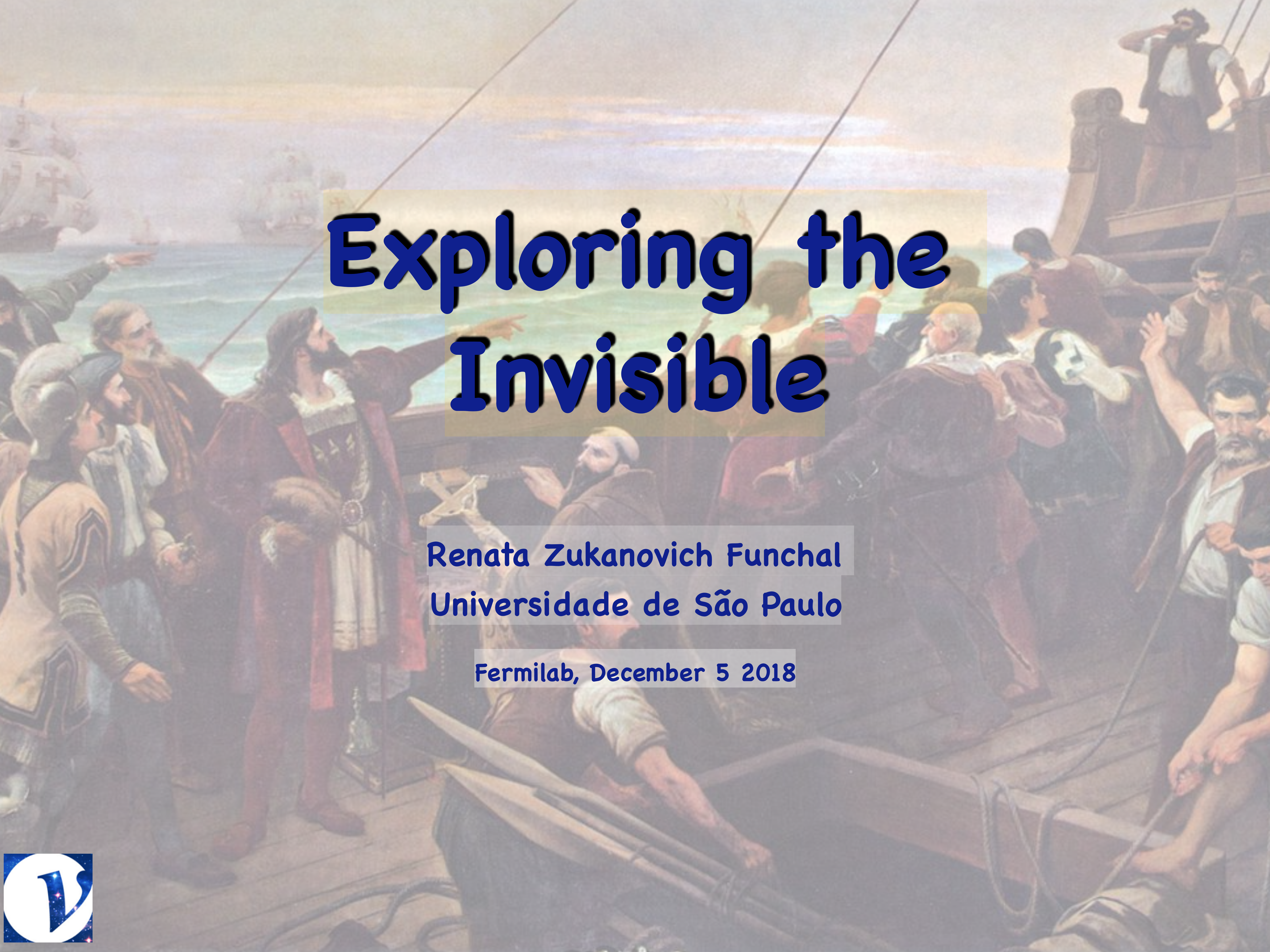


Exploring the Invisible

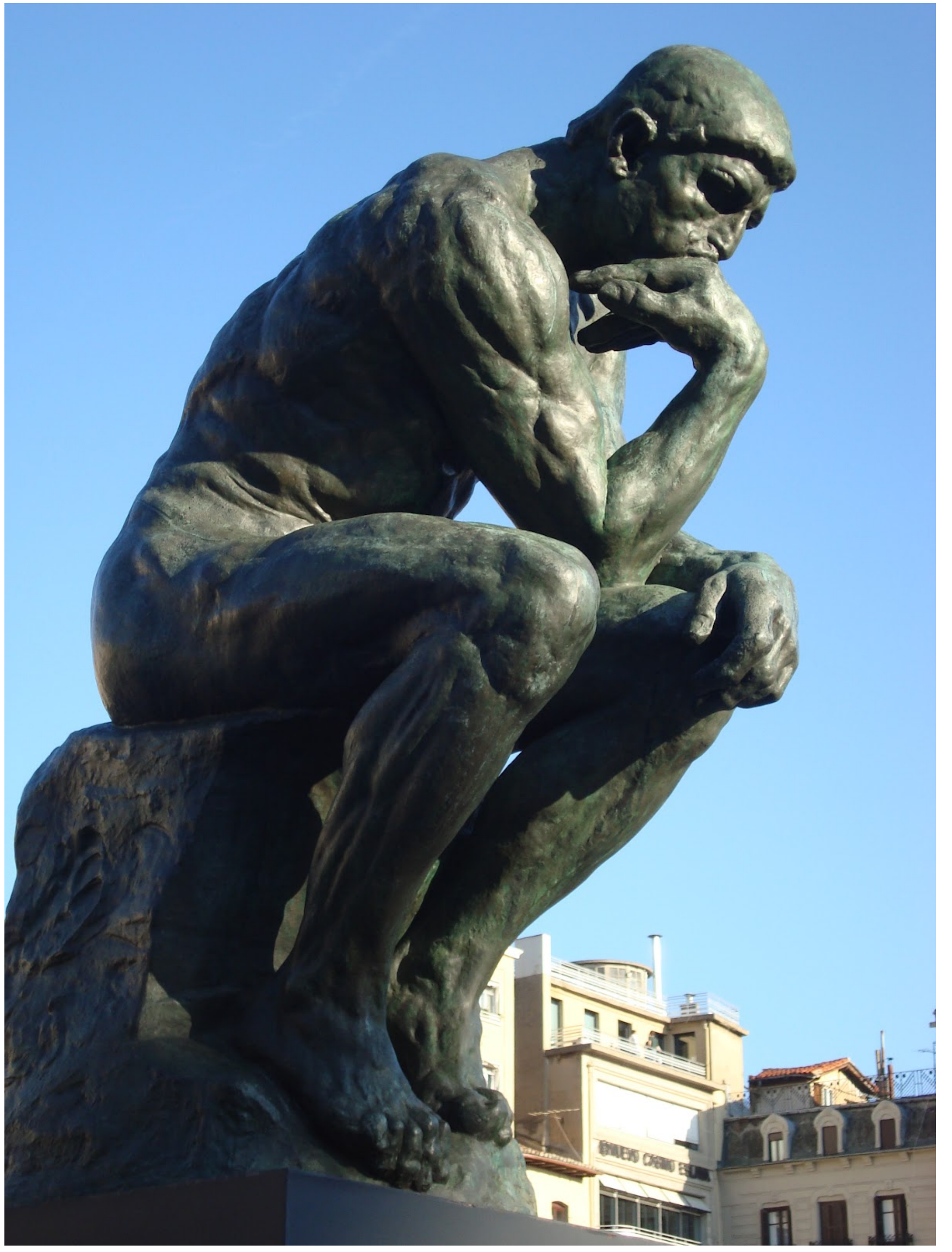
Renata Zukanovich Funchal

Universidade de São Paulo

Fermilab, December 5 2018

Route to INDIA

What is the Universe made of ?



Our Universe = The Milky Way (Via Lactea)

GRAVITY

Basic Constituents of Matter:

ELETROMAGNETISM

J.J. Thomson

1897

electron

-

light

proton

+

E. Rutherford

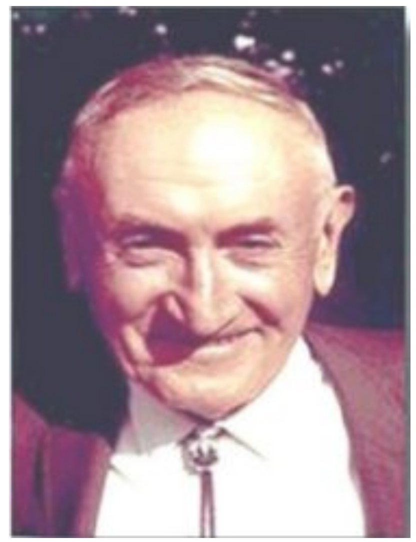
1920

"There are **more things in heaven and earth**, Horatio ..."

More Things in Heaven: Something Invisible

Andromeda is a Galaxy !

Early 1930's



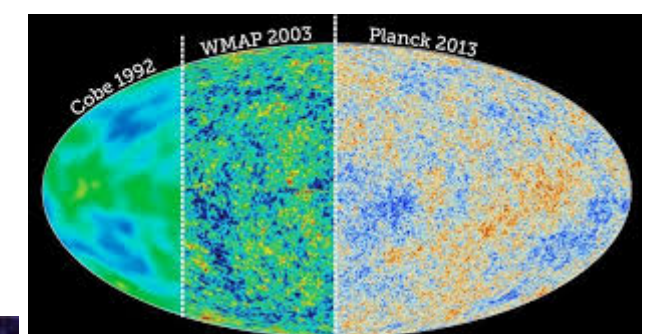
Fritz Zwicky

investigating galaxy clusters

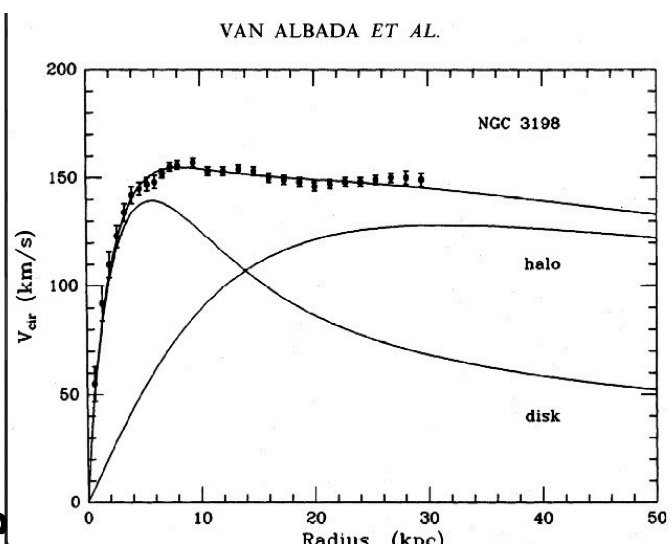
obtain evidence of unseen matter

"dunkle Materie" (Dark Matter)

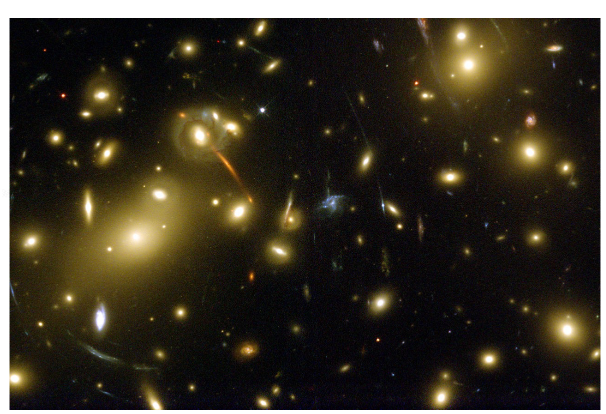
Since then many more (Gravitational) evidence of DM



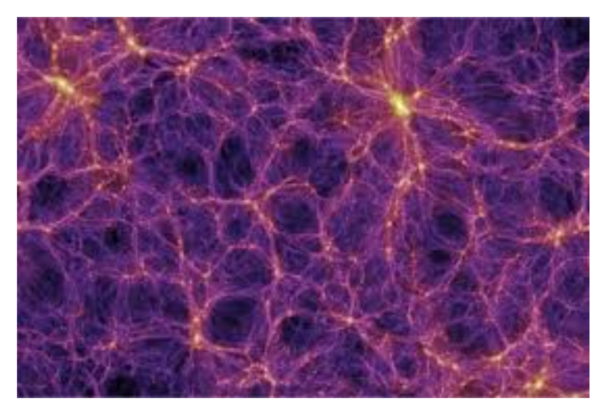
CMB



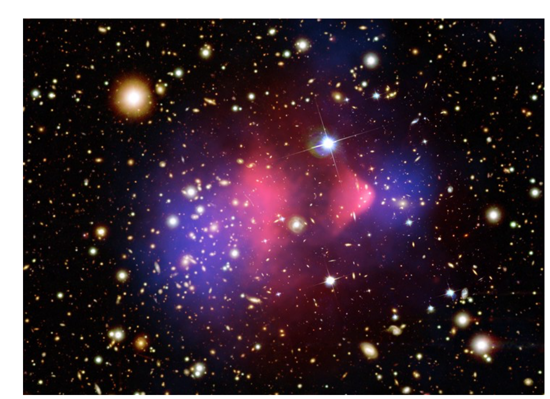
galatic rotation curves



gravitational lensing



large scale structure



bullet cluster

More Things in Heaven: Something Invisible

Energy Budget of the Universe :

13.7 billion years ago - 63% DM

Today - 27% DM

Compelling Hypothesis:

DM is a (electrically neutral) particle: i.e. a thermal relic of from hot Big Bang

DM has non-gravitational interaction:

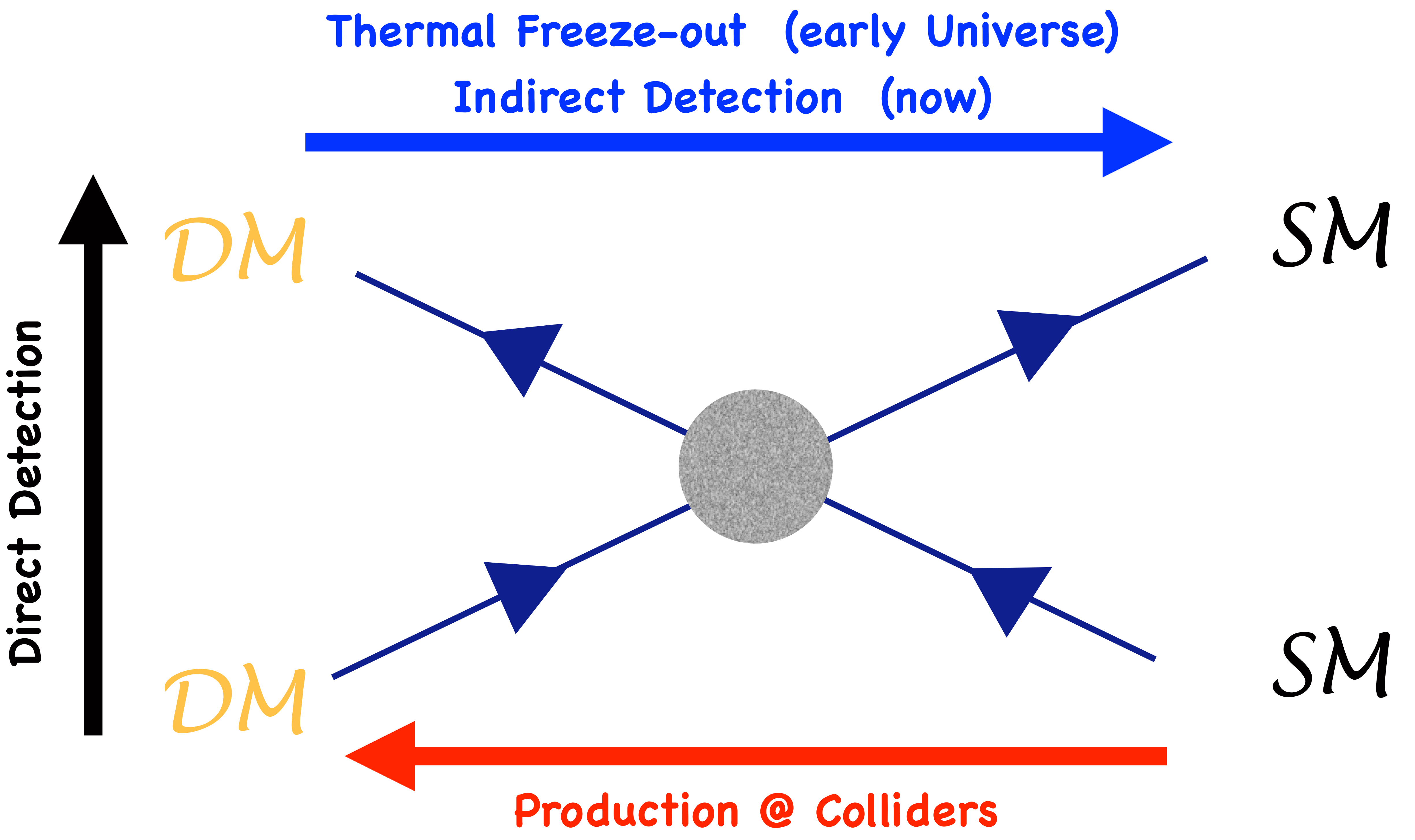
need thermal contact between DM - SM particles to deplete abundance

Canonical Approach:

Weakly Interacting Massive Particle:

DM has weak-scale mass
DM is coupled to SM particles by electroweak gauge interactions
Minimal dark sector

3 Ways of Hunting Dark Matter



What we really know about Dark Matter ?

New Possibilities that may be investigated in connection the next Invisible: Neutrinos

We really do not know the mass scale
Why not PeV, GeV, MeV, keV, meV etc.?

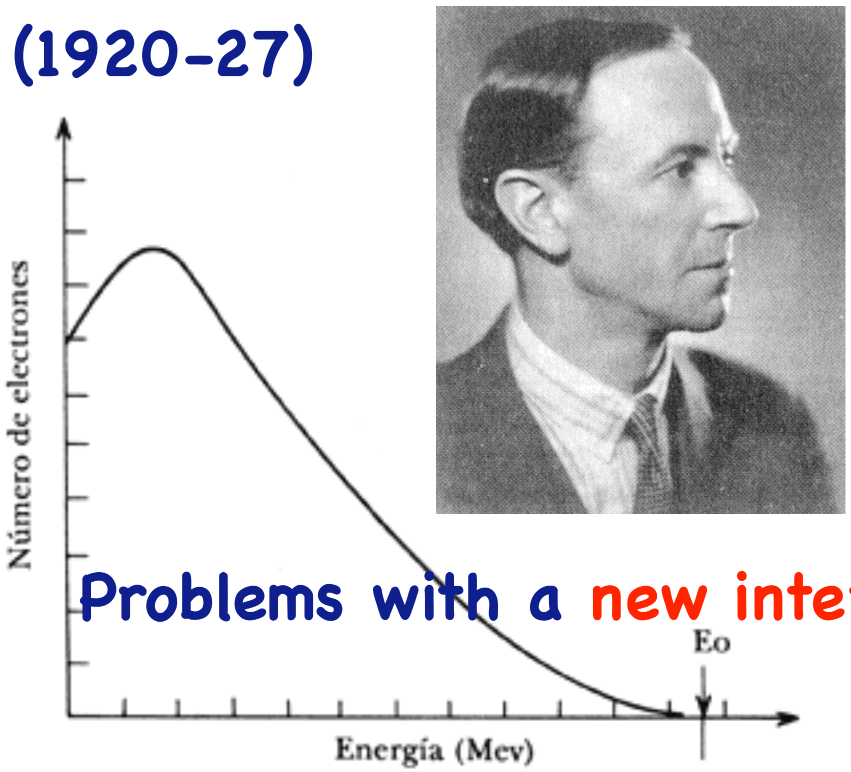
The interaction with SM particles does not have to be the gauge one
Why not use other possible portals : vector, scalar, neutrino ?

The number of DM species is undetermined
Why not a flavorful dark sector?

More Things in Earth: Something Else Invisible - Neutrinos

(1920-27)

James Chadwick



Problems with a new interaction

1930

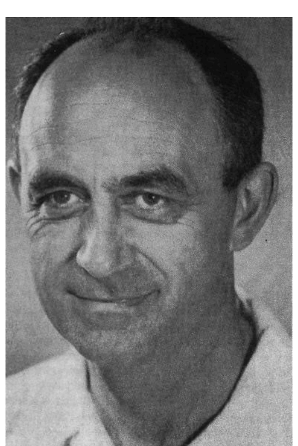
Invented and Invisible:

The neutrino is born

Wolfgang Pauli

Enrico Fermi

1933



A theory for the weak interaction

1956 : Fred Reines & Clyde Cowan ν_e

1962 : Steinberger, Lederman & Schwartz ν_μ

Standard Model

2000 : DONUT Collaboration ν_τ

When you find land … Explore!

More Things in Earth: Neutrinos Change Flavor

What have we observed so far?

- Solar ν_e transitions to ν_μ/ν_τ (Cl, Ga, SK, SNO, Borexino)
- Atmospheric ν_μ & $\bar{\nu}_\mu$ disappearing mostly to ν_τ (SK, MINOS, ICECUBE)
- Accelerator ν_μ & $\bar{\nu}_\mu$ disappear (K2K, T2K, MINOS, NOνA)
- Accelerator ν_μ reappearing as ν_e (T2K, MINOS, NOνA)
- Reactor $\bar{\nu}_e$ disappear (KamLAND, DC, Daya Bay, RENO)

More Things in Earth: Neutrinos Change Flavor

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misalignment

$$\nu_e, \nu_\mu, \nu_\tau \neq \nu_1, \nu_2, \nu_3$$

flavor eigenstates — U^ν — mass eigenstates

neutrinos undergo flavor transitions driven by mass and mixing

first evidence of Beyond SM Physics !

Exploring the Properties of Neutrinos: Mass & Mixing

Charged Current Interaction is not diagonal in the mass basis (as for quarks!)

$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{\alpha j} \left(U^\nu_{\alpha j}\, \bar{e}_\alpha \gamma^\mu P_L\, \nu_j \right) + \text{h.c.}$$

mixing matrix element

standard parametrization

$$U^\nu = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-\imath\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{\imath\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{\imath\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{\imath\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{\imath\delta} & c_{23}c_{13} \end{pmatrix} V$$

3 mixing angles + 1 fase

$$c_{ij} \equiv \cos\theta_{ij} \quad s_{ij} \equiv \sin\theta_{ij} \quad \theta_{ij} \in [0, \pi/2] \quad \delta \in [0, 2\pi]$$

$$V = \text{diag}(\alpha_1, 1, \alpha_3)$$

Exploring the Properties of Neutrinos: Mass & Mixing

neutrino flavor oscillation

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j\neq i} \mathrm{Re}[U^{\nu *}_{\alpha i} U^{\nu}_{\beta i} U^{\nu}_{\alpha j} U^{\nu *}_{\beta j}] \sin^2\left(\frac{\delta_{ij}}{2}\right) + 2\sum_{j\neq i} \mathrm{Im}[U^{\nu *}_{\alpha i} U^{\nu}_{\beta i} U^{\nu}_{\alpha j} U^{\nu *}_{\beta j}] \sin(\delta_{ij})$$

phase differences

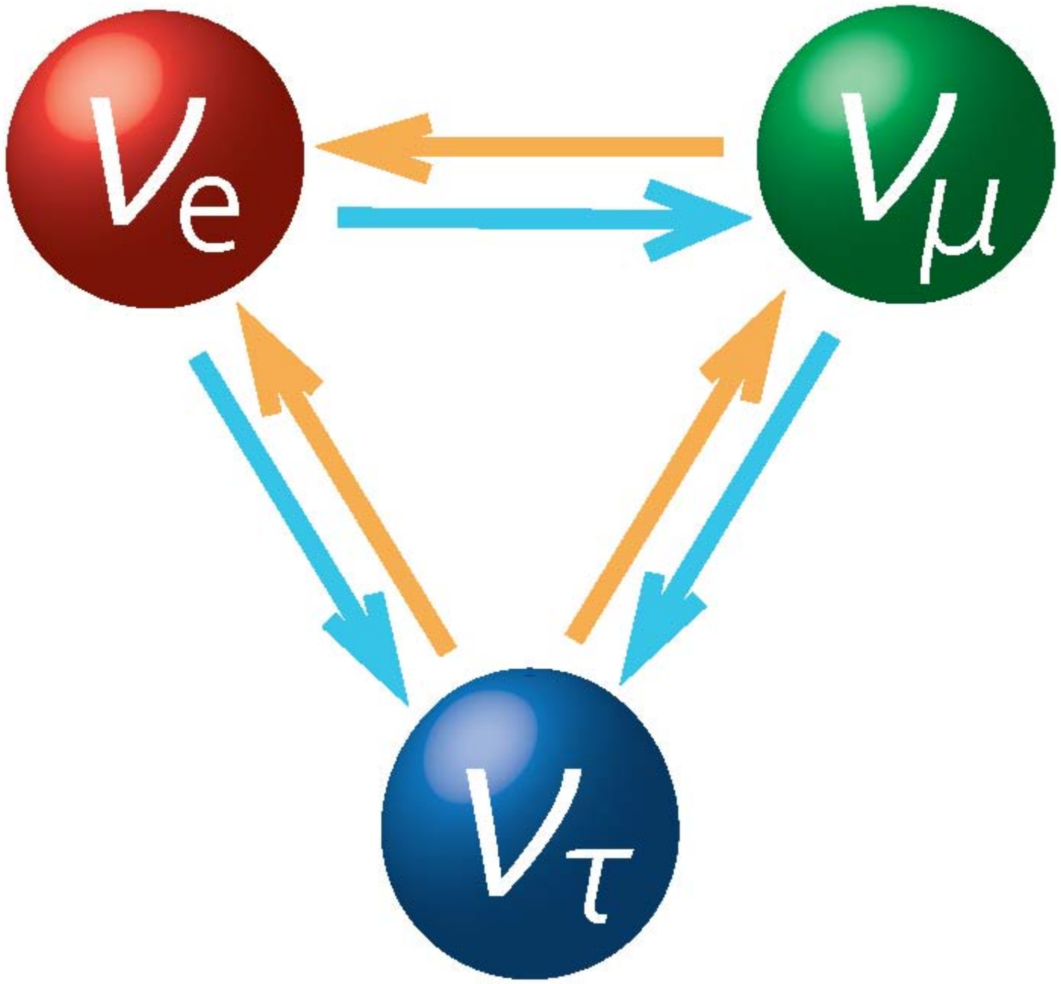
$$\frac{\delta_{ij}}{2} = (E_i^2 - E_j^2)\frac{L}{2} = 1.27\,\frac{\overbrace{(m_i^2 - m_j^2)}^{\Delta m^2_{ij}}}{\mathrm{eV}^2}\left(\frac{L}{\mathrm{km}}\right)\left(\frac{\mathrm{GeV}}{E}\right)$$

$$\Delta m^2_{31} = \Delta m^2_{32} - \Delta m^2_{21}$$

only two independent

antineutrino:

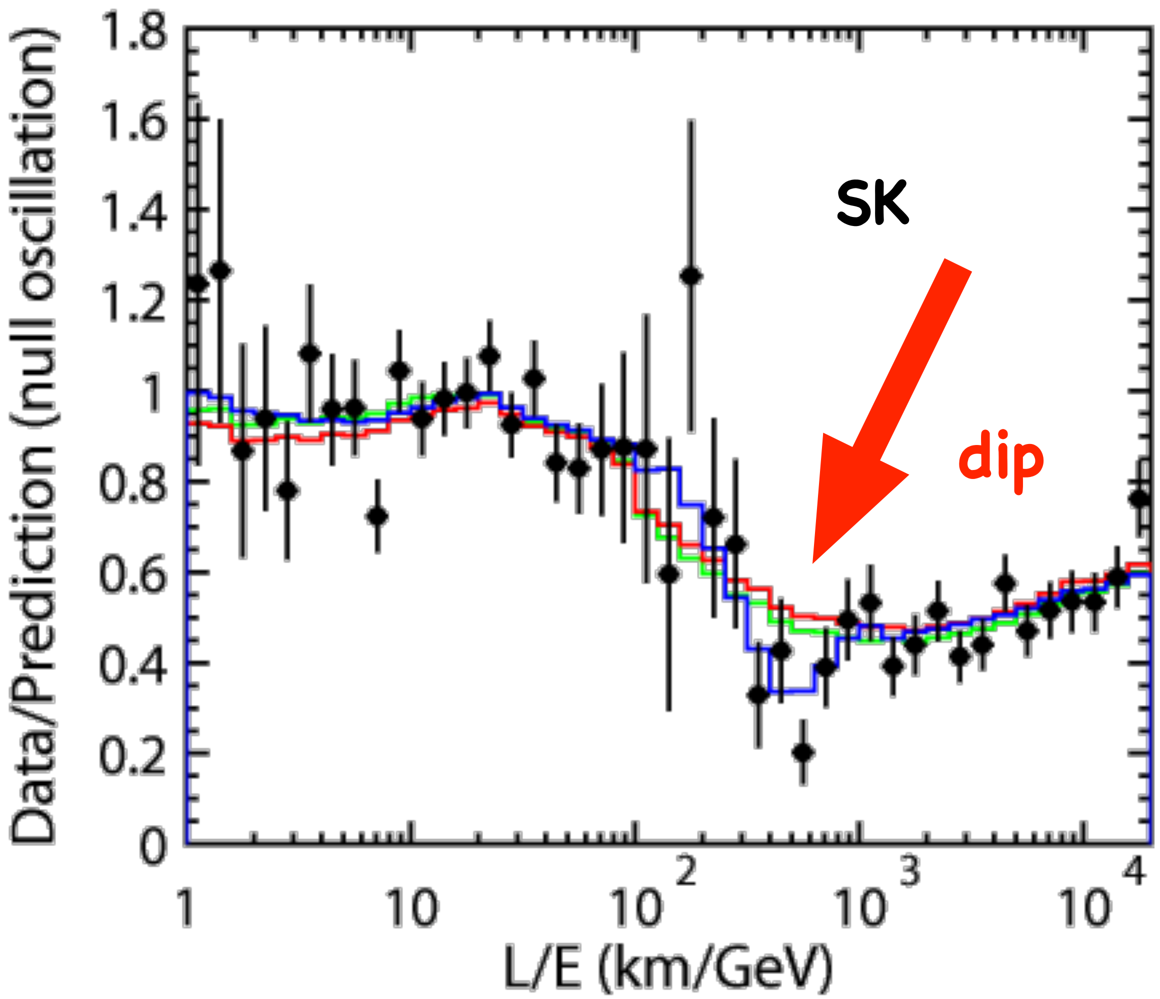
$$U^{\nu} \to U^{\nu *} \qquad \delta \to -\delta$$

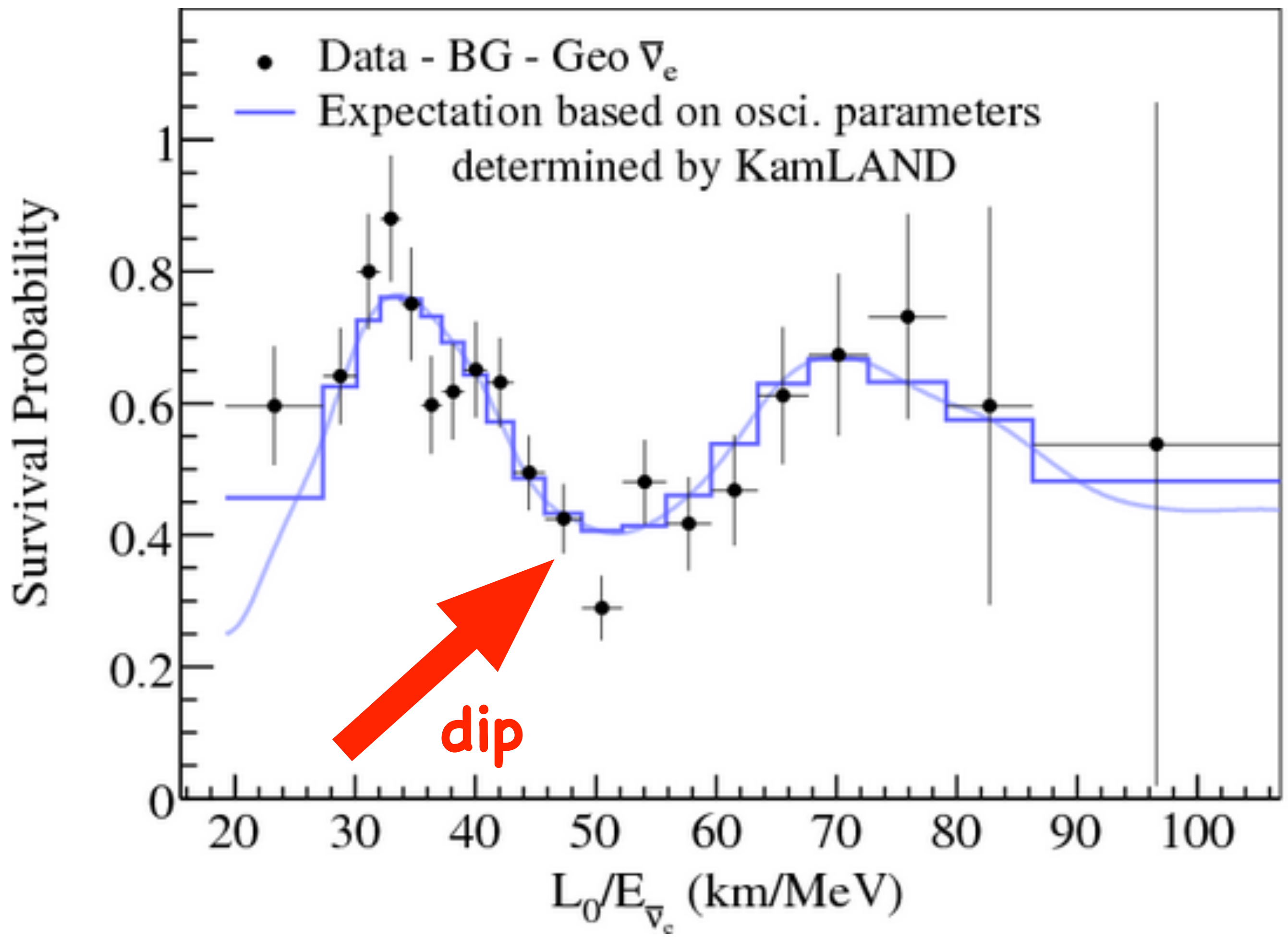


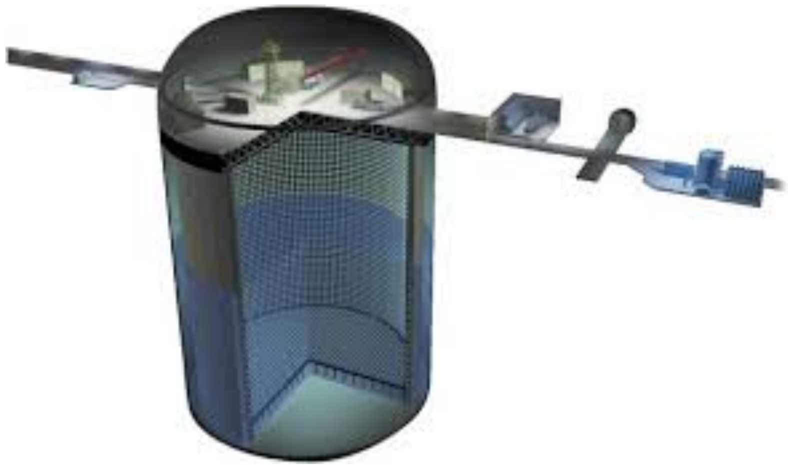
The Standard 3-ν Paradigm

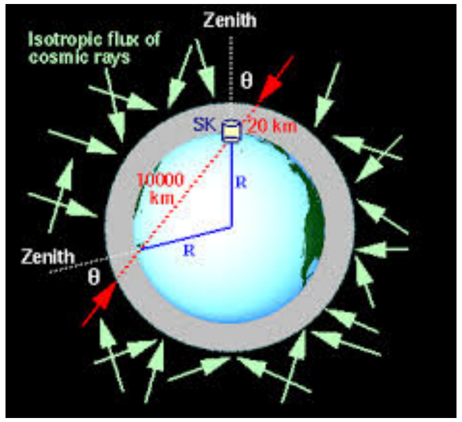
Exploring Neutrino Oscillations

We have seen L/E pattern in two frequencies

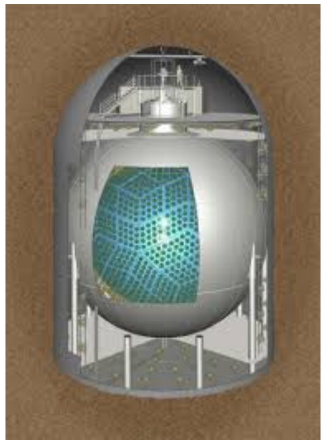






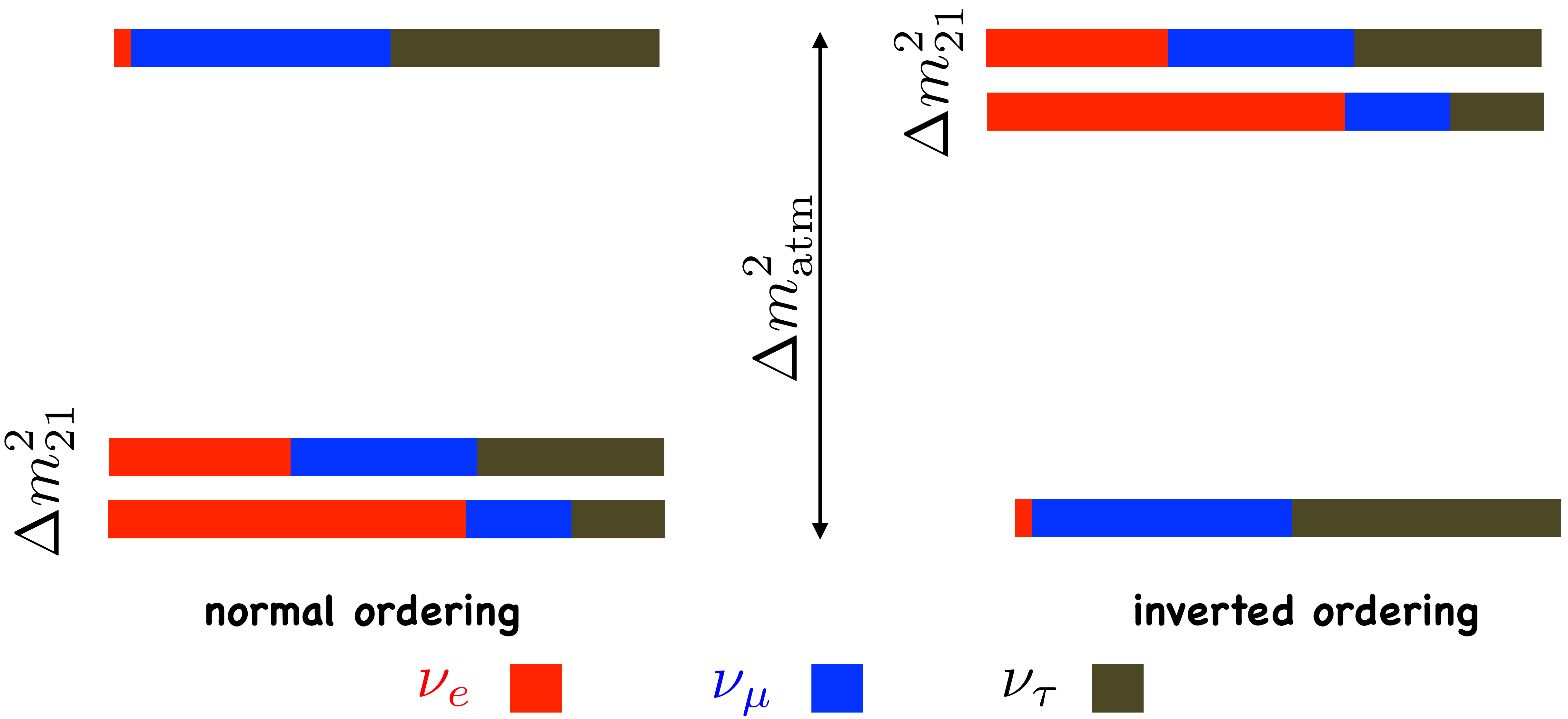


L ≈ 200 km from reactors



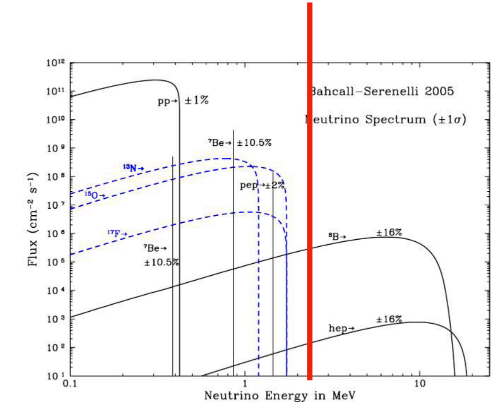
What do we know about the Mass Ordering ?

The 2 possible ordering



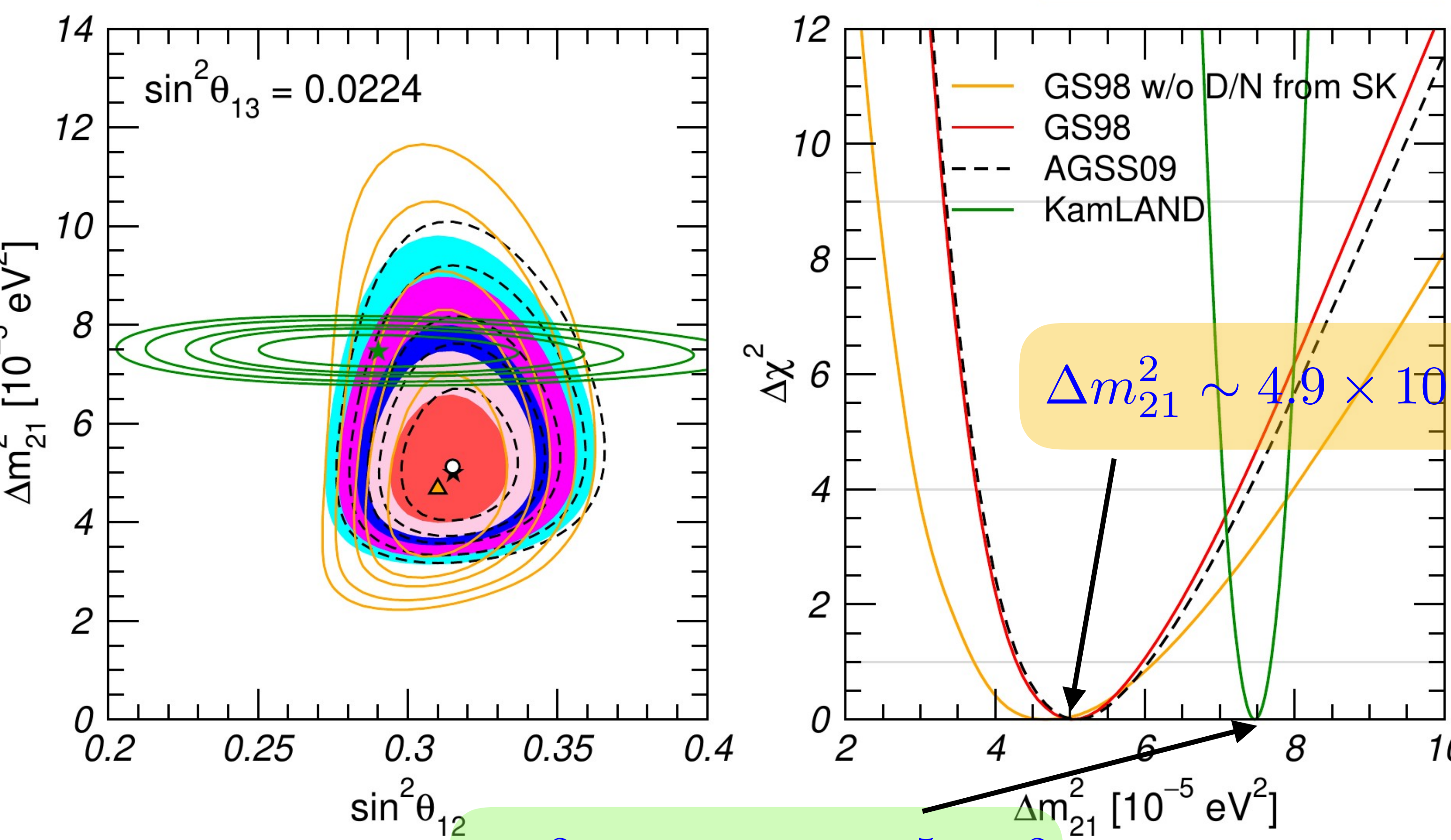
using $$|U^\nu_{e1}| > |U^\nu_{e2}| > |U^\nu_{e3}|$$

Exploring Neutrino Oscillations



EXPERIMENT	Dominant Dependence	Sub-dominant Dependence
Solar	θ_{12}	$\Delta m^2_{21}, \theta_{13}$
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12}, θ_{13}

NuFIT 4.0 (2018)



$\Delta m^2_{21} \sim 4.9 \times 10^{-5}$ eV^2

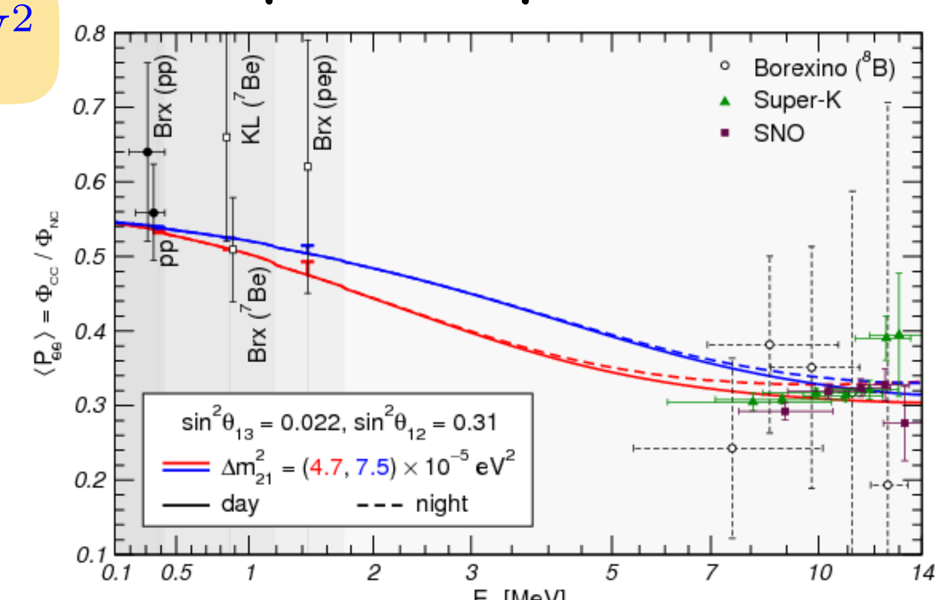
$\Delta m^2_{21} \sim 7.4 \times 10^{-5}$ eV^2

http://www.nu-fit.org

tension on Δm^2_{21}

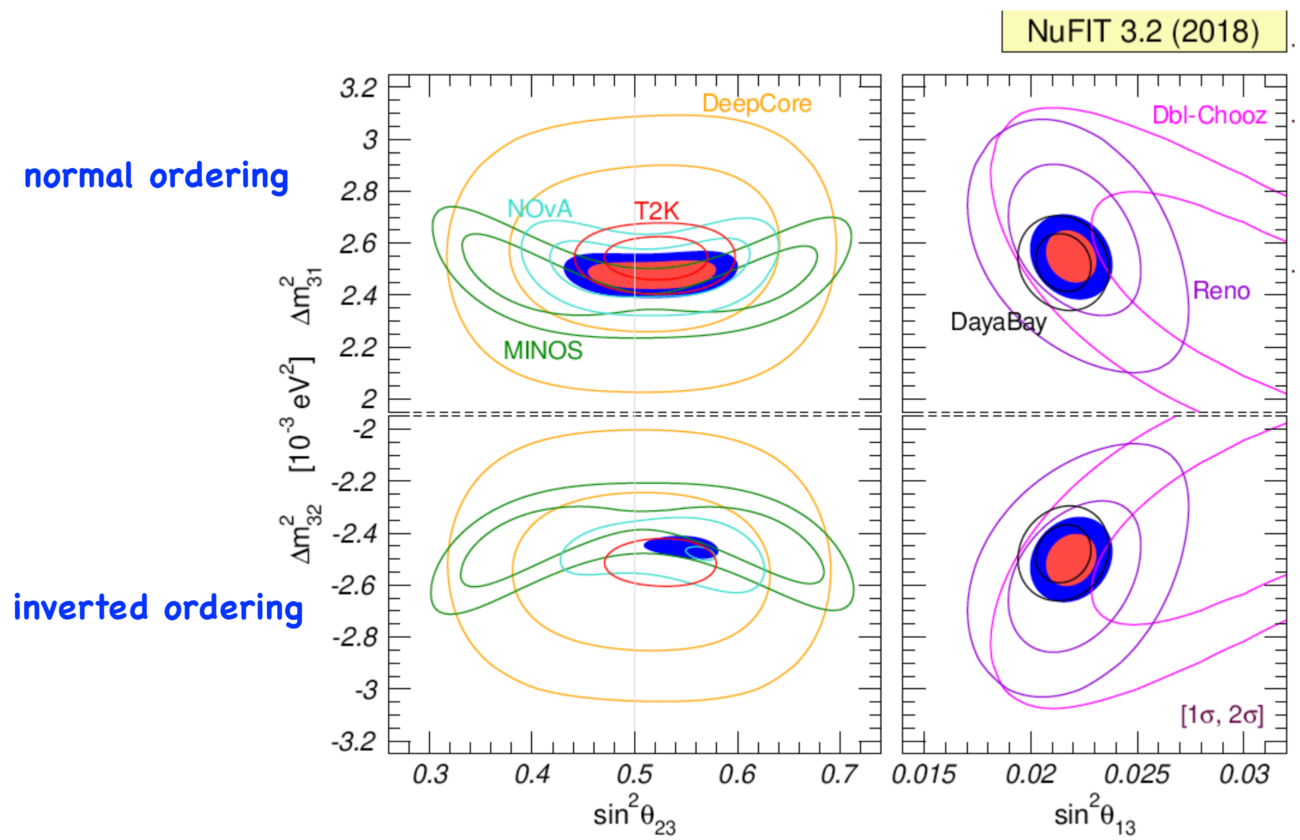
"too large" D/N @ SK

smaller than expected turn up of the spectrum

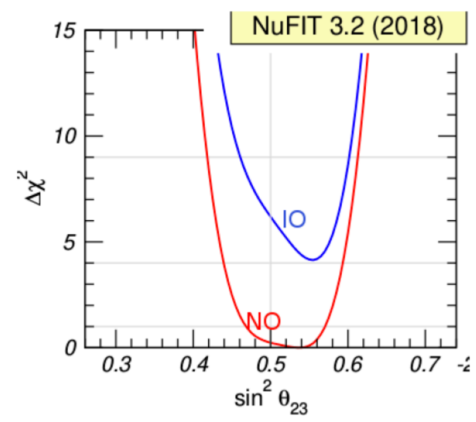


Exploring Neutrino Oscillations

EXPERIMENT	Dominant Dependence	Sub-dominant Dependence
Atmospheric	θ_{23}	$\Delta m^2_{\rm atm}, \theta_{13}, \delta$
Accelerator disappearance	$\Delta m^2_{\rm atm}$	θ_{23}
Accelerator appearance $\nu_\mu \to \nu_e$	θ_{13}	δ, θ_{23}
Reactor (Daya Bay, RENO, DC)	θ_{13}	$\Delta m^2_{\rm atm}$



- 32-sector now best determined by accelerator
- consistent $\Delta m^2_{\rm atm}$
- hint for $\theta_{23} > 45^\circ$



Exploring Neutrino Oscillations

PMNS

NuFIT 4.0 (2018)

$$|U|_{3\sigma}^{\text{w/o SK-atm}} = \begin{pmatrix} 0.797 \to 0.842 & 0.518 \to 0.585 & 0.143 \to 0.156 \\ 0.233 \to 0.495 & 0.448 \to 0.679 & 0.639 \to 0.783 \\ 0.287 \to 0.532 & 0.486 \to 0.706 & 0.604 \to 0.754 \end{pmatrix}$$

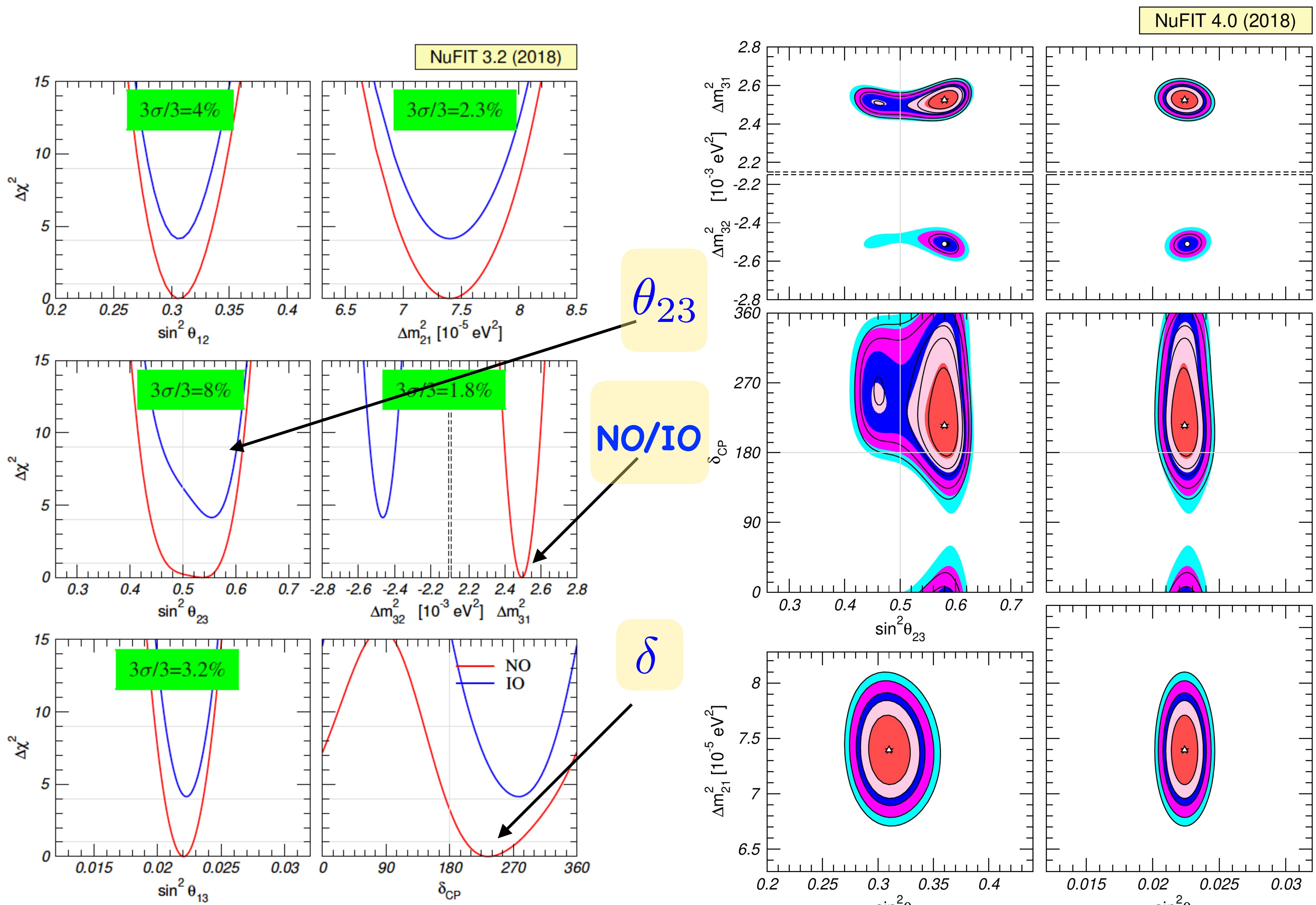
$$|U|_{3\sigma}^{\text{with SK-atm}} = \begin{pmatrix} 0.797 \to 0.842 & 0.518 \to 0.585 & 0.143 \to 0.156 \\ 0.235 \to 0.484 & 0.458 \to 0.671 & 0.647 \to 0.781 \\ 0.304 \to 0.531 & 0.497 \to 0.699 & 0.607 \to 0.747 \end{pmatrix}$$

CKM

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}.$$

Exploring Neutrino Oscillations

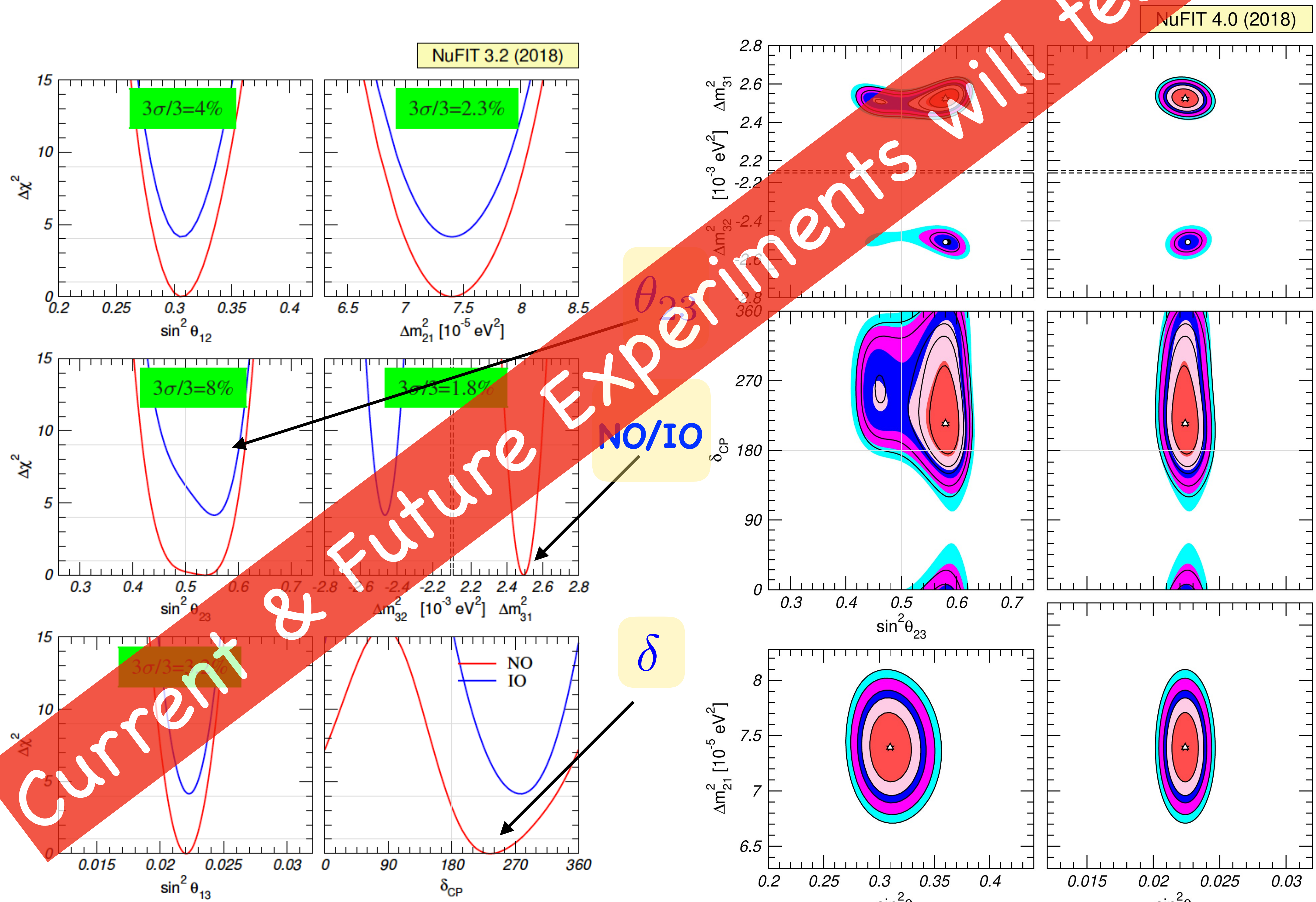
http://www.nu-fit.org



M.C.Gonzalez-Garcia (2018)

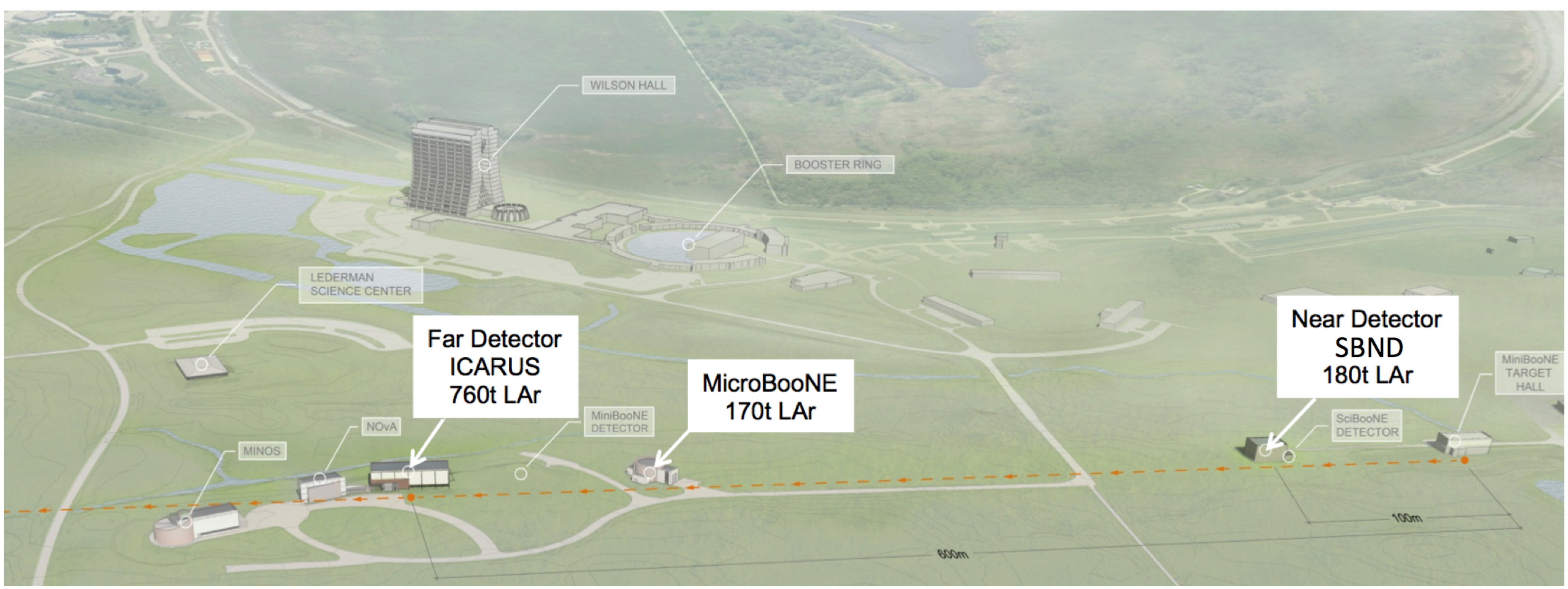
Exploring Neutrino Oscillations

http://www.nu-fit.org

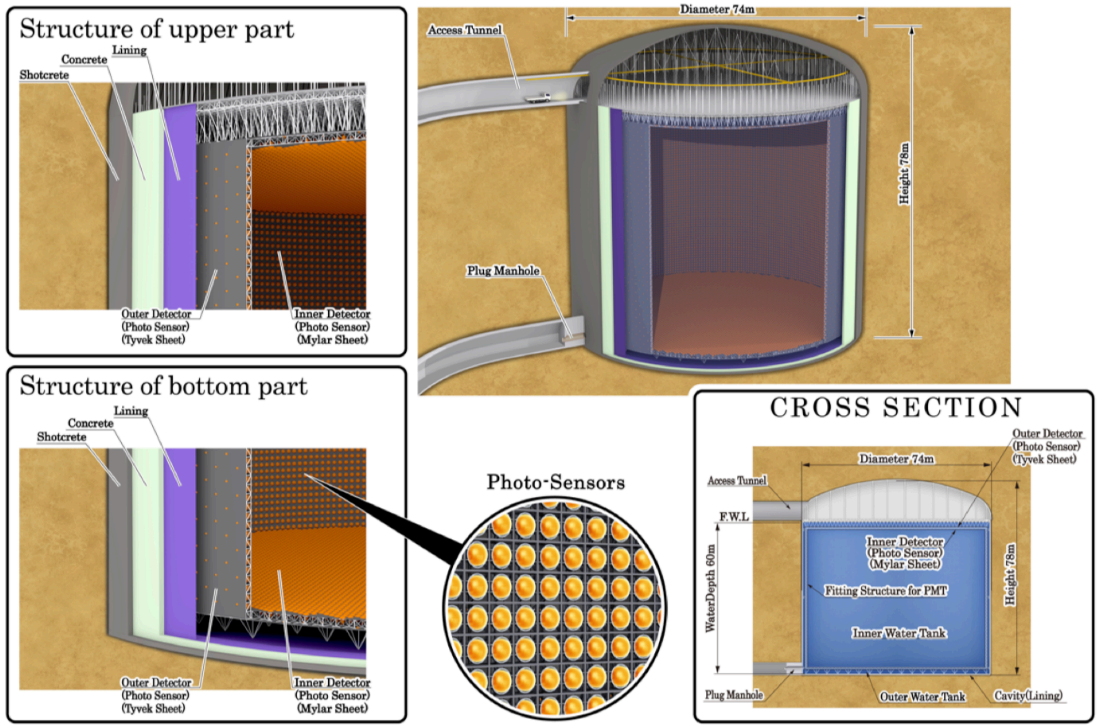


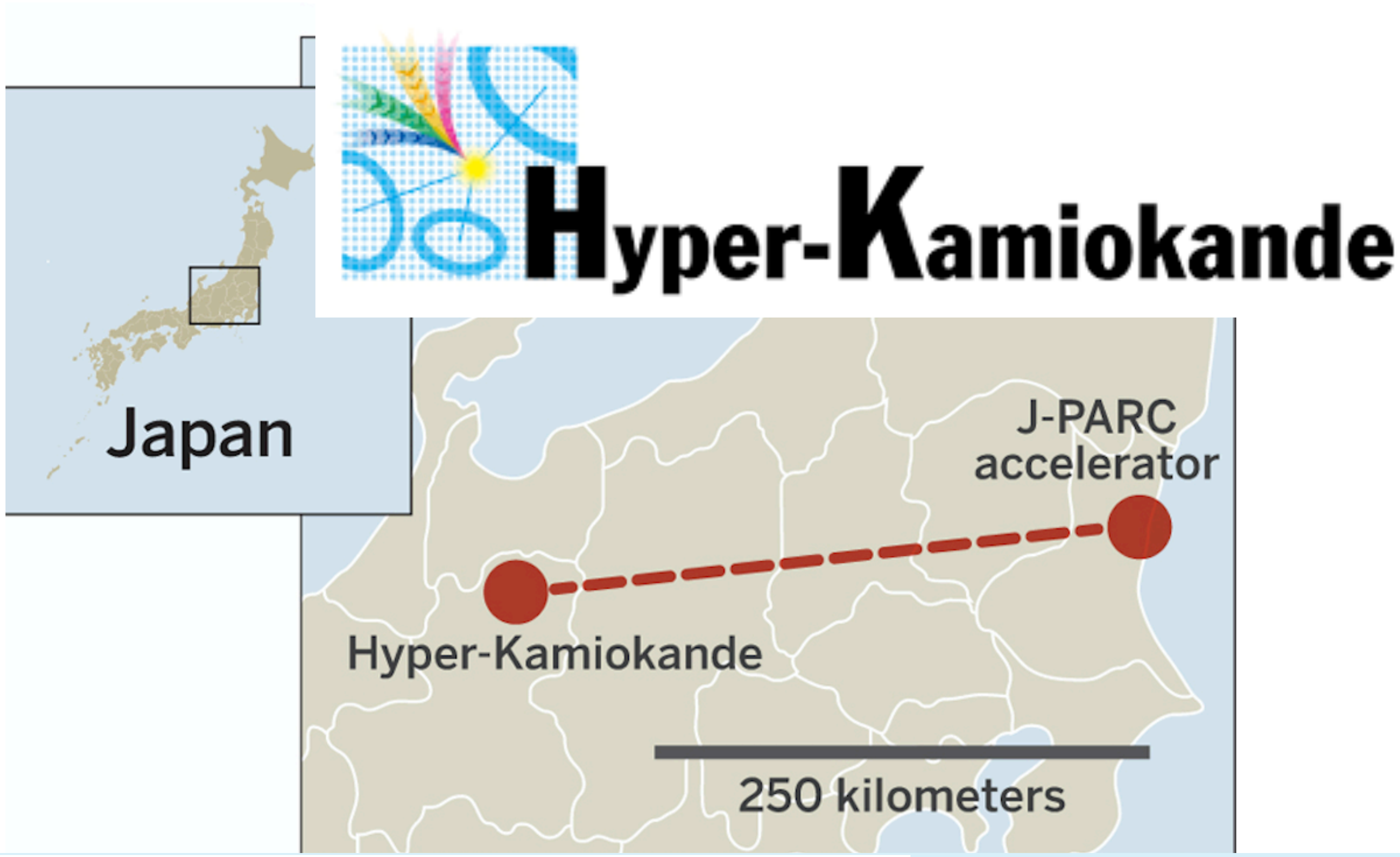
M.C.Gonzalez-Garcia (2018)

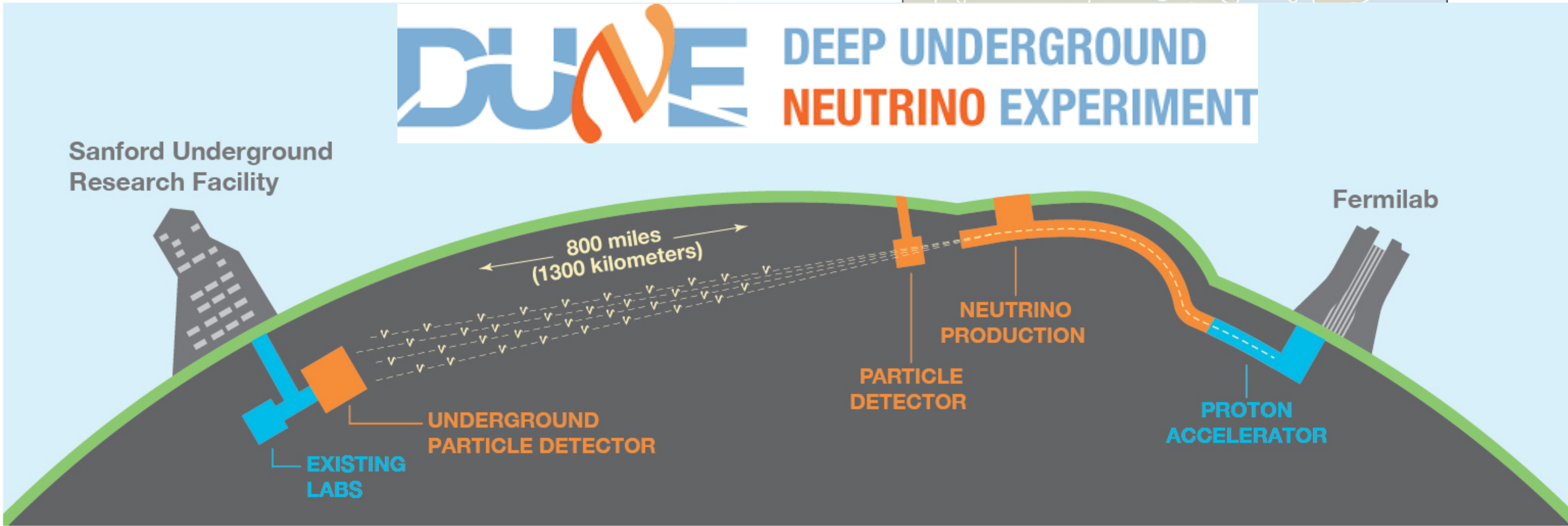
Present Accelerator Facilities



Future Accelerator Facilities



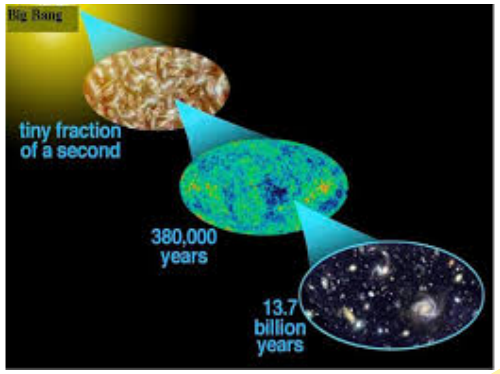




Exploring the Properties of Neutrinos: The Mass Scale

$$m_{\nu_\alpha}^{\text{eff}} = \sqrt{\sum_i m_i^2 \, |U_{\alpha i}^{\nu 2}|^2}$$

Neutrino Mass



cosmology

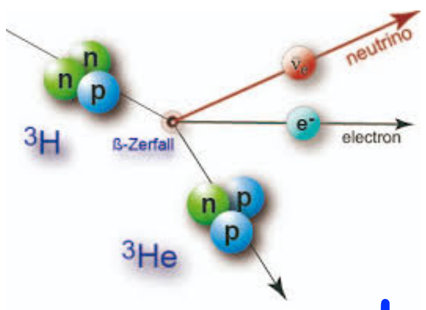
$$\sum_i m_i$$

$0\nu\beta\beta$ **decay**

$$m_{\beta\beta} = |\sum_i m_i U_{ei}^{\nu 2}|$$

Exploring the Properties of Neutrinos: The Mass Scale

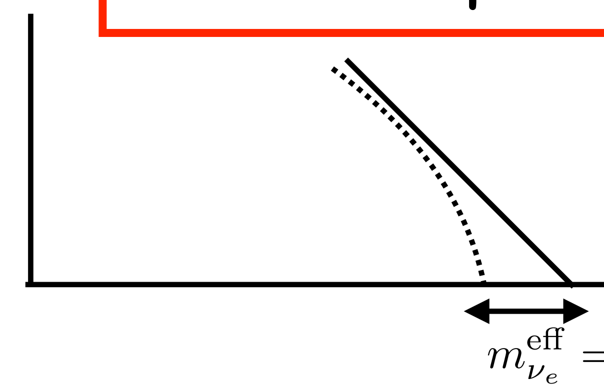
Tritium β-decay



Valid for Dirac or Majorana neutrinos

$$m_{\nu_\alpha}^{\text{eff}} = \sqrt{\sum_i m_i^2 \, |U_{\alpha i}^{\nu 2}|^2}$$

pure kinematics
model independent



neutrino mass scale

$$m_{\nu_e}^{\text{eff}} = \begin{cases} m_0^2 + \Delta m_{21}^2 c_{13}^2 s_{12}^2 + \Delta m_{31}^2 s_{13}^2 & \text{normal ordering} \\ m_0^2 + \Delta m_{21}^2 c_{13}^2 s_{12}^2 - \Delta m_{31}^2 c_{13}^2 & \text{inverted ordering} \end{cases}$$

$m_{\nu_e}^{\text{eff}} < 2.0 \text{ eV}$ **(95% CL Mainz&Troisk)**

current bound

$m_{\nu_e}^{\text{eff}} \sim (0.2 - 0.3) \text{ eV}$

KATRIN future sensitivity

other limits

$m_{\nu_\mu}^{\text{eff}} < 190 \text{ keV}$

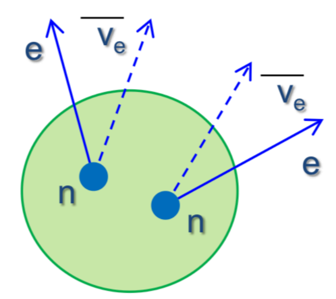
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

$m_{\nu_\tau}^{\text{eff}} < 18.2 \text{ MeV}$

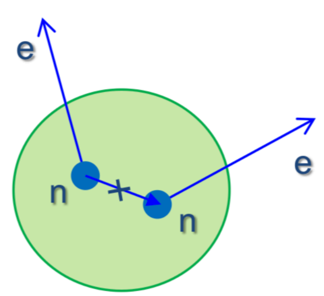
$\tau \rightarrow n\pi + \nu_\tau \qquad n \geq 3$

Exploring the Properties of Neutrinos: The Mass Scale

0νββ-decay



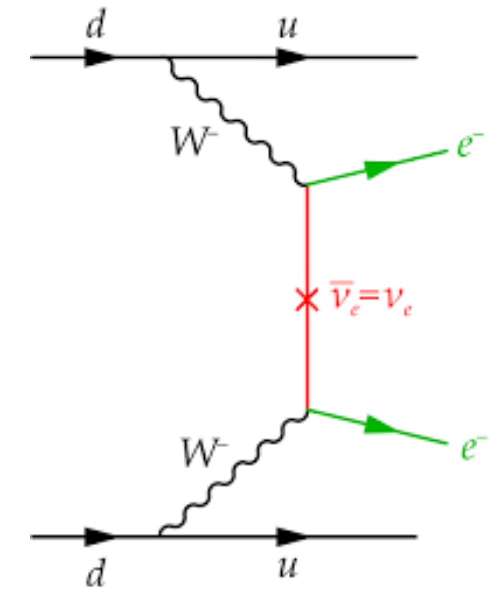
2νββ



$\overline{\nu}_e = \nu_e$
0νββ

Only occurs for Majorana neutrinos

$$m_{\beta\beta} = |\sum_i m_i U_{ei}^{\nu 2}|$$



NO/IO

$$m_{\beta\beta} = f(m_0, \mathrm{order}, \mathrm{Majorana\ phases})$$

neutrino mass scale

α_1, α_3

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} \, |M_{0\nu}|^2 \, m_{\beta\beta}^2$$ **if neutrino mass is the only source of** ΔL

$$m_{\beta\beta} < (0.06 - 0.76) \ \mathrm{eV}$$

current bound

Exploring the Properties of Neutrinos: The Mass Scale

COSMOLOGY

Valid for Dirac or Majorana neutrinos

$$\sum_i m_i$$

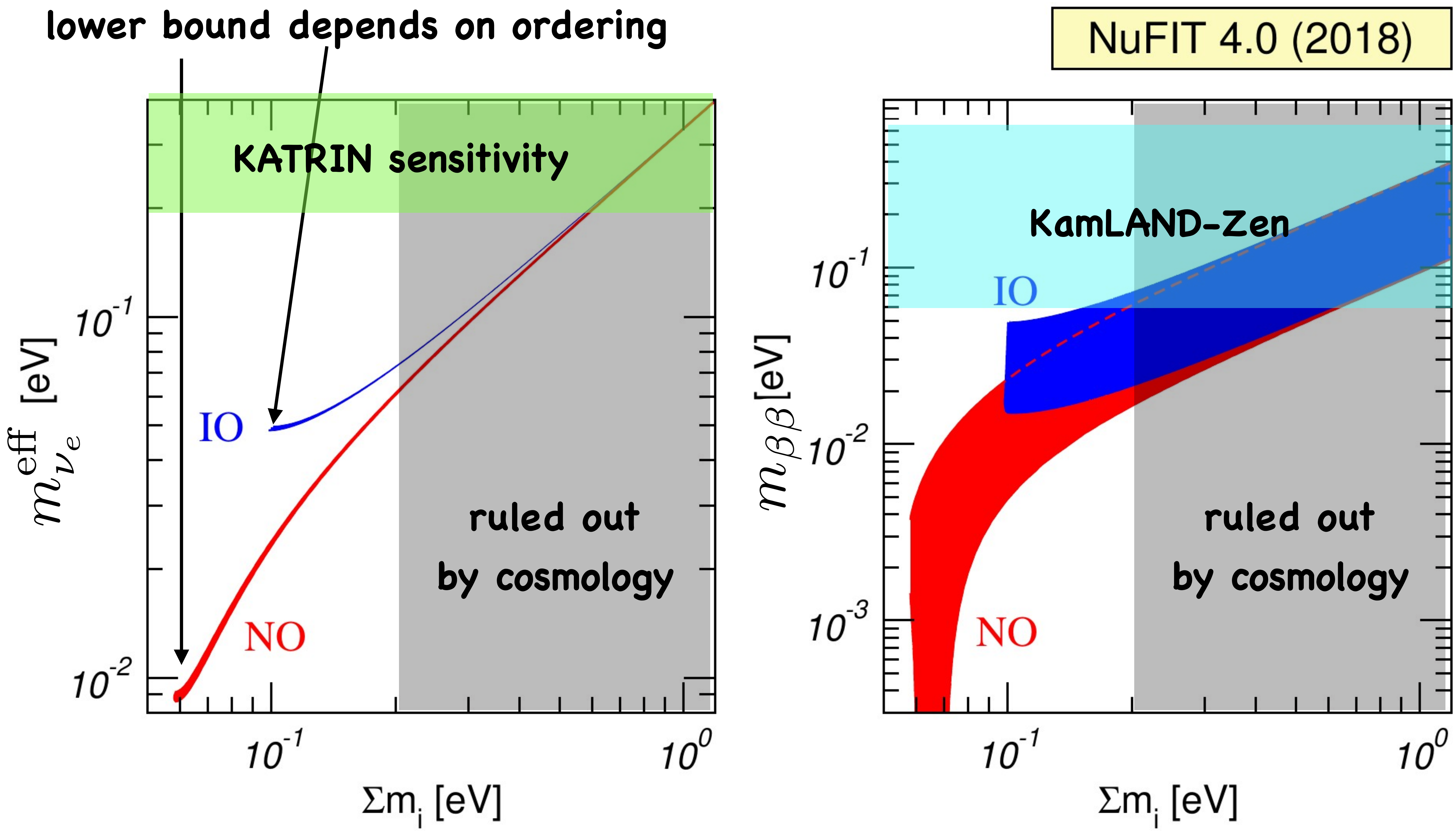
neutrino masses affect the growth of structures

$$\sum_i m_i = f(m_0, \mathrm{order}, \Delta\mathrm{m}^2_{21}, \Delta\mathrm{m}^2_{\mathrm{atm}})$$

$$\boxed{\sum_i m_i < 0.2\ \mathrm{eV}}$$

current bound

Exploring the Properties of Neutrinos: The Mass Scale



correlations between these measurements (Fogli et al. (04))

Exploring the Properties of Neutrinos: Anomalies

Some Observations do not fit the Standard Paradigm

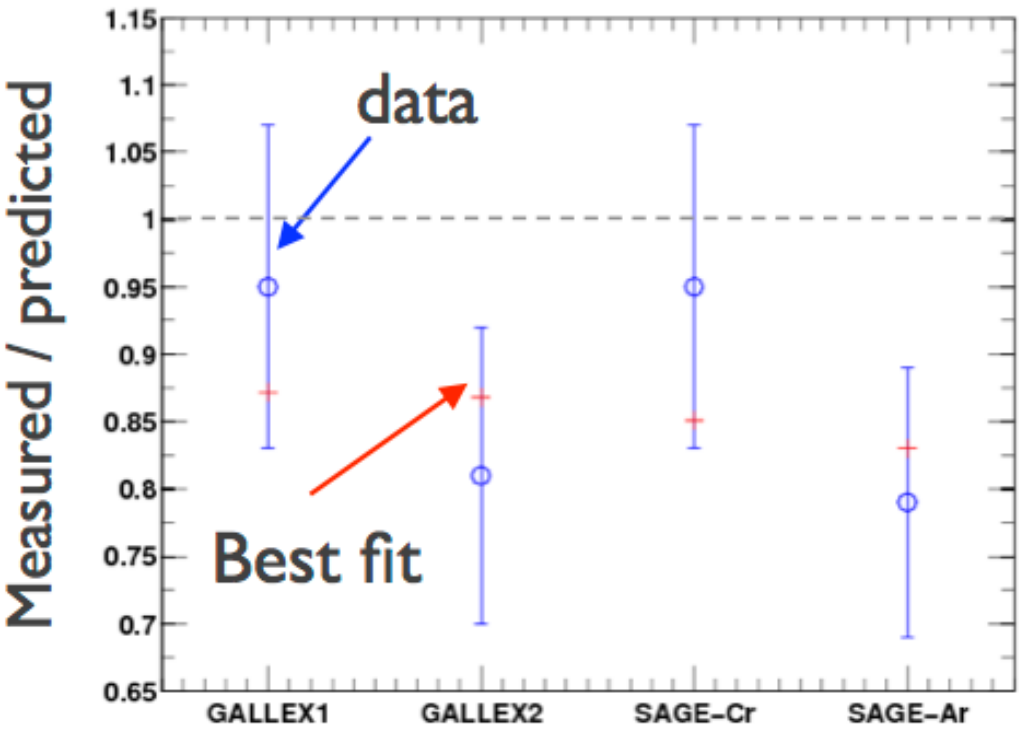
They are usually interpreted as oscillations driven by $\Delta m^2 \sim 1\,\mathrm{eV}^2$

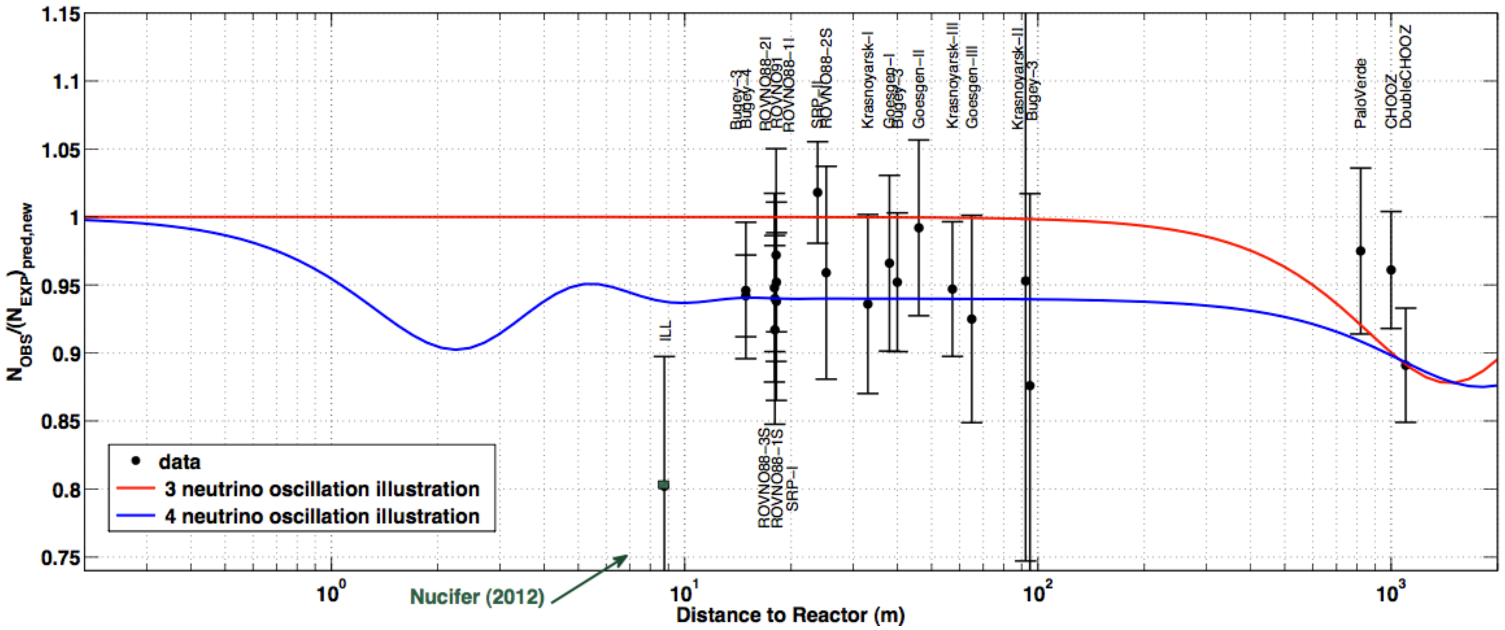
Gallium Anomaly

Radioactive Sources (^{51} Cr, ^{37} Ar)
in calibration of Ga Solar Exp.
Give a rate lower than expected

Reactor Anomaly

New reactor flux calculation
Deficit in data for $L \lesssim 100\,\mathrm{m}$





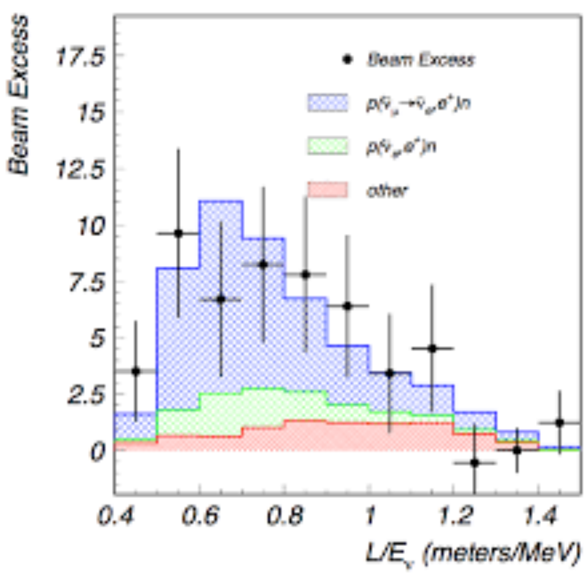
Exploring the Properties of Neutrinos: Anomalies

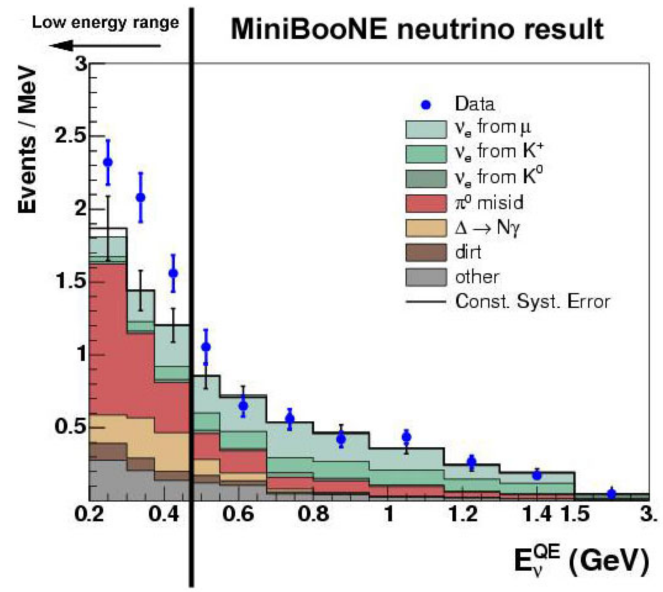
Some Observations do not fit the Standard Paradigm

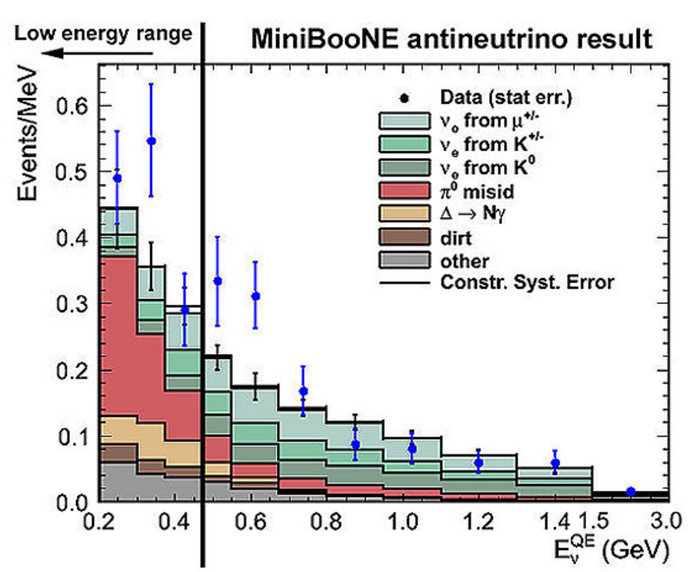
They are usually interpreted as oscillations driven by $\Delta m^2 \sim 1\,\mathrm{eV}^2$

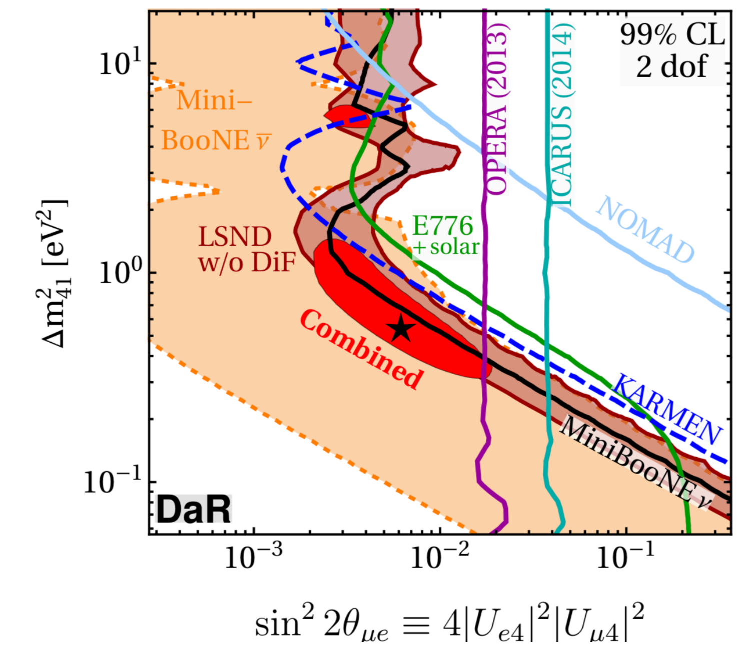
LSND/MiniBooNE

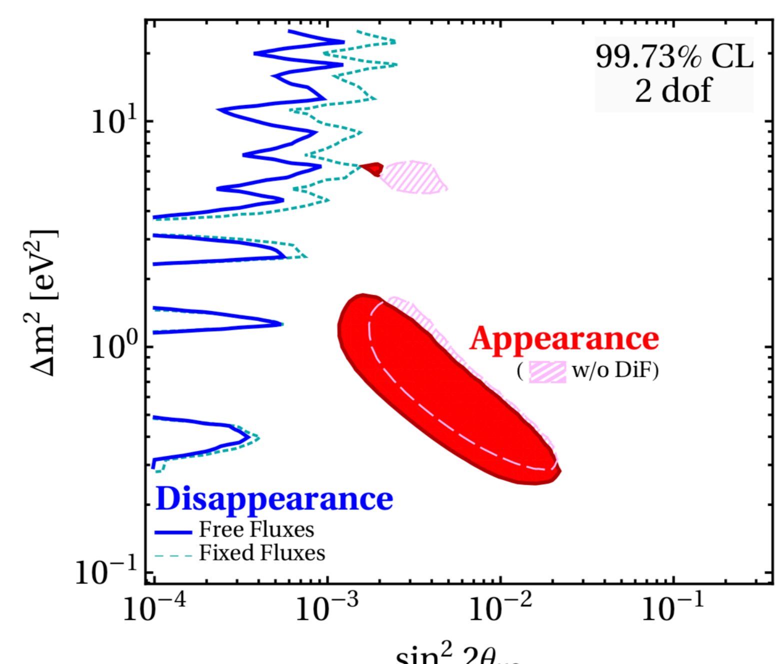
excess of e-like events





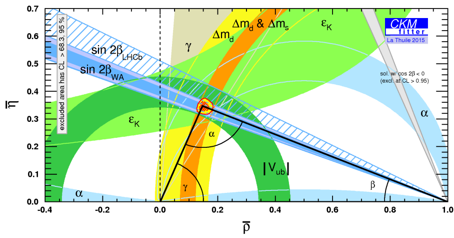






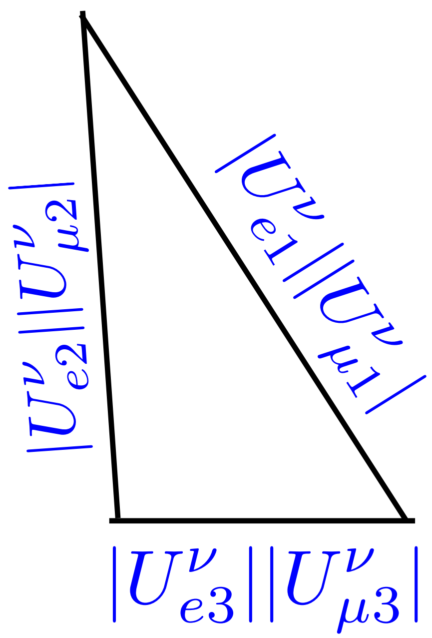
[Dentler et al., arXiv:1803.10661]

Exploring the Properties of Neutrinos: Check Unitarity



$$U^{\nu *}_{\mu 1} U^{\nu}_{e1} + U^{\nu *}_{\mu 2} U^{\nu}_{e2} + U^{\nu *}_{\mu 3} U^{\nu}_{e3} = 0$$

only unitarity triangle that does not depend on ν_τ



if non-unitarity comes from an enlarged mixing matrix

Cauchy-Schwartz inequality

$$\left| \sum_{i=1}^{3} U^\nu_{\alpha i} U^{\nu *}_{\beta i} \right|^2 \leq \left(1 - \sum_{i=1}^{3} |U^\nu_{\alpha i}|^2 \right) \left(1 - \sum_{i=1}^{3} |U^\nu_{\beta i}|^2 \right)$$

$$\left| \sum_{\alpha=e}^{\tau} U^\nu_{\alpha i} U^{\nu *}_{\alpha j} \right|^2 \leq \left(1 - \sum_{\alpha=e}^{\tau} |U^\nu_{\alpha i}|^2 \right) \left(1 - \sum_{\alpha=e}^{\tau} |U^\nu_{\alpha j}|^2 \right)$$

$\alpha, \beta = e, \mu, \tau \qquad \alpha \neq \beta$

$i, j = 1, 2, 3 \qquad i \neq j$

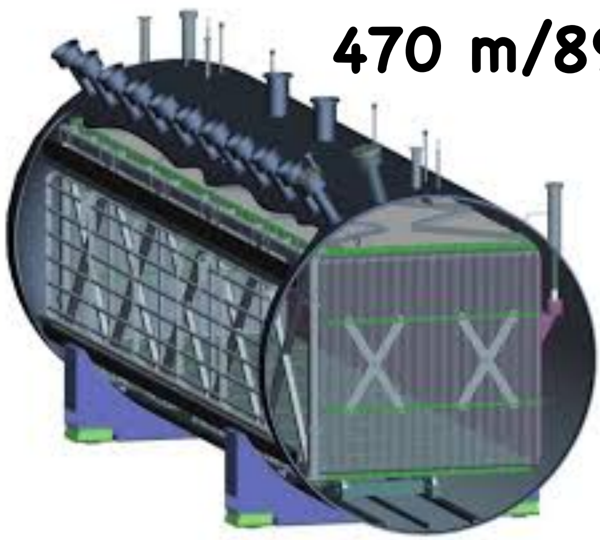
$$|U^\nu_{e1}||U^\nu_{\mu 1}| = 0 - 0.4$$
$$|U^\nu_{e2}||U^\nu_{\mu 2}| = 0.23 - 0.39$$
$$|U^\nu_{e3}||U^\nu_{\mu 3}| = 0.09 - 0.12$$

[S. Parke & M. Ross-Lonergan (2015)]

New Opportunities to Explore the Invisible

Liquid Argon detectors

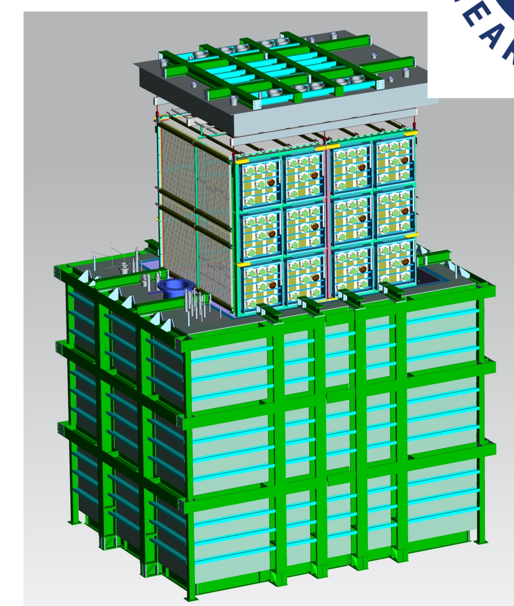
470 m/89 t

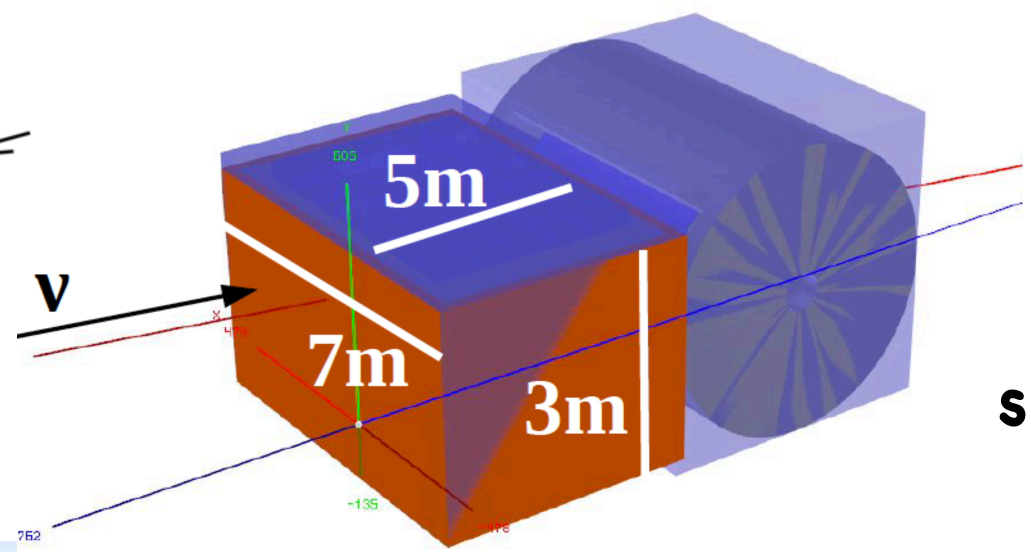


600 m/476 t

ICARUS

110 m/112 t





millimeter spatial resolution

excellent calorimetric information

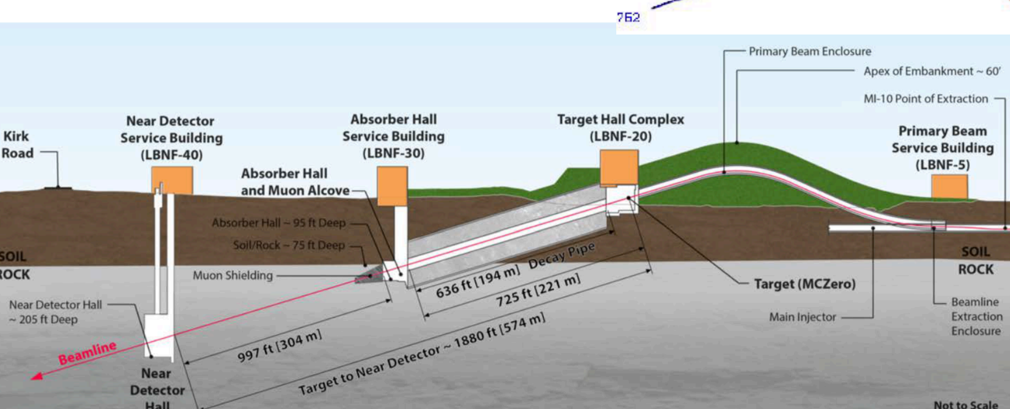
fully active detector volume

short baseline - hight intensity flux

$\gtrsim 10^{21}$ POT

possible to investigate

very rare interactions



New Opportunities to Explore the Invisible

Measure Neutrino Trident Production X-section

(rare SM process)

$$\sigma_\Psi \sim 10^{-5}\sigma_{CC}$$

$\nu_\mu \mathcal{H} \rightarrow \nu_\mu \mu^- \mu^+ \mathcal{H}$

$\nu_e \mathcal{H} \rightarrow \nu_e e^- e^+ \mathcal{H}$

NC+CC

$\nu_\mu \mathcal{H} \rightarrow \nu_e e^+ \mu^- \mathcal{H}$

$\nu_e \mathcal{H} \rightarrow \nu_\mu \mu^+ e^- \mathcal{H}$

CC

only channel observed up to this day

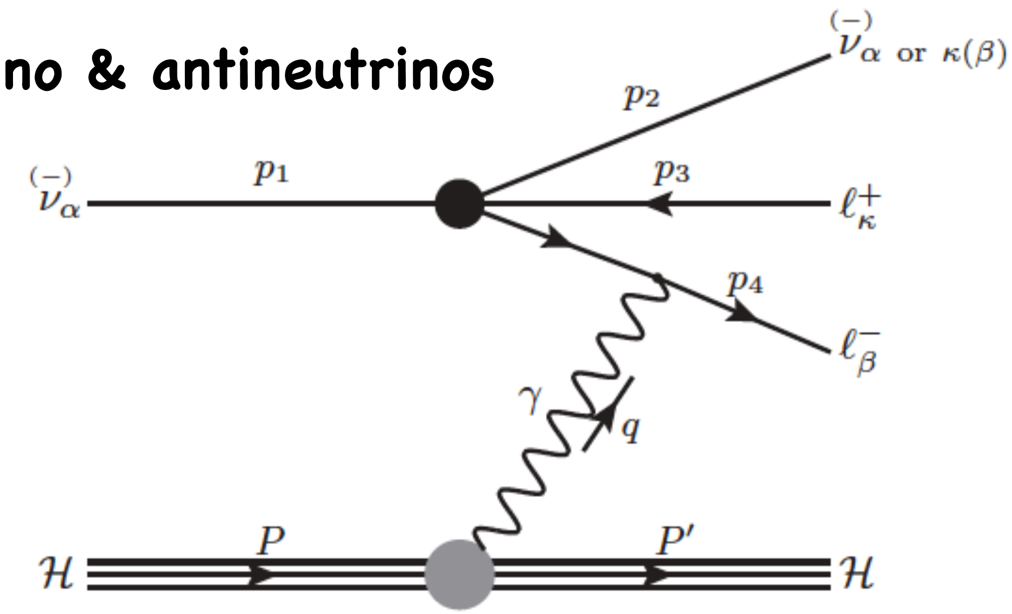
CHARM II, CCFR, NuTeV (± 100 events)

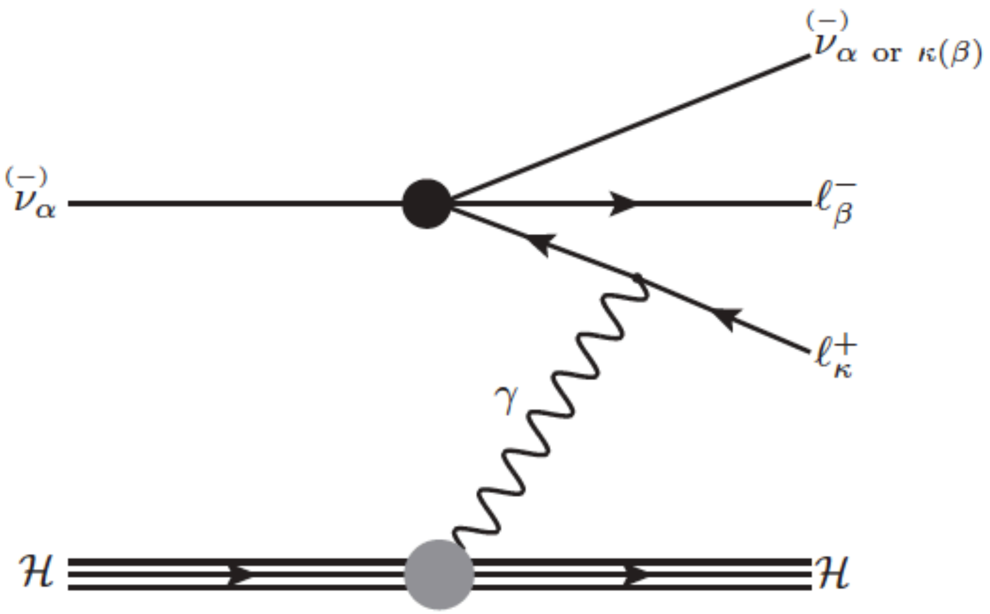
$\nu_\mu \mathcal{H} \rightarrow \nu_\mu e^+ e^- \mathcal{H}$

$\nu_e \mathcal{H} \rightarrow \nu_e \mu^+ \mu^- \mathcal{H}$

NC

for neutrino & antineutrinos





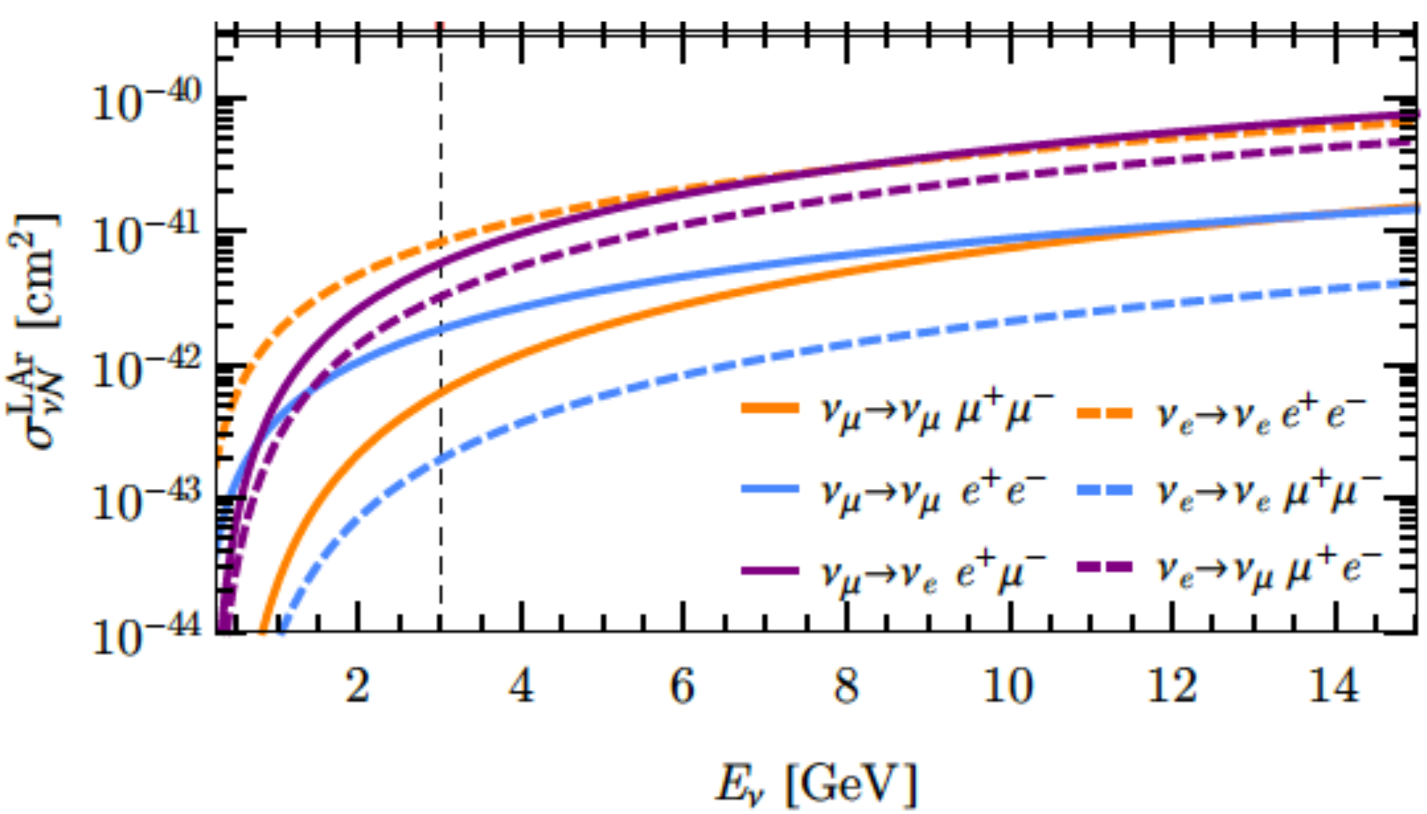
New Opportunities to Explore the Invisible

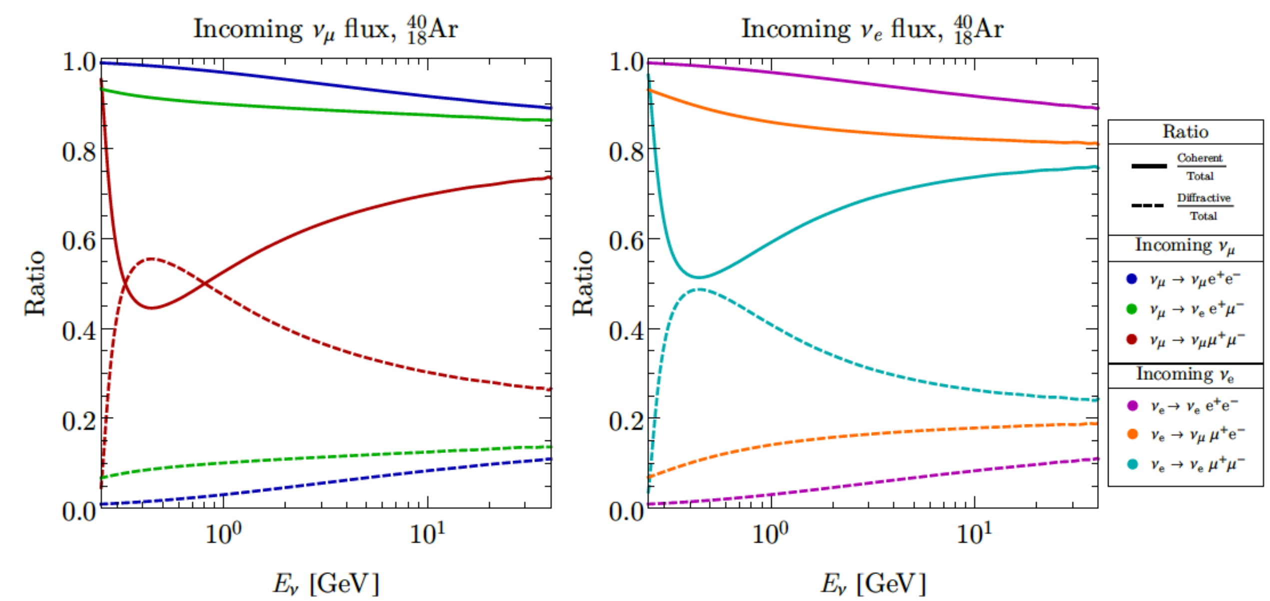
Measure Neutrino Trident Production X-section

(rare SM process)

@ DUNE x-section has two contributions: coherent + diffractive

for neutrino & antineutrinos





[P. Ballet et al. (2018)]

Expect @ DUNE ND:

$e^\pm \mu^\mp - \mathcal{O}(6000)$ events

$e^+ e^- - \mathcal{O}(2000)$ events

$\mu^+ \mu^- - \mathcal{O}(800)$ events

*50 t LArTPC & 2x 1.3 10^{22} POT

New Opportunities to Explore the Invisible

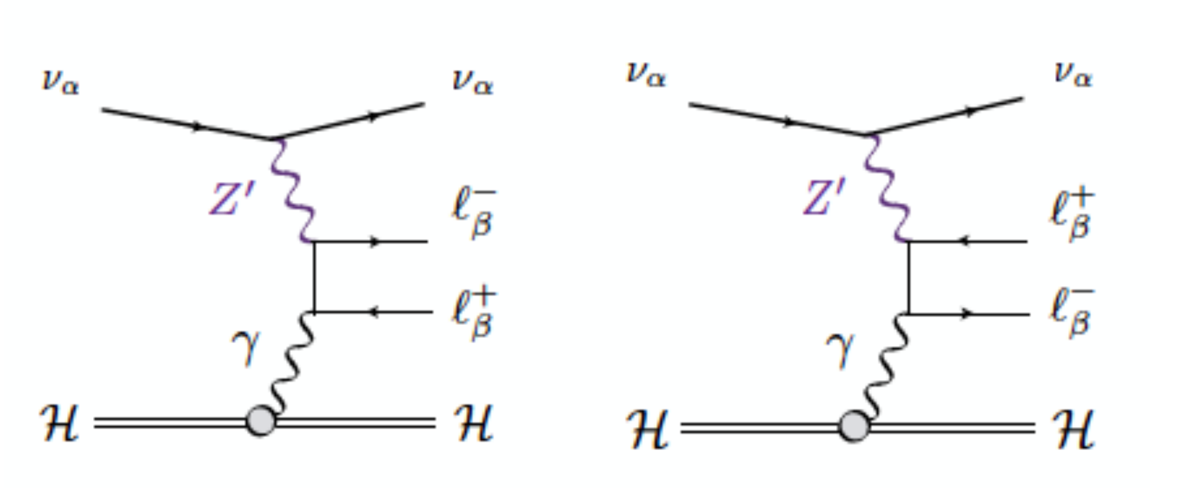
Search for a Leptophilic Z'

for the anomaly-free U(1) extensions of the SM

for instance gauging : $L_e - L_\mu$ or $L_\mu - L_\tau$

use two complementary processes:

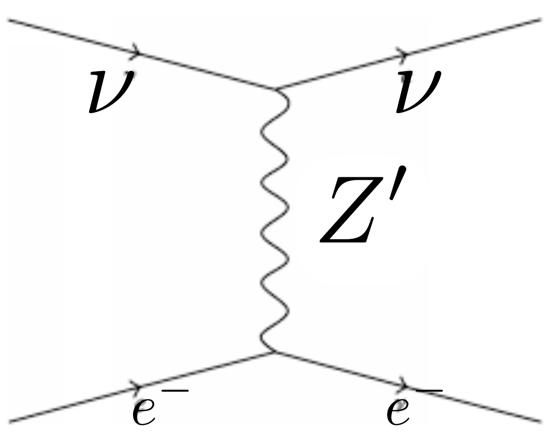
neutrino trident $e^+e^-/\mu^+\mu^-$



Extra Contributions due to Z'

elastic scattering
pure EW process

$\nu + e^- \rightarrow \nu + e^-$



very forward

Extra Contribution due to Z'

New Opportunities to Explore the Invisible

Search for a Leptophilic Z'

for the anomaly-free U(1) extensions of the SM

for instance gauging : $L_e - L_\mu$ or $L_\mu - L_\tau$

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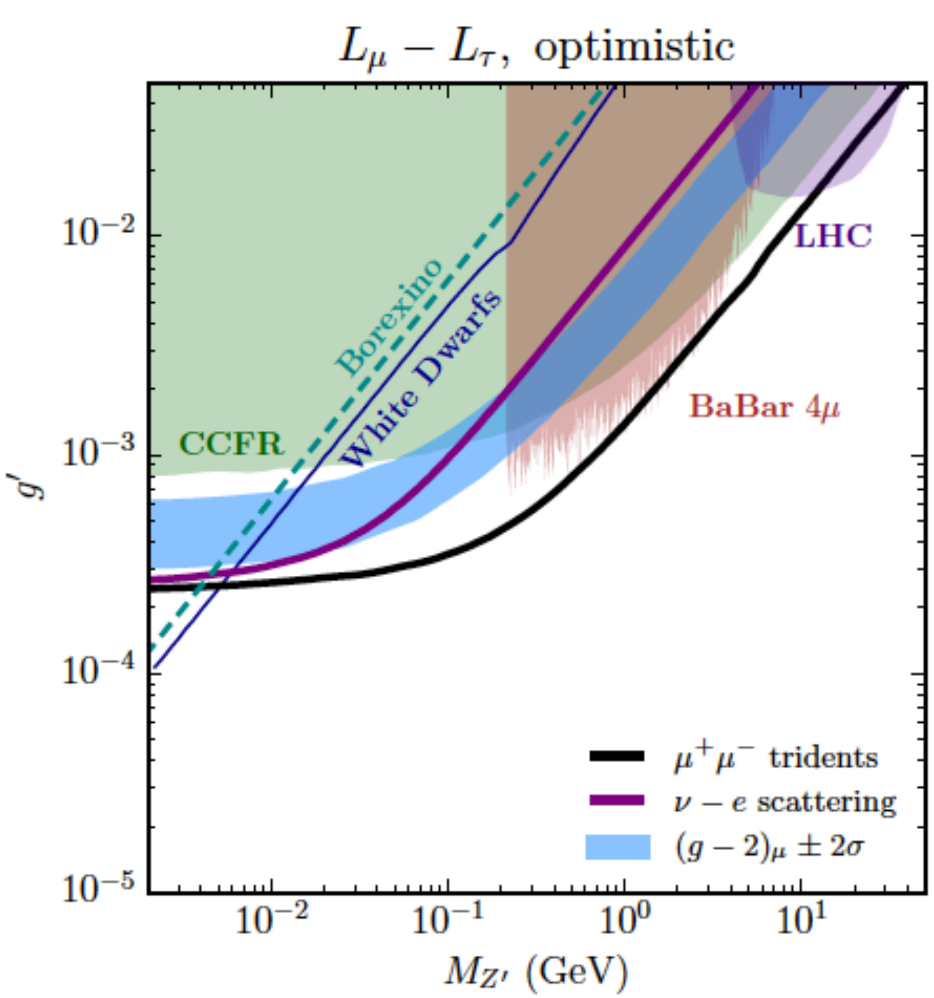
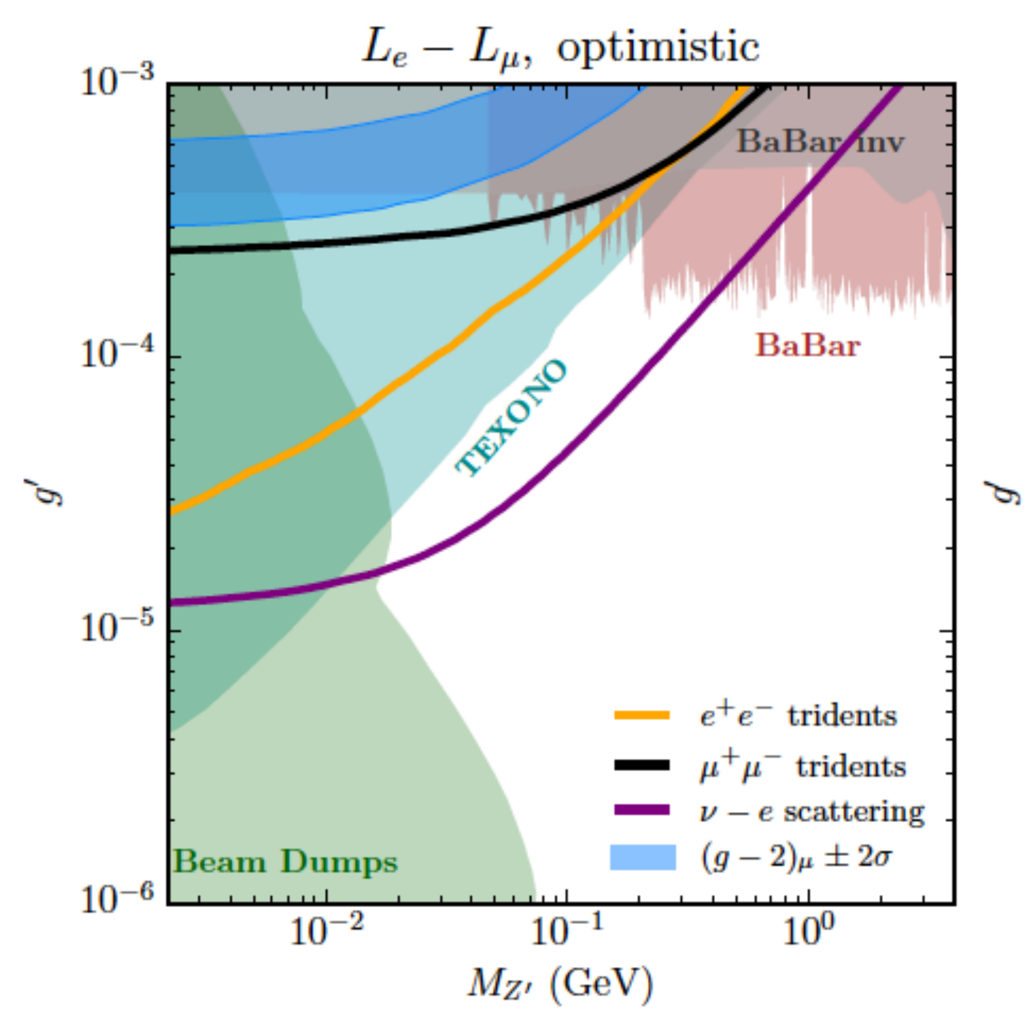
[P. Ballet et al. (2018)]





New Opportunities to Explore the Invisible

Search for Millicharged Particles

There are two ways to test the Principle of Charge Quantization:

- **Directly** (neutrality of atoms)

$$|Q_p + Q_e| < 1 \times 10^{-21} e \qquad Q_\nu < 10^{-21} e$$

$$Q_n < 0.8 \times 10^{-21}\, e$$

- **Looking for new particles with** $Q = \epsilon\, e \ll 1$

as they are weakly interacting particles
so neutrinos experiments can be useful for looking for them

New Opportunities to Explore the Invisible

Search for Millicharged Particles

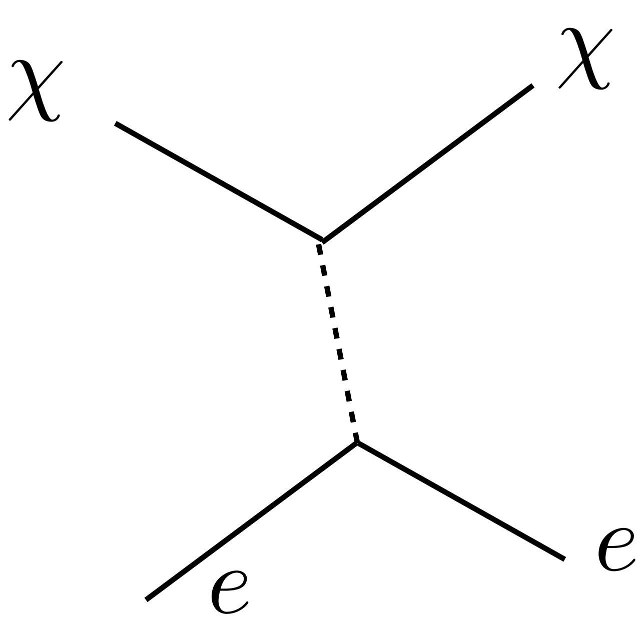
How ?

in neutrino beam dump experiments

production: $\pi^0/\eta \to \gamma\bar{\chi}\chi$ $\quad J/\Psi, \Upsilon \to \bar{\chi}\chi$ **meson decay**

detection: elastic scattering with electrons

[G. Magill et al. (2018)]



$$\sigma_{e\chi} \approx 2.6 \times 10^{-25}\ \mathrm{cm}^2 \ \times \epsilon^2 \times \frac{1\ \mathrm{MeV}}{\mathrm{E_e^{(min)}} - \mathrm{m_e}}$$

recoil energy of the electron

important to accurately measure low energy electrons

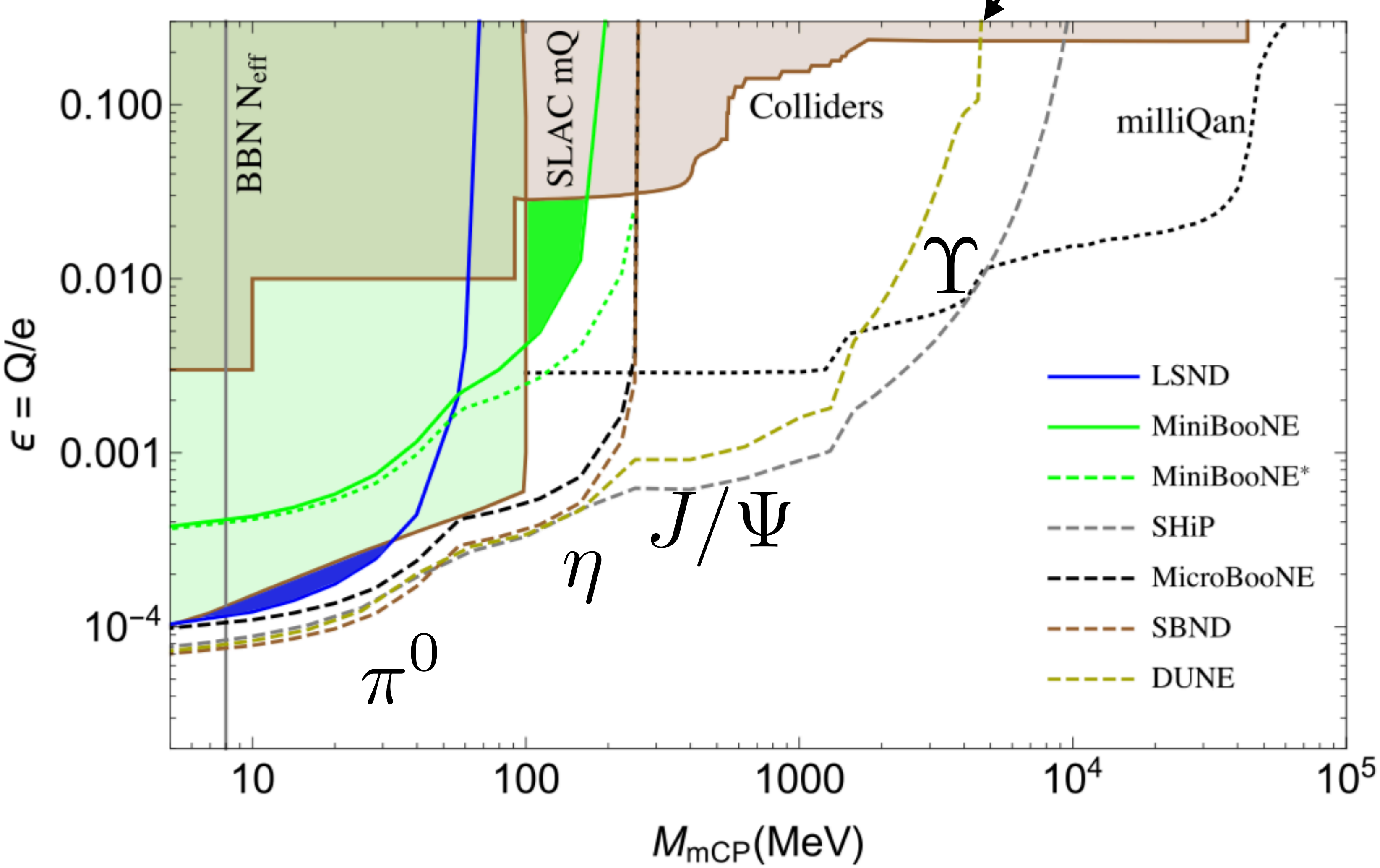
New Opportunities to Explore the Invisible

Search for Millicharged Particles

[G. Magill et al. (2018)]

DUNE

$$5\ \text{MeV} < m_\chi \lesssim 5\ \text{GeV}$$

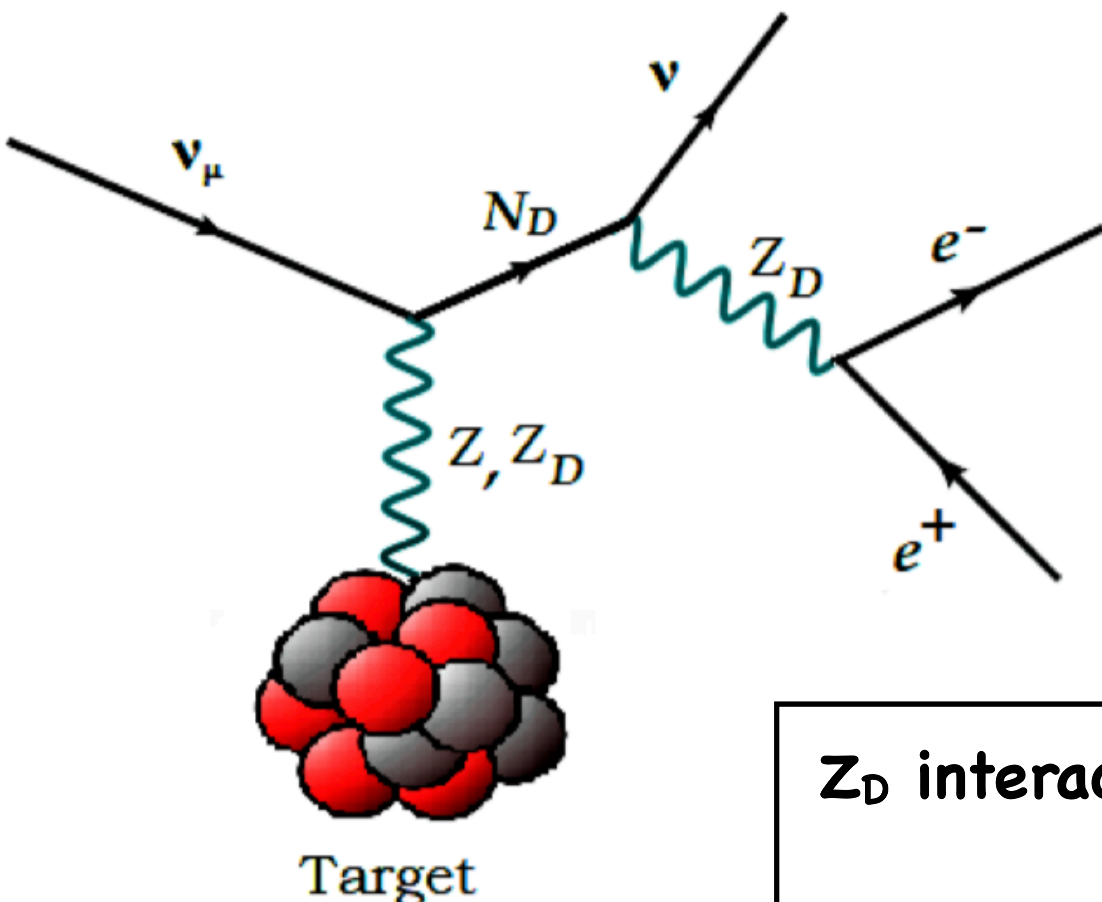


Exp.	N $[\times 10^{20}]$ π^0	η	$A_{geo}(m_\chi)[\times 10^{-3}]$ 1 MeV	100 MeV	Cuts [MeV] E_e^{min}	E_e^{max}	Bkg
LSND	130	—	20	—	18	52	300
mBooNE	17	0.56	1.2	0.68	130	530	2K
mBooNE*	1.3	0.04	1.2	0.68	18	—	0*
μBooNE	9.2	0.31	0.09	0.05	0.8	40	16
SBND	4.6	0.15	4.6	2.6	0.8	40	240
DUNE	830	16	3.3	5.1	2	40	19K
SHiP	4.7	0.11	130	220	20	50	25

New Opportunities to Explore the Invisible

Search for the Light Dark Z_D that can explain MiniBooNE electron-like excess

[E. Bertuzzo et al. (2018)]



Need a new vector boson that only directly couples to a new Dark Neutrino with has small mixing with ν_μ

Z_D interacts with charged fermion through kinetic mixing

$m_{N_\mathcal{D}} > m_{Z_\mathcal{D}}$ ➡ $N_\mathcal{D} \to \nu + Z_\mathcal{D}$ **prompt decay**

$m_{Z_\mathcal{D}} < 2\, m_\mu$ ➡ $Z_\mathcal{D} \to e^+ e^-$ **prompt decay**

New Opportunities to Explore the Invisible

Search for the Light Dark Z_D that can explain MiniBooNE electron-like excess

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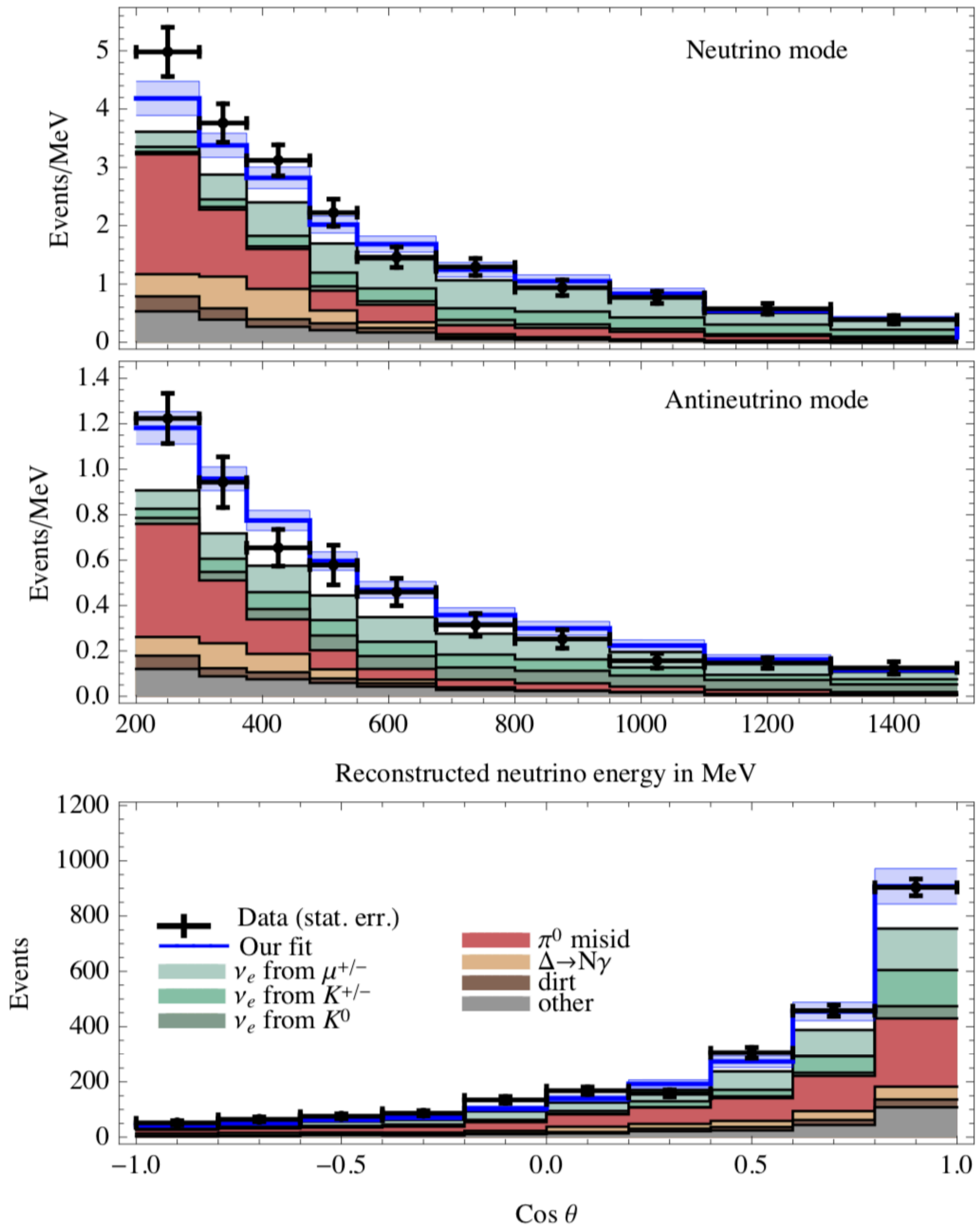
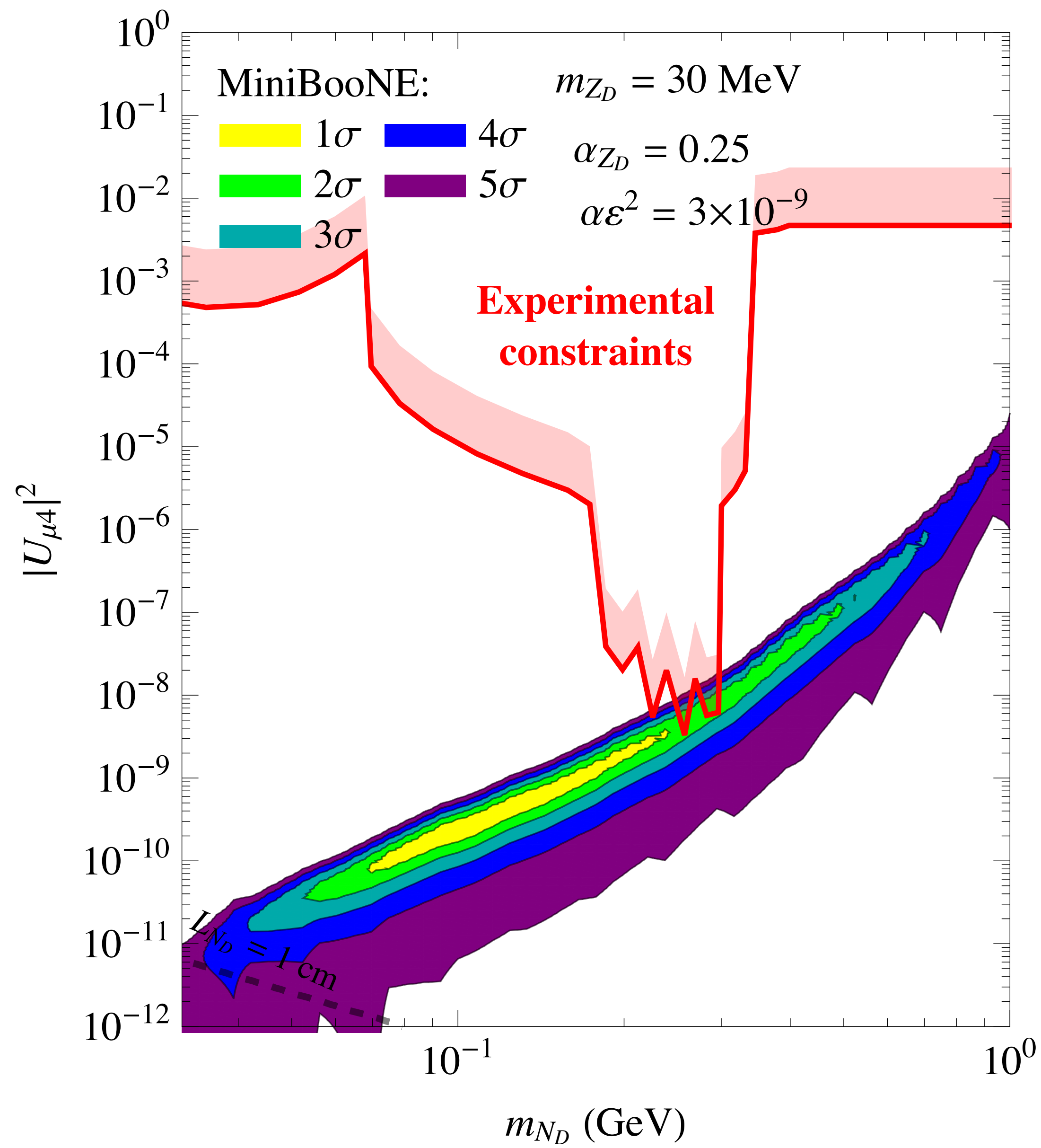
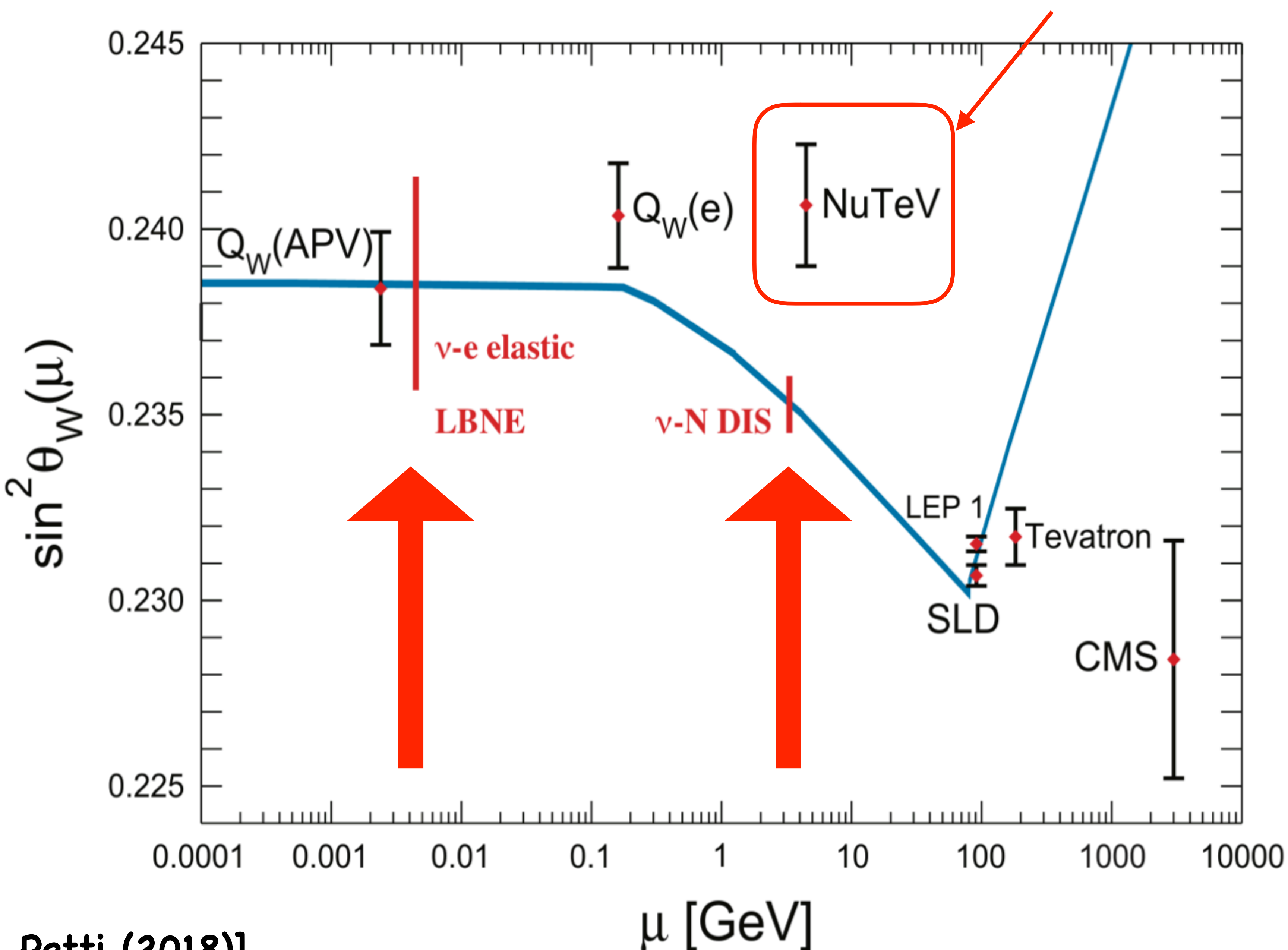




New Opportunities to Explore the Invisible

Measure $\sin^2\theta_W$ (Straw Tube Tracker : ν-H) See running

NuTeV anomaly (3 σ)



See running

ν-N in DIS

$$R^\nu = \frac{\sigma^\nu_{\rm NC}}{\sigma^\nu_{\rm CC}}$$

ν-e elastic scattering

$$R^{\nu e} = \frac{\sigma^{\bar\nu}_{\rm NC}}{\sigma^\nu_{\rm NC}}$$

[R. Petti (2018)]

New Opportunities to Explore the Invisible

Look for Boosted Dark Matter

DM expected to be relativistic

- Indirect Detection Experiments look for nearly-@-rest annihilation or decay of DM
- Direct Detection Experiments probe small nuclear recoil energies

conventional detection strategies based on the assumption that DM is a WIMP thermal relic abundance set by direct coupling to the SM

What if some DM was produced non-thermally by later-time processes is in fact relativistic?

Boosted Dark Matter

[K. Agashe et al. (2014), J. Berger et al. (2015)]

requires a multi-component DM scenario

New Opportunities to Explore the Invisible

Look for Boosted Dark Matter

Two species: DM_A & DM_B $\quad m_A > m_B$

Dominant DM component

No direct couplings to SM

Sub-dominant DM component

DM_A thermal relic abundance set by the annihilation

$$\overline{DM_A} + DM_A \longrightarrow \overline{DM_B} + DM_B$$

Boosted DM

Lorentz factor $\gamma = m_A/m_B$

[K. Agashe et al. (2014), J. Berger et al. (2015)]

New Opportunities to Explore the Invisible

Look for Boosted Dark Matter

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Dominant DM component

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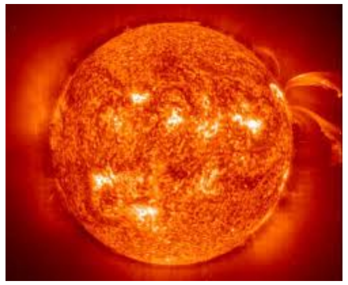
$$\overline{DM_A} + DM_A \longrightarrow \overline{DM_B} + DM_B$$

Today : DM_A captured by the Sun/Galatic Center may produce DM_B via this annihilation



[K. Agashe et al. (2014), J. Berger et al. (2015)]

New Opportunities to Explore the Invisible

Look for Boosted Dark Matter

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Dominant DM component

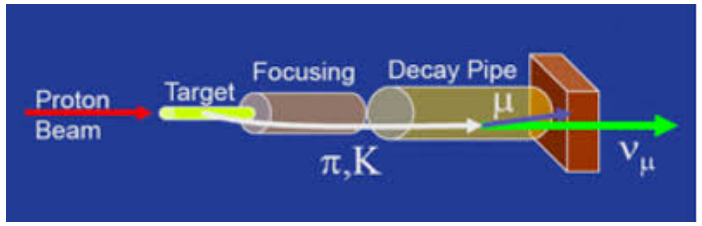
No direct couplings to SM

Sub-dominant DM component

DM_A thermal relic abundance set by the annihilation

$$\overline{DM_A} + DM_A \longrightarrow \overline{DM_B} + DM_B$$

Alternatively : DM_B could be produced in the beam



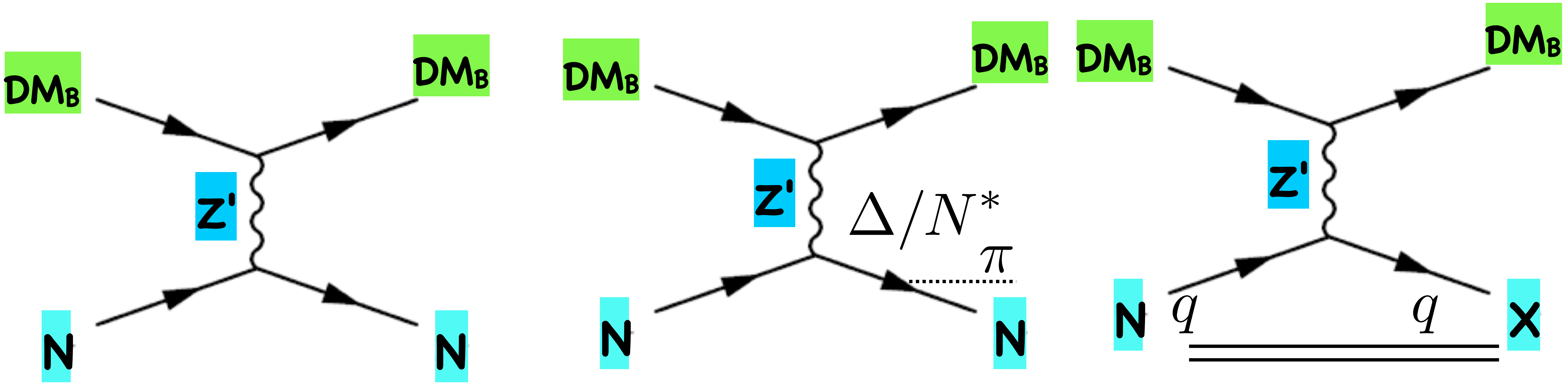
[K. Agashe et al. (2014), J. Berger et al. (2015)]

New Opportunities to Explore the Invisible

Look for Boosted Dark Matter

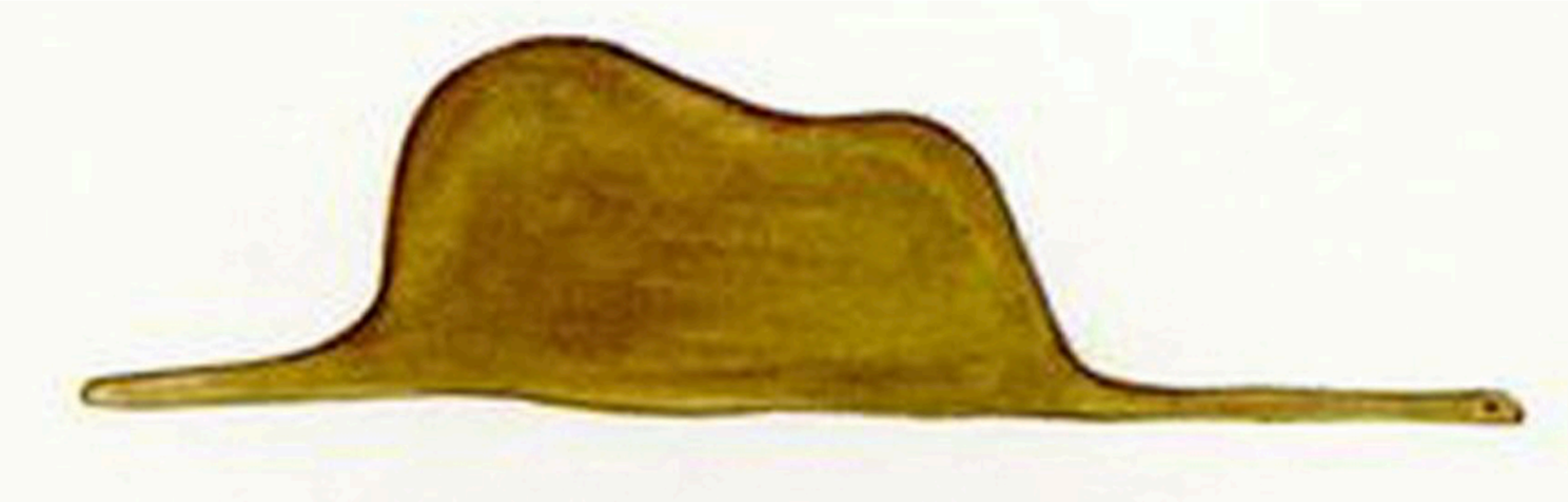
DM_B can be detected via interaction with SM particles @ neutrino detectors

$DM_B + N \longrightarrow DM_B + N^{(')}$ NC-like interaction with SM



Elastic Scattering Resonant Scattering Deep Inelastic Scattering

[K. Agashe et al. (2014), J. Berger et al. (2015)]

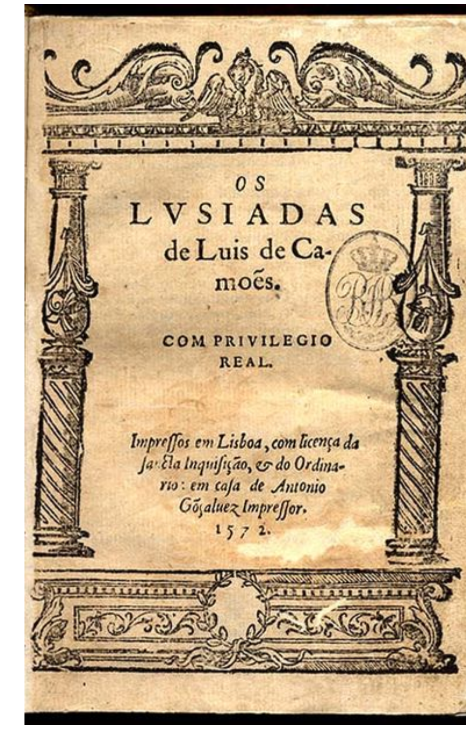


You may think this is a hat ...

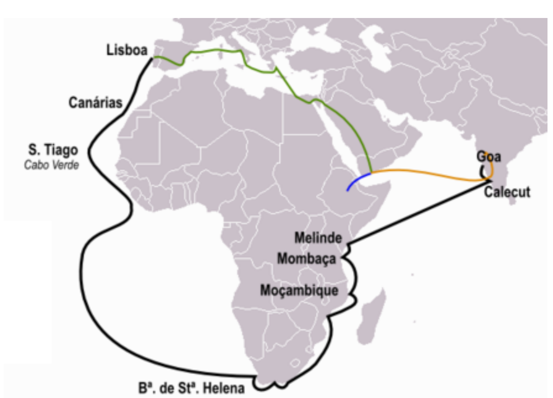
But in fact it is not!

Luís Vaz de Camões
(1525-1580)

``As armas e os barões assinalados,
Que da ocidental praia Lusitana,
Por mares nunca de antes navegados,
Passaram ainda além da Taprobana,
Em perigos e guerras esforçados,
Mais do que prometia a força humana,
E entre gente remota edificaram
Novo Reino, que tanto sublimaram; ”



The Lusiads



Vasco da Gama
route to India

“ARMS and the Heroes, who from Lisbon's shore,
Thro' seas where sail was never spread before,
Beyond where Ceylon lifts her spicy breast,
And waves her woods above the wat'ry waste,
With prowess more than human forc'd their way
To the fair kingdoms of the rising day:
What wars they wag'd, what seas, what dangers pass'd,
What glorious empire crown'd their toils at last,’