Dark Sectors at the Intensity Frontier

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Dark Interactions 2024

YORK U

Beyond the Standard Model

Gauge interactions in the SM are sizeable

$$g(m_t) \sim 0.3 - 1$$

Beyond-SM particles with SM gauge charges are severely constrained

$$m_{\text{BSM}} < 100 \text{ GeV } \;-\; \text{ few TeV excluded}$$

Example: ATLAS Limit on Leptoquark Mass

New particles without SM gauge interactions are much less constrained → Dark Sector

Who Ordered (searching for) That?

Searching for dark sector particles tests:

1) Extensions of SM effective theory with new light degrees of freedom

2) Minimal/simple dark matter models

3) Solutions to experimental anomalies

Motivation 1: Tests of generic extensions of the SM EFT

1. SM Effective Field Theory

SM is fully determined by symmetry, field content and renormalizability.

Only a handful of low-dimensional connections to potential new particles – study these first!

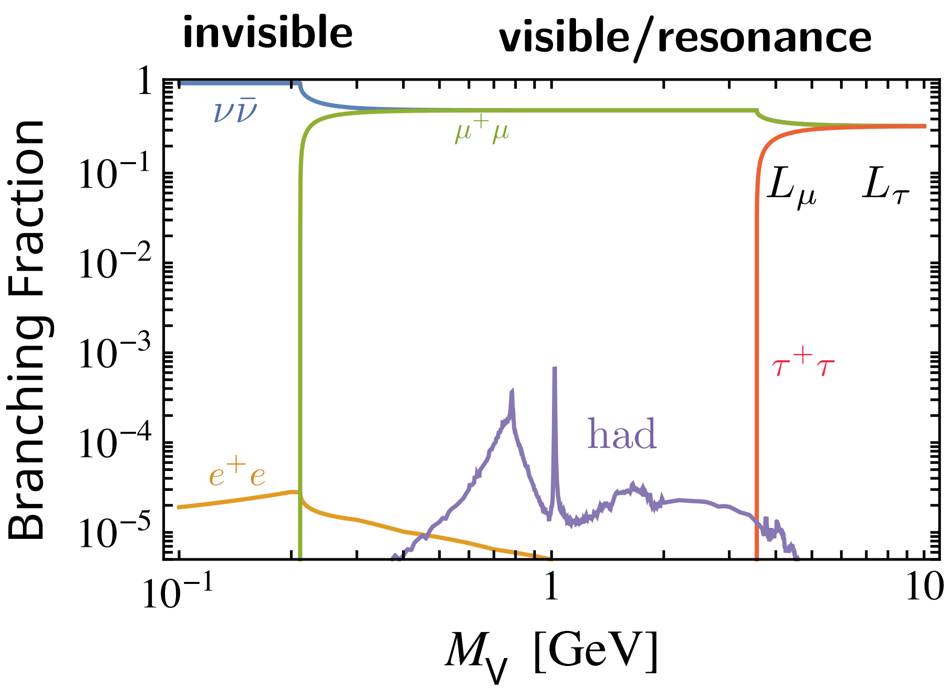
$V_\mu J^\mu$	Dark vectors $\Rightarrow$	Coupling to conserved currents
$\|H\|^2\phi^2$	Higgs portal scalar $\Rightarrow$	Coupling to fermions
LHN_R	Right-handed neutrino $\Rightarrow$	Coupling to neutrinos
$aF_{\mu\nu}\widetilde{F}^{\mu\nu}$	Pseudo-scalar $\Rightarrow$	Coupling to gauge bosons
$\vdots$		

Batell, Pospelov & Ritz (2009)

Example: Lmu – Ltau Gauge Boson

Massive vectors coupled to conserved currents:

$$\mathcal{L} \supset g_{\mu\tau} V_\alpha J^\alpha_{L_\mu - L_\tau} = g_{\mu\tau} V_\mu (\bar{\mu}\gamma^\alpha \mu + \bar{\nu_\mu}\gamma^\alpha P_L \nu_\mu - \mu \leftrightarrow \tau)$$

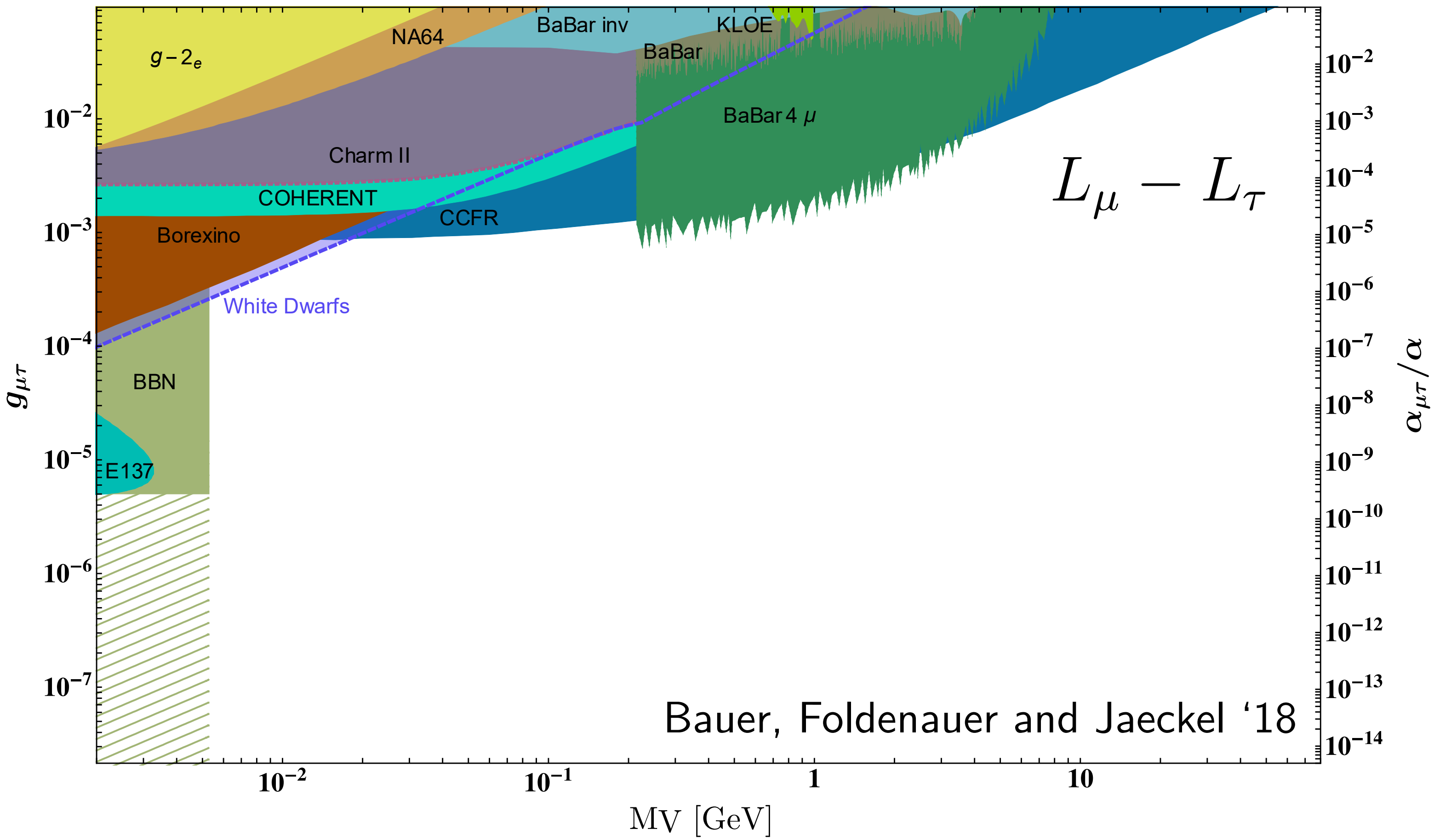


Potentially long-lived

$$\gamma c\tau_V \sim 3\ \mathrm{m} \left(\frac{\gamma}{100}\right) \left(\frac{10^{-6}}{g_{\mu\tau}}\right)^2 \times \left(\frac{100\ \mathrm{MeV}}{m_V}\right)$$

Bauer, Foldenauer and Jaeckel '18

Lmu-Ltau Parameter Space



Different experiments needed to access different regions of parameter space

Why Intensity Frontier

Ideal tool to search for particles mass in MeV ~ GeV:

1) Rates can be larger than at high energy colliders

$$N_{\mathrm{evt}} = \sigma_{\mathrm{DS}} \mathcal{L} \qquad \sigma_{\mathrm{DS}}^{(\text{fixed target})} \sim \frac{g_{\mu\tau}^2}{m_V^2}$$

$$\mathcal{L} \sim 10^3 \text{ ab}^{-1} \left(\frac{N_{\mathrm{POT}}}{10^{20}}\right) \left(\frac{n_T}{10^{23} \text{ cm}^3}\right) \left(\frac{L}{1 \text{ m}}\right)$$

Batell, Pospelov & Ritz (2009)

2) Unique sensitivity to low energy scales

via high shielding, forward detectors,...

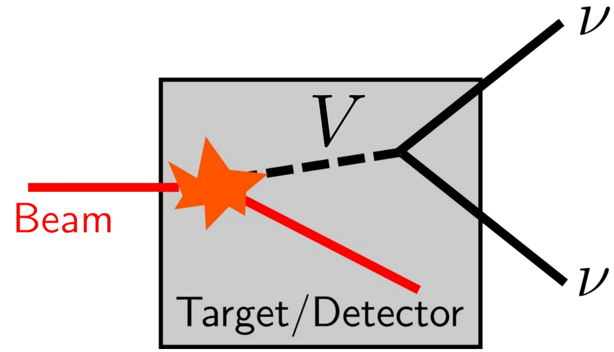
$$m_{e^+e^-}, \ \not{E}, \ p_T, \ \ldots$$

But colliders can provide complimentary sensitivity, cf. BaBar, LHCb, FASER

Search Strategies

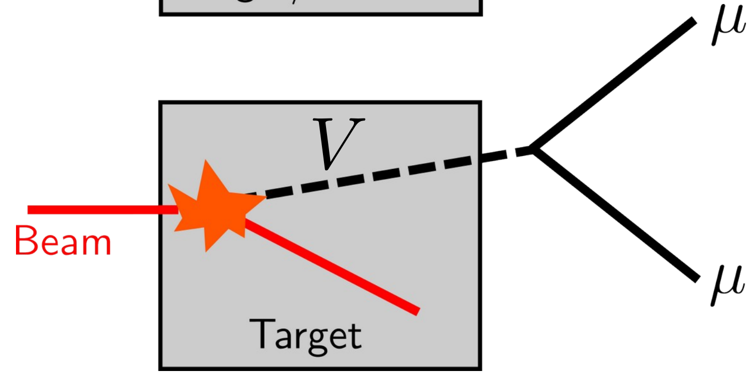
Missing Energy/Momentum

e.g.: NA62, NA64mu



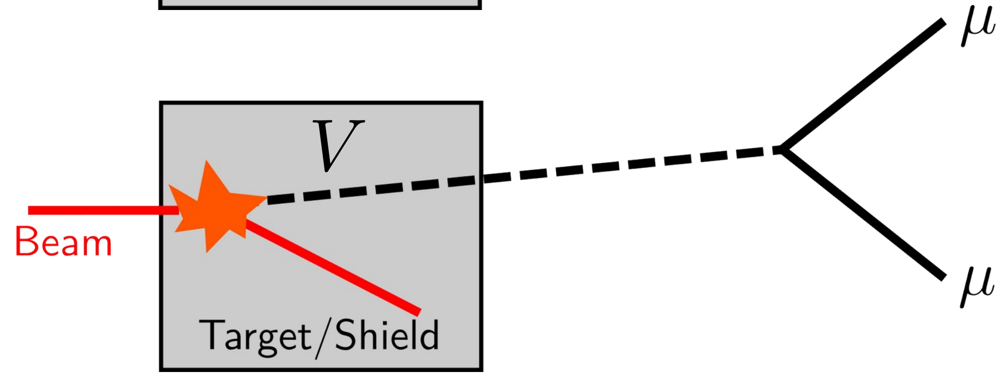
Prompt decay/resonance

e.g.: NA62, DarkQuest



Displaced Decays (LLP)

e.g.: NA62, SHiP, DarkQuest



But also: precision SM measurements, neutrino tridents, cosmo...

Motivation 2: Simple Models of Dark Matter

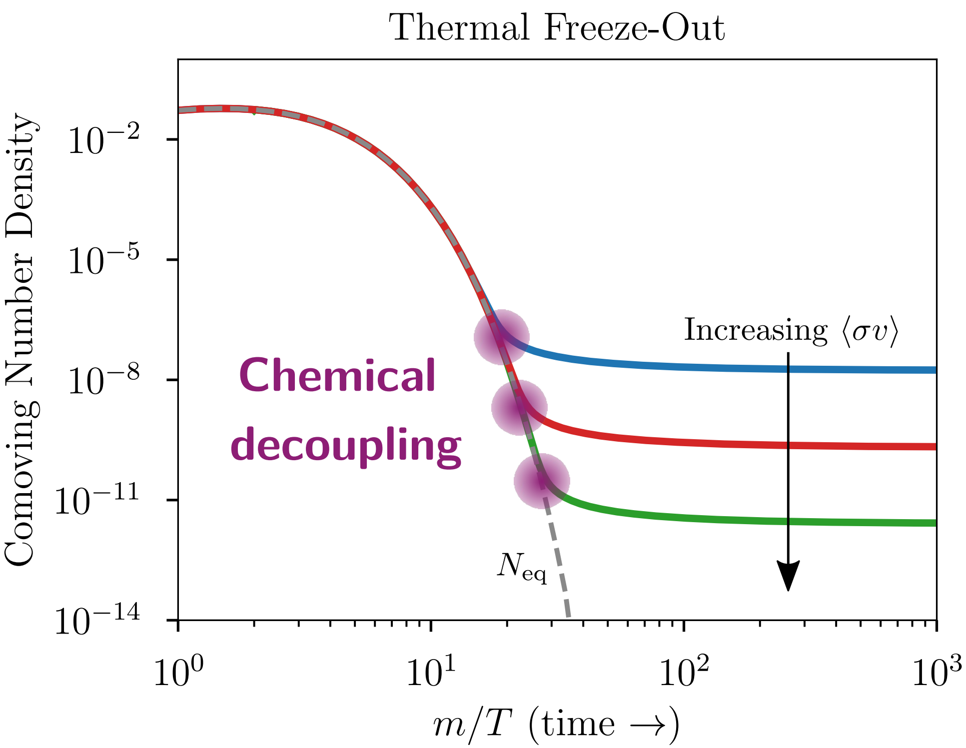
Thermal Dark Matter: Freeze-out

Light DM can be produced via freeze-out of annihilations in to SM particles (like WIMPs!)

Chemical decoupling ($=$ freeze-out) must occur to get just the right amount of DM

Correct abundance if

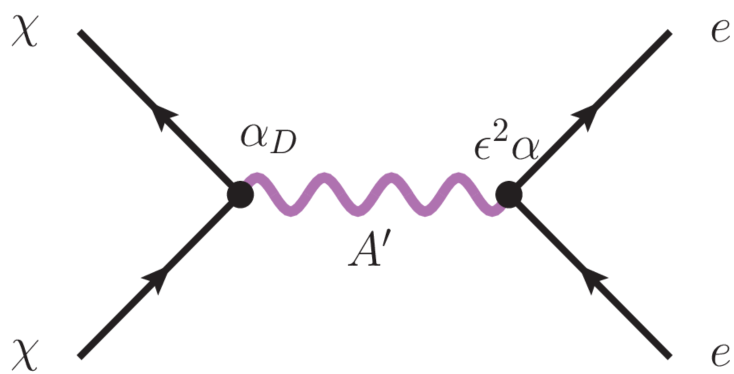
$$\langle \sigma v \rangle \approx \left(\frac{1}{20\ \mathrm{TeV}} \right)^2 \sim \frac{\lambda^4}{m^2}$$



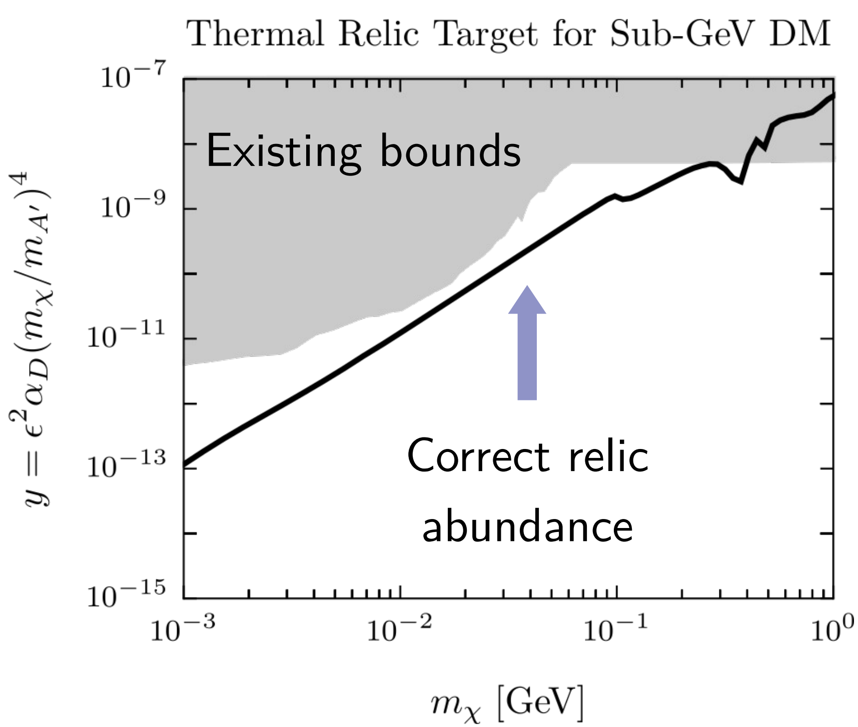
2. Thermal Dark Matter

For sub-GeV DM, this requires a dark sector

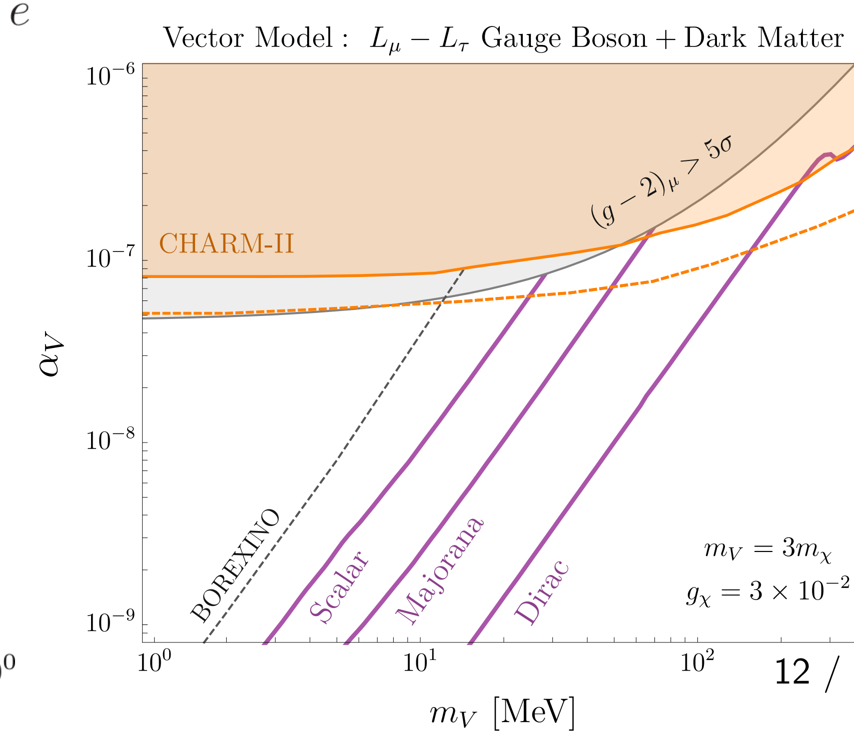
Lee & Weinberg '77; Bohm & Fayet '04



$$(m_V > 2m_\chi)$$



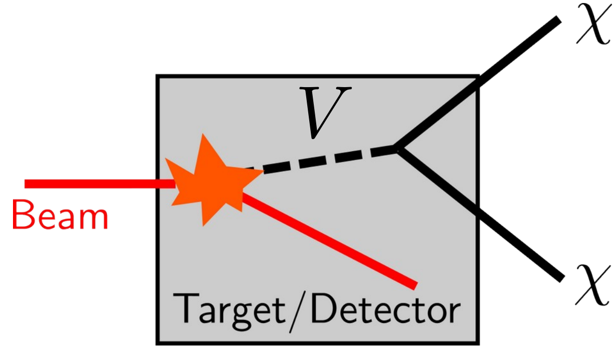
Krnjaic, Marques-Tavares, Redigolo & Tobioka '19



Signals of Freeze-Out

Missing Energy/Momentum

e.g.: LDMX, NA64

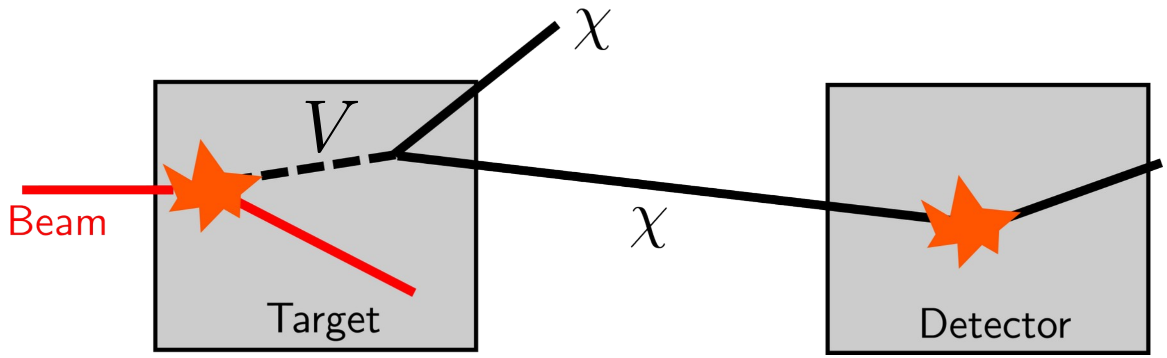


$$m_V > 2m_\chi$$

$$N_{\text{sig}} \propto \epsilon^2$$

Rescattering

e.g.: BDX, SHiP, DUNE,...



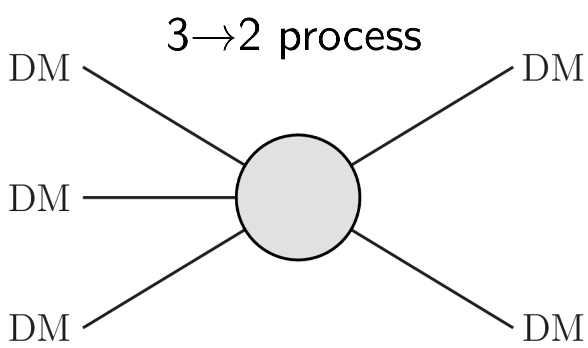
$$N_{\text{sig}} \propto \epsilon^4$$

Other Approaches to Thermal DM

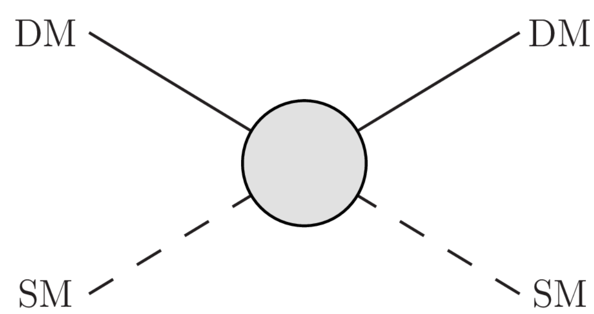
Many other implementations of light DM production

E.g. Strongly Interacting Massive Particles (SIMPs)

Carlson, Machacek and Hall (1992); Hochberg, Kuflik, Volansky and Wacker (2014)



Chemical equilibrium (within the DS)



Kinetic equilibrium (with the SM)

These models are realized in strongly-coupled sectors

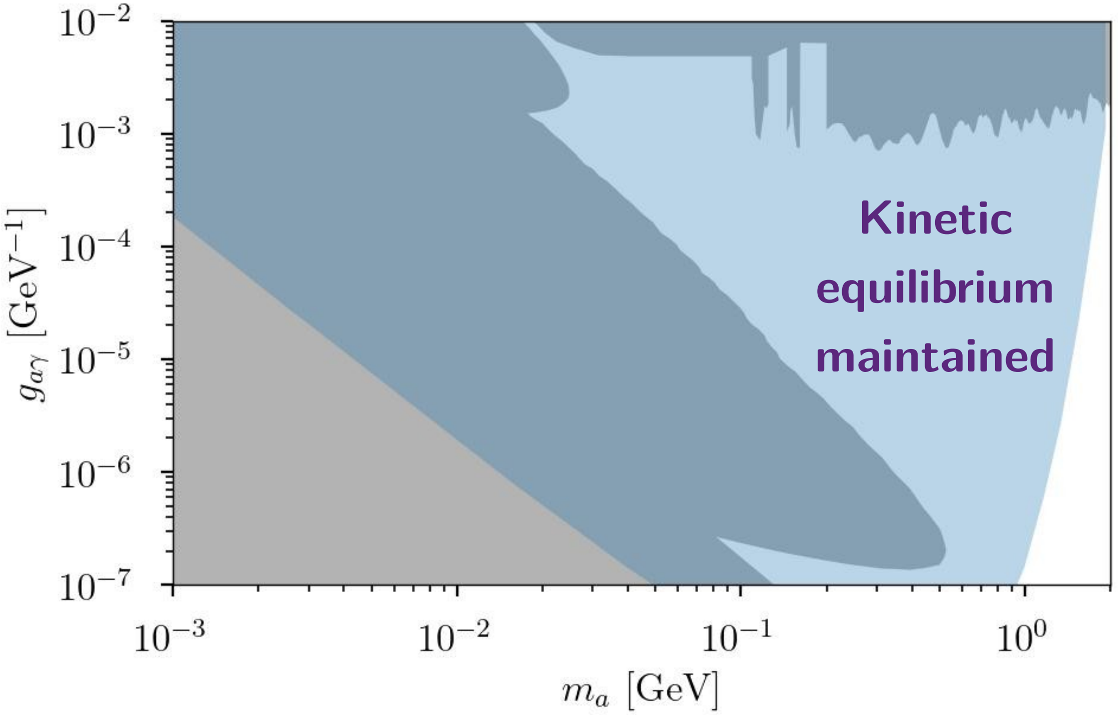
Qualitatively different signatures at FT experiments

Specific examples: see, e.g., Hochberg, Kuflik & Murayama (2015);
Berlin, NB, Gori, Schuster & Toro (2018); Hochberg, Kuflik, McGehee, Murayama & Schutz (2018)++

Kinetic Equilibrium via an ALP

$$\mathcal{L} \supset \frac{a}{4f}\widetilde{F} \cdot F + \frac{m_\chi^2}{f^2} a^2 \chi^2$$

Photon coupling



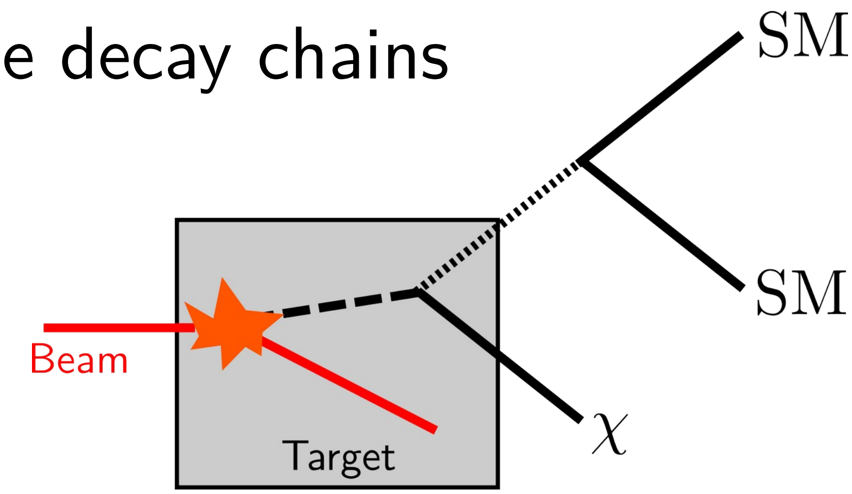
Mediator mass

Hochberg, Kuflik, McGehee, Murayama & Schutz (2018)

Other Signals of DM

In addition to missing X, rescattering "rich" dark sectors offer new signals:

- Visible long-lived mediator decays $m_{\rm med} < 2m_{\rm DS}$
- Semi-visible decay chains



$m_{\rm med} > 2m_{\rm DS}$

Essig, Schuster, Toro '09; Cohen, Lisanti, Lou '15 ++ ; Berlin NB, Gori, Schuster & Toro '18; Mohlabeng '19

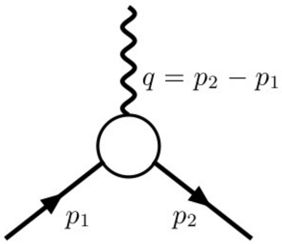
Also **see Deepak Kar's talk on Thursday**

Motivation 3: Solutions to experimental anomalies

Anomaly: g-2

Several experimental anomalies can be explained with new light physics. See, e.g., Harris, Schuster & Zupan '22

E.g. muon g-2:



$$\langle \mu_{p_2} | J^\mu(0) | \mu_{p_1} \rangle = \bar{u}_{p_2} \left[F_D(q^2)\gamma^\mu + F_P(q^2) \frac{i\sigma^{\mu\nu} q_\nu}{2m} \right] u_{p_1}$$

$$g - 2 \equiv F_P(0)$$

Melnikov & Vainshtein '06

$$a_\mu(\text{Exp}) - a_\mu(\text{Theory}) = (251 \pm 59) \times 10^{-11}$$

(but see recent lattice results: Borsanyi et al '20)

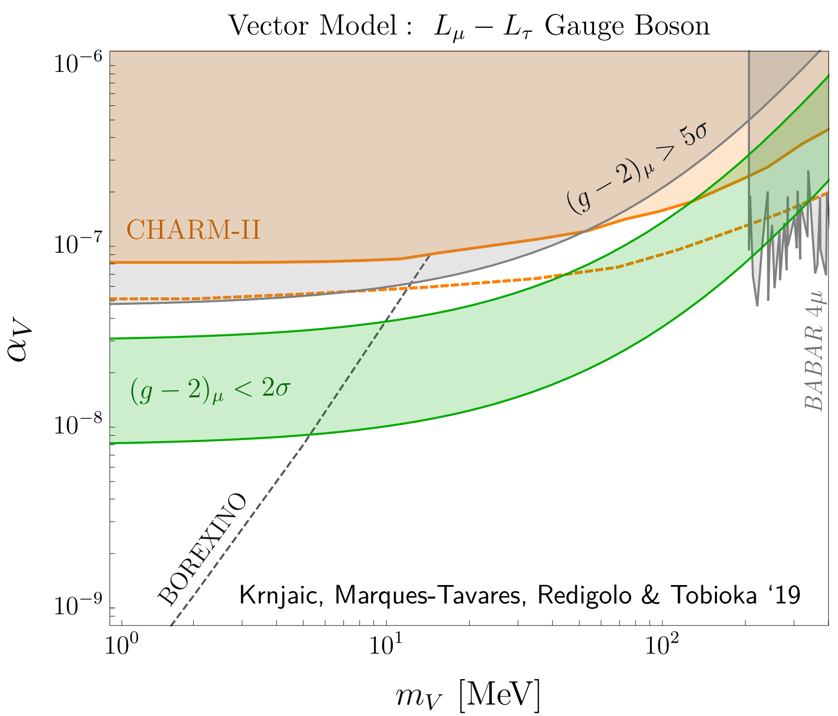
Contributions from new scalars, vectors can resolve discrepancy

Kinoshita & Marciano '90

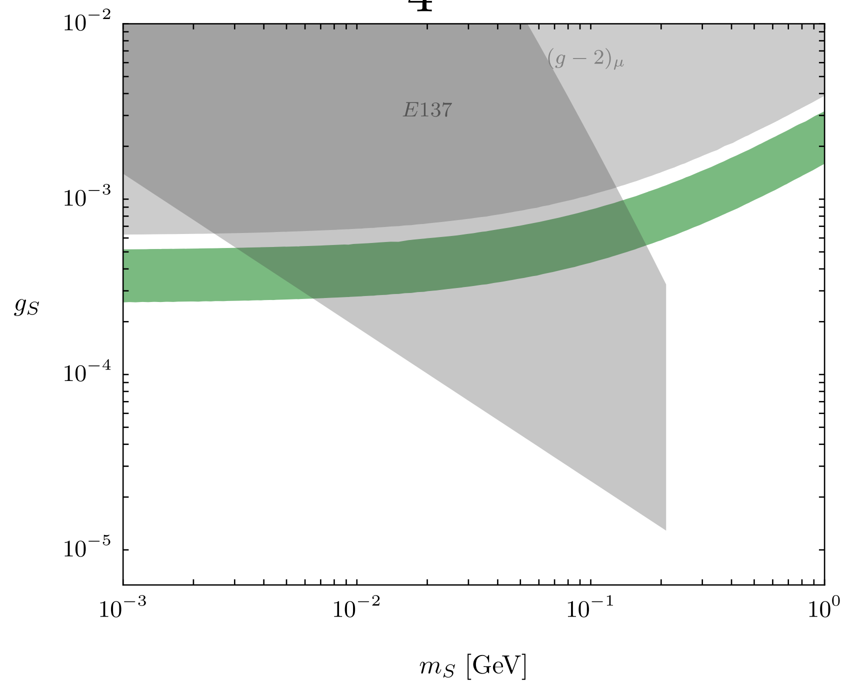
Testing g-2

Low mass explanations of g-2 can be tested with FT.

Even minimal ones, **only** with couplings to muons



$$g_S S\bar{\mu}\mu + \frac{1}{4} g_{S\gamma\gamma} S F_{\mu\nu} F^{\mu\nu}$$



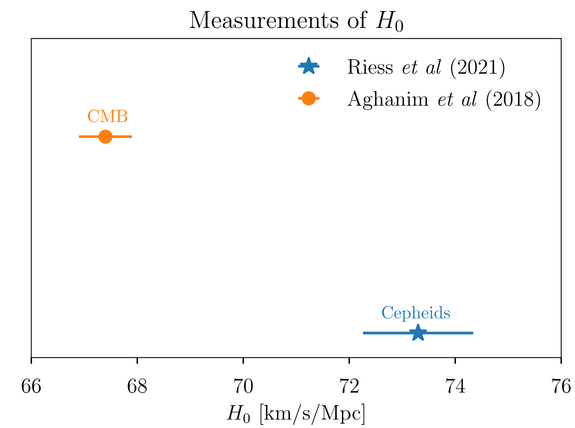
Chen, Pospelov & Zhong '17++; NB, Hamer & Gori '24

The g-2 band is a near term target for several fixed-target experiments: NA62, NA64, DarkQuest,...

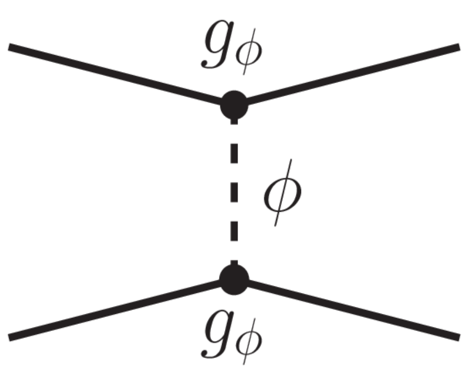
Anomaly: Hubble Tension

Self-interacting neutrinos modify extraction of H_0 from CMB

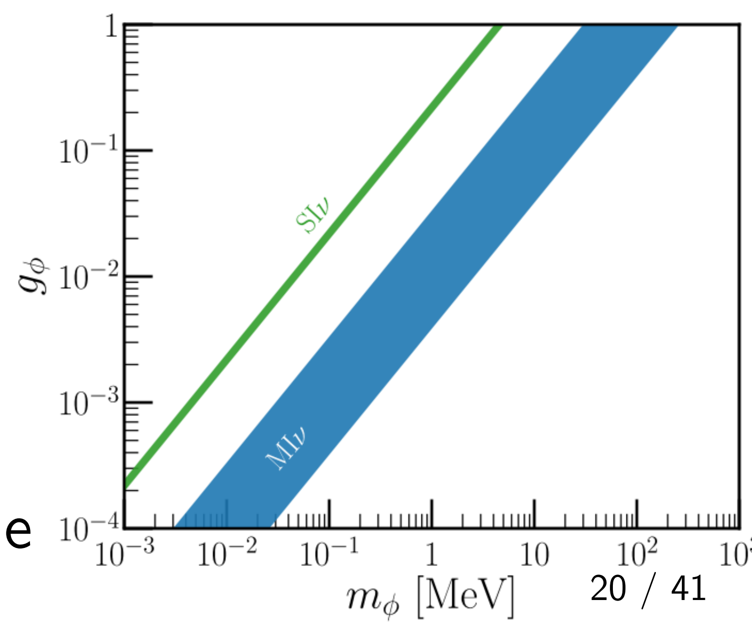
Cyr-Racine & Sigurdson (2013)++; Kreisch, Cyr-Racine & Doré (2019)



A gross oversimplification of H_0



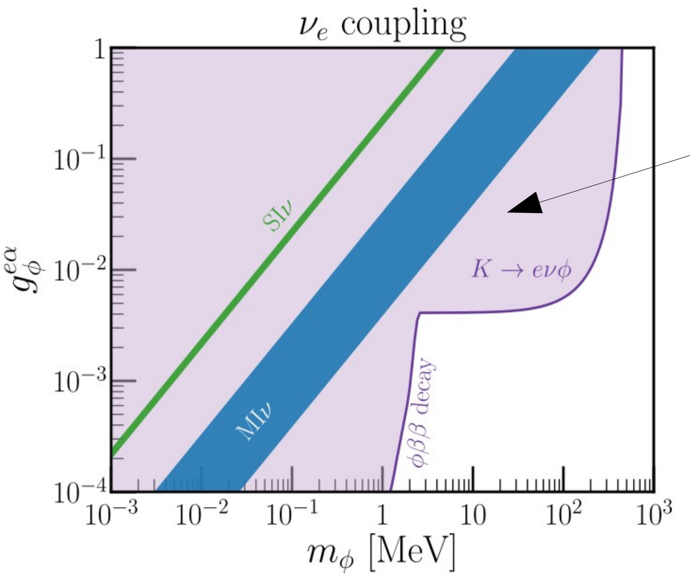
$$G_{\rm eff} = \frac{g_\phi^2}{m_\phi^2} \sim 10^9 G_F$$



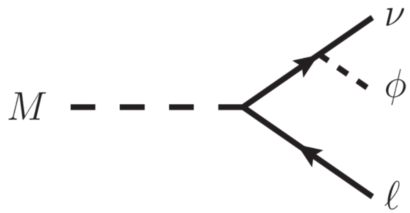
Prediction: light neutrino-coupled particle

Scalar (Majoron), vector (Lmu-Ltau)

Signals (and a Success Story)



NB, Kelly, Krnjaic, McDermott (2019)



$$\mathrm{Br}(M \to \ell\nu\phi) \propto \frac{m_M^2}{m_\ell^2} g_\phi^2$$

Constraints on

$\mathrm{Br}(M \to \ell\nu\nu\bar{\nu})$

from

NA62@CERN and PIENU@TRIUMF

PLB 719 (2013) 326; PRD 102 012001

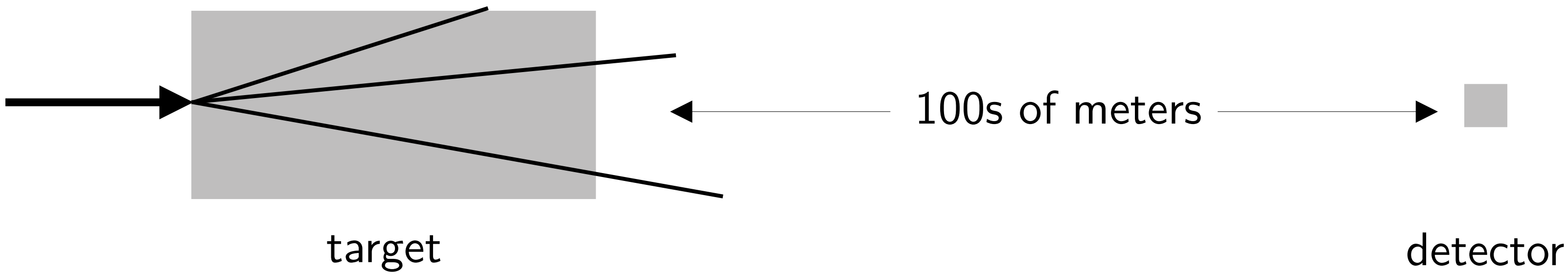
Precision measurements of SM @ intensity frontier rule out this as an explanation of the Hubble tension

There is a well-developed science case for various kinds of fixed-target experiments

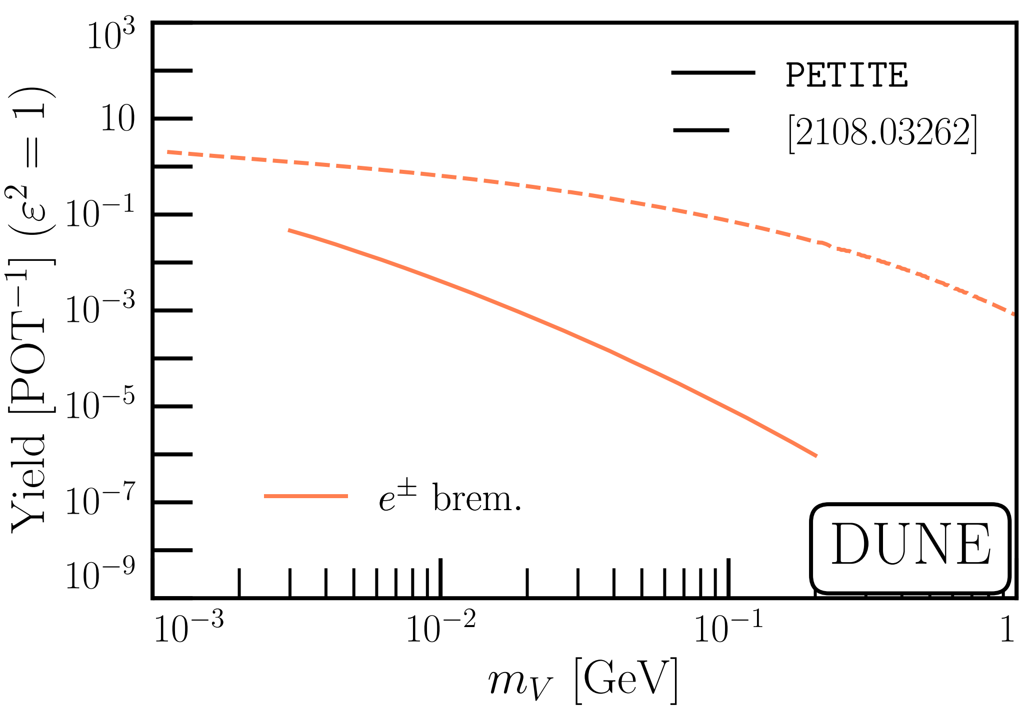
Many experiments are planned or are operating.

Theory Challenge 1: Angular Distributions

Signal rates are very sensitive to angular distribution



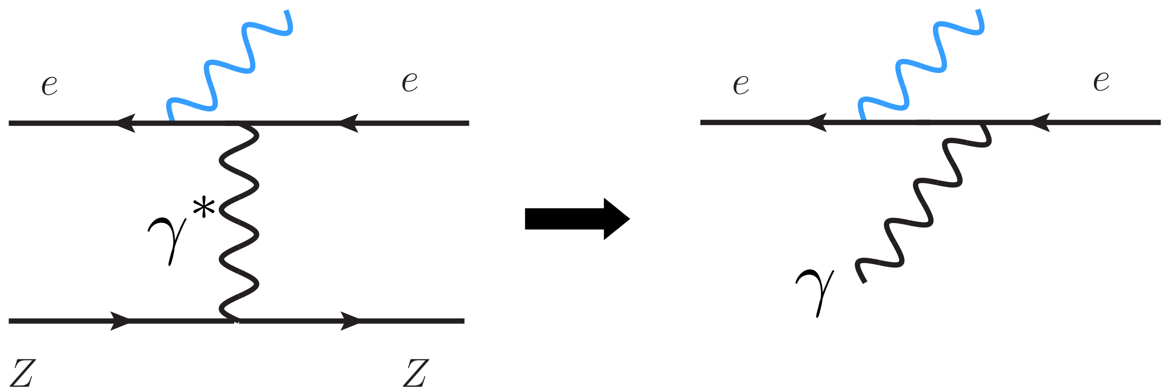
NB, Fox, Kelly, Machado and **Plestid**

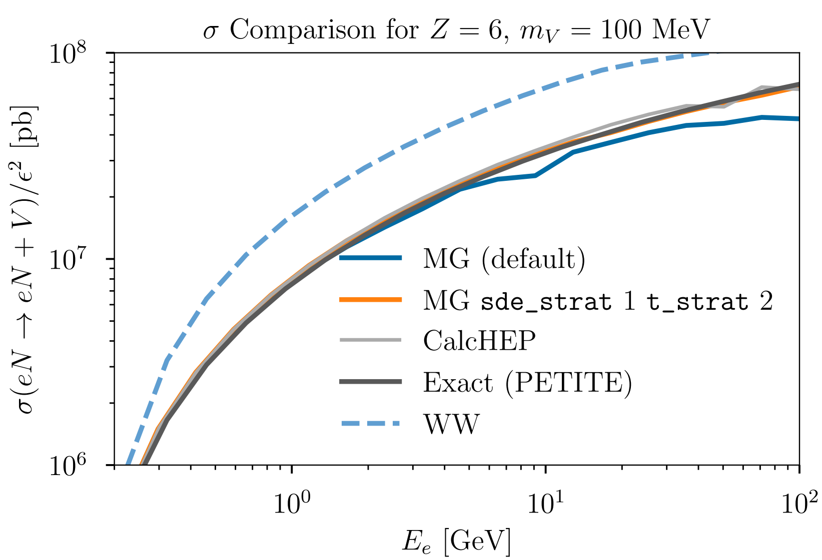


Theory Challenge 2: Simulation Difficulties

Common approx. and MC software often inadequate

Tsai '89, Bjorken, Essig, Toro and Schuster '09; Liu, McKeen & Miller '16,'17'; ++





NB with Patrick Fox, Kevin Kelly, Pedro Machado and **Ryan Plestid**

Theory Challenge 3: Many Production Modes

Many processes enabled by secondaries from hadronic and EM showers

$$eZ \to eZ + V \quad \mu Z \to \mu Z + V \quad pZ \to pZ + V$$

$$e^+e^- \to V(\gamma) \qquad \gamma e \to e + V$$

$$\text{meson} \to \text{SM} + V$$

Marsicano et al 18; Nardi et al '18; Celentano et al '20; Capozzi et al '21
NB, Fox, Kelly, Machado, Plestid & Zhou '24

Esp. important for thick targets. Their inclusion can substantially improve reach.

See talk by Ryan Plestid.

Conclusion

- Fixed target experiments are useful

New probes of DM, anomalies, EFT operators

- A broad portfolio of these experiments will answer many important questions in the **near term**

See talk by Kate Pachal for concrete examples

- Better modelling is needed for reliable predictions

Production modes have been neglected, numerous approx. used

See talk by Ryan Plestid

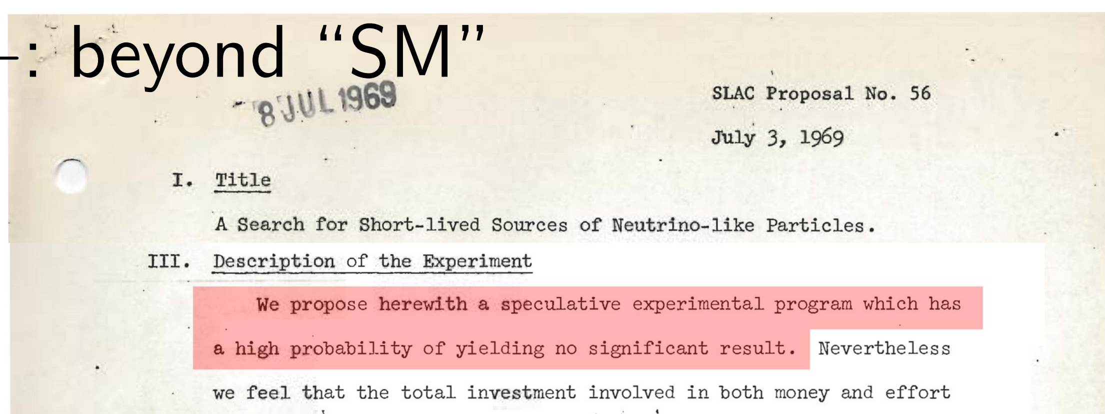
Thank you!

Appendix

Some History

One of the oldest experimental tools:

- 1900s - Rutherford Gold Foil Experiments and discovery of the nucleus
- 1950s - Bubble chambers and meson spectroscopy
- 1960s - electron-proton deep inelastic scattering
- 1960s - searches for charges e/3 and 2e/3, ++
- 1960s+: beyond "SM"



8 JUL 1969

SLAC Proposal No. 56

July 3, 1969

I. Title

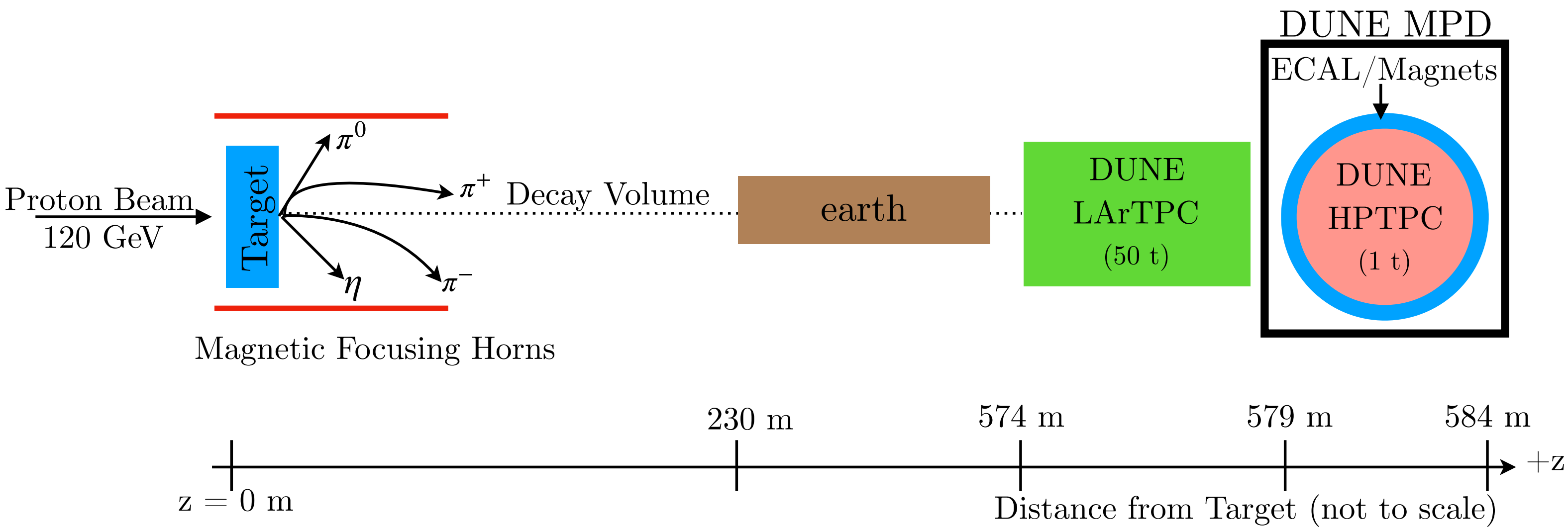
A Search for Short-lived Sources of Neutrino-like Particles.

III. Description of the Experiment

We propose herewith a speculative experimental program which has a high probability of yielding no significant result. Nevertheless we feel that the total investment involved in both money and effort

DUNE and Other Neutrino Experiments

Neutrino sources are FT experiments



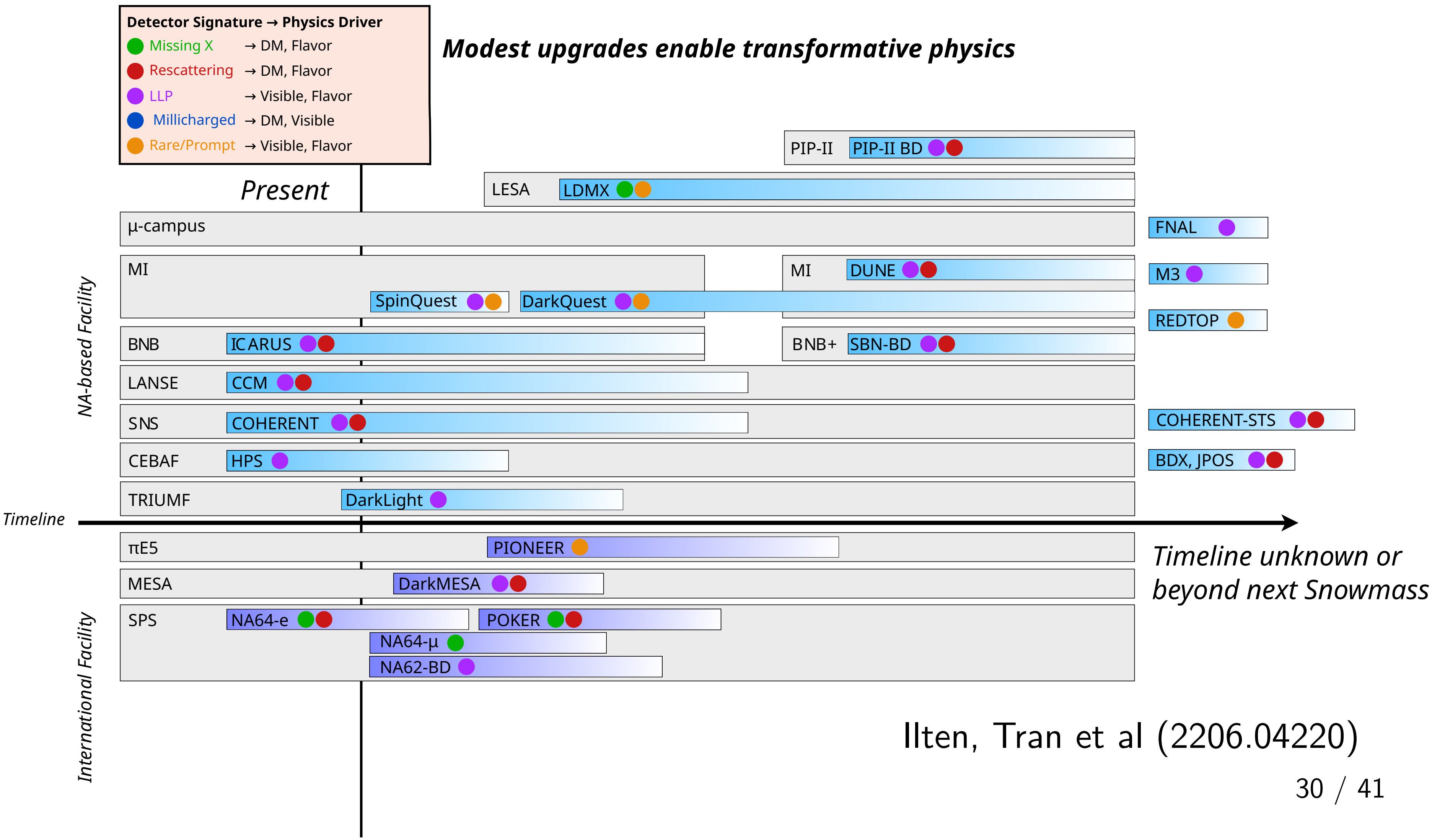
Applications of DUNE ND to BSM: Berryman et al '19

Beyond-SM searches for "free"!

See also deNiverville, Pospelov & Ritz '11++; MiniBooNE DM Results '18, Batell, Berger & Ismail '19...

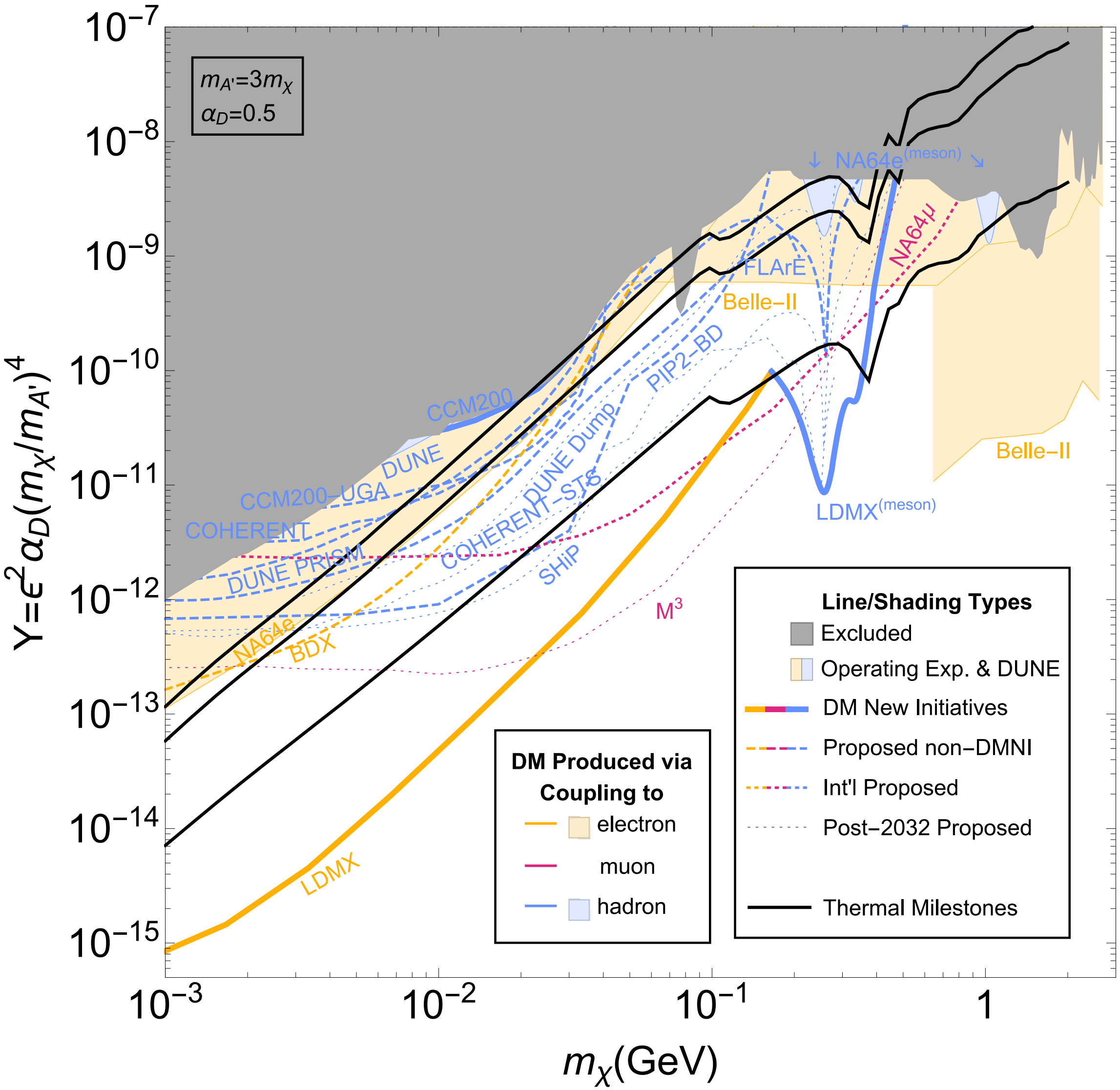
Intensity Frontier Today

Many proposed or currently-running facilities



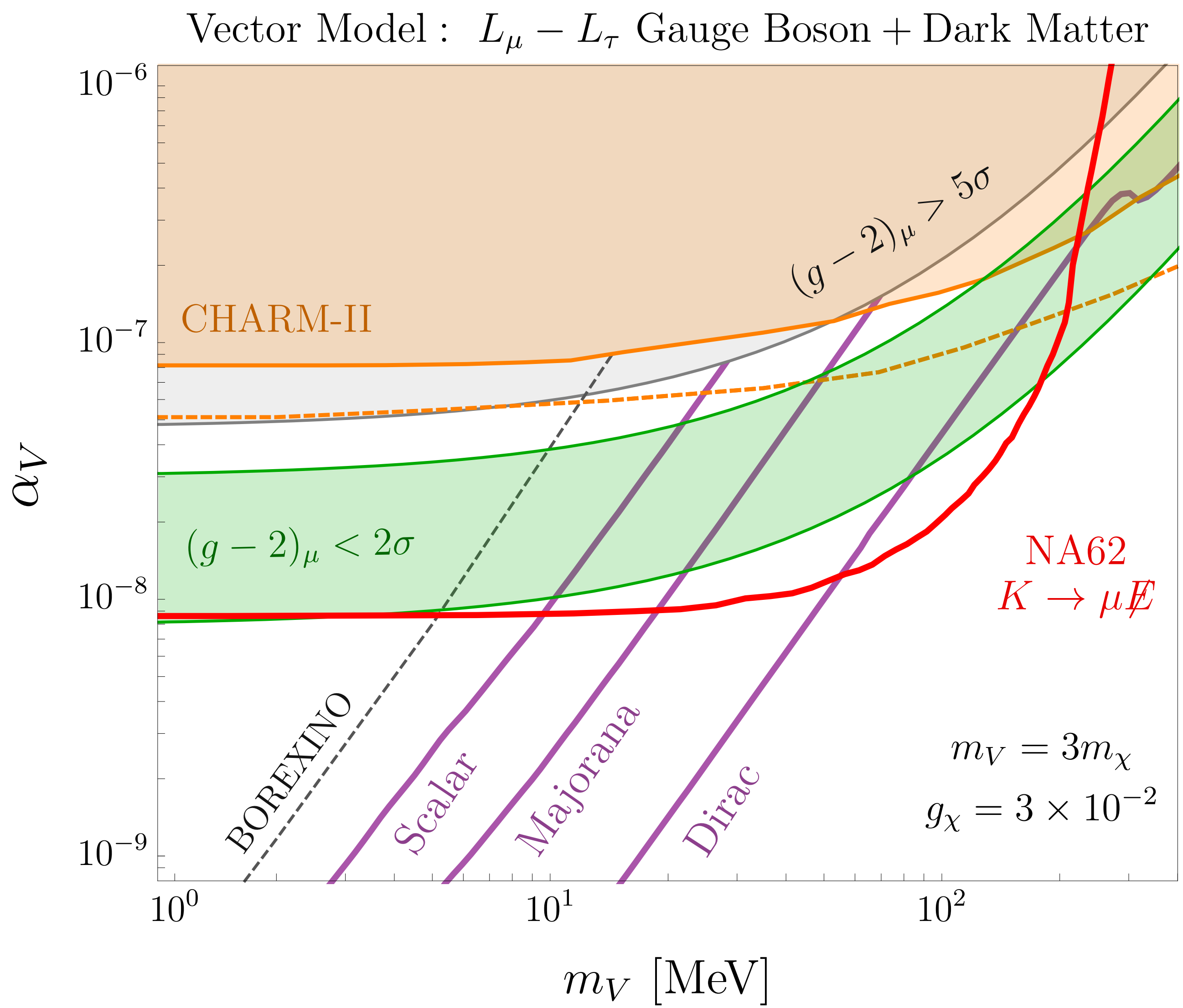
Ilten, Tran et al (2206.04220)

Dark Photon-Coupled DM



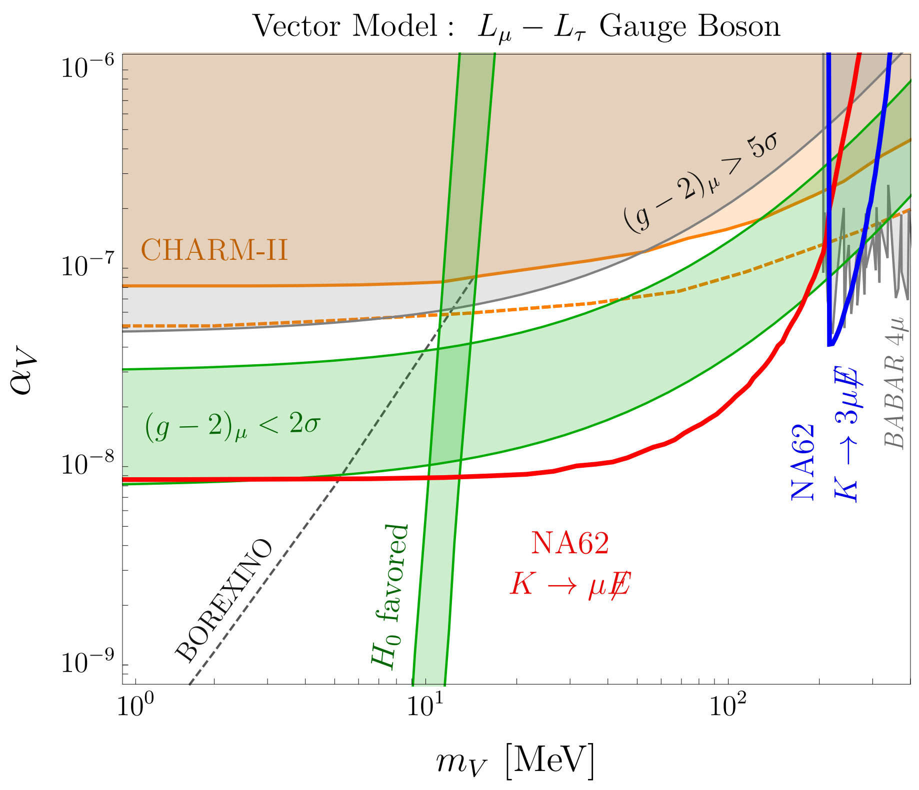
Berlin, NB, Krnjaic, Schuster & Toro '18 ; Krnjaic, Toro et al (2207.00597)

Lmu-Ltau-coupled DM

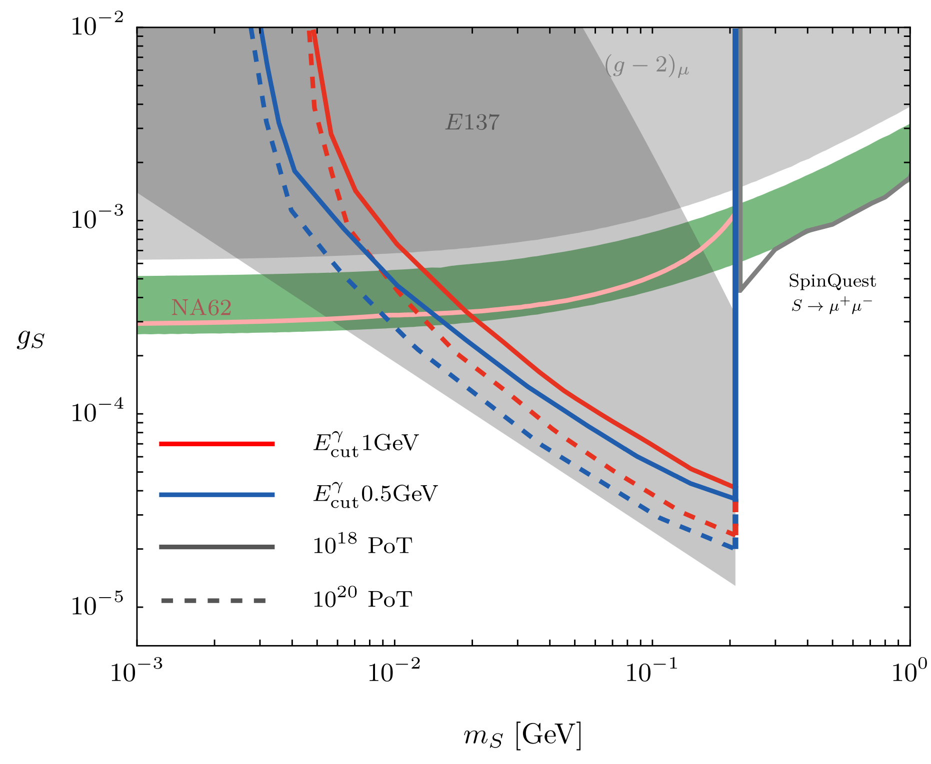


Krnjaic, Marques-Tavares, Redigolo & Tobioka '19

g-2 Models



Krnjaic, Marques-Tavares, Redigolo & Tobioka '19



NB, Hamer & Gori '24

Difficulties In Modeling Signal

Signal rate in a detector sensitive to both SM and BSM dynamics. Surprisingly challenging to predict:

1) **SM simulation effectively a black box**

Many models/approximations in GEANT, FLUKA

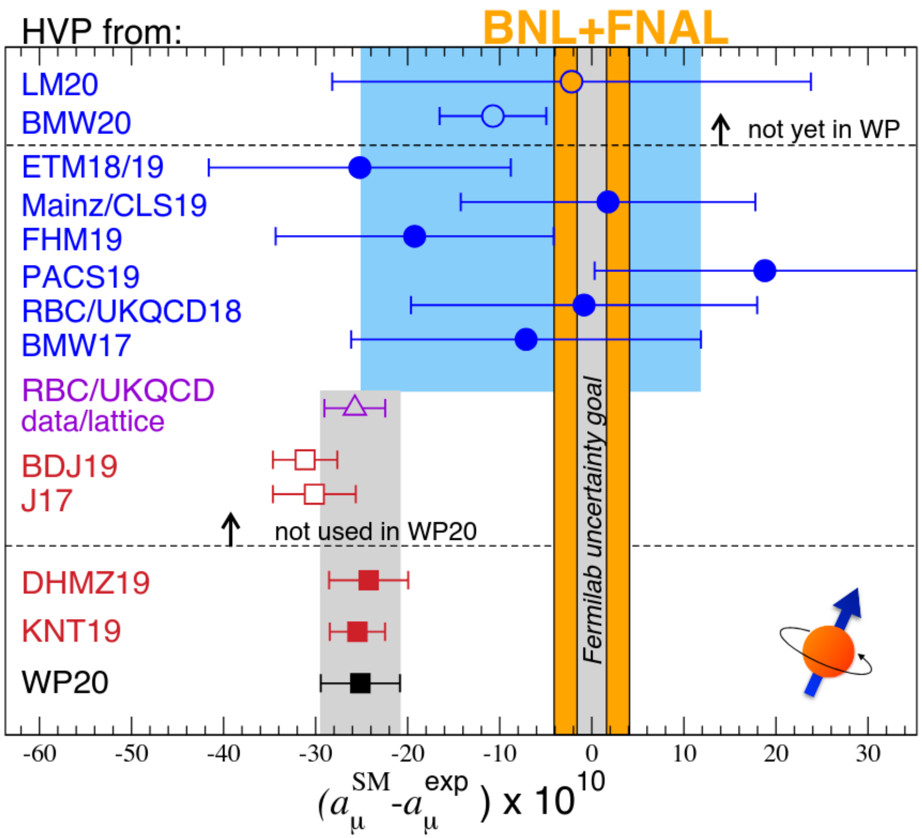
2) **BSM processes often difficult for off-the-shelf codes**

Kinematic singularities, in-medium propagation effects

3) **No standard tool chain, a la collider physics:**

MadGraph+Pythia+DELPHEs

g-2



Colangelo et al '22 (2203.15810)

Peaks in the Power Spectrum

Peak **position** depends on contents of the universe and evolution of density perturbations

$$\ell_{peak} \approx n(\pi - \delta\varphi)/\theta_s$$

b/g evolution (→ θ_s)

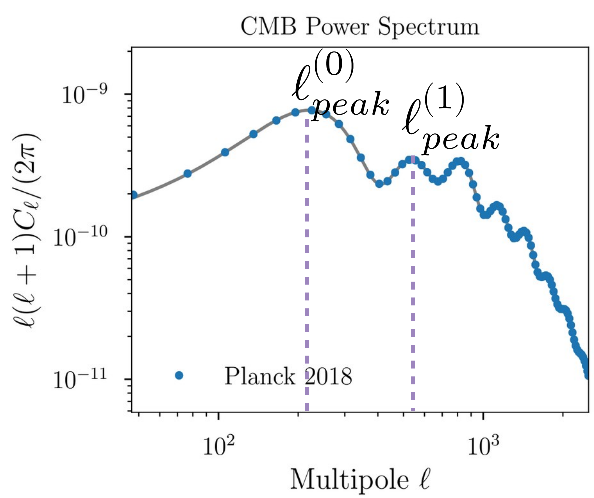
Particle densities

Measured precisely (→ ℓ_{peak})

Evolution of perturbations (→ $\delta\varphi$)

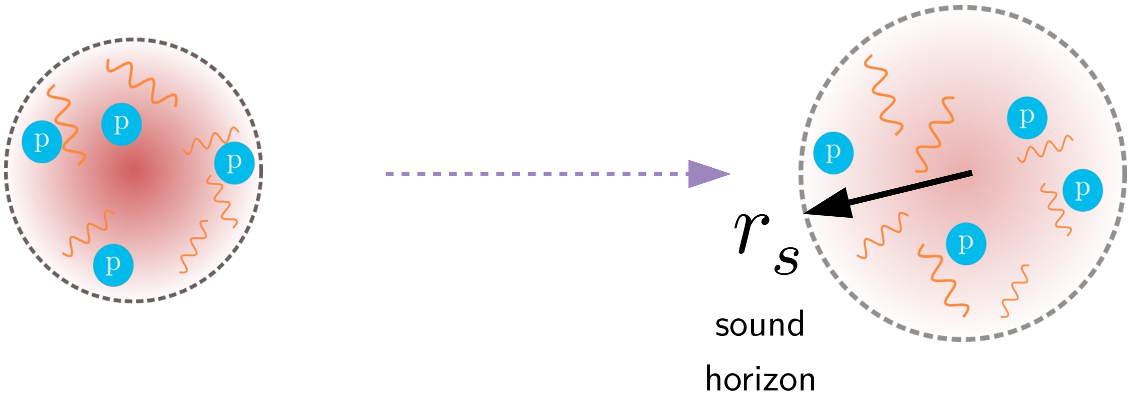
Particle Interactions

See, e.g., Pan, Knox, Mulroe & Narimani (2016)



The Sound Horizon

H_0 is ***inferred*** from the angular scale of CMB fluctuations $\theta_s \sim r_s / D_A$ where



$$r_s = \int_0^{t_{rec}} \frac{dt}{a(t)} c_s(a) = \int_0^{a_{rec}} da \frac{c_s(a)}{a^2 H(a)}$$

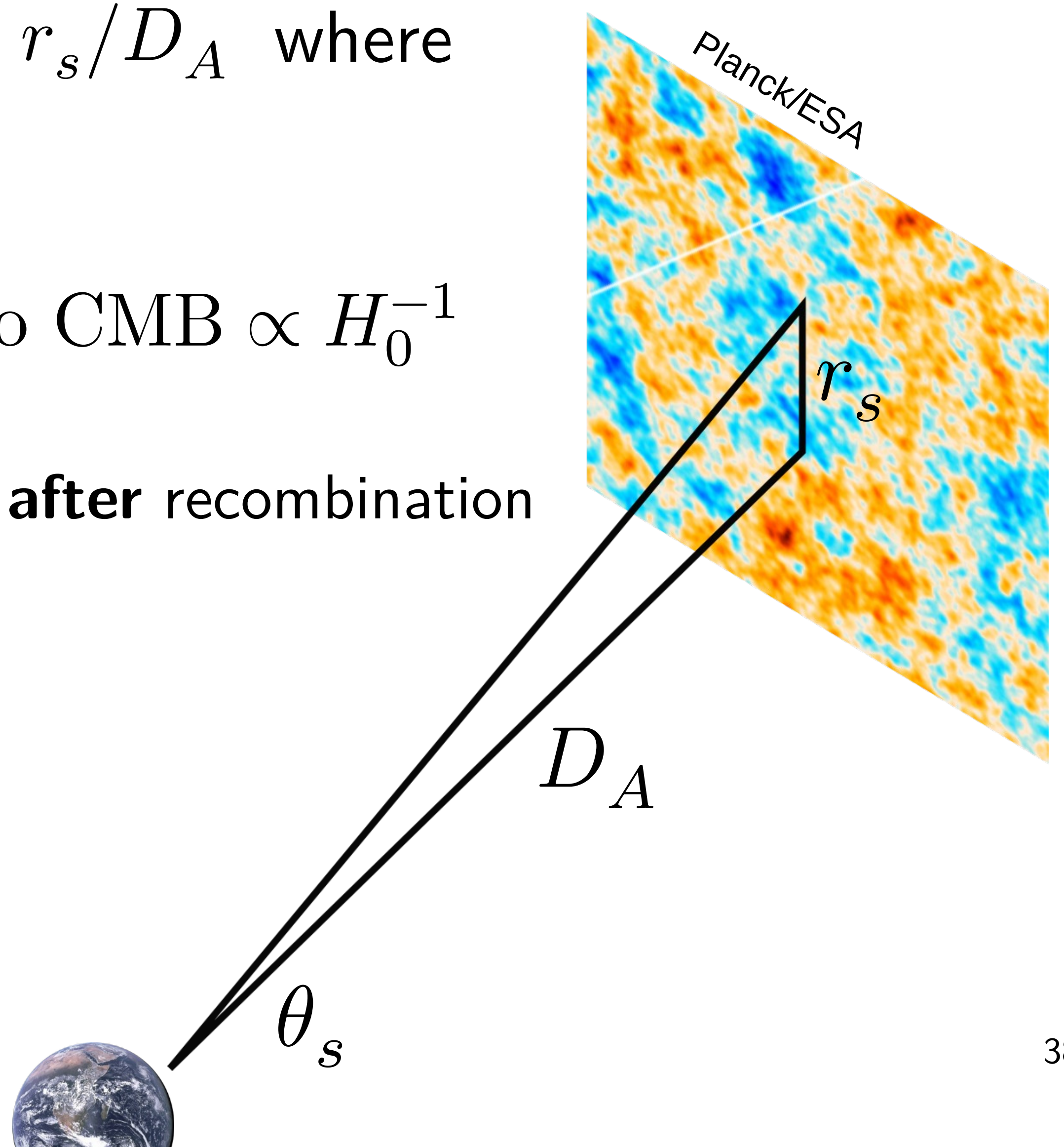
Depends on evolution **before** recombination

Distance to the CMB

H_0 is ***inferred*** from the angular scale of CMB fluctuations $\theta_s \sim r_s / D_A$ where

$$D_A = \text{distance to CMB} \propto H_0^{-1}$$

Depends on expansion **after** recombination



Hubble from the CMB

H_0 is ***inferred*** from the angular scale of CMB fluctuations $\theta_s \sim r_s/D_A$ where

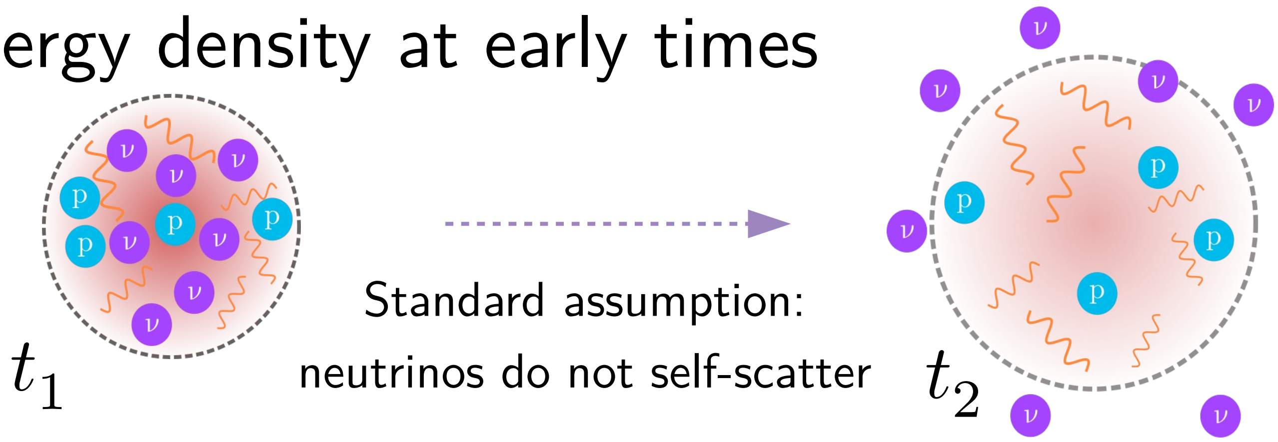
$$H_0 \propto \theta_s/r_s$$

Inference of H_0 is modified if r_s is changed!

Origin of Phase Shift: Free-streaming Nus

$$\ell_{peak} \approx n(\pi - \delta\varphi)/\theta_s$$

- Neutrinos free-stream and make up about 41% of the energy density at early times



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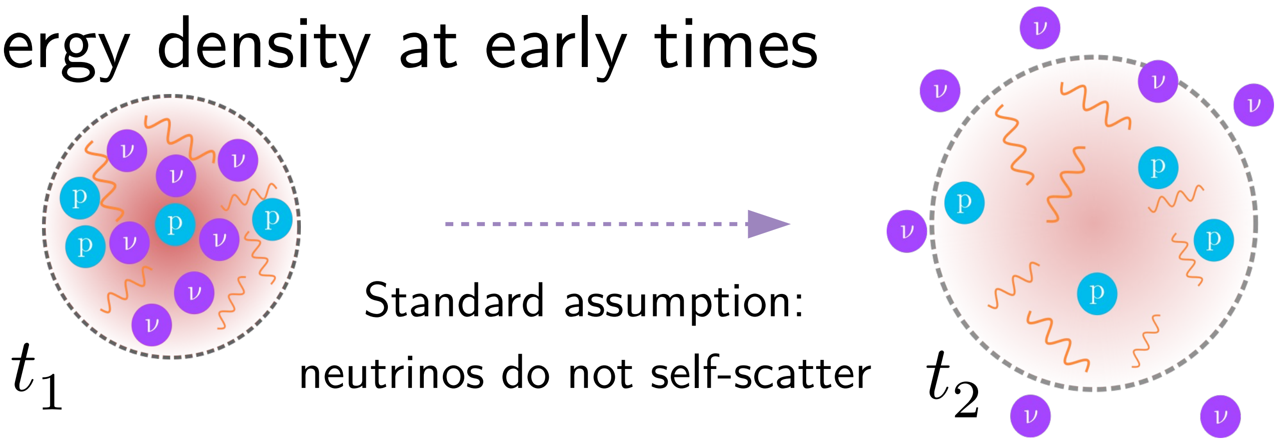
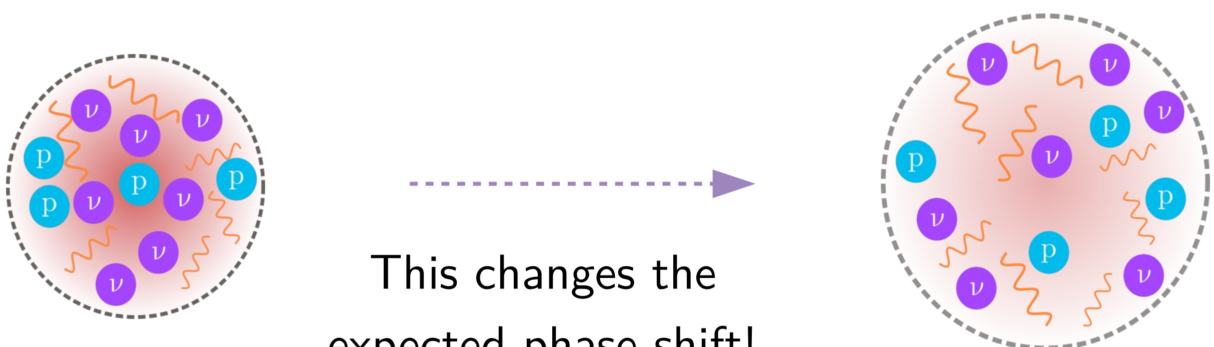


- No free-streaming if neutrinos self-interact



Solving the Hubble Tension

- Modifying amount of neutrinos changes the sound horizon
- Neutrino self-interactions can prevent free-streaming

$$\ell_{peak} \approx n(\pi - \delta\varphi)\frac{D_A}{r_s}$$

Changing neutrino properties modifies inference of H_0 !