

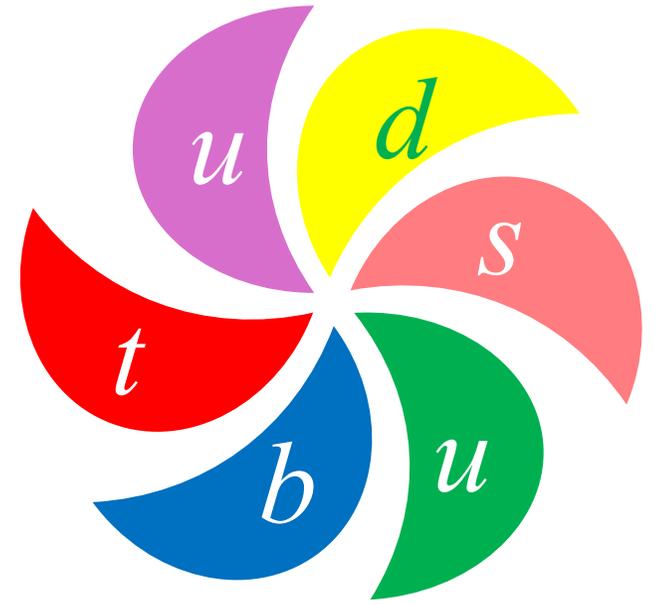
The Puzzle of Dark Matter



Feb. 1, 2026

Sanya, Hainan

味物理讲座 100期特别活动



in the Perspective of Flavor Phys.



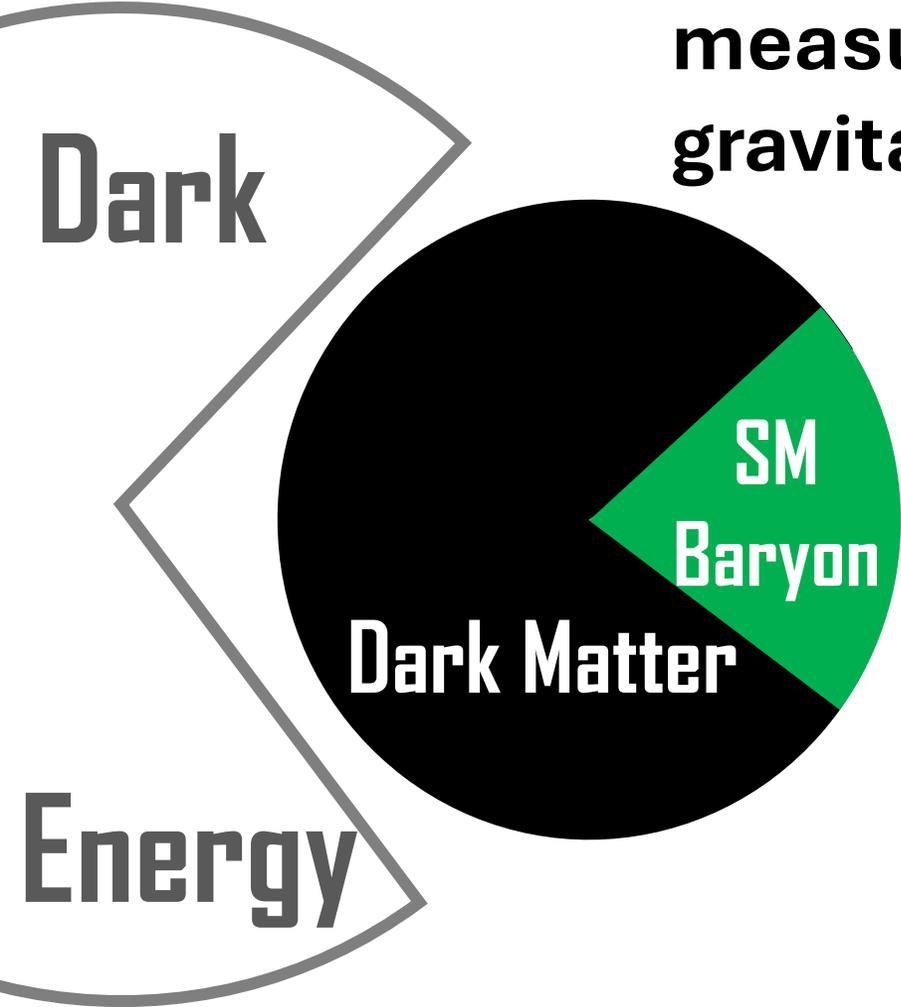
Lingfeng Li
李凌风

ICTP-AP, UCAS

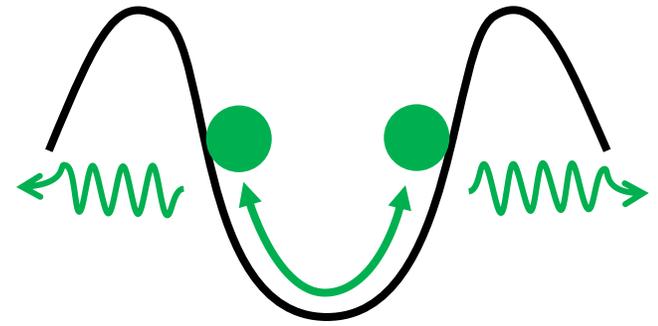
Outline

1. What about DM: evidence and features
2. What about Flavor and DM:
3. Extended thoughts: why Flavor and DM can be correlated
4. Wrap up

WARNING
Biased,
Incomplete Knowledge
Mission Impossible Anyways

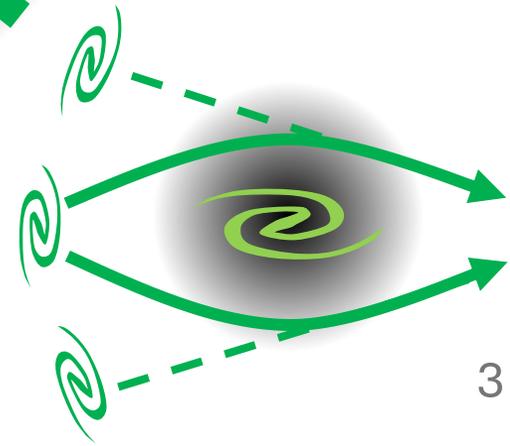


Components of universe measured from gravitational effects



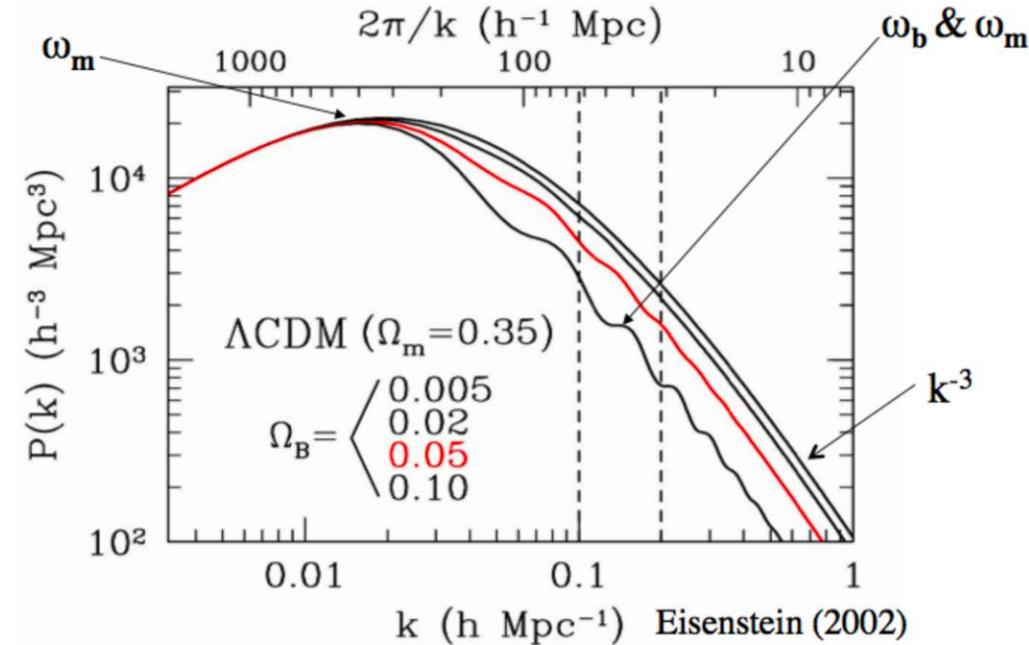
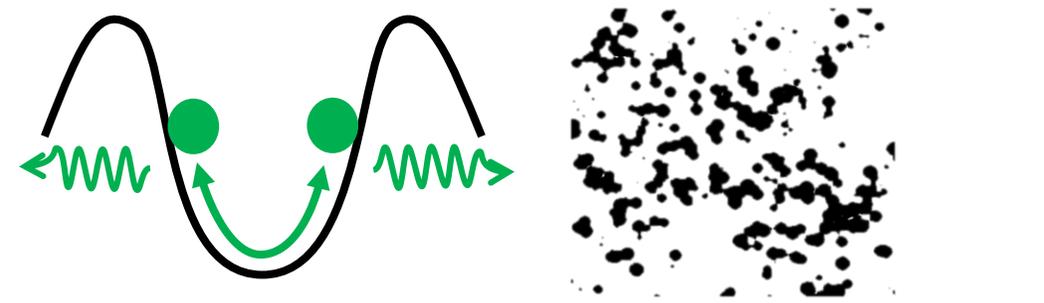
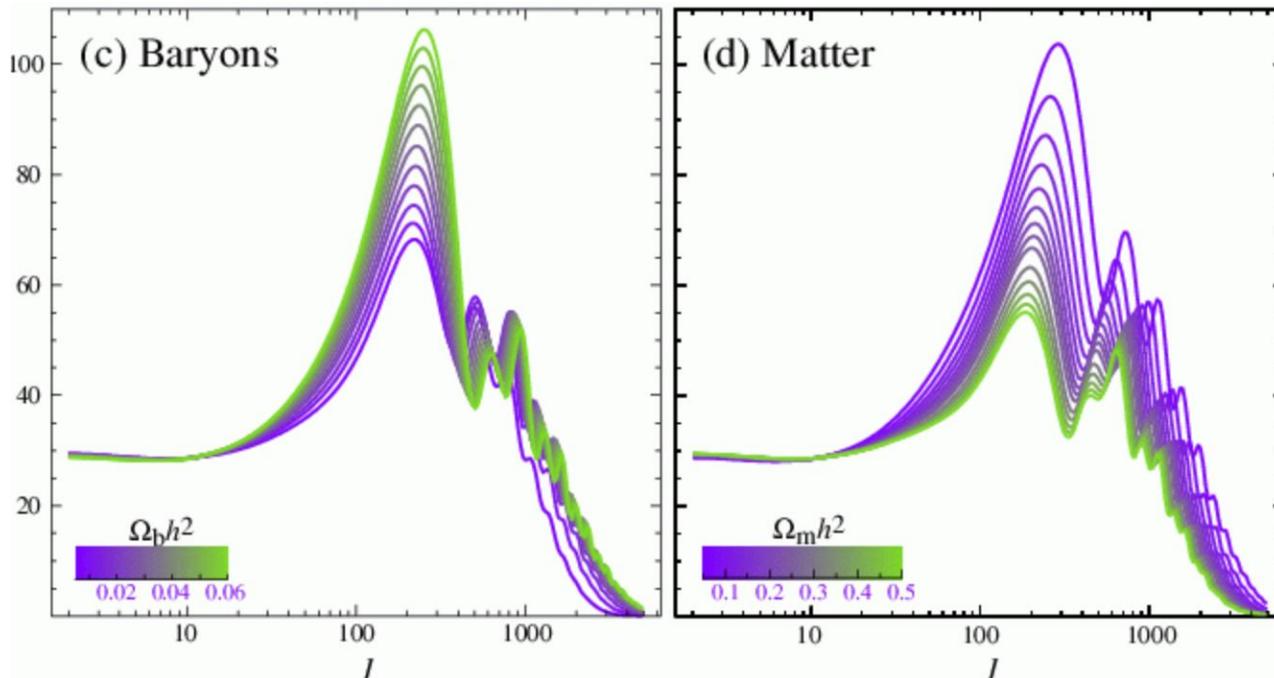
Probes

- CMB
- LSS/BAO
- Rotational curves
- Strong lensing
- Spectroscopy surveys



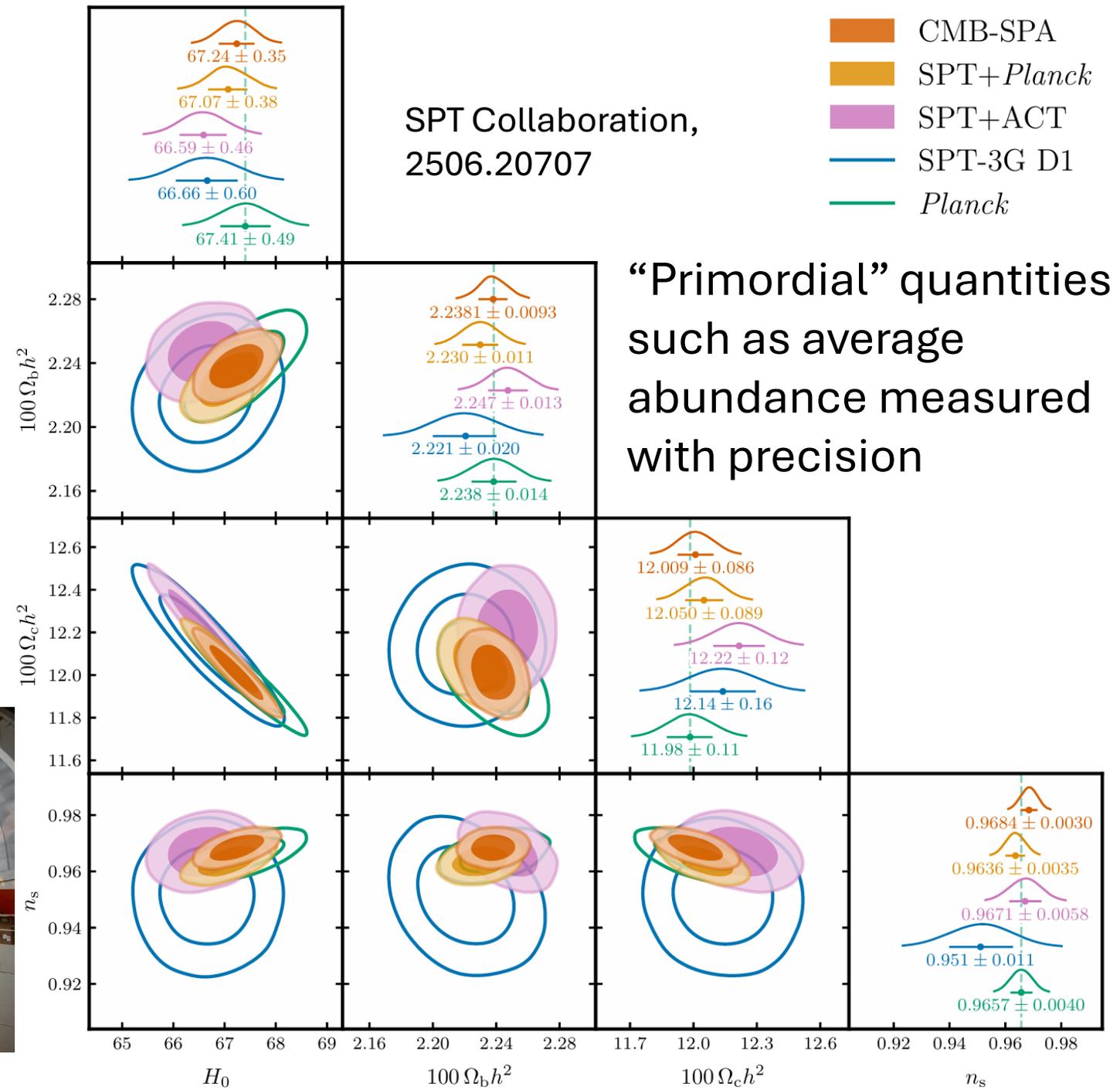
Evidence at Larger Scales

CMB power spectra: baryonic (charged) matter and cold dark matter plays different roles during recombination

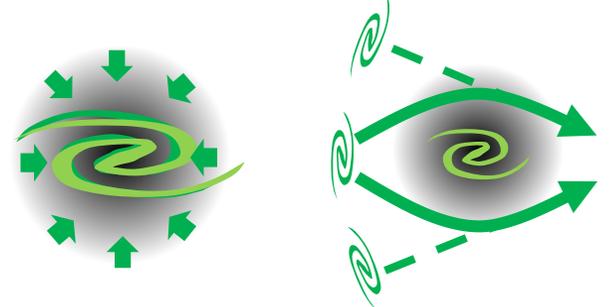


Large scale structure (linear regime) with baryon acoustic oscillation

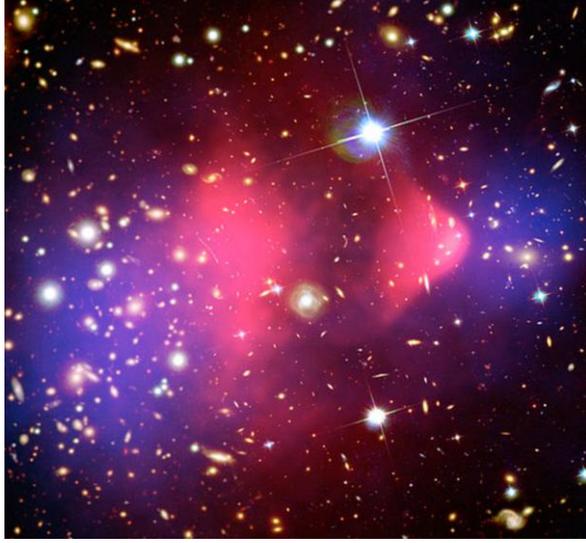
Updated Cosmological Results



Evidence at Smaller Scales

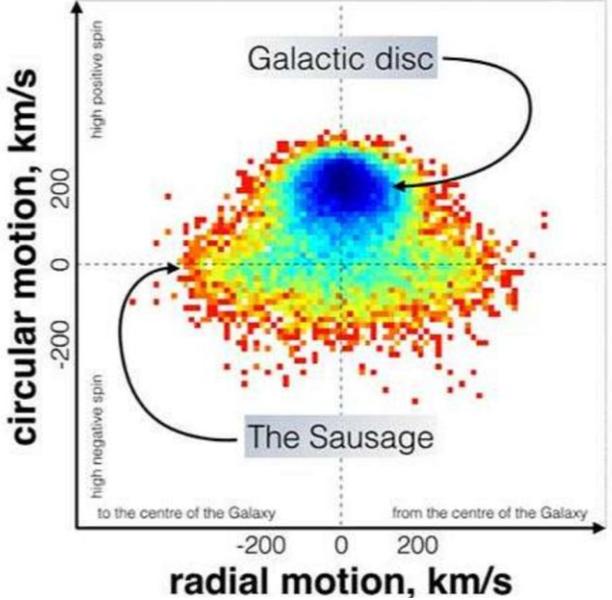


Bullet Cluster



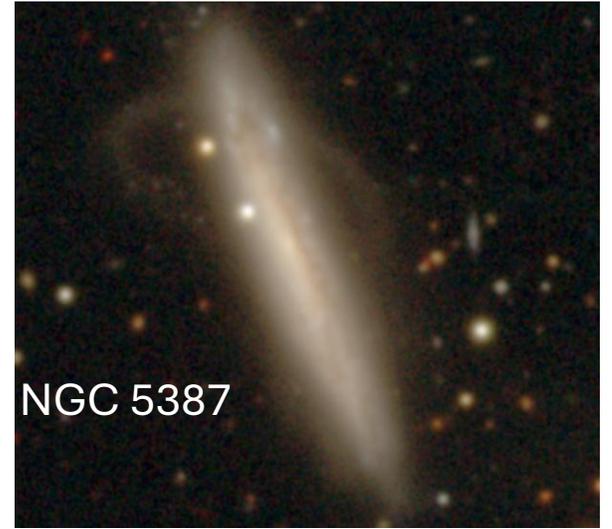
Lensing effect (blue) and gas (red) displacement

Gaia "Sausage"



DM substructure in MW galaxy indicating distant past merger events

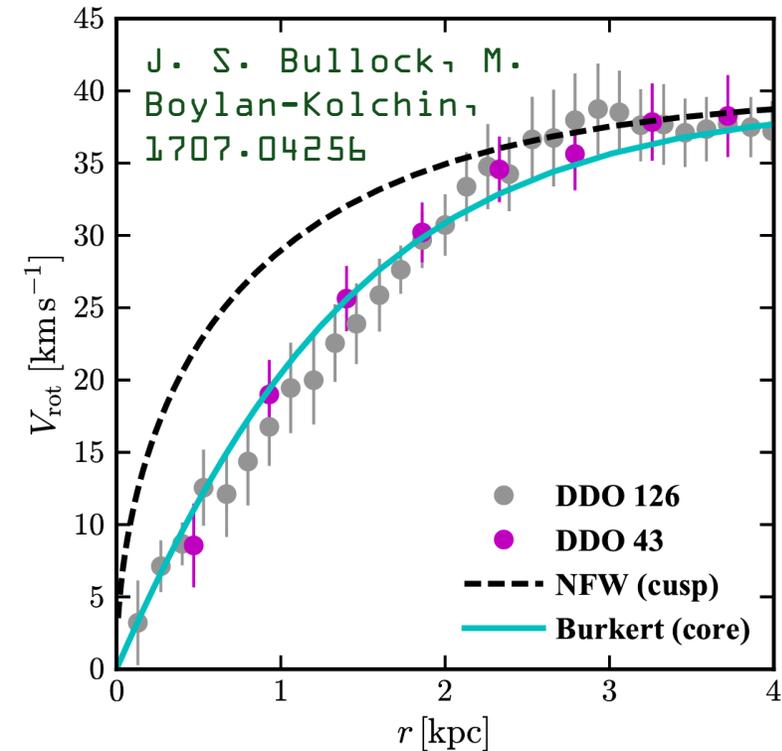
Stellar Streams



Disrupted subhalo structure indicating interactions other than baryonic gravity

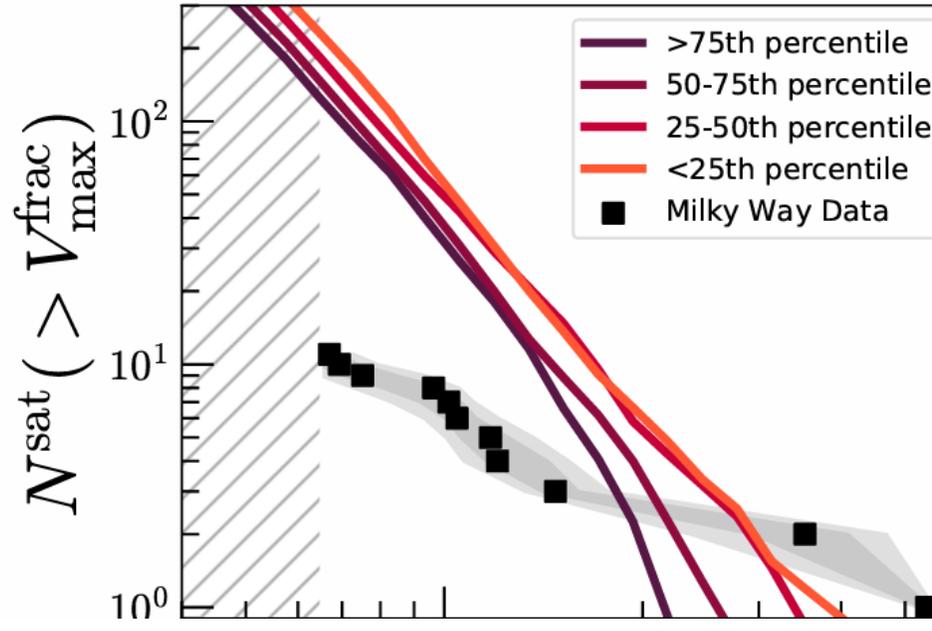
“Cracks” at Smaller Scales

M. Boylan-Kolchin, J. S. Bullock and M. Kaplinghat, 1103.0007



Core-cusp

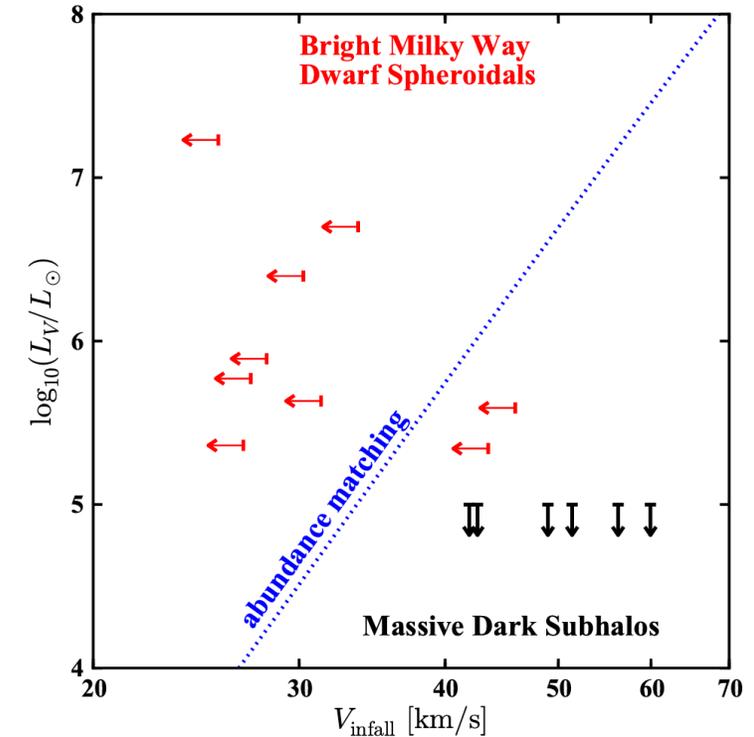
Inner halo density too steep (cusp) vs observed cores



C. E. Fielder, Y. Y. Mao, J. A. Newman, A. R. Zentner and T. C. Licquia, 1807.05180

Missing satellite

Too many predicted subhalos vs fewer observed dwarfs



Too big to fail

Most massive subhalos too dense to host known dwarfs

Responses to the Problem

“DM is self-interacting”

M. C. Straight et al., 2501.16602; X. Zhang, H. B. Yu, D. Yang and E. O. Nadler, 2409.19493; M. G. Roberts, M. Kaplinghat, M. Valli and H. B. Yu, 2407.15005

“DM is a field”

H. Lazare, J. Flitter and E. D. Kovetz, 2407.19549; Y. M. Yang, Z. C. Zhang, X. J. Bi and P. F. Yin, 2507.01686; J. Sipple, A. Lidz, D. Grin and G. Sun, 2407.17059

“Baryonic feedback can do this”

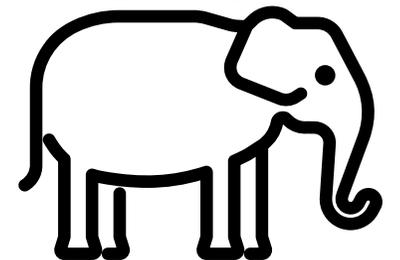
C. Muni et al., 2407.14579; S. Koudmani et al., 2409.02172

“Just observational bias/error”

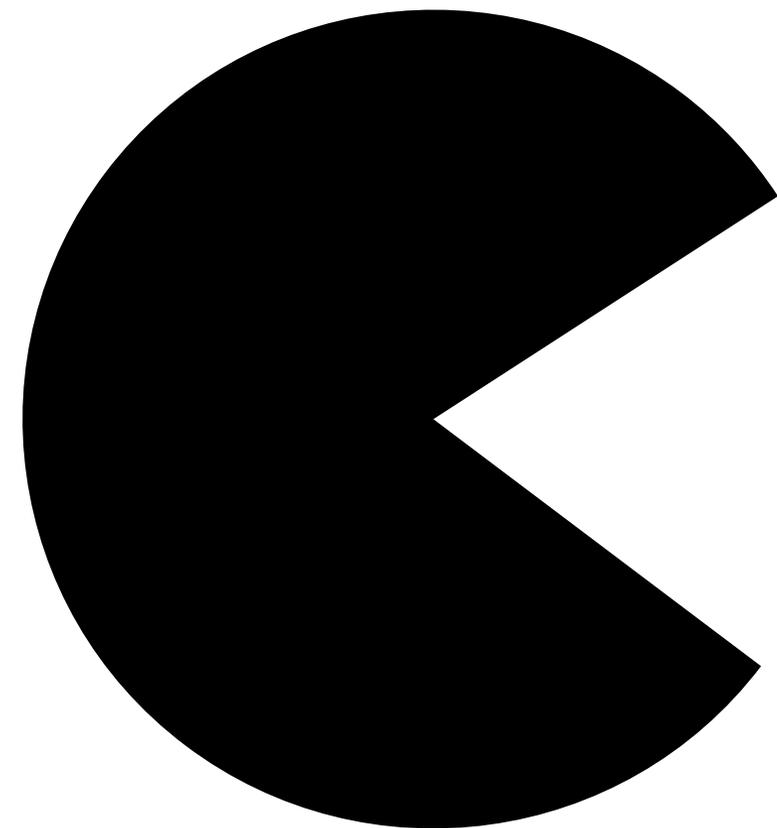
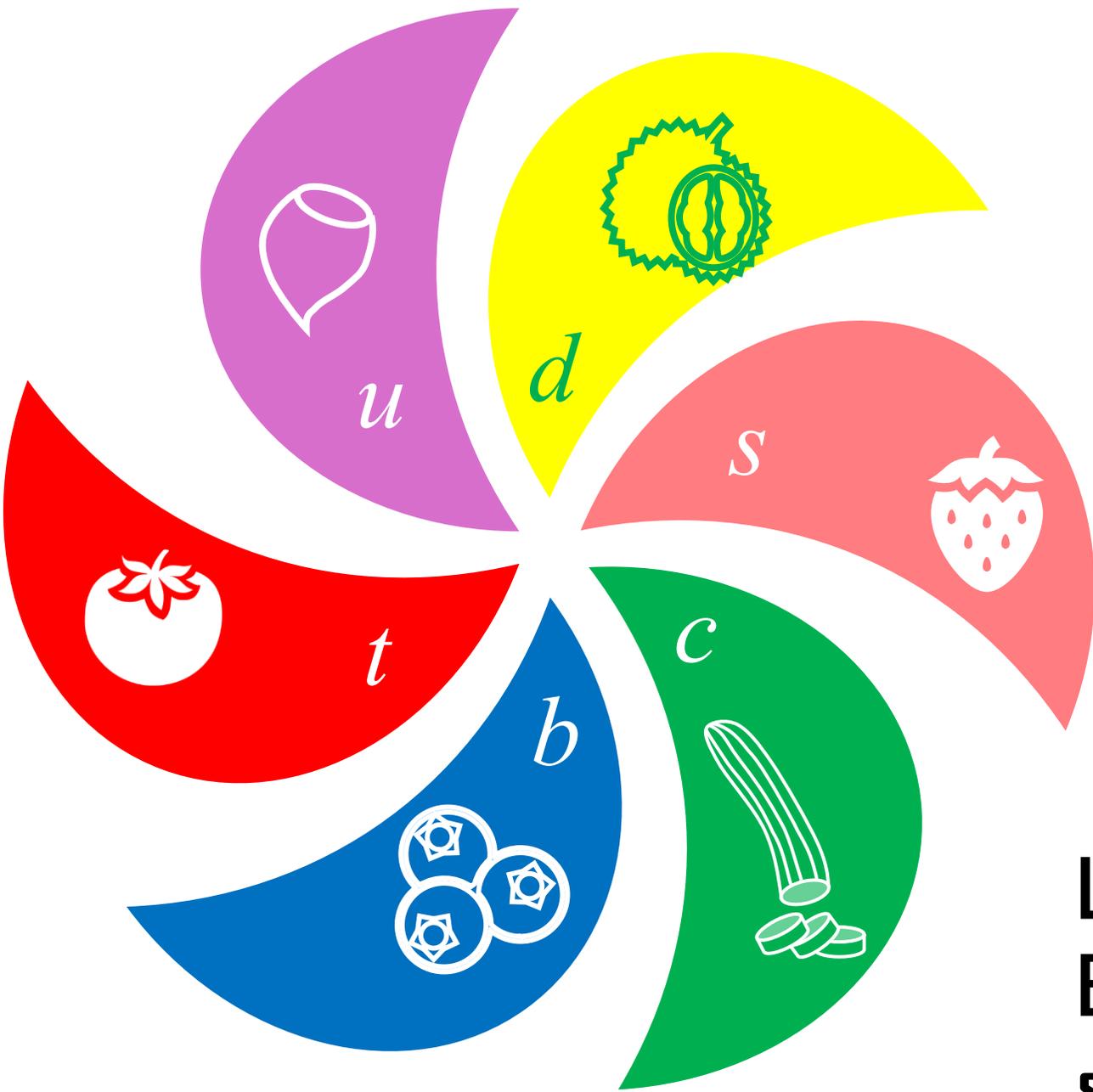
I. S. Sands, 2404.16247; DELVE and DES collaboration, 2509.12313; D. Dado et al., 2512.11033

Simulation in non-linear regime with large systematic uncertainties are known to be hard. May get very different answers from different people

We don't know if there is exactly an invisible elephant in the room, but at least something must be there



The necessity of flavor in DM research?



**LCDM observables only reach upto
BBN time ($T \sim \text{MeV}$), all flavor physics
seem hidden**

The Hidden Flavor of Universe

MATTER ASYMMETRY

RADIATION DOMINATION **DM DOMINATION**

t b c τ uds μ e

Dark Ages

EWSB

QCD

BBN

Recombination
(CMB)

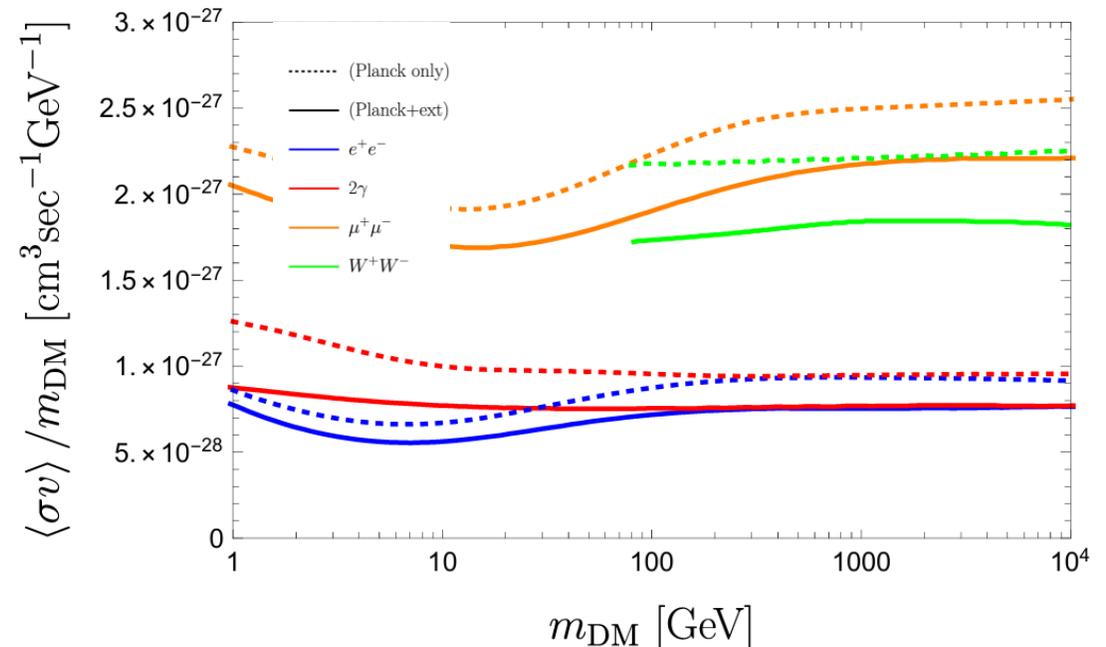
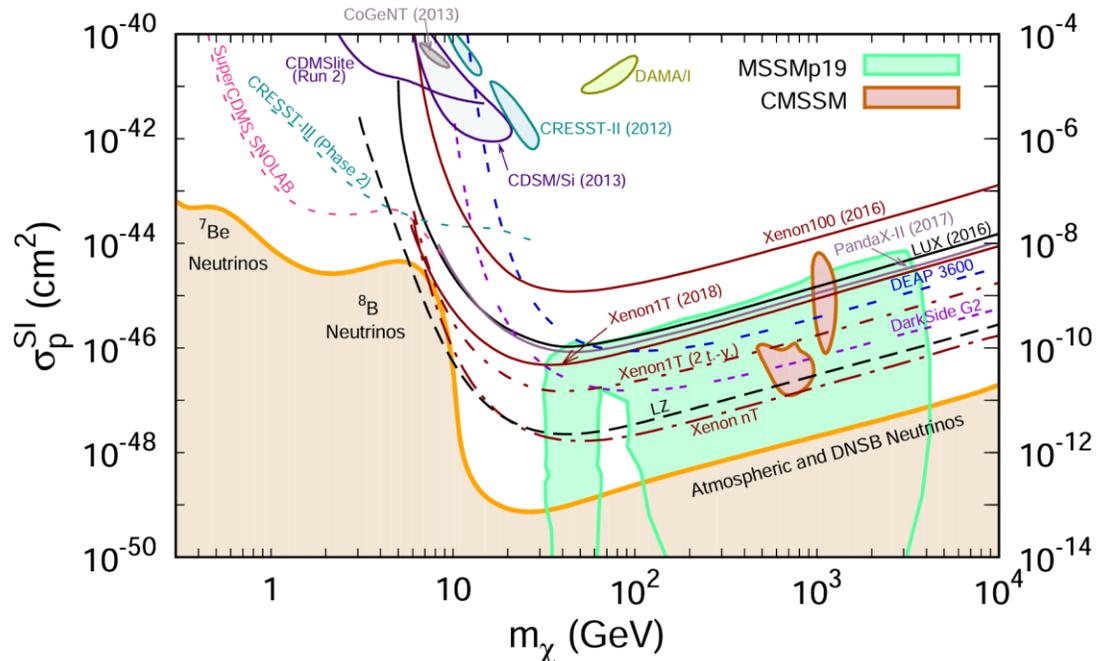
Cosmic
Dawn

Connection is not obvious
but still beneficial

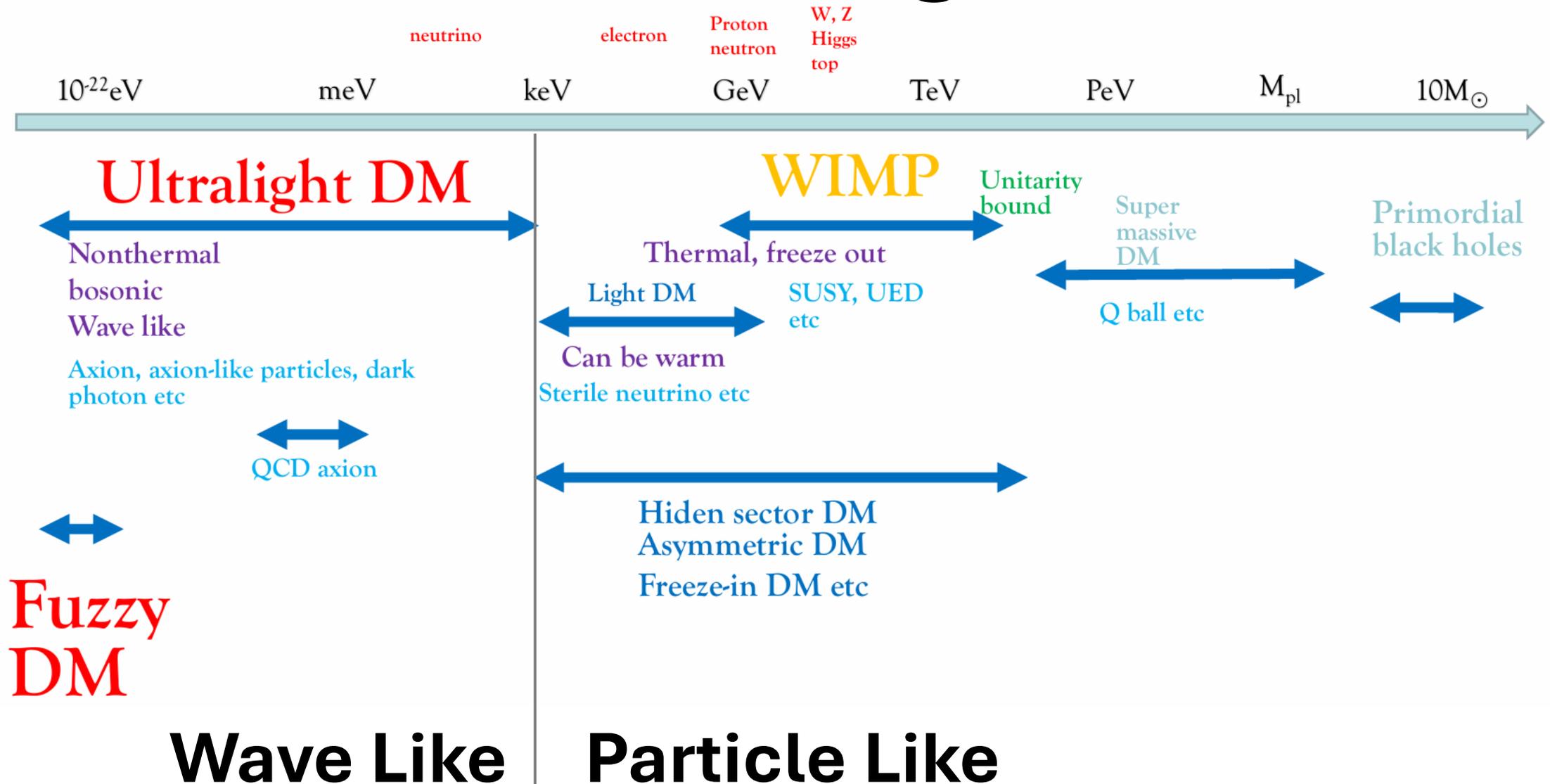
OBSERVATIONS

What Do We Know from Late Times?

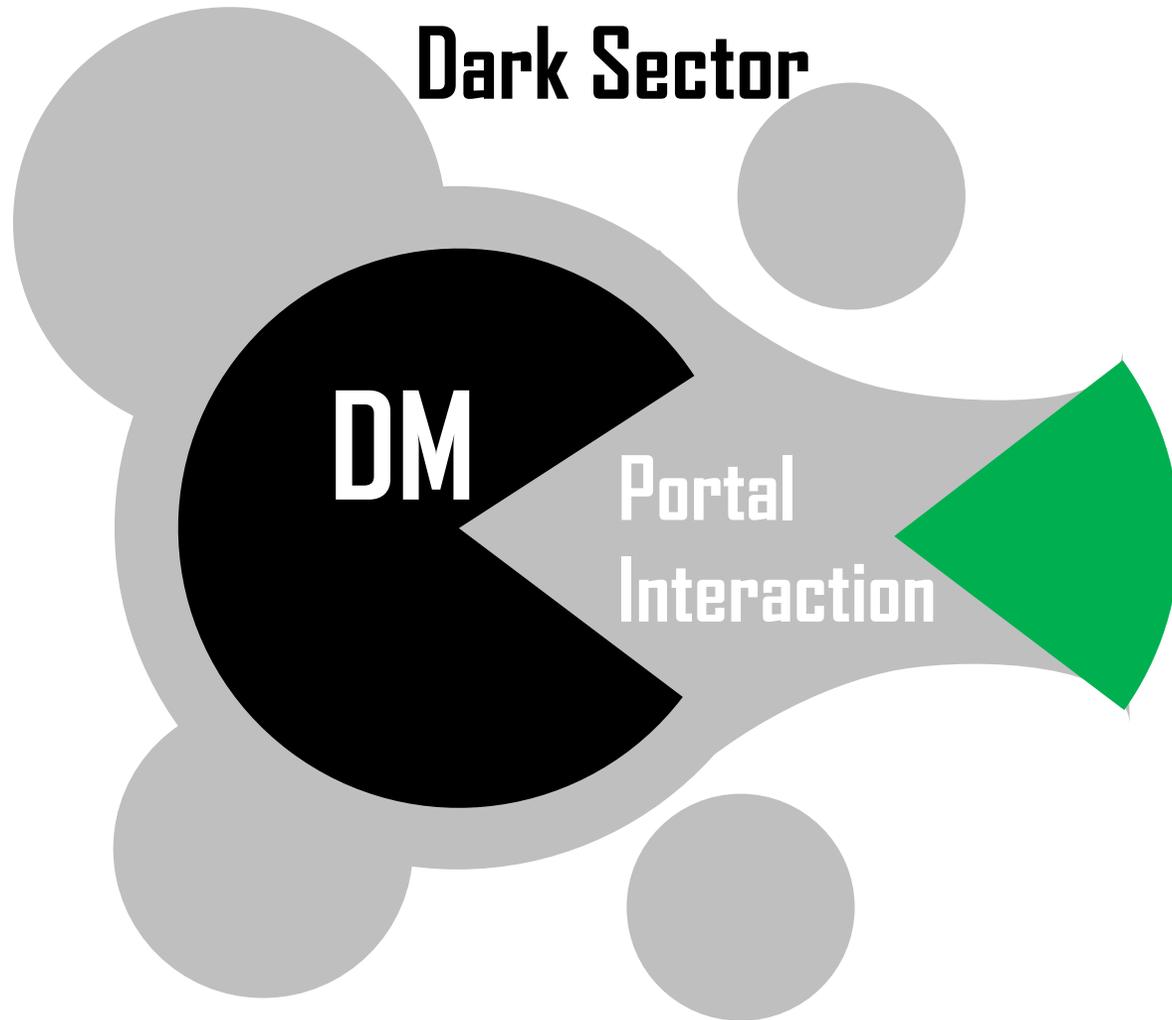
- ❑ Limited self-interaction ($< \text{cm}^2/\text{g}$, depends on velocity)
- ❑ Lifetime extremely long if decay to SM (\gg lifetime of universe)
- ❑ Annihilation signal limited (Hints from Galactic Center?)
- ❑ Scattering with the SM weakly (Typical WIMP DM not found)



Extended Mass Range of DM



Extended DM to Dark Sector (DS) and Portal Interactions



Dark Sector Candidates

Axion (ALPs), dark photon, dark Higgs, sterile neutrinos, dark hadrons

Portal interaction candidate

Scalar portal

B. Patt, F. Wilczek, 0605188

Vector Portal

J. Alexander et al., 1608.08632

Axion Portal

Y. Nomura, J. Thaler, 0810.5397

“FCNC Portal”

J. F. Kamenik, C. Smith, 1111.6402

Flavor Portal

L. Calibbi, A. Crivellin, B. Zaldivar, 1501.07268

Z/Electroweak Portal

H-C. Cheng, LFL, E. Salvioni, 2110.10691

Thermal DM Still Alive and Prosper

Freeze-in

L. J. Hall, K. Jedamzik, J. March-Russell, S. M. West, 0911.1120

Coannihilation

M. J. Baker, J. Brod, S. El Hedri, A. Kaminska, J. Kopp, J. Liu, A. Thamm, M. de Vries, X.-P. Wang, F. Yu, J. Zurita, 1510.03434

Forbidden

R. T. D'Agnolo, J. T. Ruderman, 1505.07107

Coscattering

R. T. D'Agnolo, D. Pappadopulo, J. T. Ruderman, 1705.08450

SIMP/Cannibal

Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky, J. G. Wacker, 1411.3727; D. Pappadopulo, J. T. Ruderman, G. Trevisan, 1602.04219

Codecaying

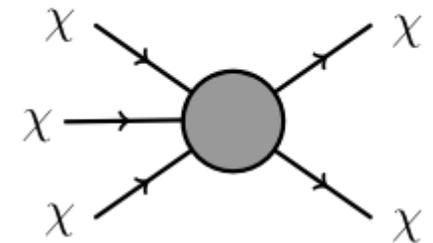
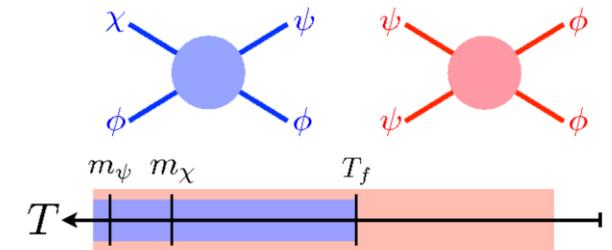
J. A. Dror, E. Kuflik, W.-H. Ng, 1607.03110

Secluded

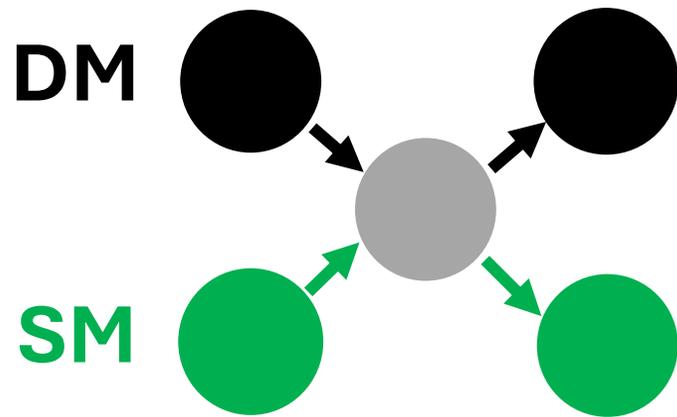
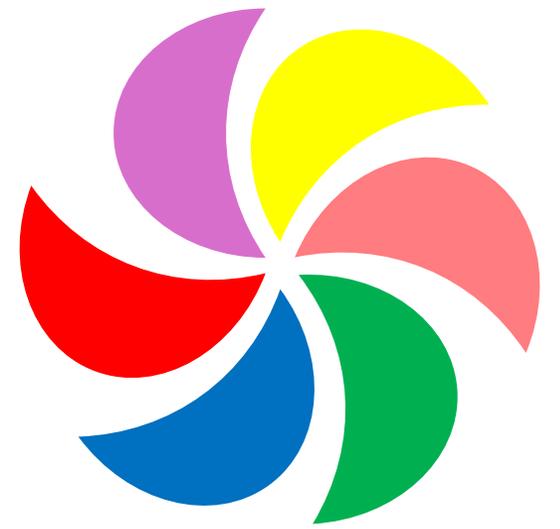
M. Pospelov, A. Ritz, M. Voloshin, 0711.4866

Heterogenous

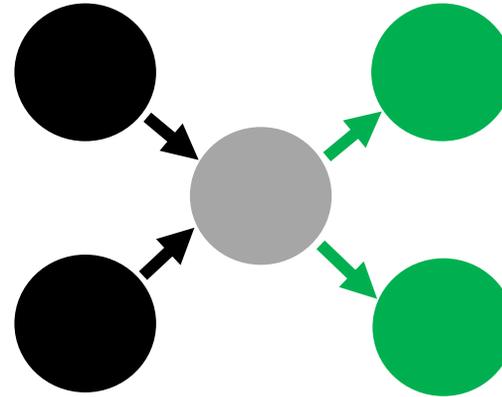
H-C Cheng, X. H. Jiang, LFL, E. Salvioni, in prep



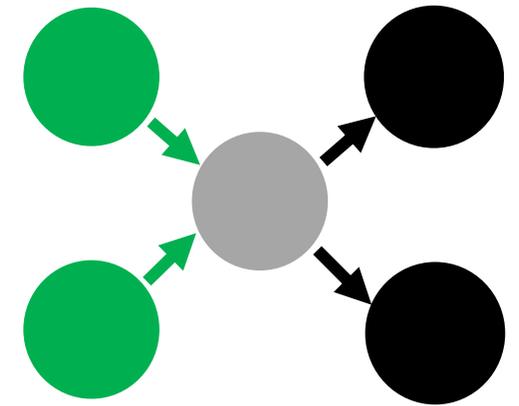
Flavor Physics in DM Detection



Direct
Detection

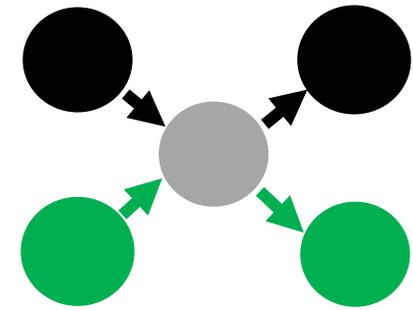


Indirect
Detection



Collider
Search

Flavor in Direct Detection



□ Isospin effect
$$\sigma_A = \frac{\mu_A^2}{M_*^4} [f_p Z + f_n (A - Z)]^2$$

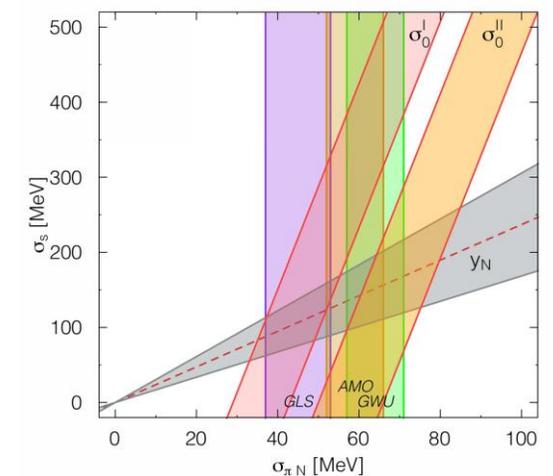
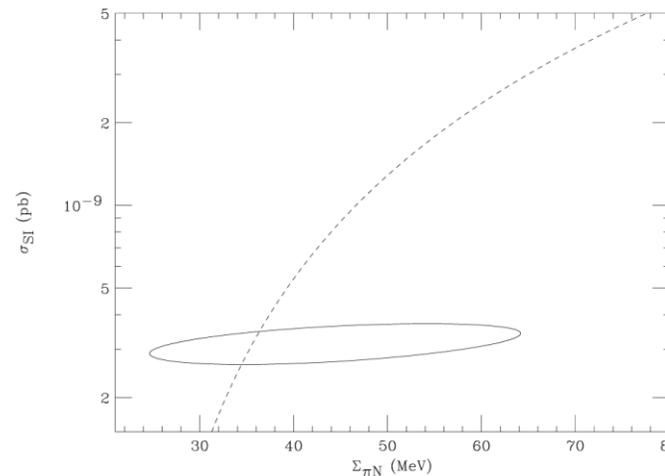
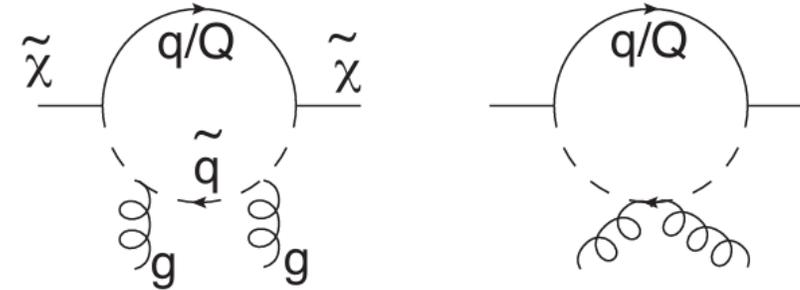
J. L. Feng, J. Kumar, D. Marfatia and D. Sanford,
1102.4331

□ Induced gluonic coupling
from heavy flavor

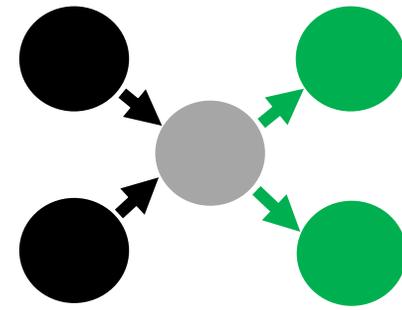
J. Hisano, K. Ishiwata and
Nagata, 1007.2601

□ Strange quark effects

R. D. Young, 1301.1765

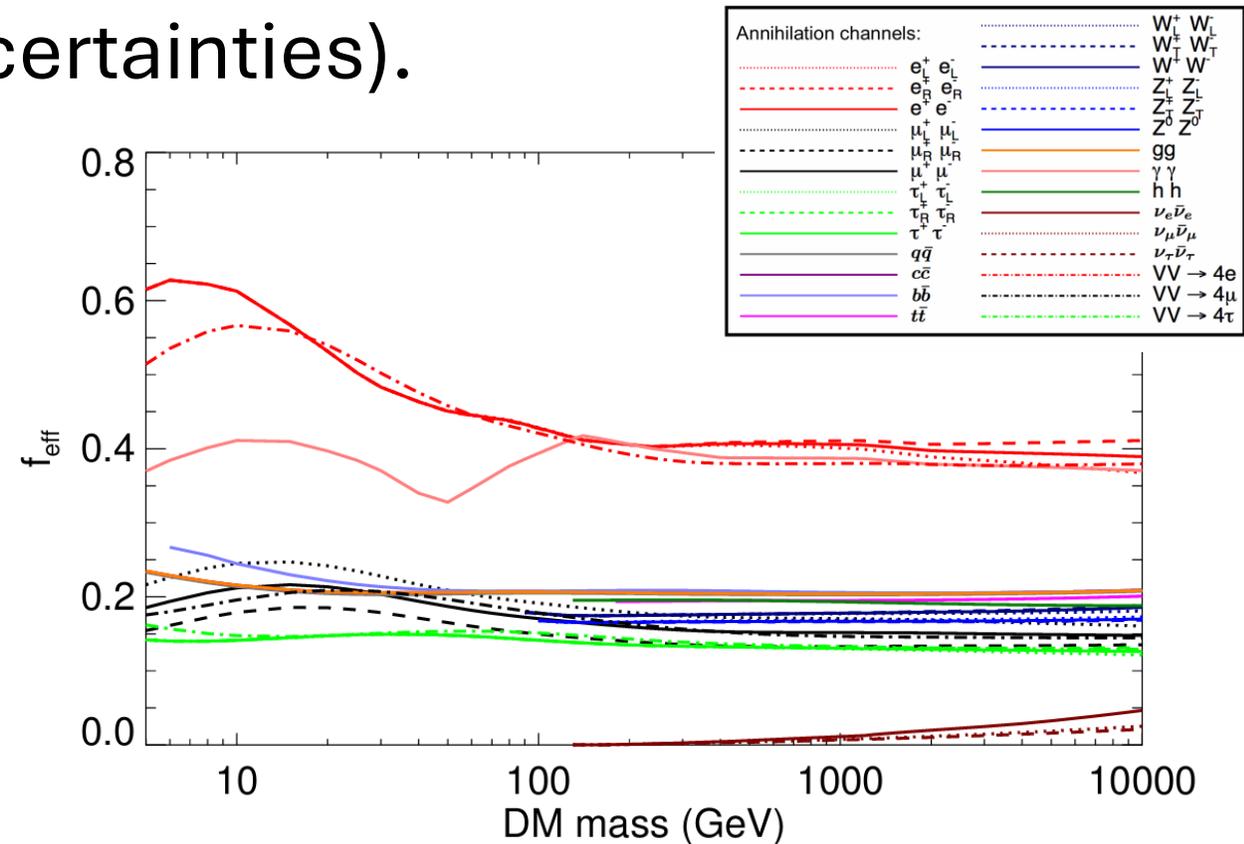


Flavor in Indirect Detection

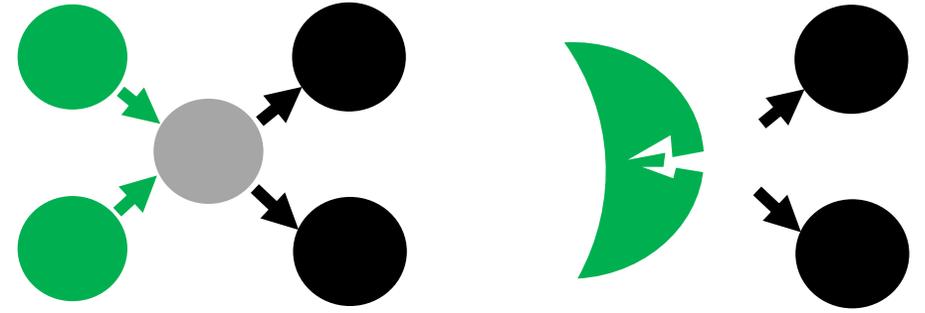


Annihilation product determines the outgoing hadron spectrum (often with large systematic uncertainties).

- Charged π , leptons \rightarrow inverse compton scattering photons (Fermi-Lat)
- Leptons, stable hadrons: cosmic ray (AMS, DAMPE)
- Neutral π : direct photon signal



Flavor in Particle Physics Searches



Dark sector particle could be lighter than B

Induced FCNC decays as probes to various dark sector, depends on the signal features

With or without MFV, one may expect interactions like

W. Altmannshofer, A. Crivellin, H. Haigh, G. Inguglia and J. Martin Camalich, 2311.14629; J. Martin Camalich, M. Pospelov, P. N. H. Vuong, R. Ziegler and J. Zupan, 2002.04623; M. K. Gaillard, M. B. Gavela, R. Houtz, P. Quilez and R. Del Rey, 1805.06465; T. Li, M.A. Schmidt and M. Yuan, 2506.08342; H-C. Cheng, LFL, E. Salvioni 2110.10691; X. G. He, X. D. Ma, M. Schmidt, G. Valencia, R. Volkas, 2403.12485

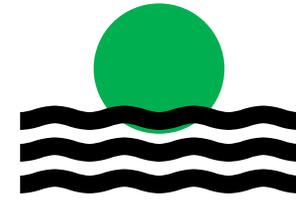
$$-(\lambda_{ij}^u \phi \bar{Q}_L^i u_R^j + \lambda_{ij}^d \phi \bar{Q}_L^i d_R^j)$$

$$-\frac{1}{\Lambda^2} (\bar{\psi} \gamma_\mu \psi) (\bar{d}_R^i \gamma^\mu d_R^j)$$

See also: Xiaogang He, Xingbo Yuan, Liang Sun, and Zuowei Liu's talk

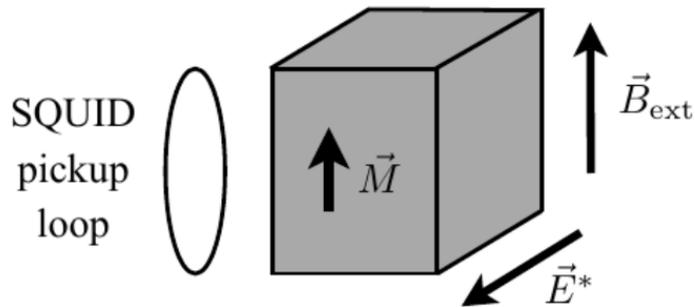
Γ_{39}	$\pi^+ \nu \bar{\nu}$	$(1.14_{-0.33}^{+0.40}) \times 10^{-10}$	
Γ_{40}	$\pi^+ \pi^0 \nu \bar{\nu}$	$< 4.3 \times 10^{-5}$	
	Γ_{582}	$\pi^+ \nu \bar{\nu}$	$< 1.4 \times 10^{-5}$
	Γ_{588}	$K^+ \nu \bar{\nu}$	$< 1.6 \times 10^{-5}$
	Γ_{589}	$\rho^+ \nu \bar{\nu}$	$< 3.0 \times 10^{-5}$

Flavor in Ultra Light DM Detection



The detection largely relies on ultralight DM (e.g. axion/ALP) couples to nucleons, need to translate to a UV description

- NMR type search

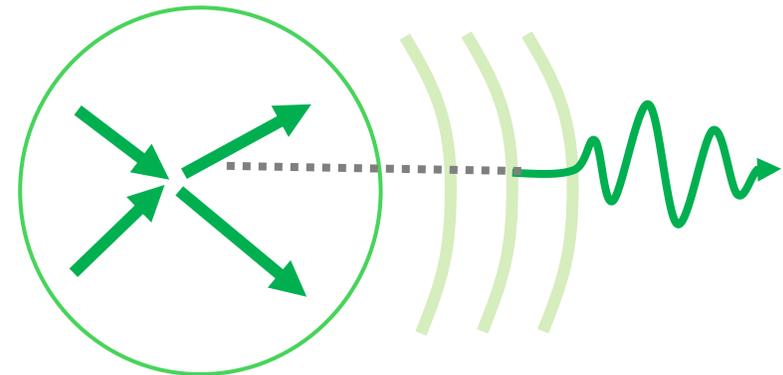


- Production in dense environment & signal

N. Iwamoto, PhysRevD.64.043002; B.J.F. Fortin, H. K. Guo, S.P. Harris, D. Kim, K. Sinha and C. Sun, 2102.12503; J. Fan, LFL, C. Sun, 2501.12440

$$\partial_\mu a \bar{N} \gamma^\mu \gamma^5 N$$

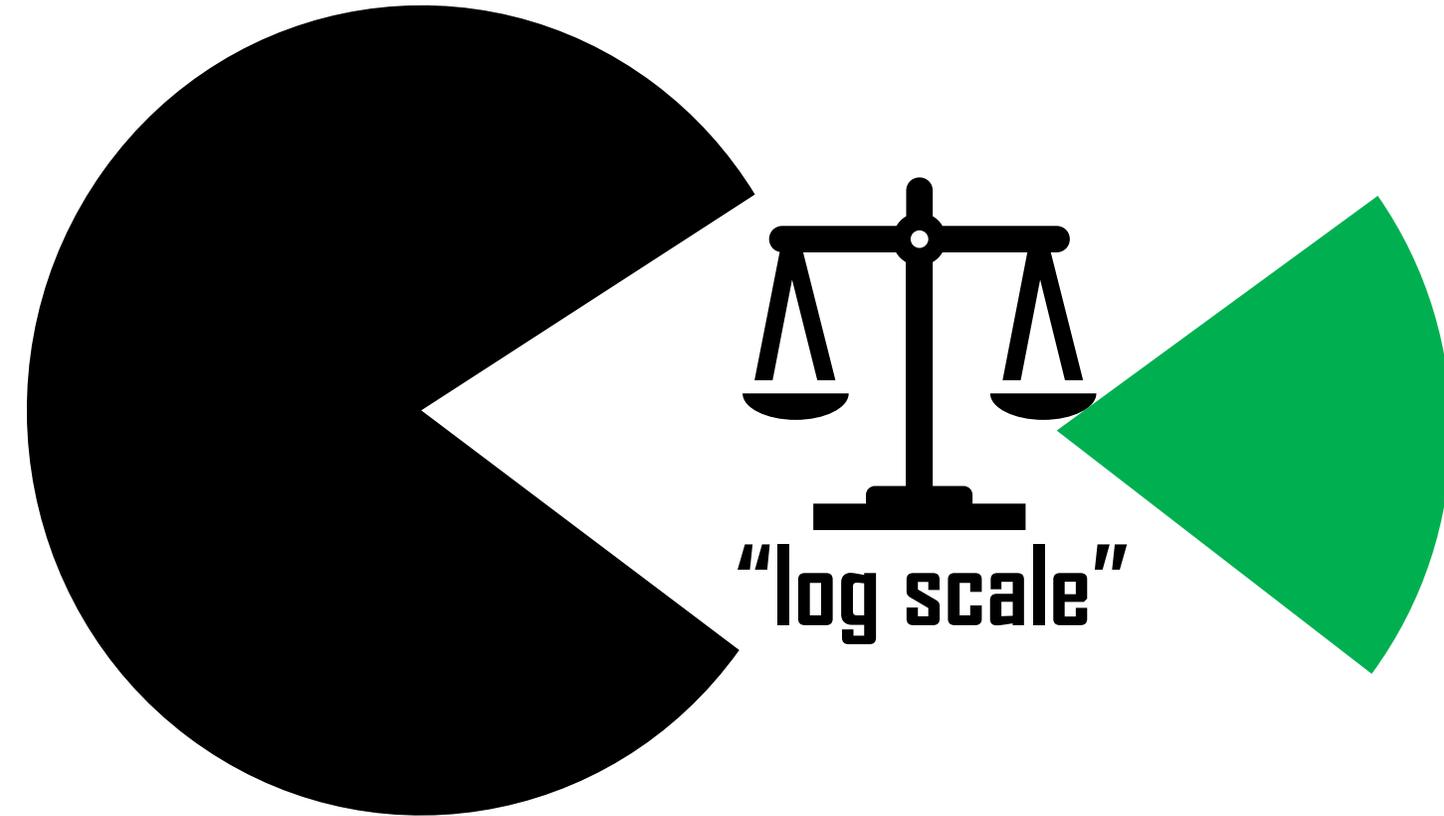
$$H_{aNN} = g_{aNN} \sqrt{2\rho_{DM}} \cos(m_a t) \vec{v} \cdot \vec{\sigma}_N$$



Budker et al., 1306.6089; Garcon et al., 1707.05312; T. Vonk, F. K. Guo and U. G. Meisner, 2001.05327

Extended Thoughts

The Puzzle of DM-SM Coincidence



Why DM and baryon density are so close?

- If the two sector was in thermal contact (equilibrium)?
- If DM and Baryon number are related to each other?

Recall the WIMP Miracle

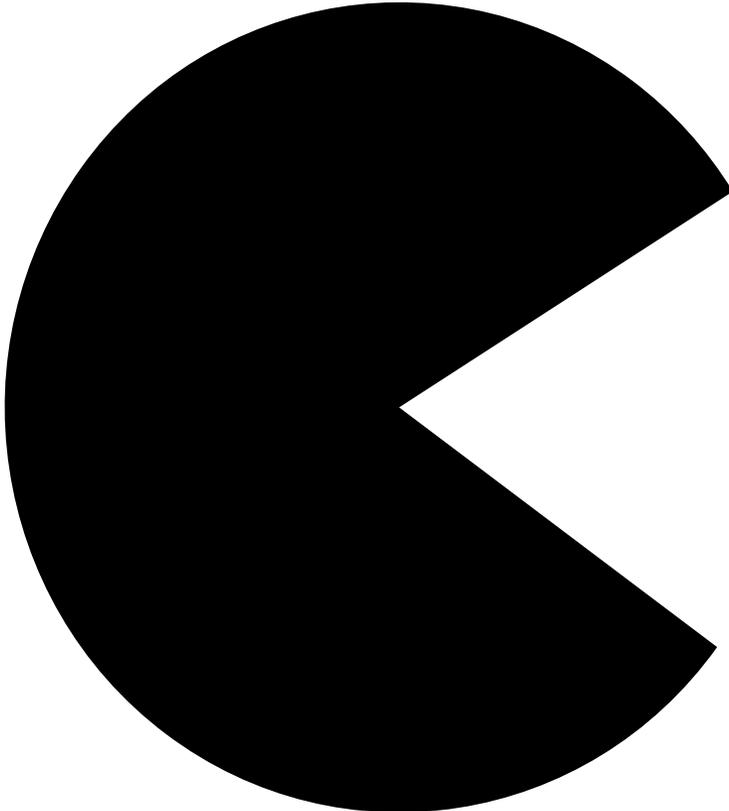
The freezeout condition:

$$n_f \langle \sigma v \rangle \simeq \frac{T_f^2}{M_{Pl}}$$
$$Y_\infty \simeq \frac{x_f}{M_{Pl} m_\chi \langle \sigma v \rangle} \simeq \eta \frac{m_p}{m_\chi}$$
$$\langle \sigma v \rangle \simeq x_f \frac{1}{\eta M_{Pl} m_p}$$
$$\sim \mathcal{O}(10^{-26}) \text{ cm}^3 \text{ s}^{-1}$$

$$\eta \approx 6 \times 10^{-10}$$

**Weak-scale annihilation
process**

DM-Baryon Cogenesis



“log scale”



DM and baryon abundance are strictly related



GeV-scale DM (DS)

Sakharov Conditions for Baryogenesis

Baryon number violation (in the SM)

C and CP violation

Out of Equilibrium Process

See also talks by Wei Chao,
Chengcheng Han, Fapeng Huang

Cogenesis: An Example

The dark mesons are not protected in general: where are they?

Driver

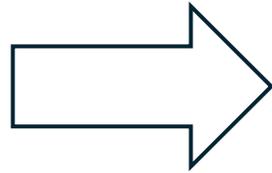
$QQQLX$

$qqqX$

NHL

.....

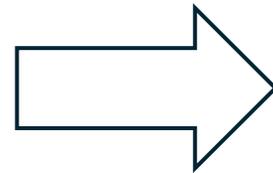
B (B-L) violating with
C & CP violation



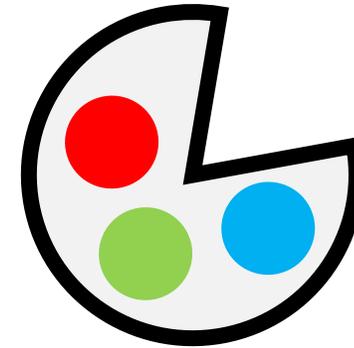
Portal

ϕqX

Baryon number gets
shared to the dark
sector or vice versa

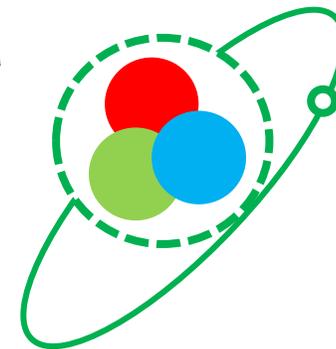
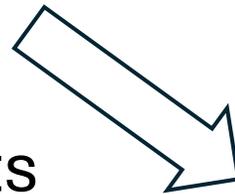


Matter



Asymmetric
dark baryons

free from
indirect search



SM baryons

Dark Shower and Dark Flavor Physics

- ❑ Dark shower may contain dark matter (e.g. dark baryons) and other stable dark hadrons (e.g. dark antibaryons)
- ❑ Other dark hadrons (e.g. dark pions) are not protected and may decay
 - If the decay is not prompt → emerging jets

P. Schwaller, D. Stolarski, A. Weiler, 1502.05409; S. Knapen, J. Shelton, D. Xu, 2103.01238; . Born, R. Karun, S. Knapen, J. Shelton, 2303.04167; J. Carrasco, J. Zurita, 2307.04847; H-C. Cheng, X. Jiang, LFL, E. Salvioni, 2408.13304

- If the decay is prompt → semi-visible jets

T. Cohen, M. Lisanti and H.K. Lou, 1503.00009; J. Carrasco, S. Kulkarni, W. Liu, J. Lockyer and J. Zurita, 2511.02918; M. Buschmann, J. Kopp, J. Liu and P.A.N. Machado, 1505.07459



Both metastable and stable components

Driver

CPV
Decays

Hylogenesis

H. Davoudiasl, D. E. Morrissey, K. Sigurdson and S. Tulin, 1008.2399

Leptogenesis induced ADM

D. E. Kaplan, M. A. Luty and K. M. Zurek, 0901.4117

Cladogenesis

R. Allahverdi, B. Dutta and K. Sinha, 1011.1286

Oscillation

B-Mesogenesis

G. Elor, M. Escudero and A. Nelson, 1810.00880

Leptogenesis from DM Oscillation

J. Berman, B. Shuve and D. Tucker-Smith, 2201.11502

Field Dynamics /FOPT

Electroweak Cogenesis

C. Cheung and Y. Zhang, 1306.4321

Afflek-Dine Cogenesis

C. Cheung and K. M. Zurek, 1105.4612

Flavored/Colored

Neutral

Hidden

Summary



What about DM

Accumulated evidence

Extended map

Sharpened constraints and challenges

What about Flavor and DM

Direct (isospin/gluon/strange)

Indirect (various)

Collider (various)

Ultralight(isospin/gluon/strange)

Why flavor and DM can be correlated

Thermal contact once
DM-baryon cogenesis

