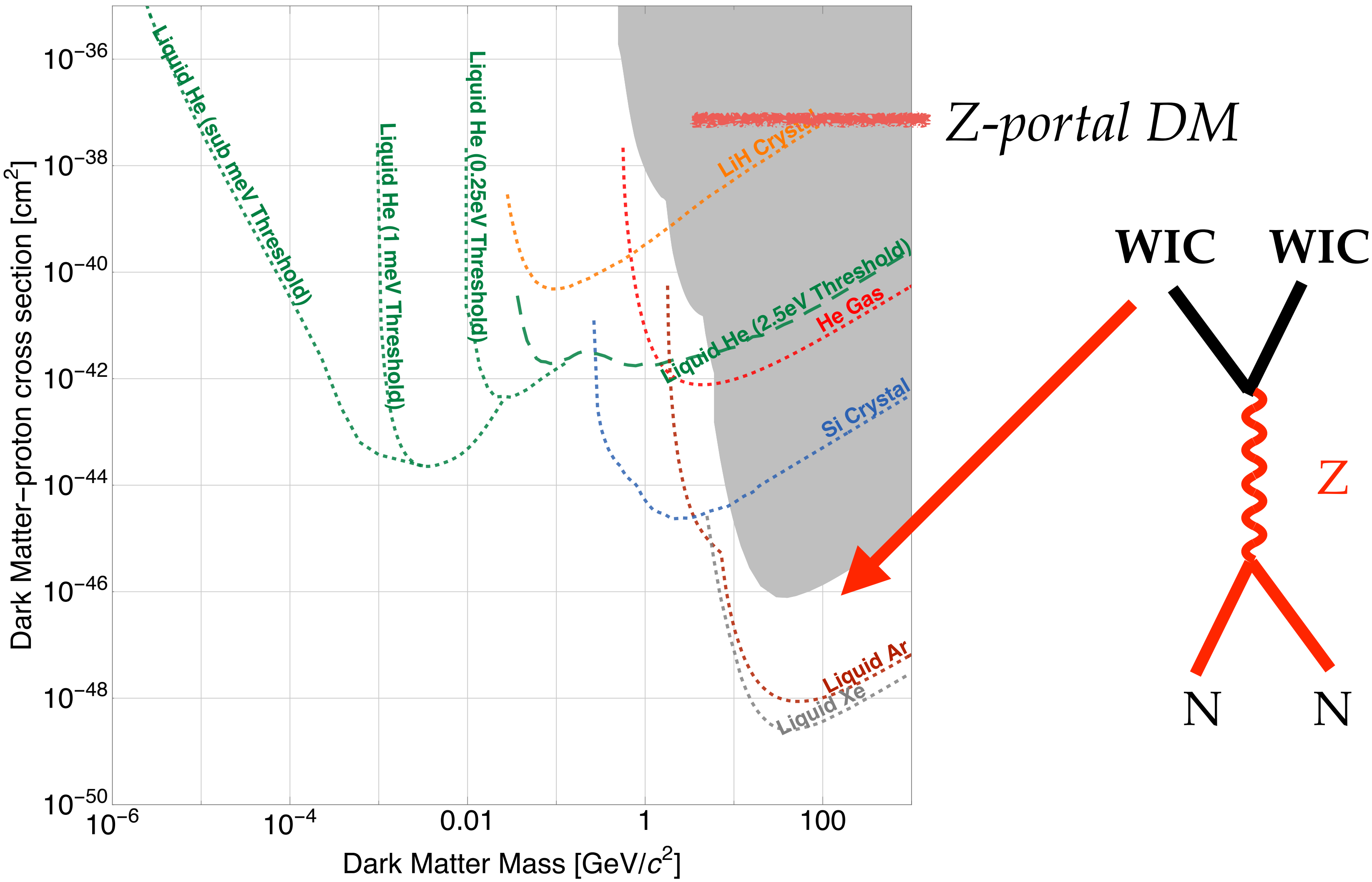
WIMP




Z-portal DM
LiH Crystal
Liquid He (sub meV Threshold)
Liquid He (1 meV Threshold)
Liquid He (0.25eV Threshold)
Liquid He (2.5eV Threshold)
He Gas
Si Crystal
Liquid Ar
Liquid Xe
Dark Matter−proton cross section [cm^2]
Dark Matter Mass [GeV/c^2]
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-6}
10^{-4}
0.01
1
100
DM
DM
Z
N
N

Weakly-Interacting Continuum (WIC)





Continuum States

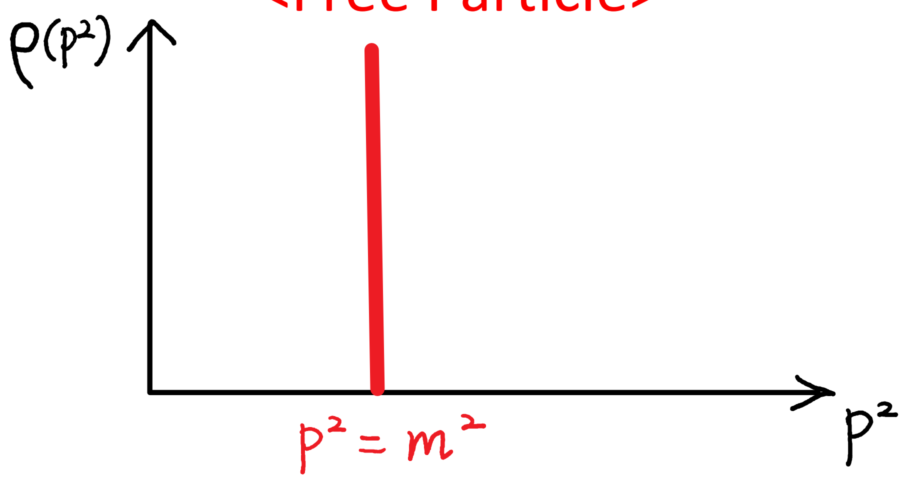
- the Källen-Lehmann representation

$$\langle 0 | \Phi(p)\Phi(-p) | 0 \rangle = \int \frac{d\mu^2}{2\pi} \frac{i\rho(\mu^2)}{p^2 - \mu^2 + i\epsilon}$$

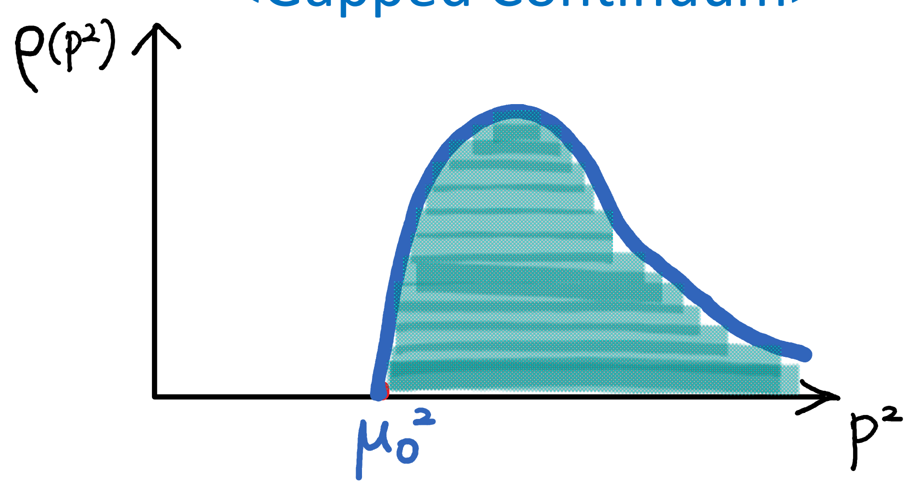
- a normal particle correlation function $\rho(\mu^2) = 2\pi\,\delta(\mu^2 - m_0^2)$

- a continuum state

<Free Particle>

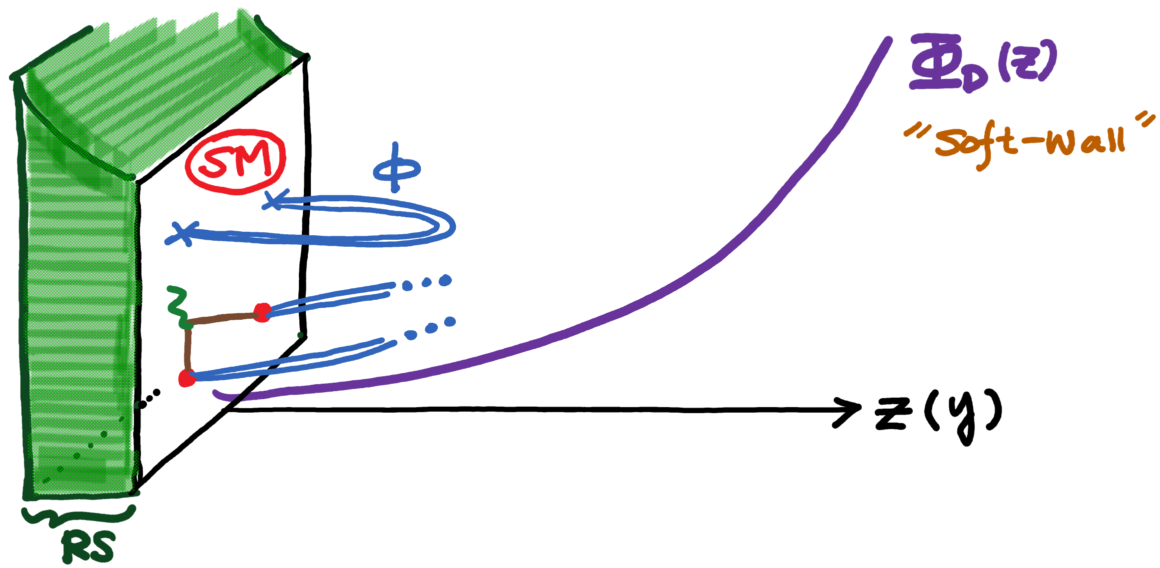


<Gapped Continuum>



Gapped Continuum from 5D UV Model

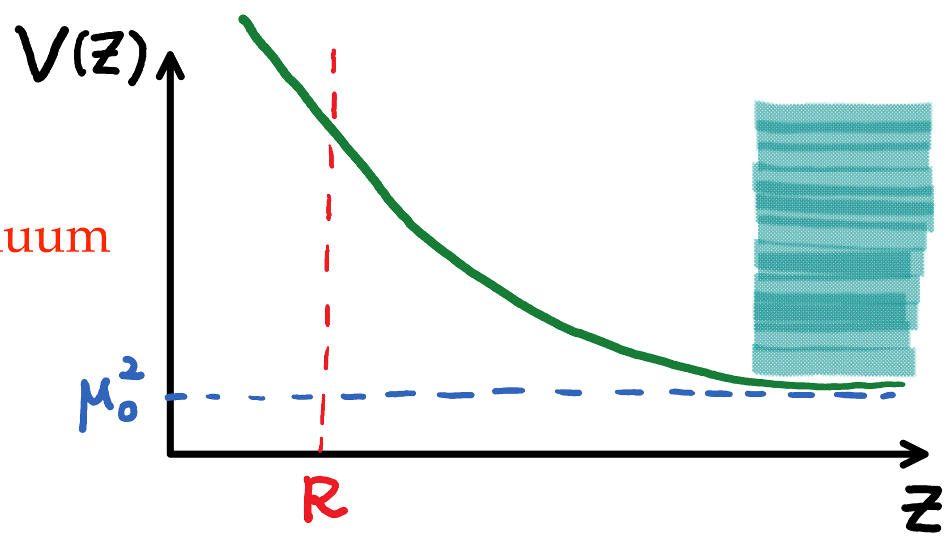
- warped 5D background



- Schrödinger equation (1D QM problem)

$$-\frac{d^2\psi}{dz^2} + V(z)\,\psi = p^2\psi$$

$V(z \to \infty) = \mu_0^2 \quad \Rightarrow$ Gapped continuum



Physics of Gapped Continuum

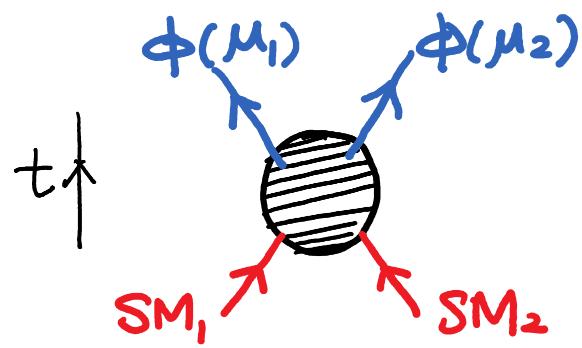
- quantization (free continuum)

$$\left[a_{\mathbf{p},\mu}, a^{\dagger}_{\mathbf{p}',\mu'}\right] = (2\pi)^4\delta^3(\mathbf{p}-\mathbf{p}')\delta(\mu^2-\mu'^2)$$

decomposition

$$\Phi(x) = \int \frac{d\mu^2}{2\pi}\sqrt{\rho(\mu)}\int \frac{d^3p}{(2\pi)^3\sqrt{2E_\mu}}\left(a_{\mathbf{p},\mu}e^{ip\cdot x} + a^{\dagger}_{\mathbf{p},\mu}e^{-ip\cdot x}\right)_{p^0=E_\mu}$$

- scattering (continuum as the final states)



Rate to produce continuum

$$\sigma = \frac{1}{2E_A}\frac{1}{2E_B}\frac{1}{|v_A - v_B|}\int\frac{d\mu_1^2}{2\pi}\rho(\mu_1^2)\int\frac{d\mu_2^2}{2\pi}\rho(\mu_2^2)\int d\Pi_{\mu_1}d\Pi_{\mu_2}(2\pi)^4\delta^4(k_1+k_2-p_1-p_2)\,|\mathscr{M}|^2$$

$d\Pi_\mu = \dfrac{d^3p}{(2\pi)^3}\dfrac{1}{2E_\mu}$ is the Lorentz-invariant phase space

Thermodynamics of Gapped Continuum

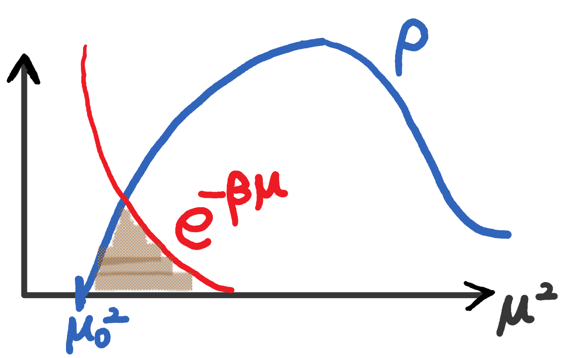
- The number density of excitations between μ^2 and $\mu^2 + \mathrm{d}\mu^2$

$$\mathrm{d}n = \frac{d\mu^2}{2\pi}\,\rho(\mu^2) \int \frac{d^3p}{(2\pi)^3}\, f(\mathbf{p}, \mu^2)$$

where the phase-space density in equilibrium

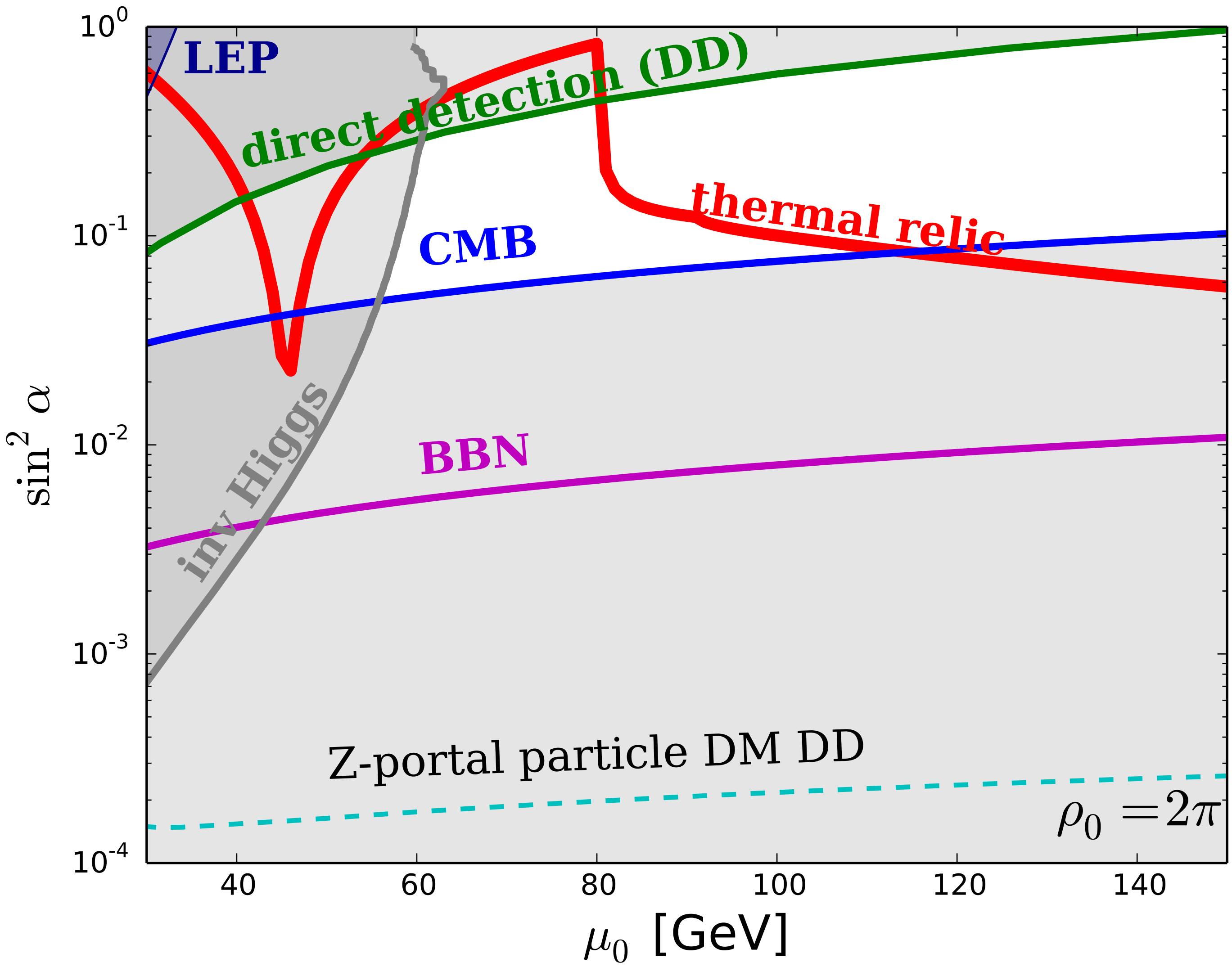
$$f(\mathbf{p}, \mu^2) \;\approx\; e^{-\beta E_\mu}$$

- When the temperature is low

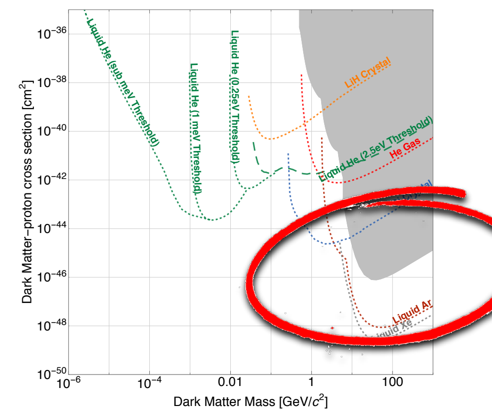


$$n_{\rm eq} = \int \frac{d\mu^2}{2\pi}\,\rho(\mu^2) \int \frac{d^3p}{(2\pi)^3}\, e^{-\beta E_\mu}$$

Z-portal Weakly Interacting Continuum



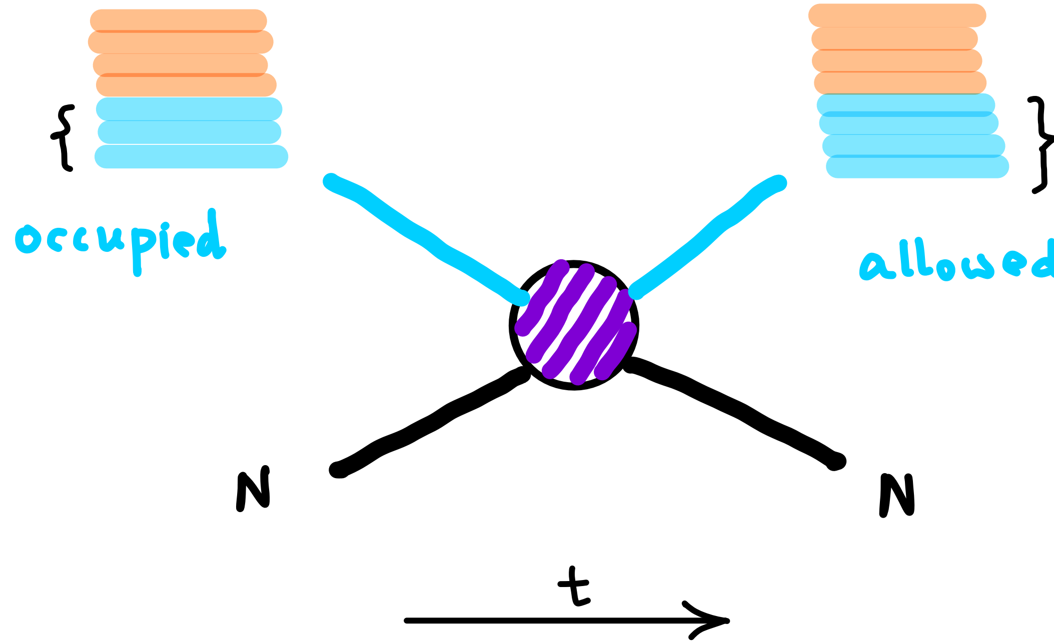
Direct detection



- scattering rate

$$\sum_{\color{red}{final}} |\langle \text{intial state} \,|\, \text{final state}\rangle|^2$$

$$= \int_{\mu_0^2}^{\color{red}{\mu_{max}^2}} d\mu_2^2 \, \rho(\mu_2^2) \times \cdots$$



- "phase space" suppression

$\color{red}{\mu_{max}} \sim v^2 \mu_0 \sim 10^{-6} \mu_0$

v is the dark matter velocity ~ 10^{-3}c

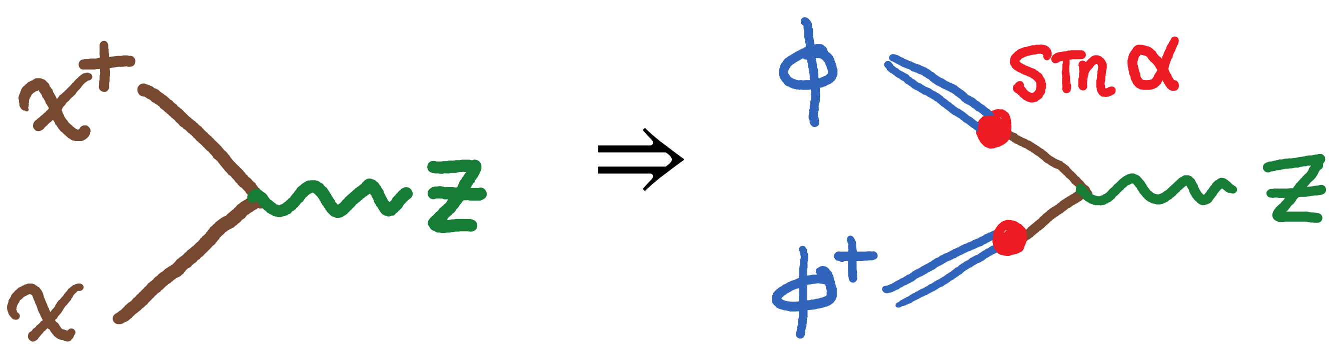
4D Effective Z-portal Model

- scalar continuum dark matter Φ with gap scale μ_0
  regular scalar χ : doublet under $\mathrm{SU}(2)_L$, $\mathrm{U}(1)_Y$ charge $-\frac{1}{2}$

- Lagrangian $\mathscr{L}_{\text{int}} = -\lambda \Phi \chi H + \text{c.c.}$

- The Higgs vev induces the mass mixing

$$\tilde{\Phi} = \cos\alpha\, \Phi + \sin\alpha\, \chi^0,$$
$$\tilde{\chi}^0 = -\sin\alpha\, \Phi + \cos\alpha\, \chi^0$$

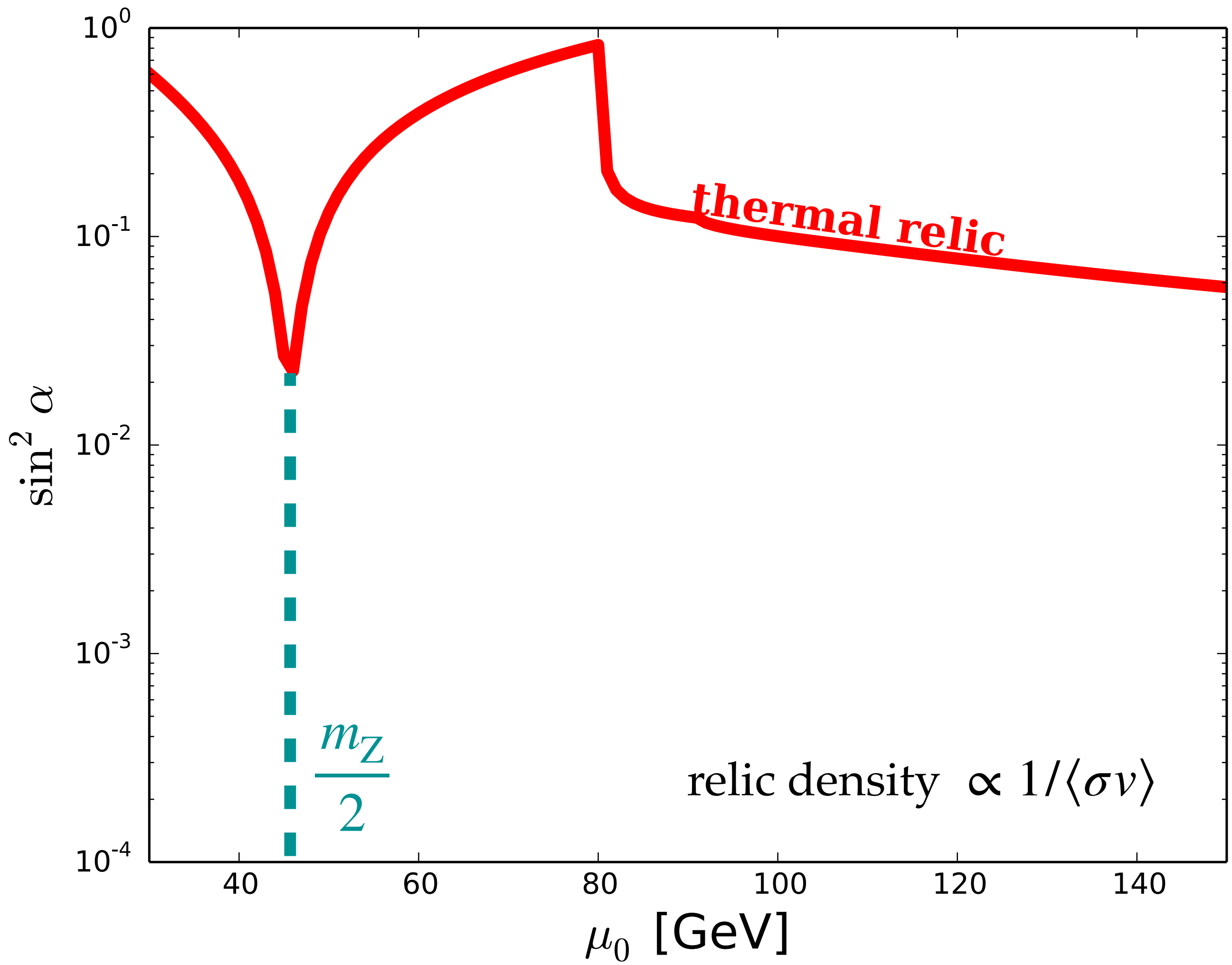


Thermal freeze-out

- $\Phi\,\Phi^\star \to \mathrm{SM} + \mathrm{SM}$

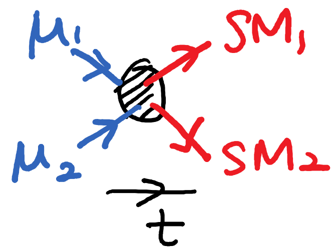
  Boltzmann equation is identical to the usual form

$$\frac{\mathrm{d}n}{\mathrm{d}t} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\mathrm{eq}}^2)$$

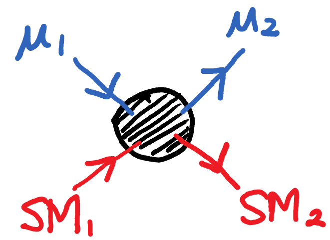


density evolution and $\Delta\mu \equiv \mu - \mu_0$

$\mathrm{T} \sim \mu_0/10$ freeze-out



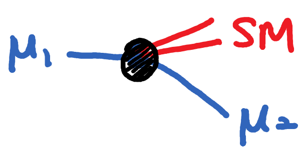
$\mathrm{T} \sim \Delta\mu$ Thermal equilibrium



$\mathrm{T}_d \sim 0.1 - 1\,\mathrm{GeV}$ $(\Gamma \sim H)$

CMB

out-of-equilibrium decay

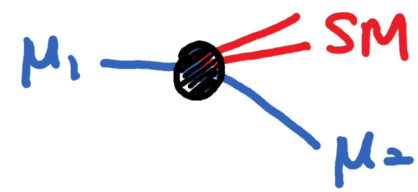


Gapped continuum in the final states

- $$\sigma \sim \int \frac{d\mu_2^2}{2\pi} \rho(\mu_2^2)\, \hat{\sigma}\left(\mu_1, \mu_2\right)$$

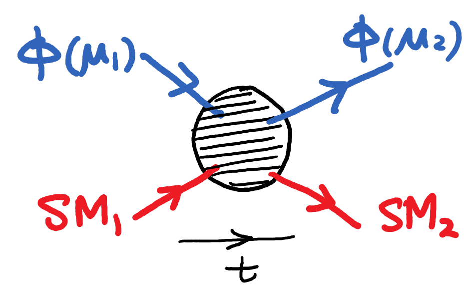
- continuum state decay (CMB)

  $$\Phi(\mu_1) \to \Phi(\mu_2) + \text{SM}$$

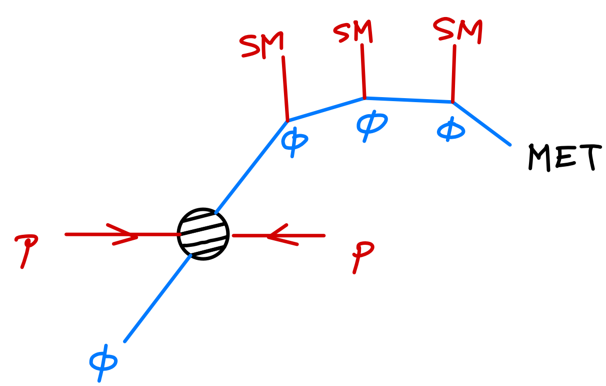


- DM direct detection

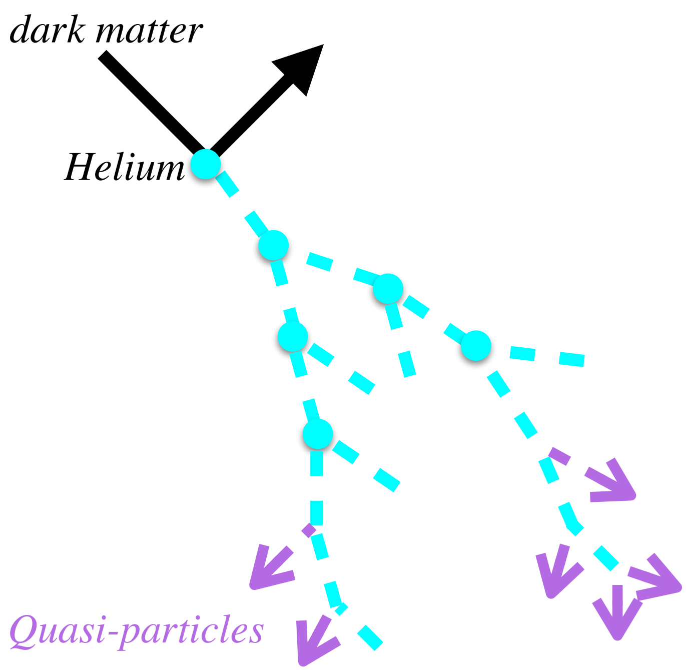
  $$\Phi(\mu_1) + \text{SM} \to \Phi(\mu_2) + \text{SM}$$



- colliders

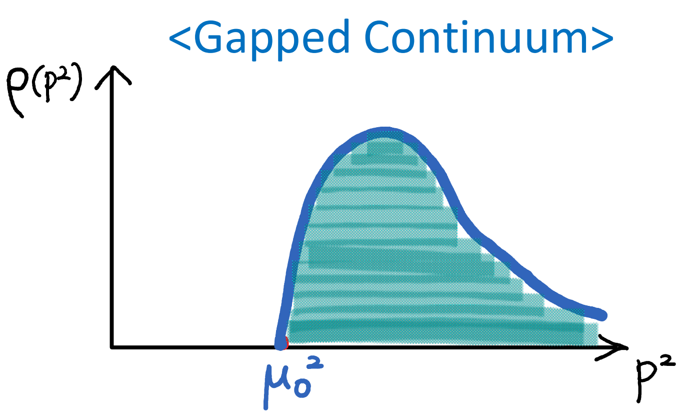


Conclusion



superfluid Helium to detect dark matter

EFT → simulation → experiment



Weakly Interacting Continuum

new continuum hidden sector

collider signals