Resonant Self-Interacting Dark Meson & Small-Scale Structure Problems

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w/ Robert McGehee & Hitoshi Murayama

arXiv:2008.08608

Theme of this talk:

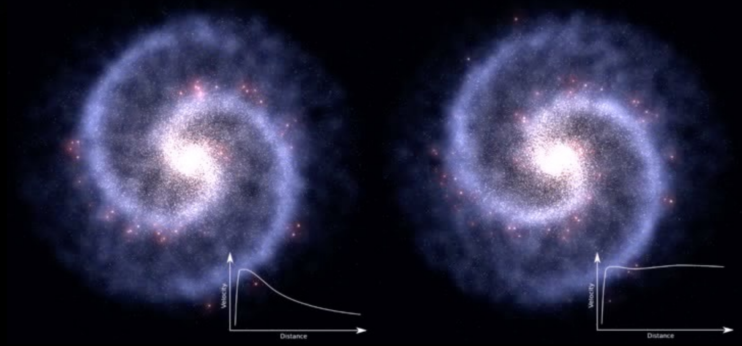
Connecting **Dark Matter** to
Standard Model QCD/Meson

Consider **observation, theory, and experiments**

Finding the **most promising testable DM**

- Galactic Rotation Curves
- Cosmic Microwave Background (CMB)
- Bullet Cluster
- …

Overwhelming
Observational
Astrophysical + Cosmological
Evidences



From: https://en.wikipedia.org/wiki/File:Galaxy_rotation_under_the_influence_of_dark_matter.ogv under the Creative Commons Attribution-Share Alike 3.0 Unported license.

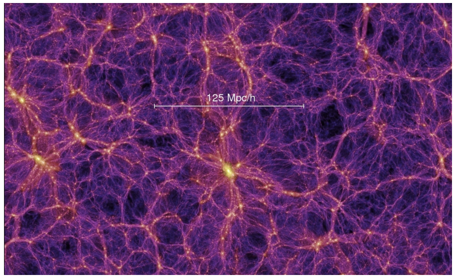
“Small-Scale” Structure of the Universe

- Study from individual (small) galaxies, **including dwarf or spiral galaxies (100 ly - 100 kly)**, to a larger object like a galaxy cluster

by Lynette Cook/science Photo Library

Ly: light-year
kly: kilo light-year

- as apposed to “large-scale” structures, galaxy clusters comprise a filamentary structure. Typical scales in hundred millions of light years.



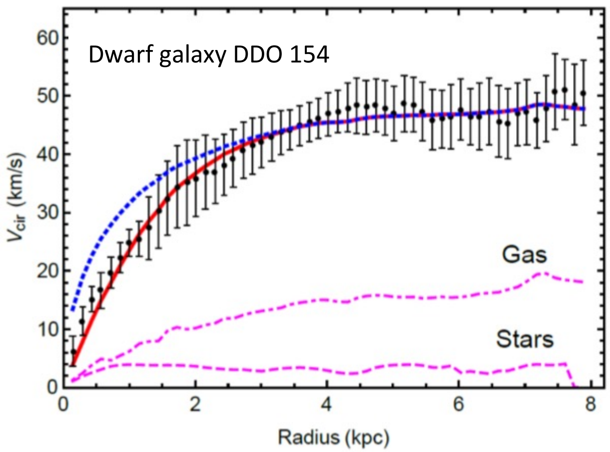
Millennium Simulation Project from Max Planck Institute for Astrophysics
https://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/index.shtml

Core-cusp problem:

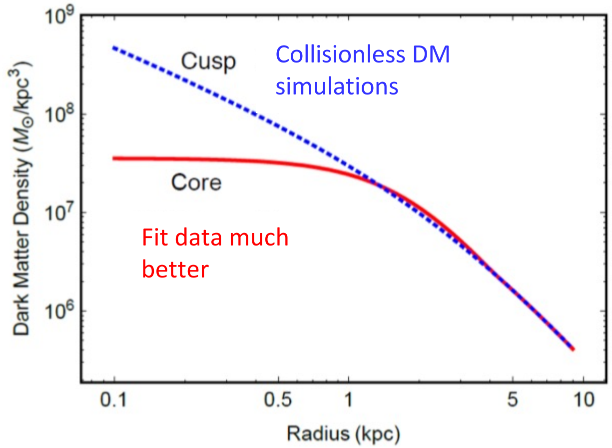
Inner halo: $\rho(r) \sim r^{\alpha}$

Theory prediction: $\alpha \sim -1$ (cusp/NFW profile)
Observations: $\alpha \sim 0$ (core)

Tulin's very clear talk: *https://indico.ibs.re.kr/event/47/session/6/contribution/15/material/slides/0.pdf*



(DDO: David Dunlap Observatory)



Tulin & Yu (in prep); Data from Oh et al [LITTLE THINGS] (2015)
Tulin & Yu, https://arxiv.org/pdf/1705.02358.pdf

Two major explanation:

1) DM interact with itself rather strongly (will explain)

2) Supernova or other processes push DM from galaxy center

(relying on the understanding of complicated galaxy evolution + simulation)

Small-Scale Structure Opportunities!

by Lynette Cook/science Photo Library

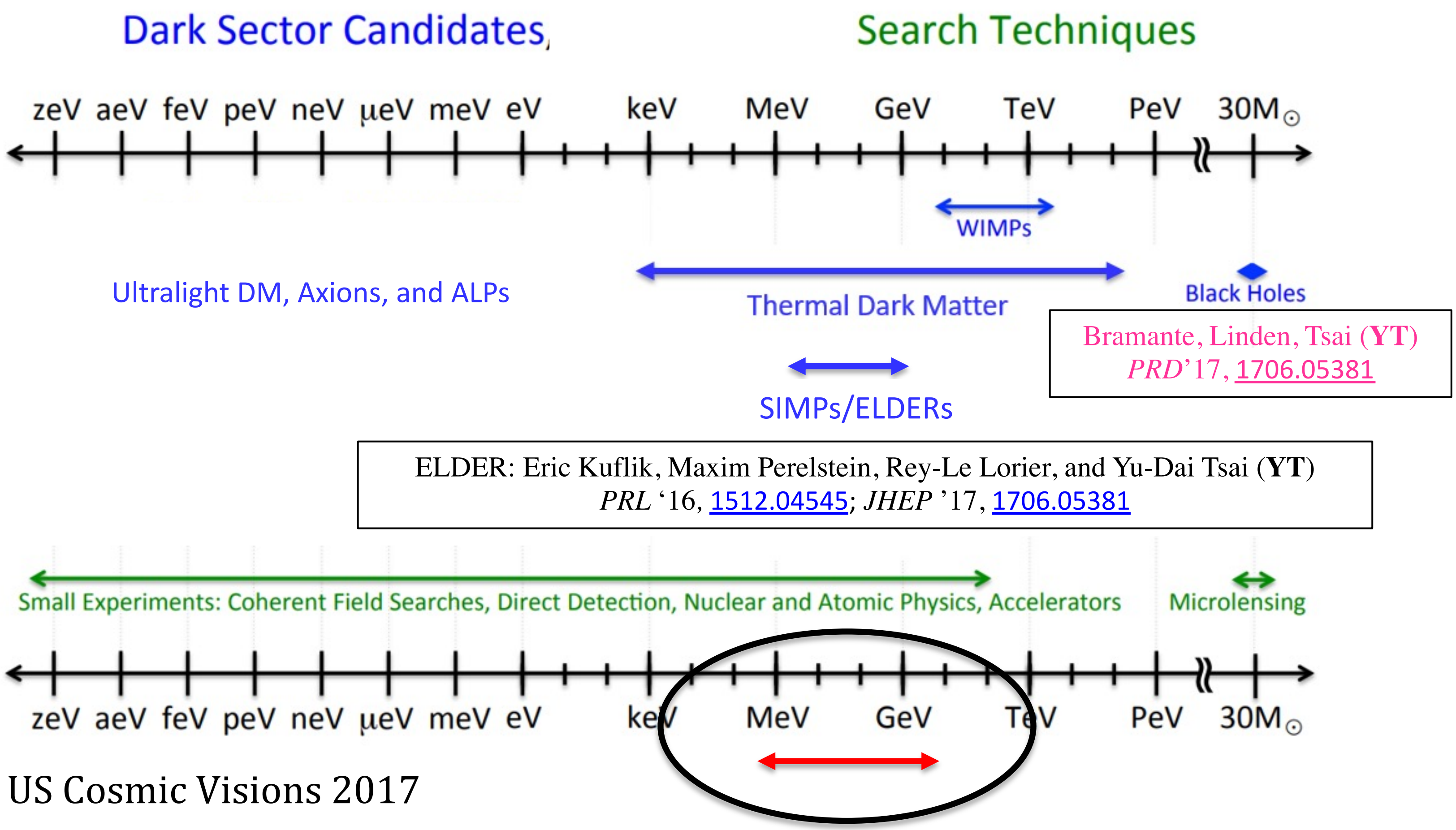
My view:

These may be one of the **only chances** we find dark matter effects **beyond gravity**, in **a galactic scale.**

Best case scenario: help us find and understand dark matter

Worst case scenario: provide strong constraints on DM interactions (still interesting!)

Exploration of Dark Matter & Dark Sector

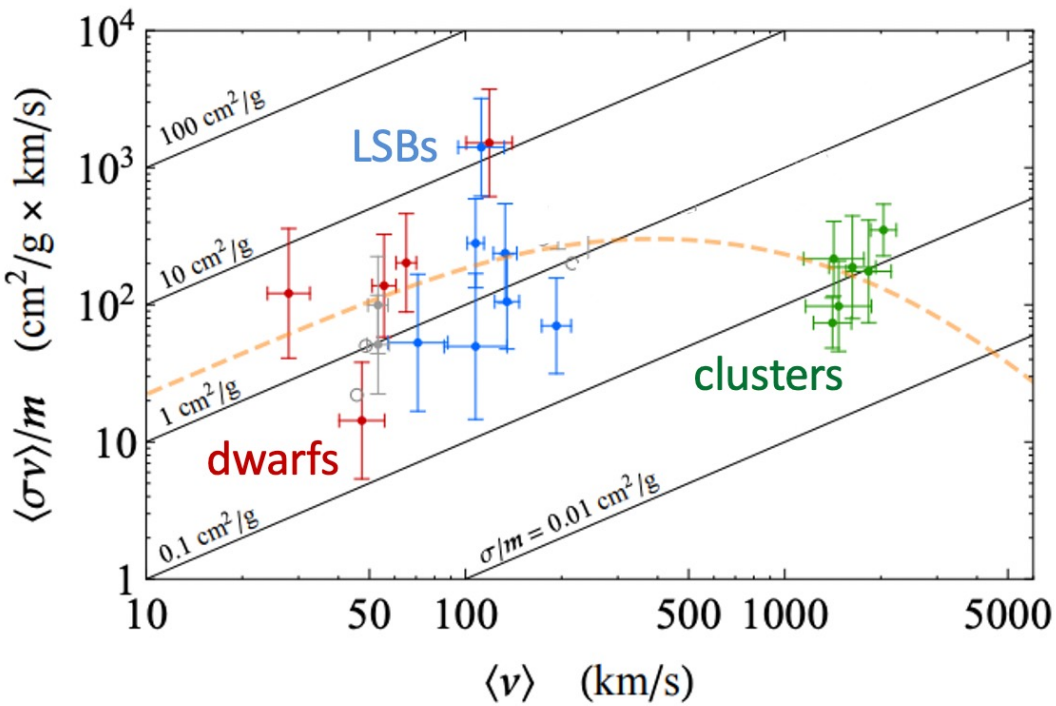


US Cosmic Visions 2017

- **Astrophysical/cosmological observations** are important to reveal the **actual story of dark matter (DM).**
- MeV – GeV regime: **thermal dark matter** & **motivated by many anomalies** (inc. **small-structure issues**)

Self-Interacting Dark Matter (SIDM)

Velocity Dependence



Self-Interacting DM (SIDM), Spergel & Steinhardt '99 + …: **DM collisions thermalize the DM particles in inner halo**

$$\text{rate} \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho(r_1)\, t_{\text{age}} \approx 1\,,$$

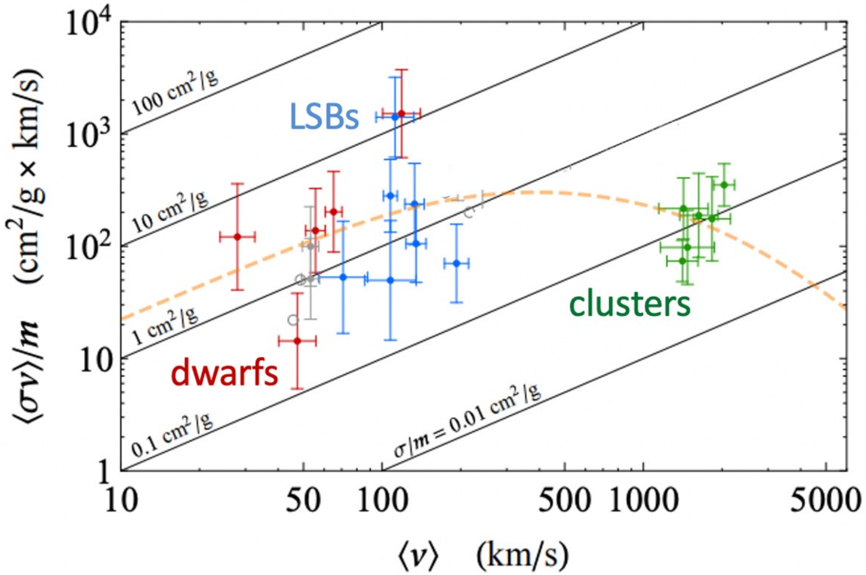
ρ is the density, r_1 is the "scattered radius"

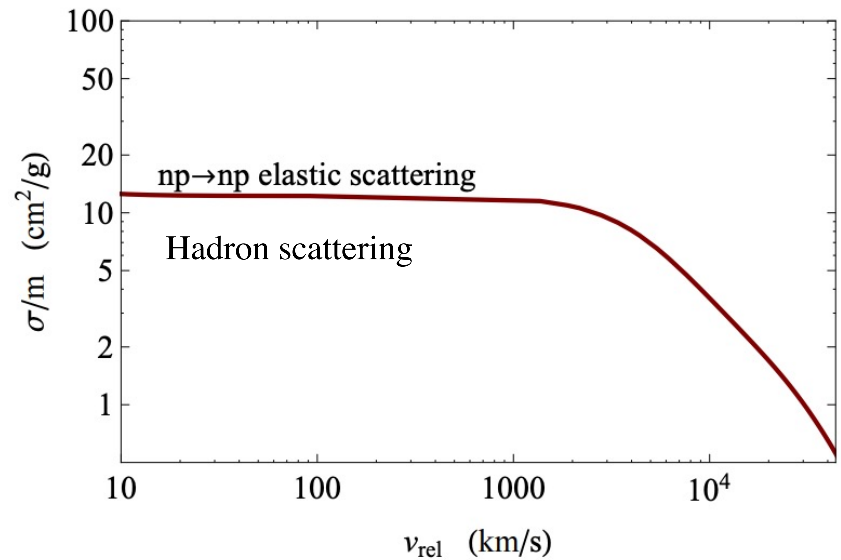
Semi-analytically "Calculate" the profile based on different <σ v> / m, and then match the profiles to the data

Kaplinghat, Tulin, Yu, arXiv:1508.03339

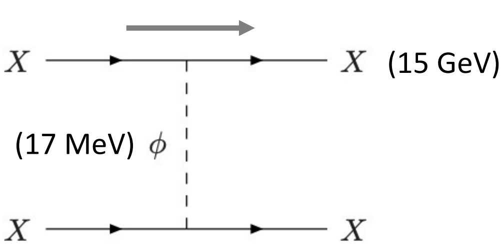
- LSBs: low surface brightness spiral galaxies
- Diagonal lines are contours of constant σ/m .
- **Horizontal line would be σ ∝ 1/v**
- **DM self-interaction prefers VELOCITY DEPENDENCE!**
- At least we learn velocity dependent constraints on cross-sections

Extra Fun: Similarity to Standard Model





$$\sigma/m \sim 1\ \mathrm{cm}^2/\mathrm{g}$$



DM self-interactions

Kaplinghat, Tulin, Yu, arXiv:1508.03339

- **DM Self-Interaction** vs **SM hadron interaction**
- Similar size of cross-section
- Hadrons are composite particles "made of quarks" and bind by QCD interaction (for the students)

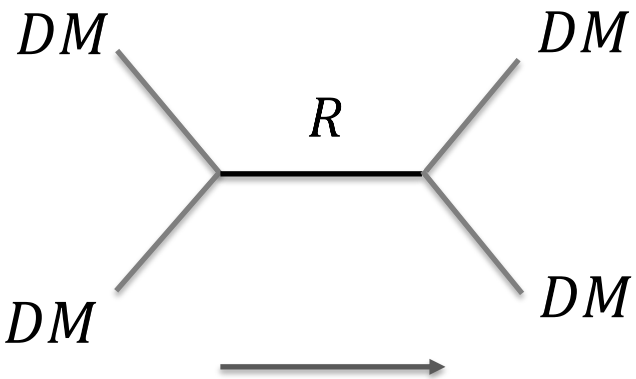
Resonant Self-Interacting Dark Meson (RSIDM)

Tsai, McGehee, Murayama,

arXiv:2008.08608, submitted to *PRL*

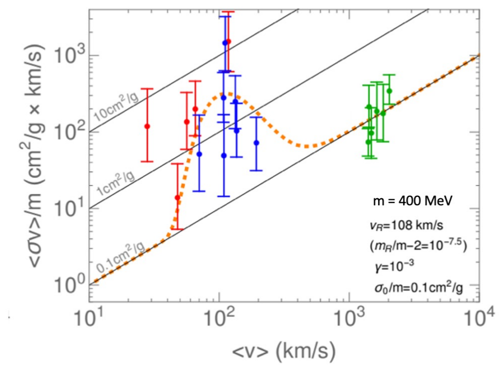
A solution to small-scale structure problems
and have interesting experimental signatures
Can be tested in near future

Resonant SIDM



$$m_R = 2\, m_{\rm DM}(1 + \Delta),$$

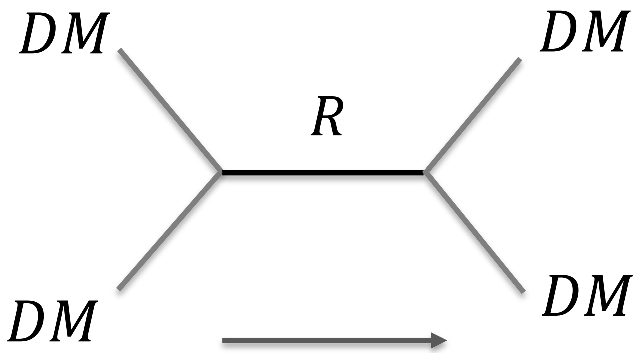
- Δ is small and positive for this talk.



The velocity dependence can be achieved with an **intermediate particle, R**, that help provide a **self-scattering cross-section** to be a sum of a **constant piece, σ0**, plus a **Breit-Wigner resonance**.

See, e.g., Chu, Garcia-Cely, Murayama, arXiv: 1810.04709, Tulin, **Tsai**, research note 2018

Resonant SIDM



Breit-Wigner resonance

for non-relativistic DM

$$\sigma = \sigma_0 + \frac{4\pi S}{mE(v)} \cdot \frac{\Gamma(v)^2/4}{(E(v) - E(v_R))^2 + \Gamma(v)^2/4}\,,$$

$$E(v) = \frac{1}{2}\frac{m}{2}v^2 \quad \text{and} \quad S = \frac{2J_R + 1}{(2J_{\rm DM} + 1)^2}\,.$$

kinetic energy — symmetry factor

constant

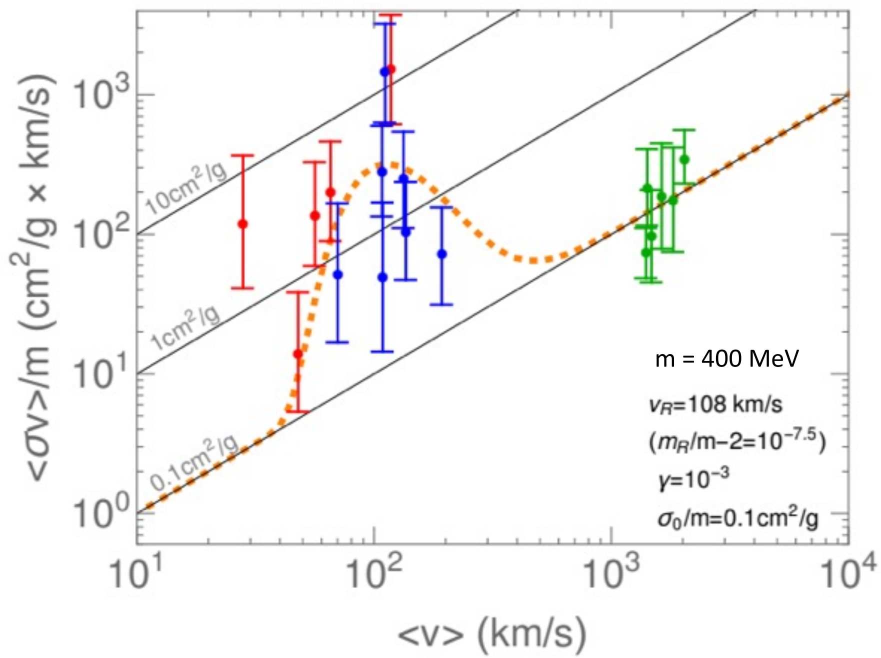
$$E(v_R) = m_R - 2m = 2\Delta m.$$

"resonance condition": the collision hits the resonance when $v = v_R$

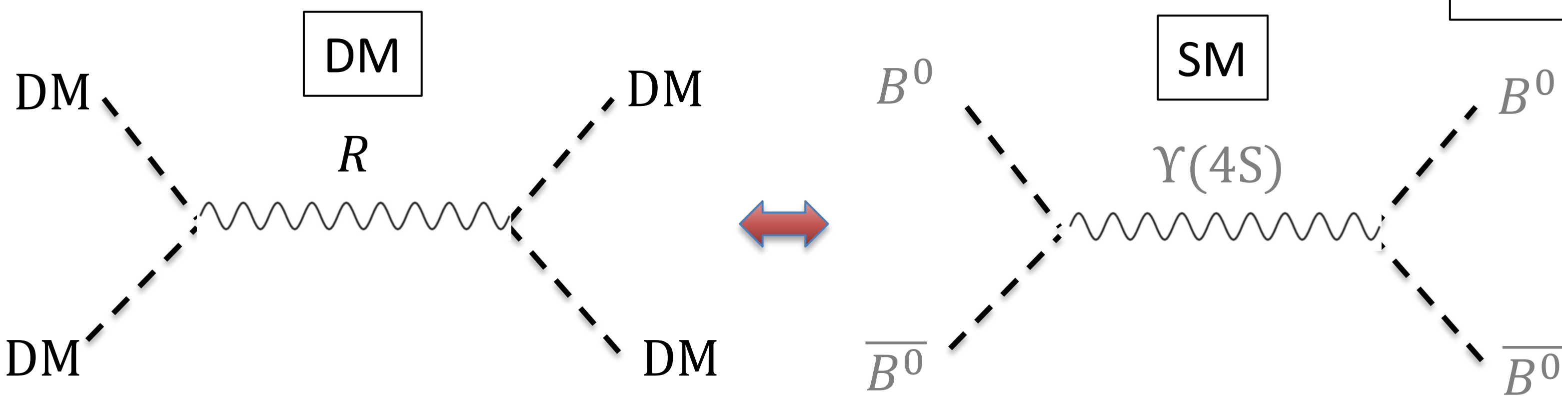
The width $\Gamma(v) = m_R \gamma v^{2L+1}$.

$$\langle \sigma v \rangle = \int_0^{v_{\max}} f(v, v_0) \sigma v dv\,, \quad f(v, v_0) = \frac{4v^2 e^{-v^2/v_0^2}}{\sqrt{\pi} v_0^3}\,.$$

Resonant SIDM: **Vector Resonance**



B^0 & $\Upsilon(4S)$ are well-known mesons



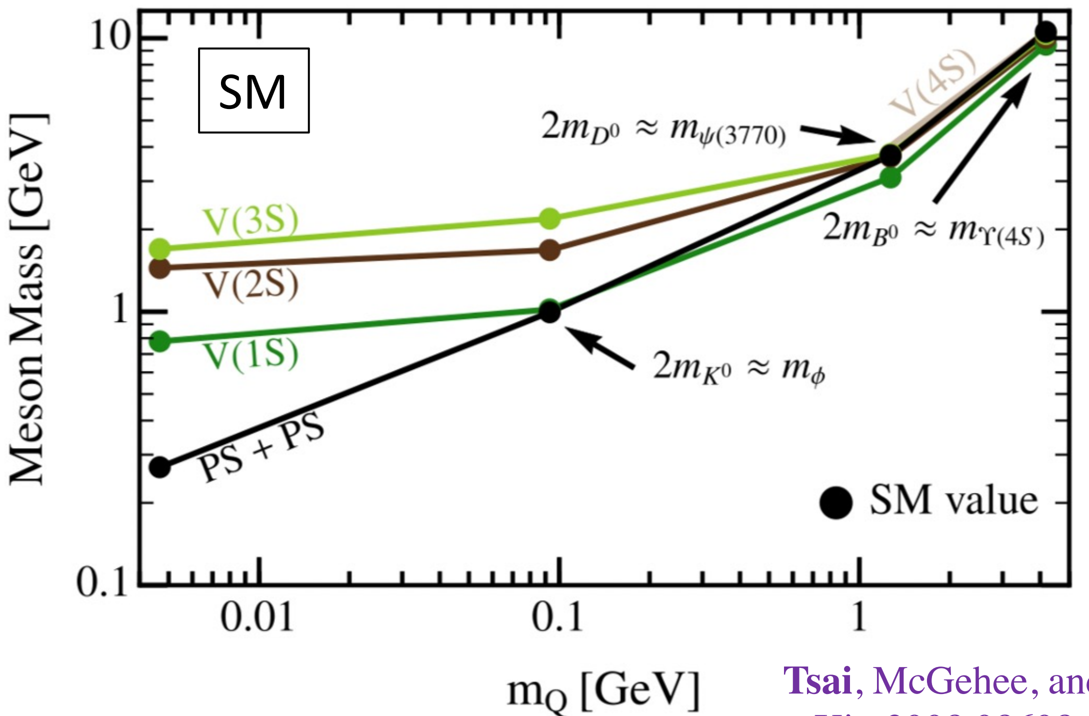
Tsai, McGehee, Murayama, arXiv:2008.08608

QCD & Meson Spectrum

Lessons from QCD. $K^+K^- \to \phi$, $B^0\overline{B}^0 \to \Upsilon(4S)$.

- $m_{K^\pm(u\bar{s}/\bar{u}s)} \approx 493$ MeV; $m_{\phi(s\bar{s})} \approx 1019$ MeV.
- $m_{B^0} \approx 5279$ MeV; $m_{\Upsilon(4S)} \approx 10580$ MeV.
- Inspired by these, we can build interesting DM models inspired by these resonances,
  Tsai, McGehee, Murayama, arXiv:2008.08608

Meson Resonances



Tsai, McGehee, and Murayama, arXiv:2008.08608

For $m_Q = m_d$,

we show π^0 as well as the average masses of the first three ρ and ω states. For $m_Q = m_s$, we show K^0 and the first three ϕ's. For $m_Q = \{m_c, m_b\}$, we show D^0 and B^0 as well as the first four ψ and Υ states, respectively.

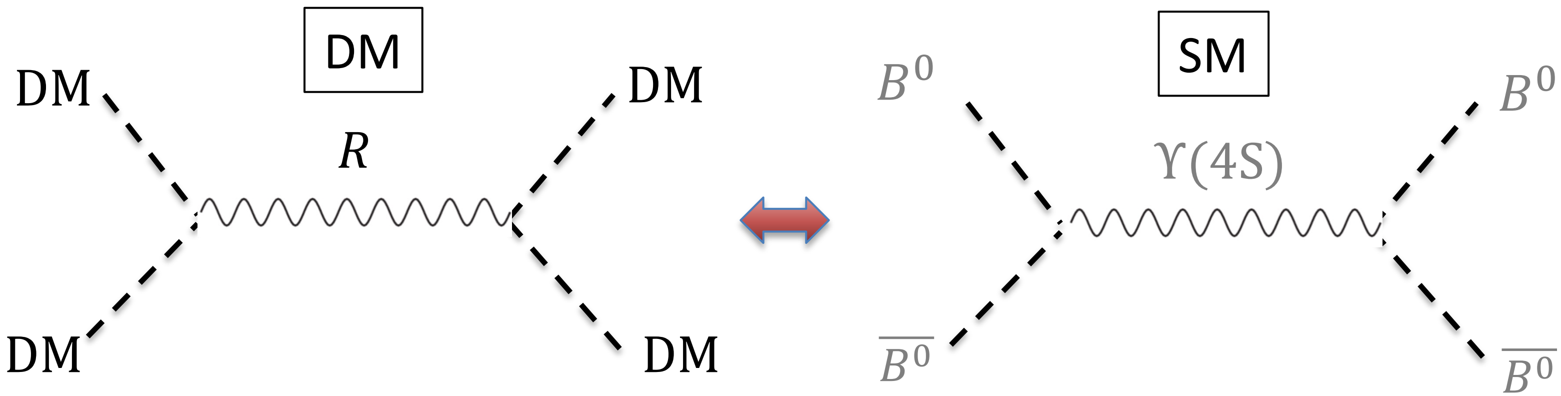
Asymmetric Resonant Dark Mesons

An asymmetric DM model

Connecting DM mystery to SM mystery

Resonant Dark Meson

Model Strategy: linking DM to SM



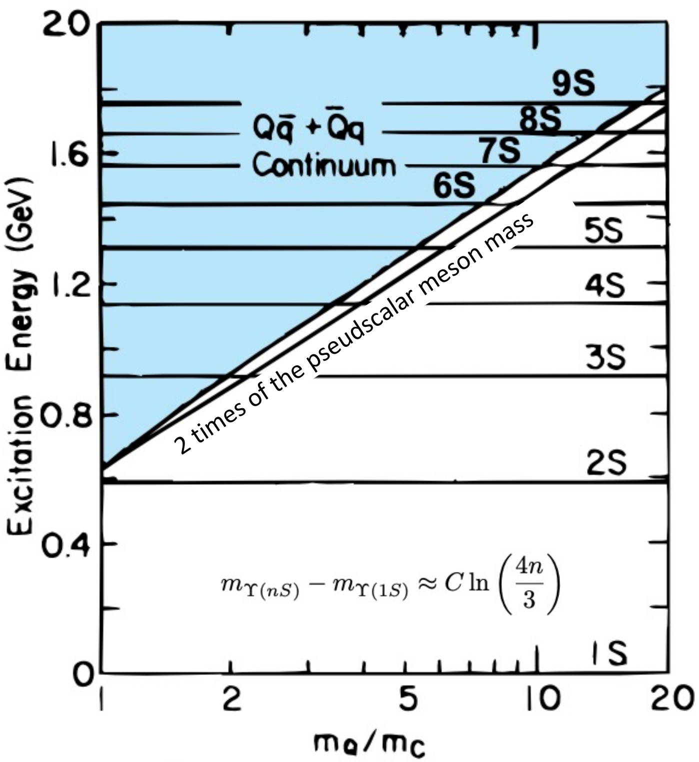
What we learn from SM?

- B^0 is bound state, $B^0(d\bar{b})$, with one heavy quark b (Q) and one light quark d (q)
- m_b is much larger than Λ_{QCD}, the QCD scale parameter.
- $\Upsilon(4S)$ is the 4th excited "Quarkonium" state of $(b\bar{b})$

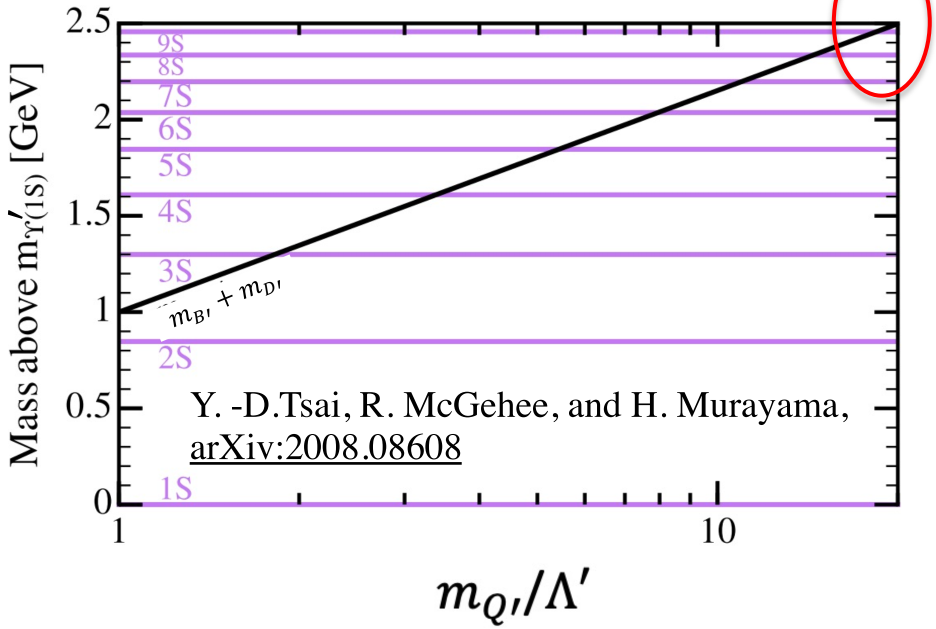
Heavy-Quark Mesons: SM vs DM

SM Modeling

DM Modeling



$$\Delta_n \equiv m_{nS} - m_{(n-1)S}$$



- C. Quigg and J. L. Rosner, "Quarkonium Level Spacings," Phys. Lett. B 71 (1977) 153–157.
- reduced-mass corrections in higher curve

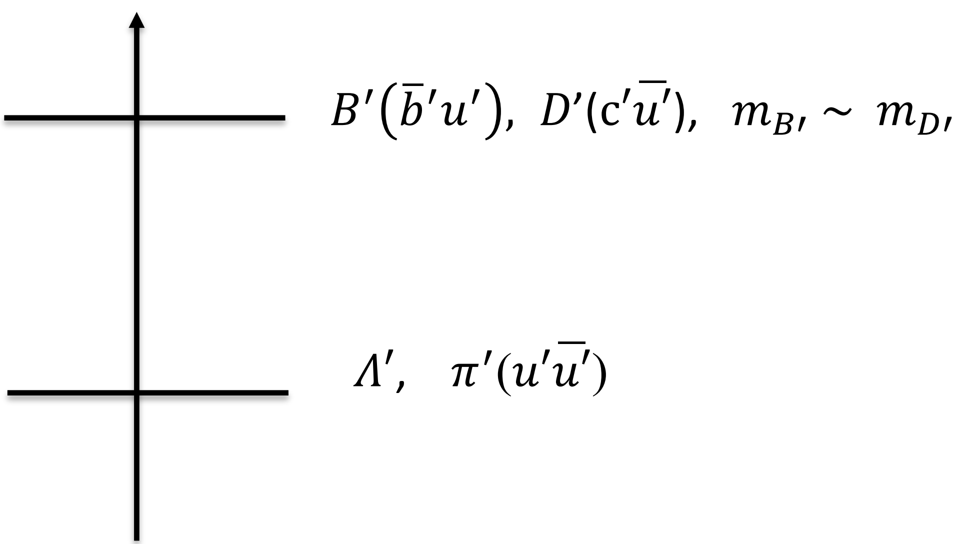
- The "**close-to-resonance-ness**", $\Delta_n/m_{Q'} \sim n^{-3}$. The smaller this is the easier to hit the resonance
- We want $m_{Q'}/\Lambda' > 20$ to go to large n state.
- With n = 10, $\Delta_n/m_{Q'} \sim 10^{-3}$.

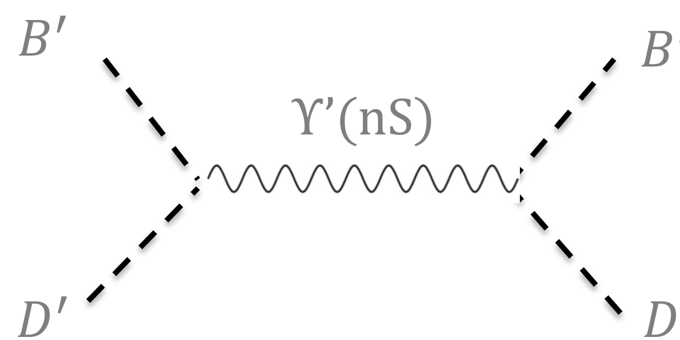
Asymmetric Dark Mesons: Ingredients

′ means all dark particles now

- One light dark quark u′ with mass $m_{u'}$
- Two heavy dark quarks c ′ and b′, setting masses $m_{c'} = m_{b'} = m_{Q'}$ (for simplicity)
- $m_{c'} \ = \ m_{b'} > \Lambda' > \ m_{u'}$ is the mass hierarchy, analogous to QCD
- Forming $B'(u'\bar{b}')$ and $D'(c'\overline{u'})$, and they are **the DM candidates**
- B' & D' abundances set by "asymmetry" (will explain later), $n_c = n_{\bar{b}}$. protected by b′, c′ quantum numbers

Dark meson mass spectrum





Υ'(nS) is the n th excited state of ($\bar{b}'c'$)

Asymmetric Dark Matter (ADM)

Fact: there are more matter than anti-matter in SM: **“asymmetry”**

Asymmetric DM model

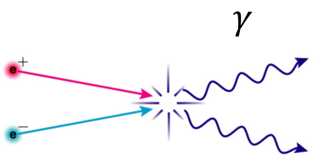
Net Number of DM’s

Assume similar origins

~

SM asymmetry

Net Number of Matter



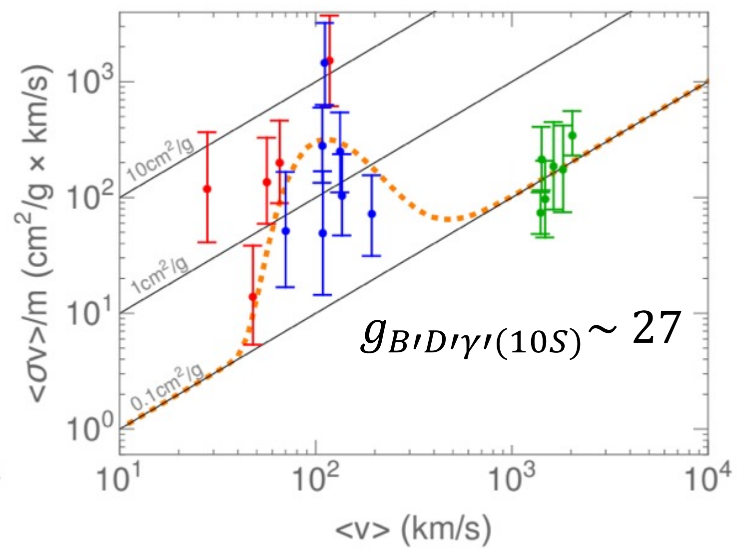
Matter-antimatter annhilation
By Imamura (U Oregon)
https://pages.uoregon.edu/imamura/122/lecture-6/nuclear.html

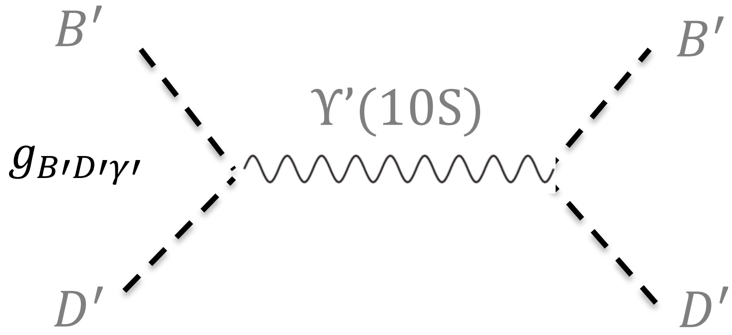
- **Asymmetry will set the number density of the DM.**
- Because DM mass abundance is ~ 5 times more than that of SM
  DM mass is ~ 5 times of SM particle mass!

$$\mathbf{m_{DM} = 5\, m_{Proton} \sim 5\ GeV}$$

See reviews of asymmetric dark matter,
e.g., Petraki & Volkas, 1305.4939 and Zurek, 1308.0338

Asymmetric Dark Matter Parameter





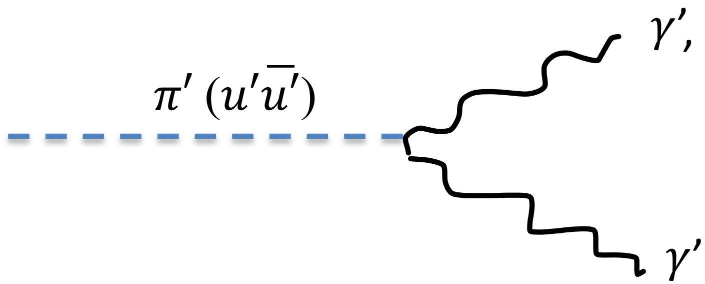
Tsai, McGehee, and Murayama, arXiv:2008.08608
Details left out. See the paper.

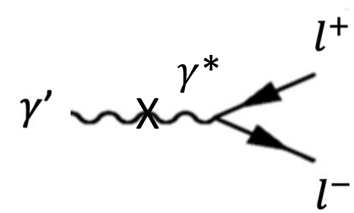
Interesting Parameter that everything works:

- $m_{B'} = m_{D'} = m_{ADM} \sim 5$ GeV, $m_{Q'}/\Lambda' \sim 20$
- $g_{B'D'\Upsilon'(10S)} \sim 27$ **needed** for the resonance (SM value, $g_{BB\Upsilon(4S)} \sim 25$)
- **lattice QCD** can improve our study (ongoing!)
- What happened to the “dark pions” $\pi'(u'\overline{u'})$?

Dark Pion Decays to "Dark Photons"

- Dropped the ′ now except for γ, but these are all dark states





- I designed an experimental proposal to search for this dark photon

- $m_{ADM} = \; m_{B'} \sim \; m_{Q'} \sim 5 \; m_P \sim 5$ GeV

- $\Lambda' \sim m_{\pi'} > 2 \; m_{\gamma'}$ (analogous to QCD)
  (assuming the dark neutral pion $\pi'(u'\overline{u}')$ decays to two dark photons γ')

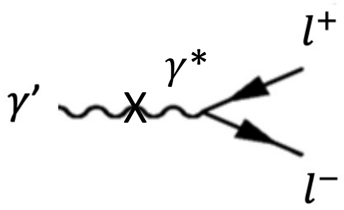
- **The lower the mass of the dark photon is, the more likely one hits the resonance**, since the mass of the dark matter is fixed to around 5 GeV

Dark-Sector Phenomenology
Studying "dark photon" portal

- **"Dark Sector":** DM + "mediators" to SM

$$\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu} + \epsilon e A'^{\mu}J^{EM}_{\mu}$$

kinetic mixing

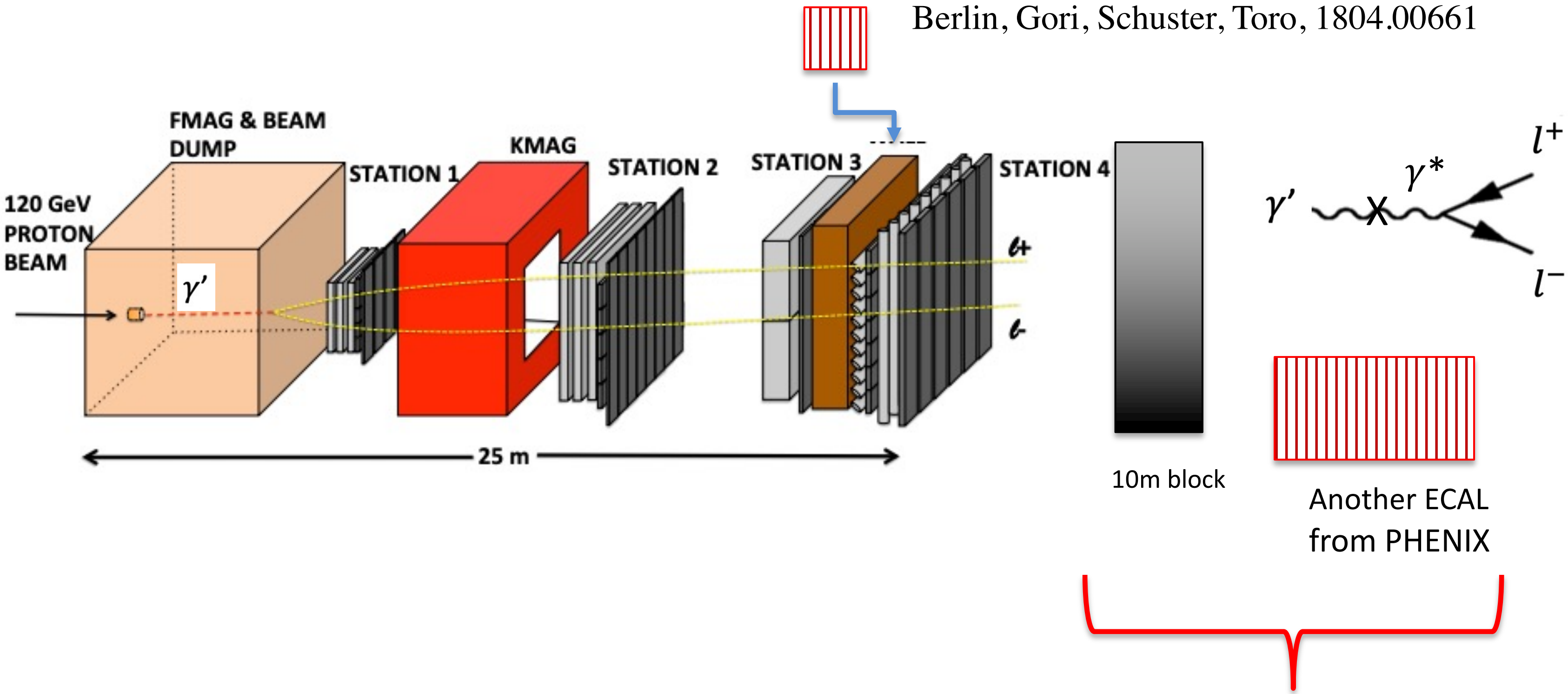


- **One of the three 4-dimentional "portals" to dark sectors**

- **These "portals" help connect dark matter to SM and is essential for GeV or sub-GeV thermal dark matter**
(see, **Lee-Weinberg Theorem**, Lee, Weinberg, PRL 77)

The LongQuest Experiment at Fermilab

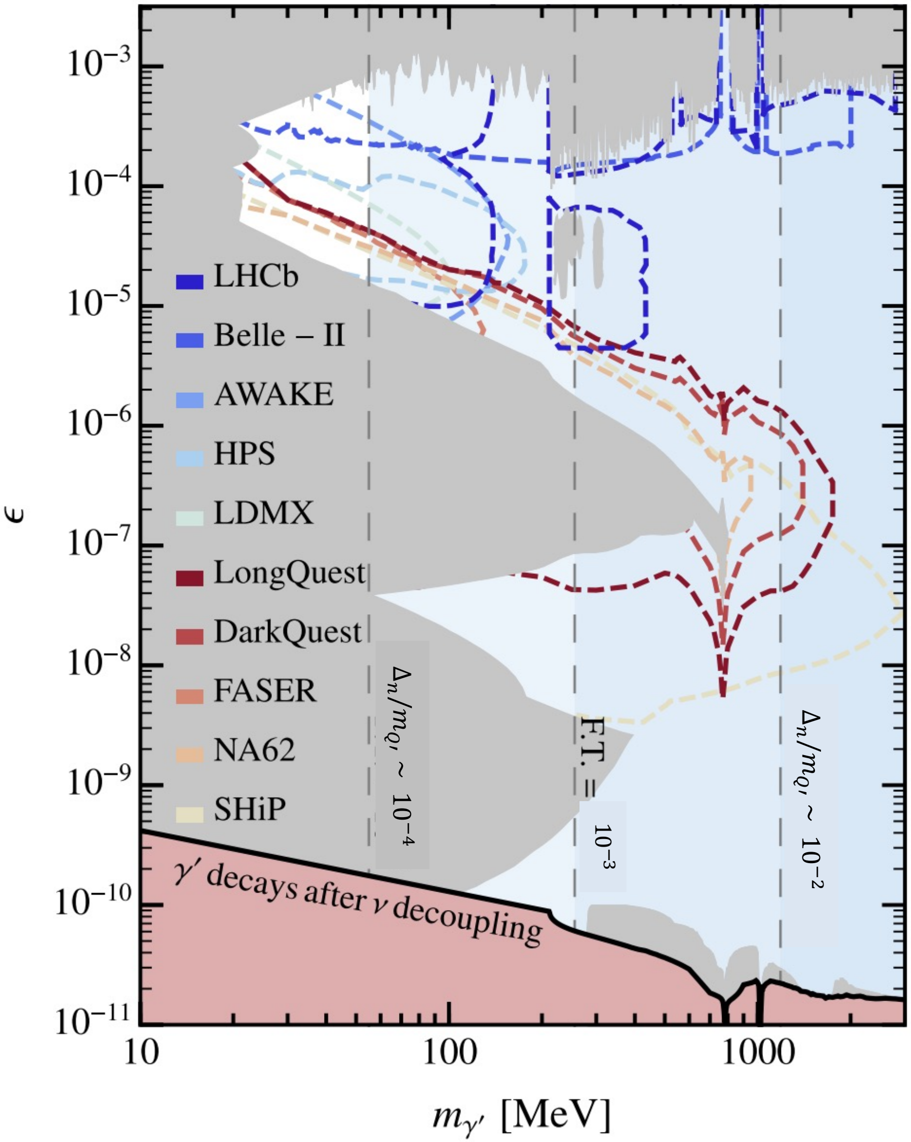
DarkQuest: Install ECAL from PHENIX
Gardner, Holt, Tadepalli,1509.00050
Berlin, Gori, Schuster, Toro, 1804.00661



LongQuest:
Far detectors: **much lower background**; **low cost**
Not interfering with quark study!

LongQuest: **Tsai**, deNiverville, Liu, 1908.07525

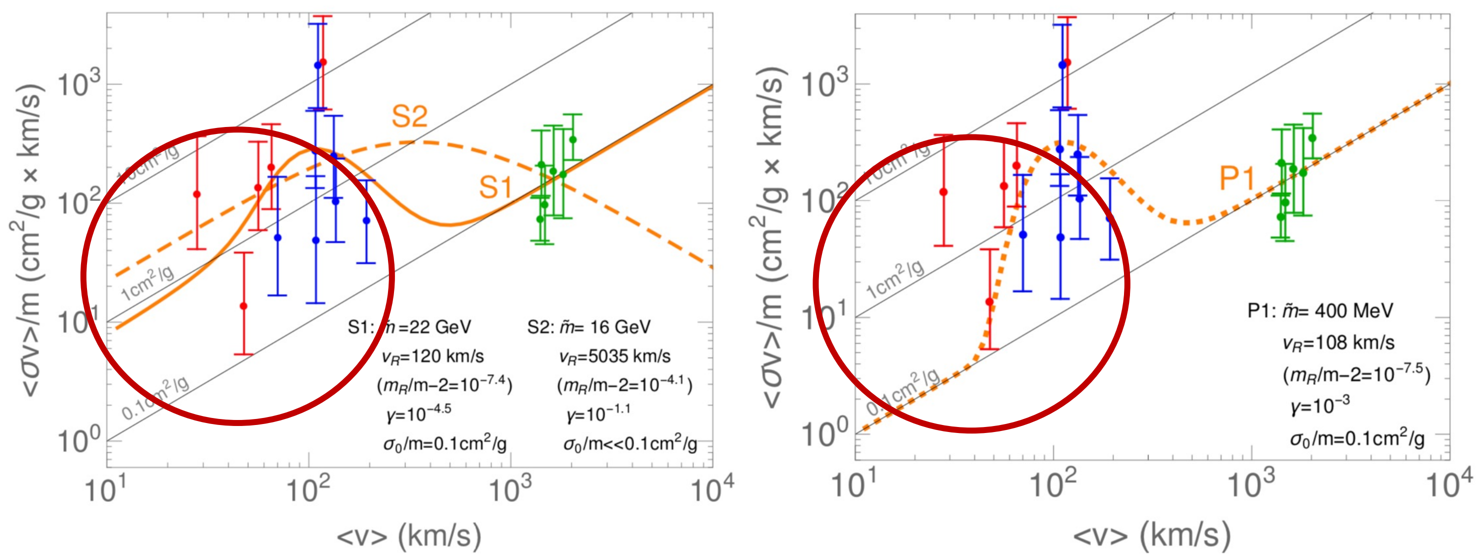
Dark photon for dark pion decay



- $m_{DM} = m_{B'} \sim m_{Q'} \sim 5$ GeV
- $m_{Q'} \sim 5$ GeV
- $m_{Q'}/\Lambda' \sim 20$ is desired
- $\Lambda' \sim m_{\pi'} > 2\, m_{\gamma'}$
- $m_{\gamma'} \sim$ 100 MeV is preferred!
- Kinetic mixing $\epsilon = 10^{-9} - 10^{-3}$

Ongoing Astro Studies

- Astrophysical studies to distinguish the models, and make predictions of the DM halo profile!
  Kaplinghat, Roberts, Valli, **Tsai**, and Yu



Hayashi et al, 2008.02529, PRD 21 suggests that RSIDM could be advantageous for ultrafaint dwarf galaxies (UFD) over other SIDM

Recap: why is this exciting?

- **General scenario** to naturally give the **resonance structure**
- Has interesting structure similar **SM QCD**
- Can easily connect to dark **lattice QCD** study (see, e.g., 1912.06505)
- Has **signatures** that can be searched for in experiments
- **Testable** also in astrophysical studies

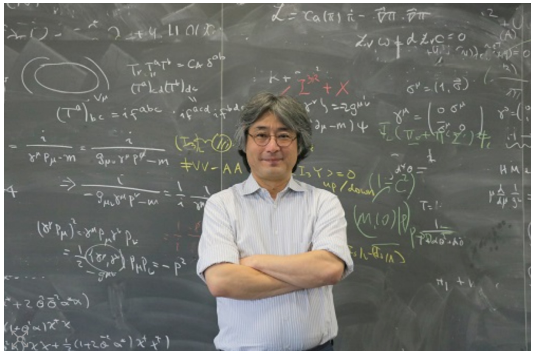
My Research Programs

- Develop **new/testable models**:
  Resonant Dark Matter Models, ELDER / KINDER DM

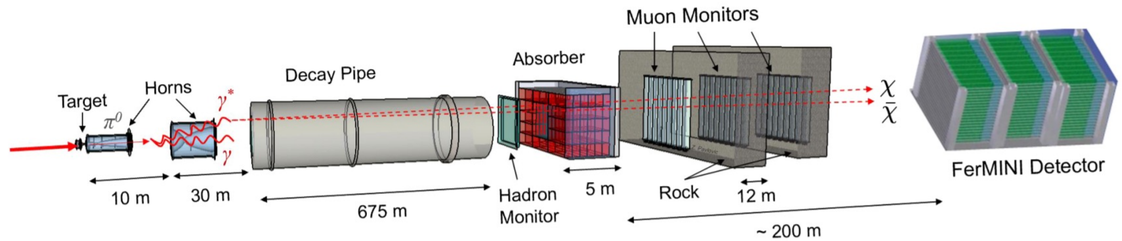
- Design **new experiments**: dark sector & millicharge searches in **accelerators** (also consider **analyses** with existing experiments), that can be applied to search for many attractive DM / new physics candidates
- My experimental proposals: **LongQuest**, **FerMINI**, **FORMOSA** (will talk more in 10 mins discussion!)

- Develop new **cosmology** & **astrophysics** studies:
  DM in neutron star, **GW170817 as PBH event**, and more…

What do I do in **Particle Physics Renaissance**



Hitoshi Murayama By Michael Banks in Tokyo, Japan



An illustration of the FerMINI experiments utilizing the NuMI facility.

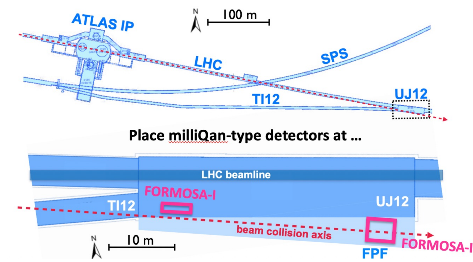
Adapted by Yu-Dai Tsai from Zarko Pavlovic's photo and milliQan detector, 1607.04669 (milliQan col.)

New models and theories

- Learning machine learning on the side

Crab Nebula, NASA, ESA, Hester &. Loll (ASU)

Collaborate with the **experts**



FORMOSA at **LHC**, Foroughi, Kling, **Tsai**

by Chantelauze, Staffi, and Bret

Be creative and make connections between subjects

Let’s find dark matter!

Thank you!

Yu-Dai Tsai, Fermilab, ‘21