Current Status and Future Directions in Particle Physics and Cosmology

Bhaskar Dutta

Texas A&M University

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Introduction

A very interesting time for particle physics and cosmology

- Many questions:

Scale of inflation; explanation of Hubble tension; origin of DM and neutrino masses; precision measurements of the Higgs coupling, new physics for various anomalies e.g., g-2 of muon, W mass measurements, LHCb flavor, MiniBooNe, LSND, Xenon1T, galactic center excess etc., relic abundance of light degrees of freedom, the origin of baryogenesis etc.

- How do we investigate these questions using various experiments, observations, Any new models? what are the new ideas

- How does the future look like?

CMB SPECTRA AND SIX BASIC COSMOLOGY PARAMETERS

Planck 2018 Paper I; Planck + BAO Results – **including EE, TE, & Lensing**

$\Omega_b h^2$	baryon density	2.24% +/-0.01%
$\Omega_c h^2$	cold dark matter density	11.93% +/-0.09%
Θ	angular scale of acoustic horizon at decoupling	0.5965^0 +/- 1"
τ	reionization optical depth	0.056 +/- 0.007
n_s	spectral index of primordial adiabatic fluctuations	0.966 +/-0.004
A_s	amplitude of perturbations	3.047 +/-0.014

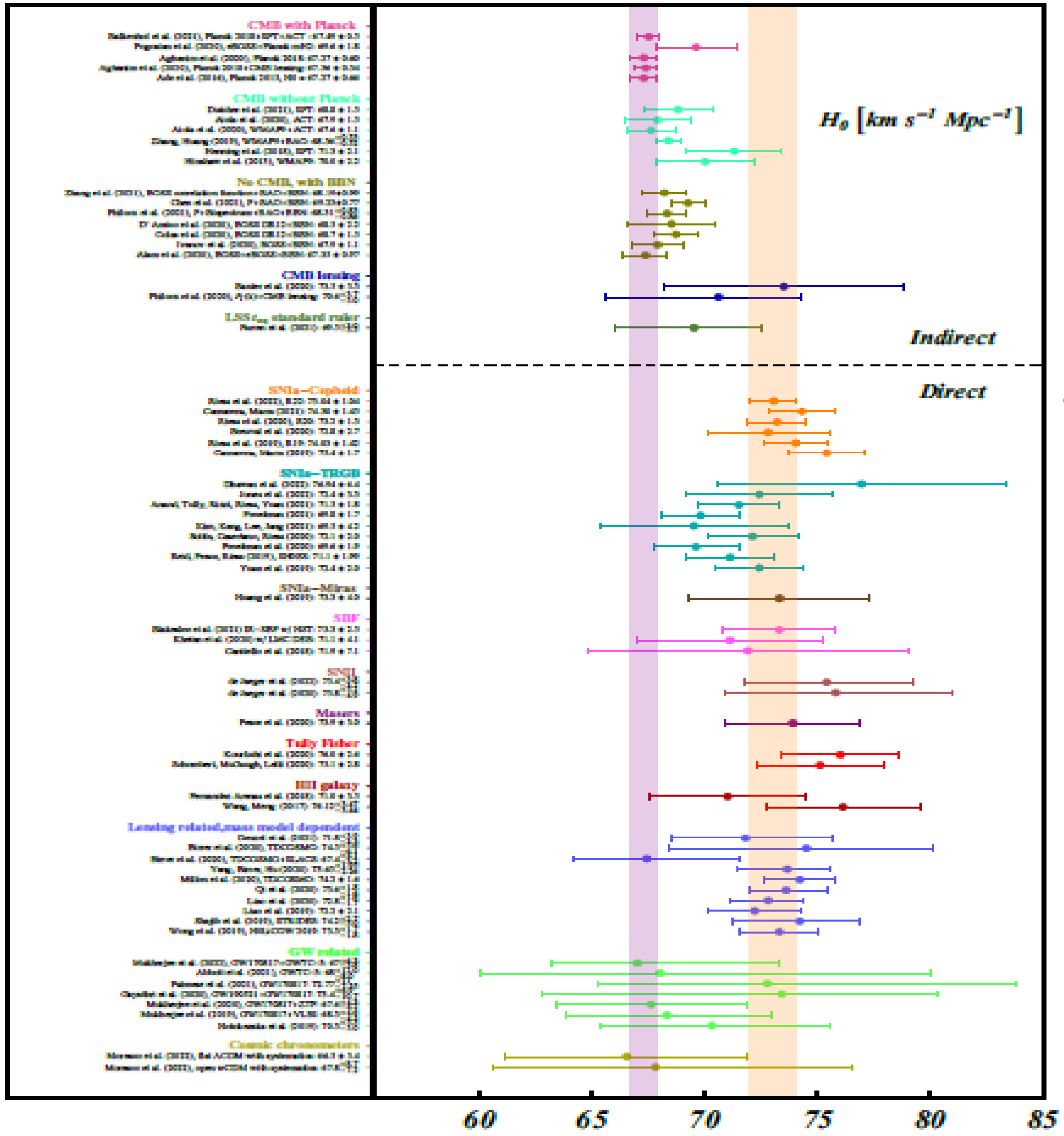
where H_0 = h * 100 km/s/Mpc, and the geometry is taken as flat.

From the above, in the context of ΛCDM, can derive Ω_Λ, Ω_m, σ_8, t_0, H_0.

Ω_Λ = 68.9% +/- 0.6%; Ω_m = 31.1% +/- 0.6%; σ_8 =0.810 +/- 0.006; t_0 = 13.79 +/- 0.02 Gyr; H_0 = 67.7+/- 0.4 km/s/Mpc

Hubble Tension

Adam Reiss



Abdalla et al, JHEAp 34 (2022) 49-211

Tension

5 σ

Also Mild Tension σ8

- Is this due to systematics?
- Is this due to new models?

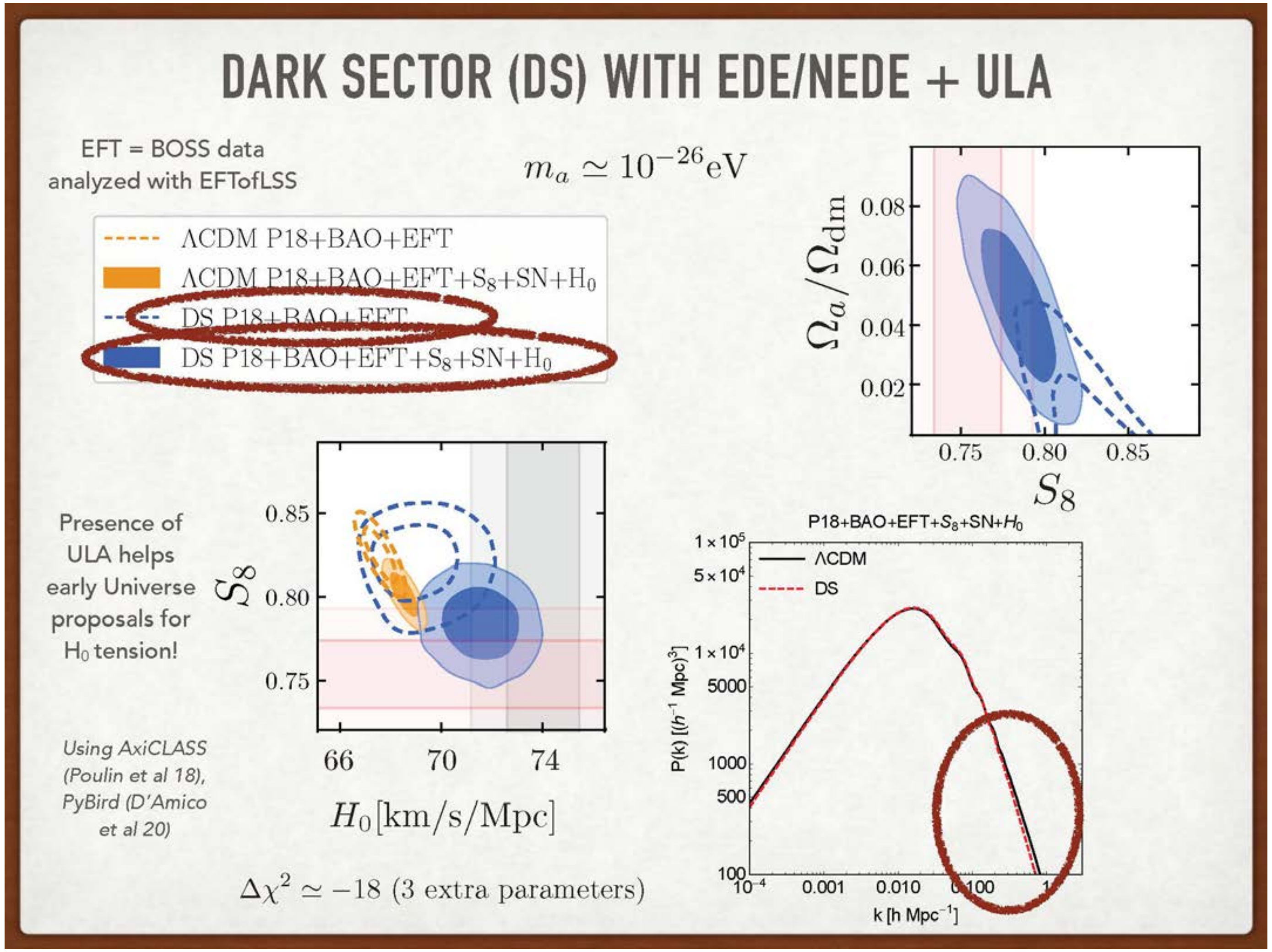
Table B1. Models solving the H_0 tension with R20 within the 1σ, 2σ and 3σ confidence levels considering the *Planck* dataset only.

Tension $\leqslant 1\sigma$ 'excellent models'	Tension $\leqslant 2\sigma$ 'good models'	Tension $\leqslant 3\sigma$ 'promising models'
Dark energy in extended parameter spaces [289]	Early dark energy [235]	Early dark energy [229]
Dynamical dark energy [309]	Phantom dark energy [11]	Decaying warm DM [474]
Metastable dark energy [314]	Dynamical dark energy [11, 281, 309]	Neutrino–DM interaction [506]
PEDE [392, 394]	GEDE [397]	Interacting dark radiation [517]
Elaborated vacuum metamorphosis [400–402]	Vacuum metamorphosis [402]	Self-interacting neutrinos [700, 701]
IDE [314, 636, 637, 639, 652, 657, 661–663]	IDE [314, 653, 656, 661, 663, 670]	IDE [656]
Self-interacting sterile neutrinos [711]	Critically emergent dark energy [997]	Unified cosmologies [747]
Generalized Chaplygin gas model [744]	$f(\mathcal{T})$ gravity [814]	Scalar–tensor gravity [856]
Galileon gravity [876, 882]	Über-gravity [59]	Modified recombination [986]
Power law inflation [966]	Reconstructed PPS [978]	Super ΛCDM [1007]
$f(\mathcal{T})$ [818]		Coupled dark energy [650]

Valentino, Mena, Pan, Visinelli, Yang, Melchiorri, Mota, Riess, Silk, Class.Quant.Grav. 38 (2021) 15, 153001

Future progress:
Experiment: JWST, Gaia DR4,5, LIGO, R^2, Euclid...

Hubble Tension…



Fabrizio Rompineve

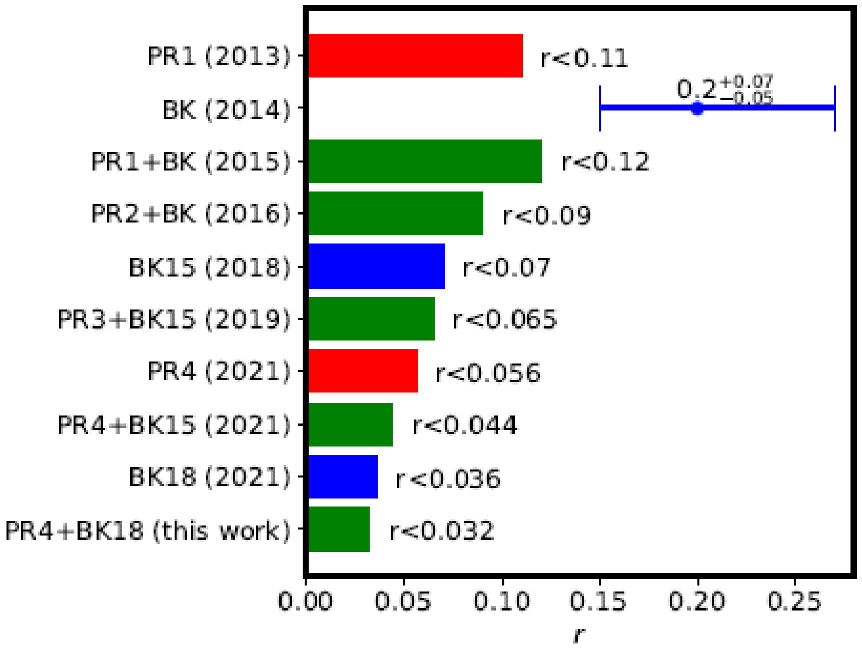
"we should test the *assumed* homogeneity and isotropy …not simply measure the model parameters with increasing `precision"

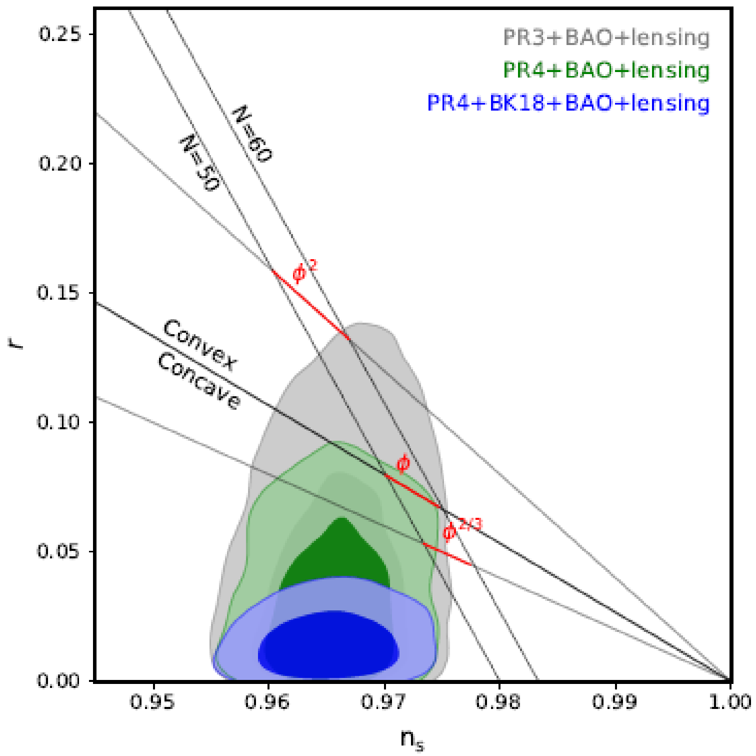
"The inference that the Hubble expansion rate is accelerating may be just an artifact of the bulk flow (and not due to a Cosmological Constant"

Subir Sarkar

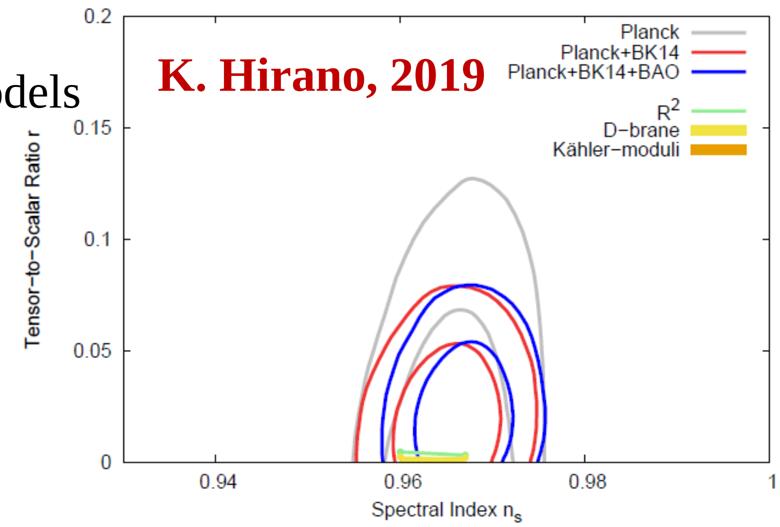
Inflation

Tensor to scalar ratio



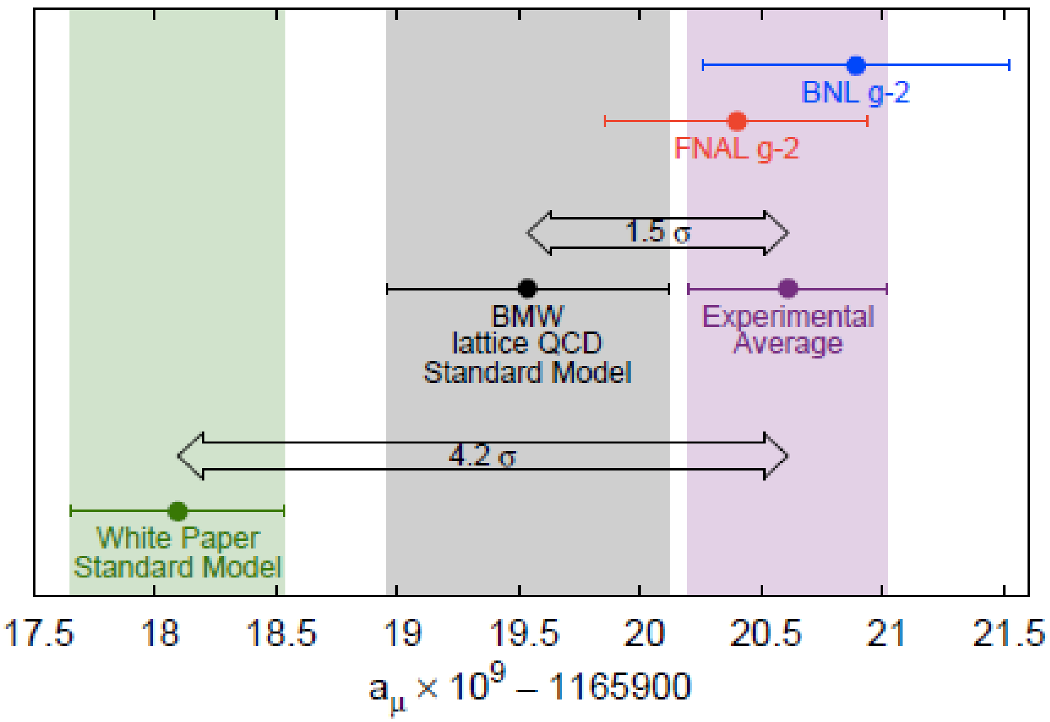


Models



"cosmological perturbations and gravitational waves with scale-invariant spectra are generated, without the need of postulating an early phase of cosmological inflation." **Robert Brandenberger**

g-2 of muon



We need more lattice results

Many particle physics models:
EW scale, sub-GeV scale etc.

Martin Hoferichter

Also g-2 of the electron:

$$\Delta a_e^{\mathrm{Cs}} \equiv a_e^{\exp}(\mathrm{Cs}) - a_e^{\mathrm{SM}} = (-8.7 \pm 3.6) \times 10^{-13}$$

$$\Delta a_e^{\mathrm{Rb}} \equiv a_e^{\exp}(\mathrm{Rb}) - a_e^{\mathrm{SM}} = (4.8 \pm 3.0) \times 10^{-13}$$

LHCb anomalies

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}\,,\quad R_{K^*} = \frac{\mathcal{B}(B \to K^*\mu^+\mu^-)}{\mathcal{B}(B \to K^*e^+e^-)}\,.$$

$\mathcal{R}_{K^+}$ with 100% of Run 1+2

$$\mathcal{R}_{K^+}^{[1.1,6]} = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

3.1σ below SM

Nature Phys. 18, 3 (2022)

$$\mathcal{R}_{K^{*0}}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

2.1σ below SM

JHEP 08, 055 (2017)

$$\mathcal{R}_{K^{*0}}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

2.4σ below SM

Manuel Sevilla

Are LHCb anomalies g-2 anomalies correlated?

Since both anomalies involve muon sectors, it is possible to explain in the context of a single model

Talks by Amarjit Soni, Farvah Nazila Mahmoudi

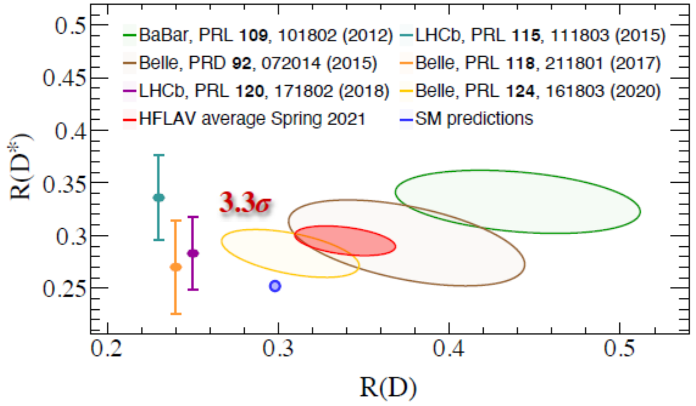
Other works, E.g., **Babu, Dev, Jana, Thapa,JHEP 03 (2021) 179,**
Dutta, Ghosh, Kumar, Huang, PRD, 105 (2022) 1, 015011;
Zheng, Zhang, PRD,104 (2021) 11, 115023; Navarro, King, PRD,105 (2022) 3, 035015

Possible LFU in $b \to c\tau\nu$ transitions

- Powerful LFU tests with ratios
  - ➡ Numerous uncertainties cancel

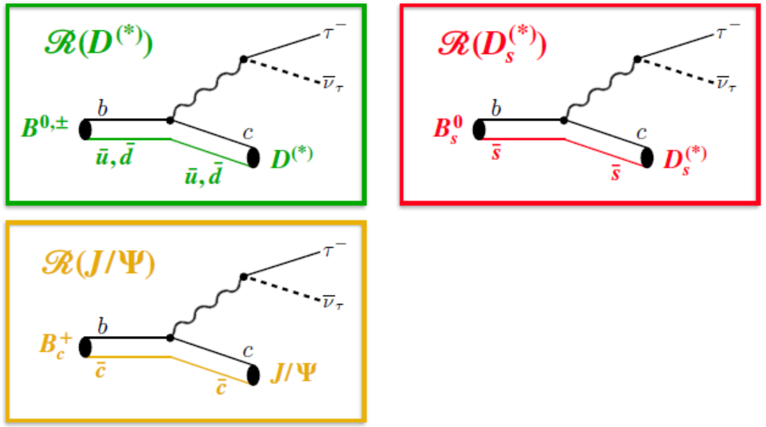
$$\mathcal{R}\left(D^{(*)}\right) = \frac{\mathcal{B}\left(\bar{B} \to D^{(*)}\tau\nu_\tau\right)}{\mathcal{B}\left(\bar{B} \to D^{(*)}\ell\nu_\ell\right)}$$

with $\ell = \mu, e$ $\qquad \mathcal{R}\left(D^{(*)}\right) \equiv \mathcal{R}(D)$ or $\mathcal{R}(D^*)$



Even 5σ on $\mathcal{R}(D)/\mathcal{R}(D^*)$ would not be sufficient to convince ourselves of NP

Important to **test other observables,** and **LHCb** has **unique ability to study $b \to c\tau\nu$ transitions**



Manuel Sevilla

LHC, Supersymmetry

- Plenty of natural parameter space under model independent measure DEW
- mu~100-350 GeV: light higgsinos!
- other sparticle contributions to m(weak) are loop suppressed- masses can be TeV->multi-TeV
- stringy naturalness: what the string landscape prefers
- predicts LHC sees mh~125 GeV
- under stringy naturalness, a 3 TeV gluino more natural than 300 GeV gluino
- landscape-> non-universal 1st/2nd gen. scalars at 20-40 TeV: natural but gives quasi-degeneracy/decoupling sol'n to SUSY flavor, CP and cosmological moduli problems
- dark matter: a mix of axions+higgsino-like WIMPs (typically mainly axions)

Howie Baer

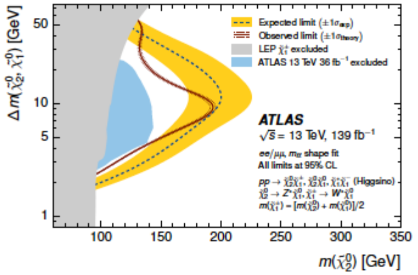
➔Natural SUSY: only higgsinos need lie close to weak scale

Soft dilepton+jet+MET signature from higgsino pair production

A light LSP in pMSSM is still possible: light $\tilde{\chi}_1^0$. Z funnel region under stress in PMSSM. Allowed region can be probed at HL-LHC through the phenomenology of heavier neutralinos.

We can see that this WIMP paradigm for a light LSP in pMSSM and NMSSM can be tested at the HL/HE LHC, ILC/CEPC and DD experiments.

Rohini Godbole



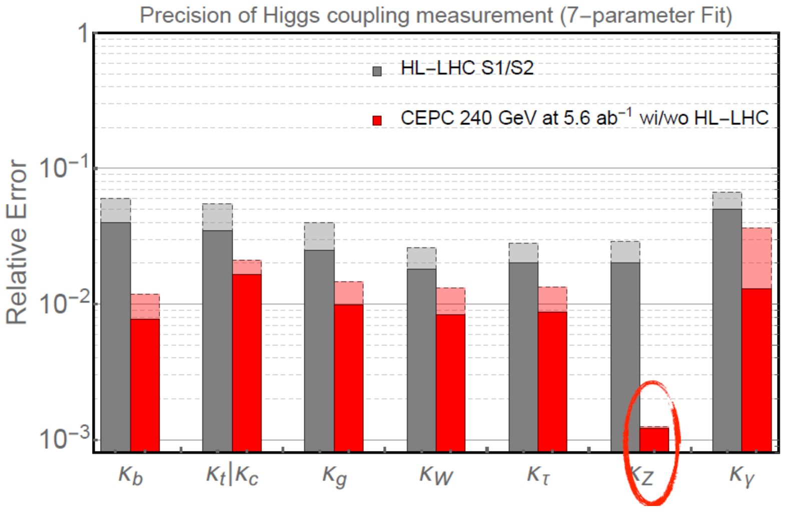
Higgs Precision era

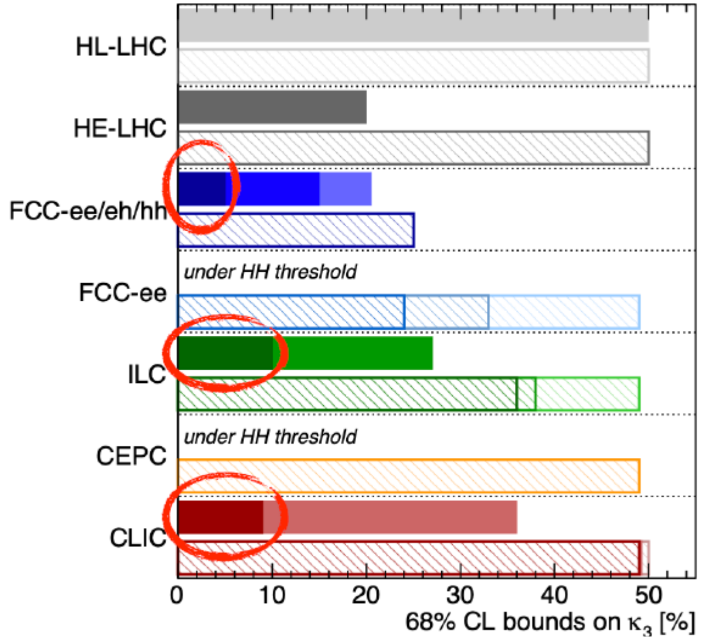
$$\kappa_f = \frac{g(hff)}{g(hff;\mathrm{SM})},\ \kappa_V = \frac{g(hVV)}{g(hff;\mathrm{SM})}$$

LHC / HL-LHC Plan

LHC is a Higgs factory: 15 M Higgs

HL-LHC: 170 M Higgs, 120 K HH pair





Higgs self-interaction

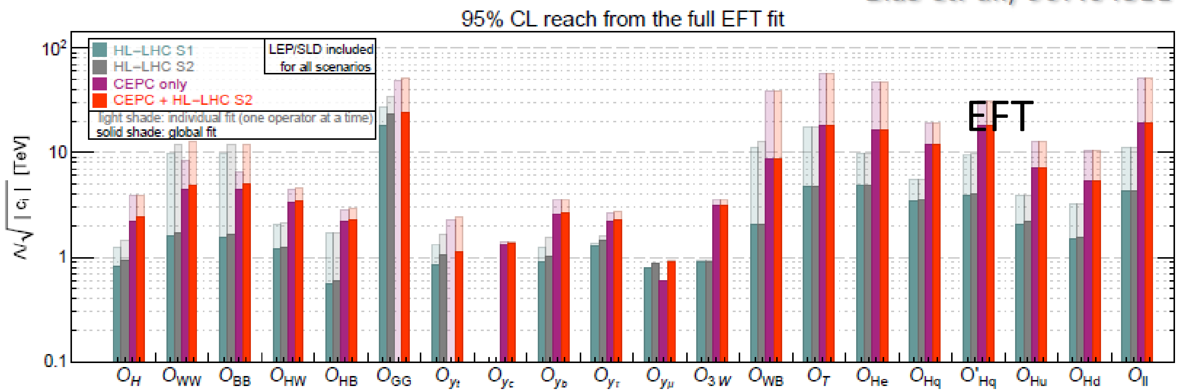
Shufang Shu

Higgs at the LHC

$$\mathcal{L}_{\rm Eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

HL-LHC/Higgs factory

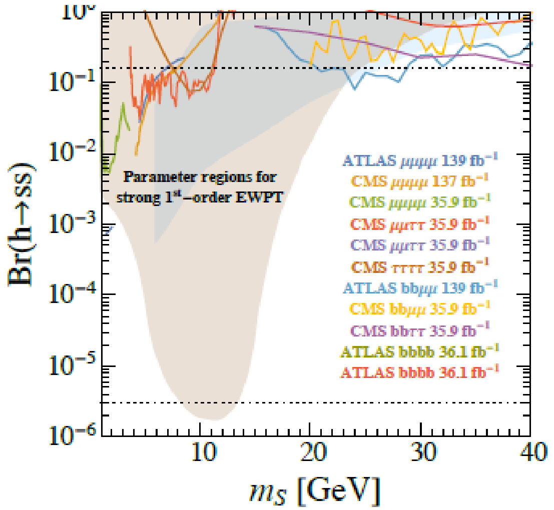
Blas et. al., 907.04311



S. Su

- At the center of many BSM scenarios:
  - Electroweak baryogenesis.
    - Interesting because need new
  - Higgs Portals.
  - Connection to DM physics.

$$V \supset \frac{a_1}{2}|\Phi|^2 S + \frac{a_2}{2}|\Phi|^2 S^2 \supset \frac{a_1 v}{2} h S + \frac{a_1}{4} h^2 S + \frac{a_2 v}{2} h S^2$$



Ian Lewis

High-Luminosity LHC

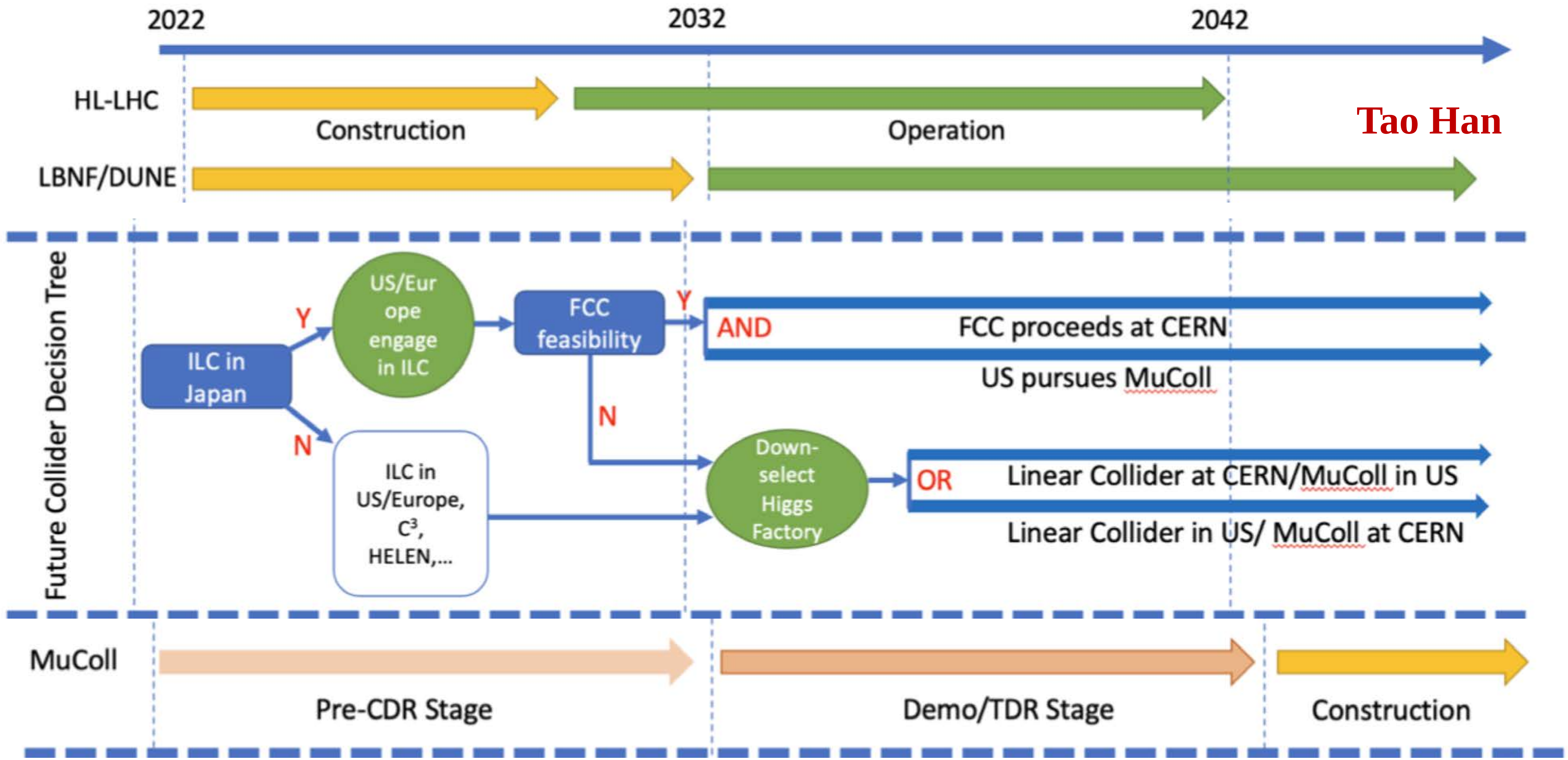
Tao Han

- Fully approved in 2016, technology available, construction well underway!

- Run 3 started: beams in April 22, 2022
- Stable beam collisions detected by ATLAS/CMS

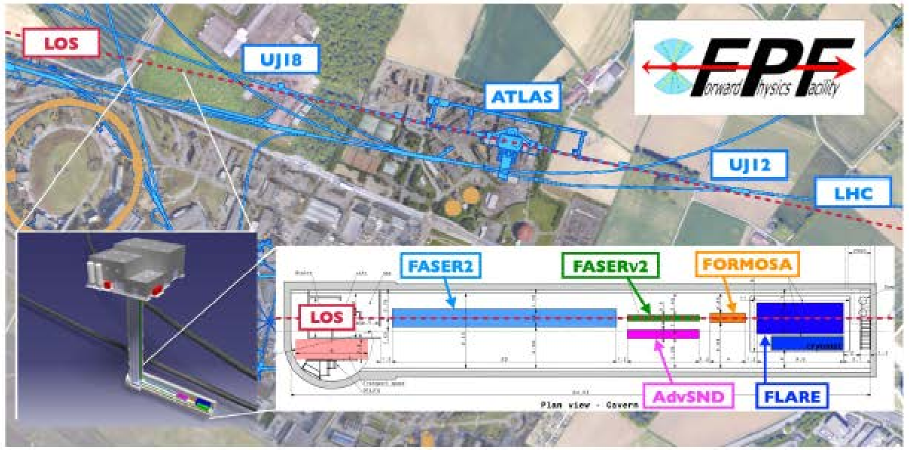
--- more excitement to come!

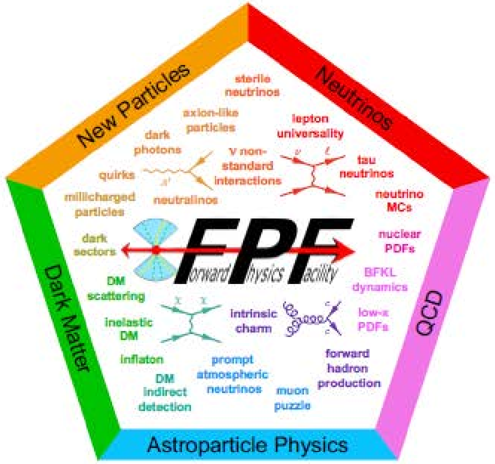
Future Collider

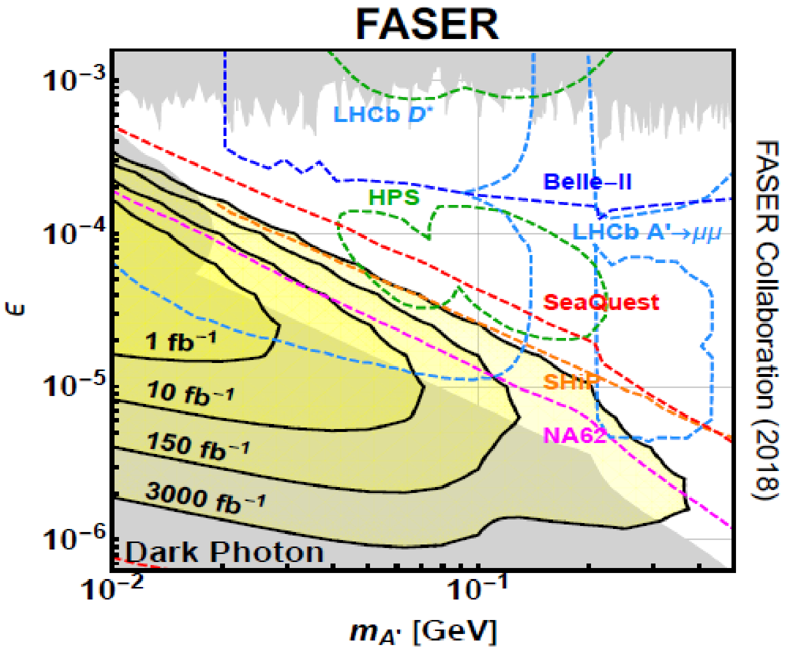


FASER

- We are currently missing half of the physics opportunities at the LHC.
- This can be rectified by putting experiments in the far forward region to catch particles produced along the beamline.
- The Forward Physics Facility is a proposal to do exactly this for the HL-LHC era from 2029-40.





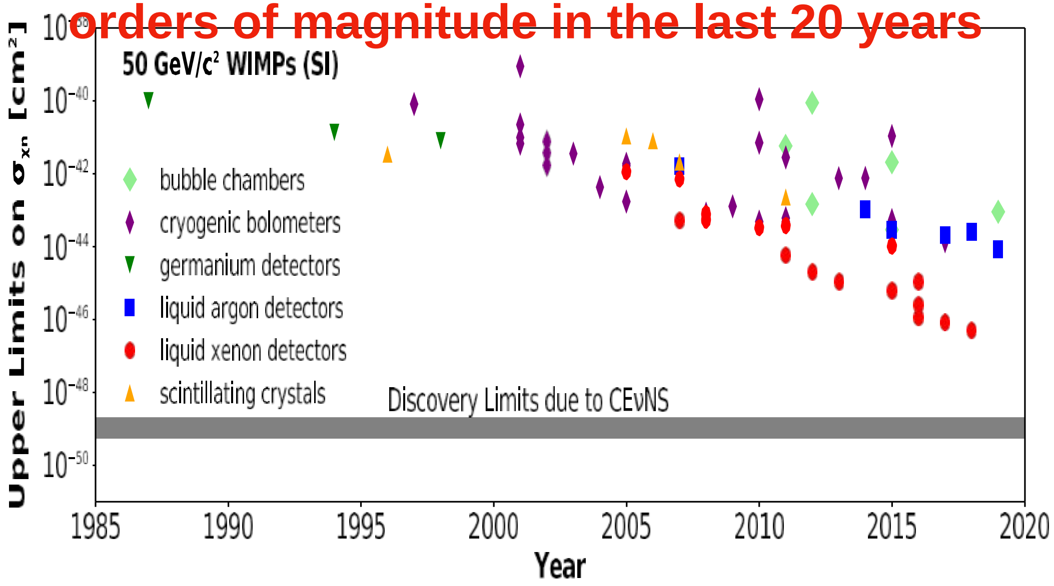


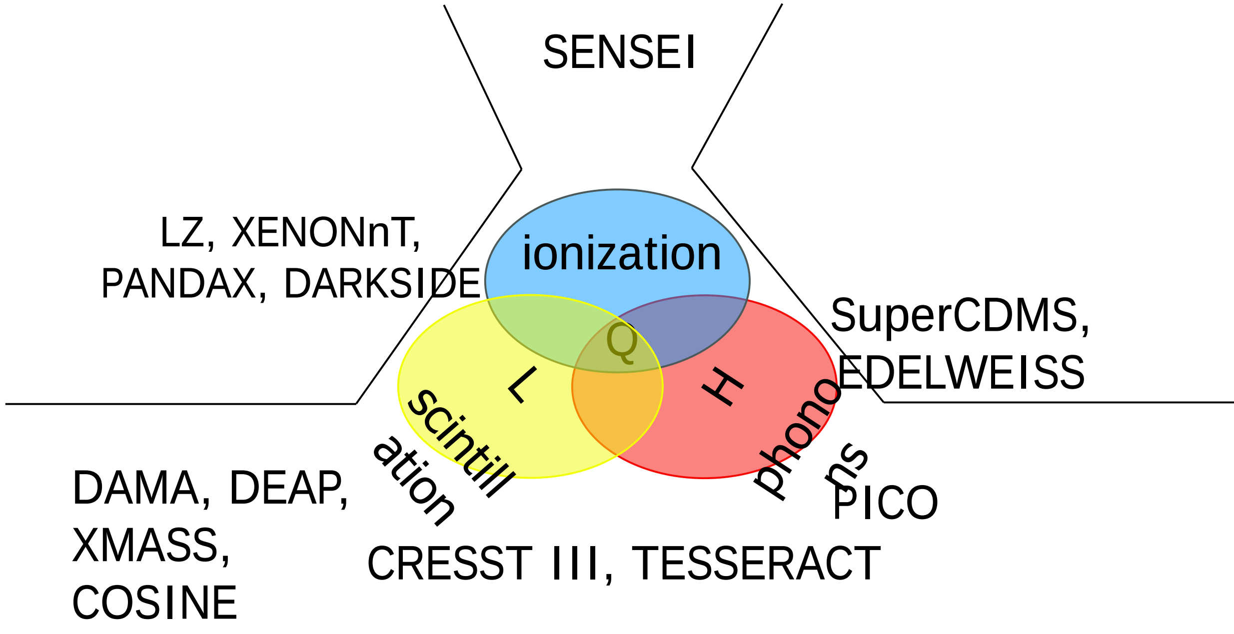
FASER probes new parameter space with just 1 fb^{-1} starting in July 2022.

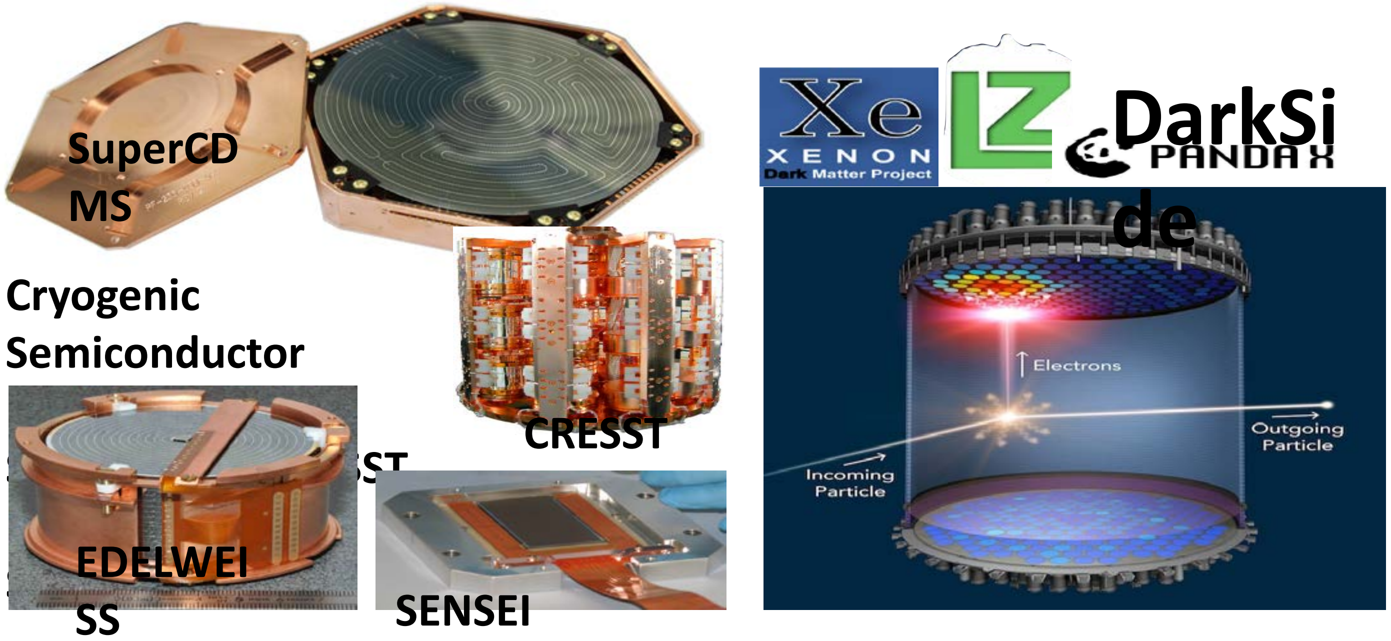
Jonathan Feng

Direct Detection

Detector sensitivity improved by 5 orders of magnitude in the last 20 years





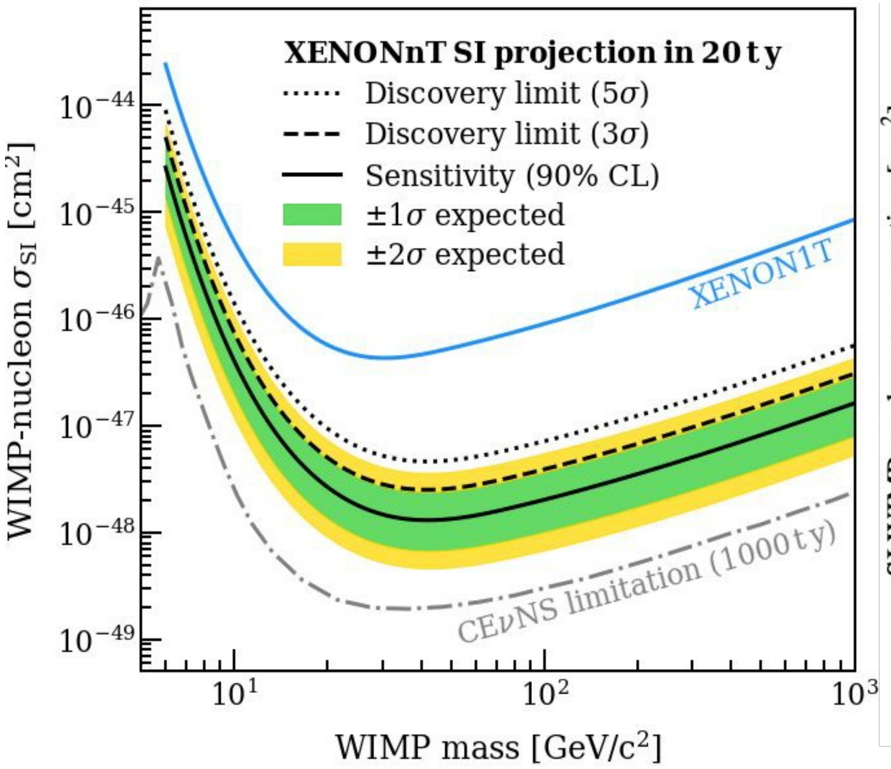


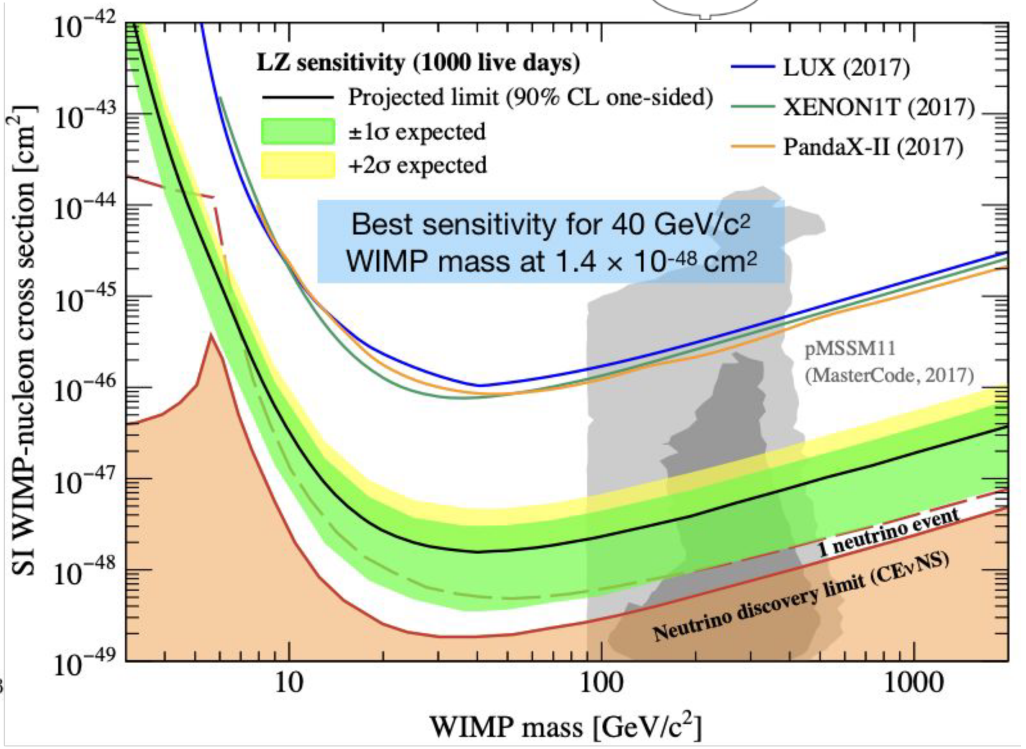
R. Mahapatra

Direct Detection: WIMP

is WIMP (10 MeV-100 TeV) in trouble?
There exist many scenarios where WIMPs are hard to detect, e.g.
Lighter wimp, hidden sector DM, coannhilations, departure from radiation domination of the early universe, loop suppressed couplings to the nucleus, velocity suppressed coupling

Dan Hooper



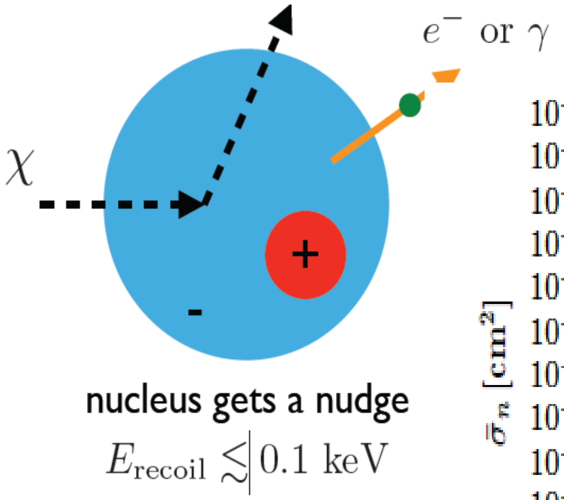


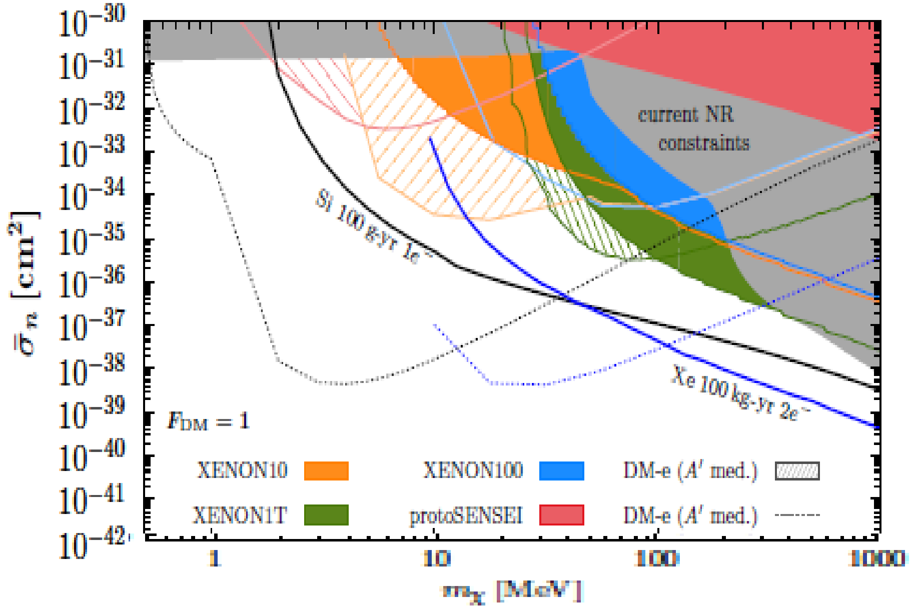
Direct Detection: Light DM

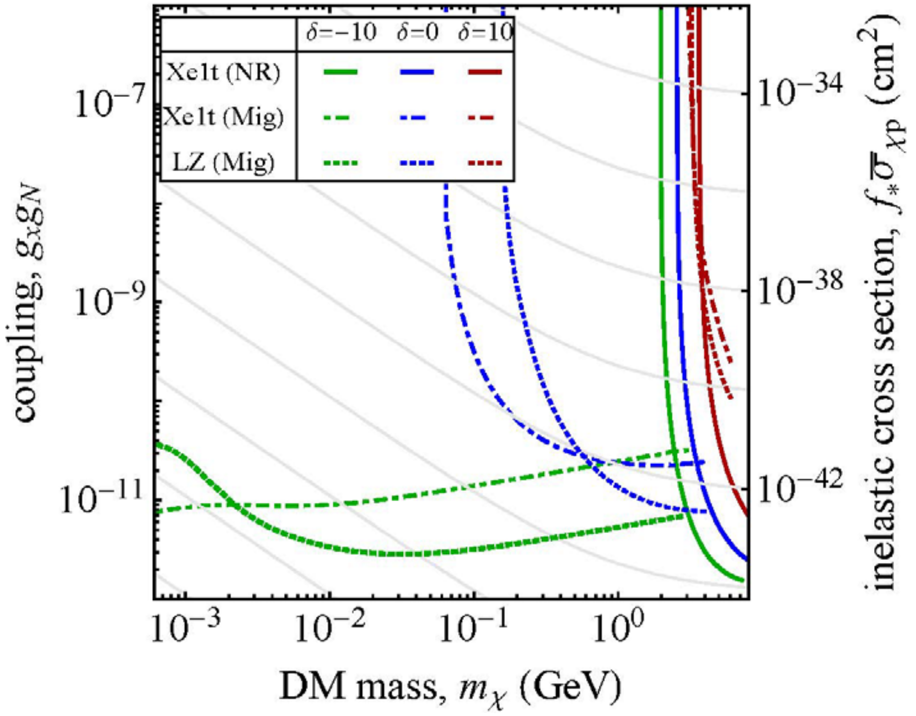
Various ways of probing Sub-GeV DM:

Ibe, Nakano, Shoji, Sujuki, 2018
Dolan, Kahlhoefer, McCabe, 2018

Migdal effect (Ionization and excitation of electron)





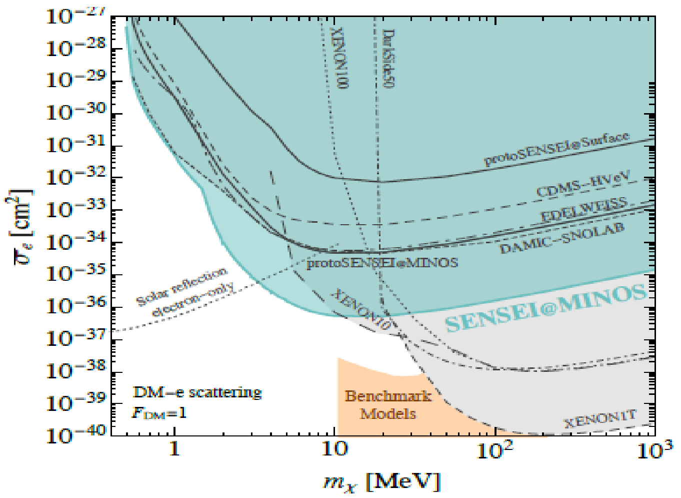


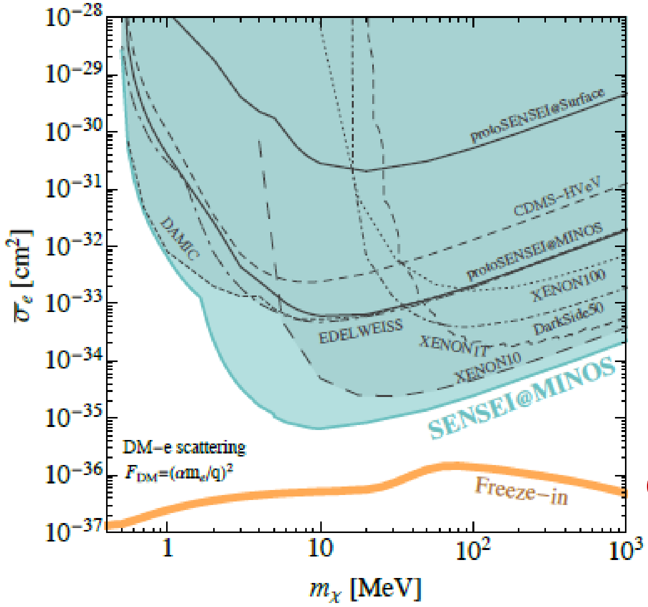
Essig, Prdaler, Sholapurkar, Yu, PRL 2020

Bell, Dent, Dutta, Ghosh, Kumar, Newstead, 2021
Flambaum, Su, Wu, Zhu, 2021

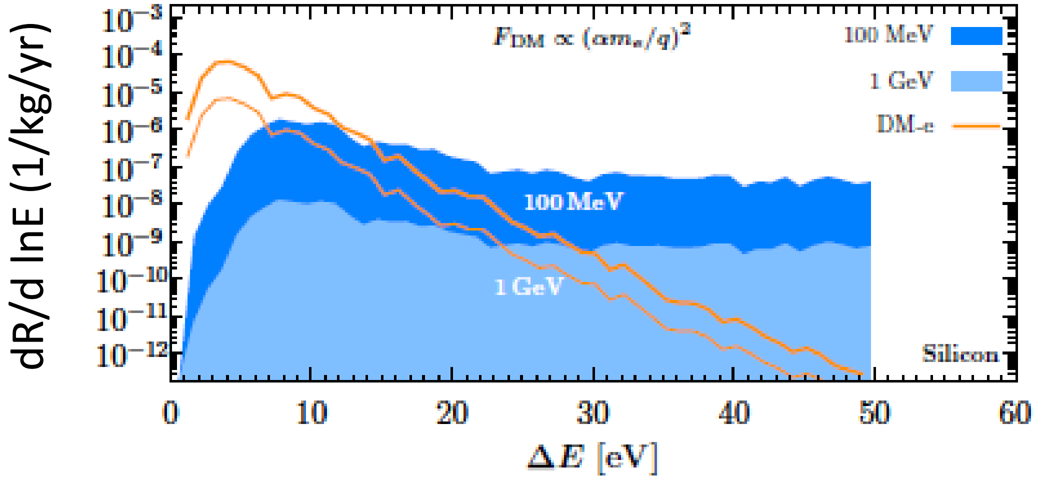
Direct Detection: DM-electron

DM-electron interaction

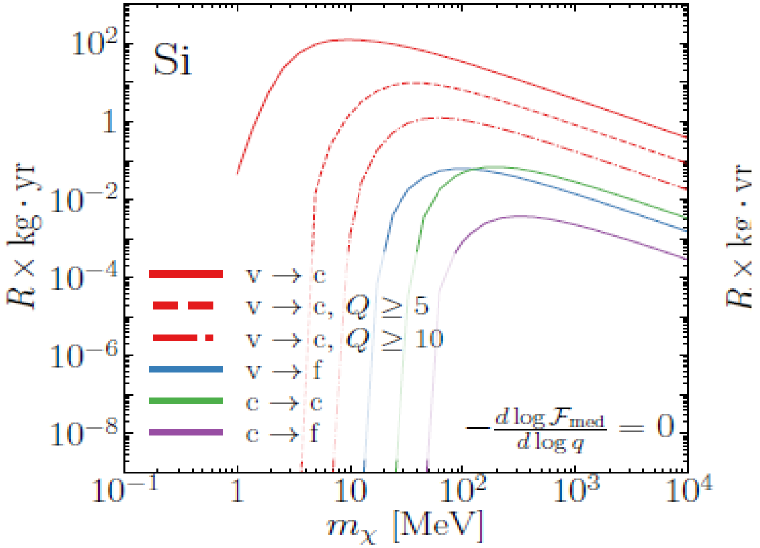




Barak et al (SENSEI) 2020



Essig, Prdaler, Sholapurkar, Yu, PRL 2020



Griffin, Inzani, Trickle, Zhang, Zurek, 2105.05253

Accurate calculations of dark matter electron scattering rates in semiconductors
➔ Important for superCDMS, SENSEI, DAMIC, EDELWEISS

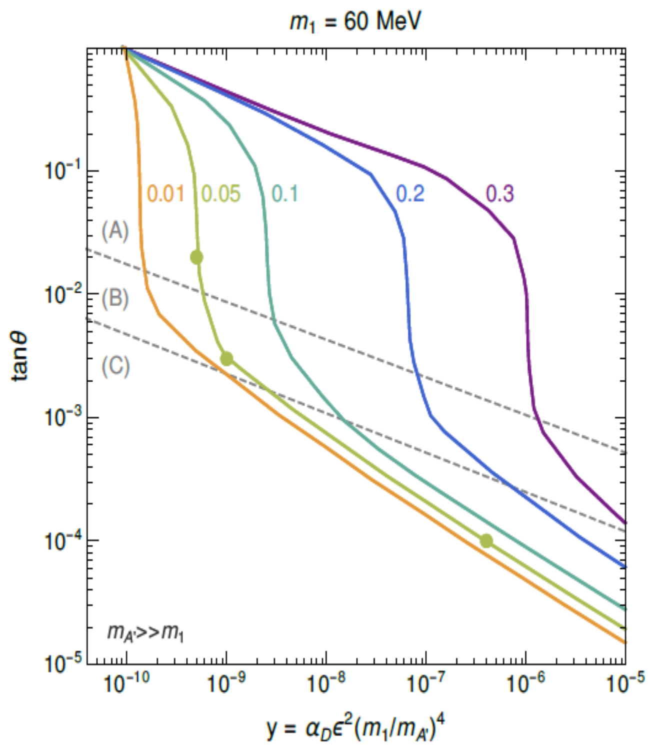
Catena, Emken, Nicola A. Spaldin, Tarantino, PRR 2020
Pandey, Singh, Wu, Chen, Chi, Hsieh, Liu, Wong, PRD 2020,
Baxter, Kahn, Krnjaic, Griffin, PRD 2020

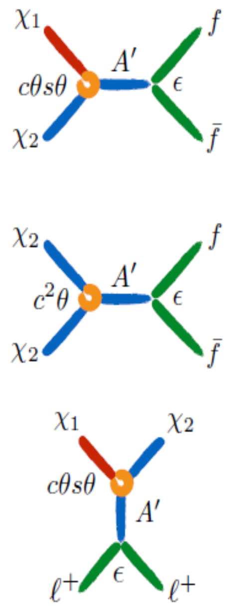
Sub-MeV DM: superconductors, superfluid He, Dirac materials, polar materials

Griffin, Knappen, Lin, Zurek, 2018

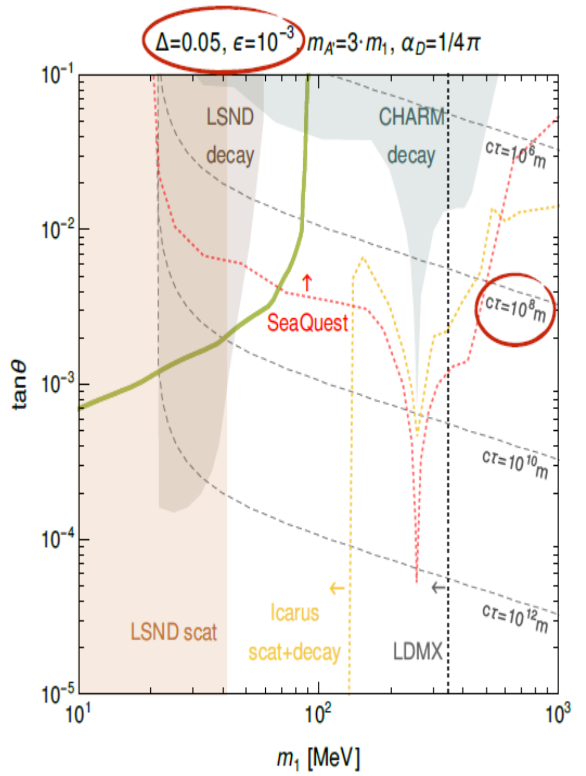
Inelastic Dirac Dark Matter

$$\mathcal{L}_{\mathrm{i2DM}} \supset -g_D A'_\mu \left[s^2\theta(\bar\chi_1\gamma^\mu\chi_1) - s\theta c\theta(\bar\chi_1\gamma^\mu\chi_2 + h.c.) + c^2\theta(\bar\chi_2\gamma^\mu\chi_2) \right]$$





Filimonova, Junius, Lopez-Honorez, SW 2201.08409 22



production:

$A' \to \chi_1\chi_2, \chi_2\chi_2$

decay:

$\chi_2 \to \chi_1 \ell^+\ell^-$

scattering:

$\chi_2 N \to \chi_2 N$

upscattering + decay:

$\chi_1 N \to \chi_2 N \to \chi_1 \ell^+\ell^- N$

Filimonova et al. 2201.08409

Susanne Westhoff

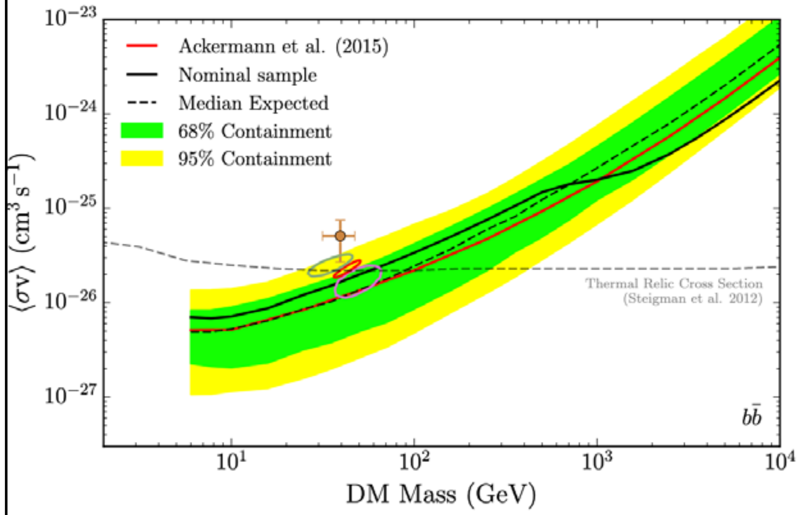
Indirect Detection

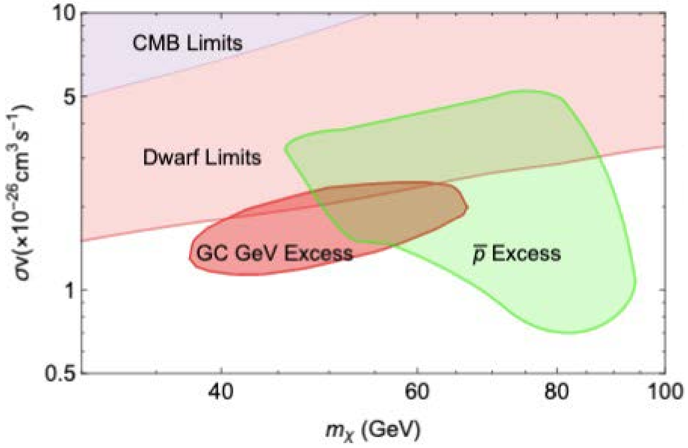
GC excess

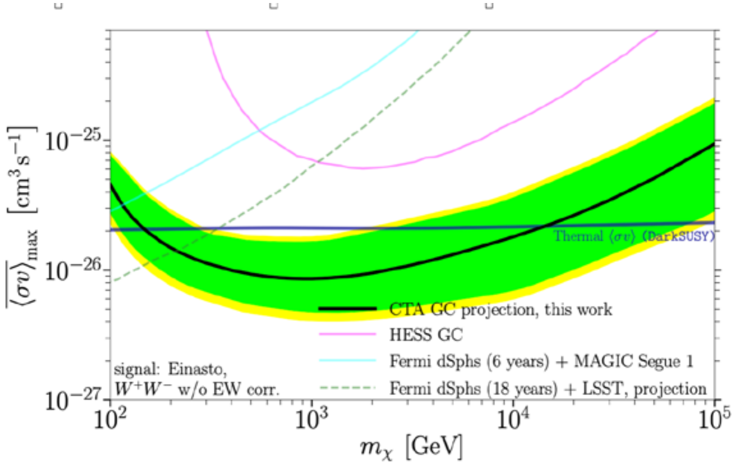
Arguments in Favor of Pulsars:
- The gamma-ray spectrum of observed pulsars
- Claims of small-scale power in the gamma-ray the Inner Galaxy
- Claims that the excess traces the Galactic Bulge/Bar

Dan Hooper

Arguments Against Pulsars:
- No millisecond pulsars have been detected in the Inner Galaxy, in tension with the measured luminosity function of gamma-ray pulsars
- The lack of low-mass X-ray binaries in the Inner Galaxy
- The relatively low luminosity of the TeV-scale emission from the Inner Galaxy

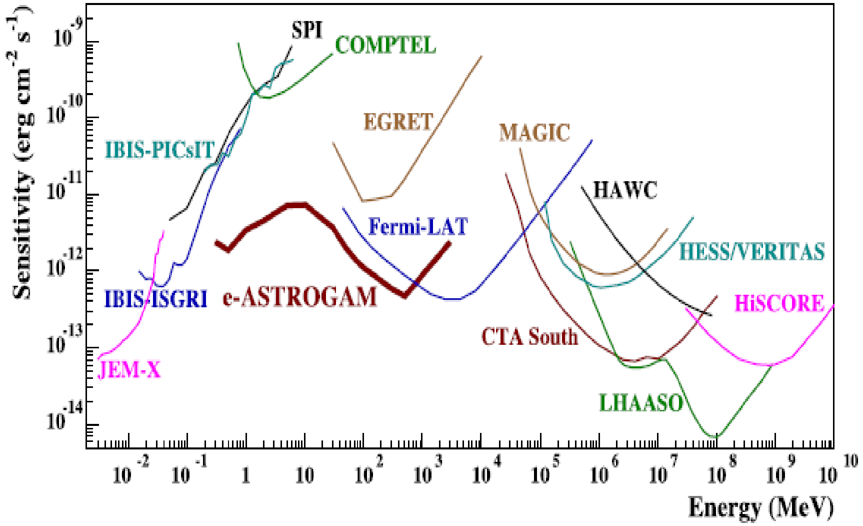






GC observations can set DM constraints below the thermal relic cross-section in the 0.2-20 TeV mass range.

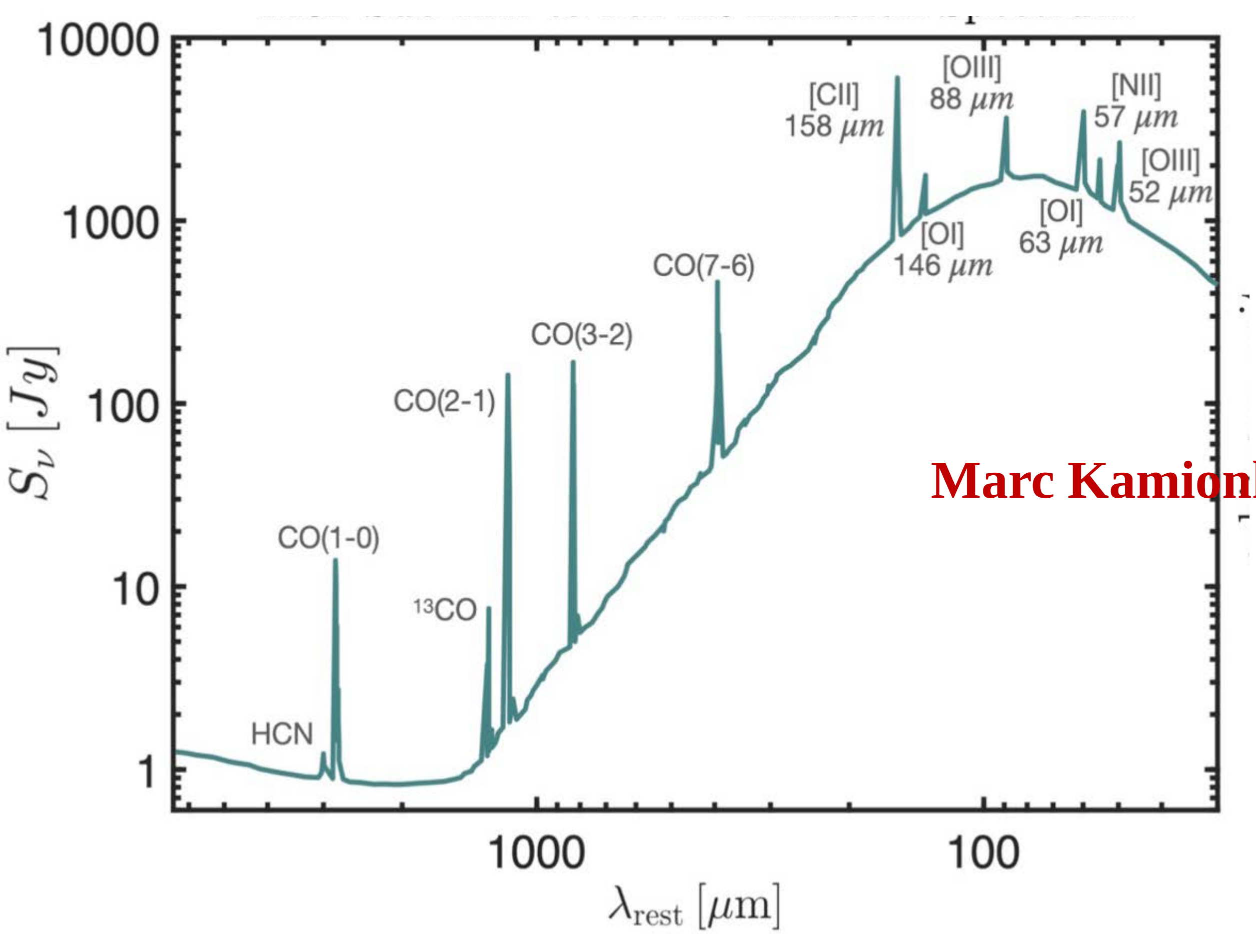
Petra Huentemeyer

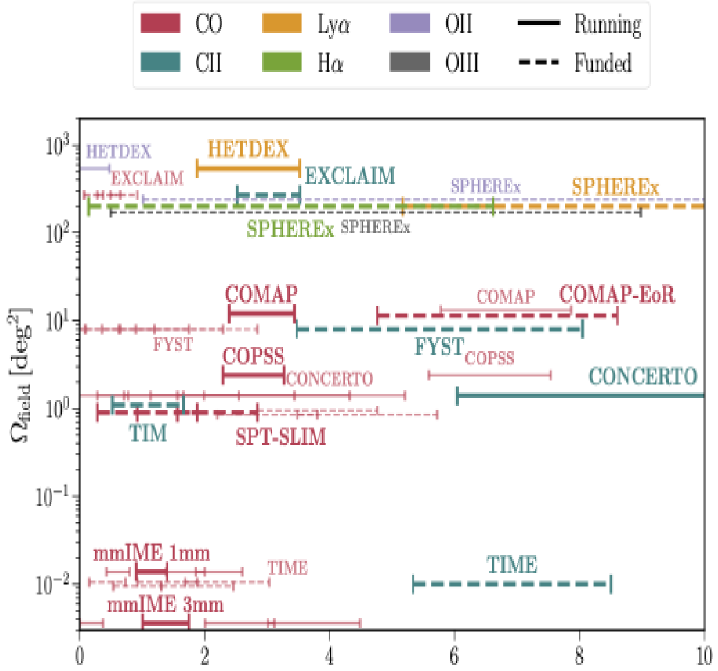


- **AMEGO, e ASTROGRAM should be able to probe DM down to MeV**

Line Intensity Mapping

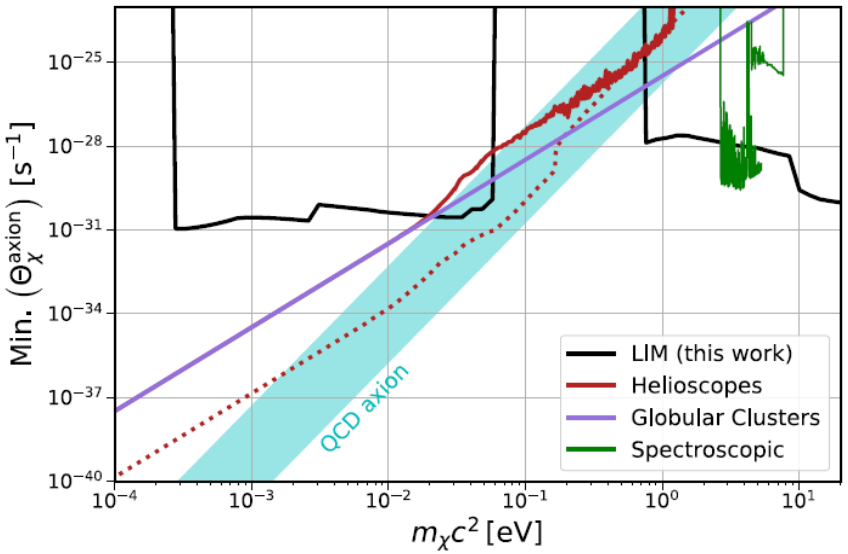
- LIM: use integrated light in given pixel on sky





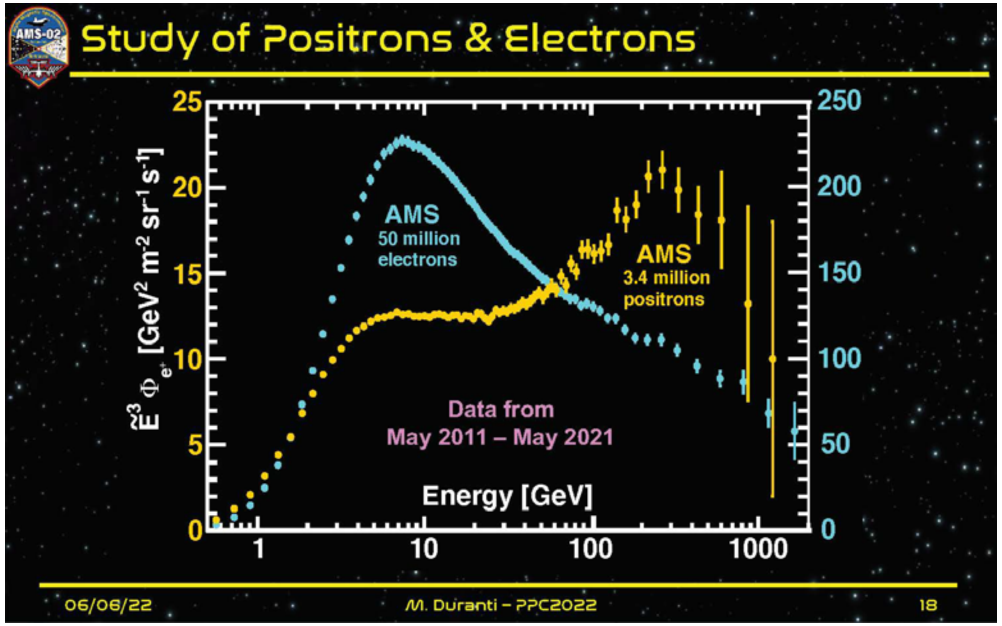
Marc Kamionkowski

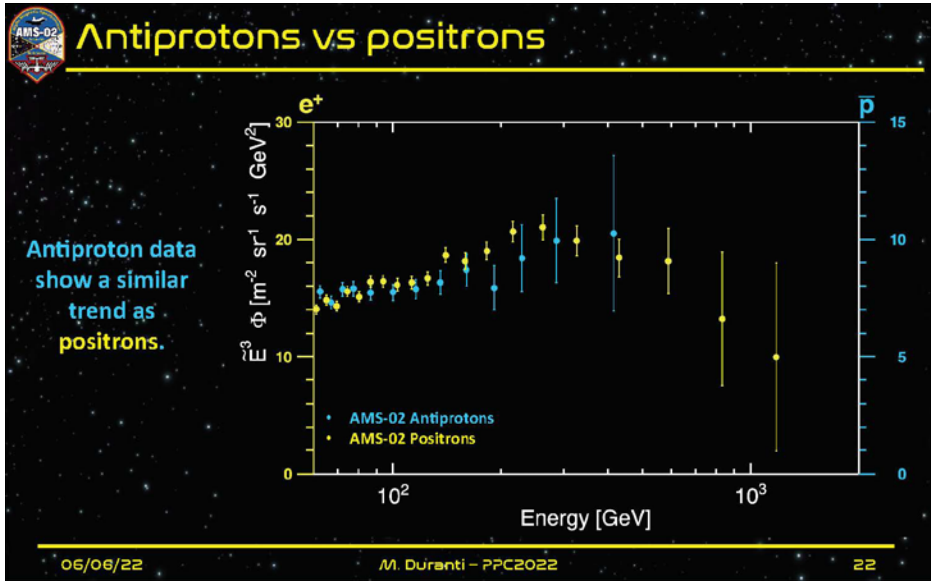
Axion sensitivity



Similar constraints: Dark Matter annihilation, decay, neutrino decay

AMS

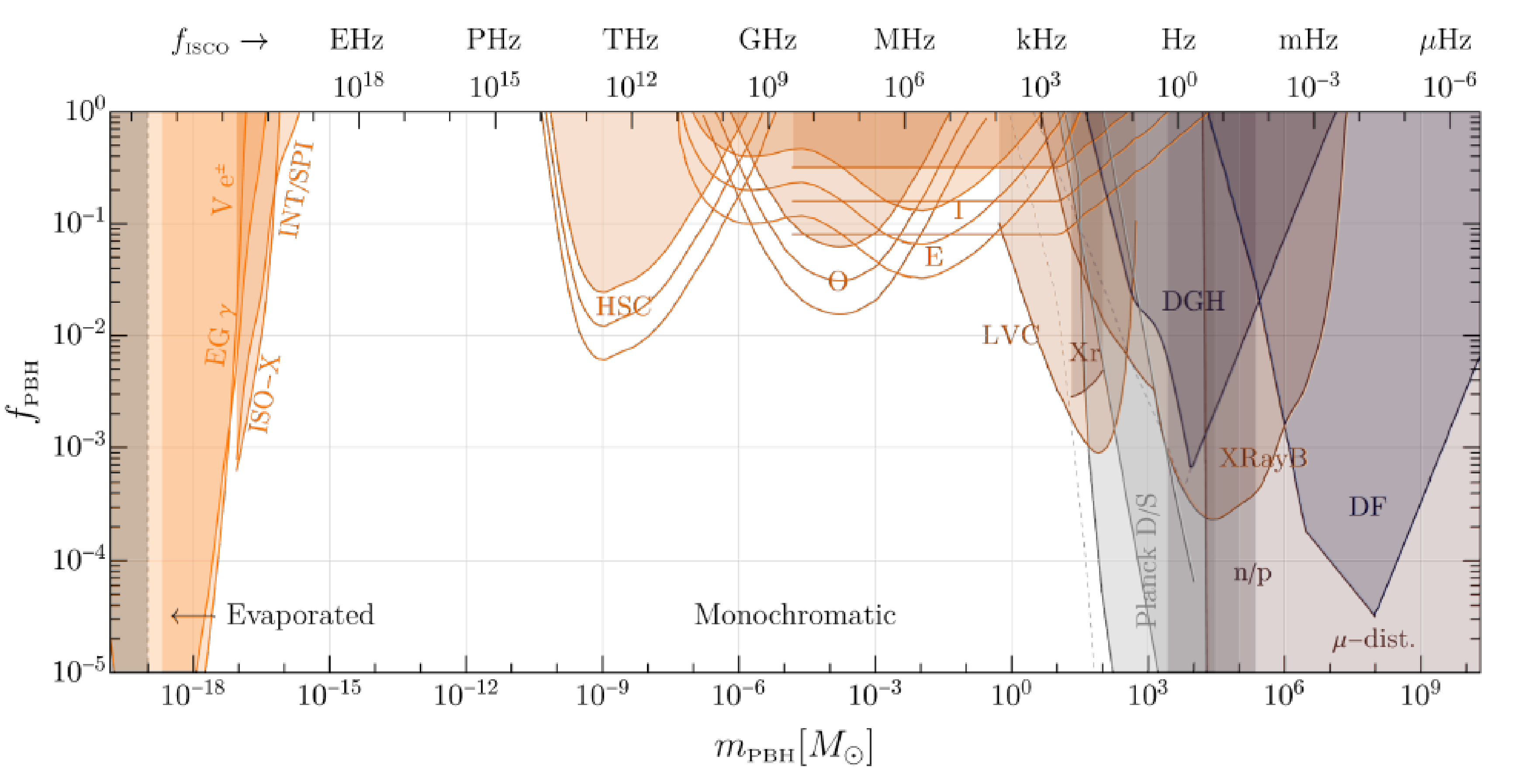




AMS will be operated for the full life-time of the ISS (2032?). In case of upgrade, some channels will have a significant boost in statistics/accuracy

M. Duranti, AMS

PBH –DM mass fraction

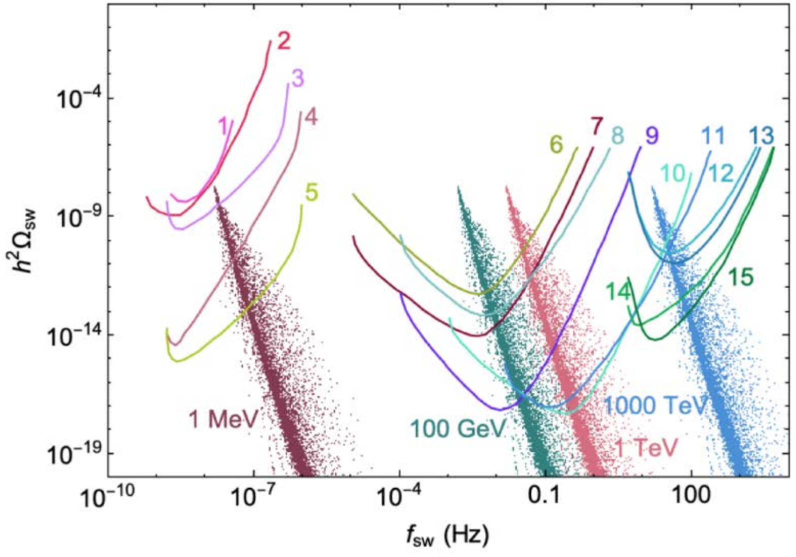


G.Franciolini, A.Maharana, and F.Muia, 2205.02153, based on
B.Carr, K.Kohri, Y.Sendouda, and J.Yokoyama, Rept.Prog.Phys. (2021), 2002.12778.

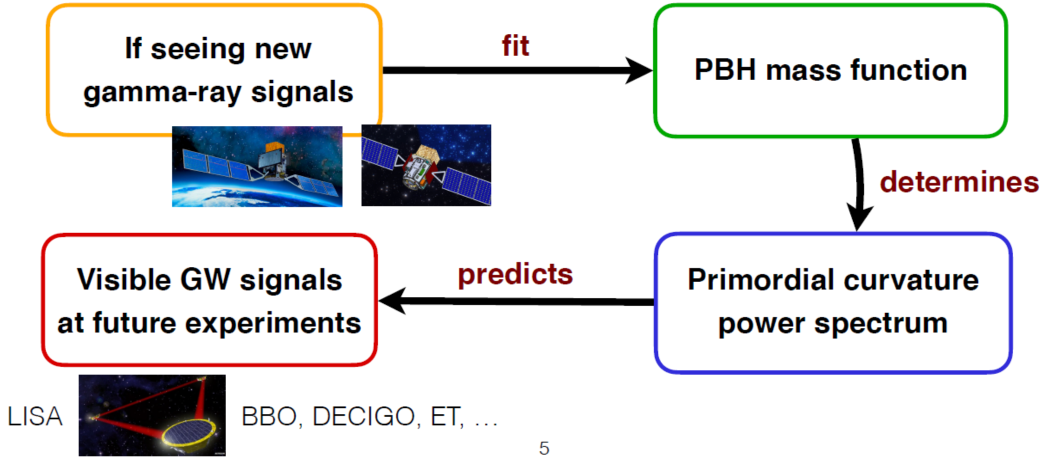
James Dent

Primordial Black Holes

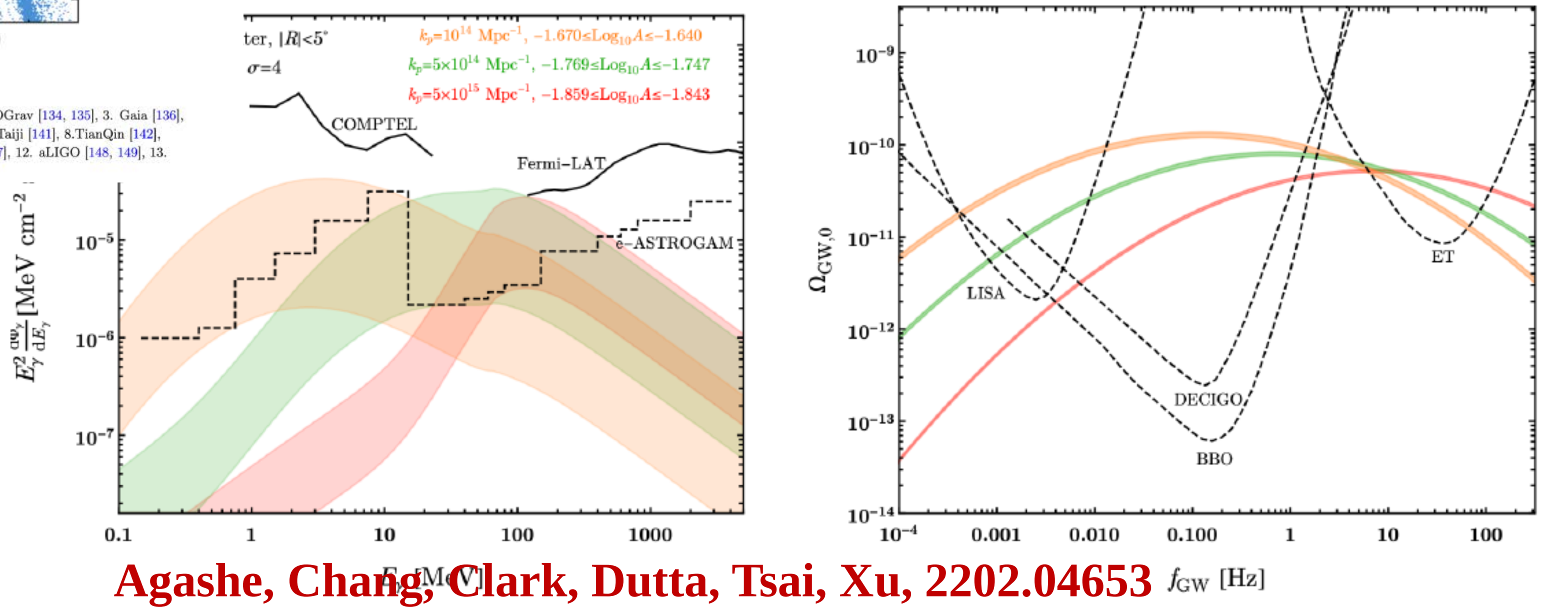
Sensitivity to Dark Sector Scales



1. EPTA [133], 2. NANOGrav [134, 135], 3. Gaia [136], 4. SKA [137], 5. THEIA [138], 6. LISA [12, 139, 140], 7. Taiji [141], 8.TianQin [142], 9. ALIA [143], 10. BBO [144, 145], 11. DECIGO [146, 147], 12. aLIGO [148, 149], 13. A+ [150], 14. ET [151], 15. CE [152].



James Dent

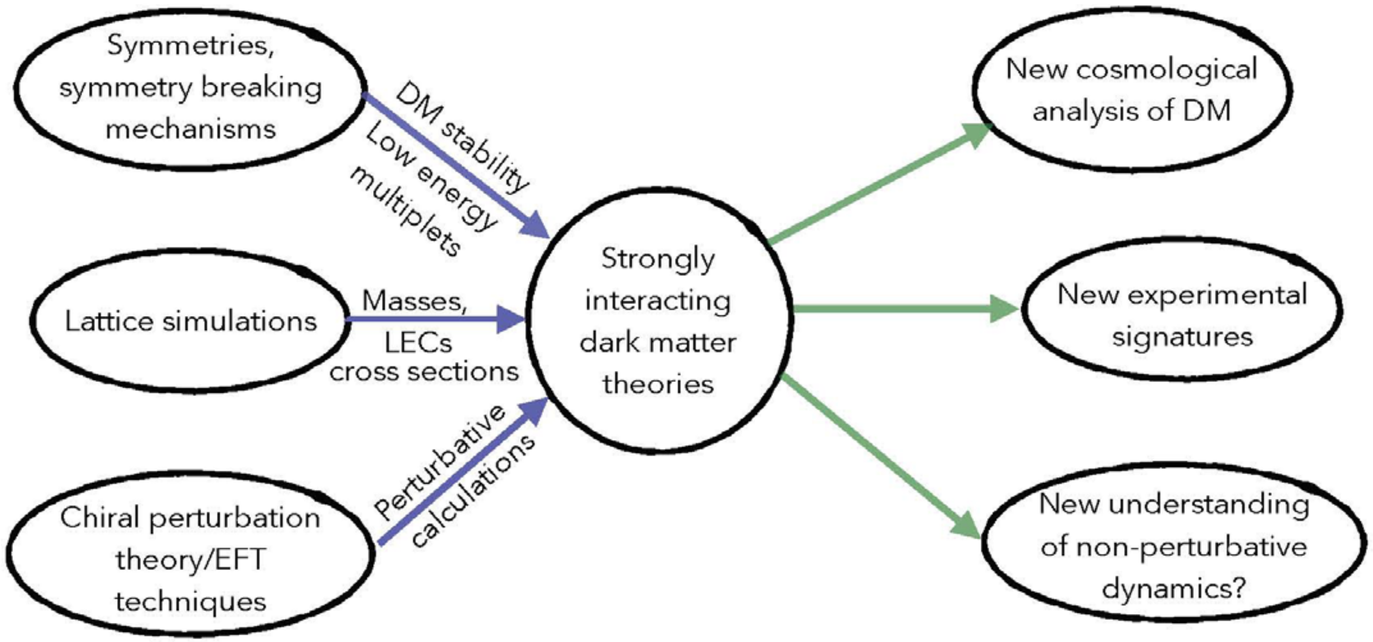


Agashe, Chang, Clark, Dutta, Tsai, Xu, 2202.04653

Strongly Interacting DM

Extensive program

A systematic analysis of strongly interacting theories is possible



- Presented several examples containing dark baryon and dark pion dark matter candidates
- DM stability is ensured either via symmetries inbuilt in the theories or via careful choices of external charges
- Multiple relic density generation mechanisms can be engineered
- Portals lead to new interesting phenomenology

Sucheta Kulkarni

New physics with neutron star mergers

LIGO should be able to constrain some parameter space.
for ultralight particles

Neutron stars can capture dark matter, which can modify the postmerger gravitational wave signal when two stars merge.

New particles can be produced in the hot, dense environment of a neutron star merger.
They could contribute to transport. BSM particle

Steve Harris

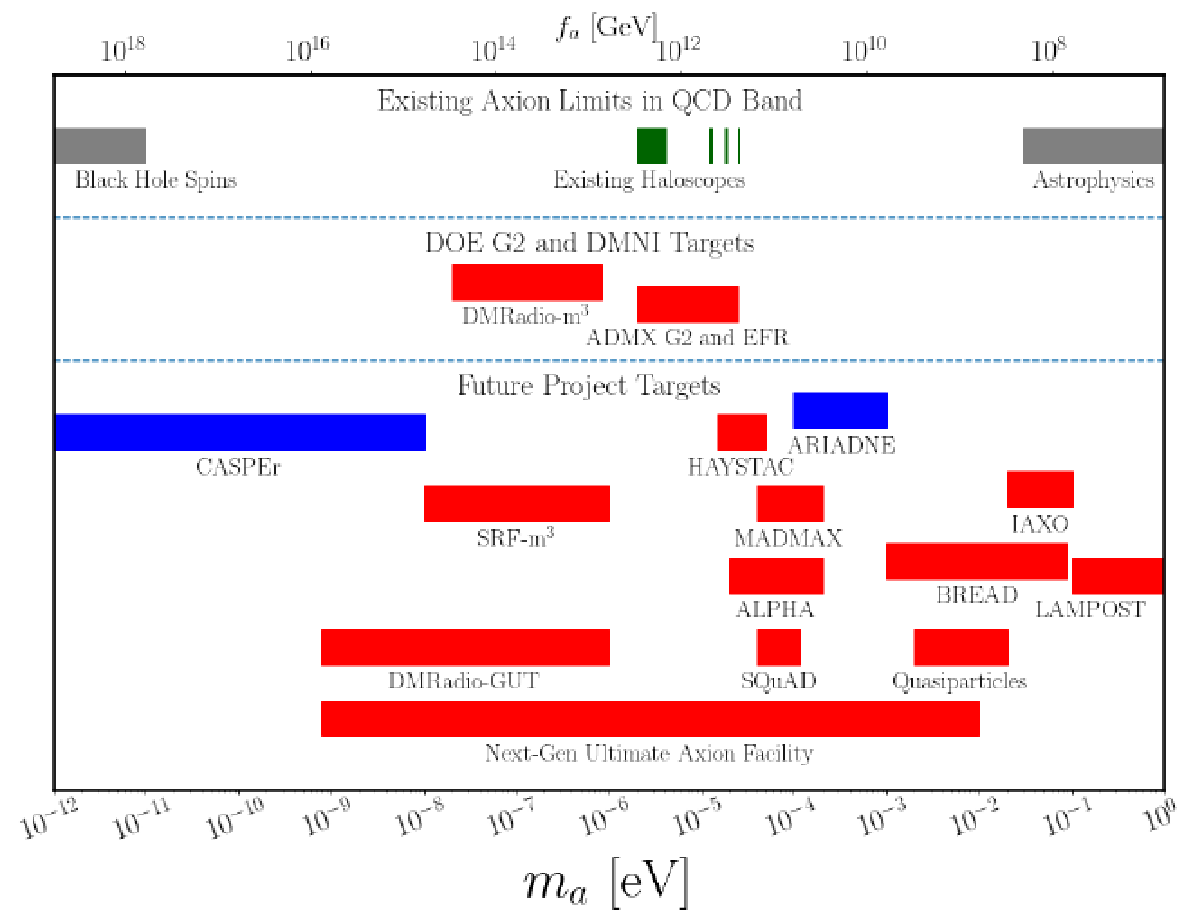
ALP Searches

$$L = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{i}{2} g_d a \bar{N}\sigma_{\mu\nu}\gamma_5 N F_{muv} + g_{aNN}(\partial_\mu)\bar{N}\gamma^\mu\gamma_5 N + g_{aie}(\partial_\mu)\bar{e}\gamma^\mu\gamma_5 e$$

- Coupling to photons
- Coupling to nucleon EDM. Causes electric dipole moments (EDMs) in nuclei/atoms/molecules
- Coupling to axion nuclear moment. Creates spin-dependent energy shifts/spin precession in fermions
- Coupling to axial electron moment. Axioelectric effect, Analogous to photoelectric effect

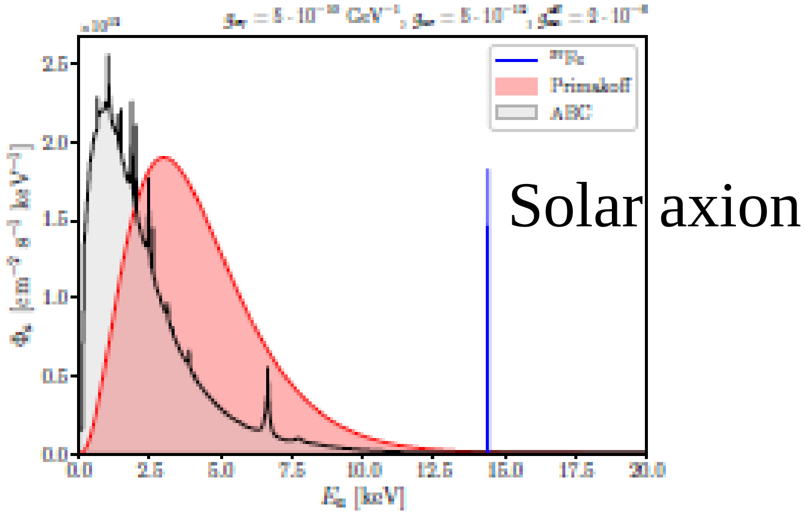
There is a broad set of detection strategies

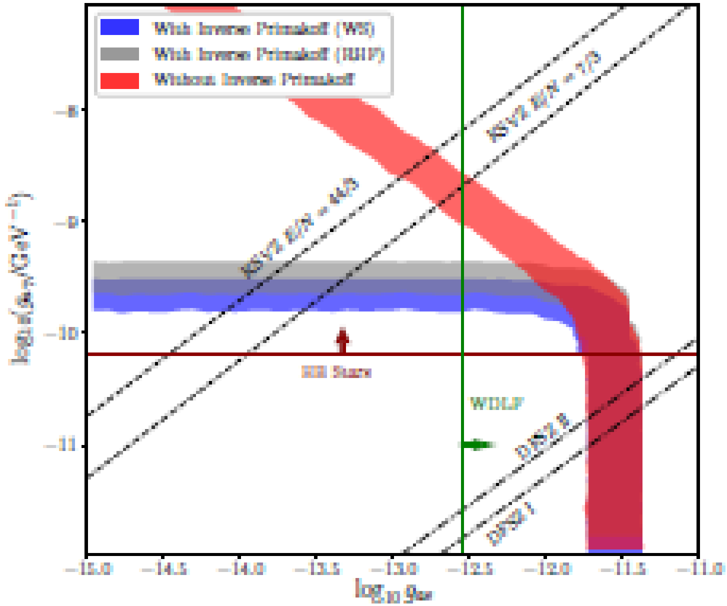
- Generate and then detect axions in the lab (or sense their force mediation)
- Detect axions generated from the sun
- Directly detect axion dark matter

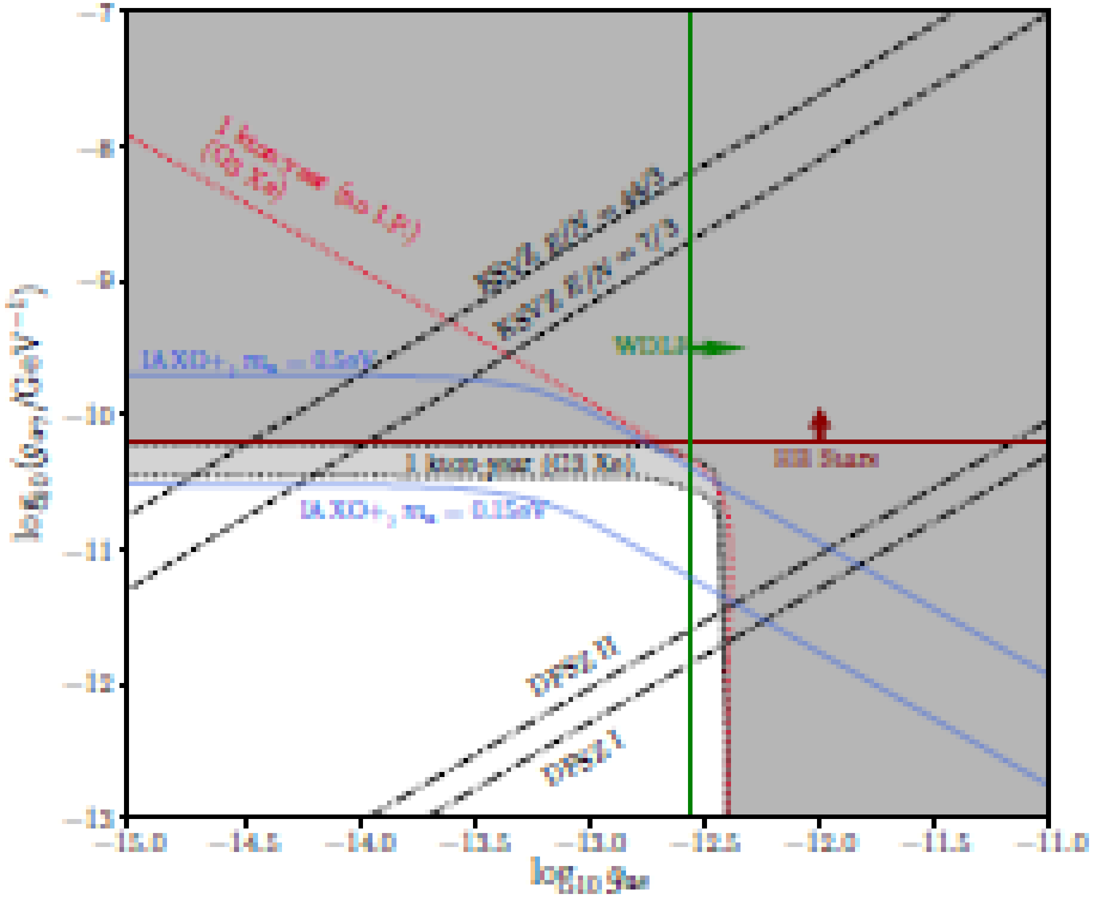


Gianpaolo Carosi

ALP at DM experiments

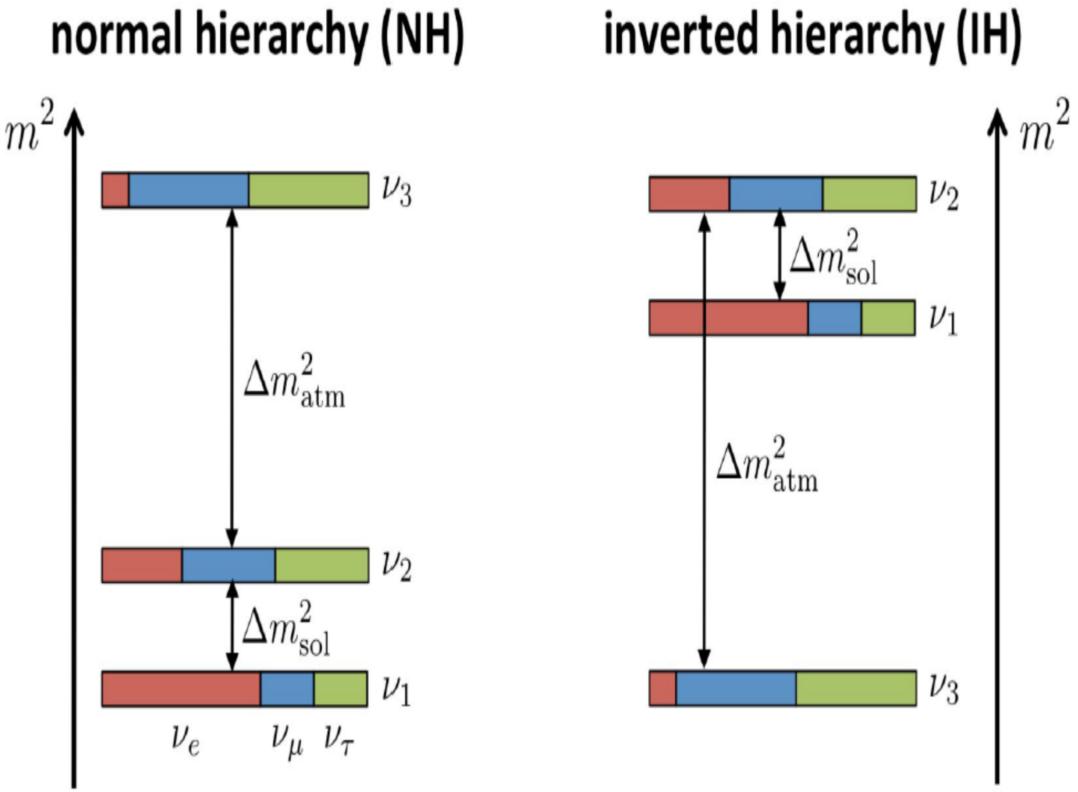






Dent, Dutta, Newstead, Thompson, Phys.Rev.Lett. 125 (2020) 13, 131805
Gao, Liu, Wang,Wang, Xue, Phys.Rev.Lett. 125 (2020) 13, 131806

Neutrino Mass



Cosmology is sensitive to the gravitational effects of the cosmic neutrino background, allowing a measurement of a sum of neutrino masses

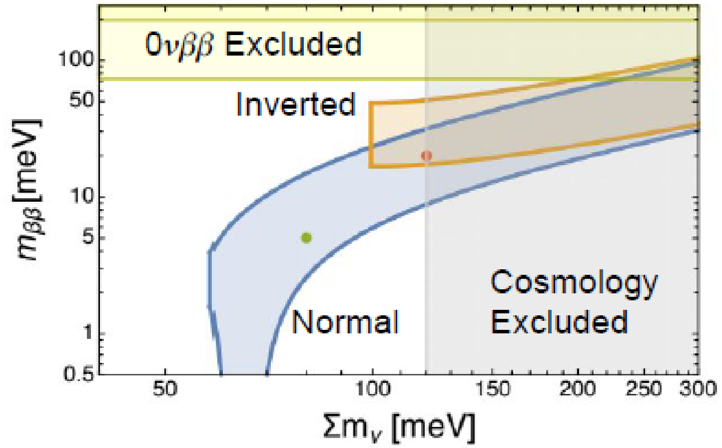
Current Planck 2018 constrain

$\sum m_\nu < 120$ meV (95% CL

$$\sum m_\nu \gtrsim 58 \text{ meV} \qquad \sum m_\nu \gtrsim 105 \text{ meV}$$

Super-Kamiokande (1999); Sudbury Neutrino Observatory (2001); CMB-S4 (2016)

Evan Grohs



"More improvements Possible"

Shun Salto

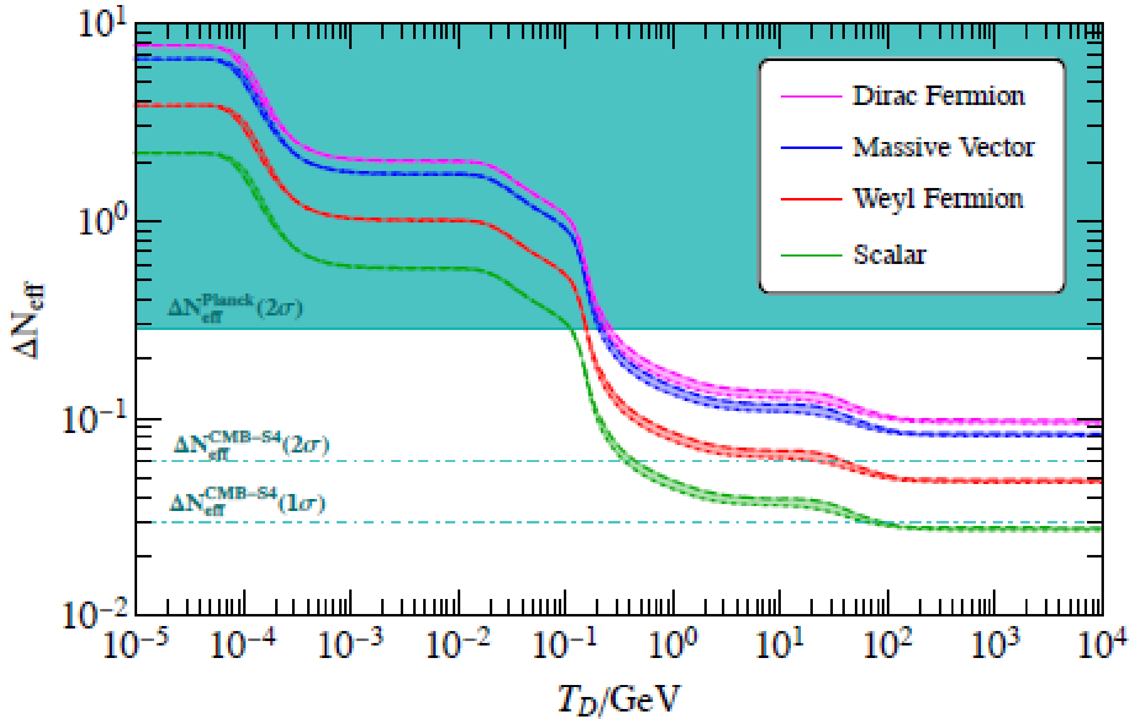
ΔN_{eff}

Francesco D'Eramo

The energy density of the cosmic neutrino background can be calculated precisely

$$N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma}$$

$$N_{\rm eff}^{\rm SM} = 3.044(1)$$

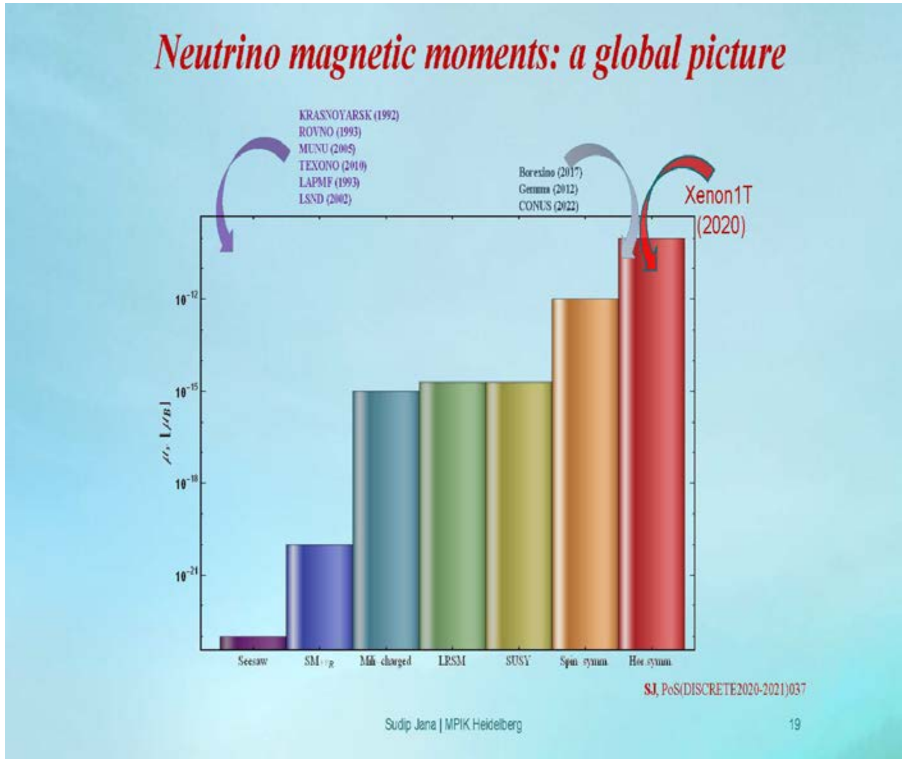


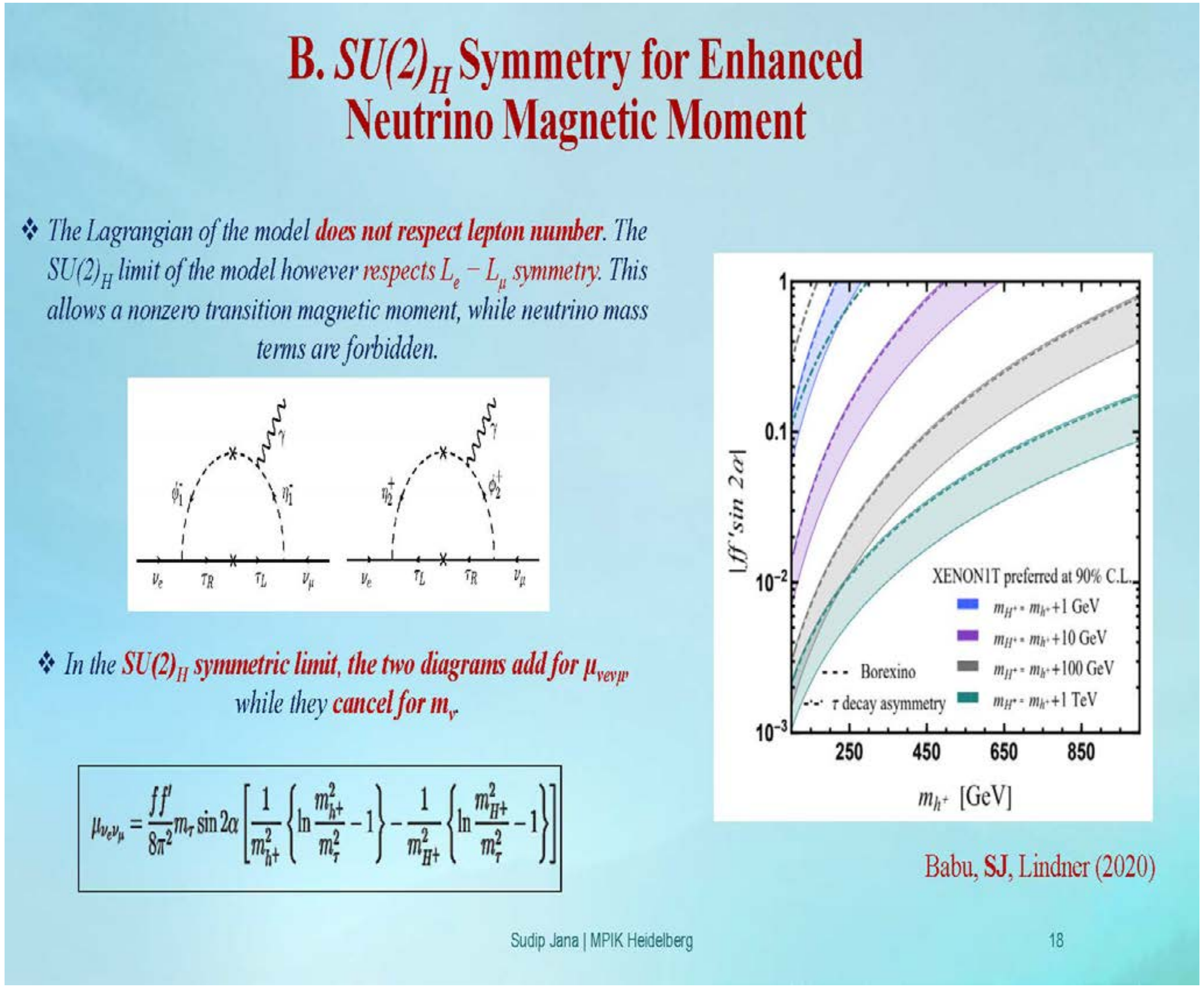
ΔN_{eff} of various particles as a function Freeze-out temperature (when production rate falls below the expansion rate)

➔**Plays a crucial role in models with light mediators**

Escudero Abenza (2020); Akita, Yamaguchi (2020); Froustey, Pitrou, Volpe (2020);Bennett, et al (2021);

Neutrino Magnetic Moment



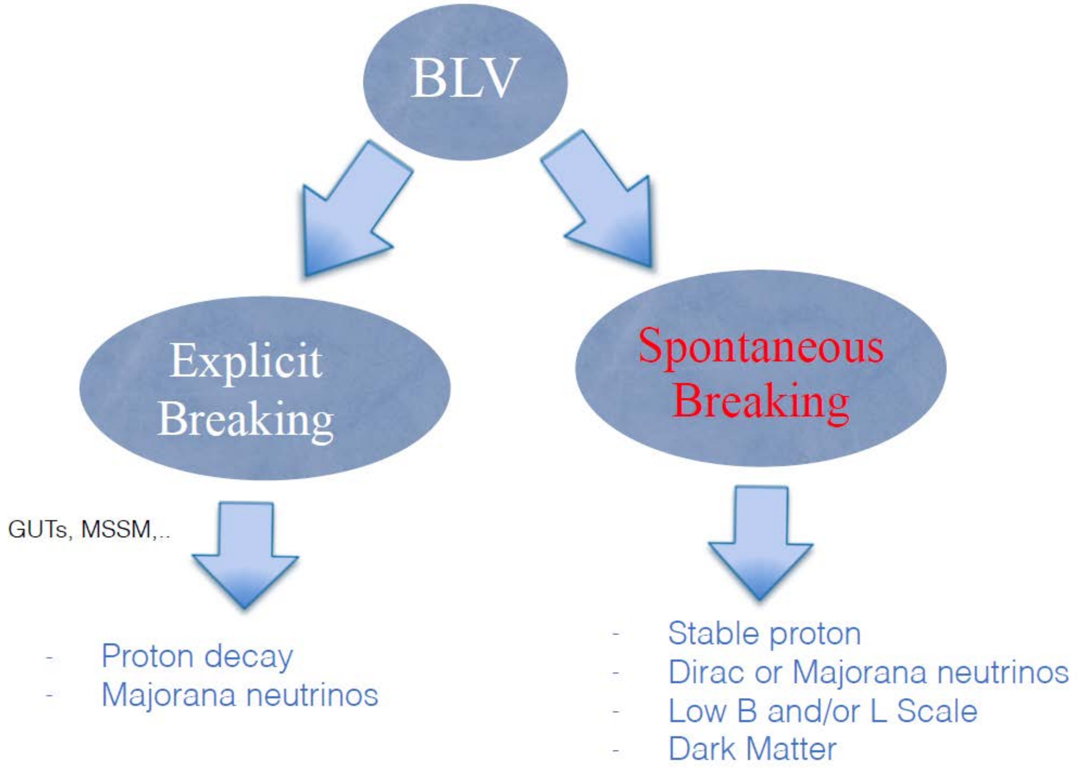


Sudip Jana

Baryon Number Violation

We need to understand the origin of B and L violation to explain

- The origin of neutrino masses
- The Matter-Antimatter Asymmetry
- The Stability of the Proton
- New Exotic BLV processes
- The SM-EFT



Pavel FileViez Perez

Dark Color unification motivated by the mini-coincidence puzzle

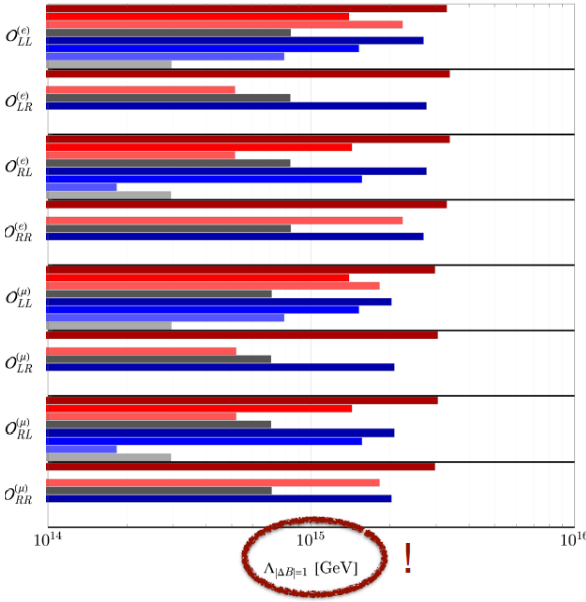
$$\frac{\Omega_{\rm DM}}{\Omega_B} = \frac{m_{\rm DM} Y_{\rm DM}}{m_p Y_B} \sim 5$$

Clara Murgui

Implications of observable BNV

Limits on $|\Delta B| = 1$ Decays

Mediated by mass dimension 6 operators in SMEFT



{Berryman, SG, & Zakeri, 2022}

$$\mathscr{L}^{(d=6)}_{|\Delta B|=1} \supset \sum_i \frac{c_i}{\Lambda^2_{|\Delta B|=1}} (qqq\ell)_i + \text{h.c.}$$

dim 6

But the origin of $|\Delta B| = 2$ processes can be distinct!

{Marshak & Mohapatra, 1980; Babu & Mohapatra, 2001 & 2012; Arnold, Fornal, & Wise, 2013....}

$$\mathscr{L}^{(d=9)}_{|\Delta B|=2} \supset \sum_i \frac{c_i}{\Lambda^5_{|\Delta B|=2}} (qqqqqq)_i + \text{h.c.}$$

dim 9

$n\bar{n}$ expt'l limit yields

$$\Gamma_{|\Delta B|=2} \gtrsim 10^{5.5}\ \text{GeV}$$

4

Neutron Stars to Limit BNV

Use pulsar binary period decay rate…

- Double pulsar (PSR J0737-3039A/B)
- Hulse-Taylor binary (PSR B1913+16)
- White Dwarf-Neutron Star (PSR J1713+0747)

Name	J0737−3039A/B	B1913+16	J1713+0747
P_b (days)	0.1022515592973(10)	0.322997448918(3)	67.8251299228(5)
$\dot{P}_b^{\rm int}$ ($\times 10^{-12}$)	−1.247752(79)	−2.398(4)	0.03(15)
$\dot{P}_b^{\rm GR}$ ($\times 10^{-12}$)	−1.247827(+6, −7)	−2.40263(5)	$-6.3(6)\times 10^{-6}$
$(\frac{\dot{P}_b}{P_b})^{\rm E}_{2\sigma}$ (yr^{-1})	8.3×10^{-13}	1.4×10^{-11}	1.8×10^{-12}
$(\frac{\dot{P}_b}{P_b})^{\Omega}$ (yr^{-1})	$1.04(7)\times 10^{-13}$	$\lesssim 2.5\times 10^{-13}$	$\approx 8\times 10^{-14}$
$(\frac{\dot{P}_b}{P_b})^{\rm BNV}_{2\sigma}$ (yr^{-1})	7.3×10^{-13}	1.4×10^{-11}	1.8×10^{-12}
$\lvert\frac{\dot{B}}{B}\rvert_{2\sigma}$ (yr^{-1})	3.7×10^{-13}	7×10^{-12}	1.1×10^{-12}

Scalars without Proton Deca

That also carry B or L charge

Scalar-fermion co

$Q_{em} = T_3 + Y$

lote
J(3)
p'ns

Scalar	SM Representation	B	L	Operator(s)	$[g_i^{ab}?]$
X_1	$(1,1,2)$	0	-2	Xe^ae^b	[S]
X_2	$(1,1,1)$	0	-2	XL^aL^b	[A]
X_3	$(1,3,1)$	0	-2	XL^aL^b	[S]
X_4	$(\bar{6},3,-1/3)$	-2/3	0	XQ^aQ^b	[S]
X_5	$(\bar{6},1,-1/3)$	-2/3	0	XQ^aQ^b, Xu^ad^b	[A,–]
X_6	$(3,1,2/3)$	-2/3	0	Xd^ad^b	[A]
X_7	$(\bar{6},1,2/3)$	-2/3	0	Xd^ad^b	[S]
X_8	$(\bar{6},1,-4/3)$	-2/3	0	Xu^au^b	[S]
X_9	$(3,2,7/6)$	1/3	-1	$X\bar{Q}^ae^b, XL^a\bar{u}^b$	[–,–]

Phenomenology of New Scalars

Constraints from many sources — Focus on first generation

i) n-n̄ (But some models do not produce it)

ii) Collider constraints

CMS: $\ell^+\ell^+$ search; cannot look at invariant masses below 8 GeV
[CMS 2012, 2014, 2016]

iii) $(g-2)_e$ [Babu & Macesanu, 2003]

Use latest exp't! [Hanneke, Fogwell, Gabrielse, 2008]

Limit: $M_1/g_1^{11} \geq 80$ GeV

[superseded by Møller expt, save fo light masses] [SG & Xinshuai Yan, 2020]

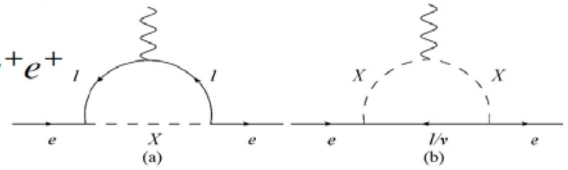
$M_{X_{1,3}}/g^{11}_{1,3} \geq 2.7$ TeV @ 90 % CL [E158] (if "heavy"

iii) Nuclear stability

SuperK ^{16}O : $pp \to e^+e^+$

[Bramante, Kumar, & Learned, 2015]

But note short-distance repulsion!



iv) $H\bar{H}$ annihilation

[Grossman, Ng, & Ray, 2018]

But beware galactic magnetic fields!

Few GeV mass window possible

16

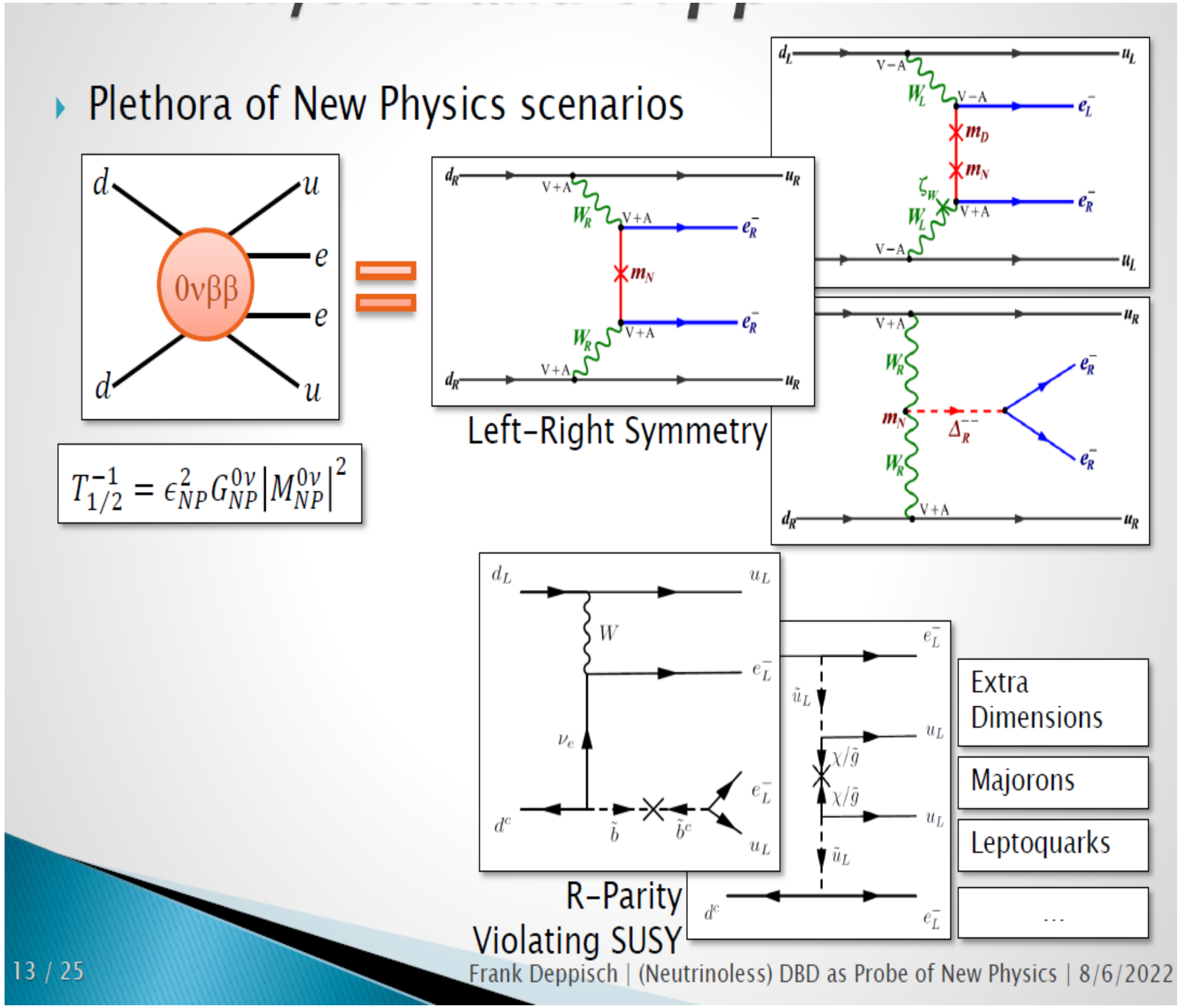
Susan Gardner

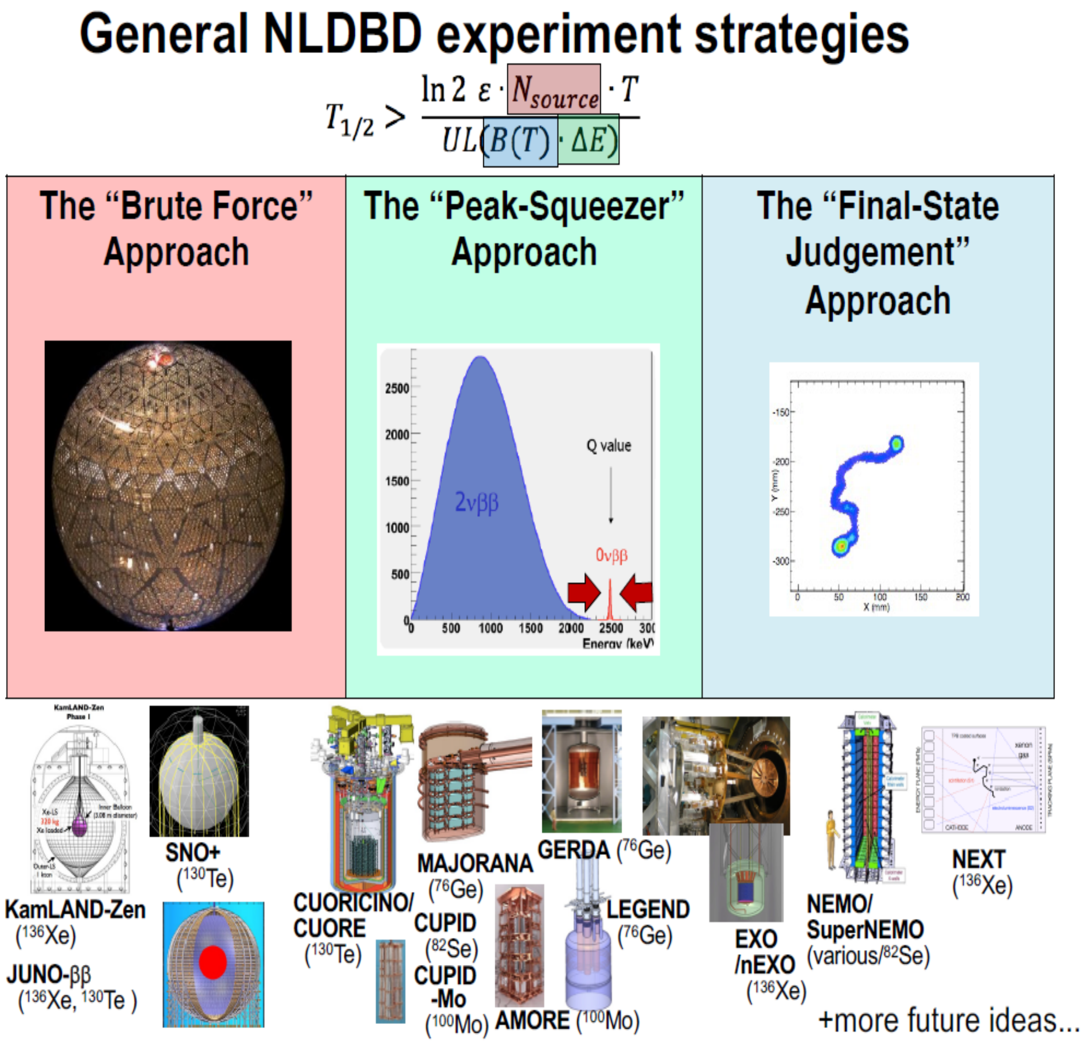
Neutrino experiments can be versatile

- Search for dark matter
- Search for ALP
- Search for various types of mediators, scalar, vector, pseudo-scalars
- Search for various kinds of models
- Variety of detectors: near and far detectors, different types of signatures at different energy regimes

➔The ongoing/upcoming neutrino experiments provide a great opportunity to study new physics

Neutrinoless double beta decay





Frank Deppisch

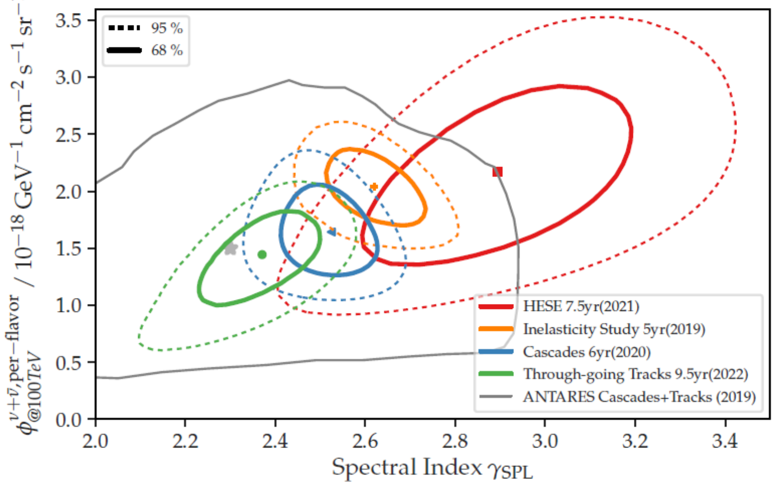
Kate Scholberg

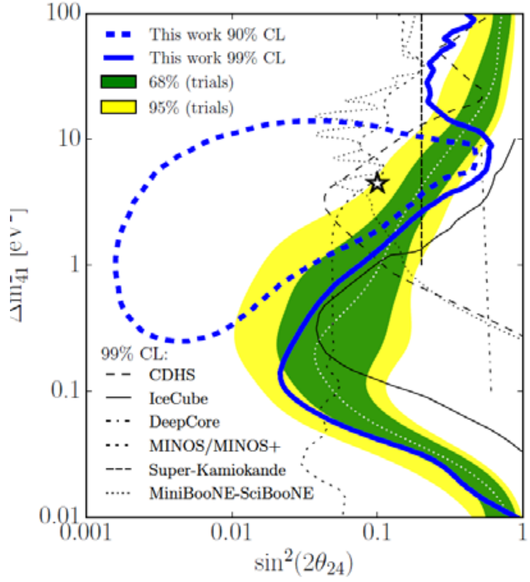
IceCubE

High Energy Astrophysical neutrinos

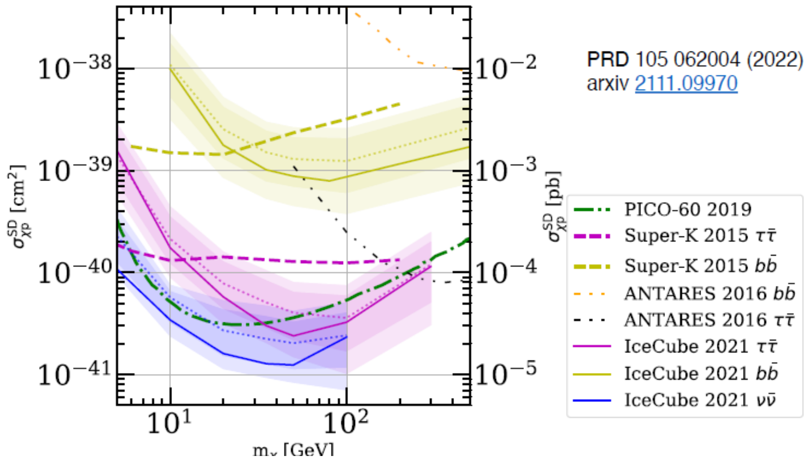
Astrophysical Neutrinos

arXiv:2203.08096



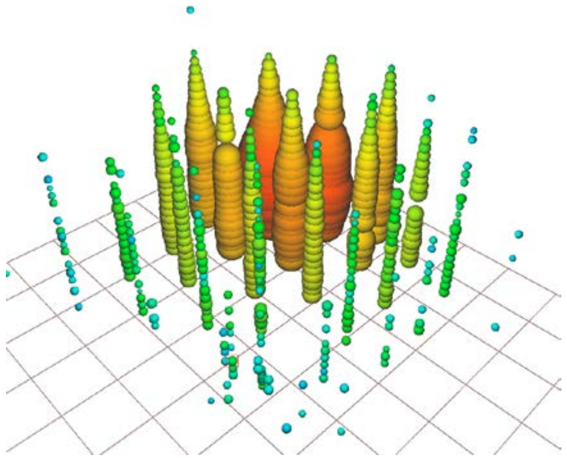


PRD 105 062004 (2022)
arxiv 2111.09970



Sterile neutrino

Solar Dark Matter

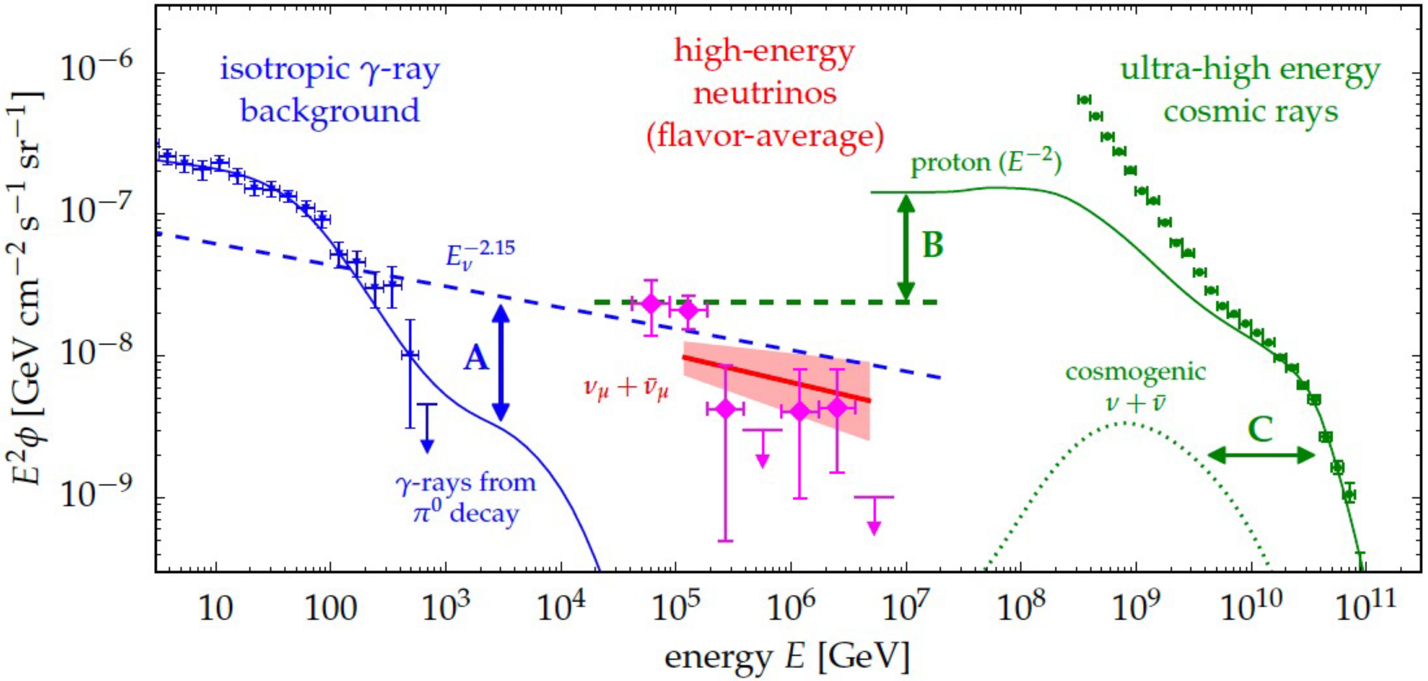


Glashow Resonance

partially contained
events identified a cascade
with ~6 PeV of energy

Brian Clark

Higher energy astrophysical neutrinos



- PUEO & RNO-G are both under construction, and the discovery of ultrahigh energy neutrinos is in sight.
- PUEO will open up discovery space at the highest energies, and will launch in 2024.
- RNO-G covers the energy range between IceCube and PUEO where astrophysical neutrinos should be, and is under construction!
- IceCube-Gen2 will incorporate a large radio array in the future

Abigail Vieregg

Neutrino Model

NuFIT 5.0 (2020)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
	$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
	$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

NSI

- Several models have been proposed to generate observable NSI
- Main challenge is to control charged lepton flavor violation and nunivesality constraints
- Some models use cancellations among d = 6 and d = 8 operators
- Light mediators help with satisfying such constraints

Collider signals of these models have been studied, especially formonojet signals

Kaladi Babu

Neutrino Model: measurements

Current experiments with ~5 yr projections (so, *c.* 2027)

Precision on θ_{12}, θ_{13}, Δm^2_{21}

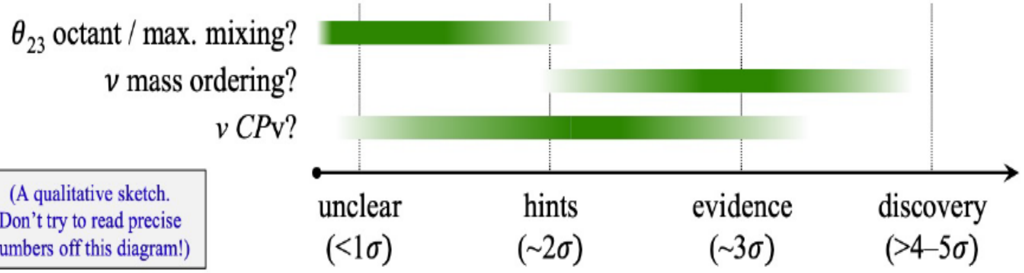
→ Minimal changes until next-gen experiments *(e.g., JUNO)*

Precision on θ_{23}, $|\Delta m^2_{32}|$

→ Some gains to come in current generation. Large gains in next-gen.

☆ **3-flavor "structural" questions**

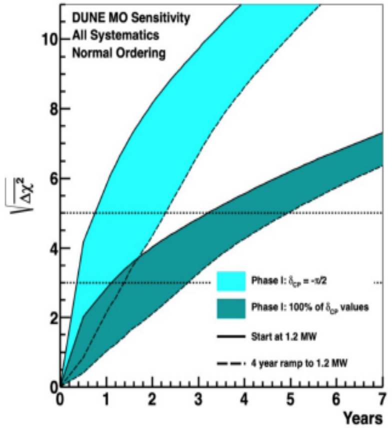
→ Reach heavily depends on (*still unknown!*) actual answers

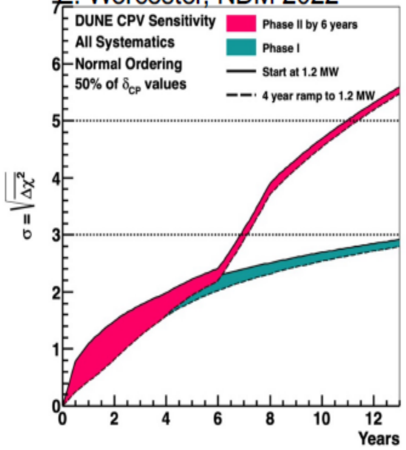


(A qualitative sketch. Don't try to read precise numbers off this diagram!)

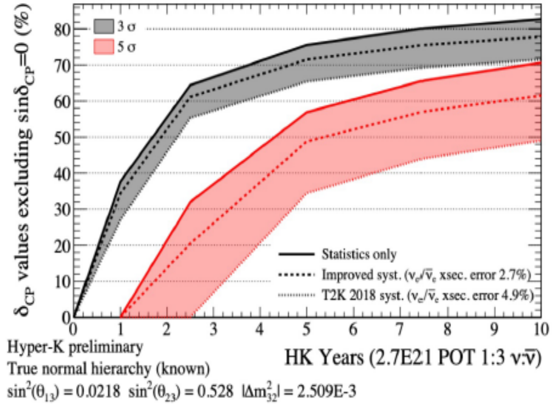
MO & CPV Sensitivity of DUNE and Hyper-K

E. Worcester, NDM 2022





DUNE will nail down MO very fast thanks to long baseline; also good CP δ sensitivity



F. Di Lodovico, NeuTel 2021

...and HK/DUNE combo helps resolve some degeneracies

... eventually limited by systematics (neutrino interactions)

Kate Scholberg

Neutrino sector: measurements/anomalies

Long-baseline beam experiments

Past → Current → Future

K2K
KEK to Kamioka
250 km, 5 kW

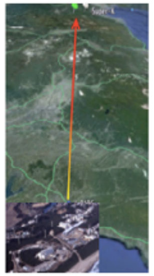
MINOS (+)
FNAL to Soudan
734 km, 400+ kW

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 400-700 kW

T2K (II)
J-PARC to Kamioka
295 km, 380-750 kW → >1 MW

LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW (→2.4 MW)

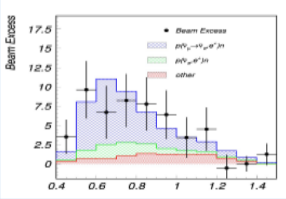


Hyper-K
J-PARC to Kamiok
295 km, 750 kW
(→1.3 MW)

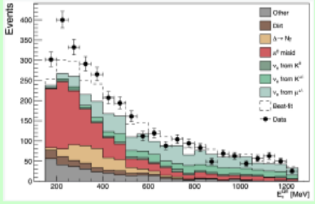
And beyond...
ESSnuB, T2HKK
neutrino factories...

Outstanding 'anomalies'

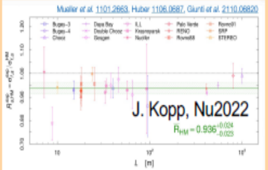
LSND @ LANL (~30 MeV, 30 m)
Excess of $\overline{\nu}_e$ interpreted as $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



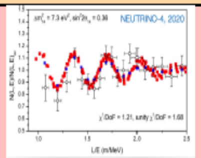
MiniBooNE @ FNAL (ν,$\overline{\nu}$ ~1 GeV, 0.5 km)
- unexplained >3 σ excess for E < 475 MeV in neutrinos
  "low-energy excess" inconsistent w/ LSND oscillation
- no excess for E > 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- small excess for E < 475 MeV in antinus



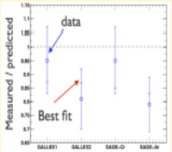
"Reactor flux anomaly"
deficit of reactor antinue absolute flux
wrt calculation



"Reactor spectral anomaly"
a wiggle, but in only one expt...

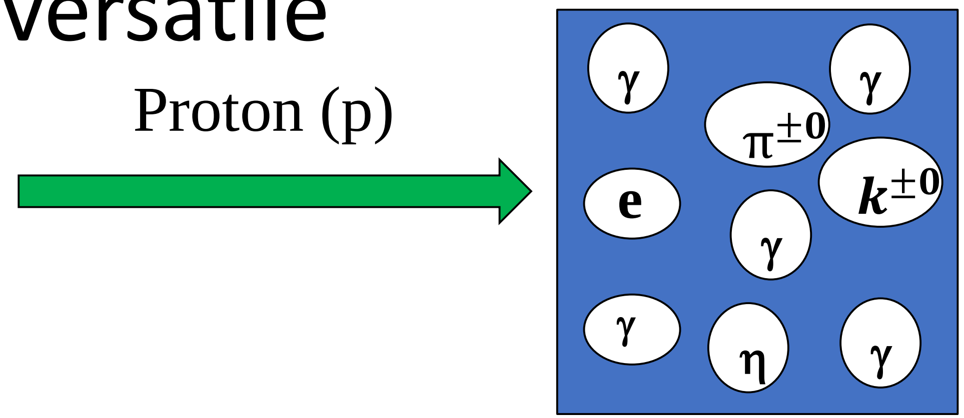


"Gallium anomaly"
~3σ deficit of nue flux from 51-Cr source in Ga



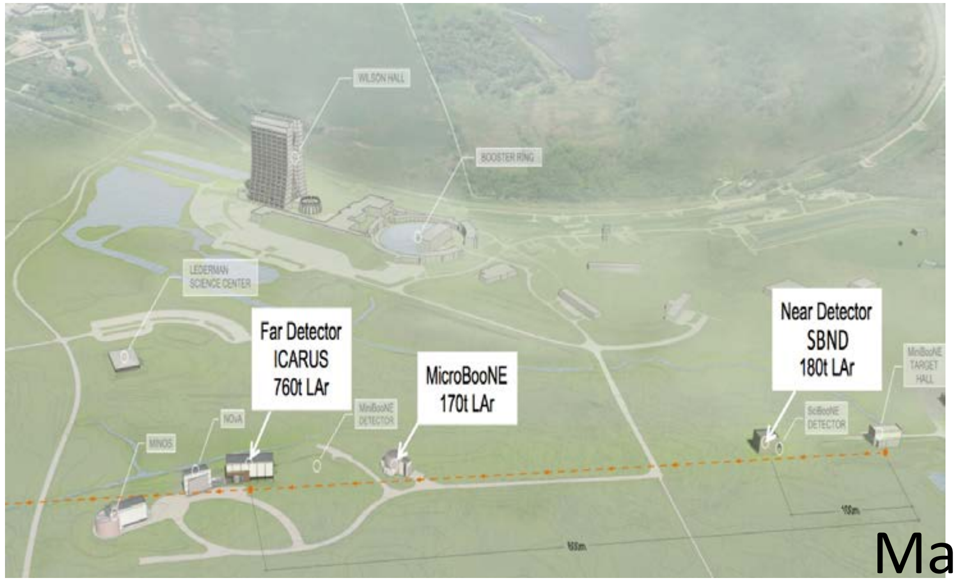
Neutrino experiments can be versatile

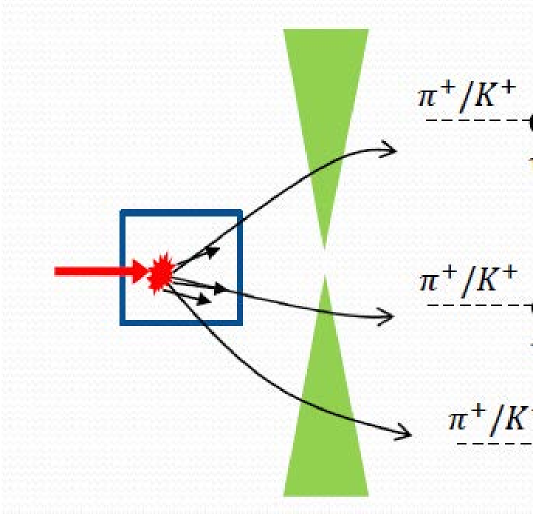
Beam dump based (proton beam) [ongoing]: 800 MeV-3 GeV: COHERENT (Oakridge), CCM (LANL), JSNS2(JPARC) Detectors, CsI, Lar, Na, GeI: ~20m away

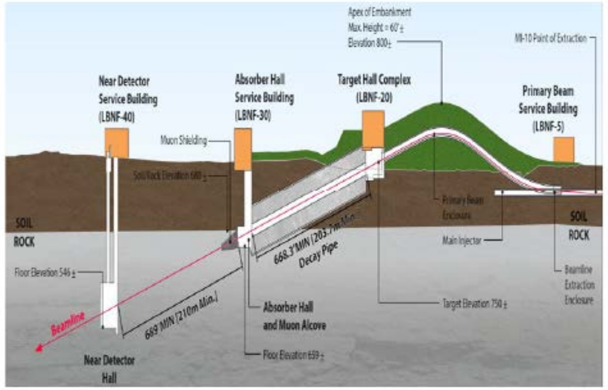


Fermilab SBN program: 120 GeV NUMI, 8 GeV BNB beams (ongoing)

DUNE (120 GeV)

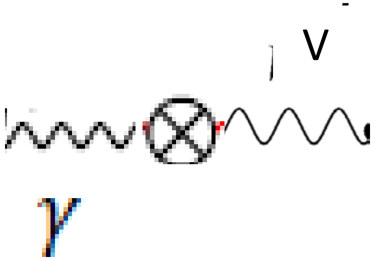


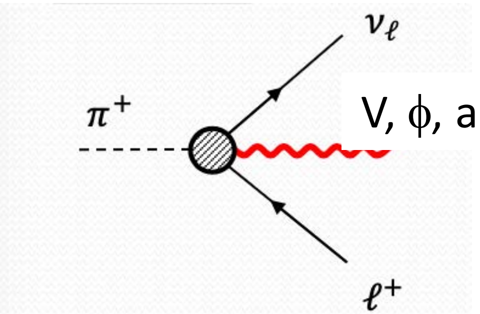




Many experiments with proton beams have different beam energies using various detectors at different locations

Neutrino experiments: New physics





$\pi^0 \to \gamma$ V

- New mediators 0 to sub GeV couple to quarks, leptons (e, μ), gammas, neutrinos

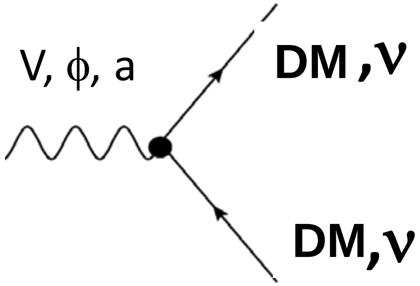
Not helicity suppressed,

Lot of pions, kaons are produced: COHERENT: 0.1 pion/proton: 10^{23} POT
MiniBooNE: 1pion/proton: 10^{21}/POT
DUNE: 3-4 pions/Proton: 10^{21}/POT

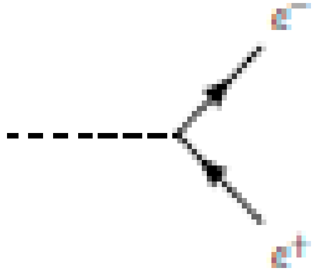
Meson can be utilized to probe new physics with variety of signatures

At the detector

E.g.,

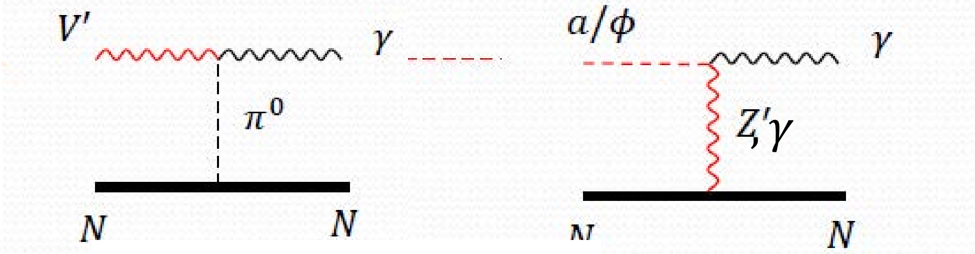


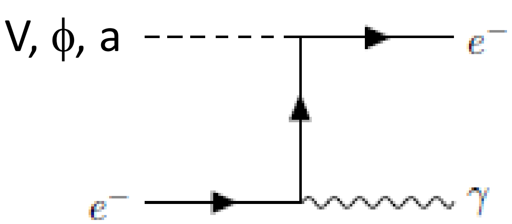
DM, ν produces nuclear/electron recoil



V, ϕ, a can be long lived,

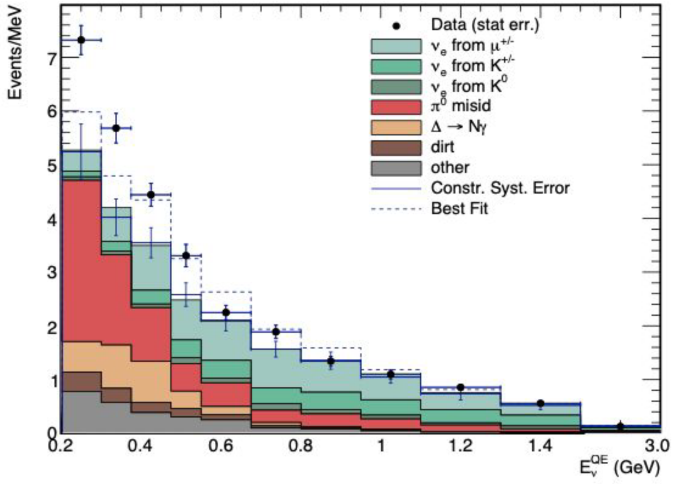
Scattered

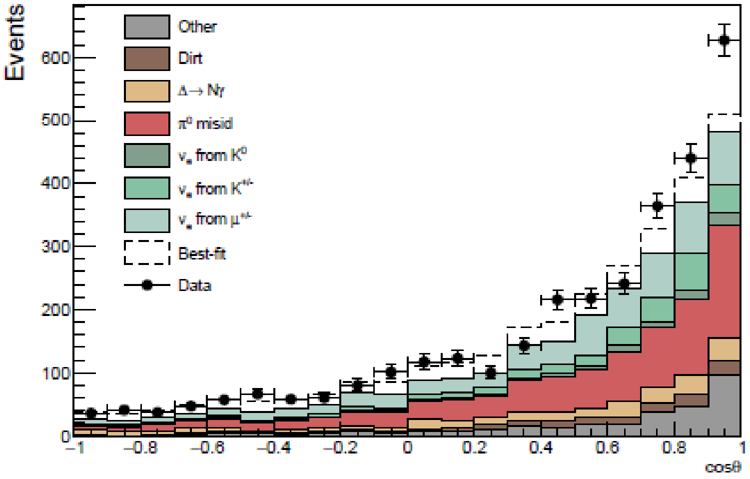


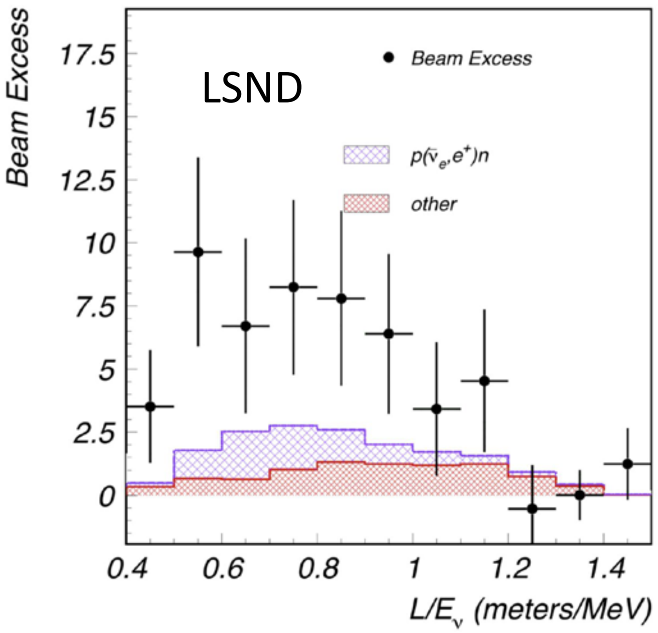


MiniBooNE anomaly

Excess is 4.8 σ





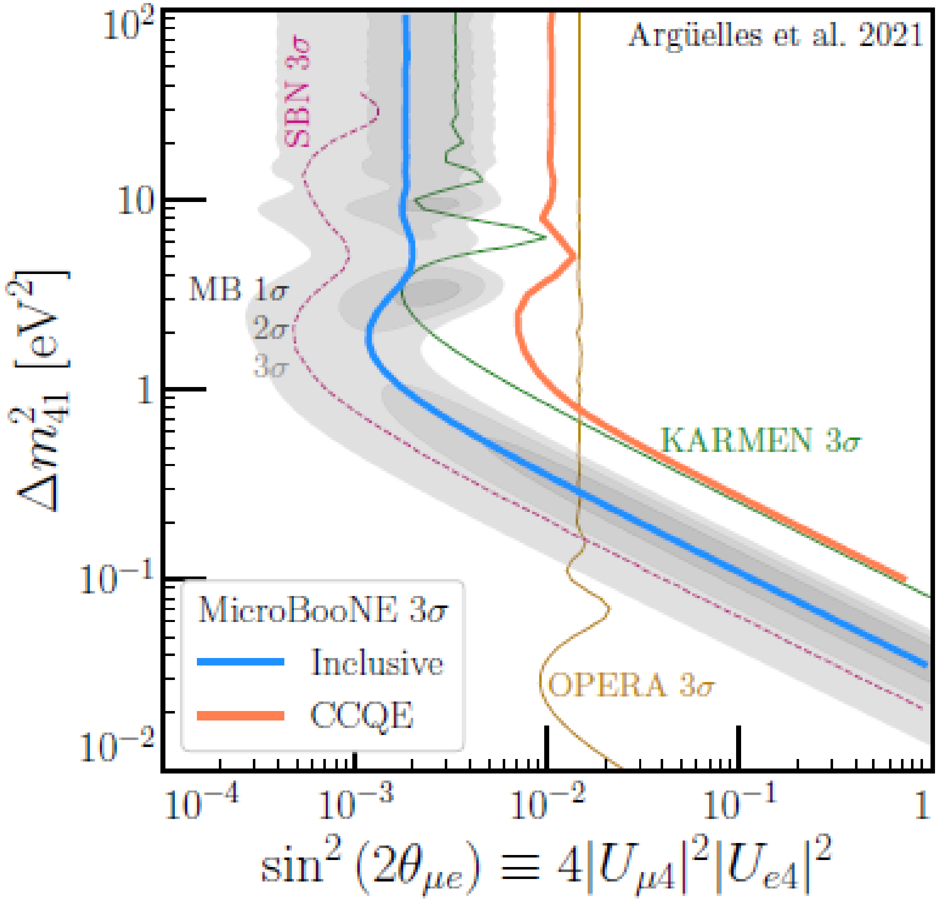


Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	107.6 ± 28.2	12.9 ± 4.3
NC π^0	732.3 ± 95.5	112.3 ± 11.5
NC $\Delta \rightarrow N\gamma$	251.9 ± 35.2	34.7 ± 5.4
External Events	109.8 ± 15.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	130.8 ± 33.4	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	621.1 ± 146.3	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	280.7 ± 61.2	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K_L^0 Decay	79.6 ± 29.9	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	8.8 ± 4.7	6.7 ± 6.0
Unconstrained Bkgd.	2322.6 ± 258.3	398.2 ± 49.7
Constrained Bkgd.	2309.4 ± 119.6	400.6 ± 28.5
Total Data	2870	478
Excess	560.6 ± 119.6	77.4 ± 28.5
0.26% (LSND) $\nu_\mu \rightarrow \nu_e$	676.3	100.0

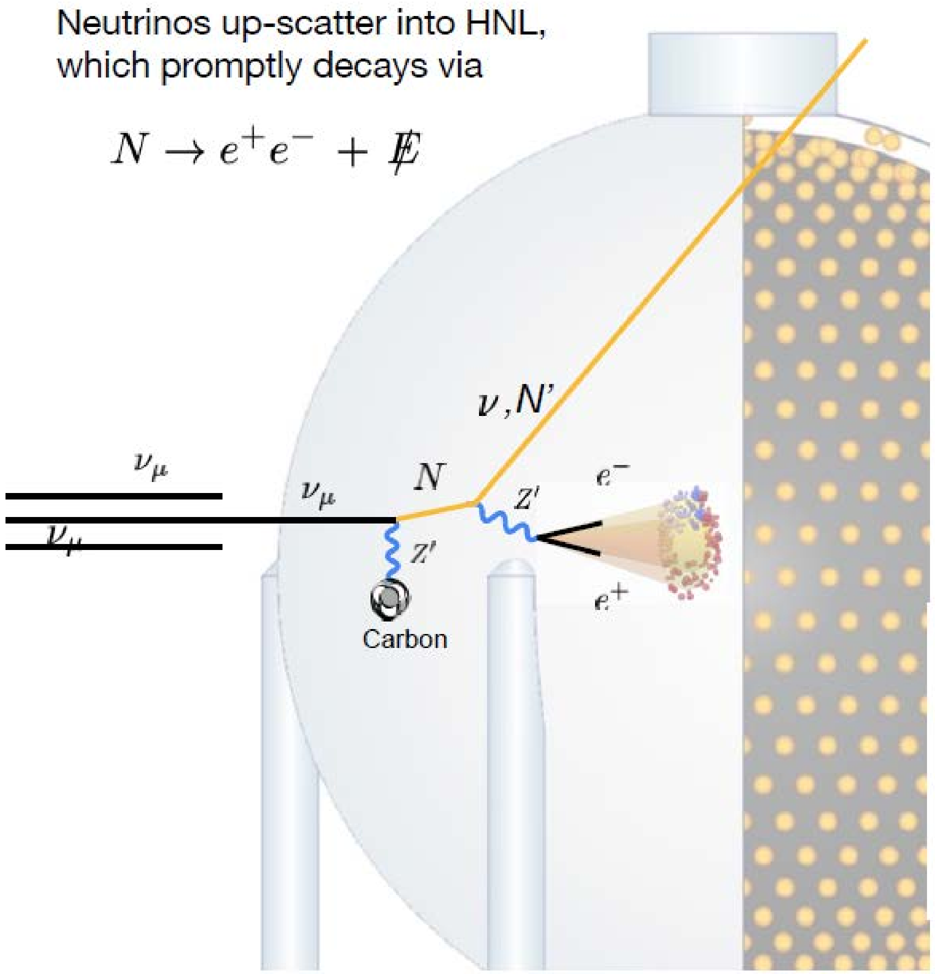
Various new physics ideas:

Model	U. Signature
3+1	Oscillations
(3+1) + inv-ν decay	Damped oscillations
(3+1) + NSI	Modified matter effects
Anomalous matter	Resonant appearance
Large extra dim	Osc with related freqs.
LNV in μ decays	$\mu^+ \rightarrow$ anti-ν_e
Lorentz violation	Sidereal time variation
Dark neutrinos	Upscattering to N → ν e⁺e⁻
Dipole portal	Upscattering to N → ν γ
(3+1) + vis-ν decay	DIF of $\nu_s \rightarrow \nu_e$
(3+1) + vis decay	DIF of N → ν γ
Dark sectors: dark matter	Upscattering to $\chi' \rightarrow \chi$ e⁺e⁻
Dark sectors: (pseudo)-scalar	Forward scattering to γ

Neutrino-based solution



Arguelles et al, 2022



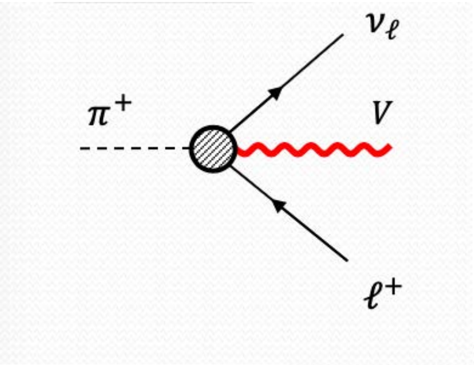
Bertuzzo, Jana, Machado, Zuanovich, Phys.Rev.Lett. 121 (2018) 24, 241801

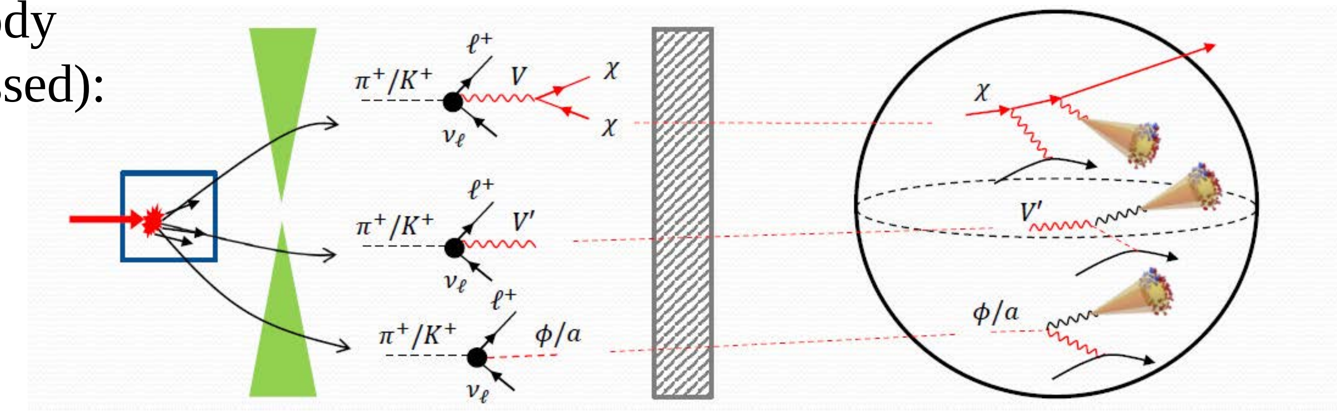
MiniBooNE anomaly: Dark sector

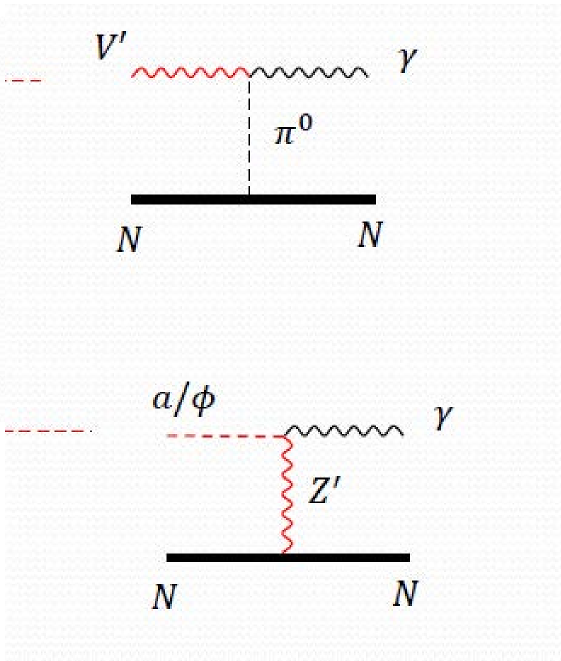
- For dark sector appearing from $\pi^0 \to V\gamma$ only: ruled out by MB dump

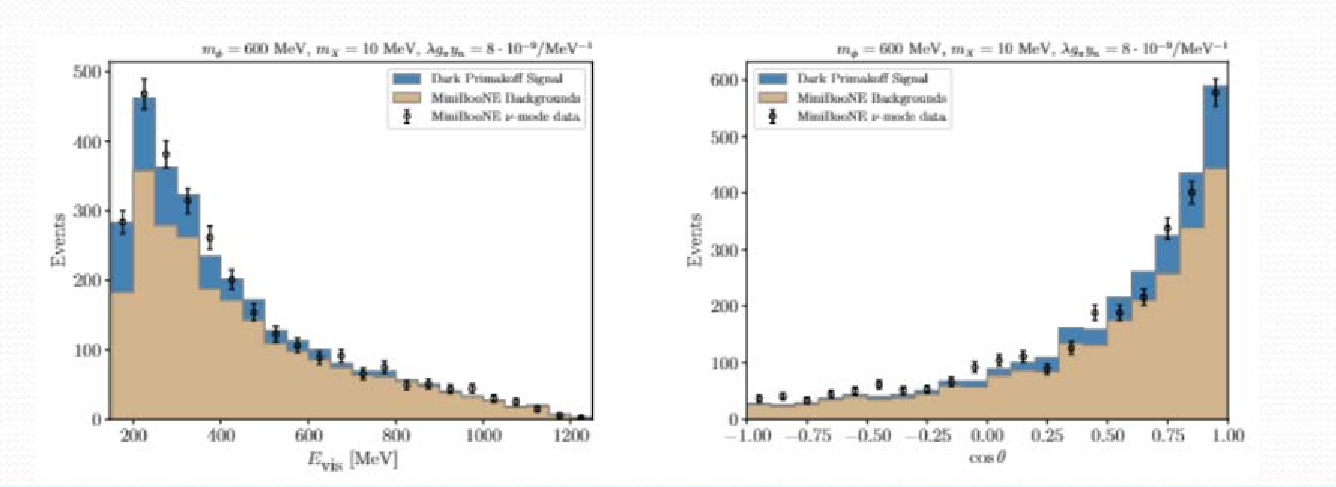
Detection

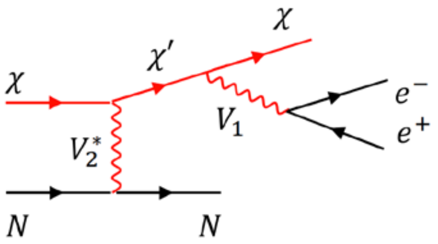
Use the charged pion 3 body
Decay (helicity unsuppressed):







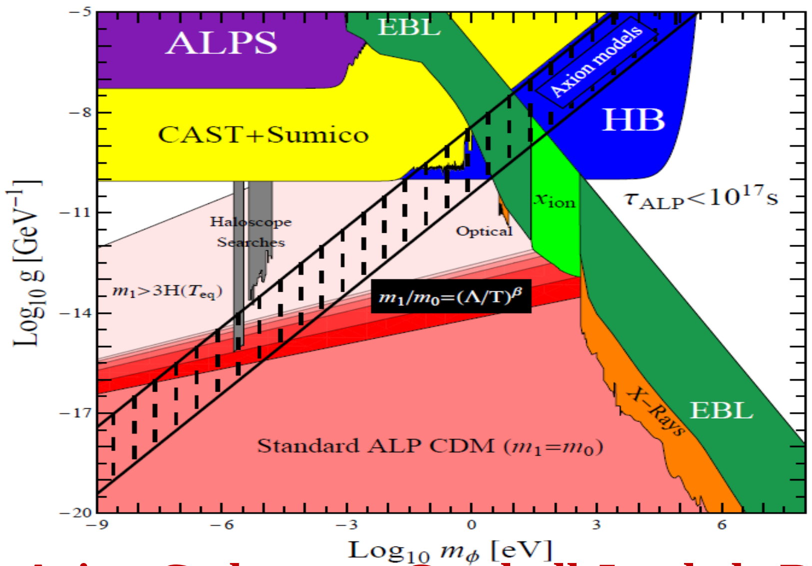




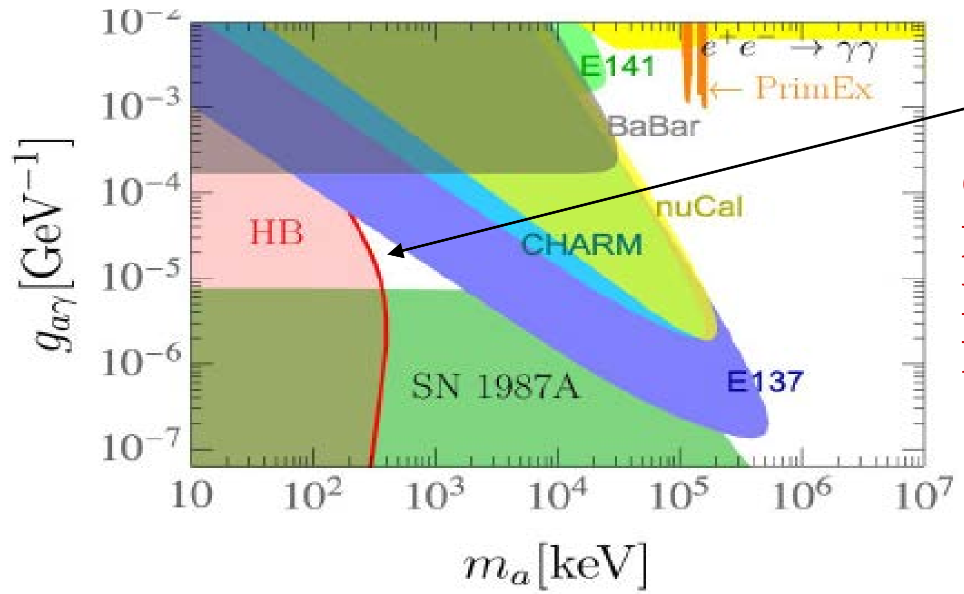
Dutta, Kim, Remington, Thompson, Van de Water, 2021

Can be checked at SBND, DUNE

ALP Parameter Space and neutrino experiments

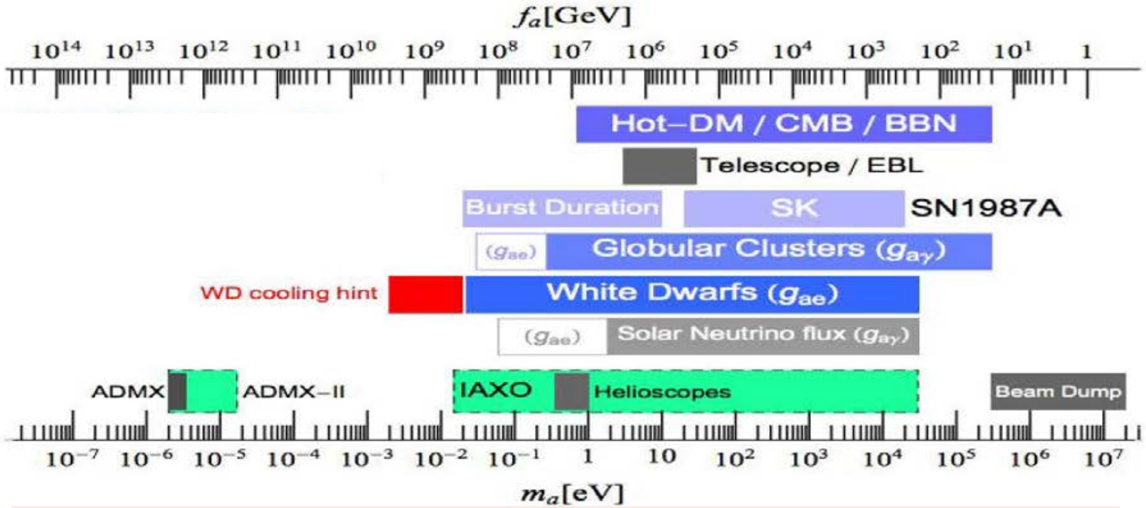


Arias, Cadamuro, Goodsell,Jaeckel, Redondo, Ringwald, JCAP 06, 013, (2012)



Cosmological triangle

Carenza, Straniero, Dobrich,Giannotti, Lucente,Mirizzi, Phys.Lett.B 809 (2020) 135709

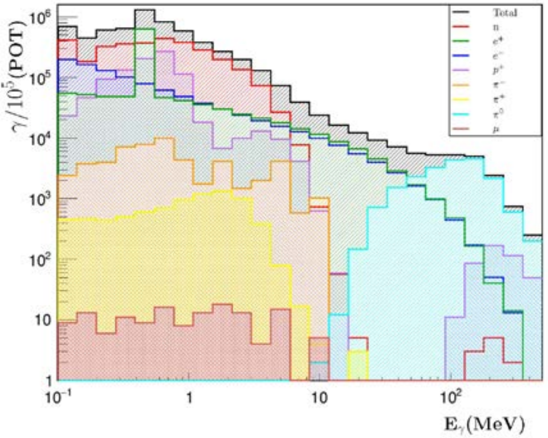


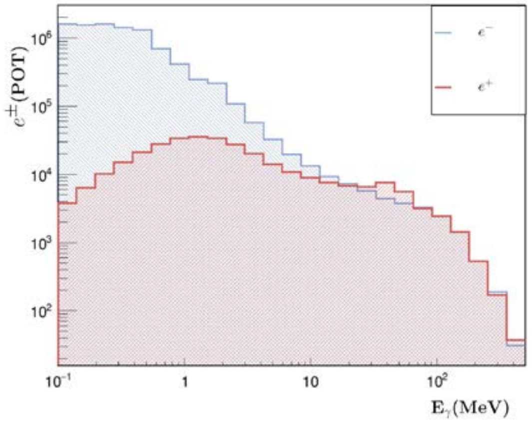
ν experiments: beam-dump/reactor

ALPs at Neutrino Experiments

We utilize the photons, electron-positrons to probe ALPs

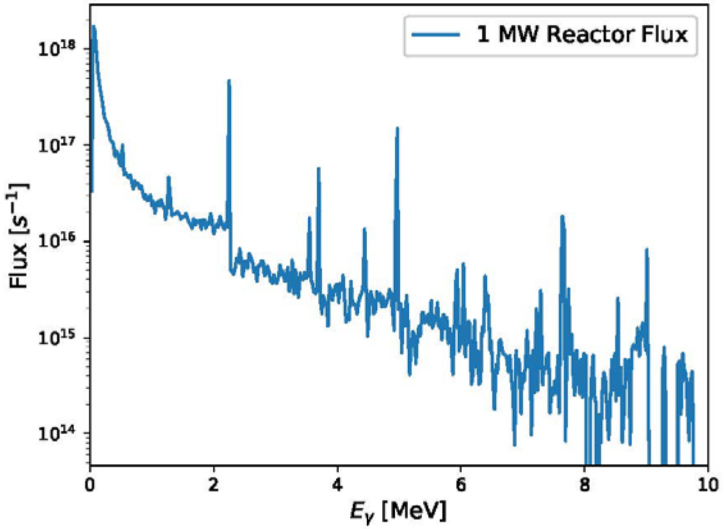
E.g., 800 MeV proton beam hitting a Tungsten target at LANL





GEANT4, 10.7, QGSP_BIC_HP

Reactor experiment

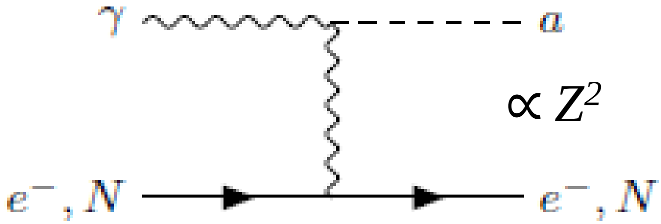


Similarly, COHERENT, JSNS2, MiniBooNE, MicroBooNE, ICARUS, DUNE

ALP at Neutrino Experiments

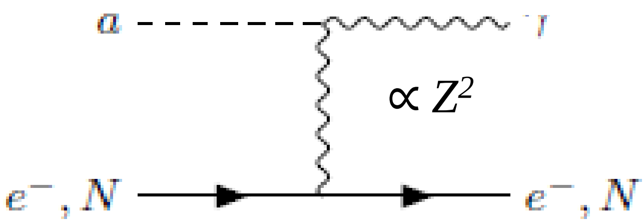
$$\mathcal{L}_{int} \supset -\frac{g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}}{4}$$

Production: ***Primakoff:***

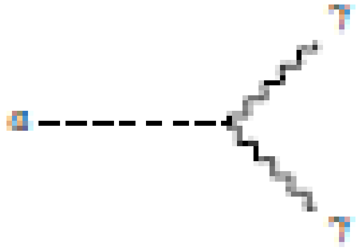


$\propto Z^2$

Detection: ***Inverse Primakoff, Decay***



$\propto Z^2$



$$\frac{d^2\sigma}{d\Omega dE_\gamma} = \frac{g^2_{a\gamma\gamma}}{16\pi^2}\frac{k_a^4}{q^4}|F(q)|^2 sin^2(2\theta)\delta(E_a - E_\gamma)$$

F(q) is the Nuclear form factor $\alpha\, Z^2$

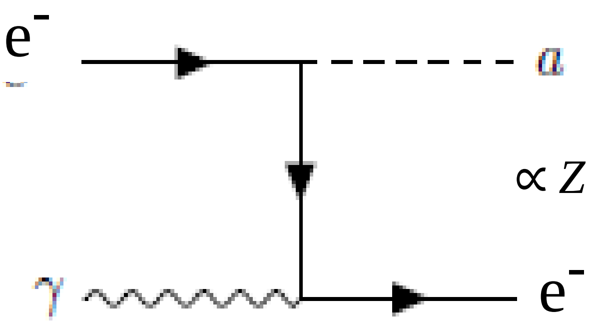
Photon does not loose energy in the conversion process to axion and back to photon

Neutrino Experiments

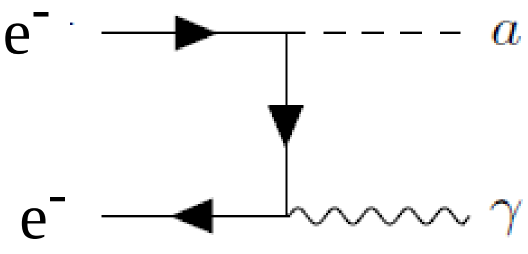
$$\mathcal{L}_{int} \supset -g_{aee} a \bar{\psi}_e \gamma_5 \psi_e$$

Production:

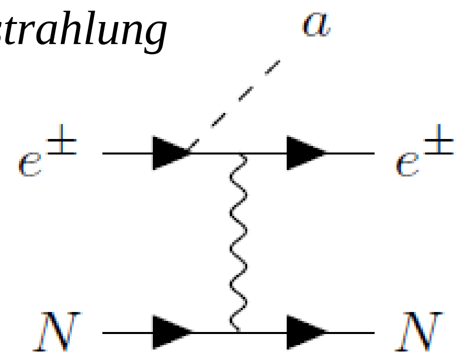
Compton

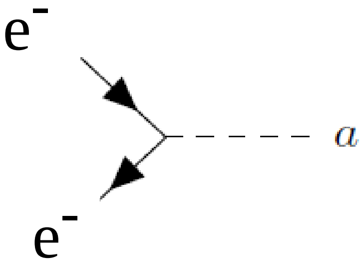


Associated



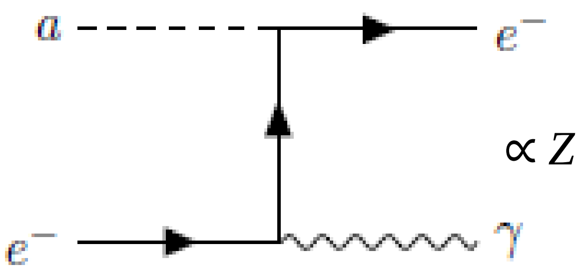
Bremsstrahlung

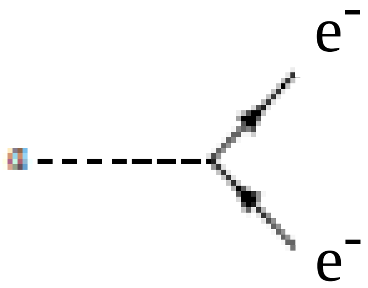


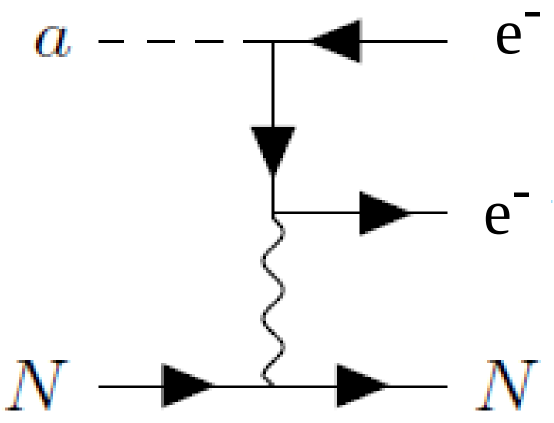


Resonance

Detection



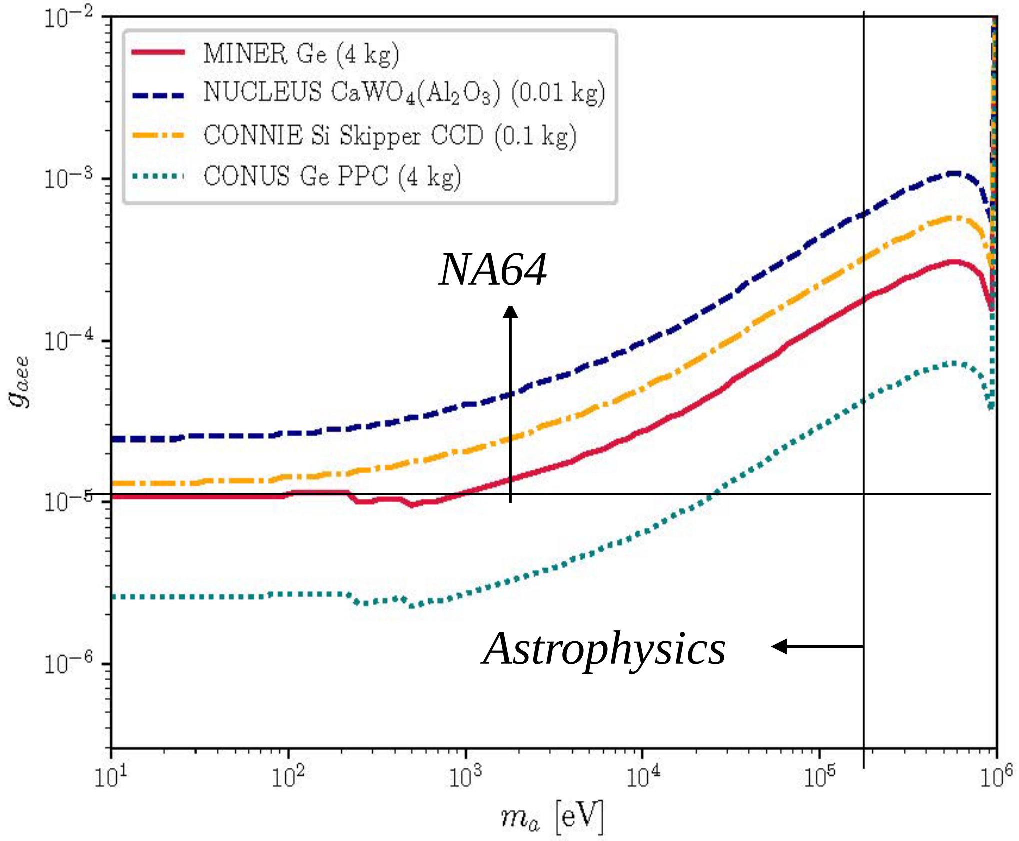


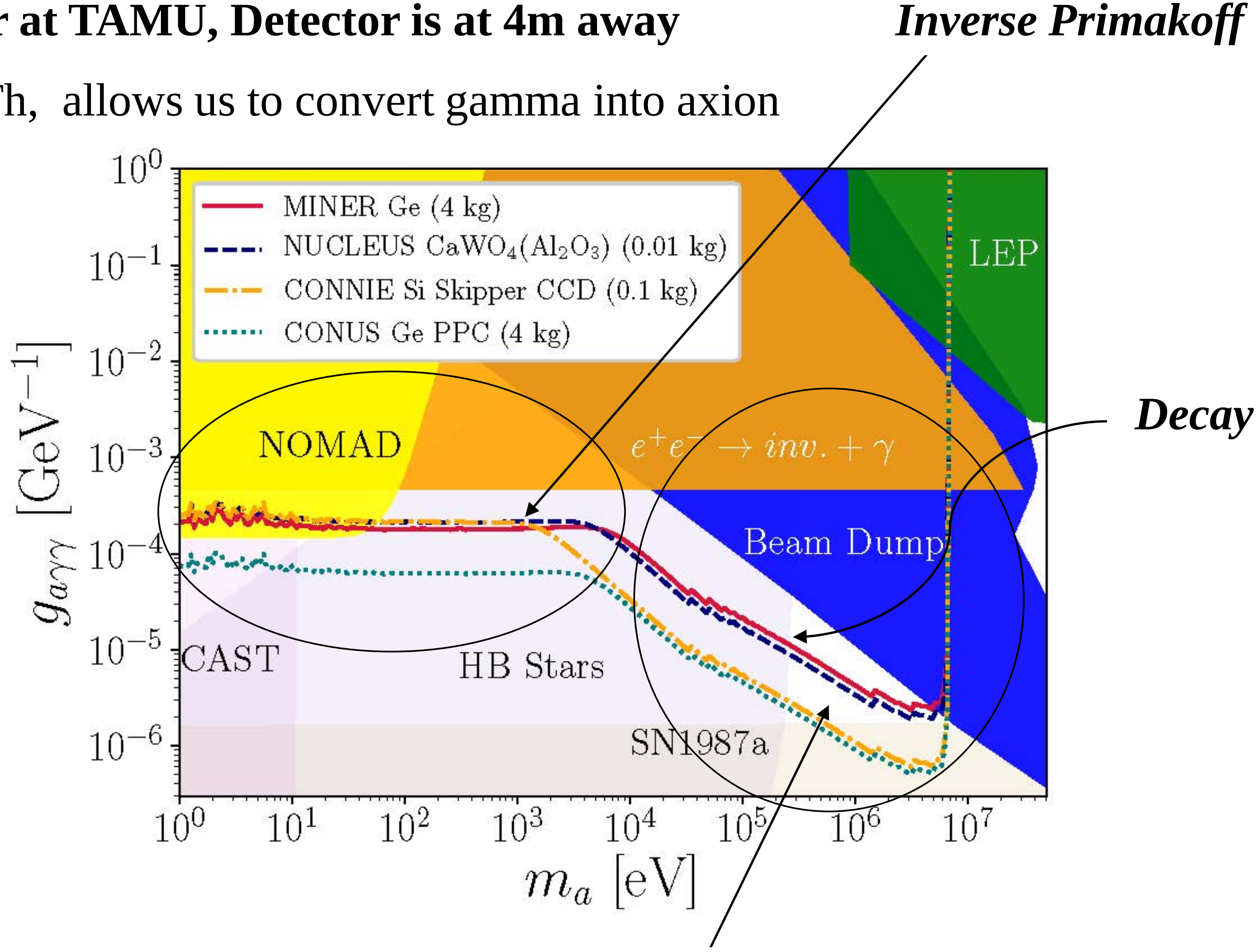


ALP at a reactor

1 MW reactor at TAMU, Detector is at 4m away

Th, allows us to convert gamma into axion





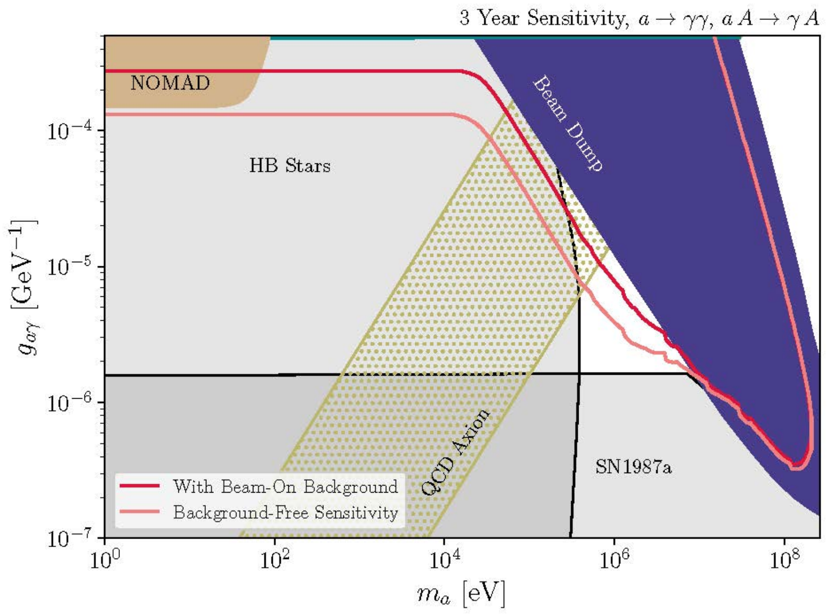
Cosmological triangle (allowed by all data)

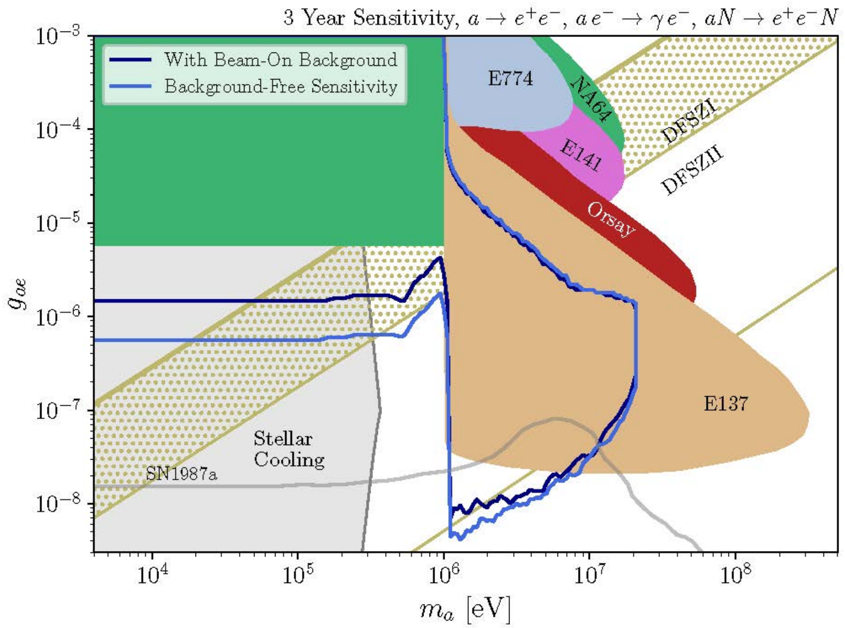
Dent, Dutta, Kim, Liao, Mahapatra, Sinha, Thompson, PRL, 2020

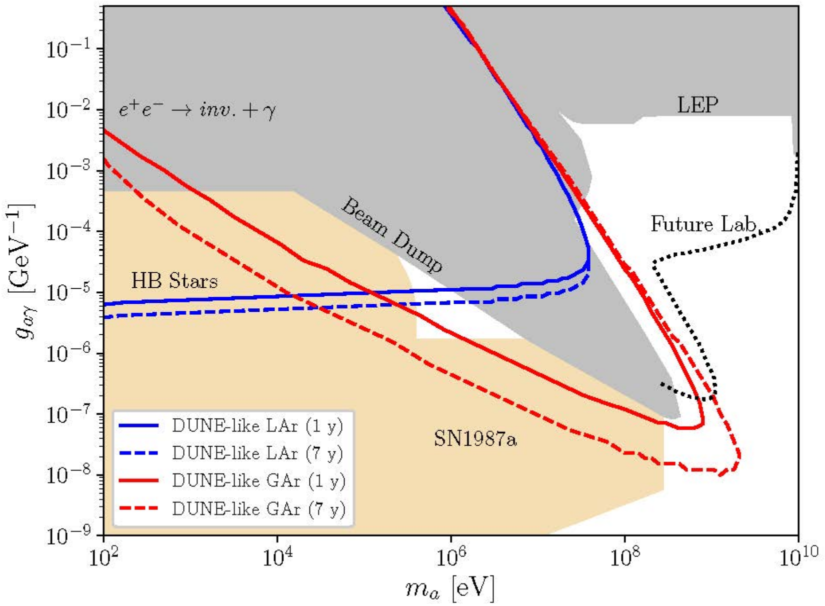
D. Aristizabal Sierra, V. De Romeri, L. Flores, D. Papoulias, JHEP 03 (2021) 294

Astrophysical constraints are model dependent

ALP at a proton beam dump: CCM (ongoing), DUNE

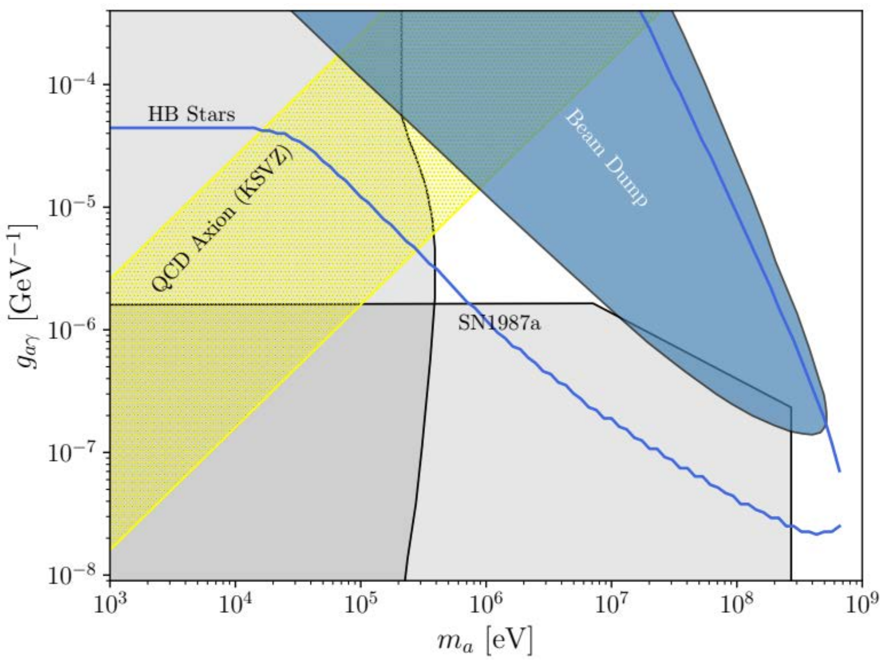


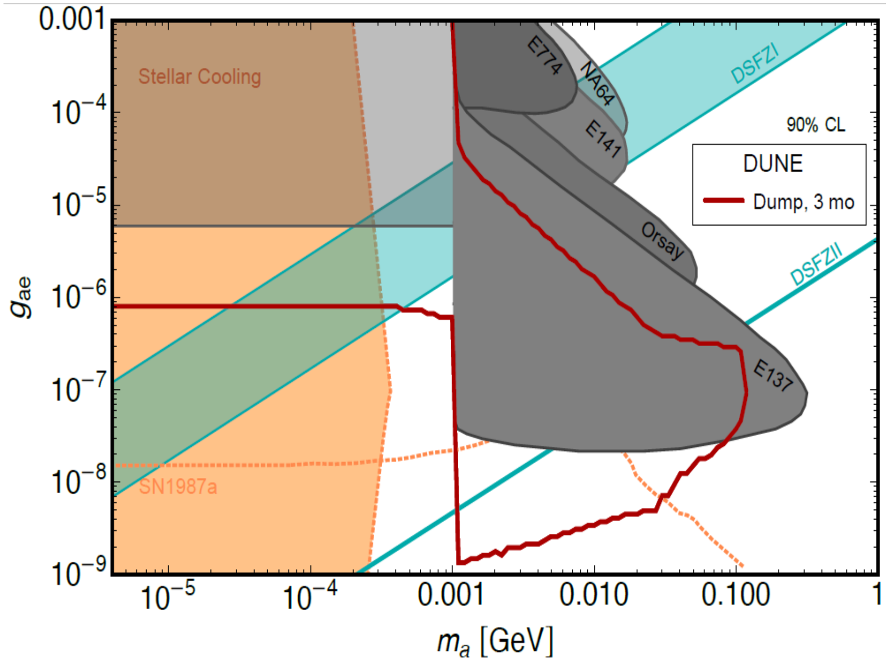




V. Brdar, B. Dutta, W. Jang, D. Kim, I. Shoemaker, Z. Tabrizi, A. Thompson, J.Yu, Phys.Rev.Lett. 126 (2021) 20, 201801

DUNE-beam-dump mode



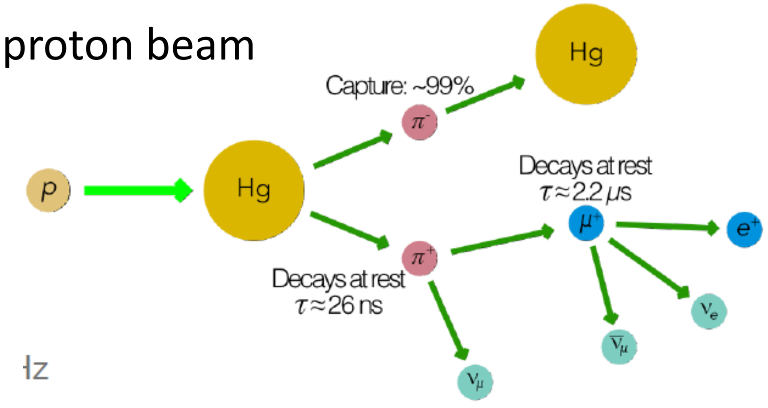


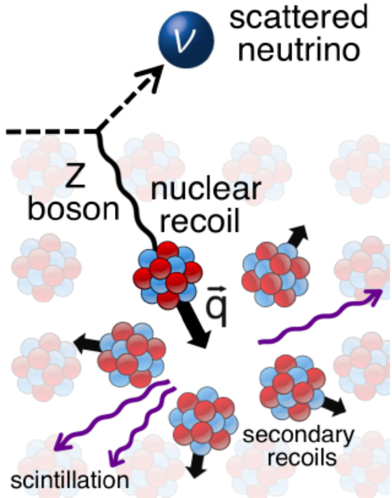
A. Bhattari, V. Brdar, B. Dutta, W. Jang, D. Kim, I. Shoemaker, Z. Tabrizi, A. Thompson, J.Yu, to appear

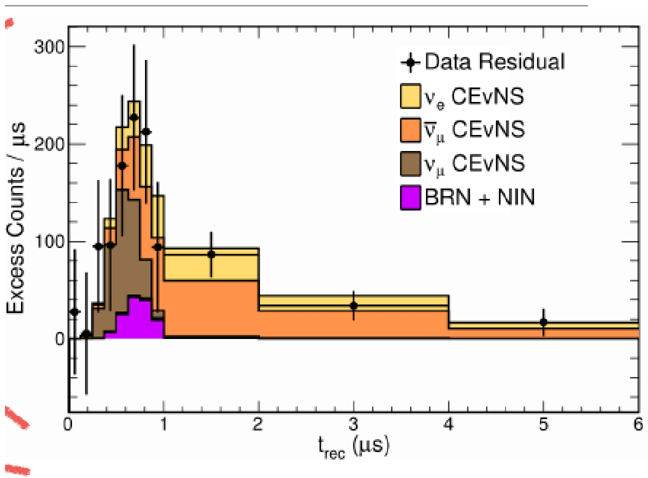
Neutrino experiments searches for DM

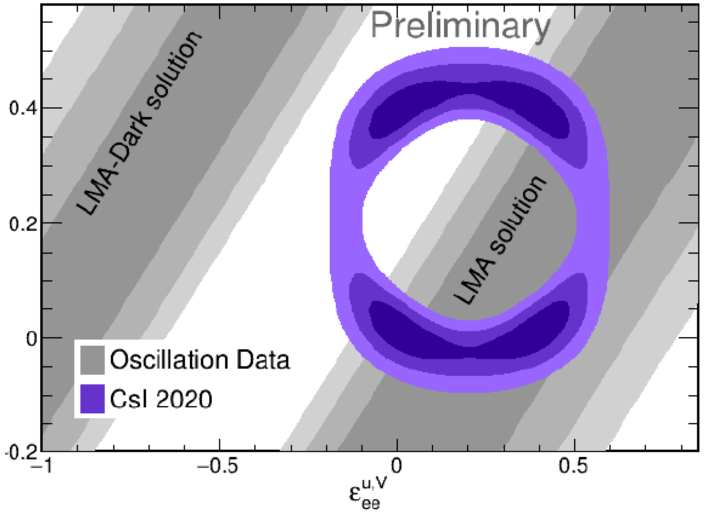
Observation of coherent elastic neutrino-nucleus scattering (**CEvNS**)

1 GeV proton beam





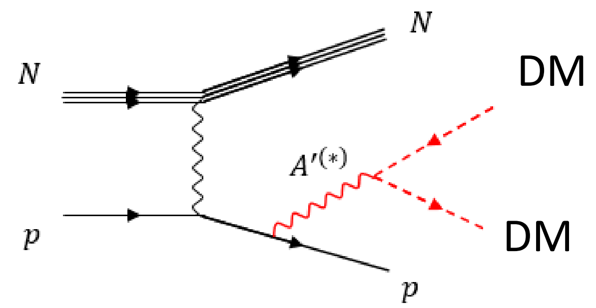




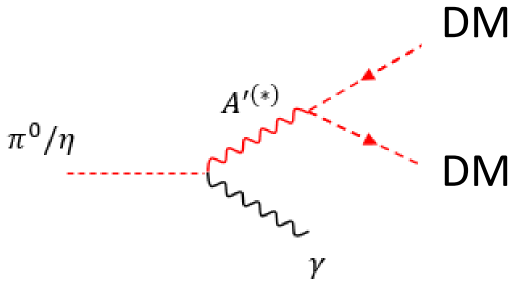
COHERENT (2017) **No CEvNS rejected at 6.7σ: CsI**
More results with LAr and CsI

CCM @ LANL is ongoing,
JSNS^2 is also ongoing

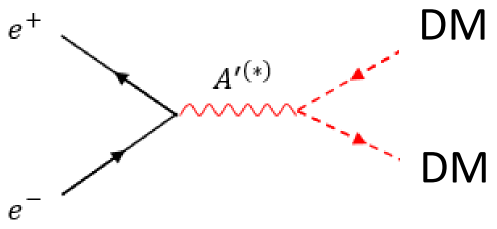
DM at ν experiments



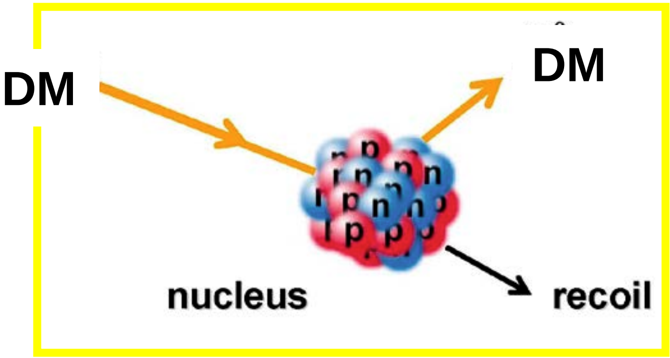
Beam bremsstrahlung



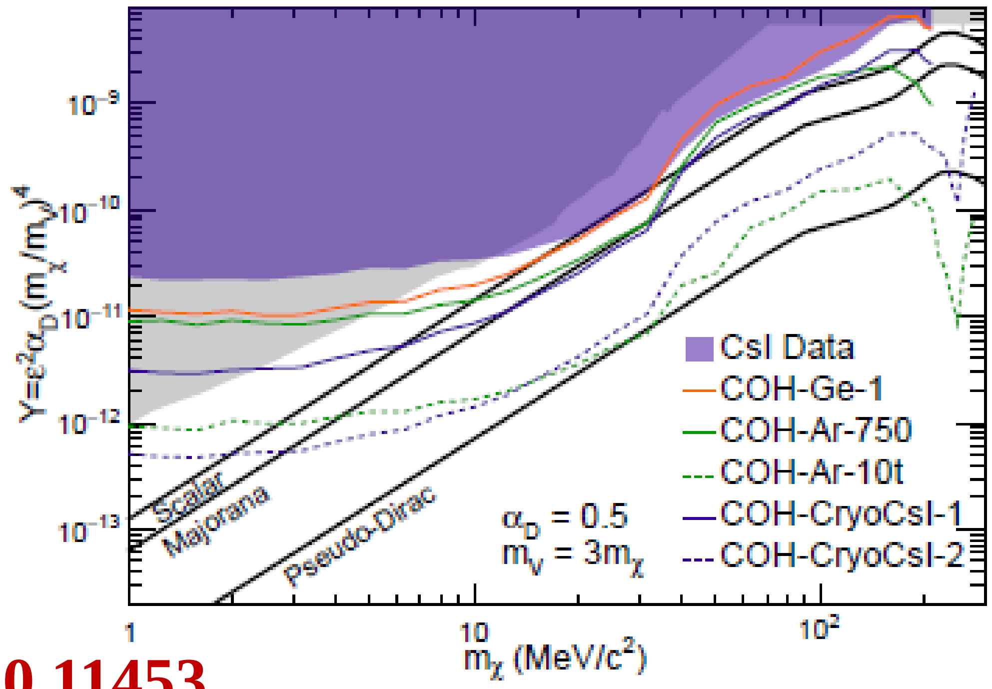
Neutral meson decays



Resonance production



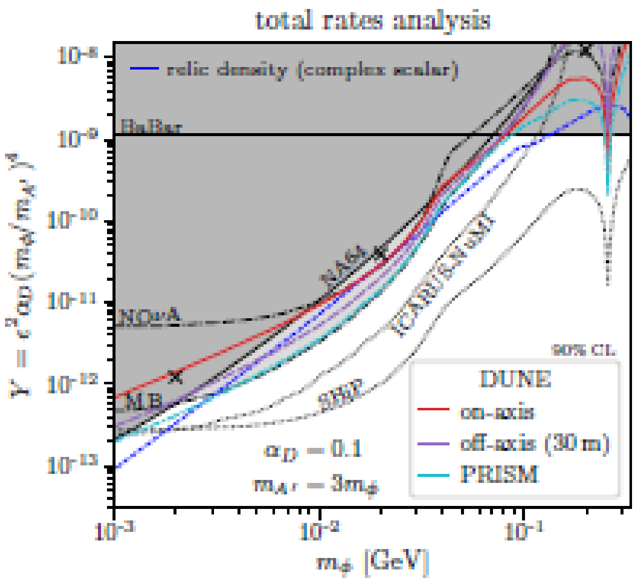
- Complimentary to direct detection Searches
- Probes low mass DM
- Uses the same interactions

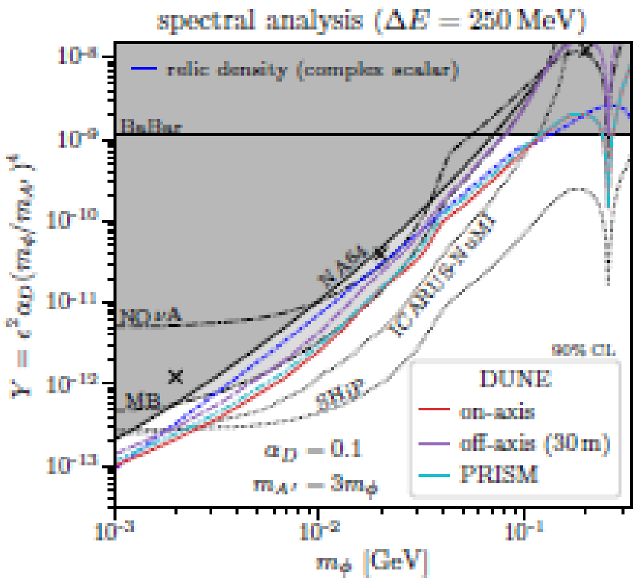


COHERENT Collaboration, arXiv:2110.11453

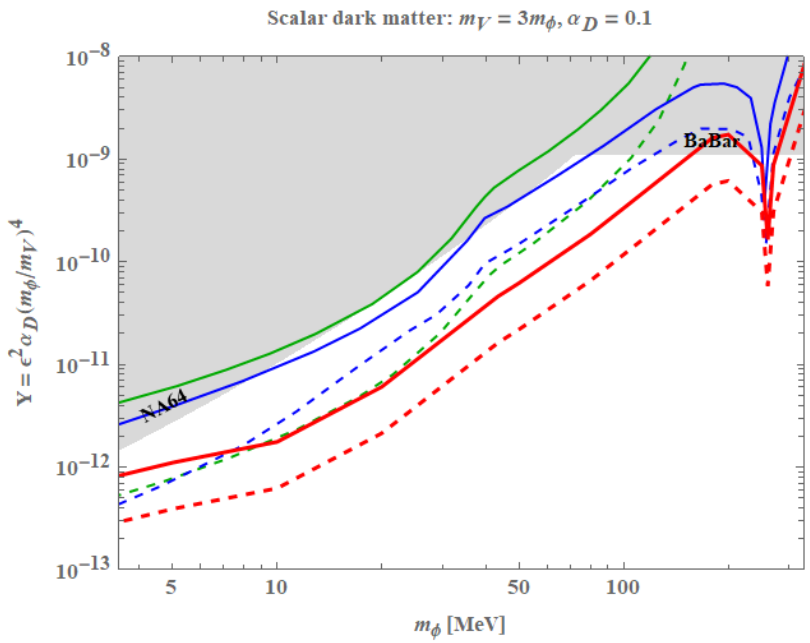
DM at ν experiments

DUNE: DM parameter space,





DUNE-beam-dump mode

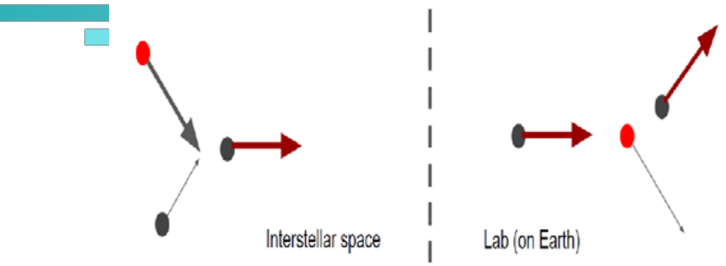


Doojin Kim

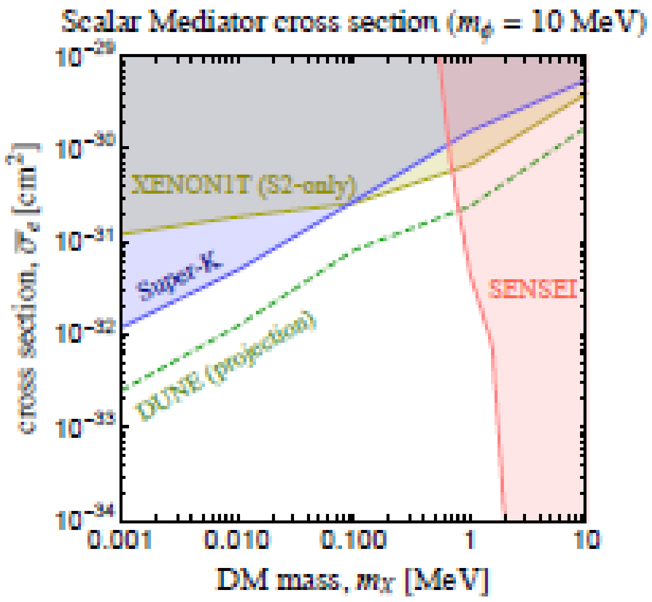
Breitbach, Buonocore,Frugiuele, Kopp, Mittnacht, JHEP 01 (2022) 048,

DUNE Far detector: New physics

Cosmic-ray boosted DM

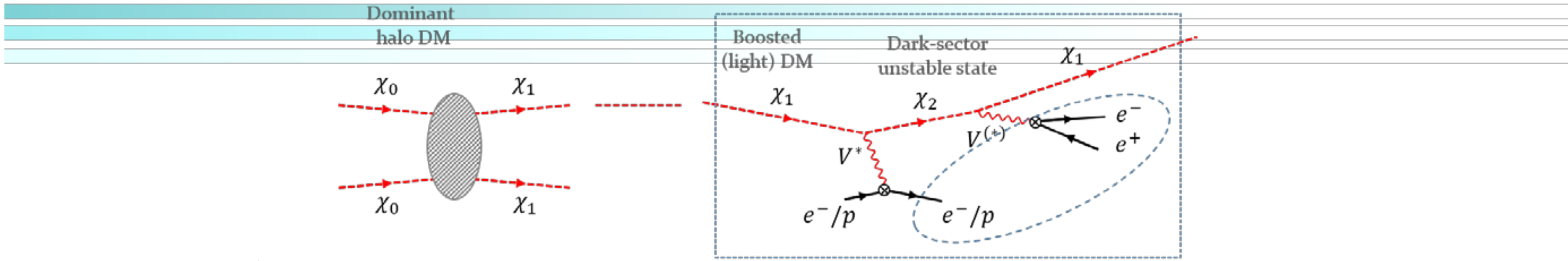


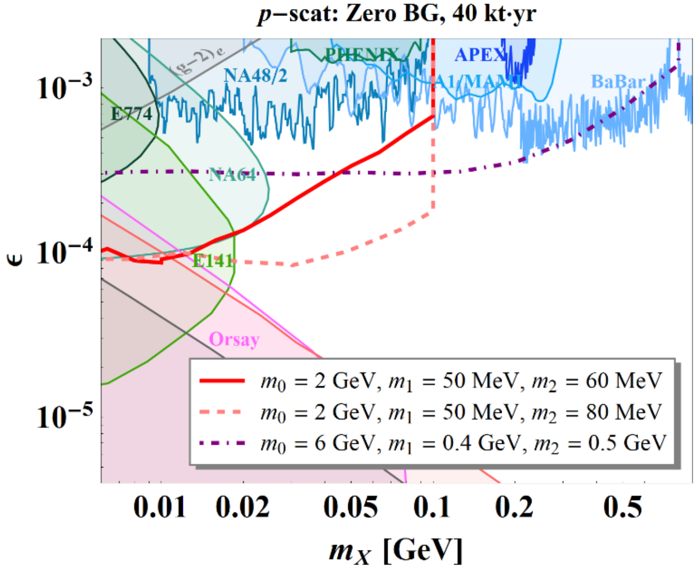
Low mass DM (up to 10 GeV) become energetic
➔ detection becomes easier

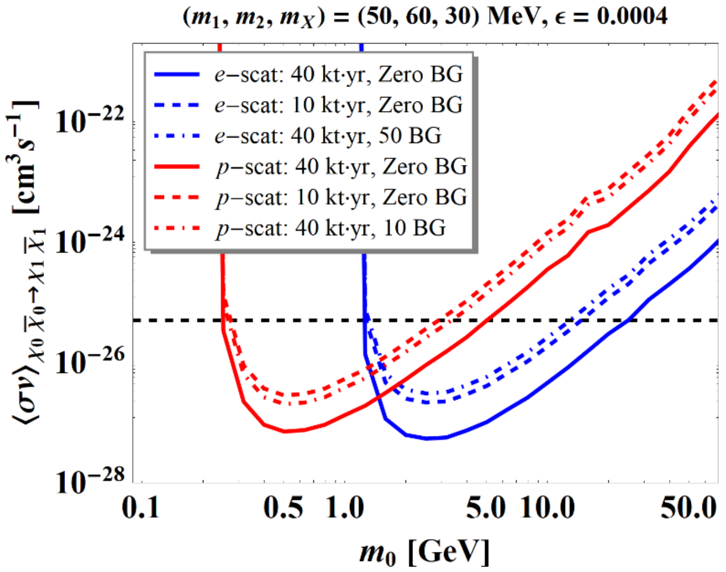


Dent, Dutta, Newstead, Shoemaker, Arellano, PRD, 2021

Inelastic Boosted Dark Matter







[De Roeck, DK, Moghaddam, Park, Shin, Whitehead, 2005.08979]

Doojin Kim

Conclusion

- It is a very interesting time -many experiments and observations are ongoing/upcoming
- Models are being constructed utilizing information from particle physics, astrophysics, and cosmology
- Major puzzles: neutrino sector (mass, mixing angles, interactions), the origin of DM, understanding inflation, Hubble tension, galactic center excess, g-2, MiniBooNe anomalies etc.
- Various ongoing and upcoming opportunities will hopefully provide us with the clue(s).