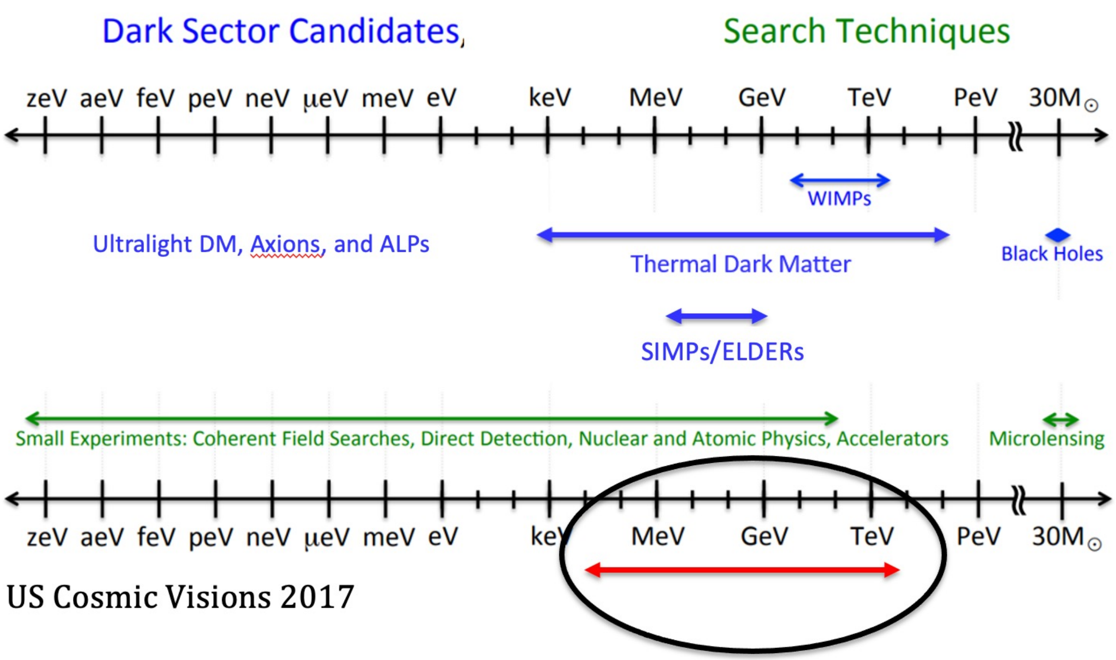
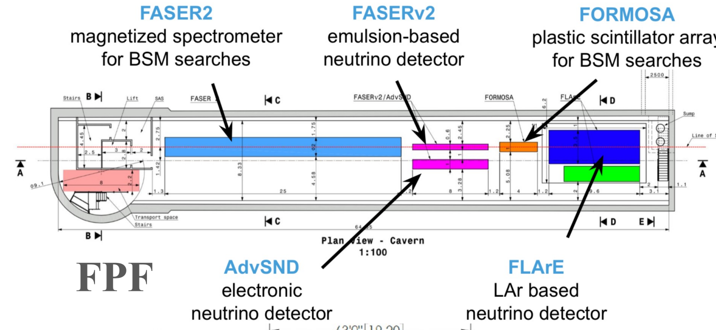
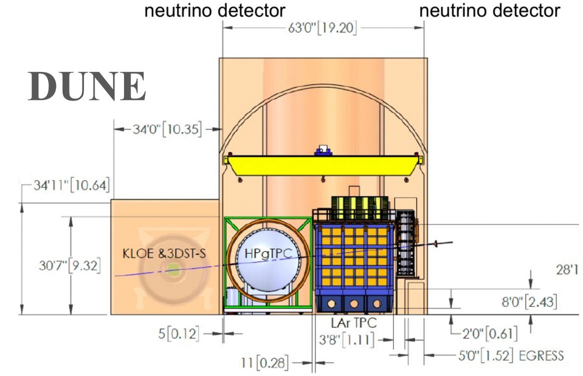






Dark Sector at the High Intensity Frontier: Theory Overview

Dr. Yu-Dai Tsai, University California, Irvine

Contact: yudait1@uci.edu ; yt444@cornell.edu

arXiv: https://arxiv.org/a/tsai_y_1.html

The relevant literatures are growing fast.

Let me know if I have not included your important works. I will include them to the slides

Contact: yudait1@uci.edu ; yt444@cornell.edu

Outline

- Why study "dark sector"?

  Why MeV to GeV+ region?

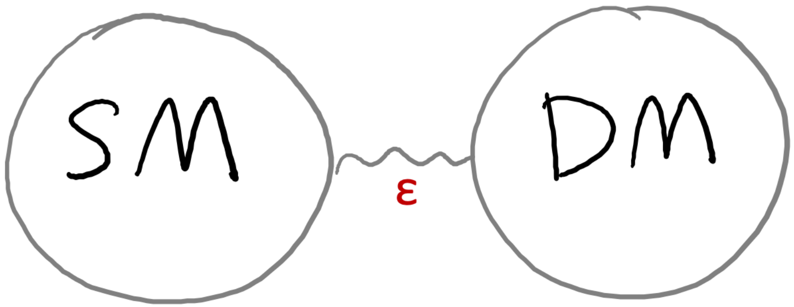
  Why accelerator (intensity) probes?

- Intro to dark sector "portals" and anomaly

  Motivated Models

- Search Overview & Specific Examples

The Rise of Dark Sector



- The Lee-Weinberg bound (1977’): below $\sim 2\ \mathrm{GeV}$, DM freeze-out through weak-Interaction (e.g. through Z-boson) would overclose the Universe.

- Could consider ways to get around this but generally light DM needs light **mediators** to freeze-out to proper relic abundance.

- Mediator is needed for a proper freeze-out: the rise of “dark sector” (DM + mediators + stuffs).

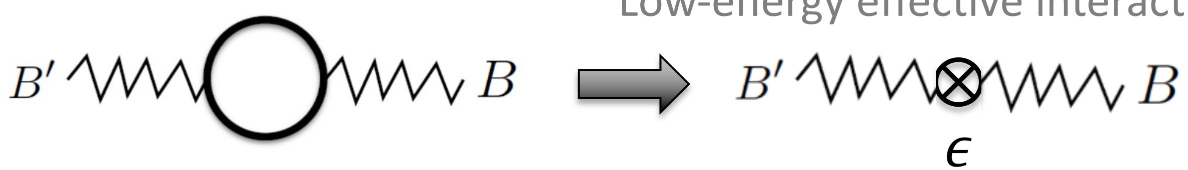
- Neutrino experiments can probe both **mediators** & **dark matter**

“Portal” Particles

- **Renormalizable interactions.**
- **High-Dim. axion portal is also popular**

$$\mathcal{L} \supset \begin{cases} -\dfrac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu} \,, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H \,, & \text{Higgs portal} \\ y_n L H N \,, & \text{neutrino portal} \end{cases}$$

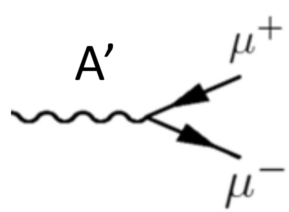
Low-energy effective interaction



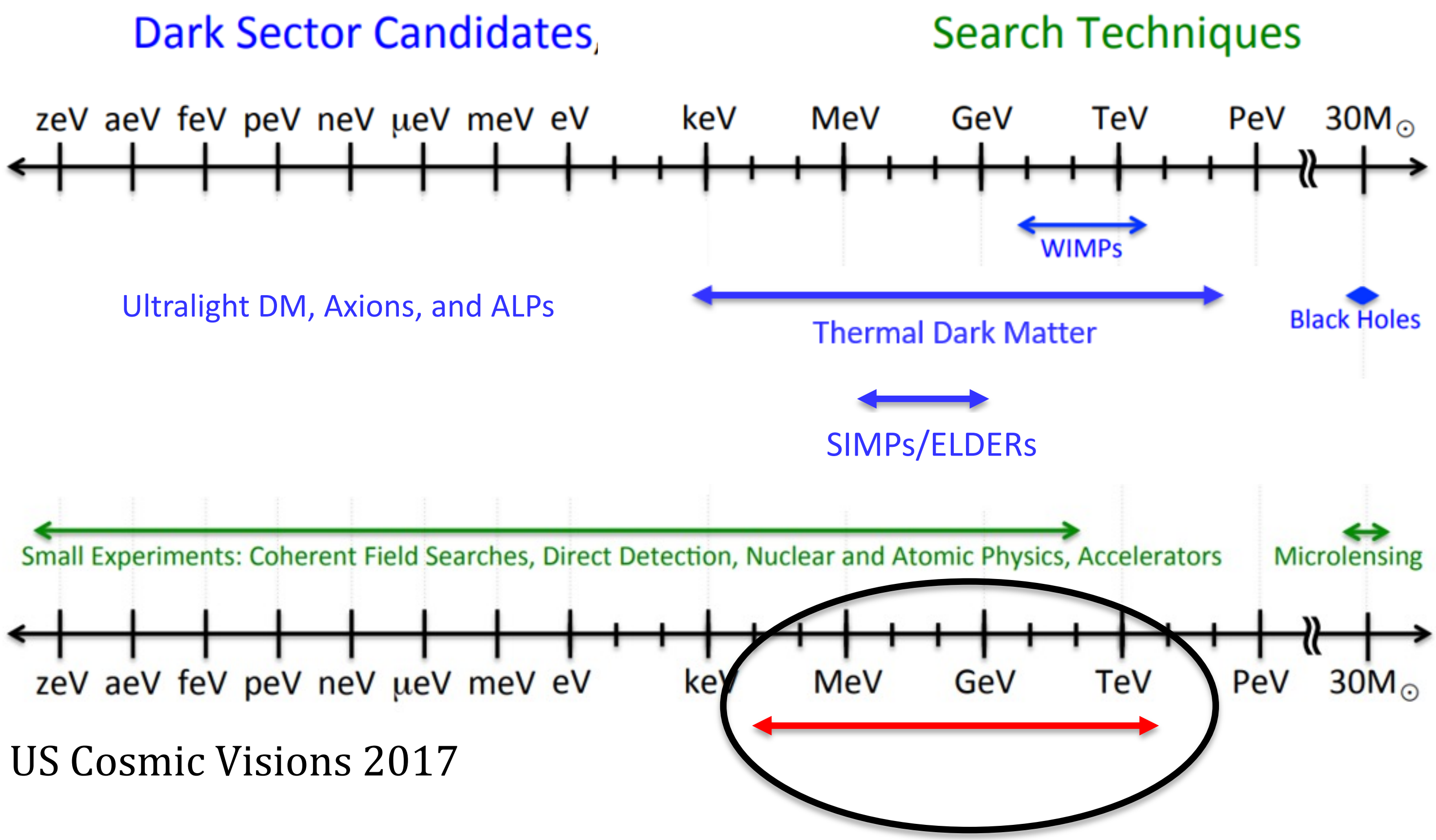
Mass from Dark Higgs or Stueckelberg

mass basis

Dark photon A’:



Exploration of Dark Matter & Dark Sector

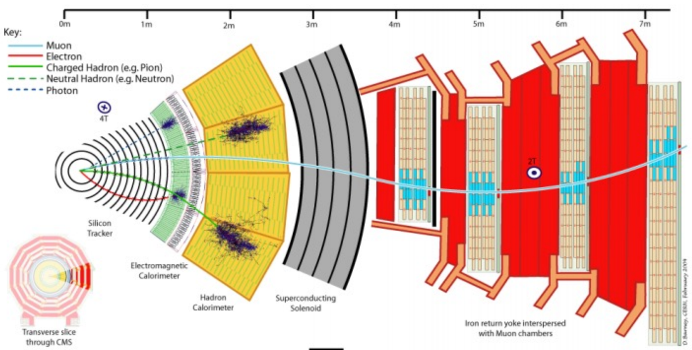


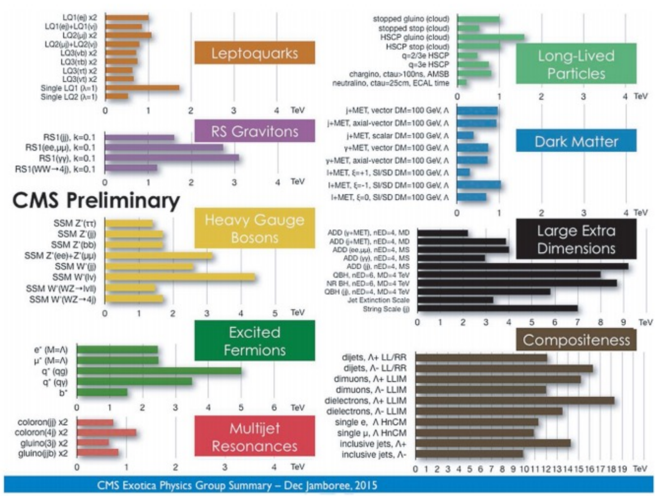
US Cosmic Visions 2017

- **Astrophysical/cosmological observations** are important to reveal the **actual story of dark matter (DM).**
- **Why accelerator experiments? And why MeV – GeV+?**

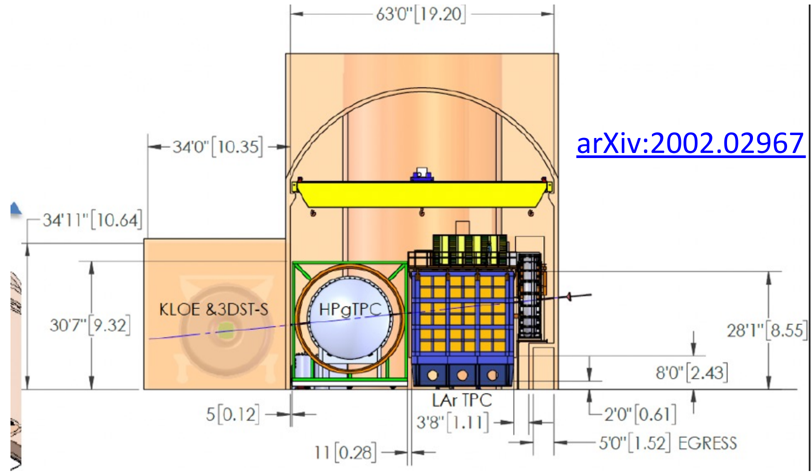
Energy vs Intensity Frontier

High energy frontier





Intensity frontier



arXiv:2002.02967

https://indico.fnal.gov/event/18430/session/8/contribution/17
redesigned from Roni Harnik's slide

Yu-Dai Tsai, UC Irvine

Not all bounds are created with equal assumptions

→ Assumptions

Or, how likely is it that theorists would be able to argue our ways around them

Accelerator-based: Collider, **Intensity Experiments**
Some other ground-based experiments

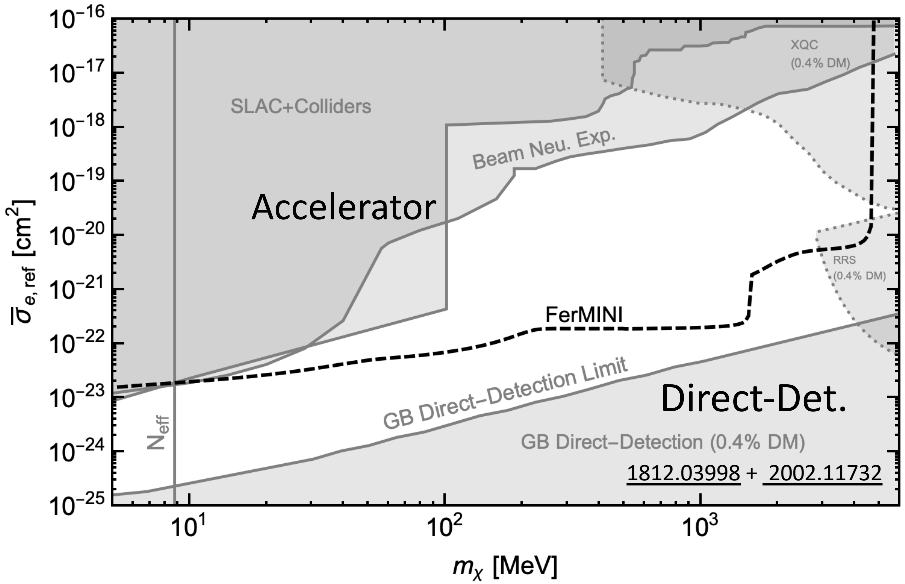
Astrophysical productions (not from ambient DM): energy loss/cooling, etc:
Rely on modeling/observations of (extreme/complicated/rare) systems (SN1987A & neutron-star mergers);

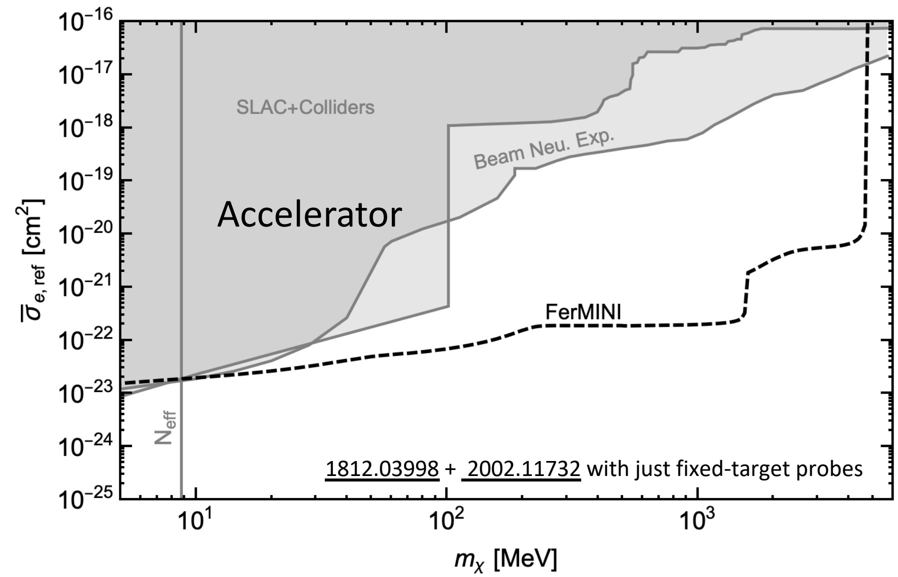
Dark matter direct/indirect detection: abundance, velocity distribution, etc

Cosmology: assume cosmological history, species, etc

DD & Cosmology: They reveal the **actual story of dark matter and cosmic evolution**

Not all bounds are created with equal assumptions
Example: Constraints on Millicharged Dark Matter





Also consider **ambient dark matter**

Produce dark particles in collisions

Same mass and interaction strength.

Different assumptions

Some details of these figures will be explained later

Why study MeV – GeV+ dark sectors?

Signals of discoveries grow from anomalies

Maybe nature is telling us something so we don't have to search in the dark? (~~or probably systematics~~?)

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

⋮

- **Muon g-2 anomaly**
- **LSND & MiniBooNE anomaly**
- **EDGES result**
- KOTO anomaly
- Beryllium anomaly

⋮

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

Overview of benchmark models

Benchmark Models for Dark-Sector Searches

Snowmass RF06 Classification

Benchmarks in Final State x Portal Organization

	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	*m_χ vs. y [m_A/m_χ=3,α_D=.5]* **$m_{A'}$ vs. y** [α_D=0.5, 3 m_χ values] <u>m_χ vs. α_D [$m_{A'}/m_\chi$=3, y=y_{fo}]</u> m_χ vs. m_A [α_D=0.5, y=y_{fo}] *Millicharge m vs. q*	<u>$m_{A'}$ vs. ϵ [decay-mode agnostic]</u> ***$m_{A'}$ vs. ϵ [decays]***	**iDM m_χ vs. y [m_A/m_χ=3,α_D=.5] (anom connection)** **SIMP-motivated cascades [slices TBD]** $U(1)_{B-L\,/\,\mu-\tau\,/\,B-3\tau}$ (DM or SM decays)
Scalar	m_χ vs. sinθ [λ=0, fix m_S/m_χ, g_D] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	*m_S vs. sinθ* [λ=0] *m_S vs. sinθ* [λ=s.t. Br(H→ss ~10^{-2})]?	Dark Higgssstrahlung (w/vector) scalar SIMP models Leptophilic/leptophobic dark Higgs
Neutrino	e/μ/τ a la1709.07001	*m_N vs. U_e* *m_N vs. U_μ* *m_N vs. U_τ* Think more about reasonable flavor structures	Sterile neutrinos with new forces
ALP	m_χ vs. fq/l [λ=0, fix m_a/m_χ, g_D] (thermal target excluded) What about f_γ, f_G?	*m_a vs. f_γ* *m_a vs. f_G* *m_a vs. f_q=f_l* *m_a vs. f_W*	FV axion couplings

Bold = BRN benchmark, *italic=PBC benchmark.* others are new suggestions. <u>Underline=CV benchmarks that were not used in BRN</u>

PBC: The Physics Beyond Colliders initiative at CERN

Krnjaic, ... **Tsai**, arXiv:2207.00597

Examples: Portal Particles & Interesting Physics Cases

Vector Portal $\mathcal{L} \supset \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}.$

- Massless dark photon can lead to millicharged particles

Neutrino Portal $\mathcal{L} \supset -y^{\alpha} L_{\alpha} H N + \text{h.c.},$

- Other neutrino coupling to new particles interesting for anomalies

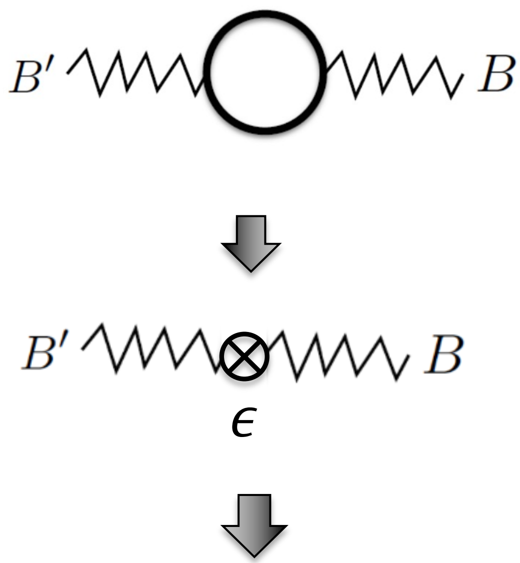
Higgs Portal $\mathcal{L} \supset -(AS + \lambda S^2) H^{\dagger} H,$

ALP Portal

$$\mathcal{L}_{\text{ALP}} \supset \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + i g_{aee} a \bar{e} \gamma^5 e + i a \bar{\psi}_N \gamma^5 (g^{(0)}_{ann} + g^{(1)}_{ann}) \psi_N,$$

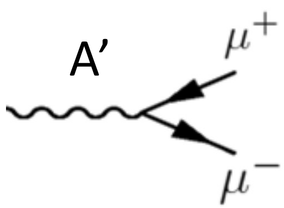
Vector Portal

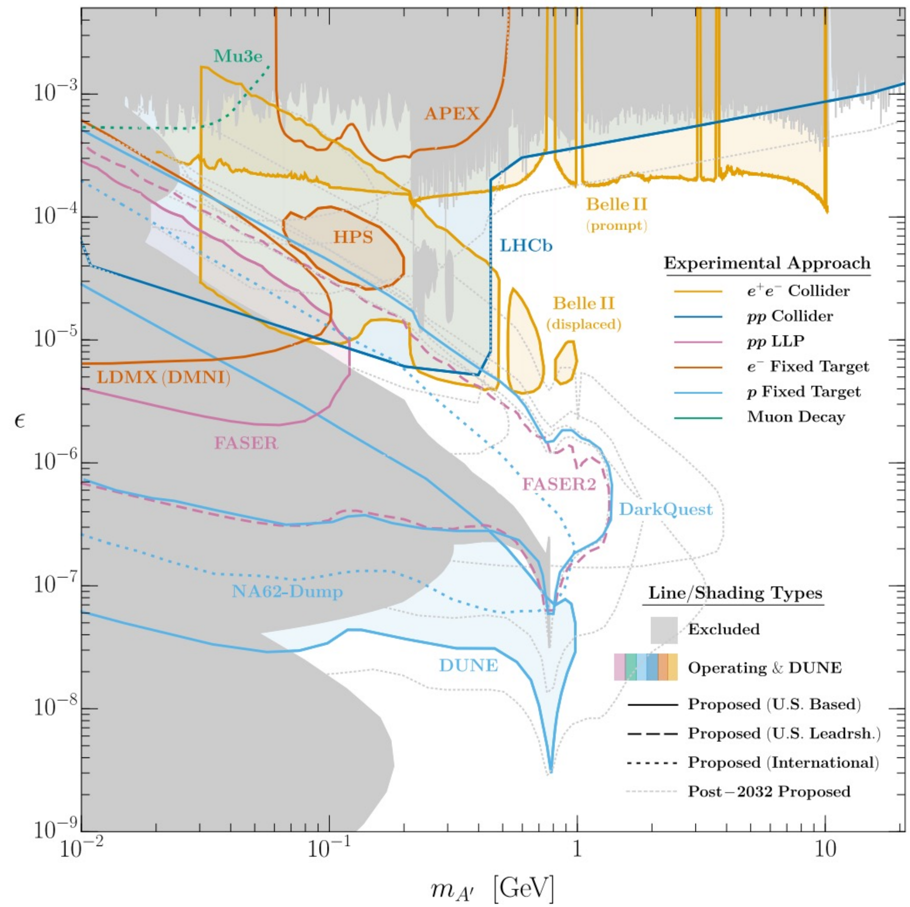
Vector Portal: Dark Photon



Dark photon A’:

mass basis

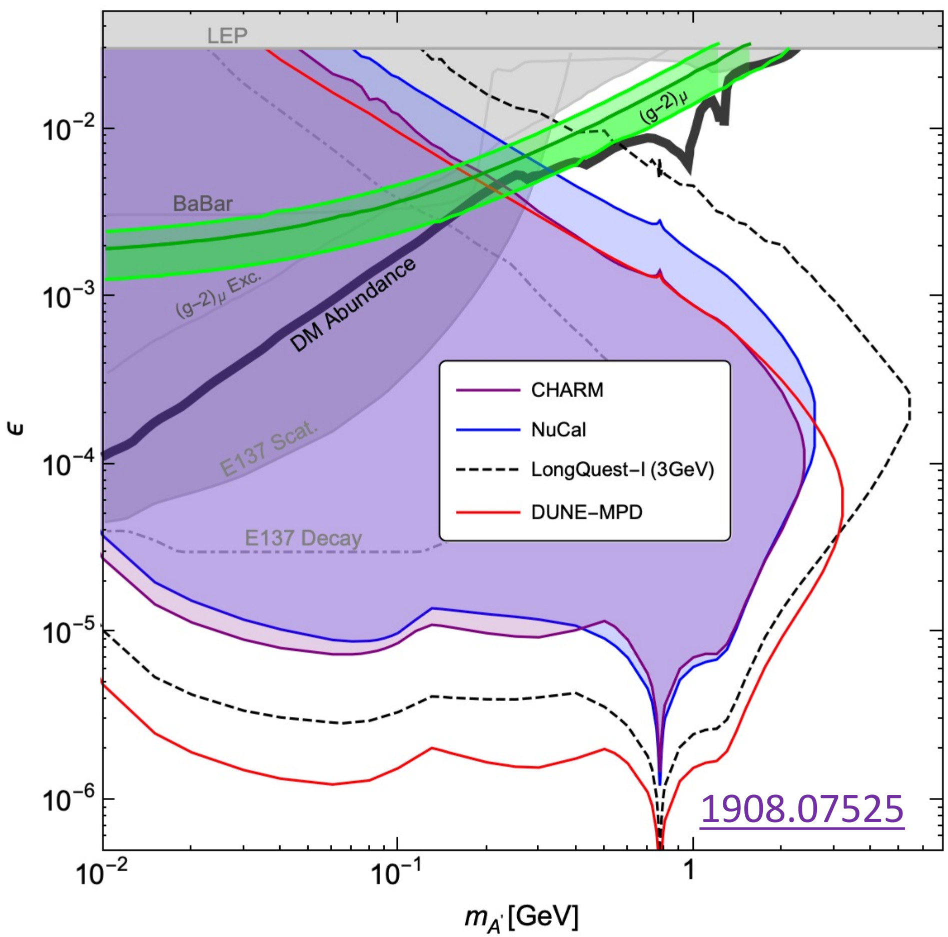




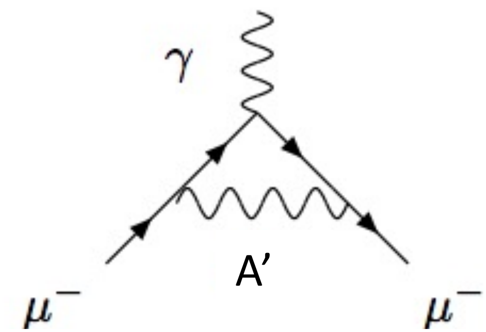
$$\mathcal{L}_{A'} = -\frac{\varepsilon}{2\cos\theta_W} A'_{\mu\nu} B^{\mu\nu} - \frac{1}{2} m_{A'} A'_{\mu} A'^{\nu}$$

- Batell, Blinov, Hearty, McGehee, 2207.06905
- See also **Tsai**, deNiverville, Liu, 1908.07525, PRL 21, for the **LongQuest** projections & CHARM / NuCal Updates

Inelastic Dark Matter
& Muon g-2 explainer

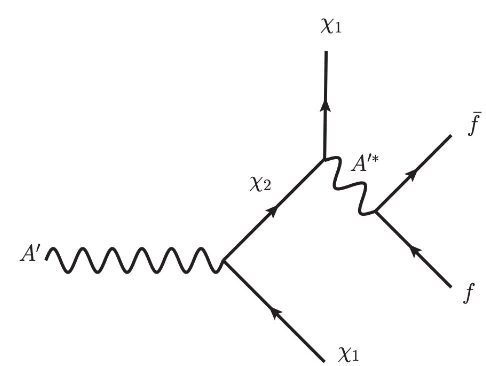


(a) iDM: $\Delta = 0.4$, α_D=0.1. With muon $g-2$ and DM regimes.
$m_{A'}/m_{x1}$ = 3, with preliminary DUNE results



$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{th} = (274 \pm 73) \times 10^{-11},$$

See, e.g., Fayet, 2007 (hep-ph/0702176)



- See also Mohlabeng PRD 20, arXiv:1902.05075

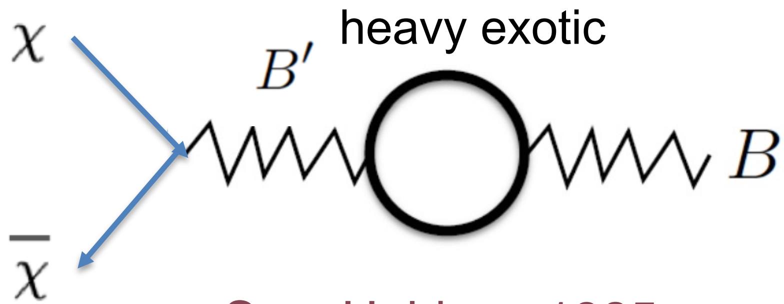
Millicharged Dark Sector

Motivations of Millicharged Particle & Dark Matter

- **Is electric charge quantized and why?** A long-standing question!
- SM U(1) allows arbitrarily small (any real number) charges.
  Why don't we see them? Motivates
  Dirac quantization, Grand Unified Theory (GUT), to explain such quantization
  (anomaly cancellations fix some SM $U(1)_Y$ charge assignments)
- MCP (not confined) is predicted by some Superstring theories:
  Wen, Witten, Nucl. Phys. B 261 (1985) 651-677
  https://www.youtube.com/watch?v=AmUI2qf9uyo (watch 15:50 to 17:28)
- Link to **string compactification** and **quantum gravity** (Shiu, Soler, Ye, PRL '13)

Kinetic Mixing and Millicharge Phase

- **Coupled to new dark fermion χ**



(SM: Standard Model)

See, Holdom, 1985

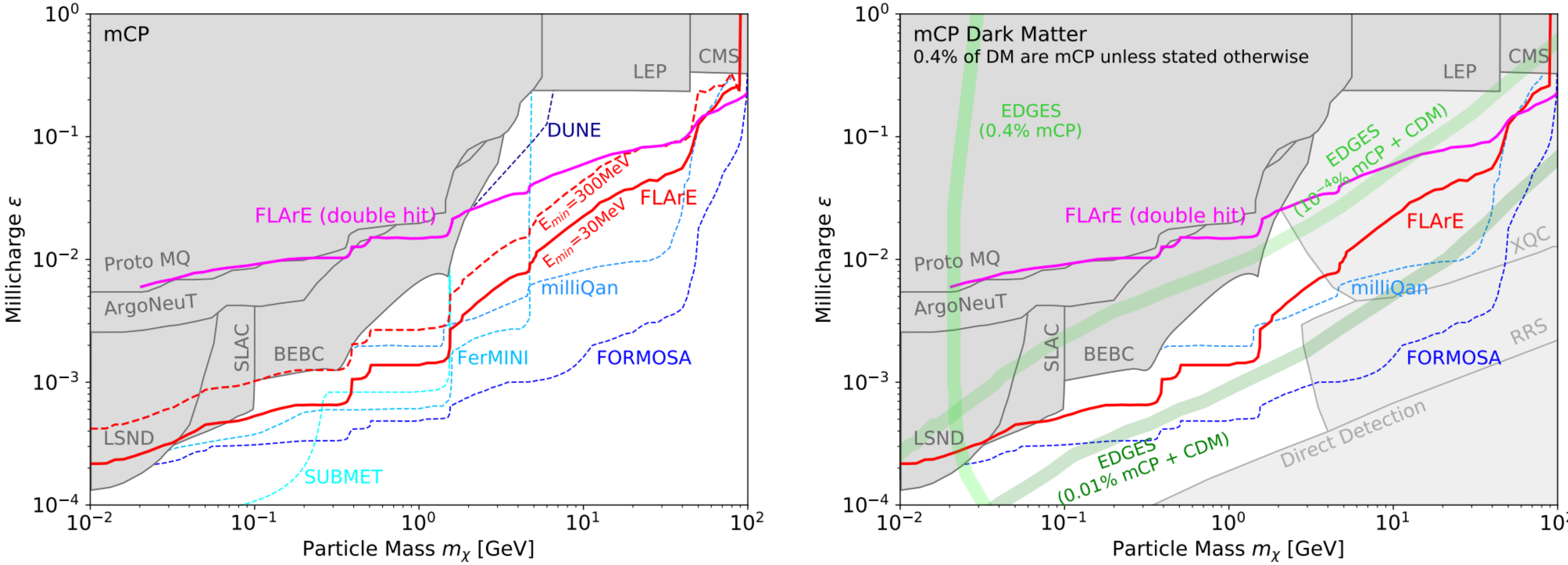
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ + ie' B\!\!\!/' + iM_{\rm MCP})\chi$$

- New fermion χ charged under new gauge boson B'.

- Millicharged particle (MCP) can be a **low-energy consequence** of **massless dark photon** (a new U(1) gauge boson) coupled to **a new fermion (become MCP** in a convenient basis.)

Yu-Dai Tsai, UC Irvine, 22

Millicharge Particles & Dark Matter

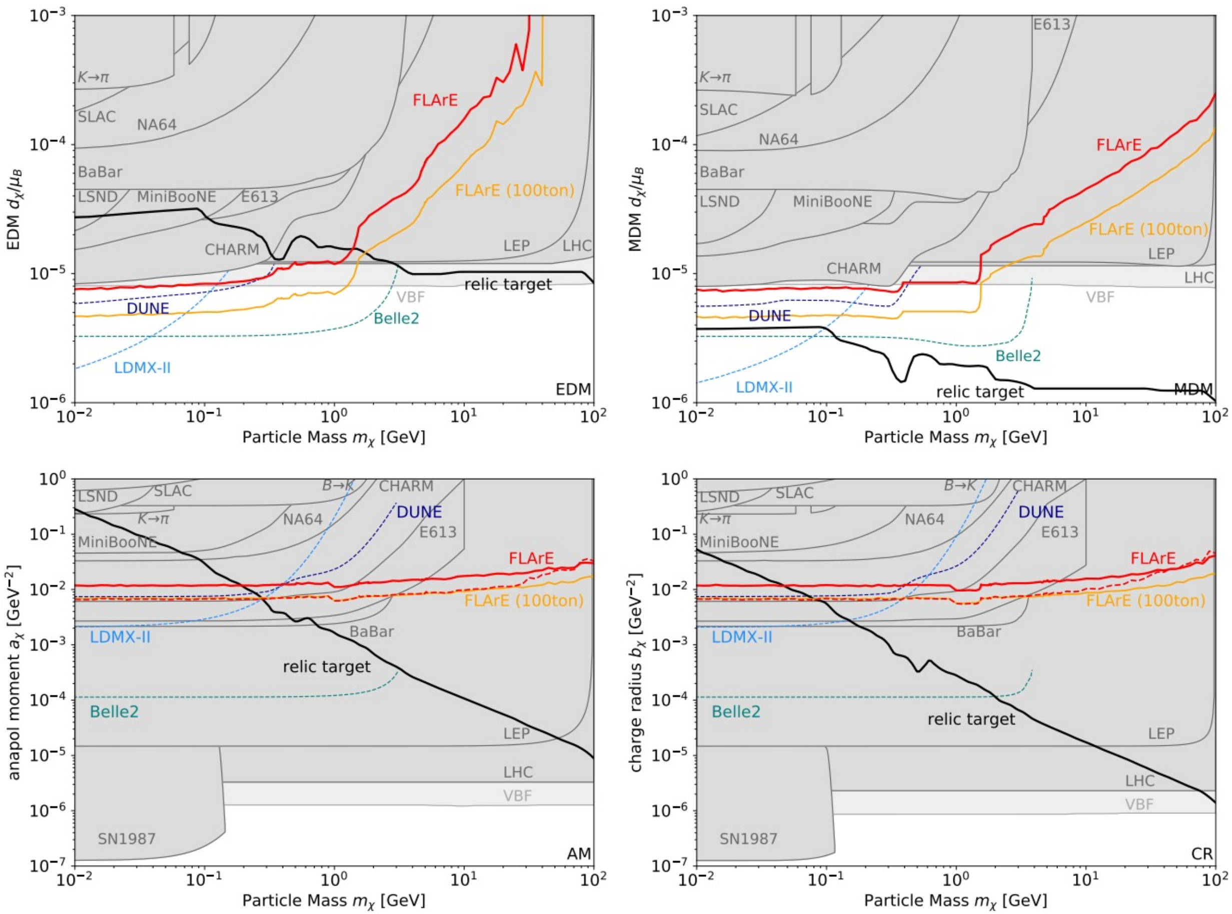


- Simply a search for particles with **{mass, electric charge}** = $\{m_\chi, \epsilon e\}$

  $\epsilon = Q_x/e$

- Cooling of gas temperature to explain the **EDGES anomaly** [EDGES collab., Nature, (2018); Barkana, Nature, (2018)].
  A small fraction of the DM as MCP can potentially explain EDGES observation of anomalous absorption of 21 cm spectrum

Dark Sector with other EM Form Factors



$$\mathcal{L}_\chi \supset \epsilon e\bar{\chi}\gamma^\mu\chi A_\mu + \frac{1}{2}\mu_\chi\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + \frac{i}{2}d_\chi\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$$
$$- a_\chi\bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu} + b_\chi\bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}\,,$$

Kling, Kuo, Trojanowski, and **Tsai,**
arXiv:2205.09137

Neutrino Portal

Heavy Neutral Lepton

$$\mathcal{L} \supset -y^\alpha L_\alpha H N + \text{h.c.},$$

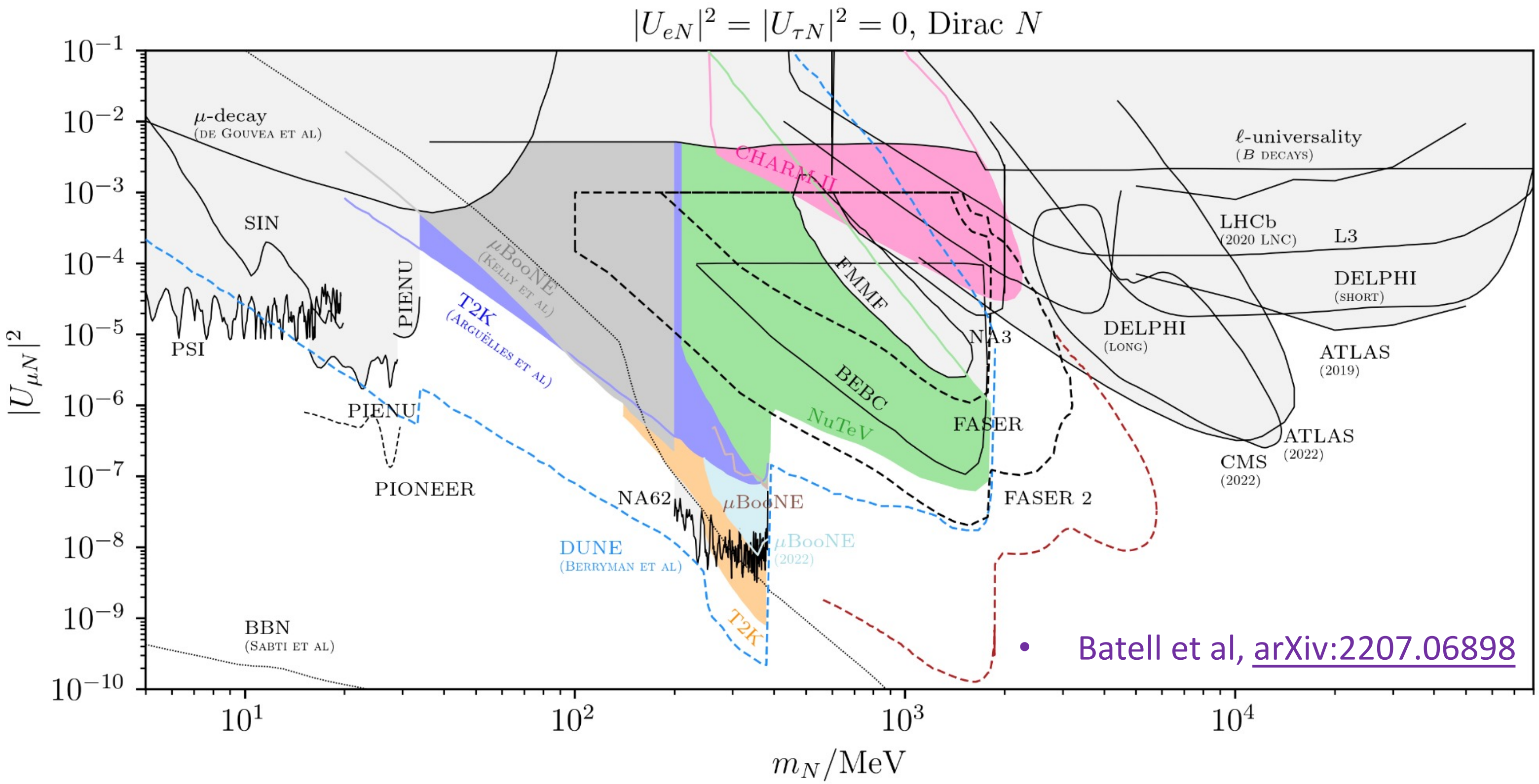
where y^α is a Yukawa coupling with $\alpha = e,\ \mu,\ \tau$.

- After EW symmetry breaking, the HNLs mix with the SM neutrinos
- Follow the convention of considering a single HNL that dominantly mixes with a specific neutrino flavor, i.e., dominant electron-, muon-, or tau- flavor mixing.
- Phenomenology characterized by the HNL mass, m_N , and mixing angle:

  $|U_{eN}|$^2 , $|U_{\mu N}|$^2 , $|U_{\tau N}|$^2

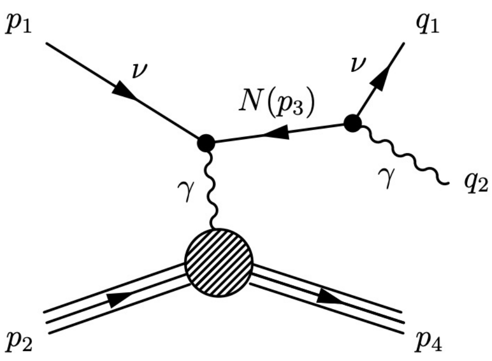
  See, e.g., Snowmass Whitepaper, Batell et al, arXIv:2207.06905

Heavy Neutral Lepton

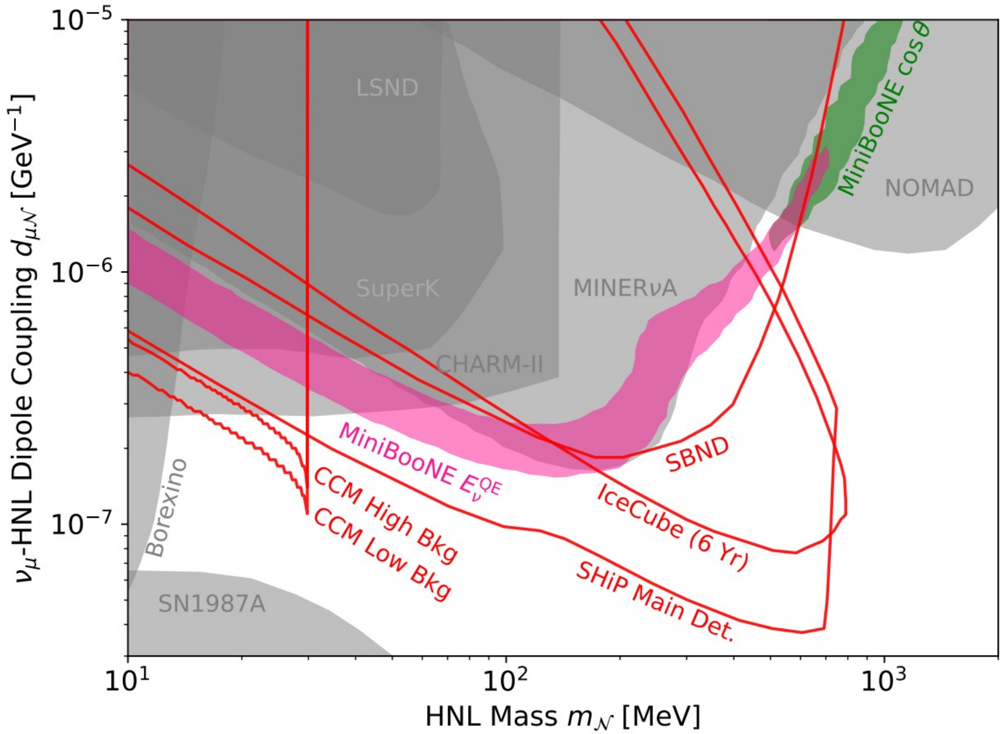


- Batell et al, arXiv:2207.06898

Dipole Portal Heavy Neutral Lepton



Magill, Plestid, Pospelov, **Tsai**, PRD 18, arXiv:1803.03262

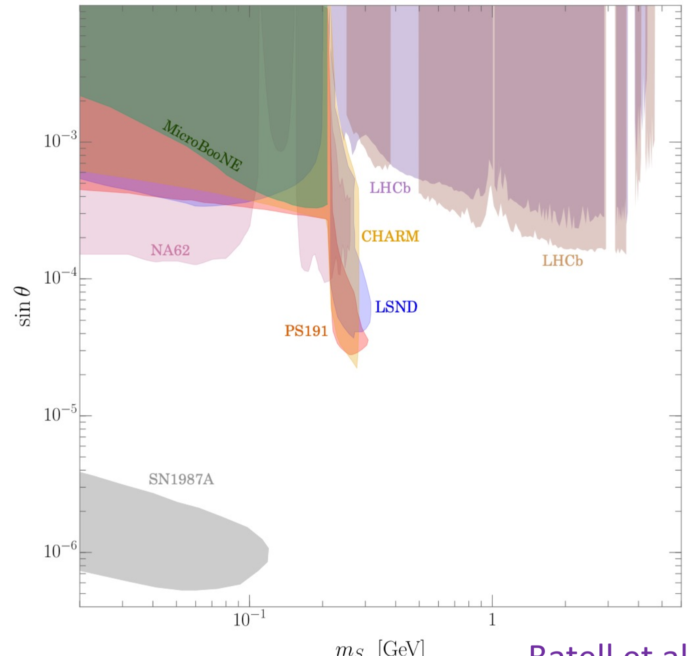


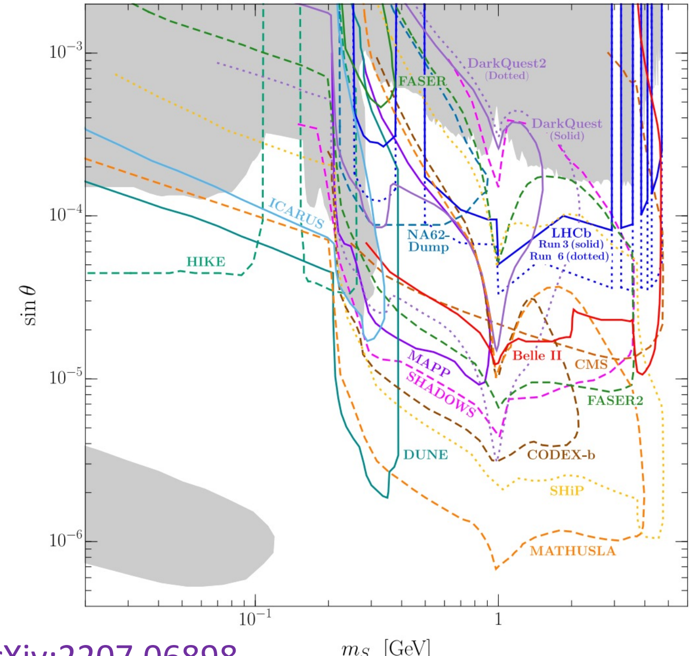
New Fig from Kamp; Ref: Batell, …, **Tsai**, arXiv:2207.06898;

$$\mathcal{L} \supset \bar{N}(i\partial\!\!\!/ - m_N)N + (d\bar{\nu}_L\sigma_{\mu\nu}F^{\mu\nu}N + h.c).$$

Higgs & ALP Portal

Higgs Portal



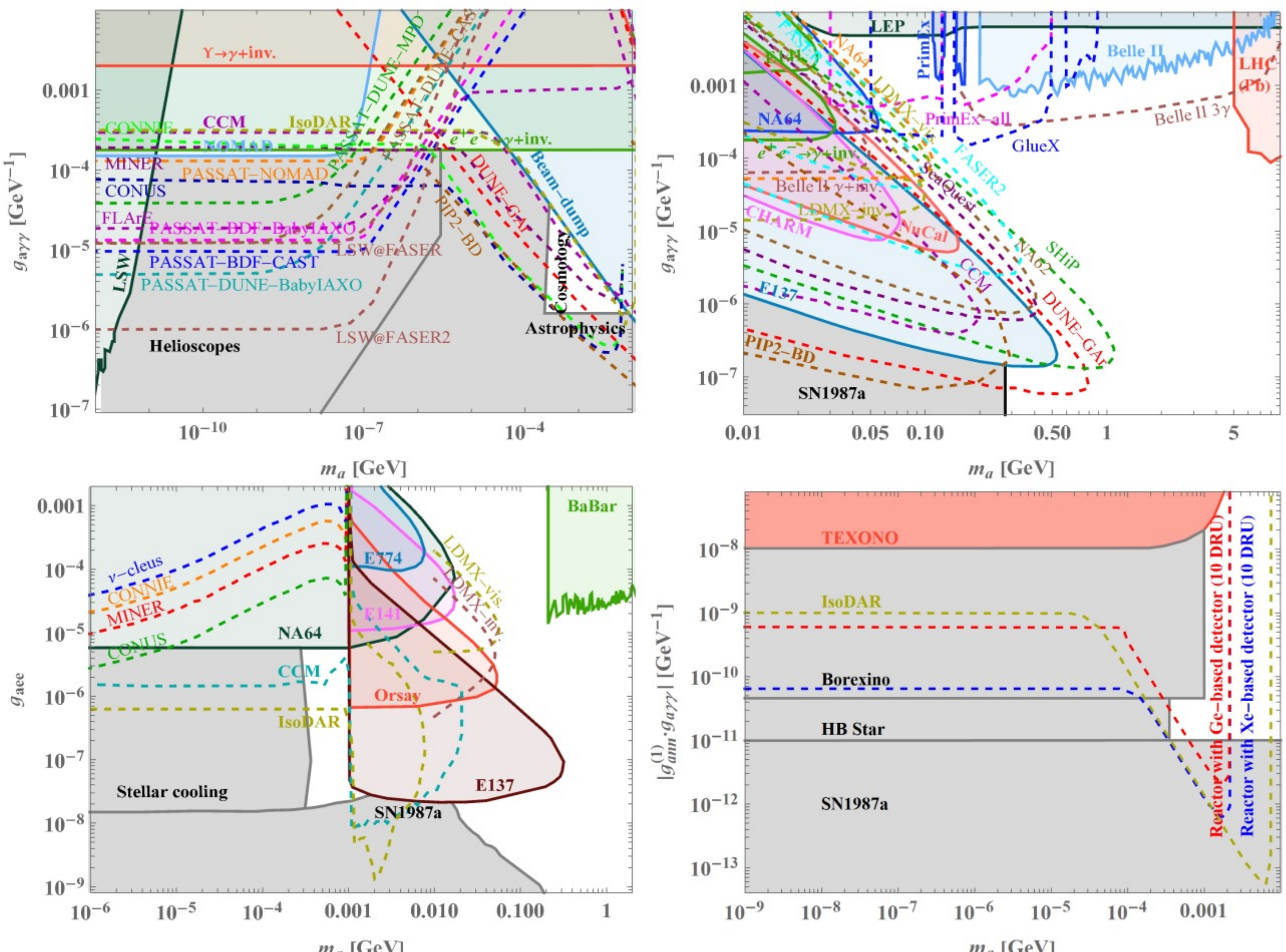


Batell et al, arXiv:2207.06898

$$\mathcal{L} \supset \sin\theta\, S \left(\frac{2m_W^2}{v} W_\mu^+ W^{\mu-} + \frac{m_Z^2}{v} Z_\mu Z^\mu - \sum_f \frac{m_f}{v} \bar{f} f \right),$$

Yu-Dai Tsai, UC Irvine, 22

ALP Portal



Batell et al, arXiv:2207.06898

$$\mathcal{L}_{\rm ALP} \supset \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + i g_{aee} a \bar{e} \gamma^5 e \ + \ldots$$

Summary & Outlook

- **Intensity searches** provide strong probes of rich dark sector motivated by **dark matter** and **experimental anomalies**
- One of the **main efforts for our community** in the next 5 to 10 years.
- Explore other models with other **theory motivations & beyond the simplified models**: connecting to **string theory, grand unification theory, early universe cosmology**, etc.
- Models with also signatures in **cosmological measurements, direct detection, and astrophysical observations**, are prime targets for the future

Thank you!

Special thanks to my collaborators and the organizers of CIPANP