Recent highlights from neutrino theory

Pedro A. N. Machado

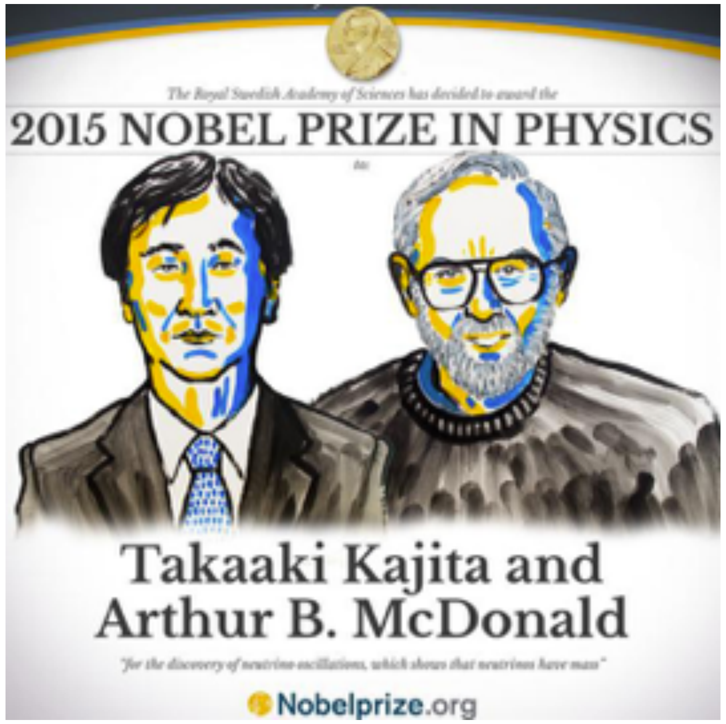
Fermilab *soon to be at LANL as junior staff member*

APS | DIVISION OF PARTICLES & FIELDS

DPF 2017

Neutrinos as a portal to new Physics

The existence of non-zero neutrino masses, inferred from neutrino oscillation measurements, is the only laboratory-based evidence of physics beyond the standard model

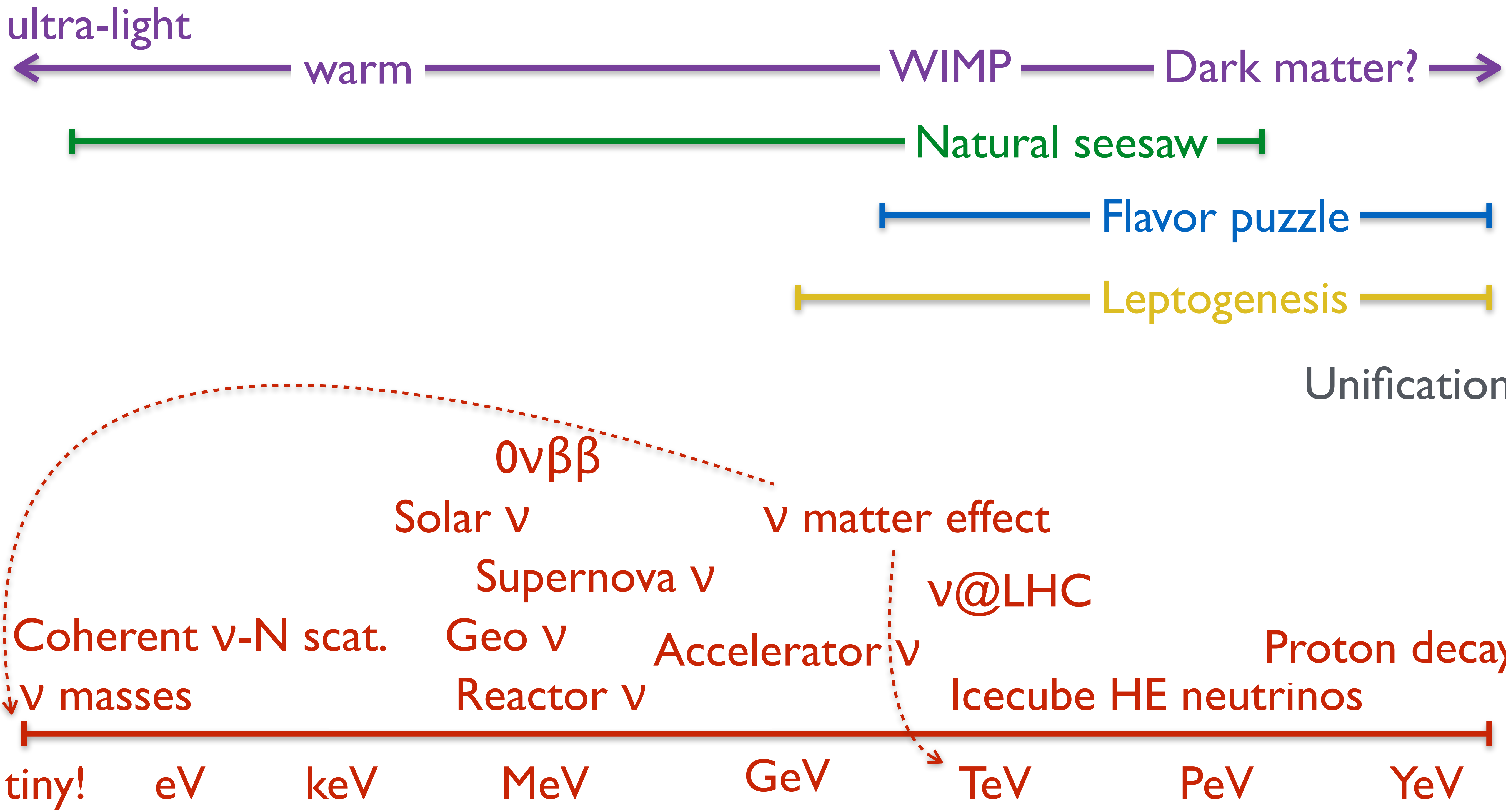


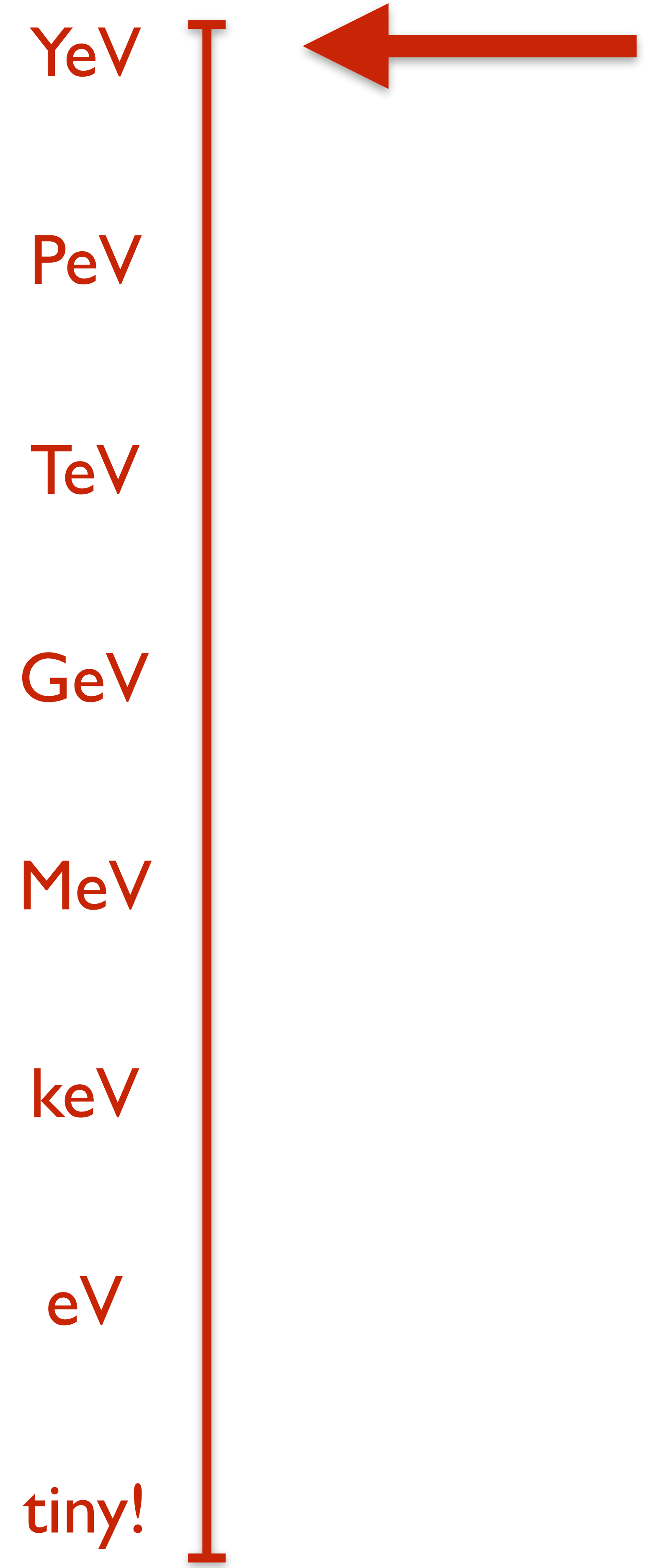
Relatively poorly known sector of the standard model

Neutrino mass mechanism is unknown

Neutrino physics relates to many energy scales

Neutrinos as a portal to new Physics

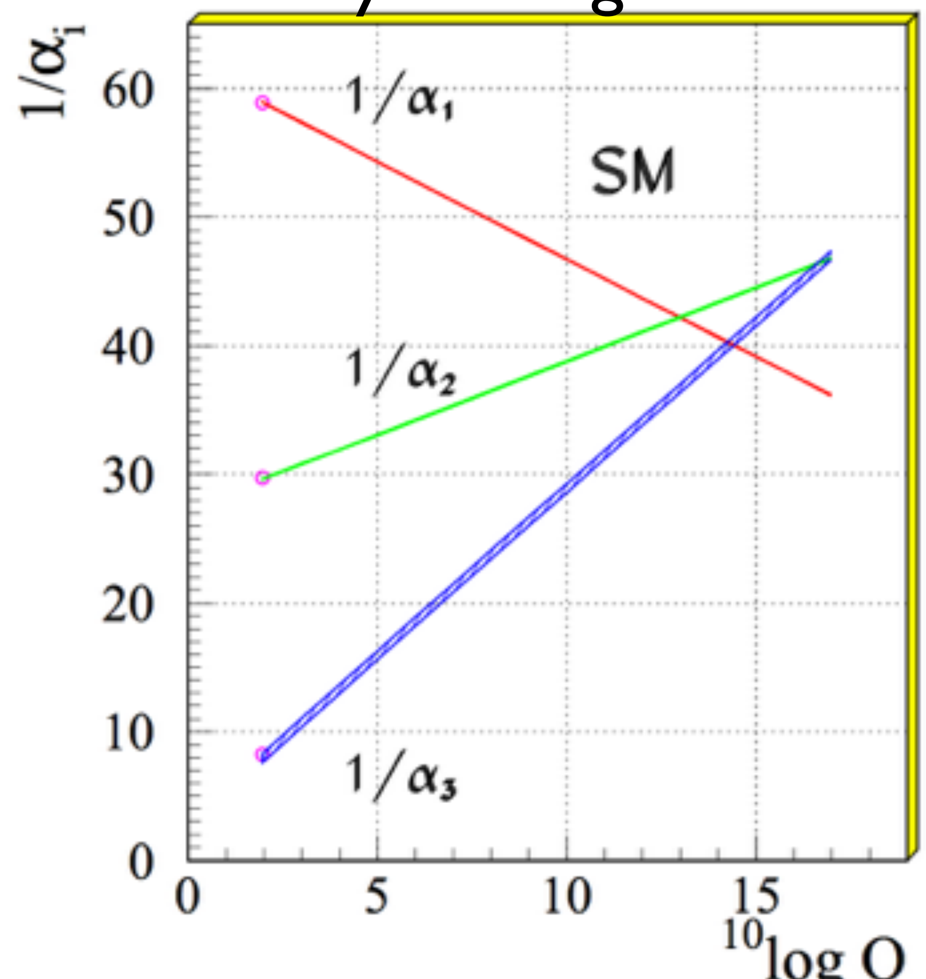



YeV
PeV
TeV
GeV
MeV
keV
eV
tiny!

Grand Unified Theories

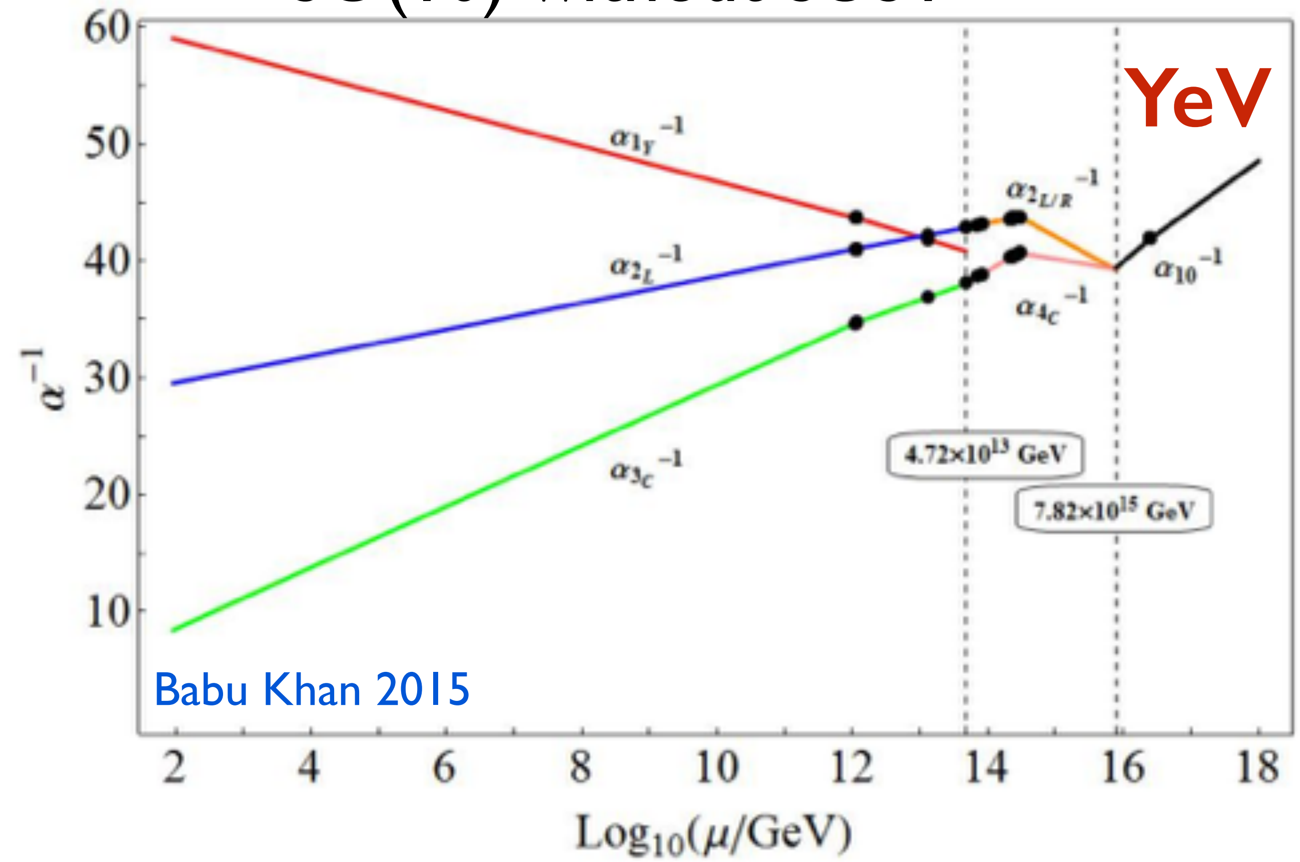
Georgi Quinn Weinberg 1974

SM gauge couplings *almost* unify at a high scale



GUTs typically predict:
Majorana neutrinos
Normal mass ordering
θ_{23} in first octant
"large" θ_{13} if θ_{12} and θ_{23} are large
No light sterile neutrino

SO(10) without SUSY



see also, e.g., Chu Smirnov 2016, Acharya Bozek Romao King Pongkitivanichkul 2016, Ellis Garcia Nagata Nanopoulos Olive 2016, Bucella Chianese Mangano Miele Morisi Santorelli 2017, Bjorkeroth Anda King Perdomo 2017, …

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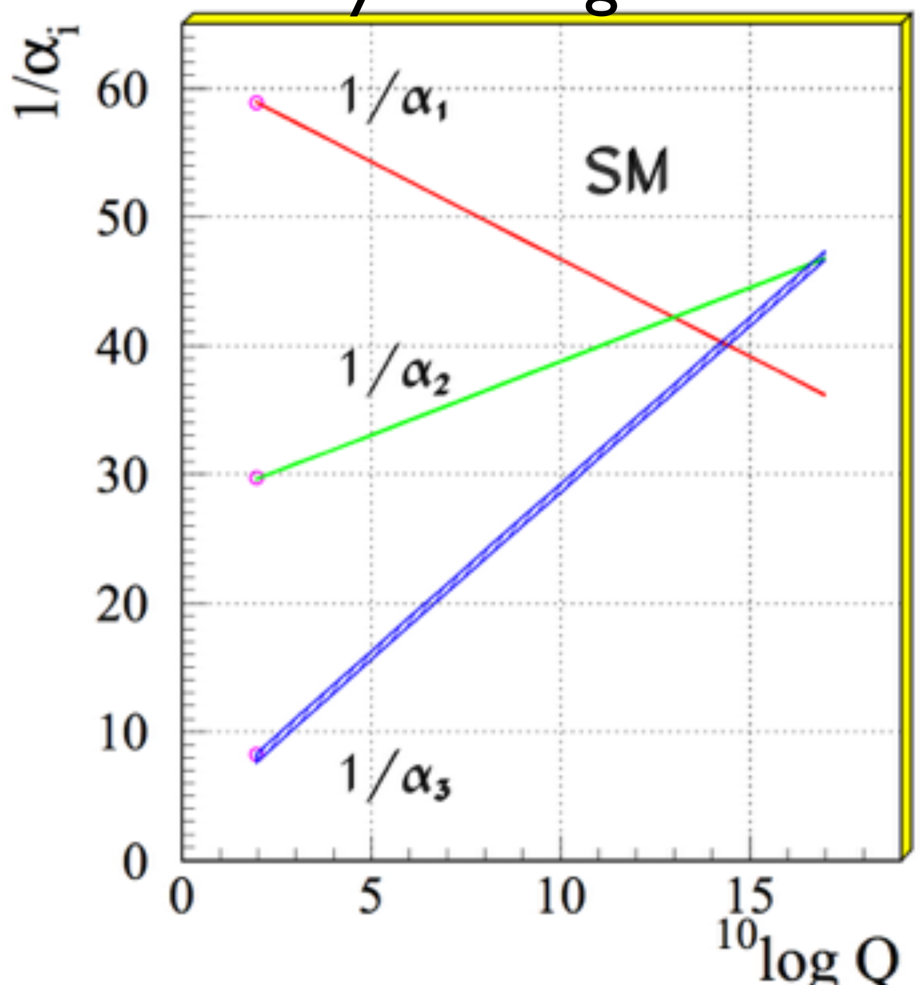

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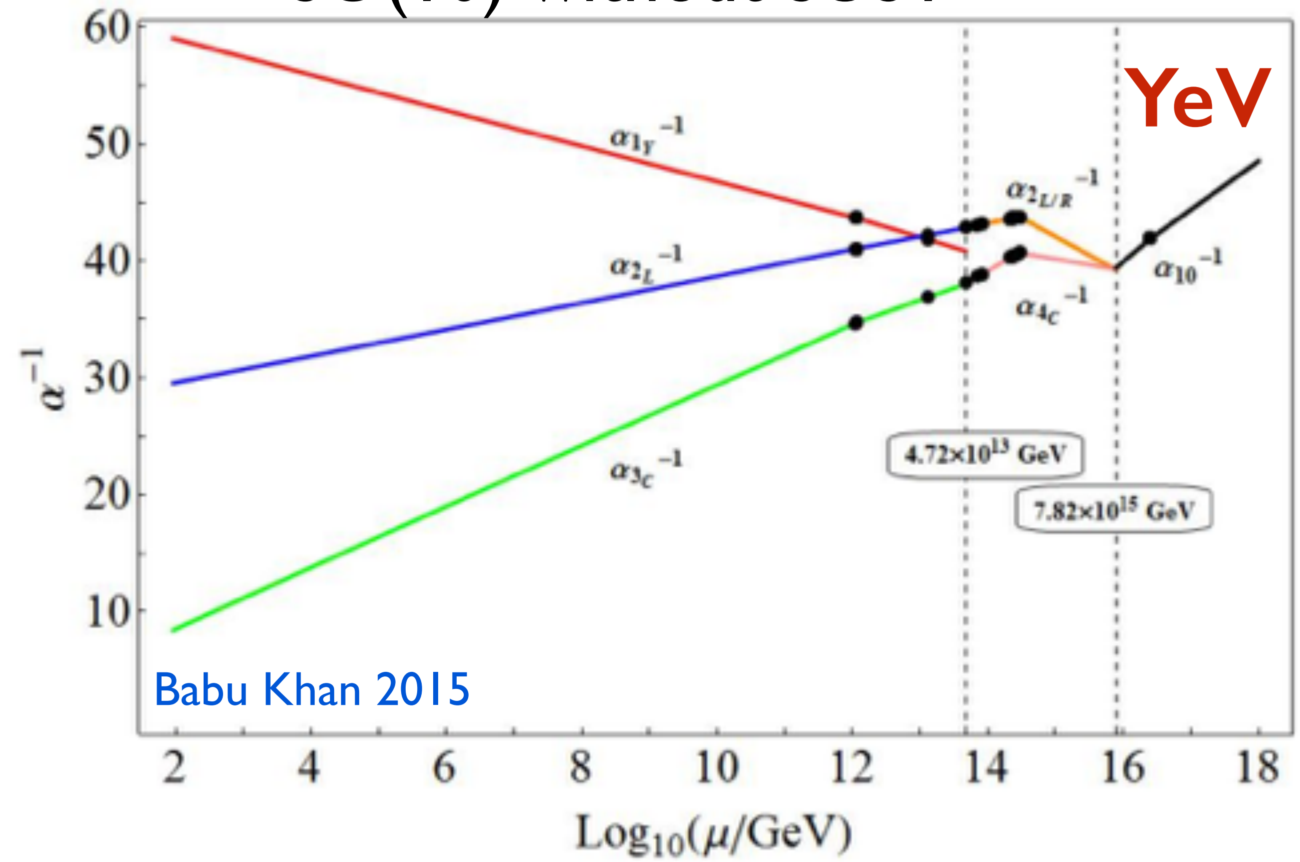

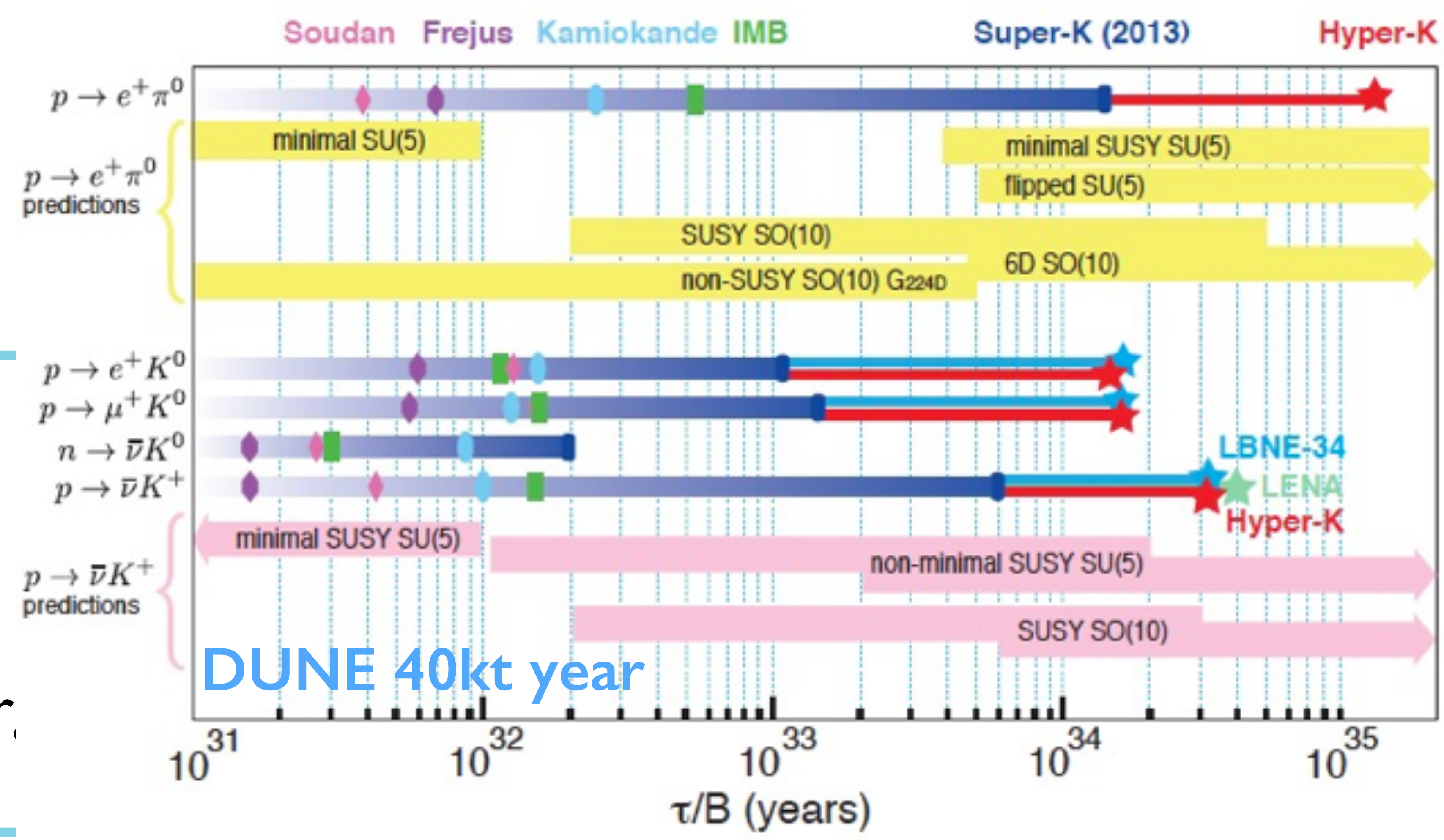

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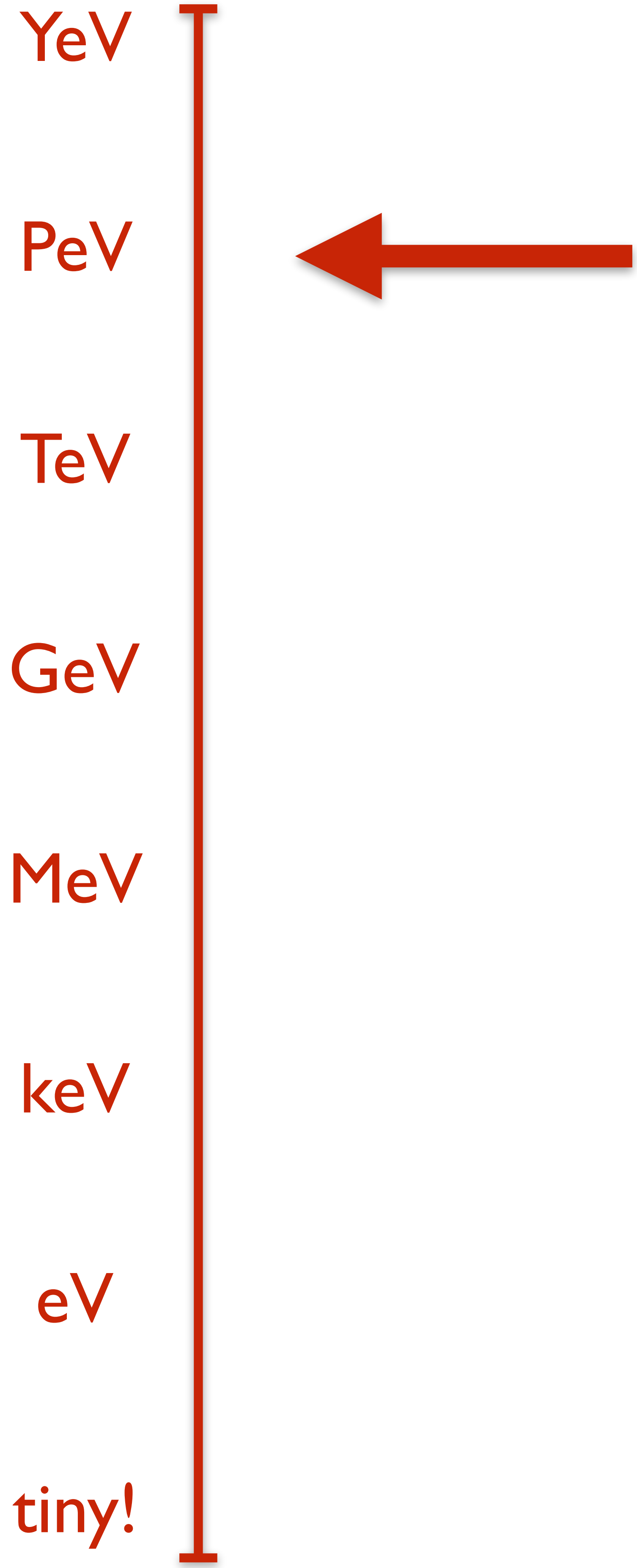
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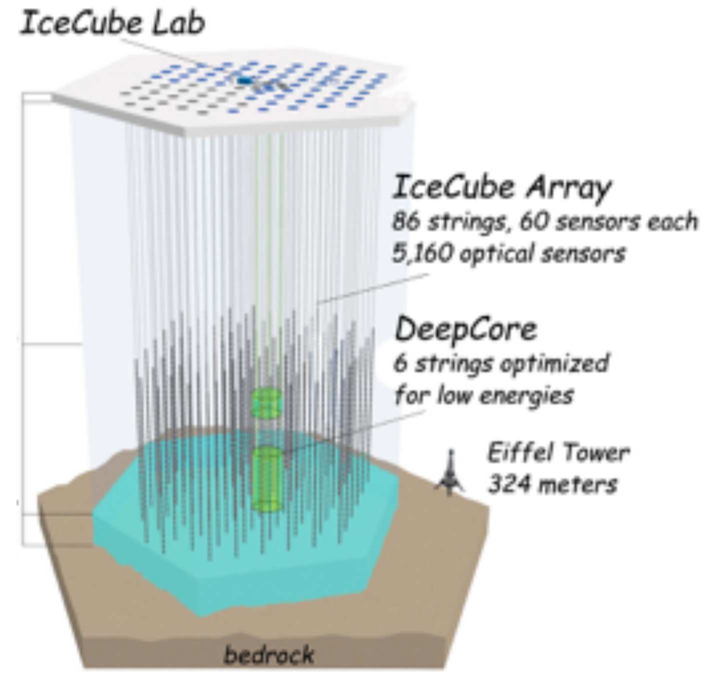
Neutrinos and new Physics

Revolution in Neutrino Astrophysics

Flavor composition of Icecube high energy neutrinos can probe new Physics unambiguously

Palomarez-Ruiz Mena Vincent 2014, Bustamante Beacom Winter 2015, Arguelles Katori Salvado 2015, Nunokawa Panes Zukanovich-Funchal 2016, Bustamante Beacom Murase 2016, Brdar Kopp Wang 2016



Neutrinos and new Physics

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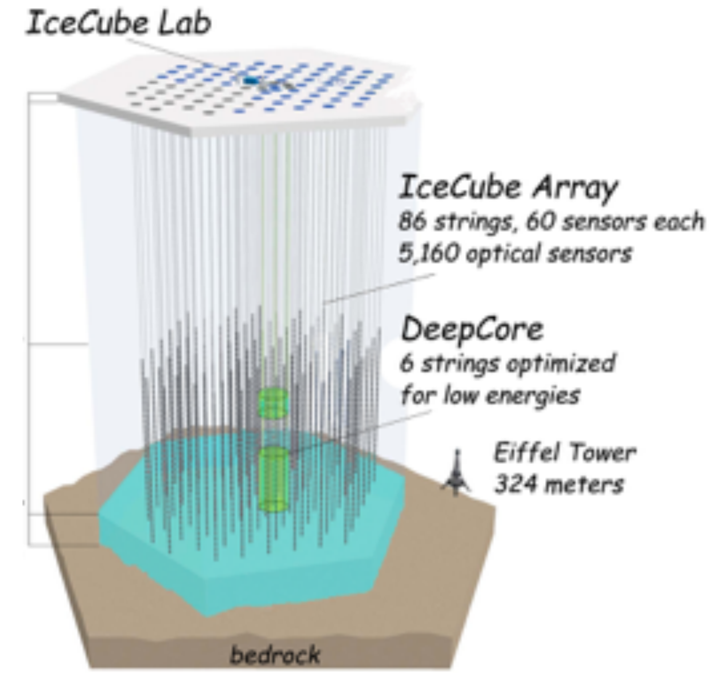

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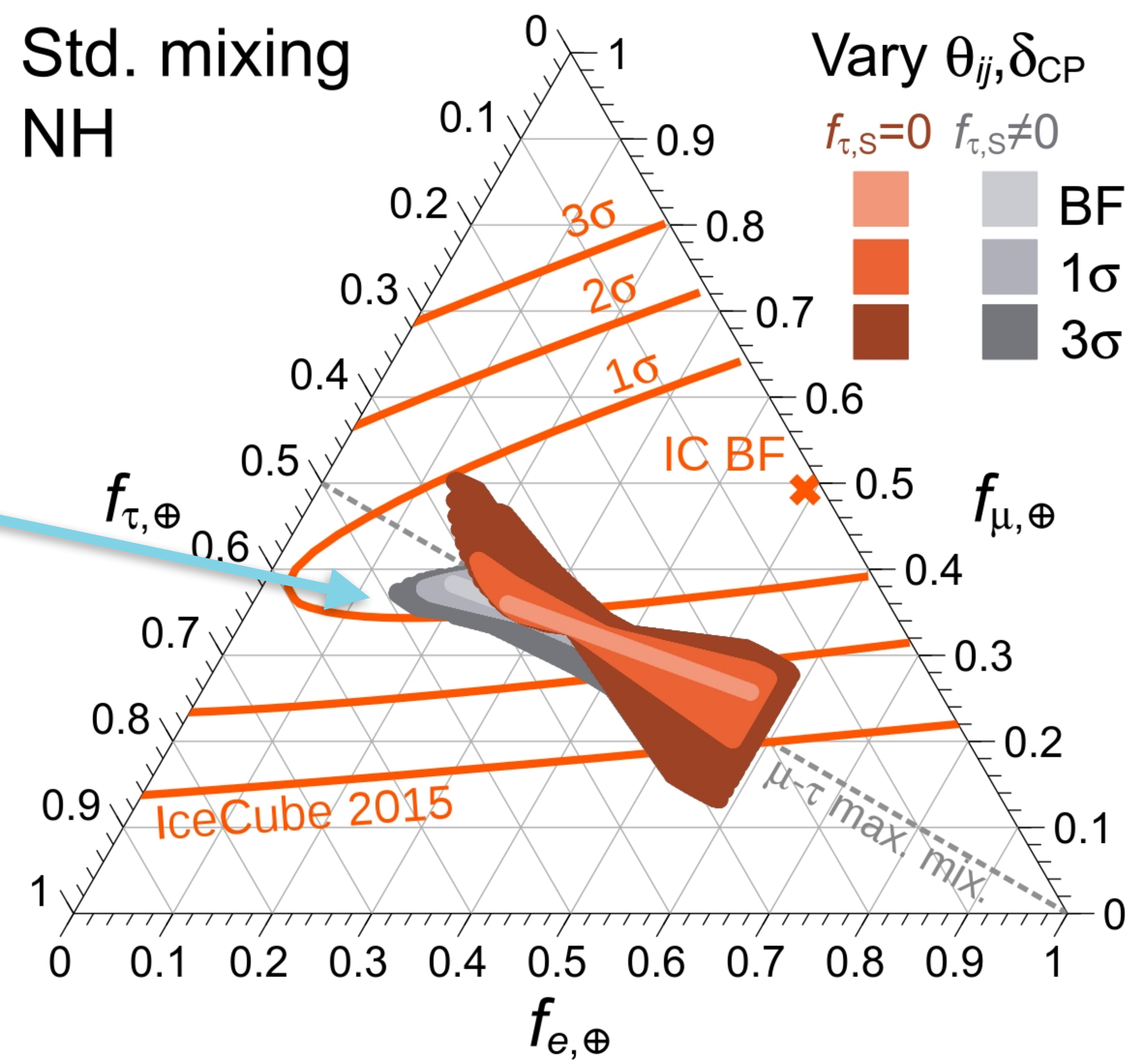
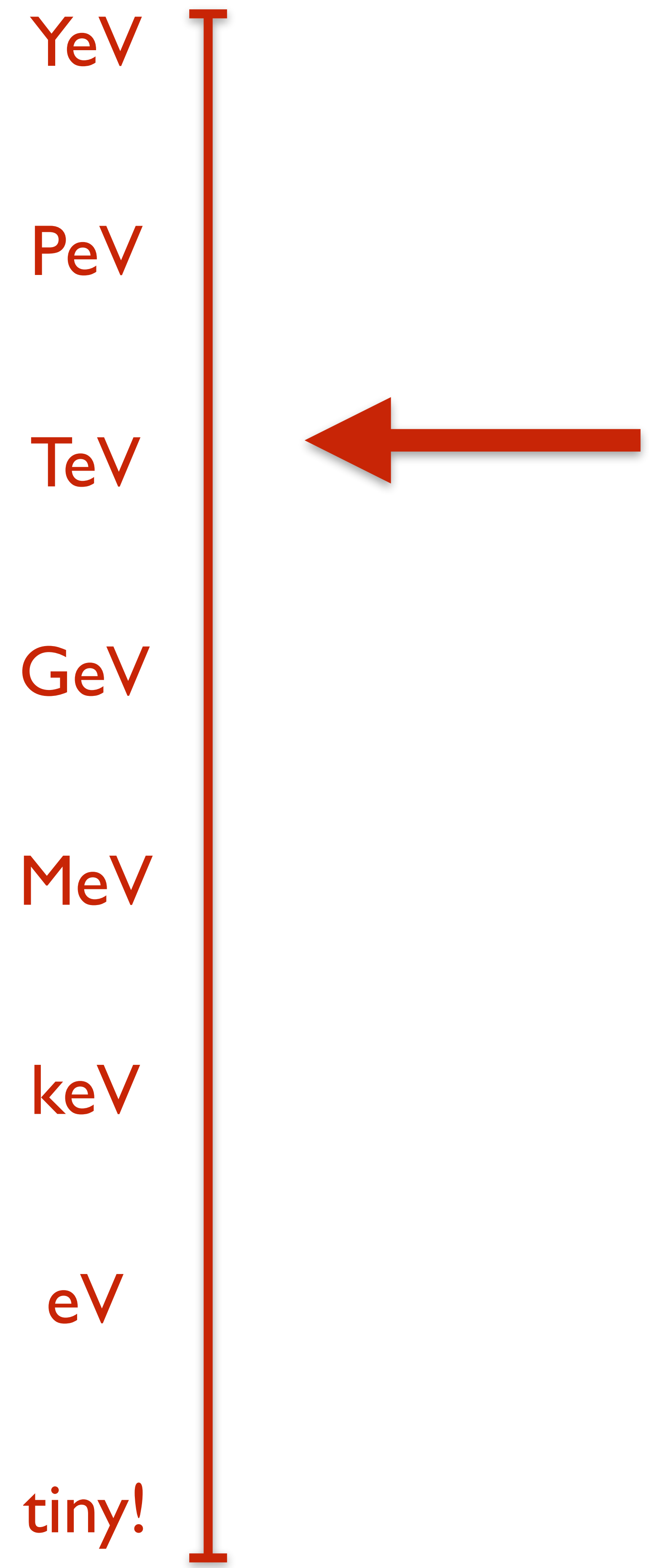
$$\bar{P}_{\nu_\alpha \to \nu_\beta}(E) = \sum_i |V_{\alpha i}(E)|^2 \, |V_{\beta i}(E)|^2$$

For any flavor composition at the source, the flavor ratio at detection is constrained by the PMNS matrix uncertainty

New experimental technique to separate EM from hadronic showers can improve the flavor ratio determination considerably

Li Bustamante Beacom 2016

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Neutrino masses could come from, e.g., type I seesaw
What is the scale of right-handed neutrinos?

Minkowski 1977, Ramond 1979, Gell-Mann Ramond Slansky 1979, Yanagida 1979, Mohapatra Senjanovic 1980, Schechter Valle 1980

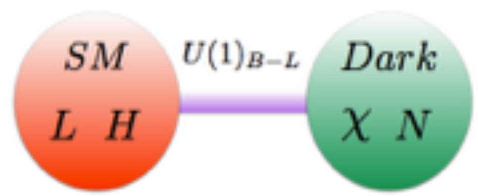
Naturalness: below 10^7 GeV
Vissani 1997

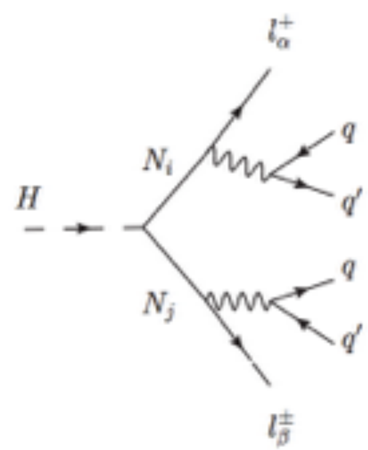
Look for seesaw where we can: LHC

(1) Collider phenomenology

New developments in NLO corrections

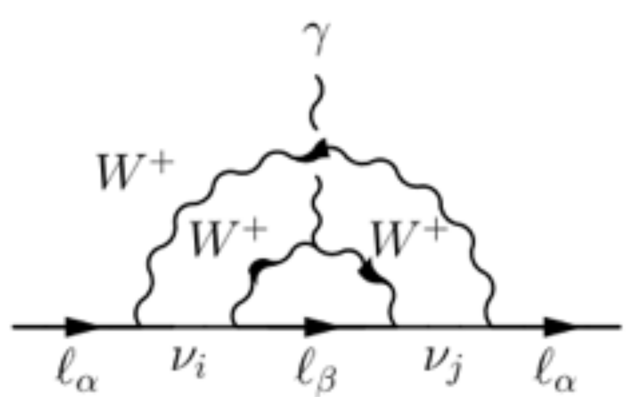
Mattelaer Mitra Ruiz 2016
Ruiz Spannowsky Waite 2017





Impact on precision Higgs data

Das Dev Kim 2017



Novel LHC searches: displaced vertices

Gago Hernandez Jones-Perez Losada Briceño 2015
Accomando Rose Moretti Olaiya Shepherd-Themistocleous 2016

(2) Model building

Dynamical lepton number breaking

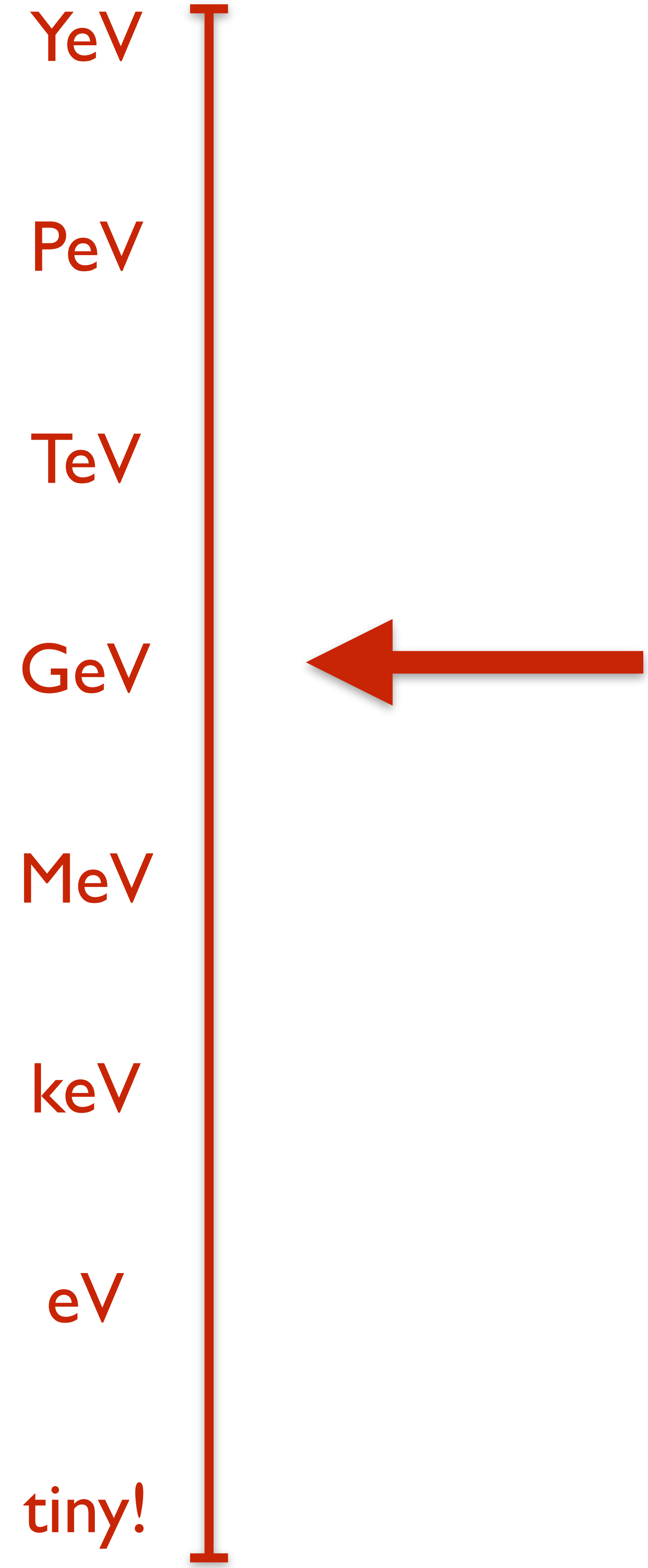
Khalil 2010, Freitas Pires Silva 2014,
Aoki Haba Takahashi 2015, Escudero Rius Sanz 2016,
Bertuzzo Machado Tabrizi Zukanovich-Funchal 2017
De Romeri Fernandez-Martinez Gehrlein Machado Niro 2017
Berryman de Gouvêa Kelly Zhang 2017

Thorough study of lepton flavor violation at LHC and meson decays

Abada De Romeri Teixeira 2015
De Romeri Herrero Marcano Scarcella 2016
Berryman de Gouvêa Kelly Kobach 2016

Constraints on light-heavy neutrino mixing via precision physics

Abada Toma 2015 de Gouvêa Kobach 2015
Fernandez-Martinez Hernandez-Garcia Lopez-Pavon Lucente 2015
Fernandez-Martinez Hernandez-Garcia Lopez-Pavon 2016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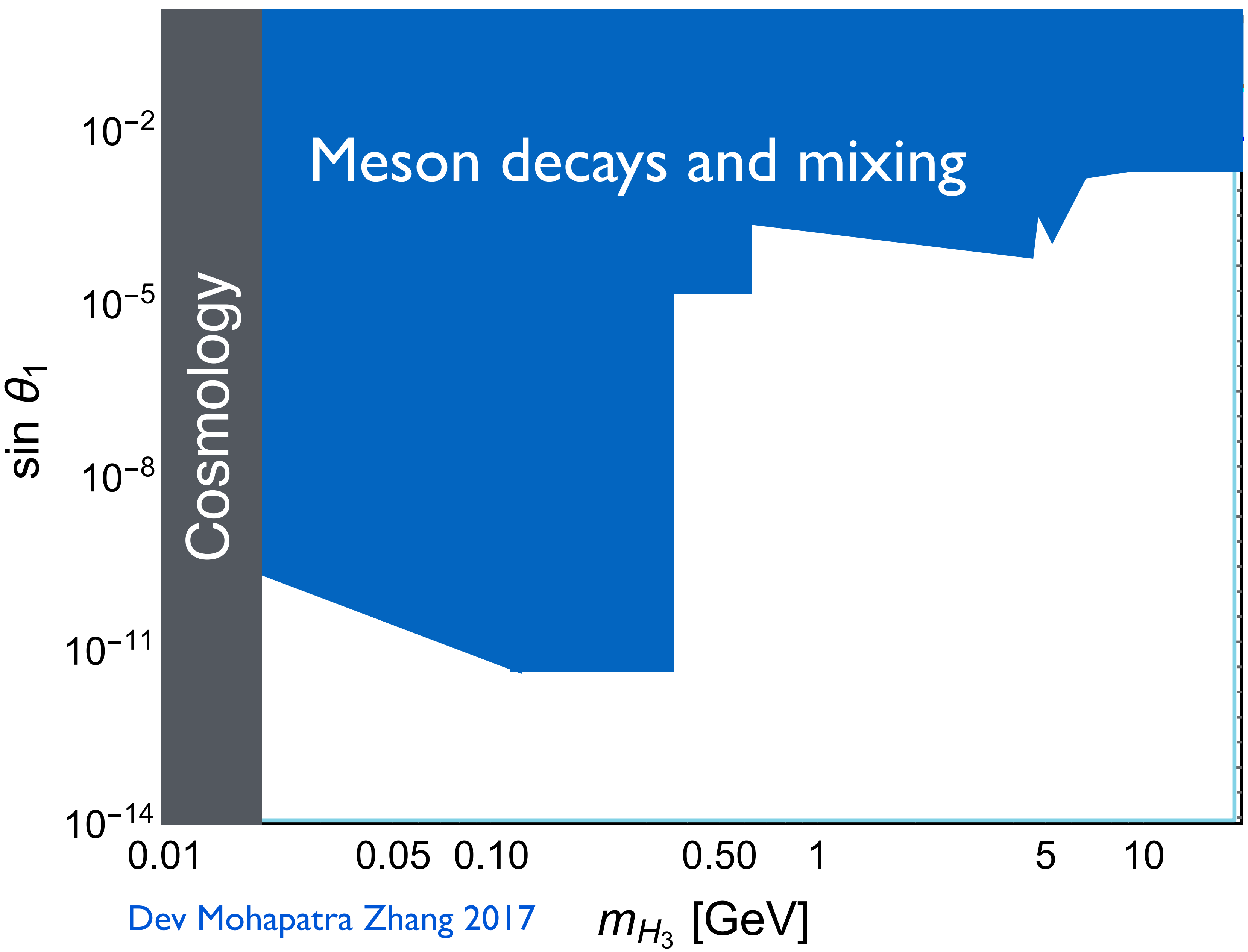
Neutrinos and low scale new Physics

TeV scale seesaw with local $U(1)_{B-L}$ can yield a GeV scalar!



Dev Mohapatra Zhang 2017

Vast phenomenology:
B and K decays
B mixing
Cosmology
LHC displaced vertices
...

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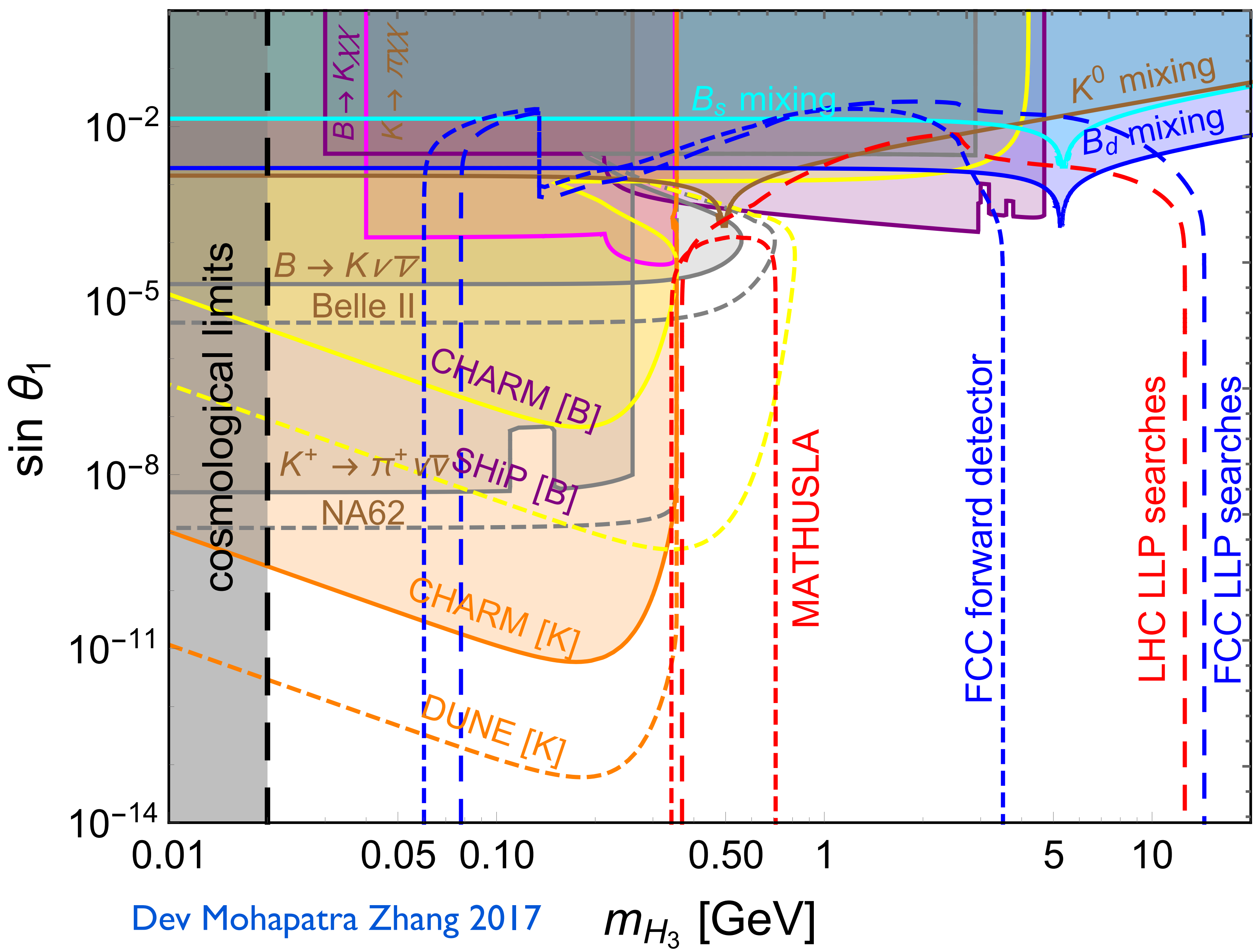

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Neutrinos and low scale new Physics

Can there be a flavor mediators at low scale???

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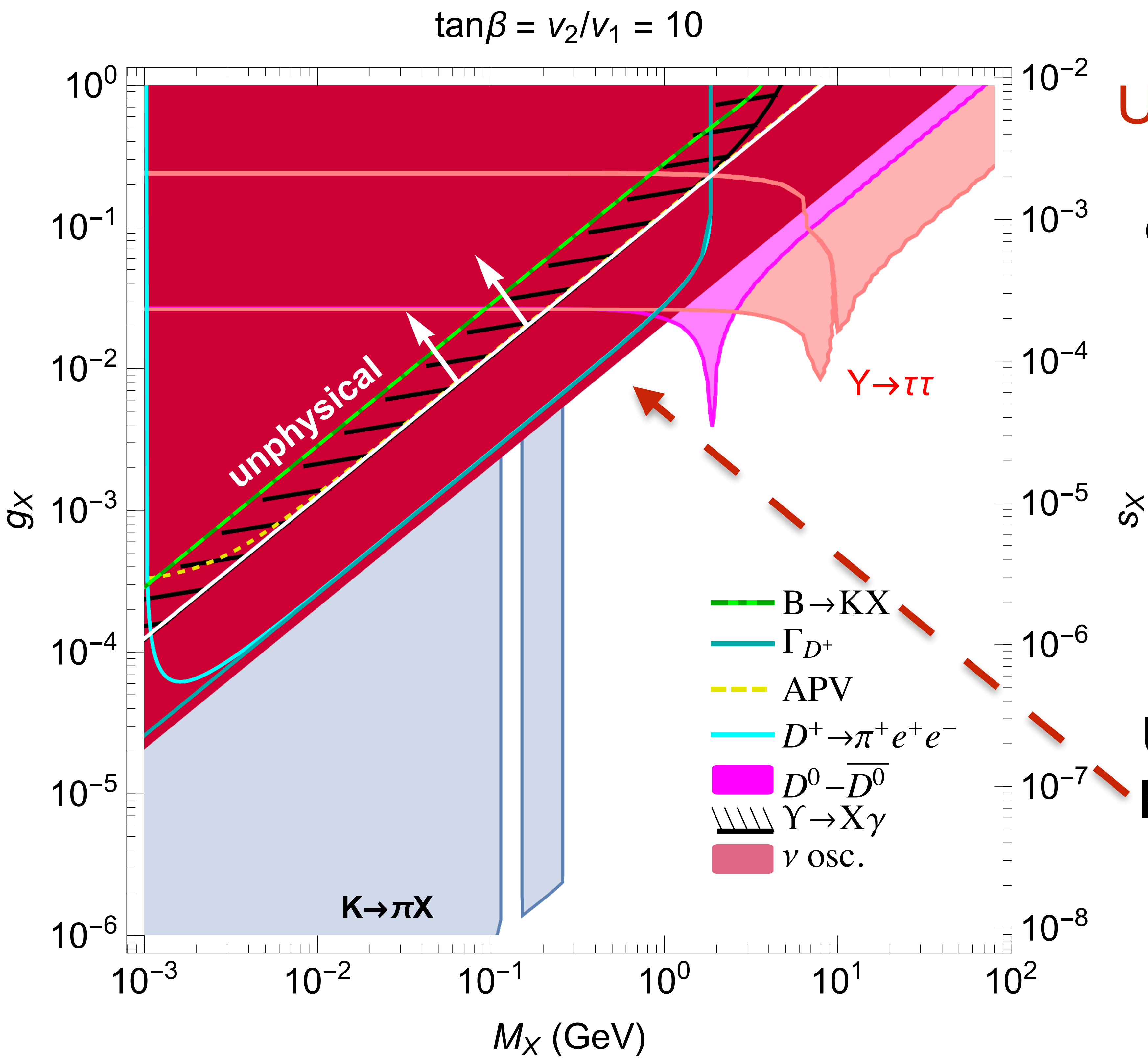


U(1) B – L of the third family

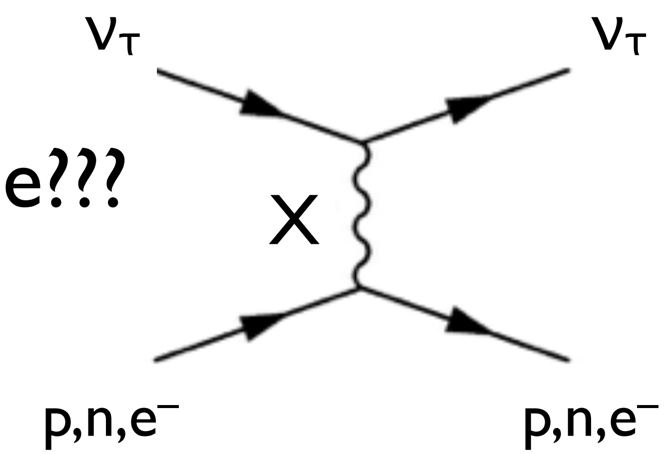
Complete model, including scalar sector and CKM generation

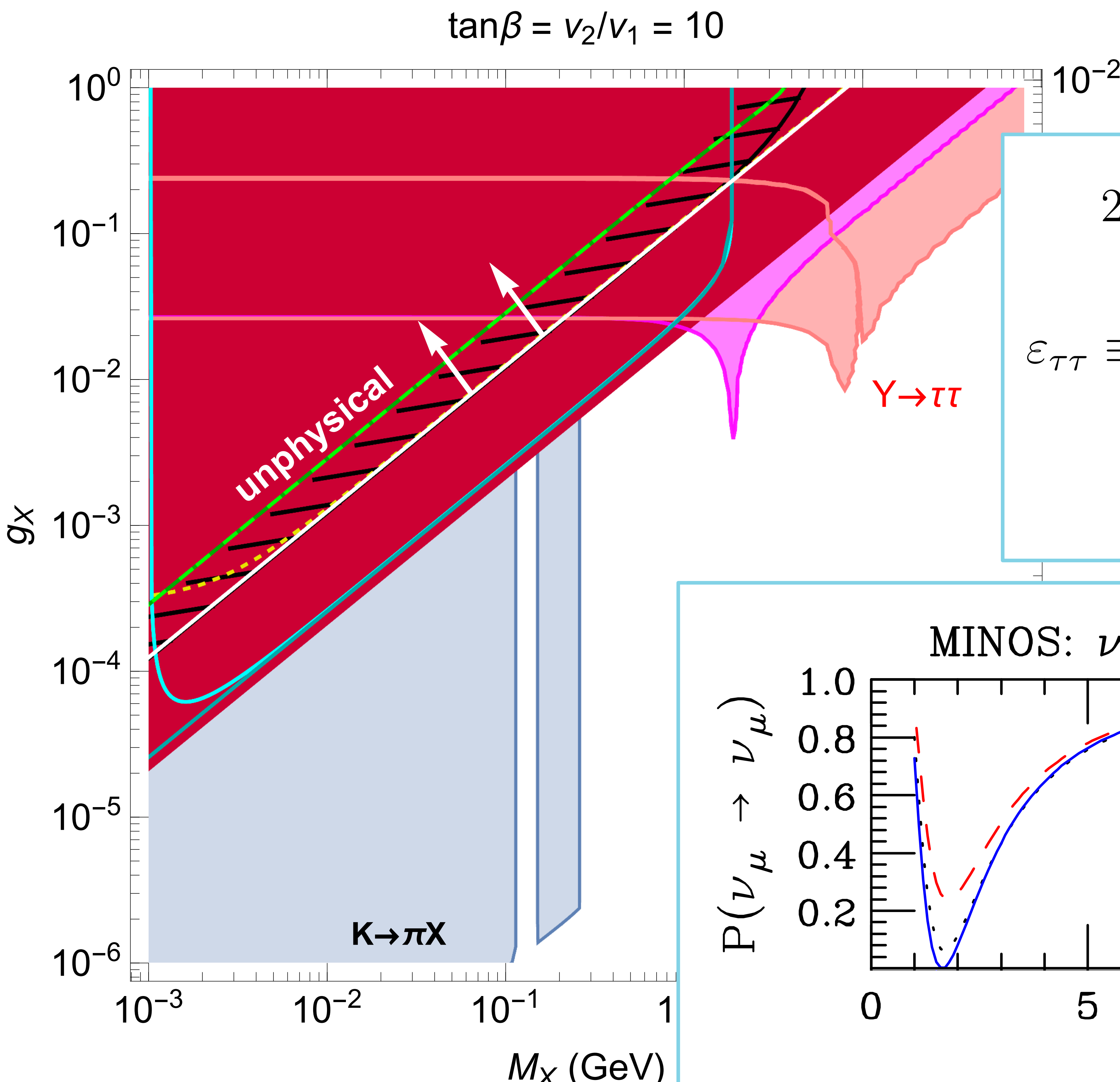
Vast phenomenology:
Z-X mixing (s_X)
D oscillations
Atomic Parity Violation
Upsilon, B, D, and K decays
Higgs, top, Z, and W decays
Neutrino oscillations
…

Babu Friedland Machado Mocioiu 2017

Neutrinos and low scale new Physics

Can there be a flavor mediators at low scale???



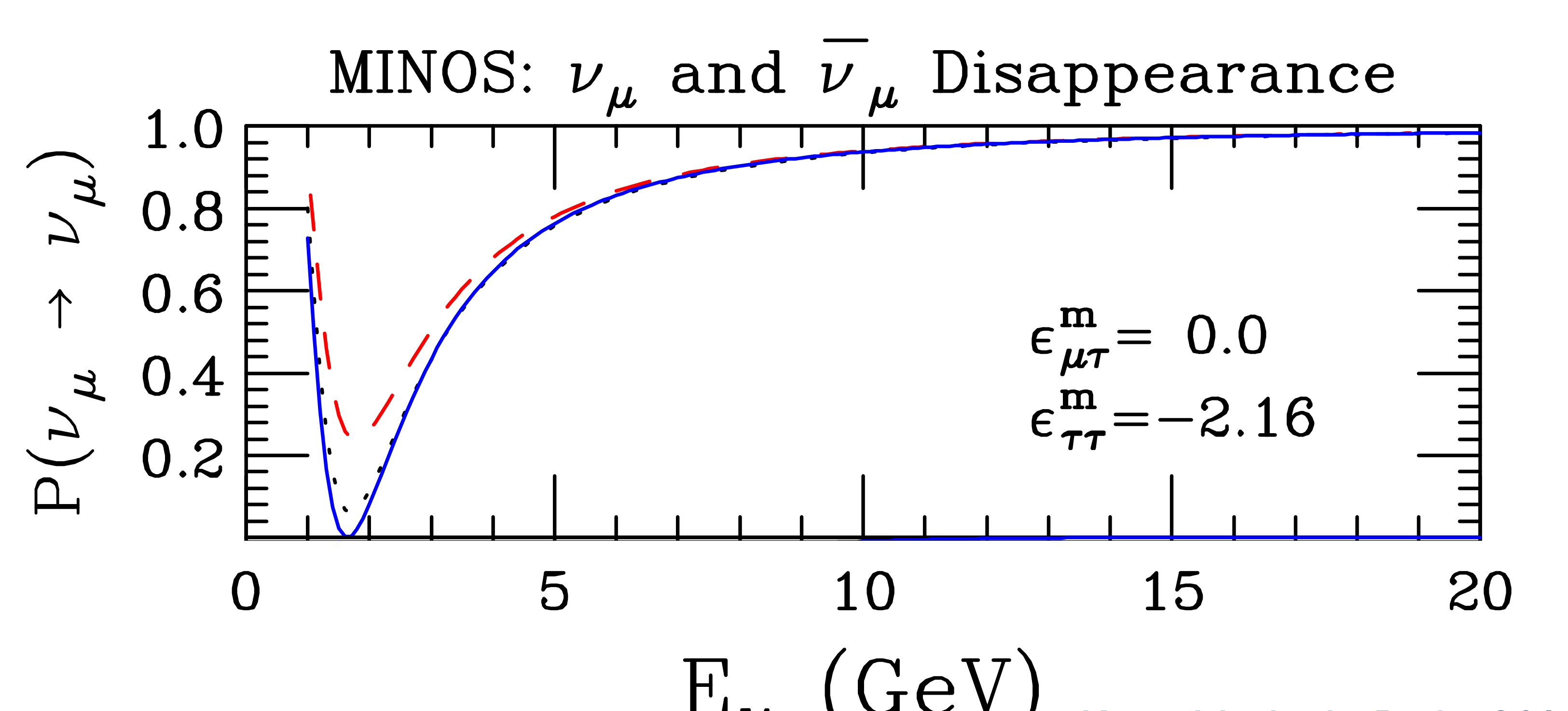


Babu Friedland Machado Mocioiu 2017

$$2\sqrt{2}G_F\varepsilon^f_{\alpha\alpha}\,\left(\bar{\nu}_{\alpha L}\gamma_\mu\nu_{\alpha L}\right)\left(\bar{f}\gamma^\mu f\right)$$

$$\varepsilon_{\tau\tau} \equiv \varepsilon^p_{\tau\tau} + \varepsilon^n_{\tau\tau} + \varepsilon^e_{\tau\tau} = 3\frac{v_1^2 v^2}{v_1^2 v_2^2 + v_s^2 v^2}$$

$$|\varepsilon_{\tau\tau}| < 0.09$$



Kopp Machado Parke 2010

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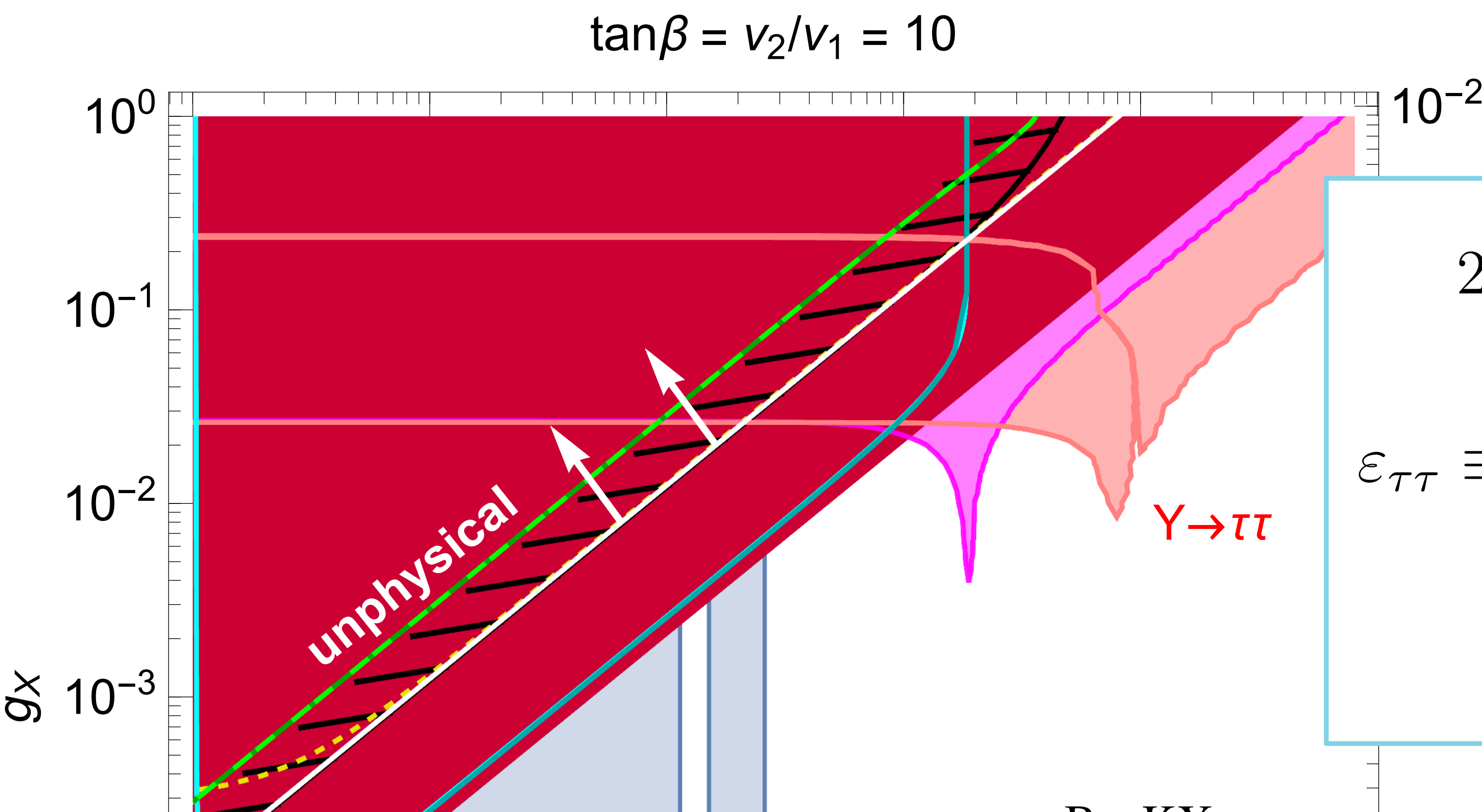

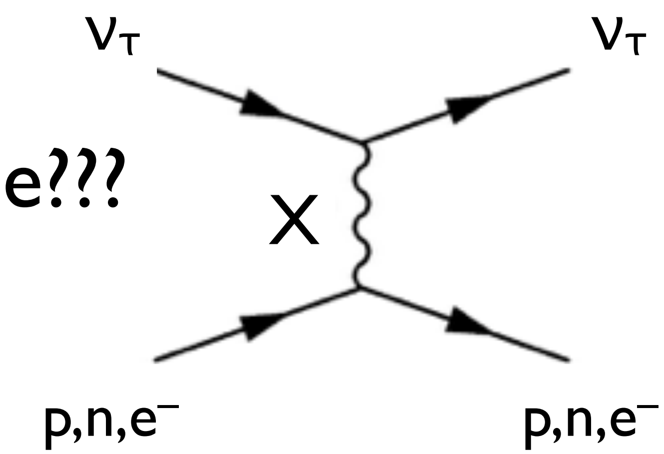

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$$|\varepsilon_{\tau\tau}| < 0.09$$

Neutrinos could probe low scale flavor physics

The third family is special: not so much for neutrinos!

Neutrino matter potential actually probes the symmetry breaking scale

$$V_{CC} = \sqrt{2}G_F N_e, \quad G_F = \frac{1}{\sqrt{2}v^2}$$

NSI: $2\sqrt{2}G_F\varepsilon^f_{\alpha\alpha}\,(\bar{\nu}_{\alpha L}\gamma_\mu\nu_{\alpha L})\,(\bar{f}\gamma^\mu f)$ → 1% NSI translate into v' ~ 10v

Babu Friedland Machado Mocioiu 2017

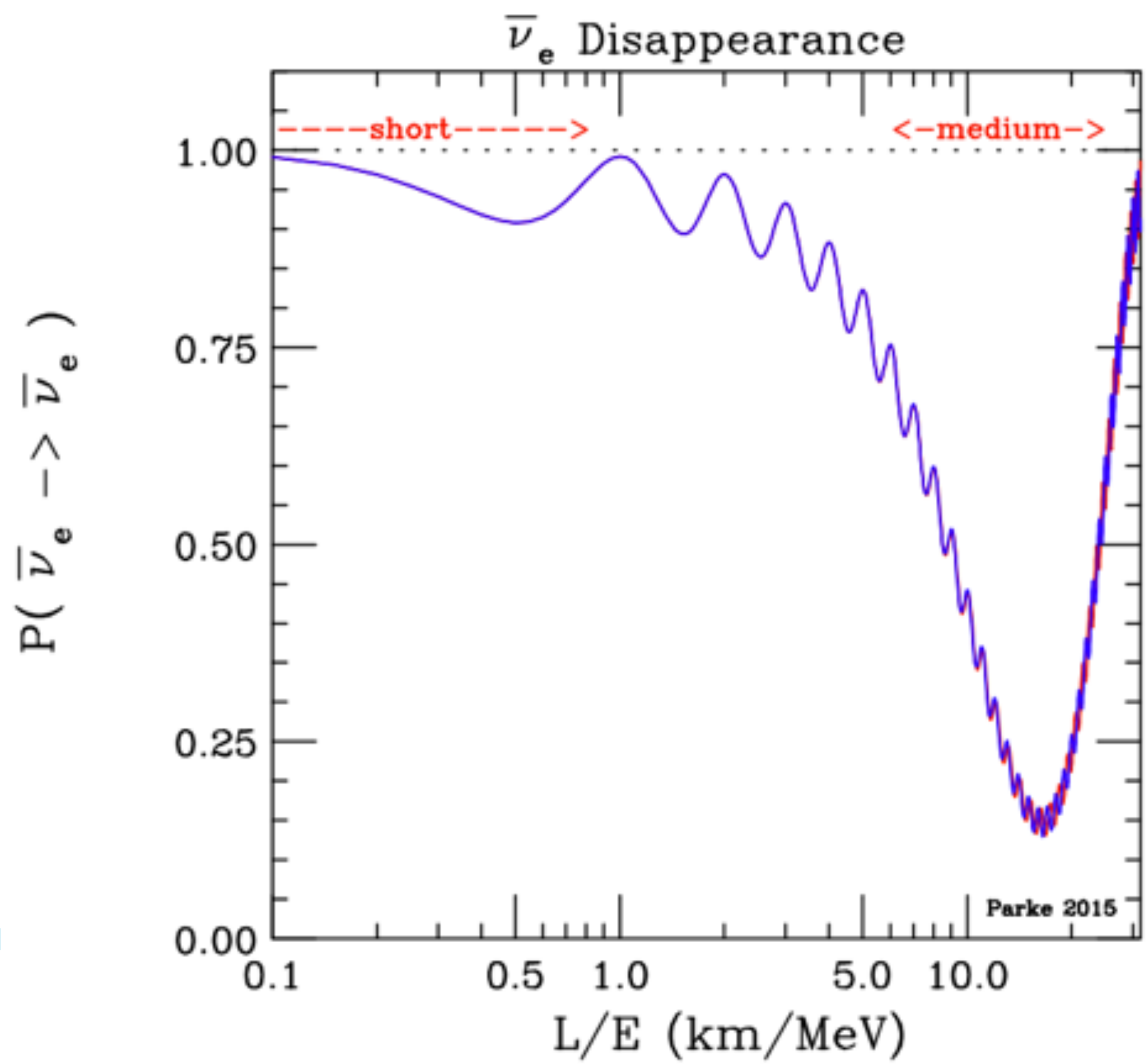
Neutrinos and new Physics

Precise determination of neutrino oscillation parameters can probe new physics

Important to understand oscillation probabilities and
what we are actually measuring

Barger Whisnant Pakvasa Phillips 1980, Arafune Sato 1996, Nunokawa Parke Zukanovich-Funchal 2005, Minakata Parke 2015, Parke 2016, Denton Minakata Parke 2016

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$



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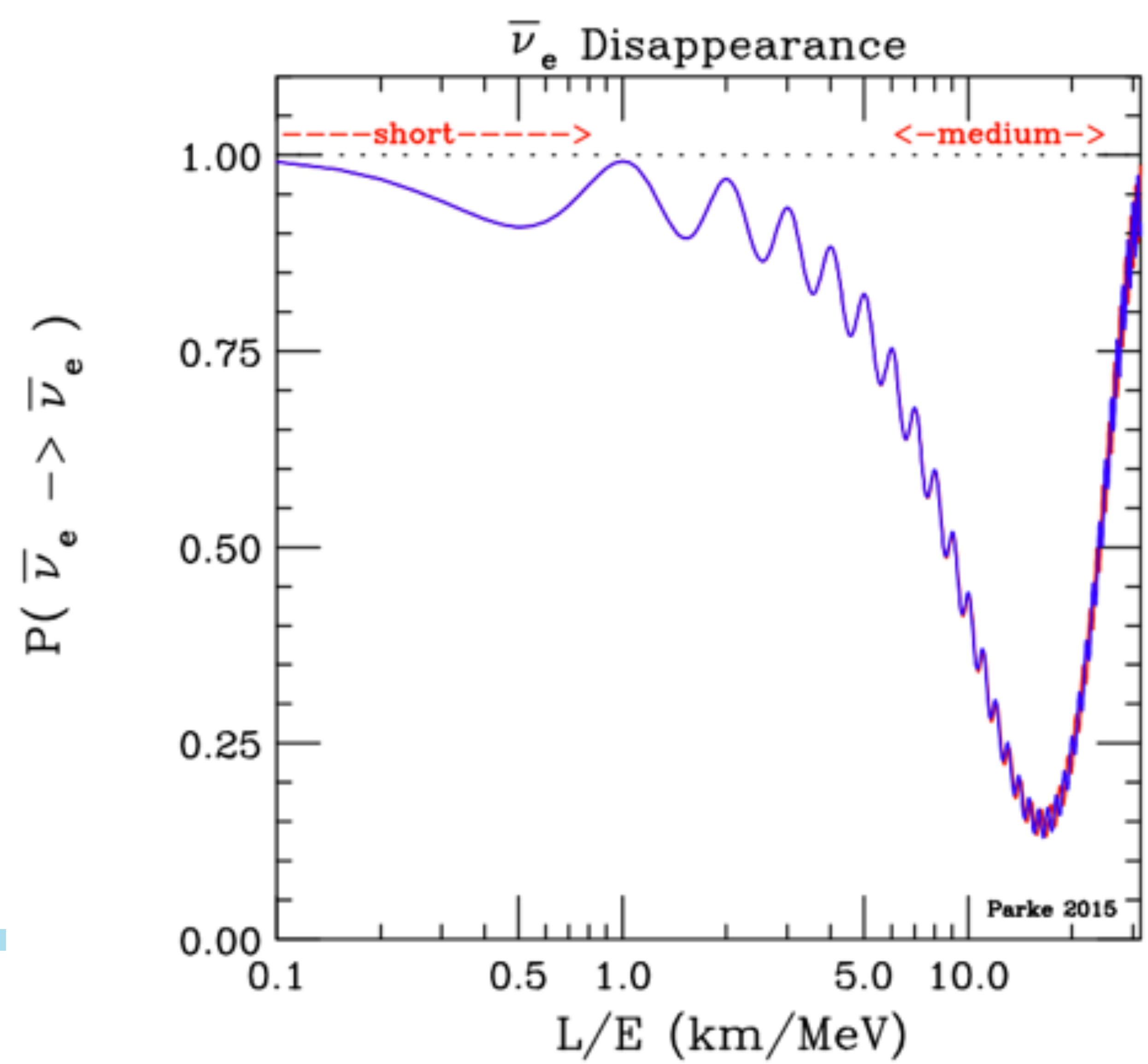
With such understanding we can
device new strategies for improving
our knowledge of neutrino oscillations

Huber Lindner Schwetz Winter 2009, Coloma Kopp Winter 2012, Machado Minakata Nunokawa Zukanovich-Funchal 2013, Minakata Parke 2013, Coloma Minakata Parke 2014, Chatterjee Pasquini Valle 2017, Raut 2017, and many others…

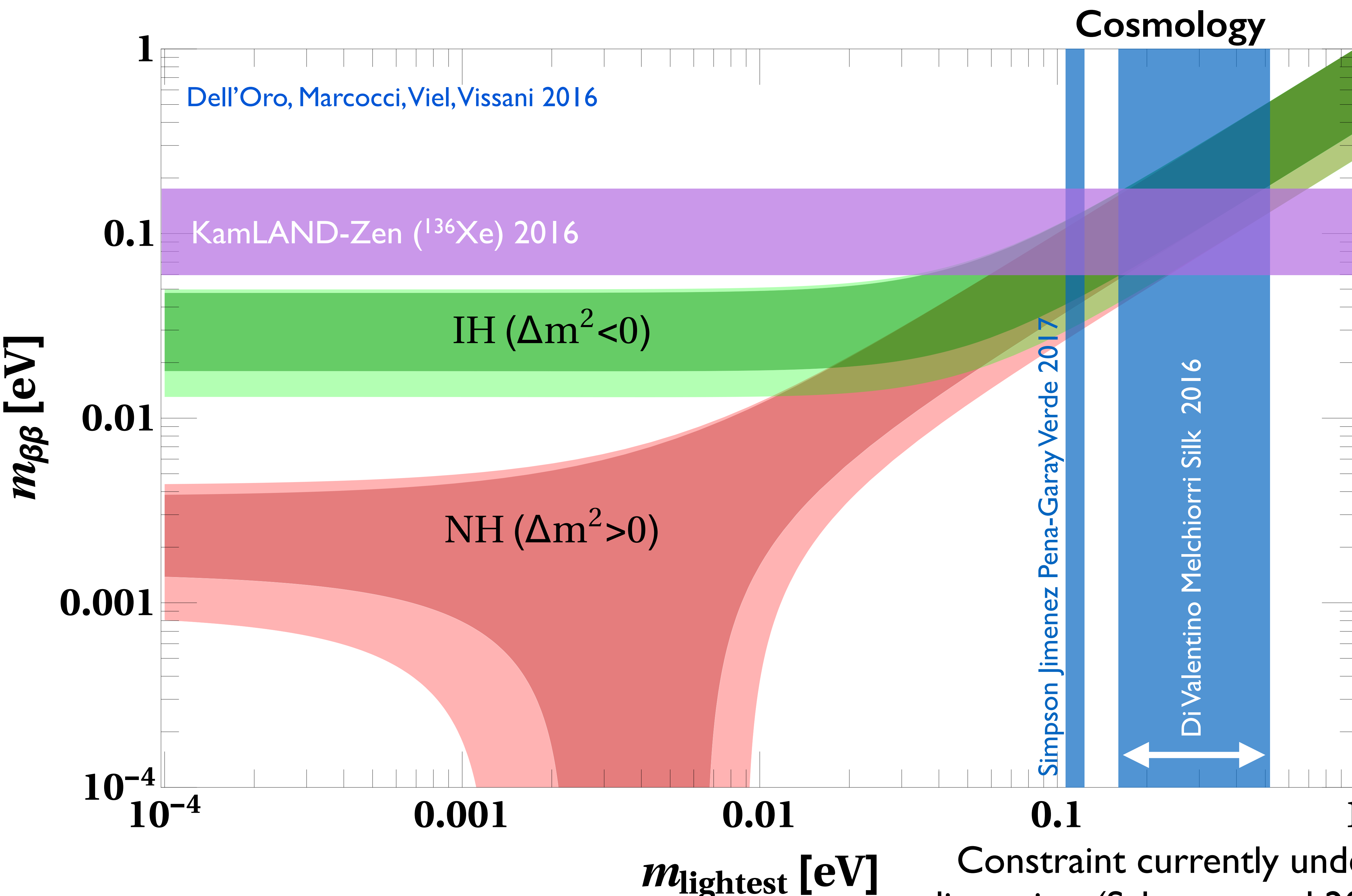


What do we learn when we measure δ_{CP}, θ_{23}, and the mass ordering??

The mass ordering

May help answering the paramount question: Are neutrinos Dirac or Majorana?

Test of standard cosmology

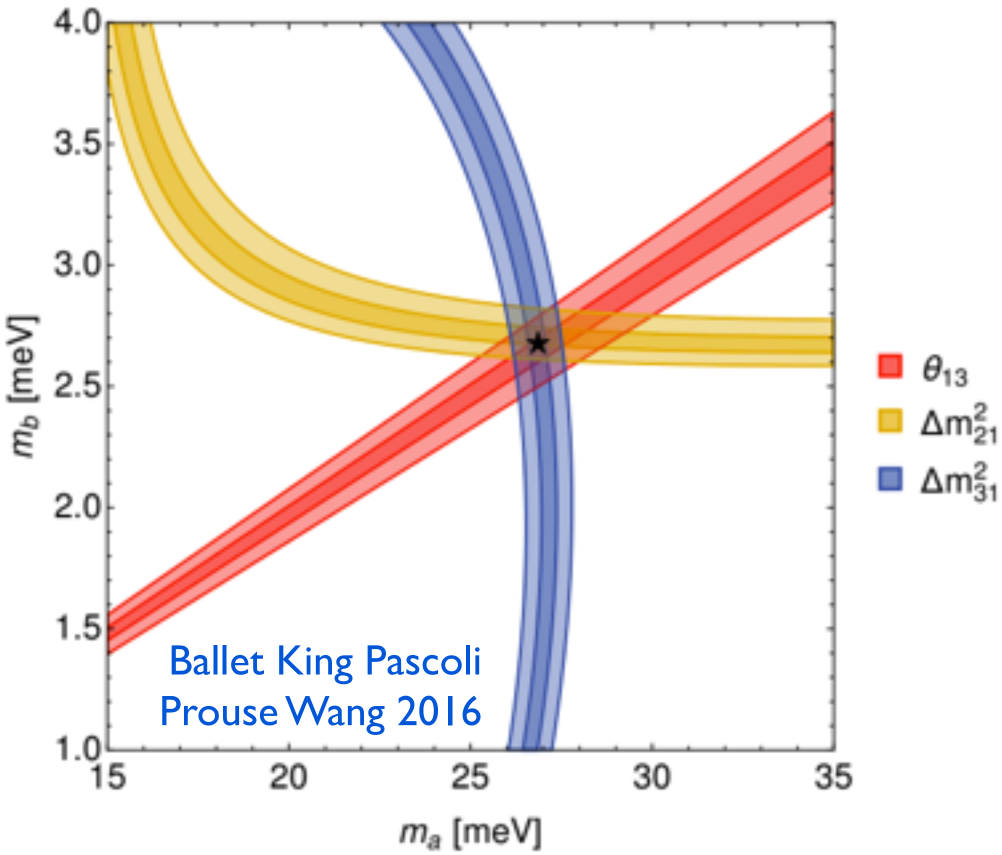


Constraint currently under discussion (Schwetz et al 2017)

The CP phase and θ_{23} octant

Insights on the generation of the matter anti-matter asymmetry

Insights on the flavor puzzle



Ballet King Pascoli Prouse Wang 2016

For a certain class of flavor groups:

1) δ_{CP} is related to the Clebsch-Gordan coefficients
2) Dependence on group and fermion representations

Chen Fallbacher Mahanthappa Ratz Trautner 2014

Some predictions

$$\delta_\ell = 227^o$$

Chen Mahanthappa 2009

$$\theta_{13} \neq 0,\ \theta_{23} = \pi/4, \text{ and } \delta_{CP} = -\pi/2$$

Ma 2016, Ma 2017

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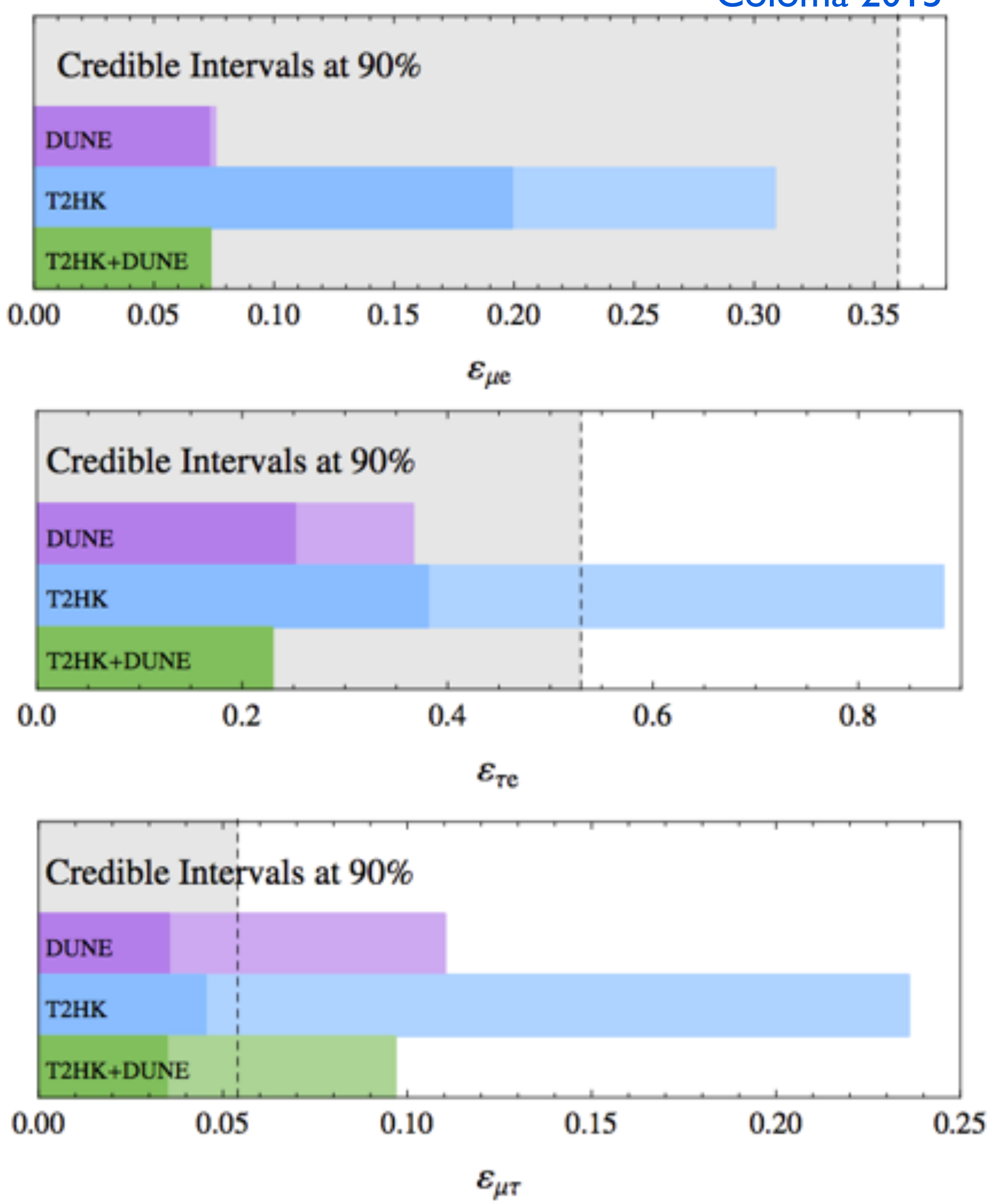
Neutrinos and new Physics

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\epsilon^f_{\alpha\beta}(\overline{\nu}_{\alpha L}\gamma^\mu\nu_{\beta L})(\overline{f}\gamma_\mu f)$$

Complete models prove that some NSIs are possible up to some extent

Farzan 2015, Farzan Shoemaker 2015, Farzan Heeck 2016, Forero Huang 2016, Babu Friedland Machado Mocioiu 2017

Coloma 2015



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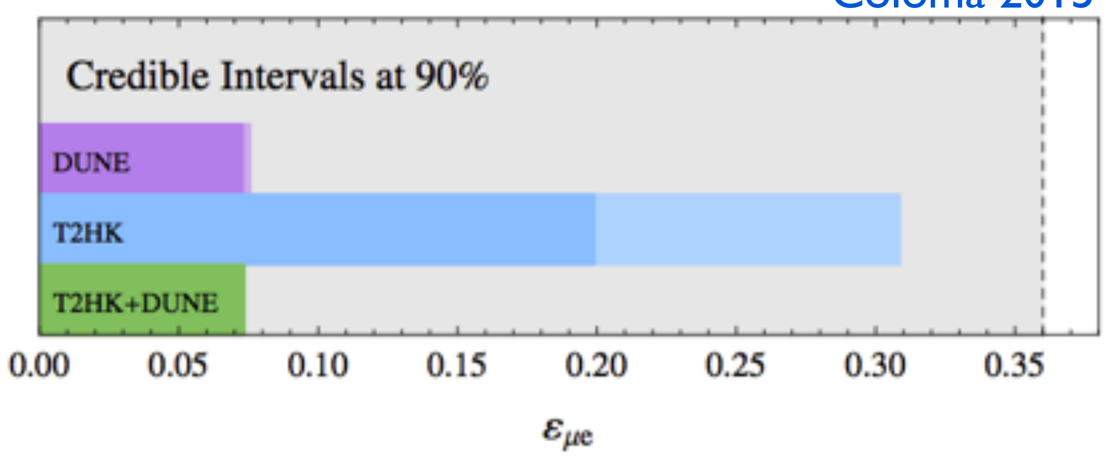
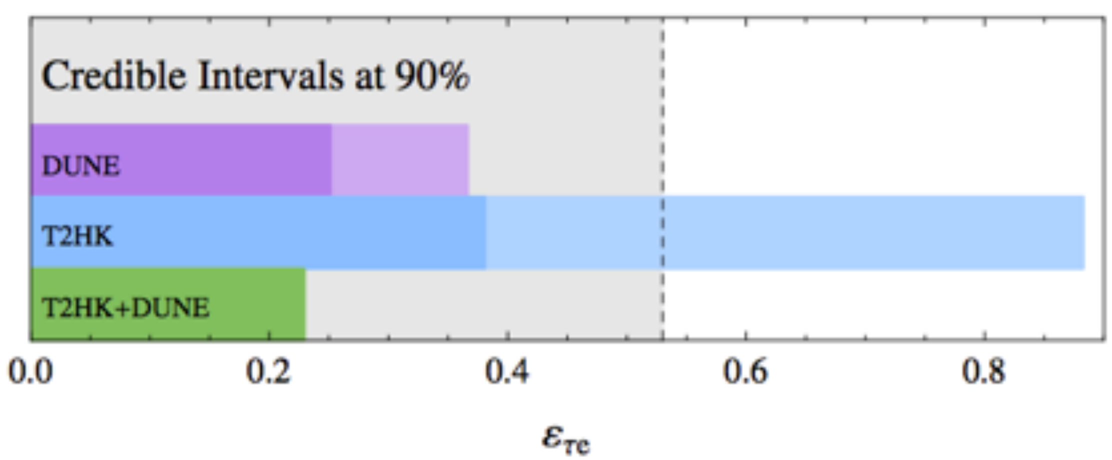
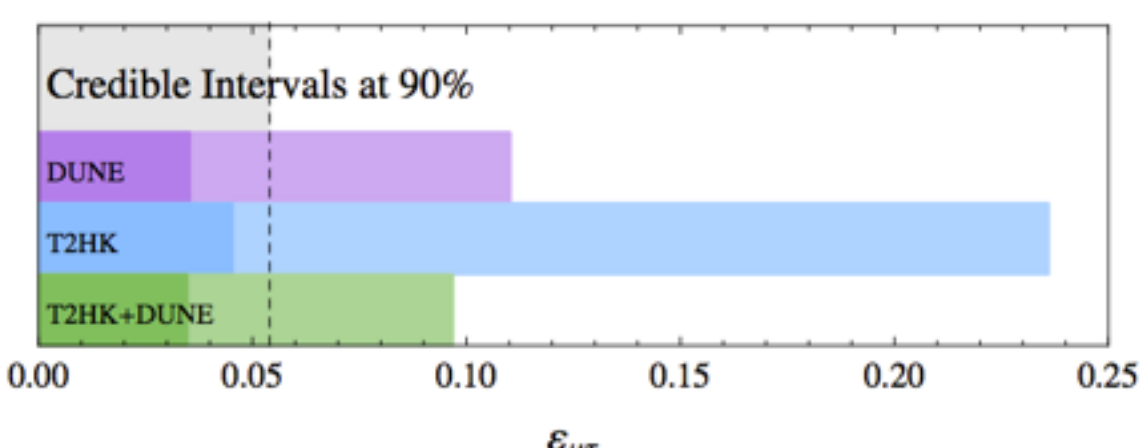






NSI induce degeneracies!

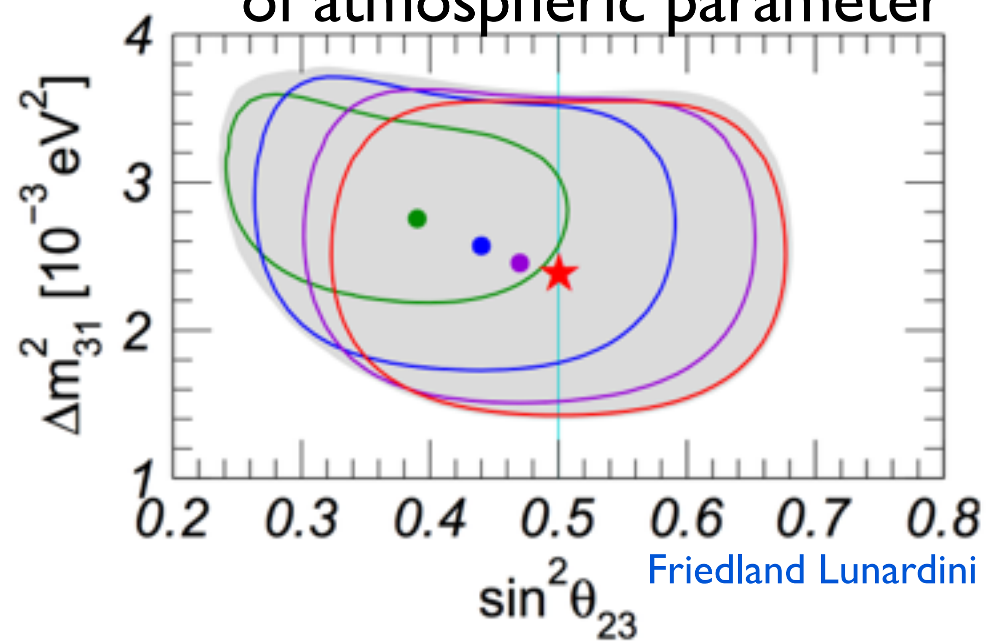
Generalized degeneracy with NSI leaves oscillation invariant for any matter potential: Large NSI can flip the sign of matter potential

Coloma Schwetz 2016

Many other approximate degeneracies exist: extra work for current and future experiments

Mocioiu Wright 2014, Babu McKay Mocioiu Pakvasa 2016, Liao Marfatia 2016, Liao Marfatia Whisnant 2016, Deepthi Goswami Nath 2016, Fukasawa Ghosh Yasuda 2016, Agarwalla Chatterjee Palazzo 2016 Liao Marfatia Whisnant 2017, Tang Zhang 2017 …

Possible effect of NSI on the determination of atmospheric parameter



Friedland Lunardini Maltoni 2004

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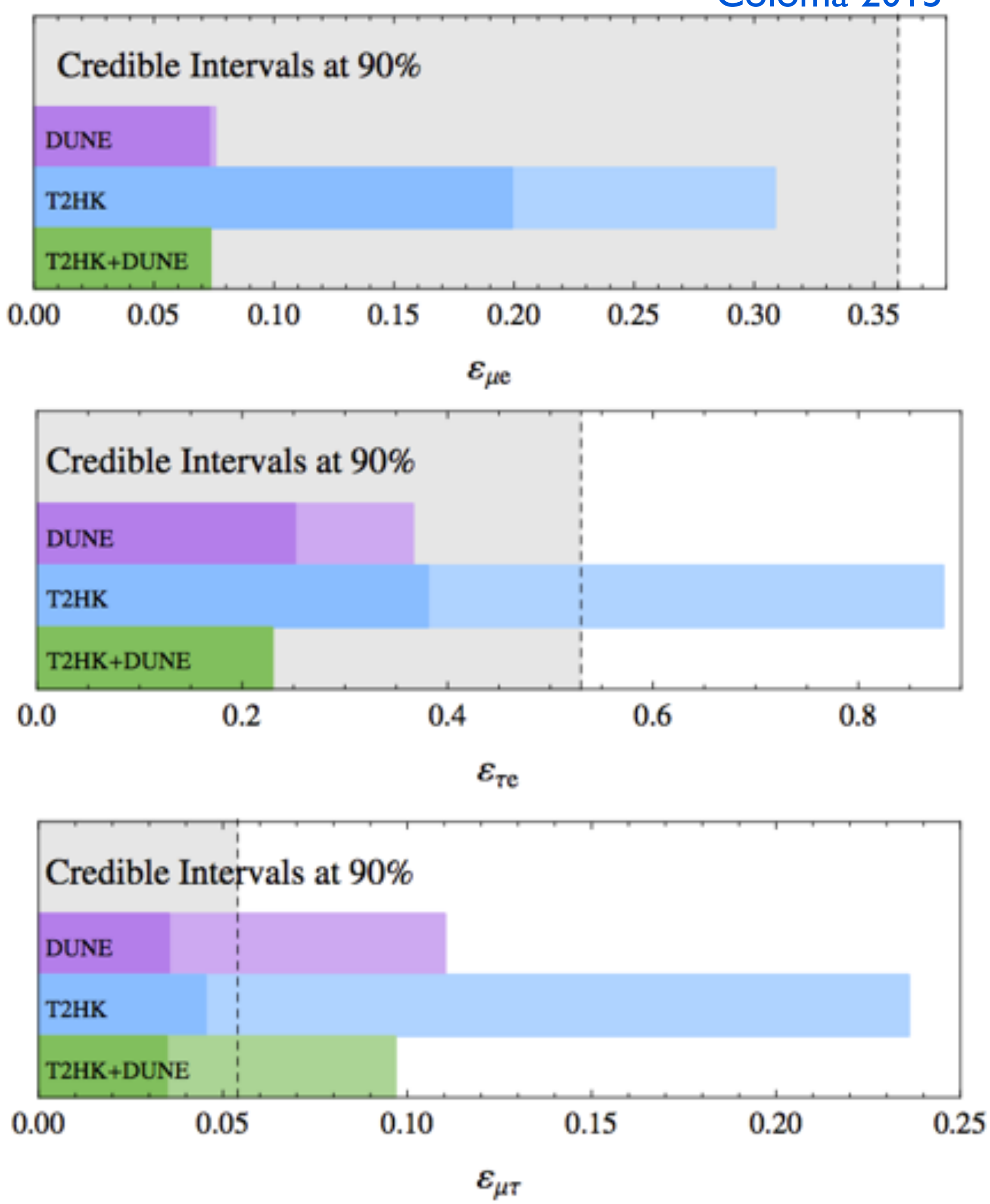
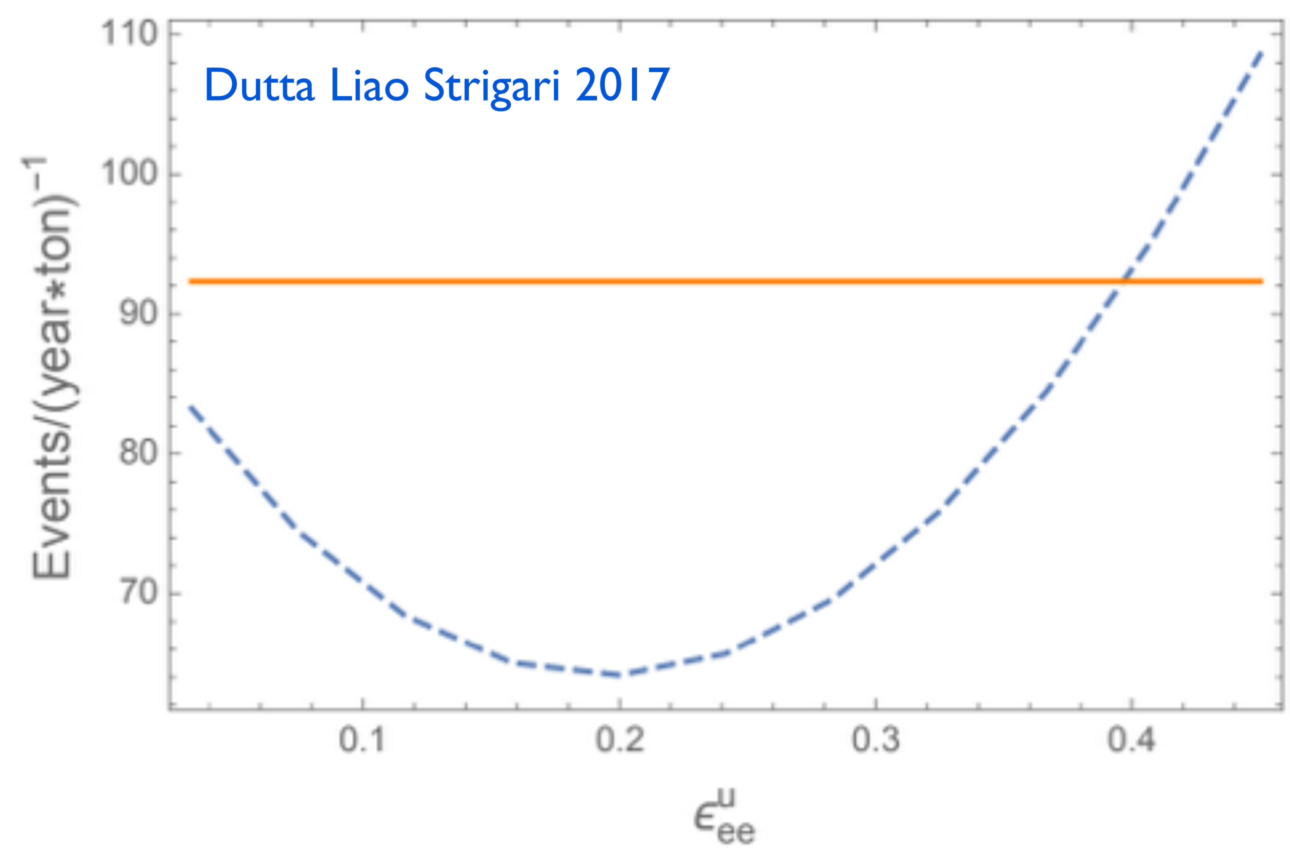
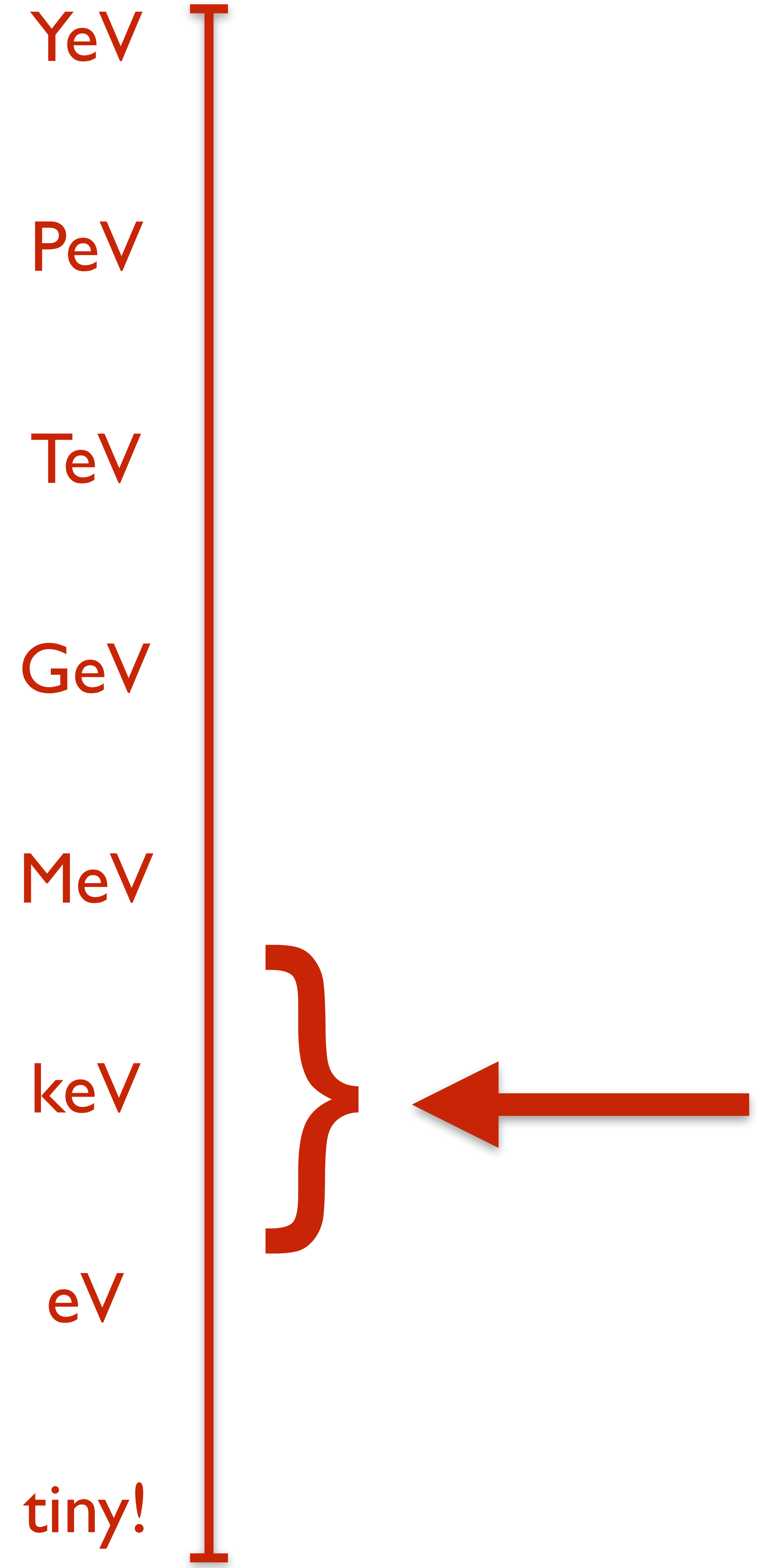


Needs scattering data to solve generalized degeneracy

Neutrino-nucleus coherent scattering!





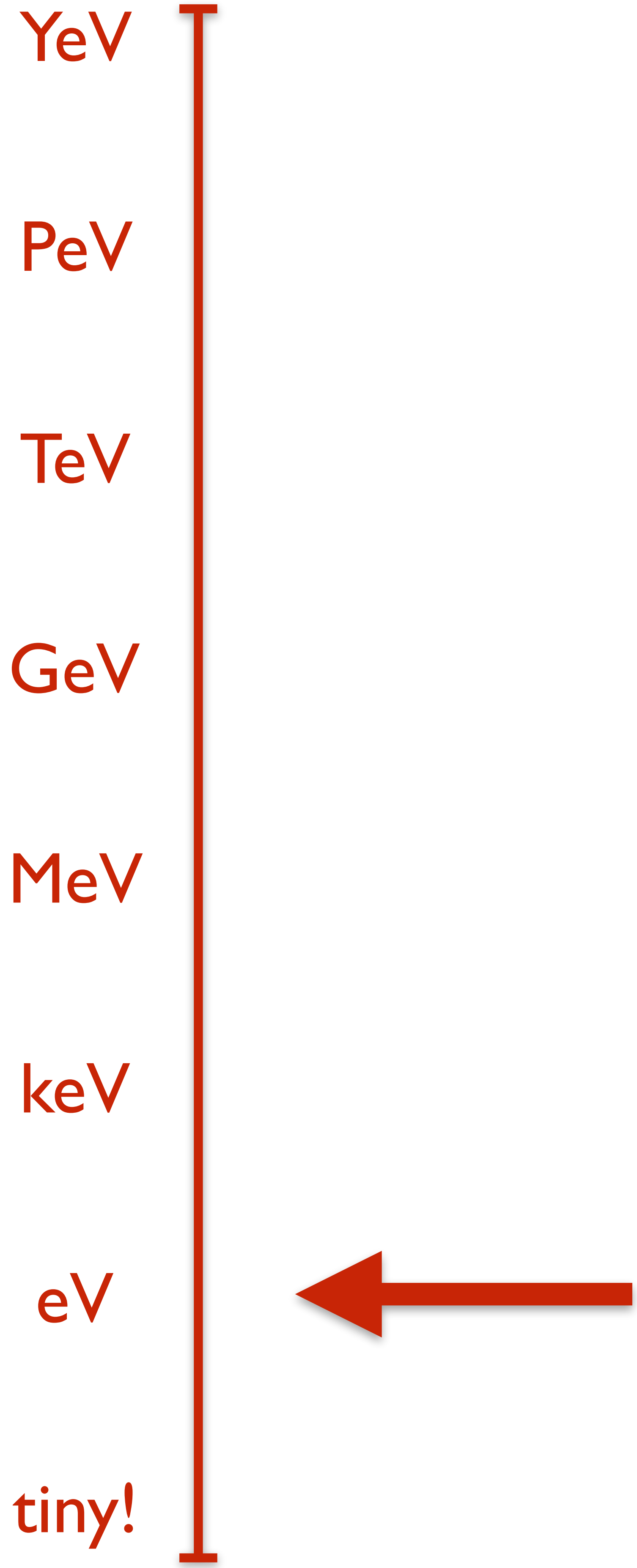
pmachado@fnal.gov

Neutrinos and new Physics

Dark matter detectors are excellent
to probe new physics with solar neutrinos:
Low background
Low energy threshold
Large detectors to compensate small cross sections

Pospelov 2011, Harnik Kopp Machado 2012, Bilmis Turan Aliev Denis Singh Wong 2015, Cerdeño Fairbairn Jubb Machado Vincent Boehm 2016, Dent Dutta Liao Newstead Strigari Walker 2016, Bertuzzo Deppisch Kulkarni Perez-Gonzalez Zukanovich-Funchal 2017, Dutta Strigari Walker 2017 …

Dedicated experiments to study coherent ν-N scattering:
CONNIE (Angra nuclear reactor)
COHERENT (Oak Ridge)
MINER (Texas A&M)


YeV
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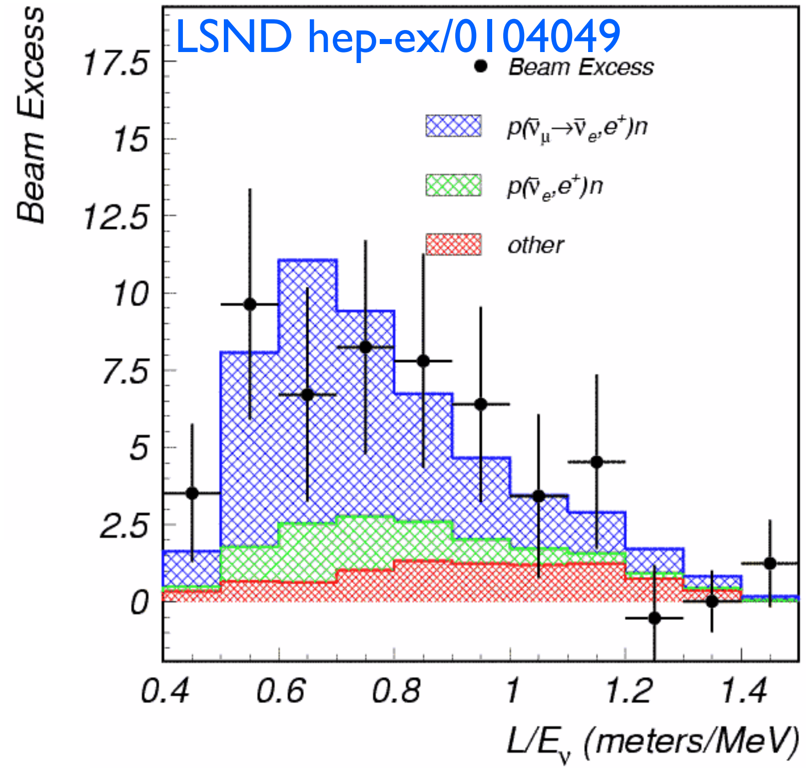
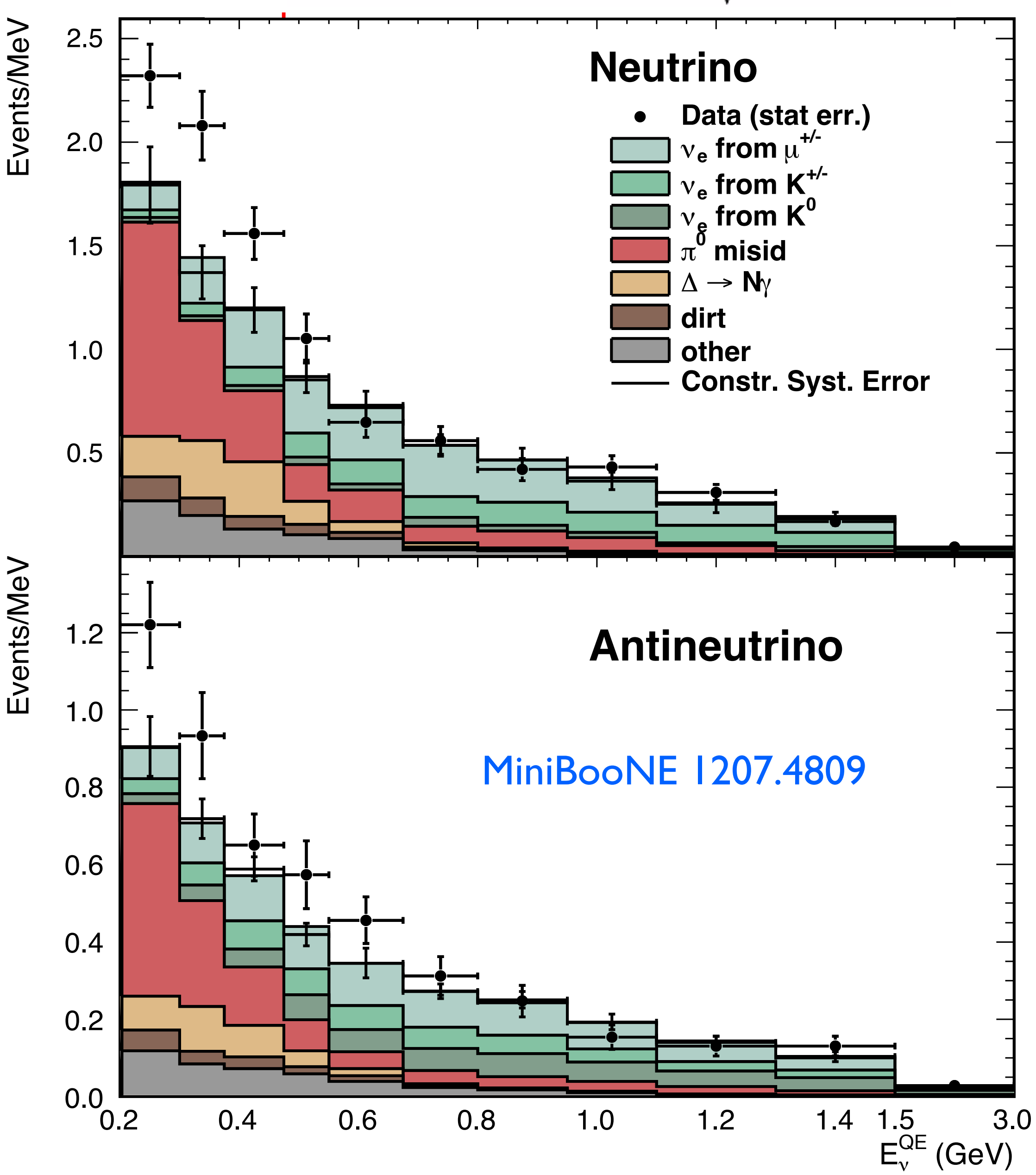
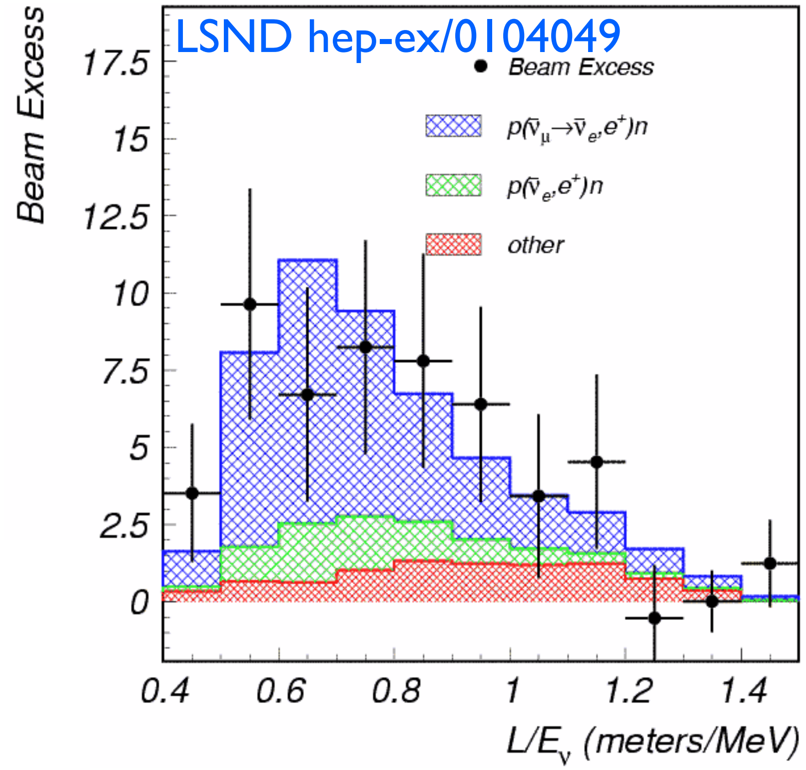
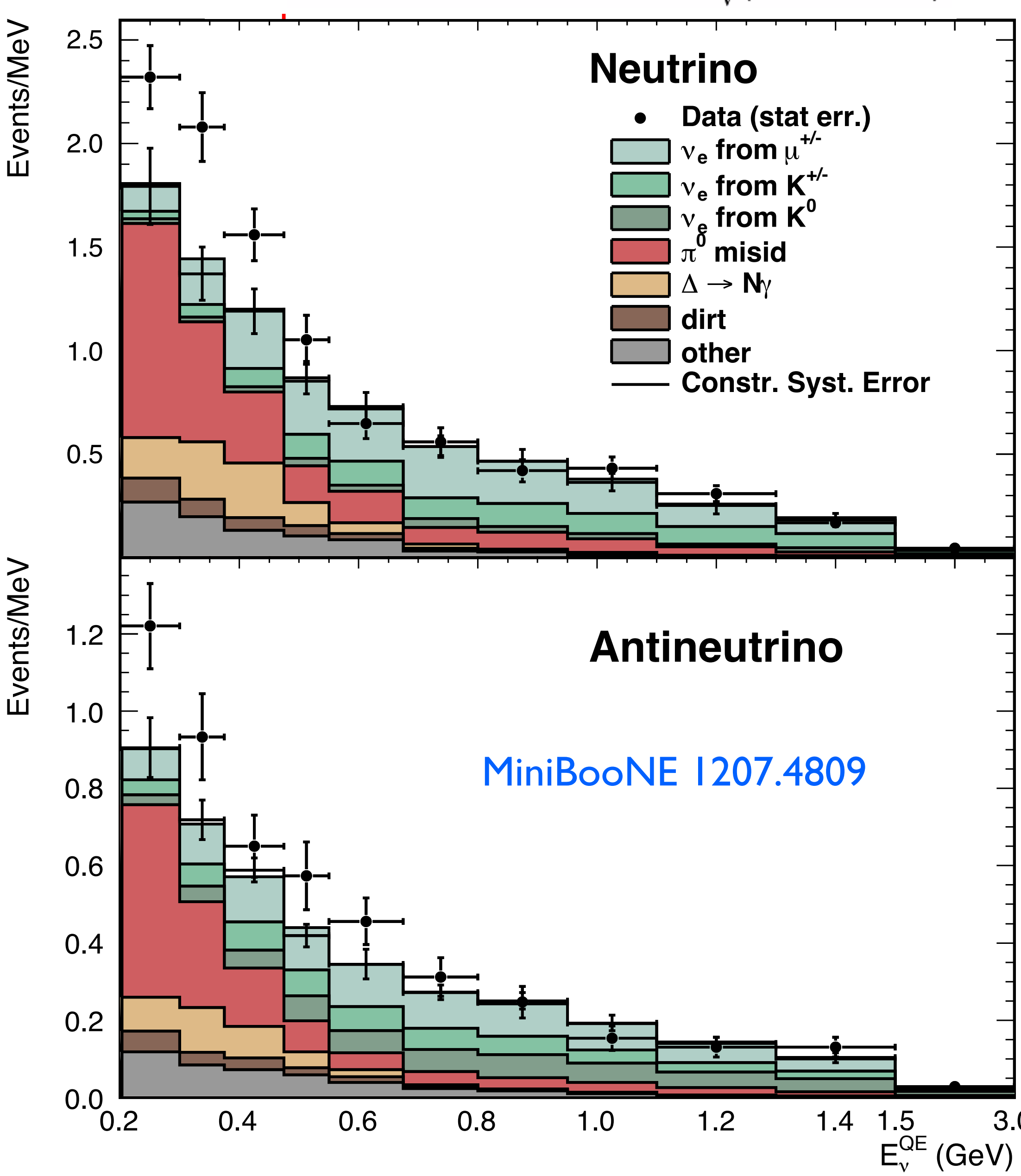
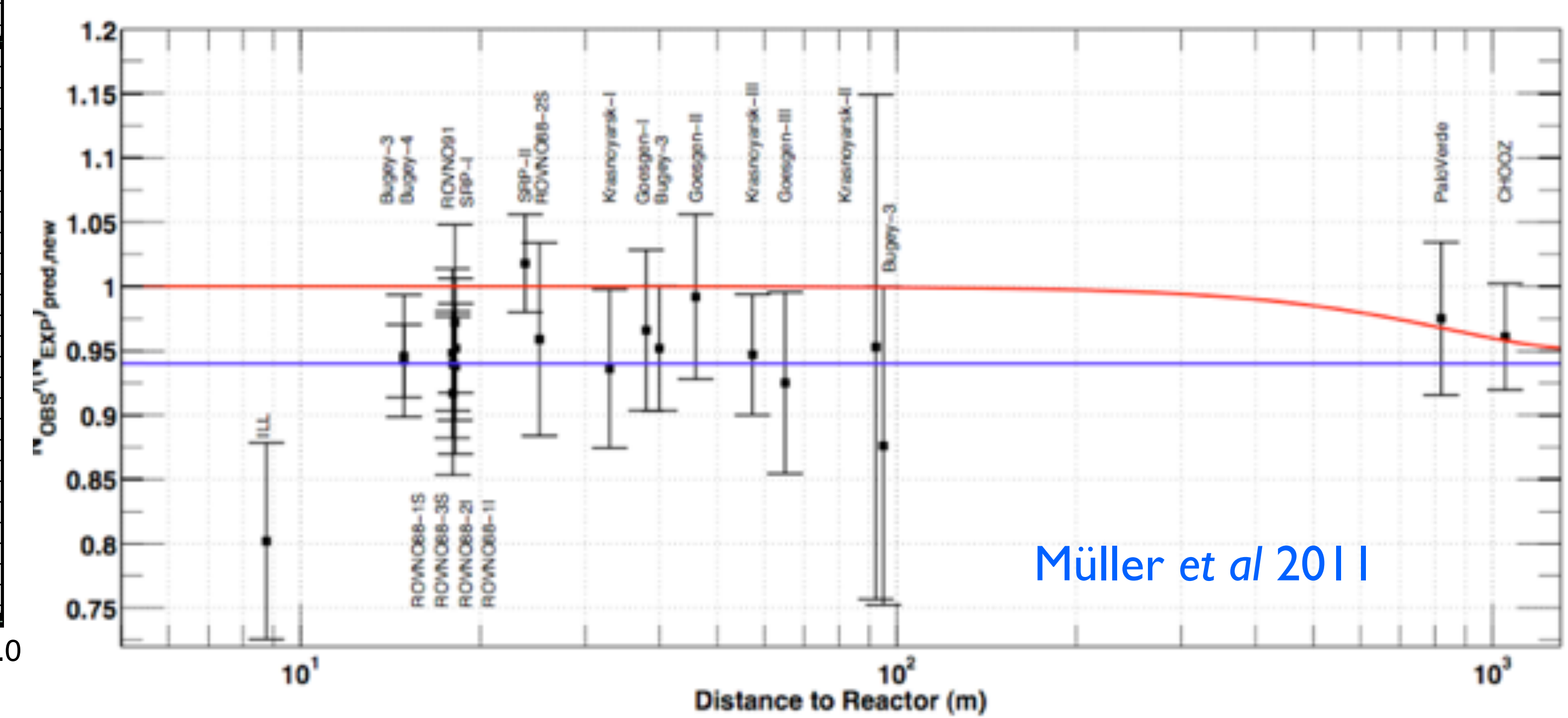
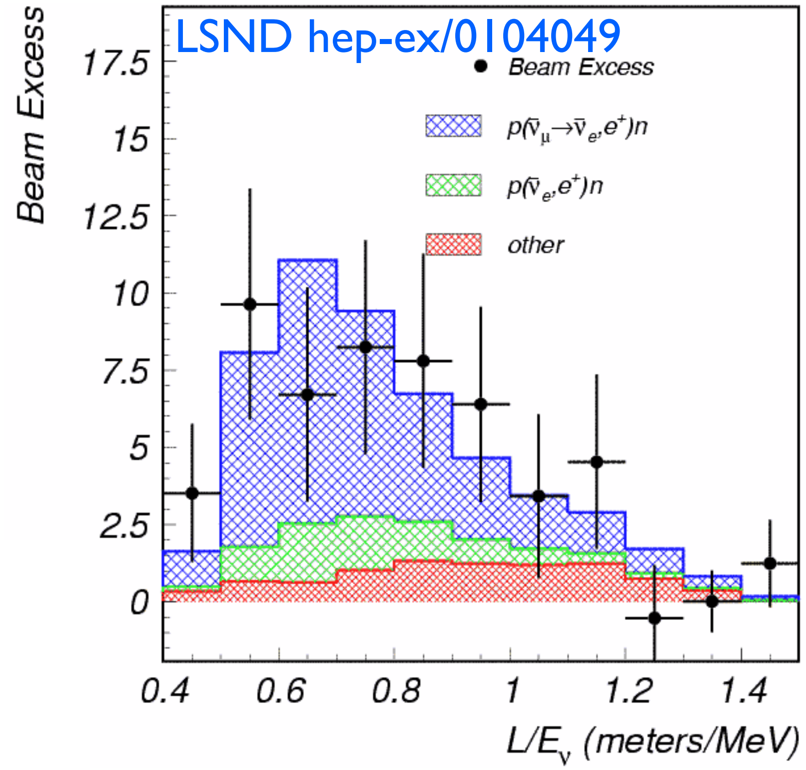

LSND hep-ex/0104049
Beam Excess
$p(\bar{\nu}_\mu \rightarrow \bar{\nu}_e, e^+)n$
$p(\bar{\nu}_e, e^+)n$
other
Beam Excess
17.5
15
12.5
10
7.5
5
2.5
0
0.4
0.6
0.8
1
1.2
1.4
L/E_ν (meters/MeV)


Neutrino
Data (stat err.)
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Constr. Syst. Error
Events/MeV
2.5
2.0
1.5
1.0
0.5
Antineutrino
MiniBooNE 1207.4809
Events/MeV
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.5
3.0
E_ν^{QE} (GeV)

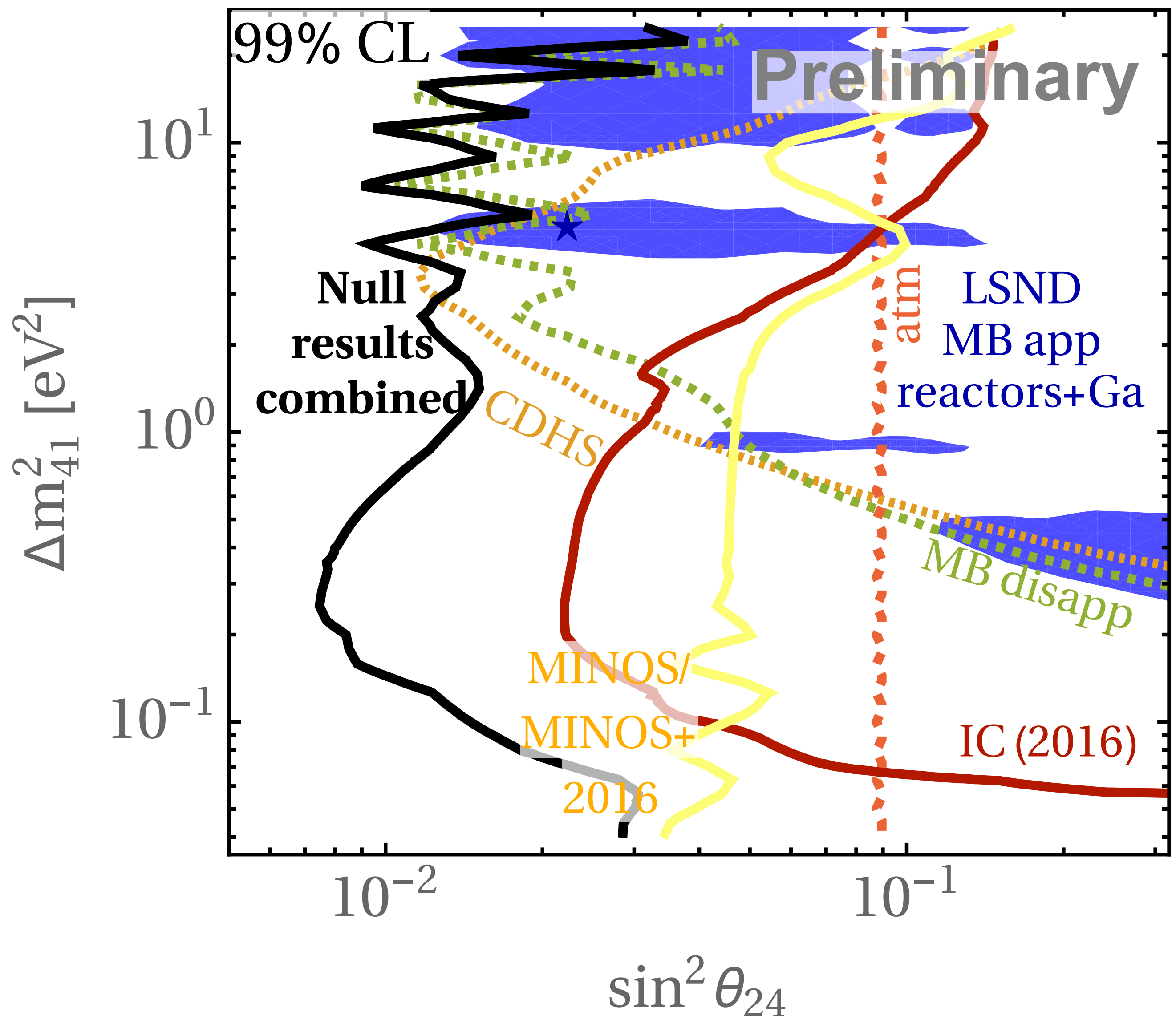

LSND hep-ex/0104049
Beam Excess
$p(\bar\nu_\mu \to \bar\nu_e, e^+)n$
$p(\bar\nu_e, e^+)n$
other
Beam Excess
L/E_ν (meters/MeV)

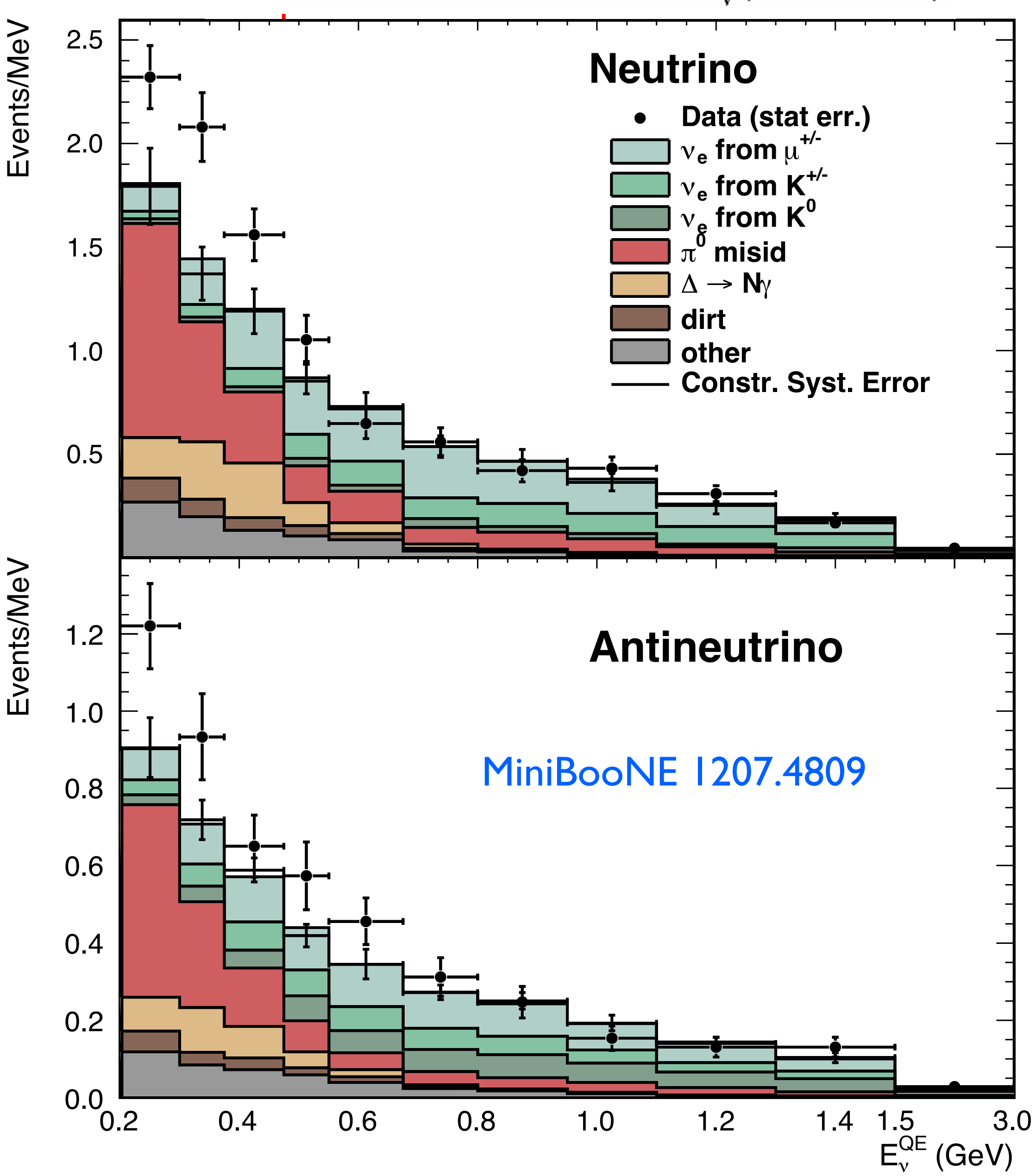

Neutrino
Data (stat err.)
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
$\Delta \to N\gamma$
dirt
other
Constr. Syst. Error
Antineutrino
MiniBooNE 1207.4809
Events/MeV
E_ν^{QE} (GeV)


Müller et al 2011
Distance to Reactor (m)
ILL
Bugey-3
Bugey-4
ROVNO91
SRP-I
SRP-II
ROVNO88-2S
Krasnoyarsk-I
Goesgen-I
Goesgen-II
Goesgen-III
Krasnoyarsk-III
Krasnoyarsk-II
Bugey-3
PaloVerde
CHOOZ
ROVNO88-1S
ROVNO88-3S
ROVNO88-2I
ROVNO88-1I

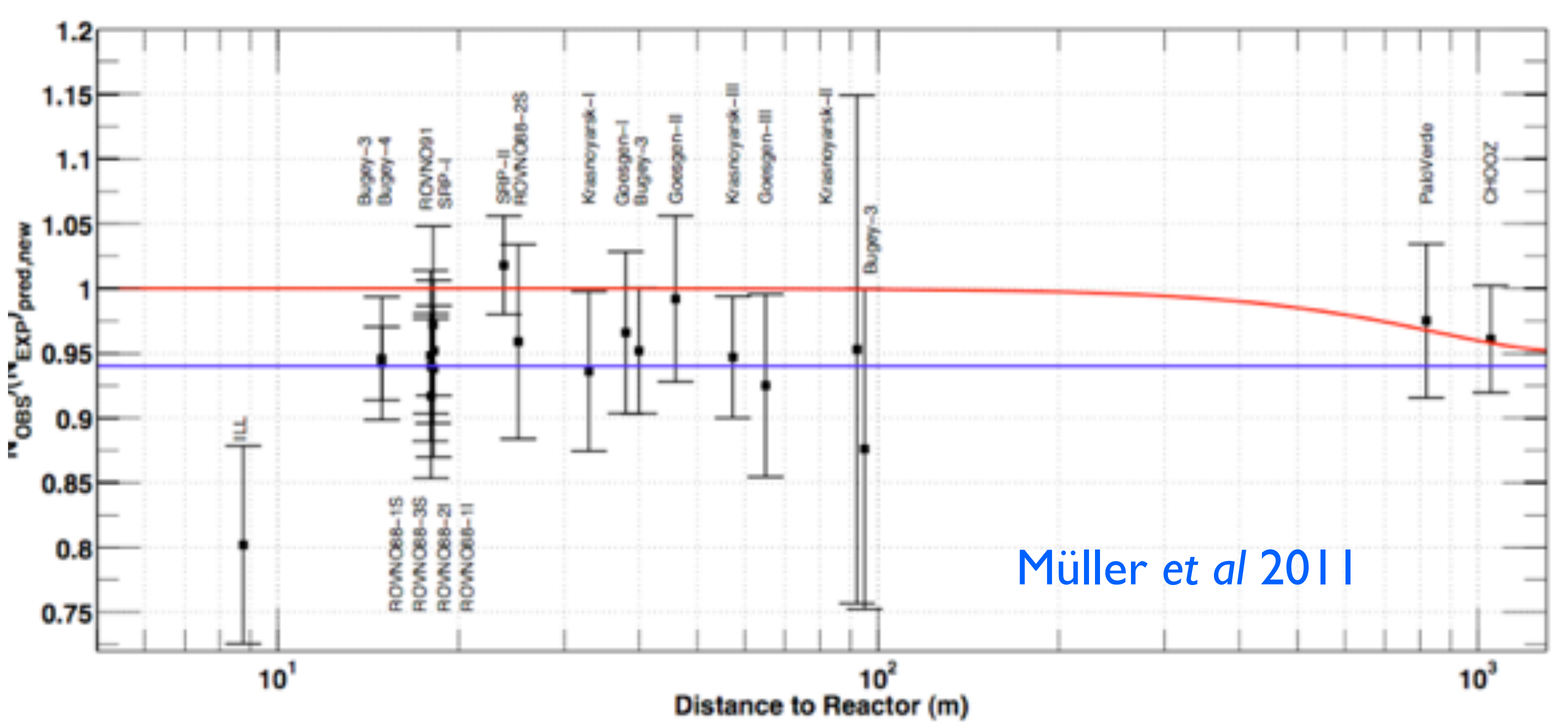


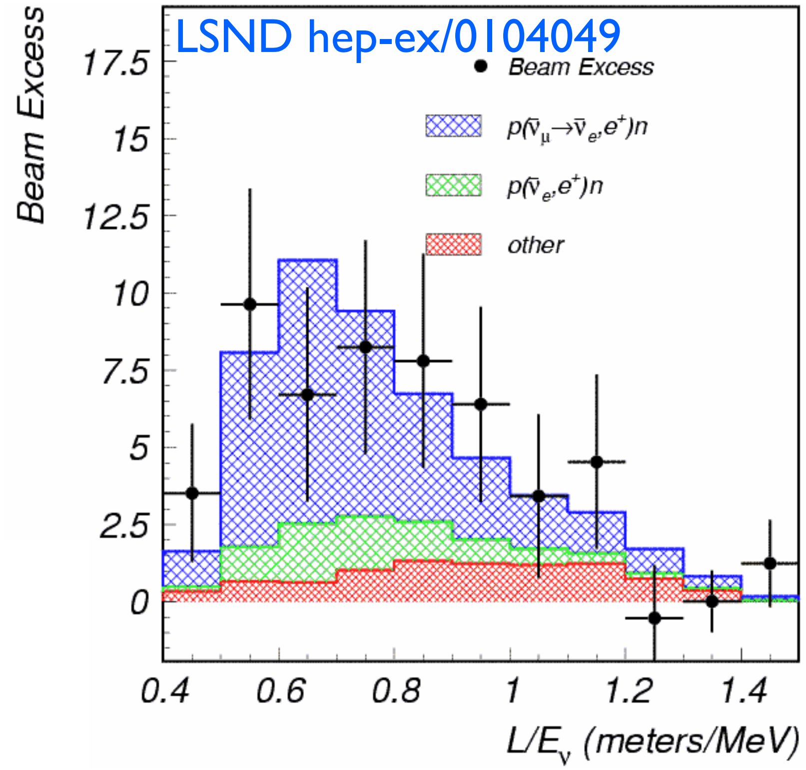
Cabezudo Dentler Kopp Machado
Maltoni Martinez-Soler Schwetz, to appear





see also Collin Arguelles Conrad Shaevitz 2016, Gariazzo Giunti Laveder Li 2017





Cabezudo Dentler Kopp Machado
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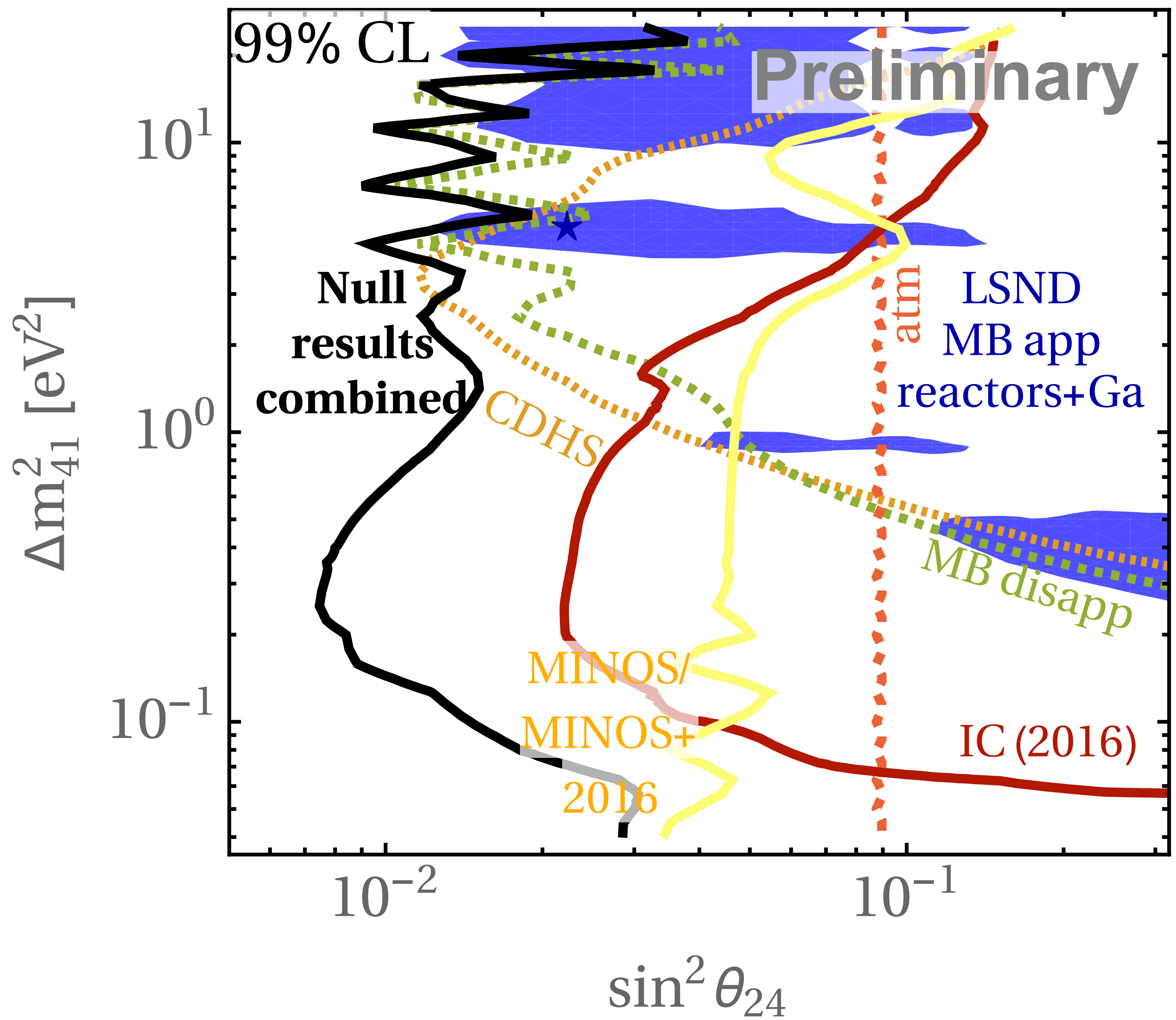
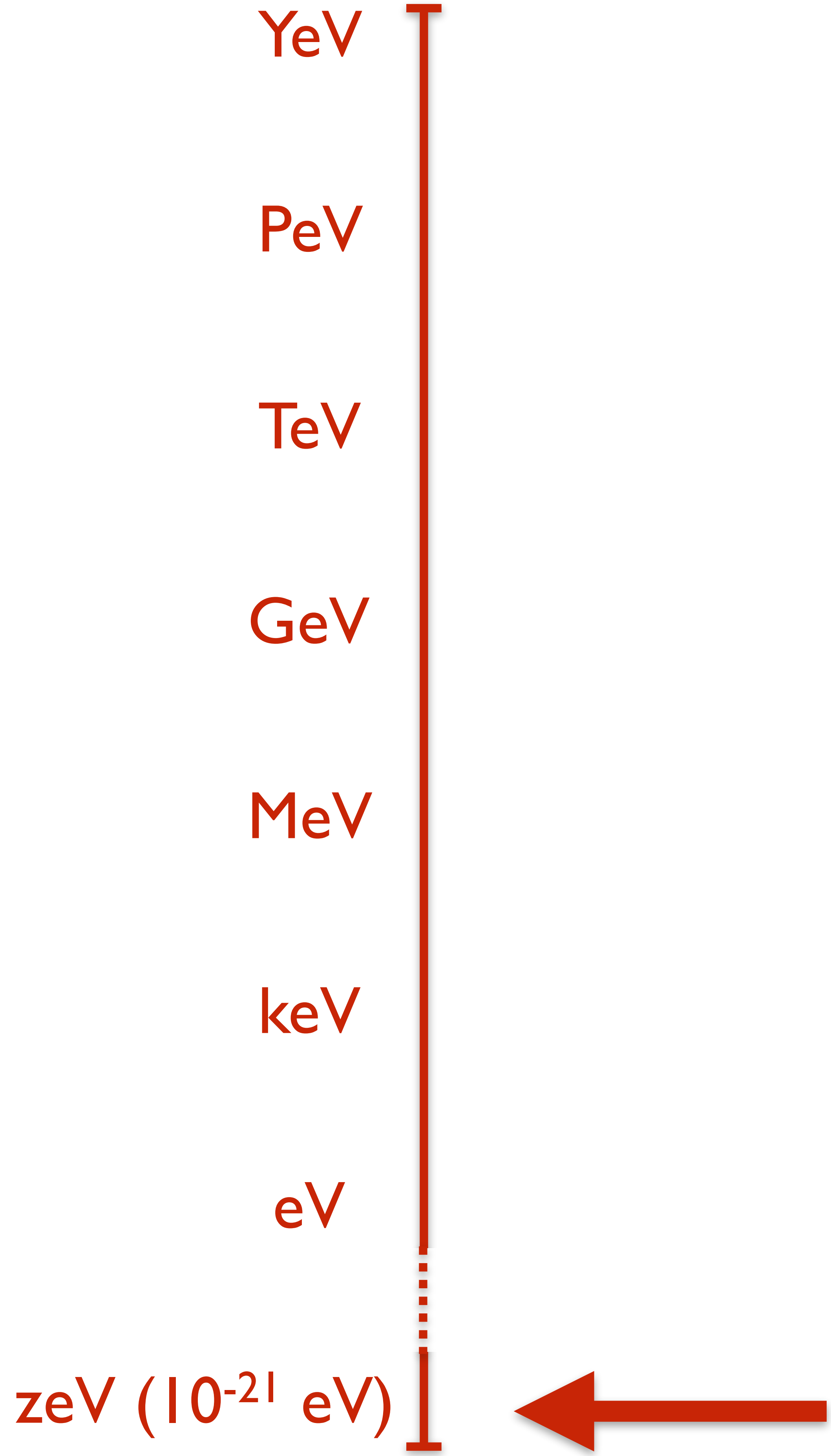


see also Collin Arguelles Conrad Shaevitz 2016, Gariazzo Giunti Laveder Li 2017

SBN Program


YeV
PeV
TeV
GeV
MeV
keV
eV
zeV (10^{-21} eV)

Neutrinos and new Physics

Going to even smaller scales:

Dark matter can be an ultra-light scalar field (e.g. $m_\varphi = 10^{-21}$ eV)

It behaves like a classical field, not like a particle

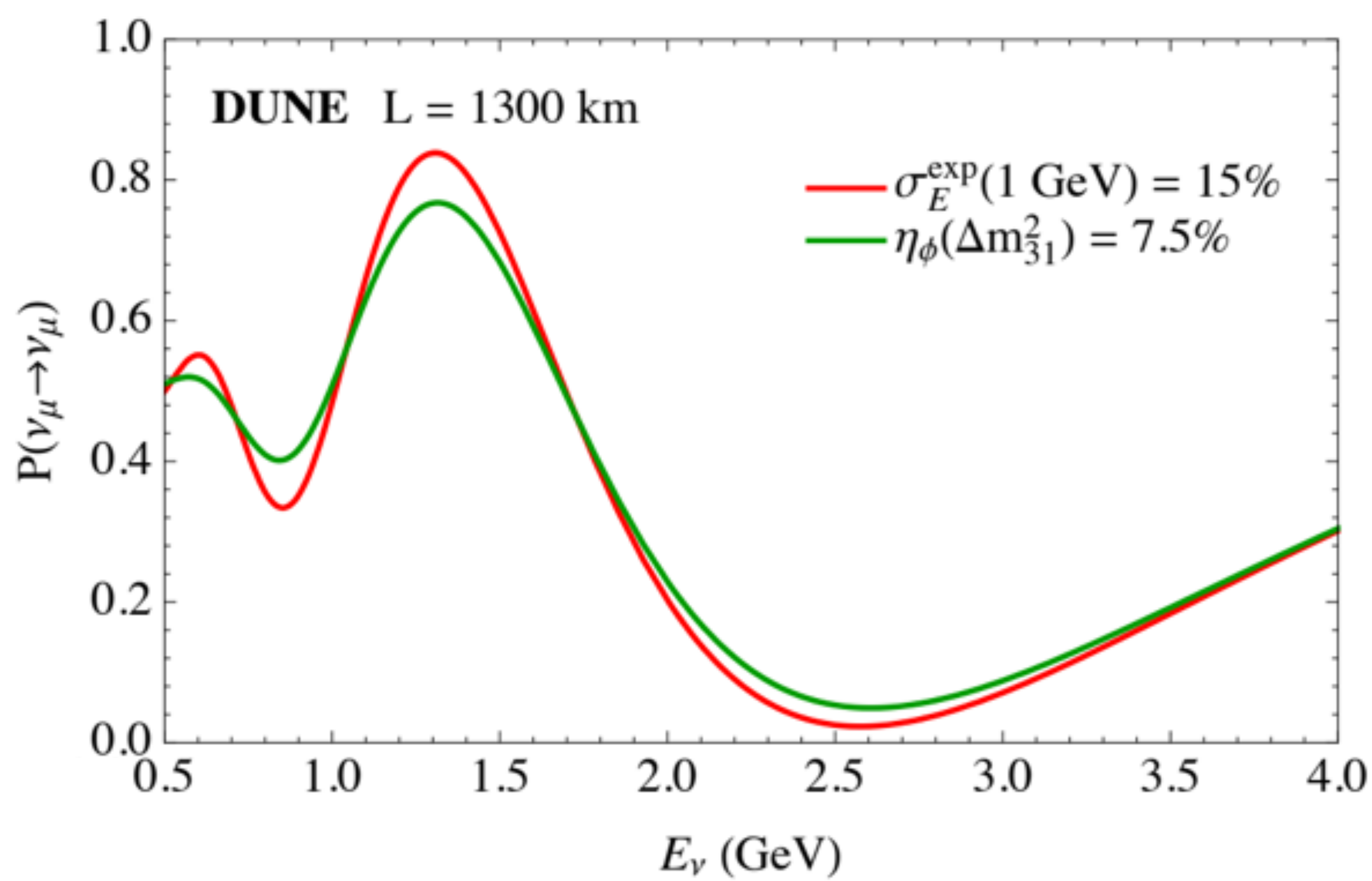
If it couples to neutrinos, it induces temporal variations in parameters

10 min < T < 10 years: modulation signal @SNO, SK

Berlin 2015

few millisec < T < 10 years: Distorted Neutrino Oscillations (DiNOs)

Krnjaic Machado Necib 2017



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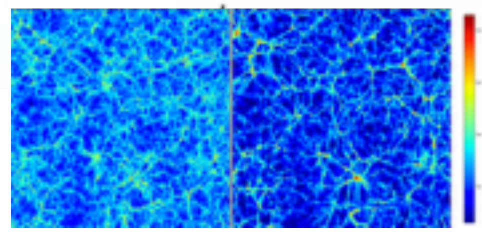
Many many many other fronts!

Neutrino cross sections (NuSTEC effort)

Neutrinos in cosmology
Early universe - BBN



Abazajian, Barbieri, Cirelli, Chizov, Di Bari, Dodelson, Dolgov, Foot, Holanda, Iocco, Kirilova, Kusenko, Mangano, Lesgourges, Pastor, Smirnov, Steigman, Volkas

Secret neutrino interactions

Dasgupta Kopp 2013, Chu Dasgupta Kopp 2015, Lundkvist Archidiacono Hannestad Tram 2016, Ghalsasi McKeen Nelson 2016, Archidiacono Gariazzo Giunti Hannestad Hansen Laveder Tram 2016, Forastieri Lattanzi Mangano Mirizzi Natoli Saviano 2017

Supernova evolution: non-linear effects from collective oscillations

Friedland 2010, Cherry Carlson Friedland Fuller Vlaesnko 2012, Chakraborty Hansen Izaguirre Raffeelt 2016, Capozzi Basudeb Dasgupta 2016, Izaguirre Raffelt Tamborra 2016, Capozzi Dasgupta Lisi Marrone Mirizzi 2017

Chen Ratz Trautner 2015

Cosmic neutrino background: ideas to measure it? Non-thermal component?

Type II, type III and radiative seesaw

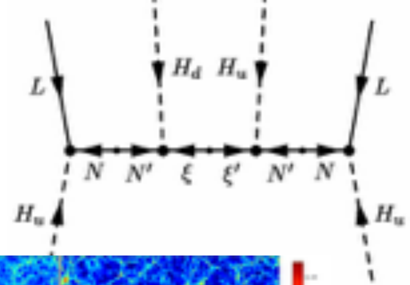
Akhmedov, Bonnet, Babu, Barbieri, Barger, Berezhiani, Ellis, Gaillard, Glashow, Hirsch, Keung, Ma, Mohapatra, Ota, Pakvasa, Schechter, Senjanovic, Valle, Yanagida, Winter, Wolfenstein, Zee, and many others

Flat extra dimensions: light sterile neutrinos

Antoniadis, Arkani-Hamed, Barbieri, Berryman, Davoudiasl, Dimopoulos, Dvali, de Gouvea, Langacker, Machado, Mohapatra, Nandi, Nunokawa, Perelstein, Peres, Perez-Lorenzana, Smirnov, Strumia, Tabrizi, Zukanovich-Funchal, …

Leptogenesis

Barenboim, Davidson, Di Bari, Dolgov, Fukugita, Kuzmin, Rubakov, Servant, Shaposhnikov, Yanagida, Zeldovich, …

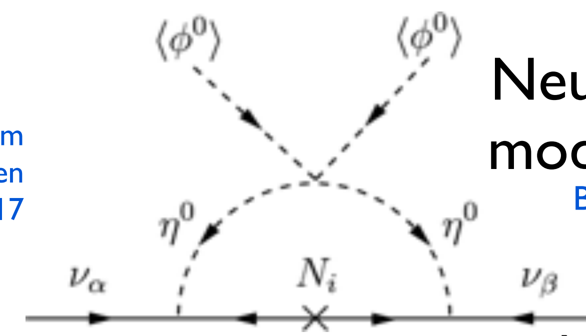


Sterile neutrino in long baseline oscillation experiments

Agarwalla, Bhattacharya, Chaterjee, Dasgupta, Dighe, Donini, Fuki, Klop, Lopez-Pavon, Meloni, Migliozzi, Palazzo, Ray, Tang, Terranova, Thalapillil, Wagner, Yasuda, Winter, …

Dark matter in neutrino detectors: light DM and light mediators

Ballett, Batell, Chen, Coloma, deNiverville, Dobrescu, Frugiuele, Harnik, McKeen, Pascoli, Pospelov, Ritz, Ross-Lonergan

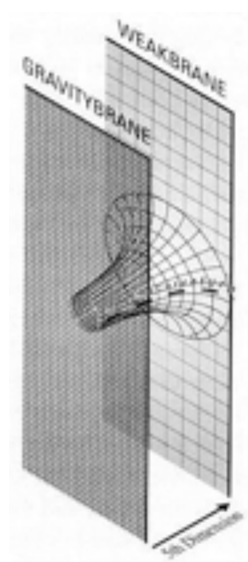


Neutrinos and the standard solar model: CNO cycle and metallicity

Bailey, Busoni, Christensen-Dalsgaard, Krief, Simone, Serenelli, Scott, Vincent, Vilante, Vissani, Vynioli, …

Neutrino magnetic moment

see e.g. Salam 1957, Barbieri Fiorentini 1988, Barbieri Mohapatra 1989, Babu Chang Keung Phillips 1992, Tarazona Diaz Morales Castillo 2015 Cañas Miranda Parada Tortola Valle 2015, Barranco Delepine Napsuciale Yebra 2017 Coloma Machado Martinez-Soler Shoemaker 2017

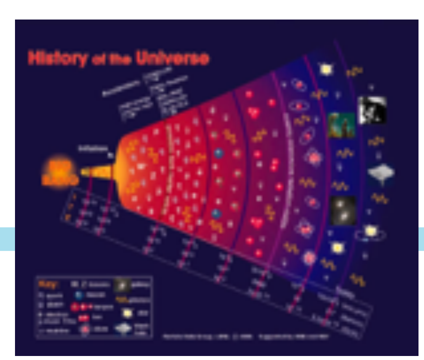


Discrete symmetries with non-zero θ_{13}

Feruglio Hagedorn Toroop 2011, Lam 2012, Lam 2013, Holthausen Lim Lindner2012, Neder King Stuart 2013, Hagedorn Meroni Vitale 2013 King Neder 2014, Ishimori King Okada Tanimoto 2014, Yao Ding 2015 , …

Effective operator approach to neutrino masses and collider/low scale pheno

de Gouvea Jenkins 2007, Boucenna Morisi Valle 2014, Nath Syed 2015, Geng Tsai Wang 2015, Chiang Huo 2015, Bhattacharya Wudka 2015, Geng Huang 2016, Quintero 2016, Mohapatra 2016, Kobach 2016



New physics in neutrinoless double beta decay, lepton number violation at the LHC, left-right models, RS models and neutrino masses, neutrinos as dark matter, and much more!

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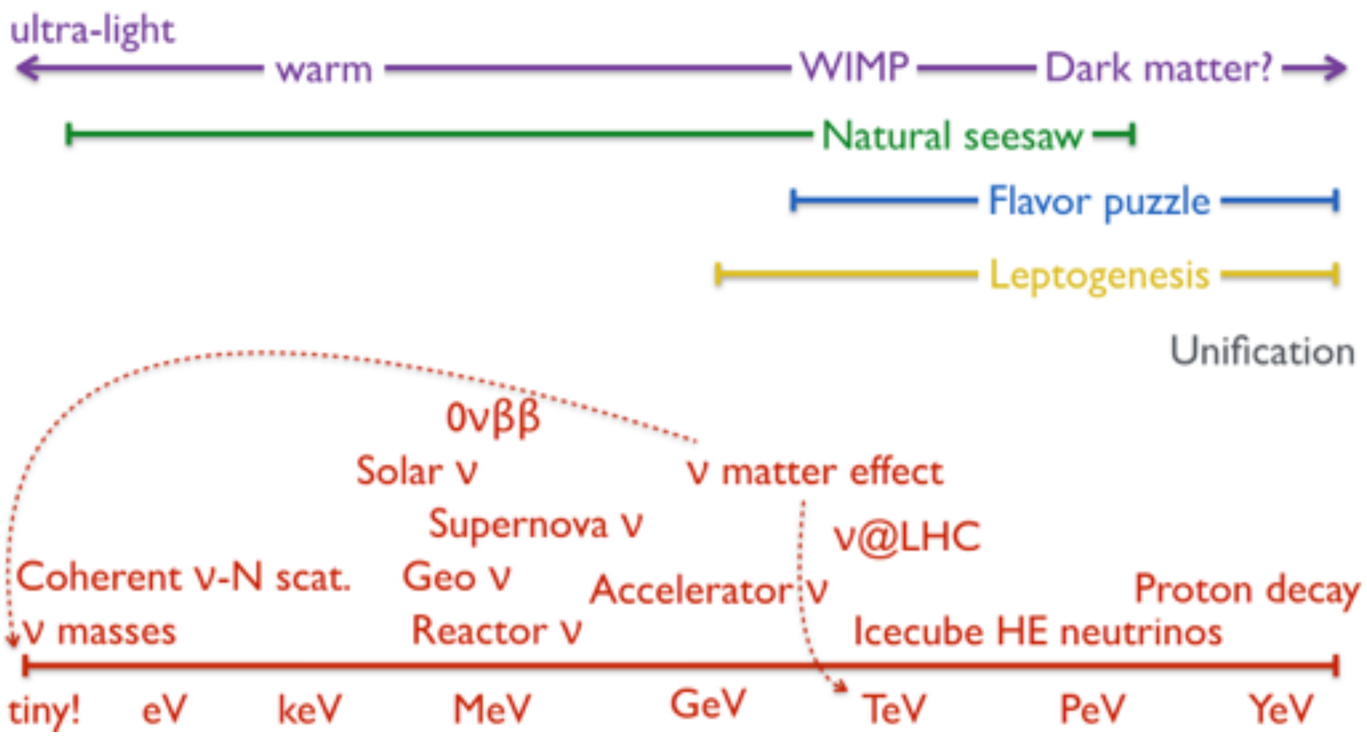
Conclusions



Neutrinos: enormous range of energy scales - experimental and theoretical fronts

Most exciting aspect of neutrino physics and also a big challenge

DUNE range:
- zeV (ν-DM couplings)
- eV (sterile ν)
- GeV, TeV (oscillations)
- YeV (proton decay)
- 45 orders of magnitude!!!

from 0.000000000000000000000000000001 to 1000000000000000 proton mass!!!

Standard predictions: essential for probing BSM with neutrinos

Ongoing TH effort: identify all BSM testable with neutrinos

A coherent neutrino theory endeavor, addressing all aspects of neutrino physics, is essential for the success of the neutrino program