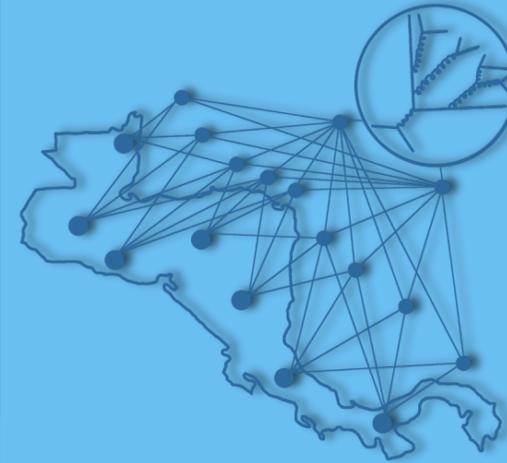


New Searches for Dark Sectors at Neutrino and Kaon Experiments

I Central American
Meeting of High Energy
Physics, Cosmology and
High Energy Astrophysics

16 November - 4 December 2020



Matheus Hostert

mhostert@umn.edu

(University of Minnesota and Perimeter Institute)



UNIVERSITY OF MINNESOTA

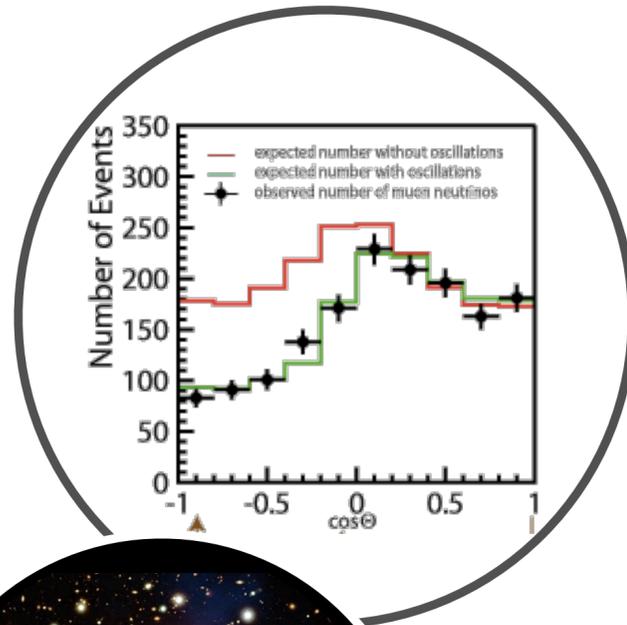


Outline

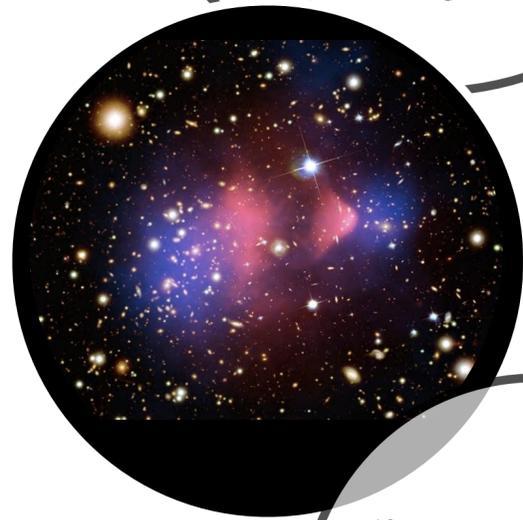
- Motivation to consider dark sectors and new physics at low scales
- New hypothesis to explain old anomalies: the MiniBooNE excess
- New experimental searches and unexplored parameter space.

Evidence for physics beyond the SM

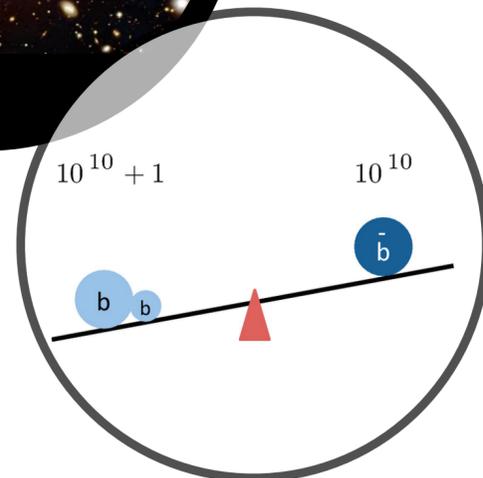
Neutrino Masses



Dark Matter



Baryon Asymmetry of the Universe



Other shortcomings of the SM:

Smallness of strong CP phase

Higgs hierarchy problem

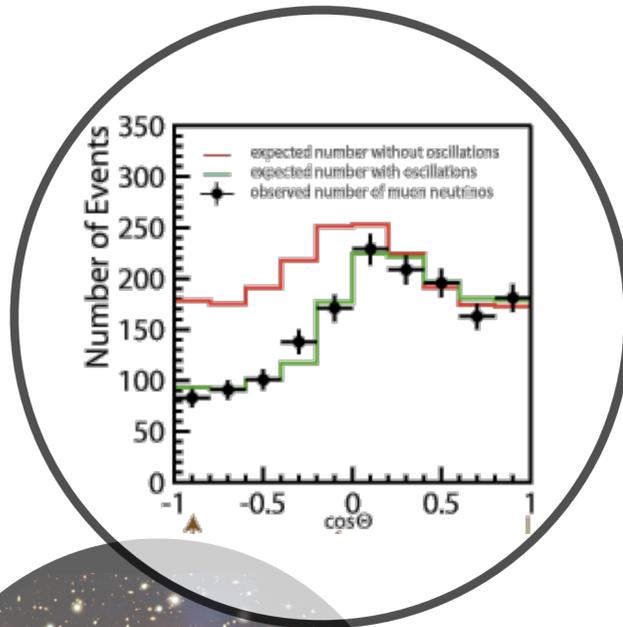
Fermion masses (flavor puzzle)

Cosmological constant

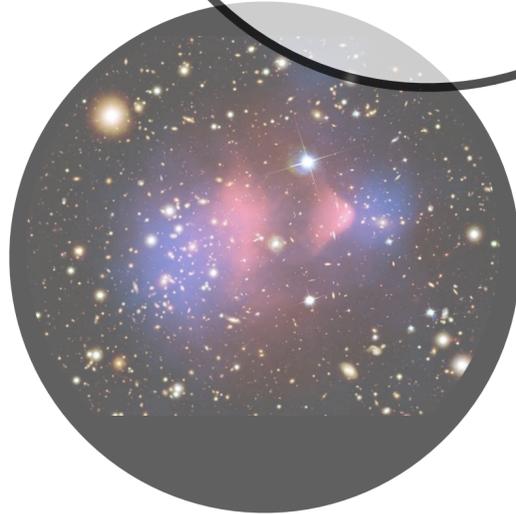
Experimental anomalies

And our ignorance about the new physics scale

Neutrino Masses



Dark Matter



Simplest Type-I seesaw Lagrangian (heavy neutrinos N):

$$\mathcal{L} \supset -y^\nu (\bar{L}\tilde{H}) N - \frac{M_N}{2} \bar{N}^c N + \text{h.c.}$$

To explain light neutrino masses (~ 0.1 eV), we require the naive estimates below: $m_\nu \approx \frac{(y^\nu v_{EW})^2}{2M_N}$

$$(y^\nu)^2 \approx 3 \times 10^{-15} \frac{M_N}{\text{GeV}} \quad |U|^2 \approx 10^{-10} \frac{\text{GeV}}{M_N}$$

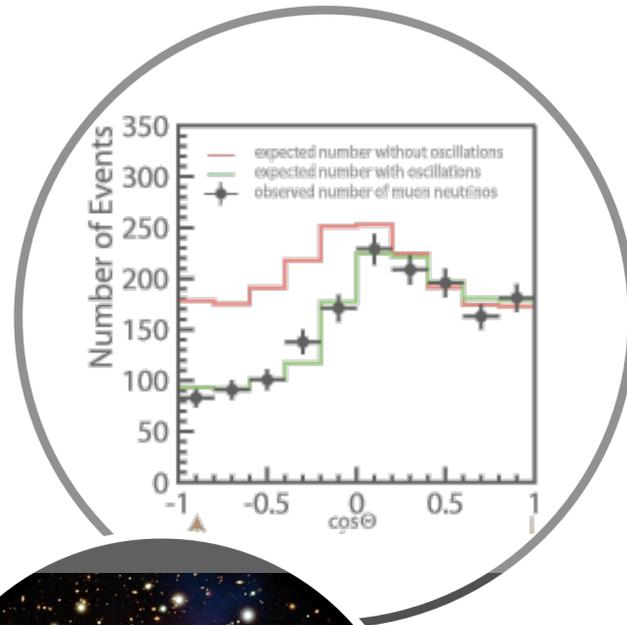
Large hierarchy of scales? Small couplings? New symmetries?

($M_N \gg$ EW scale)

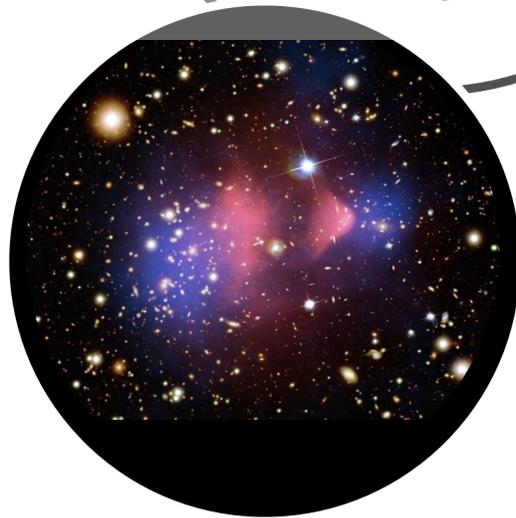
Barring theoretical prejudice against small Yukawas, the mass of N is arbitrary.

And our ignorance about the new physics scale

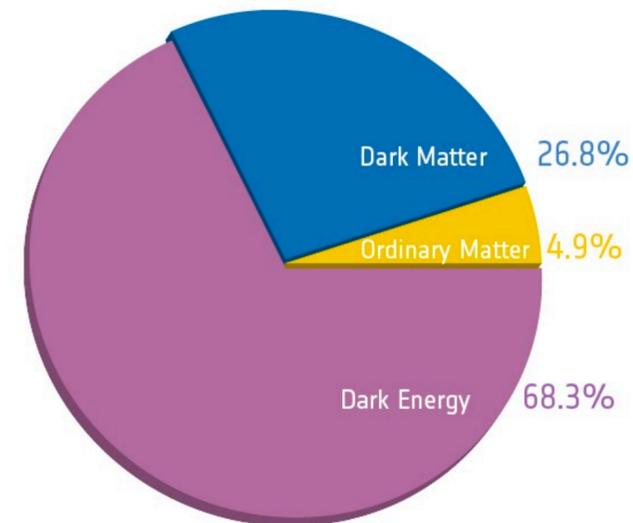
Neutrino Masses



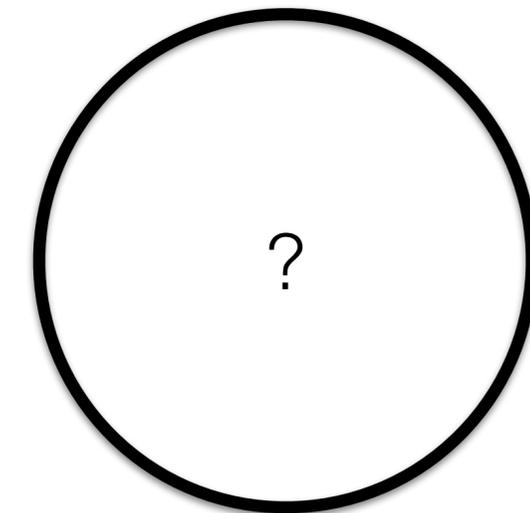
Dark Matter



Energy density



Number density



We know the energy density of dark matter and its gravitational potential...

But we do not know the **number density of DM particles in the Universe.**

- 1) What is the *mass scale* of DM?
- 2) How many dark species are there? Lots of space for *dark forces and particles.*

See talks from Thursday

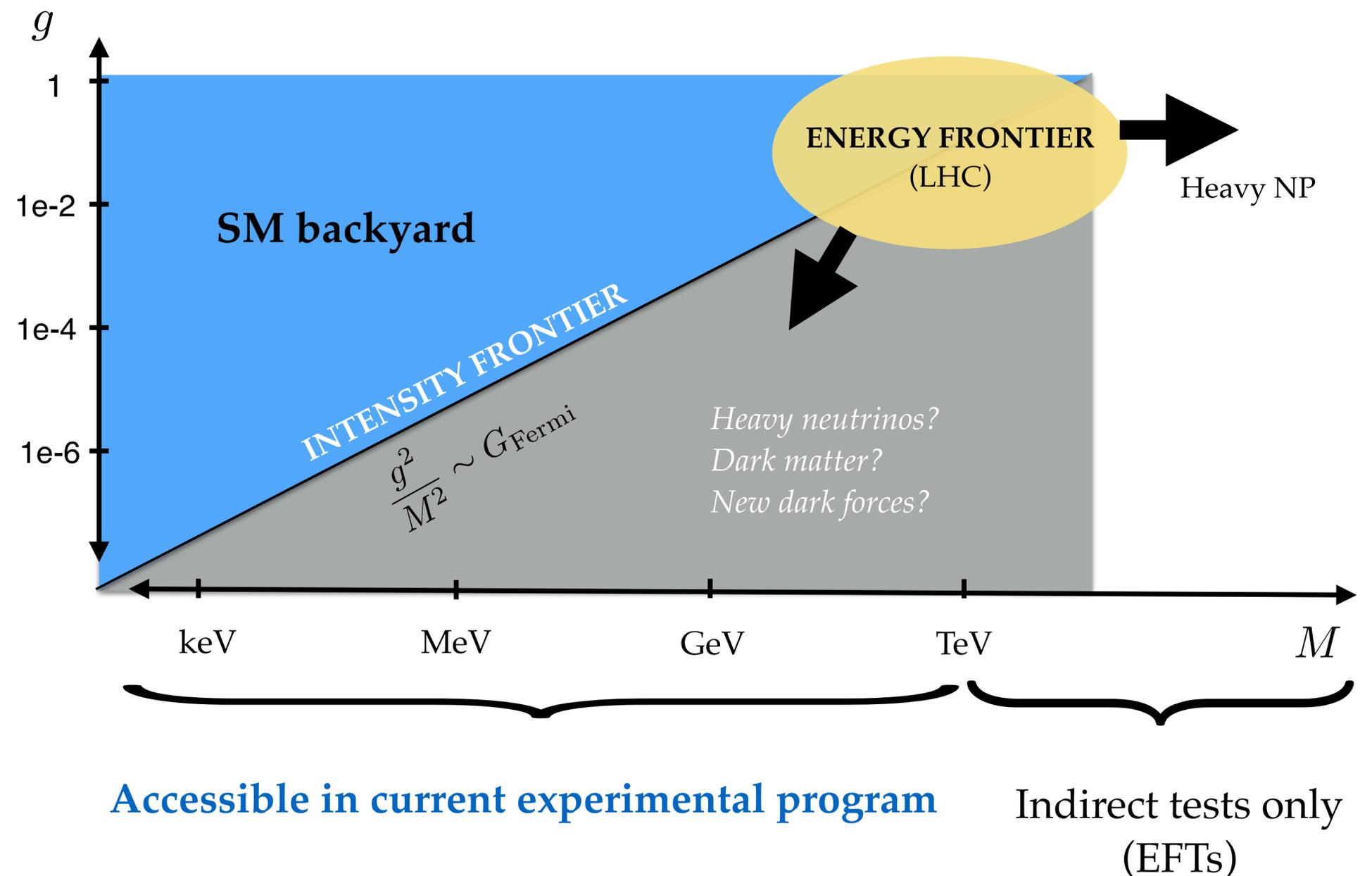
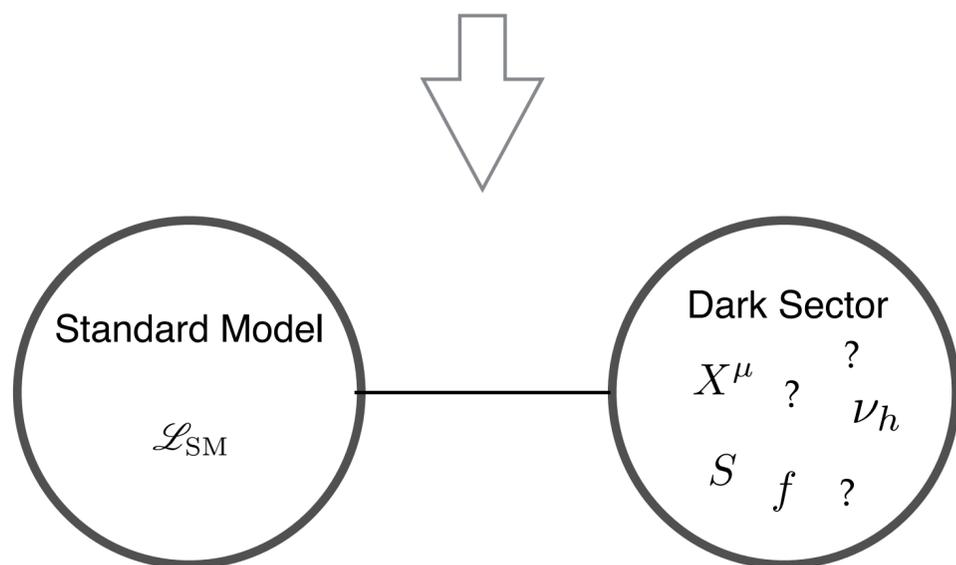
F. Calore, T. Tomei,

R. Henríquez & M. E. C. Catalan

New physics under the lamppost

Most solutions to these problems involve new sectors of gauge singlets:

1. Anomaly cancellation in the SM is a delicate construction.
2. New light states directly coupled to the SM would already have been detected.



PORTALS BETWEEN SM AND DARK SECTOS

GENERIC DARK SECTORS

$$\bar{L}\tilde{H}N$$



Neutrino portal

Heavy neutrinos

$$\frac{M_N}{2}\overline{N^c}N$$

New fundamental scale(s) in nature?

$$B_{\mu\nu}X^{\mu\nu}$$



Vector portal

Dark photons

$$G_{SM} \times U(1)_X$$

New forces and symmetries

$$S^\dagger S (H^\dagger H)$$



Scalar portal

Real or complex scalars

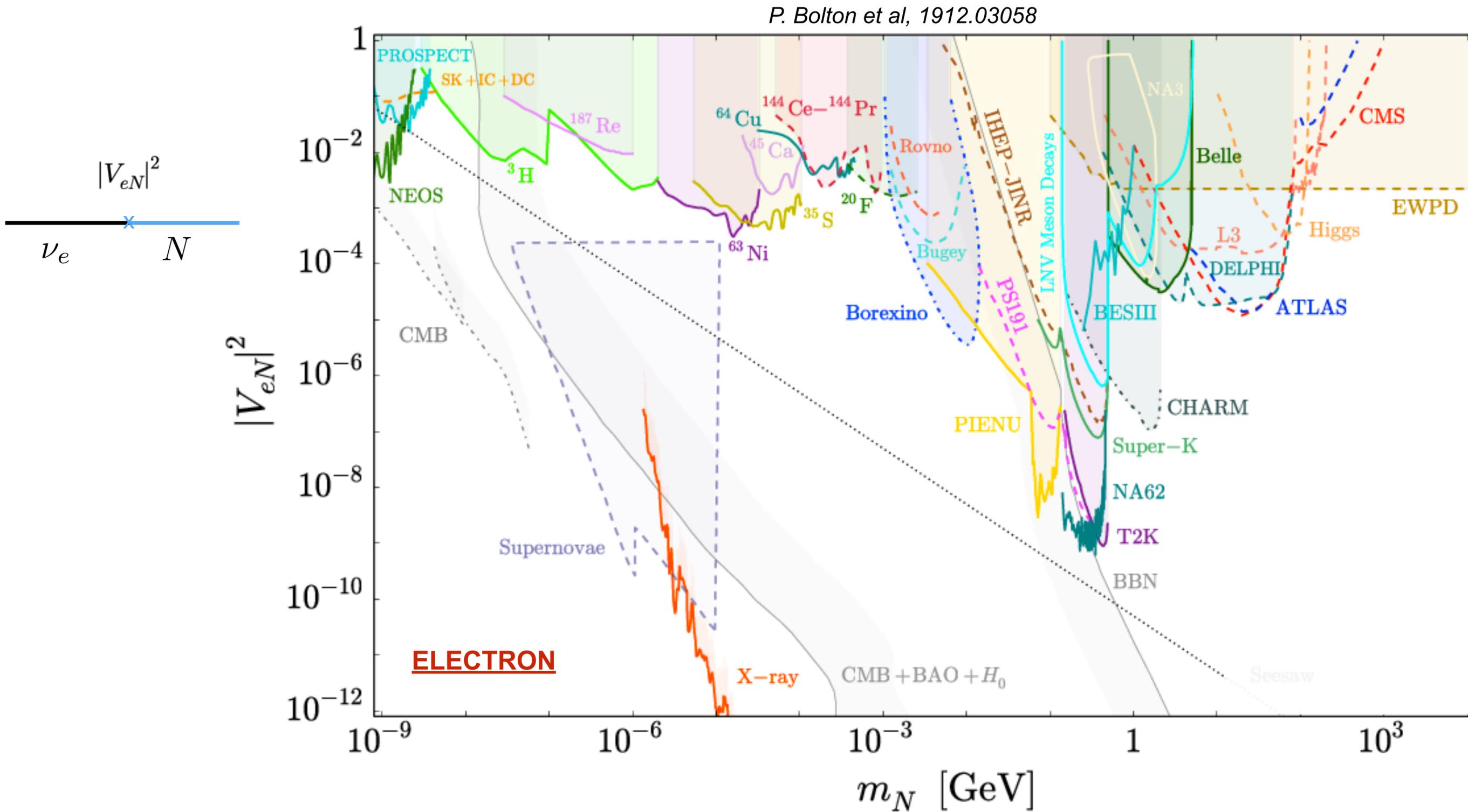
$$m_S^2|S|^2$$

New spontaneously broken symmetries?

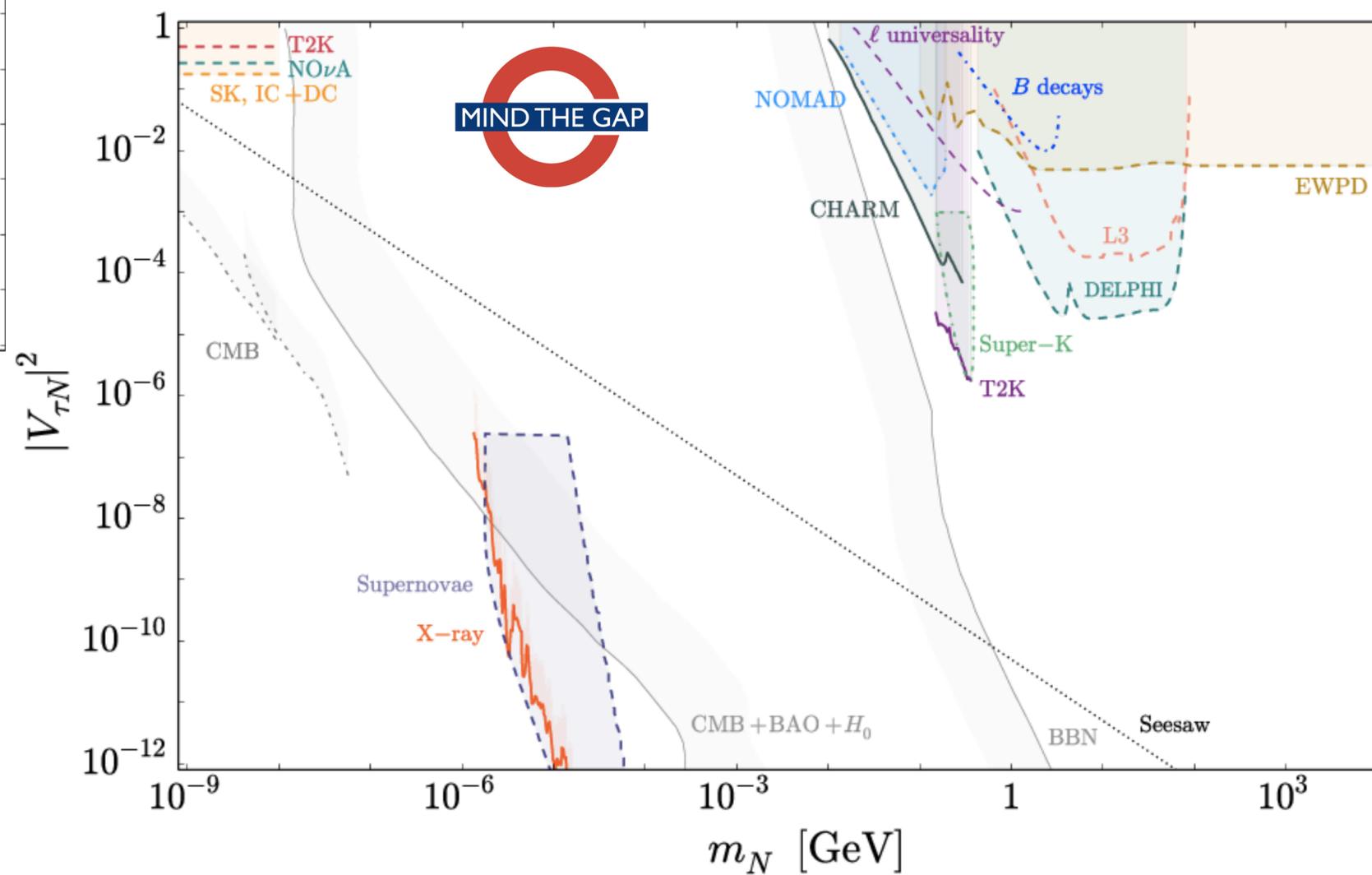
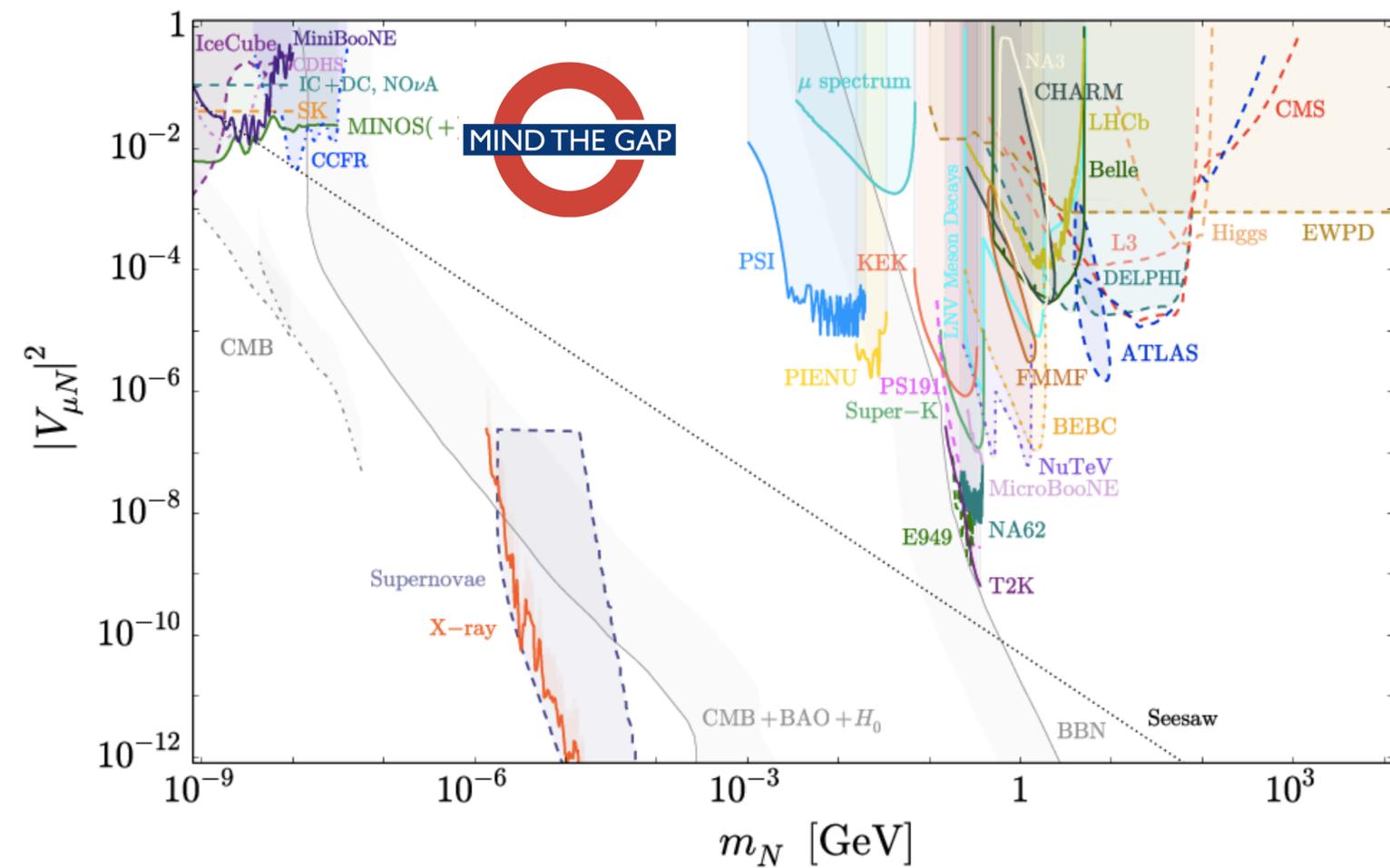
Or just singlet scalars?

\mathcal{L}_{SM}

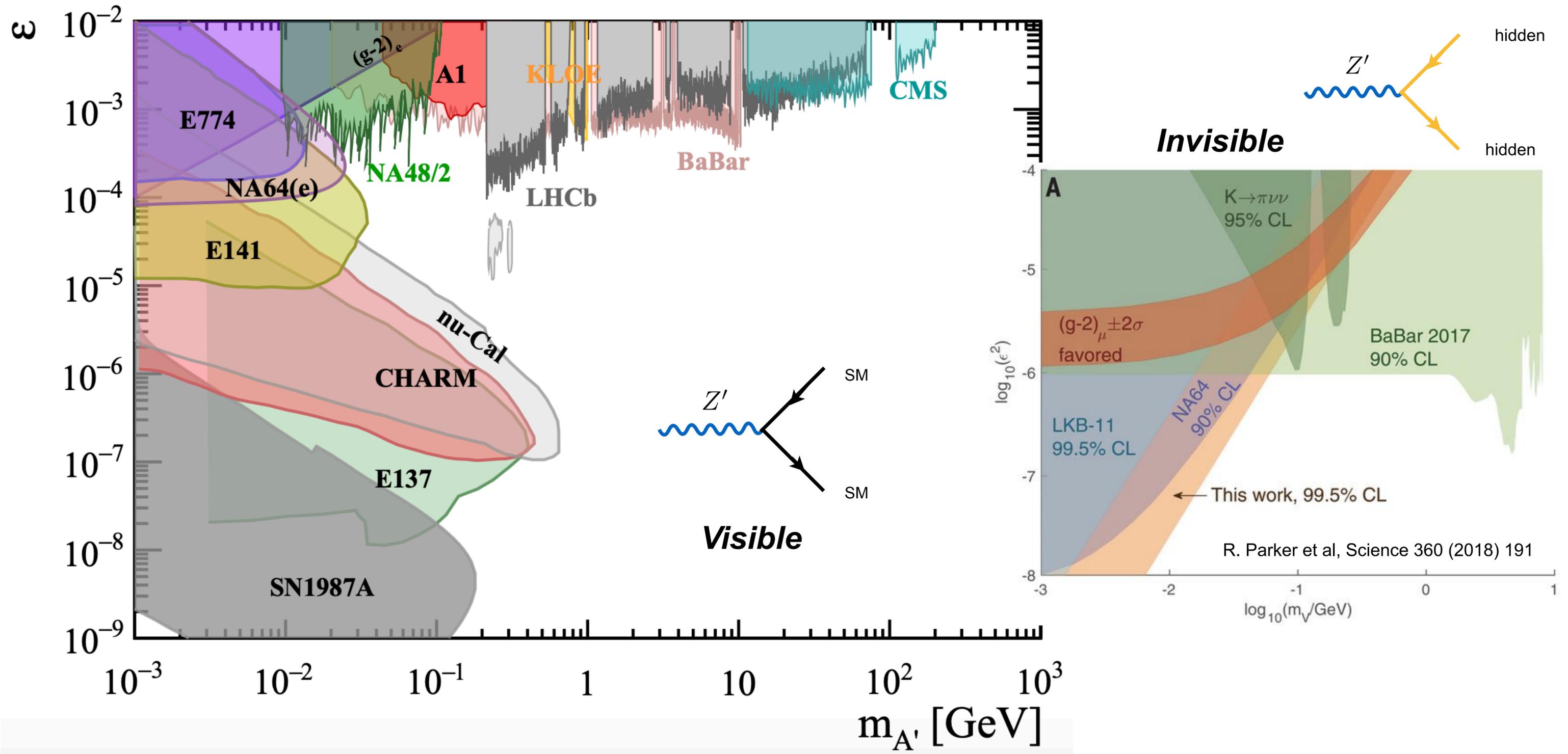
Minimal HNL Phenomenology



Minimal HNL Phenomenology



Minimal dark photon



**No (concrete) evidence for light new particles so far
and several different models are proposed every single day.**

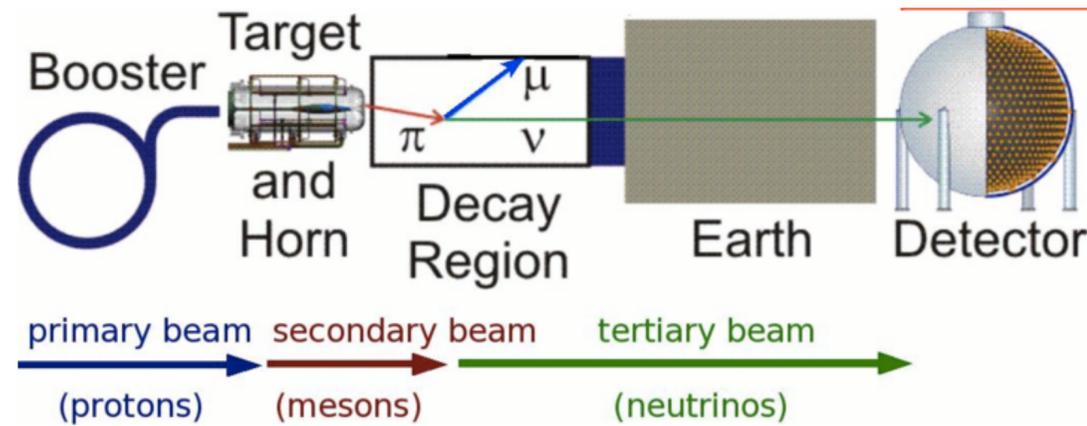
How to proceed? One option is to take a data and signature driven approach:

The MiniBooNE low-energy excess

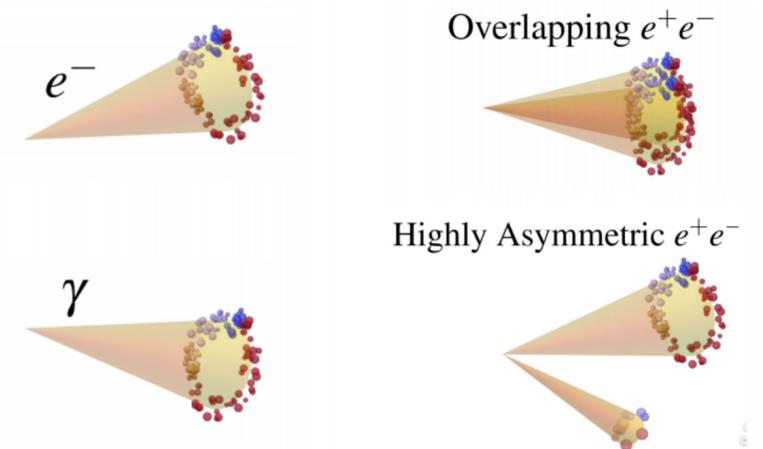
Post-pandemic MiniBooNE results:

arXiv:2006.16883

- 1) 8GeV protons, $\sim 1.9e^{21}$ POT
- 2) π decay in flight — 800 MeV E_{nu}
- 3) ν_{μ} contamination $5e^{-3}$.
- 4) 500 m baseline
- 5) 818 t mineral oil
- 6) 8 m long along ν beam

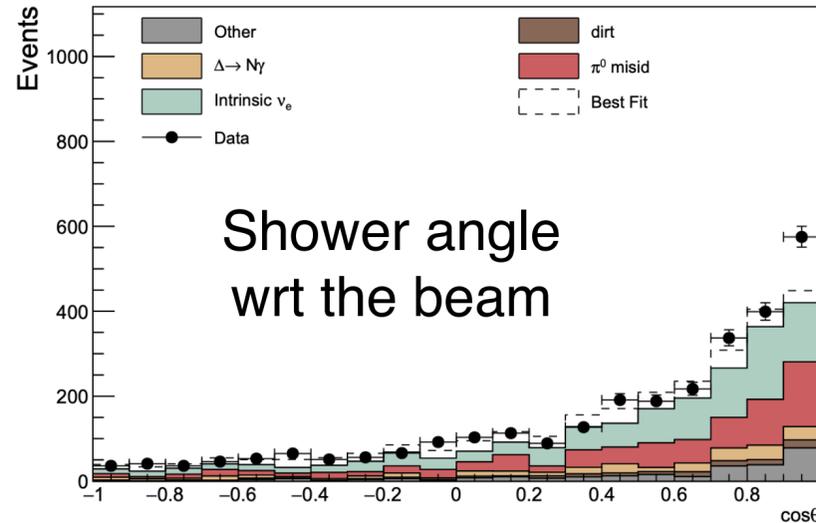
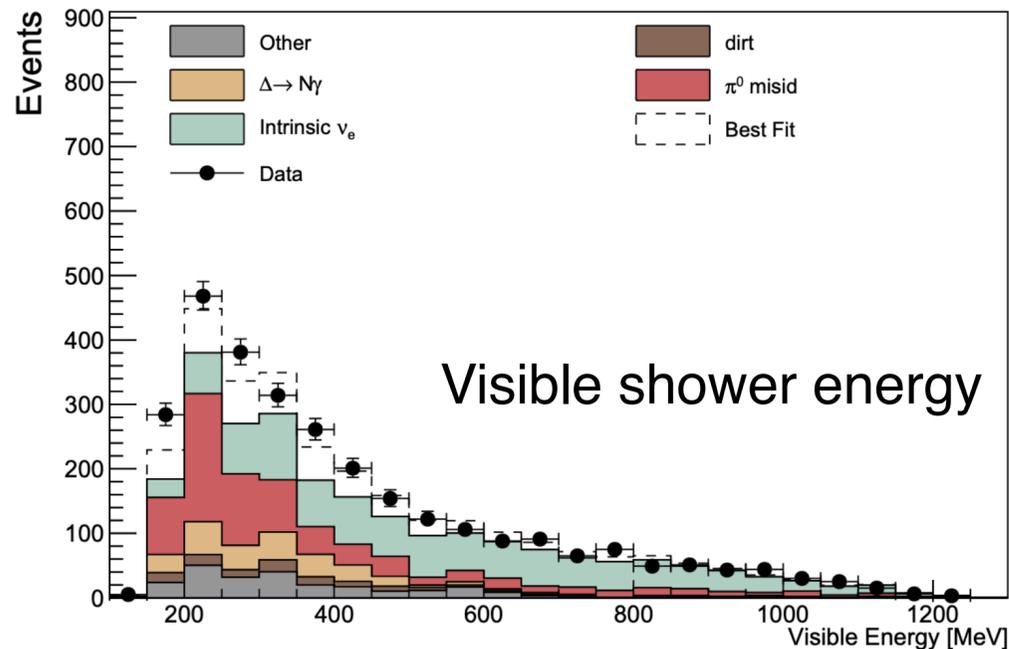


Any one of these final states may be the culprit



Strong evidence for....

- 1) Poorly modelled SM backgrounds?
- 2) SBL oscillations?
- 3) A whole set of exotic new particles?



Unconstrained Bkgd.	2322.6 ± 258.3
Constrained Bkgd.	2309.4 ± 119.6
Total Data	2870
Excess	560.6 ± 119.6
0.26% (LSND) $\nu_{\mu} \rightarrow \nu_e$	676.3

EXCESS: 560 ± 119.6 EVENTS only in ν_{μ} mode
4.8 sigma significance

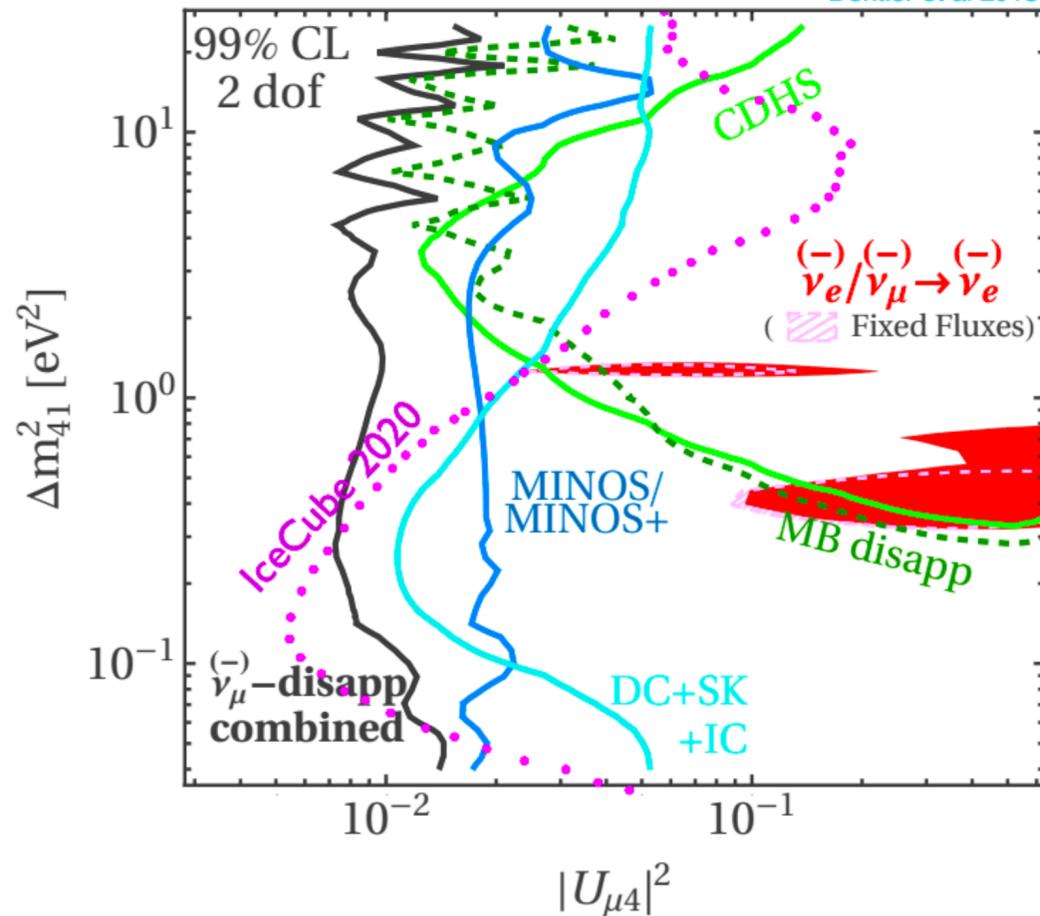
New exotic hypothesis to explain MiniBooNE

eV sterile oscillations.

Muon disappearance excludes this model*.

P. Machado - Neutrino 2020

Dentler et al 2018



* except if ν_e appearance is much larger than we thought — no consensus here, yet.

Open the floodgates to *exotica*

New signatures:
 Gninenko 1107.0279 *No LSND*
 Heavy neutrino O(MeV), magnetic moment, decay

Bertuzzo et al 1807.09877, Ballett et al 1808.02916, Arguelles et al 1812.08768
 Heavy neutrino O(1-100MeV), light Z', decay
 W. Abdallah et al 2010.06159 *No LSND*

Oscillations+:
 Asaadi et al 1712.08019
 Resonant matter effect *UV challenge*

Doring et al 1808.07460, Barenboim et al 1911.02329
 eV steriles and extra dimensional shortcuts

Liao et al 1810.01000
 Steriles + NCNSI + CCNSI *Baroque not clear*

Decay:
 O. Fischer et al 1909.09561
 Long lived HNL O(MeV) mag moment *Delayed signal?*

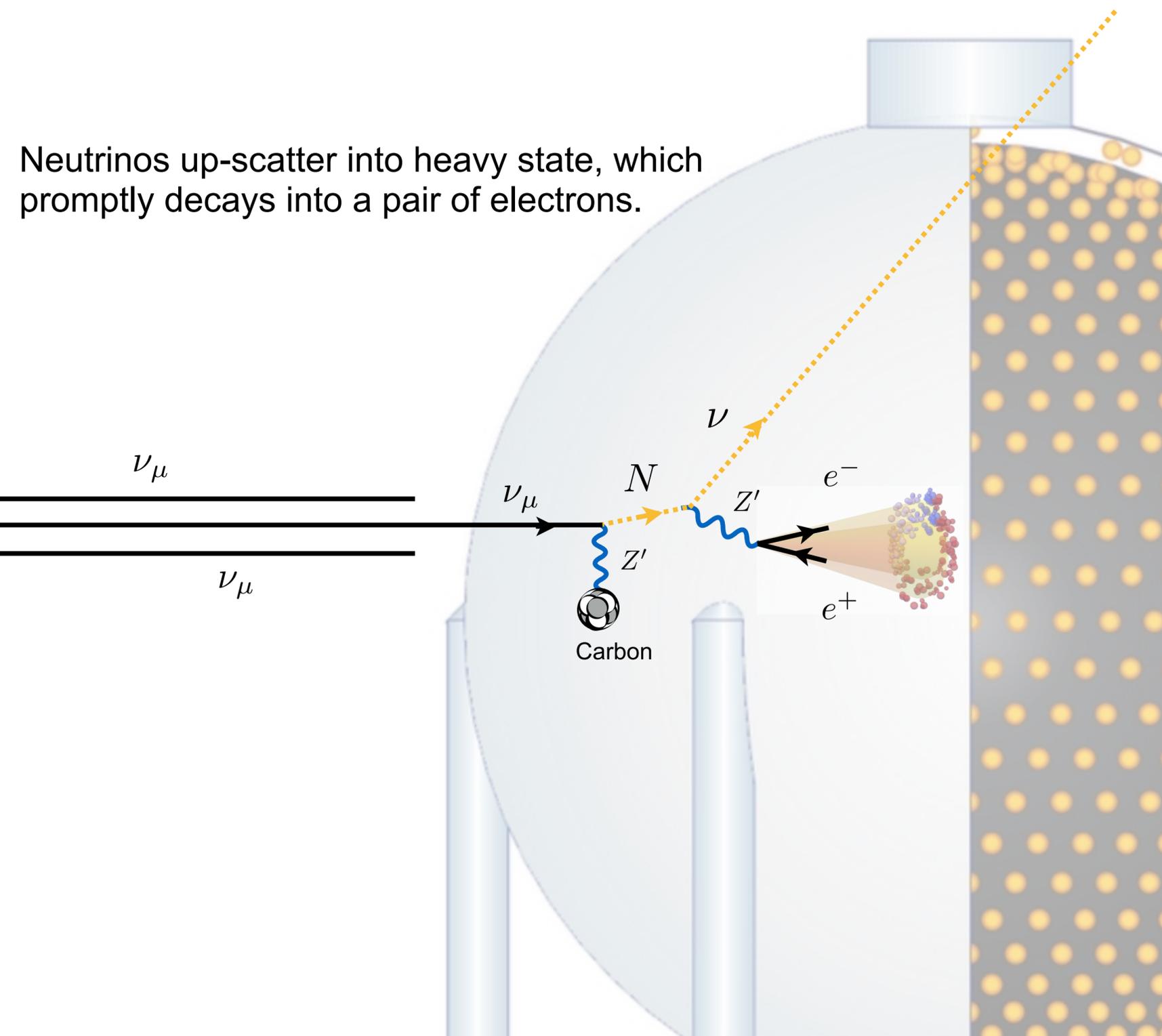
Bai et al 1512.05357, Dentler et al 1911.01427, de Gouvêa et al 1911.01447
 Heavy sterile O(keV-MeV) decay to ν_e *May work..*

New physics
In scattering

New physics
In propagation

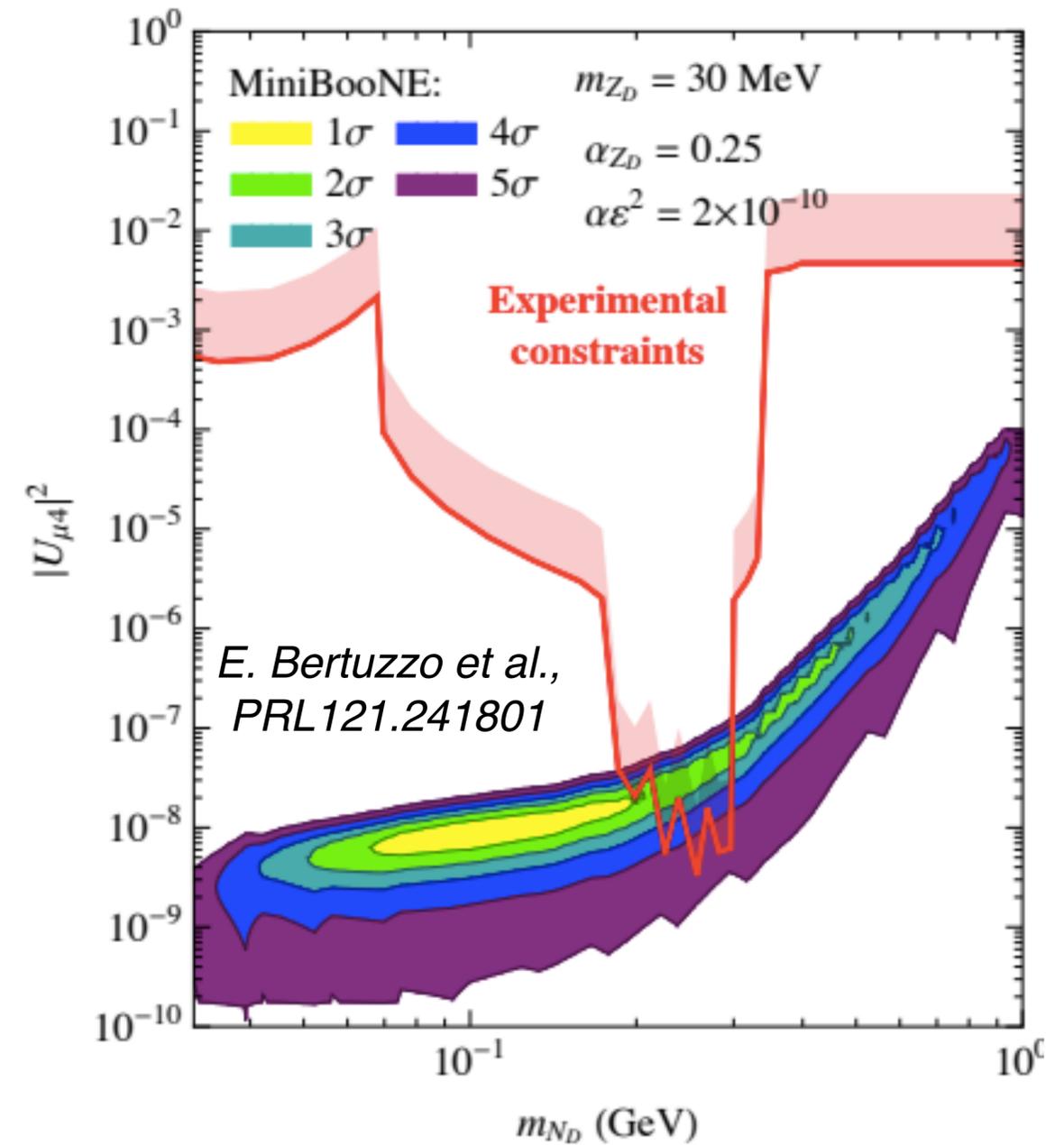
New “visible” states
in the beam

Heavy neutrinos + dark forces to solve MiniBooNE



Simplified model

Heavy neutrinos interact strongly with dark photons and weakly with SM via 2 portals: **neutrino and kinetic mixing.**



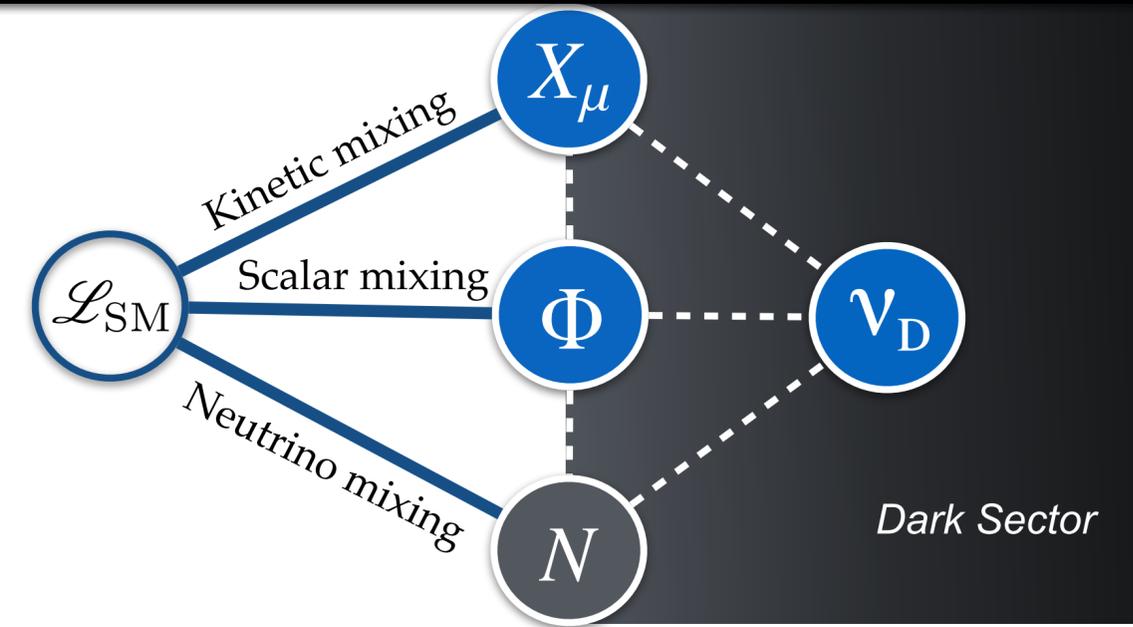
A simple neutrino mass model to accommodate MiniBooNE

A. Abdullahi, MH, S. Pascoli
 arXiv:2007.11813

1) A minimal renormalizable model:

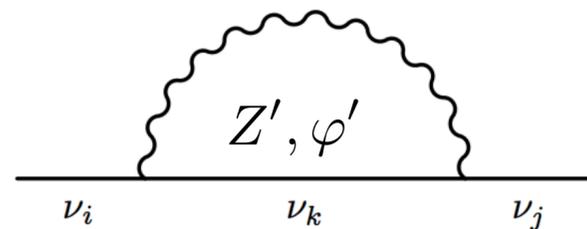
	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
N	$\mathbf{1}$	0	0
ν_{DL}	$\mathbf{1}$	0	Q
ν_{DR}	$\mathbf{1}$	0	Q
Φ	$\mathbf{1}$	0	Q

Dark neutrinos charged under a dark $U(1)$ ' symmetry, broken at the GeV scale by $\langle \Phi \rangle$.



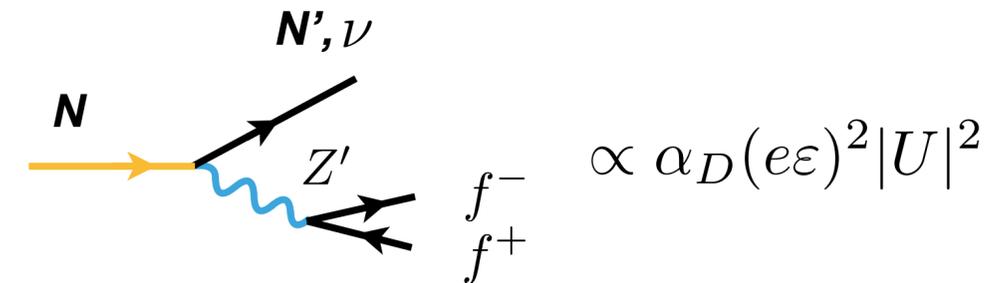
2) Neutrinos masses from LNV & dark sector scale:

$$\begin{pmatrix} 0 & M_D & 0 & 0 \\ M_D^T & M_N & \Lambda_L & \Lambda_R \\ 0 & \Lambda_L^T & 0 & M_X \\ 0 & \Lambda_R^T & M_X^T & 0 \end{pmatrix} \begin{pmatrix} \nu_\alpha^c \\ N^c \\ \nu_{DL}^c \\ \nu_{DR}^c \end{pmatrix}$$



$$M_D^T (\Lambda^T)^{-1} M_X \Lambda^{-1} M_D + \delta M_{1-loop}^{Z', \phi'}$$

3) Modified experimental landscape



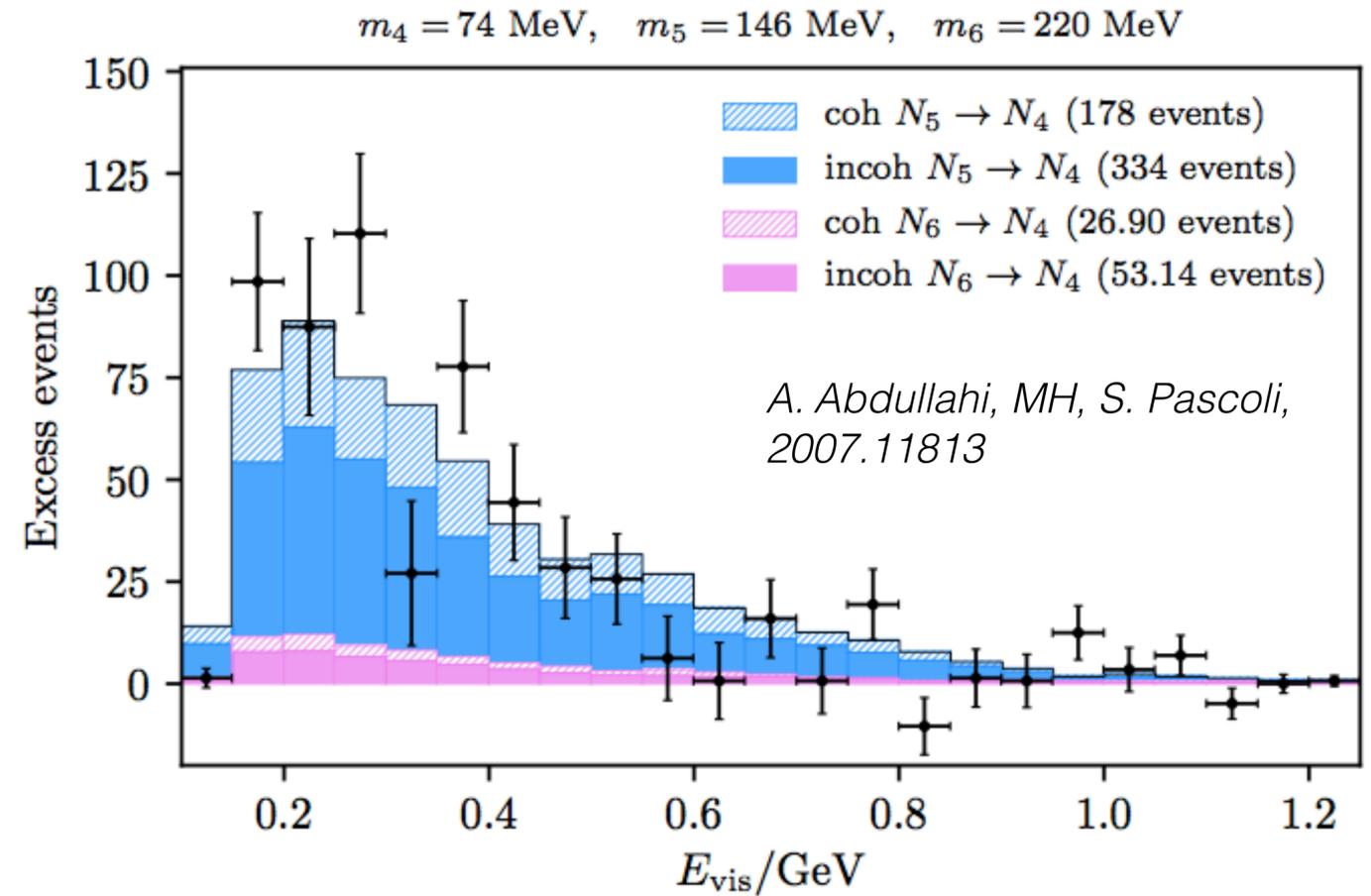
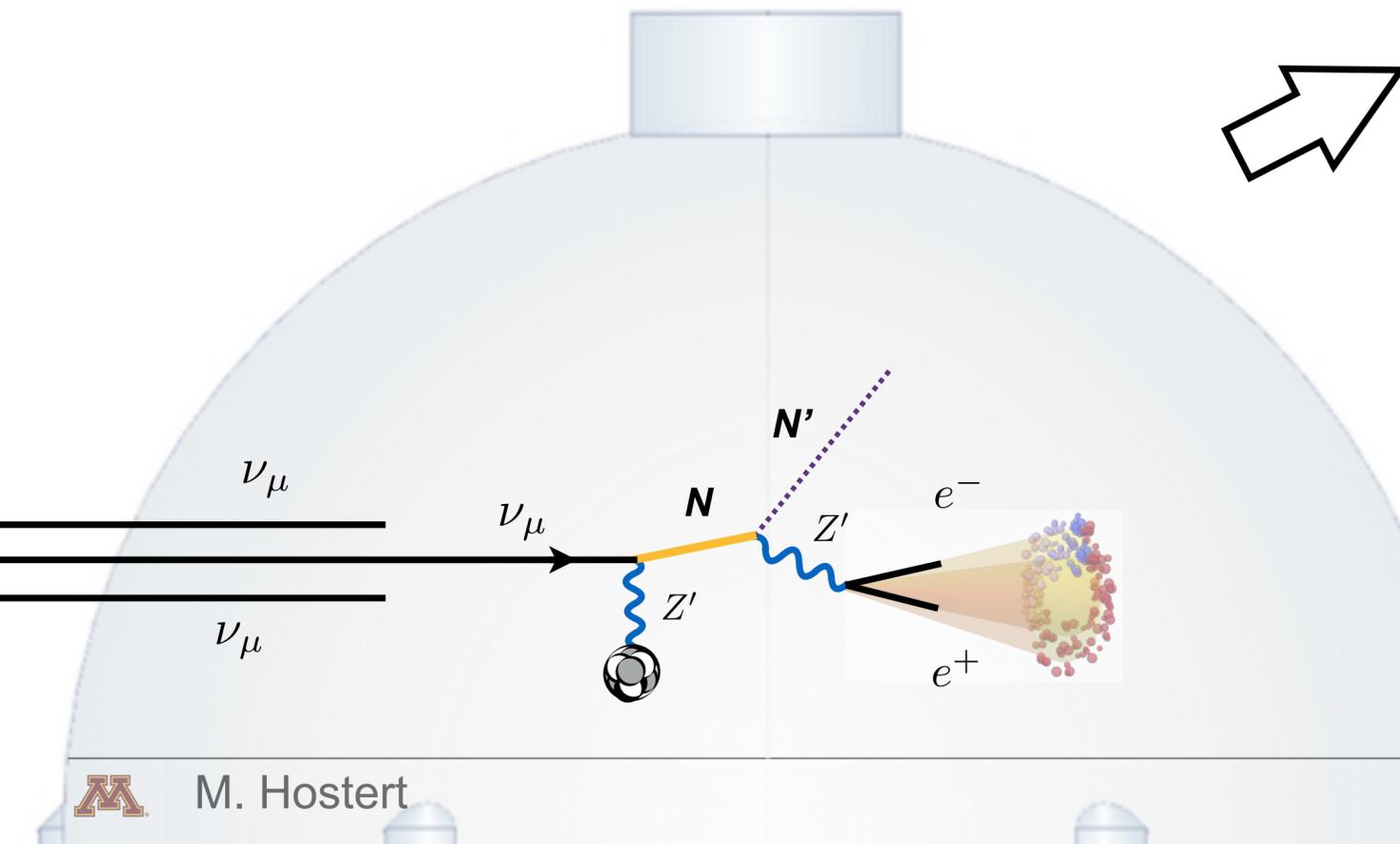
Novel production and decay channels important when vector and scalar portals are considered.

Connection to the MiniBooNE excess

HNLs produced in neutrino scattering

see also *E. Bertuzzo et al, PRL121.241801, P. Ballett et al, PRD 99.071701, + others*

Upscattering proceeds via kinetic mixing and N_5 and N_6 states decay promptly to long-lived N_4 states.



α_D	m_3 /eV	$m_4 m_5 m_6$ /MeV			$c\tau^0/\text{cm}$		
		N_4	N_5	N_6	N_4	N_5	N_6
0.39	0.05	35	120	185	1.6×10^{13}	3.0	0.26
0.32	0.05	74	146	220	1.1×10^7	2.2	0.14

$$m_{Z'} = 1.25 \text{ GeV} \text{ and } \varepsilon^2 = 4.6 \times 10^{-4}$$

Direct tests of this new hypothesis

Neutrino scattering experiments

Pseudo single photons at ν detectors:

Currently, neutrino experiments can search for photon-like showers inside their detectors.

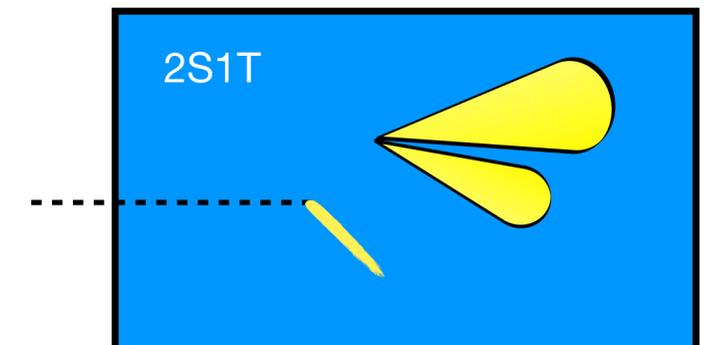
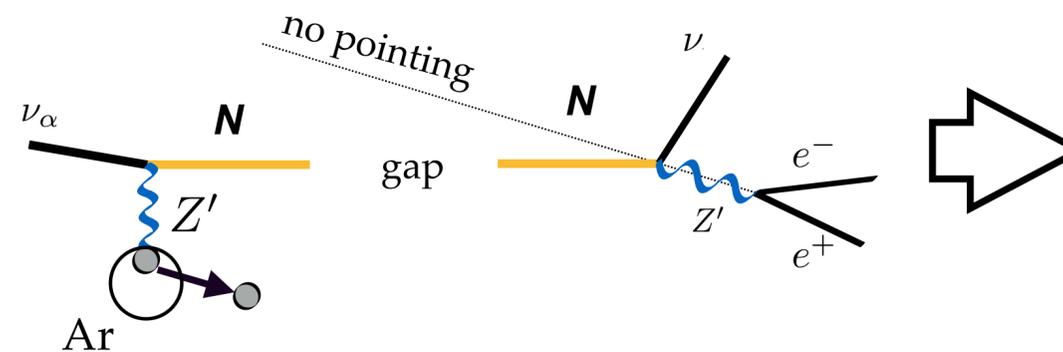
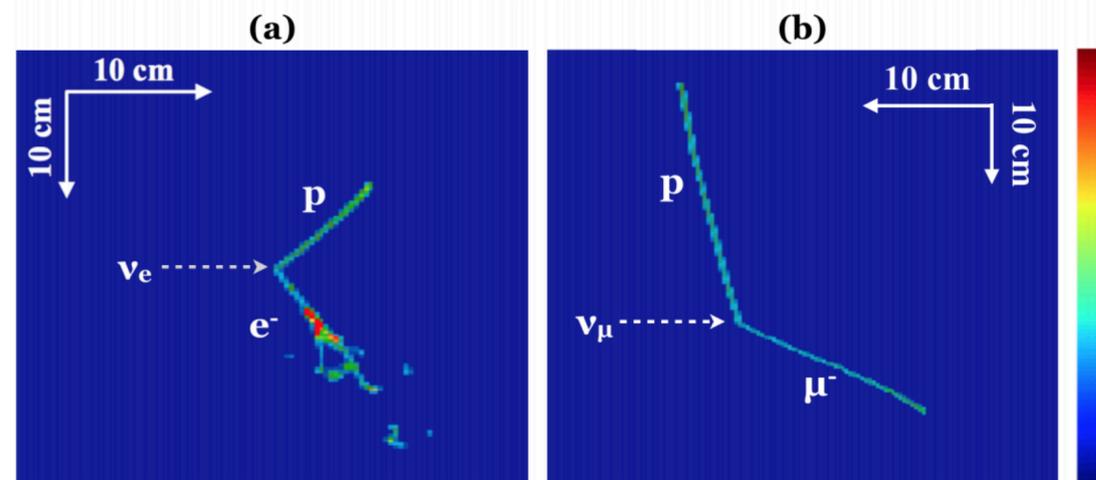


C. Arguelles, MH, Y. Tsai, PRL123.261801

Signature appears in neutrino-electron scattering analyses but unfortunately, a conclusive exclusion of “dark neutrino models” is not possible.



New generation of Liquid Argon detectors at Fermilab can search for (e+e-) events and will test MiniBooNE results.

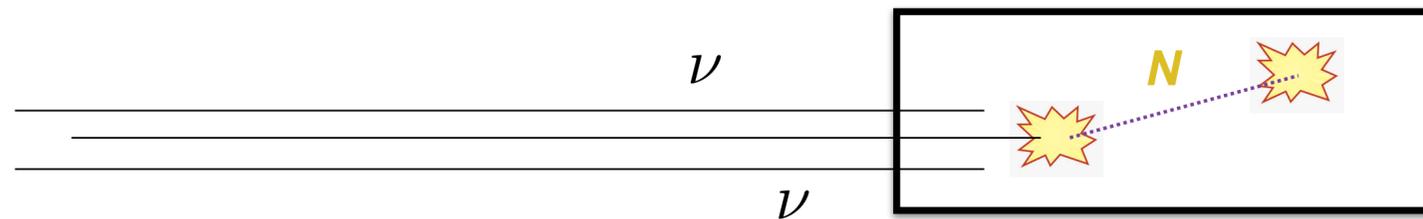


Search is on-going and will test if excess is due to single electrons or photons/e+e- pairs.

“Double-bang” events

When production and decay are distinguishable

The model also predicts double-bang like features:



NC/NC excess observed at CCFR (1990s), but no excess of NC/CC events.

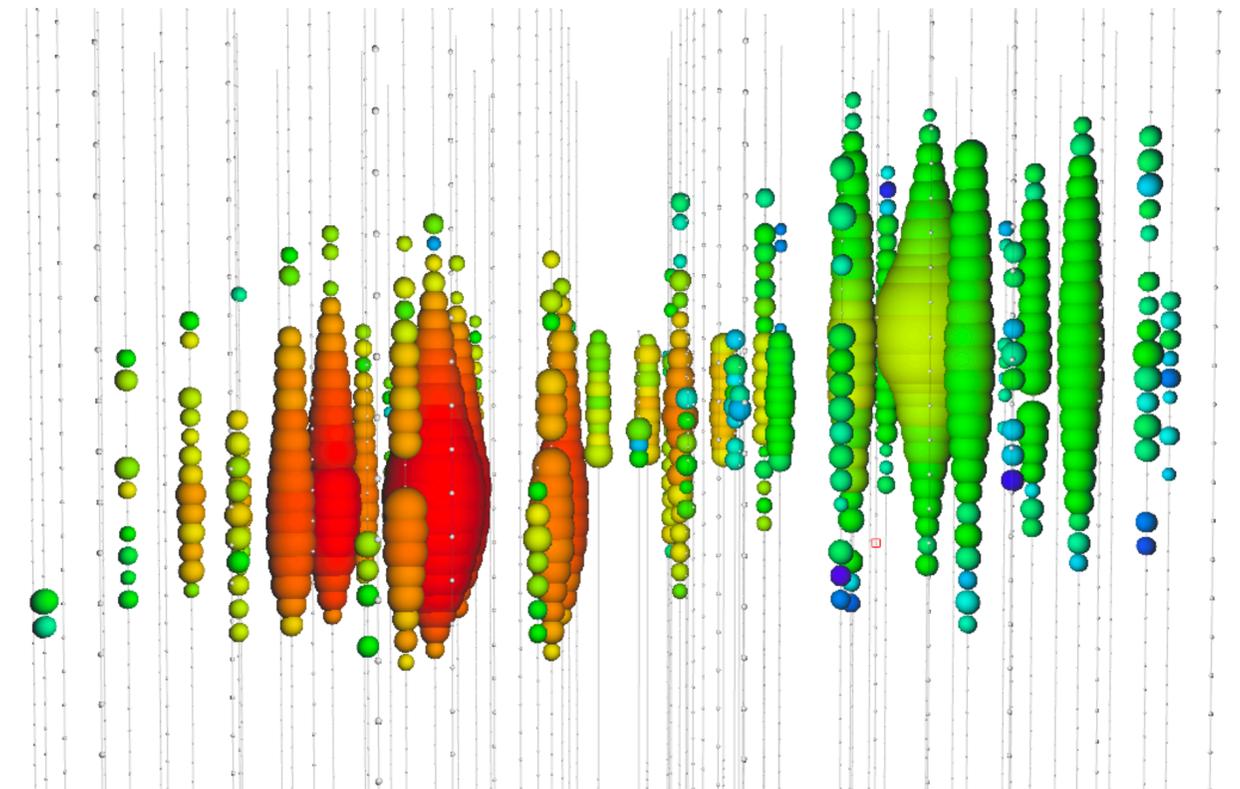
To the best of our knowledge, this is not explained to this date.
P. de Barbaro, doi.org/10.1063/1.43269

9 NC/NC observed on a background of 3 ± 0.2 (stat.) ± 0.4 (syst.)

Result was not pursued further as minimal HNLs would also lead to CC decays ($N \rightarrow \mu\pi$).

But dark HNLs only decay via NC channels.

Neutrino experiments are now much better at finding vertices, and can look for double Vertex events, especially at high energies:

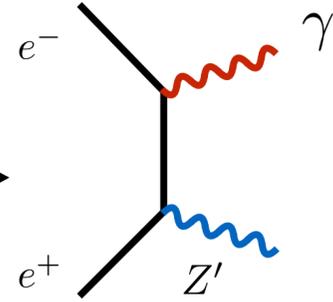
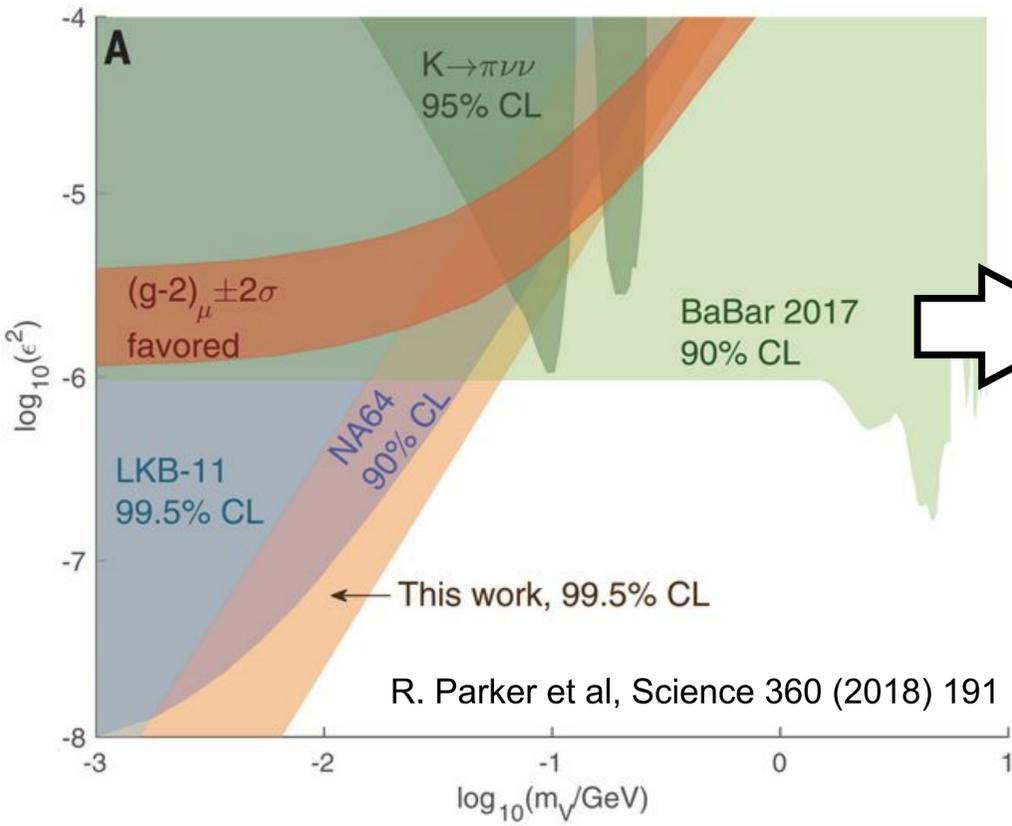


1000s of events/year at **IceCube**

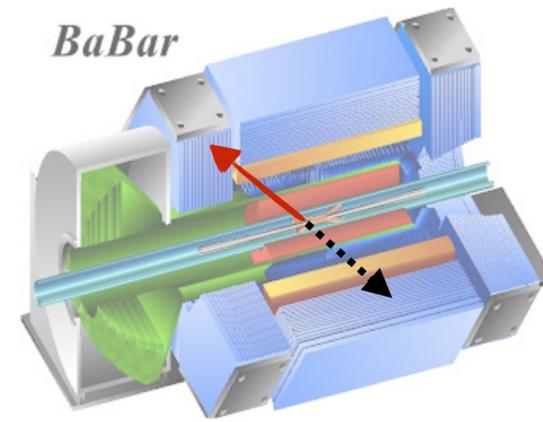
“Double-Bangs”, P. Coloma et al, PRL 119.201804

Bonus: revisiting the muon (g-2)

and re-interpreting the BaBar monophoton search

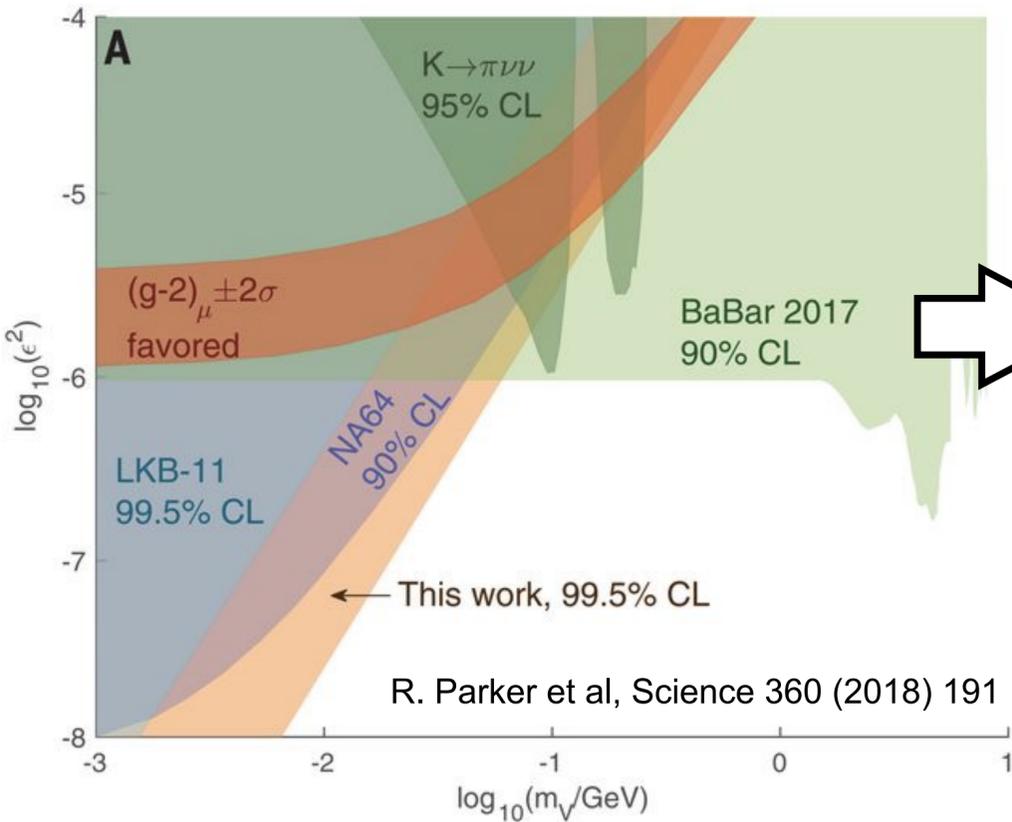


Invisible dark photon

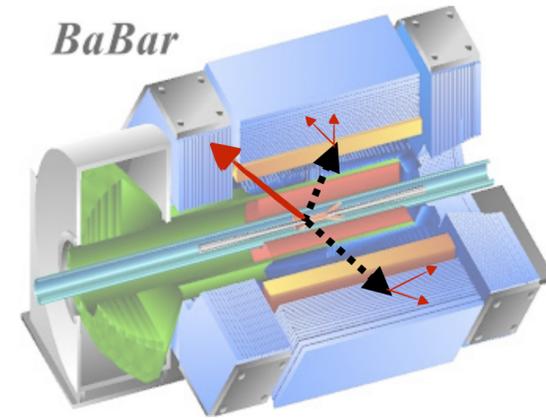
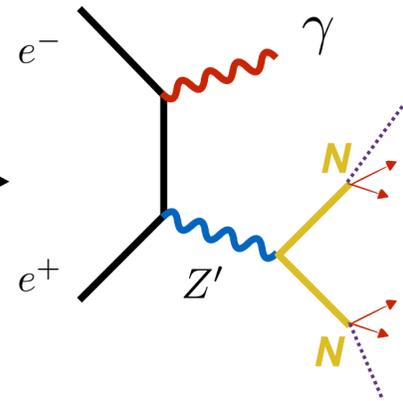


Bonus: revisiting the muon (g-2)

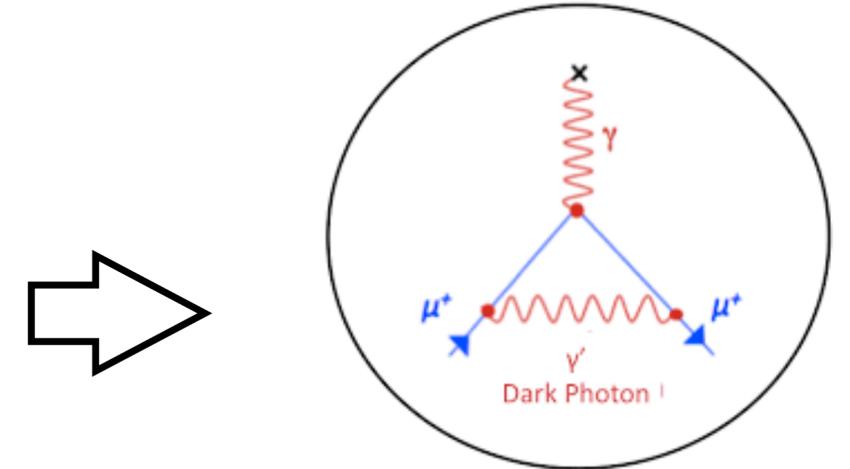
and re-interpreting the BaBar monophoton search



Semi-visible dark photon



Invisible dark photon bounds relaxed.

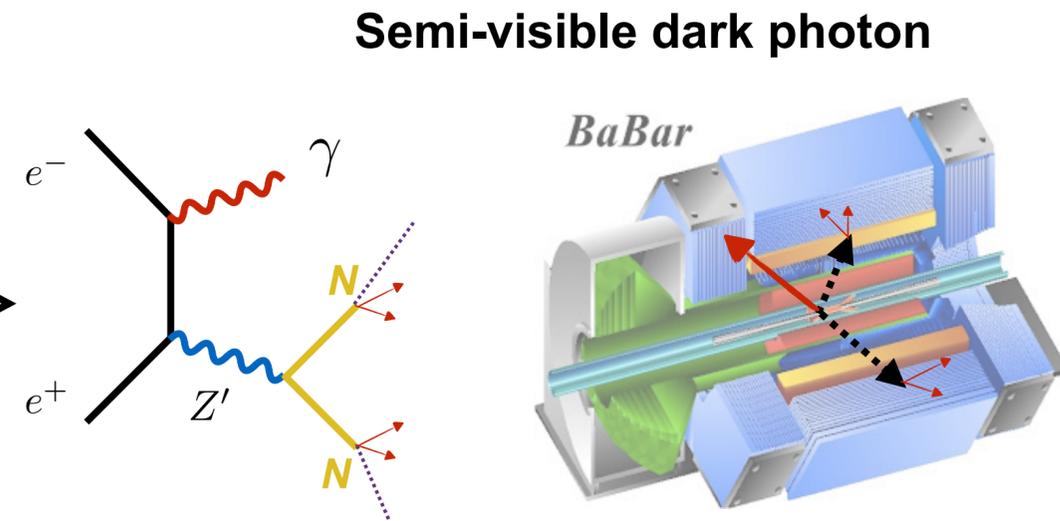
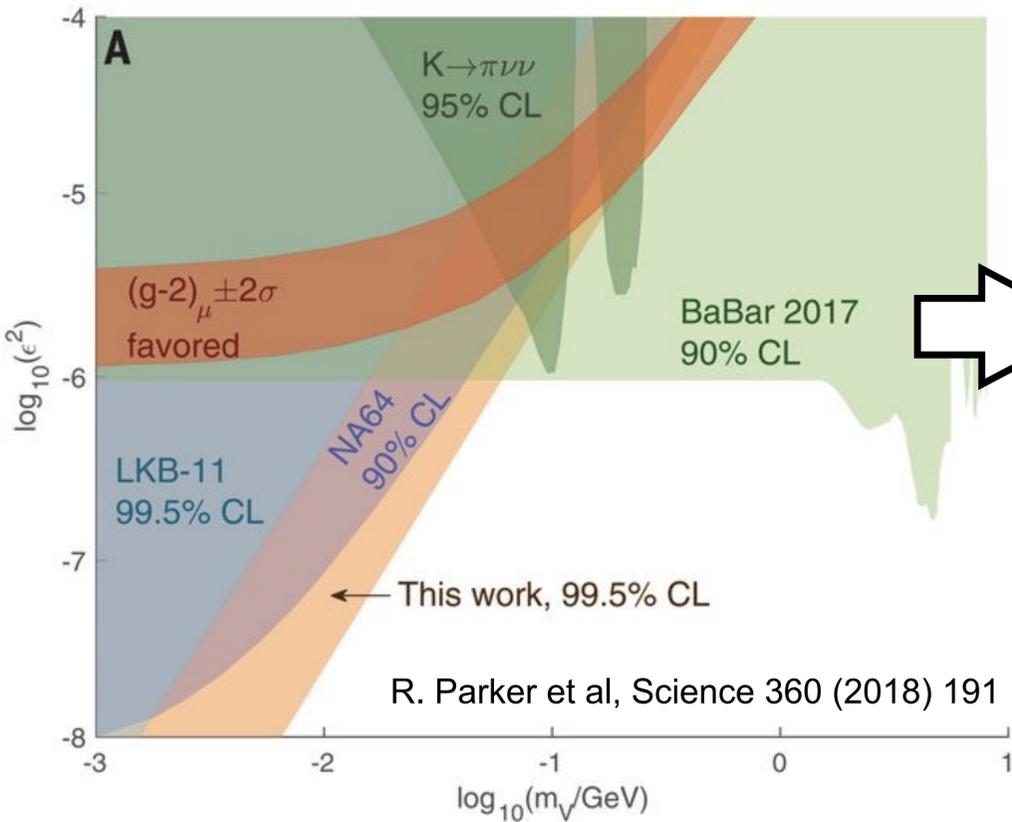


$$m_{Z'} = 1.25 \text{ GeV and } \epsilon^2 = 4.6 \times 10^{-4}$$

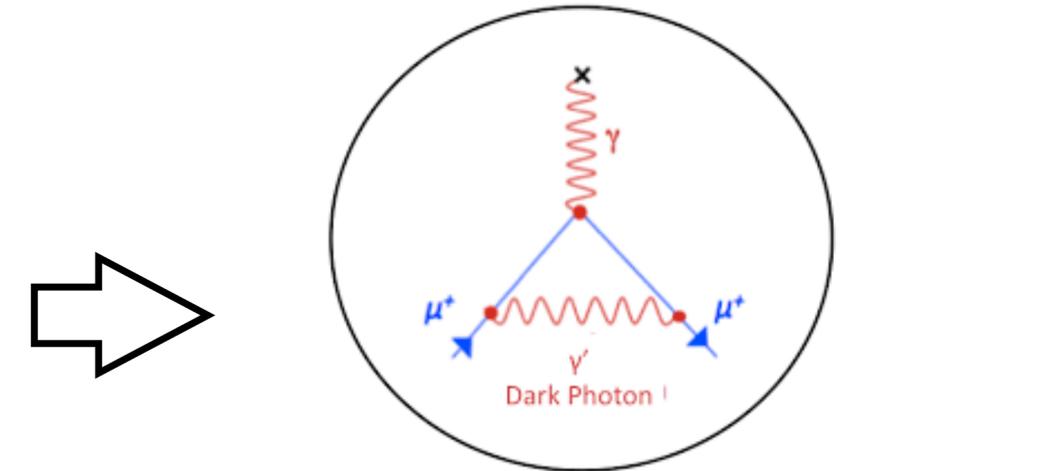
Explanation of the muon (g-2) anomaly
via a dark photon now viable?

Bonus: revisiting the muon (g-2)

and re-interpreting the BaBar monophoton search

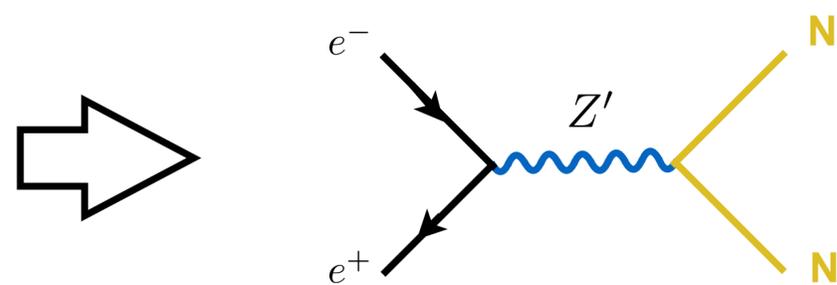


Invisible dark photon bounds relaxed.



$$m_{Z'} = 1.25 \text{ GeV and } \epsilon^2 = 4.6 \times 10^{-4}$$

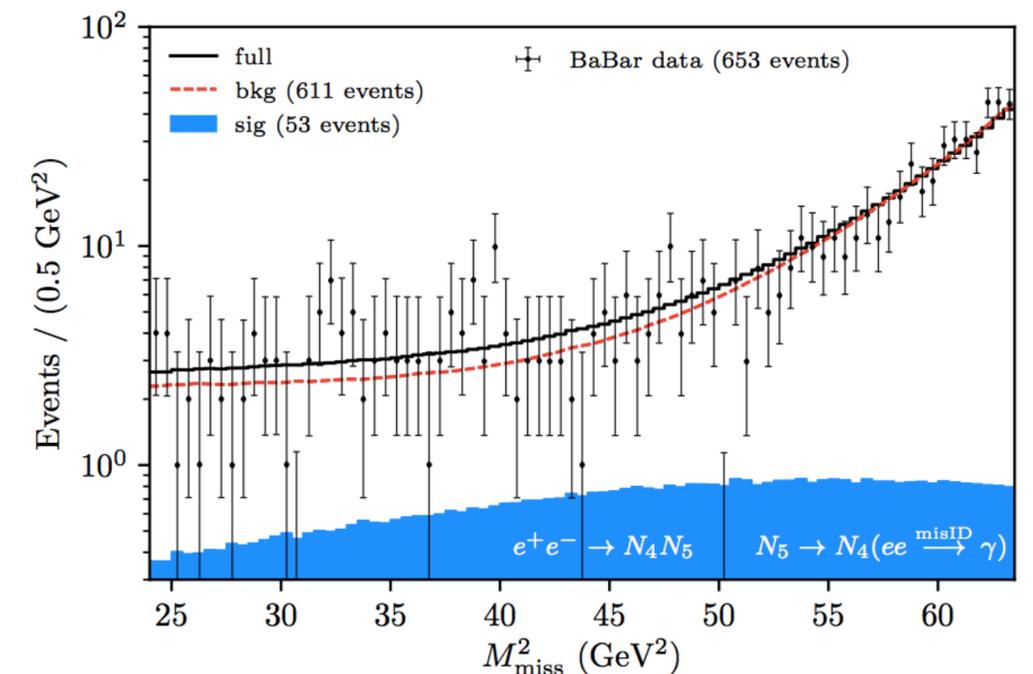
Explanation of the muon (g-2) anomaly via a dark photon now viable?



Can lead to “fake” monophoton events if N decays inside the ECAL

$\gtrsim 2\sigma$ preference for ~50 signal events

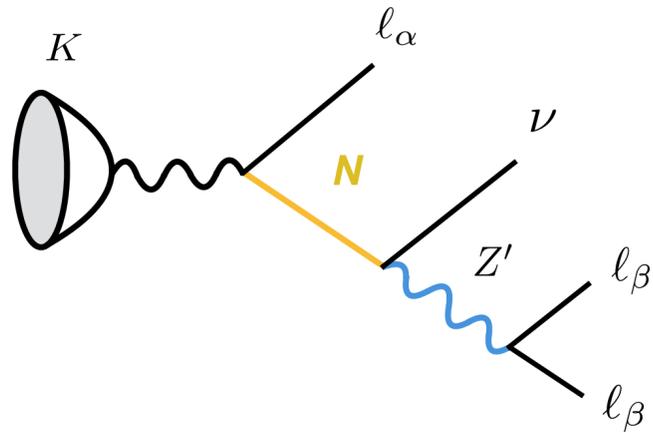
Predicts a huge rate of s-channel $e^+e^- \rightarrow NN$ production @ **BaBar** and **Belle-II** ($O(10^4)$ events).



Looking for the dark HNLs elsewhere

Smoking gun signature at kaon experiments

Rare leptonic kaon decays



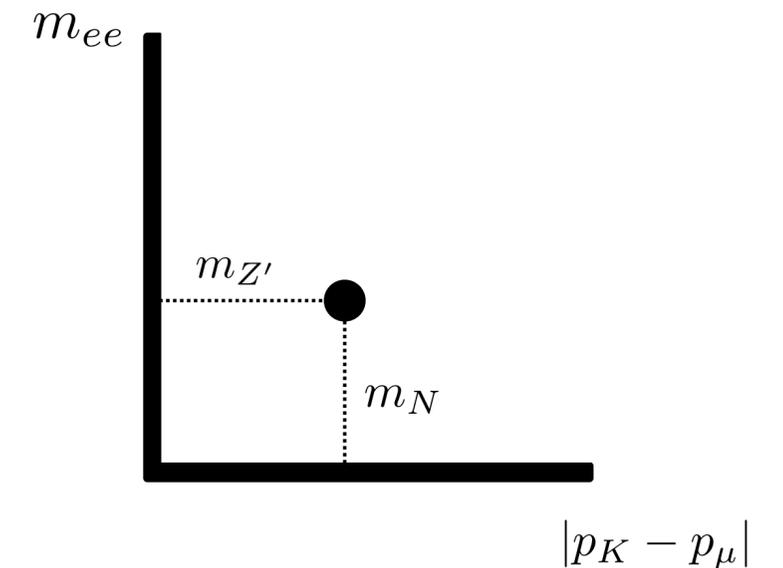
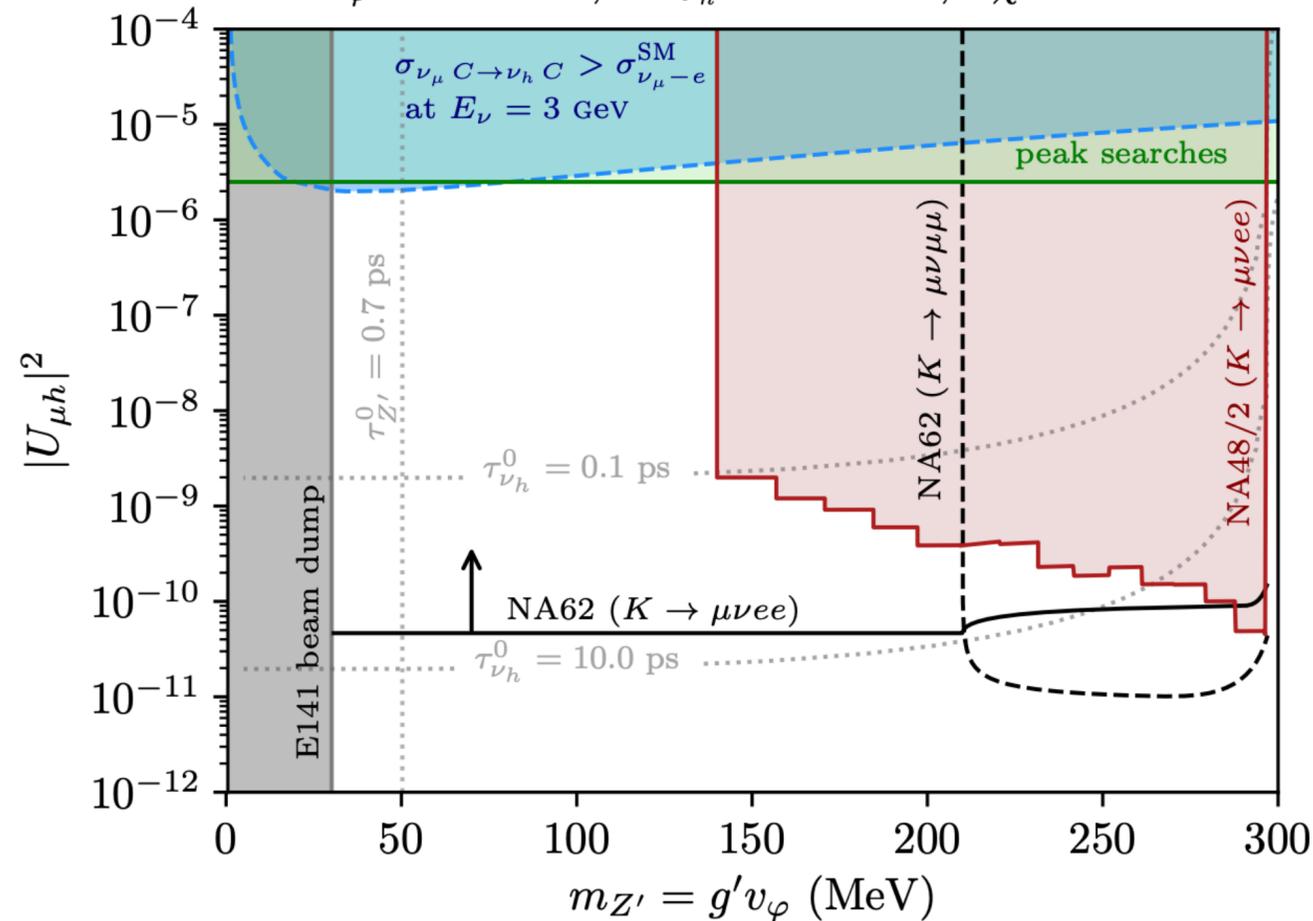
At **NA62**, would expect ~ 3000 events in existing data.

Peak search + (displaced) $e+e^-$ vertex

$$|U_{\mu 4}|^2 \gtrsim \mathcal{O}(10^{-10})$$

Light dark photon case

$$v_\varphi = 400 \text{ MeV}, \quad m_{\nu_h} = 300 \text{ MeV}, \quad \chi^2 = 10^{-8}$$



$K^+ \rightarrow \mu^+ \nu e^+ e^-$
Smoking gun peak at light dark photon and HNL mass

For heavy dark photons ($m_{Z'} > m_N$), only HNL mass is visible, and displaced vertices will typically appear.

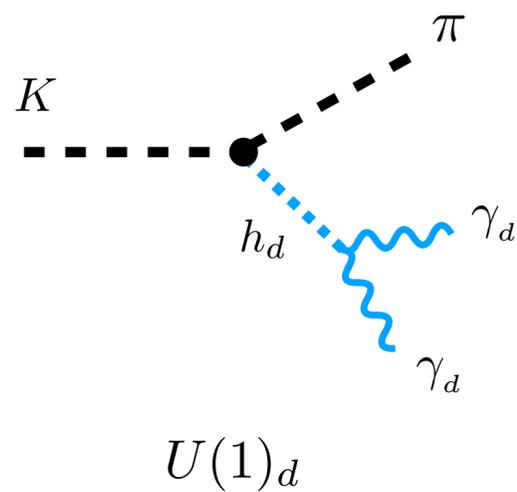
Digging deeper in rare kaon decays

Dark higgs decays to dark photon

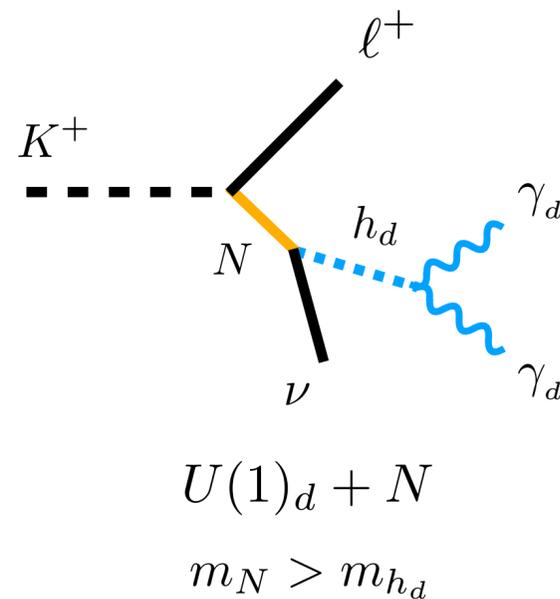
If the dark higgs is light but heavier than 2 dark photons, we also expect kaon decays with 4-leptons via a cascade in the dark sector. **Dark decays are for “free”.**

These channels have never been searched for or even calculated in the SM.
Would provide model discrimination if a signal is found in the simpler di-lepton searches.

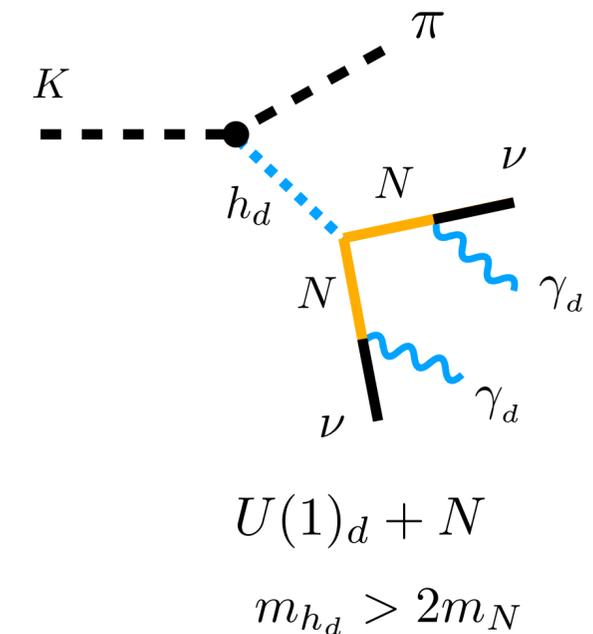
$$K \rightarrow \pi 2(e^+ e^-)$$



$$K^+ \rightarrow \ell_\alpha^+ \nu 2(e^+ e^-)$$



$$K \rightarrow \pi 2(\nu e^+ e^-)$$



Conclusions

- **Interesting to considering HNLs as part of a rich dark sector**
 - Novel interplay between portal couplings (+ pheno)
 - Neutrino masses from dark gauge symmetries.
 - Motivate unexplored experimental searches
 - New signatures ==> more potential for surprises at low energies.
- **New ideas to explain existing discrepancies in the data**
 - MiniBooNE
 - Muon (g-2)
 - Double NC vertices at CCFR
- **Interplay of several intensity frontier experiments**
 - Neutrino detectors — di-leptons and double vertices
 - Kaon factories $K^+ \rightarrow \ell^+ \nu e^+ e^-$
 - e+e- colliders $e^+ e^- \rightarrow NN$

from G. Raffelt, 9712538

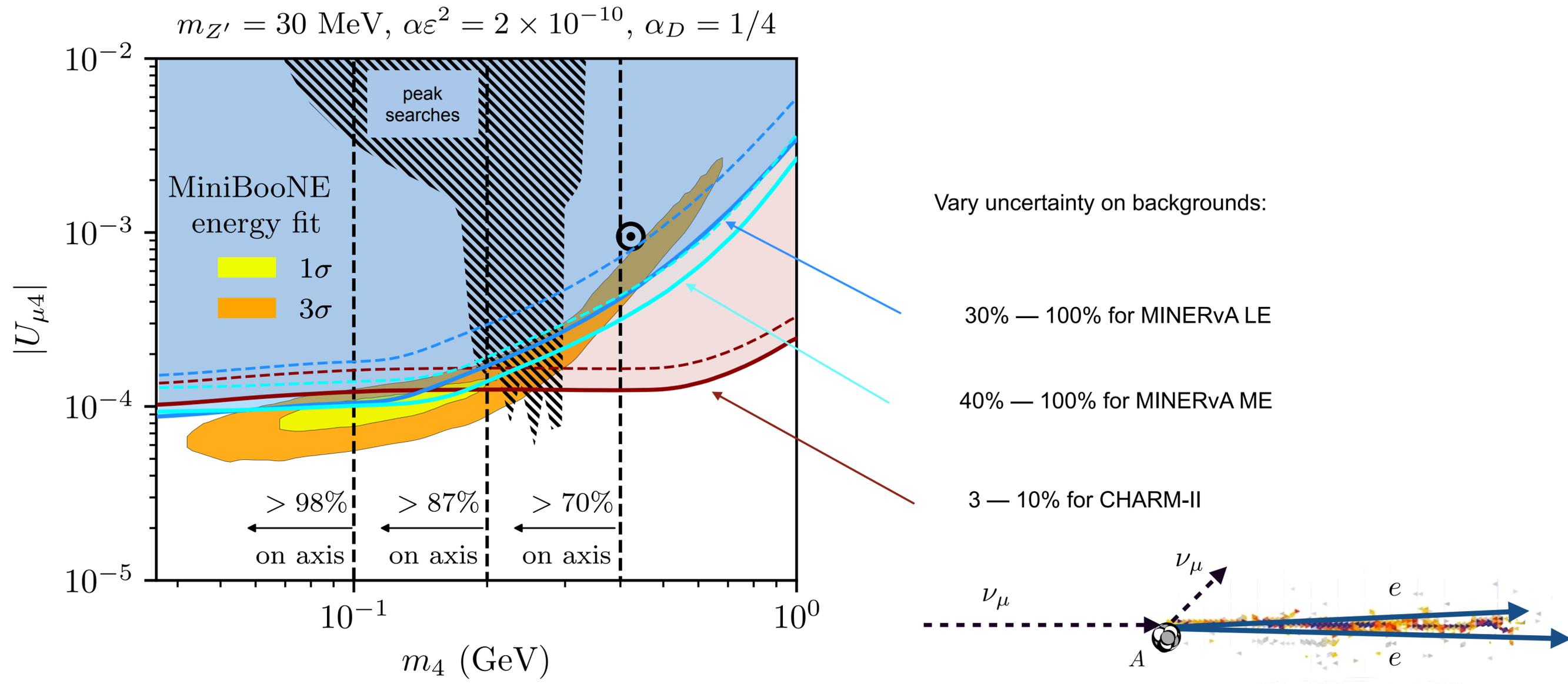


"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T SEE THEM."

THANKS!

Back-up slides

Neutrino-electron scattering constraints



C. Argüelles, MH, Y. Tsai, PRL123, 261801 (2019)

on axis = events in forward bin at MiniBooNE

Analysis can be improved with future data:

- MINERvA ME_nubar-e data
- NOvA nu-e data

THE NEUTRINO PORTAL

Motivations

Neutrino masses

Type-I seesaw, low-scale variants, and more exotic.

Baryon asymmetry of the Universe

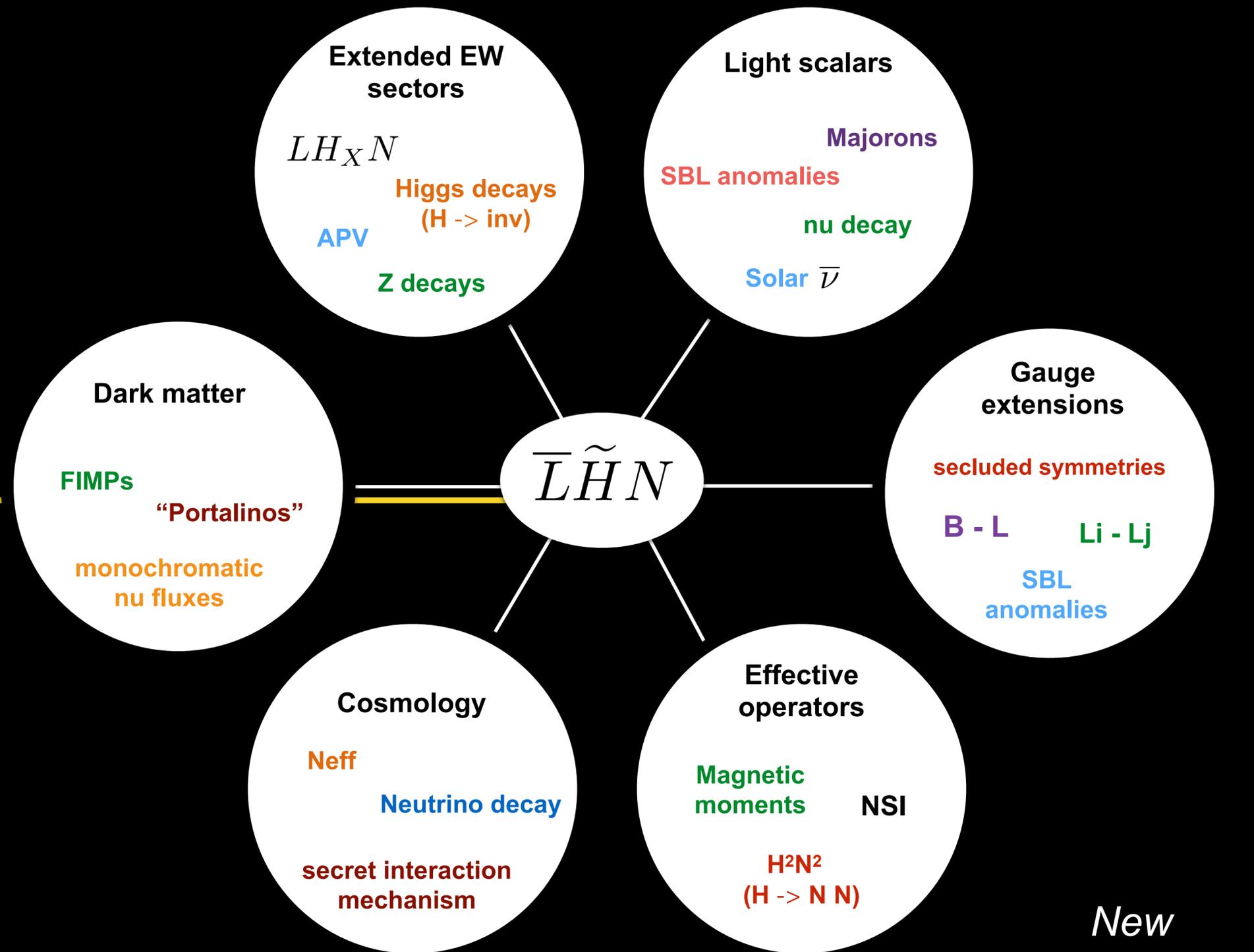
Leptogenesis, nu-assisted EW baryogenesis.

Dark matter

Warm DM or DM annihilation partner.

Experimental anomalies

Short-baselines, Hubble, XENON1T, + others.



New possibilities

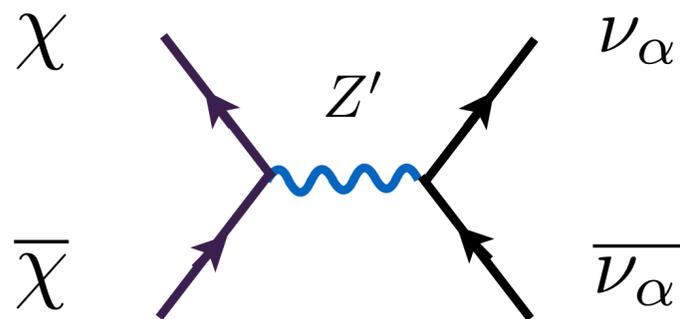
One of the most well-motivated portals also admits a variety of non-minimal realizations.

Dark Matter

Neutrino portal DM — growing literature, see, e.g.,

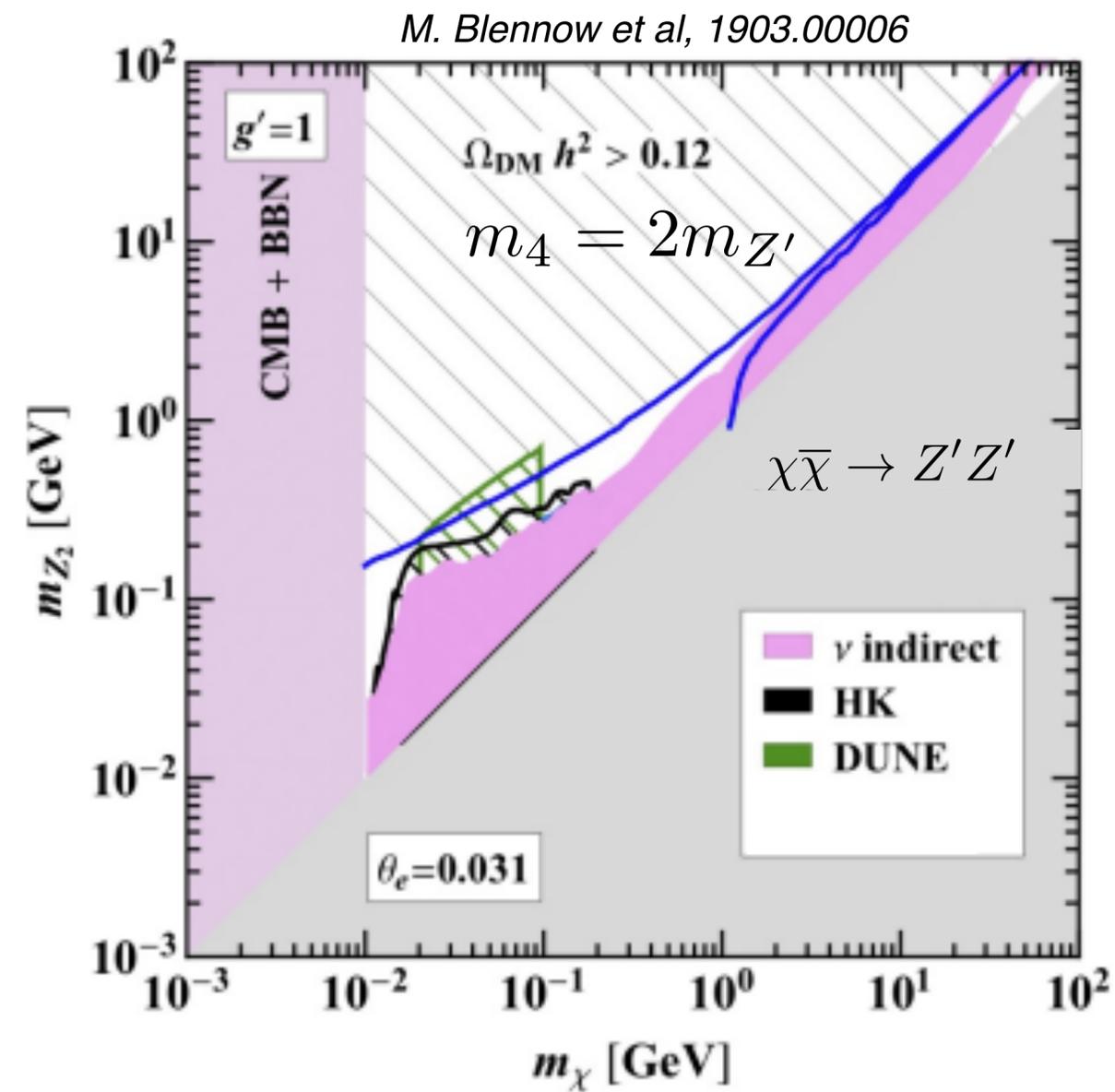
B. Bertoni et al, 1412.3113
 B. Batell et al, 1709.07001
 M. Blennow et al, 1903.00006

$$\langle \sigma v_r \rangle \approx \frac{g'}{8\pi} |U_{\alpha 4}|^4 \frac{m_\chi^2}{(4m_\chi^2 - m_{Z'}^2)^2}$$



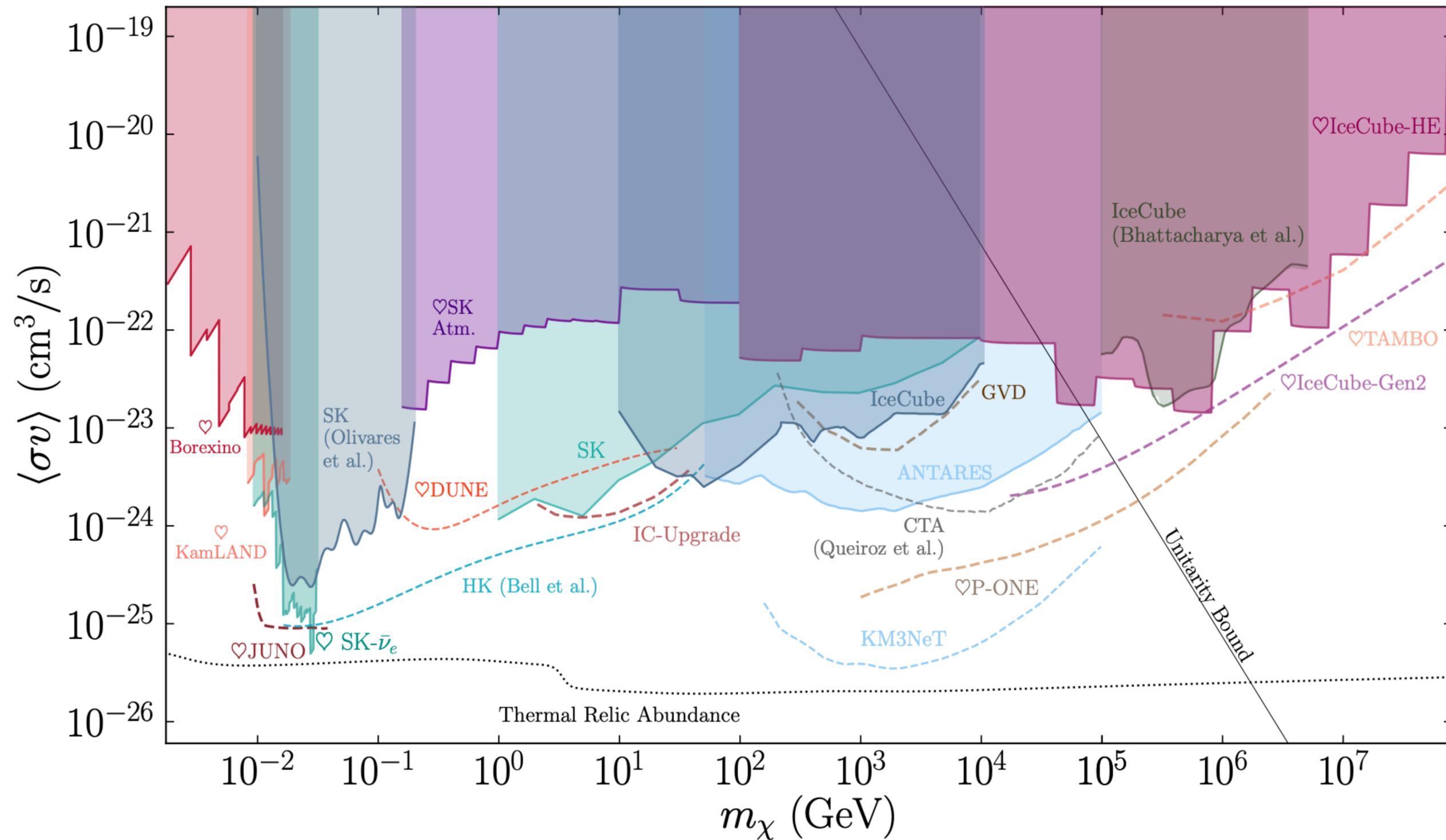
Monochromatic neutrinos from the Galaxy!

Can be searched for in large volume detectors.



Dark Matter

Arguelles et al, 1912.09486



Dark matter across scales

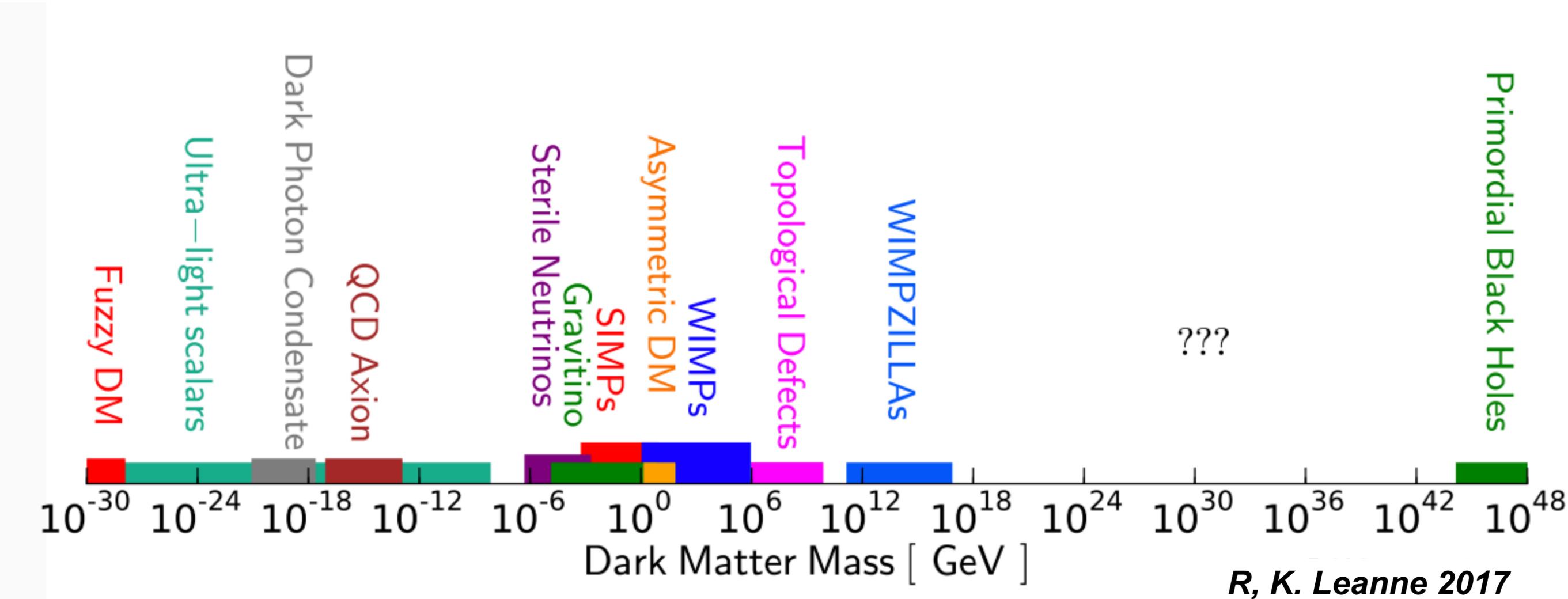
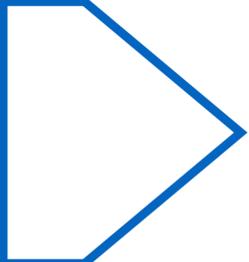
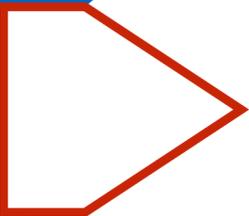
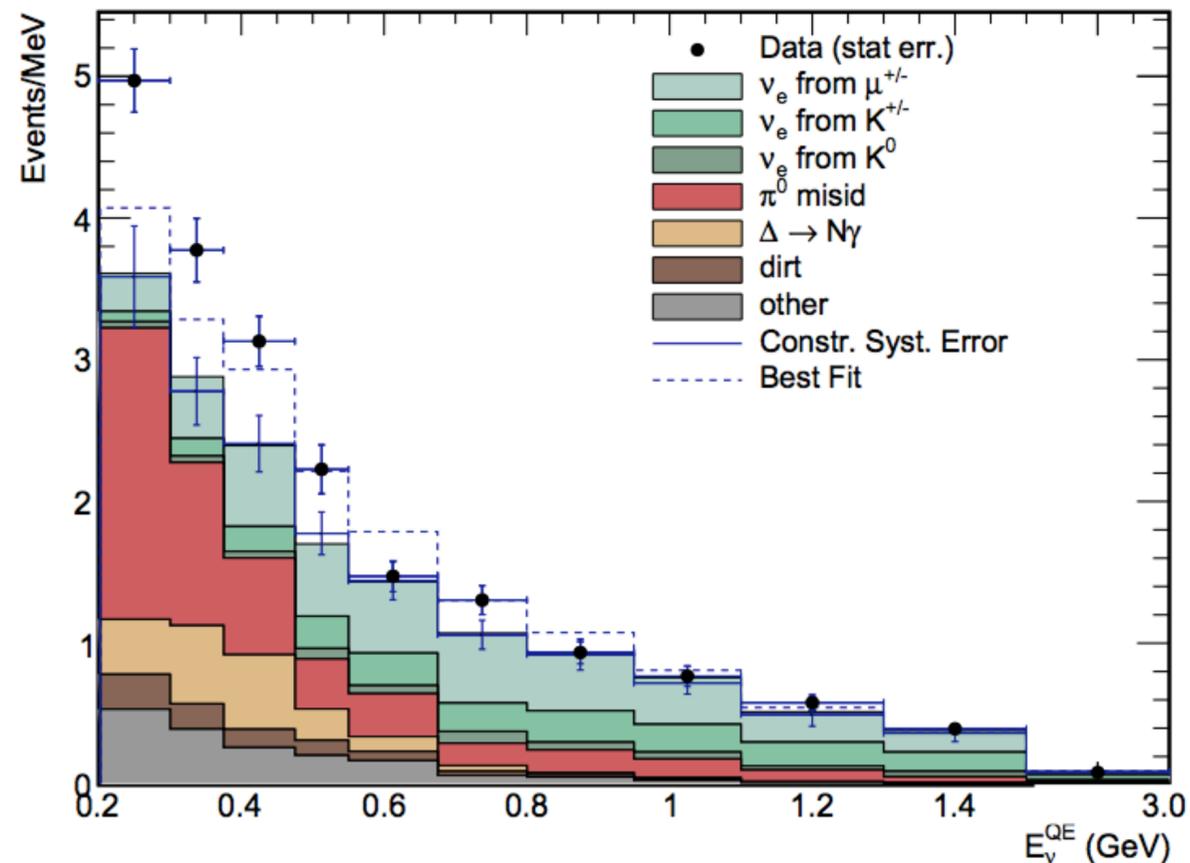


FIGURE 1.8: Dark matter candidates as a function of their mass scale.

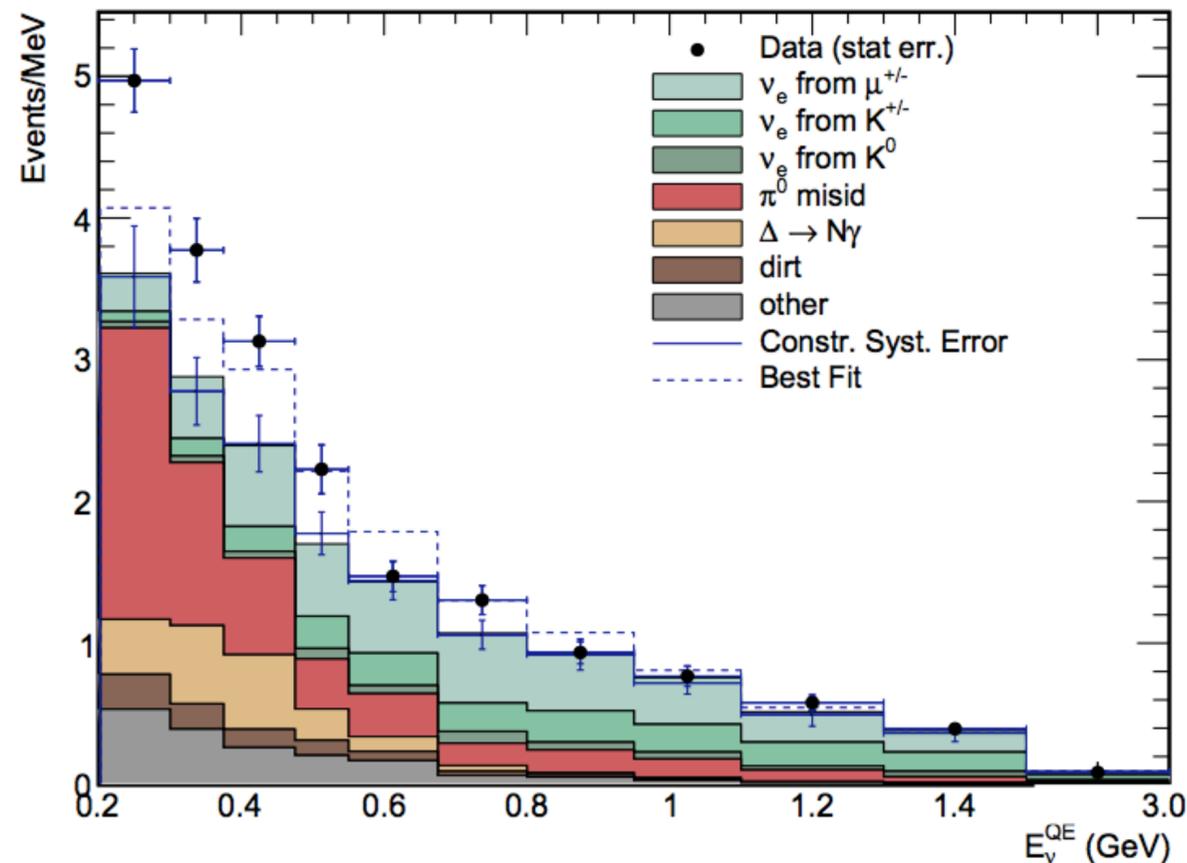
SM Backgrounds at MiniBooNE

Process	Neutrino Mode	Antineutrino Mode	
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3	 misID backgrounds
NC π^0	501.5 ± 65.4	112.3 ± 11.5	
NC $\Delta \rightarrow N\gamma$	172.5 ± 24.1	34.7 ± 5.4	
External Events	75.2 ± 10.9	15.3 ± 2.8	
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5	
ν_e & $\bar{\nu}_e$ from μ^\pm Decay	425.3 ± 100.2	91.4 ± 27.6	 intrinsic background
ν_e & $\bar{\nu}_e$ from K^\pm Decay	192.2 ± 41.9	51.2 ± 11.0	
ν_e & $\bar{\nu}_e$ from K_L^0 Decay	54.5 ± 20.5	51.4 ± 18.0	
Other ν_e & $\bar{\nu}_e$	6.0 ± 3.2	6.7 ± 6.0	
Unconstrained Bkgd.	1590.6 ± 176.9	398.2 ± 49.7	
Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6	
Total Data	1959	478	
Excess	381.2 ± 85.2	79.3 ± 28.6	



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Can populate lower energies, but always get



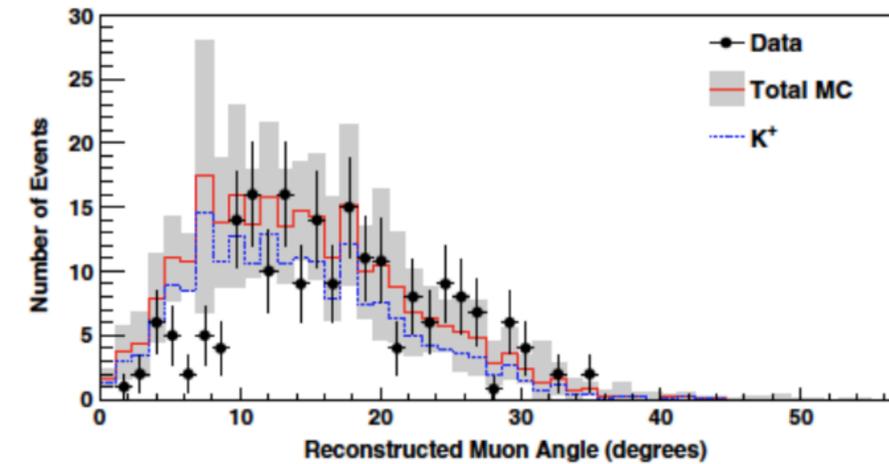
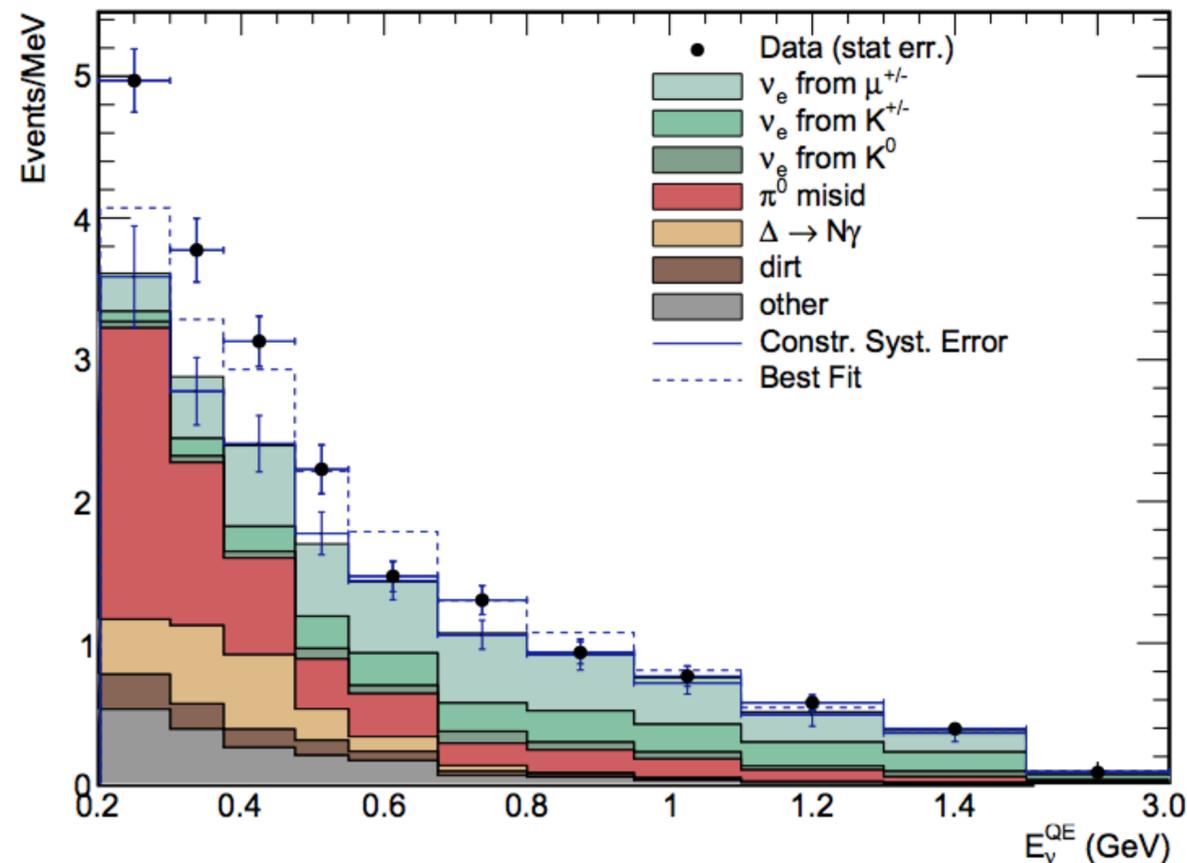
So can constrain by measuring ν_μ

Very large statistics!
Can effectively constrain parent particle spectrum
(essentially a neutrino flux measurement)

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Dominant flux component above 2 GeV
&
constrained by a *SciBooNE*
("near detector" of MiniBooNE @ 100 m)



(c) 3-Track Sample

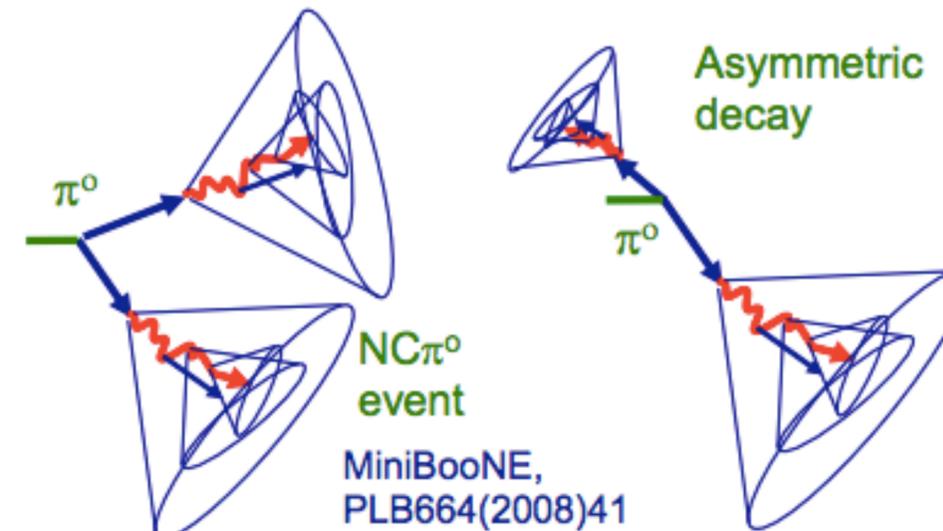
Analysis benefits from 3 track events (~CC1pi)
that are more common at higher E.

SciBooNE collaboration, 1105.2871

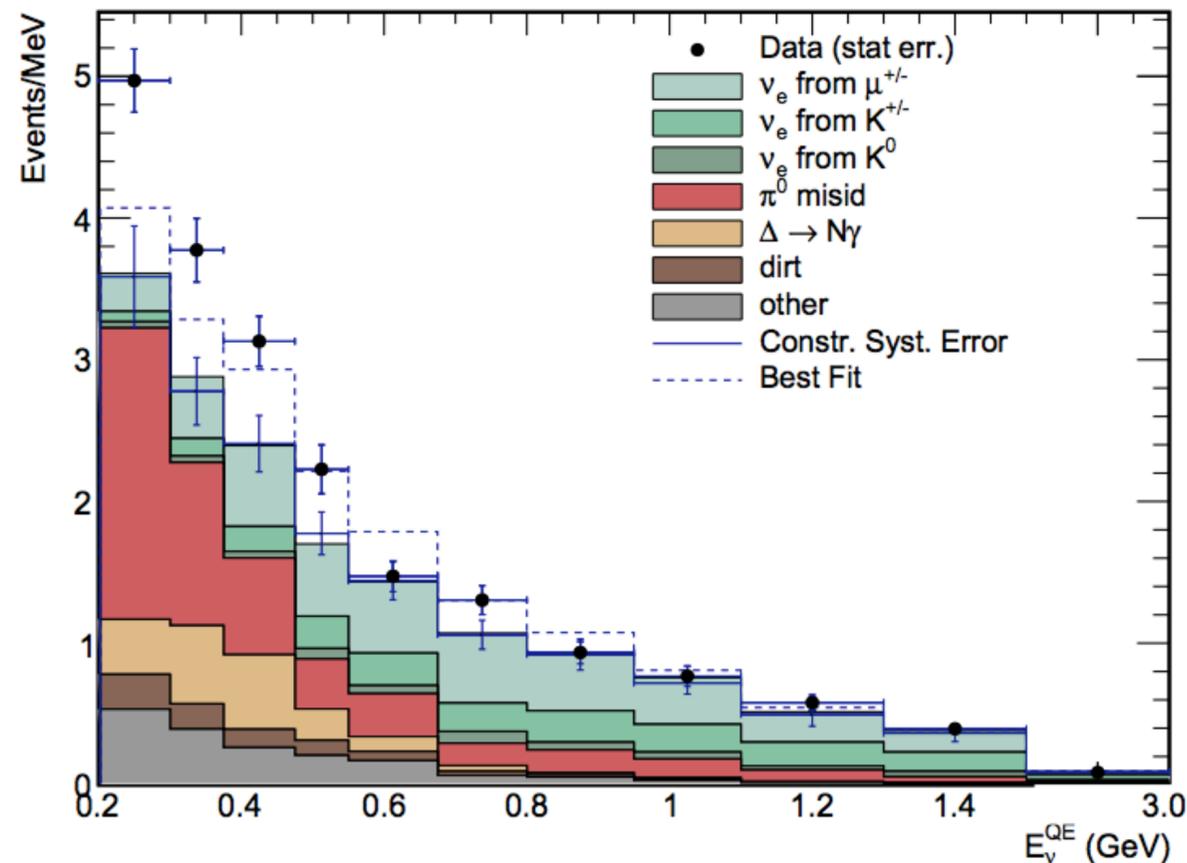
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This channel relies on pion decay being highly asymmetric

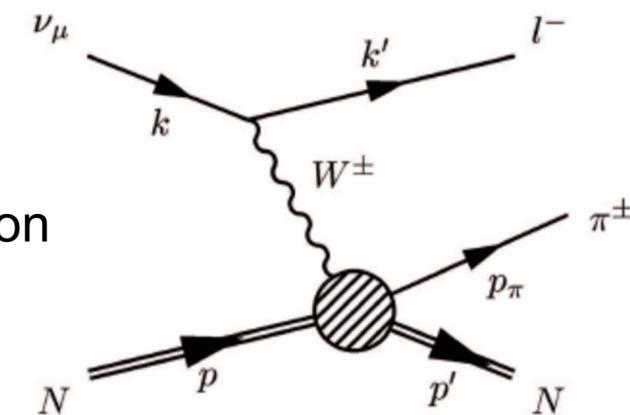


T. Katori



Effectively constrained by measuring other channels and extrapolating (somewhat model dependent):

CC/NC pion production

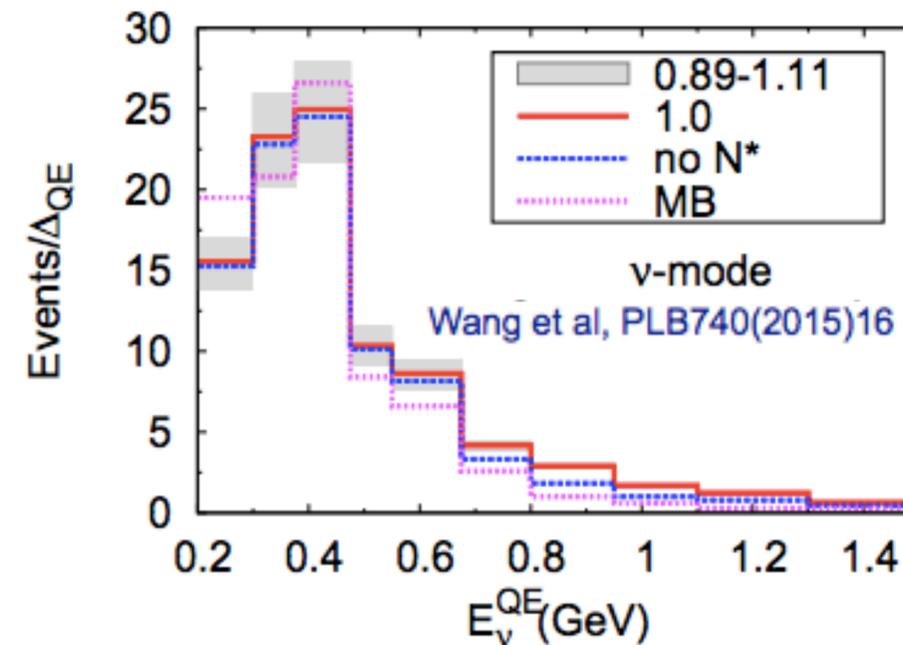
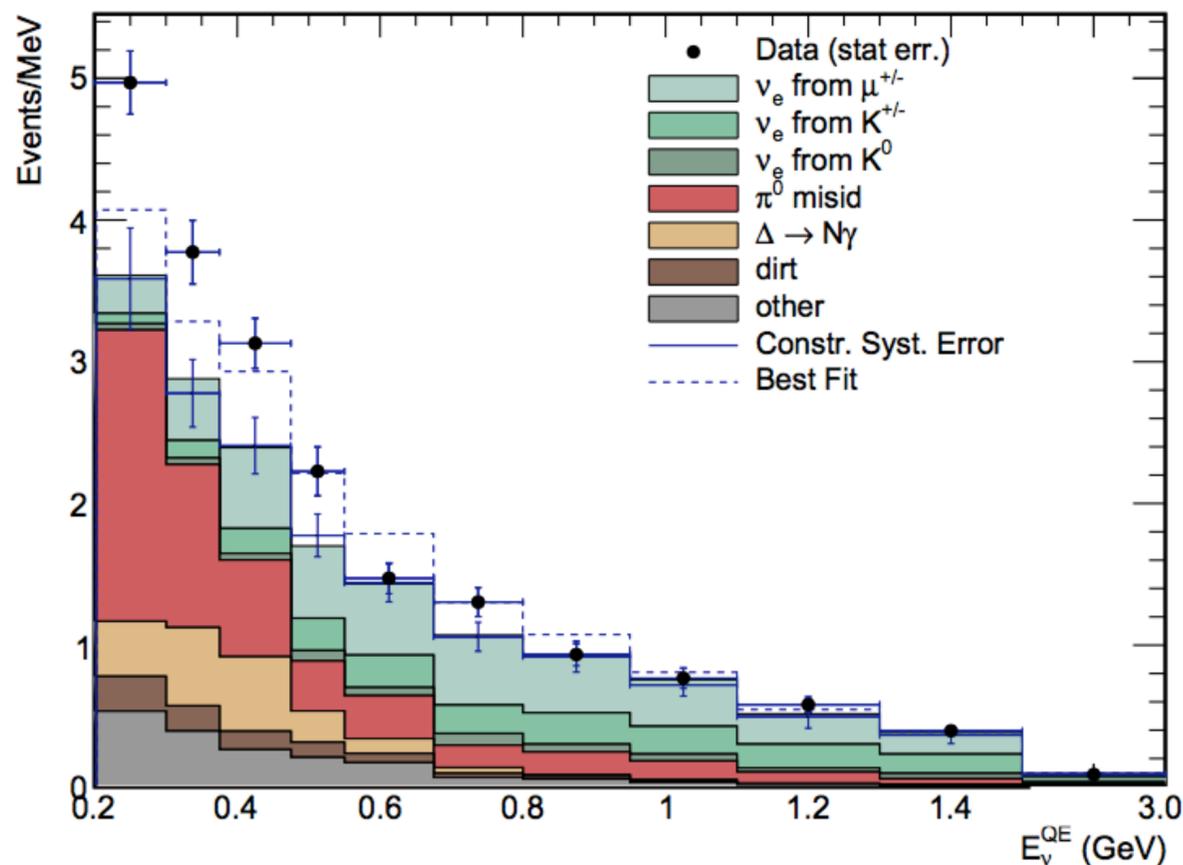
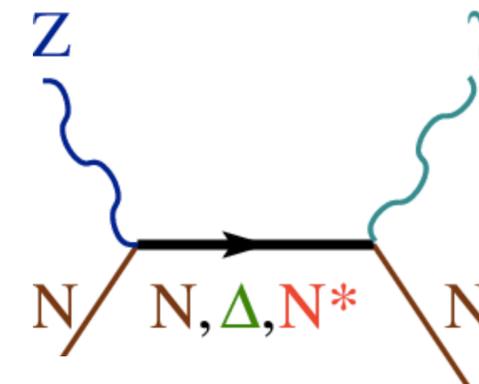


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Mostly NC resonant through Delta(1232)

Constrained by pi events



Coherent contribution shown to be small

Hill, PRD84(2011)017501
 Zhang and Serot, PLB719(2013)409
 Wang et al, PLB740(2015)16

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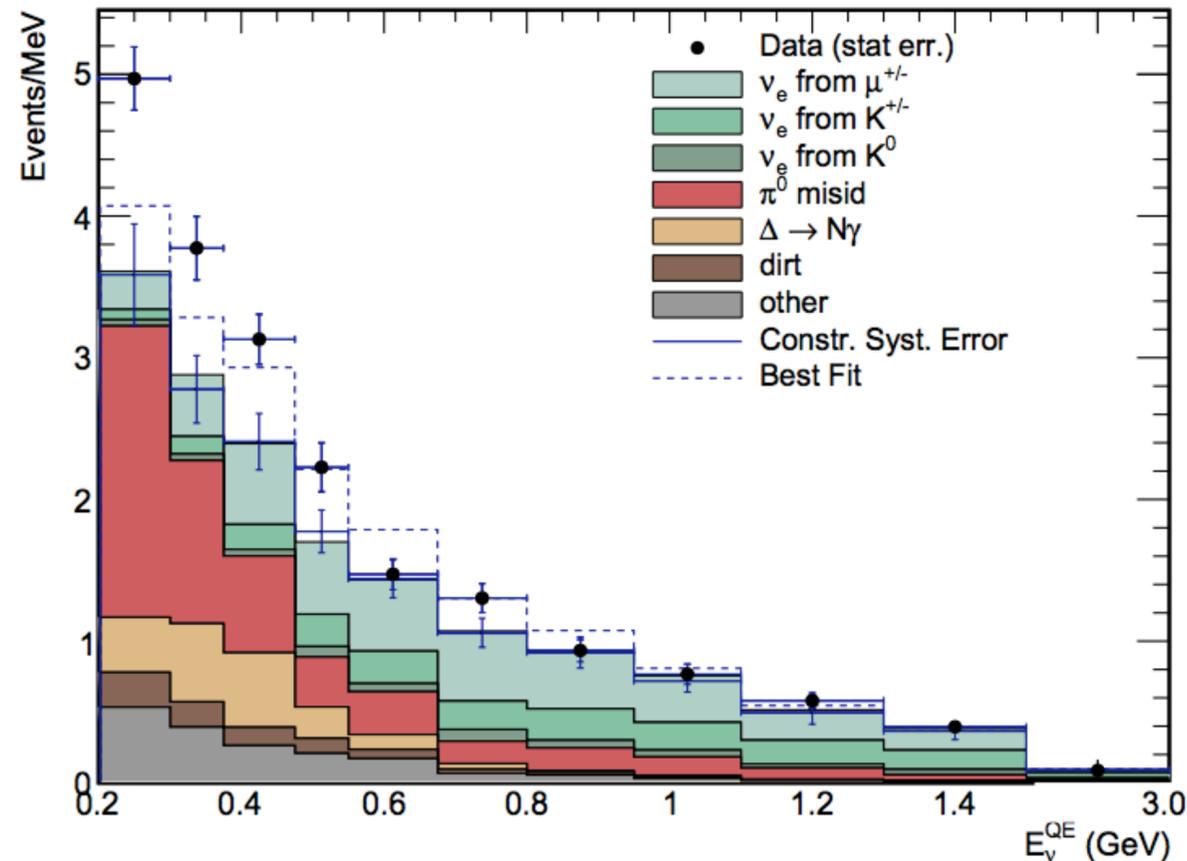


If this channel is off by a factor of

2.7

the LEE goes away.

This is 5sigma away from the MiniBooNE indirect "measurement".



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