Universidad
Católica del Norte

lawphysics
Latin American Webinars on Physics

Astroparticle physics

Roberto A. Lineros

Departamento de Física, Universidad Católica del Norte

Winter School HEP-PUC 2019 “Topics on Graviticulas”

The Plan

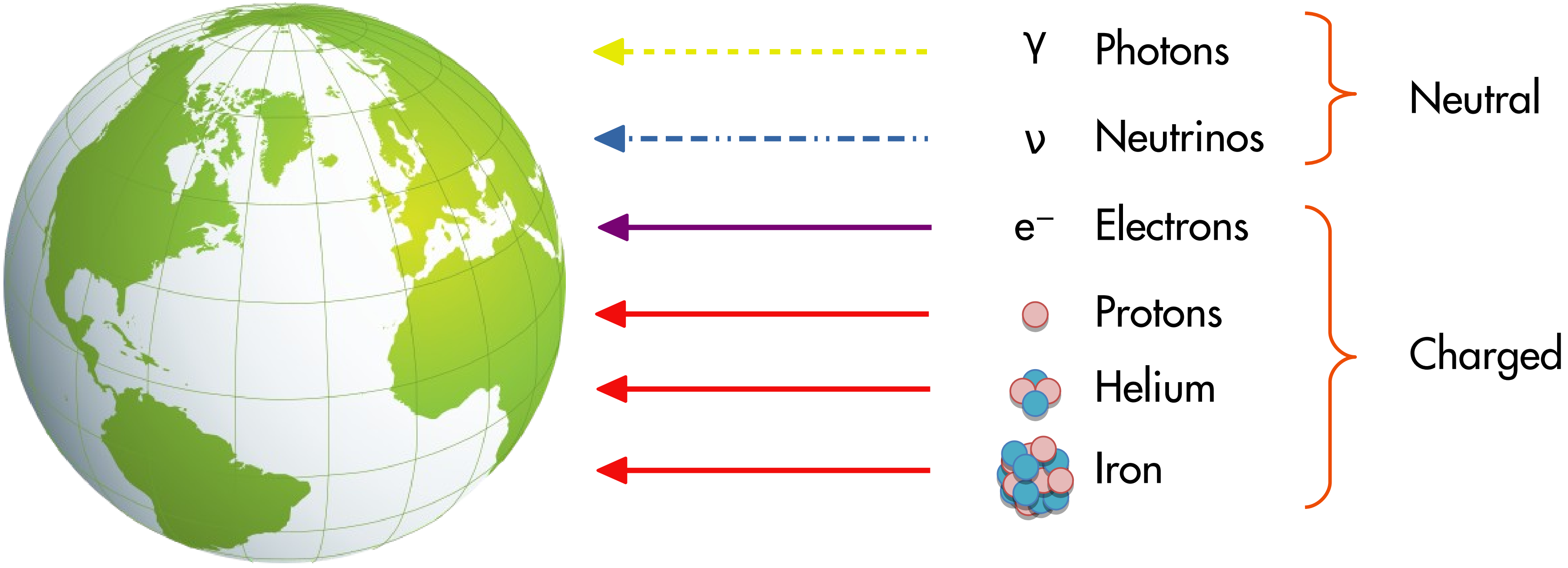
1. Astroparticles
2. Cosmic-rays
3. Neutrinos
4. Gamma-rays
5. Gravitational Waves

Dark Matter

Astrophysical Sources

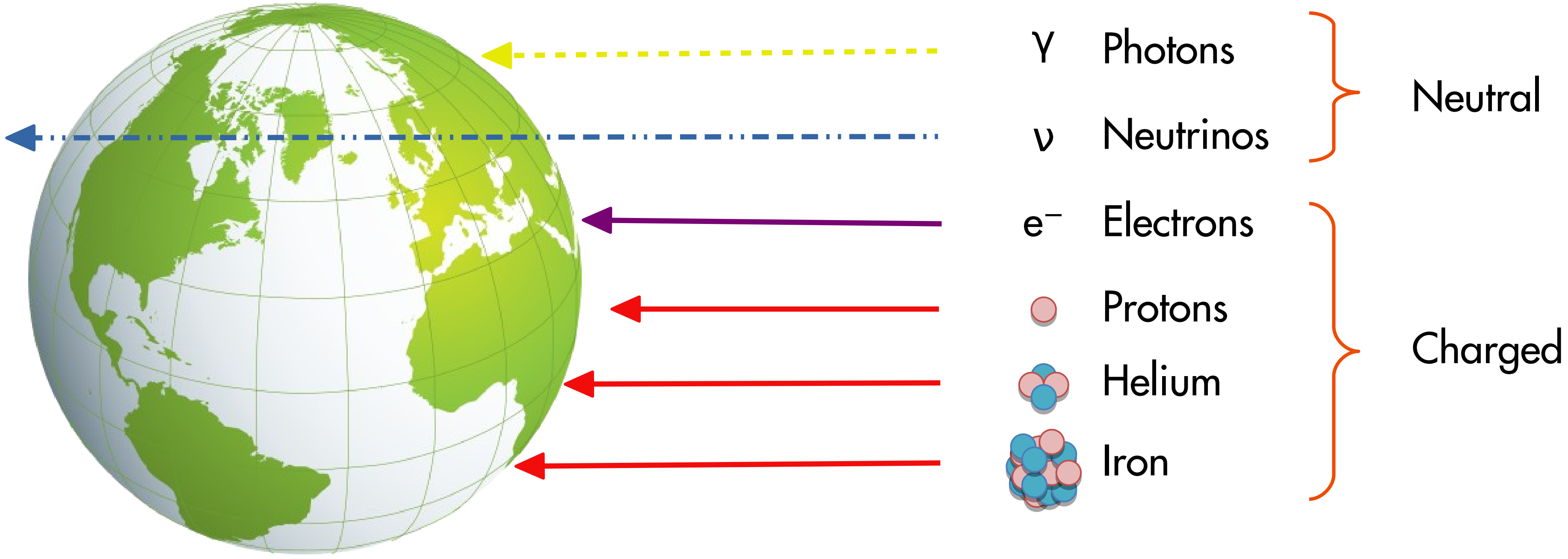
Neutrinos

Particles from outer space



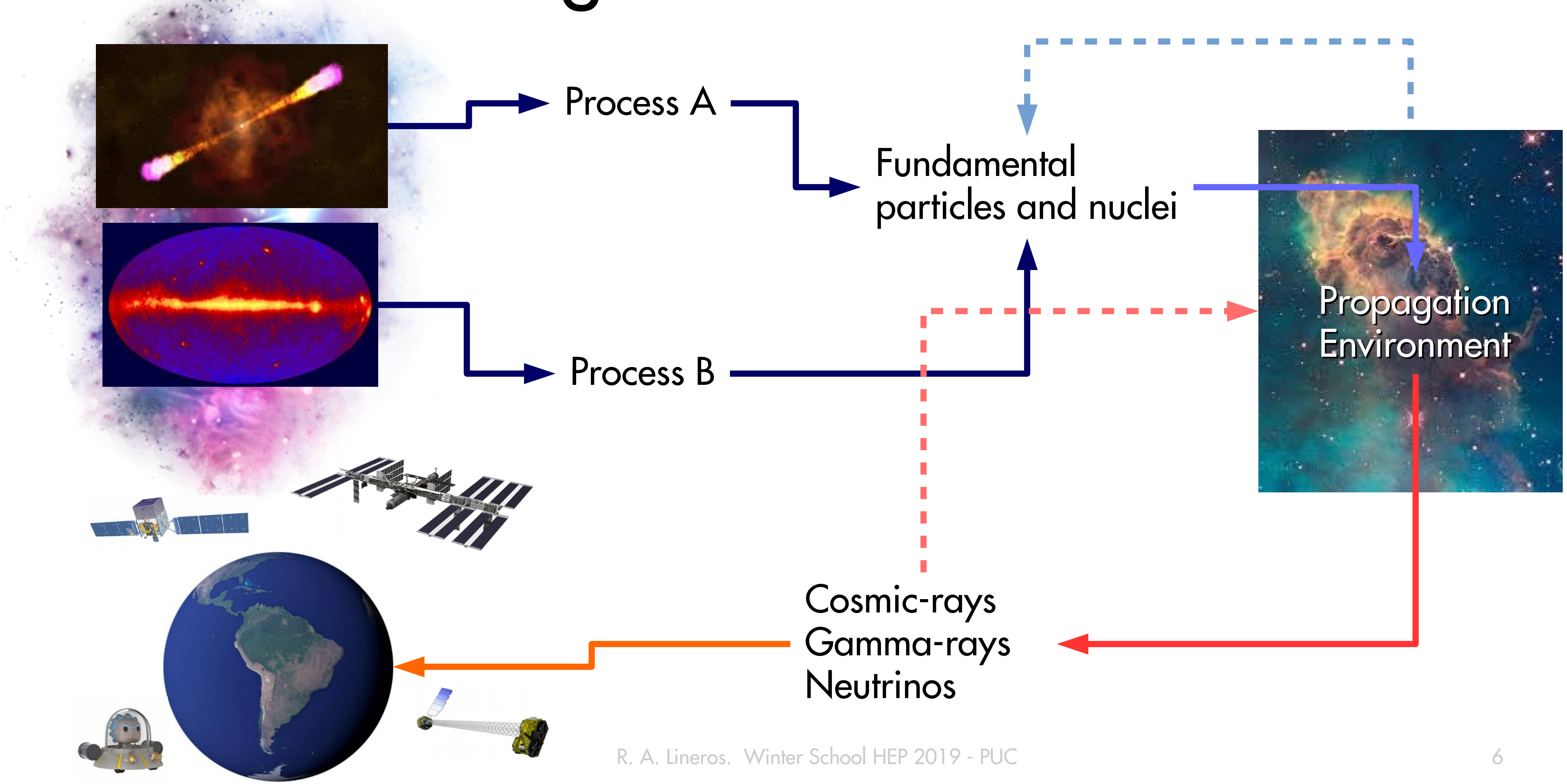
Astroparticles = Multimessenger and Multiwavelength

Particles from outer space



Neutrino can pass through Earth without any interaction

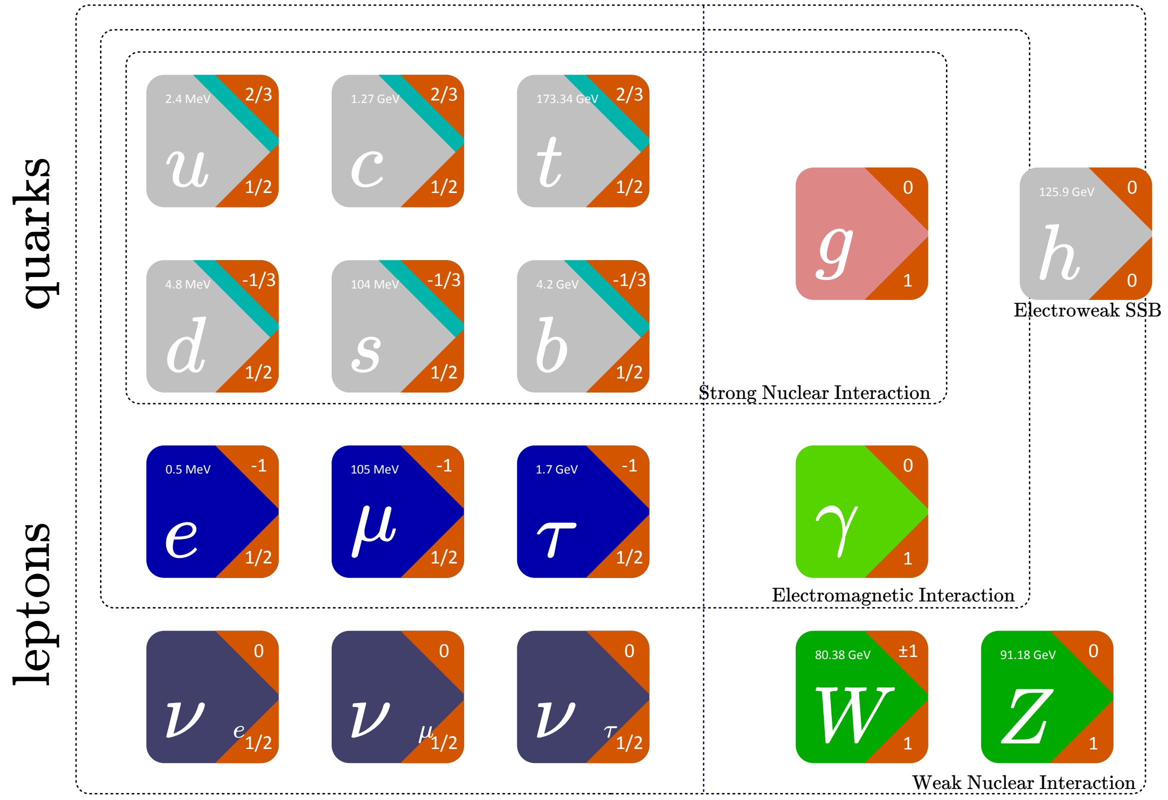
Multimessengers



Neutrino Physics

The Standard Model

SM matter families



Symmetries
- CPT
- $SU(3)_c$: Color
- $SU(2)_L$: Isospin
- $U(1)_y$: Hypercharge

Matter content
- 3 families quarks
- 3 families leptons

Higgs fields
- $SU(2)_L x U(1)_y \rightarrow U(1)_{EM}$
- Mass to fundamental particles

Neutrinos in the SM

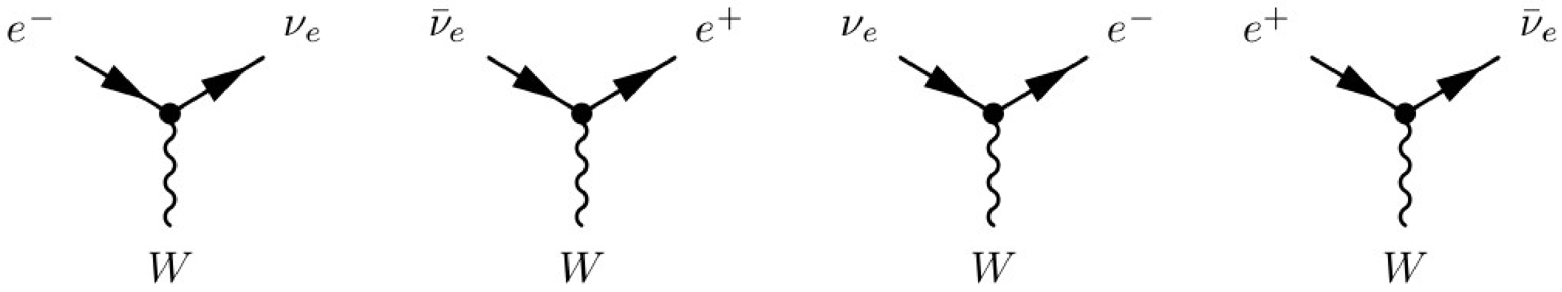
Neutrinos are part of the SU(2) of left-handed leptons

Fermion IRs under $SU(2)_L \times U(1)_Y$			SU(2) I	isospin I_3	hypercharge Y	electric charge Q
$L_{eL} \equiv \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$L_{\mu L} \equiv \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$L_{\tau L} \equiv \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	1/2	$1/2$ $-1/2$	-1	0 -1
$l_{eR} \equiv e_R$	$l_{\mu R} \equiv \mu_R$	$l_{\tau R} \equiv \tau_R$	0	0	-2	-1

$$\mathcal{L} \propto \underbrace{i\bar{L}_\alpha \gamma_\mu D^\mu L_\alpha + i\bar{l}_{R\alpha}\gamma_\mu D^\mu l_{R\alpha}}_{\text{Covariant derivatives}} - \underbrace{\left(y_{\alpha\beta}\bar{L}_\alpha \Phi l_{R\beta} + h.c.\right)}_{\text{Interaction/mass terms}}$$

Neutrinos in the SM

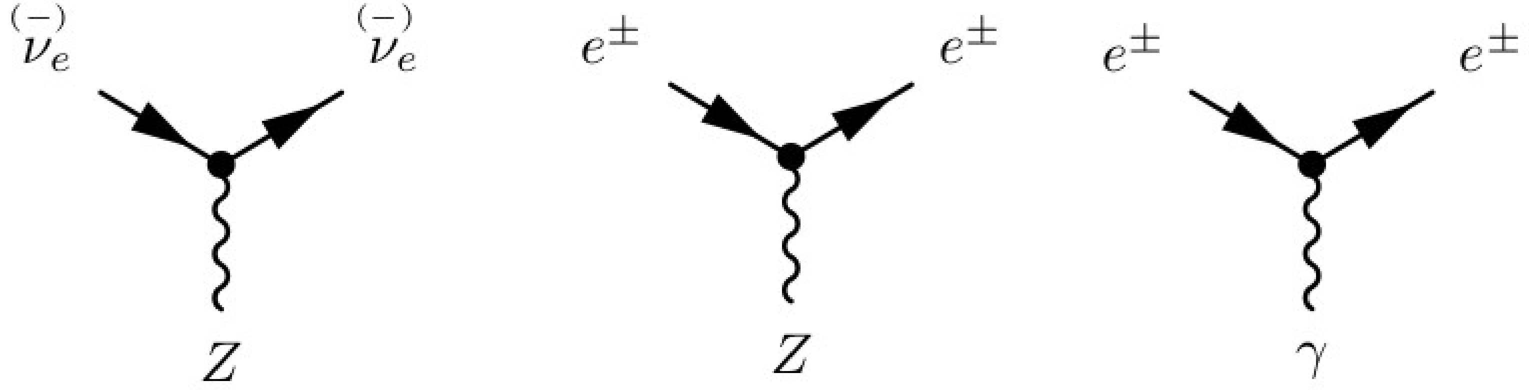
Standard Model Neutrinos only interact via weak boson: Z and W



$$\mathscr{L}_{\rm I,L}^{\rm (CC)} = -\frac{g}{\sqrt{2}}\left\{\overline{\nu_{eL}}\,\not{W}\, e_L + \overline{e_L}\,\not{W}^\dagger \nu_{eL}\right\}$$

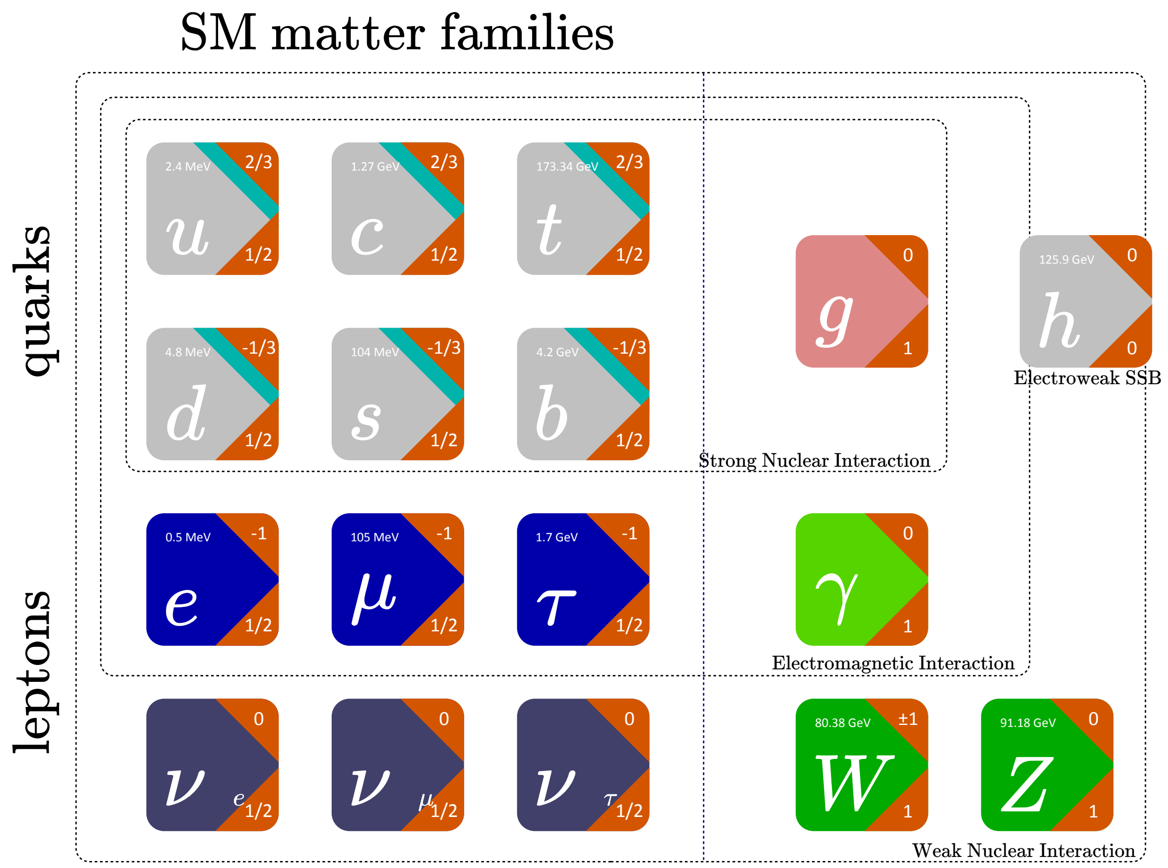
Neutrinos in the SM

Standard Model Neutrinos only interact via weak boson: Z and W



$$\mathscr{L}_{\mathrm{I,L}}^{(\mathrm{NC})} = -\frac{g}{2\cos\vartheta_{\mathrm{W}}}\left\{\overline{\nu_{eL}}\not{Z}\nu_{eL} - \left(1 - 2\sin^2\vartheta_{\mathrm{W}}\right)\overline{e_L}\not{Z}e_L + 2\sin^2\vartheta_{\mathrm{W}}\overline{e_R}\not{Z}e_R\right\}$$
$$+\, g\sin\vartheta_{\mathrm{W}}\,\overline{e}\not{A}e$$

The Standard Model (fail)



- The Standard Model predicts massless neutrinos
- Neutrino Oscillation experiments require O(eV) neutrino masses

Neutrino Oscillations

Neutrino oscillations

Flavor and mass eigenstates do not coincide $|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}|\nu_k\rangle$

Mass eigenstates evolve according to:

$$i\frac{\partial \Psi}{\partial t} = \mathcal{H}\,\Psi$$

$$\mathcal{H}_{\rm vac} = \frac{1}{2E}\,U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger$$

The final ν flavor depends on: Initial state, Source distance, Neutrino energy

With more details:

Flavor and mass eigenstates are related by a unitary transformation:

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}\,|\nu_k\rangle \qquad (\alpha = e, \mu, \tau)$$

where the eigenstates satisfy:

$$\mathscr{H}|\nu_k\rangle = E_k|\nu_k\rangle \qquad E_k = \sqrt{\vec{p}^2 + m_k^2}$$

and these states evolve according to the time-evolving operator:

$$i\,\frac{\mathrm{d}}{\mathrm{d}t}\,|\nu_k(t)\rangle = \mathscr{H}\,|\nu_k(t)\rangle \qquad |\nu_k(t)\rangle = e^{-iE_k t}\,|\nu_k\rangle$$

$$A_{\nu_\alpha\to\nu_\beta}(t) \equiv \langle\nu_\beta|\nu_\alpha(t)\rangle = \sum U^*_{\alpha k}\,U_{\beta k}\,e^{-iE_k t}$$

With more details:

Since neutrino can be detected using weak interactions, the flavor evolution is:

$$|\nu_\alpha(t)\rangle = \sum_k U^*_{\alpha k}\, e^{-iE_k t}\, |\nu_k\rangle \qquad |\nu_\alpha(t)\rangle = \sum_{\beta=e,\mu,\tau} \left(\sum_k U^*_{\alpha k}\, e^{-iE_k t}\, U_{\beta k} \right) |\nu_\beta\rangle$$

and the transition amplitude between flavors corresponds to:

$$A_{\nu_\alpha \to \nu_\beta}(t) \equiv \langle \nu_\beta | \nu_\alpha(t) \rangle = \sum_k U^*_{\alpha k}\, U_{\beta k}\, e^{-iE_k t}$$

but the observable is the transition probability:

$$P_{\nu_\alpha \to \nu_\beta}(t) = \left| A_{\nu_\alpha \to \nu_\beta}(t) \right|^2 = \sum_{k,j} U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\, e^{-i(E_k - E_j)t}$$

$$E_k - E_j \simeq \frac{\Delta m^2_{kj}}{2E}$$

With more details:

The expression for the probability is in term of time:

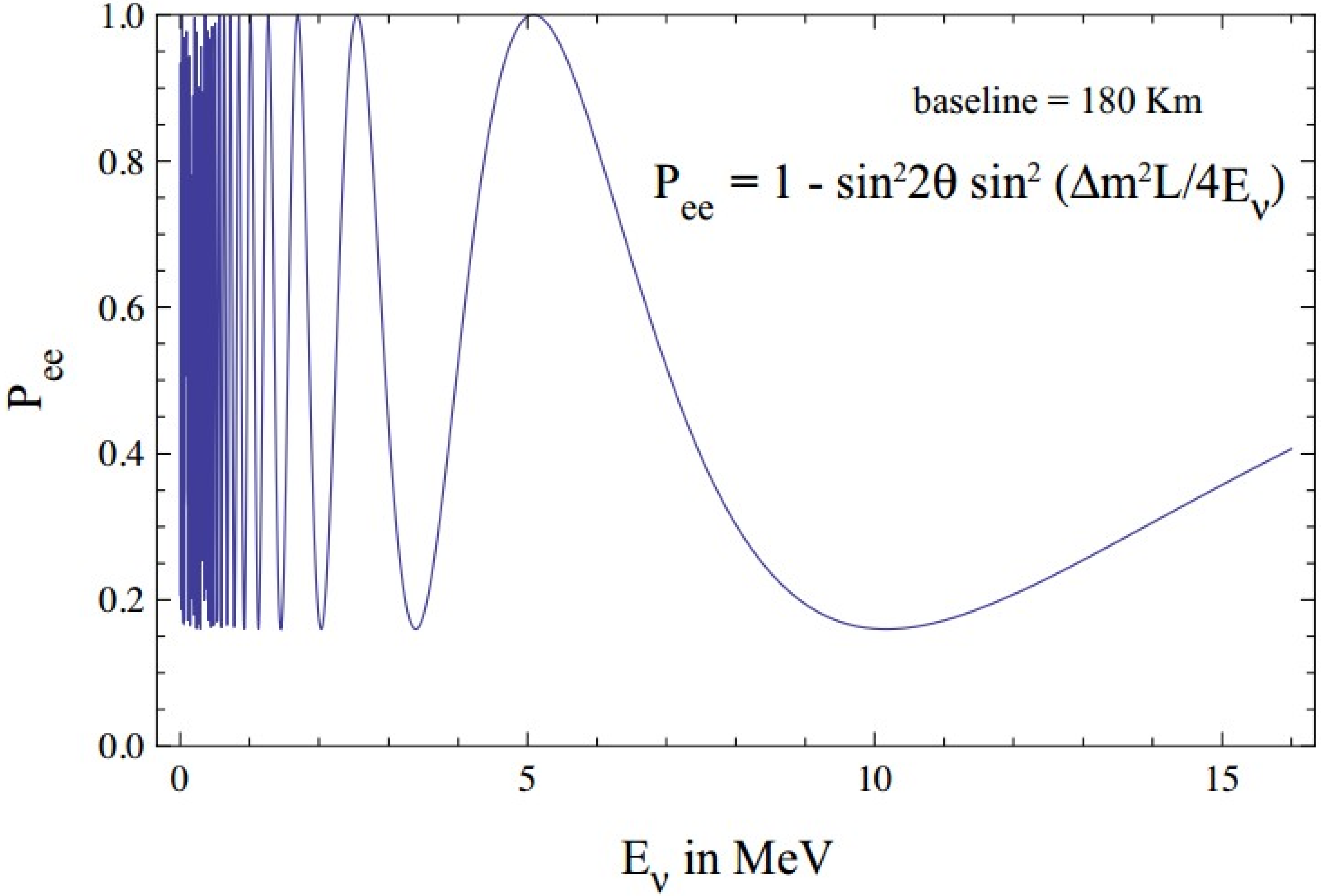
$$P_{\nu_\alpha \to \nu_\beta}(t) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} t}{2E}\right)$$

but it is more useful in term of distance:

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sum_{k,j} U^*_{\alpha k} \, U_{\beta k} \, U_{\alpha j} \, U^*_{\beta j} \, \exp\left(-i \, \frac{\Delta m^2_{kj} L}{2E}\right)$$

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \times \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})\ .$$

With more details:

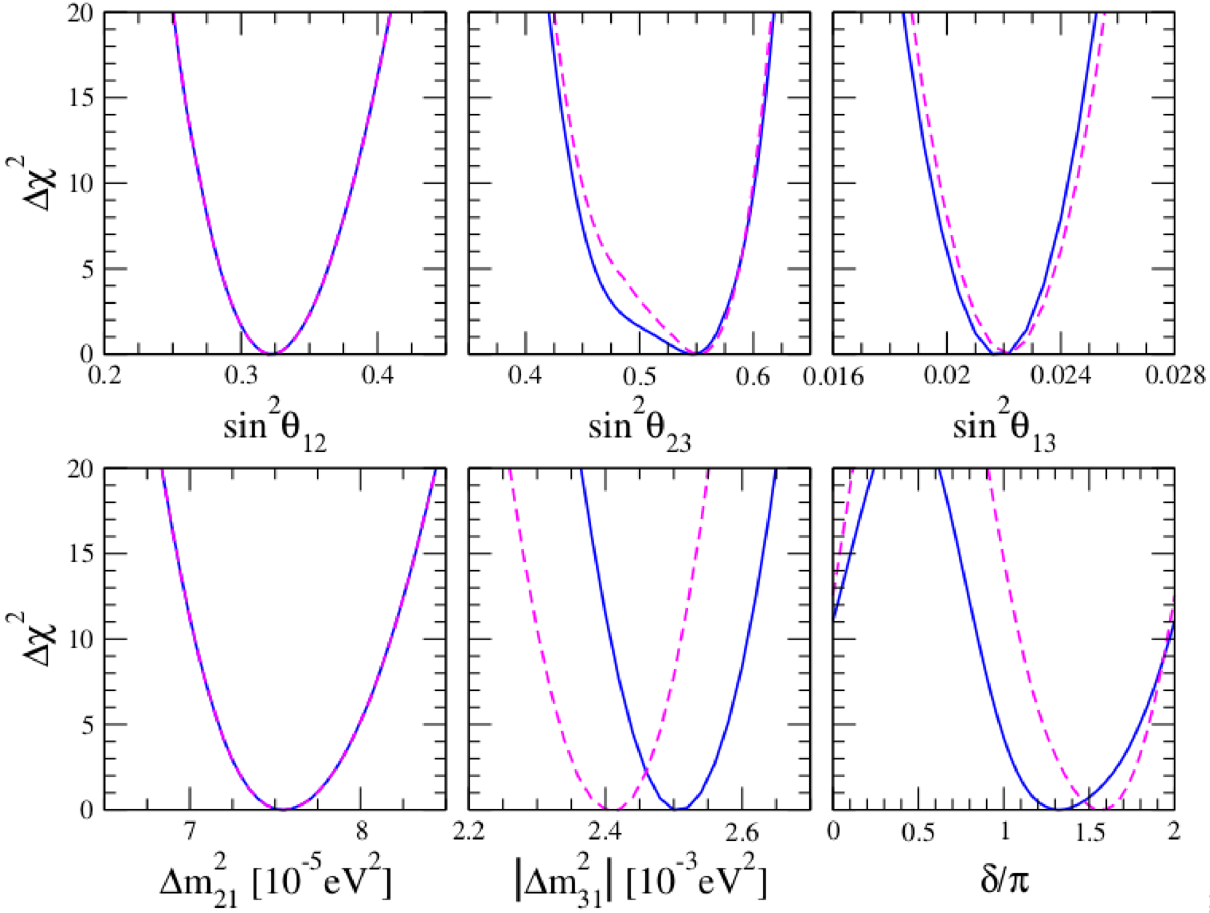


With more details:

Type of experiment	L	E	Δm^2 sensitivity
Reactor SBL	$\sim 10\,\mathrm{m}$	$\sim 1\,\mathrm{MeV}$	$\sim 0.1\,\mathrm{eV}^2$
Accelerator SBL (Pion DIF)	$\sim 1\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 1\,\mathrm{eV}^2$
Accelerator SBL (Muon DAR)	$\sim 10\,\mathrm{m}$	$\sim 10\,\mathrm{MeV}$	$\sim 1\,\mathrm{eV}^2$
Accelerator SBL (Beam Dump)	$\sim 1\,\mathrm{km}$	$\sim 10^2\,\mathrm{GeV}$	$\sim 10^2\,\mathrm{eV}^2$
Reactor LBL	$\sim 1\,\mathrm{km}$	$\sim 1\,\mathrm{MeV}$	$\sim 10^{-3}\,\mathrm{eV}^2$
Accelerator LBL	$\sim 10^3\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 10^{-3}\,\mathrm{eV}^2$
ATM	20–$10^4\,\mathrm{km}$	0.5–$10^2\,\mathrm{GeV}$	$\sim 10^{-4}\,\mathrm{eV}^2$
Reactor VLB	$\sim 10^2\,\mathrm{km}$	$\sim 1\,\mathrm{MeV}$	$\sim 10^{-5}\,\mathrm{eV}^2$
Accelerator VLB	$\sim 10^4\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 10^{-4}\,\mathrm{eV}^2$
SOL	$\sim 10^{11}\,\mathrm{km}$	0.2–$15\,\mathrm{MeV}$	$\sim 10^{-12}\,\mathrm{eV}^2$

Neutrino oscillations

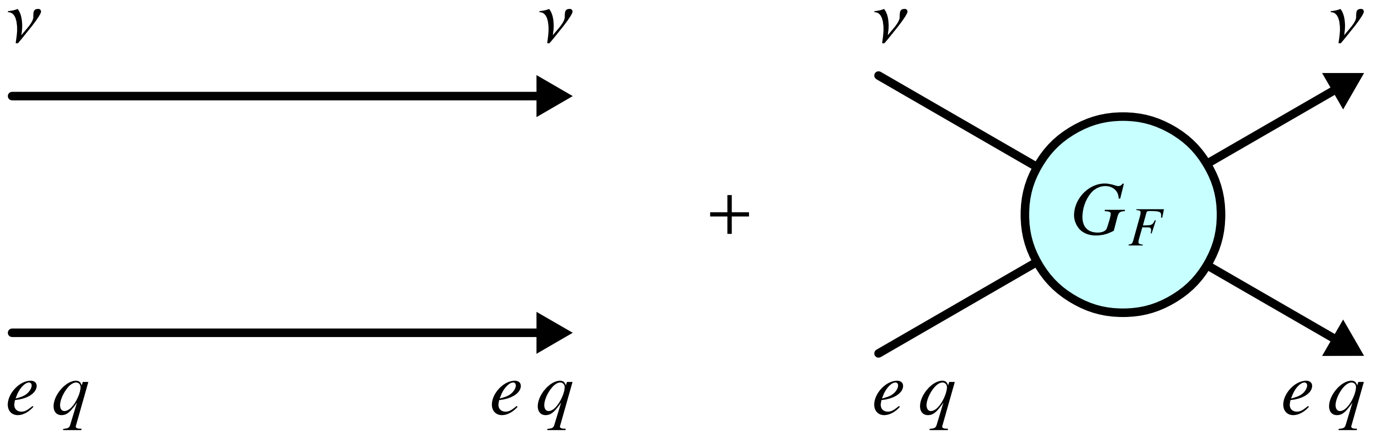
arxiv:1708.01186



- The analysis of different neutrino oscillation experiments help to constraint mixing angle and mass splitting.

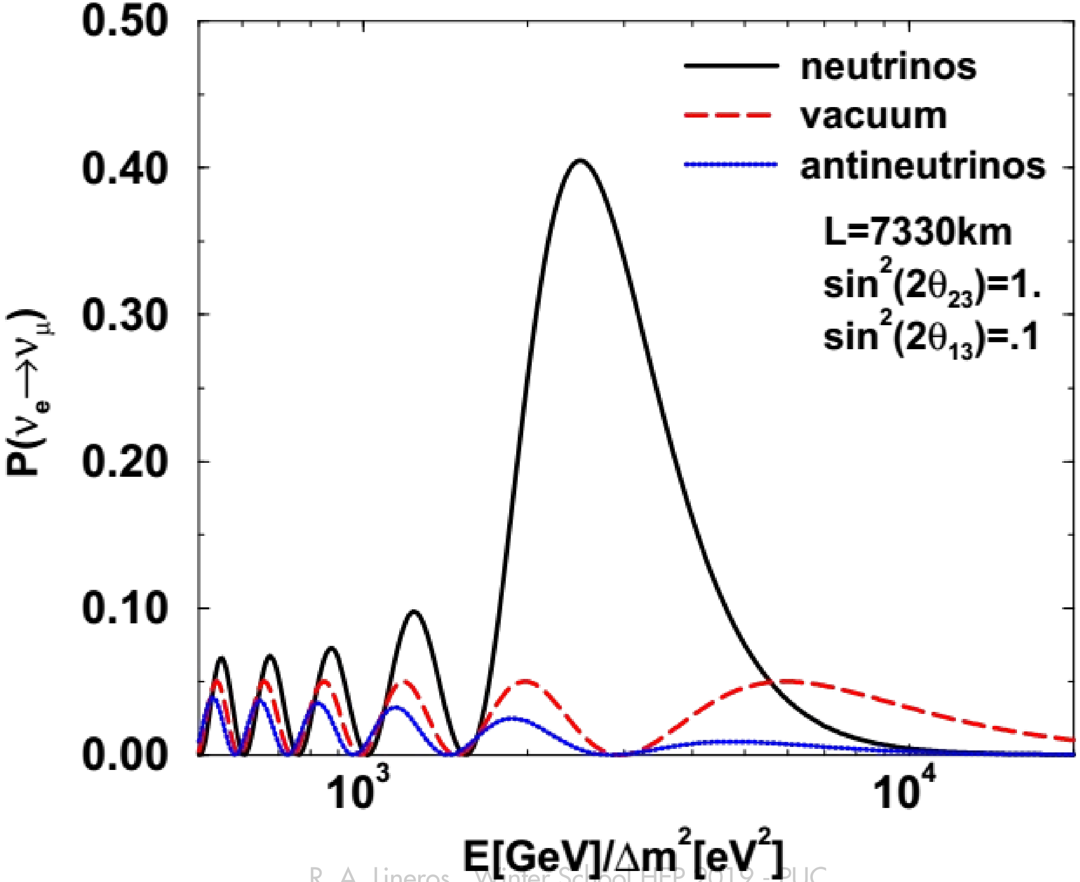
Matter effects (a.k.a. MSW effect)

The interaction with a medium modifies the oscillation patterns w.r.t. vacuum



$$\mathcal{H}_{\rm tot} = \mathcal{H}_{\rm vac} + \mathcal{V}$$

Matter effects (a.k.a. MSW effect)

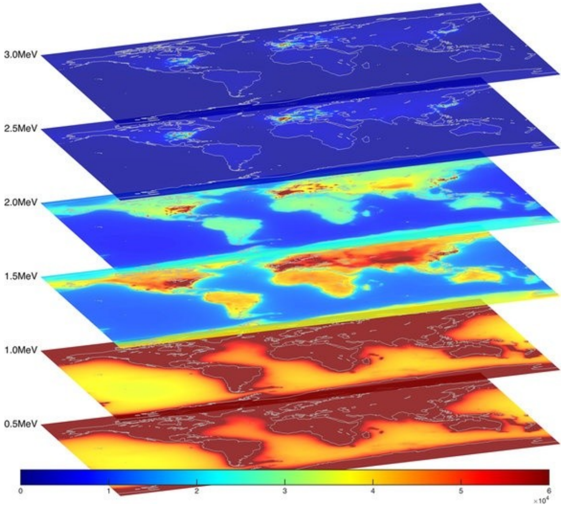


Mass Mechanisms

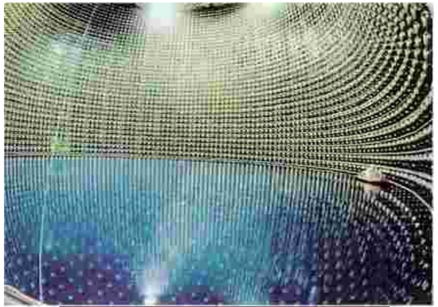
To add to the slides

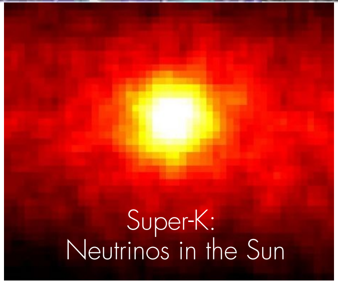
Neutrino mass mechanism
Sources of neutrinos
Astroparticles neutrinos
Solar neutrinos (DM also)
Icecube neutrinos
Cosmology neutrino

Neutrinos

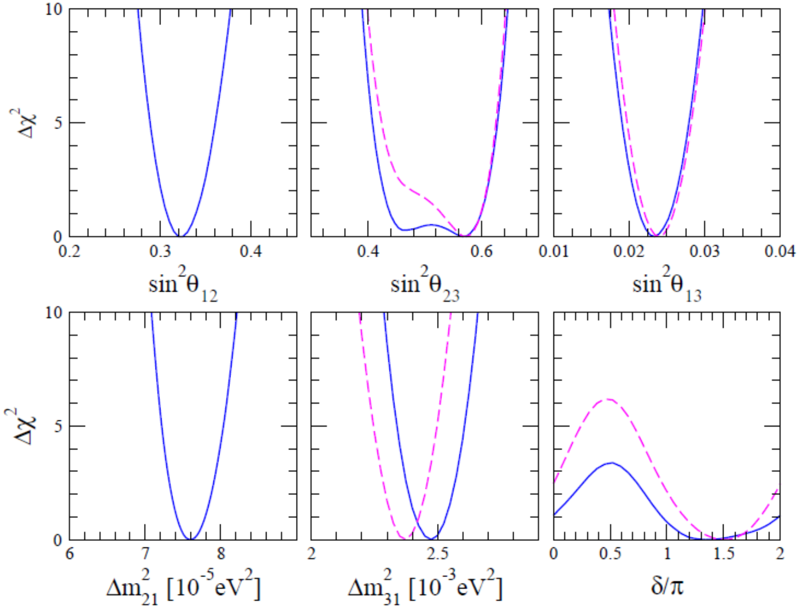


AGM2015: Antineutrino Global Map 2015





Forero, Tortola and Valle PRD 90 (2014) 093006

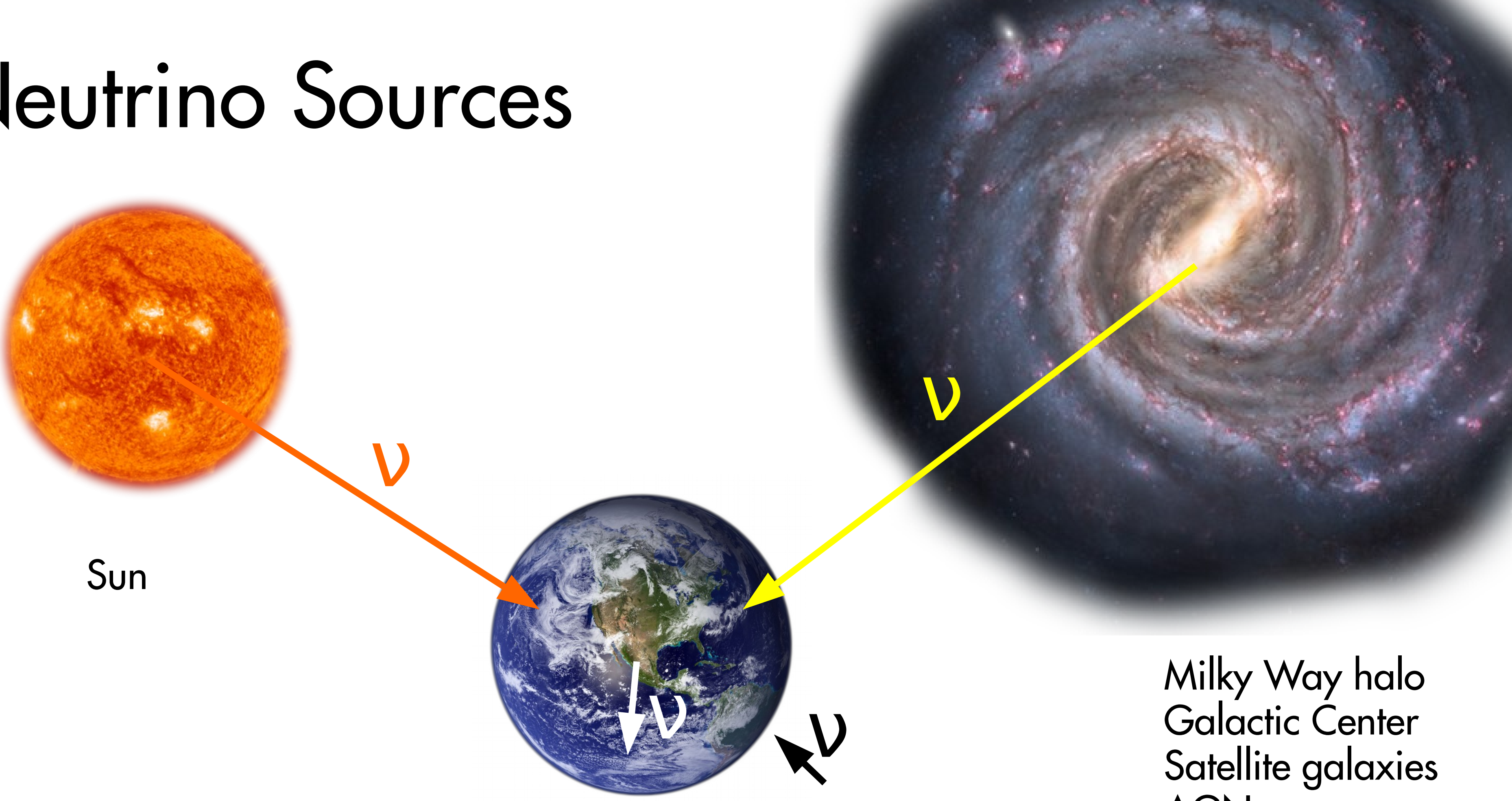


The SM predicts massless neutrinos

Physics beyond SM is needed to explain neutrino's mass spectrum and mixing angles

$$\mathcal{O}_{5ij} \propto (L_i H)^T (L_j H)$$

Neutrino Sources

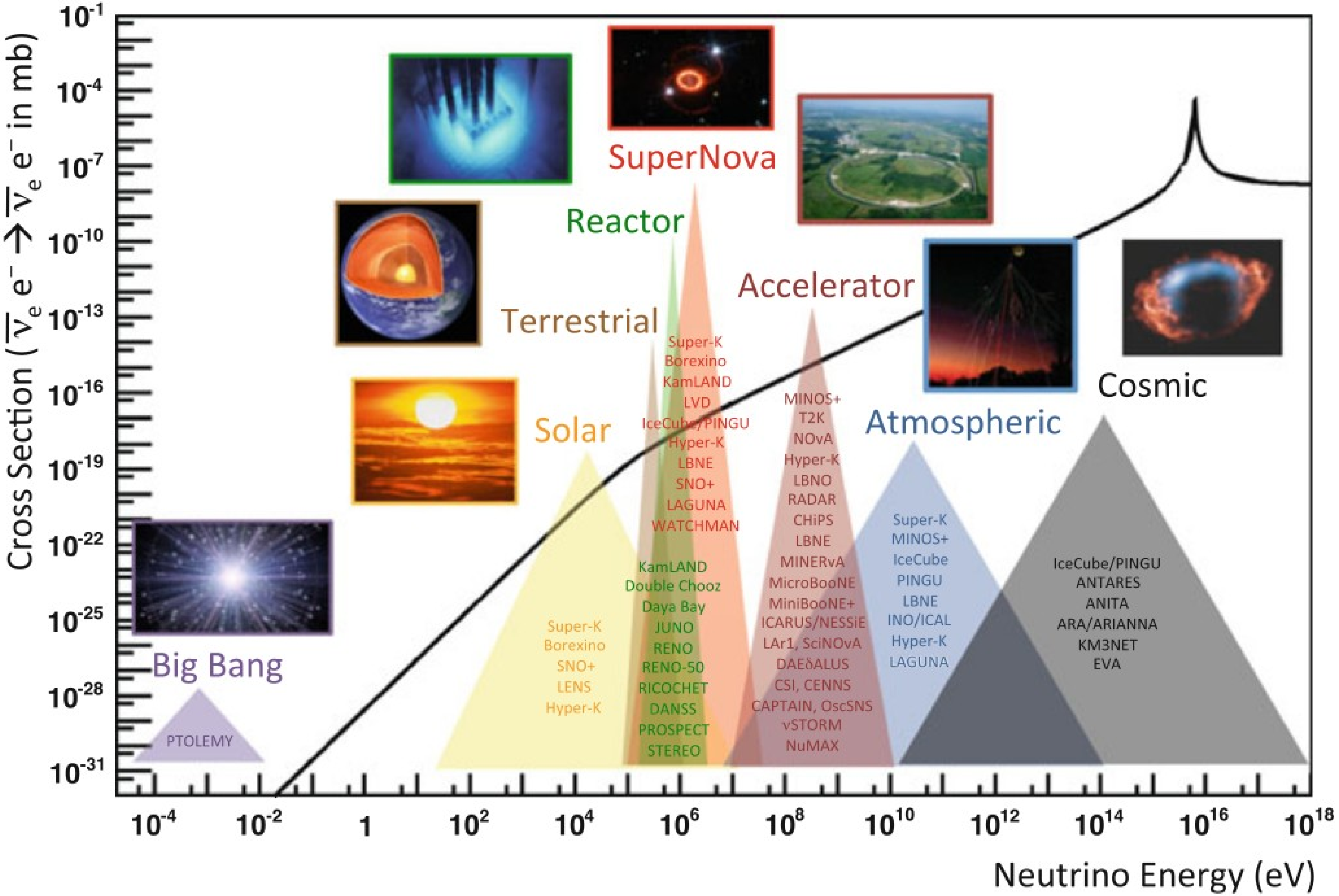


Sun

Geoneutrinos
Atmospheric

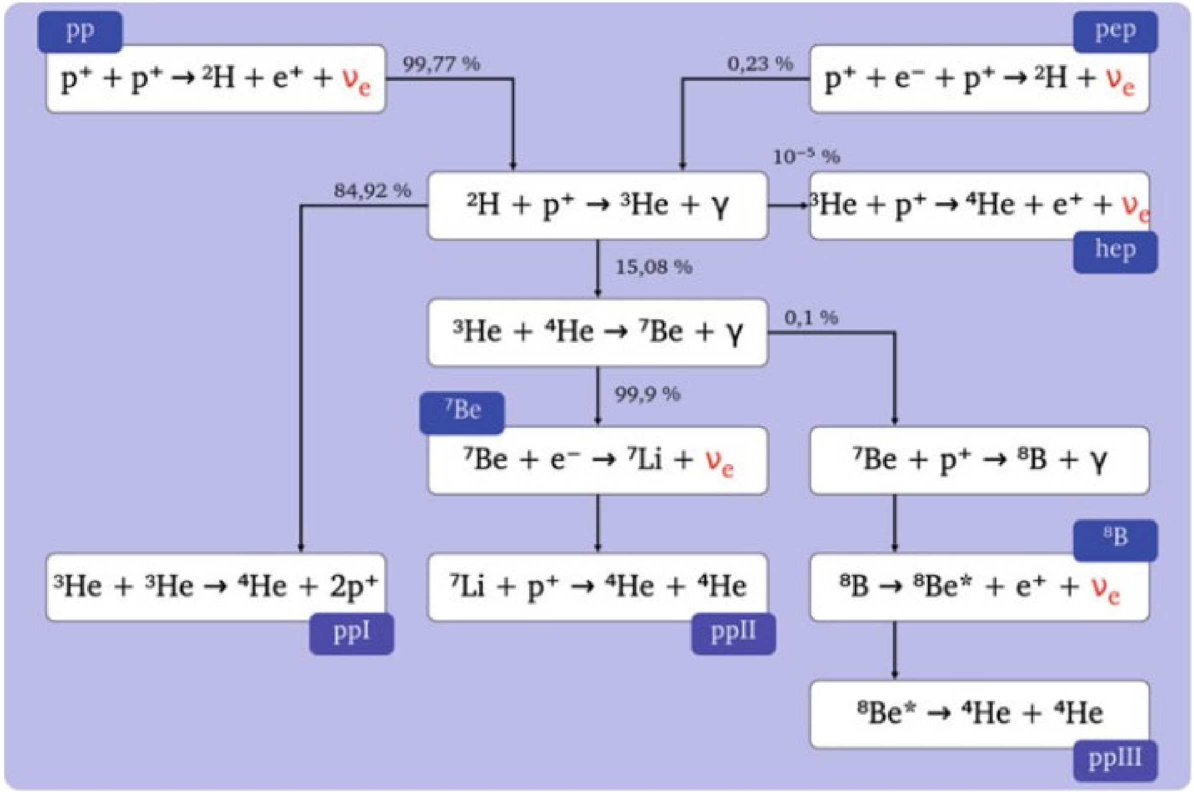
Milky Way halo
Galactic Center
Satellite galaxies
AGN

Neutrino Sources



Neutrinos from the Sun

The Sun is the brightest source of neutrinos at the MeV scale



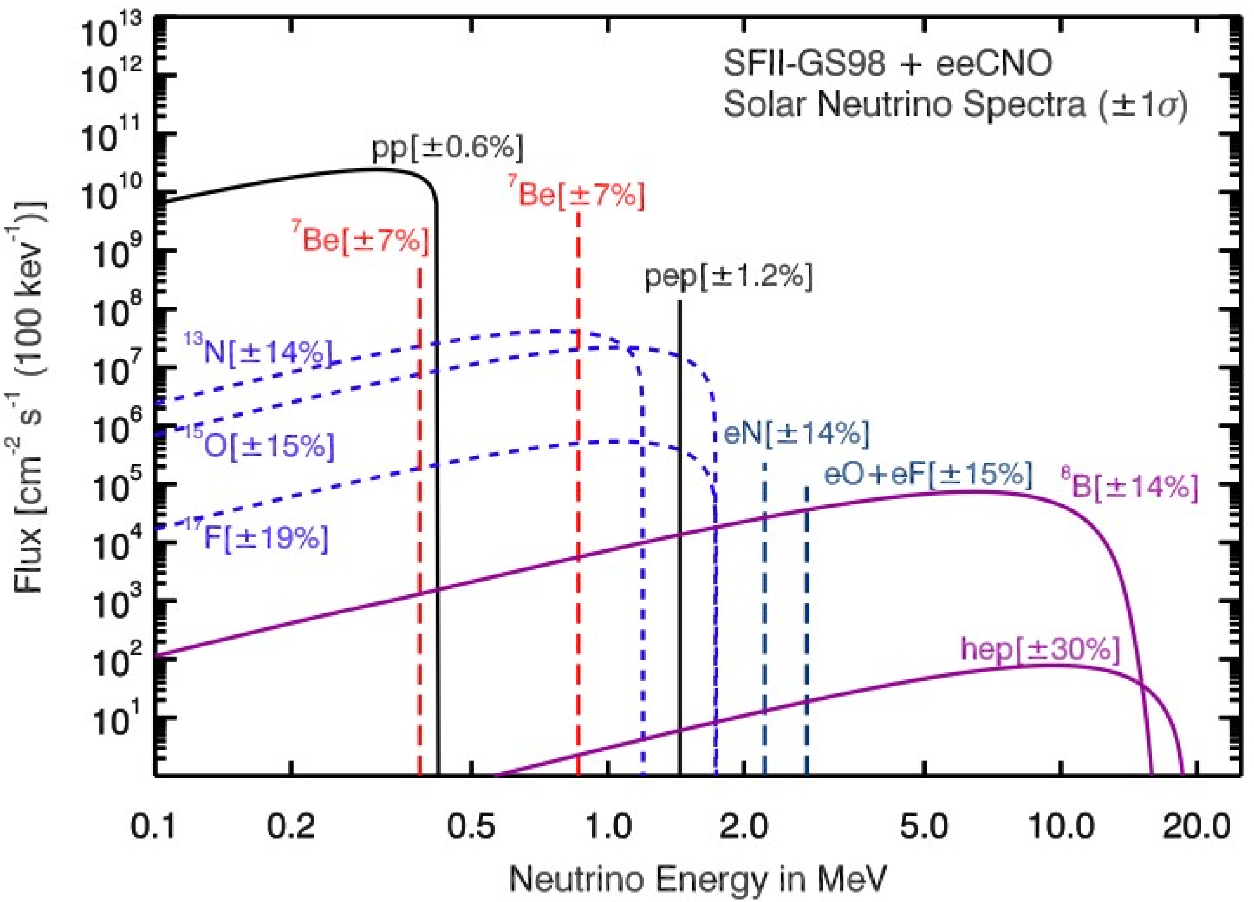
Neutrinos from the Sun

The Sun is the brightest source of neutrinos at the MeV scale

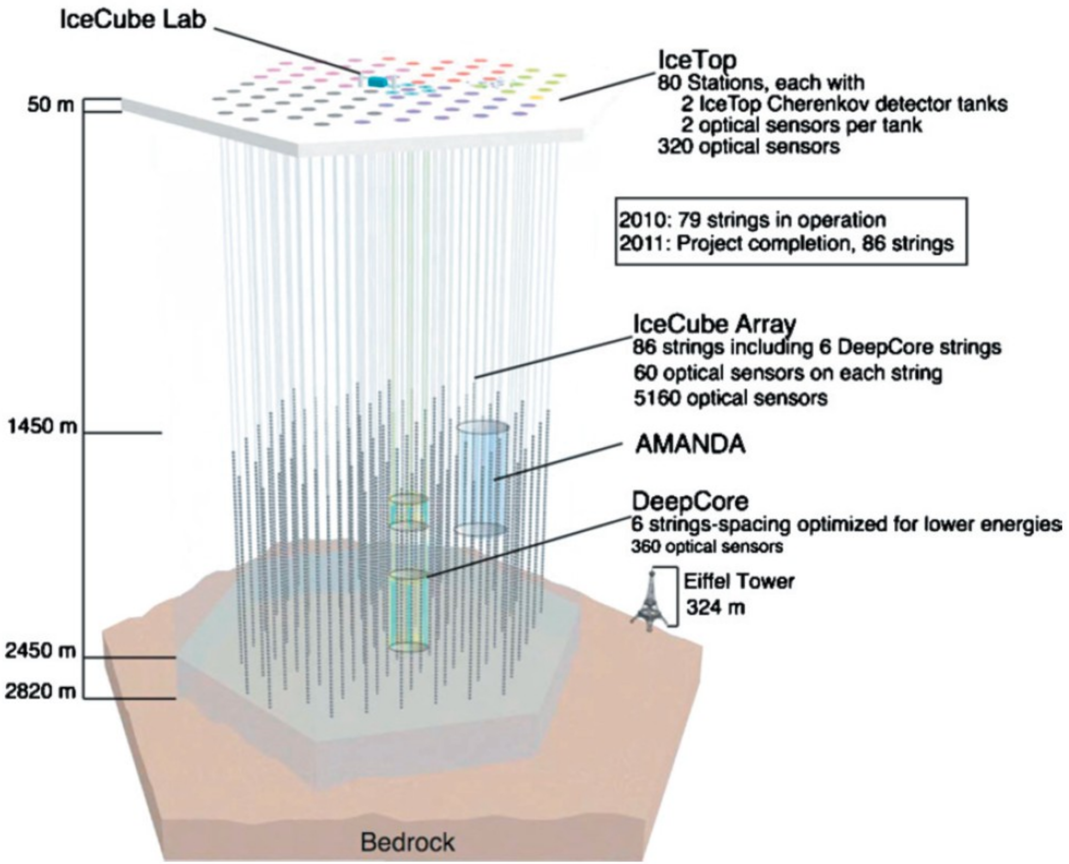
Reaction	Abbr.	Flux (cm^{-2} s^{-1})
$pp \to d\, e^+ \nu$	pp	$5.98(1 \pm 0.006) \times 10^{10}$
$pe^- p \to d\, \nu$	pep	$1.44(1 \pm 0.01) \times 10^8$
$^3\mathrm{He}\, p \to {}^4\mathrm{He}\, e^+ \nu$	hep	$7.98(1 \pm 0.30) \times 10^3$
$^7\mathrm{Be}\, e^- \to {}^7\mathrm{Li}\, \nu + (\gamma)$	$^7\mathrm{Be}$	$4.93(1 \pm 0.06) \times 10^9$
$^8\mathrm{B} \to {}^8\mathrm{Be}^*\, e^+ \nu$	$^8\mathrm{B}$	$5.46(1 \pm 0.12) \times 10^6$
$^{13}\mathrm{N} \to {}^{13}\mathrm{C}\, e^+ \nu$	$^{13}\mathrm{N}$	$2.78(1 \pm 0.15) \times 10^8$
$^{15}\mathrm{O} \to {}^{15}\mathrm{N}\, e^+ \nu$	$^{15}\mathrm{O}$	$2.05(1 \pm 0.17) \times 10^8$
$^{17}\mathrm{F} \to {}^{17}\mathrm{O}\, e^+ \nu$	$^{17}\mathrm{F}$	$5.29(1 \pm 0.20) \times 10^6$

Neutrinos from the Sun

The Sun is the brightest source of neutrinos at the MeV scale



Neutrino Observatories



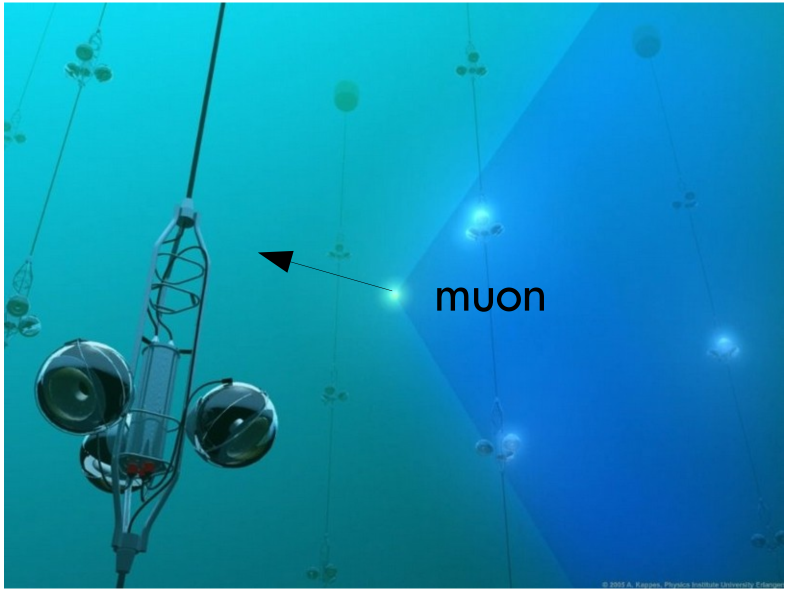
IceCube

(located in Antartica)

Neutrino Observatories

ANTARES

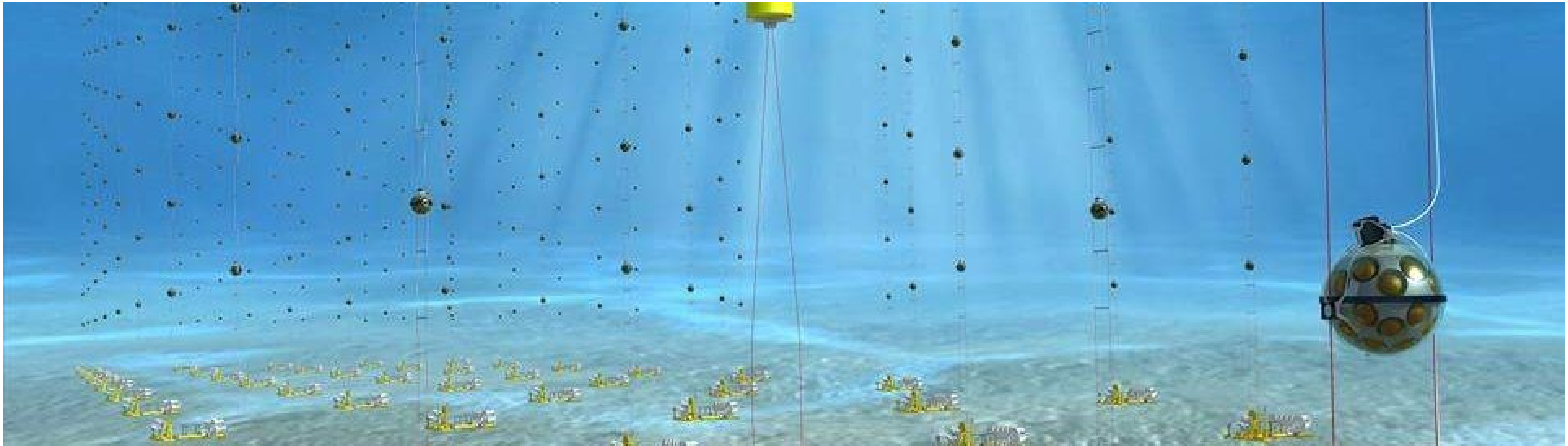
(located in the mediterrean sea)



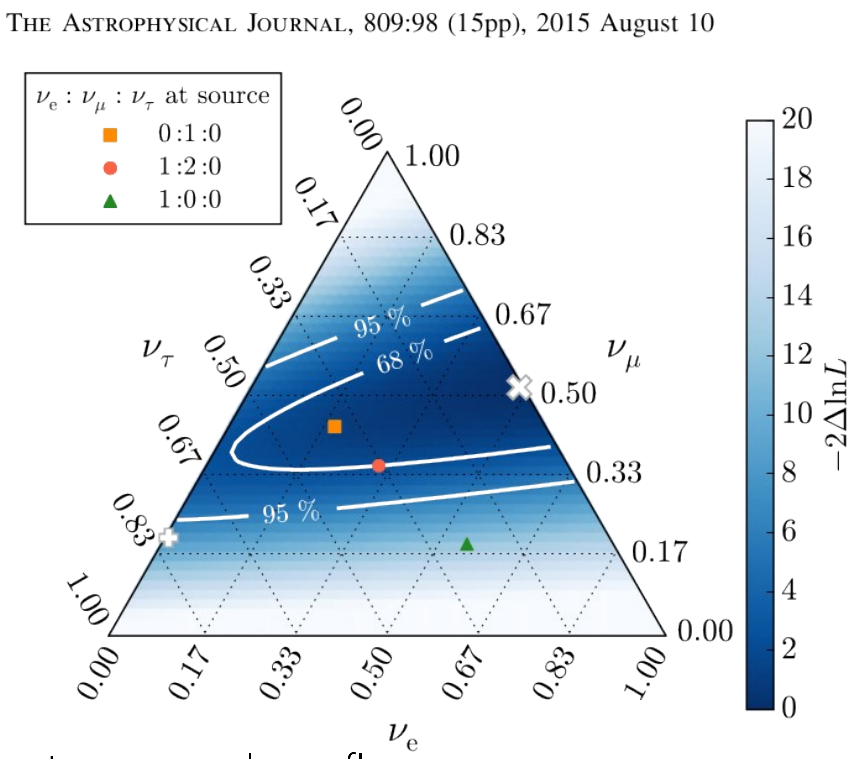
Neutrino Observatories

KM3NET

(located in the mediterrean sea)

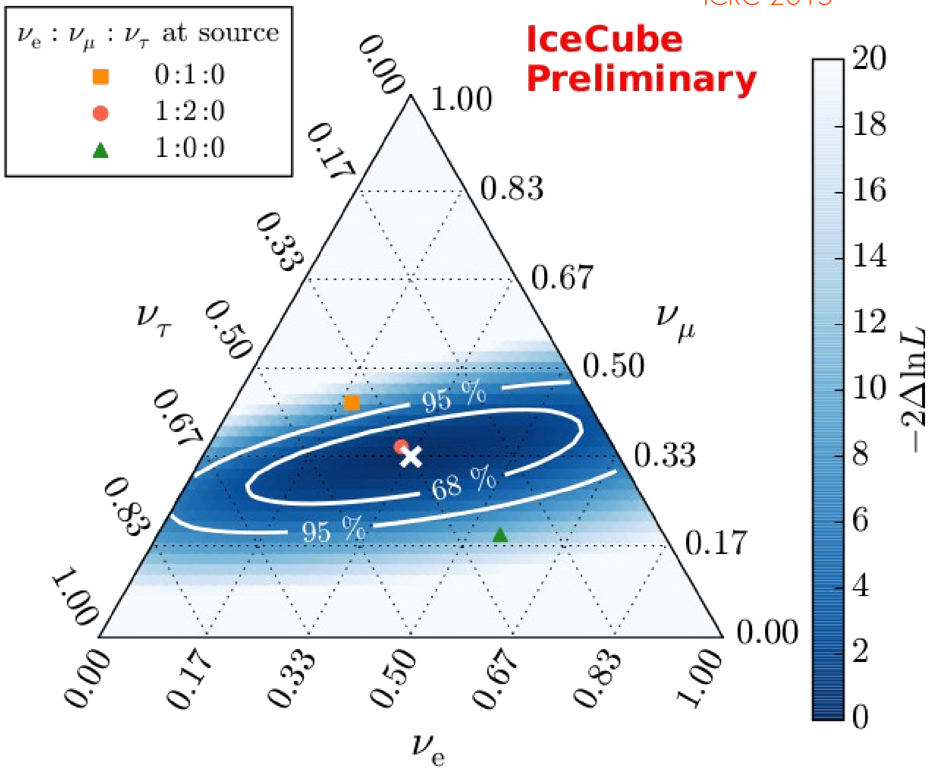


Flavor composition in IceCube



Latest result on flavor composition

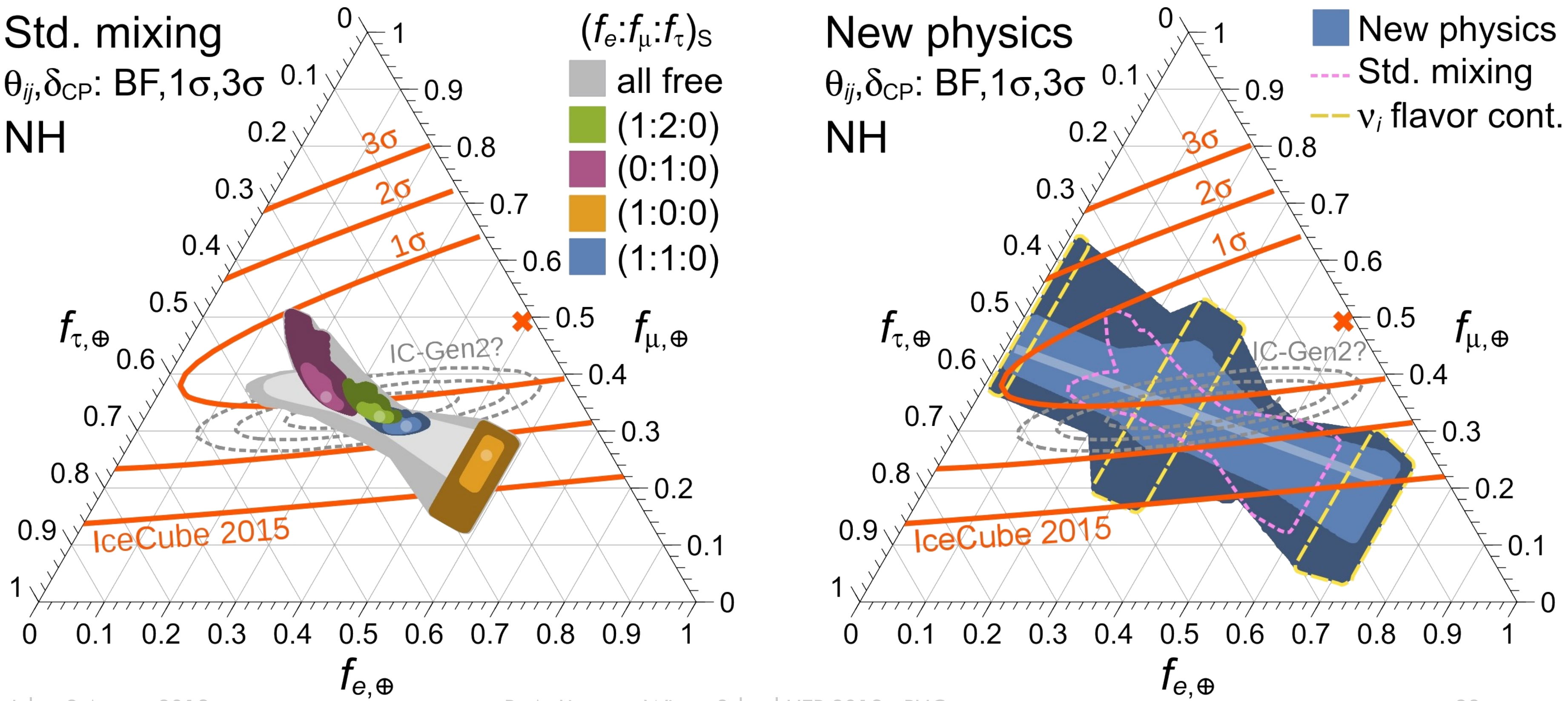
ICRC 2015



Sensitivity after 10 years

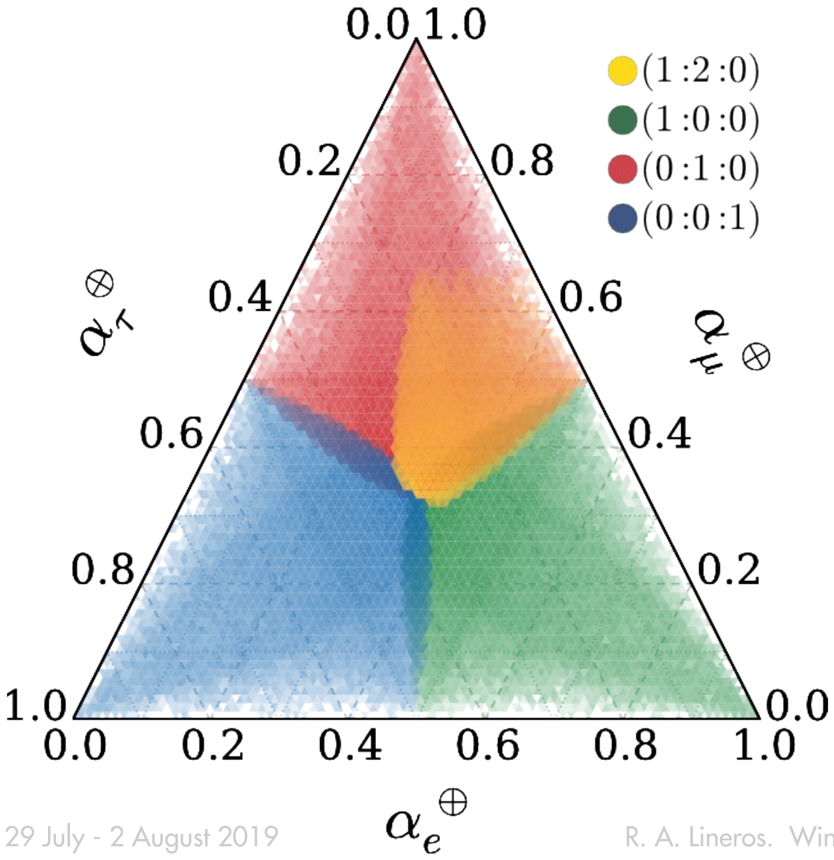
Flavor composition

M. Bustamante et al. PRL 115, 161302 (2015)



Effects from New Physics

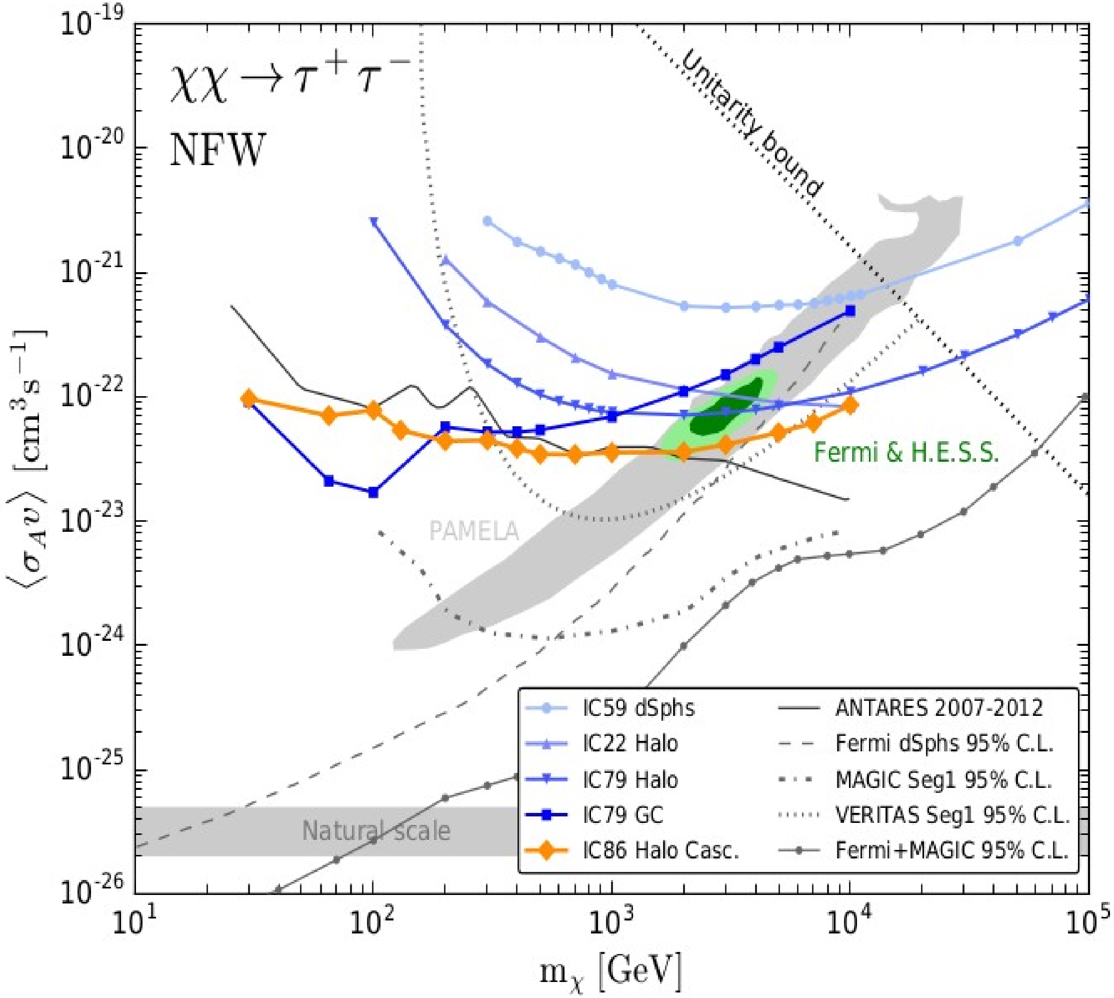
Argüelles et at. PRL 115, 161303 (2015)



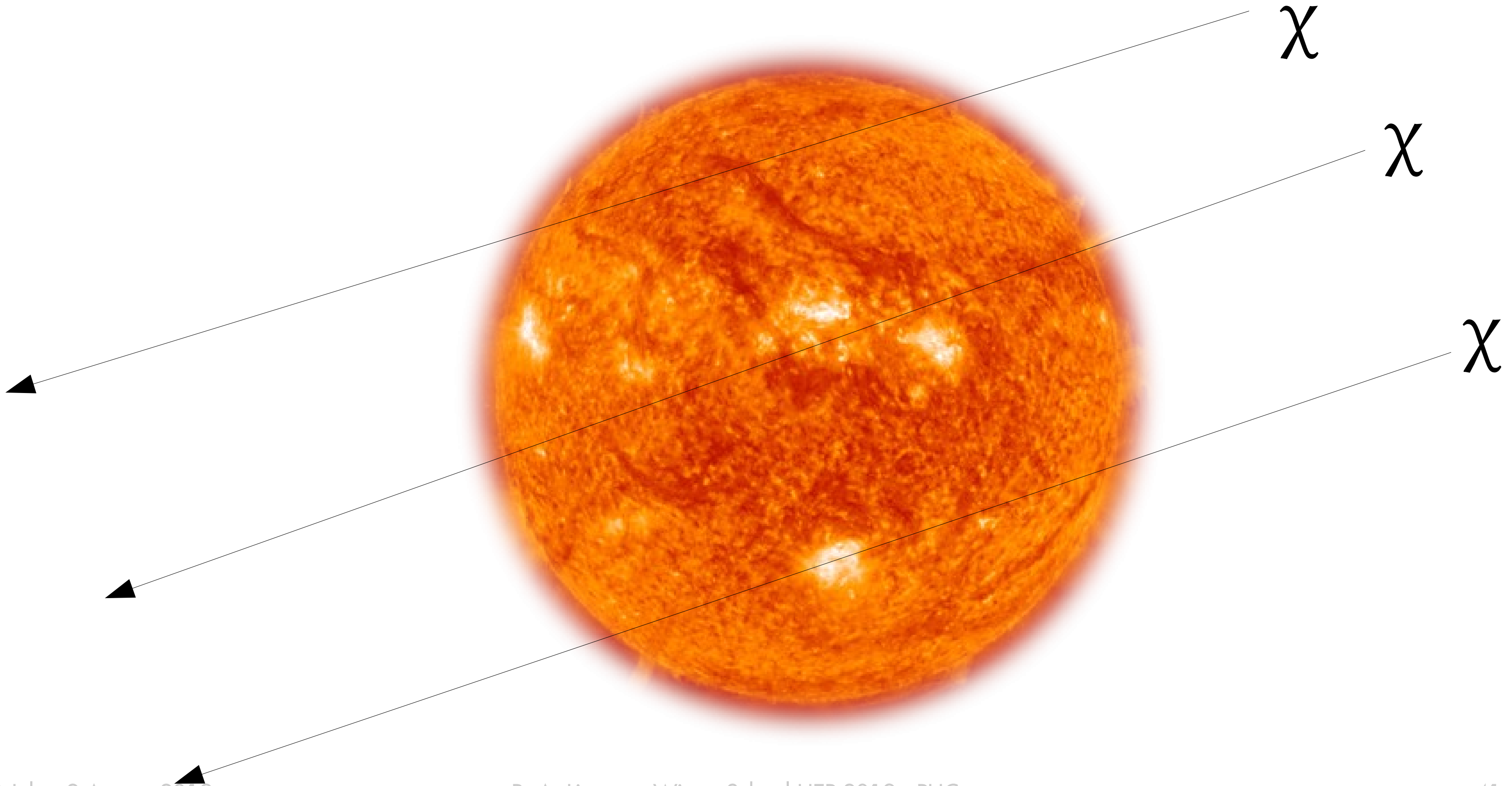
Sources of New Physics:

- Space torsion
- CPT - Lorentz violation
- Dark Matter interactions

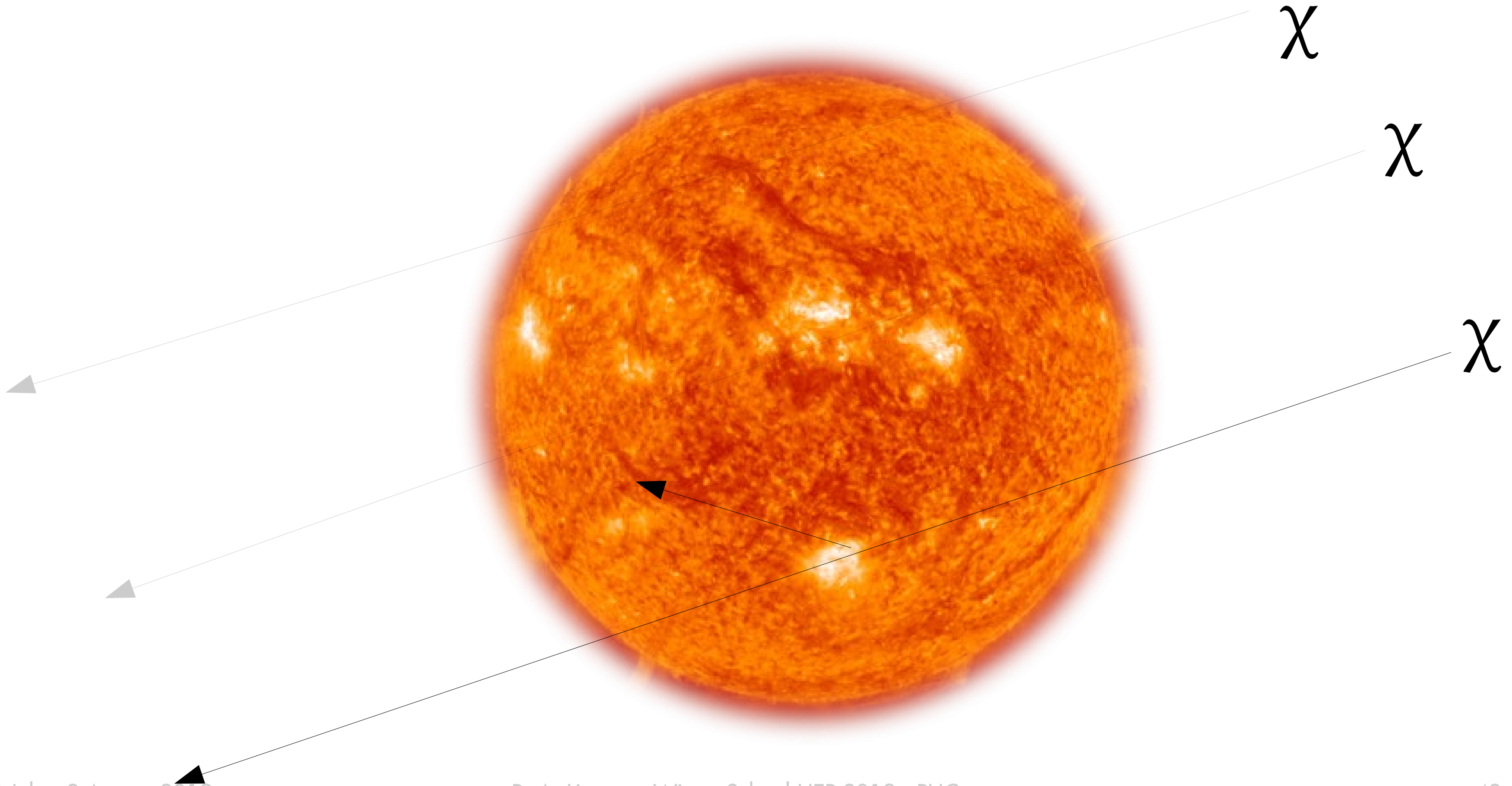
Dark Matter Searches



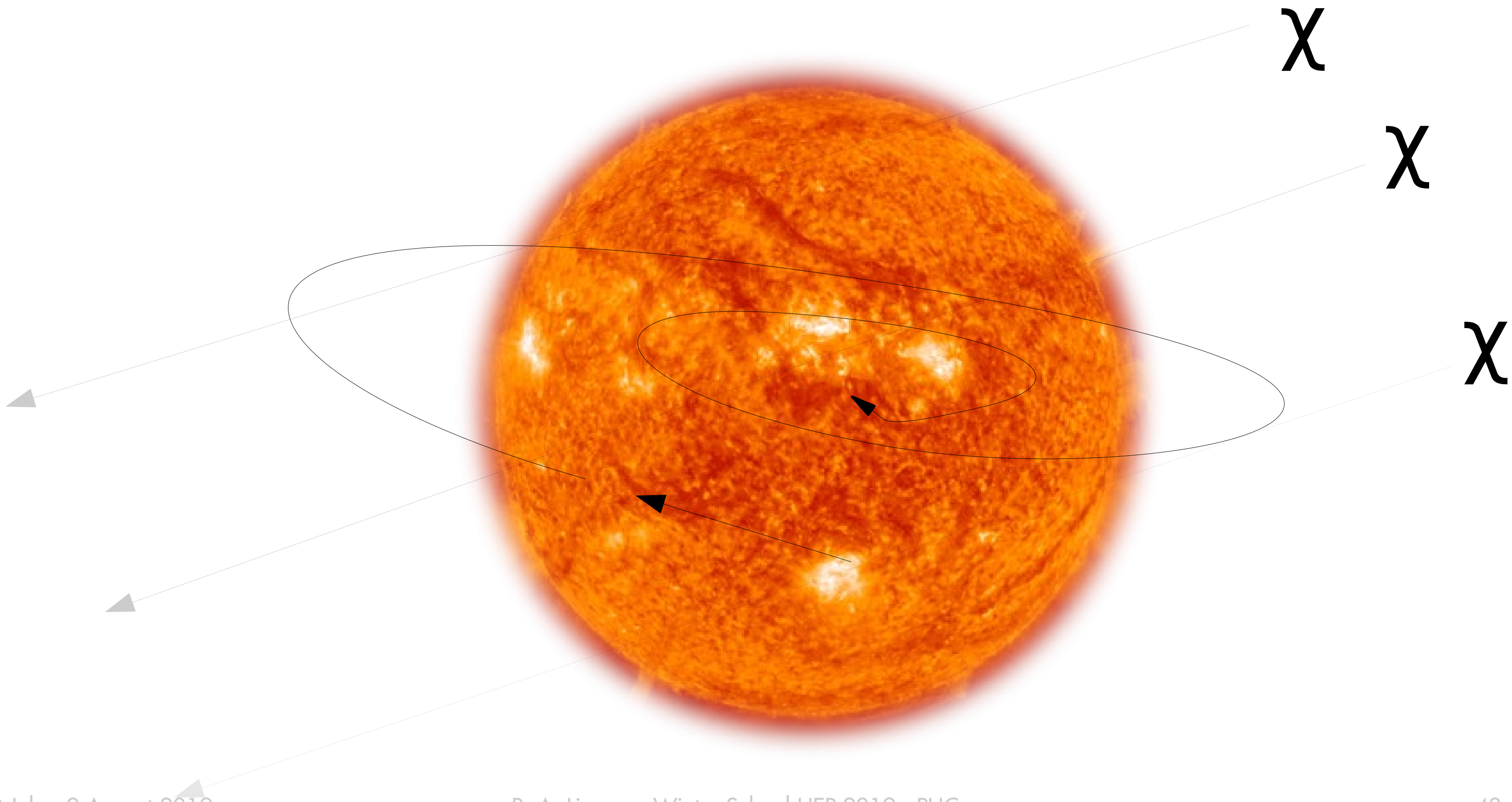
Dark Matter in the Sun



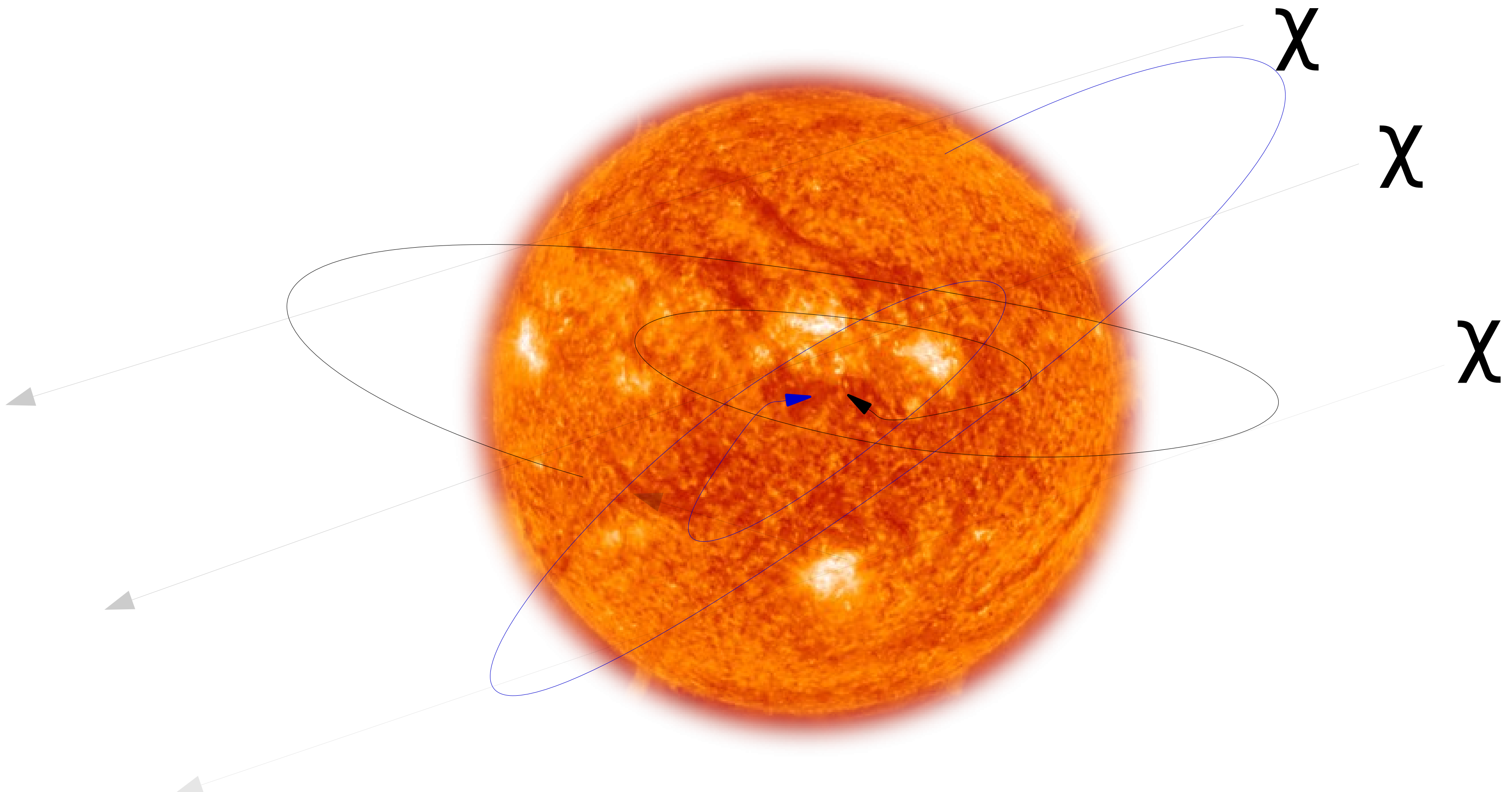
Dark Matter in the Sun



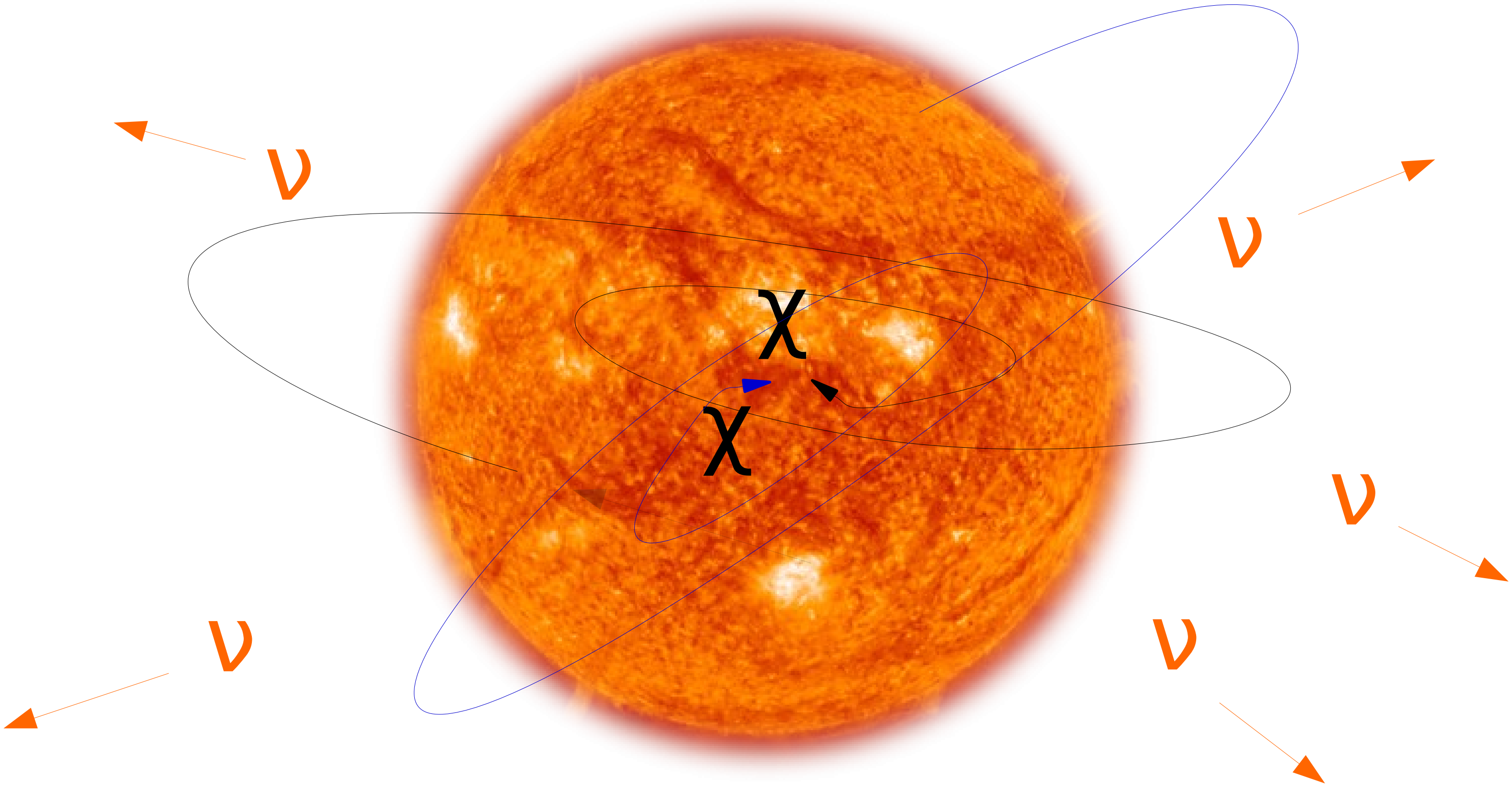
Dark Matter in the Sun



Dark Matter in the Sun

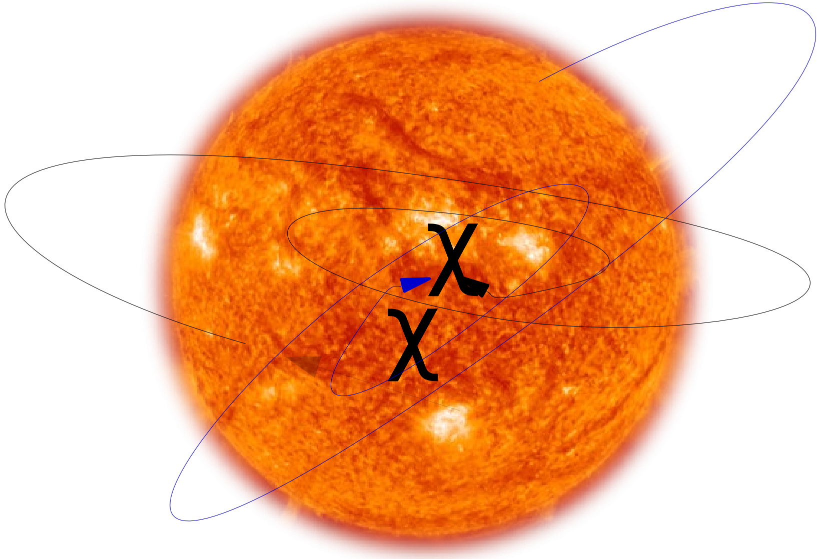


Dark Matter in the Sun



Dark Matter in the Sun

arxiv:1005.5711



$$\dot{N}_\chi = C - 2AN_\chi^2 - EN_\chi$$

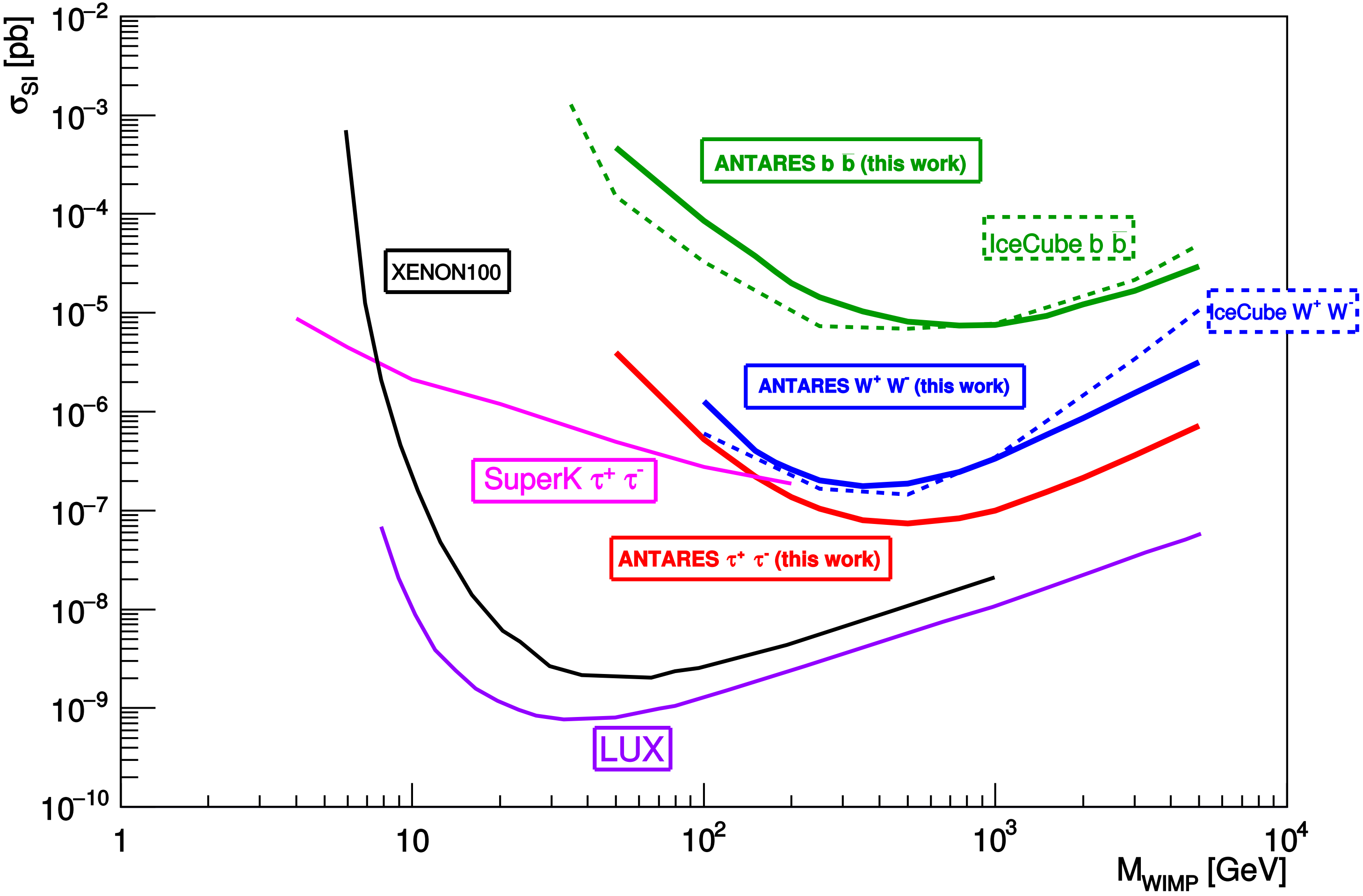
Capture

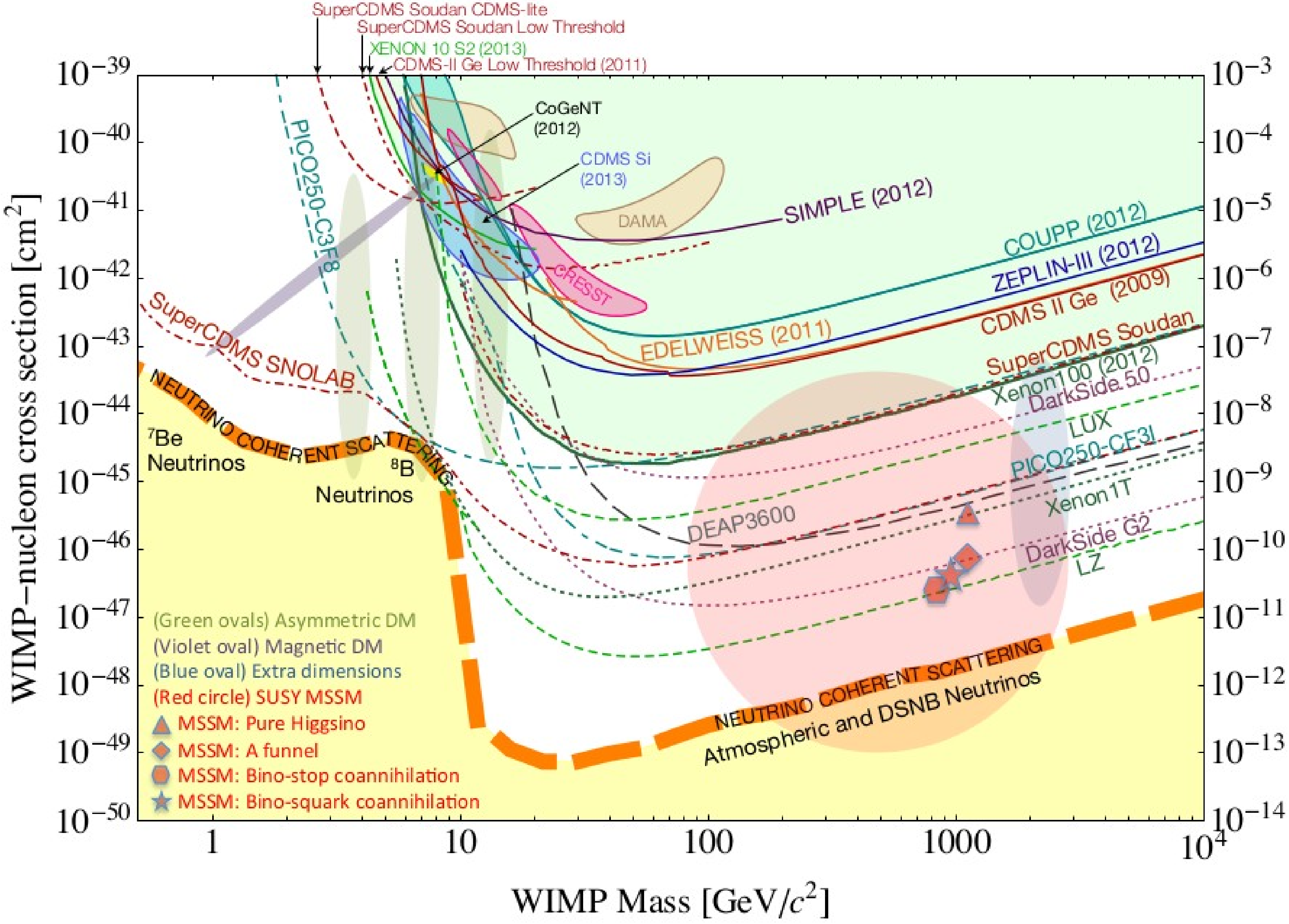
Annihilation

Evaporation

Phys.Lett. B759 (2016) 69-74

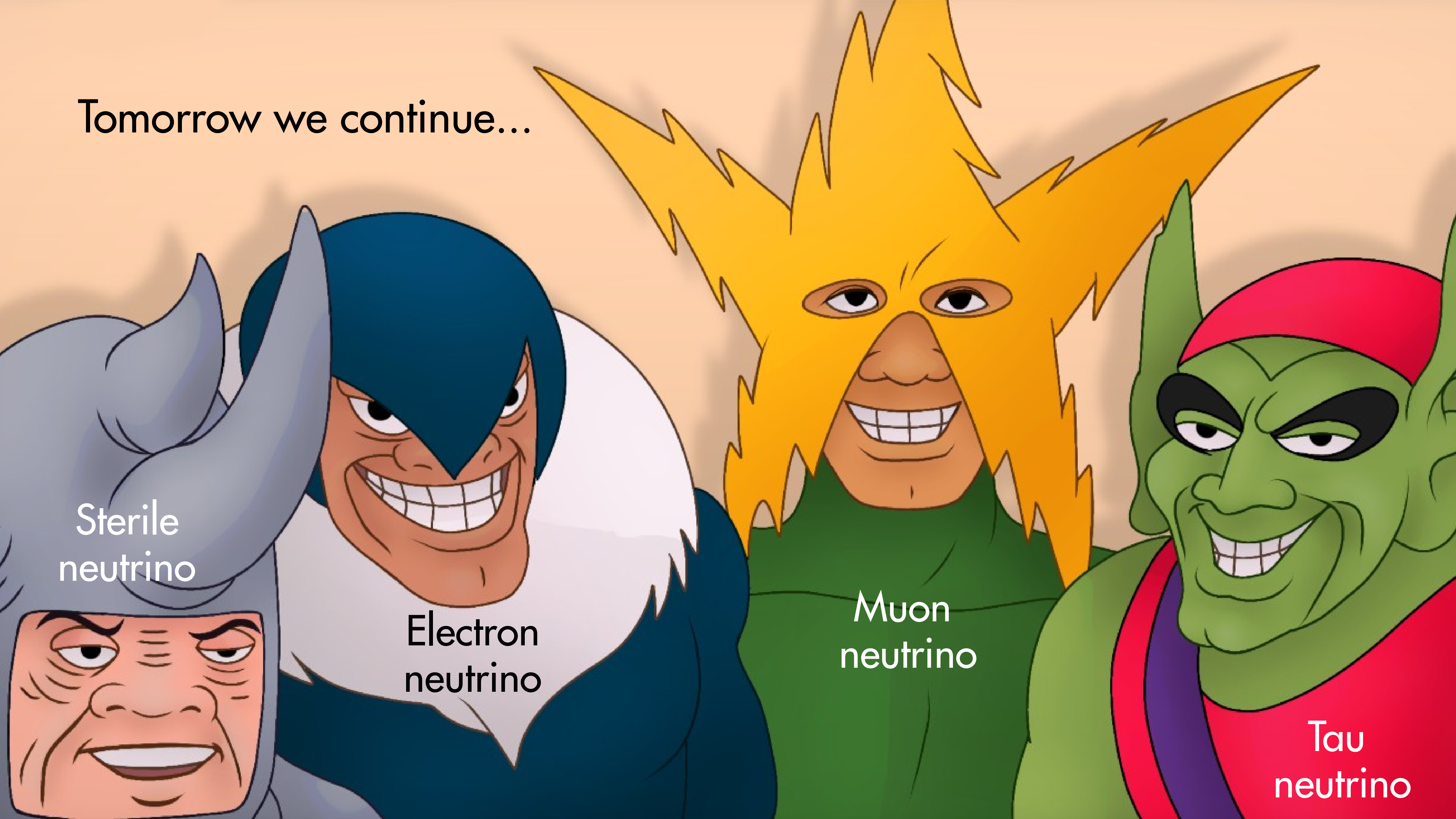
Dark Matter in the Sun





SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
PICO250-C3F8
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
SuperCDMS SNOLAB
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DEAP3600
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c2]

The Tools


Tomorrow we continue...
Sterile neutrino
Electron neutrino
Muon neutrino
Tau neutrino