

Neutrino Parameter Measurements: A theoretical Perspective

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Second International Meeting for
Large Neutrino Infrastructures

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Fermilab
US/Central timezone

Large Projects in Neutrino Physics

- ... the **scientific case** ... in long baseline studies...
 - ... **physics potential** of large neutrino infrastructures
-
- Neutrinos are a success story! We learned a lot & more important results to come: **mass hierarchy, leptonic CP, m_1 ,...**
 - How to proceed? → optimal impact, minimal risks, versus effort!
 - beware of assumptions: ←→ **prospects for more**
→ **do not restrict theory space if you don't understand why**
 - best scientific progress ←→ **balance big versus small**
→ **we would love to do table-top experiments** ←→ R&D for new ideas
→ **avoid the 'Dinosaur' route...**
 - Include physics results & technology developments expected on the project's time-scale → **is the scientific case alive, stronger, weaker when results materialize?**

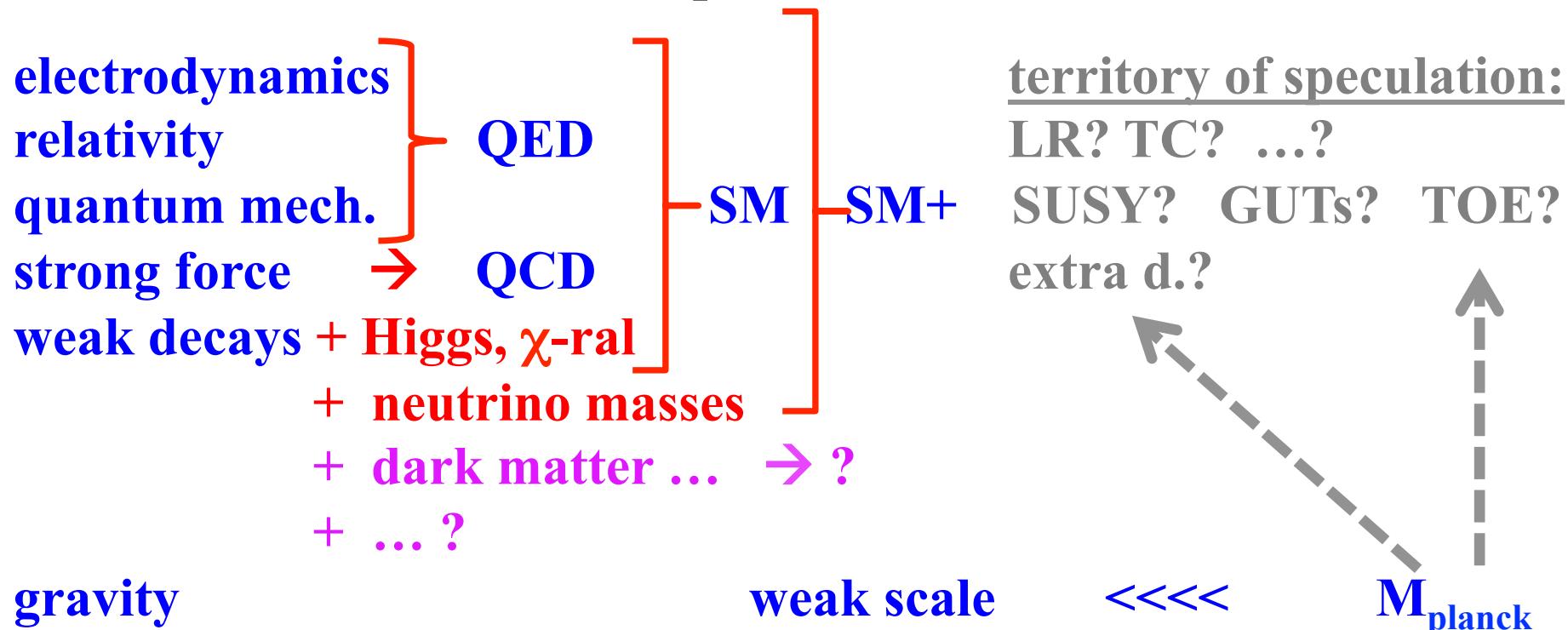
Theory: The SM –a Synergy of Concepts

d=4 QFTs:

$$\begin{array}{ccc} \text{QED} & \xrightarrow{\quad} & \text{QCD} \\ \text{U(1)}_{\text{em}} & & \text{SU(3)}_{\text{C}} \end{array} \quad \xrightarrow{\quad} \text{SM} \\ \text{SU(3)}_{\text{C}} \times \text{SU(2)}_{\text{L}} \times \text{U(1)}_{\text{Y}}$$

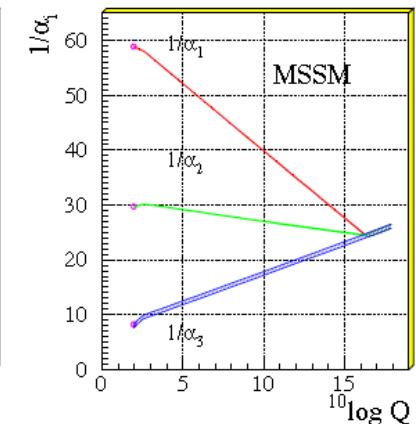
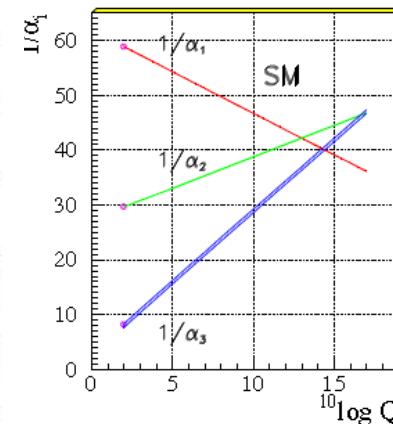
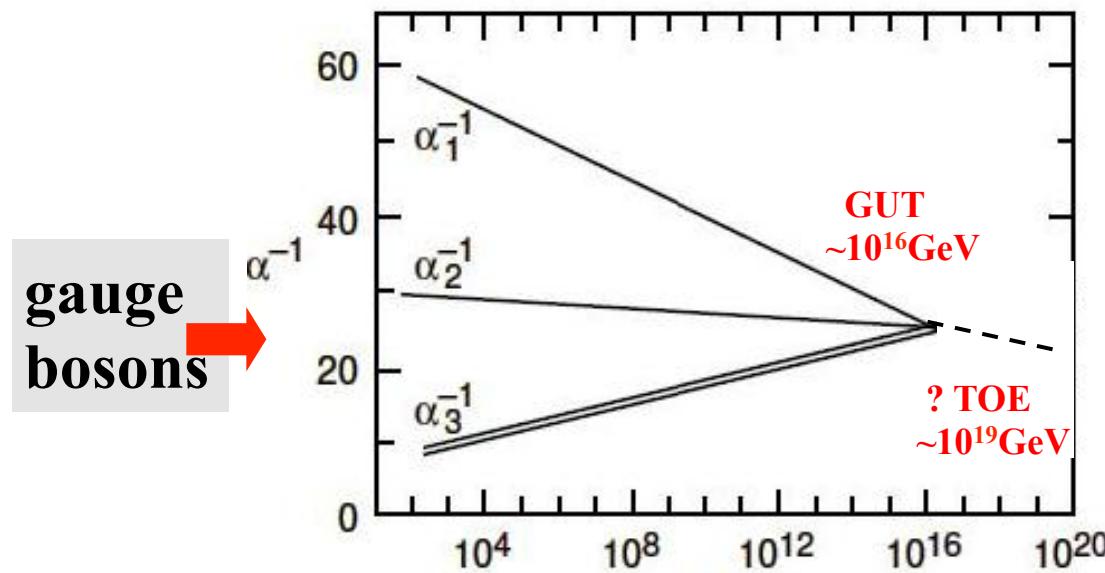
Physics: concepts (variables) \oplus equations / principles

initial conditions \rightarrow predictions



Note: GR non-renormalizable... maybe good: QFT's cannot explain scales \rightarrow other concepts

Indications pointing to SUSY + GUTs



Higgs → gauge hierarchy problem:
 $\delta m_H^2 \sim \Lambda^2$

quarks
leptons → flavour problem: 3 generations
many parameters (m_i , mixings)
unification into GUTs

$$m_v = (m_D^D)^T M_R^{-1} m_D$$

SM particles fit nicely into
GUT representations
→ evidence for some
unification

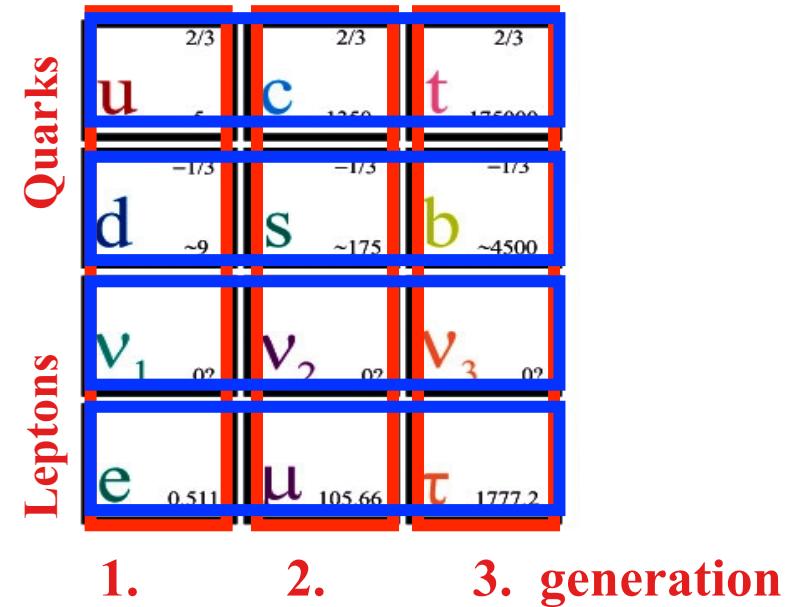
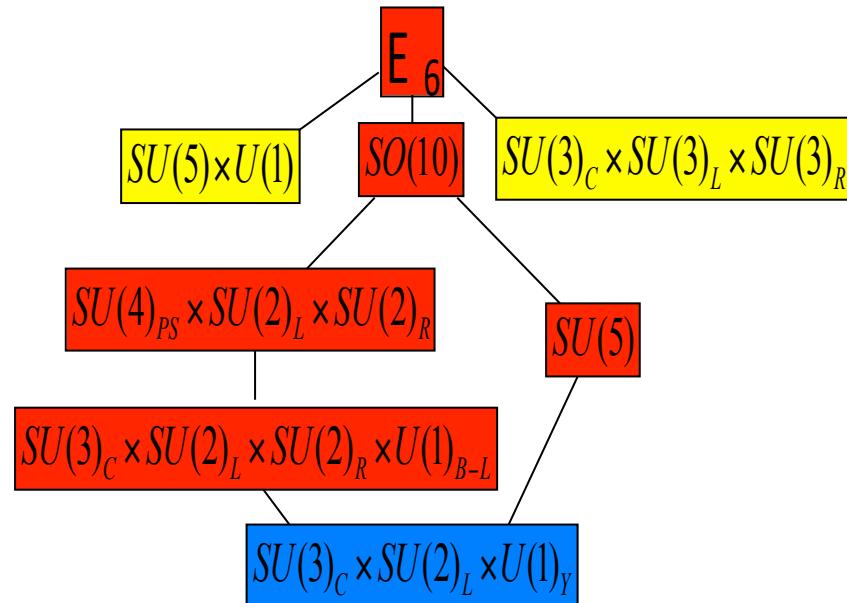
$\Lambda_{\text{GUT}} - \text{seesaw scale?}$

→ SUSY @ TeV ...

The larger Picture

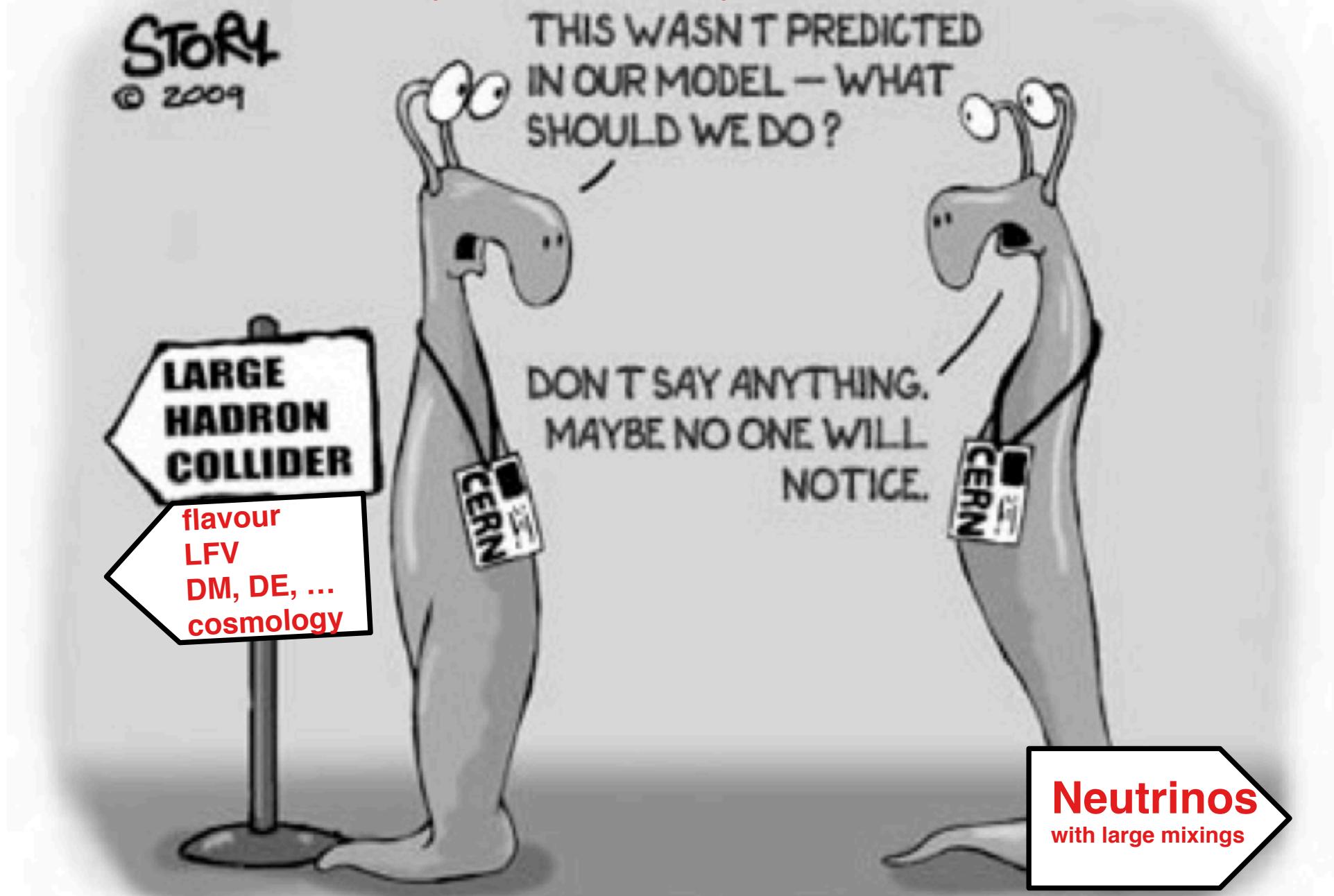
Gauge unification suggests GUTs

- unified gauge group
- unified particle multiplets $\leftrightarrow v_R$
 $\rightarrow Q, L$ Yukawa couplings connected
 \rightarrow proton decay , ...
- generations are just copies



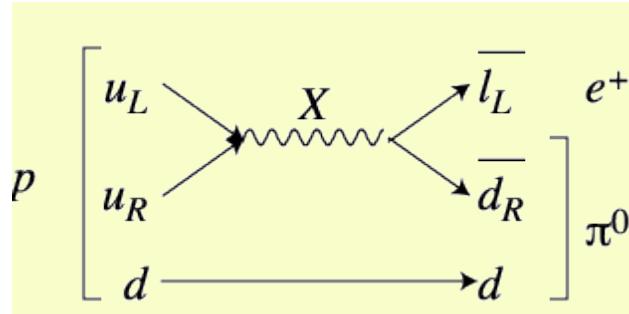
generations \leftrightarrow symmetries
- 3 generations \rightarrow representation
- regularities in q&l parameters
 \rightarrow flavour symmetries:
 $SU(3), A4, S3, D5, \dots$
IMPORTANT = flavour problem
 \leftrightarrow how precise do you have to be?
depends on question and value

BUT: Nature doesn't always behave the way we think...



Proton Decay in GUTs

- Quarks and leptons fit nicely into GUT multiplets
→ GUT gauge bosons → proton decay!



$$\Gamma \propto \left(\frac{g^2}{M_X^2} \right)^2 m_p^5$$

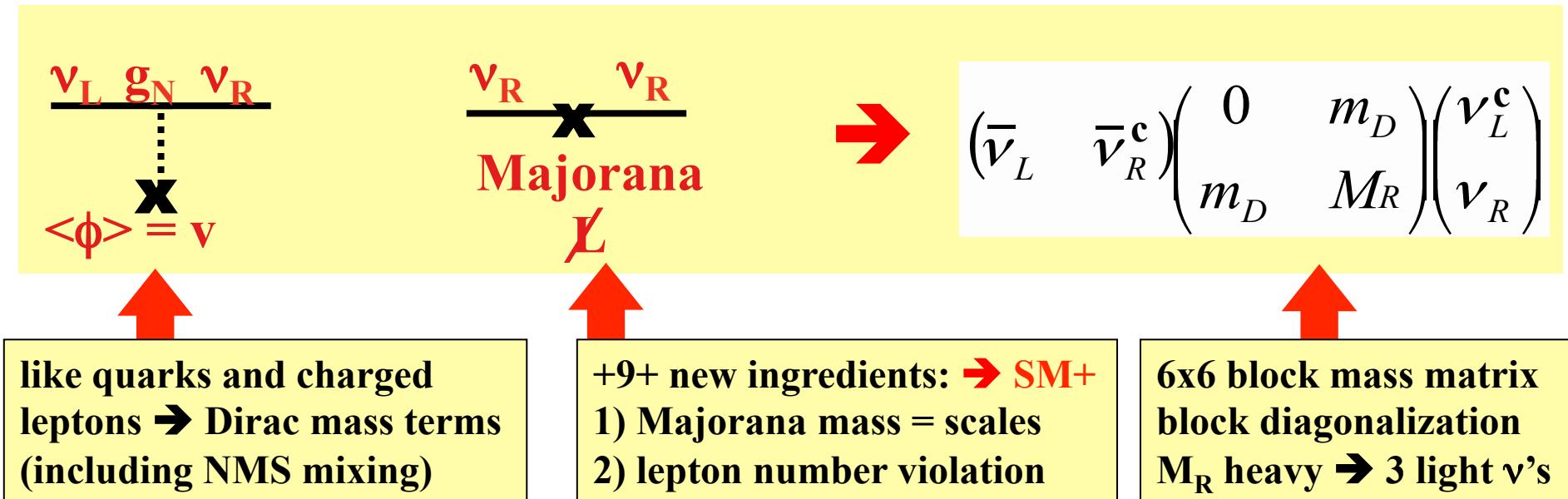
- Non-observation → higher GUT scale or ...no GUT?
→ SUSY GUTs: higher unification scale (+ no signal so far)
 - other decay modes
 - different (model dependent) scale dependence
 - other connections to model building (SUSY breaking, ..)
- Other BSM models? If nothing shows up @LHC?
- Large p-decay exp. now: High impact & high risk

Why is this relevant for Neutrinos?

- **The findings of LHC impact expectations for neutrinos:**
 - SUSY \leftrightarrow neutrino mass terms
 - W_R \leftrightarrow Majorana Yukawa couplings...
 - ...
 - nothing \leftrightarrow new ideas about EW symmetry breaking (e.g. conformal...) \leftrightarrow neutrino masses
- **The running may have a big impact:**
 - the onset of a signal \rightarrow continue running (postpone upgrade)
 - technological issues...
- **Political impact \leftrightarrow large machines after LHC**
- **Sociological impact:**
interest into various directions may change

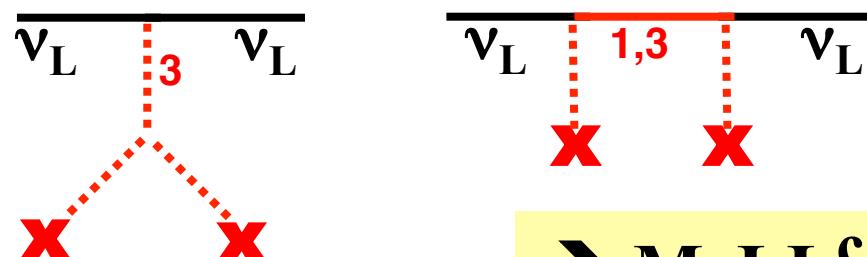
Neutrino Masses: New Physics...

Simplest possibility: assume 3 right handed singlets (1_L)



Or: add scalar triplets (3_L) or fermionic 1_L or 3_L

→ left-handed Majorana mass term:



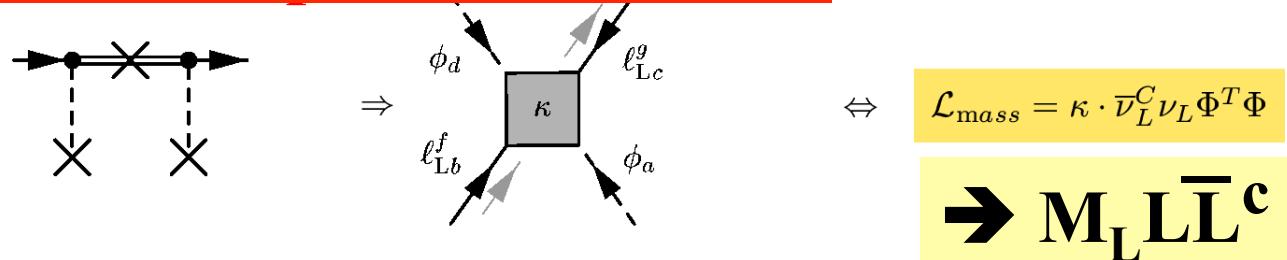
$$\rightarrow M_L \underline{L} \underline{L}^c$$

Both ν_R and new singlets / triplets:

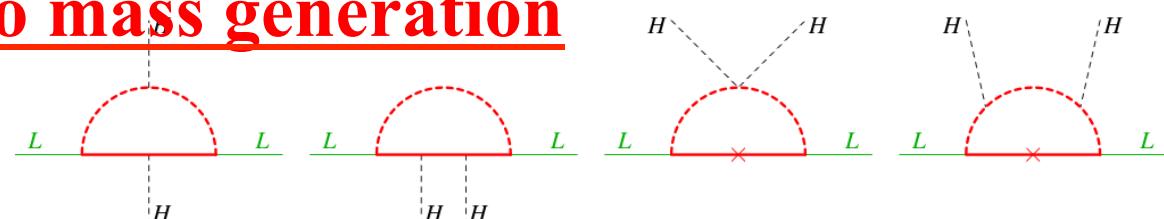
→ see-saw type II, III

$$\mathbf{m}_\nu = \mathbf{M}_L - \mathbf{m}_D \mathbf{M}_R^{-1} \mathbf{m}_D^T$$

Higher dimensional operators: d=5, ...



Radiative neutrino mass generation



SUSY, extra dimensions, ...

-
- neutrino masses can/may solve two of the SM problems:
 - leptogenesis as **explanation of BAU**
 - keV sterile neutrinos as **excellent warm dark matter candidate**
 - assumptions = new physics \leftrightarrow connections to LFV, LHC, ...

Standard 3 Neutrino Framework

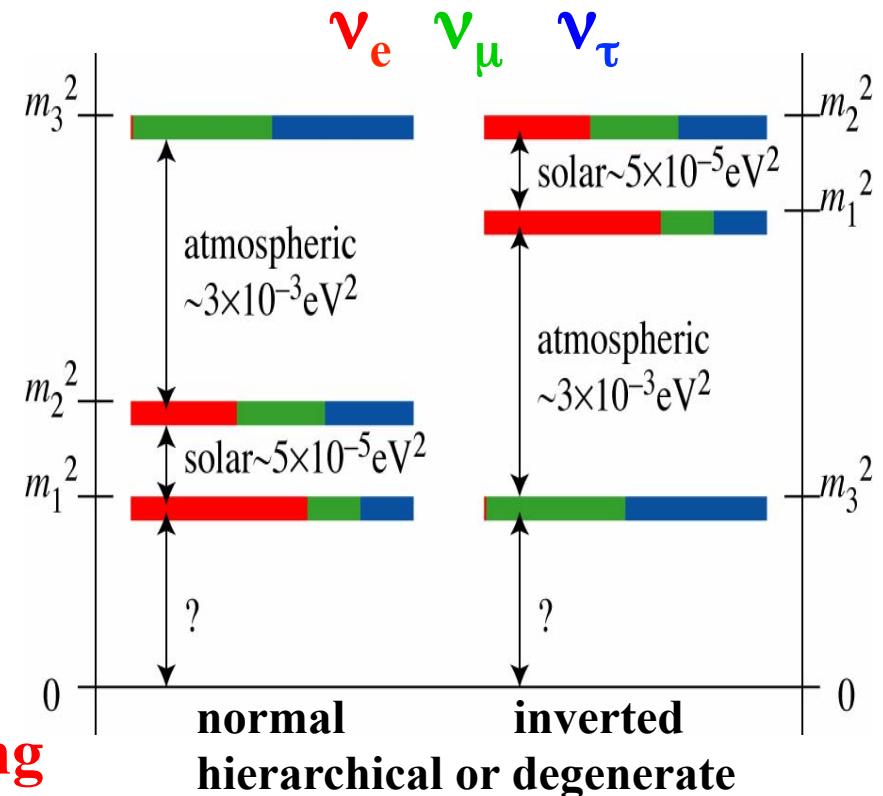
Mass & mixing parameters: m_1 , Δm^2_{21} , $|\Delta m^2_{31}|$, $\text{sign}(\Delta m^2_{31})$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \text{diag}(e^{i\alpha}, e^{i\beta}, 1)$$

Questions = the default program:

- Dirac / Majorana
- overall mass scale: m_1
- mass ordering: $\text{sgn}(\Delta m^2_{31})$
- θ_{23} maximal?
- leptonic CP violation

- guaranteed physics \leftrightarrow value
- Picture may be INCOMPLETE:
 - evidences for sterile neutrinos
 - new ideas on EW symmetry breaking



Options for Neutrino Mass Spectra

$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} M_L & m_D & M_R \\ m_D & \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

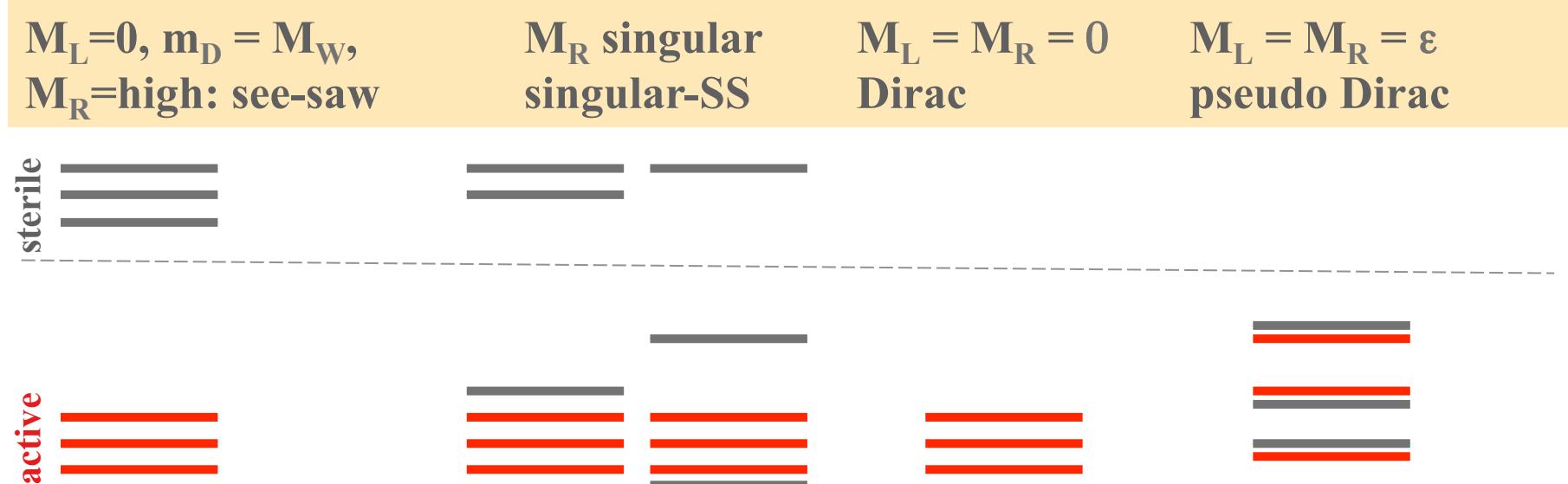
3x3 matrix 3xN NxN

3 0 ... N

M_L , m_D , M_R may have almost any form / values:

- zeros (symmetries)
- 0 + tiny corrections
- scales: M_W , M_{GUT} , ...

→ diagonalization: 3+N EV
 → 3x3 active almost unitary

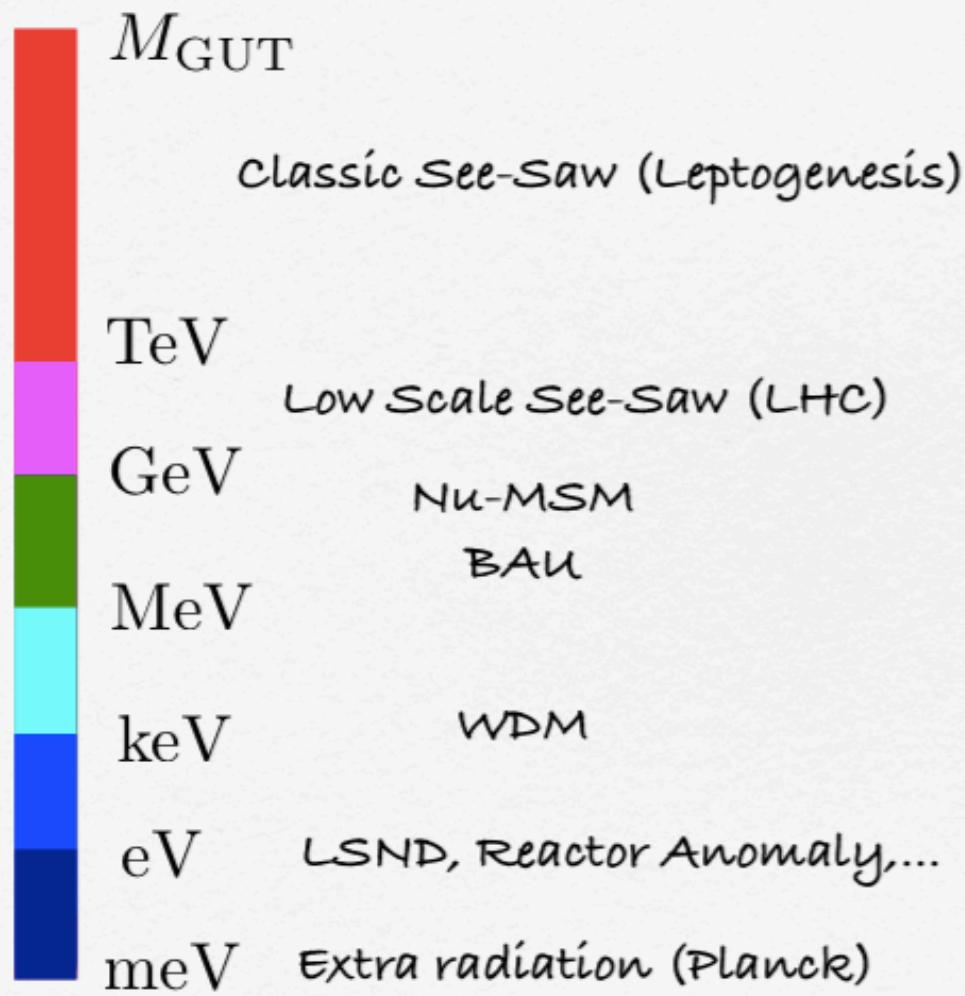


Interesting Directions: E.g. Pseudo Dirac Neutrinos

- Might be useful / indications (?) from SK-upturn (see e.g. A. Smirnov)
- May also be useful in HE neutrinos and GRBs (see e.g. Esmaili and Farzan)
- Theory ideas
 - mirror worlds (e.g. Joshipura, Mohanty, Pakvasa)
 - implications for $0\nu\beta\beta$ (e.g. P.Gu)
 - role in leptogenesis (e.g. Abel, Page)
 - left right symmetry and gauged B,L (e.g. Duerr, Perez, ML)
 - ... sugra (e.g. Dedes)
 - ... many other papers

Sterile neutrinos
= right-handed
neutrinos
(no SM charges)

There may be
 $0, 1, 2, 3, \dots n$
sterile neutrinos



Message: sterile neutrinos may exist with any mass!

→ effect on oscillations and other experiments

One example: multi-TeV steriles with tiny mixings improve EW fits

NSI Operators

- Good reasons for physics beyond the SM+ (with ν's)
 - expect effects beyond 3 flavours in many models
 - effective 4f interactions

$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2}G_F (\bar{\nu}_{L\beta} \gamma^\rho \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

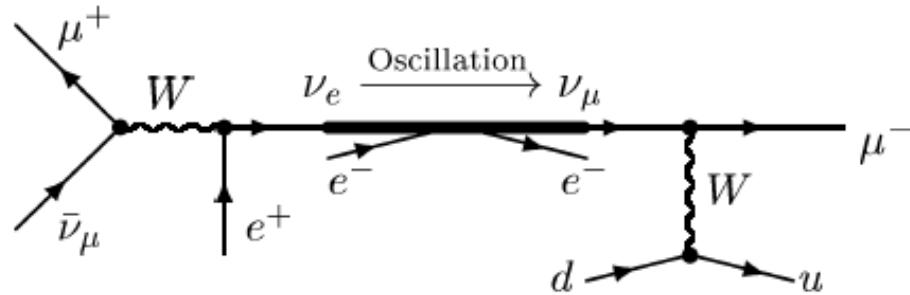
- integrating out heavy physics (c.f. $G_F \leftrightarrow M_W$)

$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

Grossman, Bergmann+Grossman, Ota+Sato, Honda et al., Friedland+Lunardini,
Blennlow+Ohlsson+Skrotzki, Huber+Valle, Huber+Schwetz+Valle, Campanelli
+Romanino, Bueno et al., Kopp+ML+Ota, ...

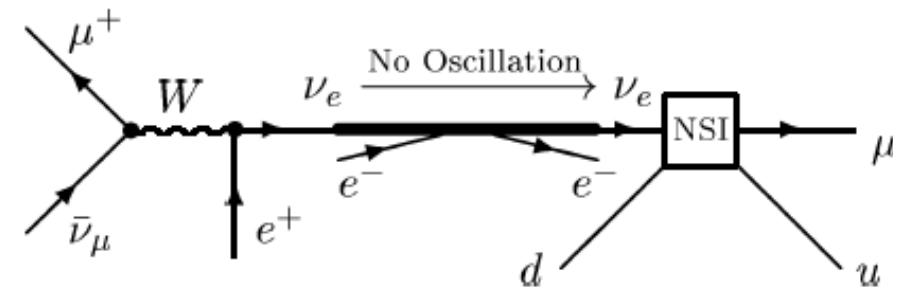
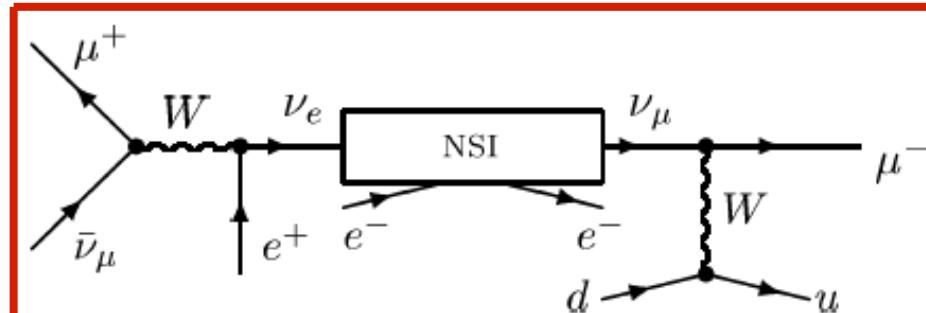
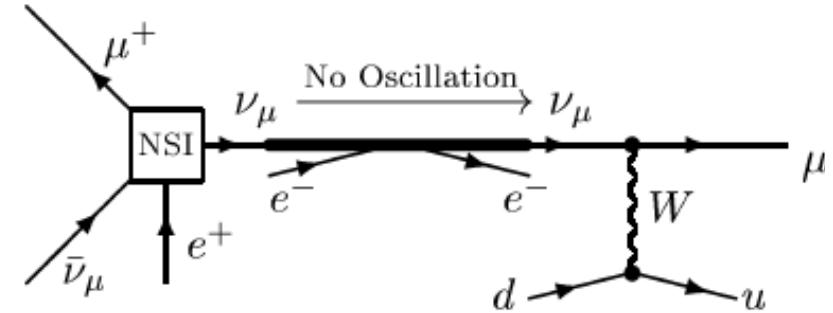
NSIs interfere with Oscillations

the “golden” oscillation channel



(a)

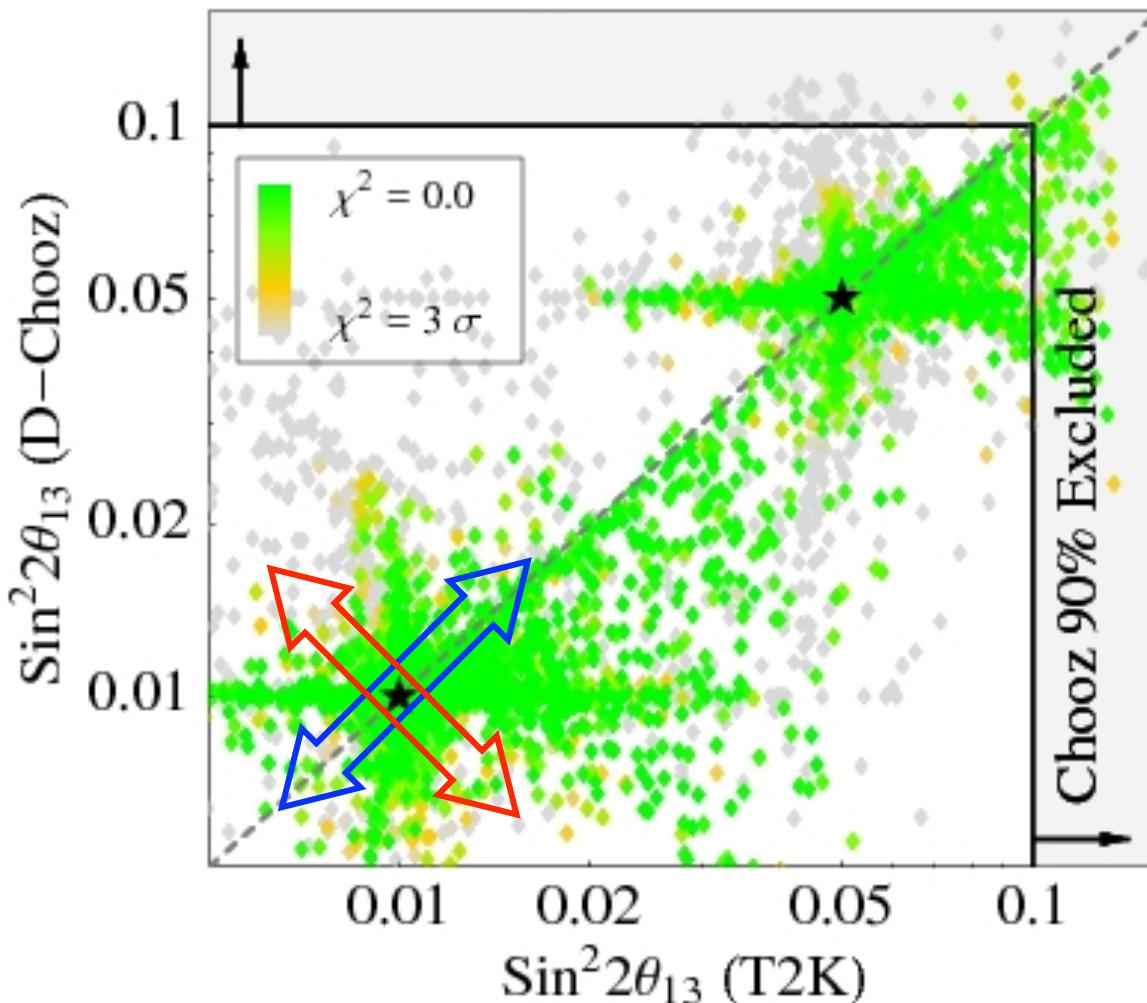
NSI contributions to the “golden” channel



note: interference in oscillations $\sim \epsilon \leftrightarrow$ FCNC effects $\sim \epsilon^2$

NSI: Offset and Mismatch in θ_{13}

T2K / Double Chooz



Redundant measurements:

Double Chooz + T2K

*=assumed 'true' values of θ_{13}

scatter-plot: ϵ values random

- below existing bounds
- random phases

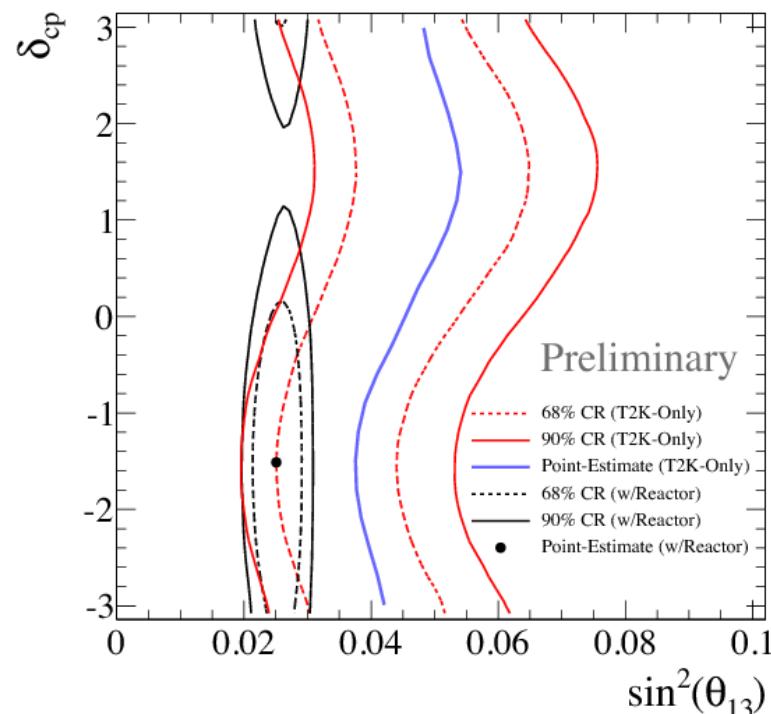
NSIs can lead to:

- offset
- mismatch
- redundancy
- interesting potential

In general: over-constraining \leftrightarrow test of non-minimal scenarios

Time Evolution & the Physics Case

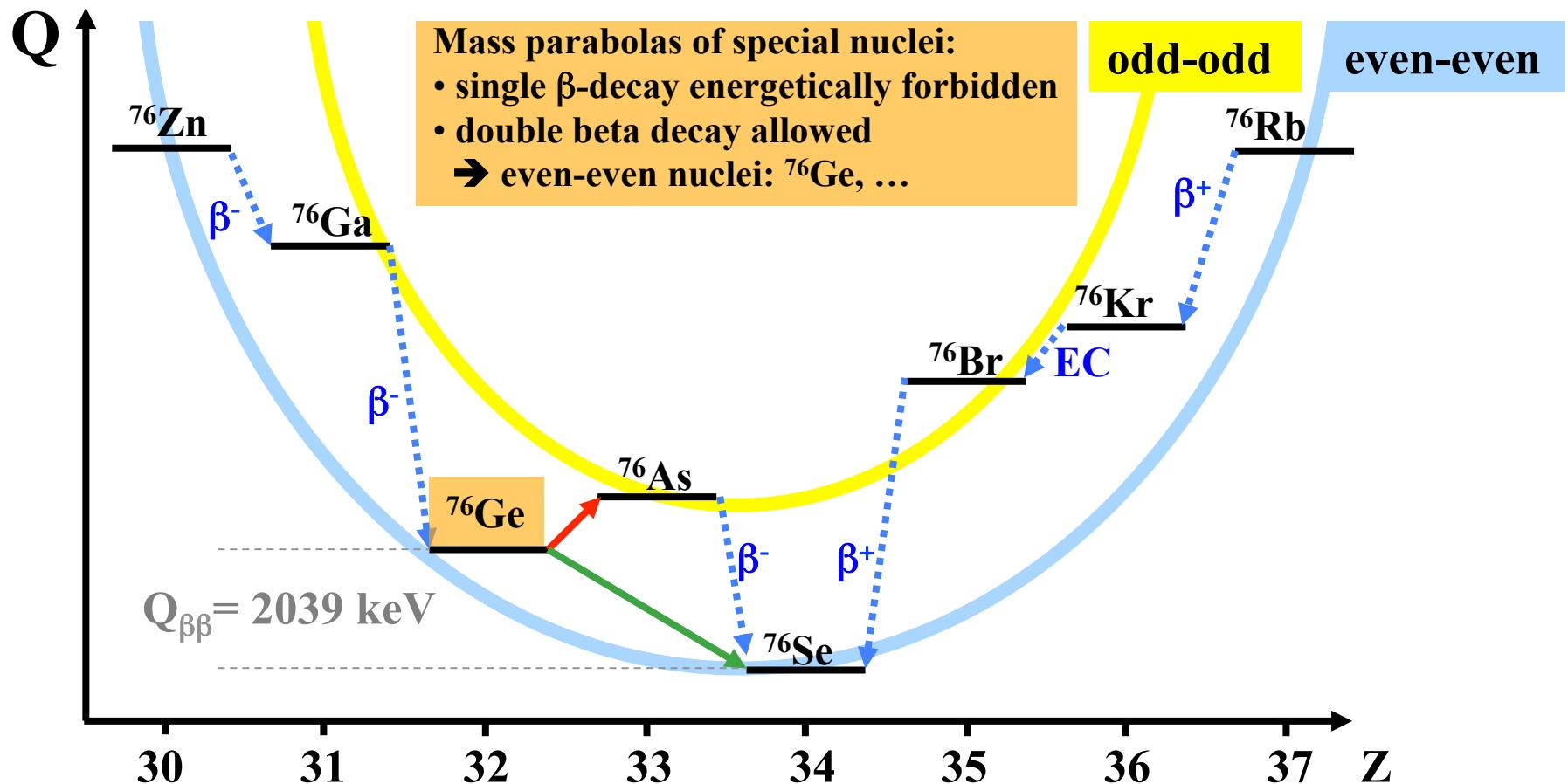
In next years: Improved 3- ν global fits combining T2K, NoVA, Double Chooz, Daya Bay, RENO see e.g. [T2K 1405.3871](#)



- Islands in $\delta\theta_{13}$ space for positive and negative mass hierarchy (here +)
- Minimal 3 neutrino framework
 - how precise to ‘learn’ something?
- Evidence or arguments for other extra physics (sterile, NSI, BSM...)
- Further input from other (earlier) experiments (like PINGU & MH ...)

Physics case will change before new large experiments come online → long term projects: **Stay flexible as long as possible!**

Double Beta Decay



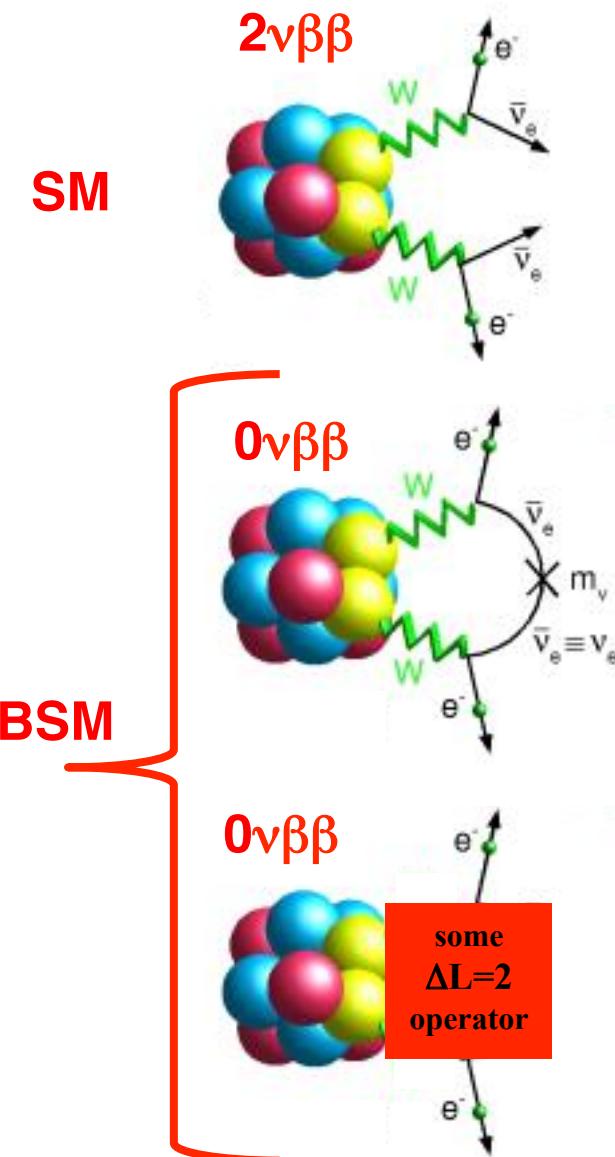
Double beta decay: $2n \rightarrow 2p + X$; $q_x = -2$; energy $Q_{\beta\beta}$ goes \sim into X if $m_X \ll \text{GeV}$

1) Standard Model: 2 weak decays $X = 2e^- + 2\nu_e \rightarrow 2\nu$ beta decay

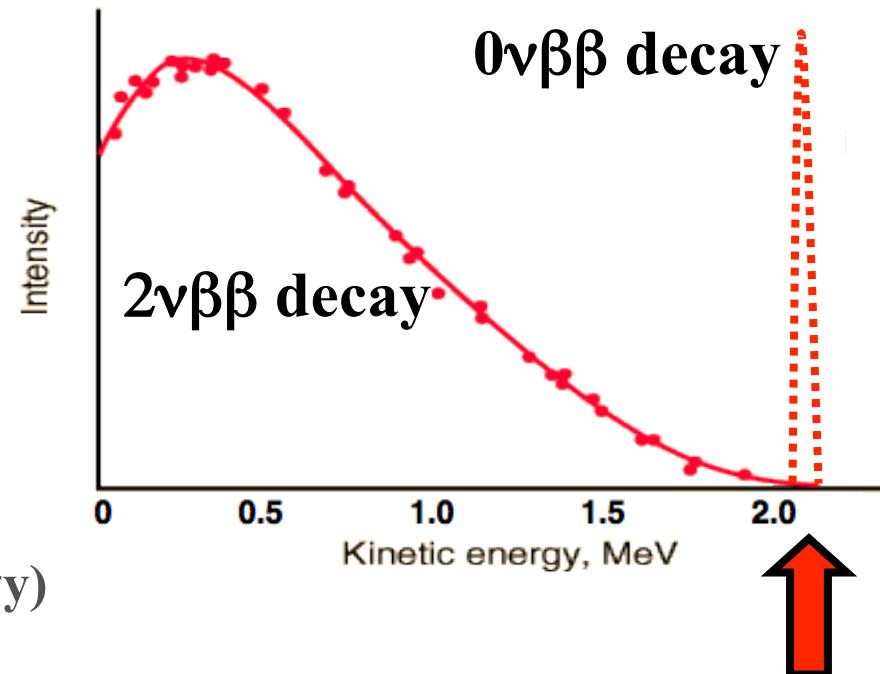
2) Beyond the SM: $X = 2e^- \rightarrow 0\nu$ (neutrino less) double beta decay → L-violation

Options: Majorana neutrino masses *OR* other $\Delta L=2$ operators

Double Beta Decay Kinematics



$2\nu\beta\beta$ decay seen for diff. isotopes (Kirsten,...)
 $T^{1/2} = O(10^{18} - 10^{21}$ years) \rightarrow up to $10^{11} \otimes T_{\text{Universe}}$



$$T^{1/2} > O(10^{24} \text{y})$$

- observe $2\nu\beta\beta$ signal
- look for $0\nu\beta\beta$ signal at $Q_{\beta\beta}$
- large amount of ^{76}Ge nuclei
- extreme low backgrounds!

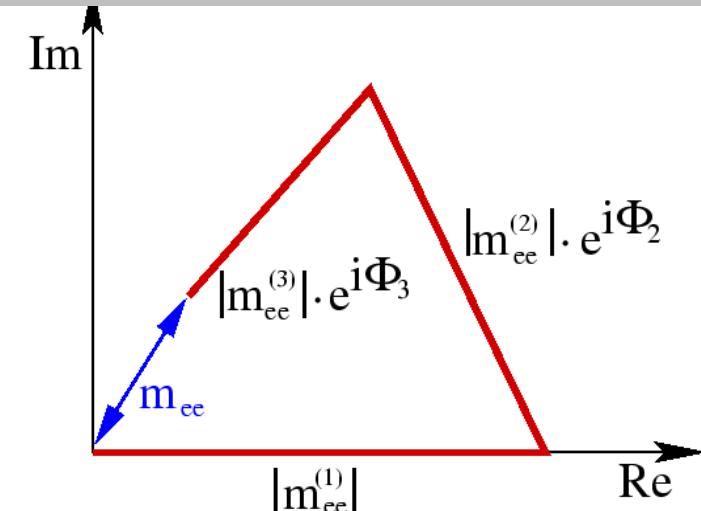
m_{ee} : The Effective Neutrino Mass

$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$$

$$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1$$

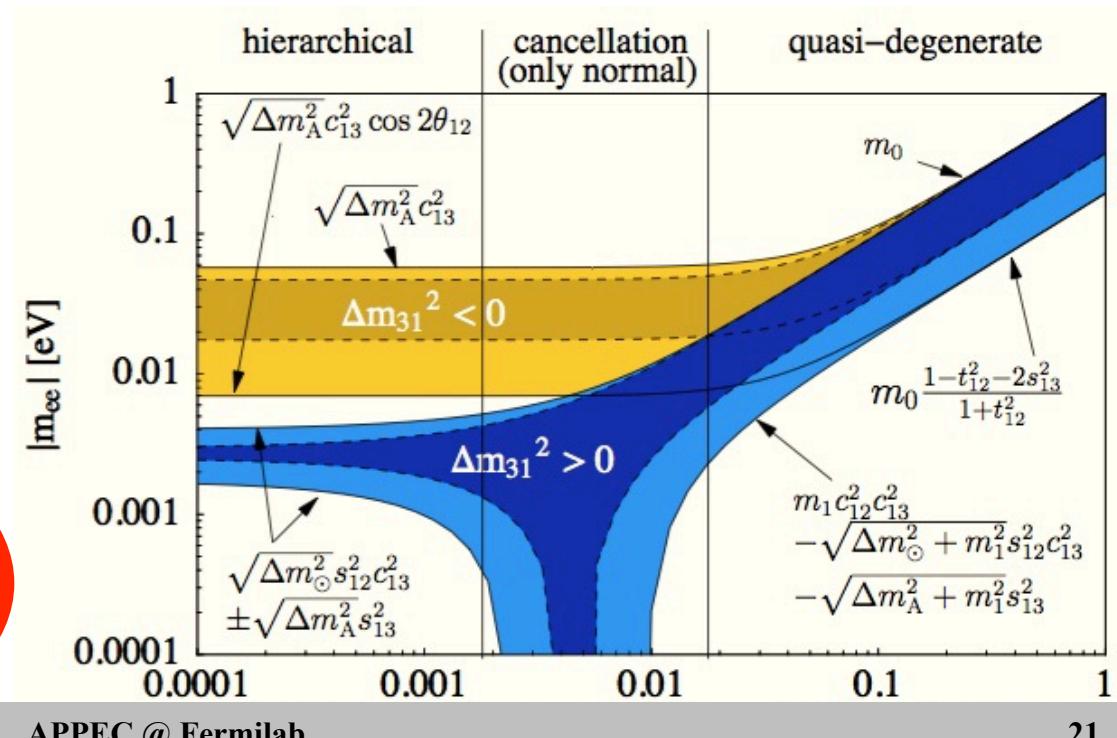
$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2}$$

$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2}$$



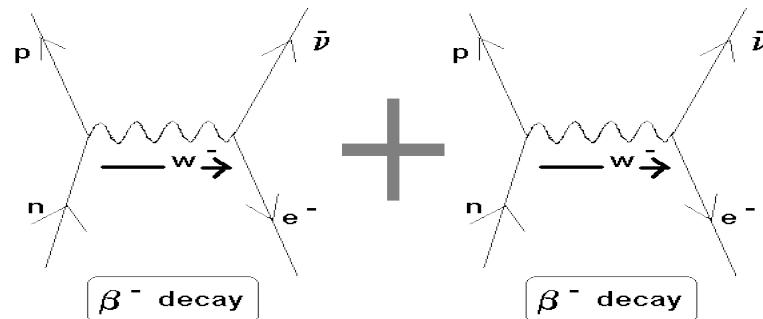
$0\nu\beta\beta$ by Majorana masses
→ limits on m_{ee}

- cosmology → limit on m
- assumption: no *other* $\Delta L=2$ physics, no sterile neutrinos up to TeV,...



Double Beta Decay Processes

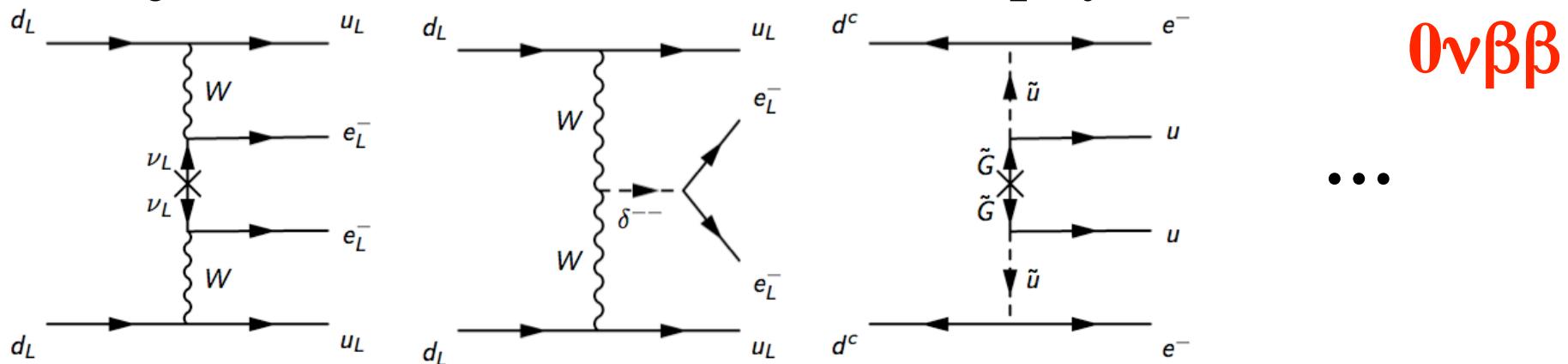
Standard Model:



→ 2 electrons + 2 neutrinos
 $2\nu\beta\beta$

Majorana ν -masses or other $\Delta L=2$ physics: → 2 electrons

$d_L \rightarrow u_L$ $d_L \rightarrow u_L$ $d^c \rightarrow e^-$ $0\nu\beta\beta$



Majorana
neutrino masses
 \leftrightarrow Dirac?

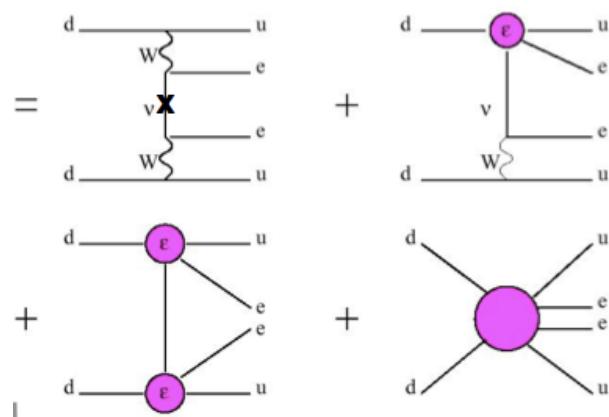
important connections to LHC and LFV ...
 sub eV Majorana mass \leftrightarrow TeV scale physics

Interference of $\Delta L=2$ Operators

Usually

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \left(\frac{|m_{0\nu\beta\beta}|}{m_e}\right)^2 |\mathcal{M}^{0\nu}|^2 G^{0\nu}.$$

with interferences



$$\begin{aligned} \left(T_{1/2}^{0\nu}\right)^{-1} &= |m_{0\nu\beta\beta}\mathcal{M}^{0\nu} + \epsilon m_e \mathcal{M}^\epsilon|^2 \frac{G^{\text{int}}}{m_e^2} \\ &= |(m_{0\nu\beta\beta} + \epsilon m_e \mathcal{M}^\epsilon (\mathcal{M}^{0\nu})^{-1}) \mathcal{M}^{0\nu}|^2 \frac{G^{\text{int}}}{m_e^2} \\ &= |m_{0\nu\beta\beta}^{\text{int}}|^2 |\mathcal{M}^{0\nu}|^2 \frac{G^{\text{int}}}{m_e^2}, \end{aligned}$$

G^{int}

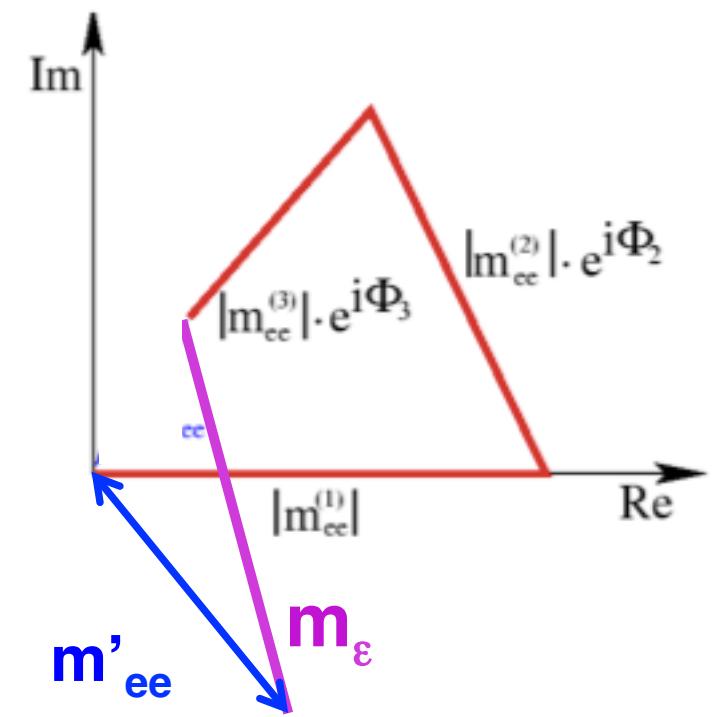
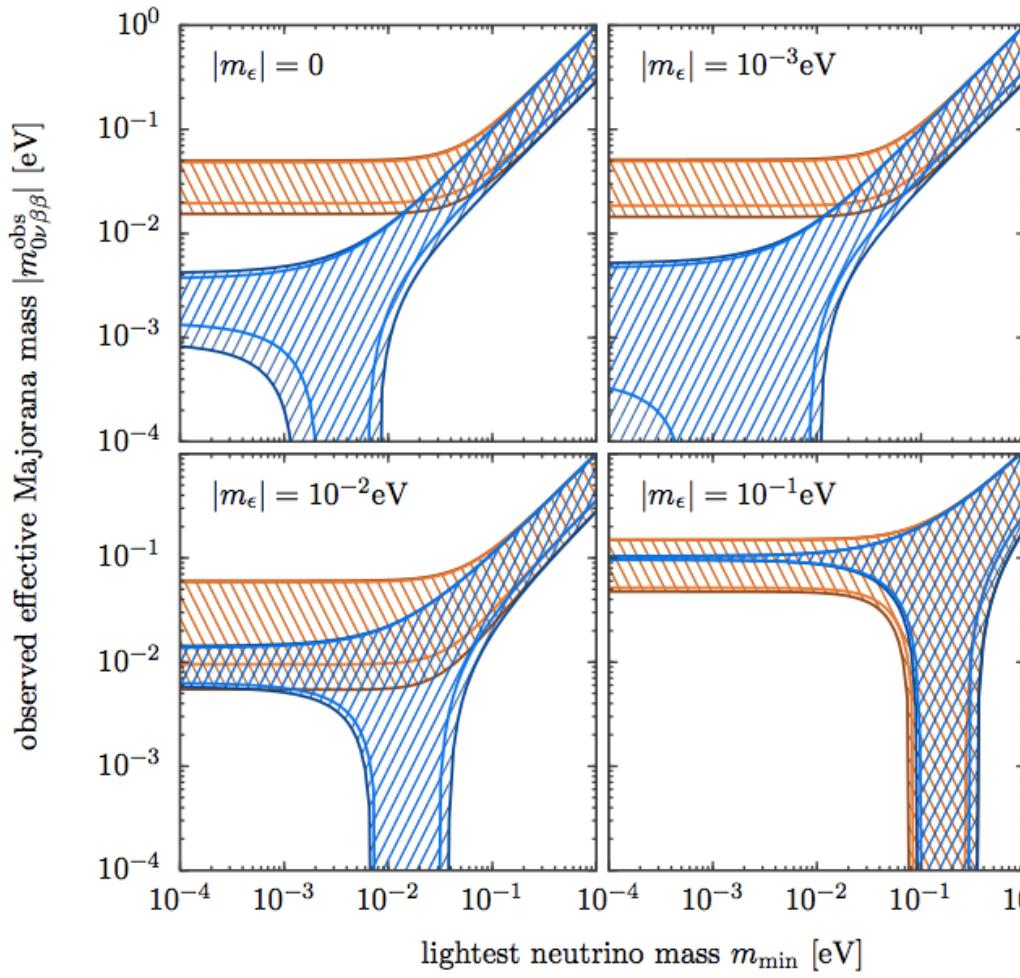
= overall phase space factor

$\epsilon m_e \mathcal{M}^\epsilon$ \leftrightarrow determined by parameters of new physics

$$m_{0\nu\beta\beta}^{\text{int}} \equiv m_{0\nu\beta\beta} + \epsilon m_e \mathcal{M}^\epsilon (\mathcal{M}^{0\nu})^{-1} \boxed{= m_{0\nu\beta\beta} + m_\epsilon.}$$

$$m_\epsilon \simeq (\Lambda_{\text{new}})^{-5}$$

$$\boxed{m_{0\nu\beta\beta} = 1 \text{ eV} \leftrightarrow \Lambda_{\text{new}} \simeq \text{TeV}}$$



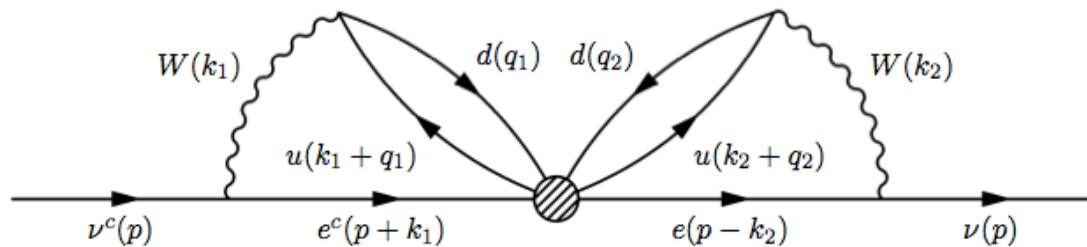
interferences

growing m_ϵ for fixed $0\nu\beta\beta$
 \rightarrow shifts of masses,
mixings and CP phases

\rightarrow sensitivity to TeV physics

Schechter-Valle Theorem induced masses

- Any $\Delta L=2$ operator which leads to $0\nu\beta\beta$ decay induces via loops a Majorana mass
- Observation of $0\nu\beta\beta \rightarrow$ proof of Majorana nature...



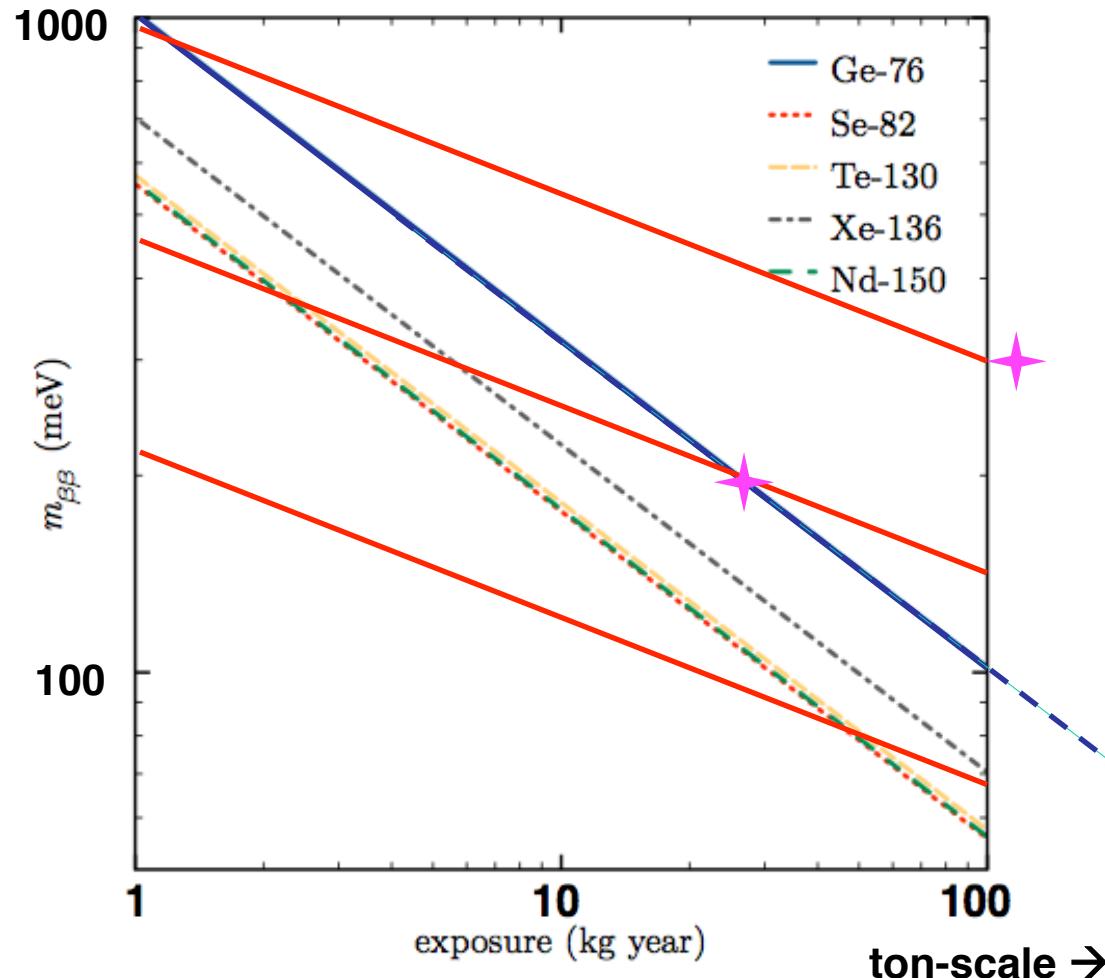
Outcome:

Dürr, ML, Merle

4 loops $\rightarrow \delta m_\nu = 10^{-28} \text{ eV} \rightarrow$ very tiny (academic interest)
 \rightarrow cannot explain observed masses and splittings
 \rightarrow explicit Dirac neutrino mass operators required

$0\nu\beta\beta \longleftrightarrow$ other BSM physics
neutrino masses \longleftrightarrow Dirac

Important for $0\nu\beta\beta$ Future: Sensitivity vs. Background



without background

$$N = \log 2 \cdot \frac{N_A}{W} \cdot \varepsilon \cdot \frac{M \cdot t}{T_{1/2}^{0\nu}}$$

N_A = Avogadro's number

W = atomic weight of isotope

ε = signal detection efficiency

M = isotope mass

t = data taking time



$$m_{\beta\beta} = K_1 \sqrt{\frac{N}{\varepsilon M t}}$$

with background

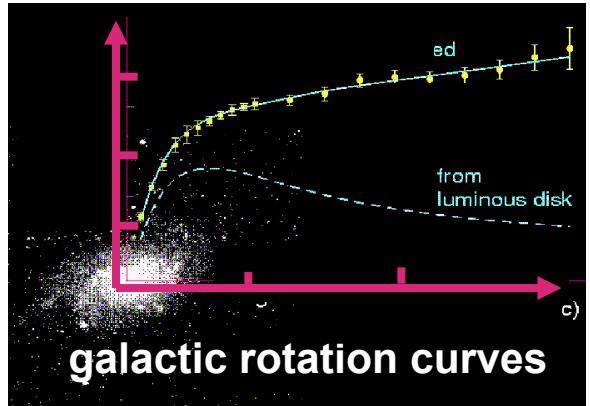
$$N' = N + N_{background}$$



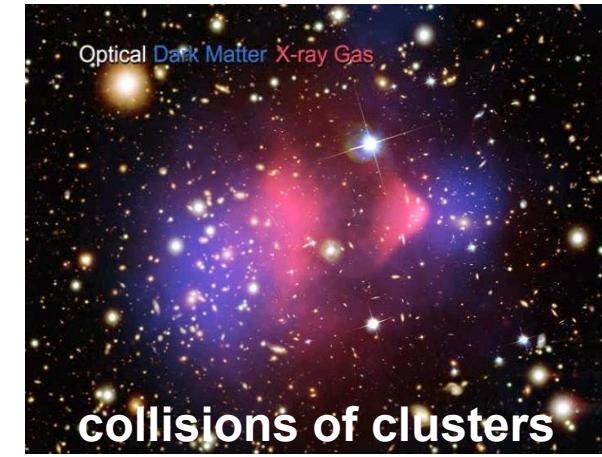
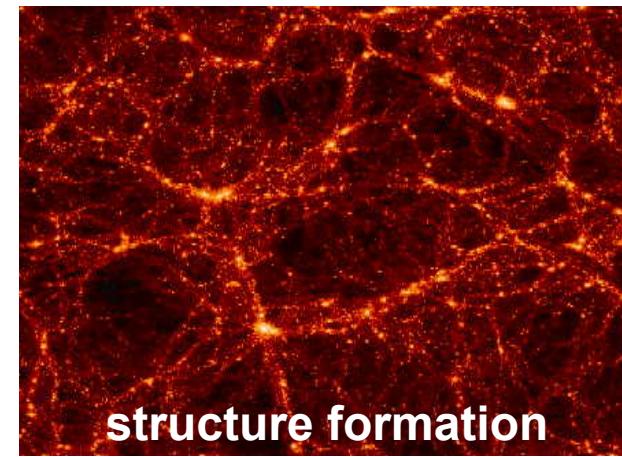
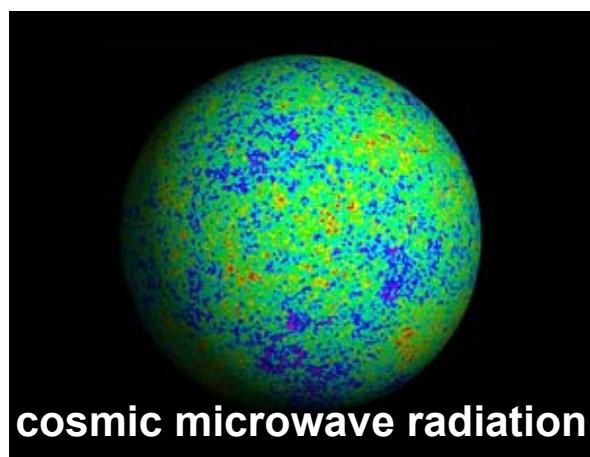
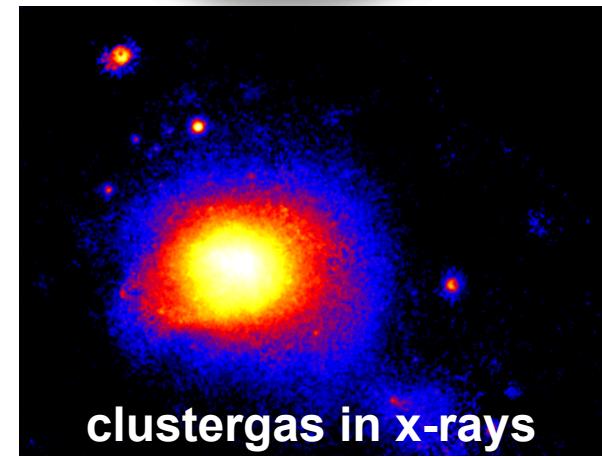
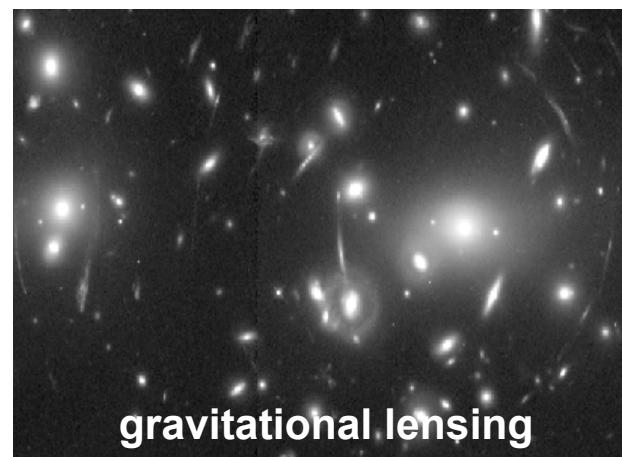
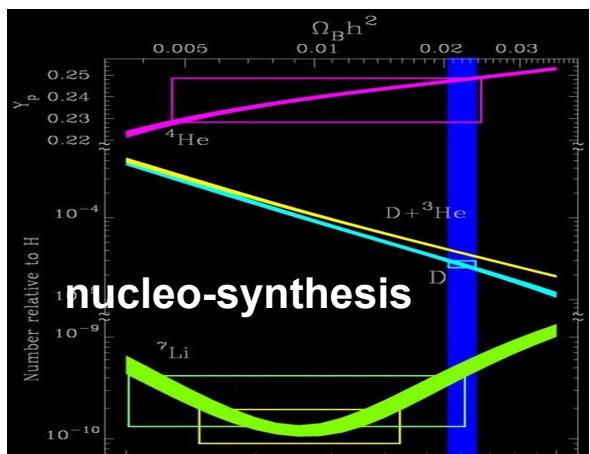
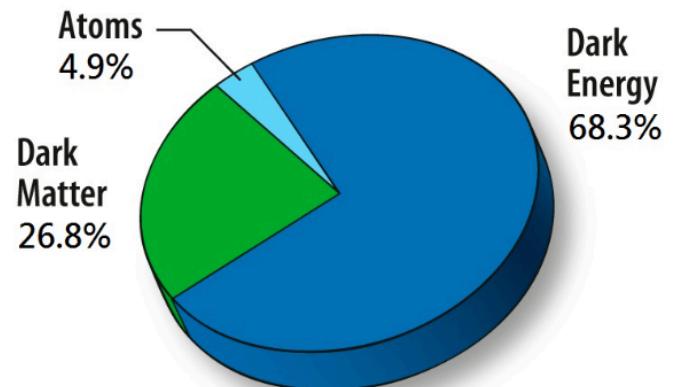
$$m_{\beta\beta} = K_2 \sqrt{1/\varepsilon} \left(\frac{c \Delta E}{M t} \right)^{1/4}$$

c = cts/keV/kg/yr ; ΔE = ROI

HdM/GERDA: stay bg free! → demonstrate! → kg*y ↔ ↔ mass versus time



Dark Sectors exist!



The Nature of Dark Matter

Gravity

MOND
one scale
modification
fails badly

OTHER
modifications
???

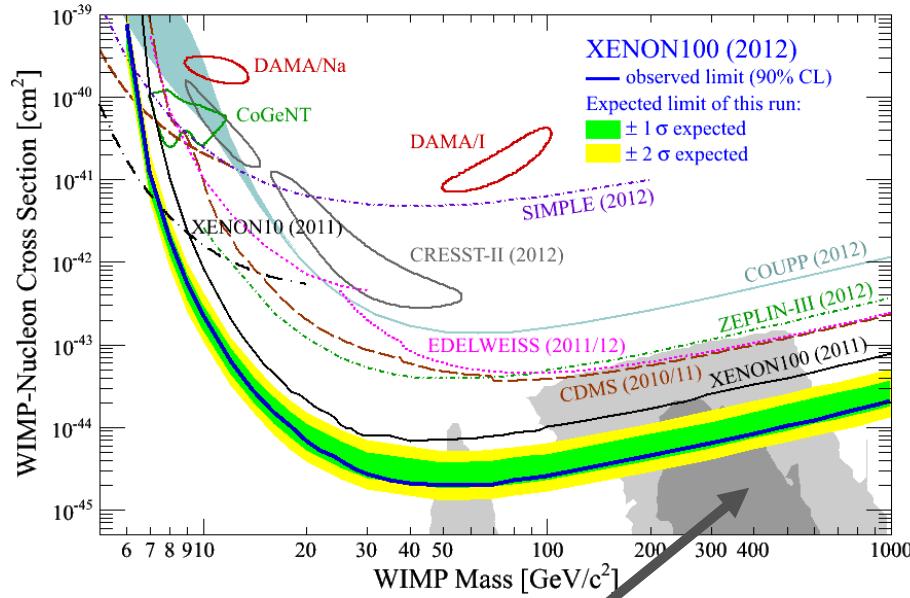
Particles

BSM
motivated:
- WIMPs
- axions
- sterile ν's
- ...

≈ automatically
correct
abundance:
- WIMPs
- asym. DM
- ...

WIMPs nicely combine
both positive aspects
→ WIMP miracle

WIMP = MSSM Neutralino Dark Matter



Buchmüller et al.

- CMSSM \leftrightarrow MSSM
- low WIMP masses?
- low x-section?
- connections to other observables
- preferred parameter ranges?

→ WIMPs in full MSSM:

- eleven free parameters

$$\tan \beta, M_1, M_2, M_3, M_A, \mu, m_{\tilde{\ell}_L}, m_{\tilde{\ell}_R}, m_{\tilde{q}_{1,2}}, m_{\tilde{q}_3}, a_0$$

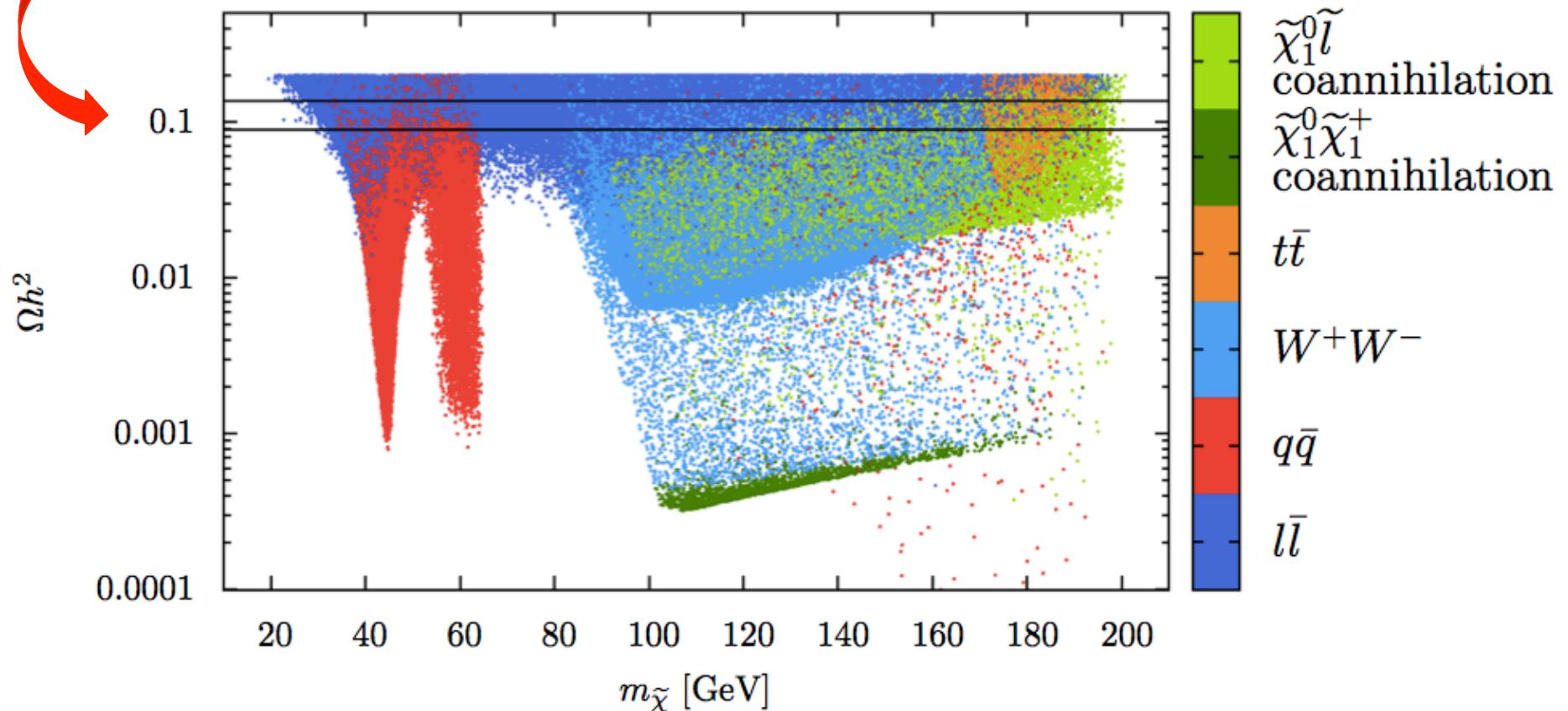
Include:

- constraint coming from pseudo-Higgs boson searches
- LEP constraints

| Quantity | |
|--|-------------------------------|
| Ωh^2 | [0.089, 0.136] |
| m_h | (121.0, 129.0) GeV |
| $\text{Br}(B \rightarrow s\gamma)$ | $[2.89, 4.21] \times 10^{-4}$ |
| $\text{Br}(B_s \rightarrow \mu^+ \mu^-)$ | $< 4.5 \times 10^{-9}$ |
| $\text{Br}(B_u \rightarrow \tau \bar{\nu})$ | $0.52 < R_{B\tau\nu} < 2.61$ |
| $\text{Br}(K \rightarrow \mu\nu)$ | $0.985 < R_{l23} < 1.013$ |
| a_μ | $[0.34, 4.81] \times 10^{-9}$ |
| $\Gamma(Z \rightarrow \tilde{\chi}_1 \tilde{\chi}_1)$ | < 3 MeV |
| $\sigma(ee \rightarrow \tilde{\chi}_1 \tilde{\chi}_{2,3})$ | < 100 fb |
| $\Delta\rho$ | < 0.002 |

The correct Cosmological Abundance

Scan parameter space for different annihilation channels $\rightarrow \Omega h^2$
Note: we will not argue for equal probability in parameter space!



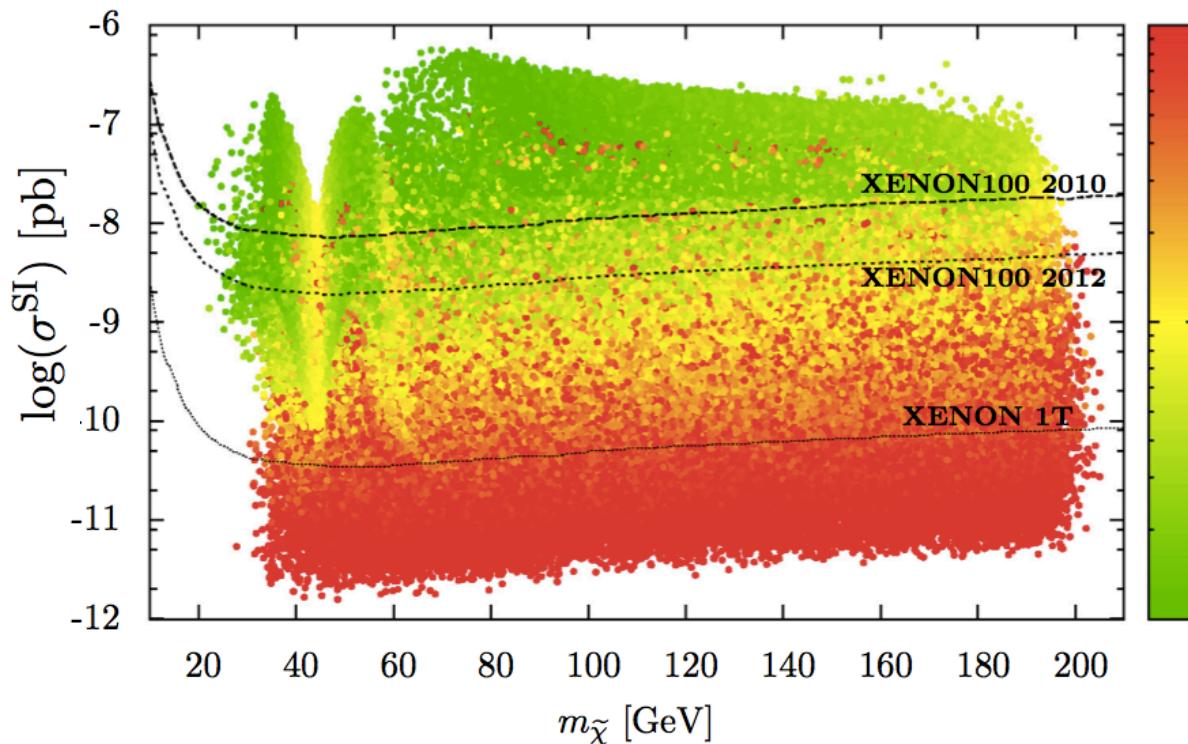
→ Select correct Ωh^2 → constrains allowed parameters

The Level of required Fine-Tuning: Δ_{tot}

- Fine-tuning measure Δ_{tot} :

$$\Delta_{\text{tot}} \equiv \sqrt{\sum_{p_i=\mu^2, b, m_{H_u}^2, m_{H_d}^2} \{\Delta p_i\}^2}$$

$$\Delta p_i \equiv \left| \frac{p_i}{M_Z^2} \frac{\partial M_Z^2(p_i)}{\partial p_i} \right| = \left| \frac{\partial \ln M_Z^2(p_i)}{\partial \ln p_i} \right|$$



$$\Delta\mu^2 = \frac{4\mu^2}{m_Z^2} \left(1 + \frac{m_A^2 + m_Z^2}{m_A^2} \tan^2 2\beta \right) ,$$

$$\Delta b = \left(1 + \frac{m_A^2}{m_Z^2} \right) \tan^2 2\beta ,$$

$$\Delta m_{H_u}^2 = \left| \frac{1}{2} \cos 2\beta + \frac{m_A^2}{m_Z^2} \cos^2 \beta - \frac{\mu^2}{m_Z^2} \right| (1 -$$

$$\Delta m_{H_d}^2 = \left| -\frac{1}{2} \cos 2\beta + \frac{m_A^2}{m_Z^2} \sin^2 \beta - \frac{\mu^2}{m_Z^2} \right| (1 -$$

1000

XENON100-2010

XENON100-2012

100

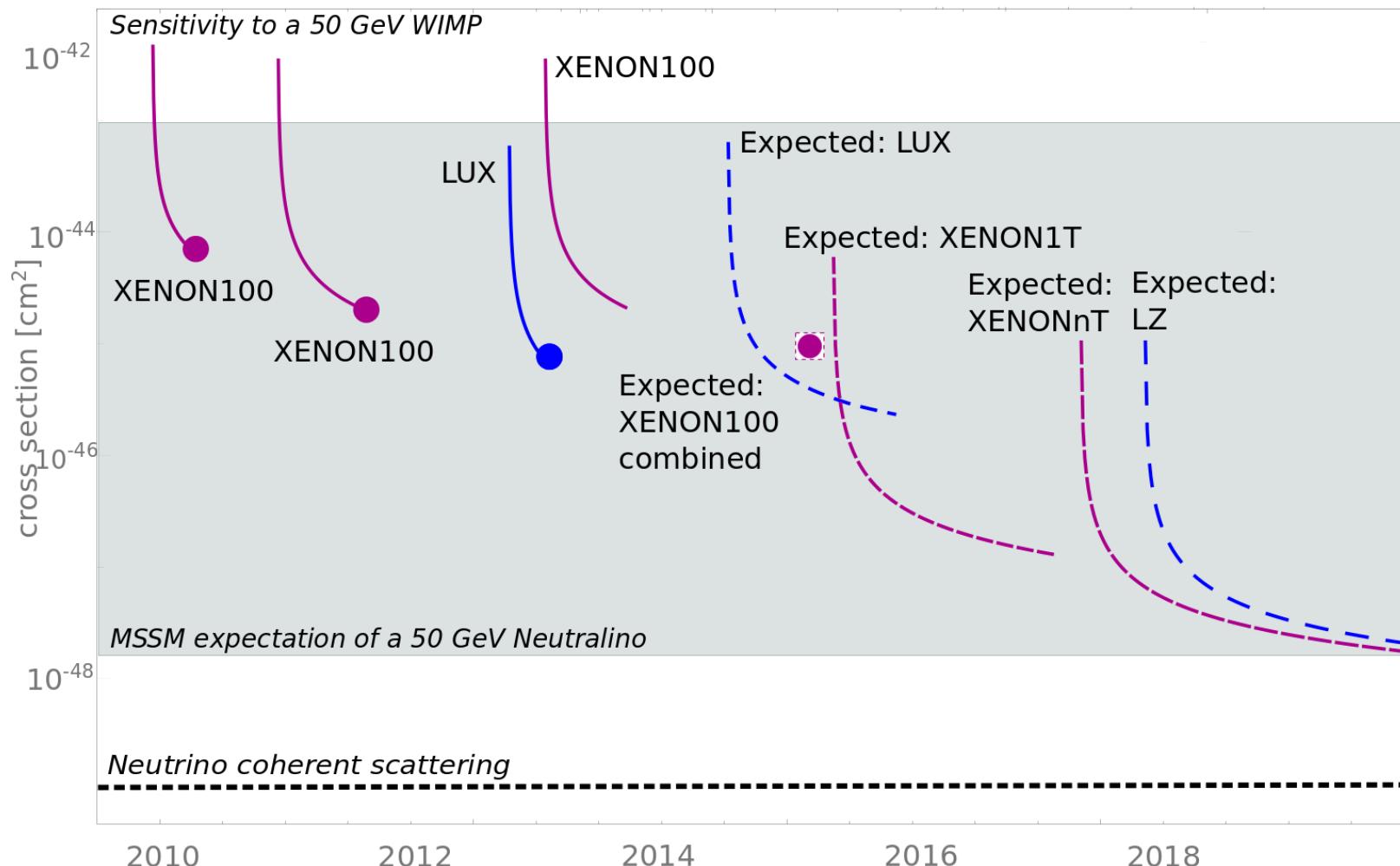
XENON1T

...more and more tuned...

→ WIMPs should show up before $\sigma \simeq 10^{-48} \text{cm}^2$

P. Grothaus, ML, Y. Takanishi

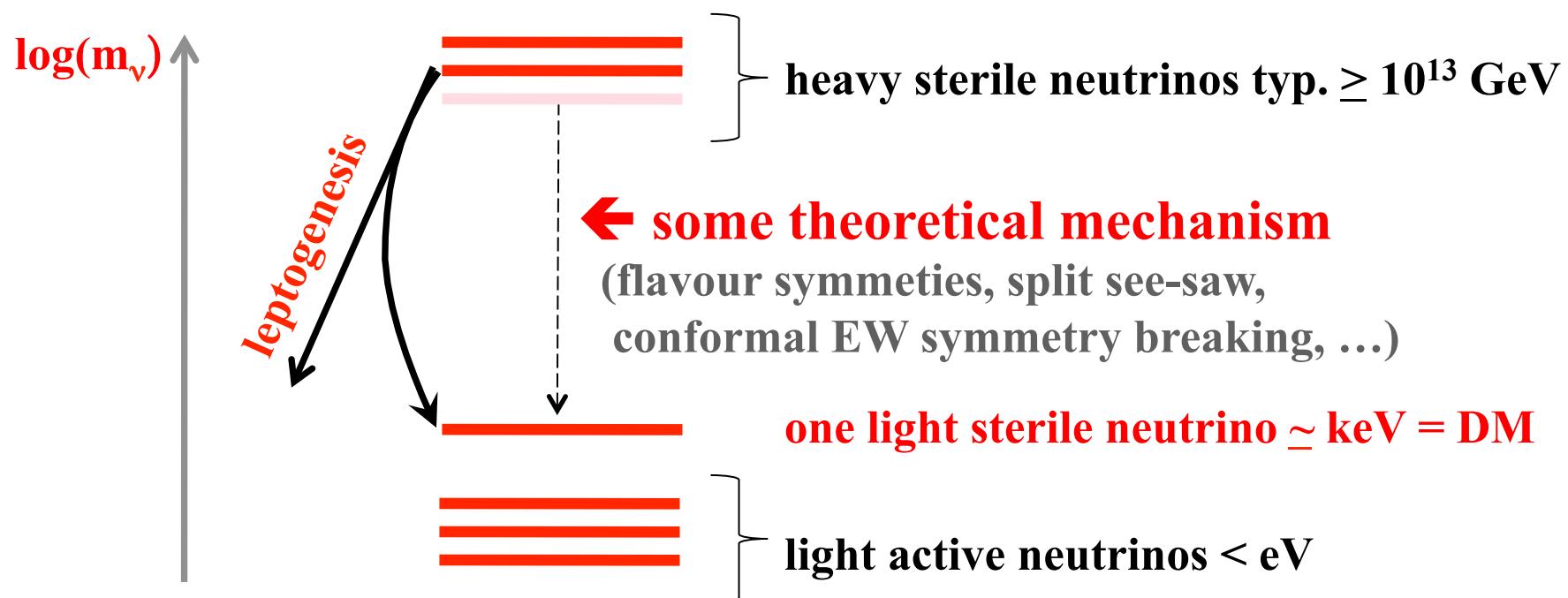
Prospects for WIMP Sensitivity (SI)



→ WIMPs should be found or other candidates become as ‘natural’: axions, keV neutrinos ←→ impacts large scale neutrino program

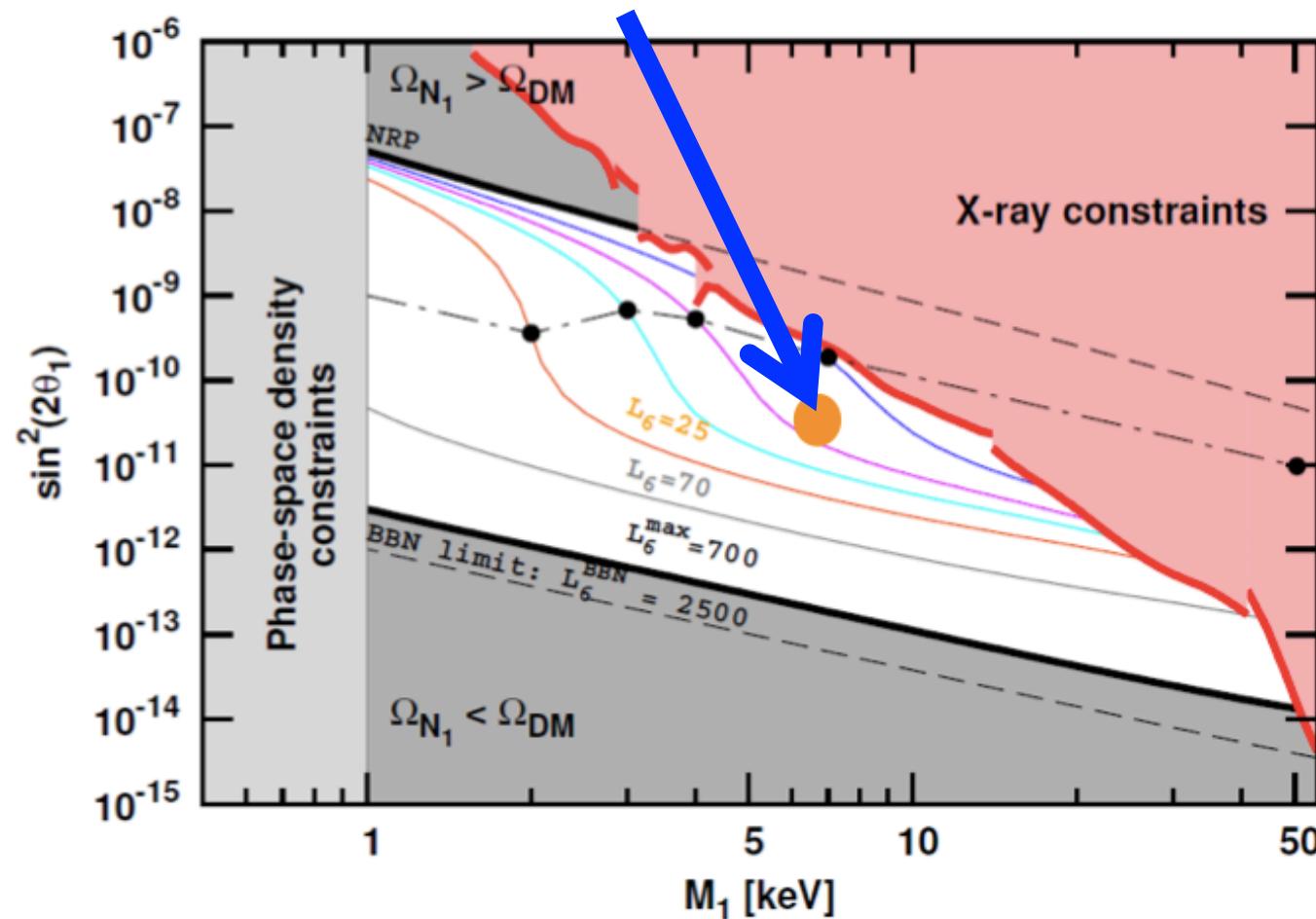
Neutrinos as Dark Matter

- active neutrinos excluded (hot, too light, but 0.3% of U)
- keV sterile ν 's → excellent warm dark matter candidate
 - right handed neutrinos probably exist $\leftrightarrow m_\nu$
 - theoretical scenarios which allow keV scale
 - never in equilibrium \leftrightarrow not counted in cosmology



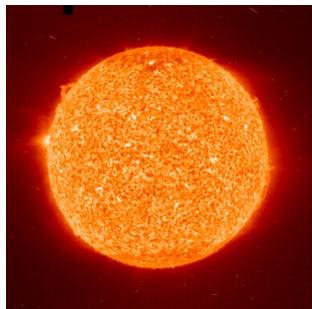
Recent Claims of a γ -Line

Bulbul et al. 1402.2301 and Boyarsky et al. 1402.4119

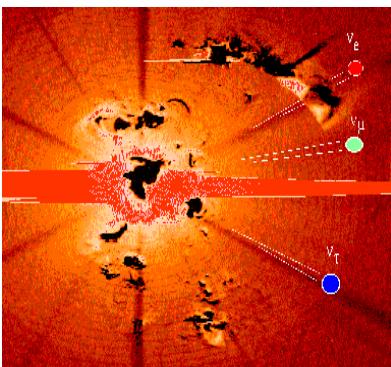


→ reliability of the signal? → ongoing discussions... → must see

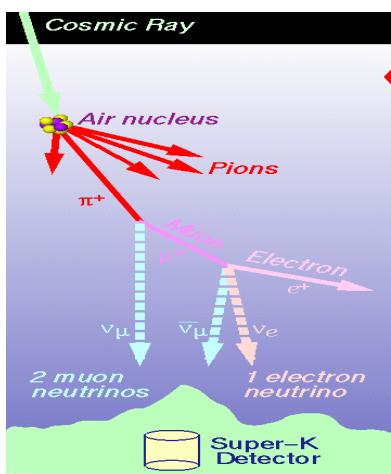
Neutrinos as Probes into Sources



←Sun



←Cosmology



←Atmosphere

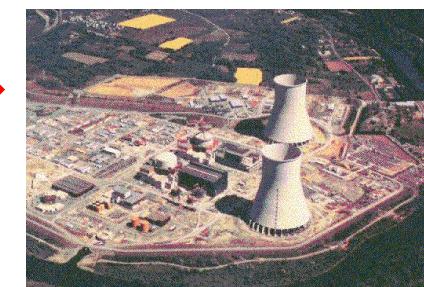


←Earth

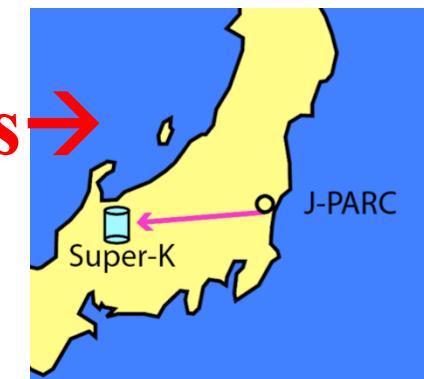
Astronomy: →
Supernovae
GRBs
UHE ν's



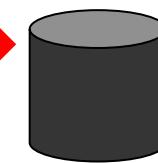
Reactors →



Accelerators →

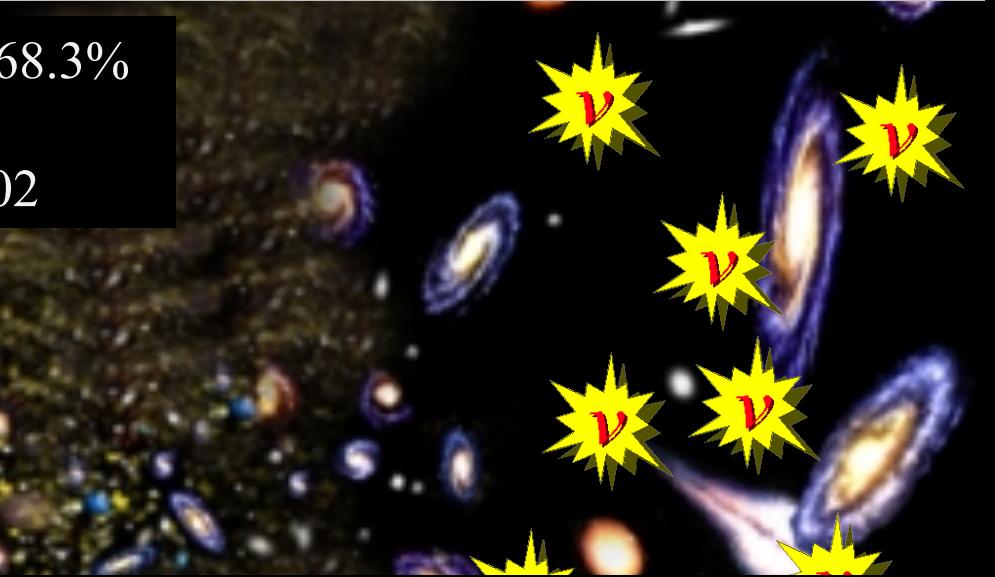
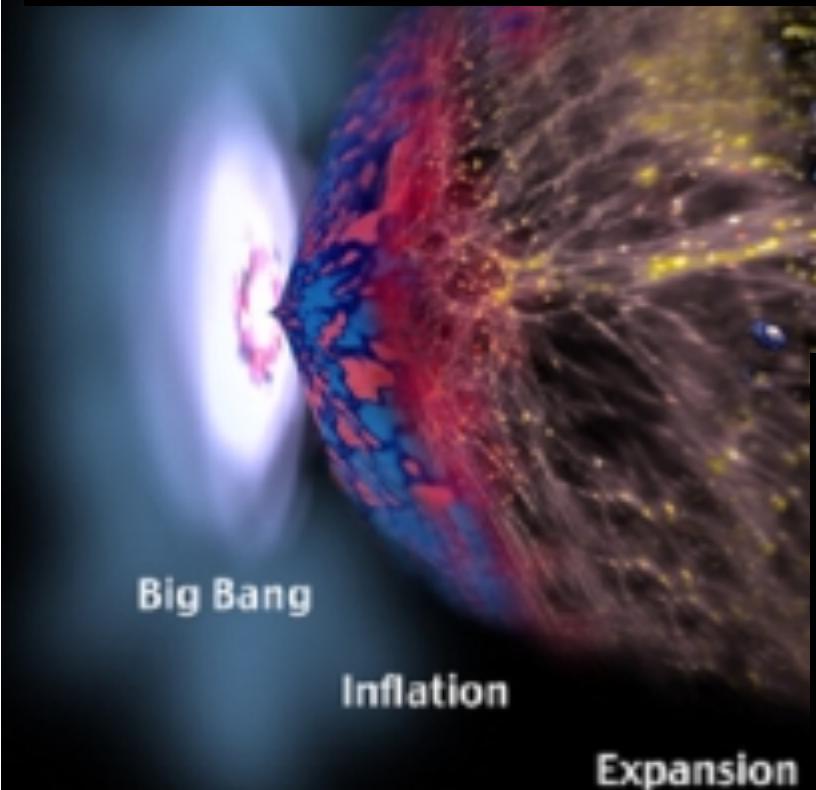


β-Sources →



Neutrinos & Cosmology

- Dark Matter $\sim 26.8\%$ & Dark Energy 68.3%
- baryonic matter $\Omega_B \sim 0.049$
- mass of all neutrinos: $0.001 \leq \Omega_\nu \leq 0.02$

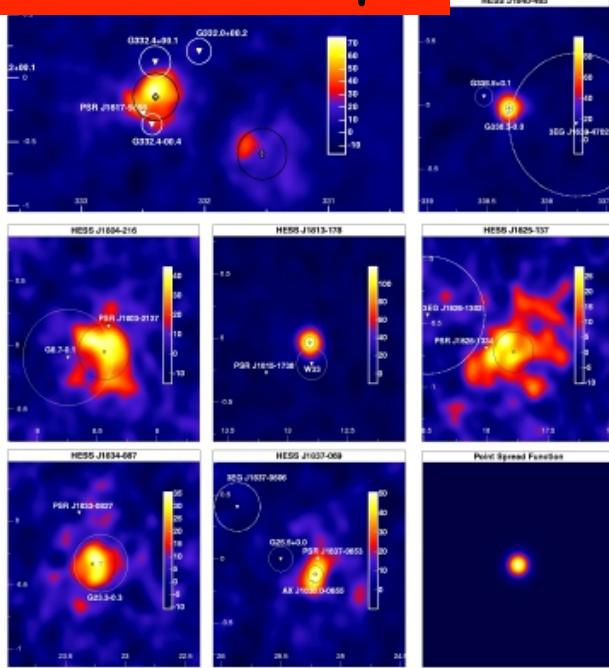


Comological impact of neutrinos:

- hot component in structure formation: $330\nu/\text{cm}^3 \times \text{mass} \rightarrow$ improved results for the sum of masses
 - Big Bang Nuklueosynthesis
 - Baryon asymmetry \rightarrow Leptogenesis?
 - ... many other topics
- \rightarrow how to measure the CvB !?

Neutrinos & TeV γ 's

HESS: TeV γ 's

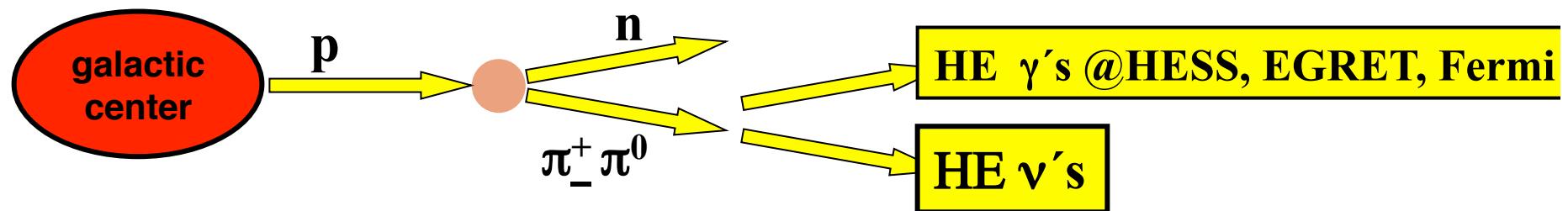


HESS and EGRET:

- TeV γ 's from galactic center and galactic plane
- various sources observed
- some are at the position of known SN remnants
- others do not correlate to anything known?

Plausible explanation:

- SN shock front acceleration
- γ 's from π^0 decay
 - ν flux from GC
 - ν signal @ km³ detectors



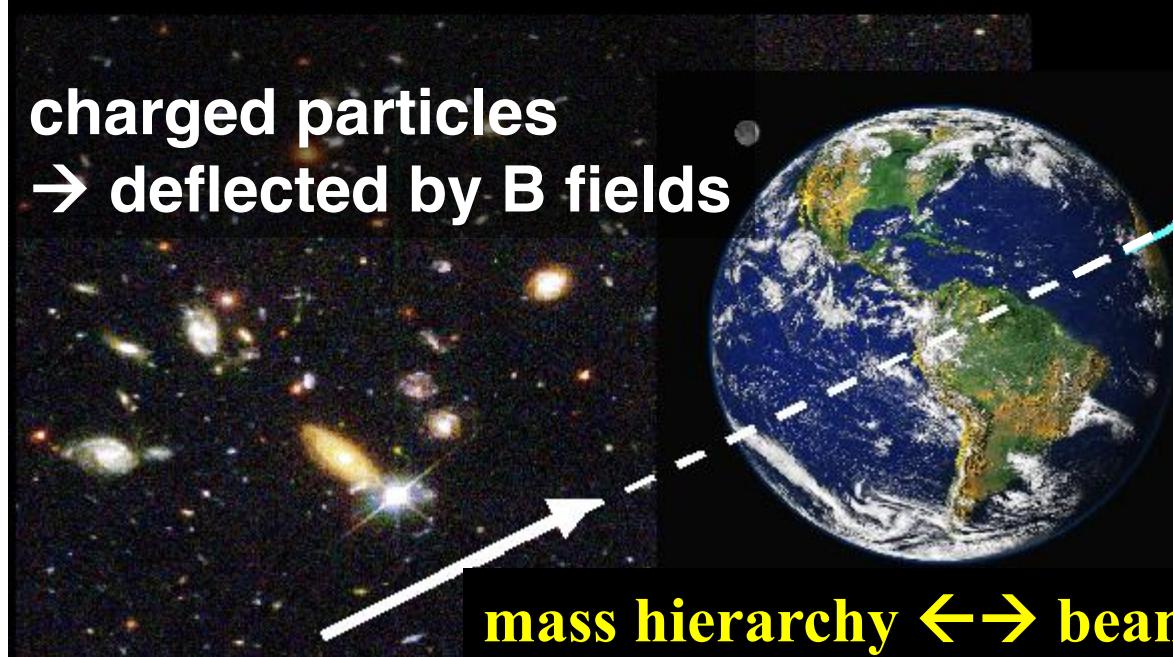
Neutrino Telescopes

ν astronomy \leftrightarrow cosmic neutrino sources

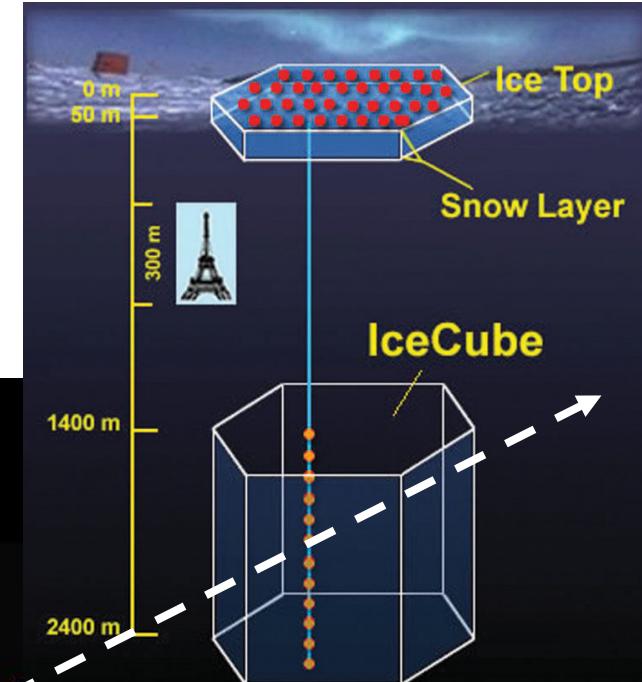
- AGN's
- black holes
- GZK cutoff
- ...

HE γ 's \rightarrow scatter of CMB

charged particles
 \rightarrow deflected by B fields



mass hierarchy \leftrightarrow beams, global optimization



Baikal, Amanda
IceCube, Antares,
DeepCore, PINGU,
ORCA, ..., Auger

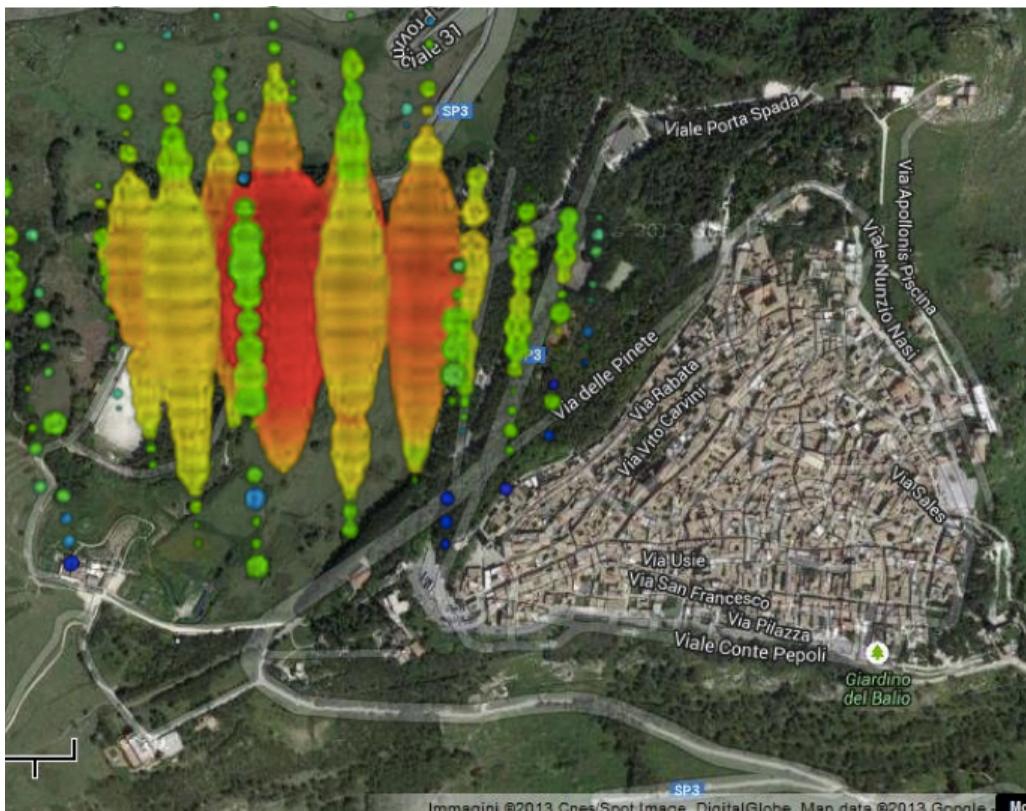
IceCube → PeV events observed

Run118545-Event6373366

NPE 6.9928×10^4

GMT time: 2011/8/8 12:23:18

$$1.1\text{PeV} = 1100000000 \text{ MeV}$$



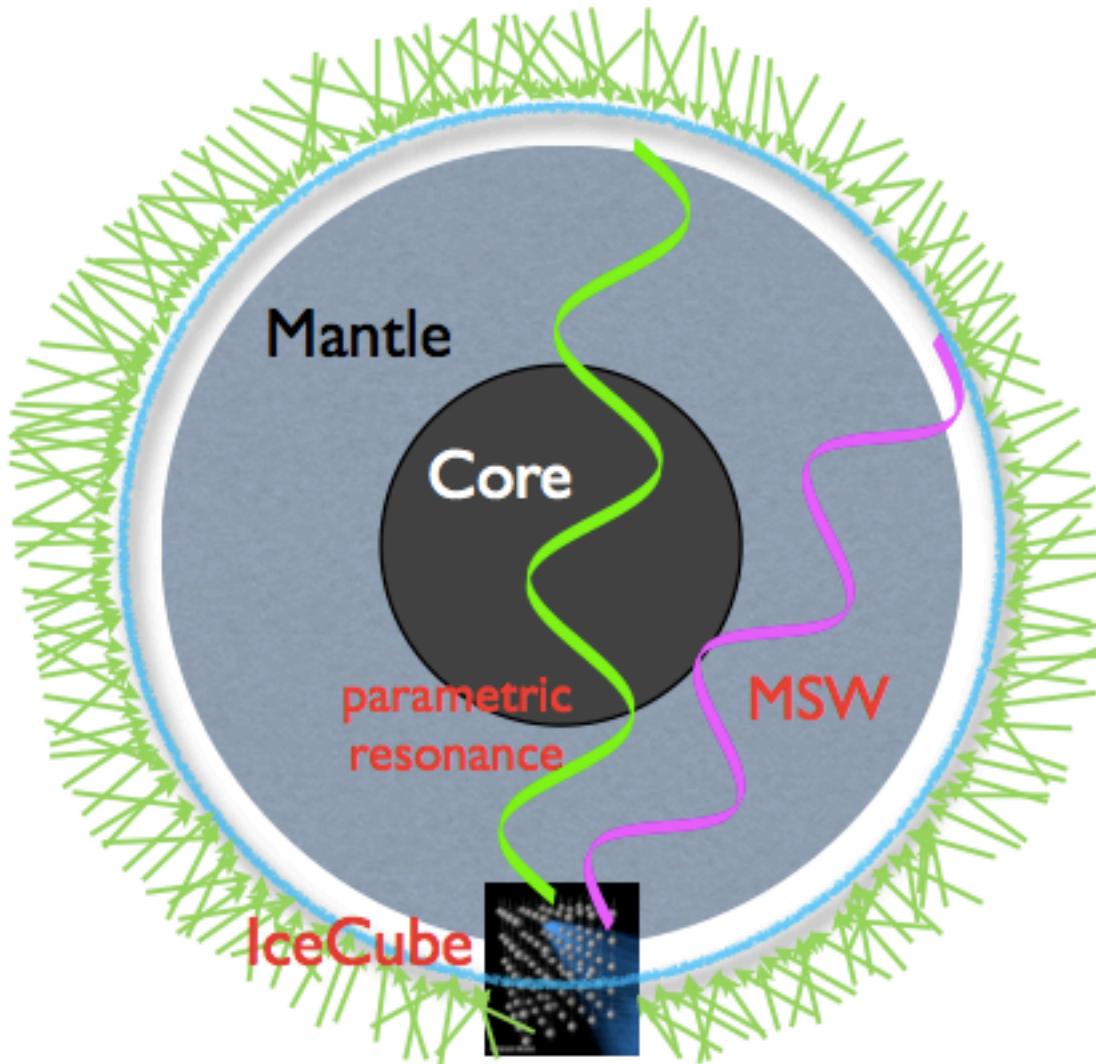
events in 2 years data:

- consistent with flavour ratio 1:1:1
 - more statistics
 - rate vs. WB bound?
 - start of ν -astronomy

atmospheric v background...

Atmospheric data and new physics:

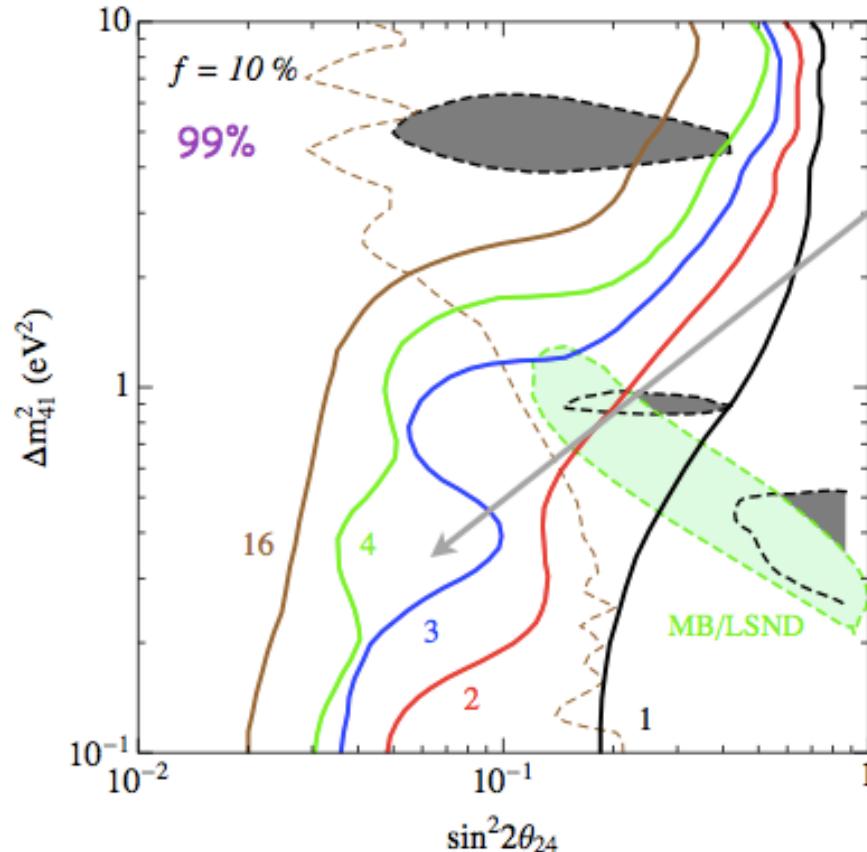
Impact of sterile neutrinos on atm ν flux



- eV mass gives resonant enhanced matter effects in the TeV region
H. Nunokawa, O. L. G. Peres,
R. Zukanovich-Funchal
Phys. Lett. B562 (2003) 279
- atmospheric neutrinos in IceCube

IceCube atmospheric ν's sensitivity to sterile neutrinos (3x IceCube-79 data are available)

A. E., A. Yu. Smirnov,
arXiv: 1307.6824



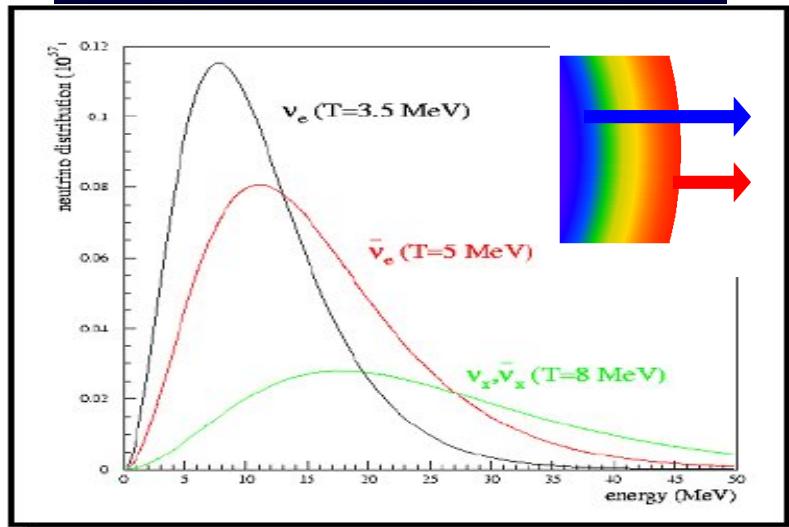
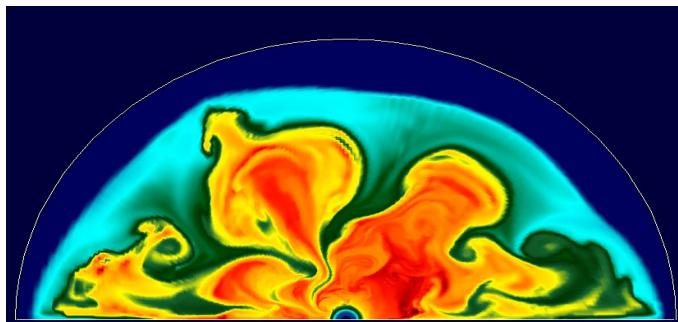
sensitivity significantly
enhanced by using energy
spectrum
(number of bins)

**IceCube can test the
LSND/MiniBooNE
“evidence”**

**It's on the tapes
→ when?**

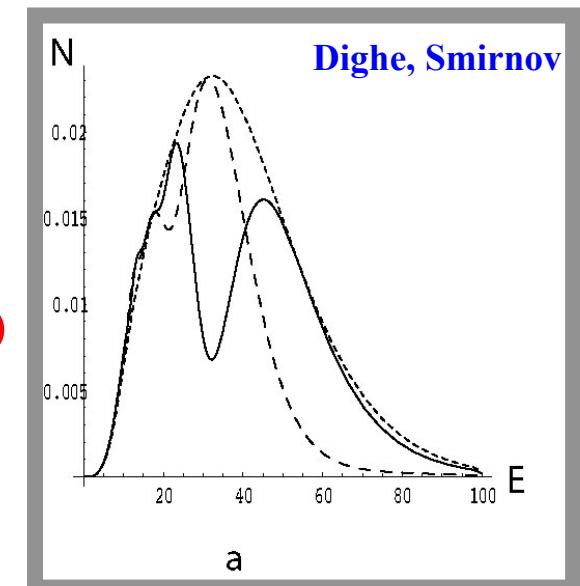
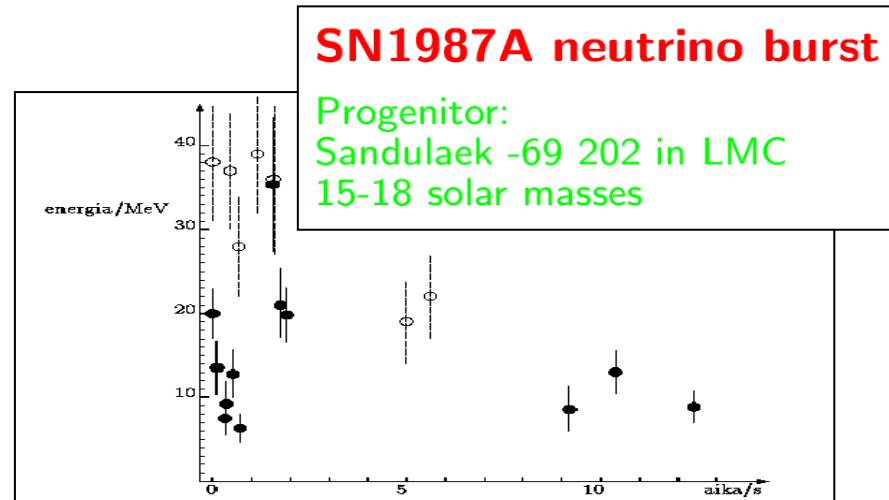
Supernova Neutrinos

- Collaps of a typical star $\rightarrow \sim 10^{57} \nu$'s
- ~99% of the energy in ν 's
- ν 's essential for explosion
- do simulations explode?
(1d \rightarrow 2d \rightarrow 3d \rightarrow convection...)



MSW: SN & Earth

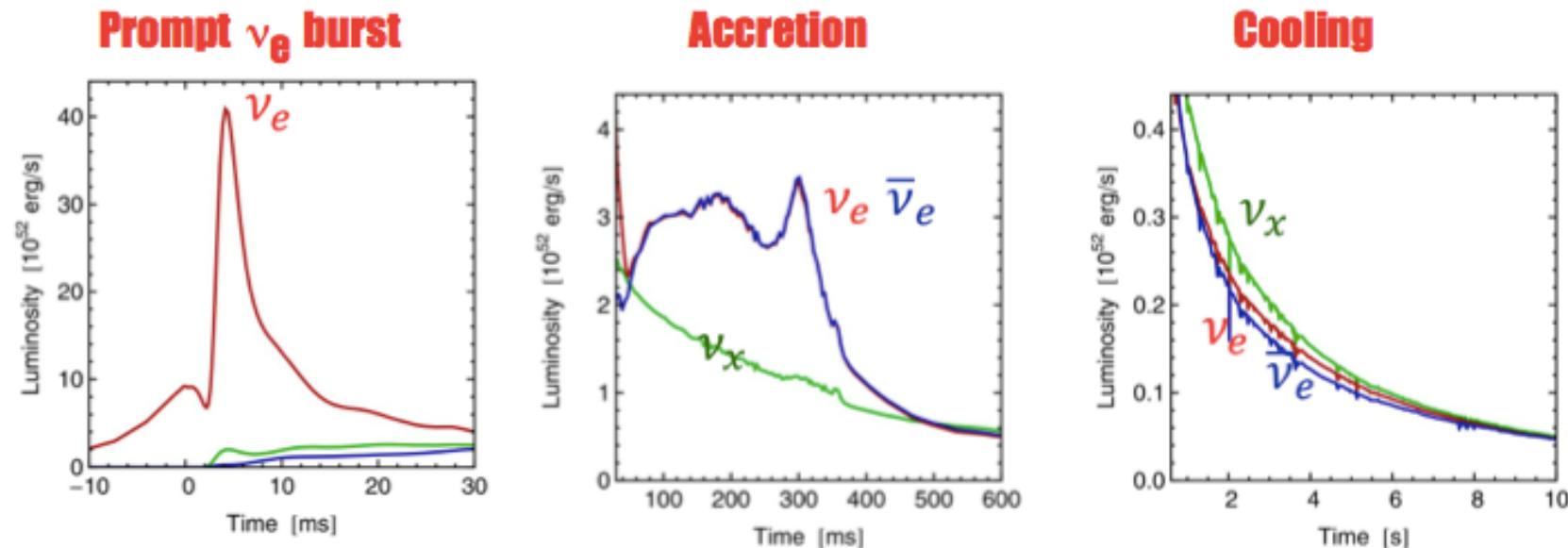
sensitive to $\text{sgn}(\Delta m^2)$



Understanding Supernovae

neutrino spectrum:

e.g. Fisher et al.

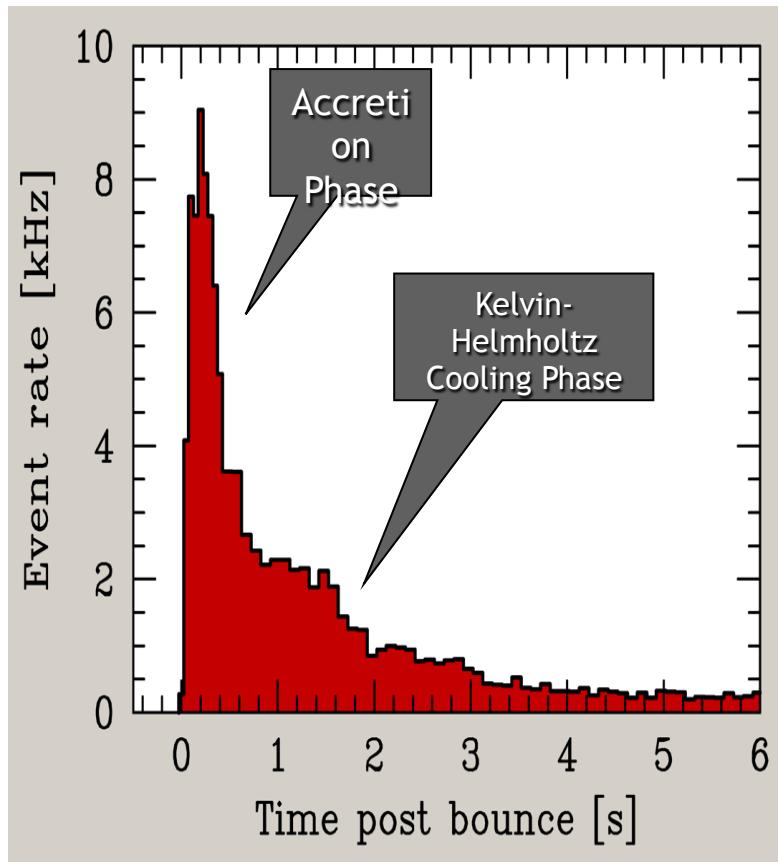


many other details: important & complex

- neutrino spectrum
- light emission
- processes
- ejected material
- gravitational waves

improved ν -nucleus x-sections
impact on dynamics and BBN

Simulated Supernova Signals



**Simulation for Super-Kamiokande
SN@10kpc**

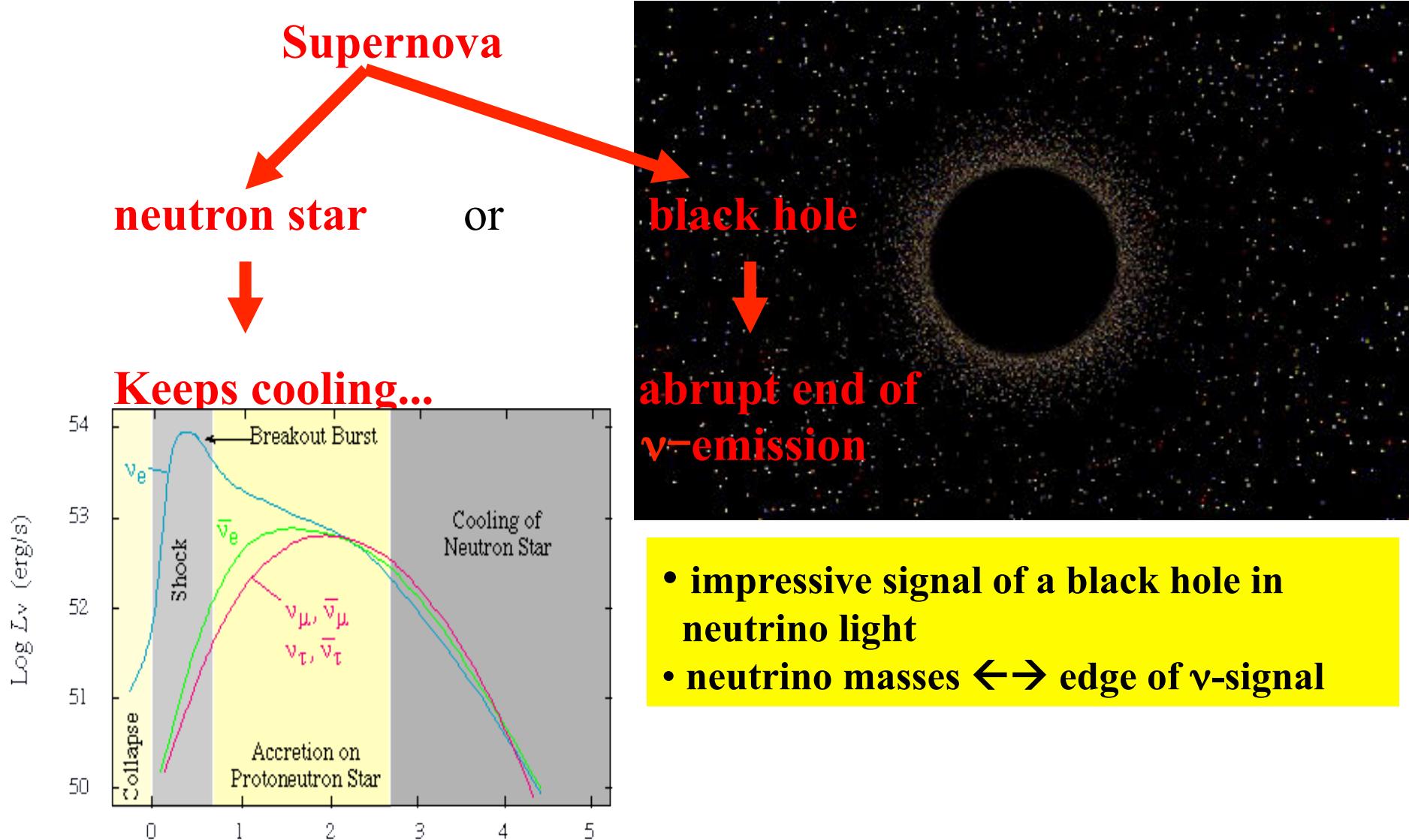
Totani, Sato, Dalhed, Wilson

| Detector | Type | Mass (kt) | Location | Events | Live period |
|----------------------|-------------|-----------|------------|---------|--------------|
| Baksan | C_nH_{2n} | 0.33 | Caucasus | 50 | 1980-present |
| LVD | C_nH_{2n} | 1 | Italy | 300 | 1992-present |
| Super-Kamiokande | H_2O | 32 | Japan | 7,000 | 1996-present |
| KamLAND | C_nH_{2n} | 1 | Japan | 300 | 2002-present |
| MiniBooNE* | C_nH_{2n} | 0.7 | USA | 200 | 2002-present |
| Borexino | C_nH_{2n} | 0.3 | Italy | 100 | 2005-present |
| IceCube | Long string | 0.6/PMT | South Pole | N/A | 2007-present |
| Icarus | Ar | 0.6 | Italy | 60 | Near future |
| HALO | Pb | 0.08 | Canada | 30 | Near future |
| SNO+ | C_nH_{2n} | 0.8 | Canada | 300 | Near future |
| MicroBooNE* | Ar | 0.17 | USA | 17 | Near future |
| NO _ν A* | C_nH_{2n} | 15 | USA | 4,000 | Near future |
| LBNE liquid argon | Ar | 34 | USA | 3,000 | Future |
| LBNE water Cherenkov | H_2O | 200 | USA | 44,000 | Proposed |
| MEMPHYS | H_2O | 440 | Europe | 88,000 | Future |
| Hyper-Kamiokande | H_2O | 540 | Japan | 110,000 | Future |
| LENA | C_nH_{2n} | 50 | Europe | 15,000 | Future |
| GLACIER | Ar | 100 | Europe | 9,000 | Future |

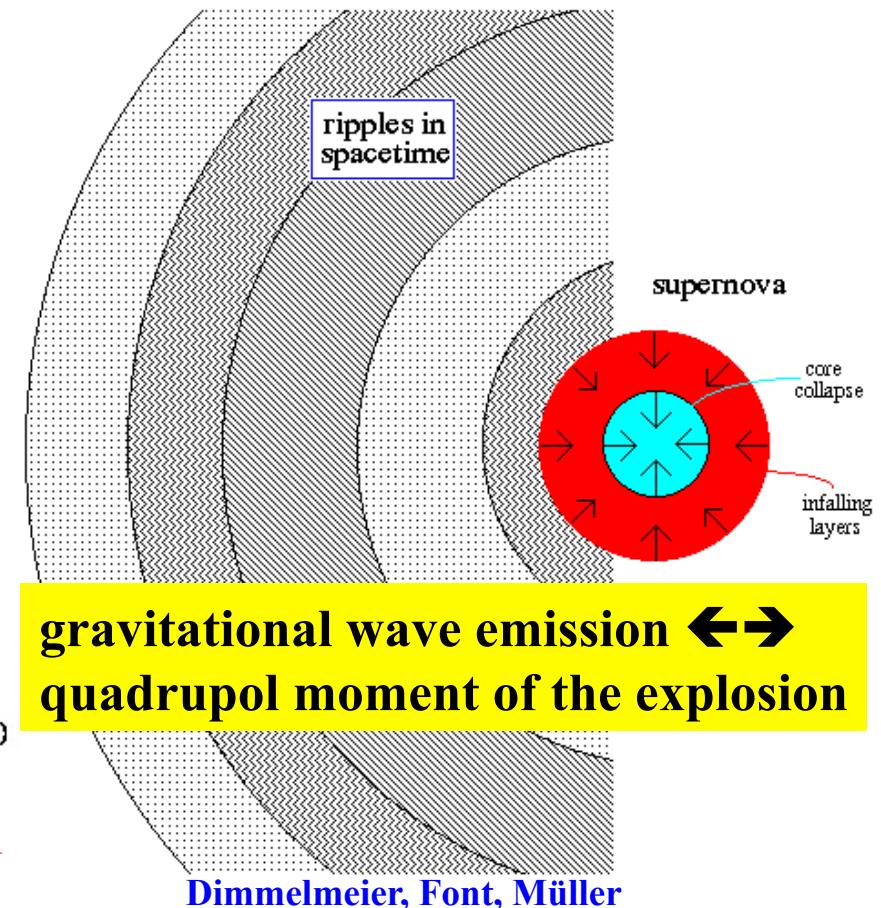
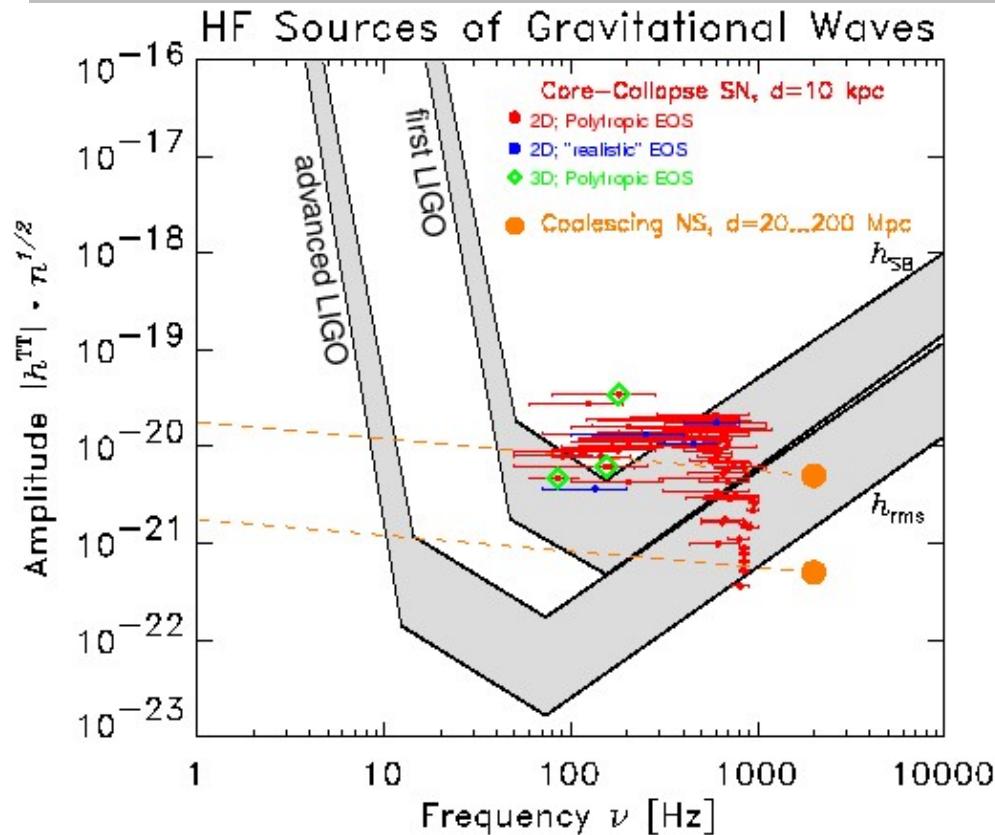
compilation by K. Scholberg

Problem: Rate – 1-3 SN per century / galaxy → bigger?

2 possibilities:



Supernovae & Gravitational Waves



- additional information about galactic SN
 - global fits: optical + neutrinos + gravitational waves
 - neutrino properties + SN explosion dynamics
 - SN1987A: strongest constraints on large extra dimensions
- further topics: failed supernovae, hidden SN , ν self-interactions (split, coherence)

Summary

Neutrino physics was and is a hot field!

- Diverse sources in labs, astrophysics & cosmology
 - Interesting results fit into 3-neutrino framework → CP, MH, m_1 ,
 - watch carefully if 3ν framework is enough
 - good reasons for more... → over-constrain & precision
 - **Neutrinos are unique probes: SN, reactors, sun, ...**
 - **Other hot and partially connected topics: Dark matter, Proton decay, LFV, ...**
 - **Even more topics:** ν magnetic moments, absolute
 ν masses, cosmological relic neutrinos, coherent scattering, de-coherence,
...
- Many ways to spend resources on big projects....

Personal Comments

We do big projects due to lack of competitive table-top ideas

Sociology: Road maps, funding opportunities, ... , politics
→ dangerous route, since we will get stalled at some level!

- 1) coordinate mega-projects (road maps etc.)
- 2) keep competition of medium size projects (proven, training of young people, attractiveness, diversity, ...)
- 3) AND: More R&D (new methods) while we do big projects
realism: only a few of many new ideas will work
→ sufficiently broad R&D = risky → needs to be protected

→ a reasonable fraction of the funding must be kept for smaller projects and also for R&D activities for the future

Thank you!