中山大學 SUN YAT-SEN UNIVERSITY

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Composite asymmetry dark matter: model and detection

复合不对称暗物质：模型和探测

第三届粒子物理前沿研讨会

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2022-07-23

Based on: *Phys.Rev.D 104 (2021) 5, 055008* MZ
Phys.Rev.D 100 (2019) 11, 115009 Myeonghun Park, MZ

Outline

1.Motivation for Composite Asymmetric Dark Matter (ADM)

2.Model Introduction: quark-philic mediator
lepton-philic mediator

3.Detection: indirect
GWs
direct
collider

4.Conclusion

Motivation of composite ADM

$$\Omega_{\rm DM} : \Omega_{\rm B} \sim 5 : 1$$

We need a asymmetry between baryon and anti-baryon:
(Sakharov condition)
1)C and CP violation
2)B-number broken
3)deviation from equilibrium

Baryon mass comes from QCD confinement

WIMP:
Heavy Majorana particle freeze out

WIMP mass is given by hand (e.g. soft term in SUSY)

Motivation of composite ADM

$$\Omega_{\mathrm{DM}} : \Omega_{\mathrm{B}} \sim 5 : 1$$

So maybe the true story is like:

Baryon-anti-baryon asymmetry:
1)C and CP violation
2)B-number broken
3)deviation from equilibrium

DM-anti-DM asymmetry:
1)C and CP violation
2)D-number broken
3)deviation from equilibrium

Baryon mass and DM (dark baryon) mass comes from QCD confinement and Dark-QCD confinement respectively.

Model framework: SU(N) in the dark sector

Visible sector

Dark sector

$SU(3) \times SU(2) \times U(1)$

$\gamma,\ g,\ l,\ q\ \ldots$

$\pi,\ \rho,\ p\ \ldots$

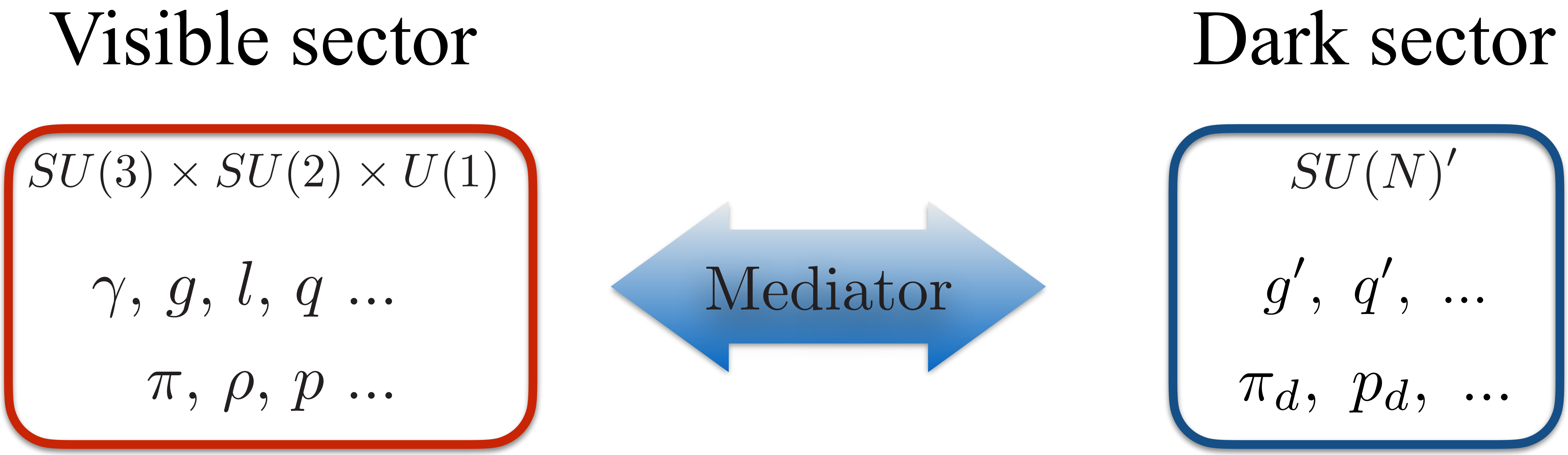
Mediator

$SU(N)'$

$g',\ q',\ \ldots$

$\pi_d,\ p_d,\ \ldots$

Model framework: SU(N) in the dark sector



Visible sector

$SU(3) \times SU(2) \times U(1)$

$\gamma,\ g,\ l,\ q\ \ldots$

$\pi,\ \rho,\ p\ \ldots$

Mediator

Dark sector

$SU(N)'$

$g',\ q',\ \ldots$

$\pi_d,\ p_d,\ \ldots$

We consider "bi-charged scalar" Φ as mediator :

quark-philic : $\mathcal{L} \supset \kappa\Phi\underset{\text{dark quark}}{\boxed{\bar{q}'}}\boxed{q}$ quark

lepton-philic : $\mathcal{L} \supset \kappa\Phi\underset{\text{dark quark}}{\boxed{\bar{q}'}}\boxed{l}$ lepton

(For baryogenesis, you need "B-L")

Why “bi-charged scalar” Φ ?

Reasons:

(1) generate baryon and D-baryon asymmetries simultaneously

(2) explain $\Lambda_{\rm QCD} \sim \Lambda'$ by IR fixed point

(3) help to espace cosmology constraints

(4) provide a detectable portal

Asymmetry generation: quark-philic model

Consider a scalar mediator Φ couple to “dark quark” and SM quark:

$$\mathcal{L} \supset \kappa\Phi\boxed{\bar{q}'}\boxed{q}$$

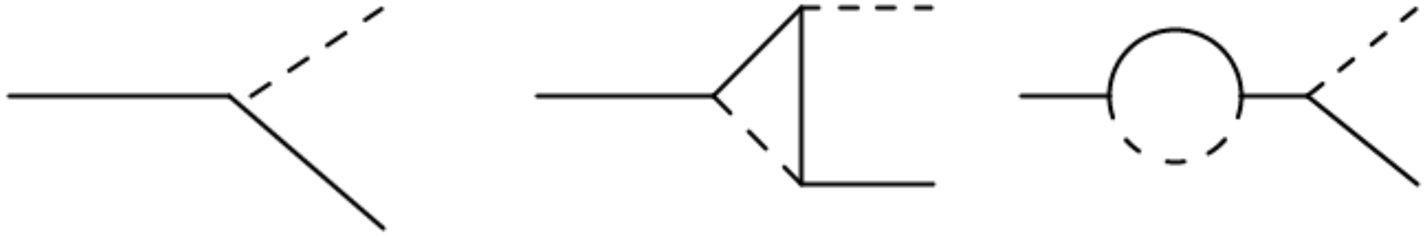
quark

dark quark

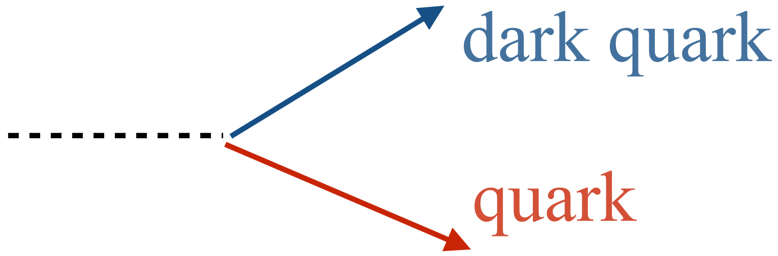
arXiv:1306.4676

Step 1: generate the asymmetry of mediator Φ. For example, CPV& out of equilibrium decay of heavy neutral particle:

$$\mathcal{L} \supset k_i \bar{Y}_1 \Phi N_i + \text{h.c.}$$



Step 2: mediator Φ decay to “dark quark” and SM quark, and thus generate “dark baryon” and baryon asymmetry simultaneously:



Asymmetry generation: lepton-philic model

Another possibility: what if Φ couples to L + q\` instead of q + q\`:

$$\mathcal{L} \supset \kappa \Phi \boxed{\bar{q}'}\boxed{l}$$

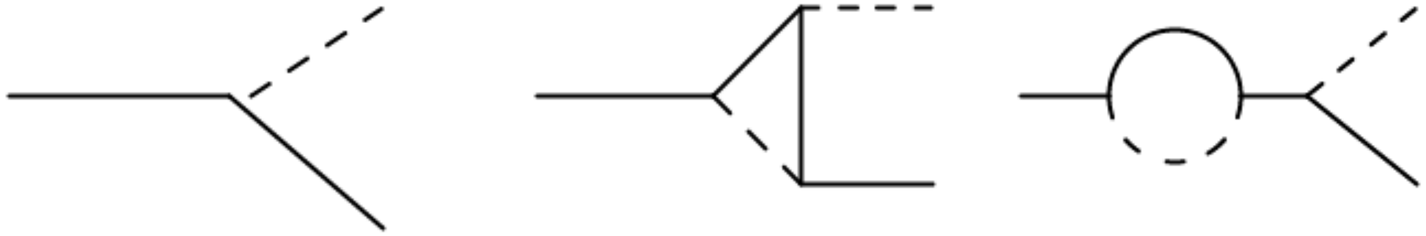
lepton

dark quark

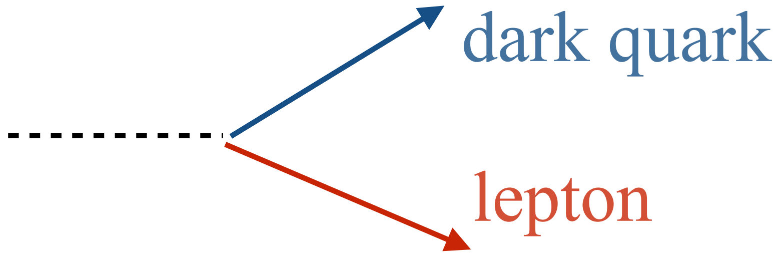
arXiv:2104.06988

Step 1: generate the asymmetry of mediator Φ . For example, CPV& out of equilibrium decay of heavy neutral particle:

$$\mathcal{L} \supset k_i \bar{Y}_1 \Phi N_i + \text{h.c.}$$



Step 2: mediator Φ decay to “dark quark” and SM lepton, and thus generate “dark baryon” and lepton asymmetry simultaneously:



Step 3: lepton number transfer to baryon number via sphaleron process:

lepton

sphaleron

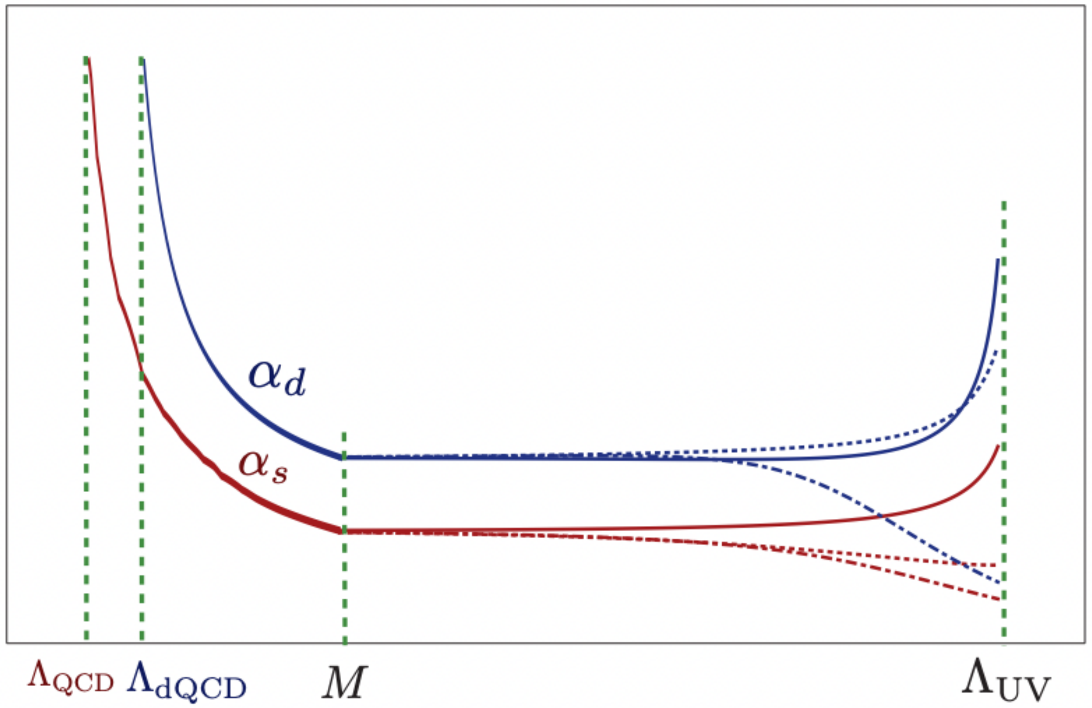
baryon

IR fixed point

We already obtained $n_B \sim n_{B'}$, but why $\Lambda_{\rm QCD} \sim \Lambda'$?

A brilliant idea from **(**arXiv:1306.4676 Yang Bai, Pedro Schwaller): IR fixed point

SM SU(3) coupling and dark SU(3) coupling are connected to each other via "bi-charged scalar" Φ



$$\begin{aligned}
\beta_c(g_c, g_d) \;=\; & \frac{g_c^3}{16\pi^2}\left[\frac{2}{3}T(R_f)\,2(n_{f_c}+N_d\,n_{f_j})+\frac{1}{3}T(R_s)\,(n_{s_c}+N_d\,n_{s_j})-\frac{11}{3}\,C_2(G_c)\right] \\
& +\frac{g_c^5}{(16\pi^2)^2}\left[\left(\frac{10}{3}C_2(G_c)+2C_2(R_f)\right)\,T(R_f)\,2\,(n_{f_c}+N_d\,n_{f_j}) \right.\\
& \qquad \left. +\left(\frac{2}{3}C_2(G_c)+4C_2(R_s)\right)\,T(R_s)\,(n_{s_c}+N_d\,n_{s_j})\;-\;\frac{34}{3}\,C_2^2(G_c)\right] \\
& +\frac{g_c^3\,g_d^2}{(16\pi^2)^2}\left[2C_2(R_f)\,T(R_f)\,2\,N_d\,n_{f_j}\;+\;4C_2(R_s)\,T(R_s)\,N_d\,n_{s_j}\right]\,.
\end{aligned}$$

Cosmology requirement

Dark baryon - anti dark baryon annihilate to dark pions:

$$B' + \bar{B}' \to \pi_d + \pi_d$$

Dark baryon B' is the dark matter: stable & cold

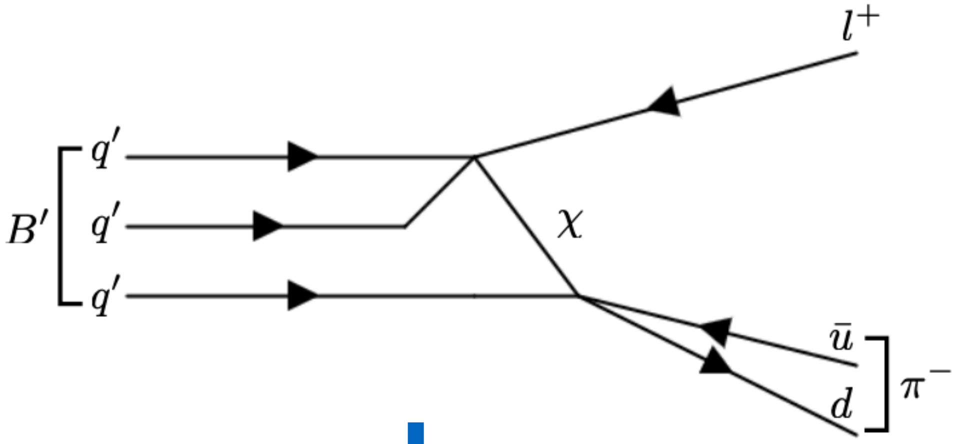
Dark pion π_d should be non-stable, otherwise:
(1) dark sector might no be cold
(2) if dark pion is heavy ==> overclosure problem
(3) if dark pion is light ==> N_eff limit

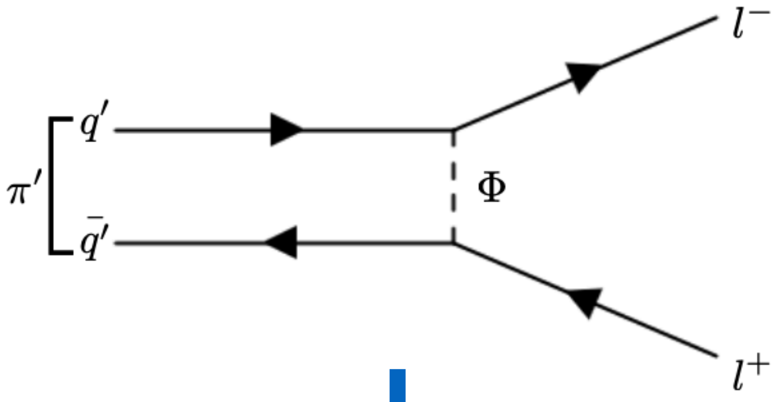
So we hope dark pion to decay

Cosmology requirement

Effective Lagrangian by integrating mediator:

$$\mathcal{L} \supset \frac{\kappa^2}{m_\Phi^2}\left(\bar{q}'_L l_R\right)\left(\bar{l}_R q'_L\right) + \left[\frac{1}{m_\chi \Lambda_1^2 \Lambda_2^2}\left(\bar{q}'^C_L l_R\right)\left(\bar{q}'^C \gamma^\mu q'\right)\left(\bar{d}_R \gamma_\mu u_R\right) + h.c.\right]$$





Dark baryon decay via
dim-9 operator: life-time
is longer than age of universe

Dark pion decay via
dim-6 operator: life-time
is shorter than 1s (before BBN)

mediator Φ can be quite light:

$$200GeV < m_\Phi < 100TeV$$

decay before EWPT
(for lepton-philic)

dark pion decay
before BBN

Detection of this model

(1) indirect search

$B' + \bar{B}' \to \pi_d + \pi_d$ → Anti dark baryon have gone!

There is (generally) no indirect search signal

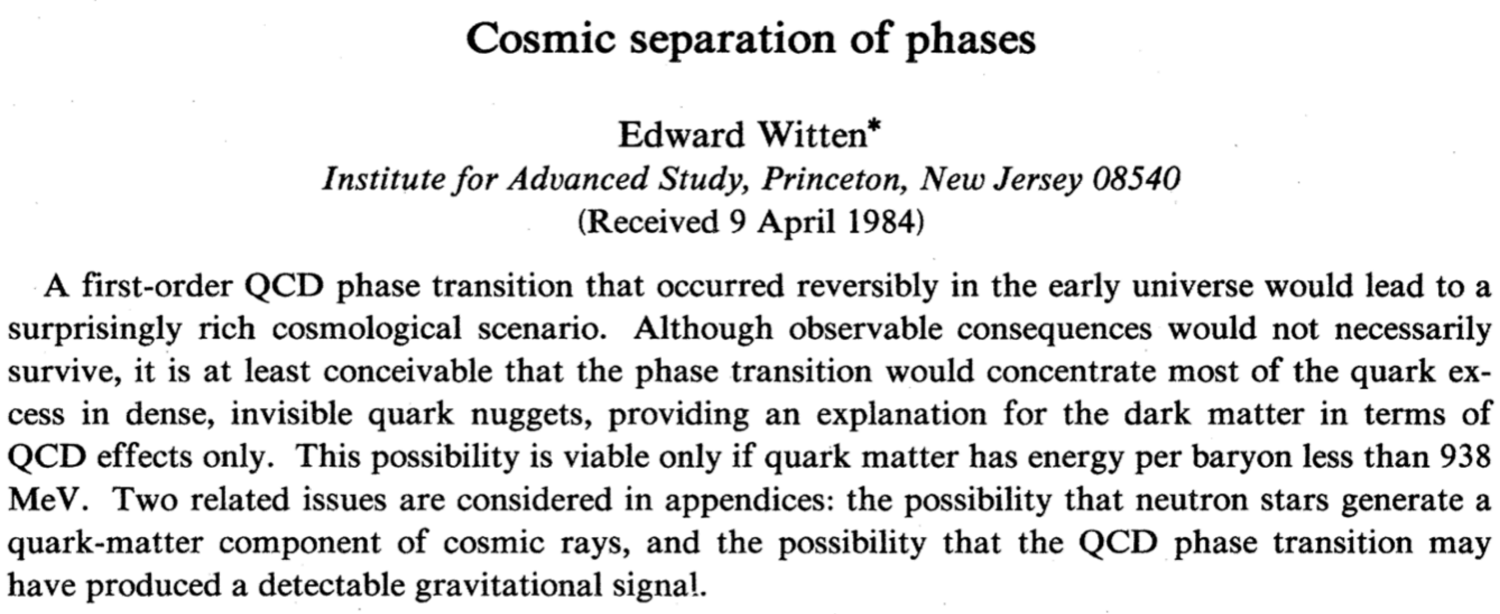
Detection of this model

(1) indirect search

$B' + \bar{B}' \rightarrow \pi_d + \pi_d$ → Anti dark baryon have gone!

There is (generally) no indirect search signal

(2) Gravitational Waves: if the dark confinement is 1st order



Cosmic separation of phases

Edward Witten*

Institute for Advanced Study, Princeton, New Jersey 08540

(Received 9 April 1984)

A first-order QCD phase transition that occurred reversibly in the early universe would lead to a surprisingly rich cosmological scenario. Although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets, providing an explanation for the dark matter in terms of QCD effects only. This possibility is viable only if quark matter has energy per baryon less than 938 MeV. Two related issues are considered in appendices: the possibility that neutron stars generate a quark-matter component of cosmic rays, and the possibility that the QCD phase transition may have produced a detectable gravitational signal.

→ **Confinement phase transition: from Polyakov Loop Models to quasi-particle model-Zhu jiang(华中科技大学)**

Detection of this model

(3) direct search

Integrating out the mediator:

$$\frac{\kappa^2}{2m_\Phi^2}(\bar{q}'_L\gamma^\mu q'_L)(\bar{q}_R\gamma_\mu q_R) \qquad \text{or} \qquad \frac{\kappa^2}{2m_\Phi^2}(\bar{q}'_L\gamma^\mu q'_L)(\bar{e}_R\gamma_\mu e_R)$$

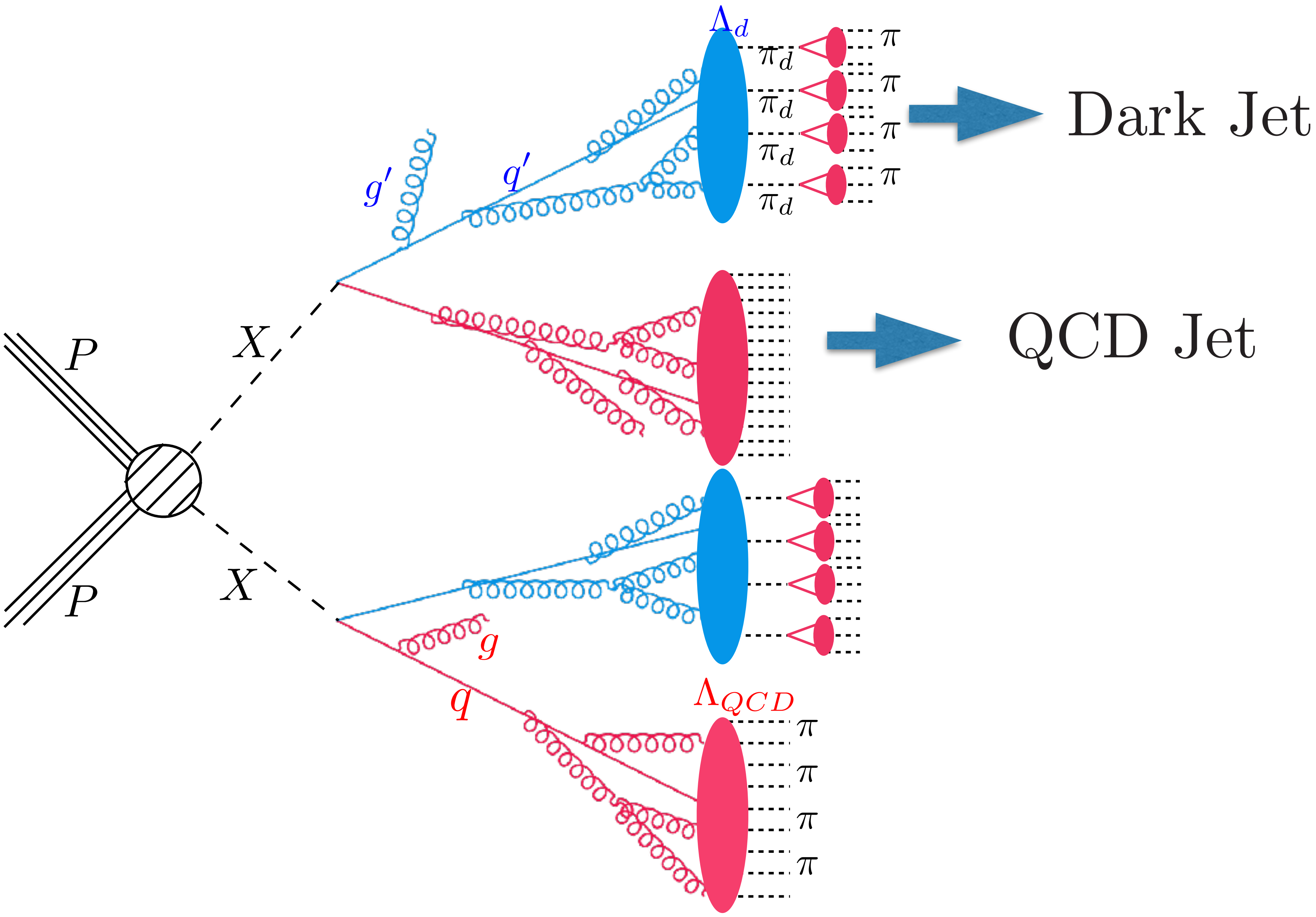
quark-philic lepton-philic

Dark baryon B' scatter with nuclear, or electron, via dim-6 operator

Detection of this model

(4) collider search

quark-philic model search at hadron collider

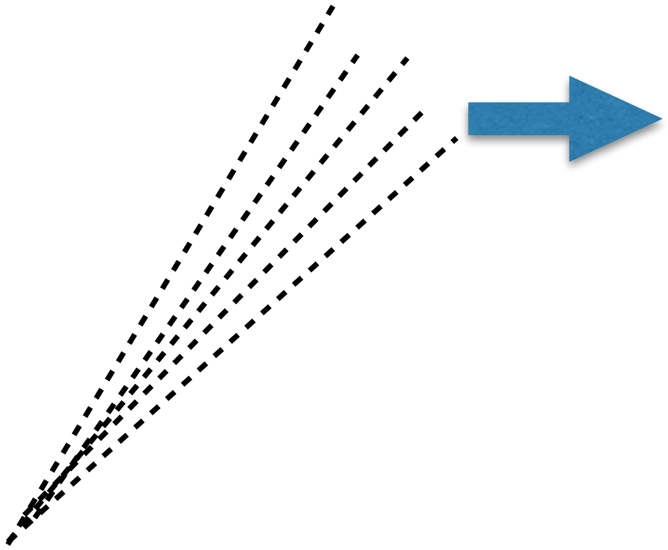


Detection of this model

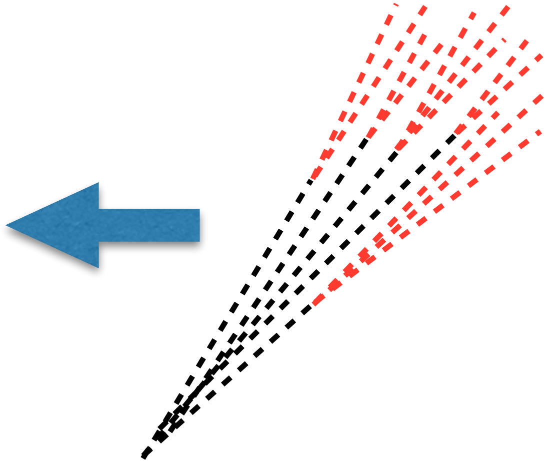
(4) collider search

quark-philic model search at hadron collider

Dark jet is very model dependent:

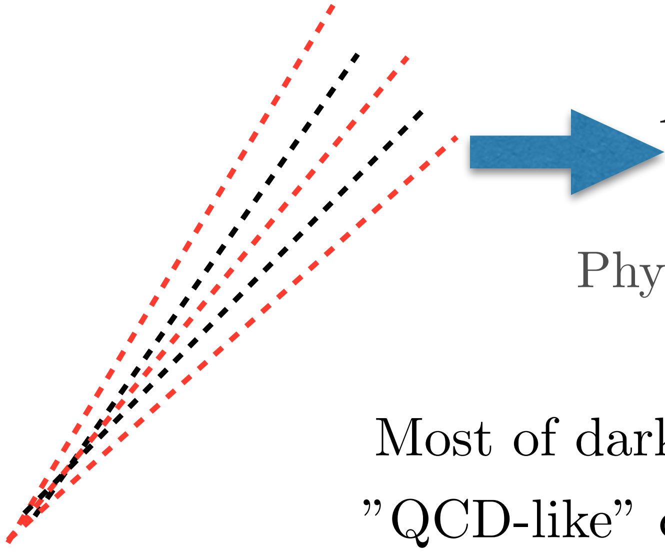


Most dark mesons are stable or stable enough.
Invisible Jet (Missing Energy)



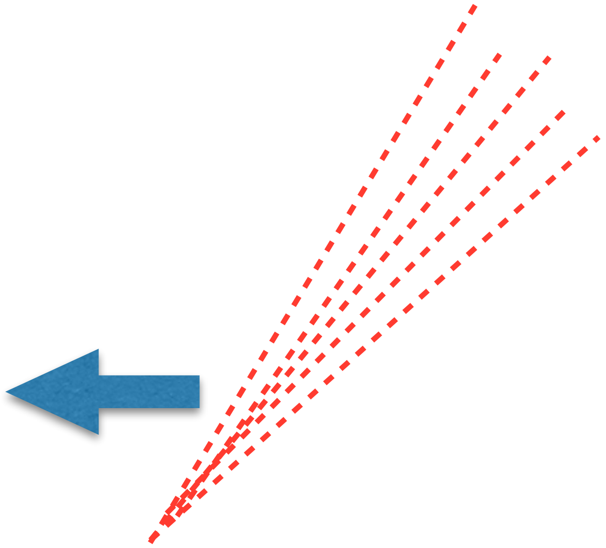
Most dark mesons are long-lived.
Emerging Jet (Displaced Track)

JHEP **1505**, 059 (2015)



A fraction of dark mesons are stable.
Semi-visible Jet (Transverse Mass)

Phys. Rev. Lett. **115**, no. 17, 171804 (2015)



Most of dark mesons decay to visible particles promptly
"QCD-like" dark jet. We can use jet sub-structure (q/g)

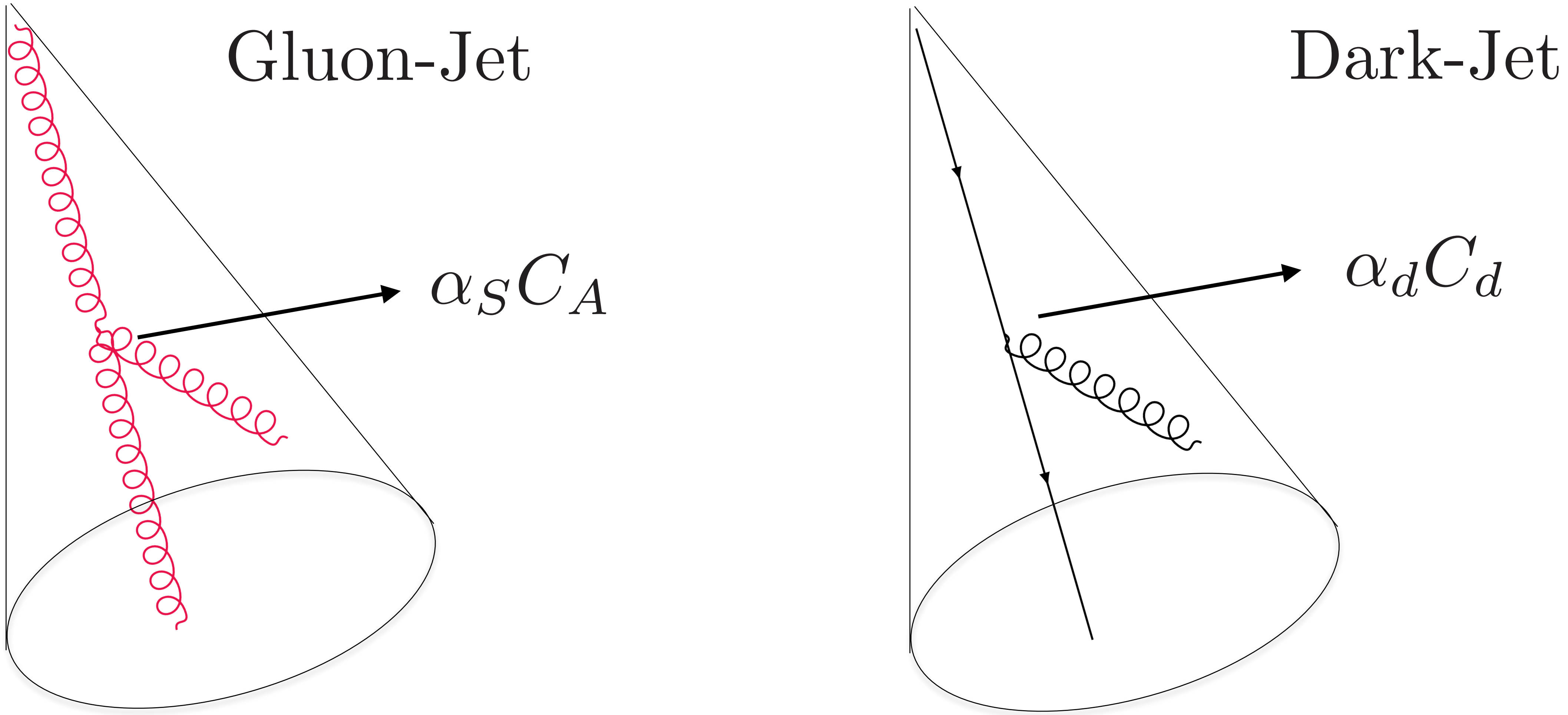
Phys.Rev.D 100 (2019) 11, 115009 Myeonghun Park, MZ

Detection of this model

(4) collider search

quark-philic model search at hadron collider

How to tag a dark jet? one-prong jet tagging problem



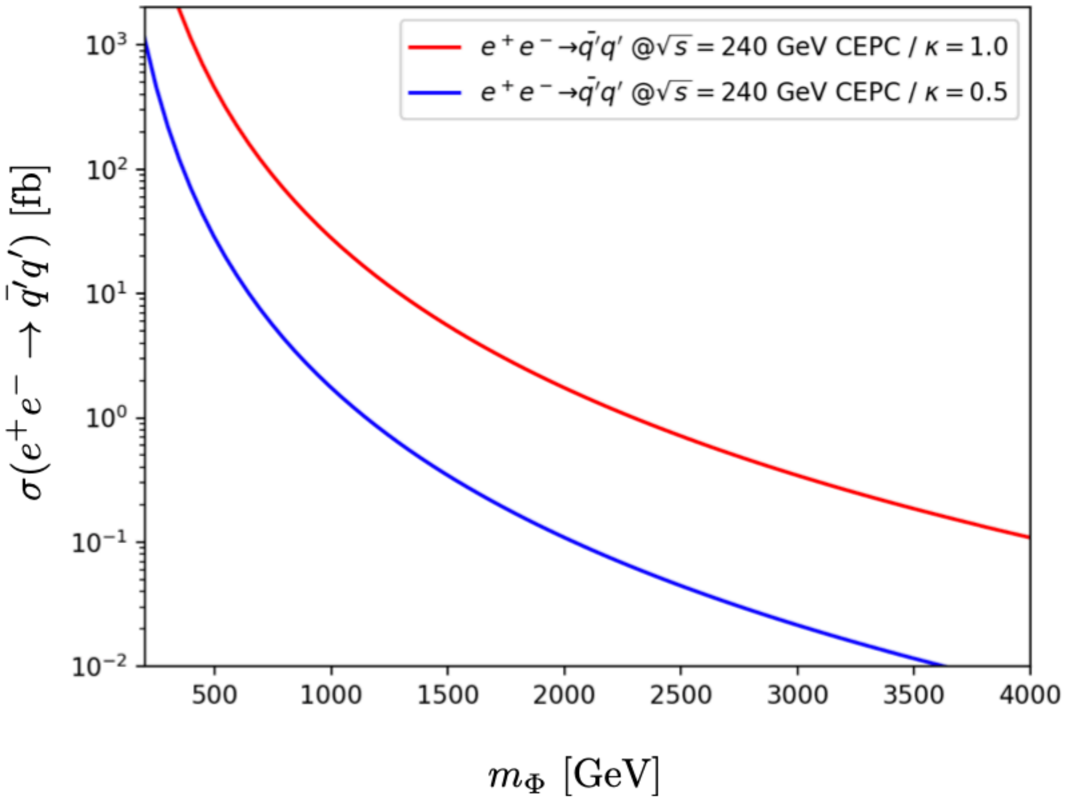
We have a modified Casimir Scaling in Gluon/Dark Jet discrimination,
C_A/C_F should be changed to $\alpha_S C_A/\alpha_d C_d$.
So, if α_d is very different with α_S ...

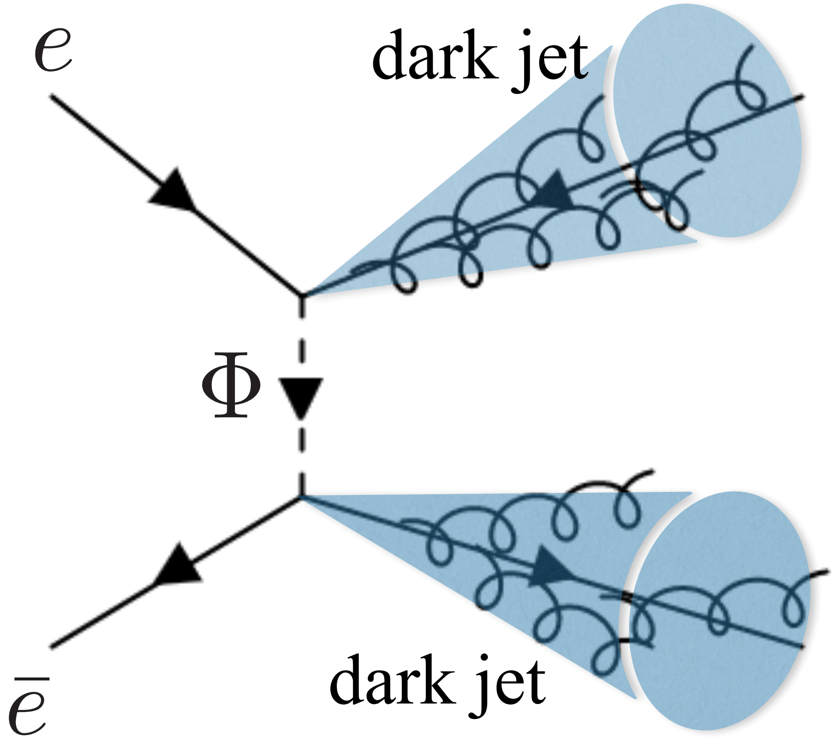
Detection of this model

(4) collider search

lepton-philic model search at electron collider

$$\frac{\kappa^2}{m_\Phi^2}\left(\bar{q}'_L e_R\right)\left(\bar{e}_R q'_L\right) \longrightarrow \sigma(e^+e^- \to \bar{q}'q') \approx \frac{\kappa^4}{256\pi}\frac{s}{m_\Phi^4}$$





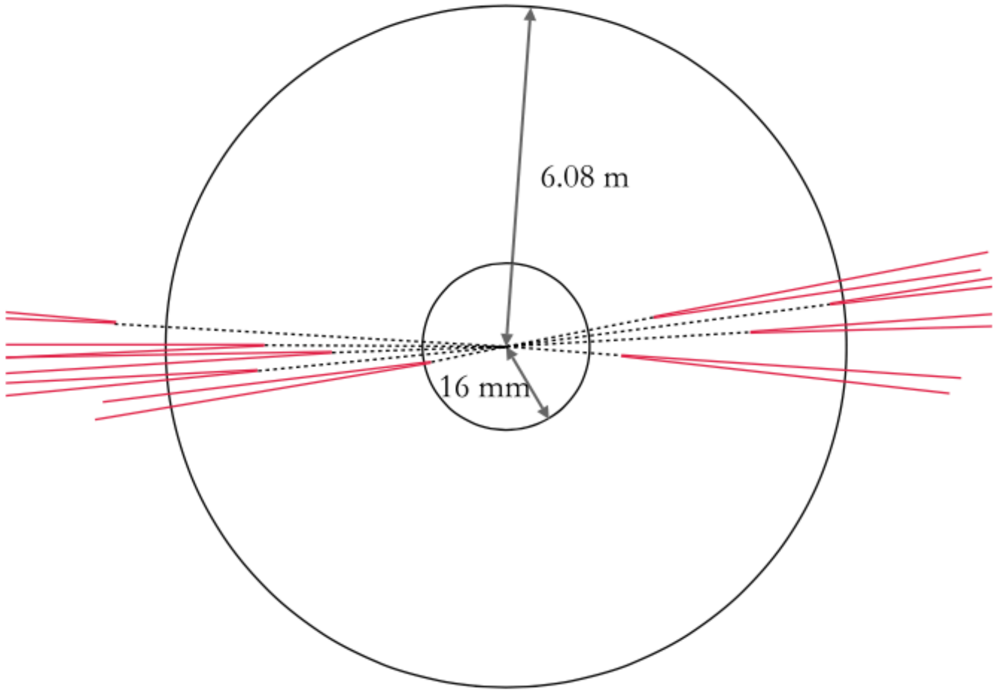
Detection of this model

(4) collider search

lepton-philic model search at electron collider

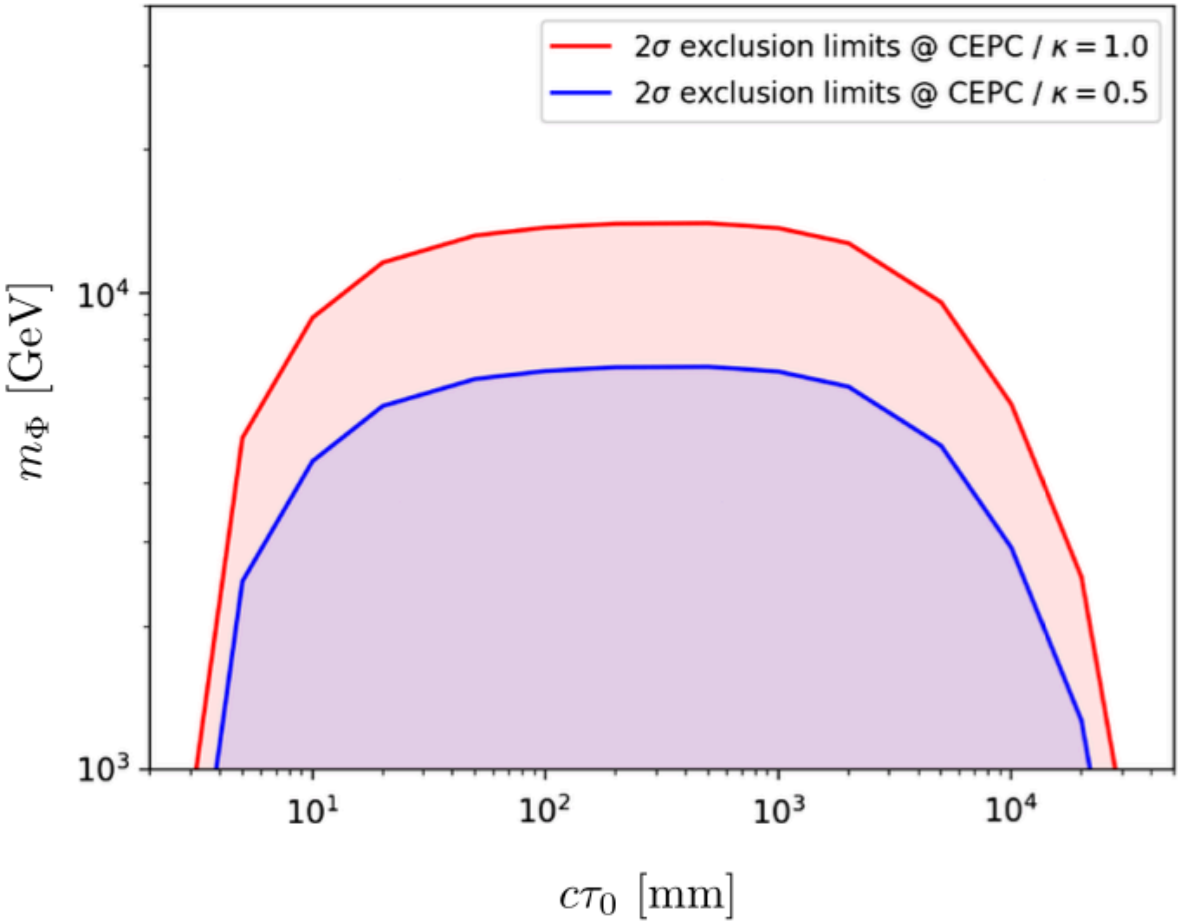
$$c\tau_0 = \frac{c\hbar}{\Gamma_{\pi'}} \approx 120\ \mathrm{mm} \times \frac{1}{\kappa^4}\left(\frac{1\ \mathrm{GeV}}{f_{\pi'}}\right)^2\left(\frac{0.1\ \mathrm{GeV}}{m_l}\right)^2\left(\frac{1\ \mathrm{GeV}}{m_{\pi'}}\right)\left(\frac{m_\Phi}{500\ \mathrm{GeV}}\right)^4$$

displaced lepton-jet , 非常干净的信号



CEPC detector

mediator mass



dark pion decay length

Conclusion

Asymmetric composite DM is well motivated

Bi-charged scalar mediator is well motivated

This model can be searched via: GWs, direct search, collider

Collider signal: dark jet / lepton jet (very novel)