Resonant Self-Interacting Dark Meson & The High Energy-Intensity Experiments

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w/ Robert McGehee & Hitoshi Murayama

arXiv:2008.08608 + many other works

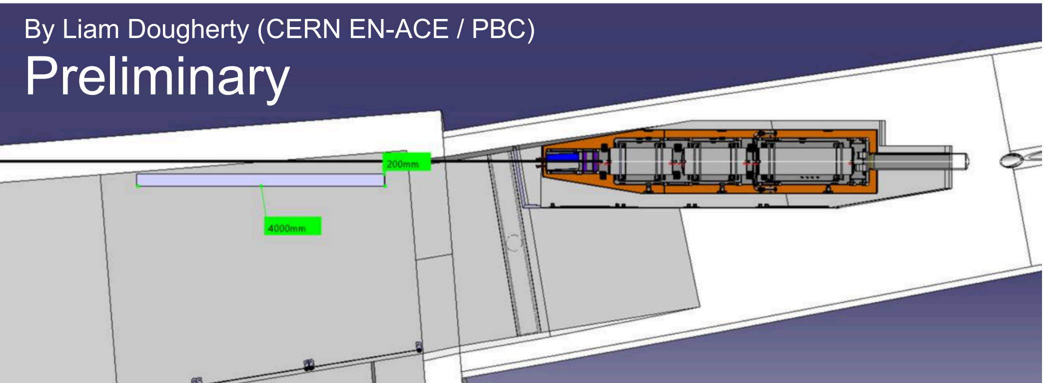
My Research Programs

- Develop **new/testable models**:
  Resonant Dark Matter Models & ELDER/SIMP Dark Matter

- 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
- Experimental proposals: **LongQuest**, **FerMINI**, **FORMOSA**

- Develop new **cosmological** & **astrophysical** studies:
  DM in neutron star, **GW170817 as PBH or DM event**,
  Studying **minor objects (TNO, exoplanets) for ultralight particles**!

FORMOSA may happen SOON

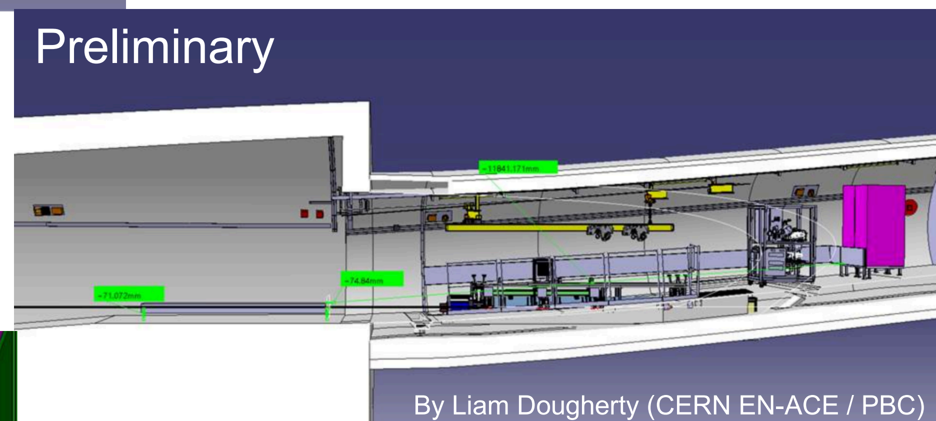


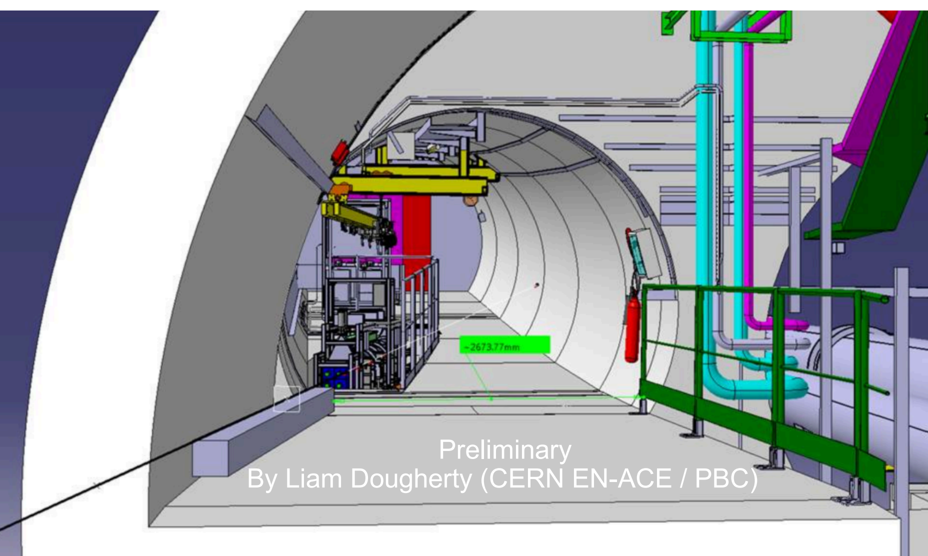
Idea: moving milliQan prototype to the LHC forward region!

Project FORMOSA - FORward MicrOcharge SeArch arXiv:2010.07941

Figures made by Liam Dougherty (CERN EN-ACE / PBC)

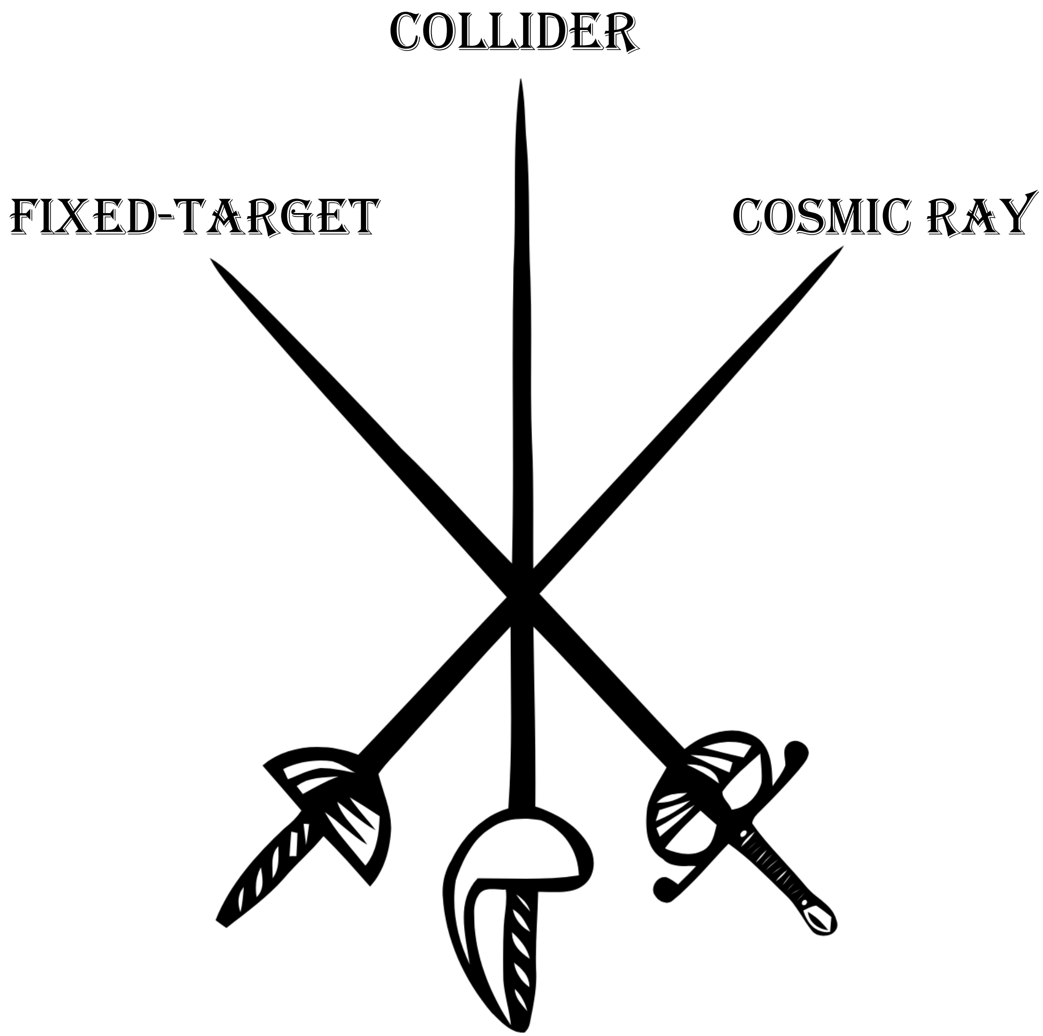
Also thank FASER+ & milliQan collaborations for discussions & J. Feng for communications.





milliQan-Prototype: milliQan Collaboration 2005.06518, new limit established!

FORMOSA: Foroughi-Abari, Kling, **Tsai**, 2010.07941, ***PRL*** reviewing



THE HIGH ENERGY-INTENSITY FRONTIER

Adapted by Yu-Dai Tsai from design of Lou Crazy (remastered by Antonu), CC BY-SA 3.0
https://commons.wikimedia.org/wiki/File:Three-Arms.svg#/media/File:Three-Arms.svg

Focusing on the proton machines at the intersection of high energy & high intensity

Outline

- **Resonant Self-Interacting Dark Matter**
  related to **small-scale structure**,
  quantum chromodynamics (QCD),
  matter-antimatter asymmetry

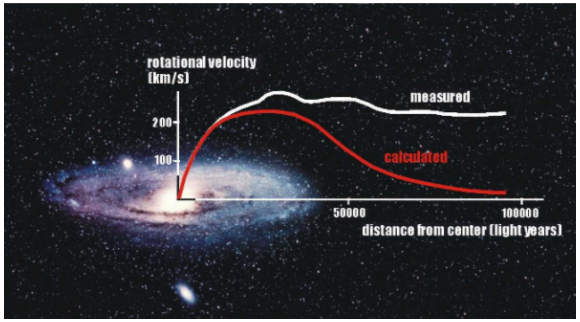
- **Millicharged Particle Searches: Analyses & Experiments I Proposed**
  probing "dark sector", related to
  neutrino experiments & neutrino physics

- **Outlook**

Deep (Independent) Mysteries

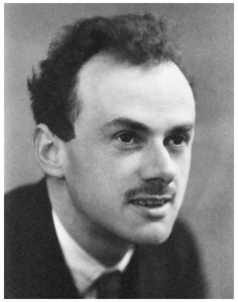
- **What is Dark Matter?**

Vera C. Rubin

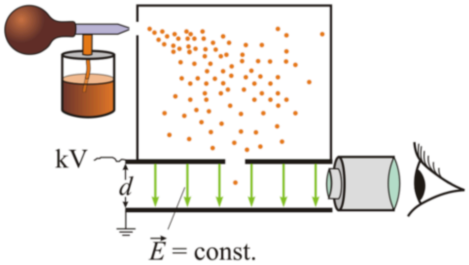


Rotation curves of the Andromeda Galaxy.
Credit: Queens University

- **Charge Quantization?**



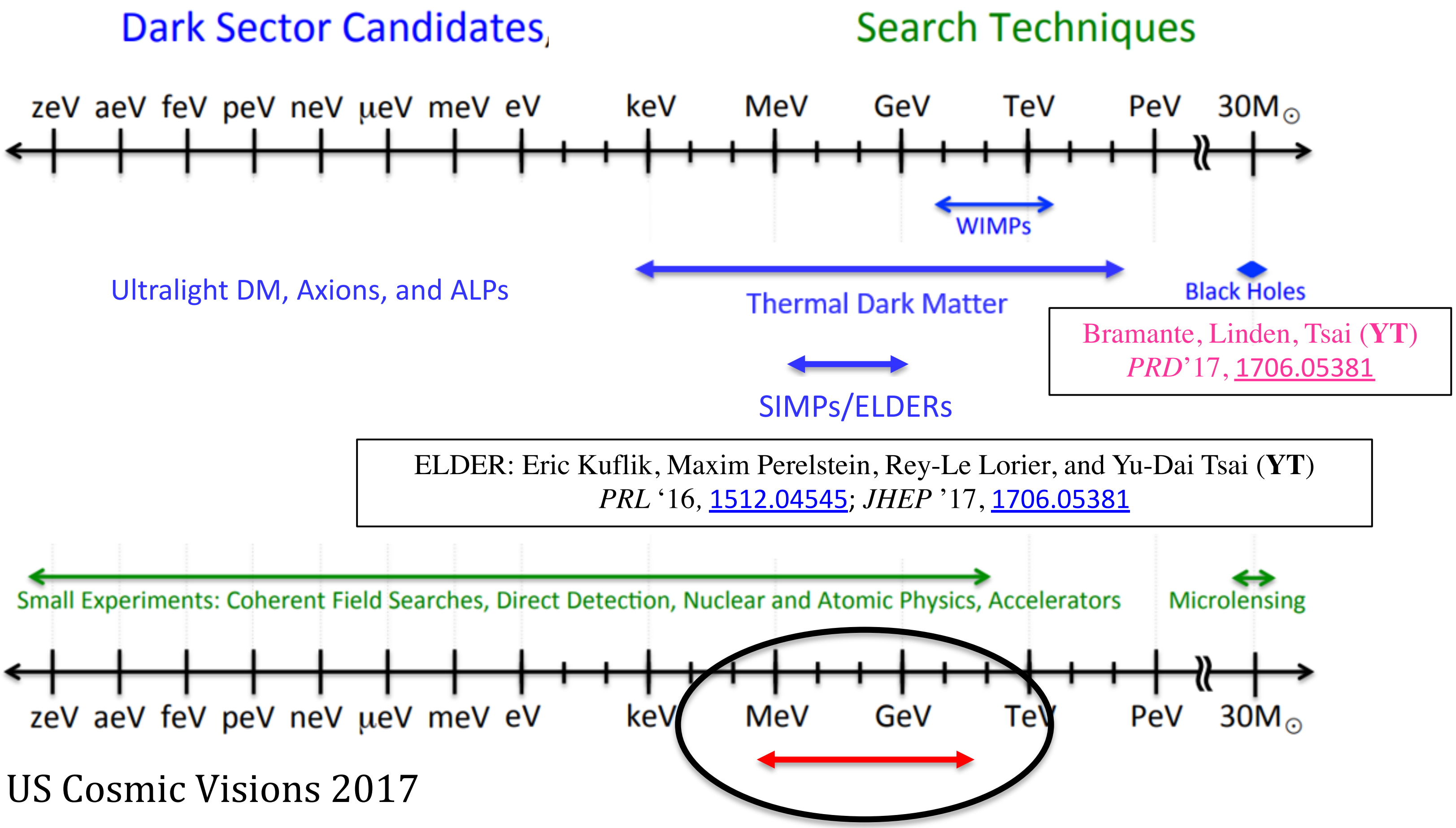
Paul Dirac



Millikan's oil drop experiment
Depicted by Theresa Knott

- **Neutrino Mass & Interactions**

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**)

Discoveries Grow from Anomalies (~~Systematics~~)

Focusing on MeV – GeV+ Dark Matter

Yu-Dai Tsai, Fermilab, 2021

Some anomalies involving **MeV - GeV+** Explanations

⋮

- **EDGES result**
- **Muon g-2 anomaly (April 7th!)**
- **LSND & MiniBooNE anomaly**
- **KOTO anomaly**

⋮

Below ~ MeV there are also **strong astrophysical/cosmological bounds** that are hard to avoid even with very relaxed assumptions

ν Hopes for New Physics

- **EDGES 21-cm absorption spectrum anomaly**

- Millicharged Particles in Neutrino Experiments, Magill, Plestid, Pospelov & **Tsai**, PRL ‘19, 1806.03310
- Cosmic-ray produced MCP in neutrino observatories, 2002.11732, PRD ‘20

- **Muon g-2 Anomaly**

- Dark Photon, Inelastic Dark Matter, and Muon g-2 Windows in CHARM, NuCal, NA62, SeaQuest, and LongQuest, **Tsai**, de Niverville, Liu, 1908.07525
- Light Scalar & Dark Photon at Borexino & LSND, Pospelov, **Tsai**, PLB ‘18, 1706.00424 (related to proton radius anomaly)

⋮

New Physics from Anomalies?

⋮

Journey to study these scenarios

- **LSND/MiniBooNE Anomalies**

- Dipole Portal Heavy Neutral Lepton,

  Magill, Plestid, Pospelov, **Tsai**, *PRD* '18, 1803.03262

- Dark Neutrino at Scattering Experiments: CHARM-II & MINERvA

  Argüelles, Hostert, **Tsai**, *PRL '20*, 1812.08768

- **What have we really learned from anomalies?**

  Dark Matter (& Neutrino)!

⋮

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

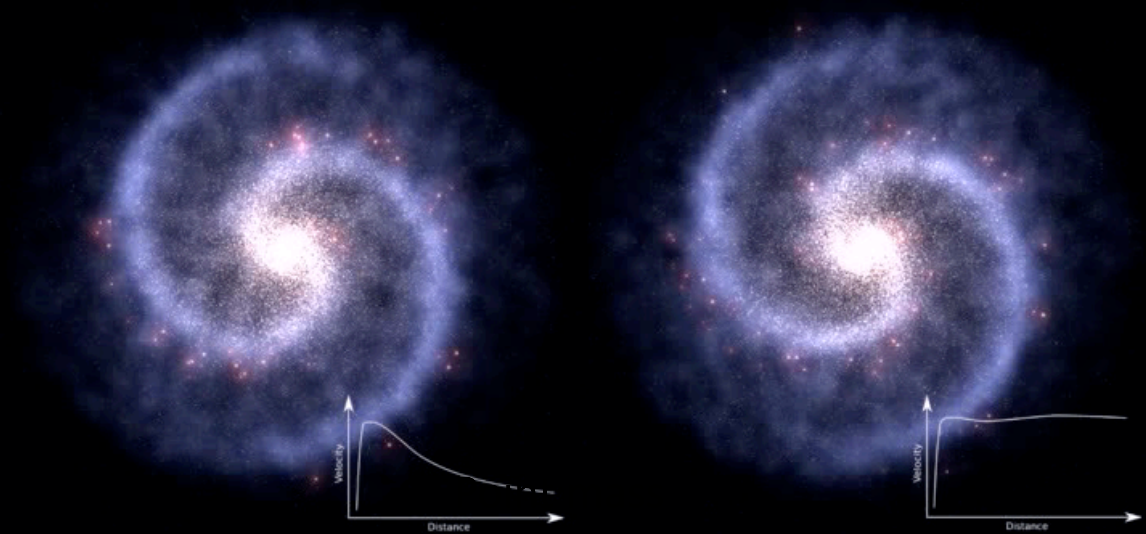
Overwhelming
Observational
Astrophysical + Cosmological
Evidences

Dark Matter Properties?

- Galactic Rotation Curves
  -> Small-Scale Structure Study
  -> Hints of Dark-Matter Self Interactions?

- Cosmic Microwave Background (CMB)
  -> Absorption Spectrum
  -> millicharge Dark Matter?

Galactic Rotation Curves



From: https://en.wikipedia.org/wiki/File:Galaxy_rotation_under_the_influence_of_dark_matter.ogv
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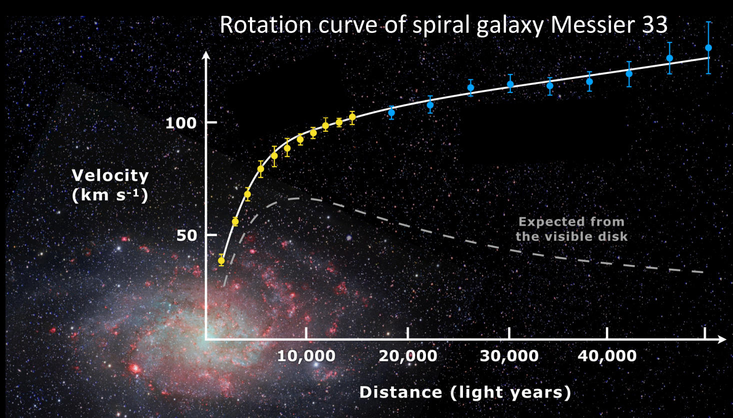


Mario De Leo-Winkler (University of California, Riverside)

Homework: Newtonian Physics Examples

$$v_c(r) = \left(\frac{GM}{r}\right)^{\frac{1}{2}}$$

Point mass M

$$v_c = \left(\frac{4\pi G\rho}{3}\right)^{\frac{1}{2}} r.$$

Constant Density ρ

Can determine the density profile ρ(r) from v_c(r)

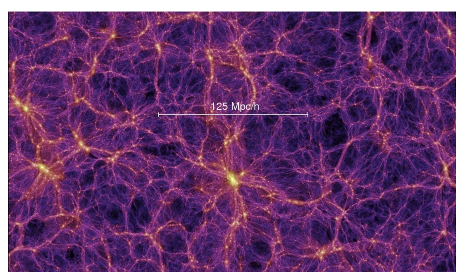
“Small-Scale” Structure of the Universe

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

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

Magnifying glass on Small-Scale Structure leads to "Problems"

- **Core vs cusp**
- Too big to fail
- Missing satellite
- Diversity problem


by Lynette Cook/science Photo Library

Some problems in these systems are now **better resolved**

through consideration of **baryonic feedback** or new & updated observations.

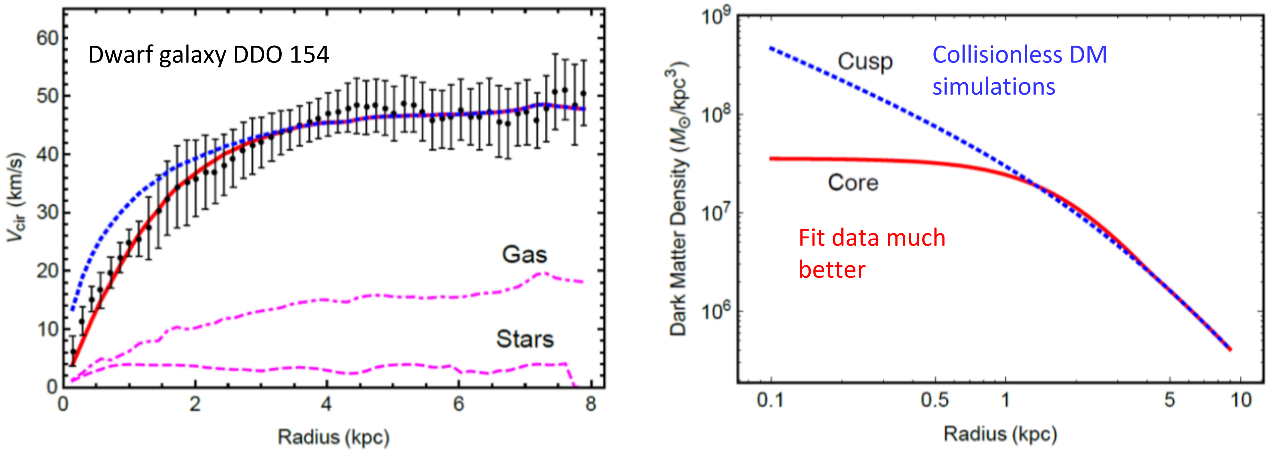
See, e.g., a review by Tulin & Yu, arXiv:1705.02358

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 galactic center

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

Why do I study potential DM solution to

- Small-scale structure "problems"?
- **Small-scale structure opportunities!**
- We have almost no idea about the nature of DM

  (Like in a true detective: all potential evidences of the crime should be investigated)

  SIDM are CDM in large scale. Why assume DM self collision-less?
- **Small-scale structure may be one of the very few places that we can learn the properties of DM**
- Cluster & galaxy provide interesting **self-interacting constraints**!

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!)

Theme of this talk:

Connecting **Dark Matter** to **Standard Model**

Consider **observation, theory, and experiments**

Finding the **most promising testable DM**

Please remind me if there are missing reference, as the literature is fast growing

Self-Interacting Dark Matter (SIDM)

Small-Scale Structure Opportunity!
Resonant Self-Interacting Dark Meson (my work)

DM Self-Interaction

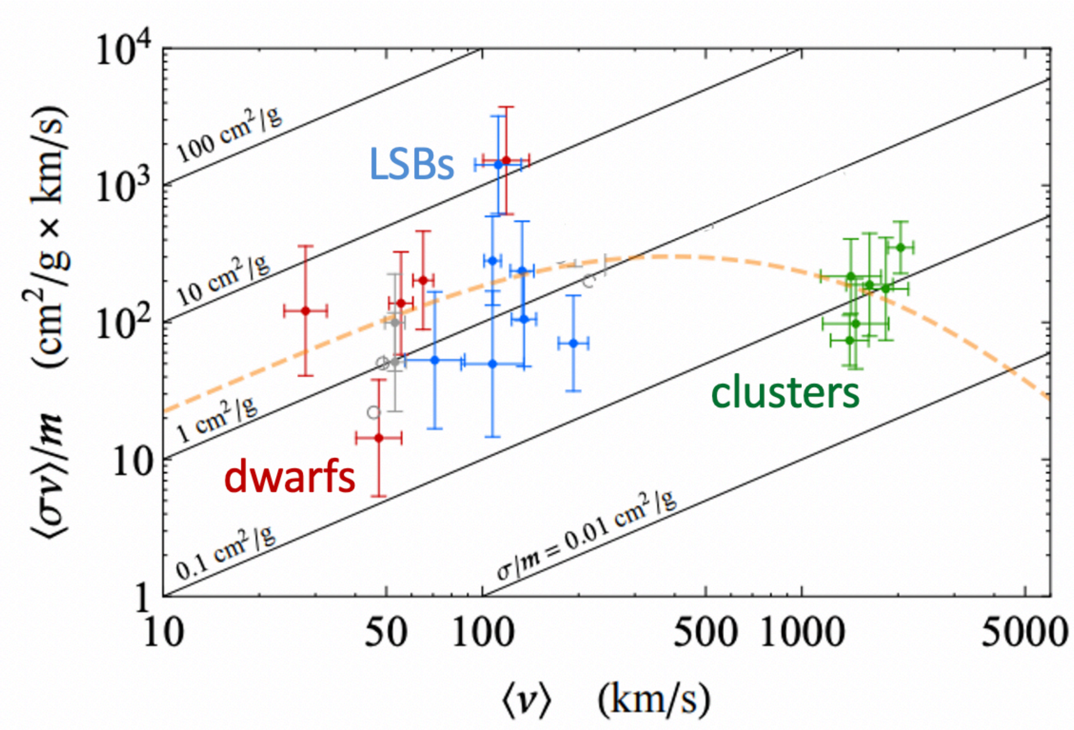
Self-Interacting DM (SIDM), Spergel & Steinhardt '99 + …:

DM collisions thermalize the DM particles in inner halo & smoothen ("core") the distribution

Halo profiles are thus related to the velocity-averaged scattering cross section per unit of DM mass, $\langle \sigma v \rangle / m$.

- v is the relative velocity between DM particles and <...> denotes averaging over a distribution.
- In **dwarf galaxies** typical velocity is **20 km/s** whereas in **clusters of galaxies** typical velocity is **2000 km/s**.

Velocity Dependence



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

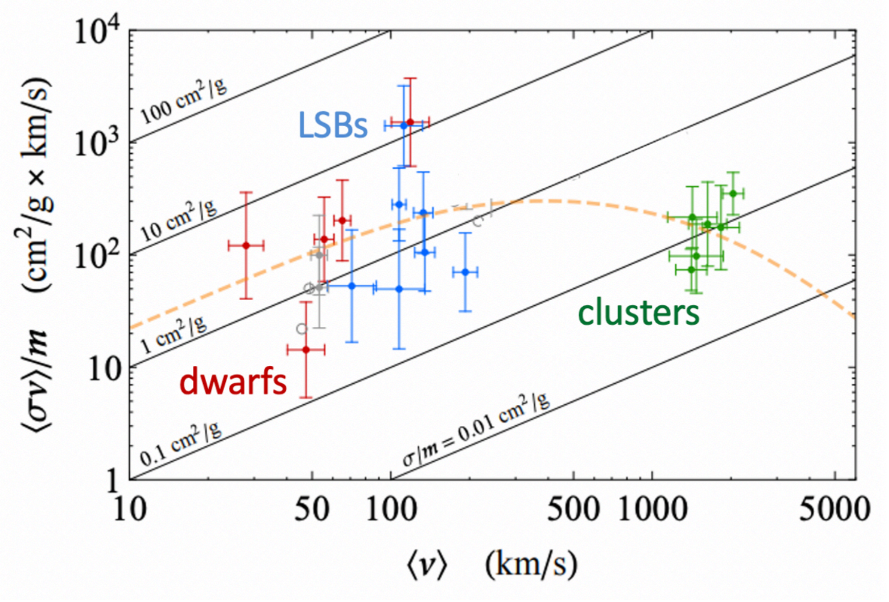
ρ is the density, r_1 is the "scattered radius"

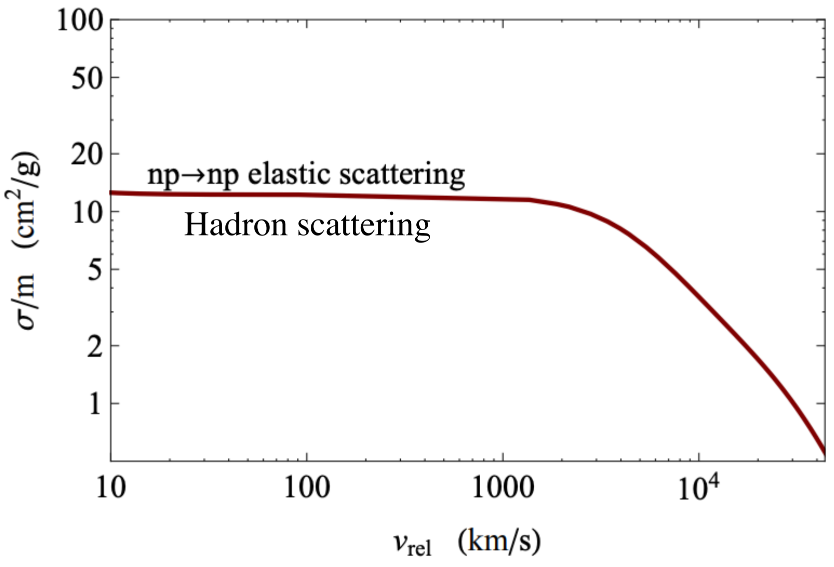
Semi-analytically "Calculate" the profile based on different <σ v> / m, and then match the profiles to the data

Kaplinghat, Tulin, Yu, arXiv:1508.03339

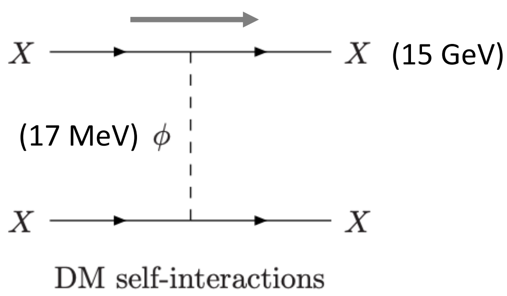
- LSBs: low surface brightness spiral galaxies
- Diagonal lines are contours of constant σ/m .
- **Horizontal line would be σ ∝ 1/v**
- **DM self-interaction prefers VELOCITY DEPENDENCE!**
- At least we learn velocity dependent constraints on cross-sections

Extra Fun: Similarity to Standard Model





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



Kaplinghat, Tulin, Yu, arXiv:1508.03339

- **DM self-interaction** vs **SM hadron interaction**
- Similar size of cross-section

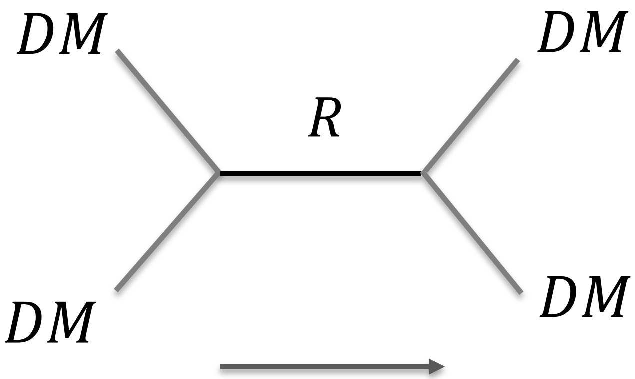
Resonant Self-Interacting Dark Meson (RSIDM)

Tsai, McGehee, Murayama,

arXiv:2008.08608, submitted to *PRL*

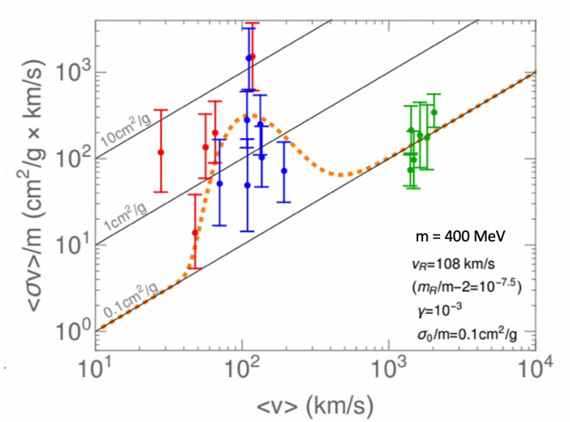
A solution to small-scale structure problems
and have interesting experimental signatures
Can be tested in near future

Resonant SIDM



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

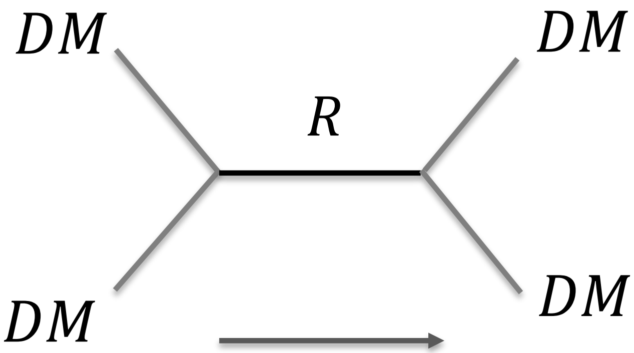
- Δ is small and positive for this talk.



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**, + 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

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

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

kinetic energy

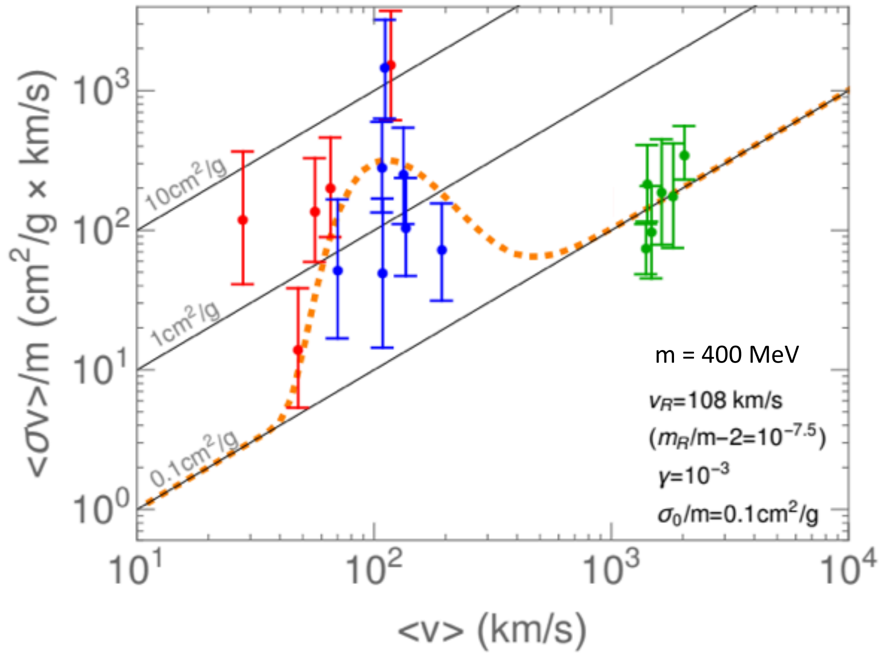
symmetry factor

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

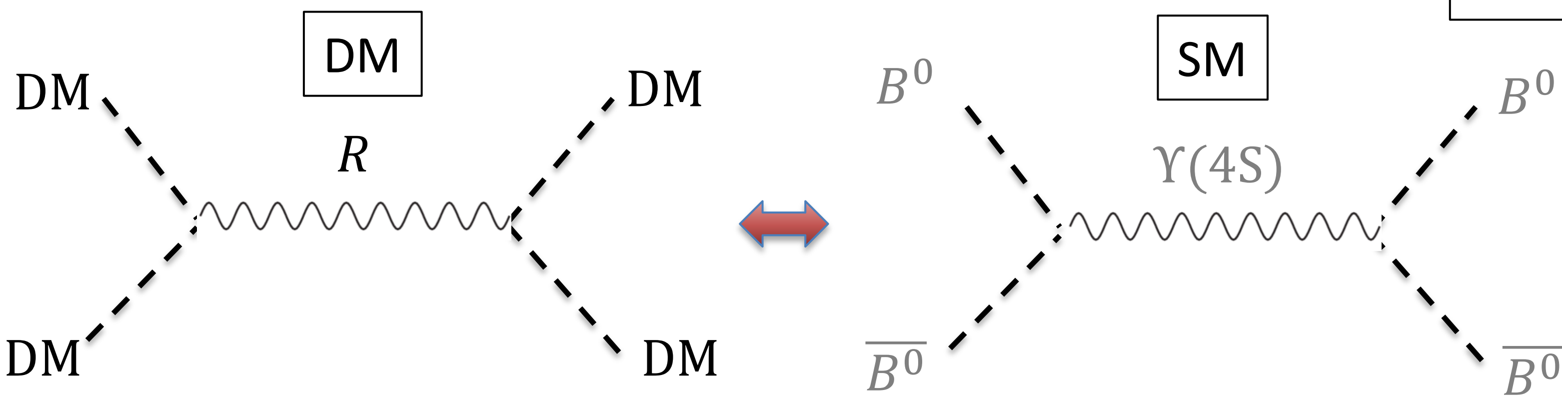
"resonance condition": the collision hits the resonance when $v = v_R$

The width $\Gamma(v) = m_R \gamma v^{2L+1}$. $\langle \sigma v \rangle = \int_0^{v_{\rm max}} f(v, v_0) \sigma v dv$, $f(v, v_0) = \frac{4v^2 e^{-v^2/v_0^2}}{\sqrt{\pi} v_0^3}$.

Resonant SIDM: **Vector Resonance**



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



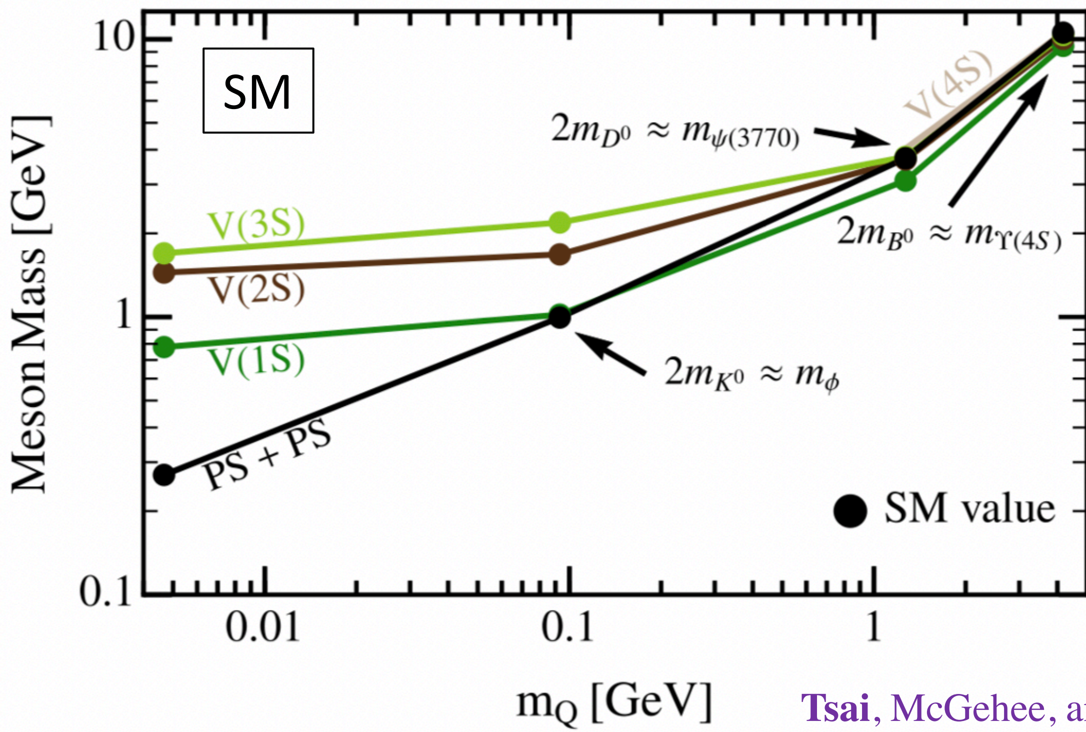
Tsai, McGehee, Murayama, arXiv:2008.08608

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.
- 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.

Other SM Resonances

$$\frac{m(^8\mathrm{Be}) - 2m(\alpha)}{m(^8\mathrm{Be})} = 0.000012,$$

$$\frac{m(^{12}\mathrm{C}^*) - m(^8\mathrm{Be}) - m(\alpha)}{m(^{12}\mathrm{C}^*)} = 0.000026.$$

Triple-alpha Process

$$\frac{m(\phi) - 2m(K^0)}{m(\phi)} = 0.024,$$

$$\frac{m(D^{0*}) - m(D^0) - m(\pi^0)}{m(D^{0*})} = 0.0035,$$

$$\frac{m(B_{s1}) - m(B^*) - m(K^0)}{m(B_{s1})} = 0.0011,$$

$$\frac{m(\Upsilon(4S)) - 2m(B^0)}{m(\Upsilon(4S))} = 0.0019.$$

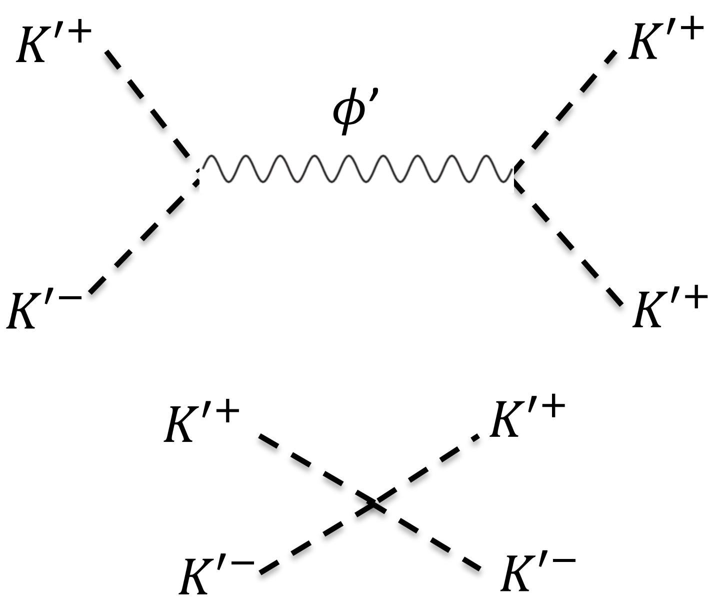
- **Triple-alpha process**: the resonance can be explained by **anthropic principle**, see, e.g. J. D. Barrow and F. J. Tipler, The Anthropic Cosmological Principle. 1988.
- First predicted by Fred Hoyle, for carbon to be formed in stars for proper **stellar nucleosynthesis.**
- The Be-8 ground state has almost exactly the energy of two alpha particles., 8Be + 4He has almost exactly the energy of an excited state of 12C. (7.66 MeV 0+ excited state of 12 C),
- Increases the probability that an incoming alpha particle will combine with beryllium-8 to form carbon.

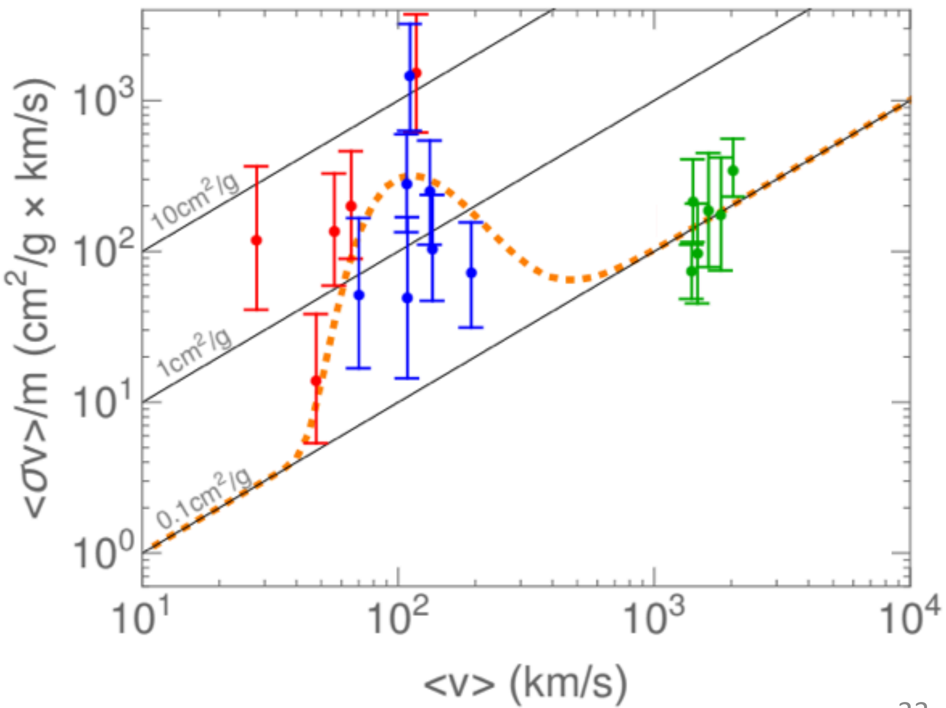
I. Dark Kaon / Light-Quark Model

From now on, all the meson labels are for dark matter particles unless otherwise stated

Resonant Self-Interaction Dark Meson

- Analogy: $K'^{\pm} \sim K^{\pm}$, ϕ' $(s'\bar{s}') \sim \phi(s\bar{s})$
- Consider $m_{DM} \sim$ GeV . $g_{\phi' K'^+ K'^-} \sim g_{\phi K^+ K^-}$.
- m_{DM} is around 1 GeV





I. Dark Kaon/Light-Quark Model

DM

We define $U = e^{2i\Pi/f_K}$, $\Pi = K^a T^a = \frac{1}{2}K^a\tau^a$, $2\mathrm{Tr}(\Pi^2) = K^a K^a$, f_K is the dark kaon decay constant. First, consider the non-derivative couplings. The relevant Chiral Lagrangian terms are:

$$\mathcal{L} = \frac{1}{2}\frac{m_K^2 f_K^2}{m_u + m_s}\mathrm{Tr}\left[U^\dagger \begin{pmatrix} m_u & 0 \\ 0 & m_s \end{pmatrix} + \begin{pmatrix} m_u & 0 \\ 0 & m_s \end{pmatrix} U\right] \tag{7}$$

$$\supset -m_K^2 K^+ K^- + \frac{m_K^2}{6 f_K^2}\left(K^+ K^-\right)^2 \tag{8}$$

The relevant derivative couplings are

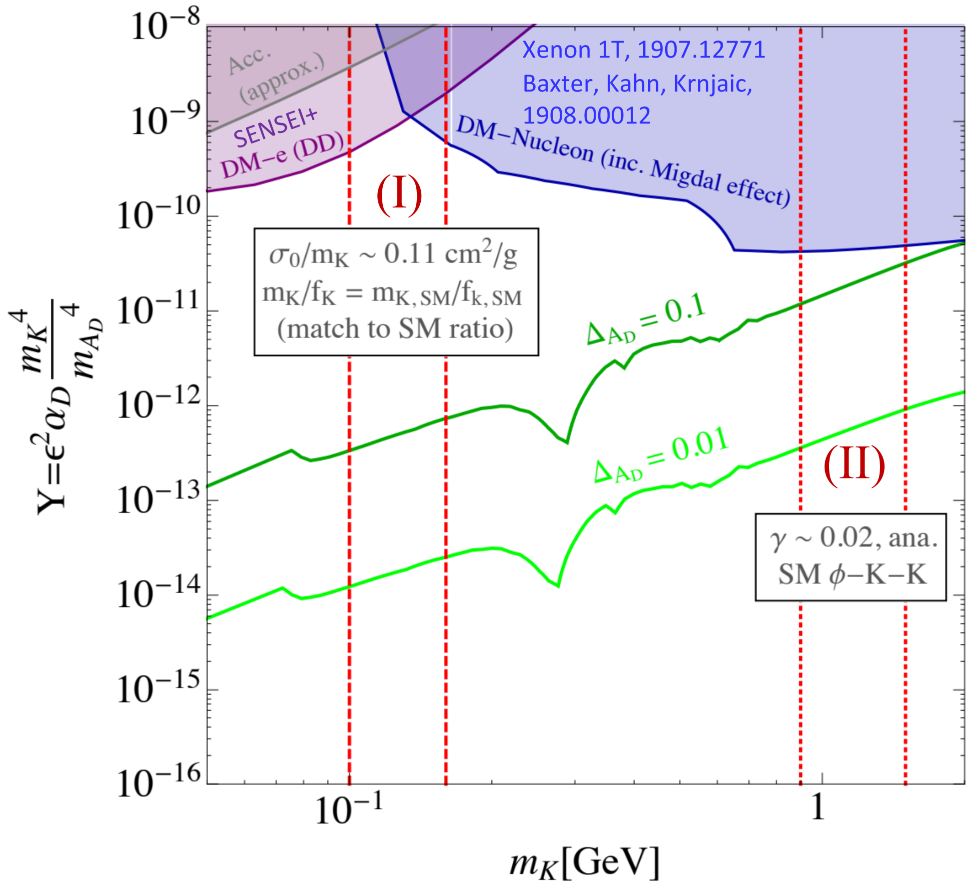
$$\mathcal{L} = \frac{{f_K}^2}{4}\mathrm{Tr}\partial_\mu U^\dagger \partial^\mu U \tag{9}$$

$$= \partial_\mu K^+ \partial^\mu K^- - \frac{2{m_K}^2}{3{f_K}^2}(K^+K^-)^2 - \frac{1}{2{f_K}^2}\left(K^+K^-\right)\partial_\mu\partial^\mu\left(K^+K^-\right) + O\left(K^6\right)$$

- 2 flavor, $m_u << m_s$

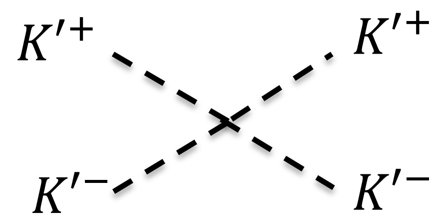
Dark Kaon Model Parameter Space

(0): Resonance condition to get the correct velocity depedence



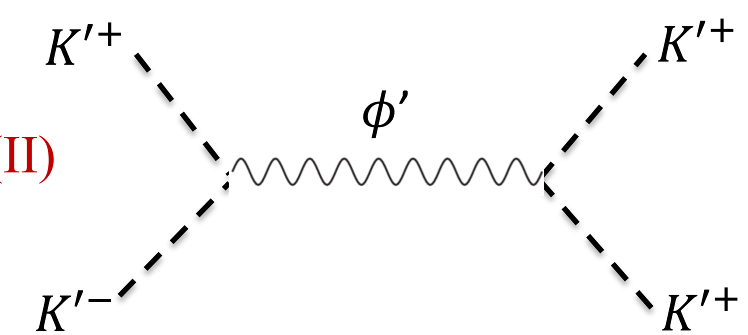
Y. -D.Tsai, R. McGehee, and H. Murayama, arXiv:2008.08608

(I)



$\sigma' / m_{K'} = \sigma_{K,SM} / m_{K,SM}$

(II)



$\gamma = g^2_{KK\phi,SM} / (384\,\pi)$

$g' = g_{SM}$

Simple Freeze-Out Mechnism

Two quark flavor, u and s

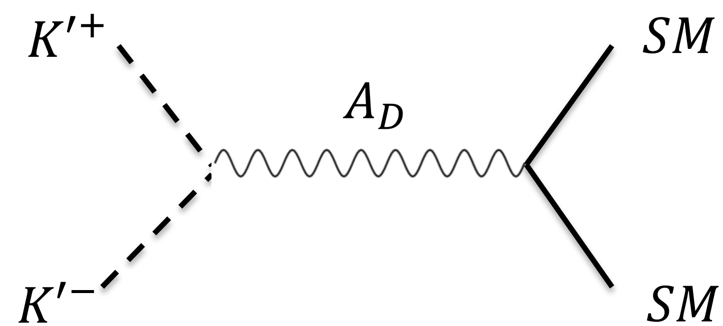
QCD-like gauge theory $SU(3)_D$

dark $U(1)_D$

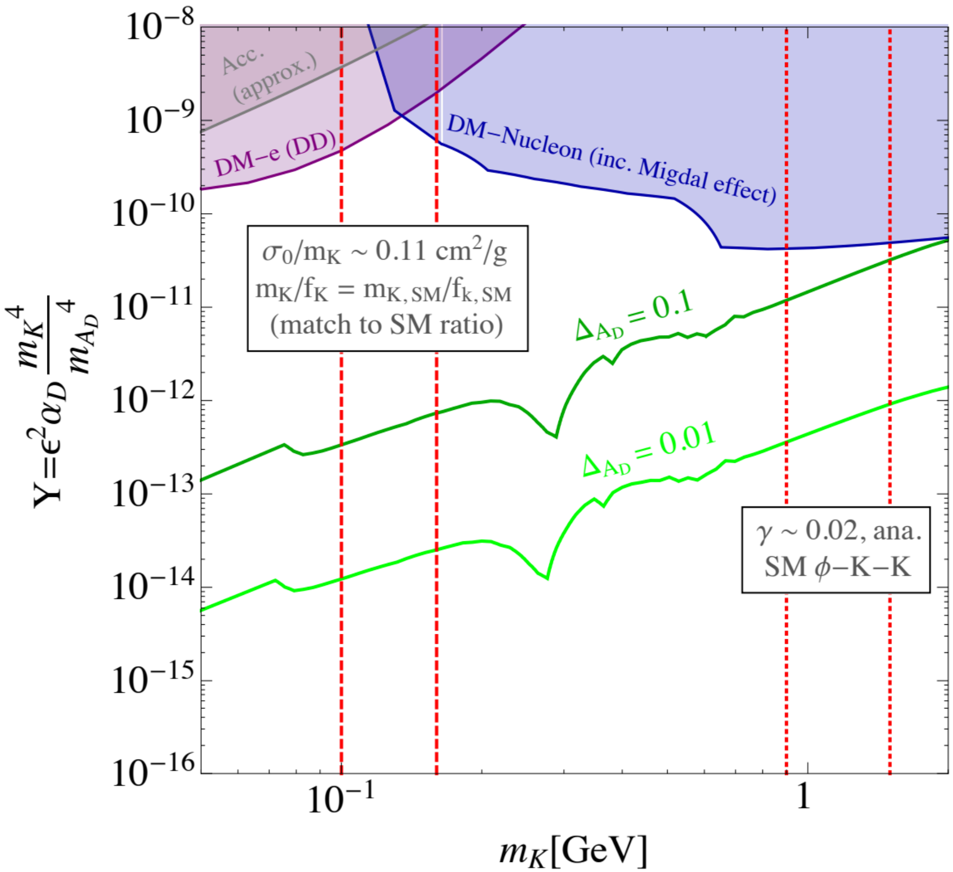
$u(+1)$ and $s(0)$

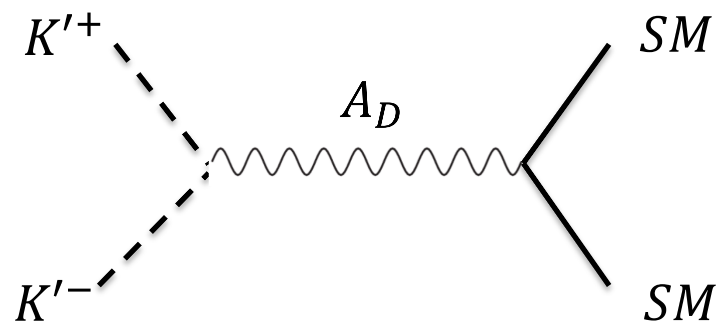
between $U(1)_D$ and $U(1)_{\mathrm{EM}}$

$\mathcal{L} \supset 1/2 \cdot \epsilon F_{\mu\nu} F_D^{\mu\nu}$.



Dark kaon model freeze-out through dark photon





$$K^+K^- \to A_D \to \text{SM}.$$

$$\Delta_{A_D} =$$

$$(m_{A_D}^2 - 4m_{\text{DM}}^2)/4m_{\text{DM}}^2 = 0.1 \text{ and } 0.01$$

Feng, Smolinsky, arXiv:1707.03835

Y. -D. Tsai, R. McGehee, and H. Murayama, arXiv:2008.08608

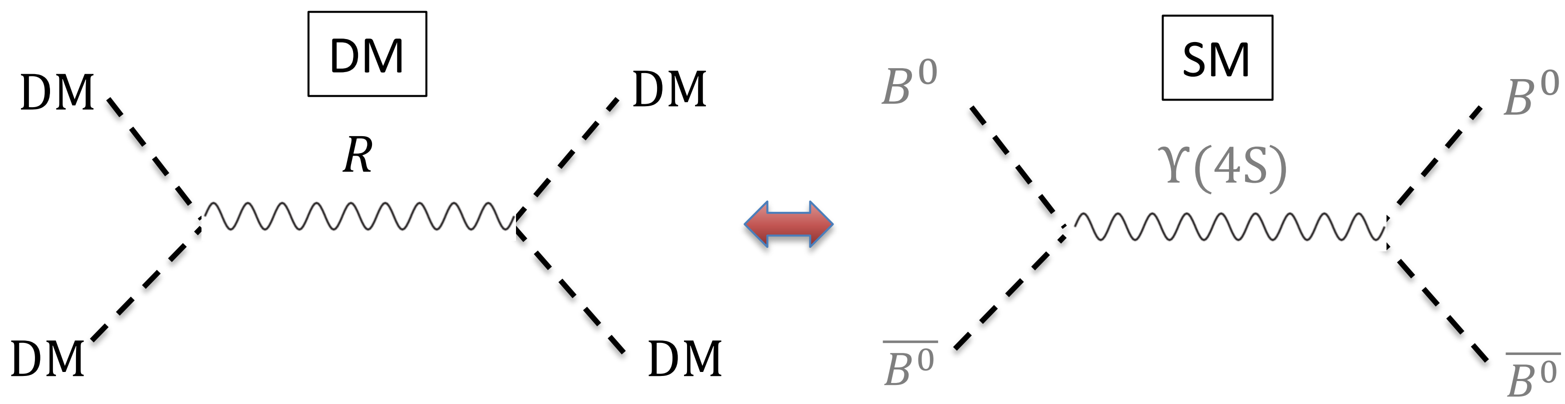
(II) Asymmetric Resonant Dark Mesons

An asymmetric DM model

Connecting DM mystery to SM mystery

Resonant Dark Meson

Model Strategy: linking DM to SM



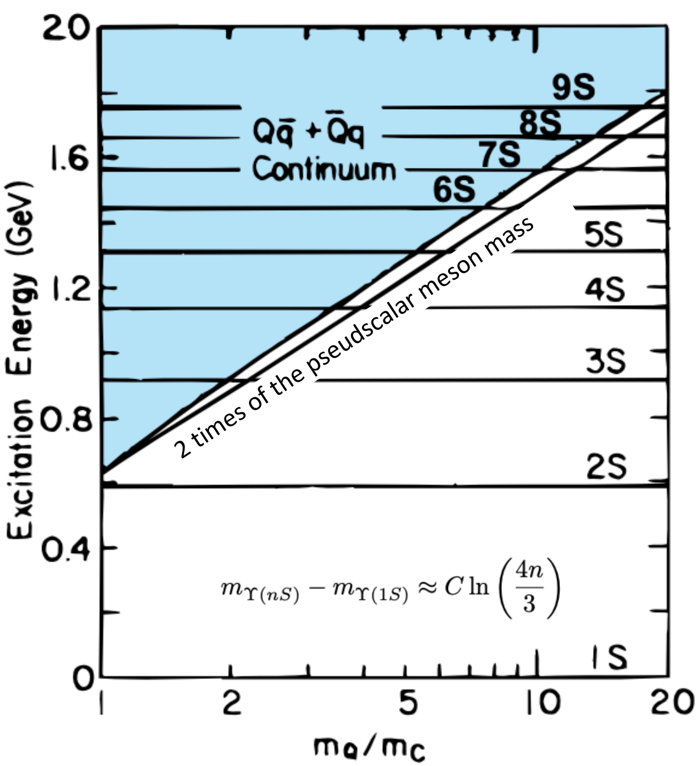
What we learn from SM?

- 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 $(b\bar{b})$

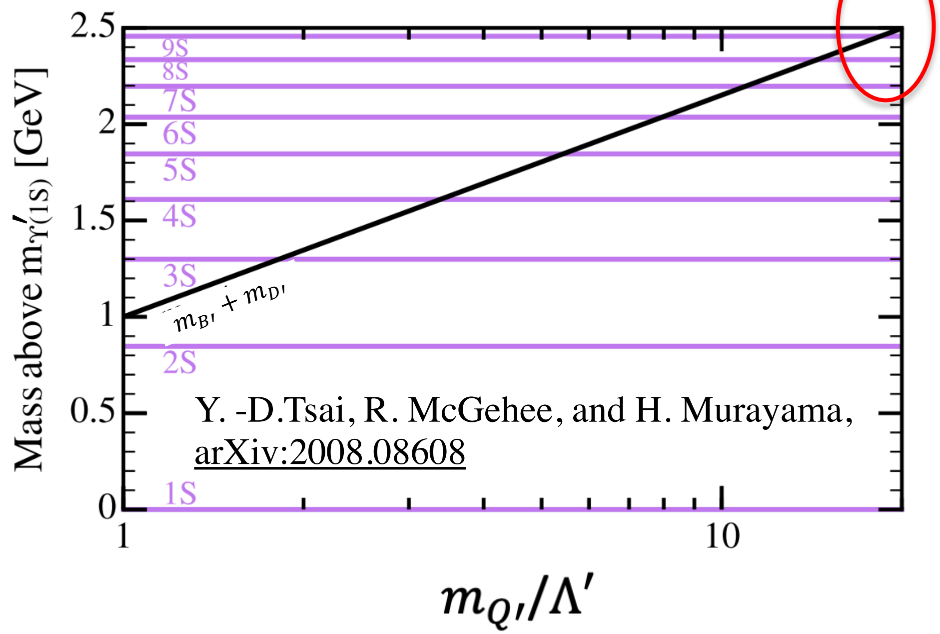
Heavy-Quark Mesons: SM vs DM

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

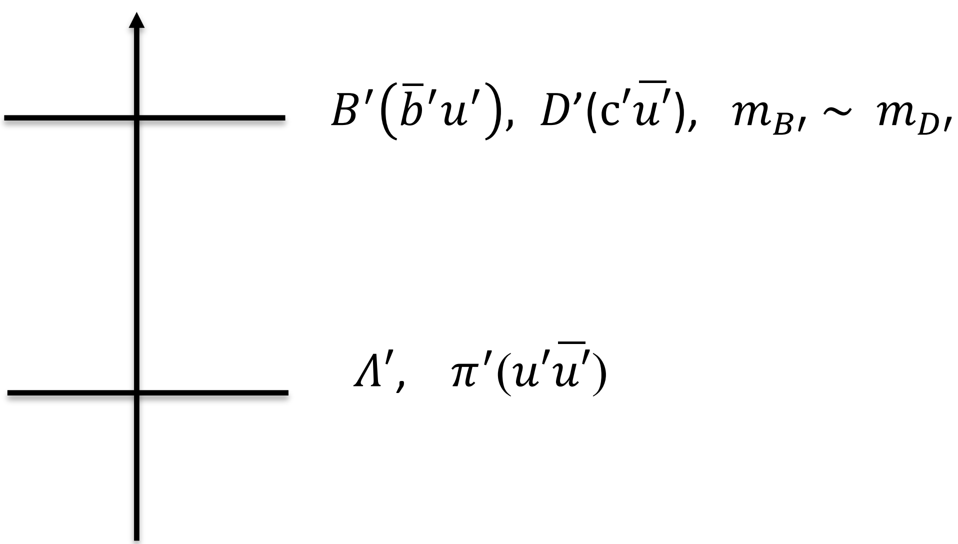
- The "**close-to-resonance-ness**", $\Delta_n/m_{Q'} \sim n^{-3}$. The smaller this is the easier to hit the resonance
- We want $m_{Q'}/\Lambda' > 20$ to go to large n state.
- With n = 10, $\Delta_n/m_{Q'} \sim 10^{-3}$.

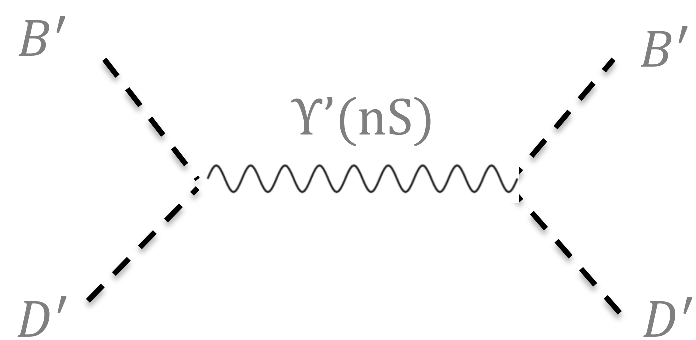
Asymmetric Dark Mesons: Ingredients

$'$ 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 $D'(c'\bar{u}')$, 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 ($\bar{b}'c'$)

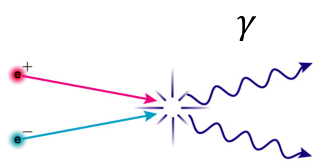
Asymmetric Dark Matter (ADM)

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

Asymmetric DM model | **SM asymmetry**

Net Number of DM’s **~** Net Number of Matter

Assume similar origins



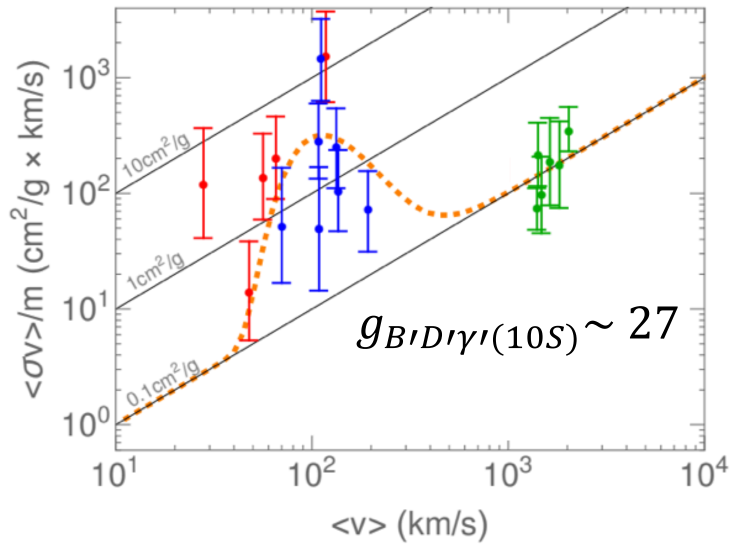
Matter-antimatter annhilation
By Imamura (U Oregon)
https://pages.uoregon.edu/imamura/122/lecture-6/nuclear.html

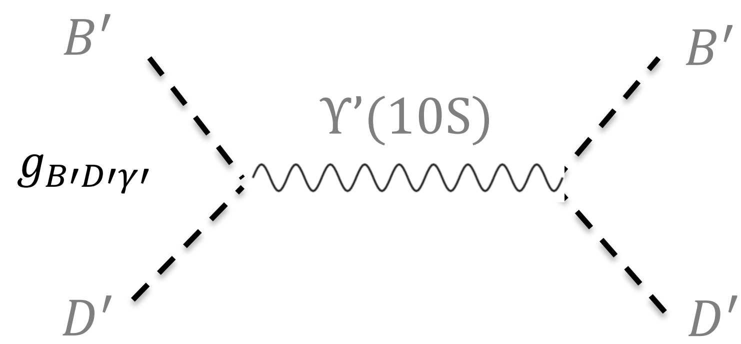
- **Asymmetry will set the number density of the DM.**
- Because DM mass abundance is ~ 5 times more than that of SM
  DM mass is ~ 5 times of SM particle mass!

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

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

Asymmetric Dark Matter Parameter





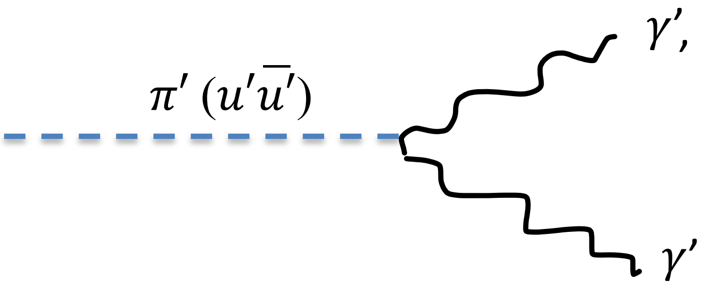
Tsai, McGehee, and Murayama, arXiv:2008.08608
Details left out. See the paper.

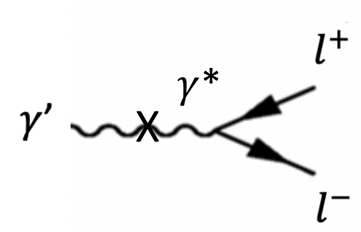
Interesting Parameter that everything works:

- $m_{B'} = m_{D'} = m_{ADM} \sim 5$ 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')

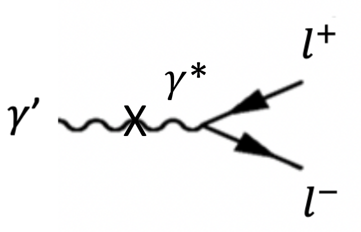
- **The lower the mass of the dark photon is, the more likely one hits the resonance**, since the mass of the dark matter is fixed to around 5 GeV

Dark-Sector Phenomenology
Studying "dark photon" portal

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

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

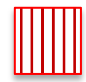
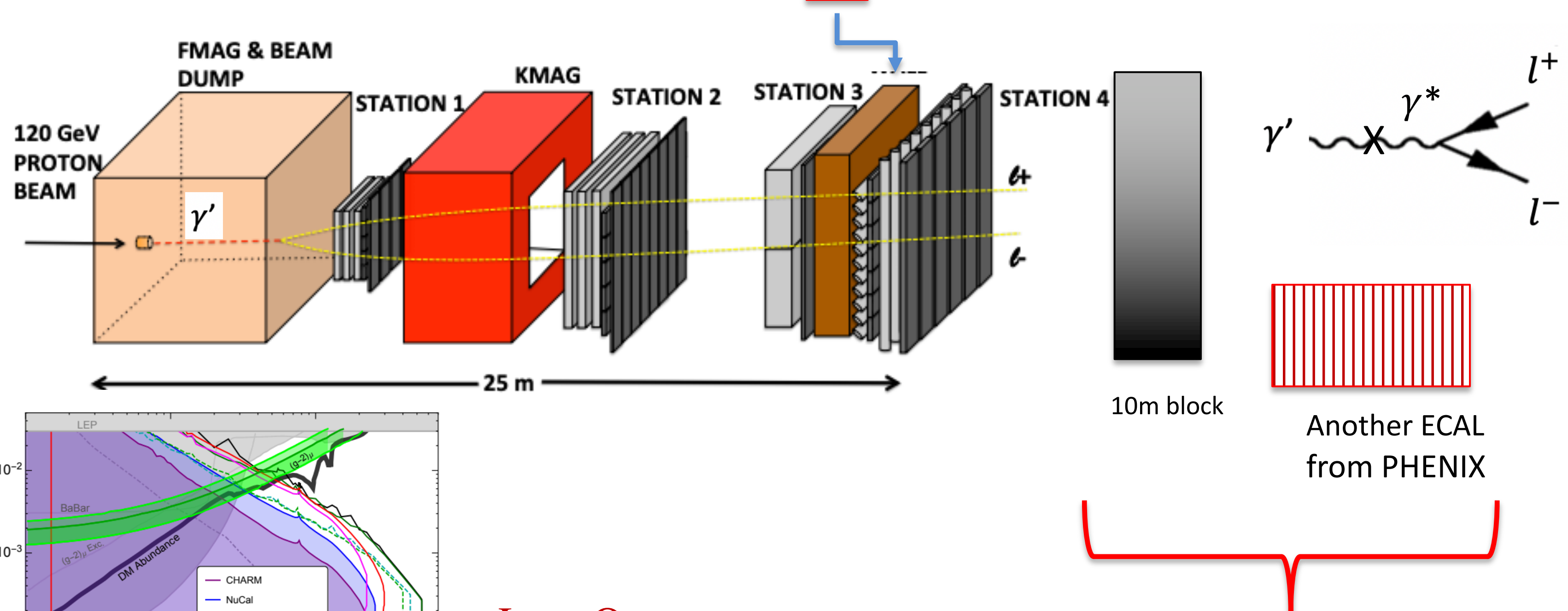
kinetic mixing

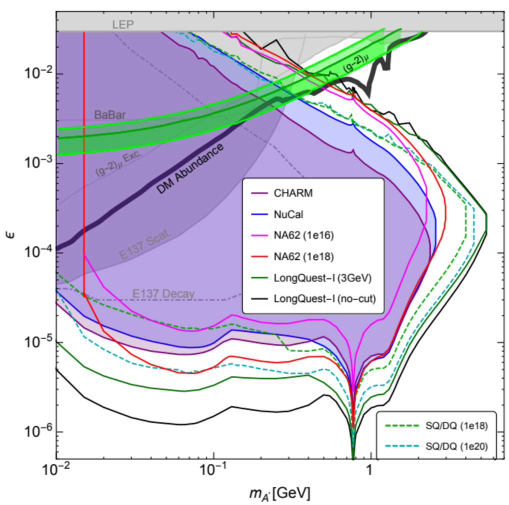


- **One of the three 4-dimentional "portals" to dark sectors**
- **These "portals" help connect dark matter to SM and is essential for GeV or sub-GeV thermal dark matter** (see, **Lee-Weinberg Theorem**, Lee, Weinberg, PRL 77)

The LongQuest Experiment at Fermilab

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



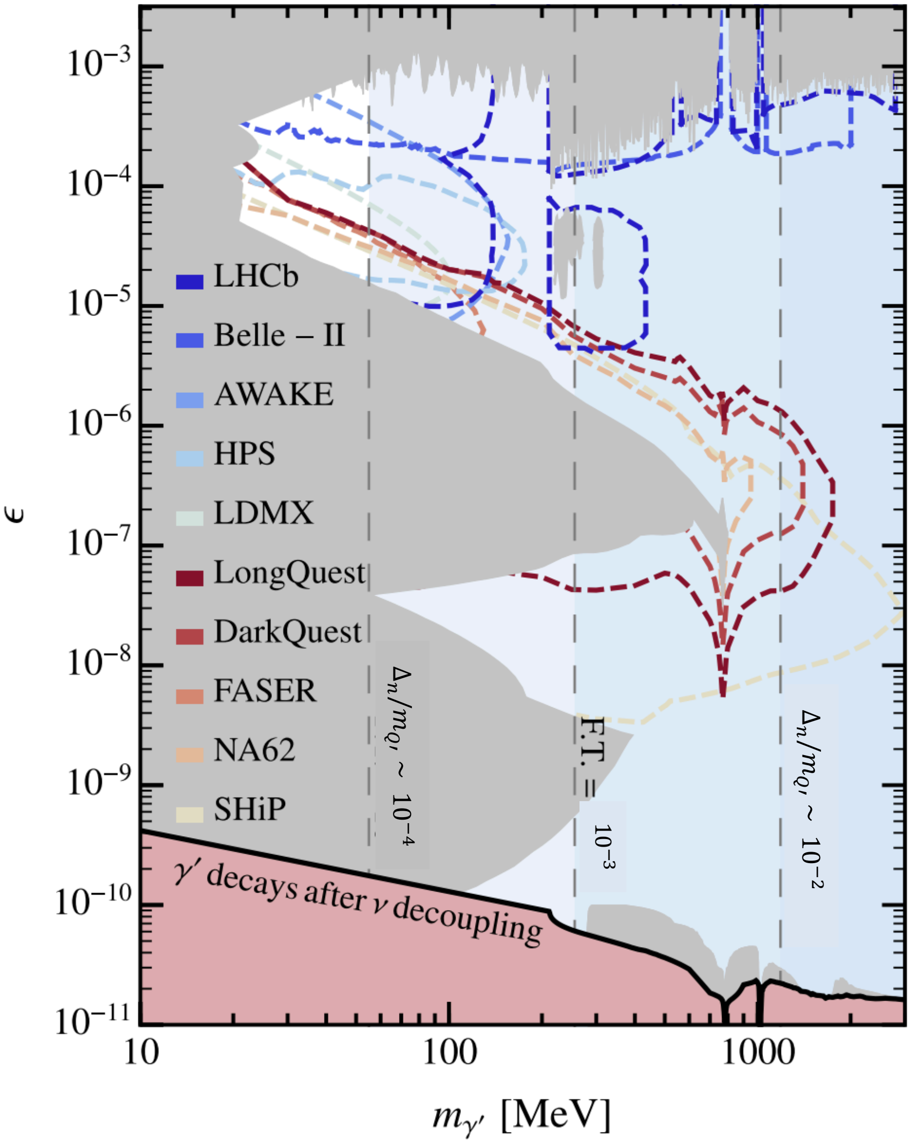
(a) iDM: $\Delta = 0.4$, α_D=0.1. With muon $g-2$ and DM regimes. (

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

LongQuest: **Tsai**, deNiverville, Liu, 1908.07525 (***PRL*** '21, accepted)

Also, can probe iDM that explains muon g-2, see 1908.07525 (PRL '21) + reference (more in the backup slides)

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 $\epsilon = 10^{-9} - 10^{-3}$

Proton Facilities: High Energy-Intensity Frontier

Current / Near Future Opportunities

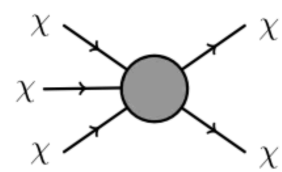
Fermilab (undergoing a Proton Improvement Plan: PIP)			
Booster Beam (BNB)	$\sim 10^{20}$ POT/yr	8 GeV	now
NuMI beam	1 - 4 x 10^{20} POT/yr	120 GeV	now
LBNF beam (future)	$\sim 10^{21}$ POT/yr	120 GeV	near-future

CERN - SPS beam			
NA62	up to 3 x 10^{18} POT/yr	400 GeV	now
SHiP	up to 10^{19} POT/yr	400 GeV	future

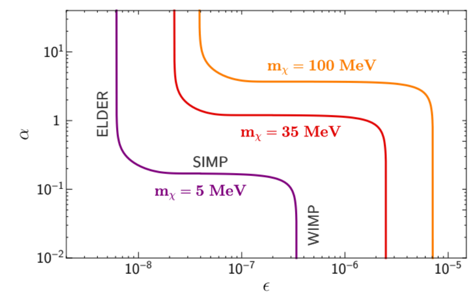
CERN – HL LHC	10^{16} POT/yr	$\sqrt{s}$ = 13 TeV	near-future

III. SIMP/ELDER Models with Lattice Results of Vector Resonances

III. SIMP / ELDER Models



SIMP: Dark matter freeze out through 3 to 2 self interaction: GeV to sub-GeV dark matter; signatures including accelerator probes. Hochberg, Kuflik, Volansky, Wacker, 1402.5143



ELDER: Dark matter elastic decoupling before 3 to 2 freeze out: another sub-GeV DM models with sharp predictions ir direct-detection experiments

Kuflik, Perelstein, Rey-Le Lorier, Tsai, 1512.04545

Resonant self interaction in SIMP ELDER model?

- 5 – pion interaction for freeze-out:
- Resonance interaction for small scale structure: perfect scenario!
- Use lattice result to decide the the exact parameter space

III. SIMP / ELDER Models

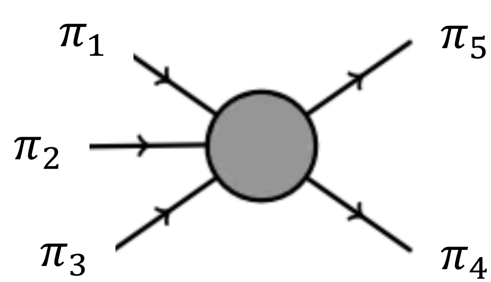
- Freeze-out: 3 to 2 for dark meson
  (Hochberg, Kuflik, Murayama,Volansky, Wacker, 1411.3727)

$$\mathcal{L}_{\rm WZW} = \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma} \sum_{\substack{i<j<k \\ <l<m}} T_{ijklm}\pi_i\partial_\mu\pi_j\partial_\nu\pi_k\partial_\rho\pi_l\partial_\sigma\pi_m .$$

$$\langle\sigma v^2\rangle_{3\to2} = \frac{5\sqrt{5}N_c^2 m_\pi^5}{2\pi^5 x^2 f_\pi^{10}}\frac{t^2}{N_\pi^3}$$

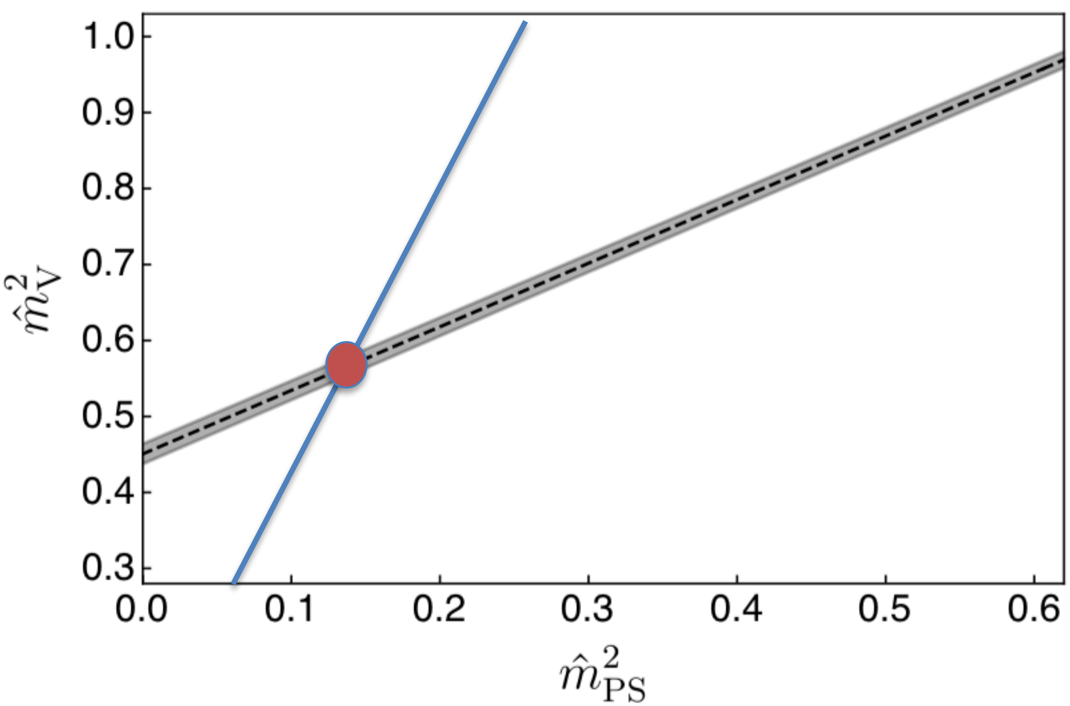
$\mathbf{G/H}$	$\mathbf{N_\pi}$	$\mathbf{t^2}$	$\mathbf{N_f^2\,(c^2+r^2/9)}$
$\mathrm{SU}(2N_f)/\mathrm{Sp}(2N_f)$	$(2N_f+1)(N_f-1)$	$\frac{2}{3}N_f\left(N_f^2-1\right)\left(4N_f^2-1\right)$	$4(N_f-1)(2N_f+1)\left(6N_f^4-7N_f^3-N_f^2+3N_f+3\right)$

Consider: Sp(4) gauge group with N_f = 2 fermions in the fundamental

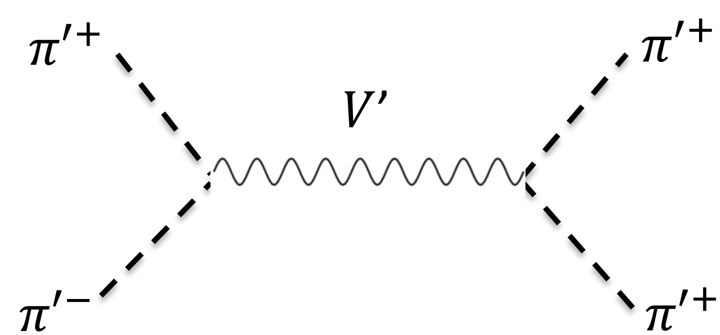


Lattice Results

Consider: Sp(4) gauge group with Nf = 2 fermions in the fundamental



$\rightarrow$ $m_\pi / f_\pi = 1.9.$



Bennett, Hong, Lee, Lin, Lucini, Mesiti, Piai, Rantaharju, Vadacchino, 1912.06505

SIMP/ELDER as RSIDM

- 3 to 2 freeze-out

$$\mathcal{L}_{\rm WZW} = \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\sum_{\substack{i<j<k\\<l<m}} T_{ijklm}\pi_i\partial_\mu\pi_j\partial_\nu\pi_k\partial_\rho\pi_l\partial_\sigma\pi_m.$$

- Resonant self-interaction: $m_\pi/f_\pi = 1.9.$

  m_V is close to resonance of $2m_\pi$, from lattice result

- Velocity independent self-interaction constraint:

$$\sigma'_{\rm scatter} = \frac{m_\pi^2}{32\pi f_\pi^4}$$

$$\frac{\sigma_0}{m_{\rm DM}} > 0.1\,\frac{\rm cm^2}{g} \quad \text{for} \quad m_\pi/f_\pi = 1.9.$$

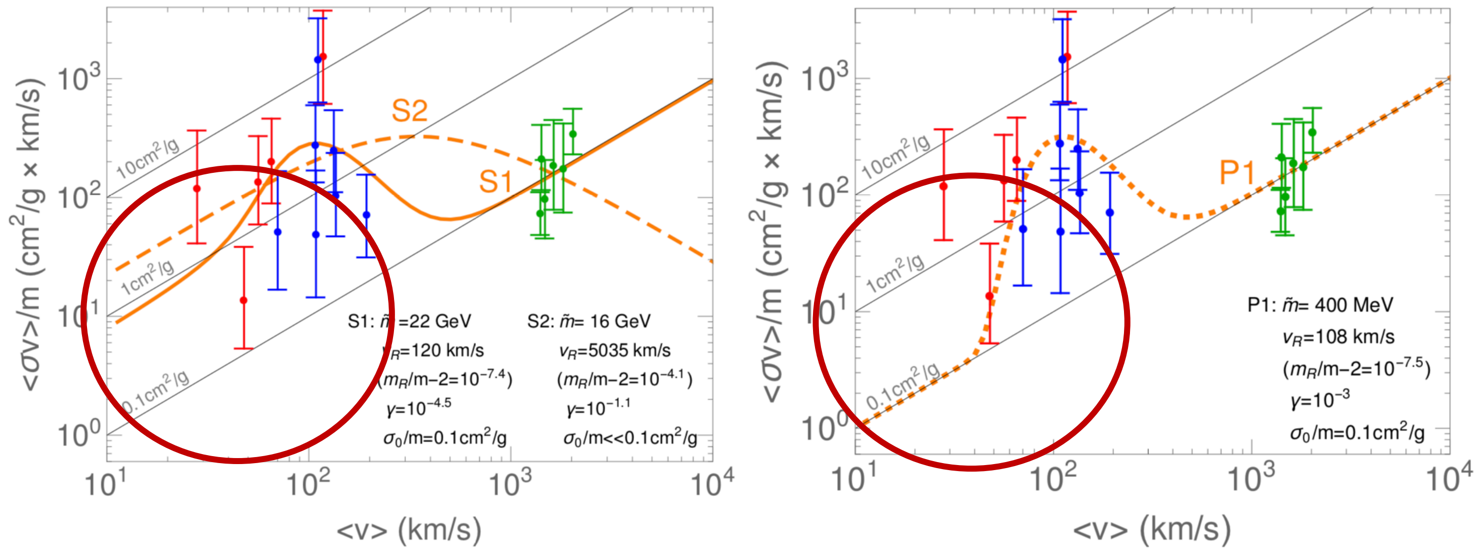
- **Tsai**, McGehee, and Murayama, arXiv:2008.08608

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

Ongoing Astro Studies

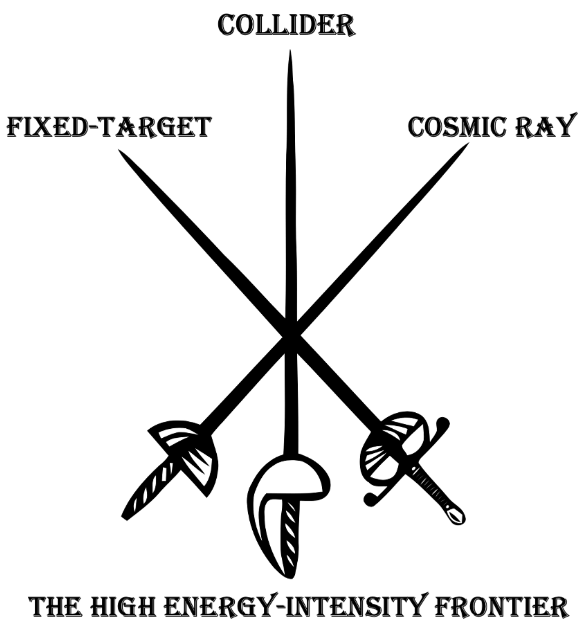
- Astrophysical studies to distinguish the models, and make predictions of the DM halo profile!
  Kaplinghat, Roberts, Valli, **Tsai**, and Yu



Hayashi et al, 2008.02529, PRD 21 suggests that RSIDM could be advantageous for ultrafaint dwarf galaxies (UFD) over other SIDM
Also, see Mahbubani, Redi, Tesi, 1908.00538 for different but interesting "resonance" structure through bound states.

Experimental Program:
Searching for Millicharge & Dark Sector Particles

My new experimental proposals & analysis of existing & future data



Adapted by Yu-Dai Tsai from design of Lou Crazy (remastered by Antonu), CC BY-SA 3.0
https://commons.wikimedia.org/wiki/File:Three-Arms.svg#/media/File:Three-Arms.svg

- Proton Fixed-Target: LongQuest + FerMINI
- Collider: FORMOSA, Nu-FLArE
- Cosmic-Ray Production: Neutrino Observatories

Millicharged Particles (mCP)

- **One of the simplest extension to SM sector:**
  A particle with a small electric charge (long-standing search)
  (SM U(1) hypercharges are fixed by anomaly cancellation, but an additional millicharged particles are possible. Why don't we them?)

- **mCP is related to massless "dark photon" theories & charge quantization**

- **Independently interesting** without assuming it to be DM
  (Connect to Superstring theory, string compactifications, etc)

- **Finding mCP: at least as interesting as finding**
  fractional Quantum Hall effect! (just an analogy)

- **Millicharge DM is also very interesting: affect cosmological measurements**
  (e.g., can help explain EDGES anomaly, backup slides for discussions)

mCP Model

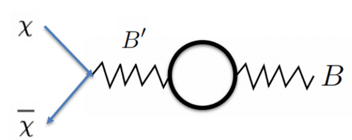
- A particle fractionally (or irrationally) charged under SM U(1) hypercharge, $\mathcal{L}_{\text{MCP}} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\text{MCP}})\chi$

- ϵ' can in principle be arbitrarily small. **Completely legal**!

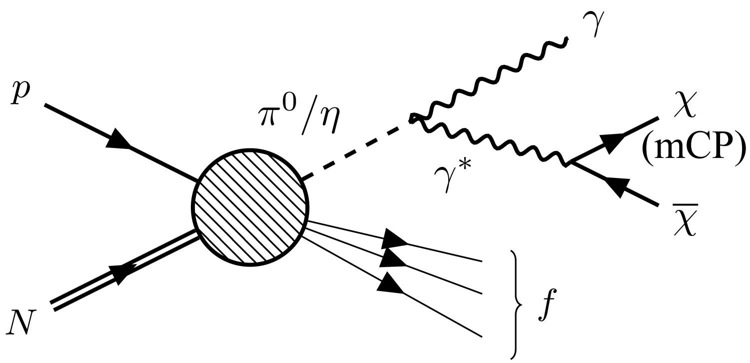
  Naively **violating the empirical charge quantization**.

- We are simply search for mCP (no need for dark photons)
  Minimal assumptions = most robust constraints/probes.
  mCP has charge Q_χ, Q_χ/e is small (Z coupling less important in low-energy)

- This could come from vector portal **Kinetic Mixing** (Holdom, '85)
  - a nice origin to the above terms
  - help give rise to **dark sectors: a dark photon model**
  - easily compatible with **Grand Unification Theory**

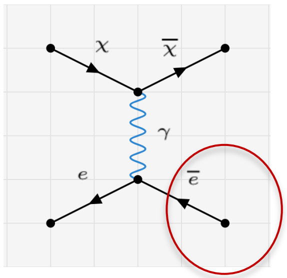


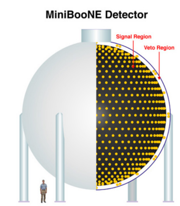
Search Methods: Scattering & Scintillation



(A) **“Hard” Electron Scattering**

~ energy exchange set by detector threshold



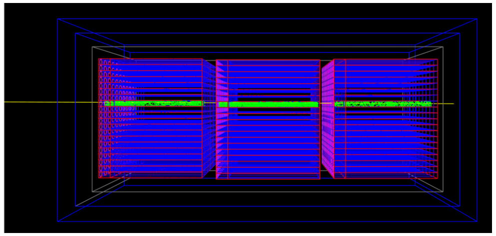


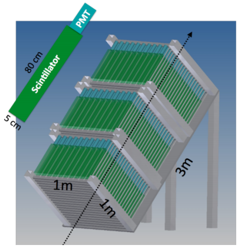
e.g.neutrino Detector
MiniBooNE (arXiv:0806.4201)

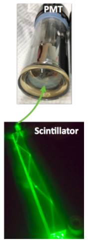
We considered **both** in
four different ways

(B) **Scintillation Study for Millicharge Particles**

~ eV-level energy exchange







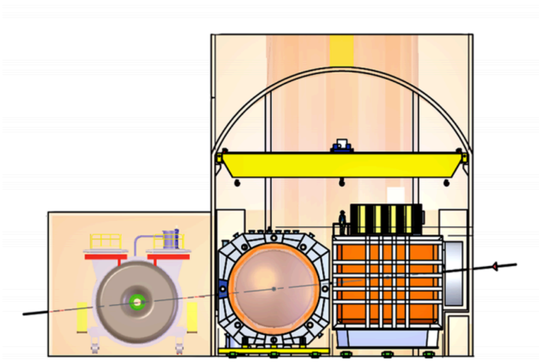
e.g., Haas, Hill, Izaguirre, Yavin, 1410.6816
milliQan design, 1607.04669 (MilliQan Collaboration)

(B’) **Machine Learning**
for ultrafaint tracks for mCP,
Future project with ArgoNeuT/DUNE people!

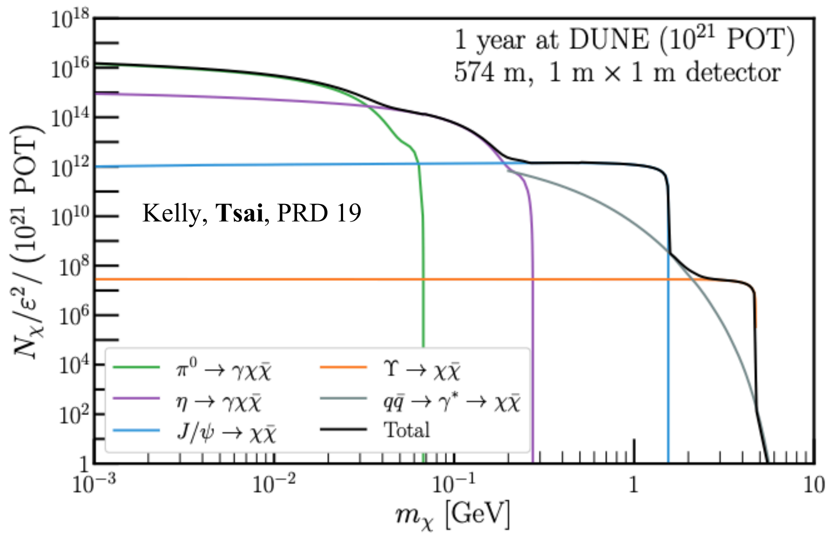
Study mCP @ "High Energy + Intensity" Frontier

(I) mCPs in fixed-target neutrino experiments, Magill, Plestid, Pospelov, **Tsai**

1806.03310, *PRL* 19



arXiv:2002.02967, DUNE TDR V - I



(II) FerMINI: dedicated Millicharge Particle Detectors at Proton Fixed-Target Experiments, Kelly, **Tsai**, 1812.03998, *PRD* 20.

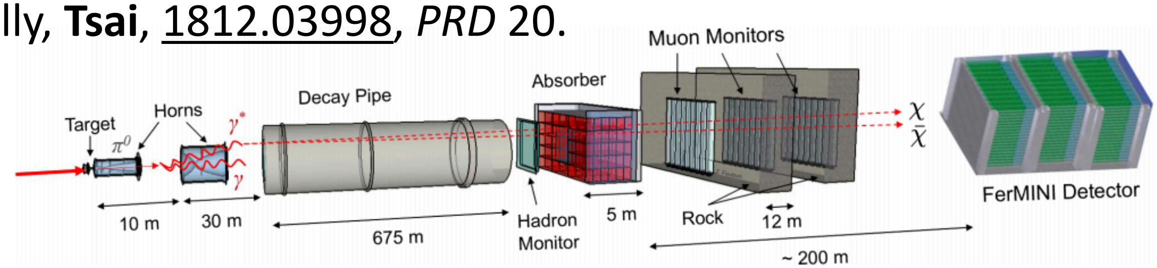
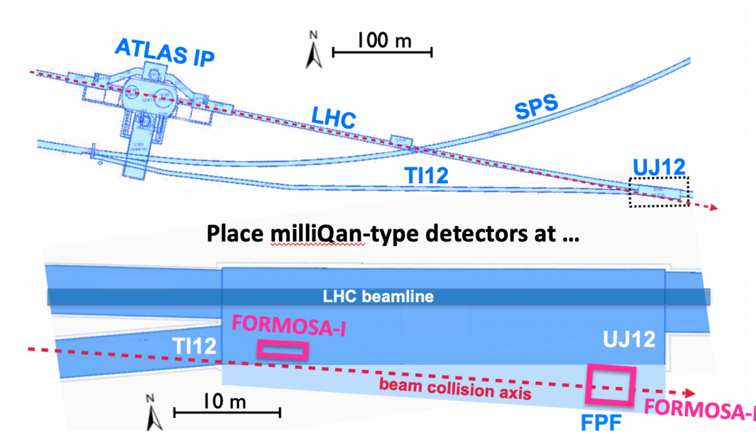


figure adapted from milliQan, 1410.6816

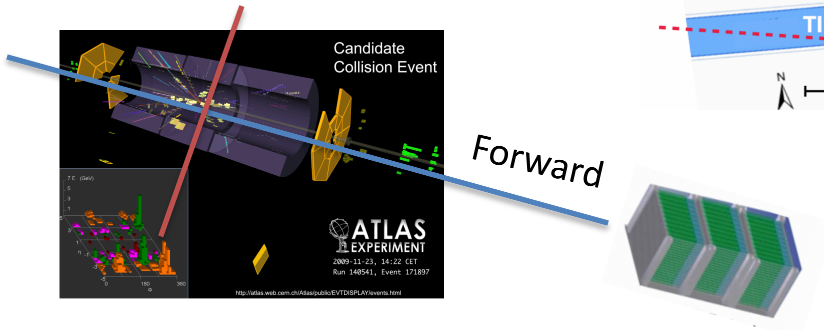
Four Ways to Study mCP

(III) FORward MicrOcharge SeArch, FORMOSA!

Foroughi-Abari, Kling, **Tsai**, 2010.07941, *PRL* reviewing



Transverse (traditional)

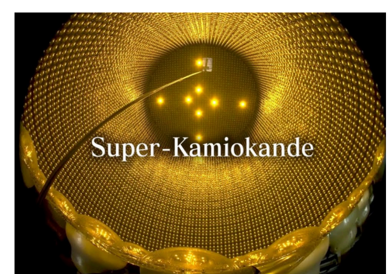


(IV) **Cosmic-ray production** and detection in **large neutrino observatories (Super-K)**,
Plestid, Takhistov, **Tsai** et al, 2002.11732, *PRD* 20. I am less familiar with cosmic rays. Eager to learn

by Chantelauze, Staffi, and Bret

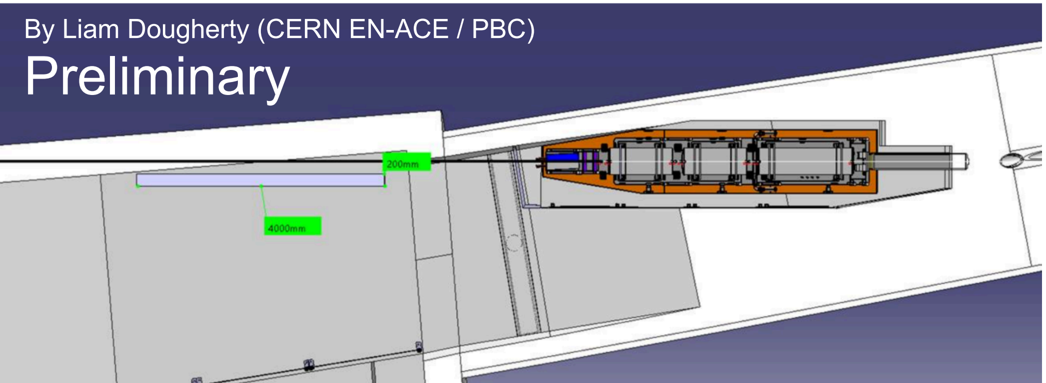
χ

$\bar{\chi}$



Super-K, http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

FORMOSA may happen SOON!

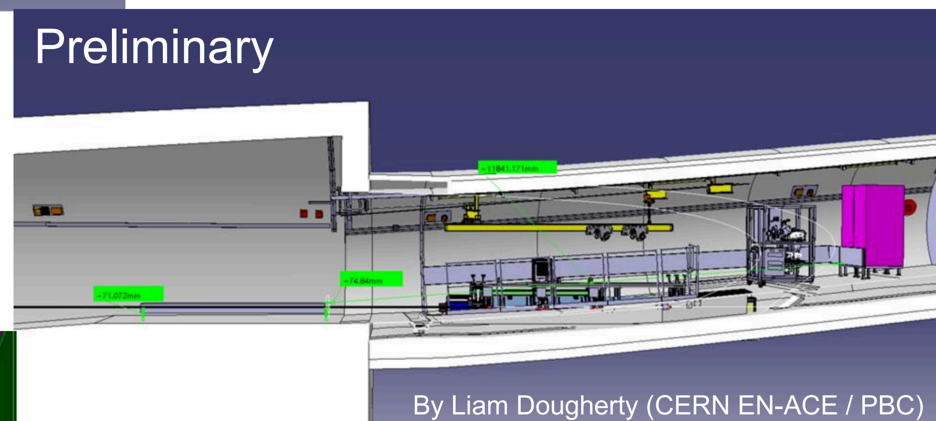


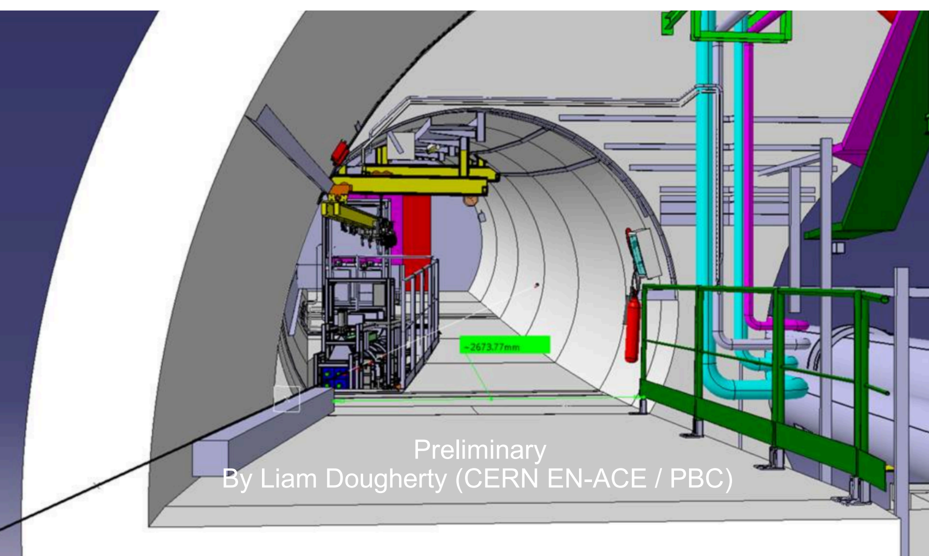
Idea: moving milliQan prototype to the LHC forward region!

Project FORMOSA - FORward MicrOcharge SeArch arXiv:2010.07941

Figures made by Liam Dougherty (CERN EN-ACE / PBC)

Also thank FASER+ & milliQan collaborations for discussions & J. Feng for communications.

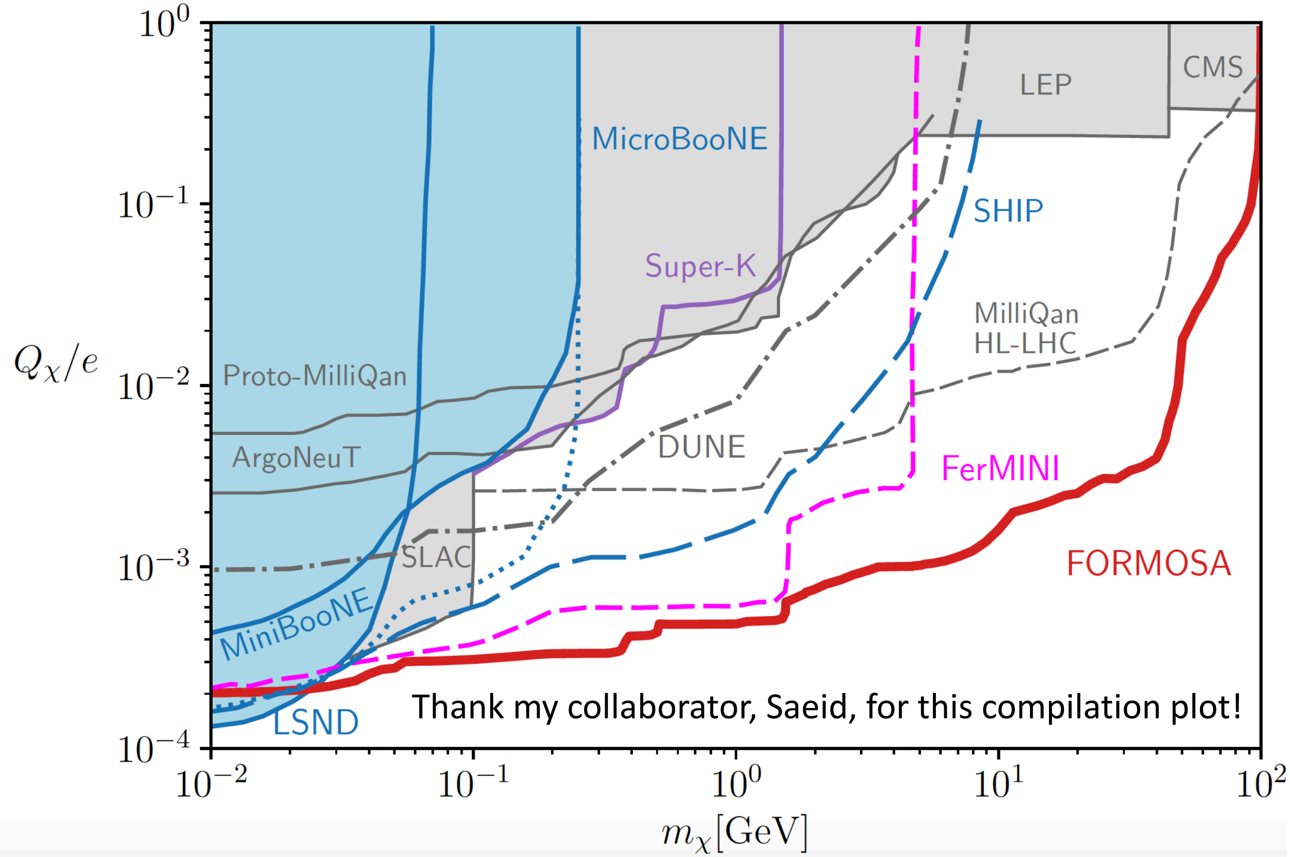




milliQan-Prototype: milliQan Collaboration 2005.06518, new limit established!

FORMOSA: Foroughi-Abari, Kling, **Tsai**, 2010.07941, ***PRL*** reviewing

Compilations of our works



FORMOSA may also be able to study:

1) **Tau Neutrino Magnetic Dipole**
2) **Dipole-Portal DM**

We just started working on it

(I) Neutrino Exp. Magill, Plestid, Pospelov, **Tsai,** *PRL* 19

(II) **Super-K**, Plestid, Takhistov, **Tsai**, et al, 2002.11732, *PRD* 20

(III) **FerMINI**: Kelly, **Tsai**, 1812.03998, *PRD* 20.

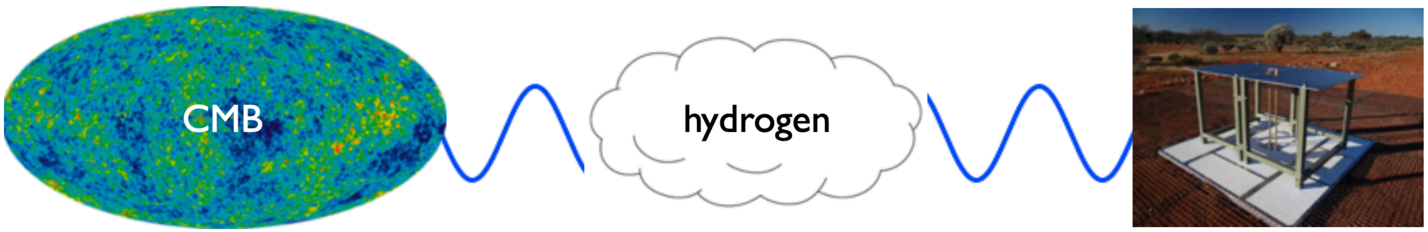
(IV) **FORMOSA**, Foroughi, Kling, **Tsai**, 2010.07941

*DUNE curve from
Harnik, Liu, Palamara, 1902.03246, JHEP 19

I am initiating a **new study with DUNE**, hope to apply machine learning techniques

New Intriguing Measurement

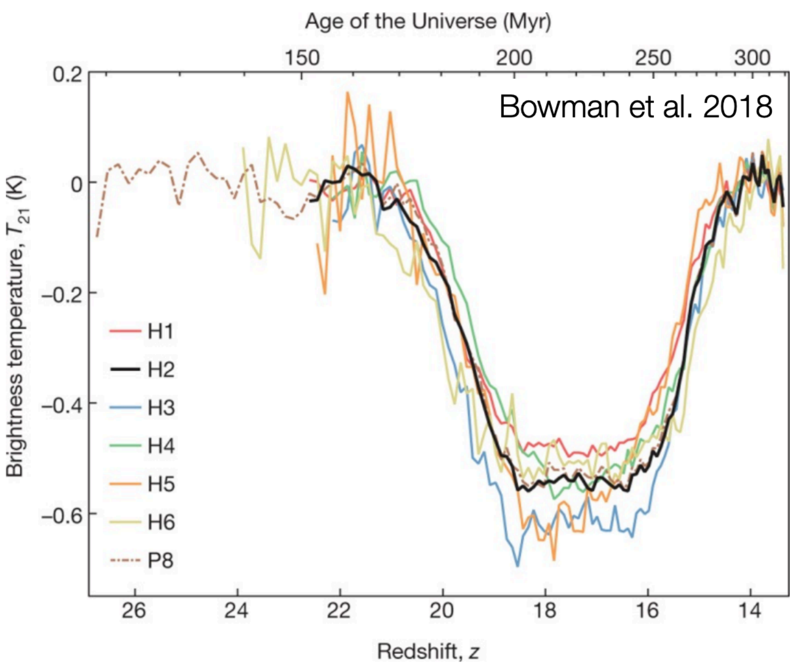
T_γ T_S δT_b



Adapted from J. Pritchard

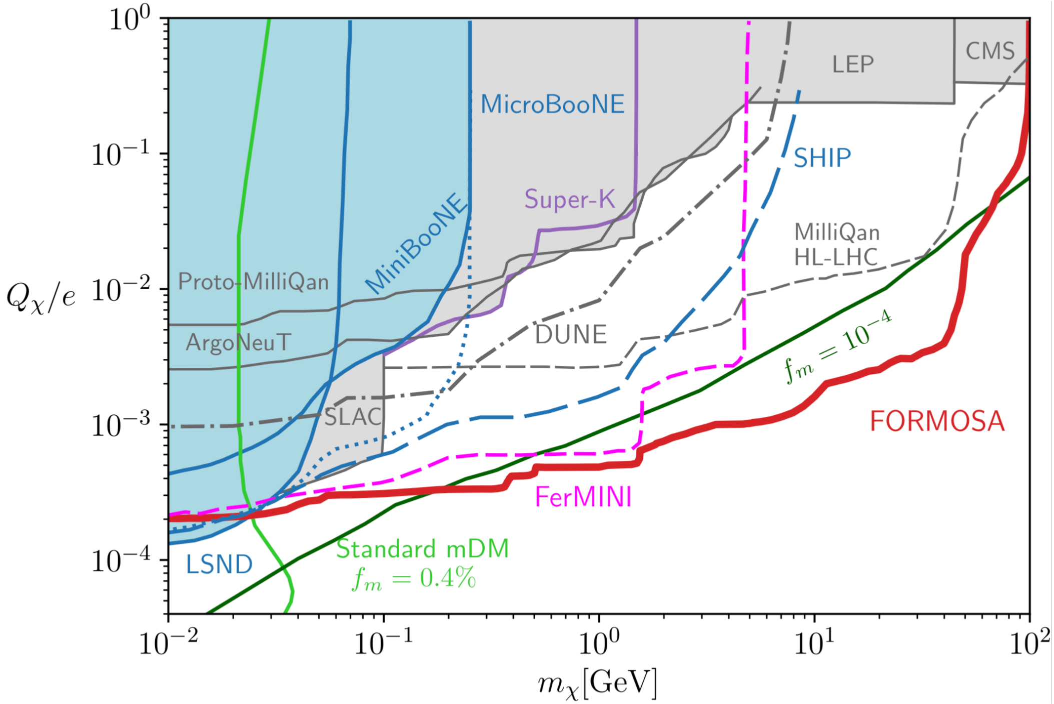
From Jordan Mirocha (UCLA)

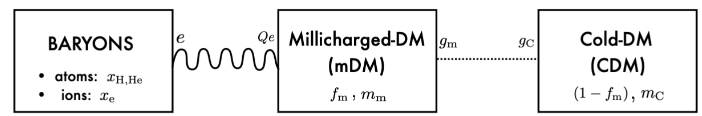
e.g., EDGES



- EDGES collab., Nature, (2018); Barkana, Nature, (2018), more **refs** listed in the end.
- The result is still heavily debated!!!
- Maybe dark matter has a small charge?

Probing Millicharged Dark Matter





Liu, Outmezguine, Redigolo, Volansky, '19

- EDGES gives another hint of dark matter property, just like small-scale structure

(I) Neutrino Exp. Magill, Plestid, Pospelov, **Tsai,** *PRL* 19

(II) **Super-K**, Plestid, Takhistov, **Tsai**, et al, 2002.11732, *PRD* 20

(III) **FerMINI**: Kelly, **Tsai**, 1812.03998, *PRD* 20.

(IV) **FORMOSA**, Foroughi, Kling, **Tsai**, 2010.07941

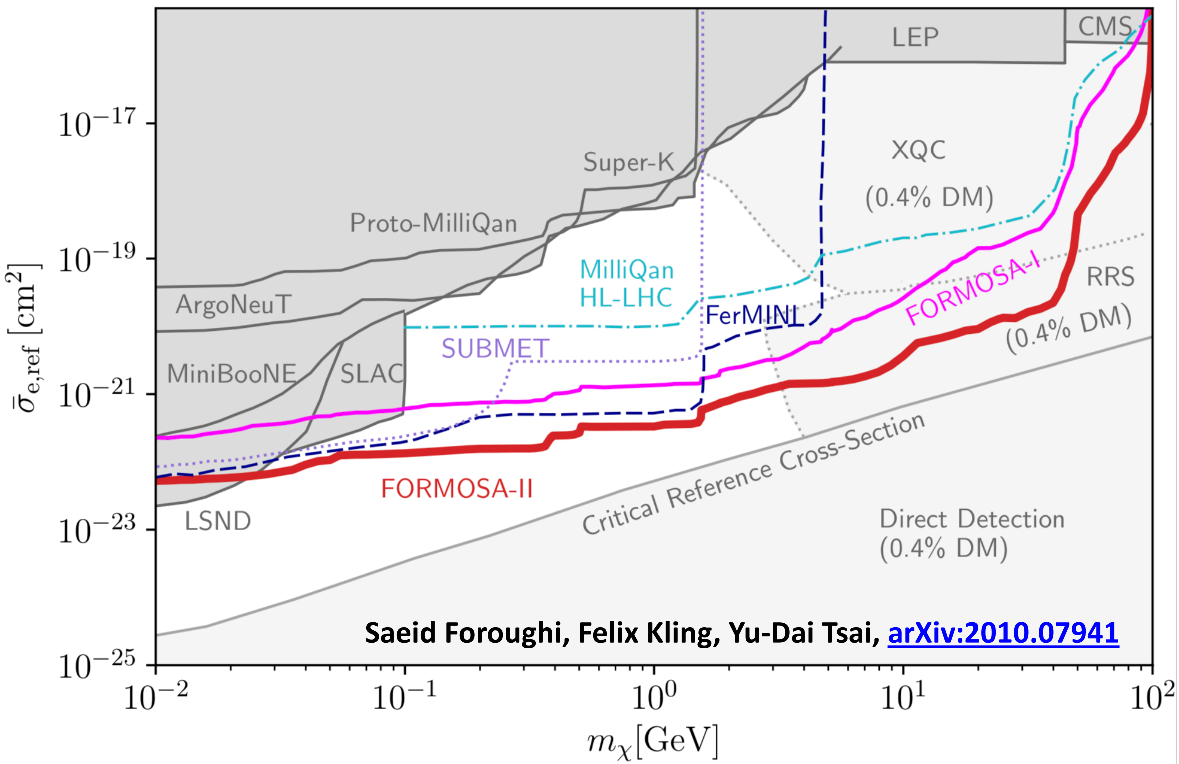
*DUNE curve from
Harnik, Liu, Palamara, 1902.03246, JHEP 19

I am initiating a **new study with DUNE**, hope to apply machine learning techniques

Strongly Interacting Millicharged DM

MCP / LDM with ultralight dark photon mediators

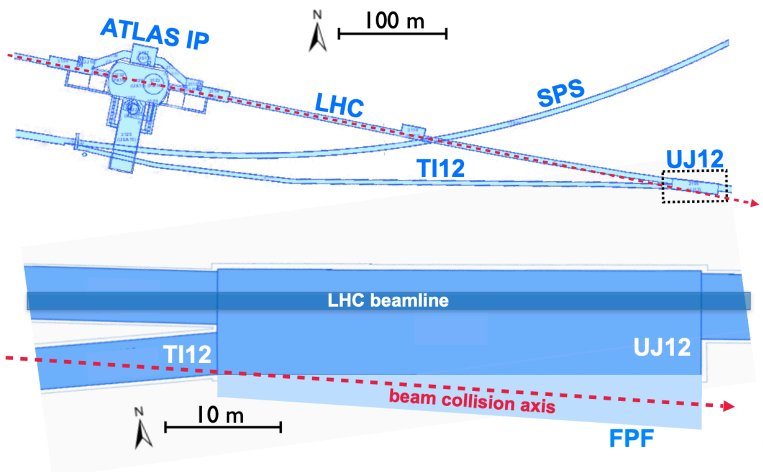
$$\bar{\sigma}_e \simeq \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{ref}^2}, \; q_{ref} = \alpha m_e$$

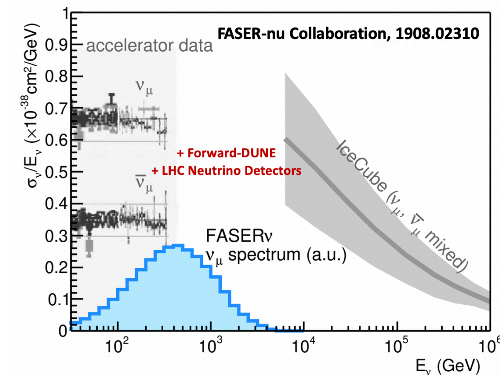


- We will add this figure with all the projections to the Snowmass White Paper

- Here we plot the **critical reference cross-section** see 1905.06348 (Emken, Essig, Kouvaris, Sholapurkar)
- **Accelerator probes can help close the Millicharged SIDM window!**
- Cosmic-ray production & Super-K detection 2002.11732

Forward Proto-DUNE & Forward Neutrino Detector(s)!
(& Forward Physics Facility)



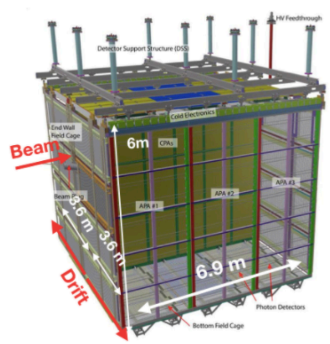


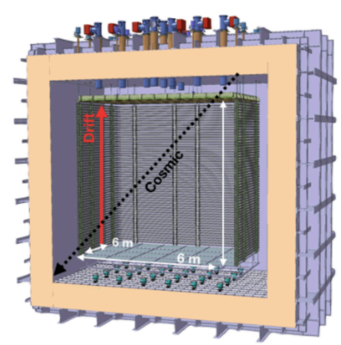
I am NOT in FASER but I will participate this fall as an associate member

New consideration!

- Forward Physics Facility (FASER Co. +)
- FLArE (Batell, Feng, Trojanowski, 2101.10338)
- **Nu-FLArE** (Feng, Pandey, **Tsai**, ongoing)

Single-Phase (SP) liquid argon time projection chamber (LArTPC)
7.2×6.0×6.9 m^3





Duel-Phase (DP) Detector
6 x 6 x 6 m^3 LAr TPC

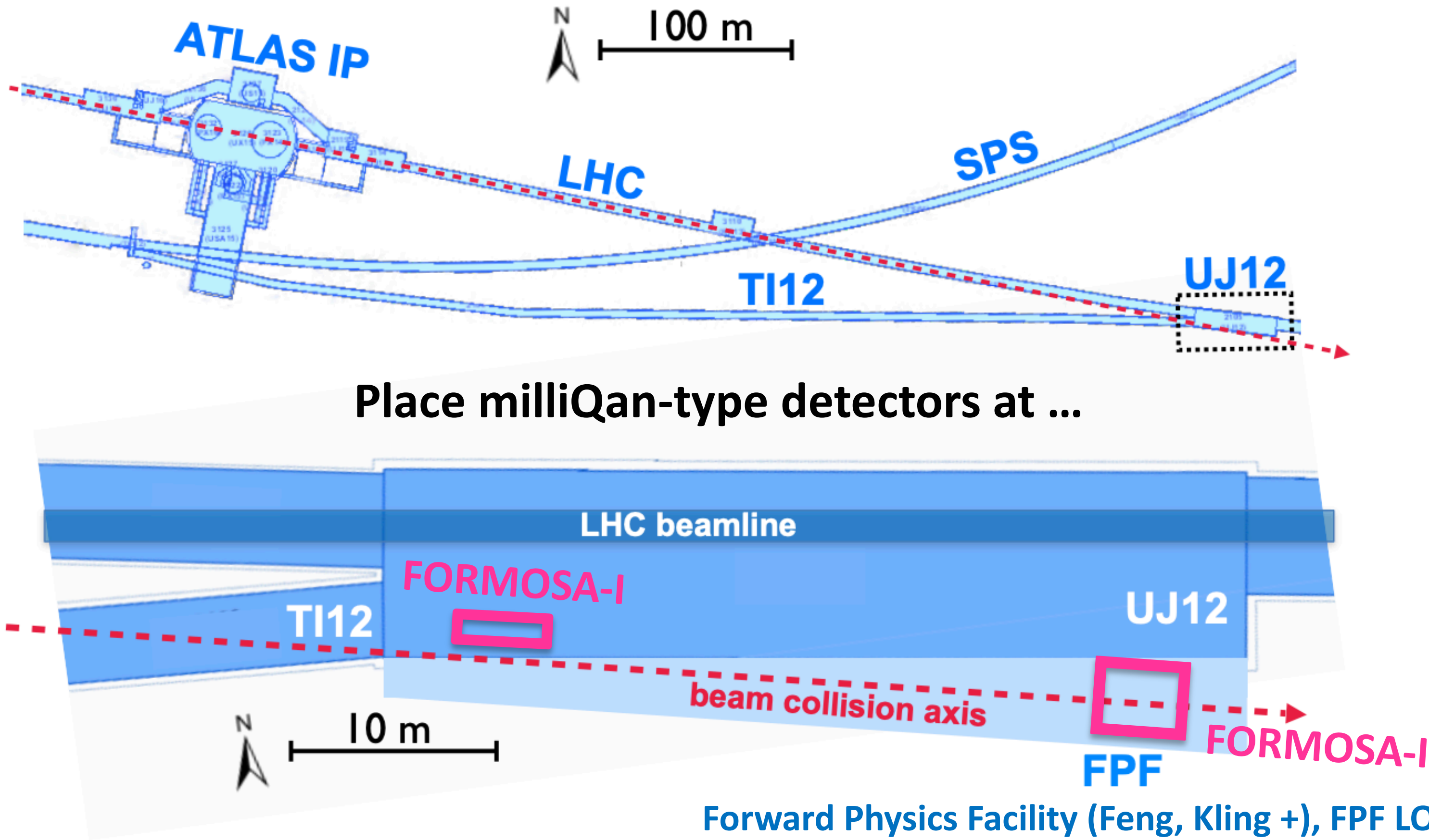
Figure 3: Left: draft of ProtoDUNE-SP [2]. Right: draft of ProtoDUNE-DP [3]

DUNE Collaboration (arXiv:1706.07081 + arXiv:1409.4405)
Updates, see, e.g. arXiv:1910.10115 & arXiv:2007.06722

Let’s find dark matter!
Thank you!

FORMOSA: FORward MicrOcharge SeArch

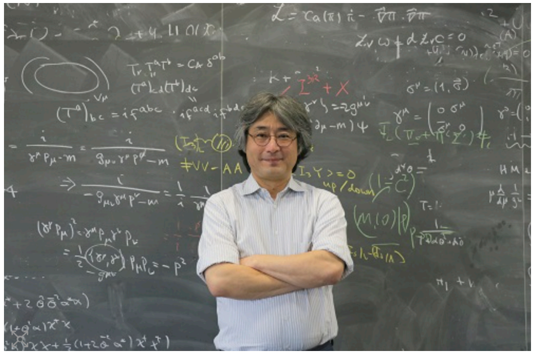
Foroughi, Kling, **Tsai**, arXiv:2010.07941



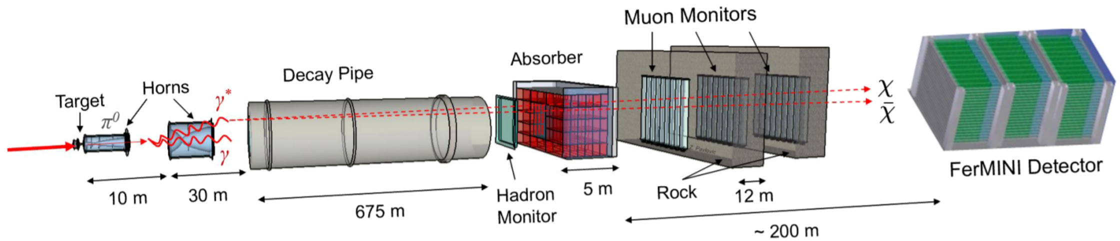
Forward Physics Facility (Feng, Kling +), FPF LOI: link

Formosa means "beautiful" in Portuguese and is the ancient name of Taiwan

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.

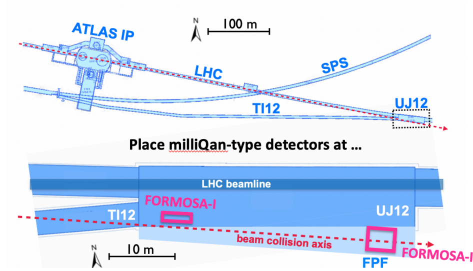
Adapted by Yu-Dai Tsai from Zarko Pavlovic's photo and milliQan detector, 1607.04669 (milliQan col.)

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

More on MCP/DM & 21-cm Cosmology

Some more reference of **Millicharged DM (mDM) and constraints**.

See, e.g.,

McDermott, Yu, Zurek, 1011.2907;

Muñoz, Dvorkin, Loeb, 1802.10094, 1804.01092;

Berlin, Hooper, Krnjaic, McDermott, 1803.02804;

Kovetz, Poulin, Gluscevic, Boddy, Barkana, Kamionkowski, 1807.11482;

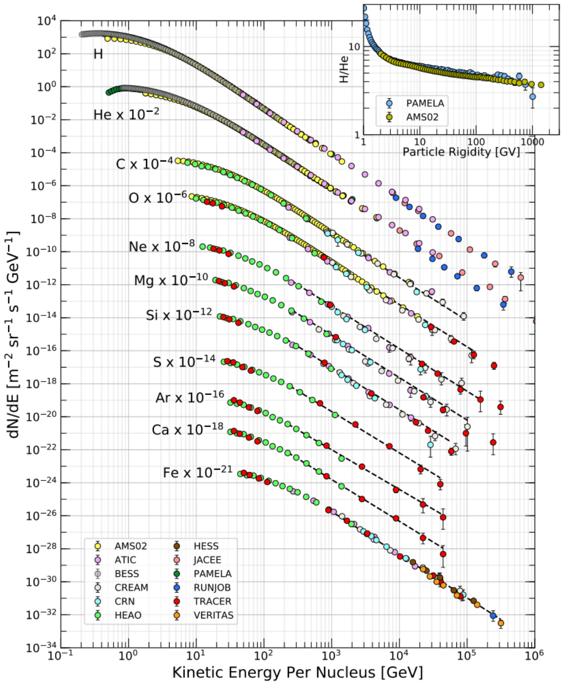
Liu, Outmezguine, Redigolo, Volansky, 1908.06986:

"Reviving Millicharged Dark Matter for 21-cm Cosmology,"

Introduces a long-range force between a subdominant mDM and the dominant cold dark matter (CDM) components. Leads to efficient cooling of baryons in the early universe. Extend the range of viable mDM masses for EDGES explanation to ~ 100 GeV.

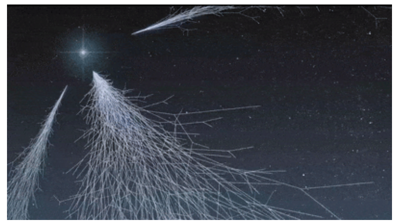
New fixed-target study: Marocco & Sarkar, arXiv:2011.08153

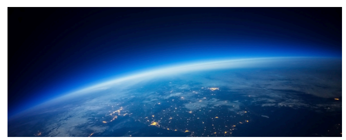
Sidenote – Dark Sector in Neutrino Observatories



PDG, RPP, 2019

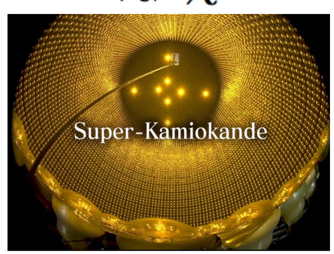
by Chantelauze, Staffi, and Bret





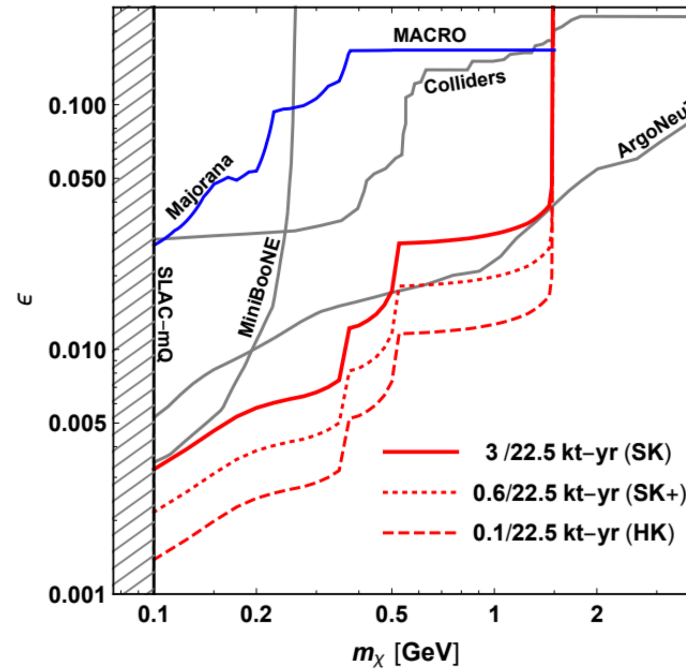
https://www.futurelearn.com/info/courses/learn-about-weather/0/steps/39415

χ $\bar{\chi}$



Super-K, http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

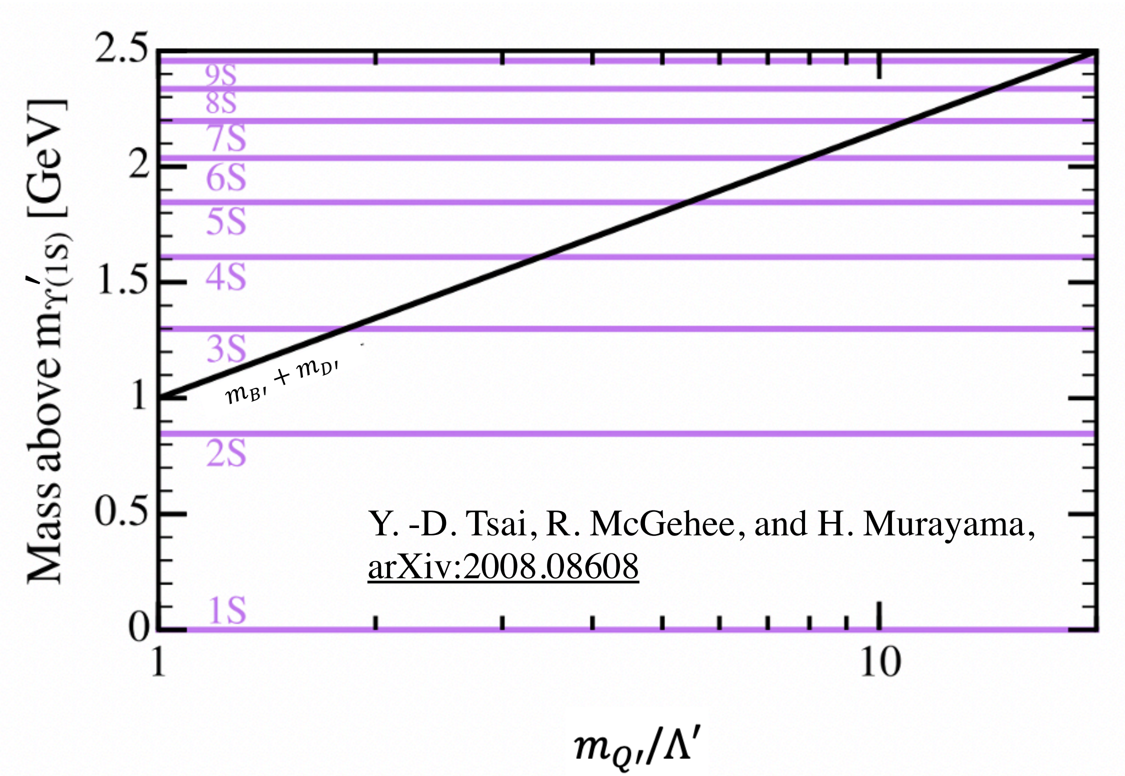
1111.5031 (Super-K Collaboration)
Supernova Relic Neutrino Search at Super−K



2002.11732 (Plestid, Takhistov, **Tsai**, Bringmann, Kusenko, Pospelov, '20)

https://arxiv.org/pdf/2002.11732.pdf

Mass Spectrum for Dark Mesons



With derivation from Quigg & Rosner, PLB '77

$$\Delta_n \equiv m_{\Upsilon(nS)} - m_{\Upsilon((n-1)S)} = C\left[\frac{1}{n} + \mathcal{O}\left(\frac{1}{n^2}\right)\right].$$

$$m_Q \approx n^2 \left(\frac{4}{3e}\right)^2 \Lambda.$$

C can be calculated w lattice QCD, set C ~ Λ for analytical estimation

- 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 nS state. With n > 10, $\Delta_n/m_Q < 10^{-3}$

Heavy Quark Meson ADM

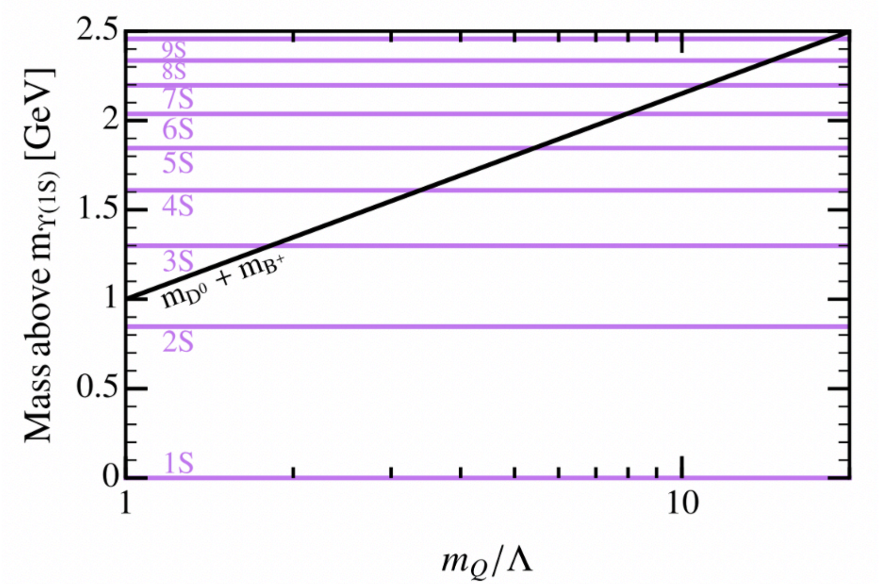
- We consider one light quark u and two heavy quarks c and b and assume the c and b abundances are fixed by their asymmetry

$$V(r) = C \ln(r/r_0)\,,$$

$$m_{\Upsilon(nS)} - m_{\Upsilon(1S)} \approx C \ln\left(\frac{4n}{3}\right)$$

in the large n limit. The mass splitting is

$$\Delta_n \equiv m_{\Upsilon(nS)} - m_{\Upsilon((n-1)S)} = C\left[\frac{1}{n} + \mathcal{O}\left(\frac{1}{n^2}\right)\right].$$



The mQ which allows the sum of the pseudoscalar mesons' masses to fall between n-1 & n state, is

$$\Delta_n/m_Q \sim n^{-3}$$

$$m_Q \approx n^2 \left(\frac{4}{3e}\right)^2 \Lambda.$$

- C. Quigg and J. L. Rosner, "Quarkonium Level Spacings," Phys. Lett. B 71 (1977) 153–157.