Beyond the Standard Model

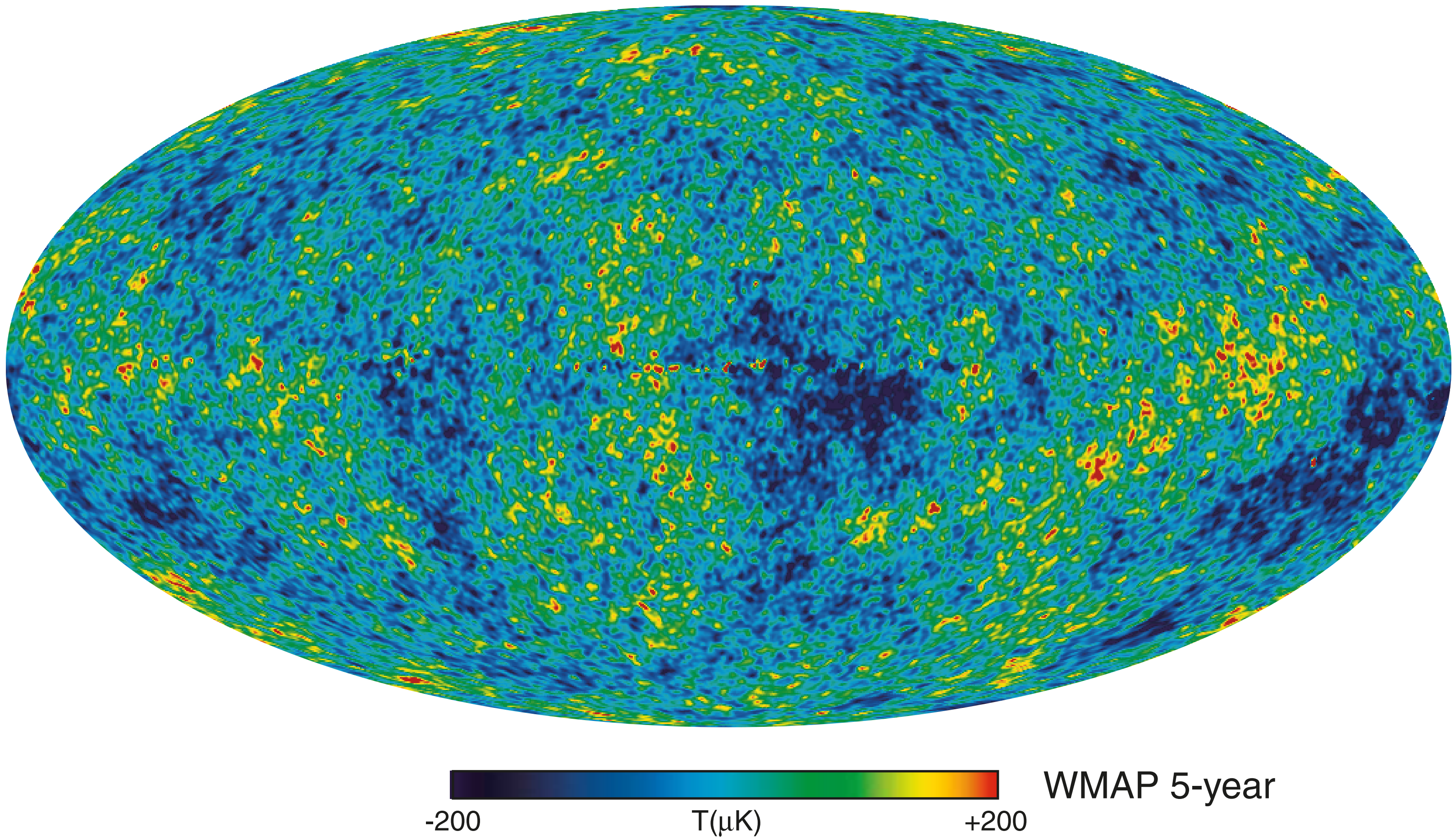
Summary of the course

Successful application of the particle physics and gravity to the Universe as a whole

- ✓ Laws of gravitation over the whole Universe $\Rightarrow$ expansion of the Universe. Hubble law
- ✓ Laws of thermodynamics. $\Rightarrow$ Hot Big Bang theory.
- ✓ Atomic physics. Thomson scattering $\Rightarrow$ properties of cosmic microwave background radiation
- ✓ Nuclear physics. Nuclear cross-section. Binding energy $\Rightarrow$ Primordial synthesis of elements. Helium abundance
- ✓ Particle physics. Weak interactions (Fermi theory) $\Rightarrow$ decoupling of neutrinos (primordial element abundance)
- ✓ Particle physics of the curved space time $\Rightarrow$ inflationary theory. Generation of primordial perturbations

Did we succeed?

CMB temperature is anisotropic over the sky with $\delta T/T_{\text{CMB}} \sim 10^{-5}$



WMAP-5 results with subtracted galactic contribution (courtesy of WMAP Science team)

- The temperature anisotropy $\delta T(\hat{n})$ is expanded in spherical harmonics $Y_{lm}(\hat{n})$:

$$\delta T(\vec{n}) = \sum_{l,m} a_{lm} Y_{lm}(\hat{n})$$

- a_{lm}'s are Gaussian random variables (before sky cut)
- CMB anisotropy **(TT) power-spectrum**: 2-point correlation function

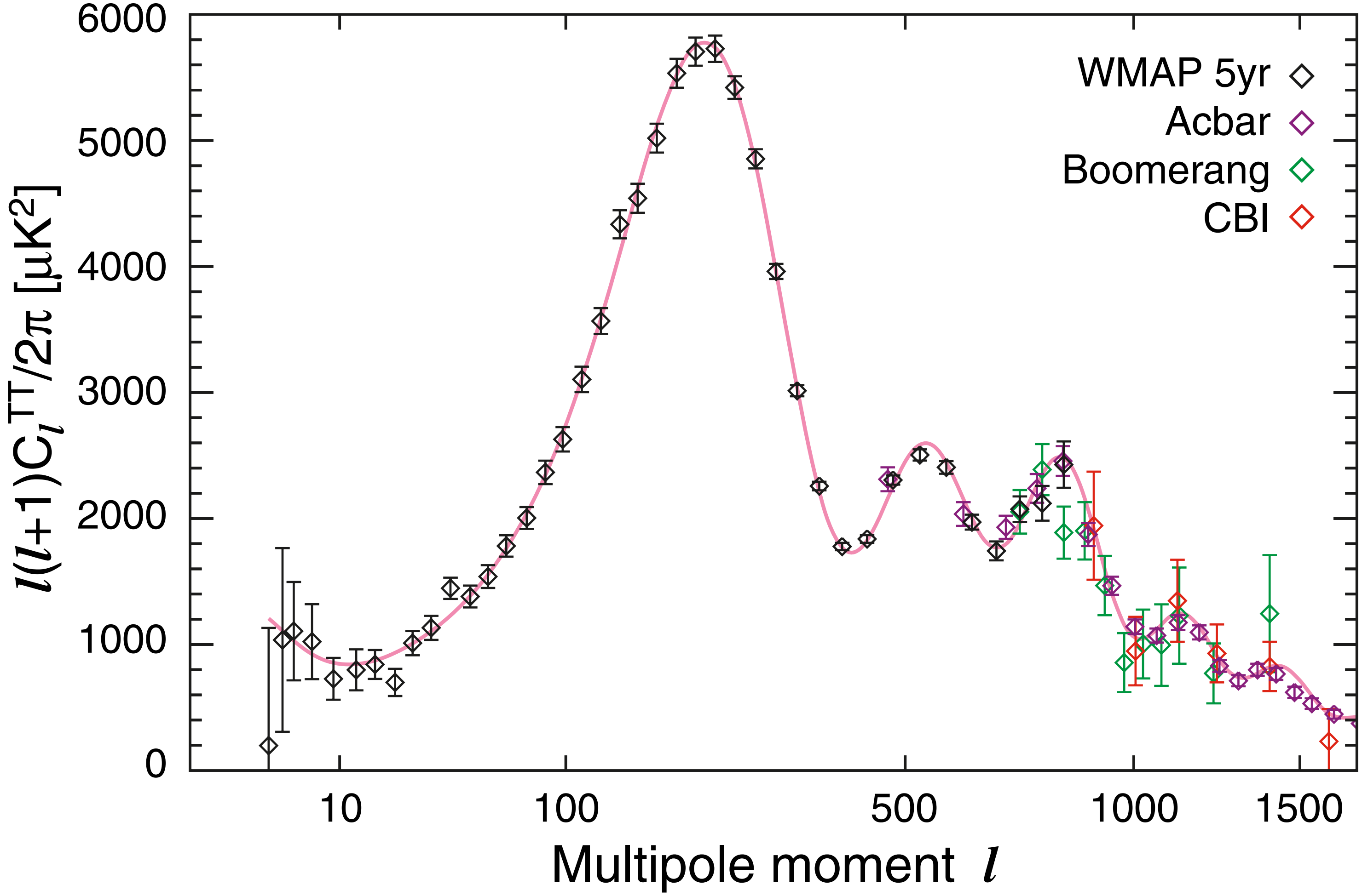
$$\boxed{\langle \delta T(\hat{n})\, \delta T(\hat{n}') \rangle = \sum_{l=0}^{\infty} \frac{2l+1}{4\pi} C_l P_l(\hat{n}\cdot\hat{n}')}$$

$P_l(\hat{n}\cdot\hat{n}')$ – Legendre polynomials

- **Multipoles C_l's**

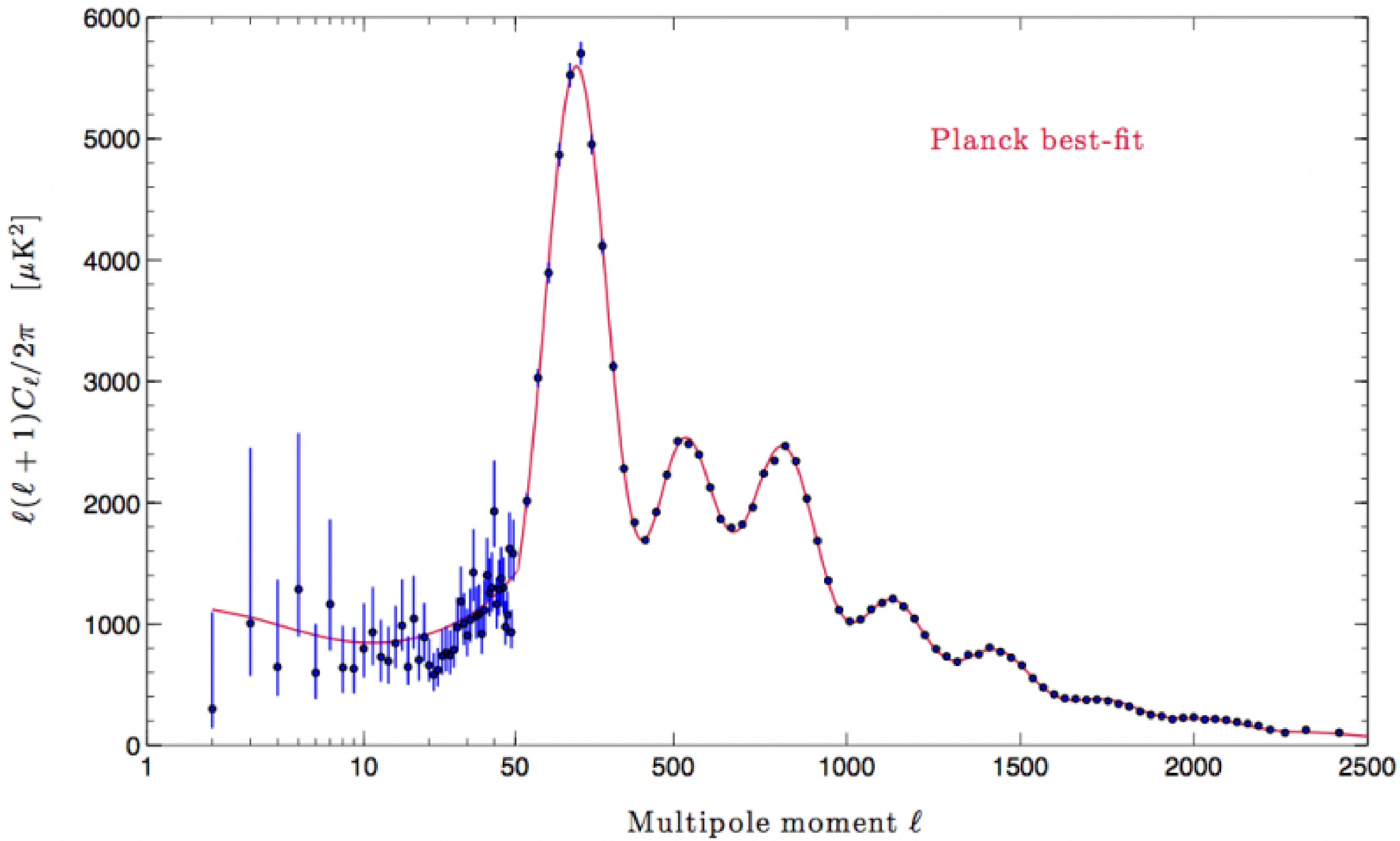
$$\boxed{C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2}$$

probe correlations of angular scale $\theta \sim \pi/l$

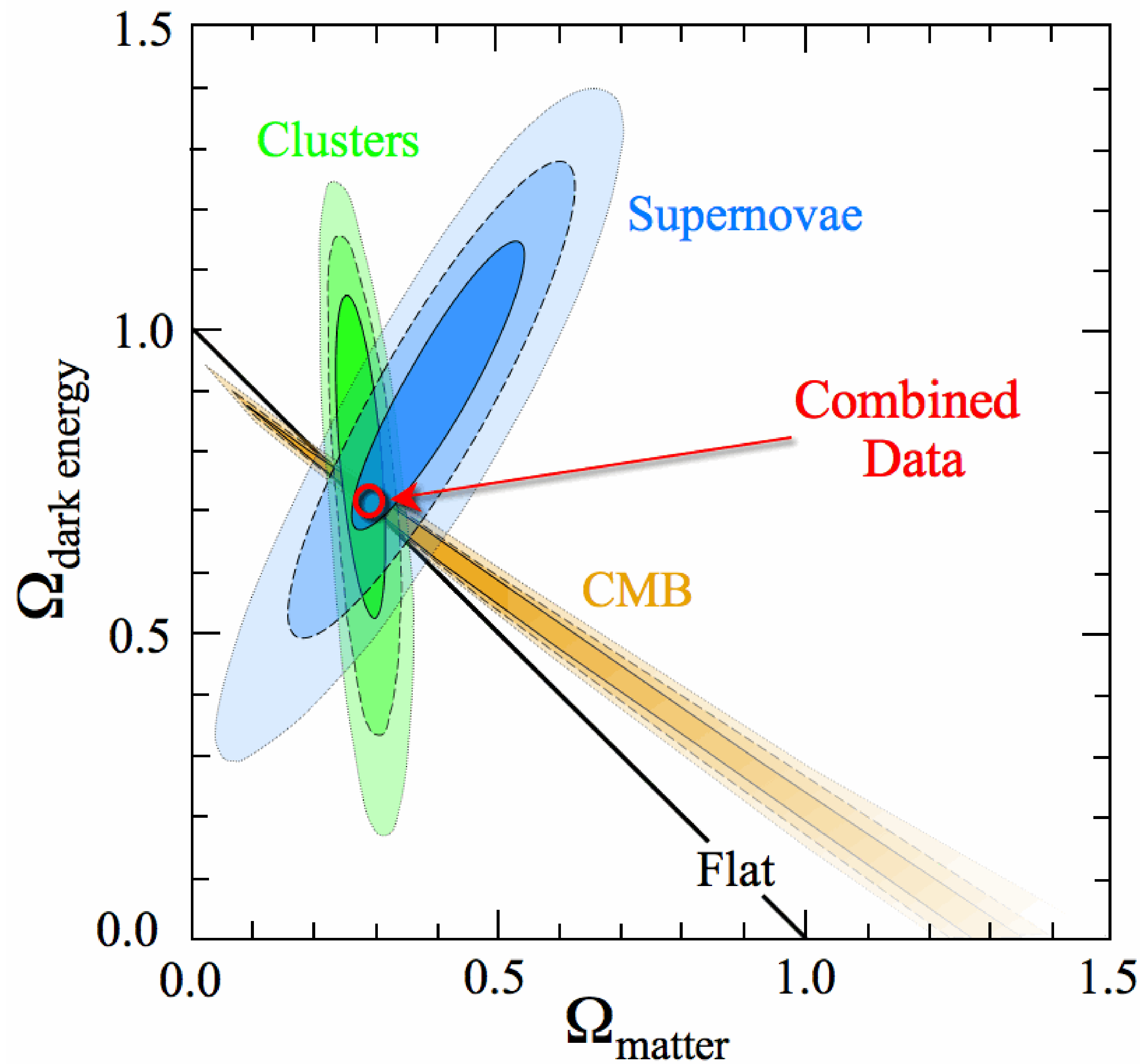


The WMAP 5-year TT power spectrum along with recent results from the ACBAR (Reichardt et al. 2008, purple), Boomerang (Jones et al. 2006, green), and CBI (Readhead et al. 2004, red) experiments. The red curve is the best-fit ΛCDM model to the WMAP data.

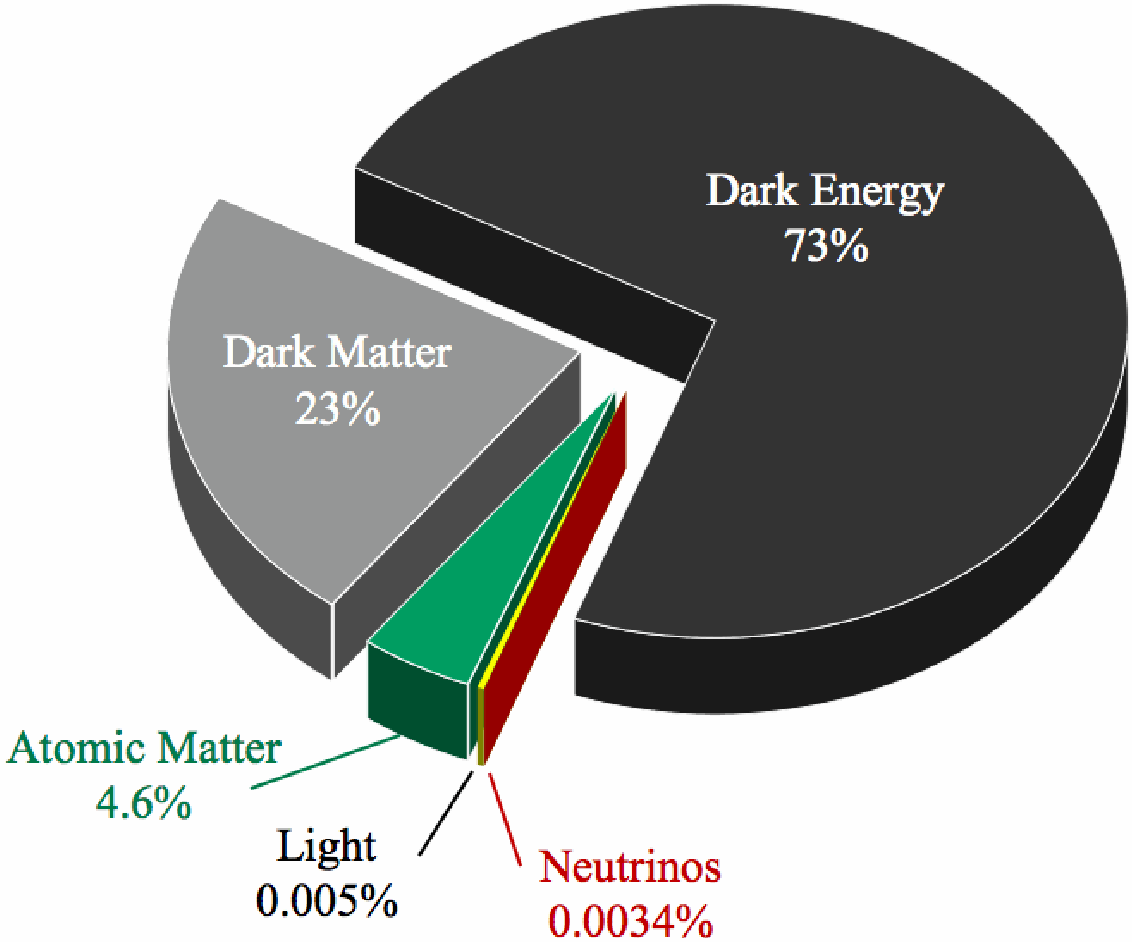
Is this a success?



- Starting from $\ell \sim 100$ or so we do not even see error bars on the data points
- Yet the model successfully predicts all the wiggles


Clusters
Supernovae
Combined Data
CMB
Flat
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
$\Omega_{\text{dark energy}}$
Ω_{matter}

Is this a complete success?



- We understand only about 5% of the total composition of the Universe

Beyond the Standard Model problems

- Why is our universe devoid of **anti-matter**? What violated symmetry between particles and anti-particles in the early Universe?

- Why neutrinos **oscillate** – disappear and then re-appear in a different form? What makes them massive?

- What is **Dark Matter** that accounts for some 86% of the total matter density in the Universe and have driven the formation of structure in the early Universe?

- What drives **inflation**?

- Why cosmological constant is **almost** zero?

BSM problems

New dark matter particle?

- To create a dark matter particle is easy:
  - assume heavy neutral particle, no interacting with the Standard Model.
  - Assume its coupling to something in the very early Universe
  - Produce something that serves as cold dark matter but does not have any observable signatures!

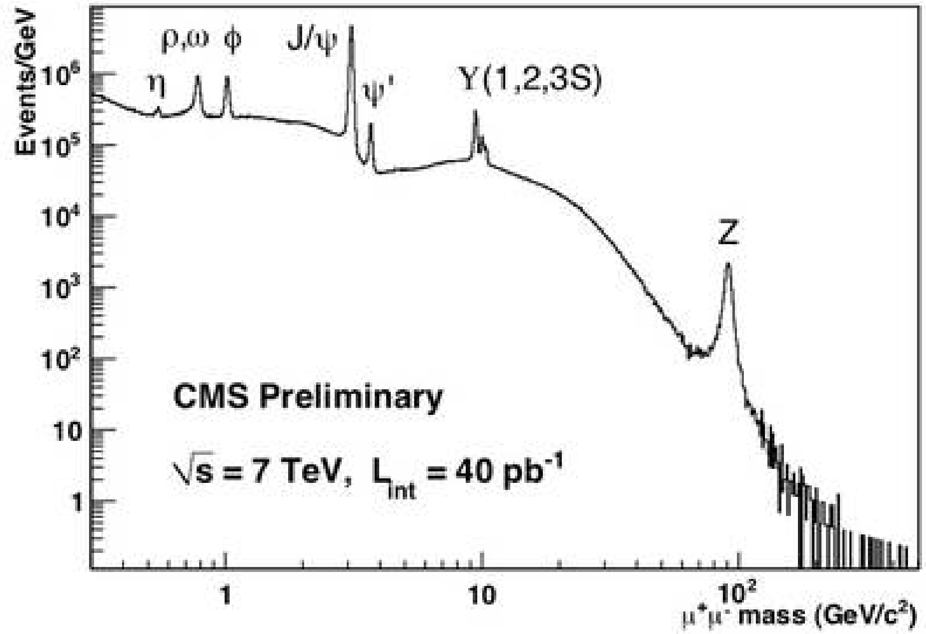
- **Not a physical model** – makes no predictions

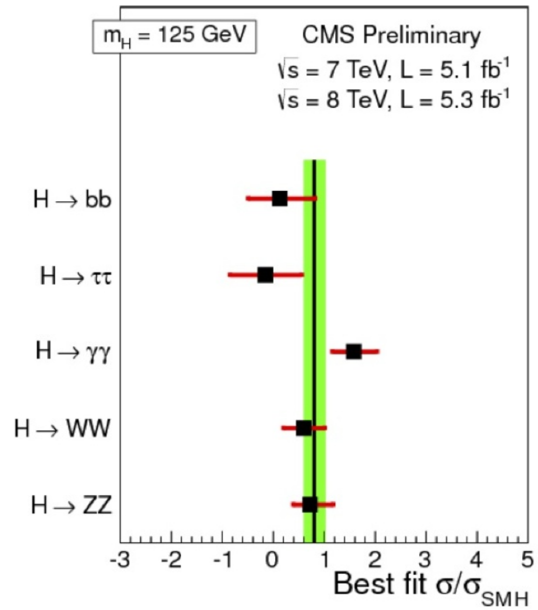
- A model for baryon asymmetry of the Universe:
  - Assume a lepto-quark (particle X that decays $X \to \bar{q} + \bar{\ell}$ and $X \to q + q'$
  - Assume that X freezes out non-relativistic (a la WIMP) and then decays
  - Assume CP-violation in the processes $X \to qq$ and $X \to \bar{q}\bar{q}$

- Good baryogenesis scenario (all numbers may be made to work), but again not testable

A model that would allow to solve not one but several problems with few assumptions ("Okkam's razor").

Testable predictions



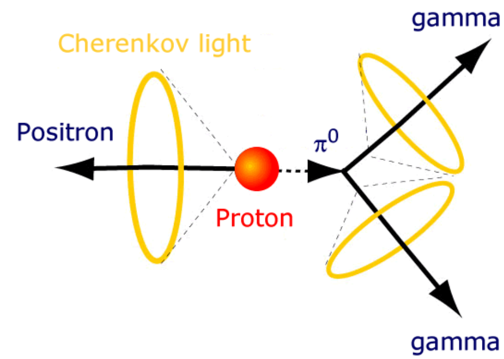


- Accelerator searches had confirmed Standard Model again and again. Different experiments had verified each others findings

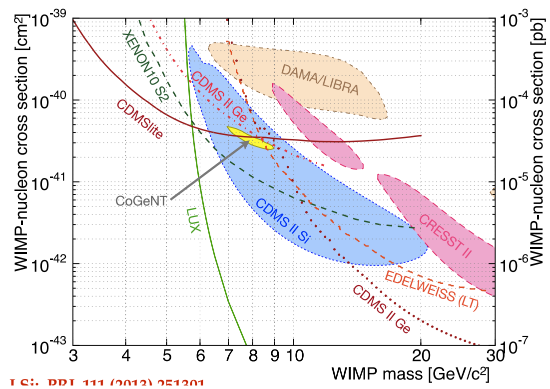
- All predicted particles have been found

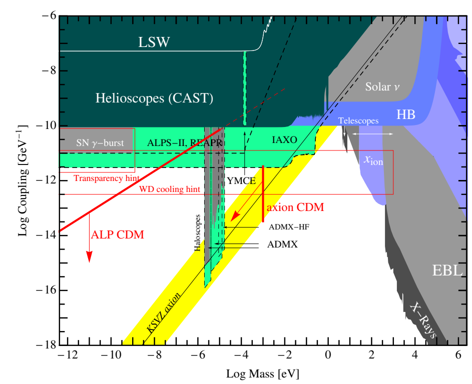
No new physics (Exotics)

- × Proton decay: $\tau_{p\to\pi^0+e^+} > 8.2\times 10^{33}$ years
  baryon number violation

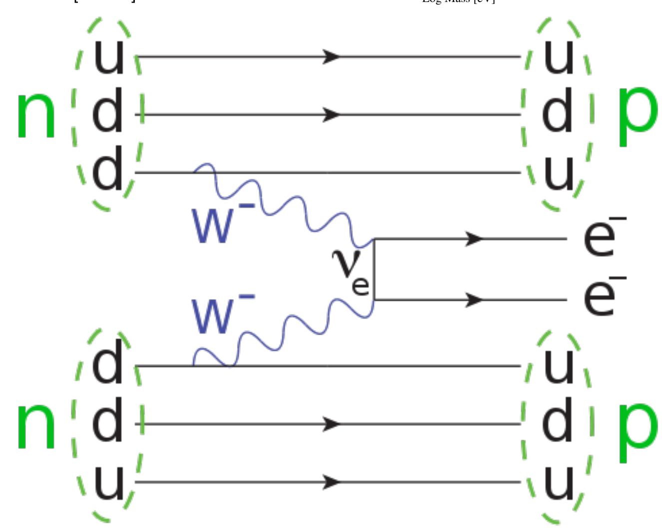


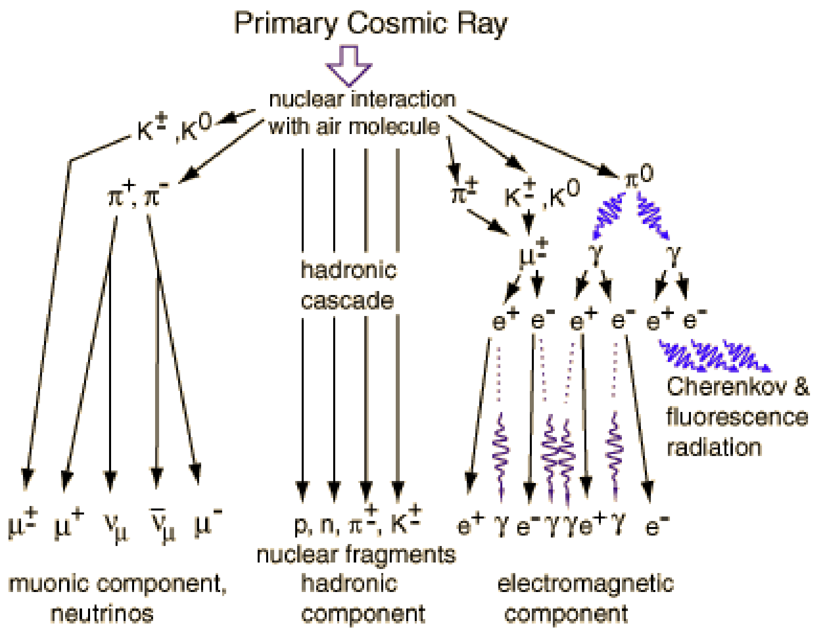
- × New weakly interacting massive particles

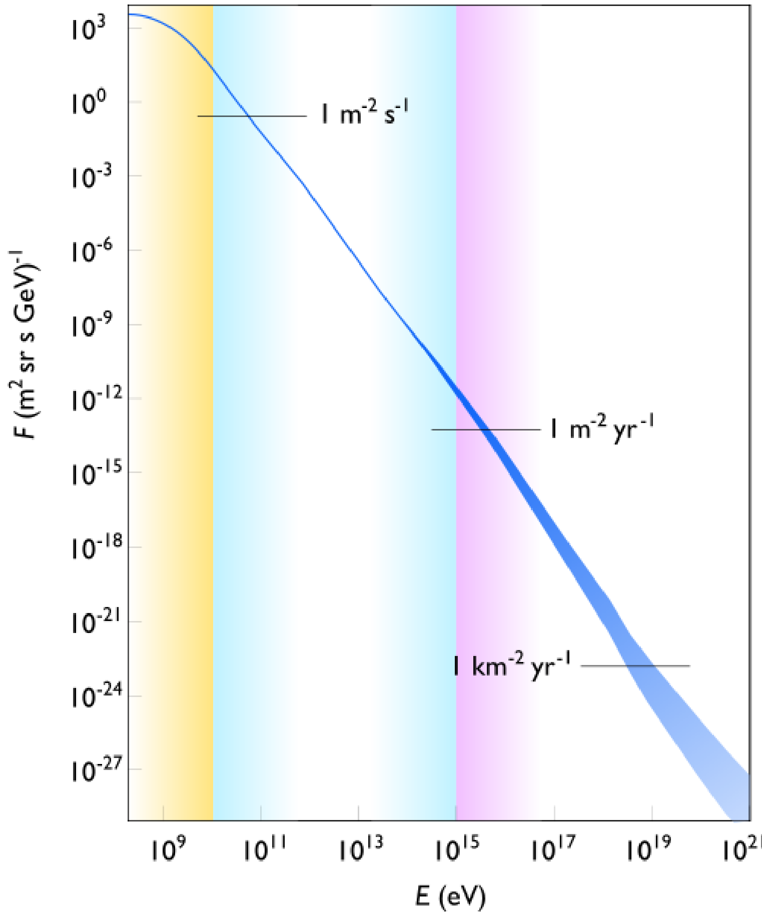




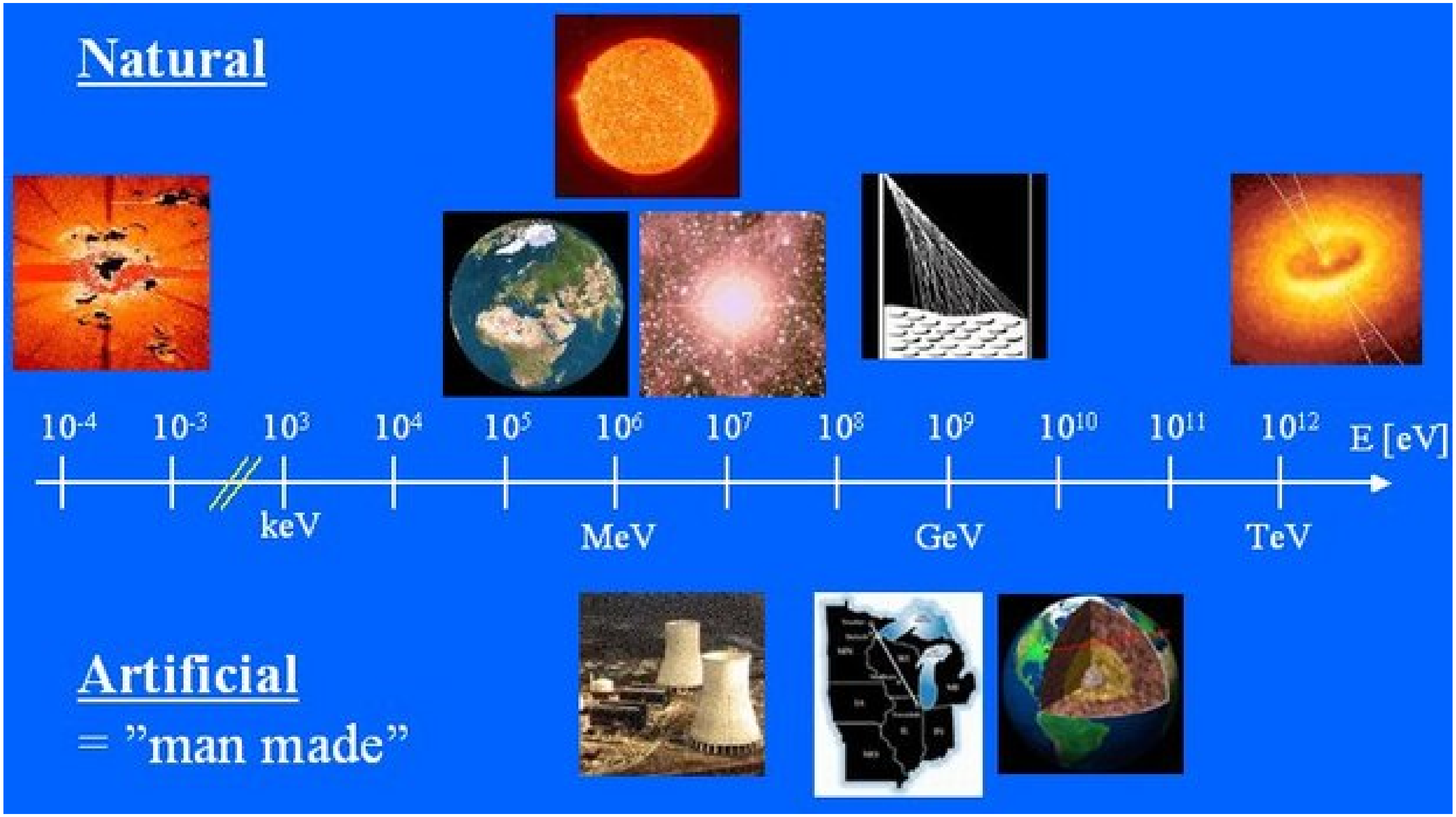
- × Axion searches
- × Millicharges
- × Paraphotons
- × Neutron electric dipole moment
  CP violation in strong interactions
- × Neutrinoless double beta decay
  Lepton number violation
- × No $\mu\to e+\gamma$ or $\mu^+\to e^+e^-e^+$







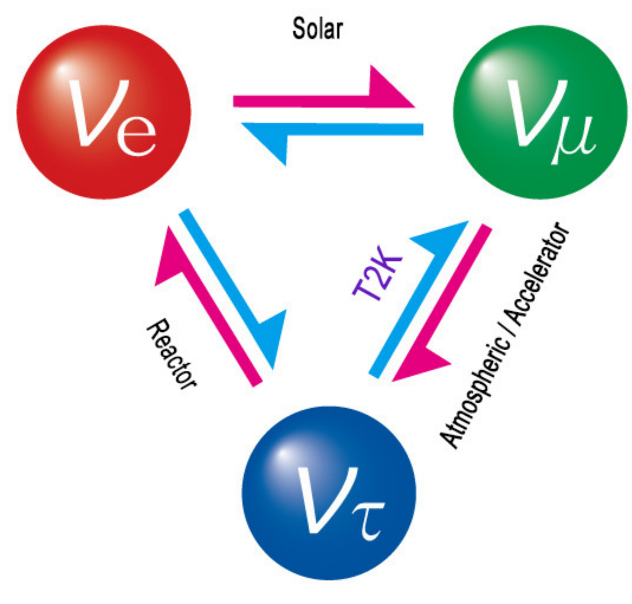
- Historically cosmic rays were the first accelerators (positron, muons, . . .)
- Today we detect photons, electrons/positrons, protons/antiprotons, nuclei (iron), neutrinos up to very high energies
- Everything is consistent with our knowledge of astrophysics and particle physics



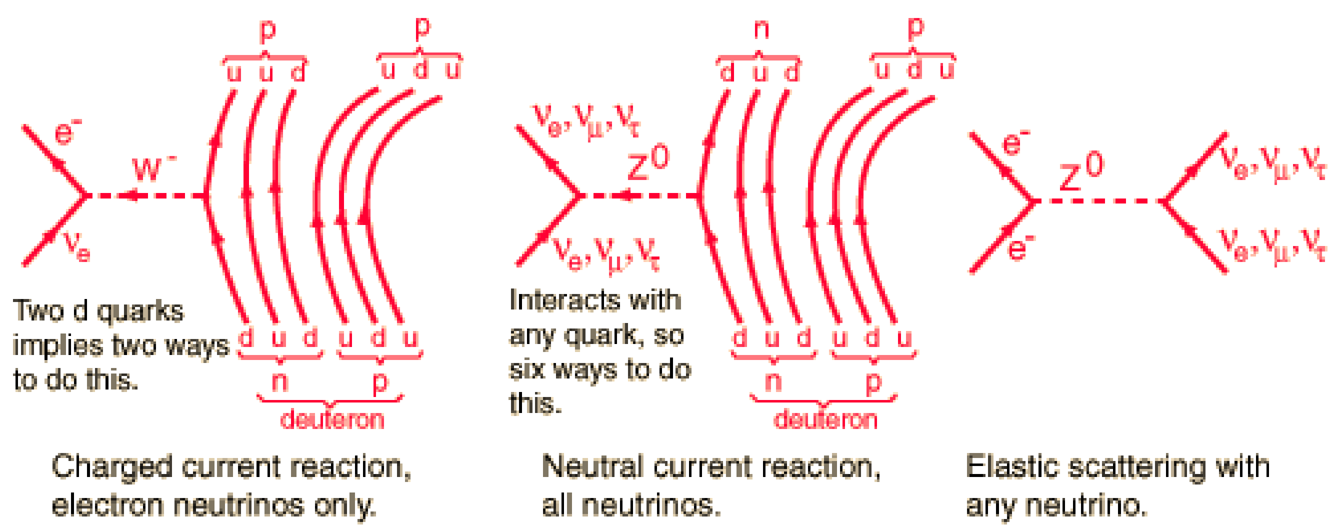
- **Natural:** The Sun; The Earth's atmosphere; Supernovae within our galaxy; The Earth's crust; Cosmic accelerators
- **Man made:** Nuclear power plants; Neutrino superbeams and factories

- **40 years ago:** neutrino were thought **strictly flavour lepton number was conserved** (no $\mu \to e + \gamma$, no $\tau \to eee$, etc.)

- **Today:** neutrino oscillations confirmed by many **independent** experiments (both **appearance** and **disappearance** data)



Neutrino oscillation between three generations



Neutrino detection at SNO

- Consider the simplest case: two flavours, two mass eigen-states. Matrix U is parametrized by one **mixing angle** θ

$$\begin{aligned} |\nu_e\rangle &= \cos\theta\,|1\rangle + \sin\theta|2\rangle \\ |\nu_\mu\rangle &= \cos\theta|2\rangle - \sin\theta|1\rangle \end{aligned}$$

- Let take the initial state to be ν_e (created via some weak process) at time $t = 0$:

$$|\psi_0\rangle = |\nu_e\rangle = \cos\theta\,|1\rangle + \sin\theta\,|2\rangle$$

- Then at time $t > 0$

$$|\psi_t\rangle = e^{-iE_1 t}\cos\theta\,|1\rangle + \sin\theta\,|2\rangle\, e^{-iE_2 t}$$

- We detect the particle later via another weak process (e.g. $\nu_? + n \to p + \mu^-/e^-$)

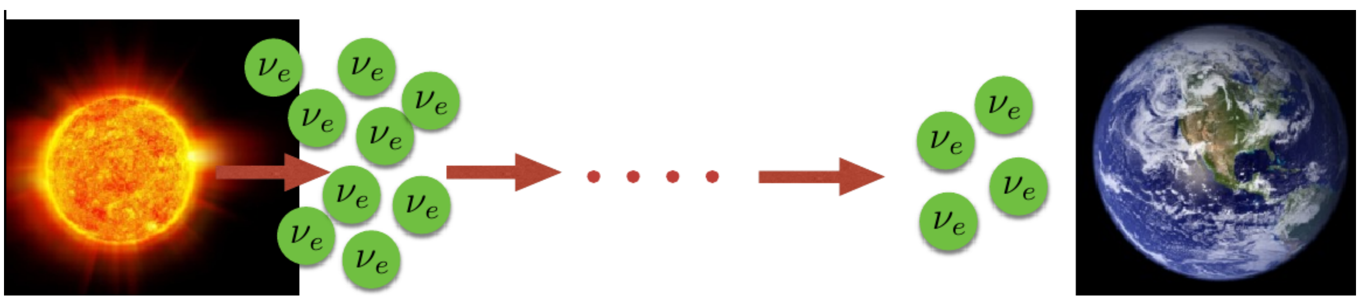
Neutrino oscillations

- The probability of conversion $\nu_e \to \nu_\mu$ is given by

$$P(\nu_e \to \nu_\mu) = |\langle \nu_\mu | \psi_t \rangle|^2 = \sin^2(2\theta) \sin^2\left(\frac{(E_2 - E_1)t}{2}\right)$$

- The probability to detect ν_e is give by

$$P(\nu_e \to \nu_e) = |\langle \nu_e | \psi_t \rangle|^2 = \cos^2(2\theta) \sin^2\left(\frac{(E_2 - E_1)t}{2}\right)$$



Fermion number conservation?

- Apparent violation of flavour lepton number for neutrinos **can be explained** by the presene of the non-zero neutrino mass

$$\mathcal{L} = \begin{pmatrix} \bar\nu_e \\ \bar\nu_\mu \\ \bar\nu_\tau \end{pmatrix} \underbrace{\left[i\partial\!\!\!/ - V_{\text{Fermi}} \right]}_{\text{conserves flavour number}} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} + \begin{pmatrix} \bar\nu_e \\ \bar\nu_\mu \\ \bar\nu_\tau \end{pmatrix} \begin{pmatrix} m_{11} & m_{12} & \dots \\ m_{21} & m_{22} & \dots \\ \dots & \dots & \dots \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

- In this case only **one** fermion current (total lepton fermion number) is conserved:

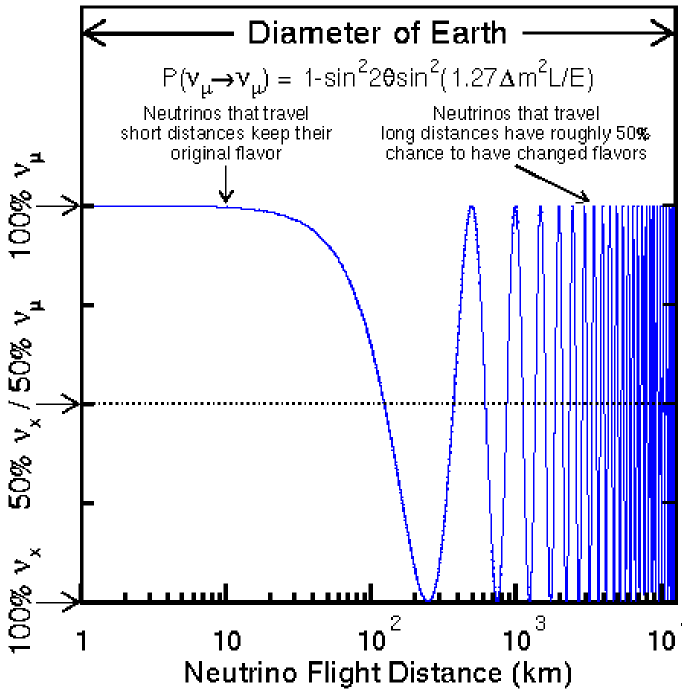
$$J^\mu = \sum_{i=e,\mu,\tau} \bar\nu_i \gamma^\mu \nu_i \tag{1}$$

while any independent $J_i^\mu = \bar\nu_i \gamma^\mu \nu_i$ is not conserved.

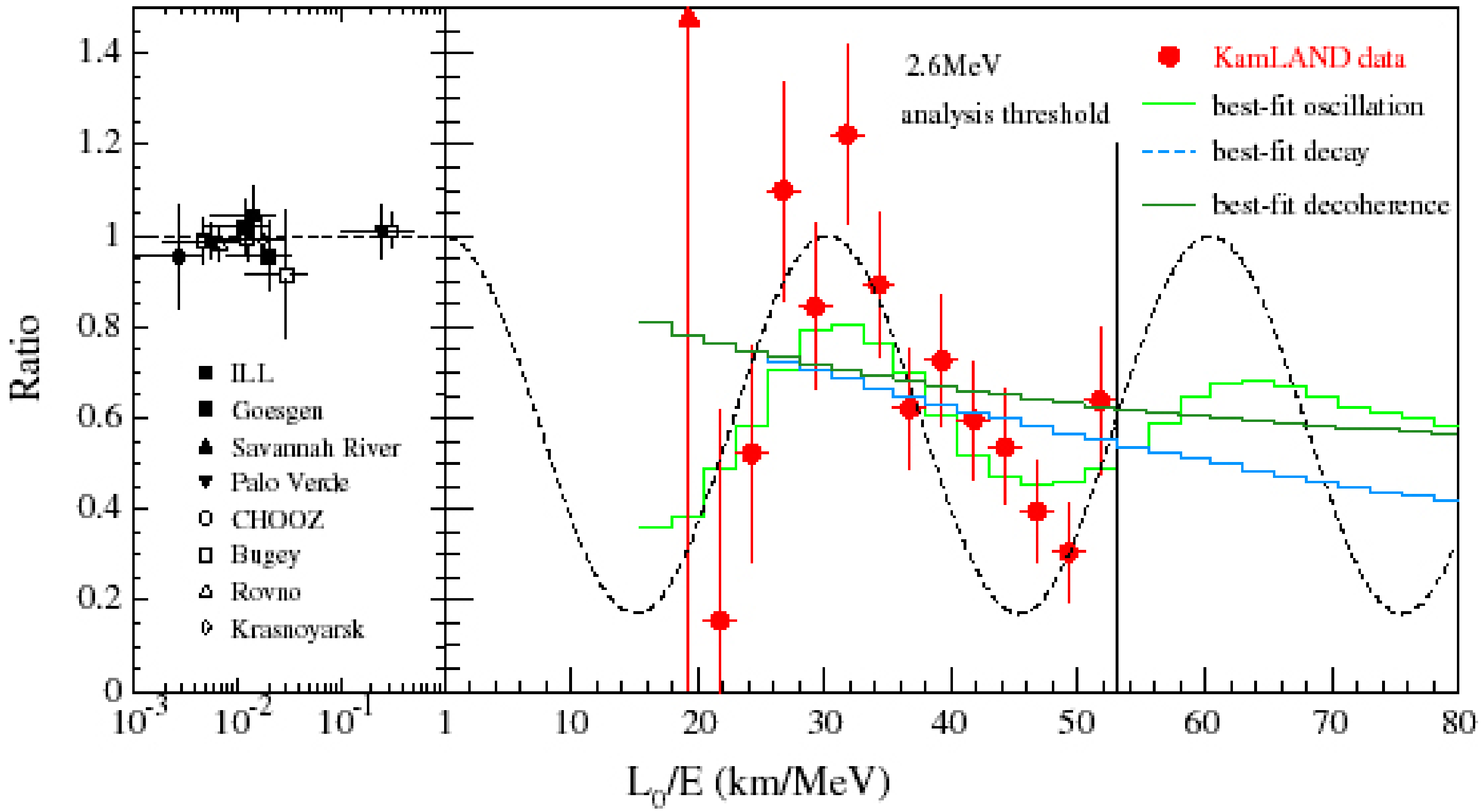
- The prediction is: neutrinos **oscillate**, i.e. probability to observe a given flavour changes with the distances travelled:

$$P_{\alpha\to\beta} = \sin^2(2\theta)\,\sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{\mathrm{GeV}}{\mathrm{eV}^2\,\mathrm{km}}\right) \qquad (2)$$

Mass difference: Δm^2, Neutrino energy: E (keV-MeV in stars, GeV in air showers, etc. Distance traveled: L



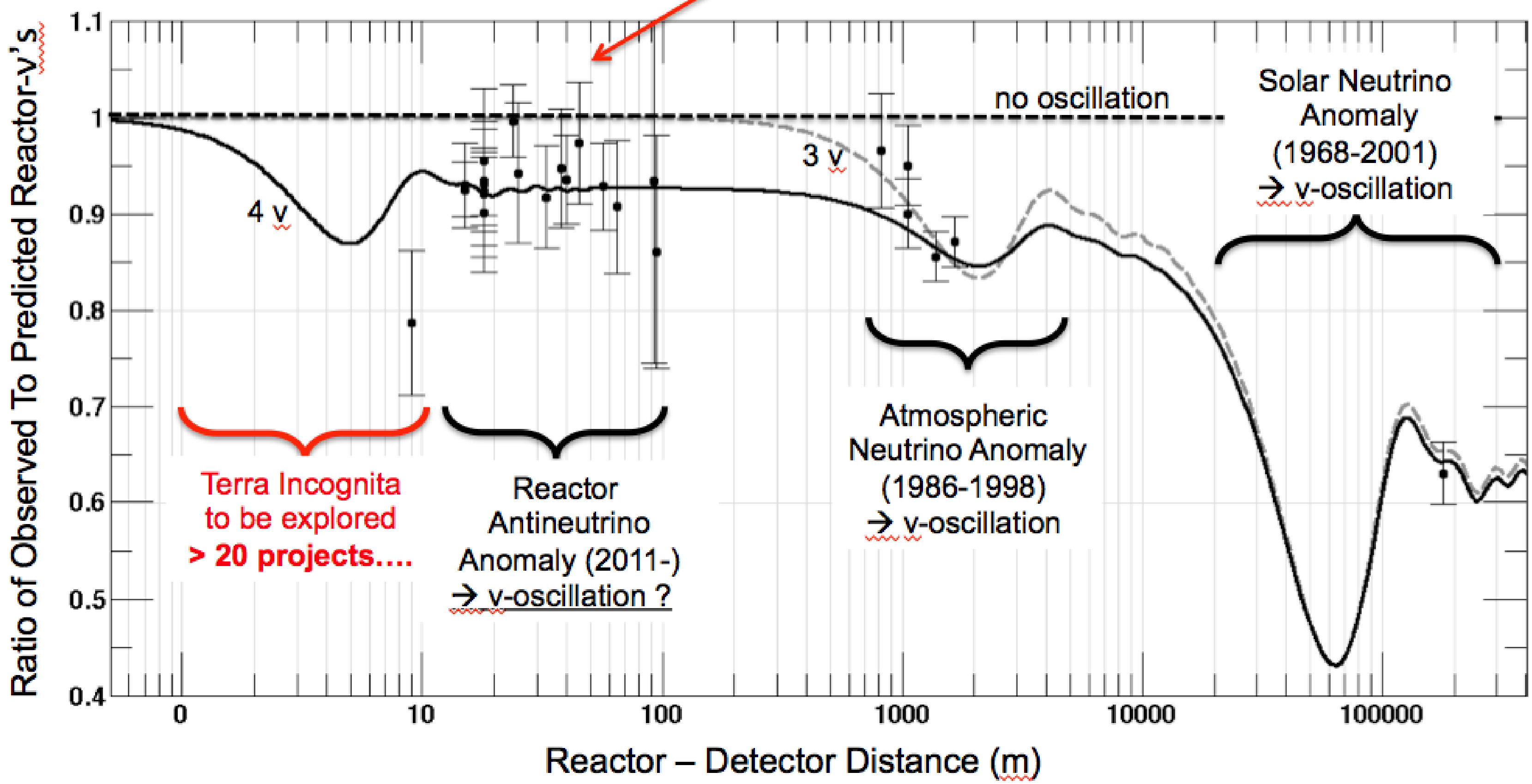
- Eq. (2) predicts that probability oscillates as a function of the ratio E/L. This is indeed observed:



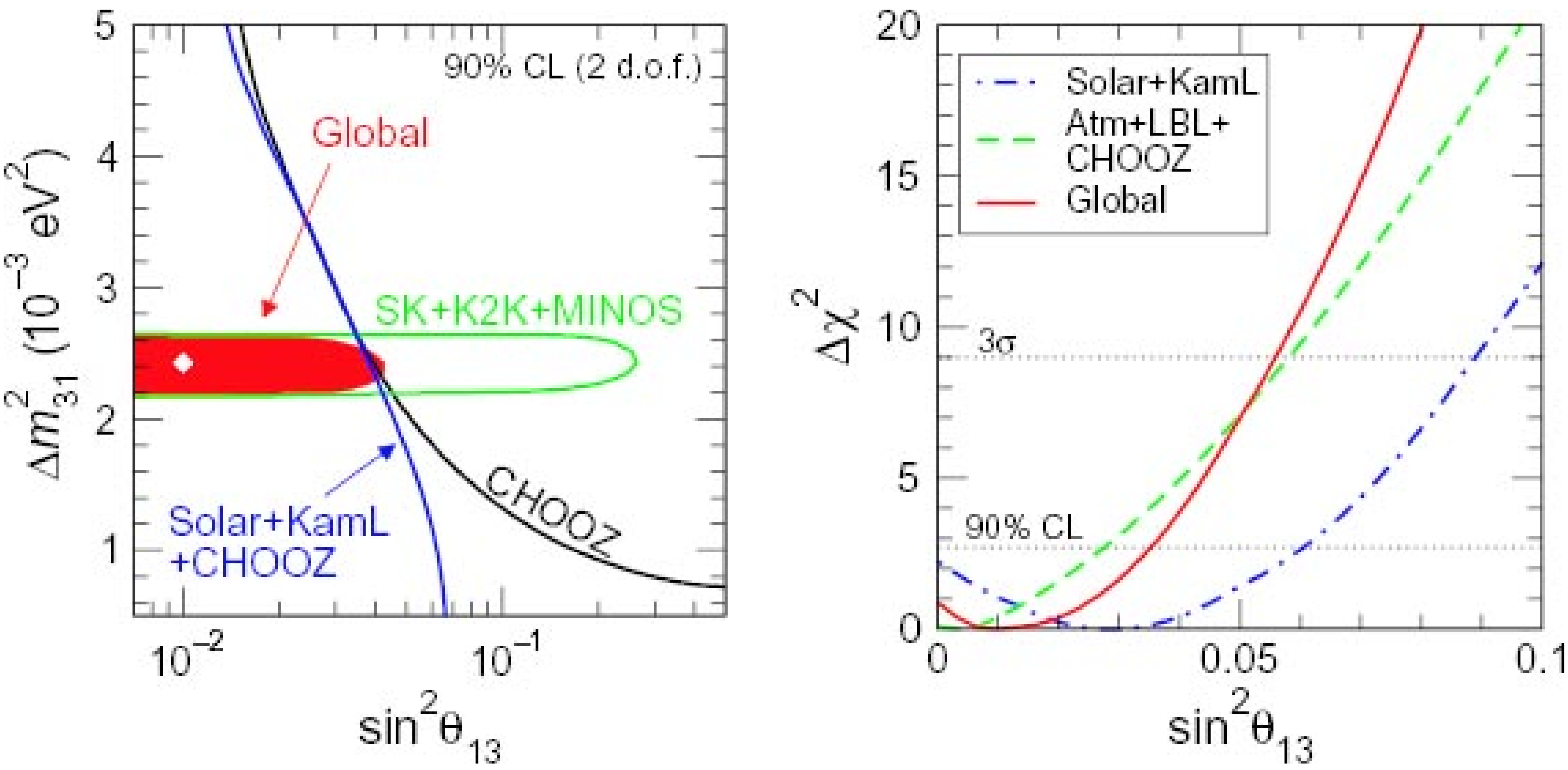
in this plot the distance between reactor and detector is fixed and the energy of neutrinos is different, therefore E/L is different

The Reactor Antineutrino Anomaly

- **Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)**

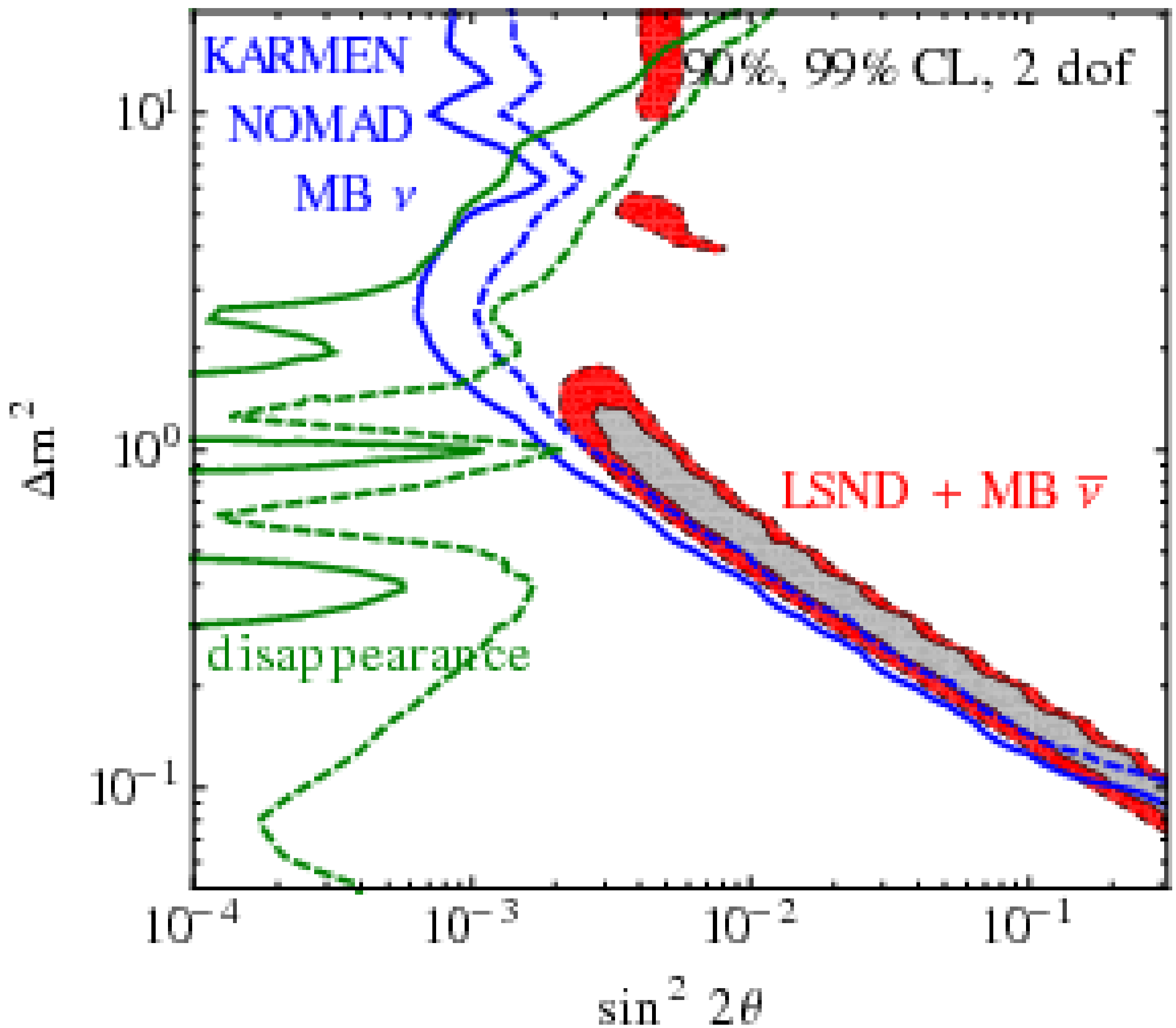


Th. Lasserre – TPC-Paris 2012



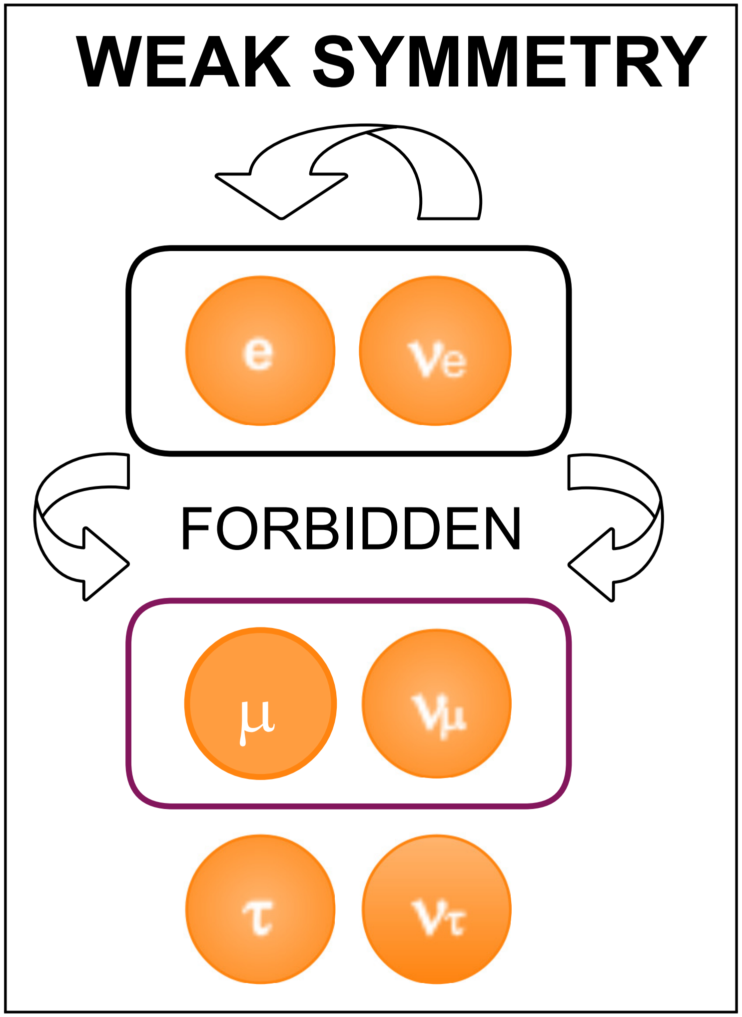
- Data from different experiments are consistent and allow to provide a **global fit** to the neutrino oscillations parameters

All anomalies together cannot be true!



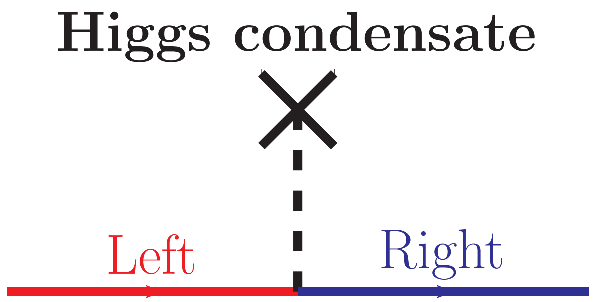
All data would be consistent **if** **red** contours were to the **left** of both **green** and **blue** contours

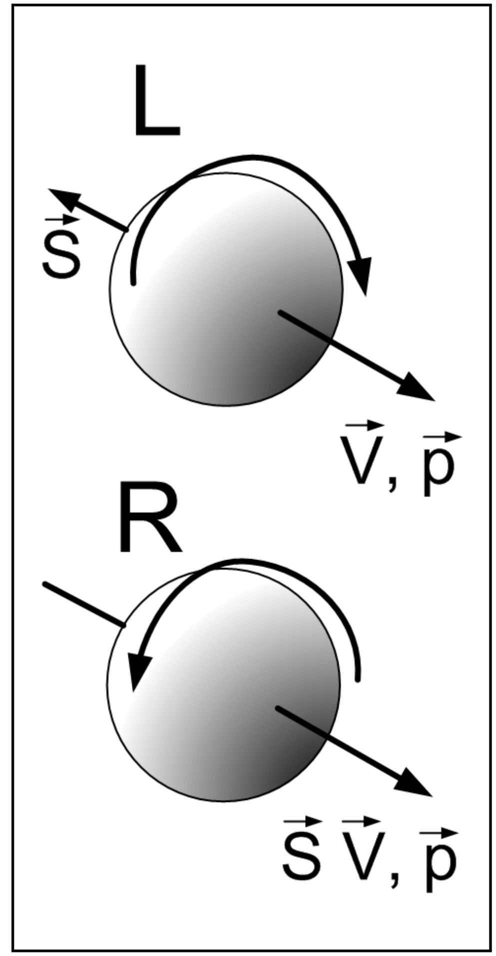
Beyond the Standard Model physics
Example



- Number of leptons is conserved in each generation
- i.e. we know with high precision that muons μ cannot convert into electrons e.
- By virtue of the electroweak symmetry neutrinos do not change their types (i.e. $\nu_e \not\leftrightarrows \nu_\mu$)
- To **break symmetry** between electron and neutrino we need **Higgs boson**

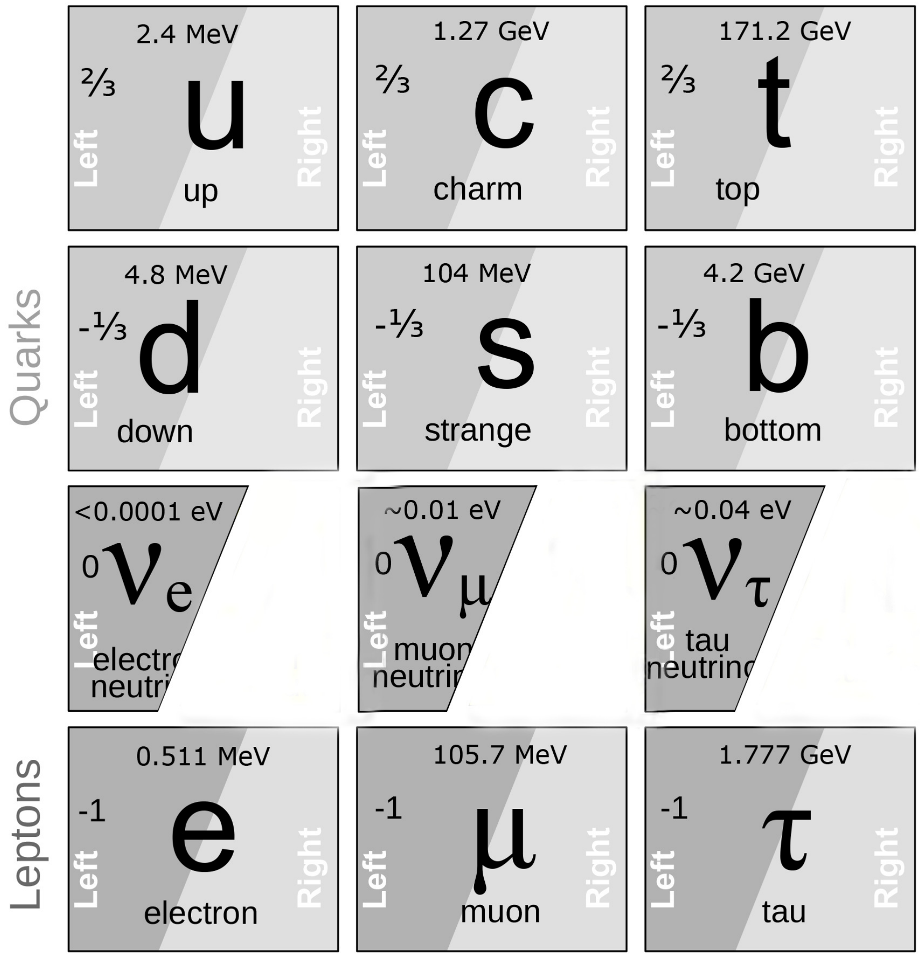
Mass term and Higgs

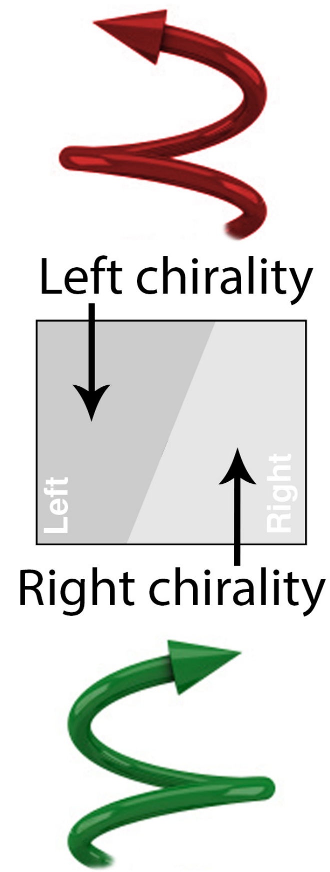




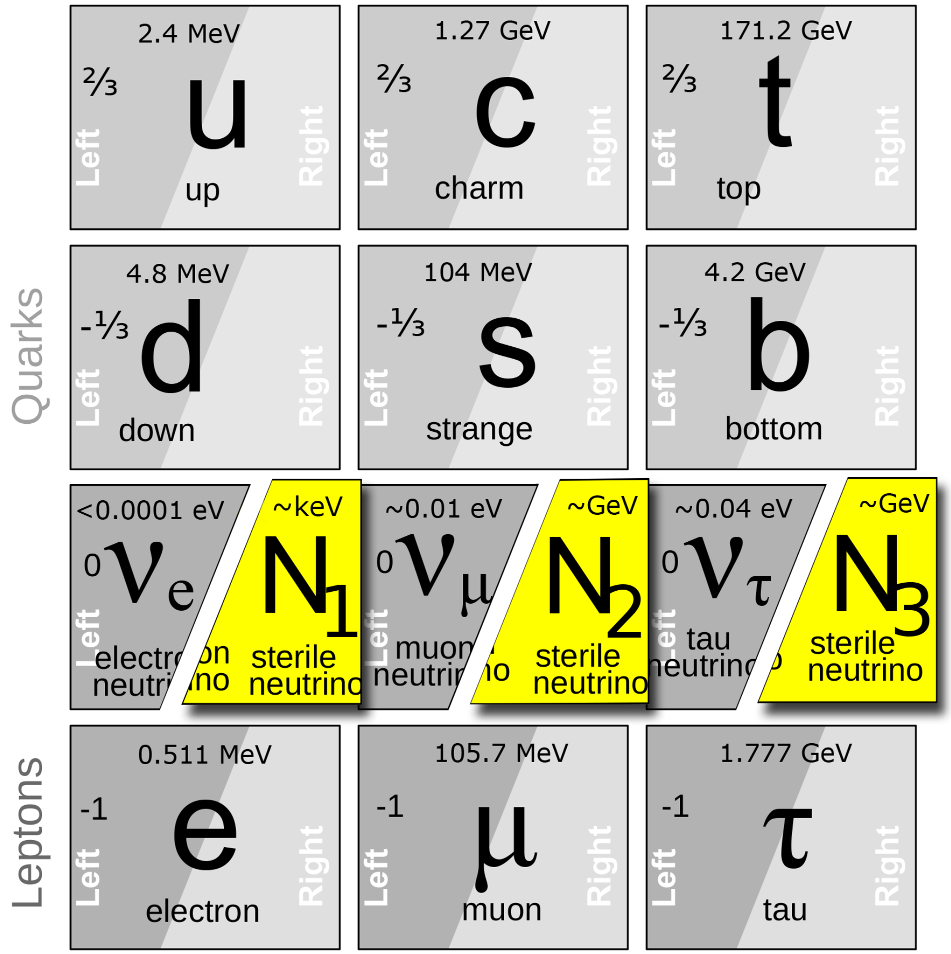
- Higgs boson (spin-0 particle) couples left to right chiralities of fermion
- In the absence of mass term left and right components are independent
- Gauge transformations should rotate left and right by the same phase (otherwise mass term won't be gauge invariant)

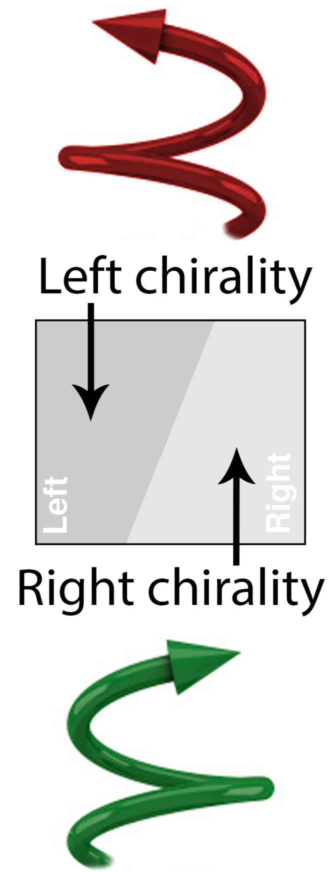
$$\bar{\psi}(i\gamma^\mu\partial_\mu - \cancel{m})\psi = \begin{pmatrix}\psi_R^* \\ \psi_L^*\end{pmatrix}\begin{pmatrix} \cancelto{0}{-m} & i(\partial_t + \vec{\sigma}\cdot\vec{\nabla}) \\ i(\partial_t - \vec{\sigma}\cdot\vec{\nabla}) & \cancelto{0}{-m}\end{pmatrix}\begin{pmatrix}\psi_L \\ \psi_R\end{pmatrix} = 0$$


2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
top
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
<0.0001 eV
0
ν_e
~0.01 eV
0
ν_μ
~0.04 eV
0
ν_τ
0.511 MeV
-1
e
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
Left
Right
Quarks
Leptons


Left chirality
Left
Right
Right chirality

Oscillations ⇒ new particles!





Right components of neutrinos?!

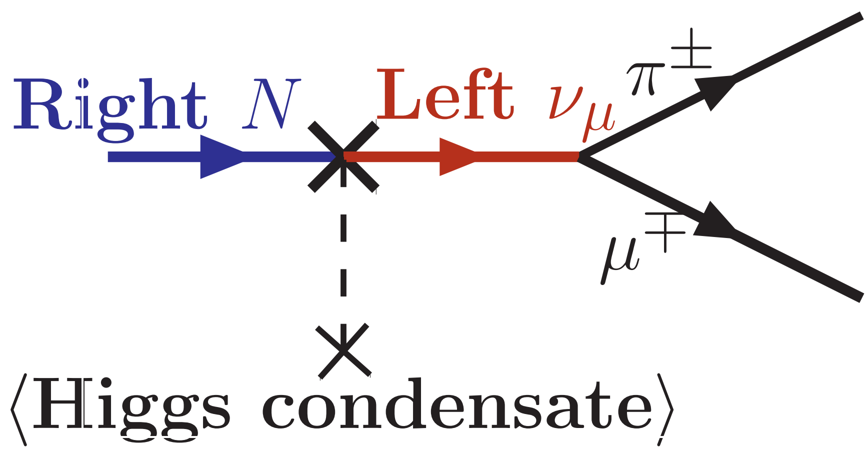
- New particles (N_1, N_2, N_3) carry no charges with respect to known interactions

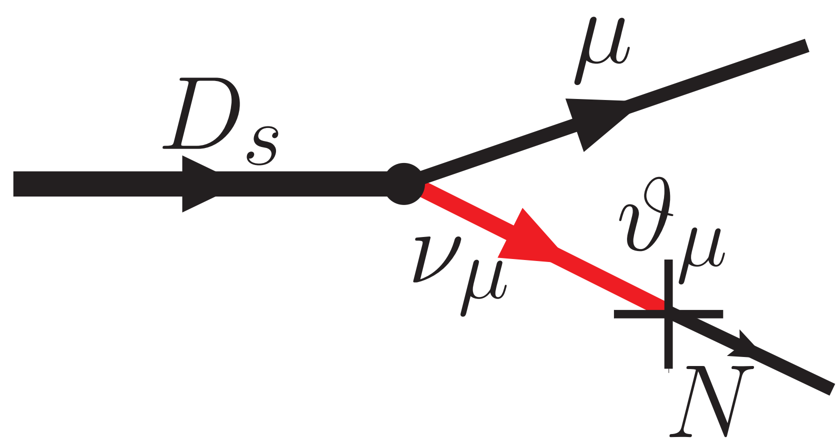
that is why they are often called **sterile neutrinos**

- They have different mass from left neutrinos

that is why they are sometimes called **heavy neutral leptons**

- They are **heavier** than ordinary neutrinos but interact **much weaker**





Sterile neutrinos behave as **superweakly interacting** massive neutrinos with a smaller Fermi constant $\boxed{\vartheta \times G_F}$

- This **mixing strength** or **mixing angle** is

$$\vartheta^2_{e,\mu,\tau} \equiv \frac{|M_{\text{Dirac}}|^2}{M^2_{\text{Majorana}}} = \frac{\mathcal{M}_{\text{active}}}{M_{\text{sterile}}} \approx 5 \times 10^{-11} \left(\frac{1\text{ GeV}}{M_{\text{sterile}}}\right)$$


WANTED
Massive neutral particle
Interacting weaker than neutrino

Baryogenesis with sterile neutrinos

Sterile neutrinos may provide all conditions necessary for successful baryogenesis:

- Their “weaker-than-weak” interaction (ϑG_F) means that they go out of equilibrium much earlier than even neutrinos
- Their mass matrix may contain additional CP-violating phases (*a la* CP violating phases of CKM matrix)
- Their Majorana masses violate lepton number

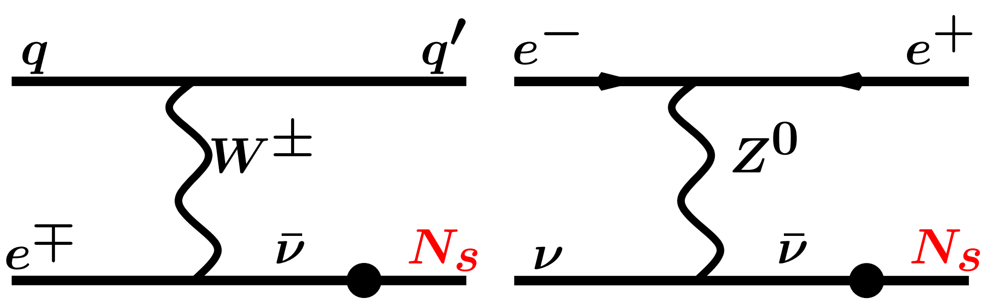
This class of scenarios is called LEPTOGENESIS

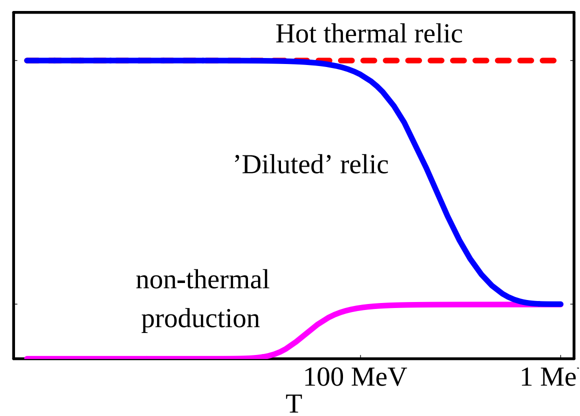
- **Sterile neutrino** is a new neutral particle, interacting **weaker-than-neutrino**
- Never was in thermal equilibrium in the early Universe $\Rightarrow$

Dodelson & Widrow'93; Dolgov & Hansen'00

$\Rightarrow$ Its abundance **slowly builds up** but **never reaches the equilibrium** value

$\Rightarrow$ avoids Tremaine-Gunn-like bound

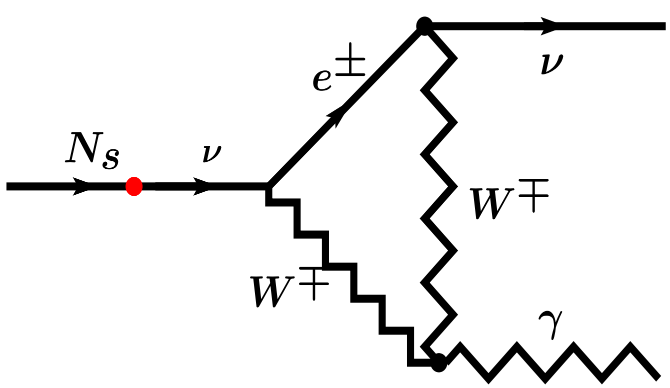




- Once every $\sim 10^8\,\mathrm{div}\,10^{10}$ scatterings a sterile neutrino is created instead of the active one

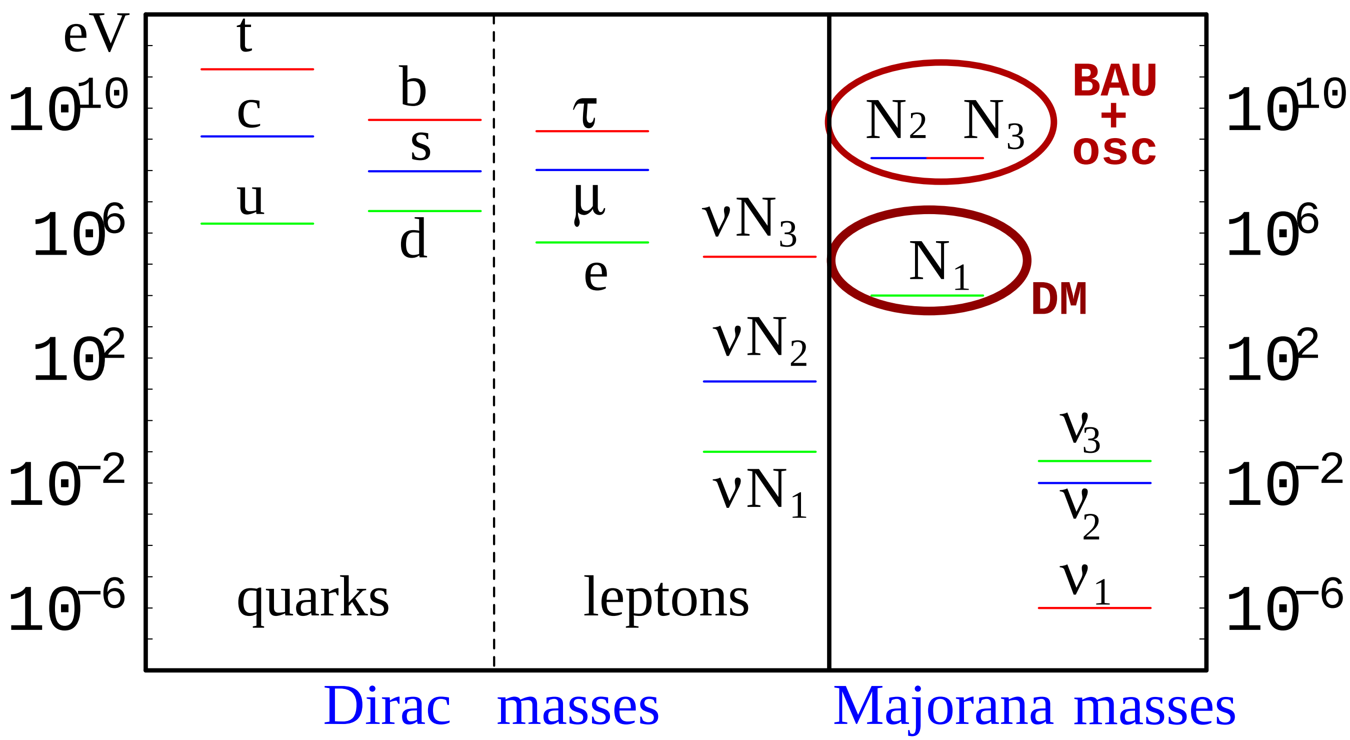
Sterile neutrino dark matter

- Very hard/impossible to search at LHC
- Very hard/impossible to search in laboratory experiments
- Can be **decaying** with the lifetime exceeding the age of the Universe
- Can we detect such a rare decay?
- **Yes!** if you multiply the probability of decay by a large number – amount of DM particles in a galaxy (typical amount $\sim 10^{70}$–10^{100} particles)



One assumption about physics behind neutrino oscillations (existence of new particles N_1, N_2, N_3) may also explain the existence of dark matter and matter-antimatter asymmetry of the Universe

M. Shaposhnik
and many
others



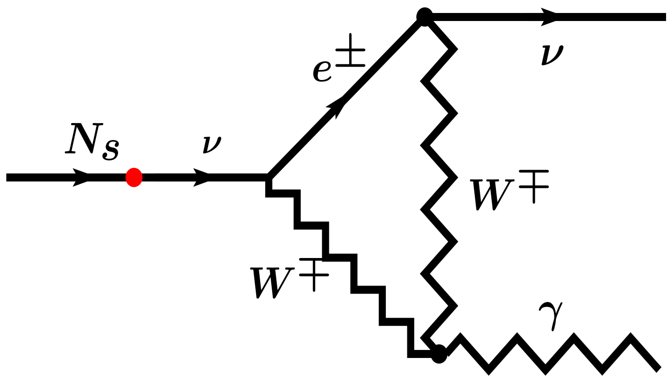
Masses of sterile neutrinos as those of other leptons
Yukawas as those of electron or smaller

Neutrino Minimal Standard Model == νMSM

νMSM predicts that this picture holds up to the "Planck scale energies" (when Compton wavelength $\sim$ Schwarzschild radius of particle)

How to test this model?

- Can be **decaying** with the lifetime exceeding the age of the Universe
- Can we detect such a rare decay?
- **Yes!** if you multiply the probability of decay by a large number – amount of DM particles in a galaxy (typical amount $\sim 10^{70}$–10^{100} particles)



- Two-body decay into two massless particles (DM $\to \gamma + \gamma$ or DM $\to \gamma + \nu$) $\Rightarrow$ narrow decay line

$$E_\gamma = \frac{1}{2} m_{\text{DM}} c^2$$

- The width of the decay line is determined by **Doppler broadening**

Detection of An Unidentified Emission Line

Detection of An Unidentified Emission Line

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

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Submitted to ApJ, 2014 February 10

[1402.2301]

We detect a weak unidentified emission line at E=(3.55-3.57)+/-0.03 keV in a stacked XMM spectrum of 73 galaxy clusters spanning a redshift range 0.01-0.35. MOS and PN observations independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is significantly detected in all three independent MOS spectra and the PN "all others" spectrum. It is also detected in the Chandra spectra of Perseus with the flux consistent with XMM (though it is not seen in Virgo)...

Detection of An Unidentified Emission Line

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

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[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

[1402.4119]

We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters. Although the line is weak, it has a clear tendency to become stronger towards the centers of the objects; it is stronger for the Perseus cluster than for the Andromeda galaxy and is absent in the spectrum of a very deep "blank sky" dataset…

Our data

M31 galaxy	XMM-Newton, center & outskirts
Perseus cluster	XMM-Newton, outskirts only
Blank sky	XMM-Newton

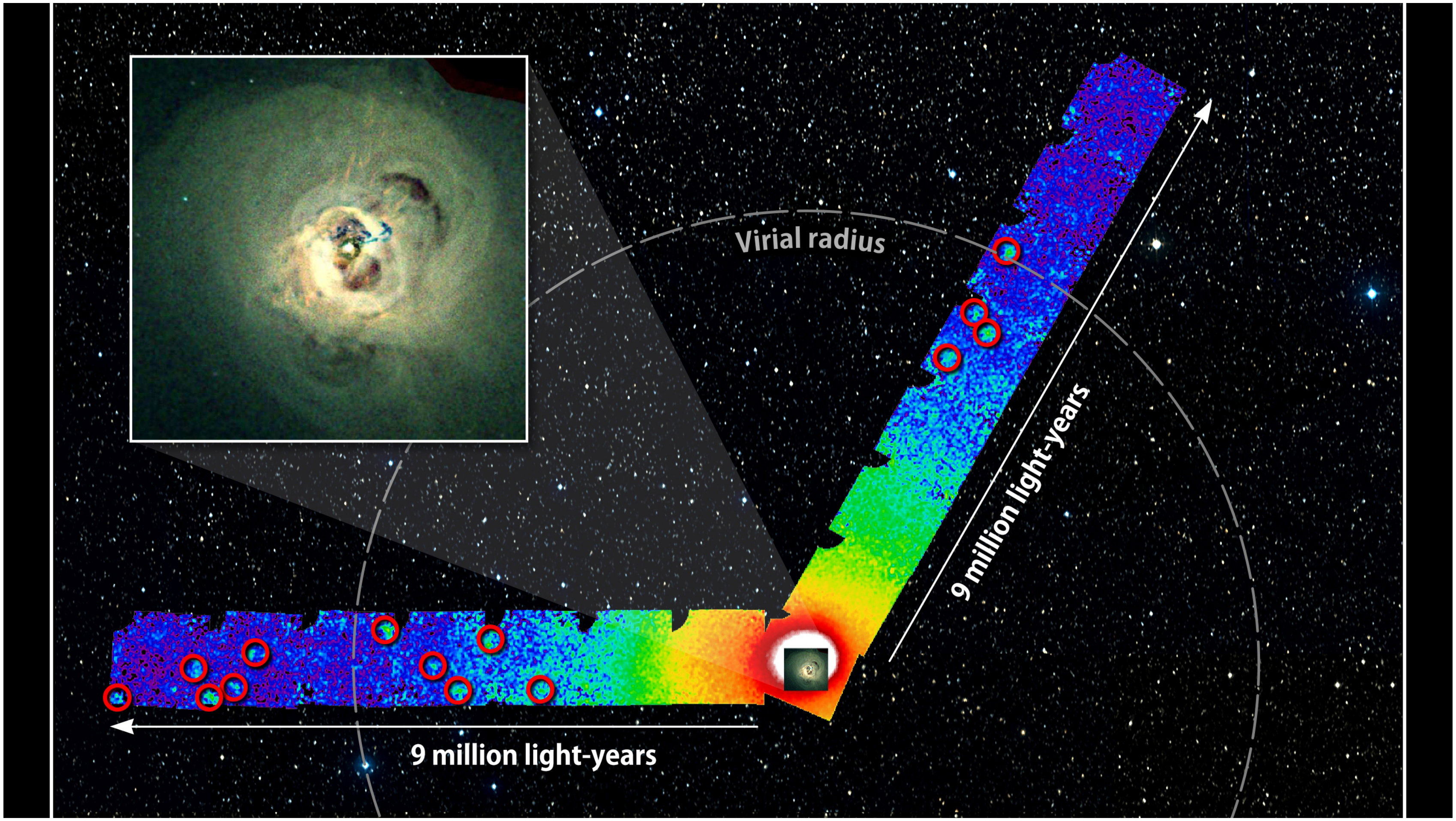
Bulbul et al. 2014

73 clusters	XMM-Newton, central regions of clusters only. Up to $z = 0.35$, including Coma, Perseus
Perseus cluster	Chandra, center only
Virgo cluster	Chandra, center only

Position: 3.5 keV. Statistical error for line position $\sim\ 30$ eV. Systematics (~ 50 eV – between cameras, determination of known instrumental lines)

Lifetime: $\sim 10^{28}$ sec (uncertainty $\mathcal{O}(10)$)

Perseus galaxy cluster

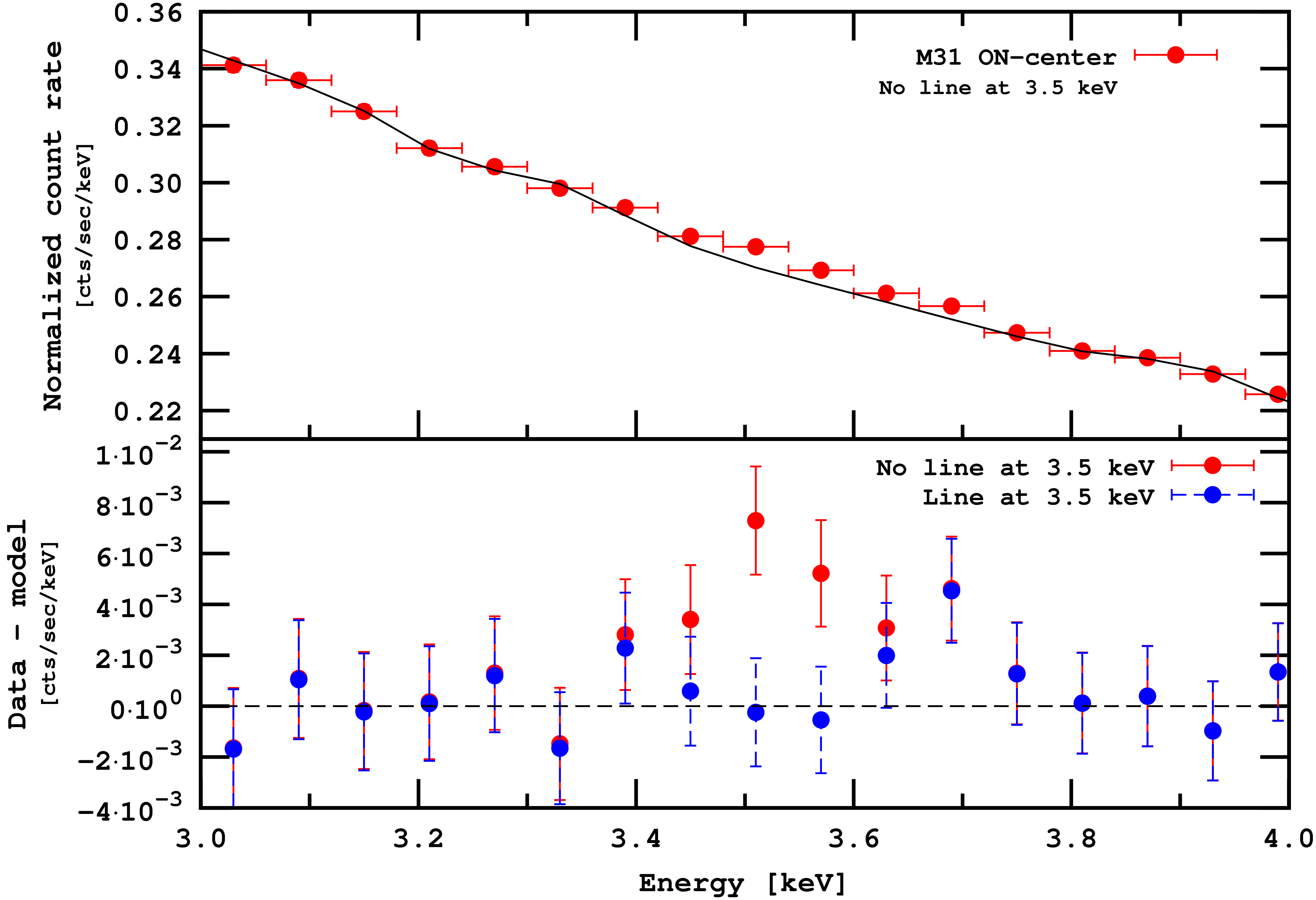


Bulbul et al. took only 2 central XMM observation – $14'$ around the cluster's center

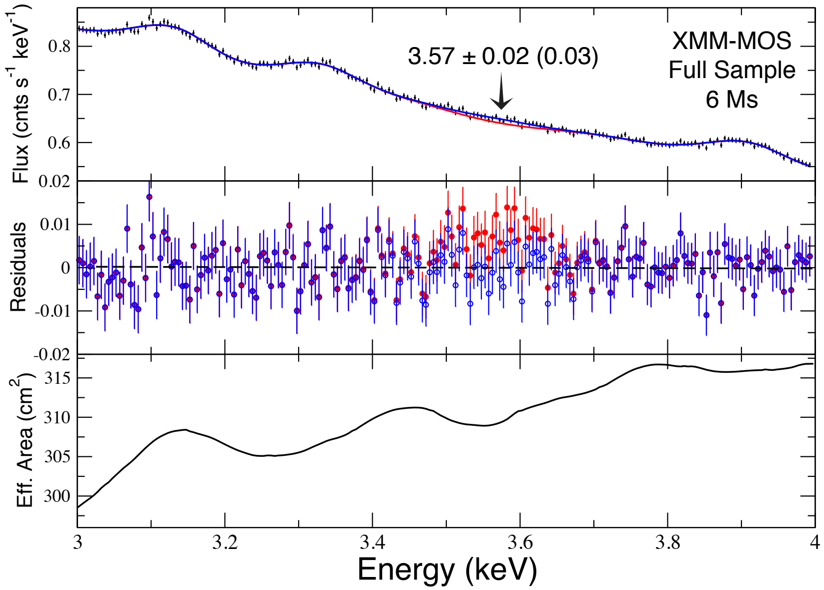
We took 16 observations **excluding** 2 central XMM observations to avoid modeling complicated central emission

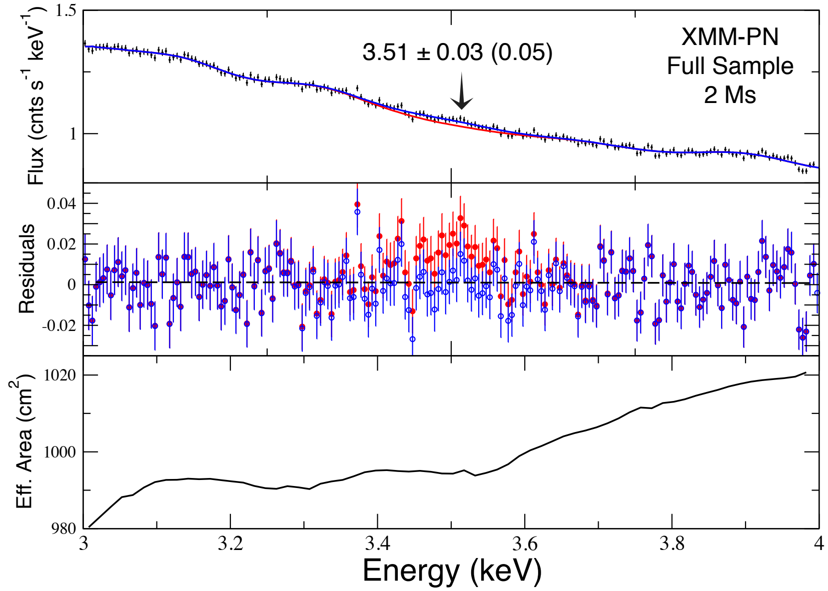
Andromeda galaxy (zoom 3–4 keV)

[1402.4119]

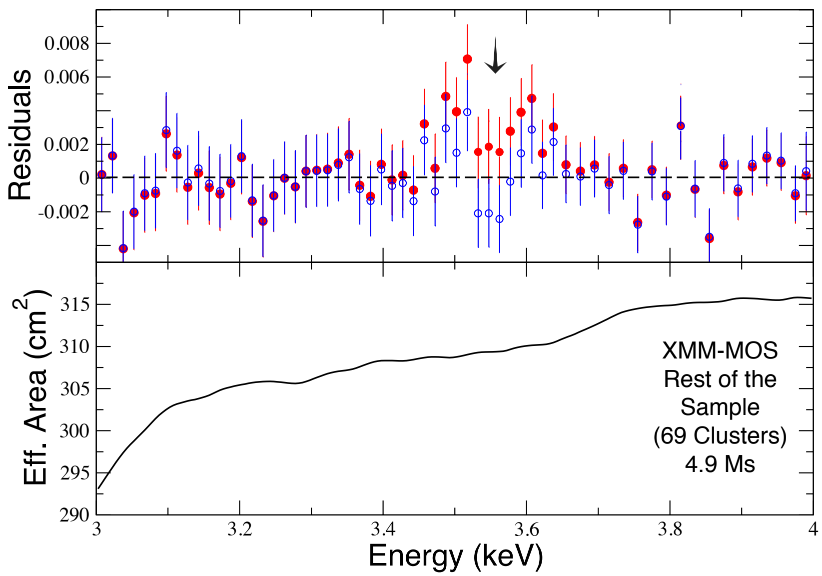


Full stacked spectra





Bulbul et al. [1402.2301]



- All spectra blue-shifted in the reference frame of clusters
- Instrumental background processed similarly and **subtracted**

A dedicated experiment

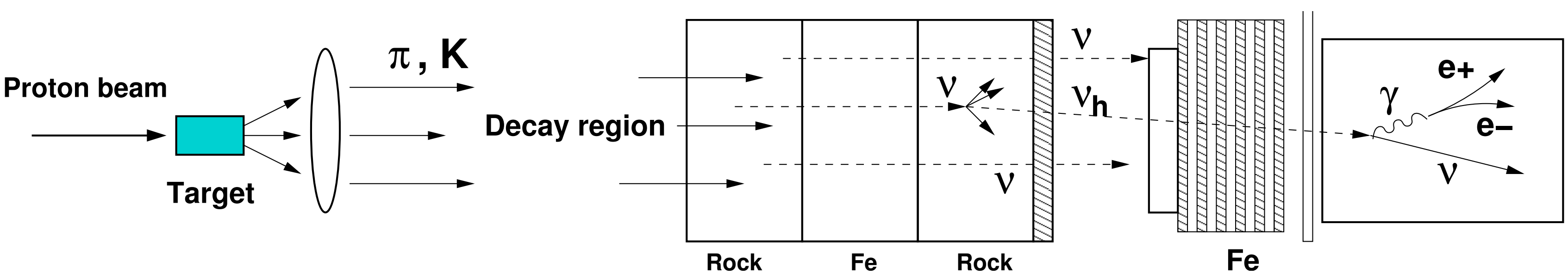
[arXiv:1310.17

W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, **O. Ruchayskiy**, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille

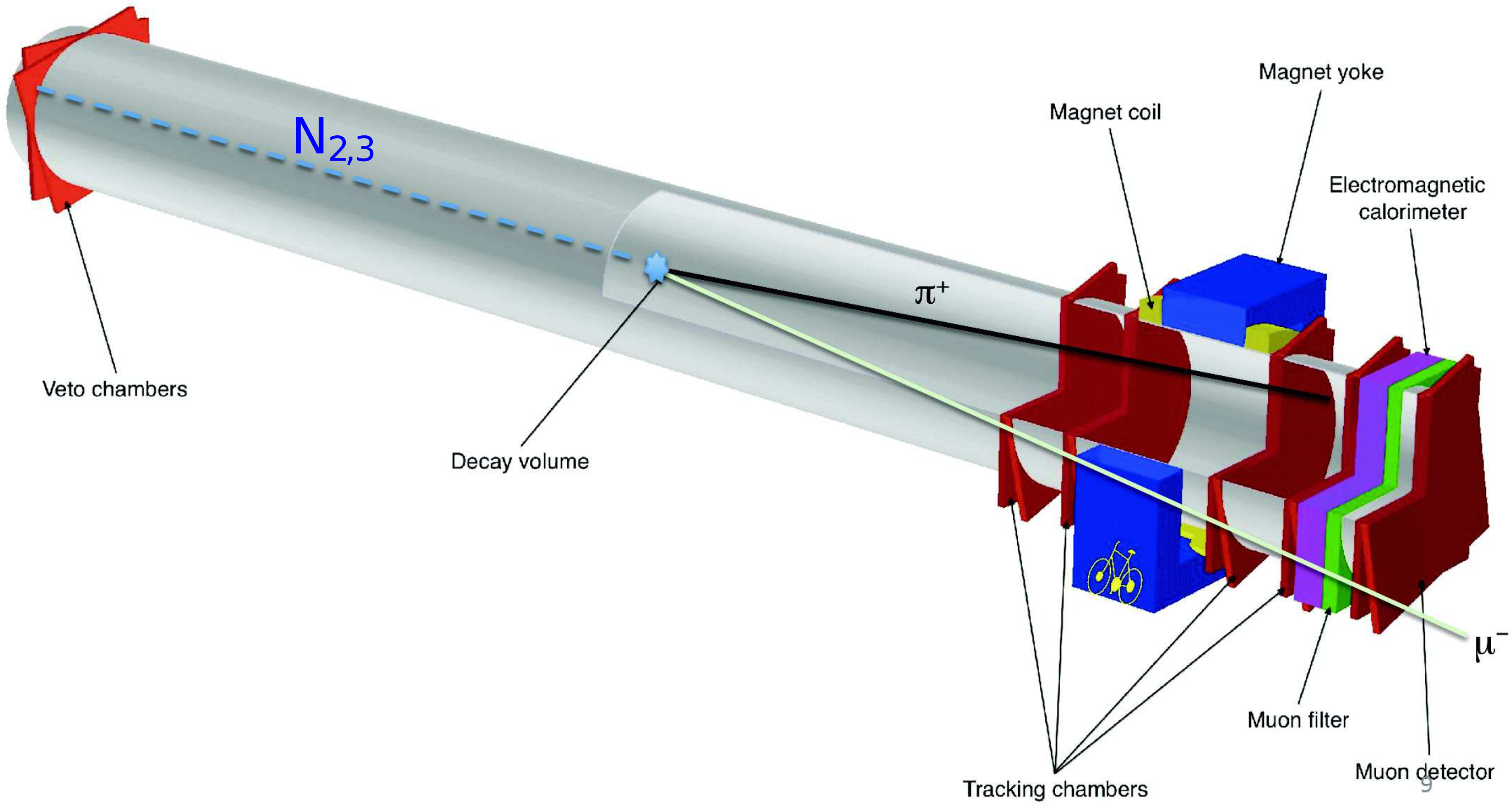
Proposal to Search for Heavy Neutral Leptons at the SPS

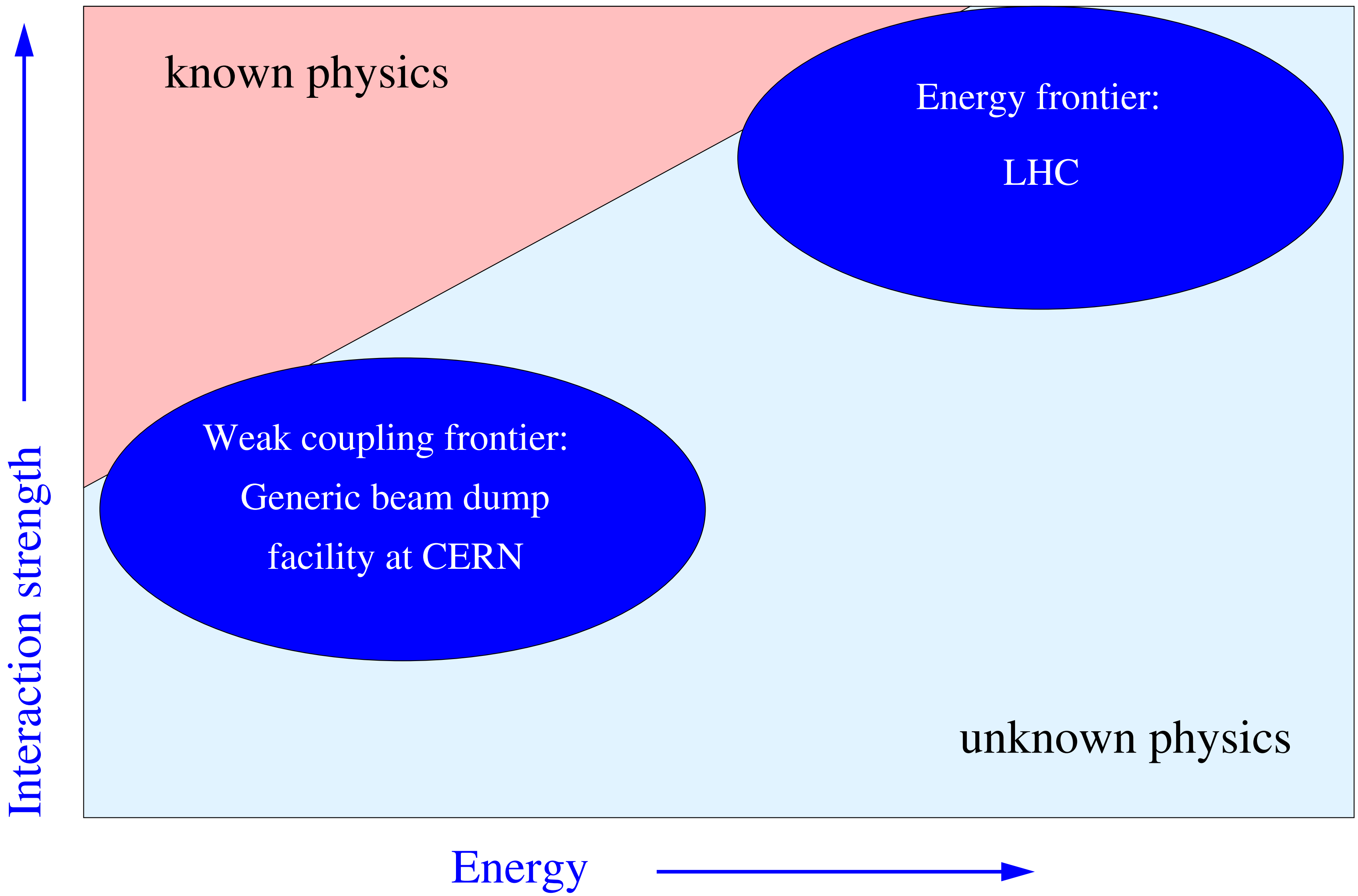
Expression of Interest. Endorsed by the CERN SPS council

SHiP
Search for Hidden Particles



A dedicated experiment




known physics
Energy frontier:
LHC
Weak coupling frontier:
Generic beam dump
facility at CERN
unknown physics
Interaction strength
Energy

Other examples?

- Grand Unification theory (combine all gauge interactions into one big gauge group):