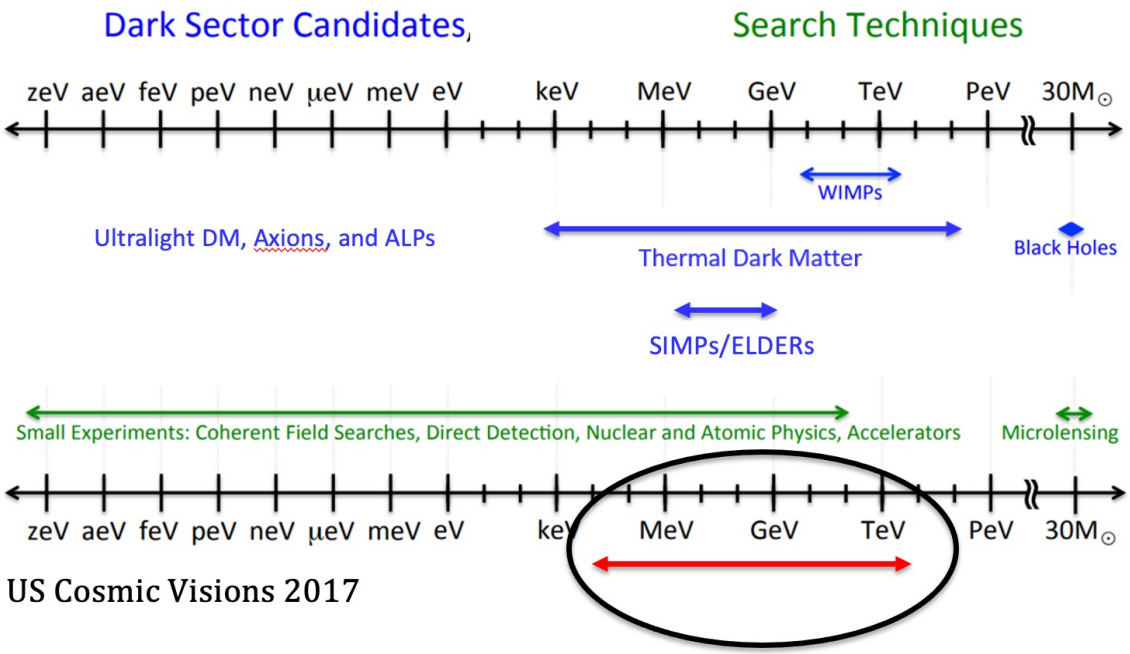
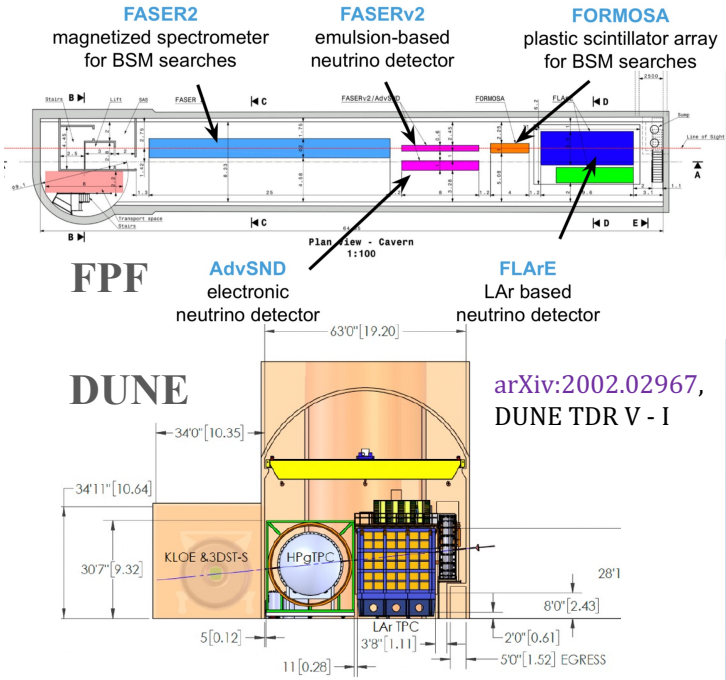




Dark Sector in High-Intensity Experiments

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

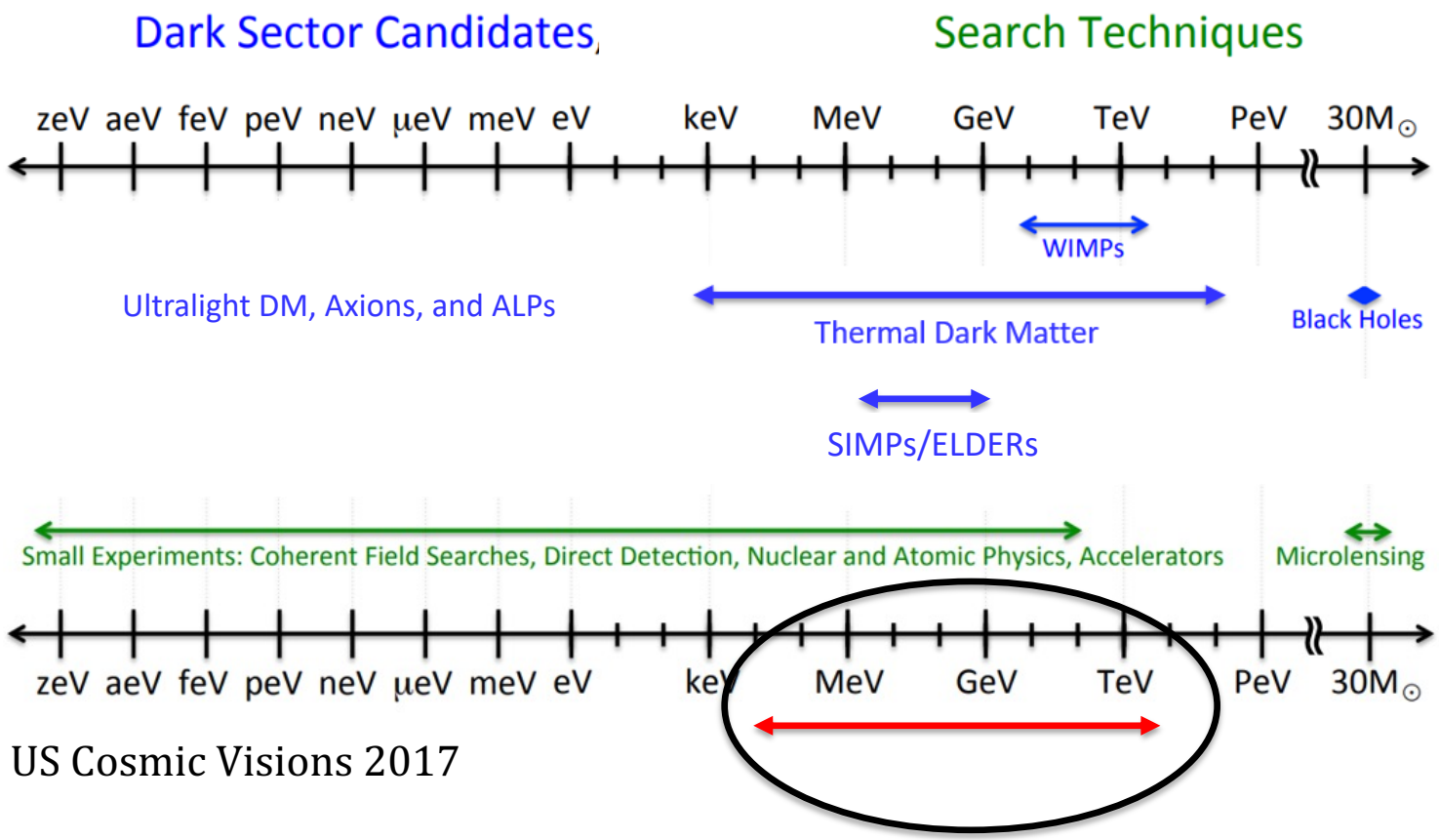
Outline

- Why study “dark sector” theories?

  Why sub-MeV to GeV+ region?

  Why accelerator (intensity) probes?
- Intro to dark sector “portals”, dark matter, and anomaly motivated models
- Search overview: accelerator experiments
- Search overview: large (neutrino) observatories

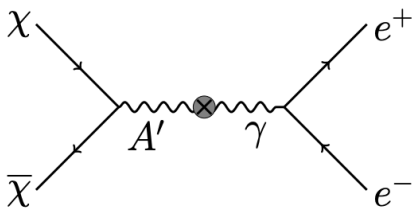
Exploration of Dark Matter & Dark Sector



US Cosmic Visions 2017

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

Thermal Dark Matter & The Rise of Dark Sector



From Krnjaic

- The Lee-Weinberg bound (1977'): below $\sim 2\ \mathbf{GeV}$, DM freeze-out through weak-Interaction (e.g. through Z-boson) would overclose the Universe (**not strong enough!!**).

- 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).

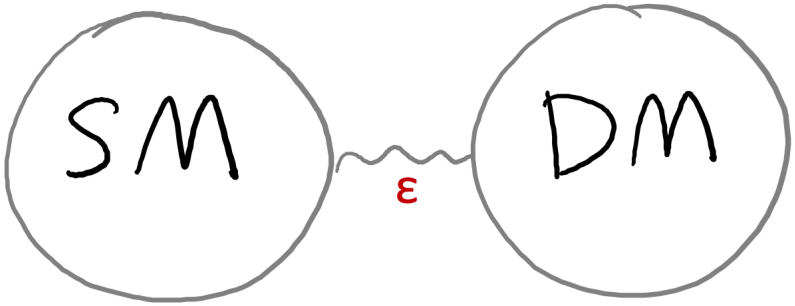
- Neutrino experiments can probe both **mediators** & **dark matter**

“Portal” Particles

- **Renormalizable interactions.**

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

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



Why study sub-MeV – GeV+ region?

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 **sub-MeV - GeV+** Explanations

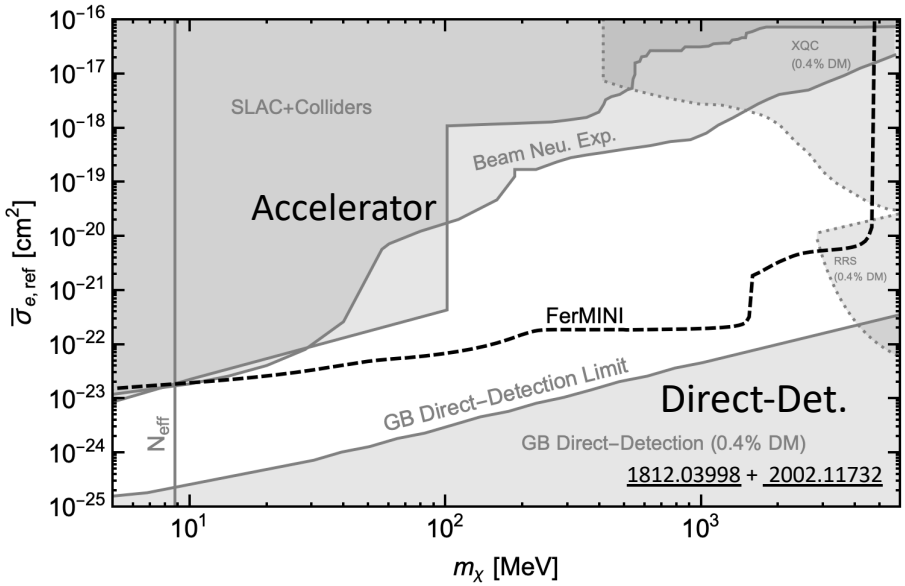
⋮

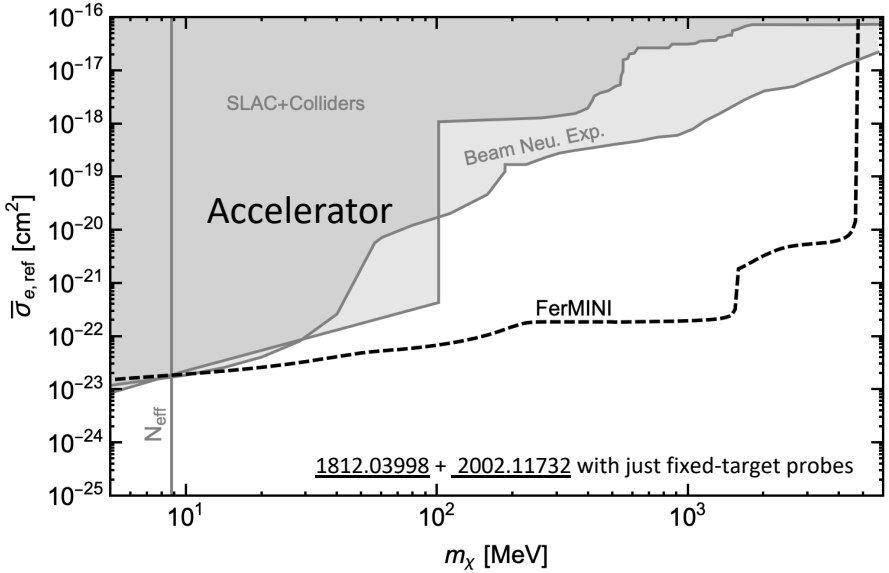
- **Muon g-2 anomaly**
- **LSND & MiniBooNE anomaly**
- **EDGES result**
- KOTO anomaly
- Beryllium anomaly

⋮

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

Advantage of Accelerator (Intensity) Searches: Robust Probes & Constraints





Also consider **ambient dark matter**

Produce dark particles in collisions

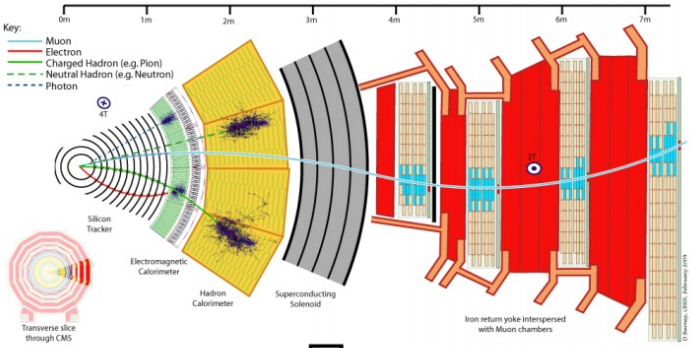
Same mass and interaction strength.

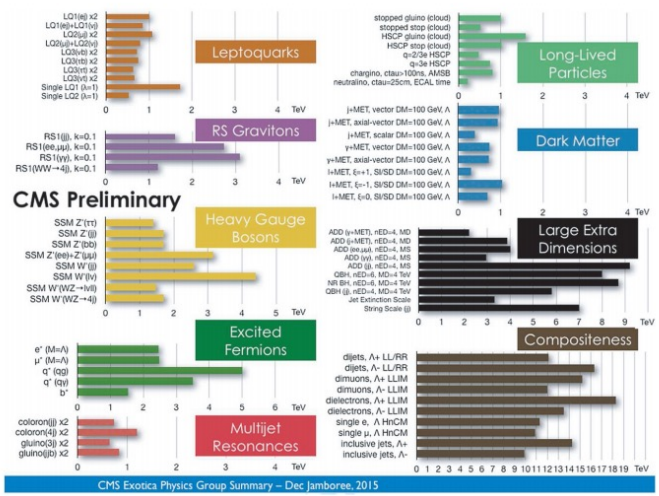
Different assumptions

Some details of these figures will be explained later

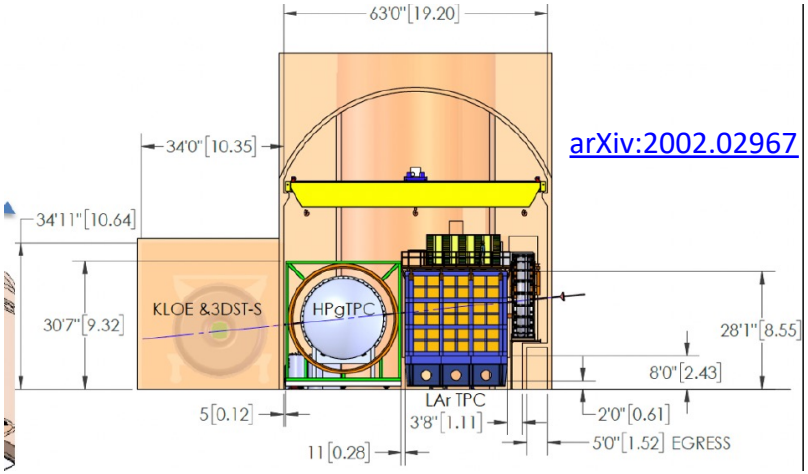
Energy vs Intensity Frontier

High energy frontier





Intensity frontier



arXiv:2002.02967

https://indico.fnal.gov/event/18430/session/8/contribution/17

redesigned from Roni Harnik's slide

Benchmark Models for Dark-Sector Searches

Snowmass RF06 Classification

Benchmarks in Final State x Portal Organization

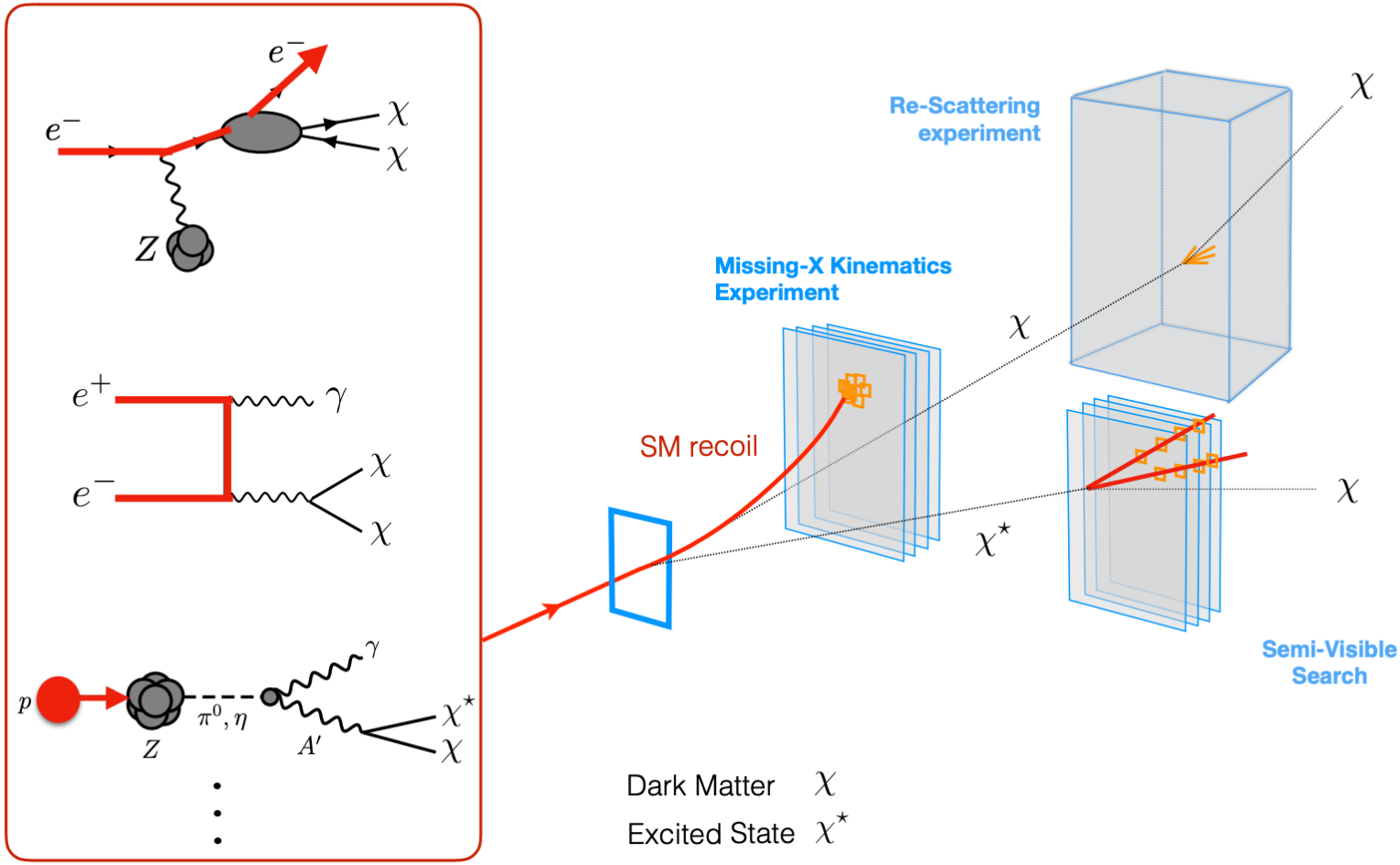
	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	*m_χ vs. y [m_A/m_χ=3,α_D=.5]* **$m_{A'}$ vs. y** [α_D=0.5, 3 m_χ values] m_χ vs.α_D [$m_{A'}/m_\chi$=3, y=y_{fo}] m_χ vs. m_A [α_D=0.5, y=y_{fo}] *Millicharge m vs. q*	$m_{A'}$ vs. ϵ [decay-mode agnostic] ***$m_{A'}$ vs. ϵ [decays]***	**iDM m_χ vs. y [$m_{A'}/m_\chi$=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. Underline=CV benchmarks that were not used in BRN

PBC: The Physics Beyond Colliders initiative at CERN

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

Mimicking Big Bang Dark Matter Production at Accelerators



Krnjaic, Toro, et al, arXiv:2207.00597

YT is charge of the millicharged section, if you have any questions/suggestions regarding that section, (e.g., BDX, see Smith' talk tomorrow)

Overview of benchmark models

Interesting models include:

1. Deep Theoretical Motivations
2. Thermal Dark Matter
3. Explain Anomalies
4. Connect to Cosmological or Astrophysical Measurements

Portal Particles, Dark Matter, & Anomalies

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

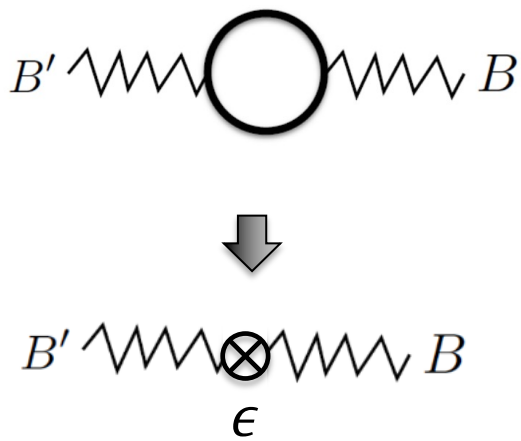
$$\mathcal{L}_{\text{ALP}} \supset \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + i g_{aee} a \bar{e} \gamma^5 e + i a \bar{\psi}_N \gamma^5 (g^{(0)}_{ann} + g^{(1)}_{ann}) \psi_N,$$

- I will discuss cosmogenic ALP in large neutrino observatories

Vector Portal

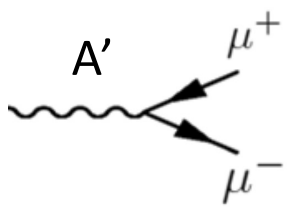
Yu-Dai Tsai, UC Irvine, 22

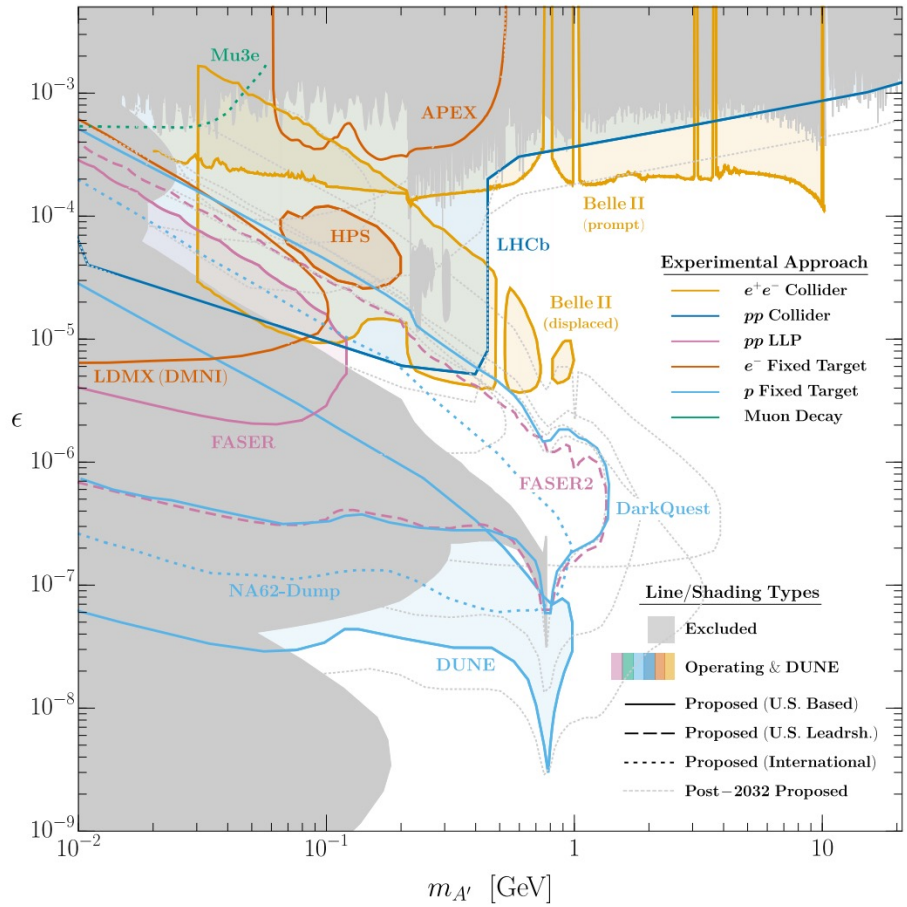
Vector Portal: Dark Photon



Dark photon A':

mass basis

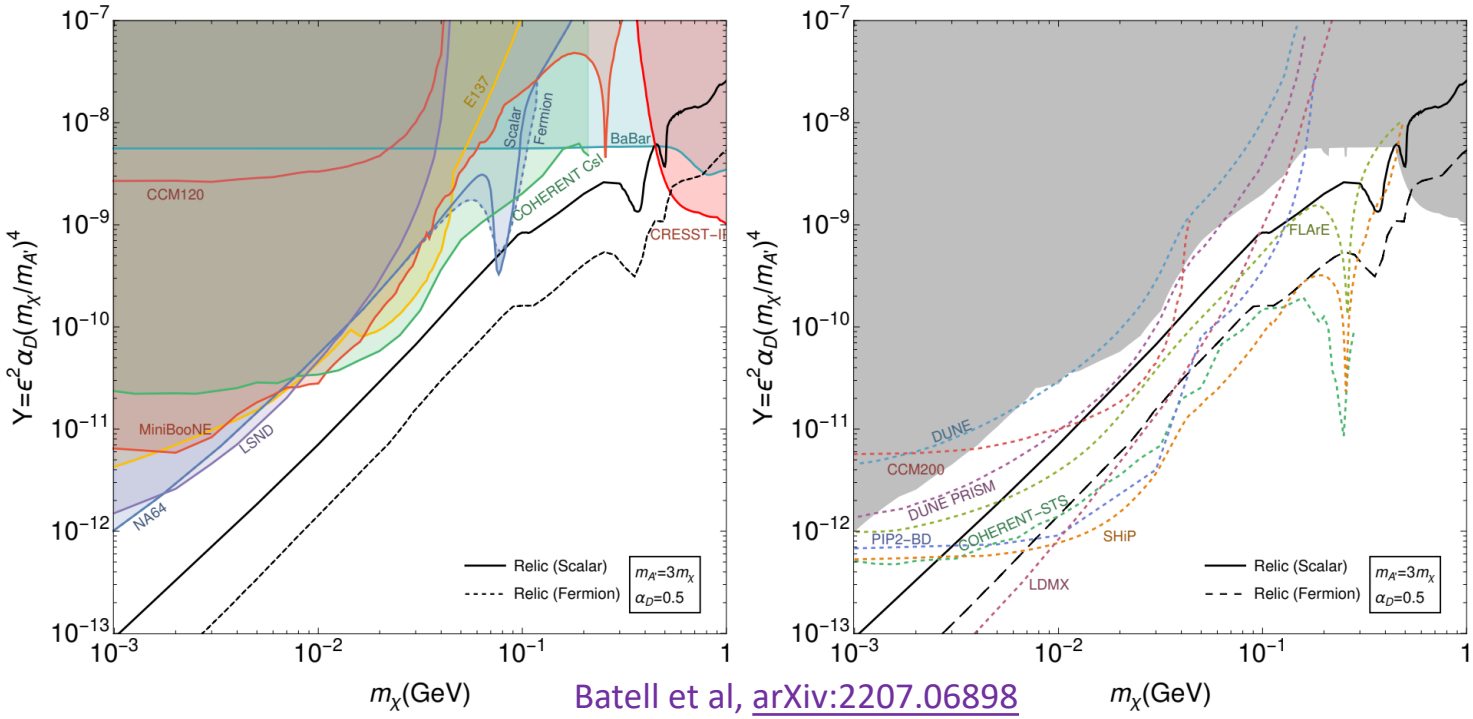




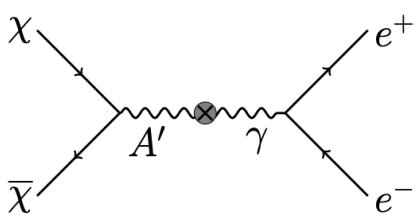
$$\mathcal{L}_{A'} = -\frac{\varepsilon}{2\cos\theta_W} A'_{\mu\nu} B^{\mu\nu} - \frac{1}{2} m_{A'} A'_\mu A'^\nu$$

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

Vector Portal Dark Matter



Batell et al, arXiv:2207.06898



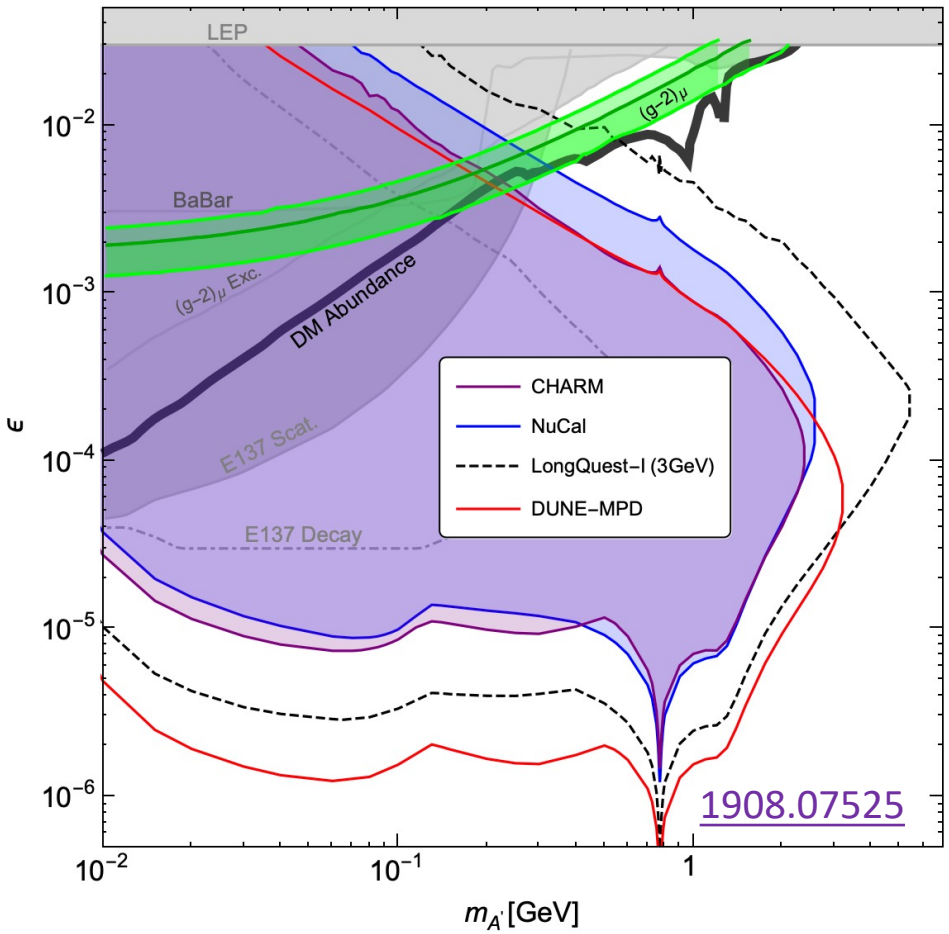
From Krnjaic

$$\mathcal{L}_\chi = i g_D A'^\mu J^\chi_\mu + \partial_\mu \chi^\dagger \partial^\mu \chi - m_\chi^2 \chi^\dagger \chi,$$

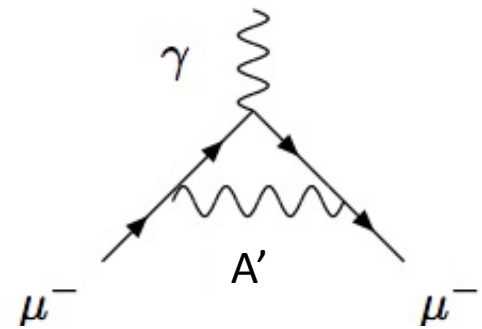
$$J^\chi_\mu = [(\partial_\mu \chi^\dagger)\chi - \chi^\dagger \partial_\mu \chi]$$

$$\alpha_D \equiv g_D^2/4\pi$$

Inelastic Dark Matter & Muon g-2 explainer



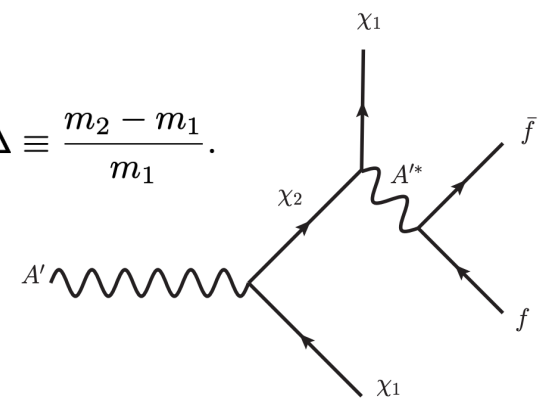
(a) iDM: $\Delta = 0.4$, α_D=0.1. With muon $g-2$ and DM regimes.
$m_{A'}/m_{x1}$ = 3, with preliminary DUNE results



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

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

$$\Delta \equiv \frac{m_2 - m_1}{m_1}.$$



- See also Mohlabeng PRD 20, arXiv:1902.05075

Millicharged Dark Sector

Yu-Dai Tsai, UC Irvine, 22

Motivations of Millicharged Particle & Dark Matter

- **Is electric charge quantized and why?** A long-standing question!

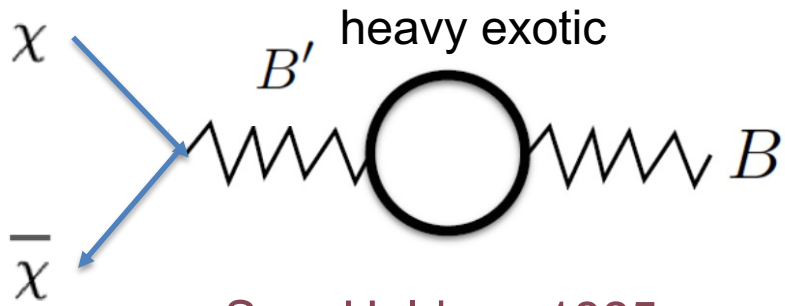
- SM U(1) allows arbitrarily small (any real number) charges.
  Why don't we see them? Motivates
  Dirac quantization, Grand Unified Theory (GUT), to explain such quantization
  (anomaly cancellations fix some SM $U(1)_Y$ charge assignments)

- 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)

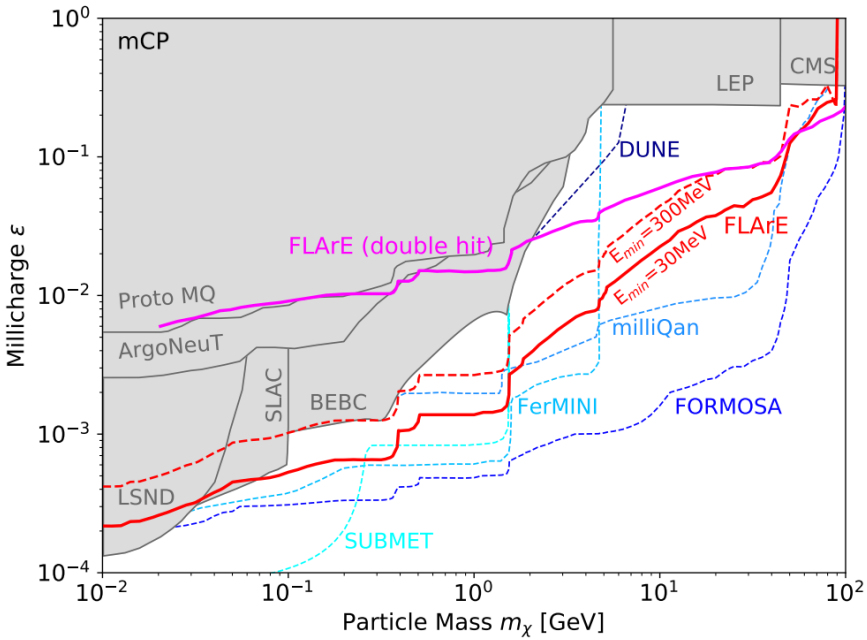
See, Holdom, 1985

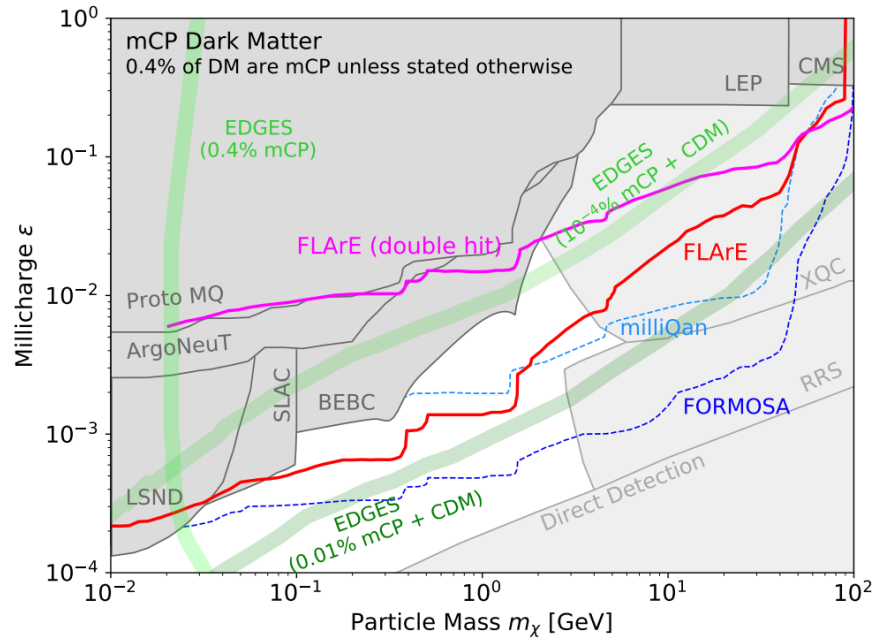
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu} + i\bar{\chi}(\not{\partial} + ie'\not{B}' + iM_{\rm MCP})\chi$$

- 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.)

Millicharge Particles & Dark Matter



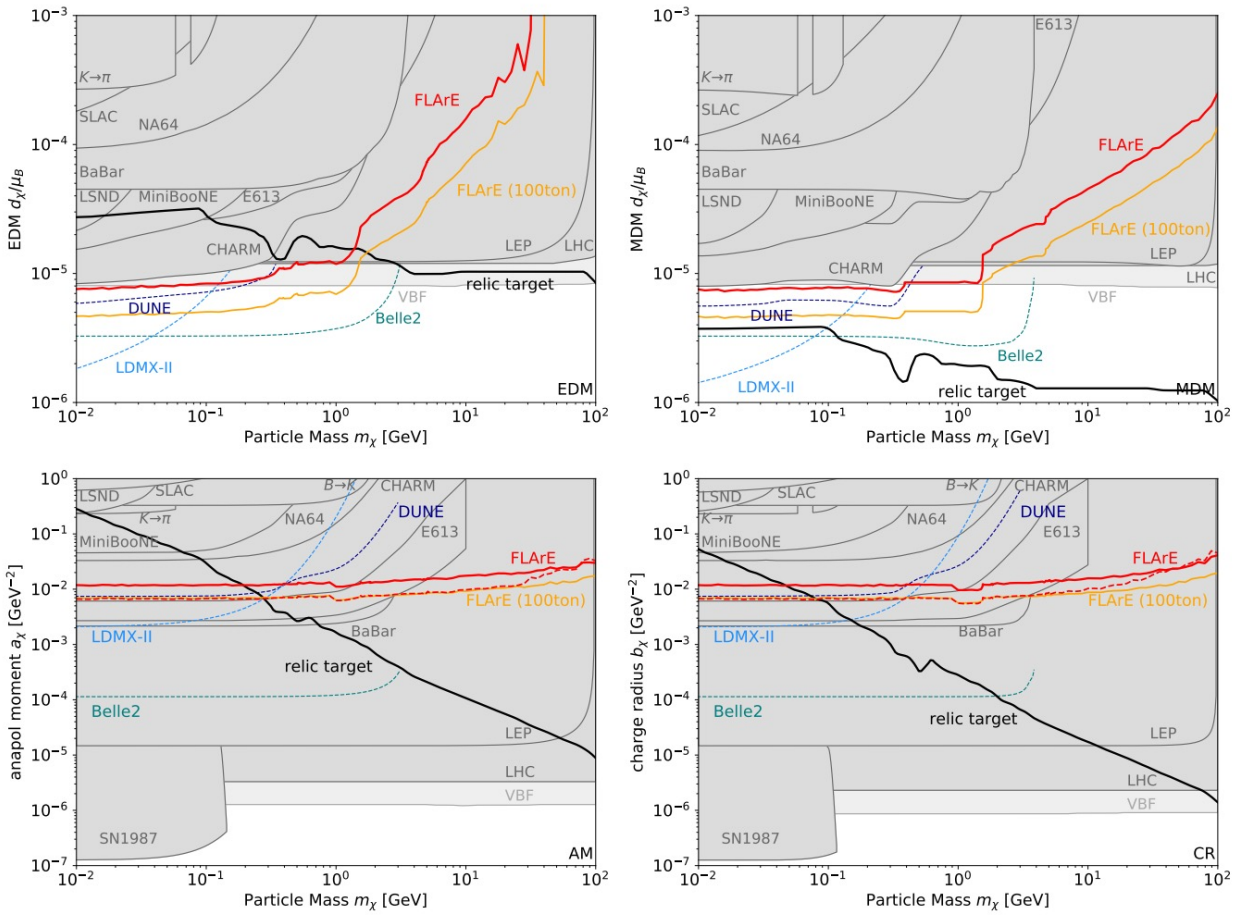


- Simply a search for particles with **{mass, electric charge}** = $\{m_\chi, \epsilon e\}$

  $\epsilon = Q_x/e$

- Probes include our works on Neutrino Experiments: Magill, Plestid, Pospelov, **Tsai,** arXiv:1806.03310, PRL19;
  Neutrino Observatories: Plestid, Takhistov, **Tsai**, et al, arXiv:2002.11732, PRD20;
  FORMOSA: Foroughi-Abari, Kling, **Tsai,** arXiv:2010.07941, PRD 21;
  FLArE: Kling, Kuo, Trojanowski, **Tsai**: arXiv:2205.09137

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

Yu-Dai Tsai, UC Irvine, 22

Heavy Neutral Lepton

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

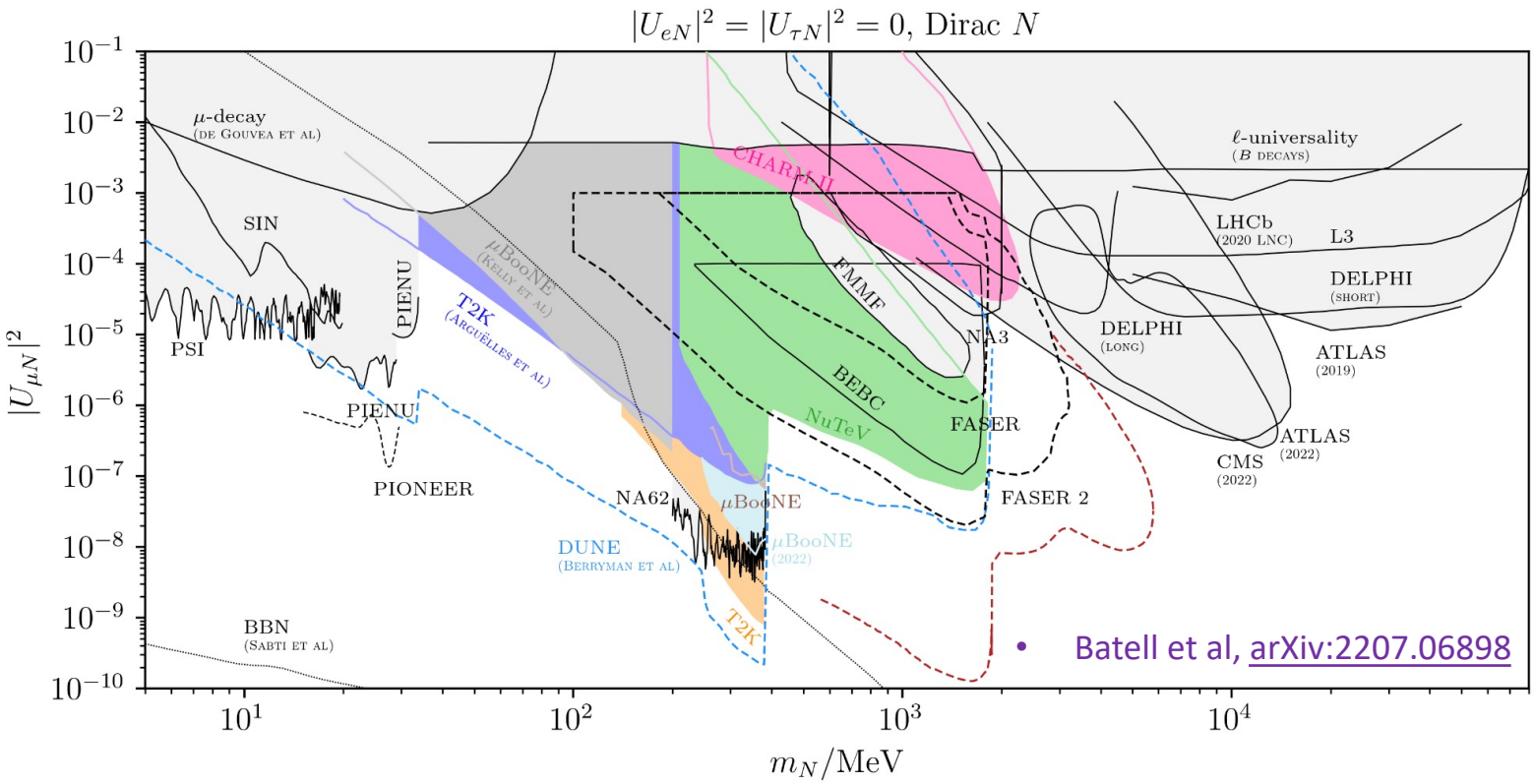
where y^{α} is a Yukawa coupling with $\alpha = e, \mu, \tau$.

- 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

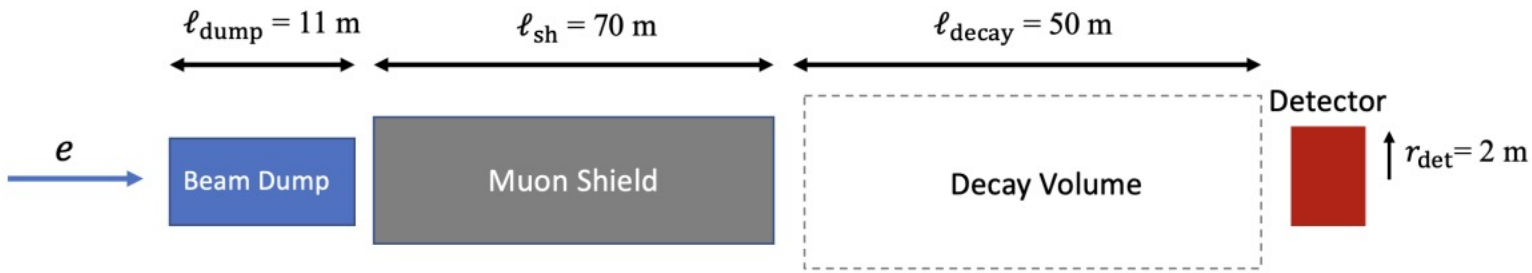
  See, e.g., Snowmass Whitepaper, Batell et al, arXIv:2207.06905

Heavy Neutral Lepton

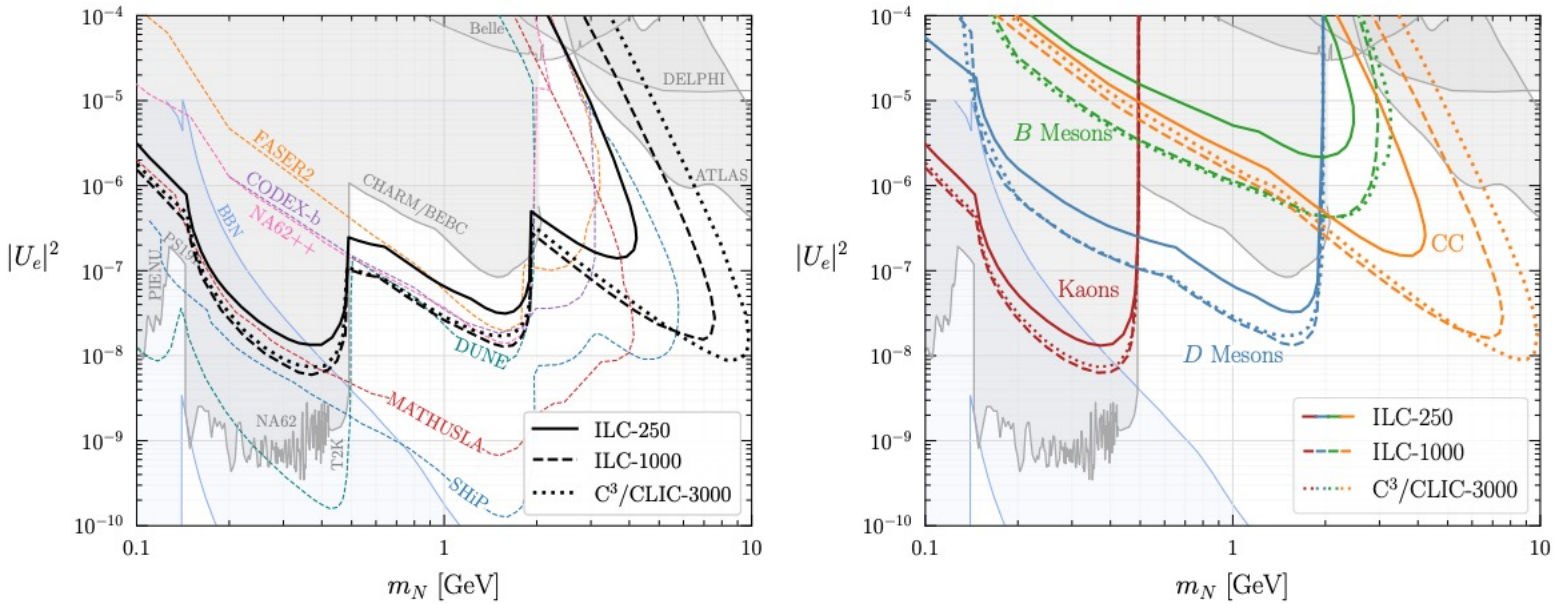


- Batell et al, arXiv:2207.06898

Electron Collider Beam-Dump Searches for HNL

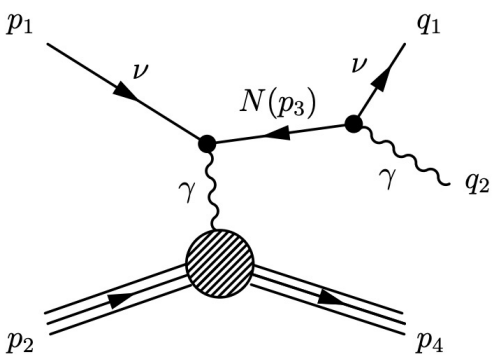


Can be designed for other e +e − colliders as ILC, C3 , CLIC, FCC-ee, and CEPC.

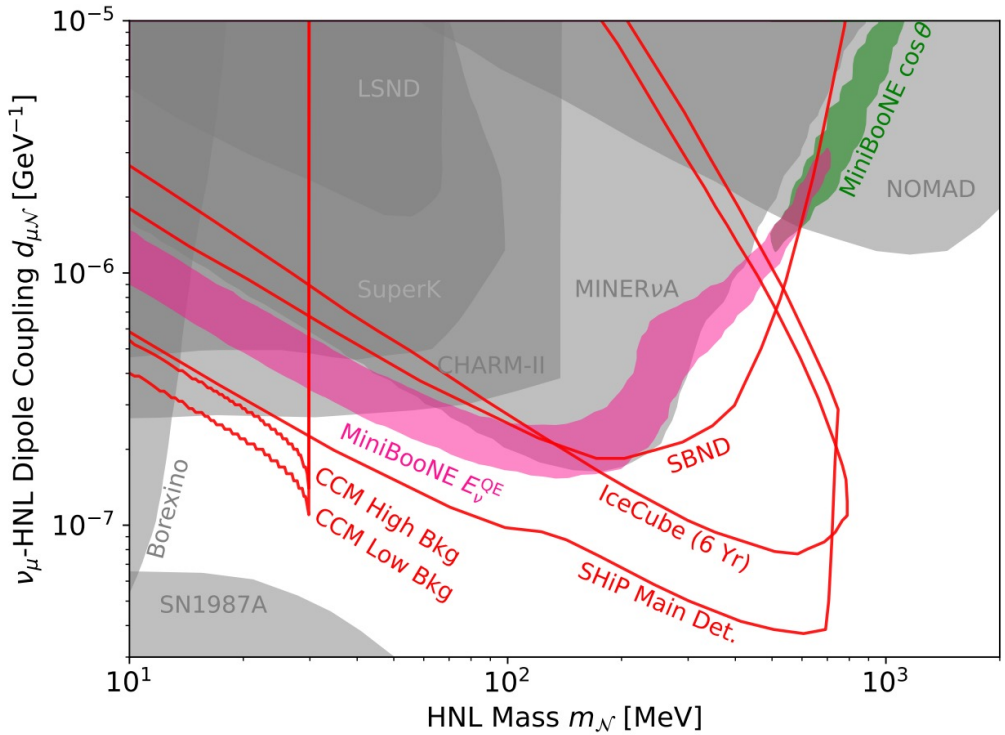


- Giffin, Gori, **Tsai**, Tuckler, arXiv:2206.13745
- Nojiri, Sakaki, Tobioka, Ueda, arXiv:2206.13523

Dipole Portal Heavy Neutral Lepton



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



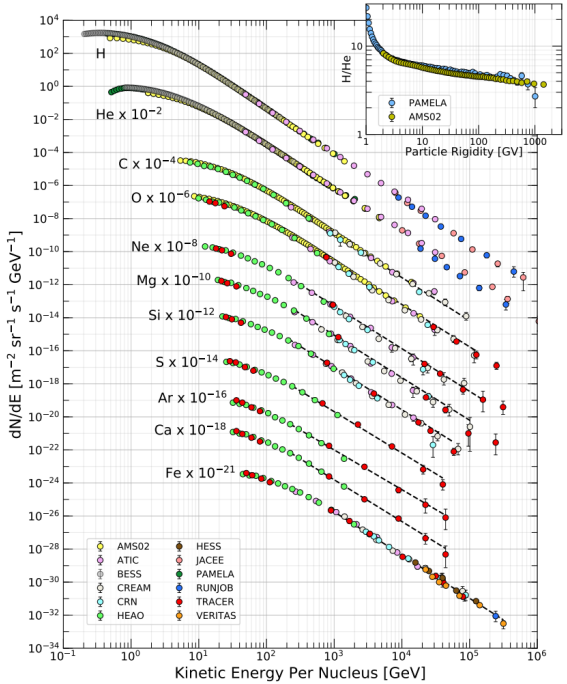
New Fig from Kamp; Ref: Batell, …, **Tsai**, arXiv:2207.06898;

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

Searches in Large Neutrino Observatories

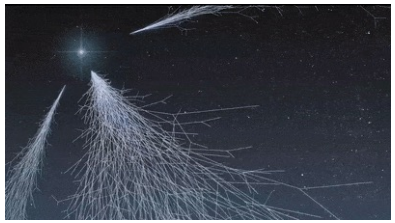
Yu-Dai Tsai, UC Irvine, 22

Millicharge Searches at Neutrino Observatories

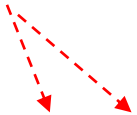


PDG, RPP, 2019

by Chantelauze, Staffi, and Bret

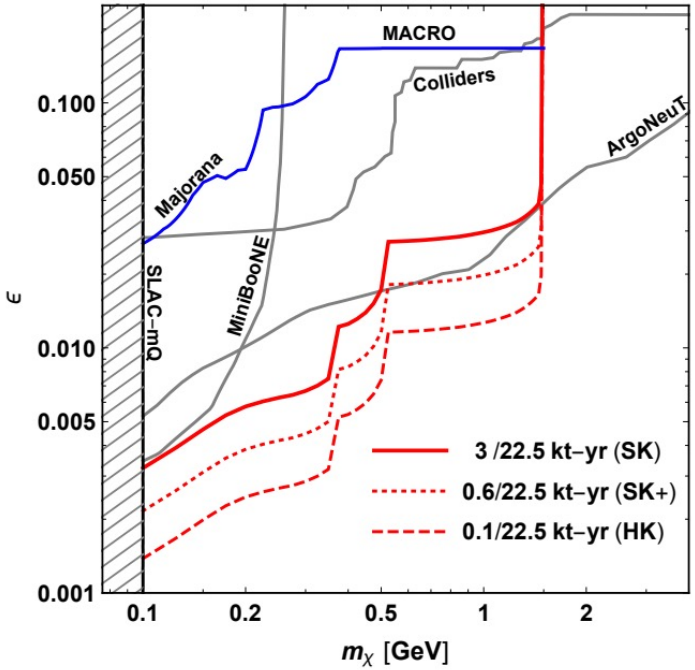


https://www.futurelearn.com/info/courses/learn-about-weather/0/steps/39415



$\chi \quad \bar{\chi}$

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

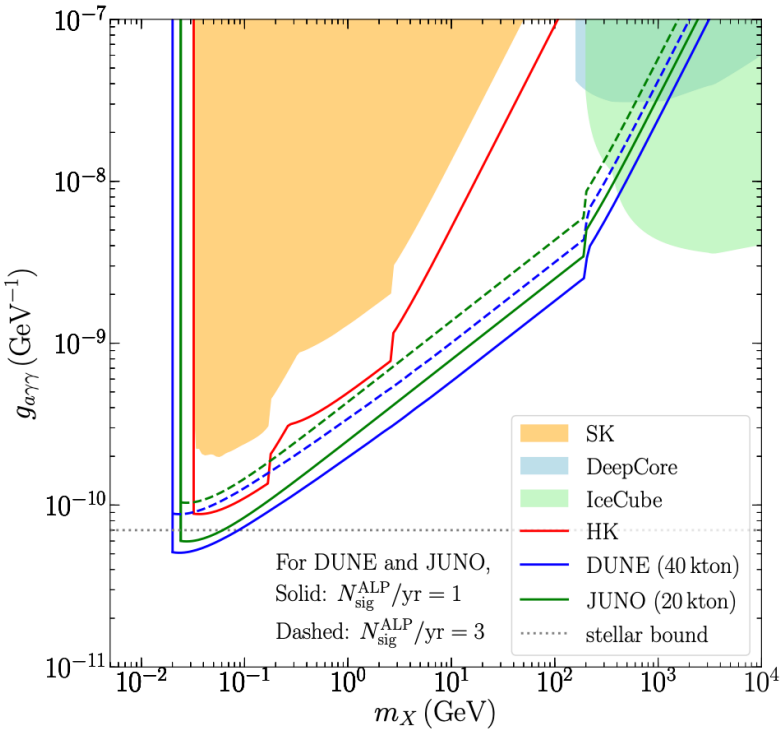


arXiv:2002.11732 (Plestid, Takhistov, **Tsai**, Bringmann, Kusenko, Pospelov, PRD 20)

1111.5031, Super-K Collaboration, PRD12

Supernova Relic Neutrino Search at Super–K

Cosmogenic Axion-Like Particles (ALP) at Neutrino Observatories



$$\mathcal{L}_{\rm ALP} \supset \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Cui, Kuo, Pradler, and **Tsai**, arXiv:2207.13107

Interesting models include

1. Deep Theoretical Motivations
2. Thermal Dark Matter
3. Explain Anomalies
4. Connect to Cosmological or Astrophysical Measurements

Yu-Dai Tsai, UC Irvine, 22

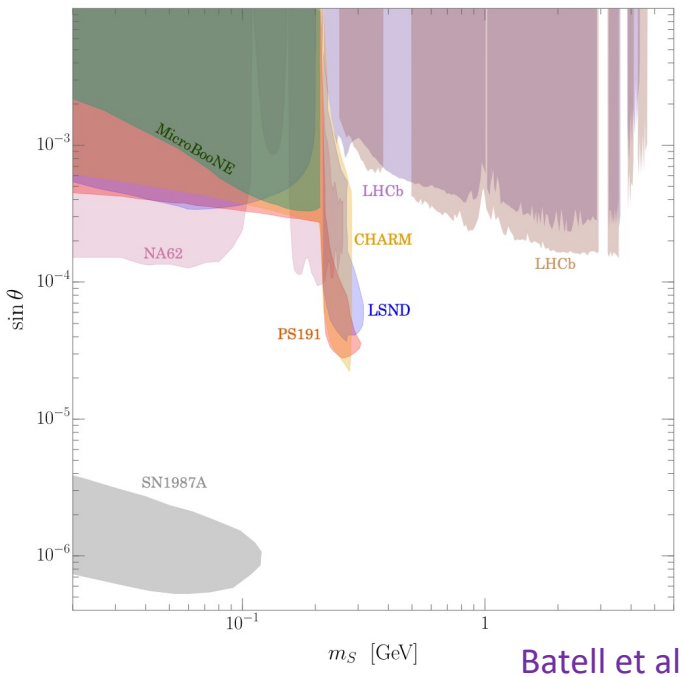
Summary & Outlook

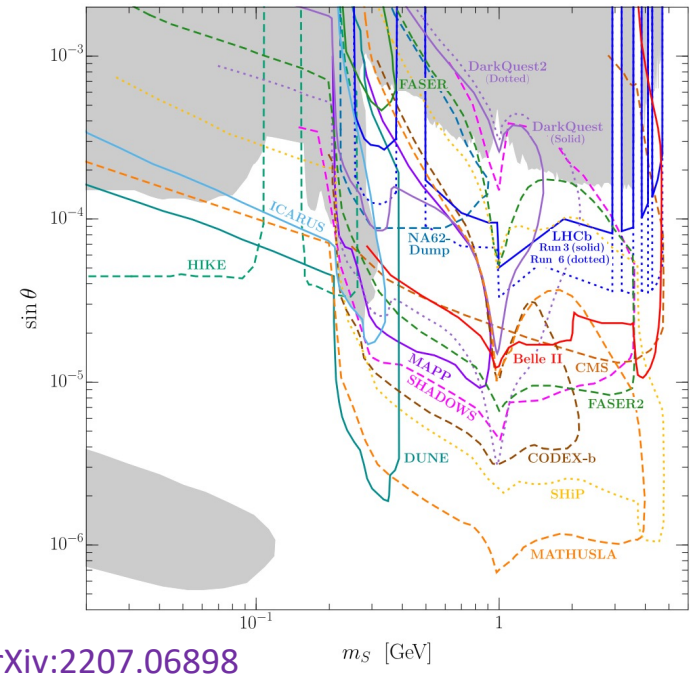
- **Intensity searches** provide strong probes of rich dark sector motivated by **dark matter** and **experimental anomalies**
- One of the **main efforts for our community** in the next 5 to 10 years.
- Explore other models with other **theory motivations & beyond the simplified models**: connecting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

Higgs & ALP Portal:

Both have very interesting dark matter phenomenology; only show minimal models here

Higgs Portal

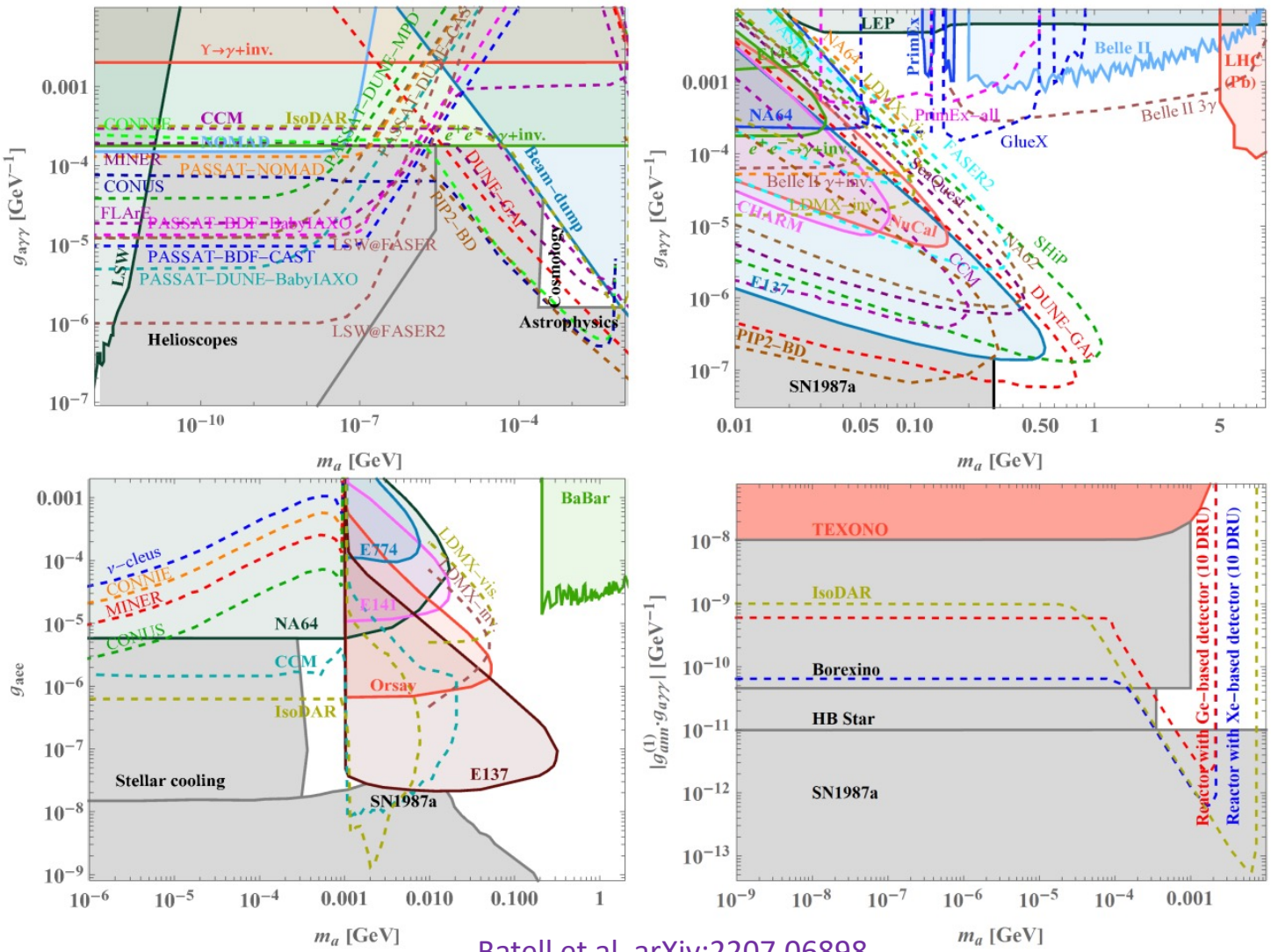




Batell et al, arXiv:2207.06898

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

ALP Portal



Batell et al, arXiv:2207.06898

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

Thank you!

Yu-Dai Tsai, UC Irvine, 22