Outlook

Manfred Lindner

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

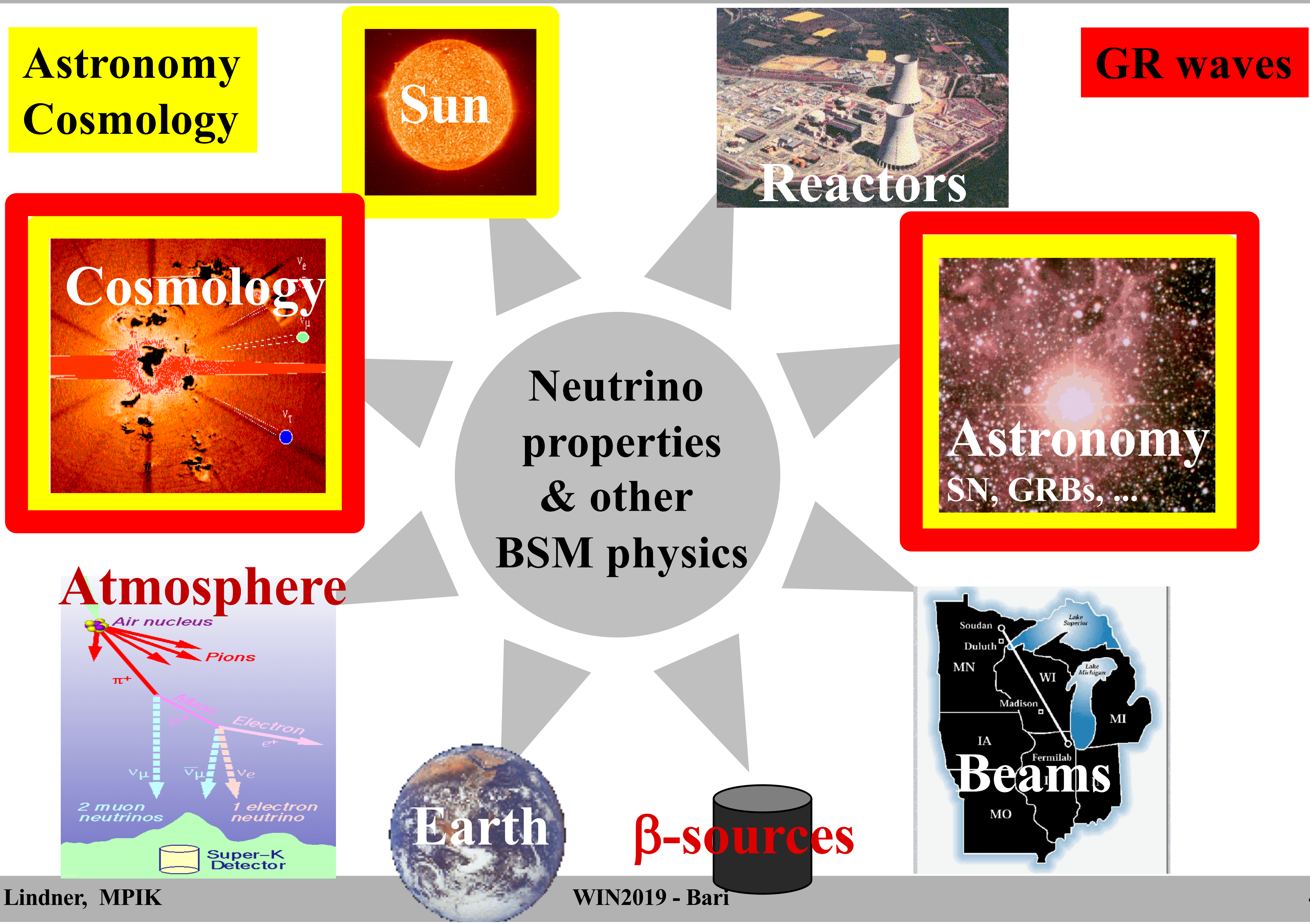
WEAK INTERACTIONS AND NEUTRINOS
2019
BARI ITALY


START

Outline

- **Neutrinos**
  - A little advertisement break
- **Dark Matter**
- **Beyond the Standard Model**
- **Other**

Neutrinos



Astronomy
Cosmology
Sun
Reactors
GR waves
Cosmology
ν_e
ν_μ
ν_τ
Neutrino
properties
& other
BSM physics
Astronomy
SN, GRBs, ...
Atmosphere
Air nucleus
Pions
π^+
Muon
Electron
e^+
ν_μ
$\bar{\nu}_\mu$
ν_e
2 muon neutrinos
1 electron neutrino
Super–K Detector
Earth
β-sources
Soudan
Duluth
MN
WI
Madison
MI
IA
Fermilab
MO
Lake Superior
Lake Michigan
Beams

Directions in Neutrino Physics

- How many neutrinos?
  - 3 massive ν's
    - precision flavor physics: θ_{ij}, δ ➔ origin of flavour
    - more BSM: origin of fermion masses, EW symmetry breaking, L-genesis,…
  - More states: sterile ν's
    - >3 flavours, unitarity
    - keV ν' as warm DM
    - BSM: like 3ν plus many more…

The Standard 3 Neutrino Framework

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

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

Questions = the default program:

➔ Dirac / Majorana

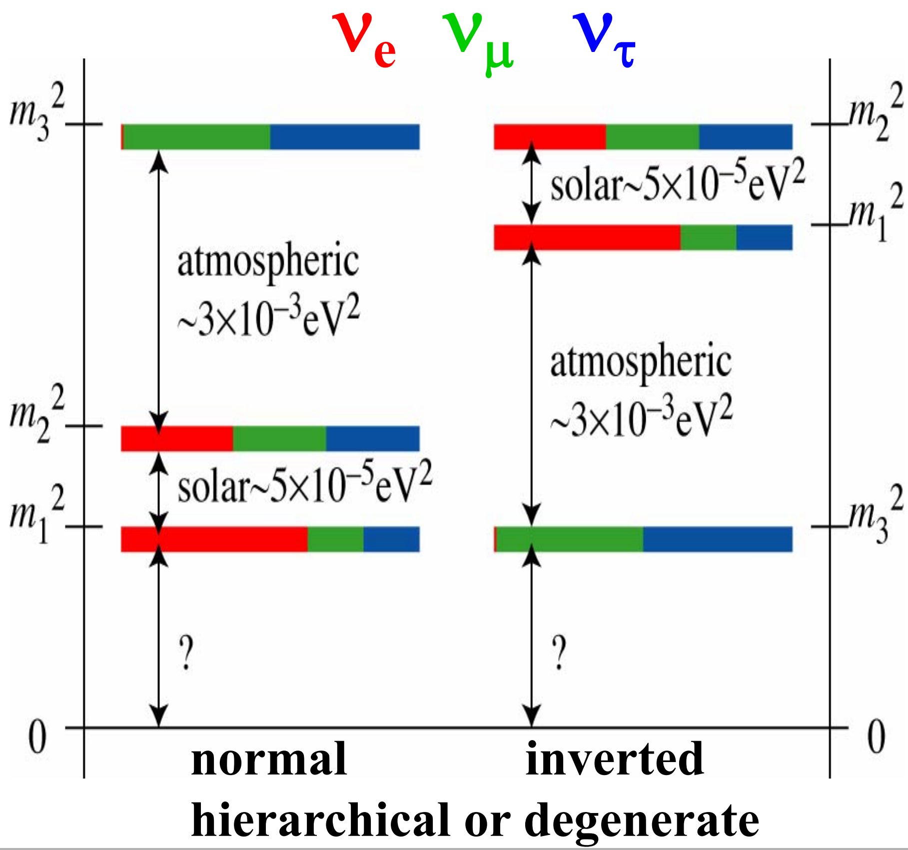
➔ overall mass scale: m_1

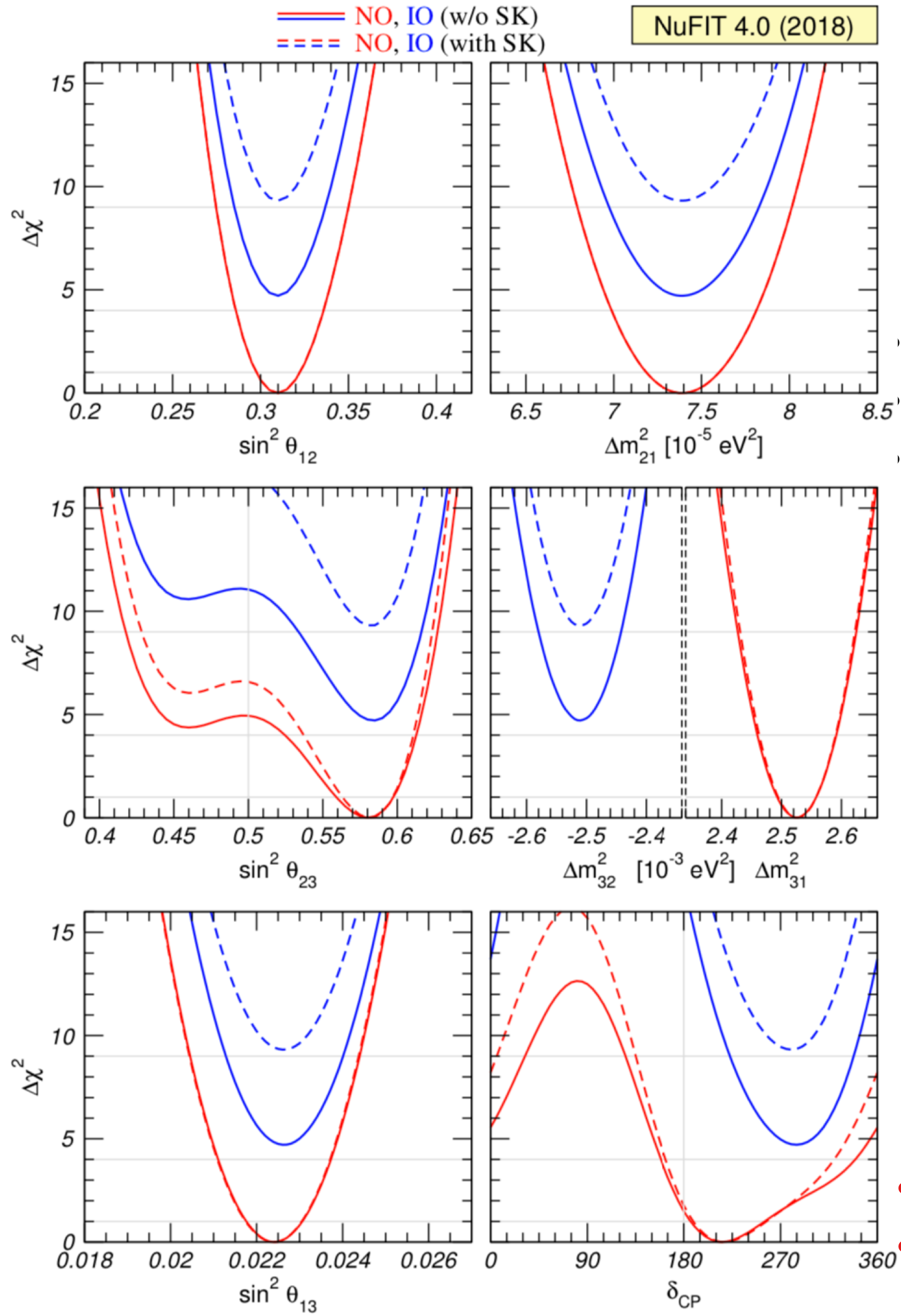
➔ mass ordering: sgn(Δm^2_{31})

➔ θ_{23} maximal?

➔ leptonic CP violation

➔ **Warning: The picture may be INCOMPLETE!**



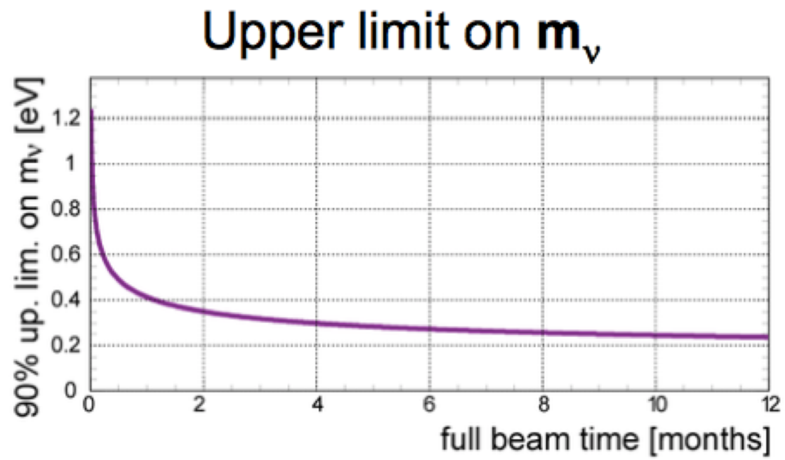


The Parameters (3f)

← **Esteban, Gonzalez-Garcia, Hernandez-Cabezudo, Maltoni, Schwetz**

- **Absolute limits (Mainz, Troitsk: $m_1 < 2.2$ eV**
- **Limits from cosmology: 0.14-0.2 eV**
- **Future:**

KATRIN ➔ started operation ➔ 0.2eV

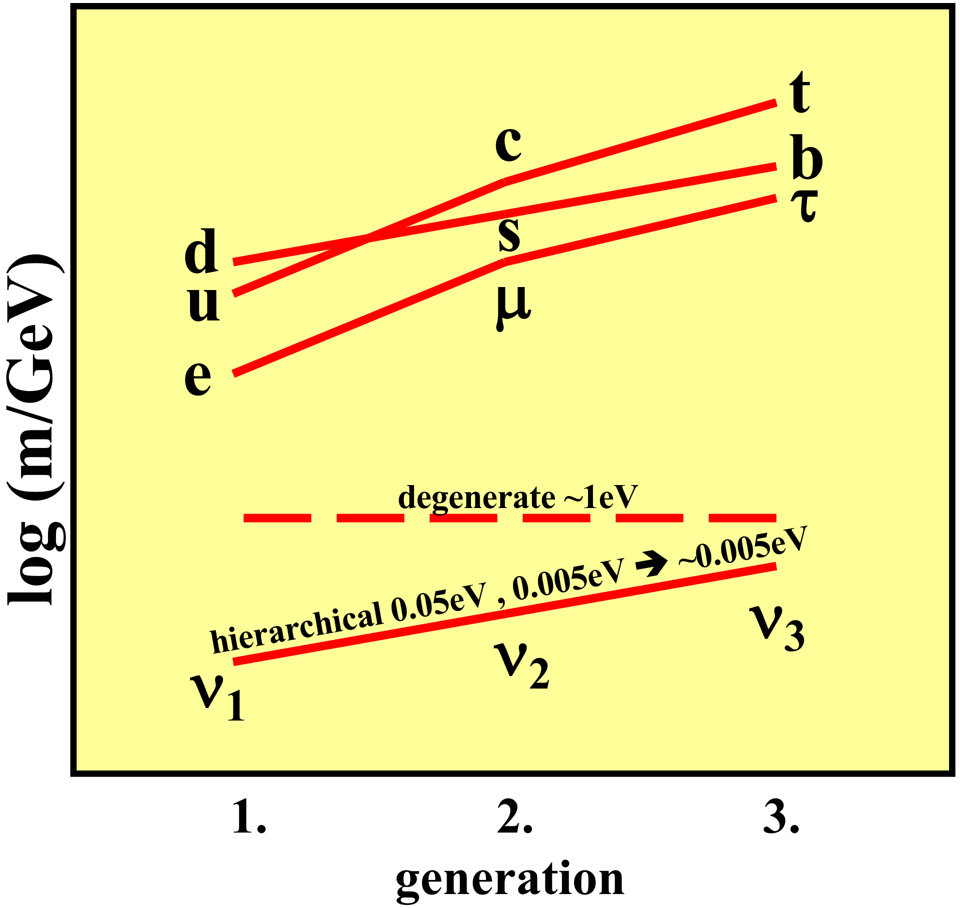


Project8, …

- **Both T2K and NOvA prefer NO individually**
- **Inclusion of the atmospheric neutrino results further increases Δχ2 of IO to the 3σ level.**

Empirical Observations

Quarks & charged leptons ➔ hierarchical masses ➔ neutrinos?



Quarks and charged leptons:

$m_D \sim H^n$; $n = 0,1,2$ ➔ $H \geq 20...200$

Neutrinos: $m_\nu \sim H^n$ ➔ $H \leq \sim 10$

See-saw:

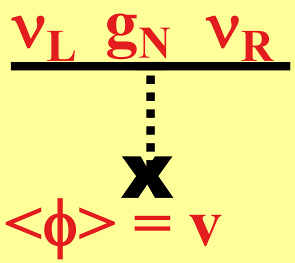
$$m_\nu = -m_D^T M_R^{-1} m_D$$

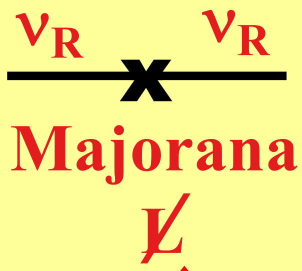
	m_ν	m_D^T	M_R^{-1}	m_D
H	$\simeq 10$	≥ 20	?	≥ 20

- **less hierarchy in m_D or correlated hierarchy in M_R ? ➔ theoretically connected!**
- **mixing patterns: not generically large, why almost maximal and θ_{13} small?**

Neutrino Masses: New Physics...

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





→

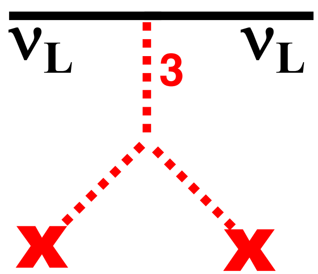
$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

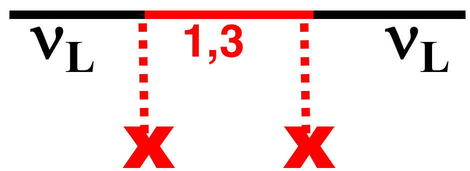
like quarks and charged leptons → Dirac mass terms (including NMS mixing)

+9+ new ingredients: → SM+
1) Majorana mass = scales
2) lepton number violation

6x6 block mass matrix
block diagonalization
M_R heavy → 3 light ν's

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





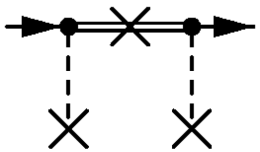
→ left-handed Majorana mass term: → $M_L L L^c$

Both ν_R and new singlets / triplets:

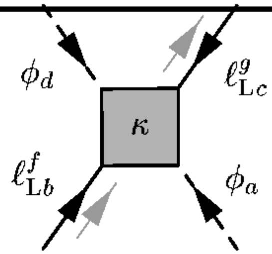
➔ see-saw type II, III

$$m_\nu = M_L - m_D M_R^{-1} m_D^T$$

Higher dimensional operators: d=5, …



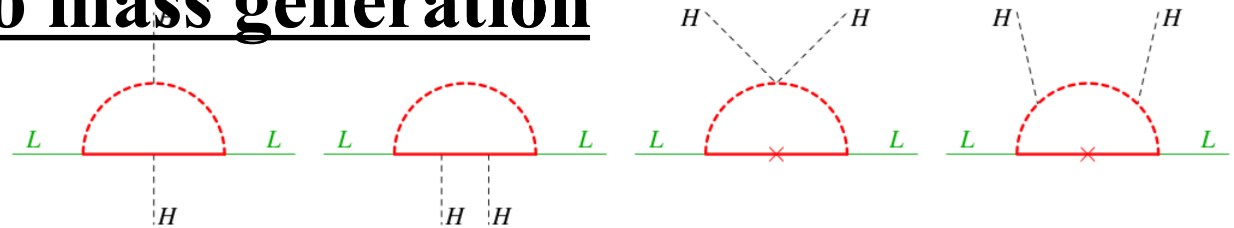
$\Rightarrow$



$\Leftrightarrow$ $\mathcal{L}_{mass} = \kappa \cdot \overline{\nu}^C_L \nu_L \Phi^T \Phi$

➔ $M_L \overline{L} L^c$

Radiative neutrino mass generation



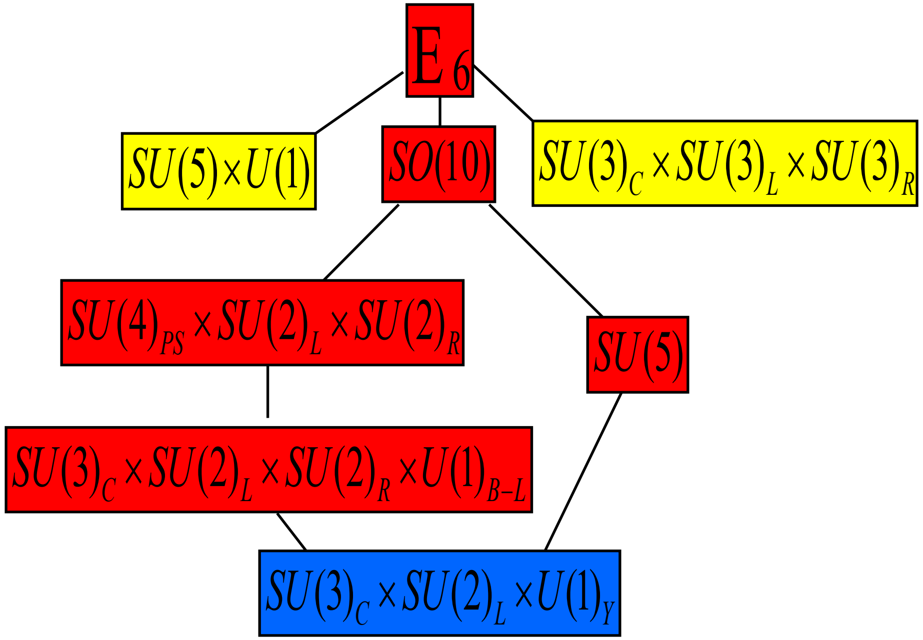
SUSY, extra dimensions, …

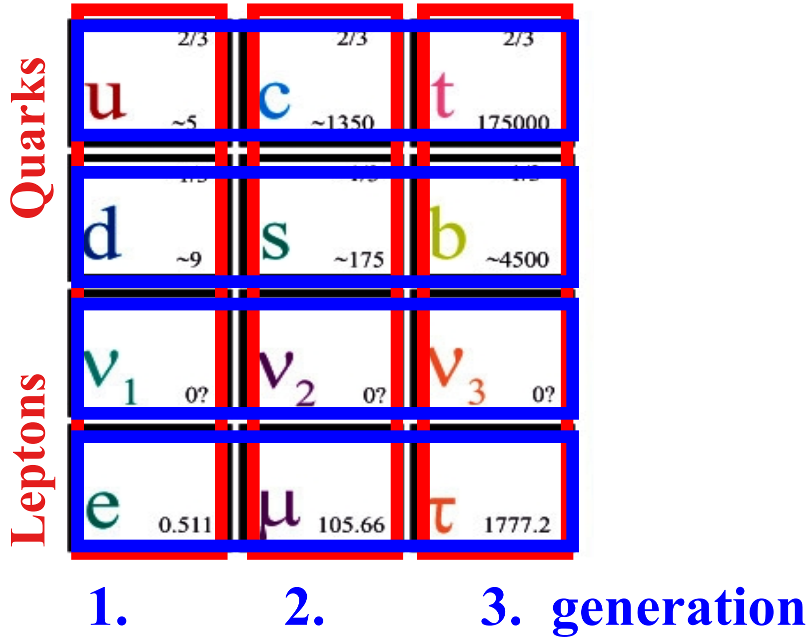
➔ Many routes to explain what we know: a few numbers…
two mass splittings, 3 mixing angles, ~ CP phase

Neutrinos as Probes of Flavour Models

Gauge unification suggests GUTs

- unified gauge group
- unified particle multiplets ⇔ ν_R
  - ➔ Q,L Yukawa couplings connected
  - ➔ proton decay , …
- generations are just copies





generations related by a symmetry?

- 3 generations ➔ representation
- regularities in masses and mixings
  - ➔ flavour symmetries: A4, S3, D5, T', ...

➔ predictions for each model

➔ test of models with precision ν-physics

➔ how precise: theory - experiment

Outlook for 3 massive Neutrinos

determine masses and mixings as precisely as possible

- oscillations
- absolute mass
- $0\nu\beta\beta$ – decay: Dirac or Majorana

➔ Current experiments...
➔ Next generations: DUNE, HyperK, JUNO, ...

Goal:

precise flavour information ←→ origin of mass/flavour?
lever arm to other new physics →!
learn about sources

Question: How much precision is needed to learn something about the origin of flavor and fermion masses?

Mass Models & Renormalization

low energies:
- **small masses**
- **large mixings**

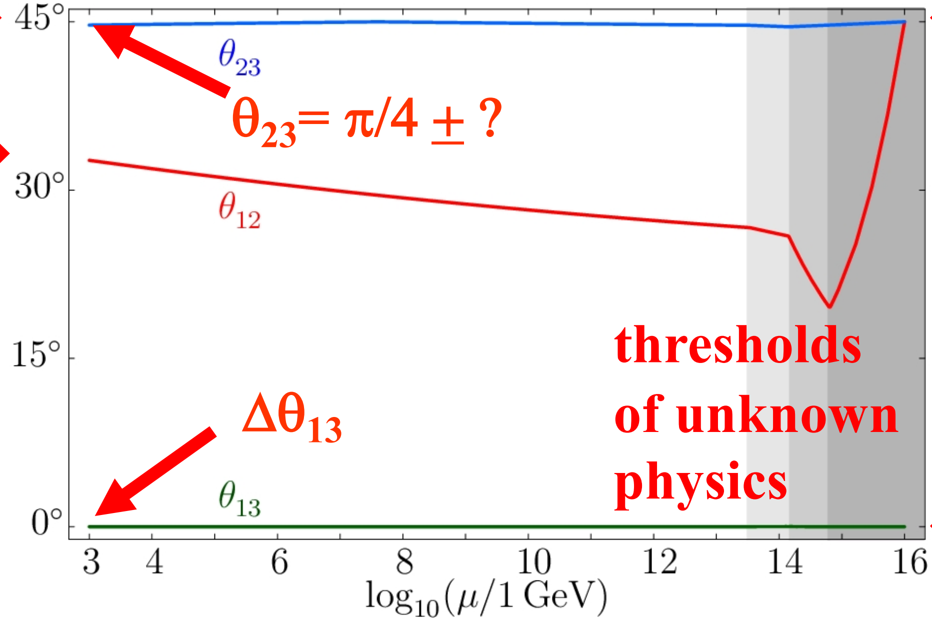
renormalization group revolution
←→ quantum effects

high energy theory:
- **mass models**
- **flavour-symmetries**
- **GUT-models, ...**

atmospheric →

solar →

reactor →



← bi-maximal

← small

MSSM example:
Antusch, Kersten, **ML**, Ratz

Outlook for >3 Neutrinos

Some options

- sterile neutrinos
- extra L-violation ⇐⇒ any one of them is a major discovery!
- NSIs
- large magnetic moments
- …

methods: precision for ➔ θ_{ij} , m_1, Δm_{ij}^2, MH, CP, $0\nu\beta\beta$, ...

➔ over-constraining the 3f picture

➔ test PMNS unitarity, L/E in osc. , new interactions,...

➔ Previous large scale experiments and overconstraining

➔ Dedicated projects with lower cost, but high potential

- examples: sterile neutrions, NSIs, ...

E.g. 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 ⟷ M_W)**

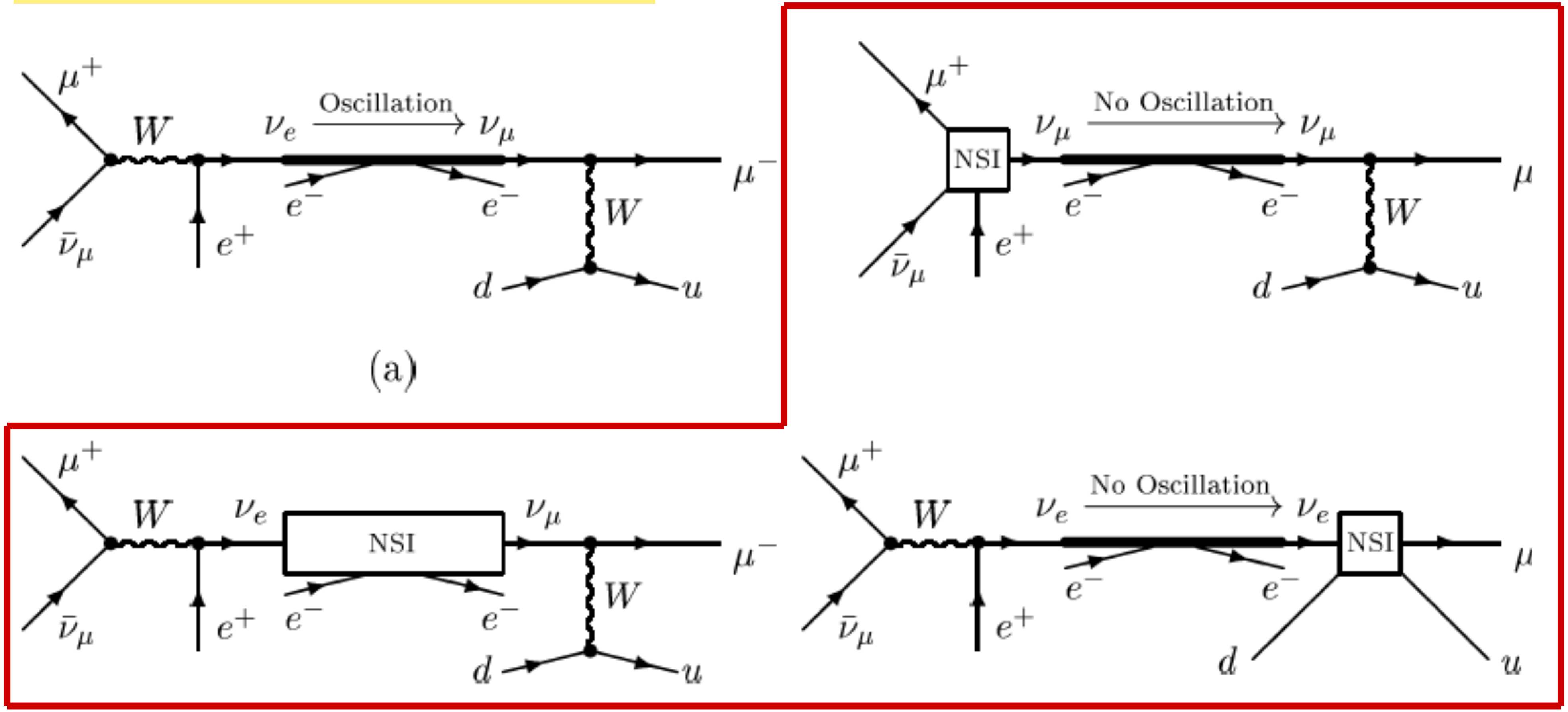
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

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, … many more…

NSIs interfere with Oscillations

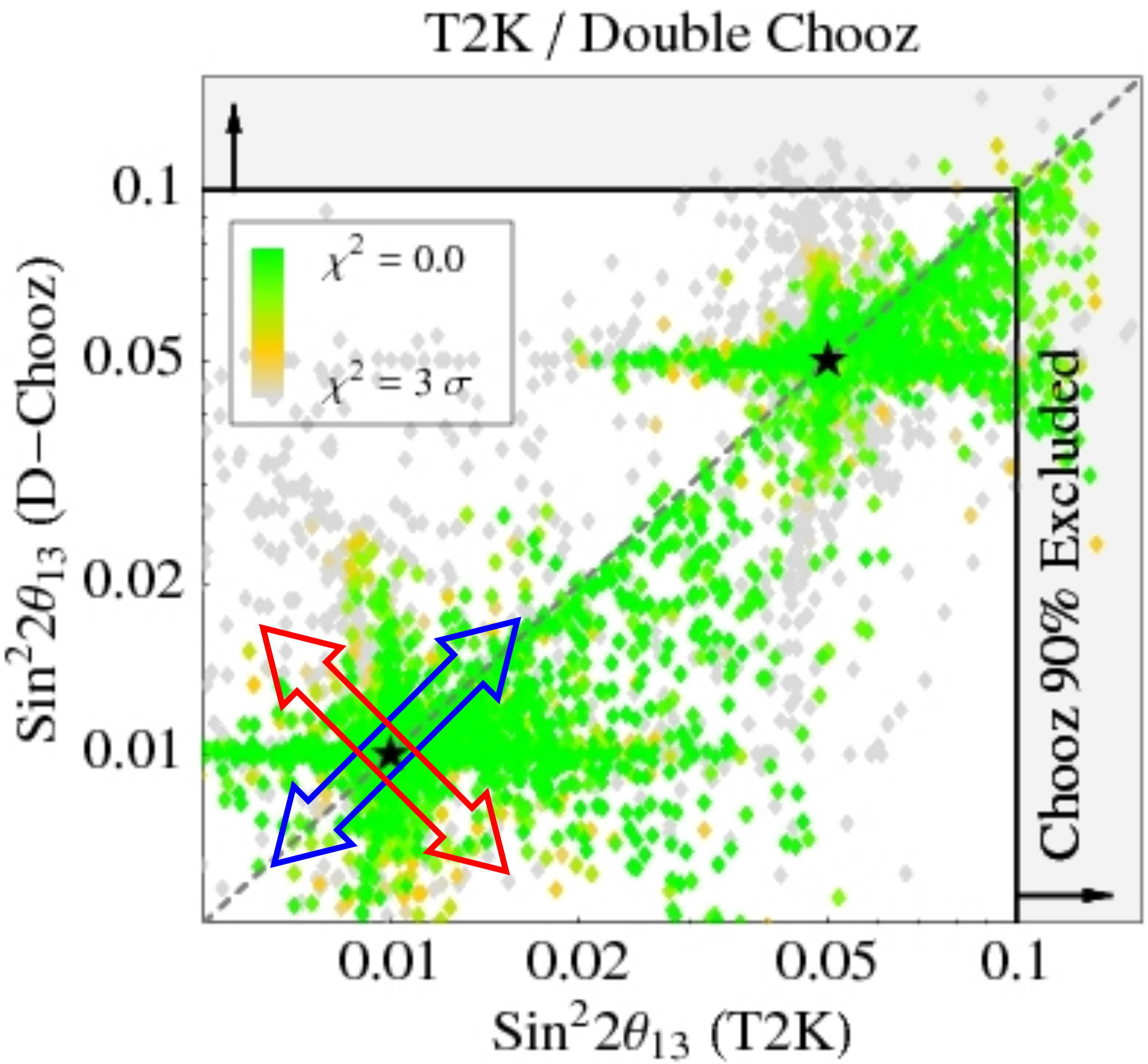
the "golden" oscillation channel

NSI contributions to the "golden" channel



<u>note:</u> interference in oscillations ~ε ⇔ FCNC effects ~ε²

NSI: Offset and Mismatch in θ_{13}



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**

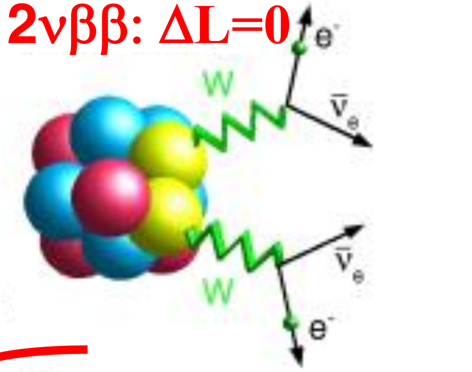
➔ **interesting potential**

➔ **over-constraining!**

Double Beta Decay & L-Violation

SM

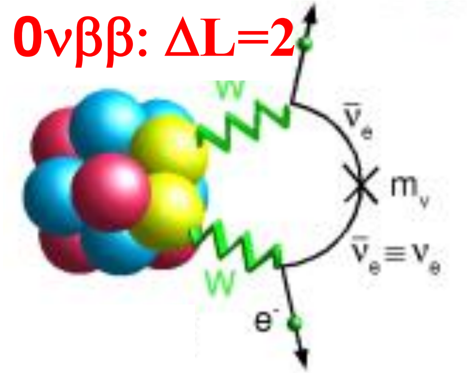
2νββ: ΔL=0



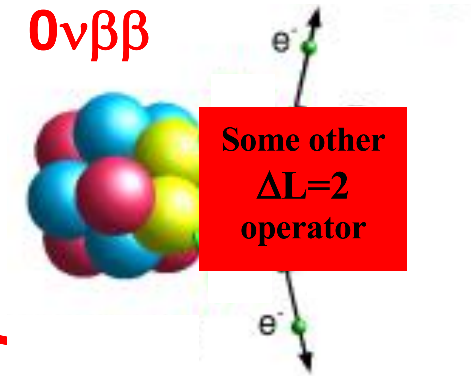
BSM

$T^{1/2} >$ $O(10^{25}y)$

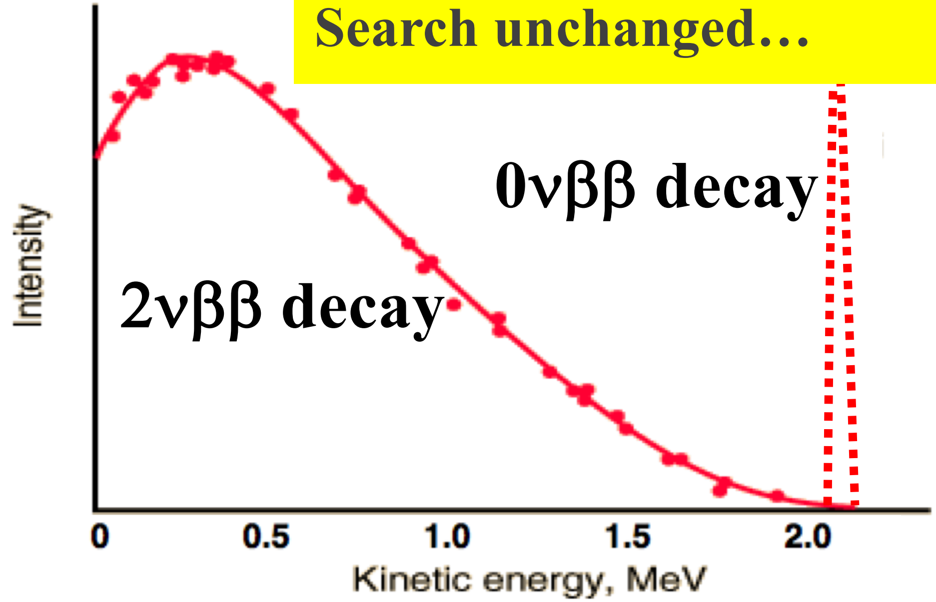
0νββ: ΔL=2



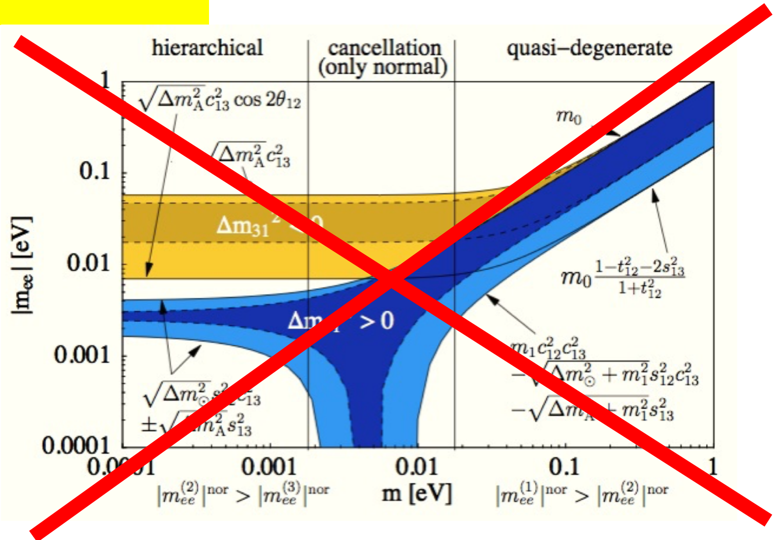
0νββ



Search unchanged…



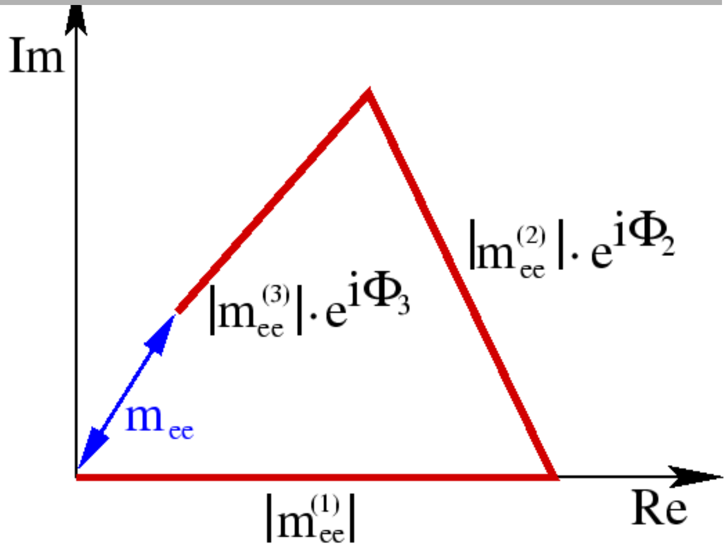
…interpretation:



m_{ee}: The Effective Neutrino Mass

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

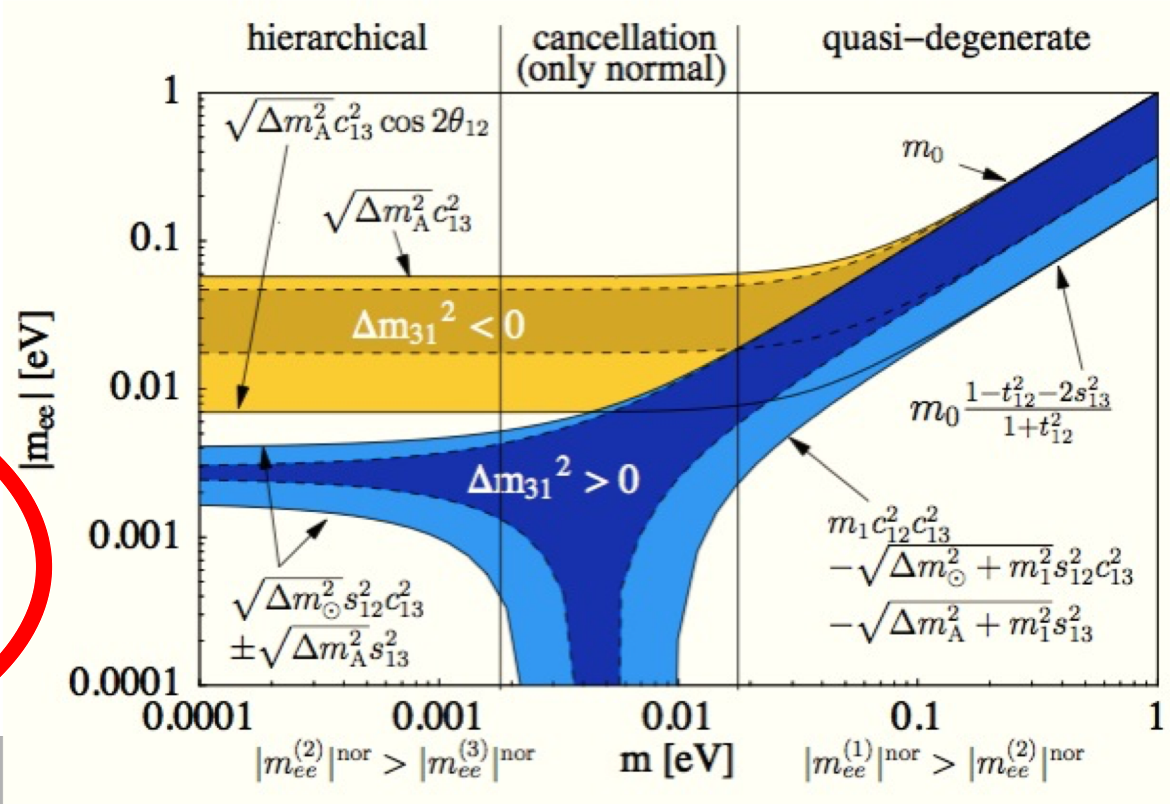
$$\begin{aligned} |m_{ee}^{(1)}| &= |U_{e1}|^2 m_1 \\ |m_{ee}^{(2)}| &= |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2} \\ |m_{ee}^{(3)}| &= |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2} \end{aligned}$$



0νββ by Majorana masses
→ limits on m_{ee}

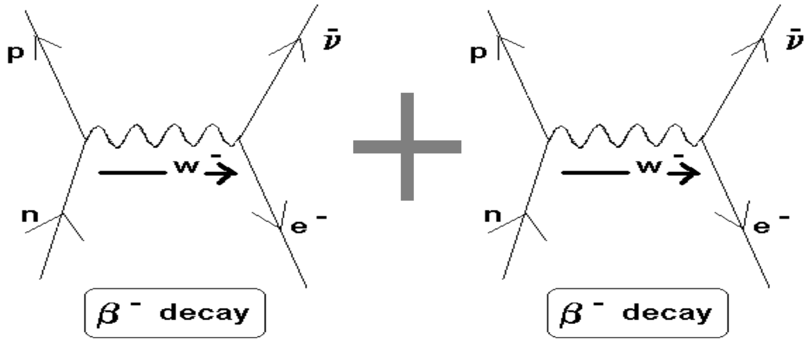
GERDA, EXO, KamLand-Zen, CUORE, ...

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



Double Beta Decay Processes

Standard Model:

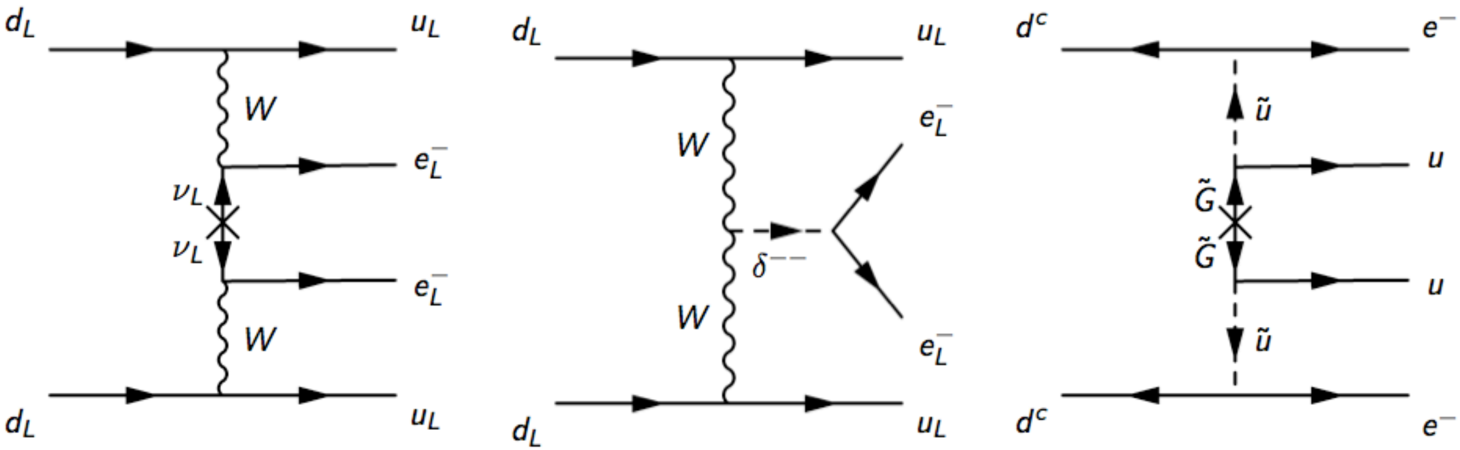


➔ 2 electrons + 2 neutrinos

2νββ

Majorana ν-masses or other ΔL=2 physics: ➔ 2 electrons

0νββ



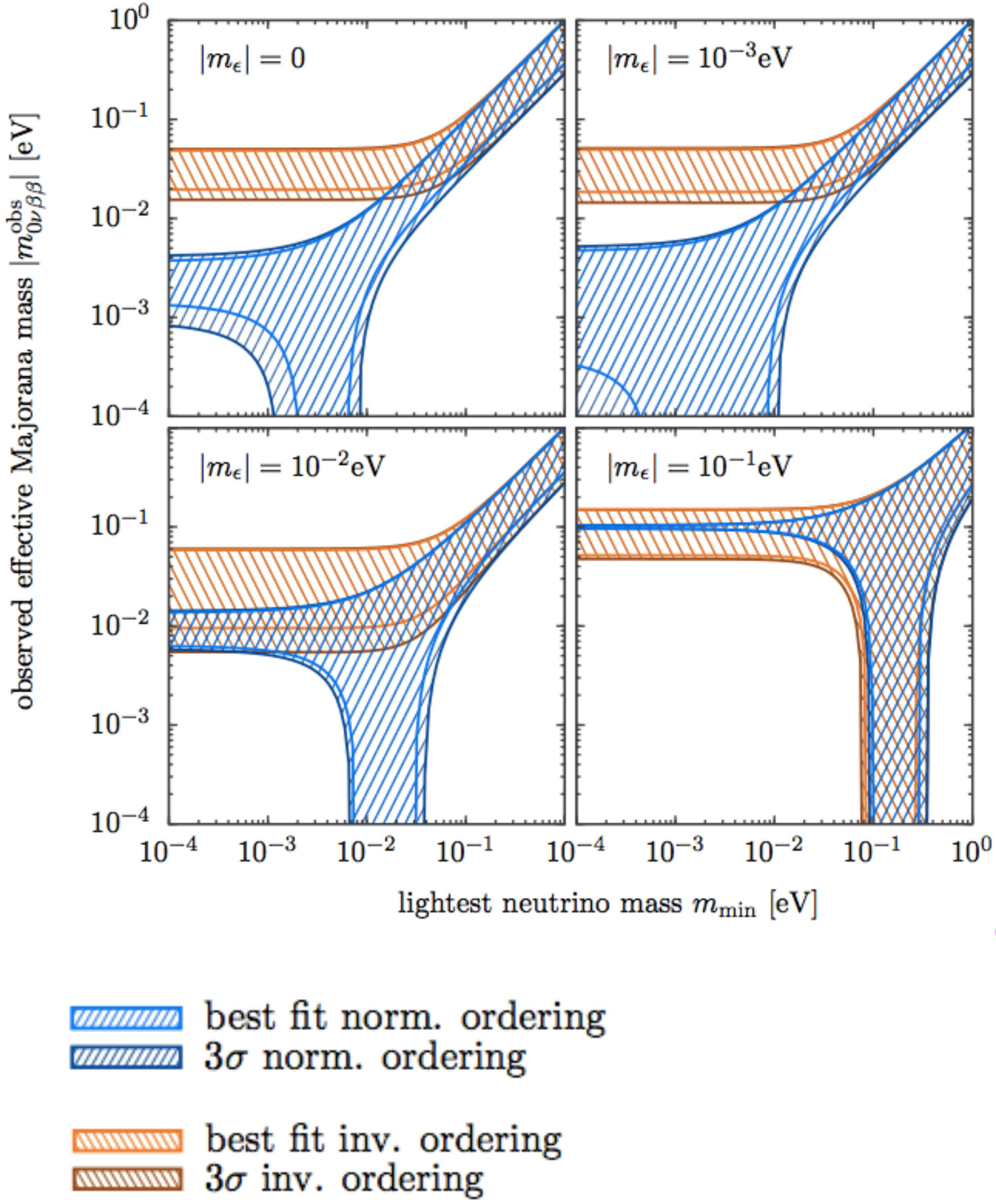
…

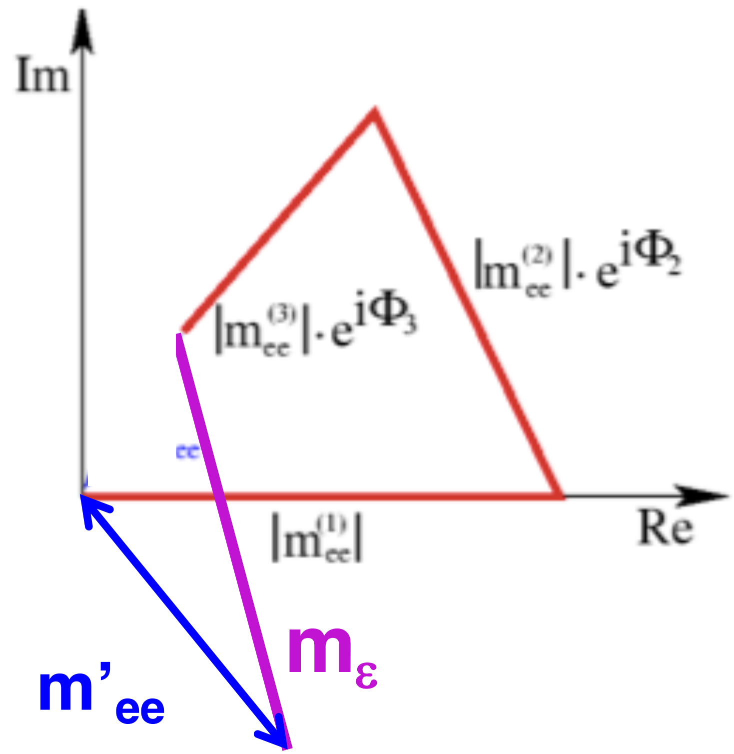
Majorana neutrino masses ←→ Dirac?

SM + Higgs triplet

e.g. SUSY

important connections to LHC and LFV …
sub eV Majorana mass ←→ TeV scale physics





interferences

growing m_ε for fixed $0\nu\beta\beta$

→ shifts of masses, mixings and CP phases

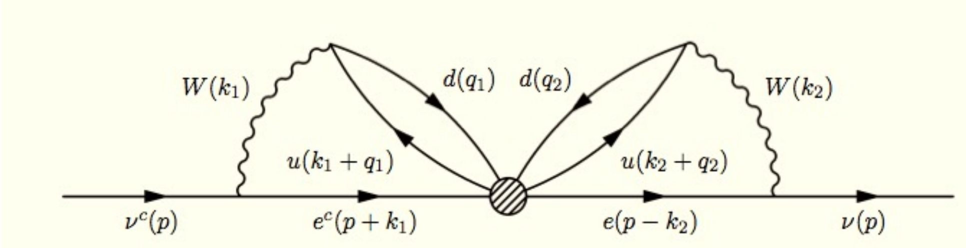
→ sensitivity to TeV physics

Does 0νββ Decay imply Majorana Masses?

- <u>Schechter-Valle Theorem</u> ➔ **is misleading**

  Any ΔL=2 operator which mediates the decay induces via loops Majorana mass terms ➔ unavoidable: Majorana neutrinos…!?

0νββ➔ some ΔL=2 operator



Dürr, ML, Merle

4 loops ➔ enforce $\delta m_\nu = 10^{-25}$ eV ➔ very tiny (academic interest)

➔ cannot explain observed ν masses and splitting's

Extreme possibility:

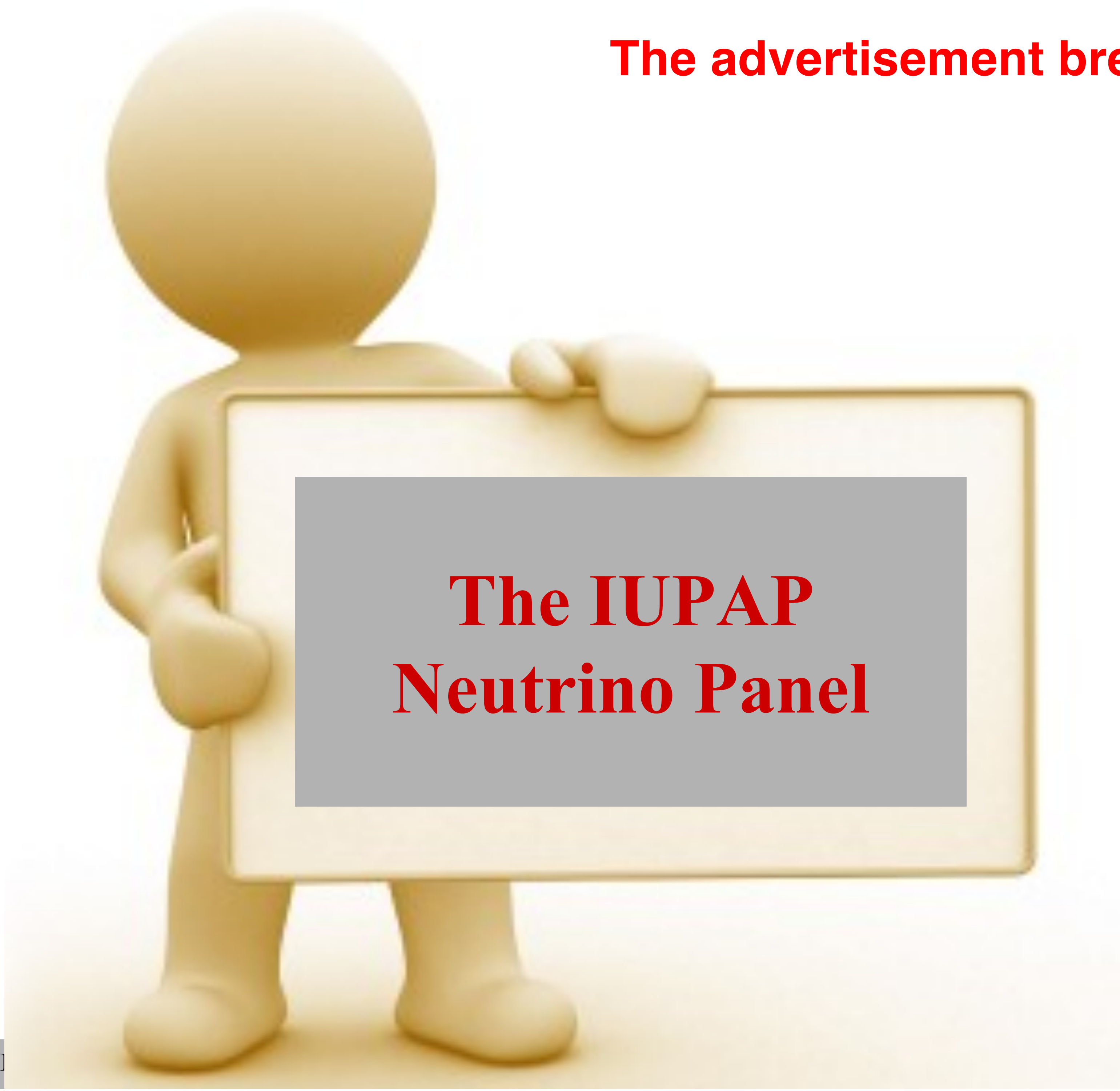
- 0νββ = L violation = other BSM physics
- neutrino masses = Dirac (plus very tiny Majorana corrections)

\+ Dirac leptogenesis, + ...

Observation of 0νββ ➔ L-violation ➔ Majorana neutrinos???

And don't forget: We may have to reach the normal hierarchy…!

The advertisement break



IUPAP has established the Neutrino Panel with the mandate:

"to promote international cooperation in the development of an experimental program to study the properties of neutrinos and to promote international collaboration in the development of future neutrino experiments to establish the properties of neutrinos."

➔ A scientifically driven balanced overview of opportunities, potential of new routes, synergies with other fields, risks and challenges.

Panel members:

M. Sajjad Athar	AMU, Aligarh, India
Steve Barwick	UCI Physics and Astronomy
Thomas Brunner	McGill University
Jun Cao	IHEP, Beijing
Mikhail Danilov	Lebedev Physical Inst., Russian Acad. of Sci.
Renata Zukanovich Funchal	University of São Paulo
Kunio Inoue	Tohoku University
Takaaki Kajita (+)	University of Tokyo
Marek Kowalski	DESY
Manfred Lindner (+)	Max Planck Institute for Nuclear Phys.
Ken Long	Imperial College, London
Nathalie Palanque-Delabrouille	CEA
Heidi Schellman	Oregon State University
Kate Scholberg	Duke University
Seon-Hee Seo	IBS, Center for Underground Physics
Nigel Smith (+)	SNOLAB
Walter Winter	DESY-Zeuthen
Sam Zeller	Fermilab

(+) Co-chairs

Objectives of the IUPAP Neutrino Panel

Through consultation with the broad neutrino-physics community the panel will carry out a review of:

a) The present status of the global neutrino physics programme and the development that can be expected on a 5 to 10-year timescale through a
➔ science driven white paper

b) R&D measures (including software development) that are required for the near-term (<10-year) and medium- to long-term (10-25-year) program to fulfil their potential

The Panel will identify opportunities within neutrino physics, mutual benefits of global connections within neutrino physics and other fields, as well as the synergies of an international programme

- **report to C11 Commission of IUPAP**
- **final report to the IUPAP General Council by October 2020**

➔ Invitation to the community

Dark Matter: A long List of Evidences…

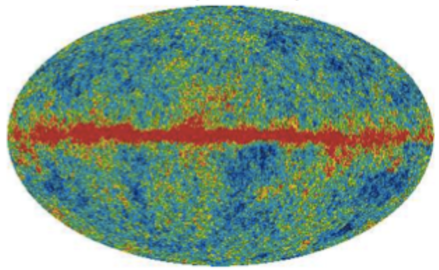
+ Galactic rotation curves
+ Galaxy clusters & GR lensing
+ Bullet Cluster
+ Velocity dispersions of galaxies
+ Cosmic microwave background
+ Sky Surveys and Baryon Acoustic Oscillations
+ Type Ia supernovae distance measurements
+ Big Bang Nucleosynthesis (BBN)
+ Lyman-alpha forest
+ Structure formation
+ …

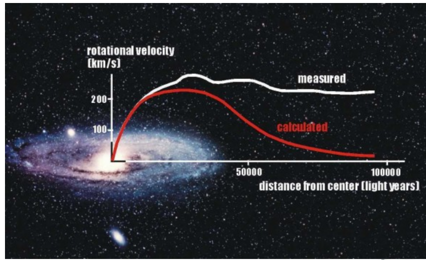
➔ strong indirect evidence for a large dark sector

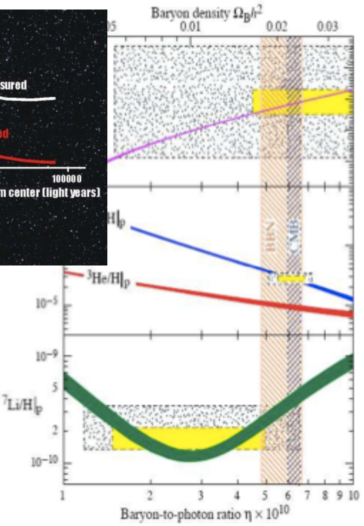
➔ dynamic, static, radiation, …

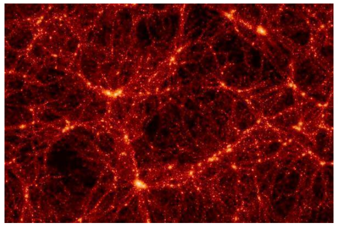
➔ cannot be explained by ordinary matter

CMB (WMAP)

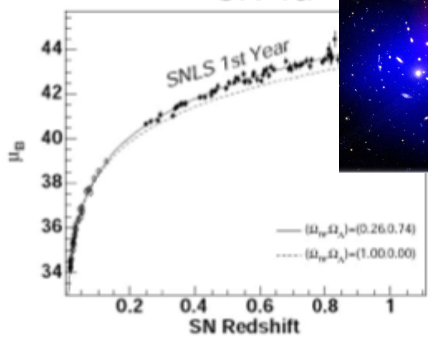




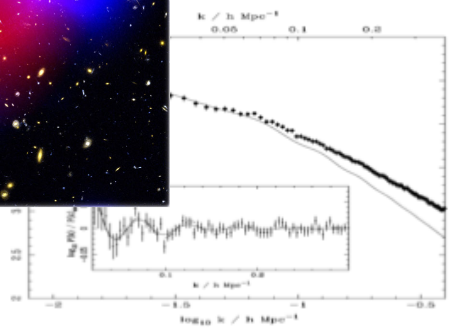


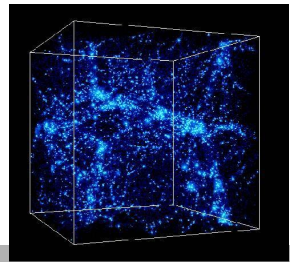


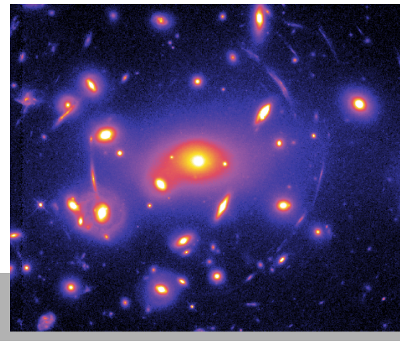
SN 1a



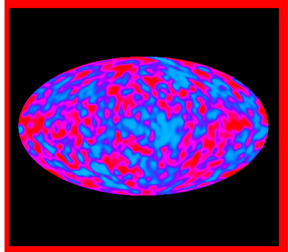
BAO







The cosmic Budget



radiation:
0.005%

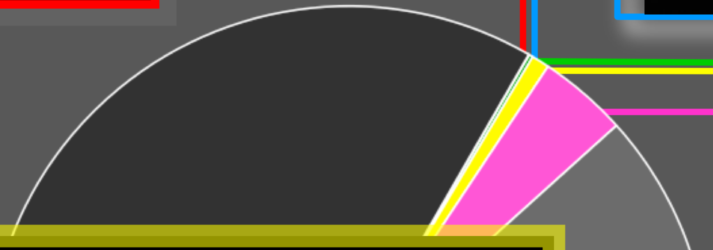
chemical elements:
(not H & He) 0.025%

ν_e ν_μ ν_τ

neutrinos = CνB:
0.17%

stars:
0.8%

H & He:
gas 4%



?

dark matter: 26.8%
→ many indications

- is DM one component?
- mixtures?
- …?

→ composition of DM:
1) ν's are ~0.5% of DM
2) Black holes x%
3) …what else?

?

dark energy: 68.3% → ???...

Dark Matter Directions

Gravity

MOND
simple one scale modification
→ fails badly

Other GR
Other GR modifications

or

a suitable population (mass, number) of black holes

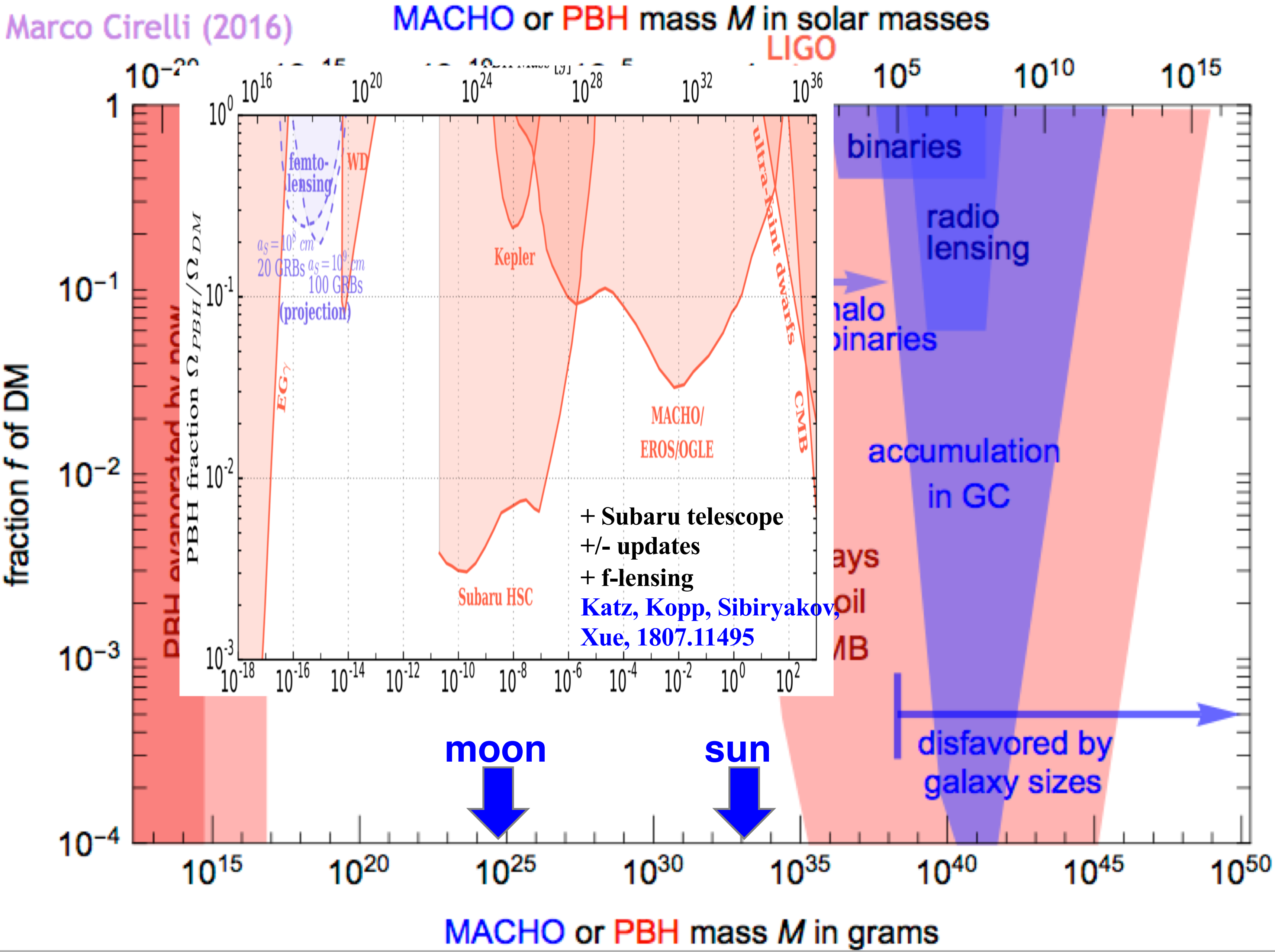
Matter = new Particles

BSM motivated
(SM problems)
- axions
- sterile ν's
- many other particles
-...

Abundance or model motivated
- various candidates
- ...

WIMPs combine both aspects in an attractive way + WIMP miracle

Black Holes or MACHOs as Dark Matter



Neutrinos as Dark Matter

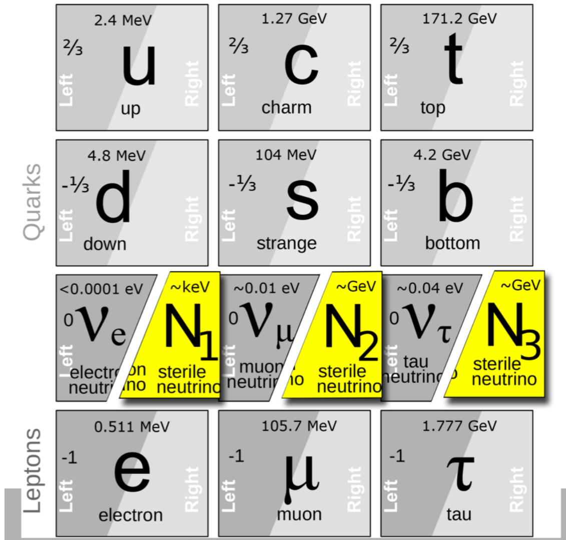
Active neutrinos as DM:

- primordial number density n_ν = 112 cm^{-3} (per flavour)
- correct dark matter abundance requires $\Sigma\, m_\nu \sim 11\text{eV}$

  ➔ **known neutrino masses are too small**
  ➔ **active ν's are hot DM ←→ problem: small scale structure**

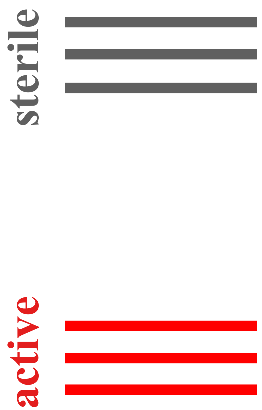
BUT: Neutrinos are Dark Matter even if they contribute only 0.5%

Sterile neutrinos as DM ←→ **simplest explanation of neutrino masses**



add 3 right-handed singlets
➔ see-saw mechanism

$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$



← DM?

Bounds for sterile Neutrino DM

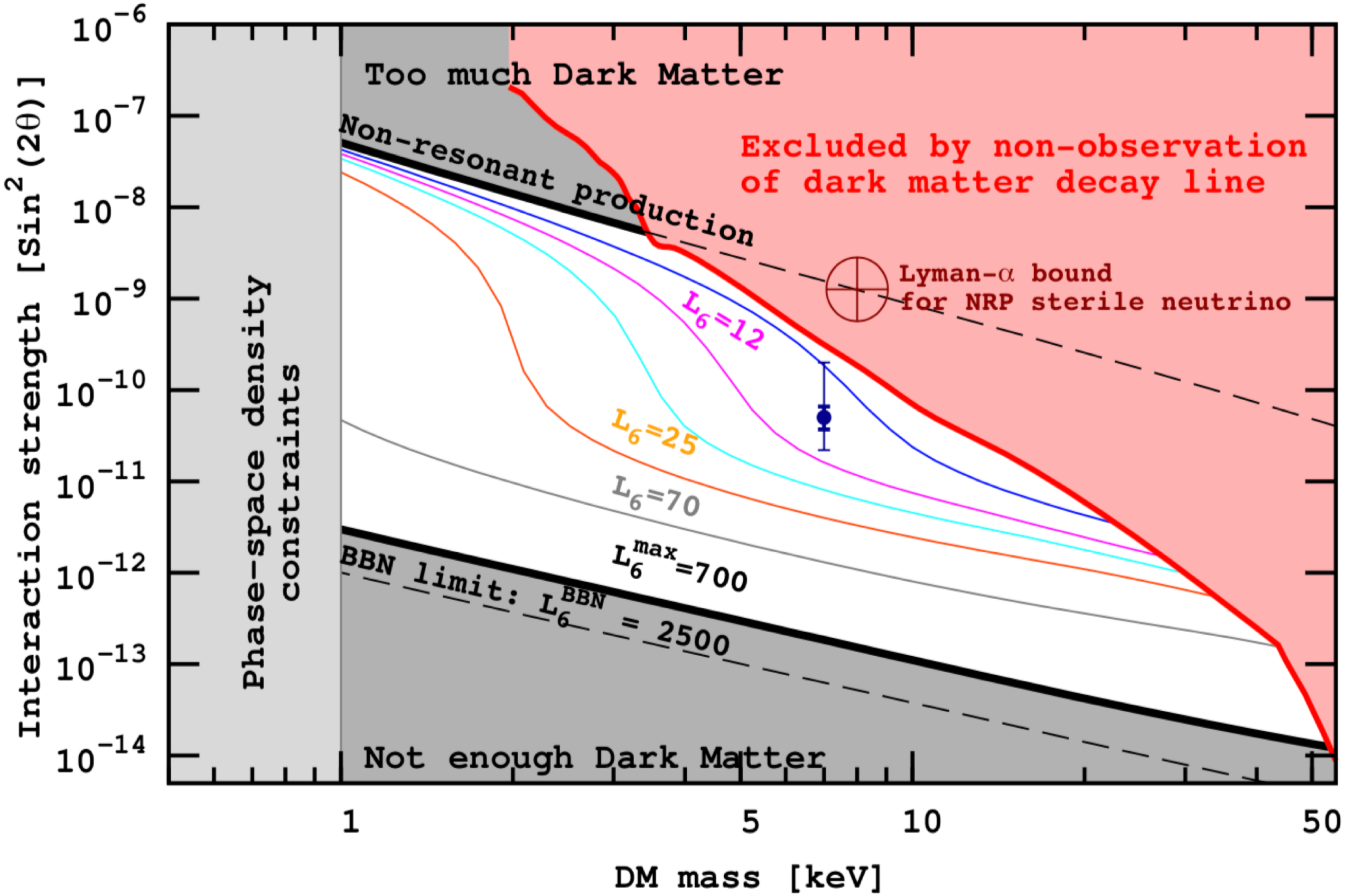
Tremaine-Gunn bound:

light ν's cannot form small galaxies ←→ too many required

➔ violation of the Pauli exclusion principle

➔ minimal mass for fermion dark matter ~ 300 – 400 eV

Lyman-α forest...
X-ray bounds...
too much DM...
too little?...

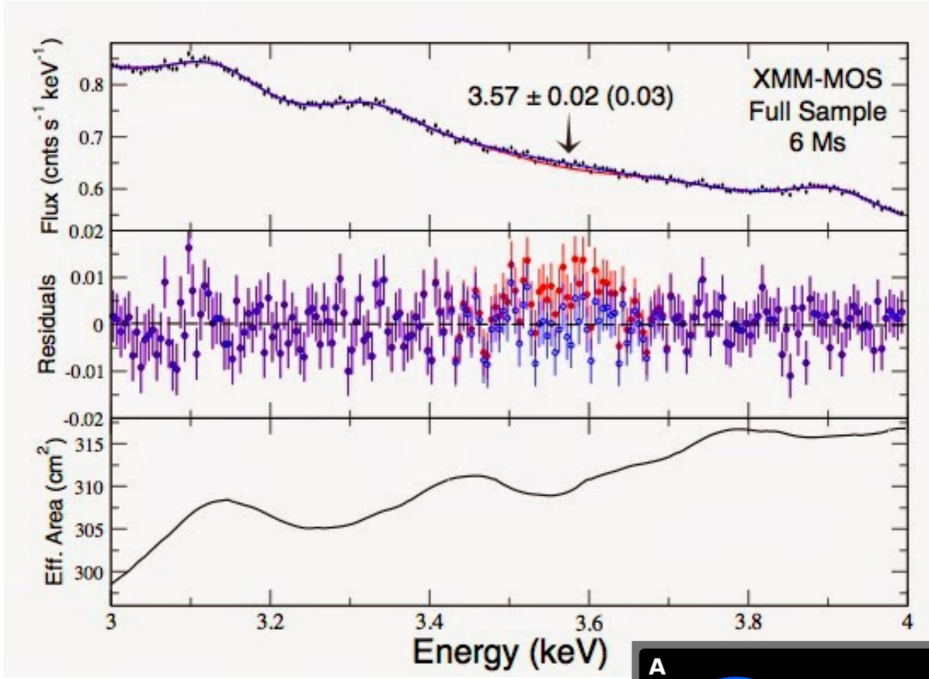


Claims for a decay signal

$\nu_s \rightarrow \nu_a + \gamma$

➔ γ line at $E = m_s/2 = 3.6$ keV

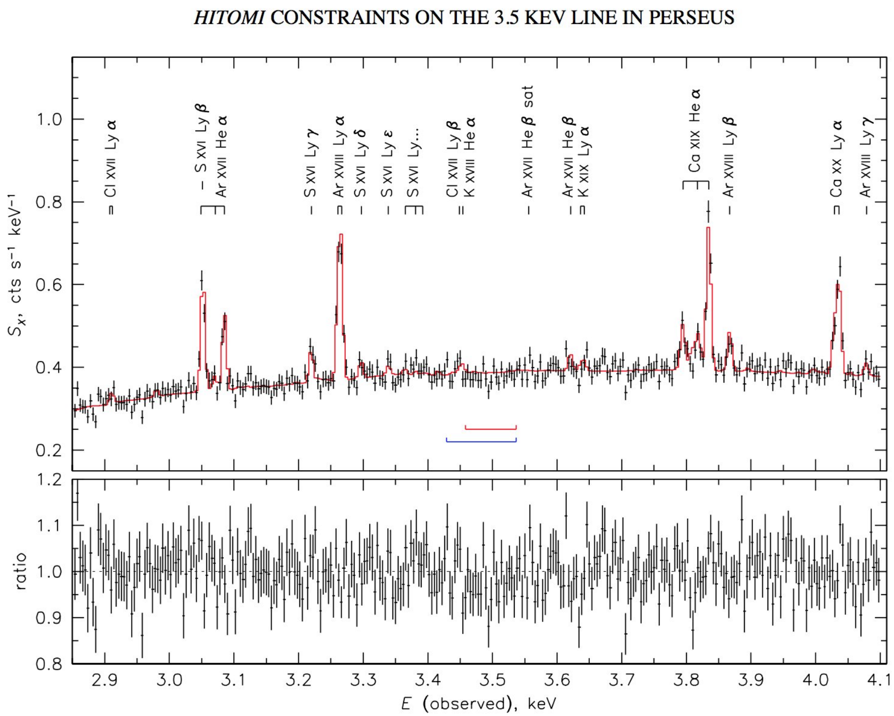
Discussion



A 3.6 keV line could come from the decay of a 7.2 keV sterile ν

parameters are in allowed window

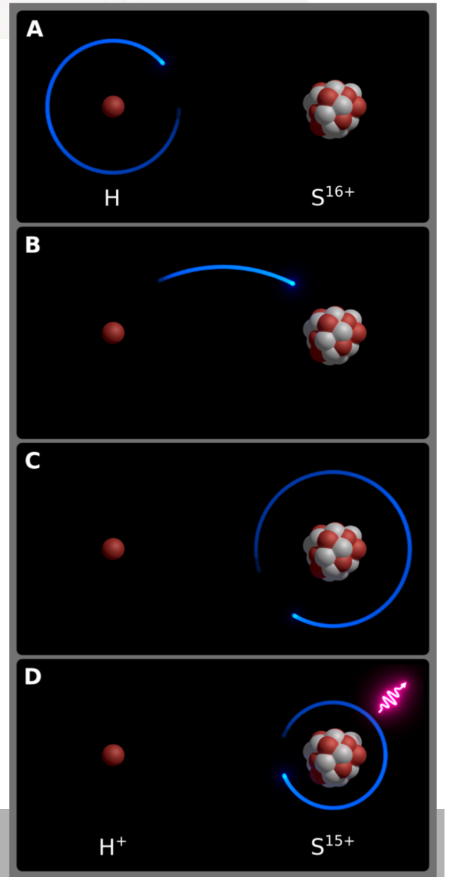
how robust is the signal?
Hitomi satelite...



Alternative explanation:
Charge exchange reactions
H + S16$^+$ ➔ H$^+$ + S^{15+} + γ

C. Sah et al. 1608.04751

➔ much harder to proof that a keV-ish line is from sterile neutrino decay



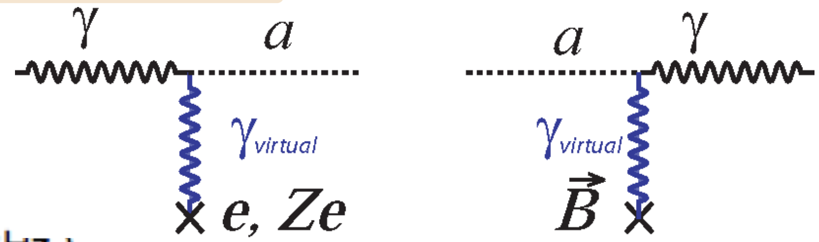
Axions and the Strong CP Problem

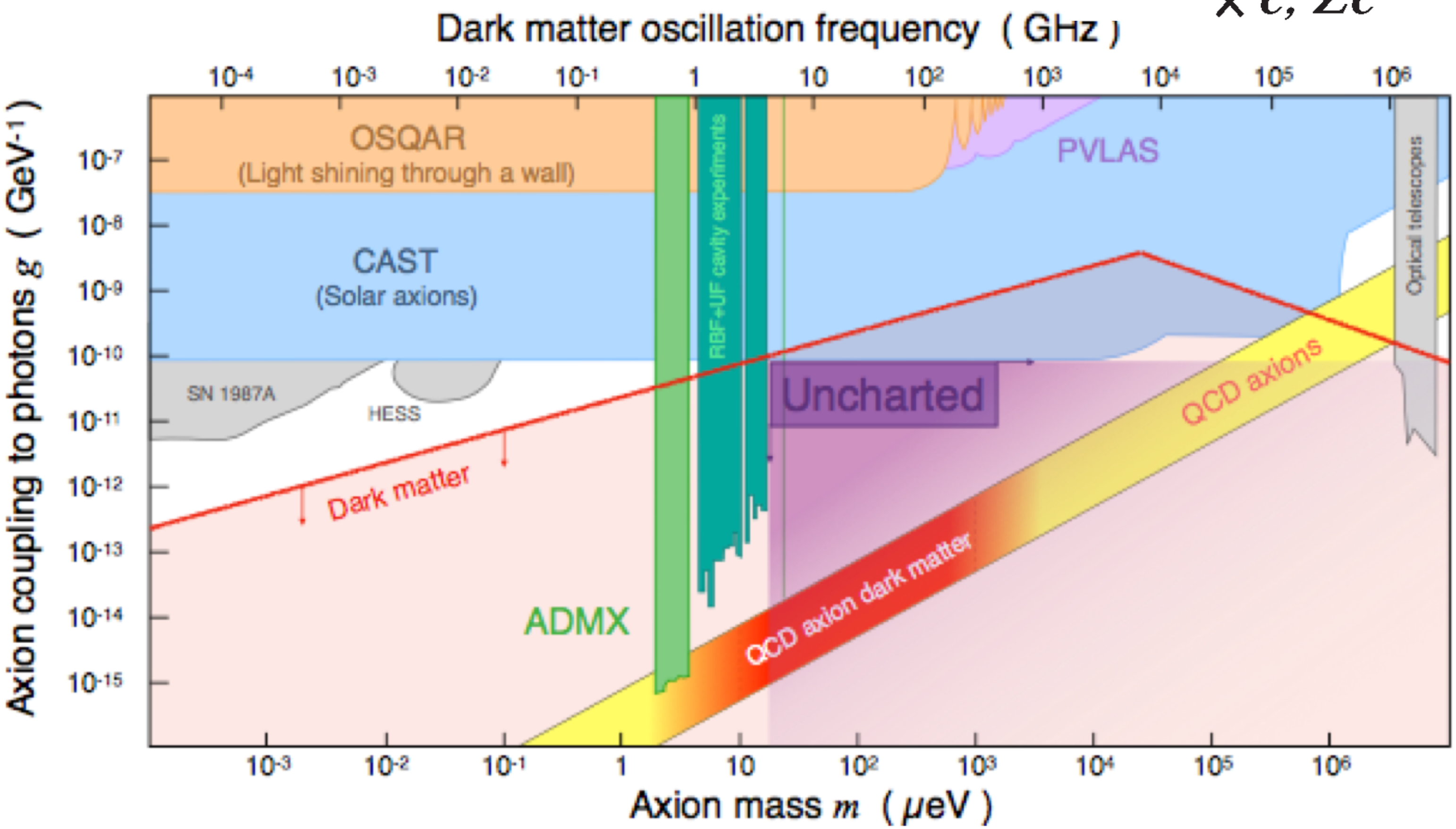
$$\mathcal{L}_\theta = \theta \frac{\alpha_s}{8\pi} G^{(a)}_{\mu\nu} \tilde{G}^{\mu\nu(a)} \rightarrow \mathcal{L}_a = \frac{a(x)}{f_a} \frac{\alpha_s}{8\pi} G^{(a)}_{\mu\nu} \tilde{G}^{\alpha\beta(a)}$$

$$d_n \approx 3.6 \times 10^{-16} \theta_{QCD}\, e \text{ cm}$$

➔ invent axion

➔ Primakov effect





L.Chevalier

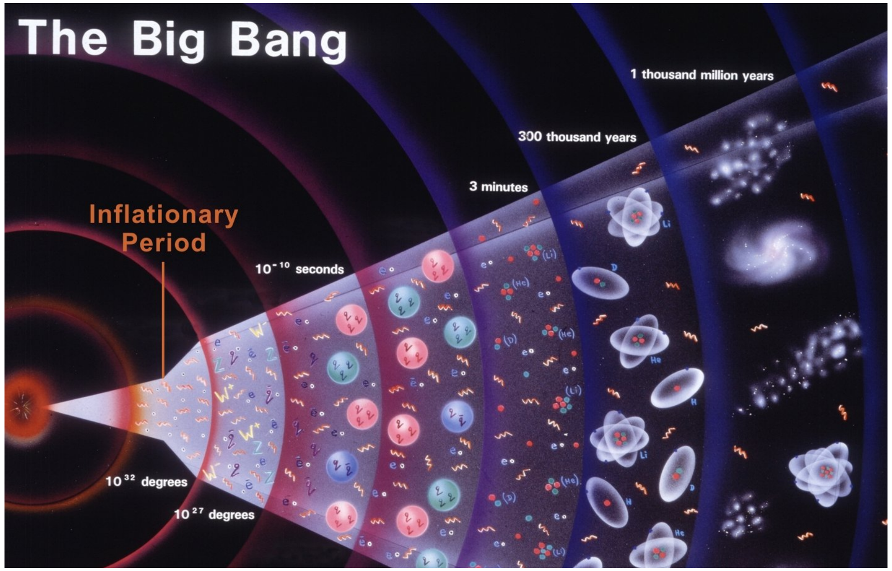
Many future experiments...

The WIMP Miracle

inflation ➔ many e-folds

Reheating ➔ all particle types produced

Evolution of original plasma by:
- **expansion (dilution)**
- **decays**
- **interactions → conversion processes**

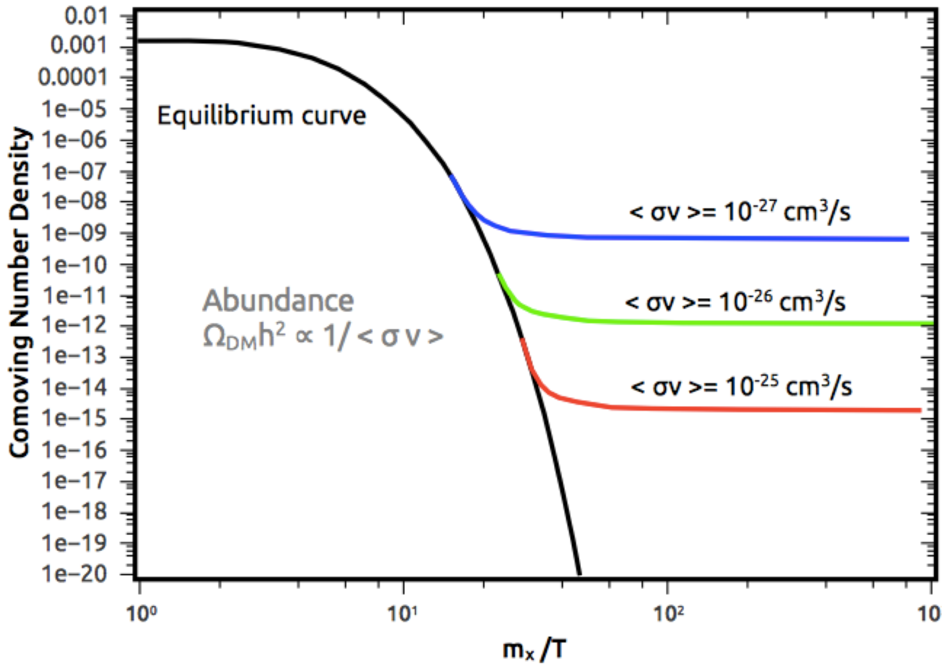


Evolution of original DM density:

➔ Boltzmann equation

$$\frac{dn_\chi}{dt} + 3H(T)n_\chi = -\langle\sigma v\rangle(n_\chi^2 - n_{\chi,eq}^2)$$

➔ thermal freez-out

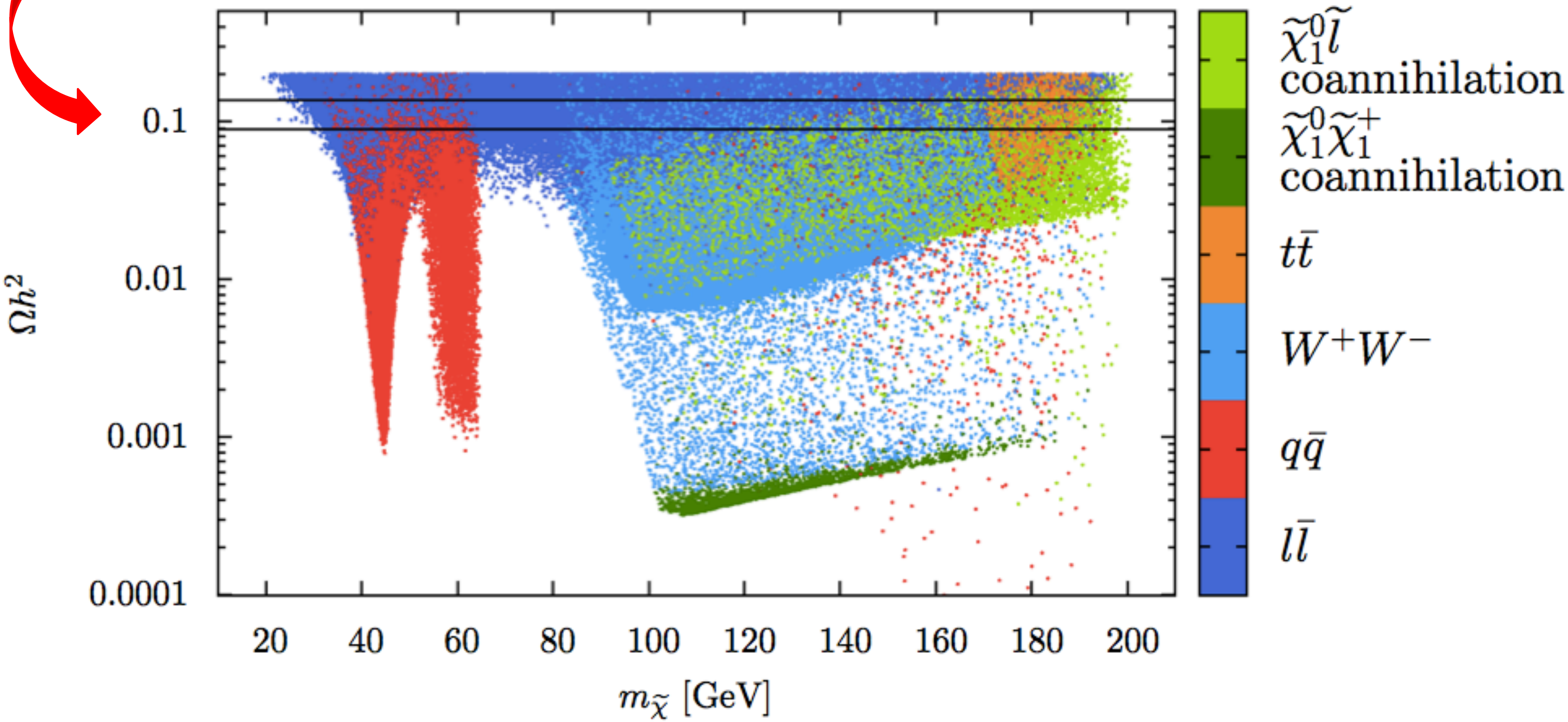


BSM motivated physics @TeV scales:
A WIMP-like particle produces automatically ~ correct abundance

Hierarchy Problem ➔ MSSM ➔ Vanilla WIMP

- **LSP=Neutralino ➔ WIMP miracle ➔ correct abundance**

Scan parameter space for different annihilation channels → Ωh^2
Note: we will not argue for equal probability in parameter space!

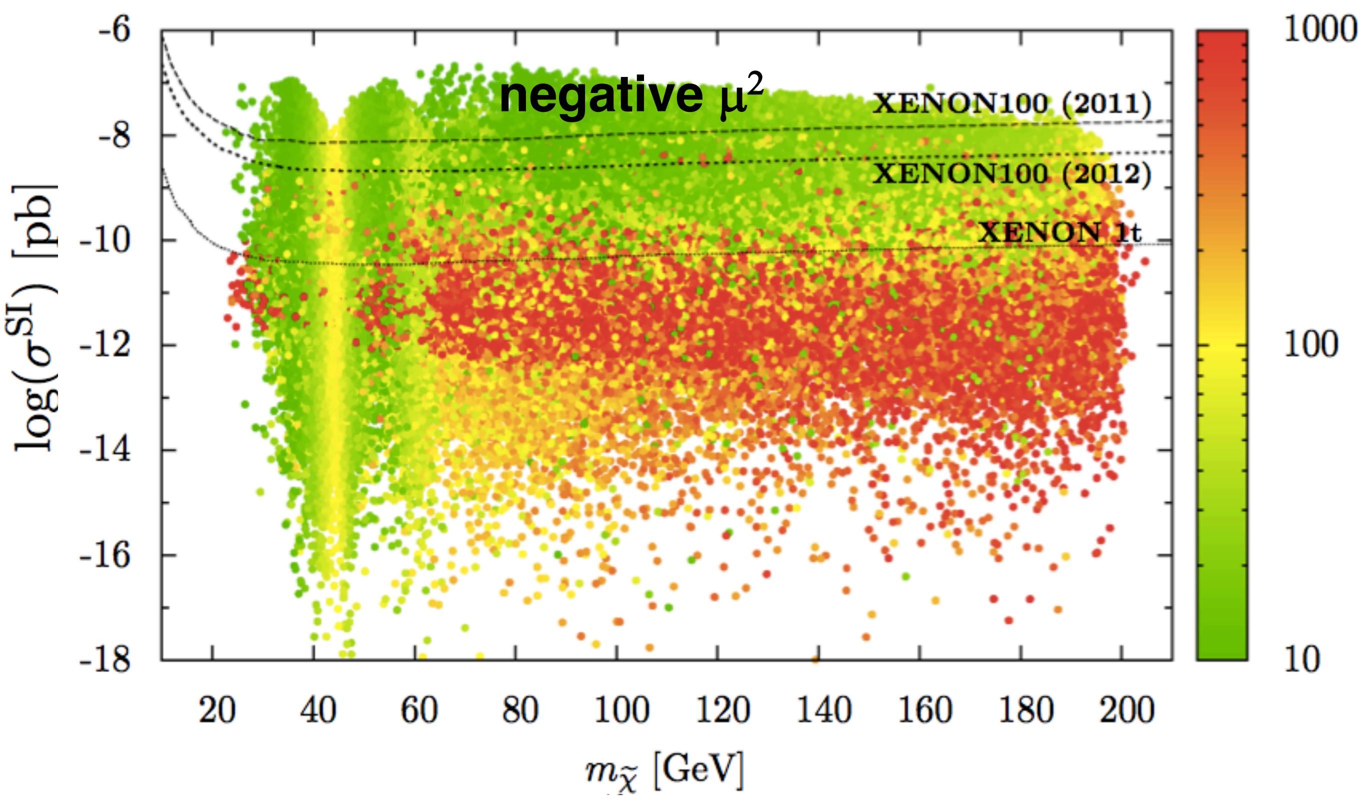


➔ **Select correct range of Ωh^2 ➔ constrains parameter ranges**

How fine-tuned are the paramaters?

- **MSSM neutralino: Level of fine-tuning → Δ_{tot}**

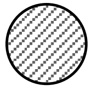
$$\Delta p_i \equiv \left| \frac{p_i}{M_Z^2} \frac{\partial M_Z^2(p_i)}{\partial p_i} \right| = \left| \frac{\partial \ln M_Z^2(p_i)}{\partial \ln p_i} \right| \qquad \Delta_{tot} \equiv \sqrt{\sum_{p_i=\mu^2, b, m_{H_u}^2, m_{H_d}^2} \{\Delta p_i\}^2}$$



- **XENON1T cuts already into expected space**
- **XENONnT will cover more (linear scale)**
- **How deep can it go?**

Grothaus, ML, Takanishi: full MSSM, not CMSSM, pMSSM, NMSSM…

Generic WIMP Cross Section

Wavelength $\lambda \sim 1/\text{mass}$ ➔ "size":  $\simeq \pi\lambda^2 = \pi/m^2$

➔ cross section: area × coupling strength

$\sigma \sim O(0.001\text{-}1.0)^2 \quad g_2^2 \quad \pi/m^2$

model parameters — some weak coupling — area

or tuning, symmetry, …

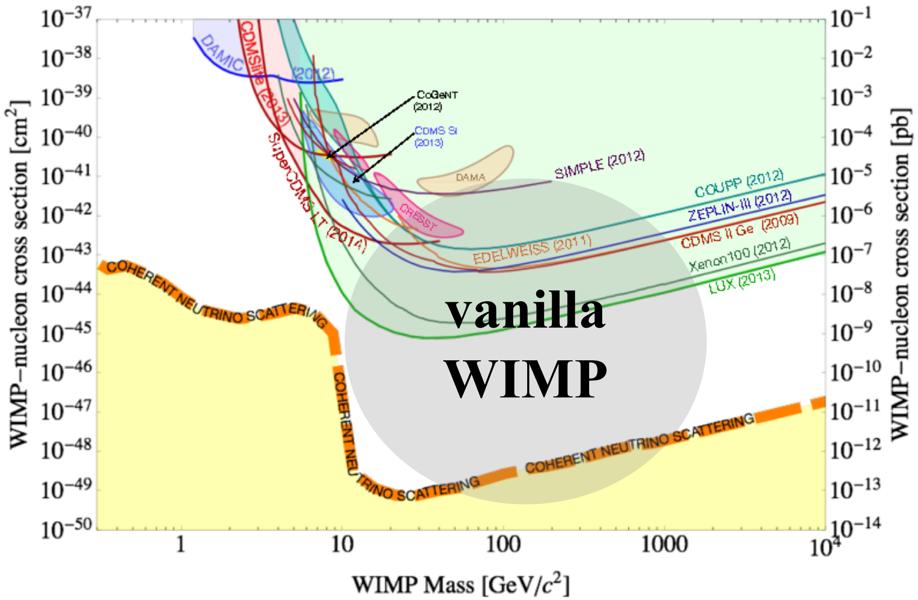
←→ abundance

➔ natural range for a 50GeV WIMP: $\sigma \sim 10^{-42} - 10^{-49}\ \text{cm}^2$

known amount of DM

- ➔ abundance ➔ WIMP flux
- ➔ rate@direct detection
- ➔ required size/sensitivity of a detector which can cover the most interesting natural WIMP space

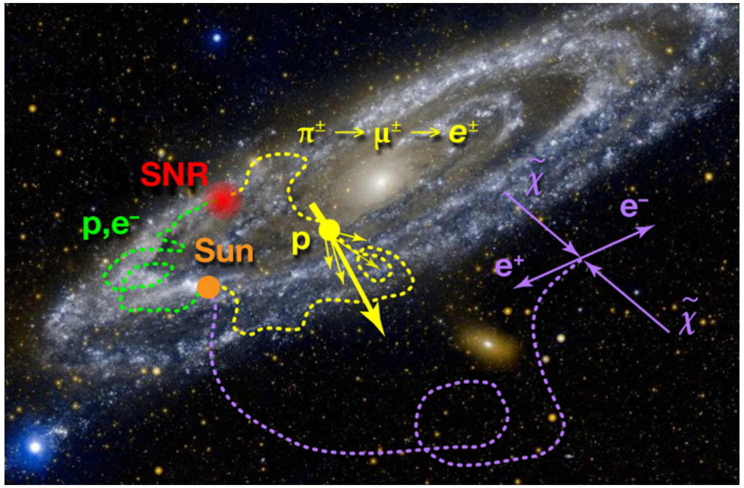
How much is left? …linear…



Hunting WIMPS in different Ways

Standard Model particles interact with WIMPs: assumptions…

indirect detection



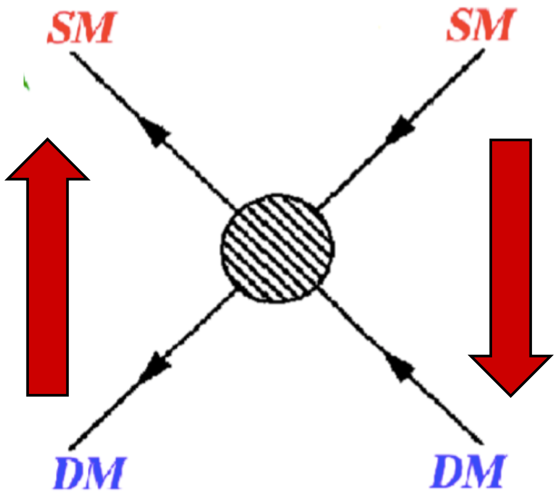
FERMI, PAMELA, AMS, HESS, IceCube, …

astro. uncertainties...

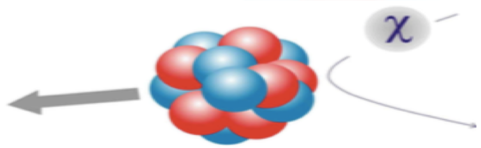
→ DM signal w/o doubt?

example: keV lines

↔ atomic physics

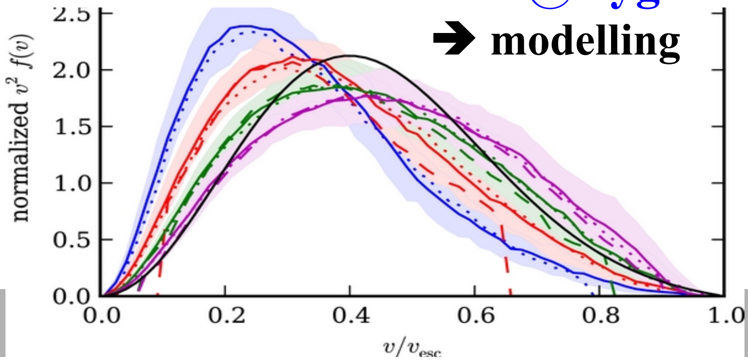


direct detection

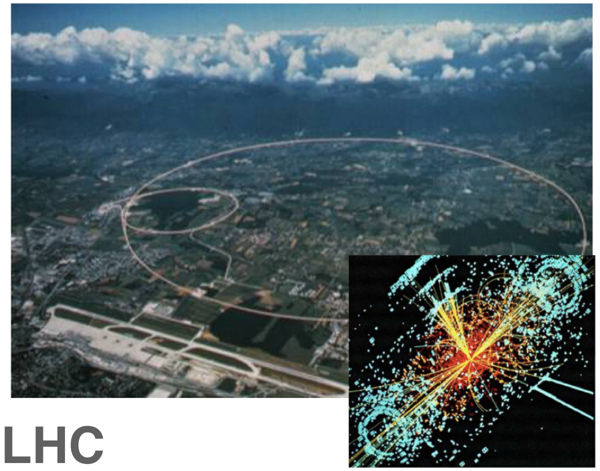


WIMP wind : 220km/s @Cygnus

➔ modelling



colliders



LHC

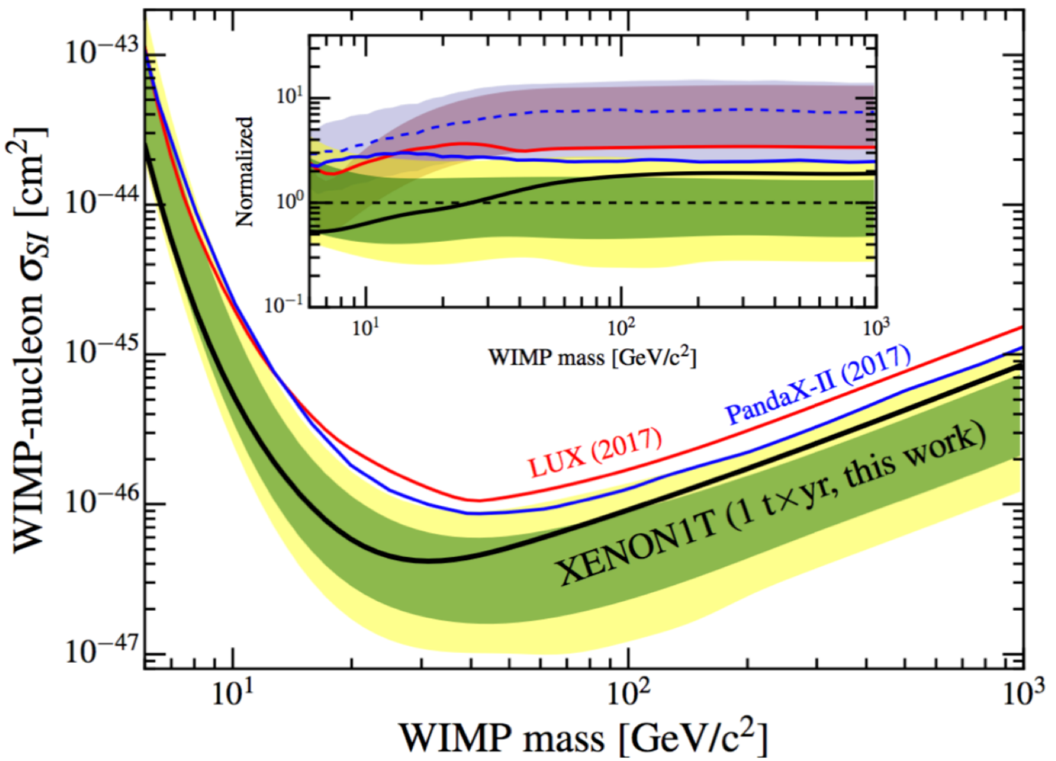
may detect new particles, but is it DM (lifetime, abundance)?

So far nothing seen…

- → impact on theory…
- → SUSY → higher scale
- → other SB motivated WIMPs
- → new ideas/candidates

Direct Detection of WIMPs

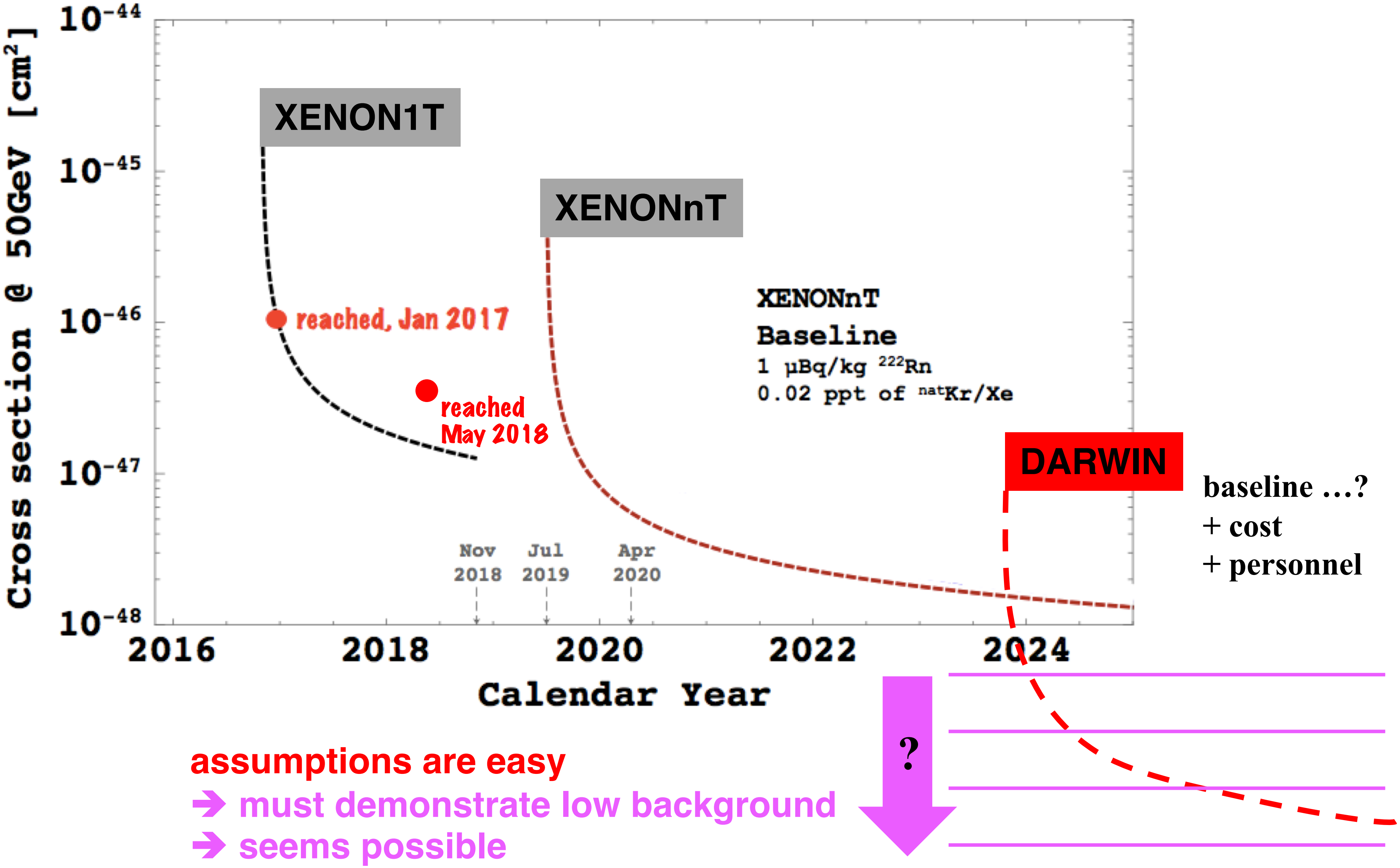
SI limits on WIMPs:



XENON1T stopped 12/2018
➔ modifications for XENONnT
➔ operations ~fall/winter 2019
➔ x20 improvement expected

In addition: LZ, PandaX, DarkSide, CRESST, DAMA/Libra, ...
And other results...

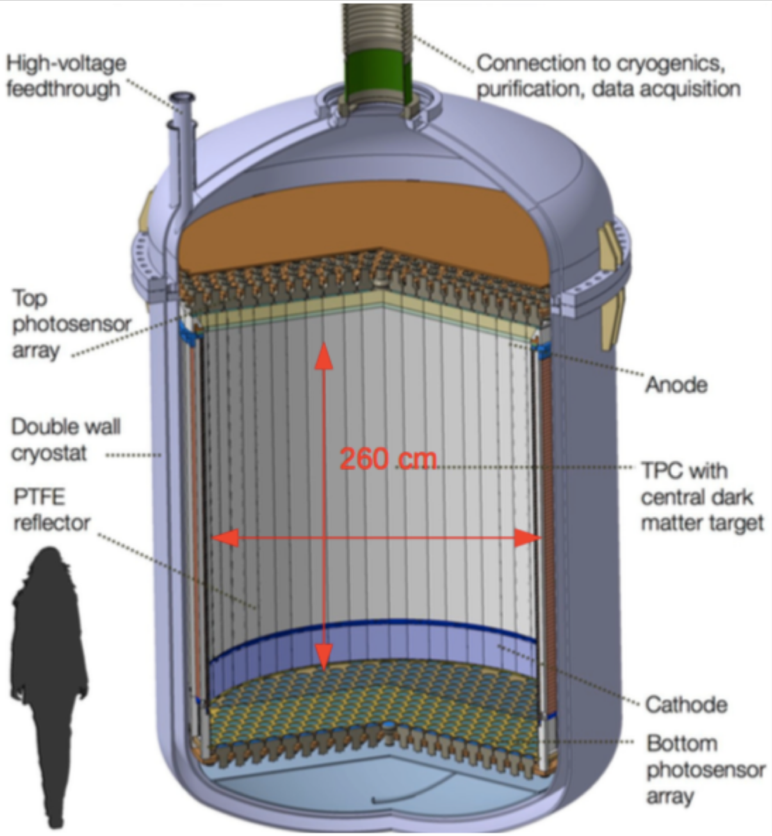
Going beyond XENONnT: DARWIN



baseline …?
+ cost
+ personnel

assumptions are easy
➔ must demonstrate low background
➔ seems possible

DARWIN Conceptual Design



JCAP 11, 017 (2016)

DARWIN

www.darwin-observatory.org

- **Baseline: 50t LXE**
- **40t LXe TPC, aim at 200 t*yr**
- **TPC dimension 2.6m x 2.6m**
- ~1800 * 3” PMTs (or ~1000 4” PMTs)
- Low-background cryostat
- PTFE reflector panels
- Copper E-field shaping rings
- Water Cherenkov shield (~14m diameter)
- Liquid scintillator neutron veto under study
- Possible location LNGS
- **aim at sensitivity of a few 10^{-49} cm^2, limited by irreducible ν-backgrounds**
- R&D and initial design now
- **Timescale: after XENONnT**
- **Cost effective:**
  - use existing Xe gas; buy more & re-sell
  - no enrichment (also faster)

The DARWIN Collaboration

France:
- Subatech
- LAL
- LPNHE

Germany:
- University of Münster
- MPIK, Heidelberg
- University of Freiburg
- KIT, Karlsruhe
- University of Mainz
- TU Dresden
- Heidelberg University

Great Britain:
- Imperial College London

Italy:
- INFN, Sezione LNGS
- INFN, Sezione di Bologna

Israel:
- Weizmann Institute of Science

The Netherlands:
- Nikhef, Amsterdam

Portugal:
- University of Coimbra

Sweden:
- Stockholm University

Switzerland:
- University of Zürich

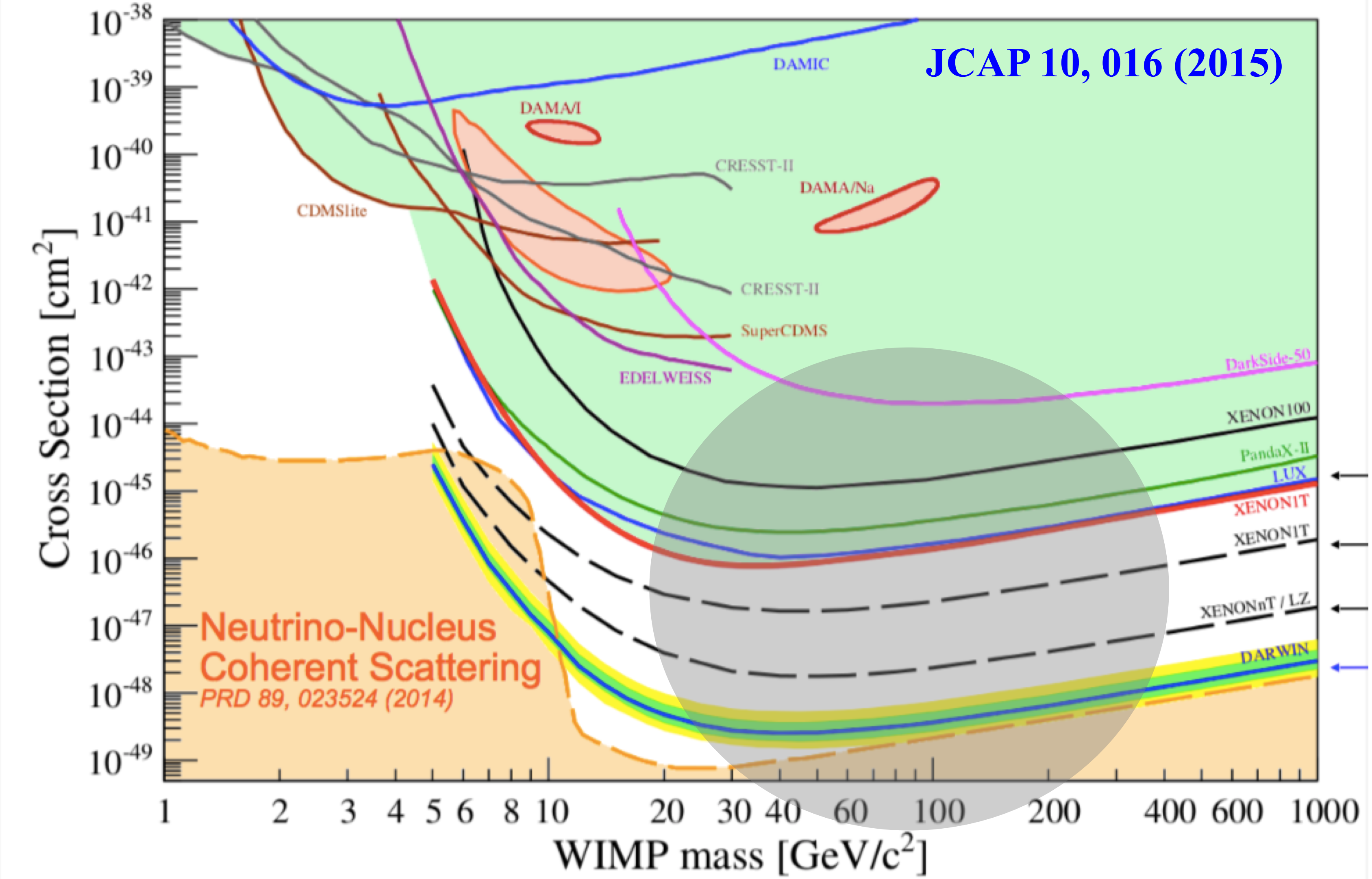
USA:
- Columbia University
- UCLA
- Arizona State University
- Purdue University
- Rice University
- UCSD
- University of Chicago
- Rensselaer Polytechnic Institute

Abu Dhabi:
- New York UniversityAbu Dhabi

Expertise of XENON
+ new groups

Seed funding exists

Spin Independent (SI) WIMP Interaction



tests most of the generic WIMP space

➔ a declining WIMP case w/o discovery?

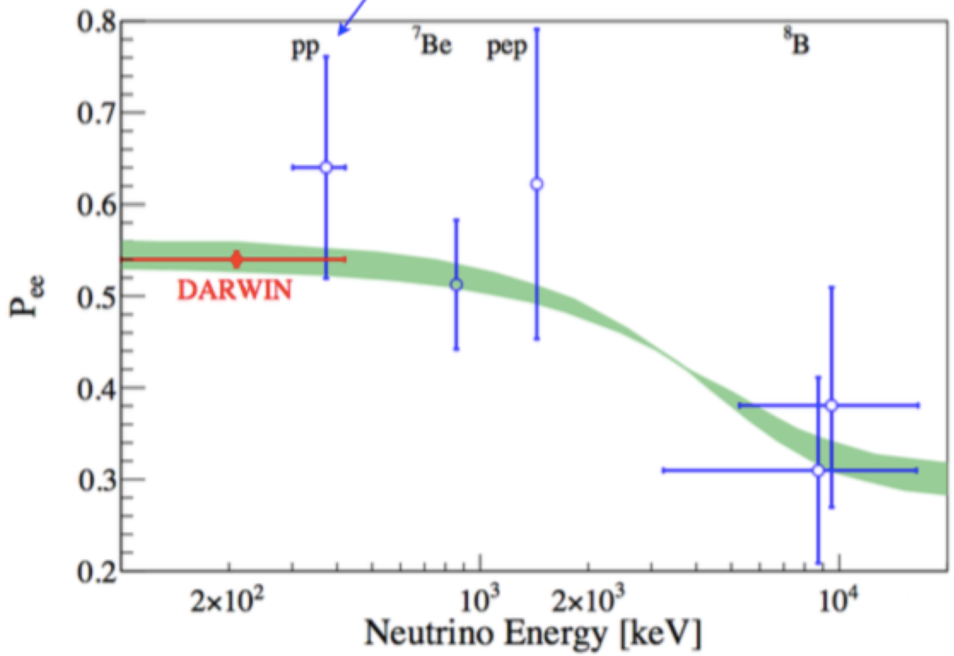
➔ solar neutrino signal & CNNS: 200 t*yr

Neutrino Physics with DARWIN

➔ **Coherent Neutrino-Nucleus Scattering (CNNS)**
200 t*yr ➔ ca. 200 (25) events for > 3 (4) keV$_{NR}$

➔ **Low energy solar neutrino signal: pp, ^{7}Be** **JCAP 01, 044 (2014)**
~1% statistical uncertainty for 100 t*yr ➔ solar models & ν properties

Borexino (Nature 512, 383-386, 2014)

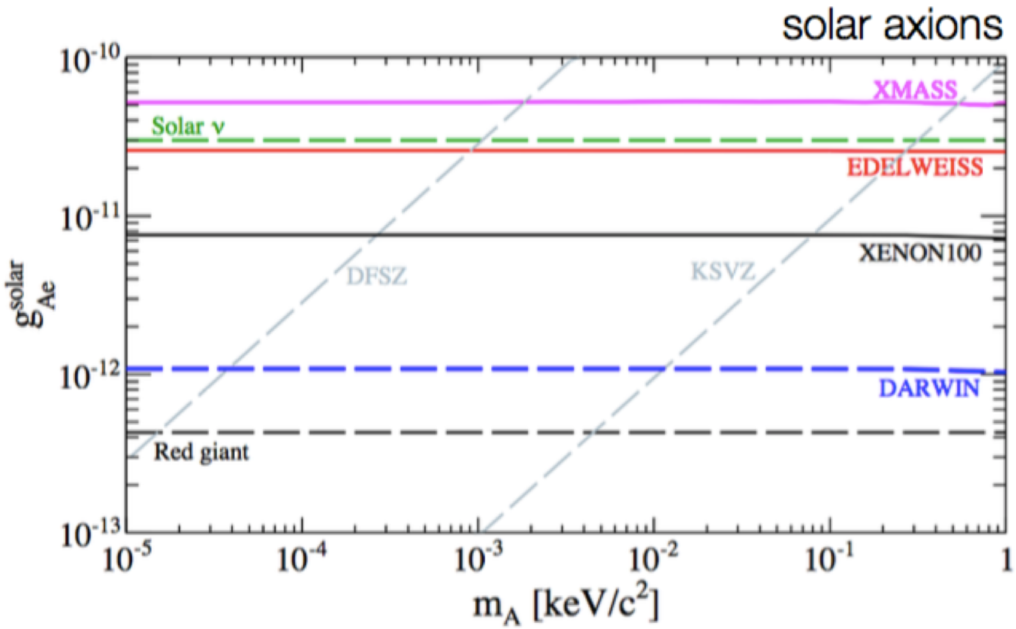


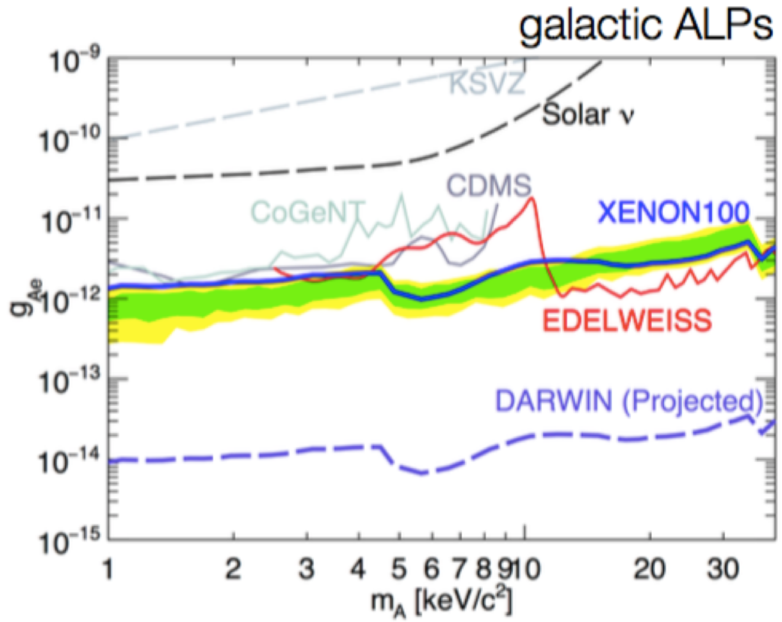
real-time measurement of the solar neutrino flux:
→ 7.2 events/day from pp
→ 0.9 events/day from 7Be

➔ **Supernova neutrinos:**
→ 5σ sensitivity for a 27M☉ SN progenitor at 10 kpc (~700 events)
→ flavor-insensitive neutrino energy measurement **Phys. Rev. D 94 (2016)**

Axions and ALPS

- measurement via axio-electric effect (ER channel) **JCAP 11, 017 (2016)**
- expect mono-energetic peak at the particle mass
- moderate sensitivity to axions (weak dependence of the coupling on the exposure: $g_{Ae}^{solar} \propto (MT)^{-1/8}$
- sensitivity to ALPs two orders of magnitude better than current limits $\left(g_{Ae}^{ALP} \propto (MT)^{-1/4}\right)$
- dominant backgrounds: solar neutrinos and 2νββ of ^{136}Xe





0νββ with ^{136}Xe

8.9% natural abundance

➔ 3.5 t ^{136}Xe in 40t without any enrichment

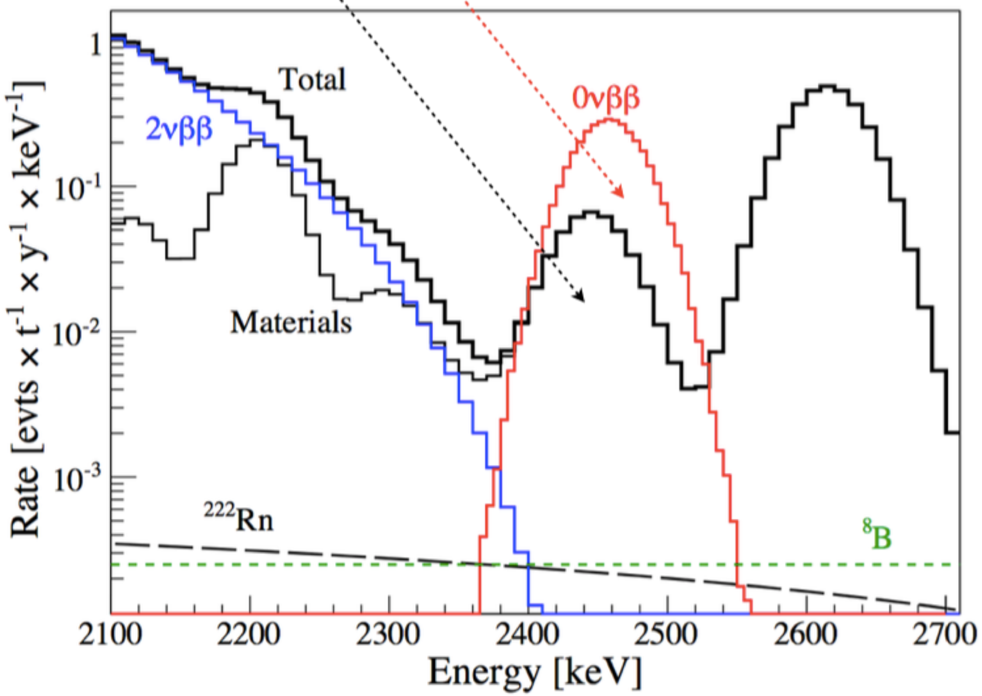
$Q_{\beta\beta}$ = (2458.7 ± 0.6) keV

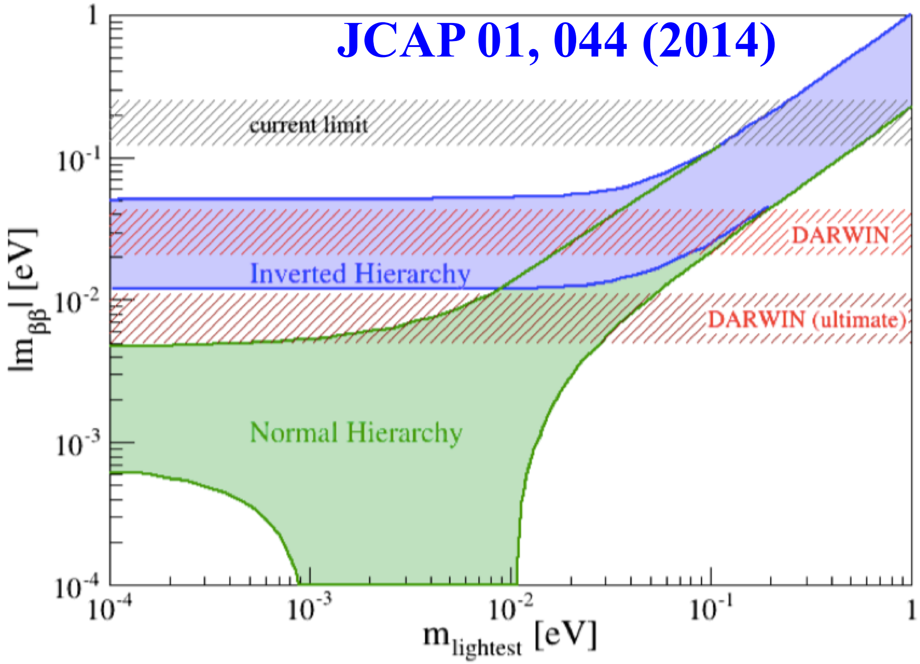
Assume:

- 6t fiducial
- energy resolution at $Q_{\beta\beta} \simeq 1\%$

^{214}Bi → ^{214}Po + e⁻ + γ (2448 keV)

4.6 events/year within ±3σ





Sensitivity @ 95% CL:

- 30 t*yr → $T_{1/2} > 5.6 \times 10^{26}$ yr
- 140 t*yr → $T_{1/2} > 8.5 \times 10^{27}$ yr

IMPORTANT: DARWIN might become a powerful, cost effective and time-wise competitive 0νββ experiment:
Xenon= commodity, no enrichment

Dark Matter Production at Colliders

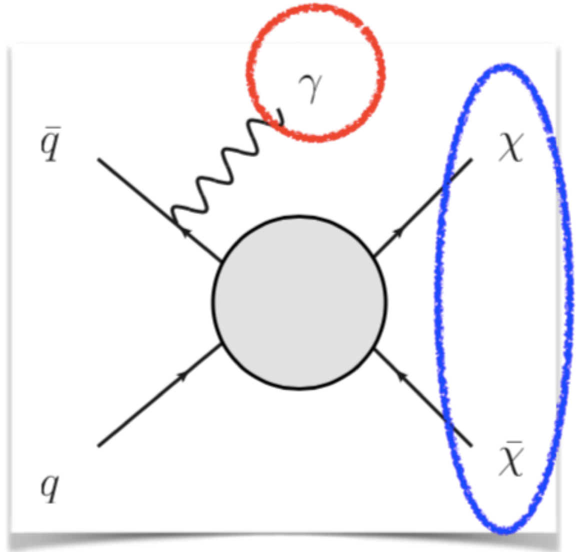
DM particles do not interact via electromagnetic interaction

➔ no DM tracks in a detector

DM particles carry energy & momentum

➔missing energy

trigger and momentum offset in transverse plane



missing energy

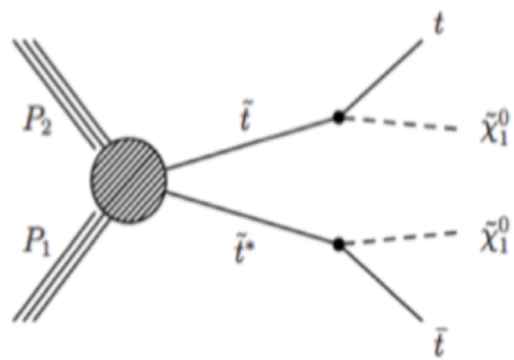
two approaches at colliders for DM search:

1) direct production of DM particles

annihilation of standard model particles into a pair of DM particles

2) indirect production of DM particles

search for dedicated decay chains with DM-like particles using a dedicated model (e.g. SUSY)



Drawbacks:

- a signal does not guarantee a long life-time
- unrelated to DM density in the Universe

EFT Interpretation

For q << mediator mass M_{med}

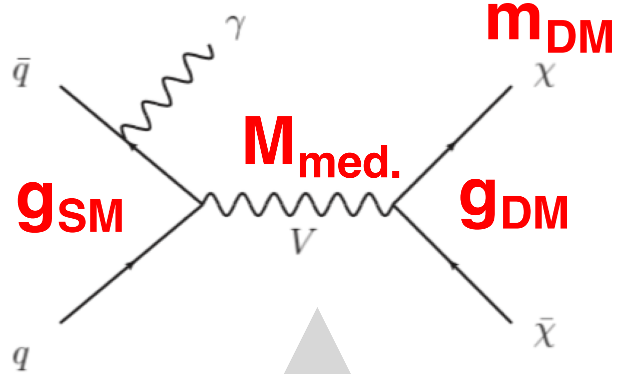
➔ M_{med}, g_{DM} and m_{DM}

type of interaction ➔ different operators

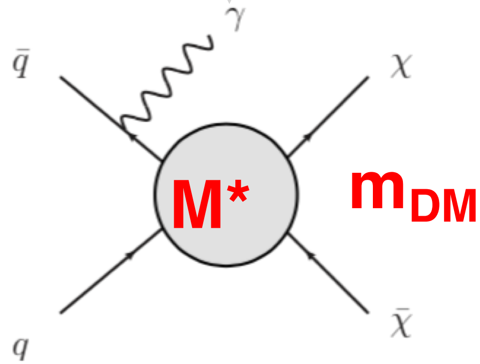
most common:

Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^\mu q$
D9	qq	tensor	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G^s_{\mu\nu})^2$

D1, D5, D11 spin independent (SI), D8, D9 = SD



$$\frac{g^2}{(q^2 + M^2_{Med.})} \xrightarrow{q^2 \ll M^2_{Med.}} \frac{g^2}{M^2_{Med.}}$$



Mediator induces also SM➔SM processes

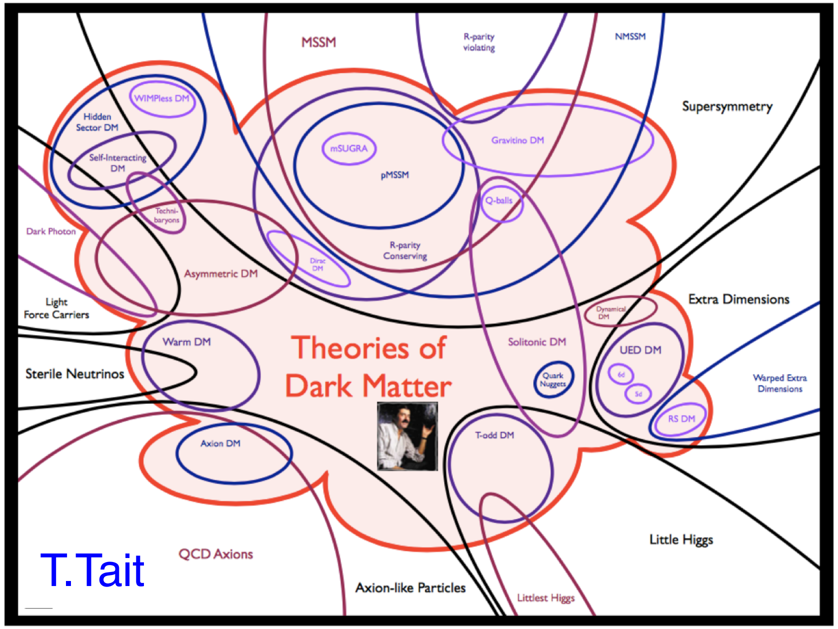
➔ LHC sets limits on **g^2_{SM}/M^2_{med}** (mod. m_{DM})

➔Unless g_{SM} is tiny TeV-ish limits on **$M_{med.}$**

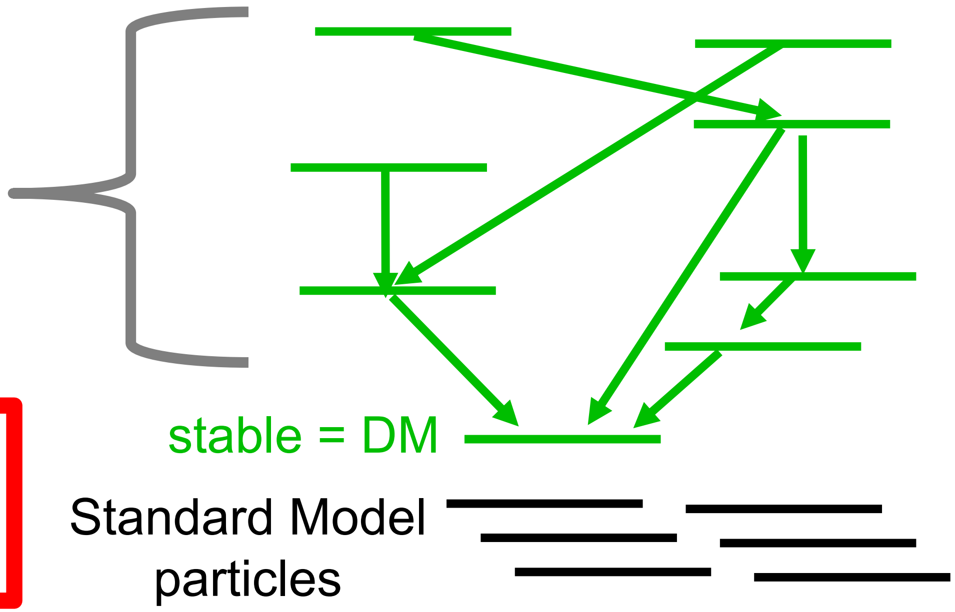
g_{DM} =1 is an assumption ➔ could be tiny ➔ weaker DM limits

***or* a full model** ➔more signatures/effects & constraints

DM motivated Extensions have other Consequences



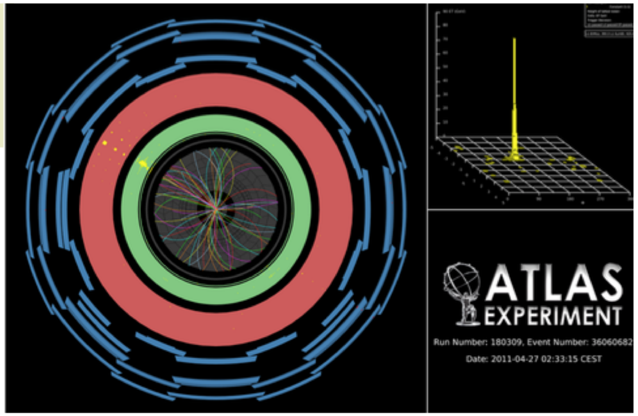
- More particles…
- All existing particles produced in Big Bang and later (decays, …)
- Some particles may be stable
- Very long-lived due to small parameters → natural?
- Effects of unstable states +/-
  ➔ on the early Universe
  ➔ on collider physics



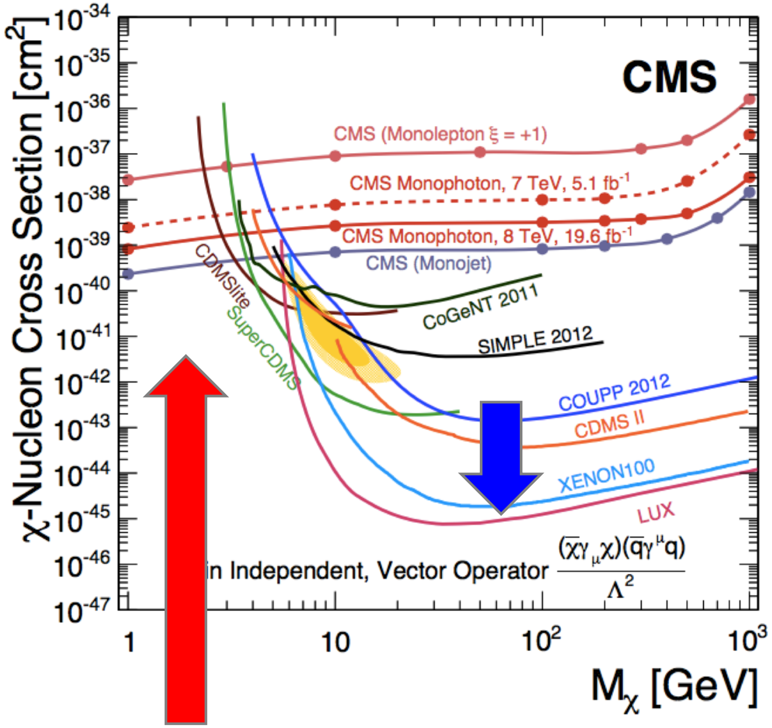
Warning: Your DM model may affect many other known things!

Dark Matter at the LHC

- **Generic signature** $pp \to \not{E}_T + X$



- **Generic kinematics:** weak dependence on WIMP mass for $m_{DM} \ll$ beam energy



light WIMPs
$\mathcal{L}$ ➔ timing

heavy WIMPS
→ direct searches

←→ CRESST-III, SuperCDMS ➔ GeMMC

- **Life is more complex…**
  - many conceivable candidates
  - detection efficiencies, ...
  - ➔ EFT or simplified models =parametrizion – not always appropriate
  - g_{DM} = assumptions *or* full model +...
- **LHC:**
  - can exclude a DM candidate
  - can establish a candidate
  - does not test if it is DM in Univ.: long lived? abundance?

What if...

...during the coming years we close in on the expected ranges and none of the leading DM candidates shows up?

→ must think wider:

- **Other particles**
- **Black holes**
- **Gravity...**

Beyond the Standard Model

SM: success of renormalizable QFTs in d=4 with local symmetries

QED →	QCD →	SM
$U(1)_{em}$	$SU(3)_C$	$SU(3)_C \times SU(2)_L \times U(1)_Y$

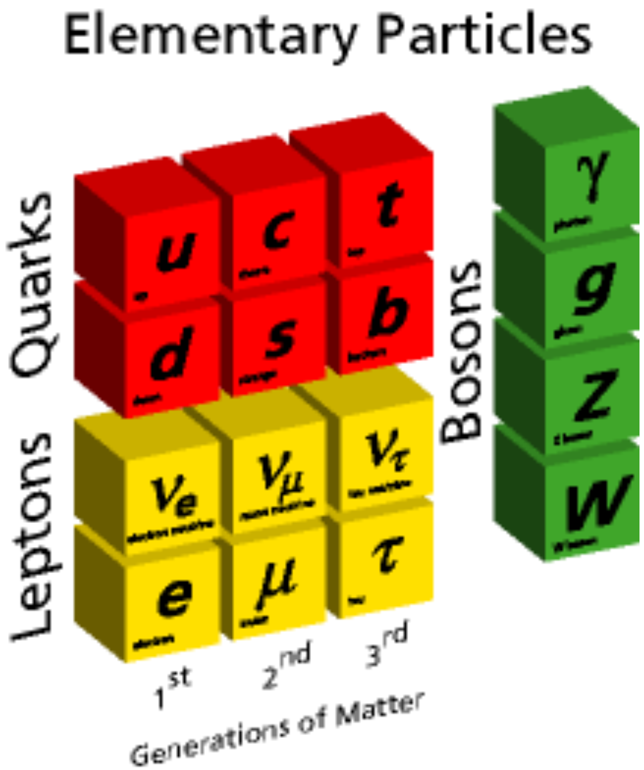
Symmetry, renormalizability, no anomalies
→ particle content (representations)

- gauge sector – fixed by gauge group
- scalar sector – must break EW symmetry, $\sim 2_L$
- fermions – anomaly free combinations

- various conceptual ingredients = questions:

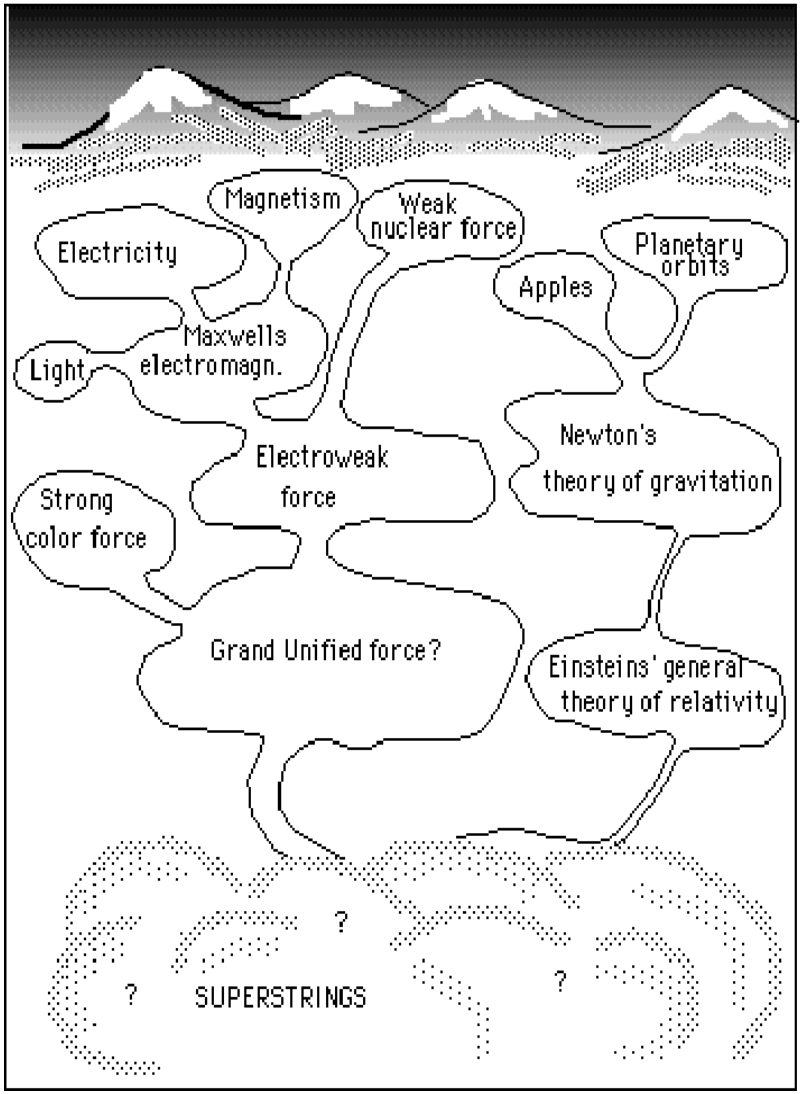
- quantum fields
- chiral fermions, anomaly free combinations
- gauge group, d=4, three generations = copies

- unexplained parameters...



→ impressive progress

Reasons to go Beyond the Standard Model



Theoretical:

SM does not exist without cutoff
(triviality, vacuum stability)
Gauge hierarchy problem
Gauge unification, charge quantization
Strong CP problem
Unification with gravity
Global symmetries & GR anomalies
Why: 3 generations, representations,
d=4, fields, many parameters, ...

Experimental facts:

- Electro-weak scale << Planck scale
- Gauge couplings almost unify
- Neutrino masses & large mixings
- Flavour: Patterns of masses & mixings
- Baryon asymmetry of the Universe
- Dark Matter
- Inflation
- Dark energy

BSM Routes…

d=4 QFTs:

QED ➔	QCD ➔	SM
$U(1)_{em}$	$SU(3)_C$	$SU(3)_C \times SU(2)_L \times U(1)_Y$

electrodynamics
relativity → QED
quantum mech.
strong force → QCD
weak decays + Higgs → SM
\+ neutrino masses → SM+
\+ dark matter …
\+ … ?

gravity

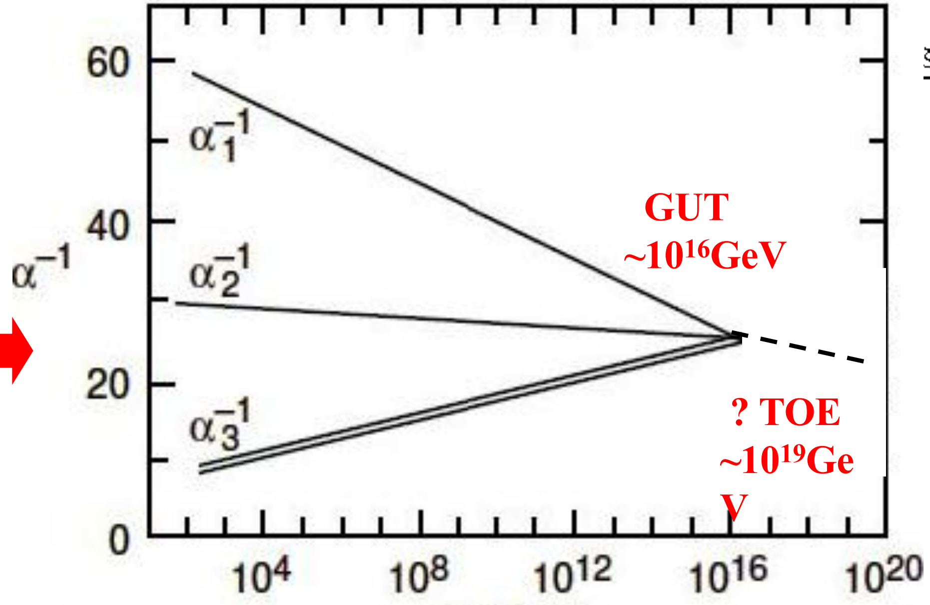
territory of speculation:
LR? TC? …?
SUSY? GUTs? TOE?
extra d?

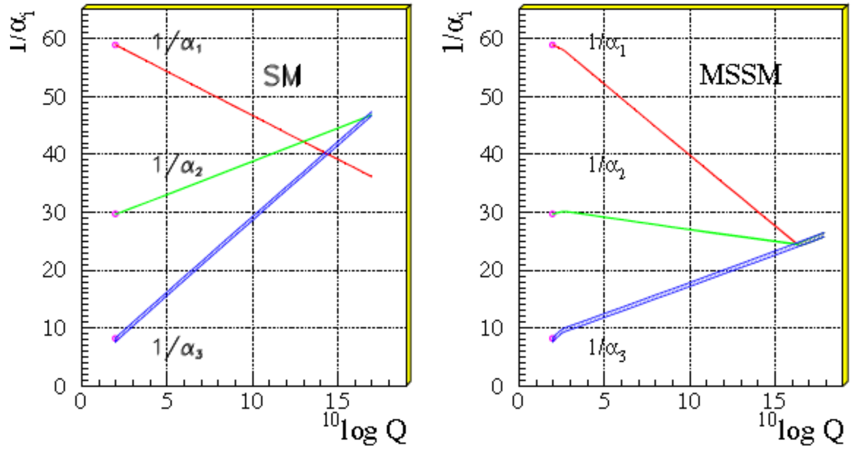
weak scale <<<<< M_{planck}

Note: GR non-renormalizable… maybe good: QFT's cannot explain scales → other concepts

Indications pointing to SUSY + GUTs

gauge bosons





Higgs

gauge hierarchy problem:

$\delta m_H^2 \sim \Lambda^2$

with SUSY only $\log(\Lambda)$

quarks leptons

flavour problem: 3 generations

many parameters (m_i, mixings)

unification into GUTs

$m_\nu = (m^D)^T M_R^{-1} m_D$

SM particles fit nicely into GUT representations

➔ hint for some unification?

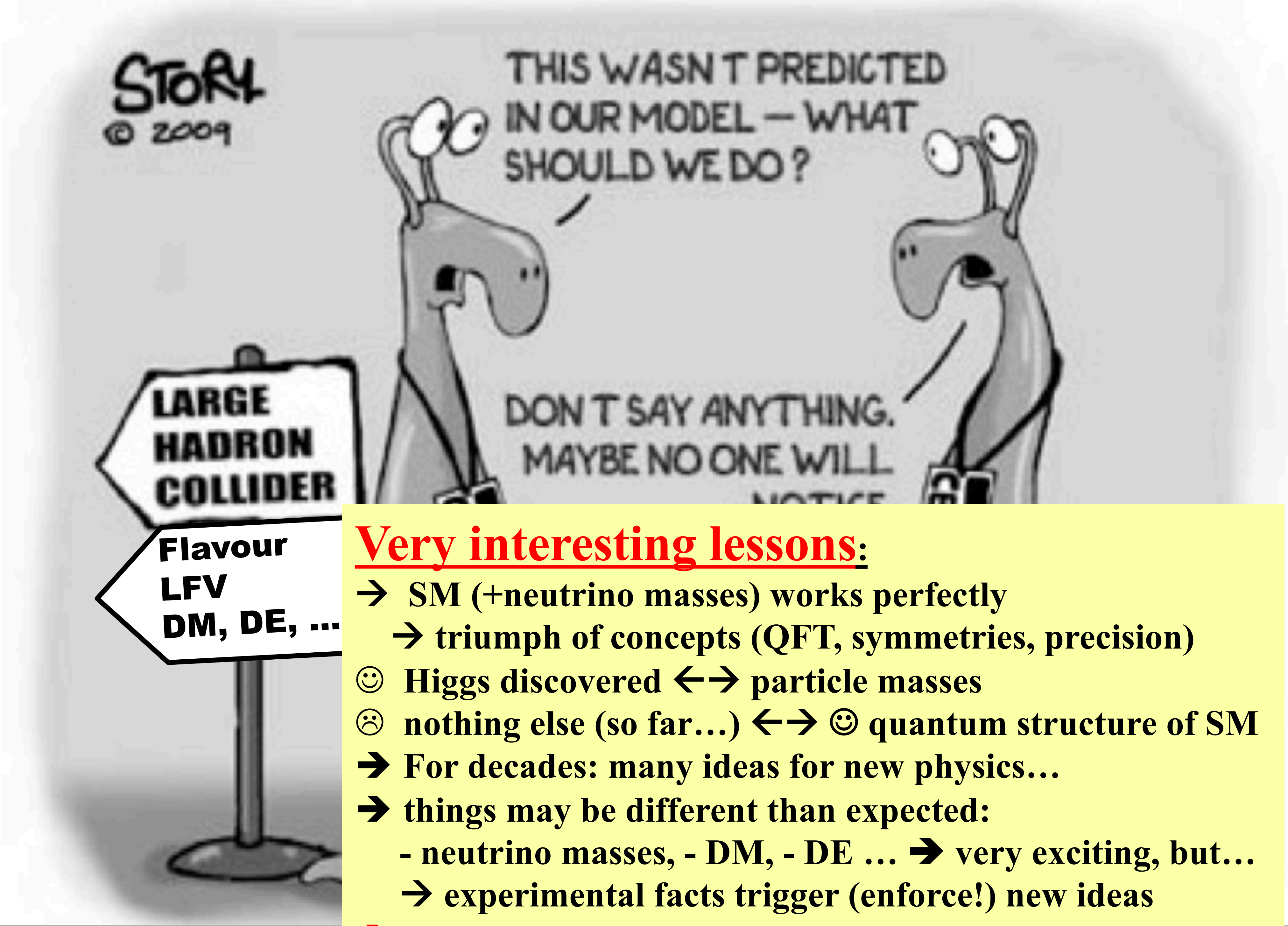
SUSY GUTs ➔ higher Λ_{GUT}

➔ proton decay limits OK

➔ expect SUSY @ TeV

➔ or other physics @ TeV

➔ main LHC motivation



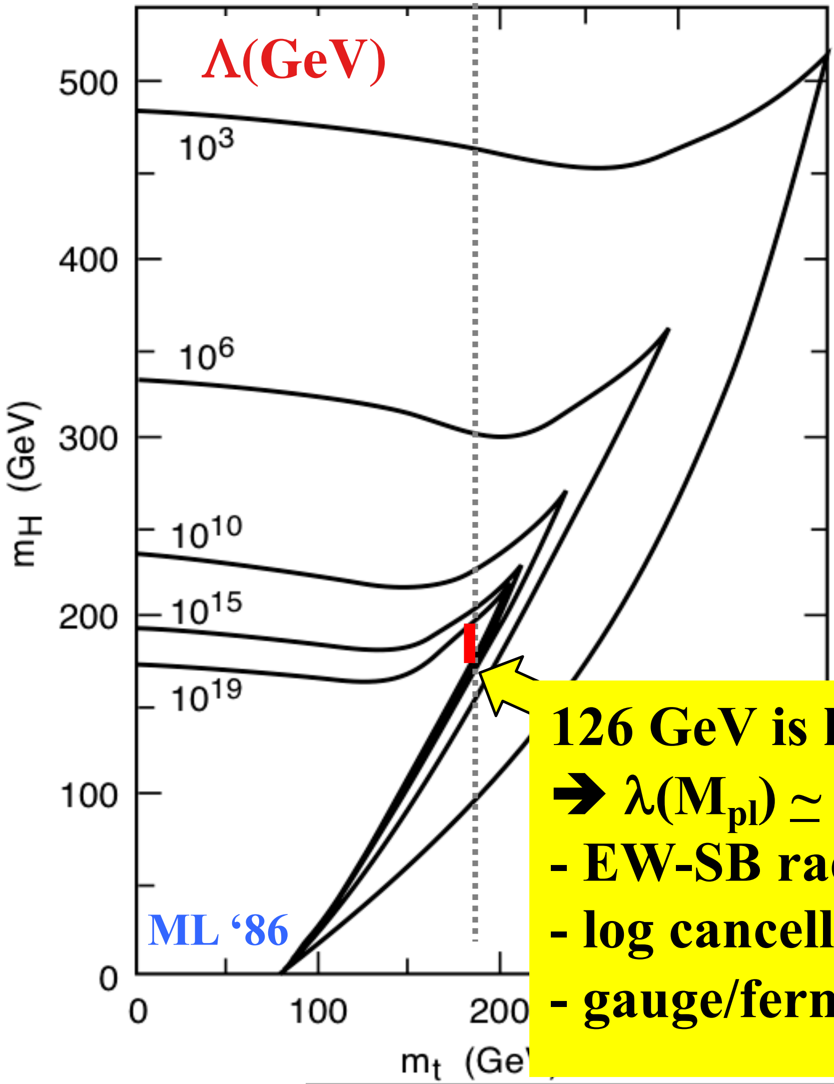
Very interesting lessons:

→ SM (+neutrino masses) works perfectly
  → triumph of concepts (QFT, symmetries, precision)
☺ Higgs discovered ←→ particle masses
☹ nothing else (so far…) ←→ ☺ quantum structure of SM
➔ For decades: many ideas for new physics…
➔ things may be different than expected:
  - neutrino masses, - DM, - DE … ➔ very exciting, but…
  → experimental facts trigger (enforce!) new ideas
➔ Maybe it is time to re-think some aspects…

A remarkable Coincidence

➔ SM is a renormalizable QFT like QED w/o hierarchy problem

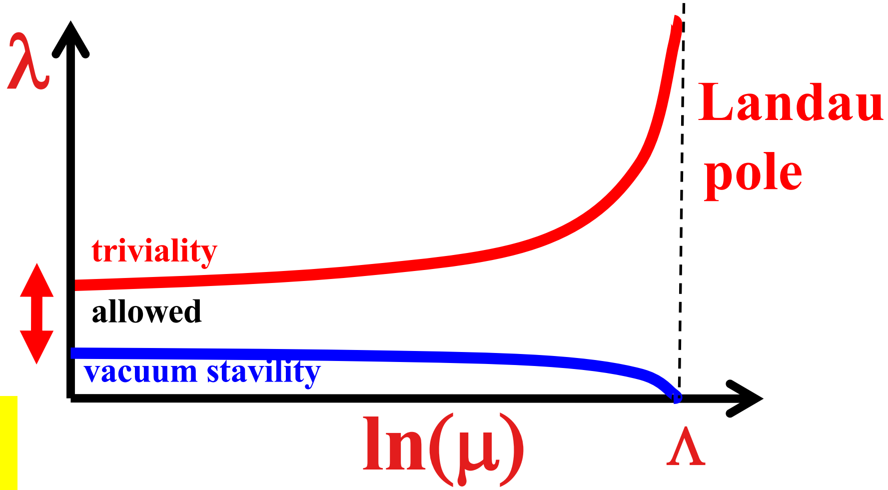
➔ Cutoff "Λ" has no meaning ➔ triviality, vacuum stability



126 GeV is here!
➔ $\lambda(M_{pl}) \simeq 0$
- EW-SB radiative
- log cancellations
- gauge/fermion/scalar

126 GeV < m_H < 174 GeV

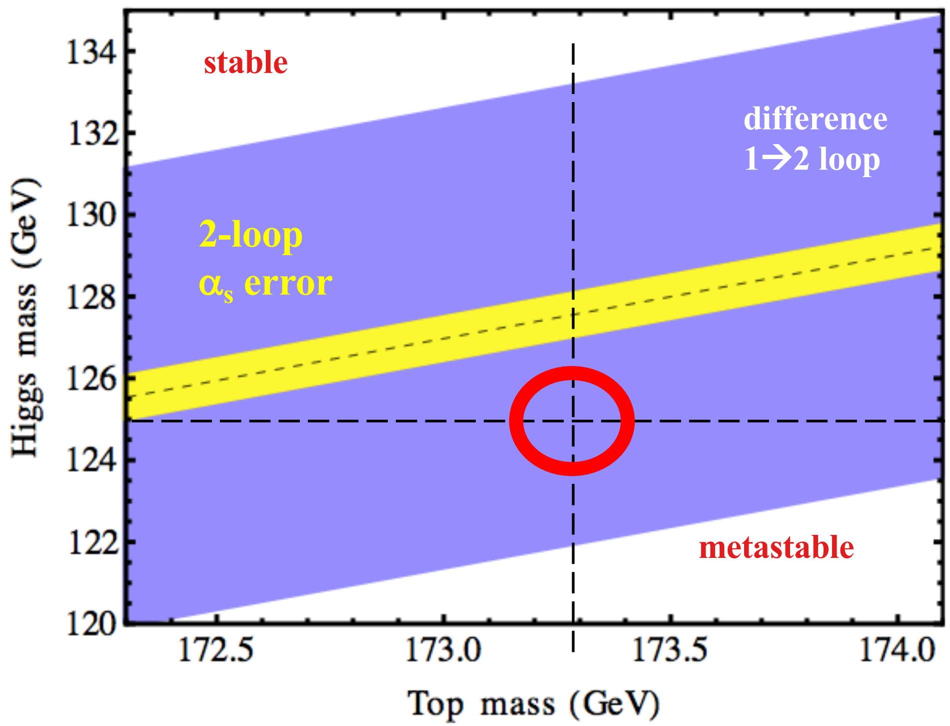
SM does not exist w/o embedding
- U(1) coupling , Higgs self-coupling



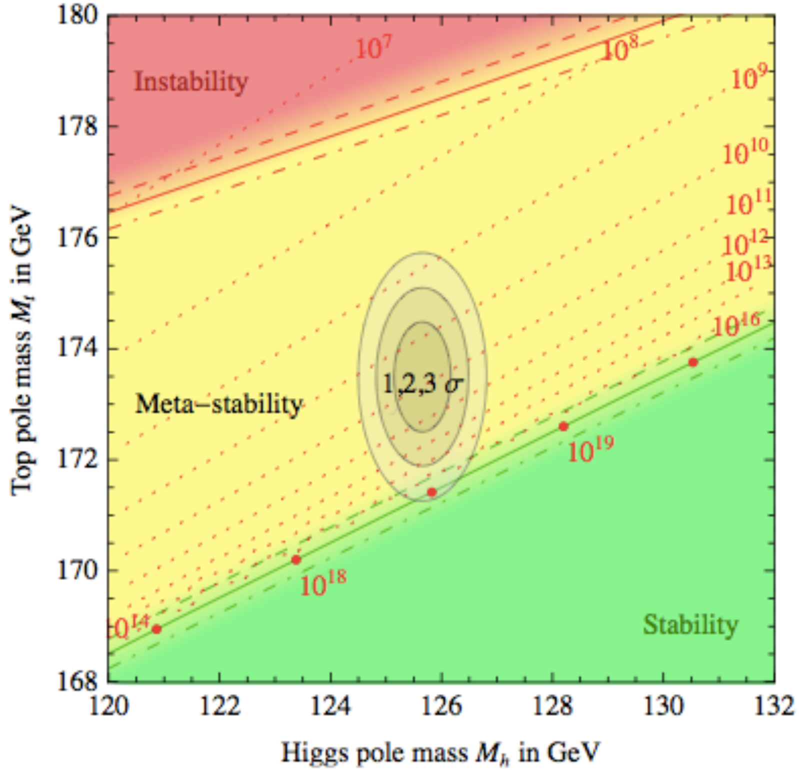
➔ RGE arguments seem to work
➔ but we need some embedding

Is the Higgs Potential at M_{Planck} flat?

Holthausen, ML, Lim
12 Dec 2011



Elias-Miro, Espinosa, Giudice, Isidori, Riotto, Strumia
13 Dec 2011



Experimental values point to metastability. Is it fully established?

➔ we need to include DM, neutrino masses, …? are all errors (EX+TH) fully included?

➔ be cautious about claiming that metastability is established

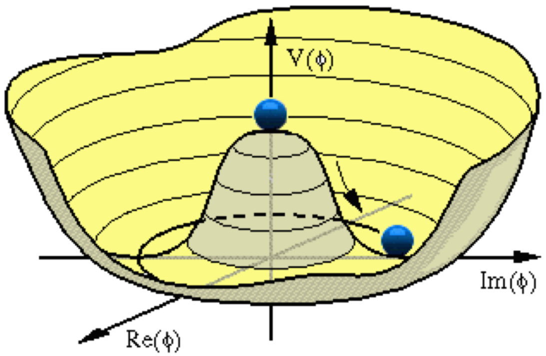
➔ **May be a very important observation:**

- remarkable relation between weak scale, m_t, couplings and M_{Planck} ←→ precision
- remarkable interplay between gauge, Higgs and top loops (log divergences – not Λ^2)

Is there a Message?

- $\lambda(M_{Planck}) \simeq 0$ ➔ implies big log cancellations
  M_{planck}, M_{weak}, gauge, Higgs & Yukawa couplings **are unrelated**

- **remember: μ is the only single scale of the SM ➔ special role**
  - consider $\mu^2 = 0$ ➔ $V(M_{Planck}) \simeq 0$
  - flat Mexican hat (<1%) at the Planck scale! ➔ **a message?**



➔

➔ **conformal (or shift) symmetry as solution to the HP?**

➔ **combined conformal & EW symmetry breaking (models…)**

➔ realizations vie Higgs portals: $\lambda\,(\phi^+\phi)(\Phi^+\Phi) \to \underbrace{\lambda <\phi^+\phi>}_{\mu^2 \neq 0}(\Phi^+\Phi)$

➔ implications for neutrino masses and DM

Example: Consequences for Neutrino Masses

Conformal symmetry: explicit Majoran or Dirac masses forbidden
➔ all masses must arise from suitable VEV * Yukawa coupling

$$\mathcal{M} = \begin{pmatrix} 0 & y_D \langle H \rangle \\ y_D^T \langle H \rangle & y_M \langle \phi \rangle \end{pmatrix}$$

Yukawa seesaw:

SM + ν_R + singlet

$$\langle \phi \rangle \approx \mathrm{TeV}$$

$$\langle H \rangle \approx 1/4\, \mathrm{TeV}$$

➔ generically one would expect a TeV seesaw
BUT: y_M can be tiny

➔ wide range of sterile masses ➔ including pseudo-Dirac case
➔ suppressed $0\nu\beta\beta$

More Consequences

- **BSM physics ➔ less easy to find at LHC**
- **Modified neutrino physics ➔ many more options**
- **New dark matter candidates**
- **Important conceptual consequences...**

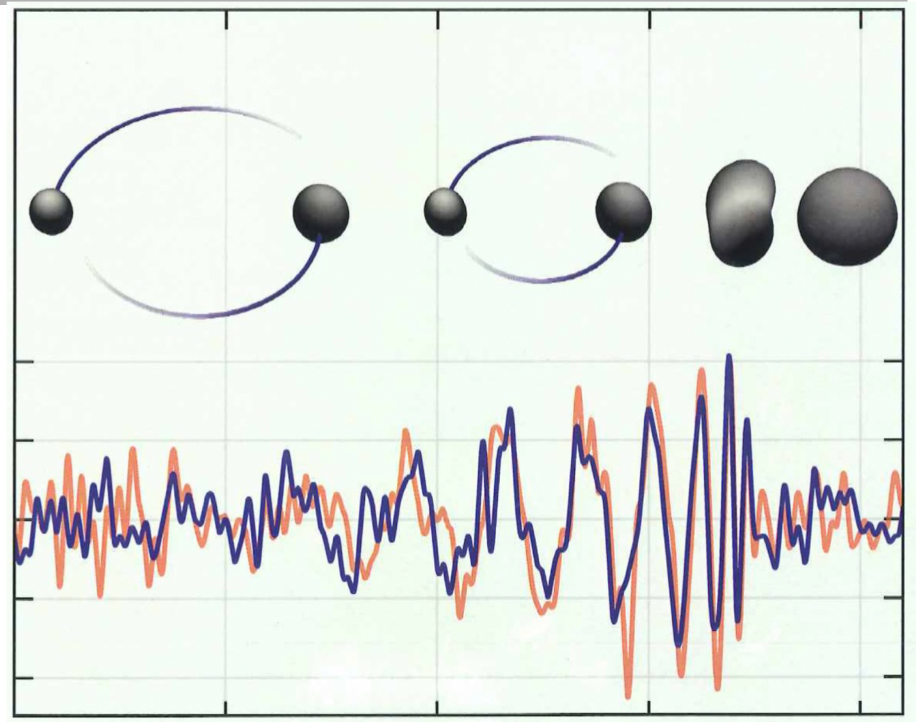
The general situation from no new particles @LHC:

- **Keep looking ....**
- **SUSY models with little hierachy**
- **New ideas: conformal, ...**

➔ There must be some new physics!

A new Player: GR Waves

Gravitational waves from merging super massive objects: BH, NS, ...

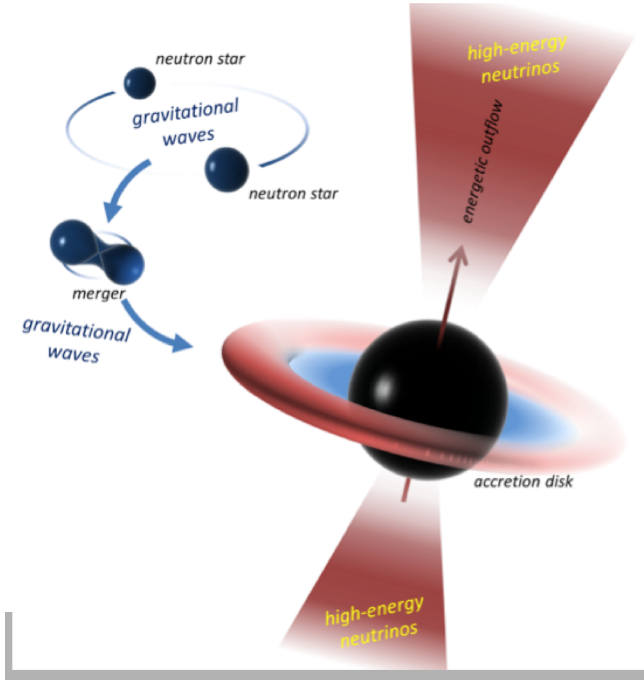


Characteristic down-spiral:
- increasing frequency & amplitude

➔ distance, masses, size, ...

1st detection: Sep. 14, 2015

Today: ~1 merger/week ➔ many events...



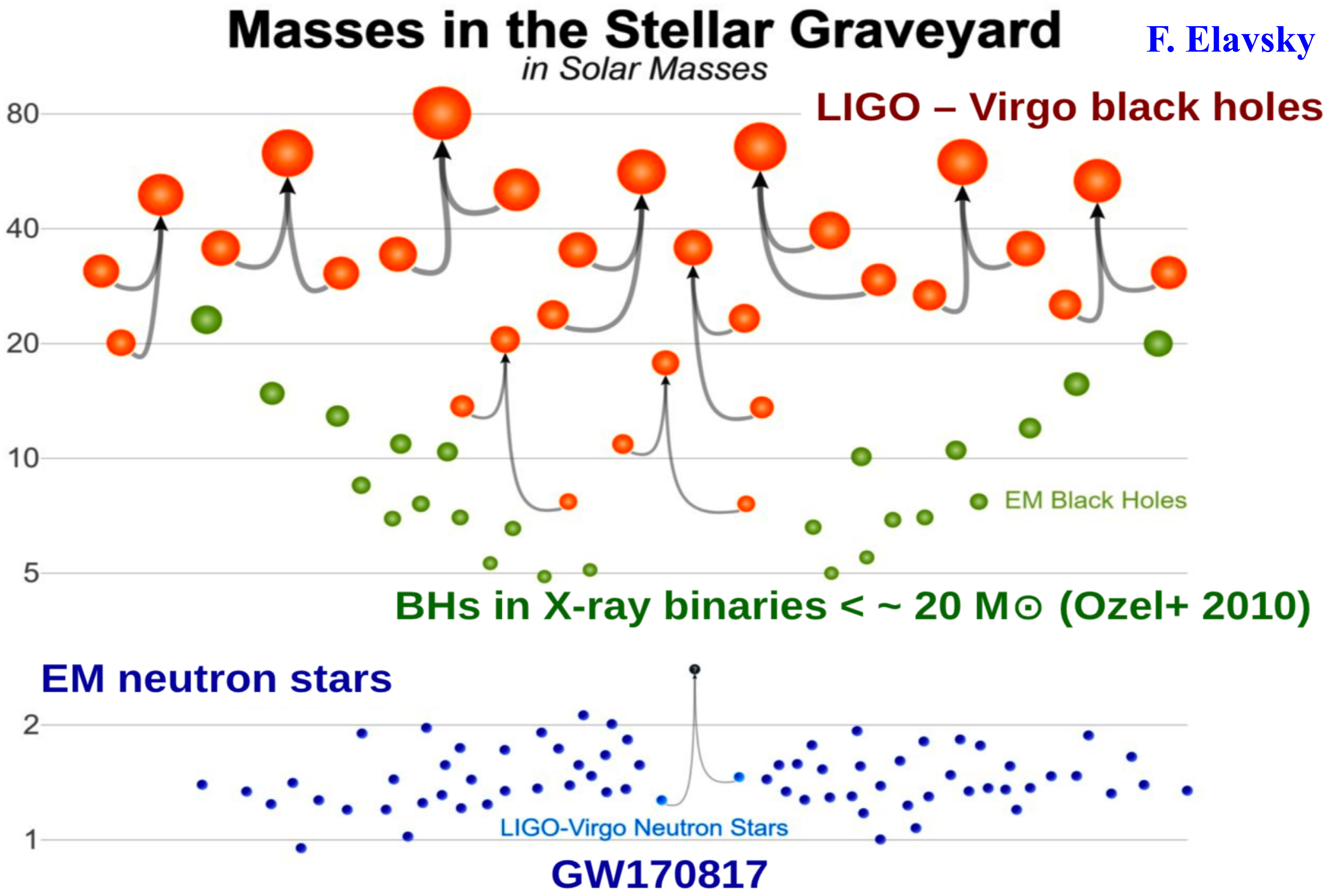
Some mergers have jet-like processes

➔ jets ➔ occasionally pointing towards us

➔ GR waves + light + neutrinos

➔ multi-messenger observations @ Mpc

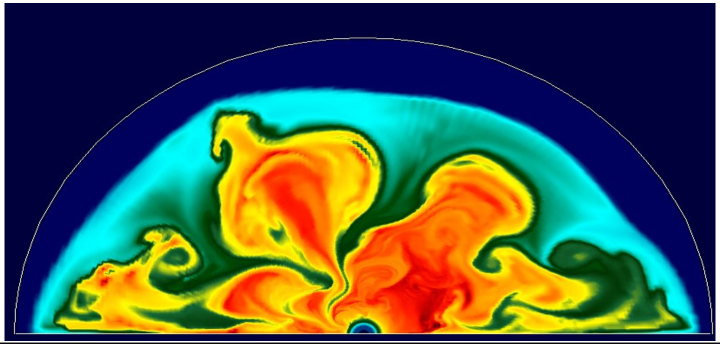
➔ enormous lever arm (c, mass dispersion, sources)

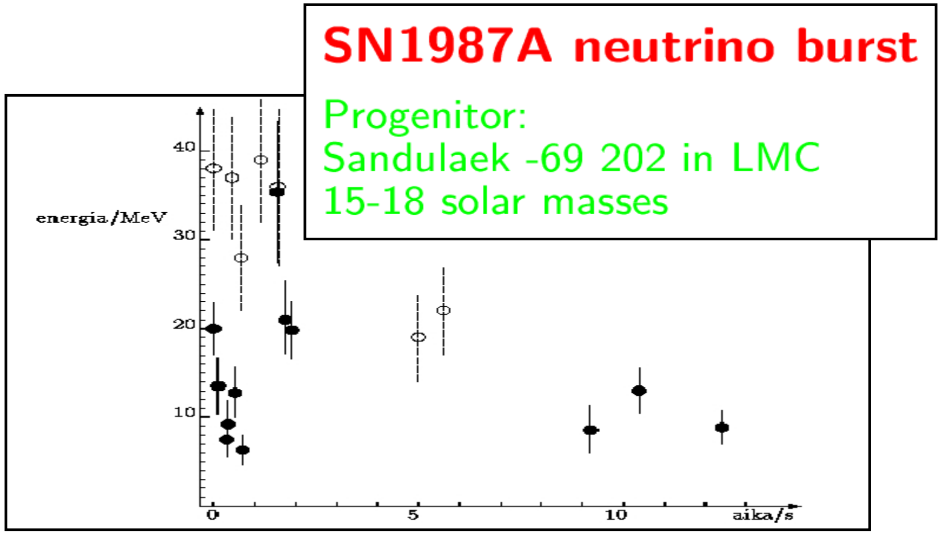


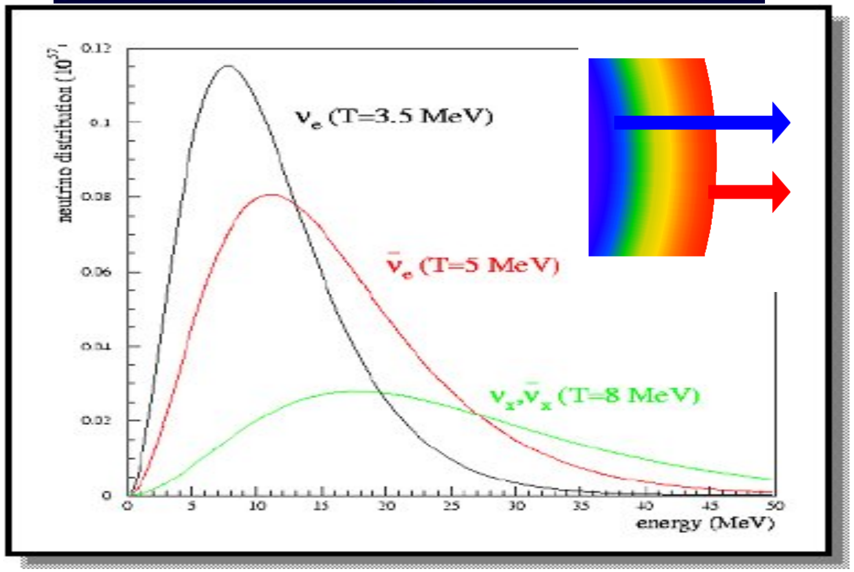
Q: BH population ←→ primordial BHs, ←→ early U ←→ BSM, DM, ν's, ...
NS-mergers ←→ nucleosynthesis ←→ SN ←→ ν's, BSM, DM
...other connections...

Supernova Neutrinos

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



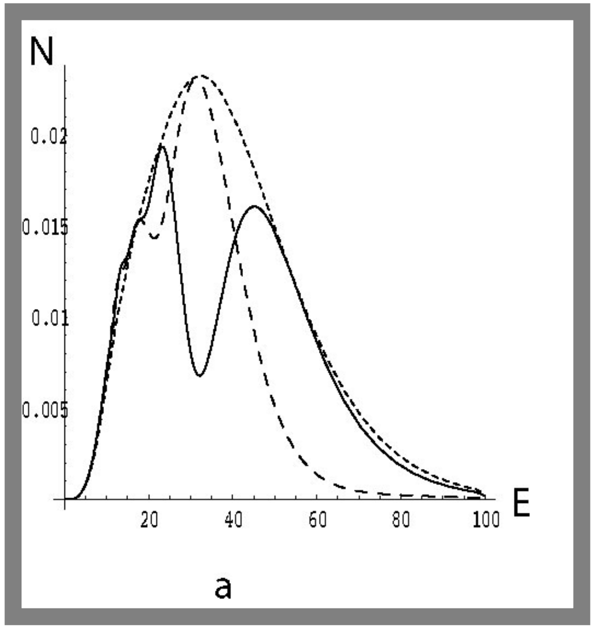




In SuperK:
O(10k) evts. @10kpc

MSW: SN & Earth

sensitive to sgn(Δm^2)
+other ν-parameters

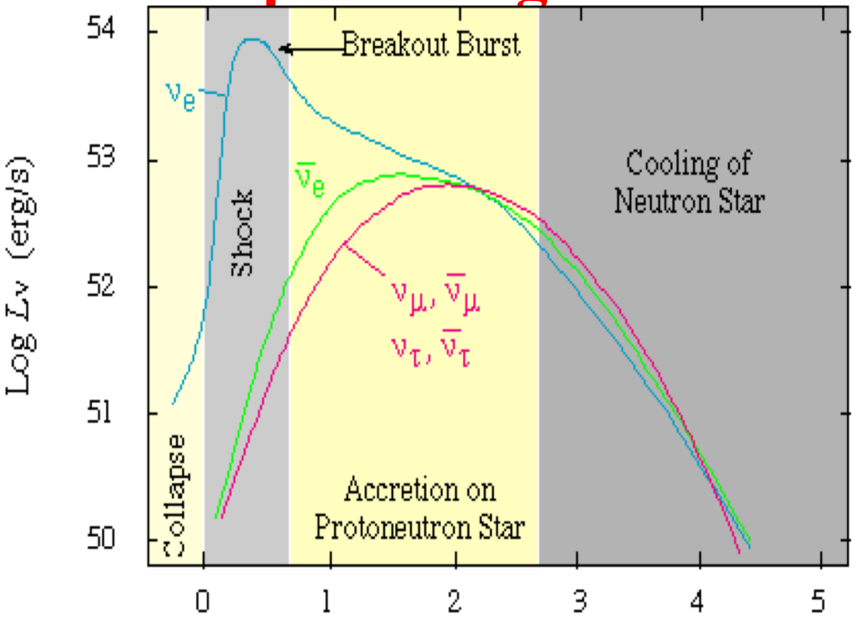


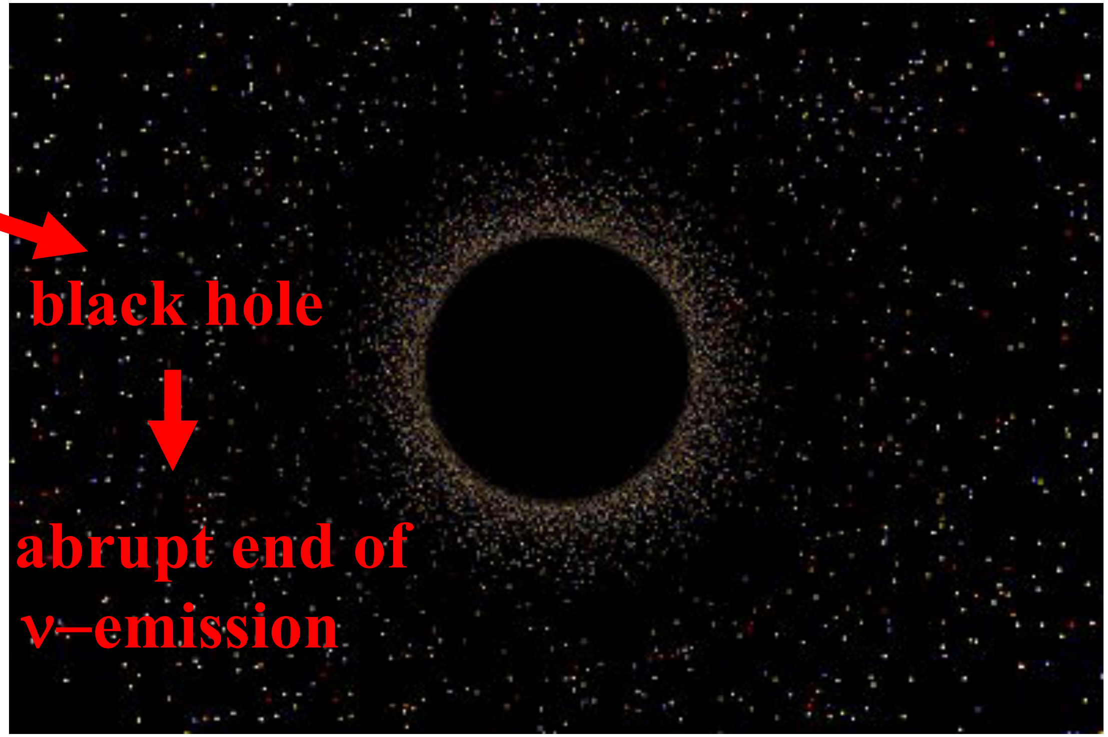
2 possibilities:

Supernova

neutron star or **black hole**

Keeps cooling...

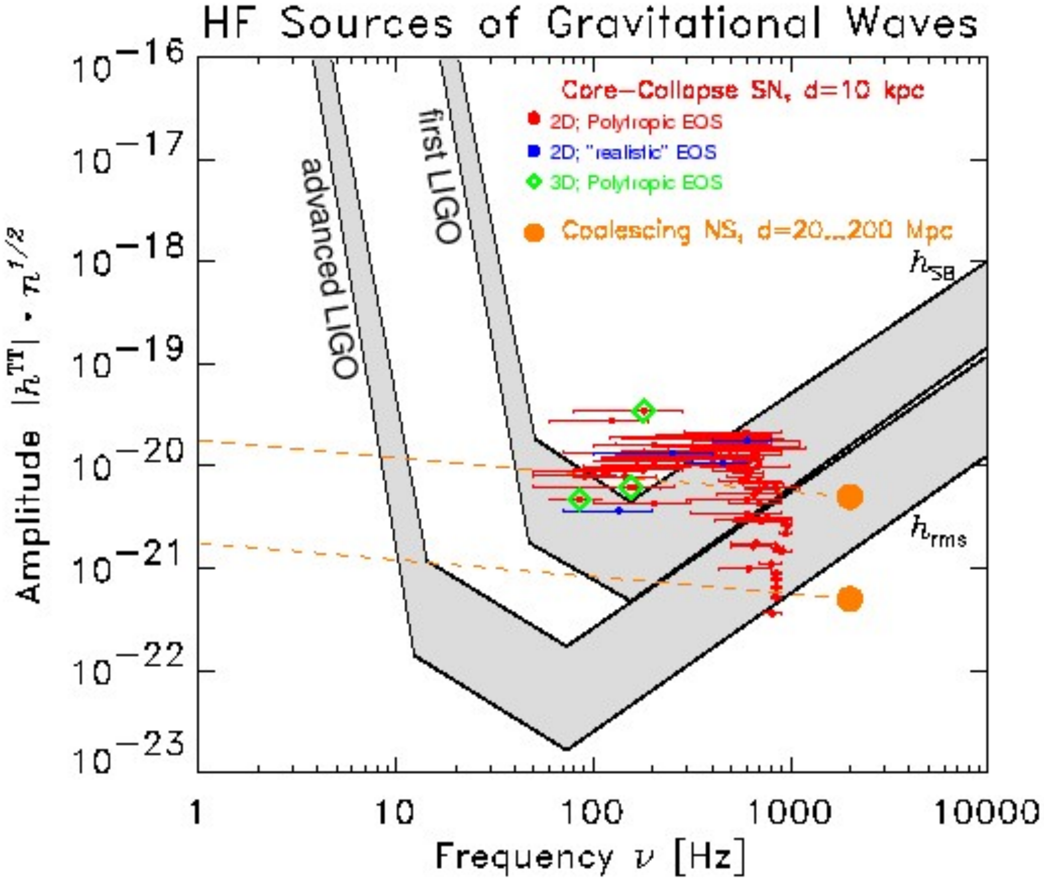


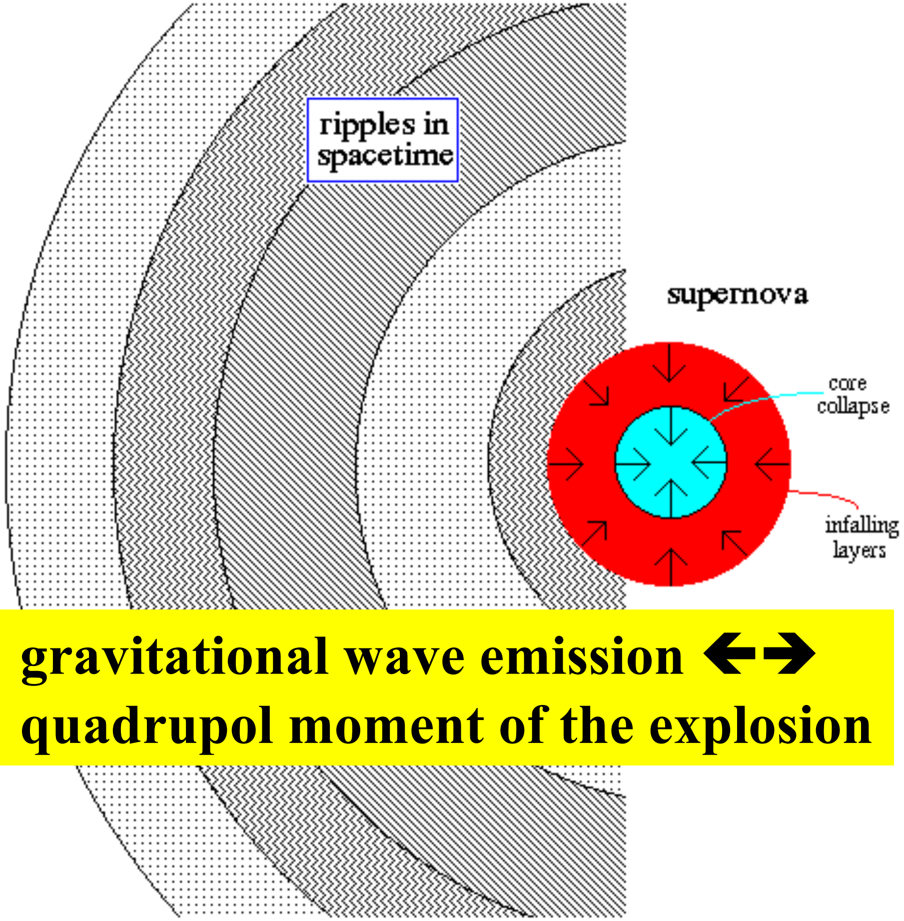


abrupt end of ν–emission

- **impressive signal of a black hole in neutrino light**
- **neutrino masses ←→ edge of ν-signal**

Supernovae & Gravitational Waves





gravitational wave emission ←→ quadrupol moment of the explosion

Dimmelmeier, Font, Müller

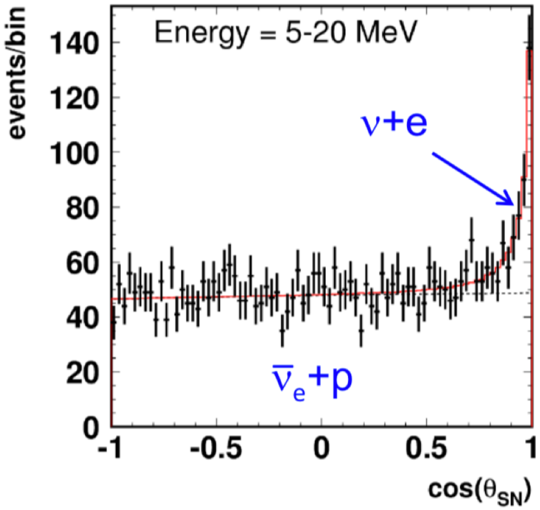
- ➔ additional information about galactic SN
- ➔ **global fits:** optical + neutrinos + gravitational waves
- ➔ neutrino properties + SN explosion dynamics
- ➔ SN1987A: strongest constraints on large extra dimensions

further topics: failed supernovae, hidden SN , **ν self-interactions (split, cohernece)**

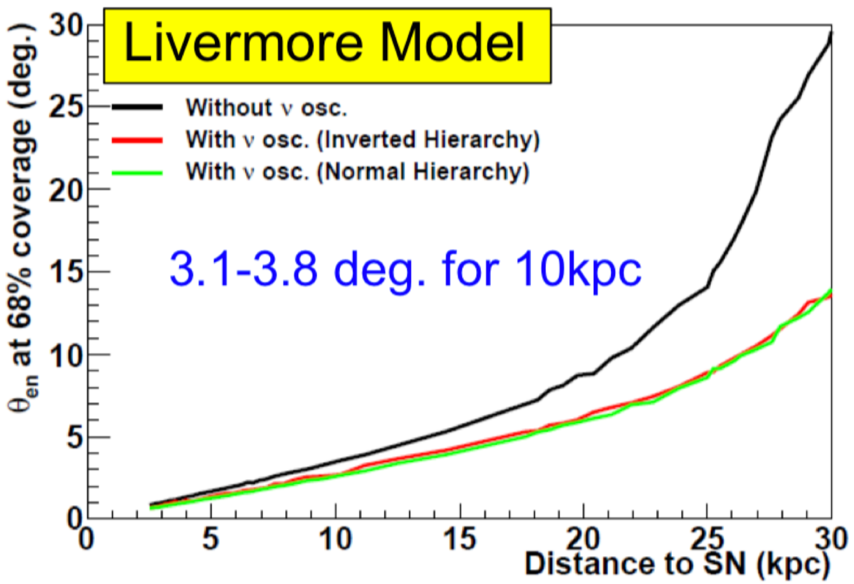
Supernova Pointing

Nakahata
Super-K directional information

➔ **HyperK**

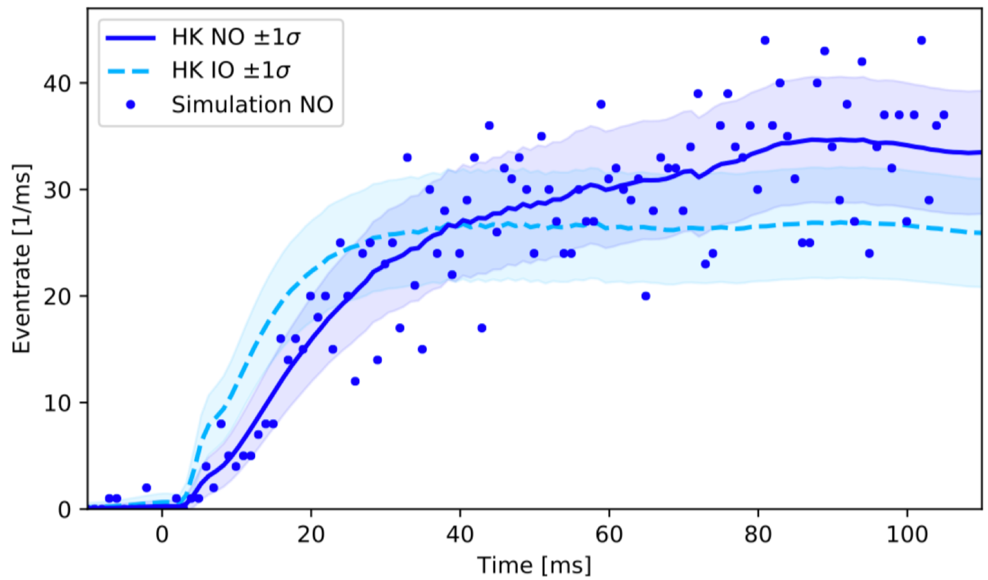


Distance vs. pointing accuracy



Another method: Hansen, ML, Scholer

➔ **Timing of the ν-burst (typ. 10kpc)**



HK, IC, JUNO, ... ➔ sub ms timing

➔ **triangulation**

$$1.8^\circ \lesssim \delta\theta_{\mathrm{IC,HK}} \lesssim 14.5^\circ$$
$$0.6^\circ \lesssim \delta\theta_{\mathrm{HK,JUNO,BH}} \lesssim 8.4^\circ$$

ν's + BH formation ➔ dispersion

➔ **neutrino mass down to 0.28 eV**

Conclusions

- **Neutrinos:**
  - 3ν or more? ←→ big and small experiments
- **DM:**
  - how many components? particles ←→ gravity/BHs
  - what if none of the prime candidates is found?
- **BSM:**
  - Higgs! → SM reigns – this is a tremendous success!
  - two surprises: no BSM particle, m_H ←→ stability
  - BSM may still pop up ←→ new ideas: conformal, ...
- **Other:**
  - GR waves, B-physics, coherent ν–scattering, ...
  - growing inter-connectivity: ν-BSM-DM-GR waves+...

➔ very interesting options! Allow for them in road maps