Workshop Summary

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HEIDELBERG



The Standard Model of Particle Physics

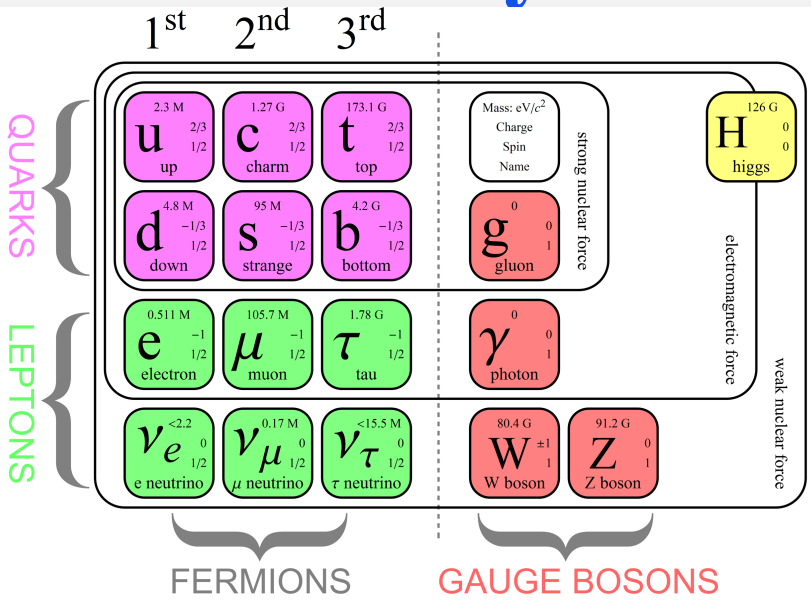
The Standard Model of Particle Physics works perfectly

- endpoint of a very successful development:
  role model: Quantum Electro Dynamics (QED)
  d=4 renormalizable gauge theory, symmetry

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

- describes essentially all known (particle) physics

- many questions: group, generations, gravity, 4d, ...



The Standard Model of Particle Physics

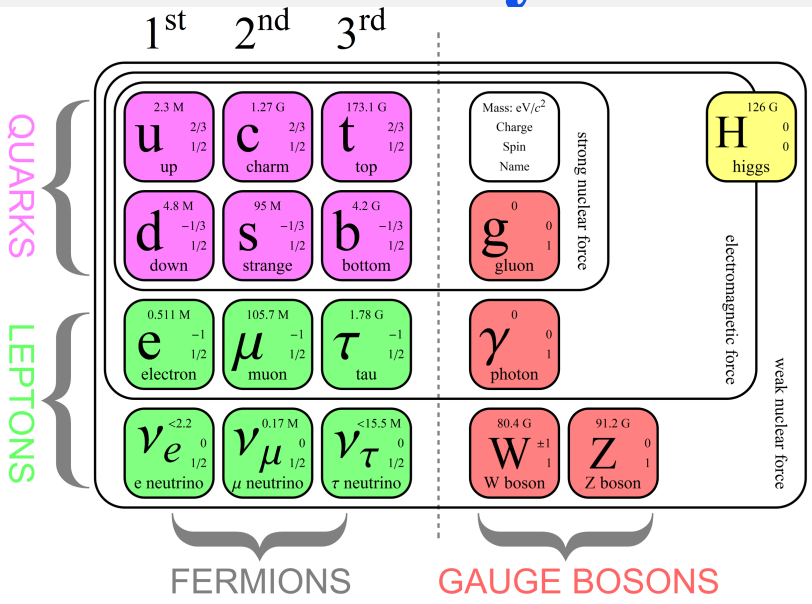
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- many questions: group, generations, gravity, 4d, ...



Experimental facts, hints, problems:

- 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
- Dark Energy

Theoretical problems:

SM does not exist without cutoff
(triviality, vacuum stability)
Gauge hierarchy problem – became worse
Gauge unification &charge quantization
Strong CP problem
Unification with gravity
3 generations, reps., d=4, many parameters

The Standard Model of Cosmology: ΛCDM

- **General Relativity: Einstein's field eqns.**

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

how geometry of spacetime is curved	cosmological constant

$T_{\mu\nu}$: energy-momentum tensor
mass, energy, momentum, ...

- **Cosmological Principle:** homogeneous isotropic Universe @large scales → FLRW metric
  → Friedmann eqs. with scale factor $a(t) = R(t)/R_0$; data from CMB, structure, ...

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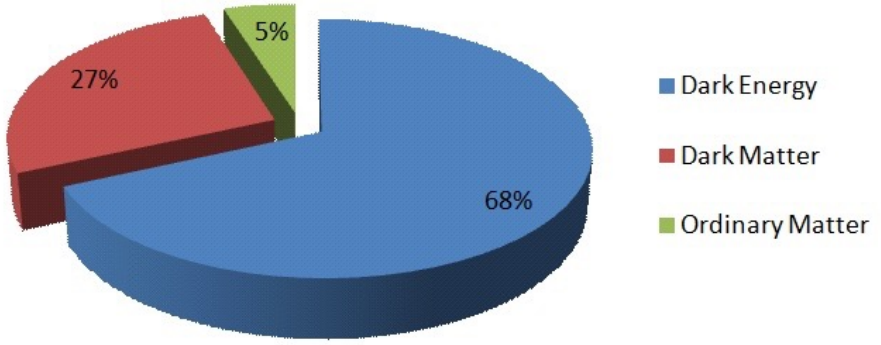
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how geometry of spacetime is curved | cosmological constant

$T_{\mu\nu}$: energy-momentum tensor
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- **Cosmological Principle:** homogeneous isotropic Universe @large scales → FLRW metric
  → Friedmann eqs. with scale factor $a(t) = R(t)/R_0$; data from CMB, structure, ...

→ works very well:



Requires BSM physics:
- **dark matter**
- **dark energy**
- **baryon asymmetry**

- **Potential problems (experiment):**
  - Hubble tension
  - dynamical DE?
  - ...

- **Theoretical problems:**
  - GR is not renormalizable → other GR
  - QFT: no absolute scale ←→ $\Lambda \neq 0$
  - ...

Amazing overall Situation

- two perfectly working standard models:

  - Standard Model of particle physics (SM)
  - Standard Model of cosmology (ΛCDM)

- interconnected (by data and conceptually)
- strong theoretical & experimental arguments for BSM and BΛCDM
- very many BSM and BΛCDM ideas...

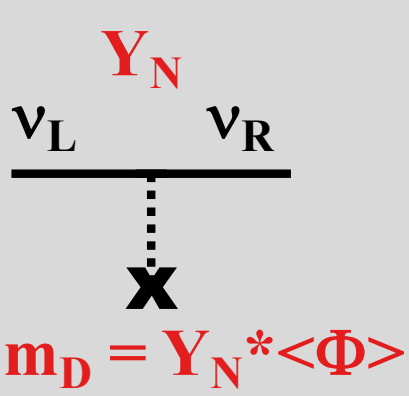
➔ **interpreting trends...**

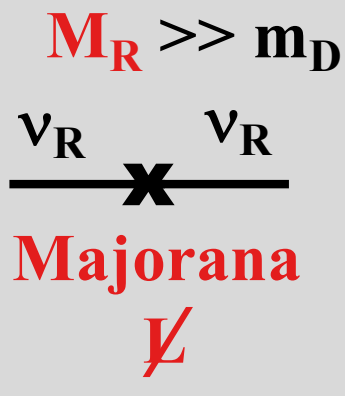
- what are we going to learn in coming years
- focus on some topics where things may change in a few years
- ...in addition, potential for surprises...

- massive neutrinos➔ **1st solid evidence for BSM physics ➔ more?**

Adding Neutrino Masses to the SM

Simplest possibility: add 3 right-handed neutrino fields







6x6: see-saw → block diagonalization

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

6x6 mass matrix with 3x3 blocks

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

new ingredients:
1) Majorana mass (explicit)
2) lepton number violation

3 active ν's → m^2_D/M_R
3 heavy sterile ν's → M_R
tiny a/s mixings → m_D/M_R

significant NEW ingredients:

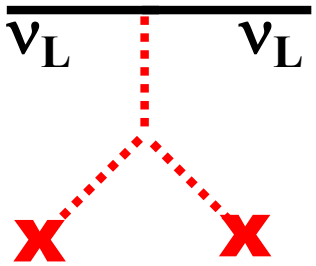
- SM=1-scale theory → multi-scale theory
- modified global symmetries (L, henn – egg)
- 9 more parameters

→ **call it at least SM+** → **see-saw, $m_\nu = (m_D)^2/M_R$; mass ≡ L violation**

Many other Neutrino Mass Opions

2) new Higgs triplets Δ_L:

➔**left-handed Majorana mass term:**



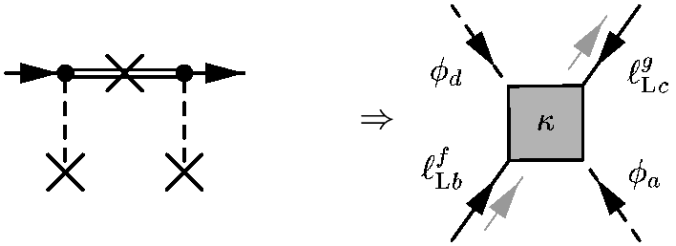
➔ $M_L \bar{L} L^c$

3) Both ν_R and new Higgs triplets Δ_L:

➔ **see-saw type II**

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

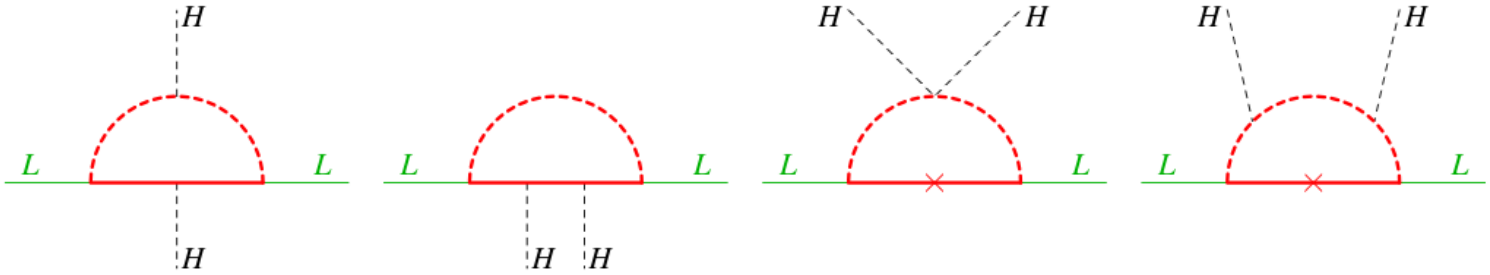
4) Higher dimensional operators: d=5, …



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

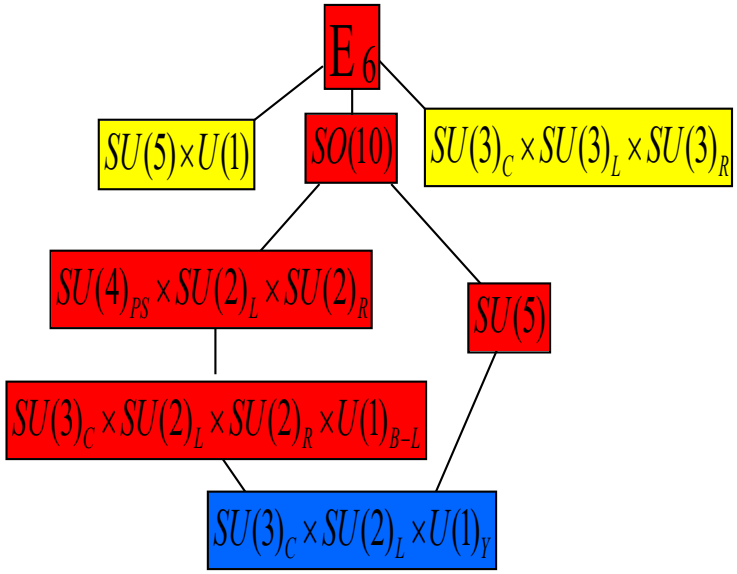
➔ $M_L \bar{L} L^c$

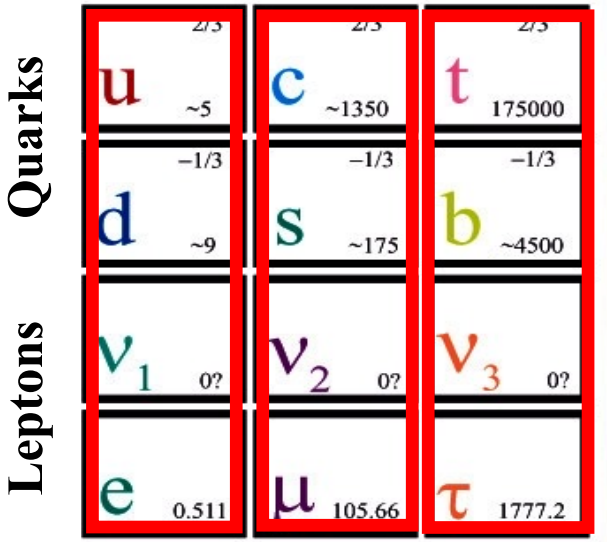
5) Radiative neutrino mass generation ←→ BSM



Even more Options / Requirments

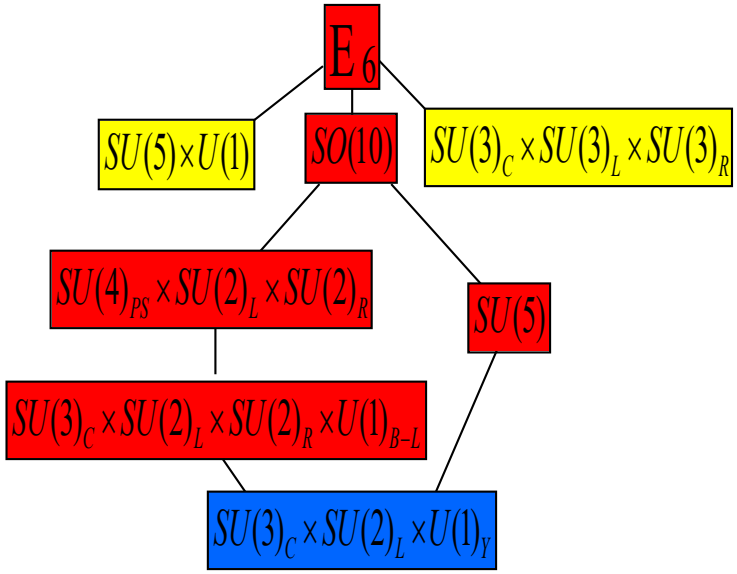
6) Gauge unification, GUTs and Flavour symmetries





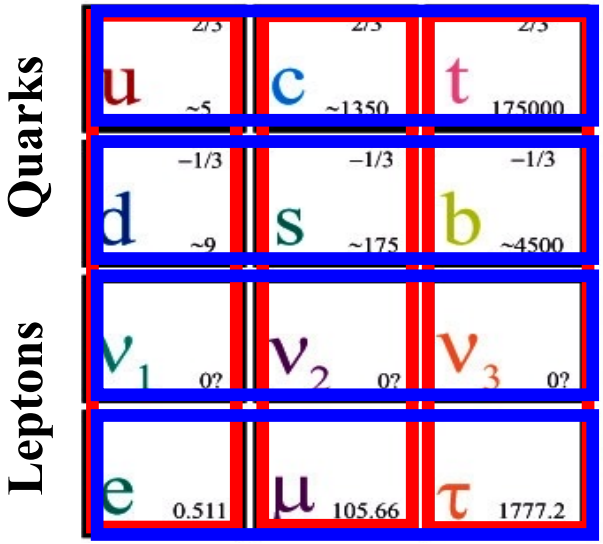
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Generations are only copies
➔ horizontal symmetries?
A4, S3, D5, T‘, ...
breaking...
➔ explain regularities

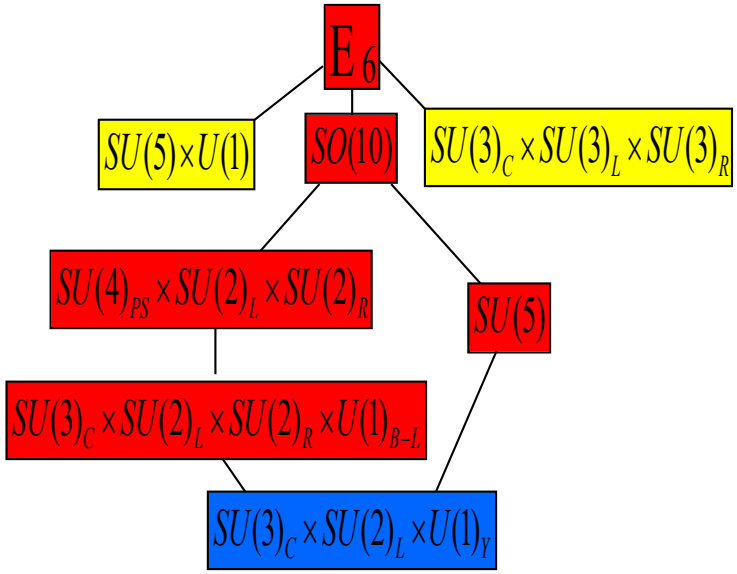
more options ←→ more constrains, precision



generation 1. 2. 3.

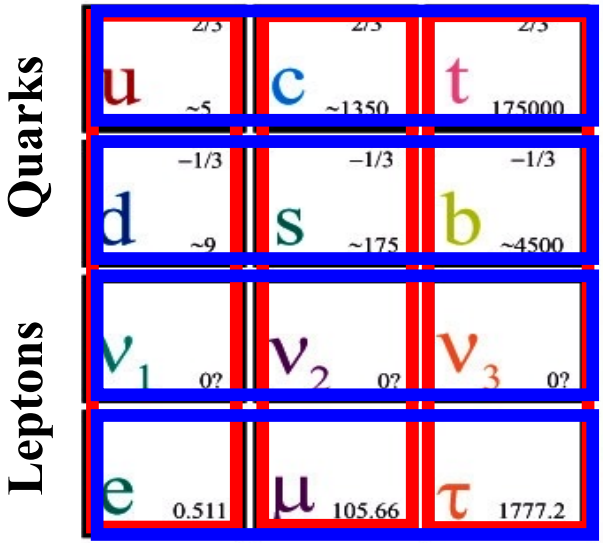
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generation 1. 2. 3.

7-N) More: further ν‘s, SUSY, gauge groups, extra d, strings,…

- ‘neutrino’ is the most frequent name in titles of papers on INSPIRE...
- many ways to ‘explain’ neutrino masses
- mass mechanism & required extra fields are *NOT* known (ν_R, ϕ, Δ,...)
- all BSM information is so far encoded into 3 masses and mixings

➔ BSM physics affects oscillations, 0νββ and interactions (CEνNS)

Motivation for Precise Masses & Mixings

Scenarios:

1) minimal = SM+: 3 neutrino framework only (masses, mixing, unitarity,...)
2) expanded: very many scenarios beyond SM+

Goals of precision oscillation and absolute mass measurements:

a) Deviations from 3ν framework:
- tests of 3 flavour unitarity & searches for sterile neutrinos → aa, ss, a-s $\lesssim$ 1%
- effects of additional BSM particles & interactions → $\approx g^2/M^2$
  → precision is very valuable to verify/exclude BSM effects
  → new effects would not be surprising, since SM+ is only simplest option
  → where?

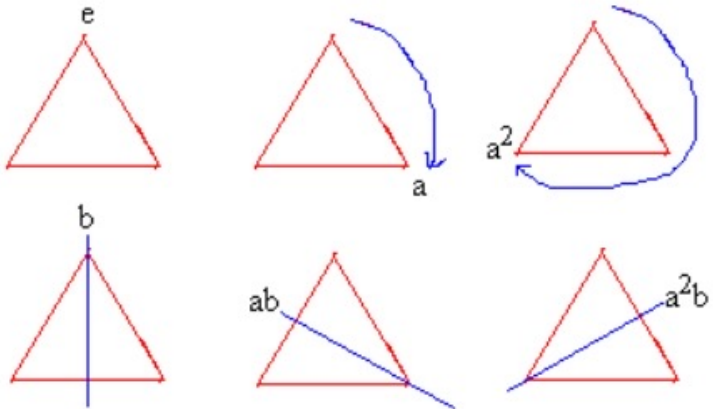
a) Understanding the origin of fermion masses:
- apparent regularities of quark and lepton masses and mixings
  → cries for an explanation → how can this be understood?
  → neutrinos are very valuable: theoretically and experimentally "cleaner"

Understanding Flavour

- the basic idea:
- horizontal symmetry (discrete, continuous)
- broken at some high scales by ``flavons''
  ➔ explain observed masses and mixings

e.g. dihedral groups D_n

geometric origin of D_3:



Many groups and breaking scenarious
→ phenomenologically promising examples: e.g. D_5 Hagedorn, ML, Plentinger
→ many other examples... ←→ precision to test

task: search for mass terms which are for suitable Higges singlets under D_5

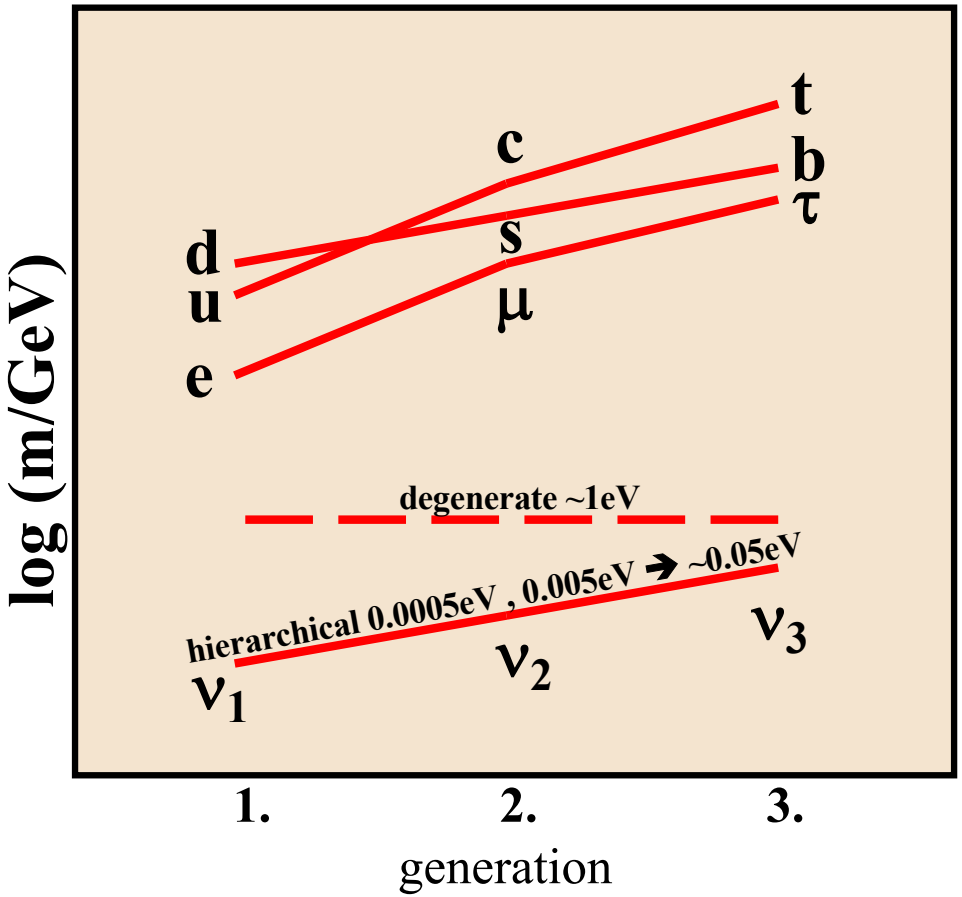
1) assign all fermions to representations $L = \{L_1, L_2, L_3\}$

2) all possible mass term using scalars ←→ singlet under symmetry ➔ mass structure
3) problem: many scalars (flavons), special VEVs, ... ➔ many models ...

➔ **by now: big number of models ←→ improved precision ???**

Puzzeling empirical Regularities

Quarks & charged leptons ➔ mass hierarchy pattern ➔ neutrinos?



Quarks and charged leptons:

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

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

See-saw:

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

H	~10	≥20	?	≥20

- neutrinos are least hirarchical ←→ See-saw suggests amplified hierarchy?
- less hierarchy in m_D or correlated hierarchy in M_R ? ➔ theoretically connected?
- no problem if neutrinos are Dirac particles!

Hints for Neutrino Masse Hierarchy

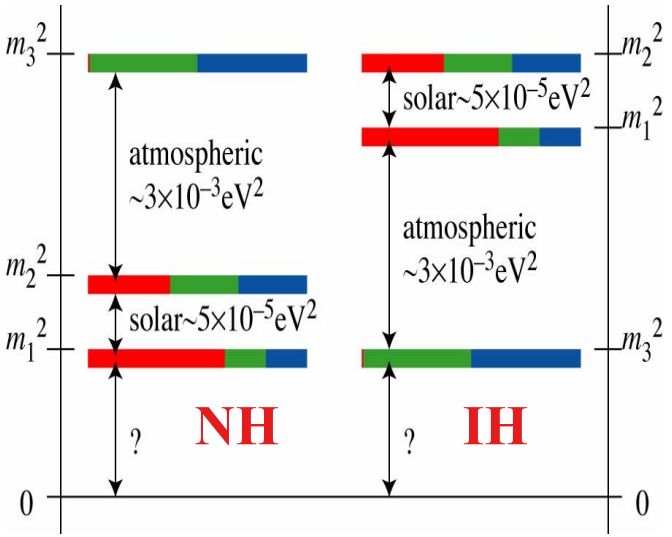
Neutrino masses and mixings constraint by:

- **absolute mass measurements:**
  $m_\nu < 0.45$ eV @90%CL (KATRIN)
- **oscillations – dominated by two flavor contributions**

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta) \cdot \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

→ dominant two flavour picture:
- normal hierarchy (**NH**) → $\Sigma m_\nu \gtrsim 50$ meV
- inverted hierarchy (**IH**) → $\Sigma m_\nu \gtrsim 100$ meV

- mass ordering is in oscillations ≈ a small sub-leading effect
- excellent global fits; sterile neutrino evidences ≈ gone



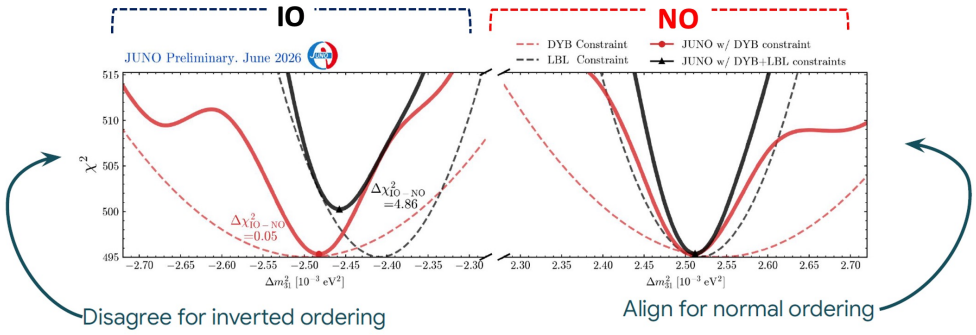
Global fits work excellent for 3ν case

- Remaining tension:
  Dirac CP phase δ from T2K and NOvA
  → NSI operator $|\varepsilon_{\mu\tau}| \approx 0.15$ →M_X=500 GeV?

- combining all data ➔ preference for NH; e.g.:
  I. Martínez Soler, NOW 2026
  F. Marcone, NOW 2026

  B. Caccianiga (on behalf of JUNO), NOW2026 ➔

QUANTITATIVELY: Combining JUNO+Daya-Bay (Reactor) with MINOS, NoVA, T2K (LBL)



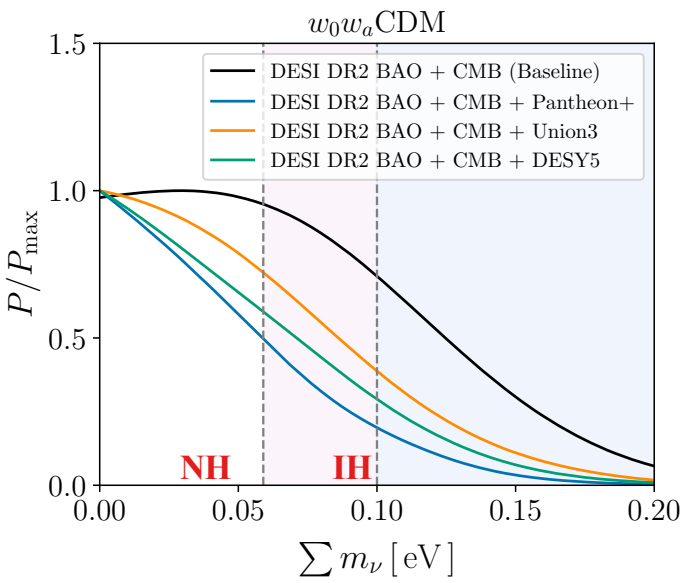
Normal Ordering is preferred with $\Delta\chi^2$=4.86

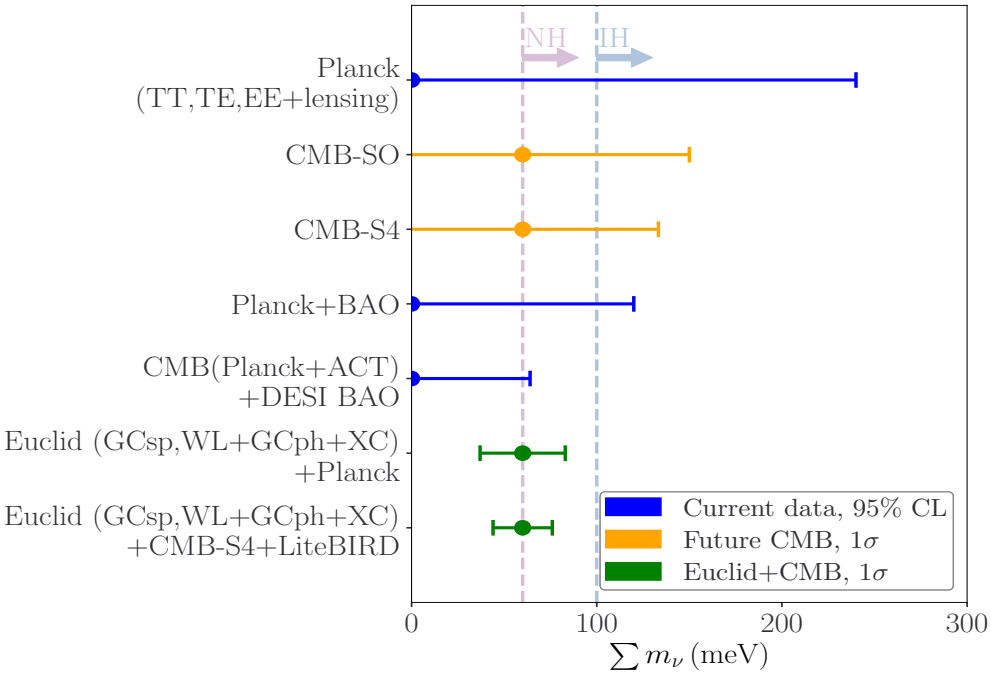
* NuFit 6.0 - JHEP 12 (2024) 216 [arXiv:2410.05380]; www.nu-fit.org

more data ➔ further improvements to come

Cosmology: Σm_ν – Now & Future

M. Archidiacono, Erice 09/2026





Combining everything → now:

- more and less aggressive analyses...
- trend towards NH: $\Sigma m_\nu \gtrsim 50$ meV
- +limited sum → $\Sigma m_\nu \lesssim 50$ meV

  ≈ 50 meV atmospheric

  ≈ 5 meV solar

  ≈ 0.5 meV ≈ 0

Future (within in a few years...):

- significantly reduced errors for Σm_ν
- central value: NH, IH or other?
- consistency with lab results?

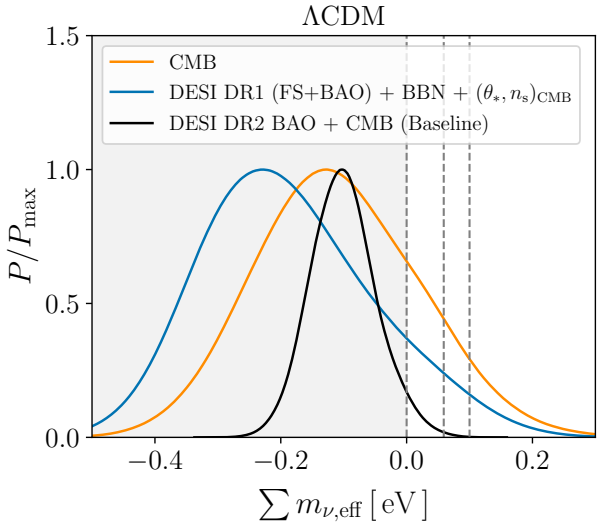
  yes: both SM's OK → NH or IH

  no: → BSM → particles/cosmology?

Combined Situation within a few Years...

a) Cosmology and lab results are inconsistent:

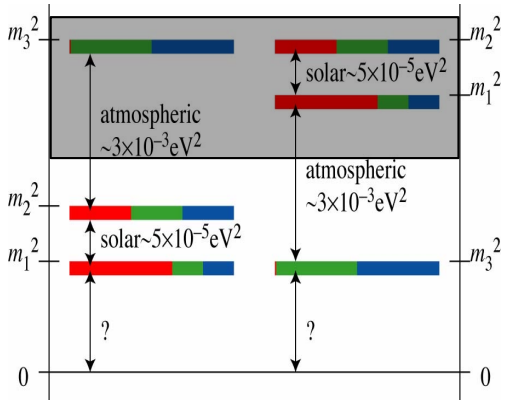
- **BSM (or systematics) in cosmology or particle physics**
- examples:
  * modified cosmology:
    systematics... ←→ negative fit parameter $\Sigma m_{\nu,\mathrm{eff}}$?
    dynamical dark energy ; $p_{\mathrm{DE}} = w(a)\,\rho_{\mathrm{DE}}$, ...
  * particle physics:
    if both NH and IH were 'excluded'? → decay?
  * various more things one could think of... → exciting!



DESI Collaboration, Elbers et al., 2025

b) Cosmology and lab results are consistent:

- indicates that both SM's work even better ➔ IH or NH
- limits BSM ideas
  * role of ν's in cosmology
  * particle physics: neutrino mass models

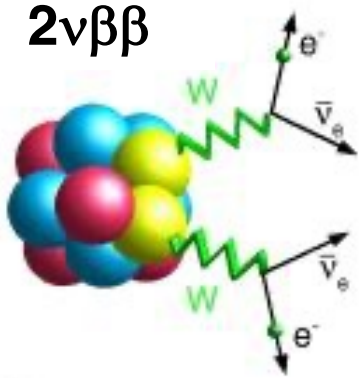


planned 0νββ projects test IH; NH is extremely challenging, requiring many years

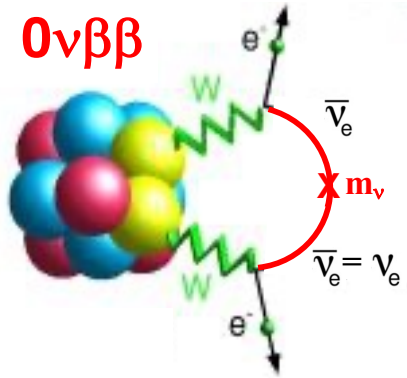
➔ time to think about consequences for 0νββ if trend to NH persists?

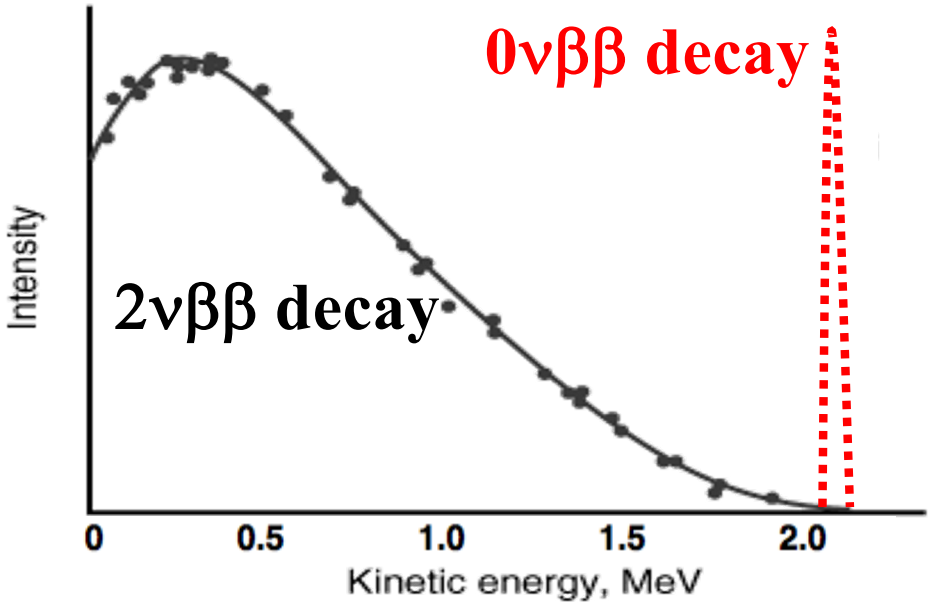
Majorana Neutrino Interpretation of 0νββ

SM



assume Majorana mass





$$1/\tau = G(Q,Z)\,|M_{nucl}|^2\,\langle m_{ee}\rangle^2$$

lifetime τ

NMEs have uncertainties…

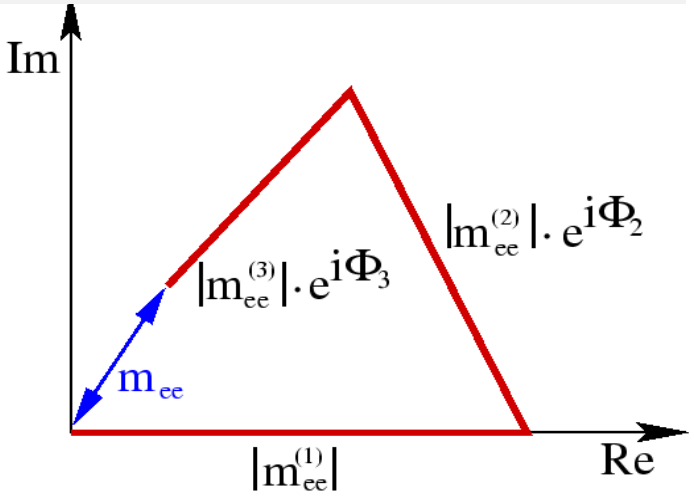
- observe expected 2νββ signal
- look for a line at $Q_{\beta\beta}$

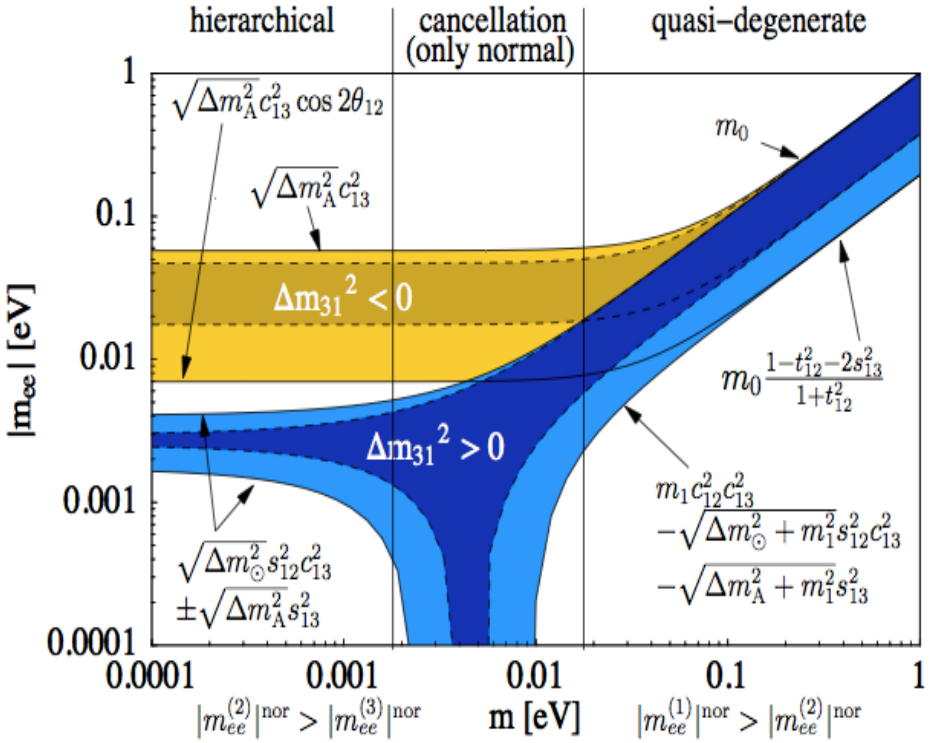
interprete signal **as Majorana mass**

m_{ee}: The effective Neutrino Mass

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

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





Comments:

- known Δm^2 from oscillations
- m_1 = free parameter (within limits)
- NMEs ➔ unavoidable theory errors
- TH + EX errors → bands

- ton-scale projects aim at covering IH

often claimed: seeing 0νββ ➔

- Majorana neutrino masses
- ν_R exists

Beware of Assumptions

- **The magnitude of 0νββ and it's relation to the physical mass**

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

➔ $m_\nu = m^2_D/M_R$ **plus:** $M_R >> M_D$

➔ **claiming that 0νββ implies Majorana masses is a consequence of assumptions**
➔ obvious if $M_R = 0$ ➔ Dirac masses

- **partial Majorana component: e.g. conformal extensions of the SM**

- Dirac mass terms as before: $m_D = y_D * \langle H \rangle$ (Yukawa coupling * EW-Higgs-VEV)
- Majorana masses ←→ scales? ➔ $M_R = y_M * \langle \Phi \rangle$ (Majorana Yukawa * new heavy scalar VEV)

➔ very interesting consequences:

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

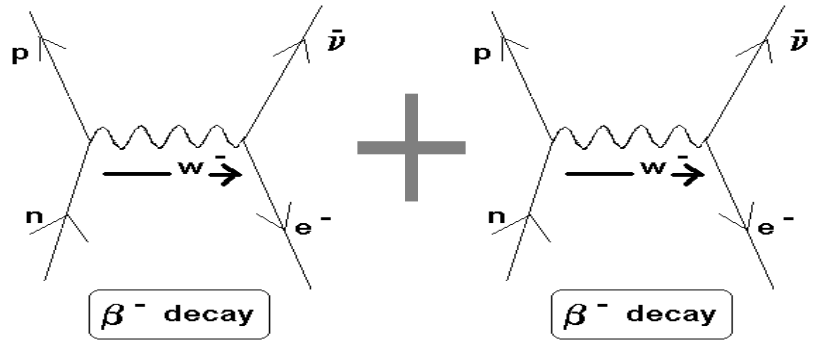
- Yukawa couplings are typically tiny: $y_M \ll 1 \rightarrow M_R \ll m_D$ ➔ eigenvalues: $m = m_D \pm M_R$
  ➔ pseudo Dirac neutrinos with a tiny Majorana component

NB: works for any neutrino mass model: M ➔ $y_x * v_x$ ➔ very rich phenomenology

➔ **we do not know which fraction of neurtrino masses is L-violating!**

Other Double Beta Decay Processes

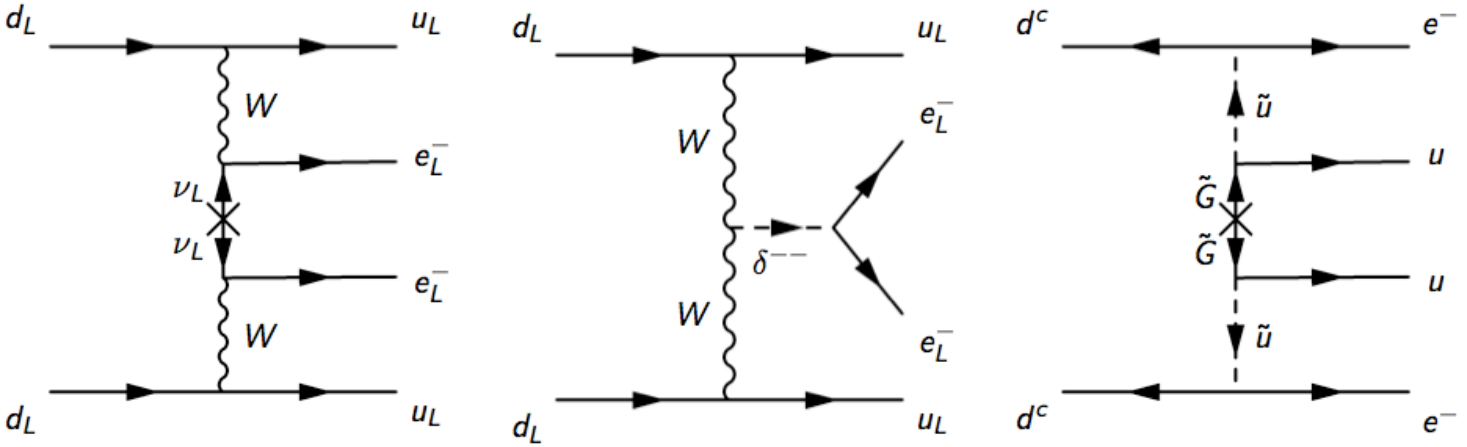
Standard Model:



➔ 2 electrons + 2 neutrinos

$2\nu\beta\beta$

Contributions from all ΔL=2 physics: ➔ 2 electrons $0\nu\beta\beta$



…

SM + Higgs triplet

SUSY

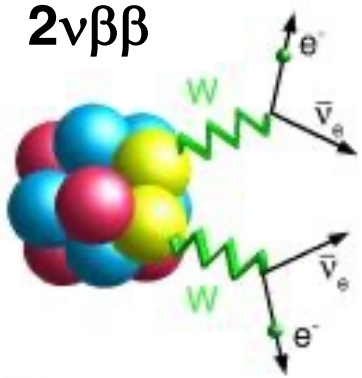
Majorana part only
of neutrino masses
Majorana ←→ Dirac

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

More general BSM L-Violating Processes

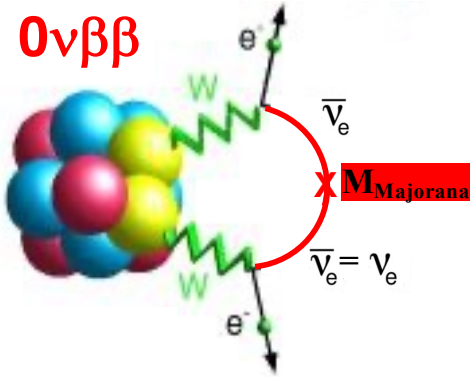
SM

2νββ

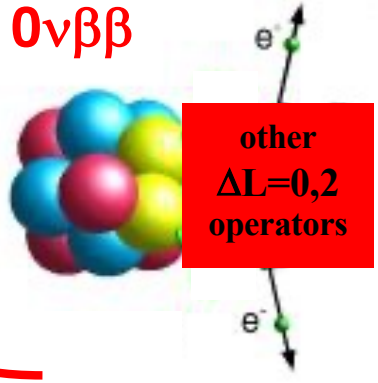


BSM

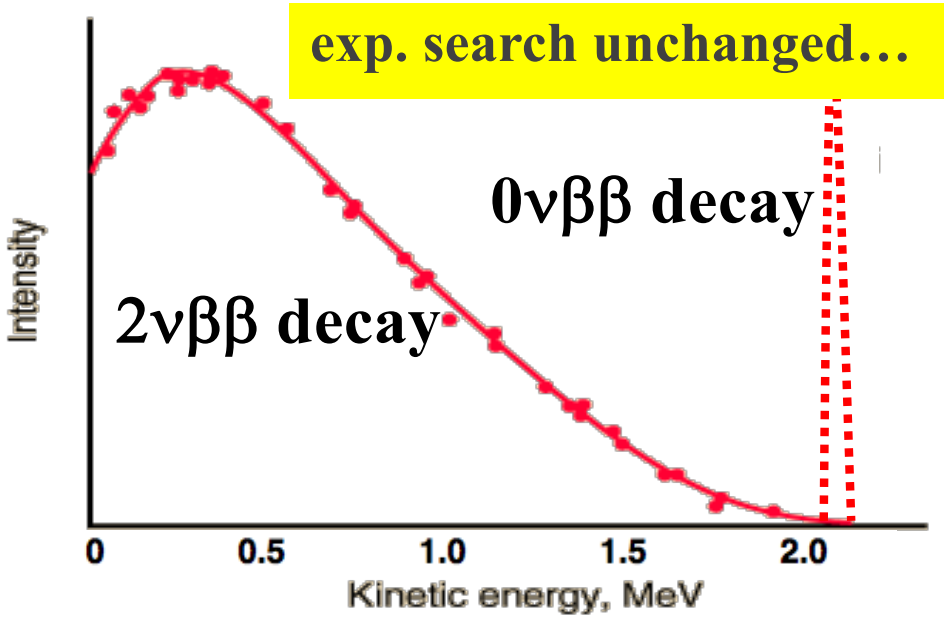
0νββ



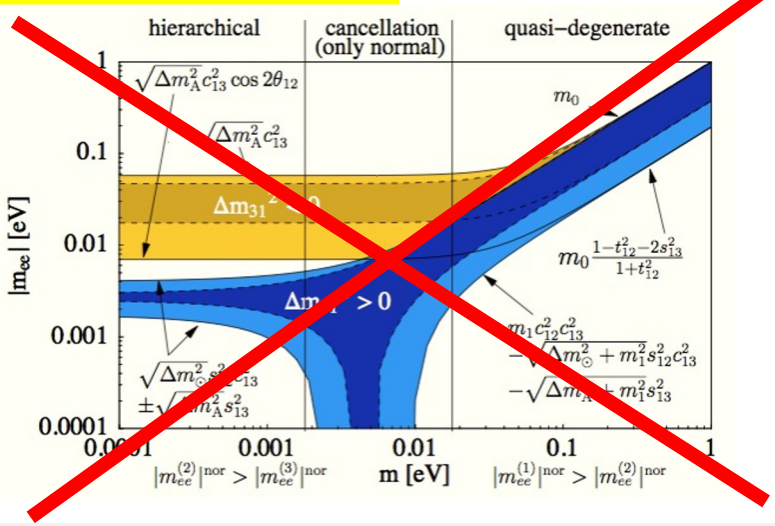
0νββ



exp. search unchanged…

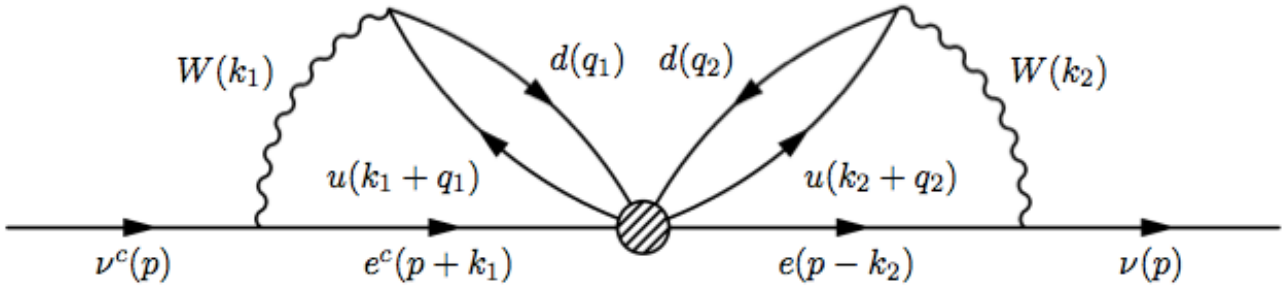


…interpretation changes:



The Schechter-Valle Theorem induced Mass

- SV: any ΔL=2 operator which leads to 0νββ decay **induces via loops** Majorana masses: observing 0νββ → neutrinos have Majorana mass
- assume 0νββ signal in today's experiments: e.g. @IH → how much indiced?
  → calculate the relevant 4-loop diagram **Dürrr, ML, Merle**



→ $\delta m_\nu = 10^{-25}$ eV → extremely tiny (only of academic interest)
→ cannot explain observed n masses and splitting's
→ Dirac neutrino mass term required to explain observed masses

Extreme (misleading) possibility:

- 0νββ = L violation induced by other BSM physics
- neutrino masses = Dirac (plus very tiny correction)

The overall 0νββ Situation

- **There exist many options for neutrino mass generation**
  - ➔ introducing only ν_R is a simple but strong assumption
  - ➔ there exist many other well motivated scenarios for more
- **0νββ is a consequence of all contributing L violation**
  - ➔ there exist many ways to violate L
    - neutrino masses: fraction of m which violates L
      - * see-saw: all of m ←→ ν_R only is an assumption
      - * Dirac: no L violation
      - * anything in-between (see example)
    - other ΔL=2 operators → many options
  - ➔ interpreting 0νββ results:
    - the effect is a mixture of all L violating components
    - observed L-violation guarantees only tiny contributes to neutrino mass
- experiment may observe anything between 0 and current limits

  ➔ unique potential for discovery of much more

Baryon Asymmetry of the Universe

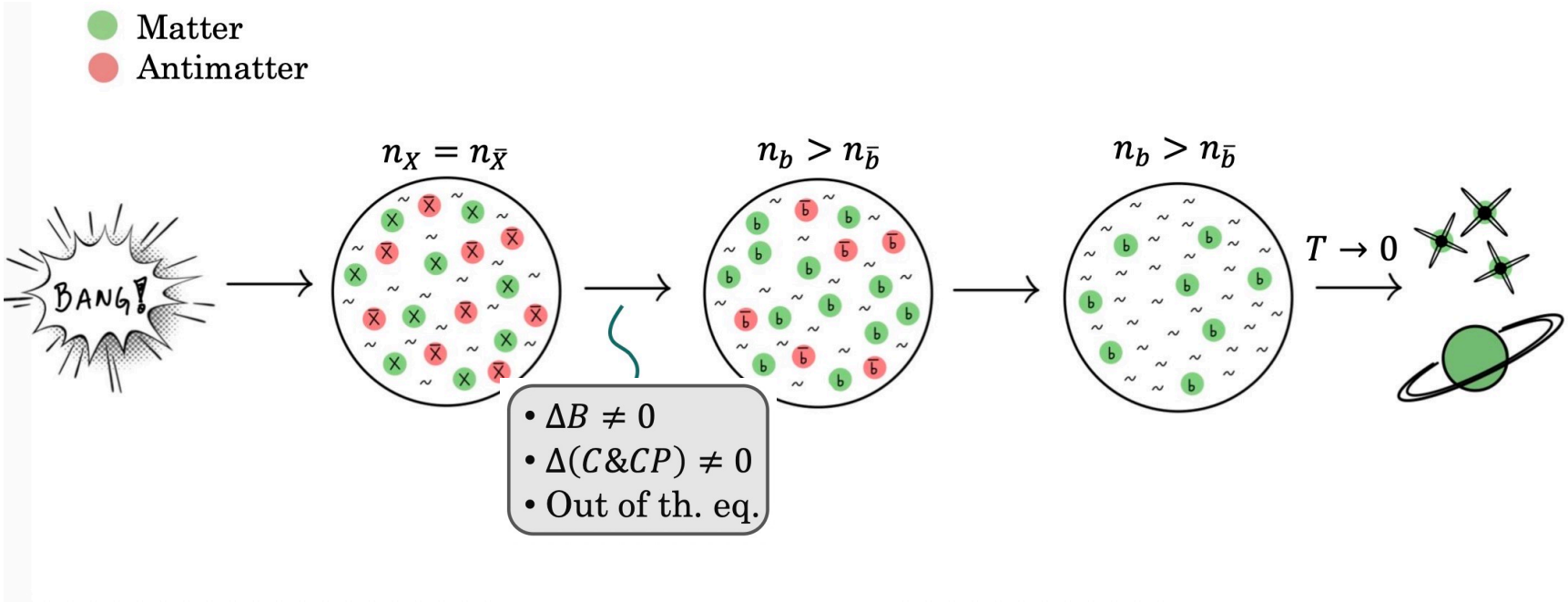
Baryon asymmetry of the Universe (BAU):

observation $\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6.1 \times 10^{-10}$

Any explanation must fulfill the Sakharov conditions:

1. Baryon number violation
2. C & CP violation
3. Out of thermal equilibrium decays

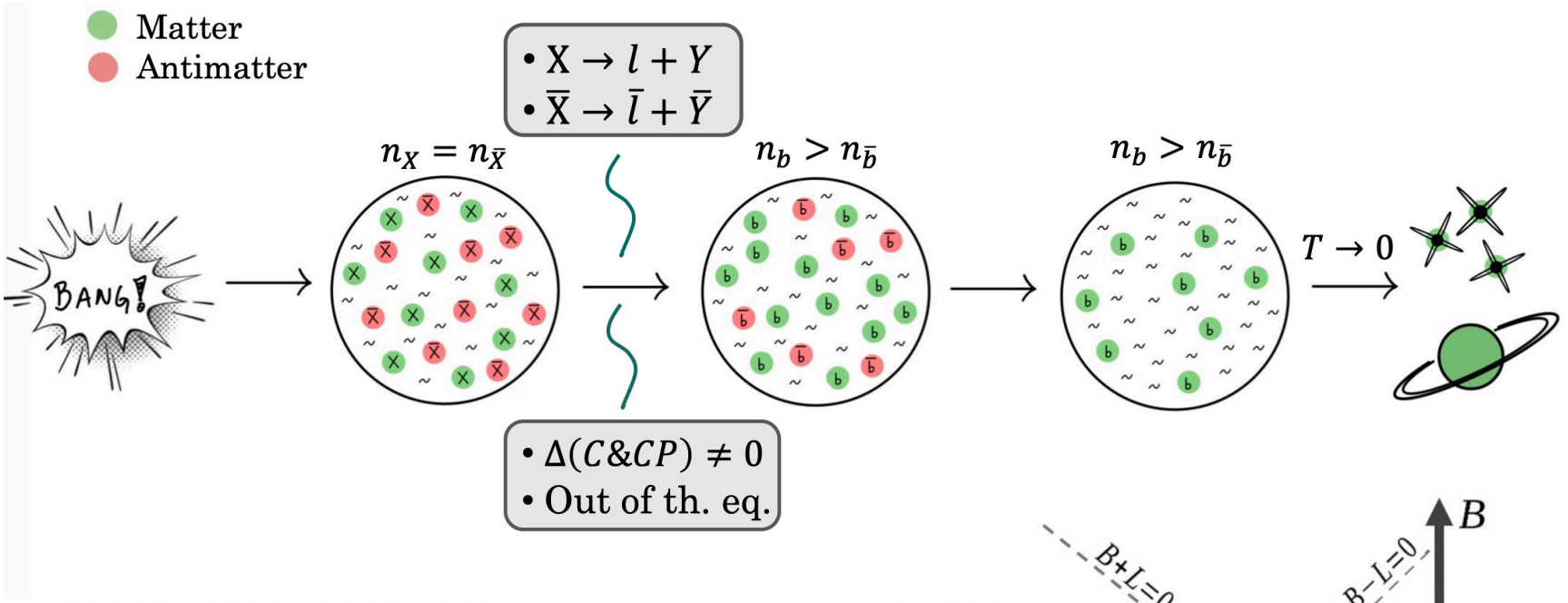
→ fulfilled by SM

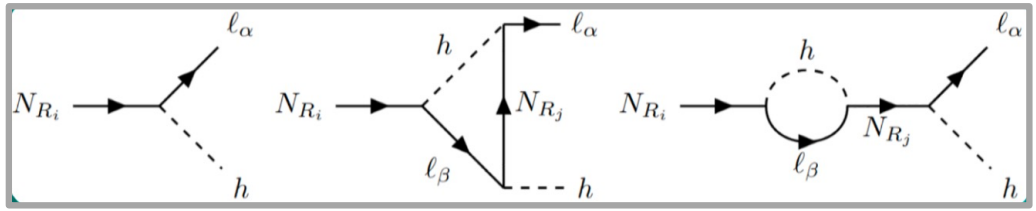


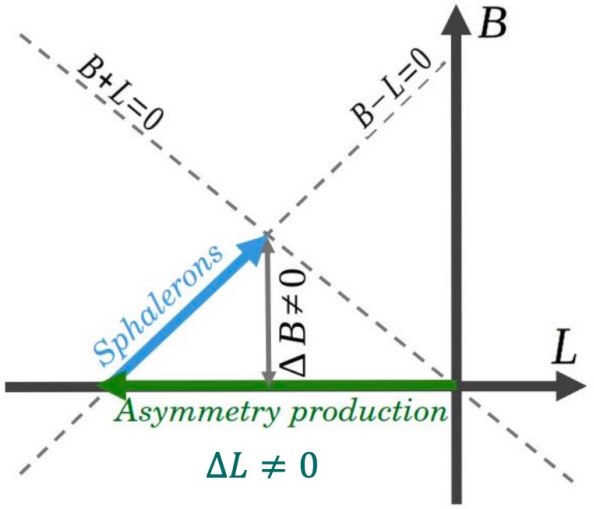
calculate in the SM $\eta_B^{SM} \sim 10^{-19}$ much smaller than required ➔ **BSM required!!!**

Leptogenesis

Heavy Majorana Neutrinos N_R with very large M_R ➔ X



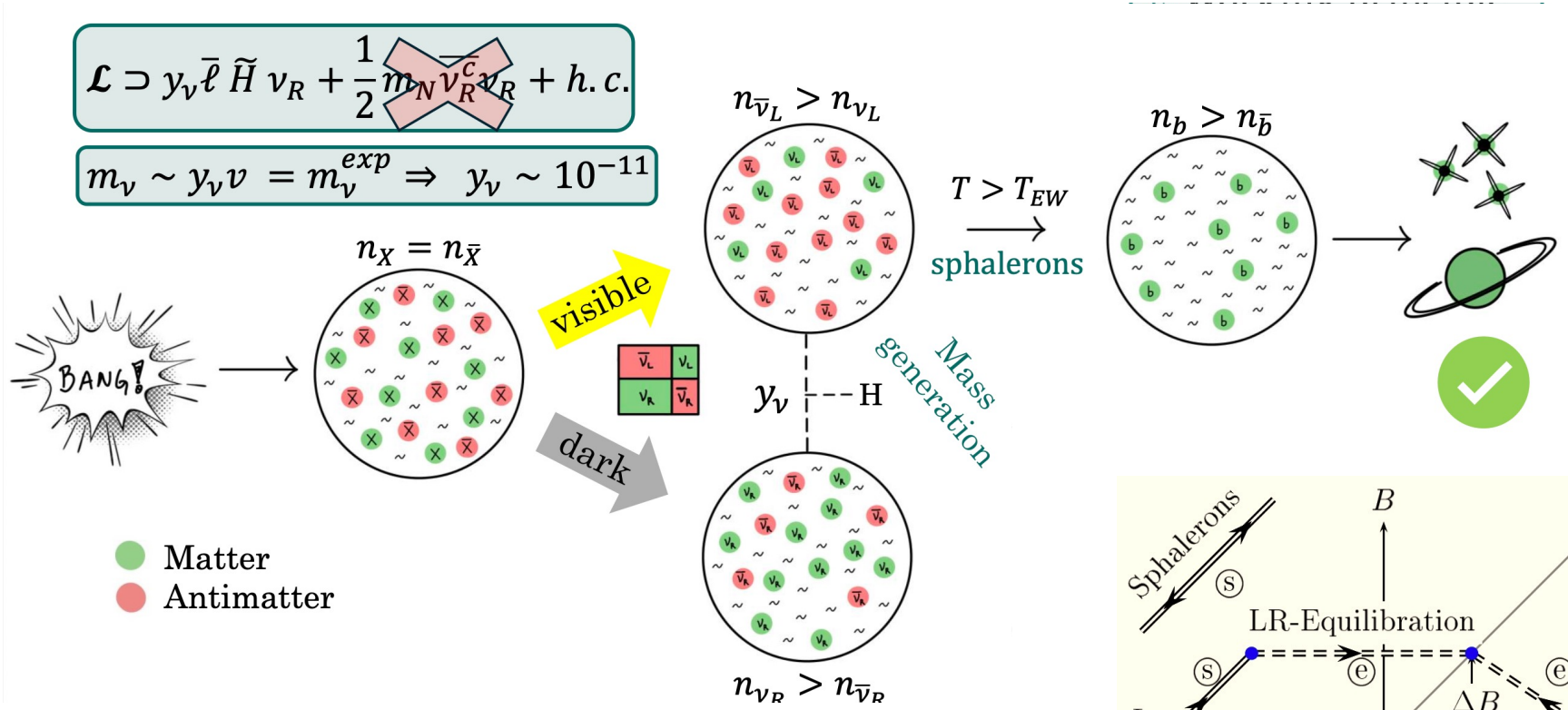


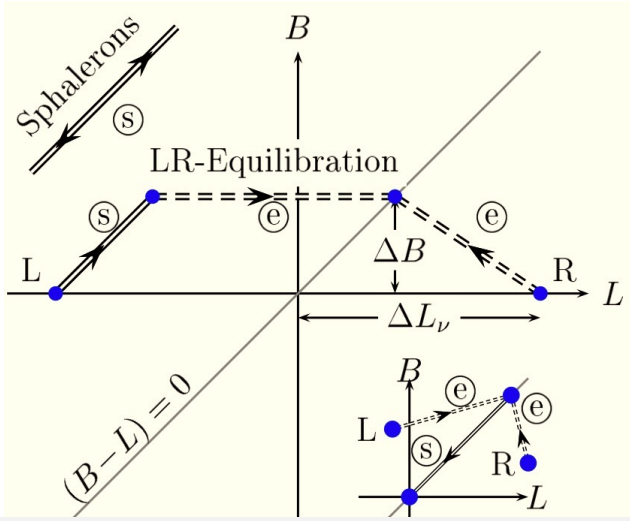


B violation by combined L violation and B+L violation

Other BAU with and without Neutrinos

- **ARS mechanism** Akhmedov, Rubakov, Smirnov
  BAU generated by CP-violating flavor oscillations of sterile (right-handed) neutrinos
- **Dirac leptogenesis** (with Dirac neutrino masses) Dick, ML, Ratz, Wright





The overall BAU Situation

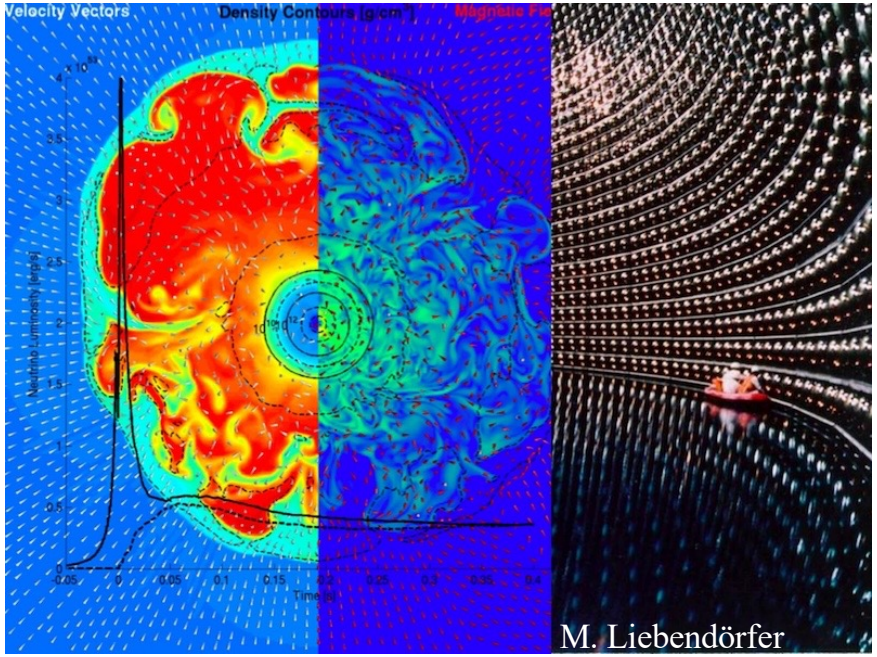
- many BAU mechanisms
  - standard leptogenesis ←→ Majorana neutrinos
  - Dirac neutrinos (ARS-oscillation, Dirac leptogenesis)
    ➔ no $\Delta L=2$ and not connected to $0\nu\beta\beta$
  - without neutrinos (BSM phase transitions)

- leptogenesis cannot be proven – even if all data suggest ν_R only

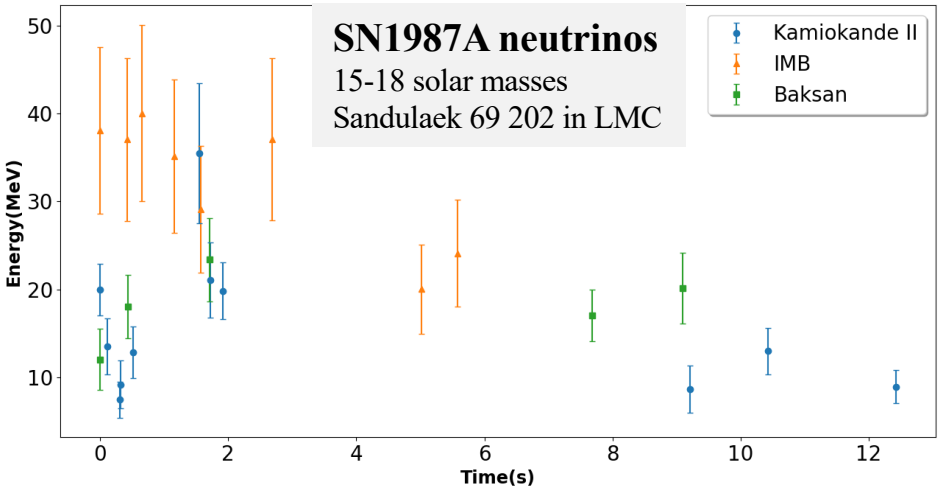
➔ standard leptogenesis is over-sold since it is only one out of many BAU options

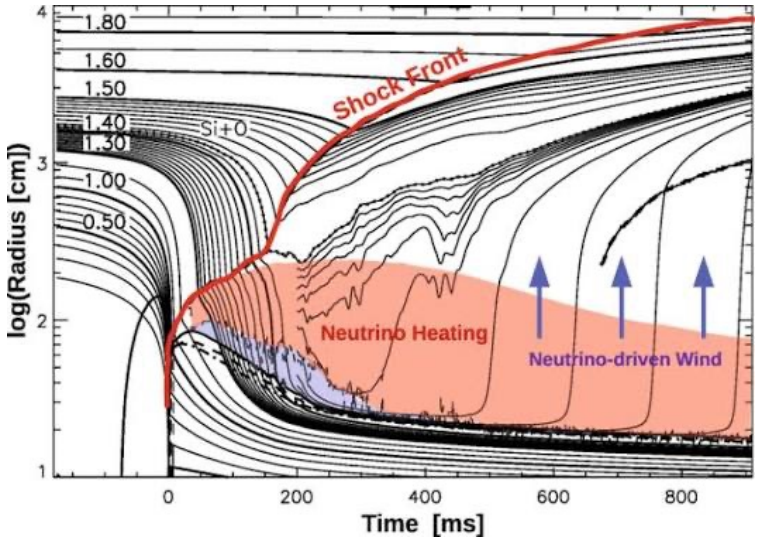
Supernova Neutrinos

- 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!



SN1987A simulation magnetic fields Super Kamiokande ν-emmission





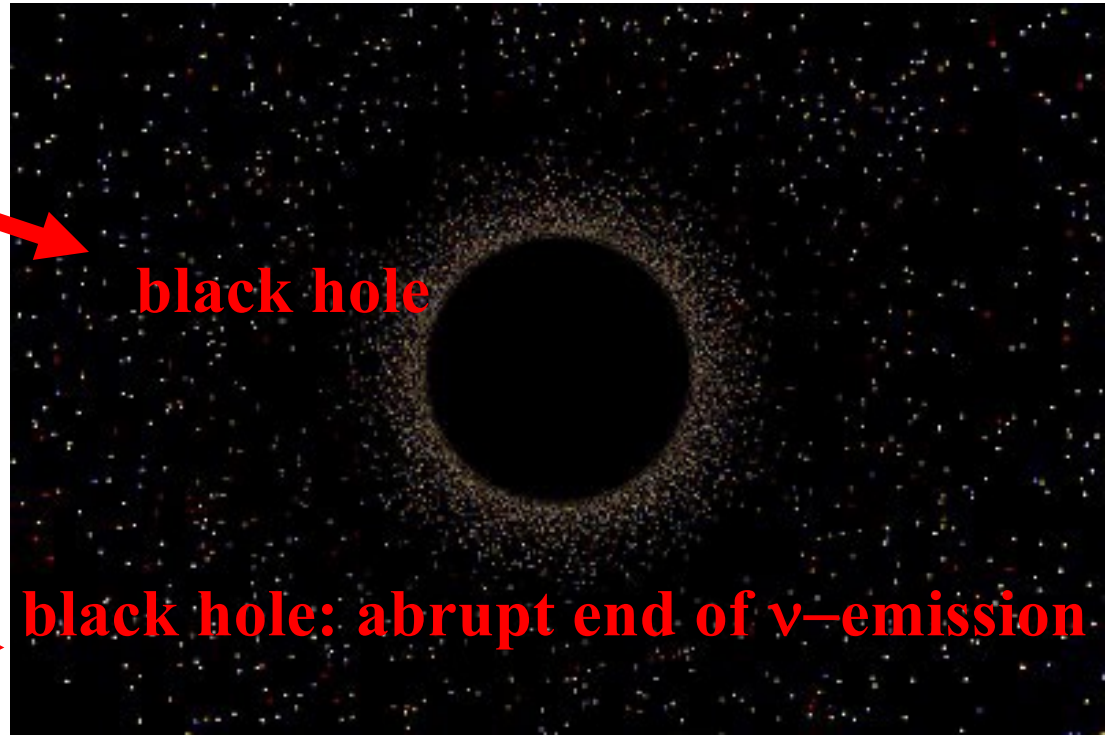
very detailed simulations; e.g. T. Janka

➔ **wating for the next galactic SN...**

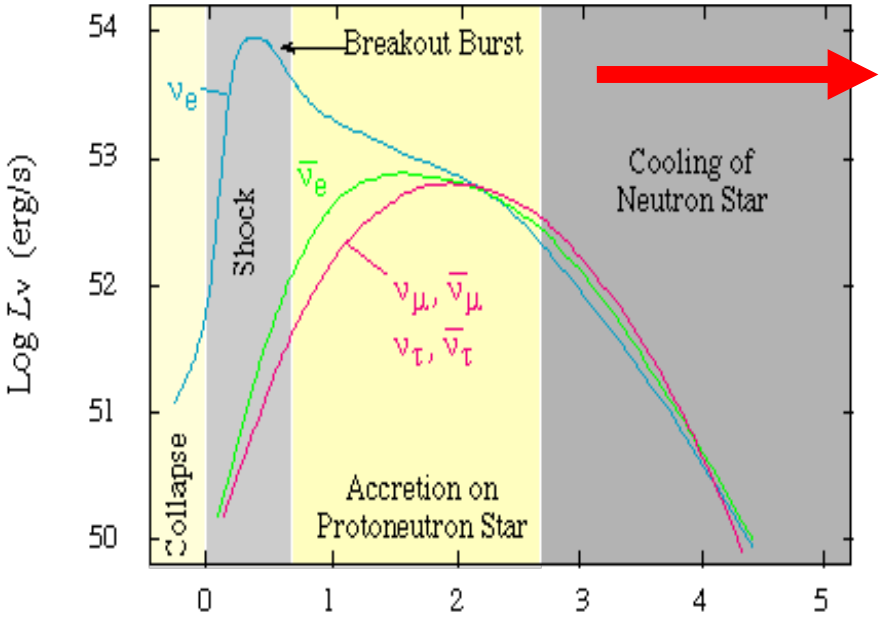
two exciting possibilities:

Supernova

proto neutron star or **black hole**



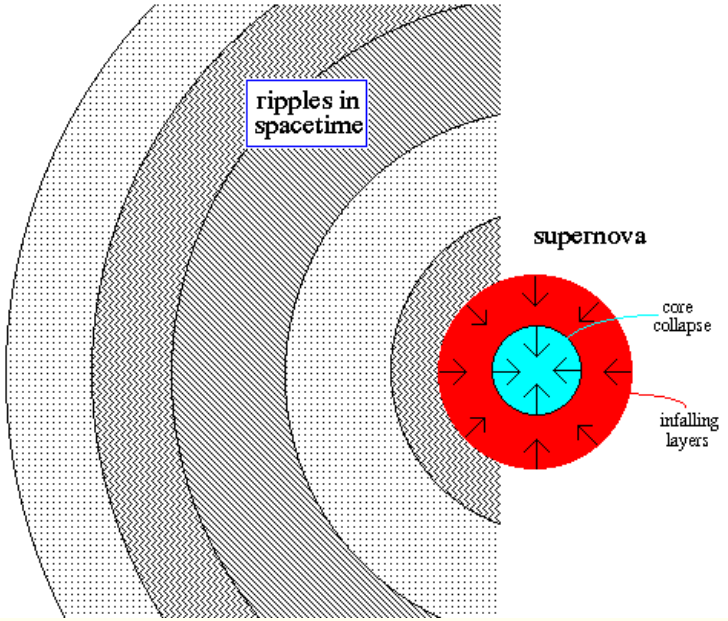
keeps cooling...



black hole: abrupt end of ν–emission

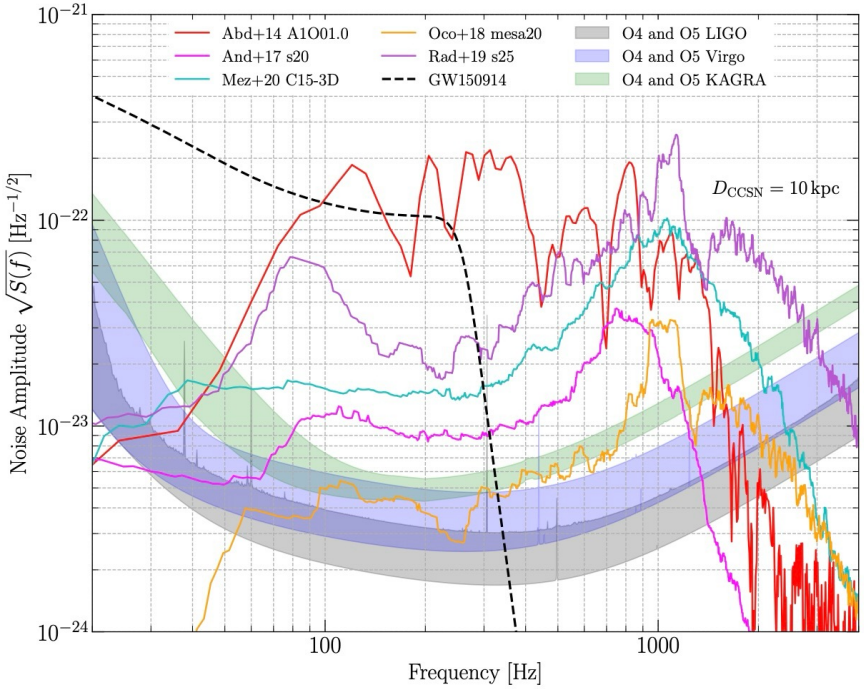
- impressive signal of black hole formation in neutrino light
- neutrino masses ←→ edge of ν-signal

Supernovae & Gravitational Waves



gravitational wave emission ←→ quadrupole moment of the explosion

Dimmelmeier, Font, Müller ; Szczepanczyk et al. 2104.06462



➔ very detailed information about galactic SN and involved processes:

- **optical + neutrinos + gravitational waves** →e.g timing ν‘s vs. GR waves
- **neutrinos**: mass, self-interactions (split, coherence), MSW, other interactions, ...
- **explosion dynamics:** explosiveness, failed SN rate, hidden SN, pointing, ...
- **nuclear physics:** details of element synthesis, ...

➔ **expect enourmous scientific output... when will the next galactic SN occur?**

CEνNS: The simple Picture

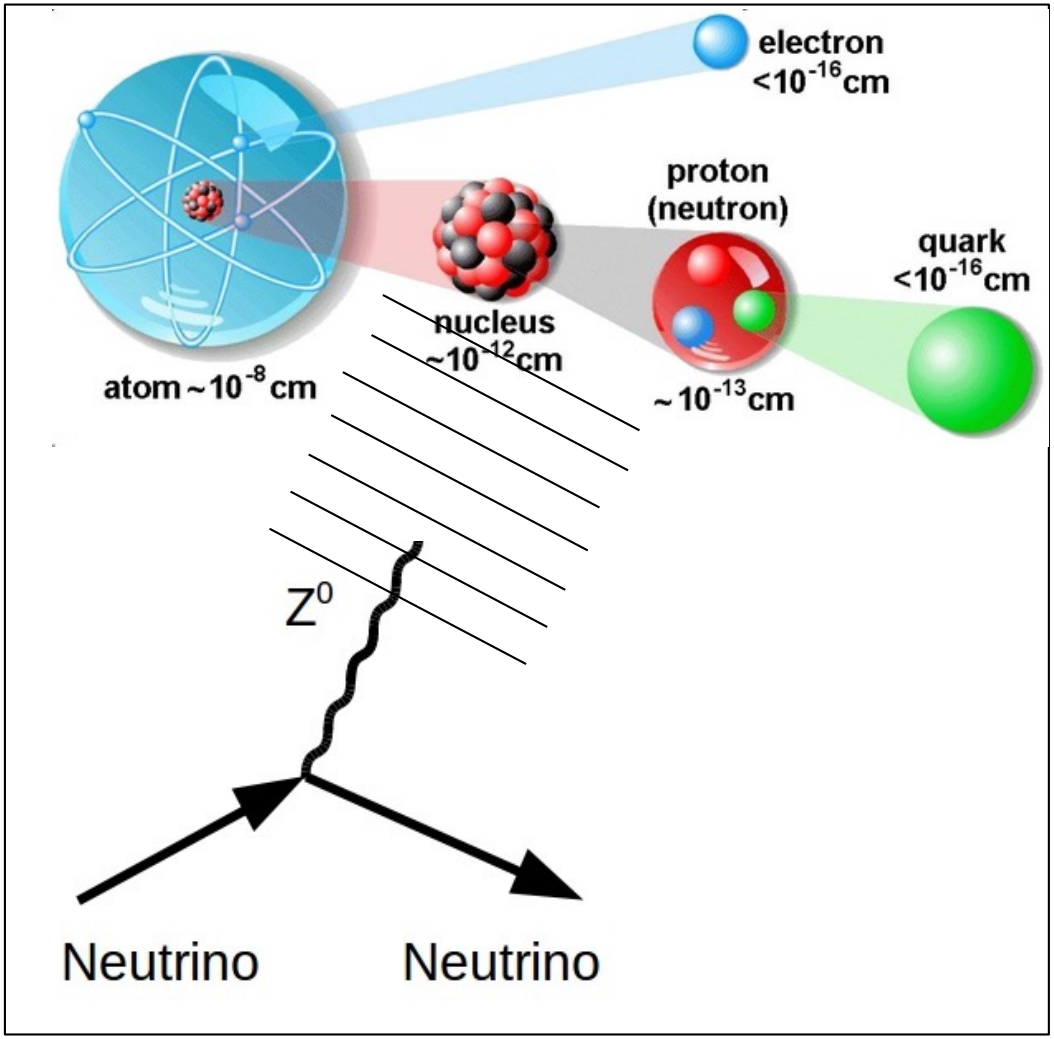
coherent scattering:

1. ν-wavelength big enough
   →Z scattering @whole nucleus
2. small momentum transfer
   → low detection threshold

- **coherence length ~ 1/E ←→ size**
  - stopped π: E_ν below O(50) MeV
    ➔ nuclear form factor $F(q^2)$
  - reactor ν's: E_ν <10 MeV
    ➔ fully coherent: $F(q^2) = 1$

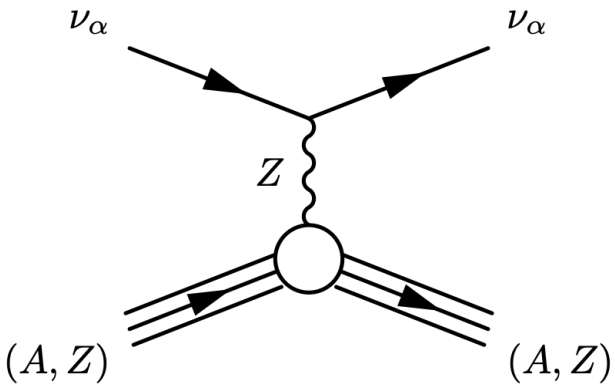
- **cross section ~ $(E_\nu)^2$**
  → compensate:
  - very high ν flux close to reactor
  - coherence ~ N^2

←→ detector size

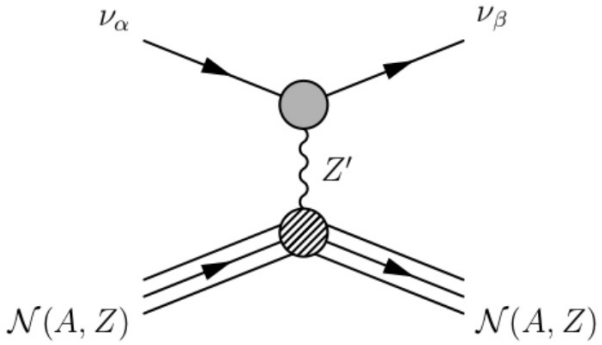


BSM Physics with CEνNS

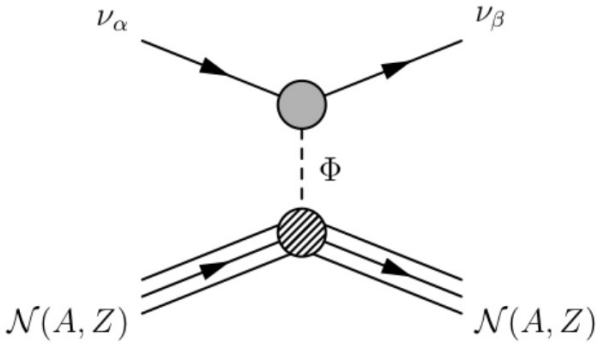
reference: SM neutral current



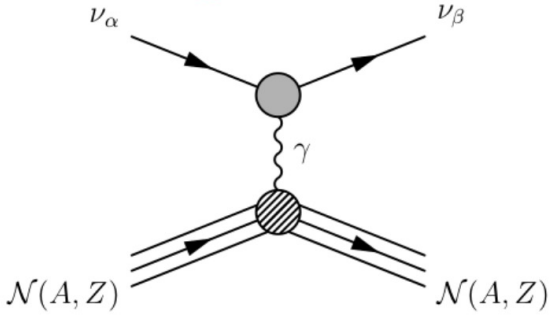
BSM Vector Mediator



BSM Scalar Mediator



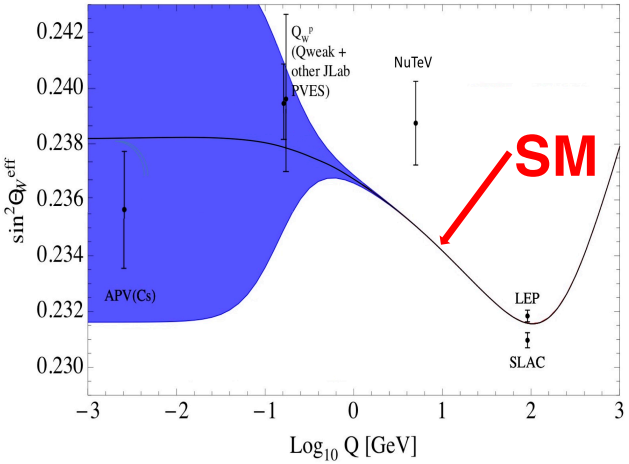
Electromagnetic Interactions



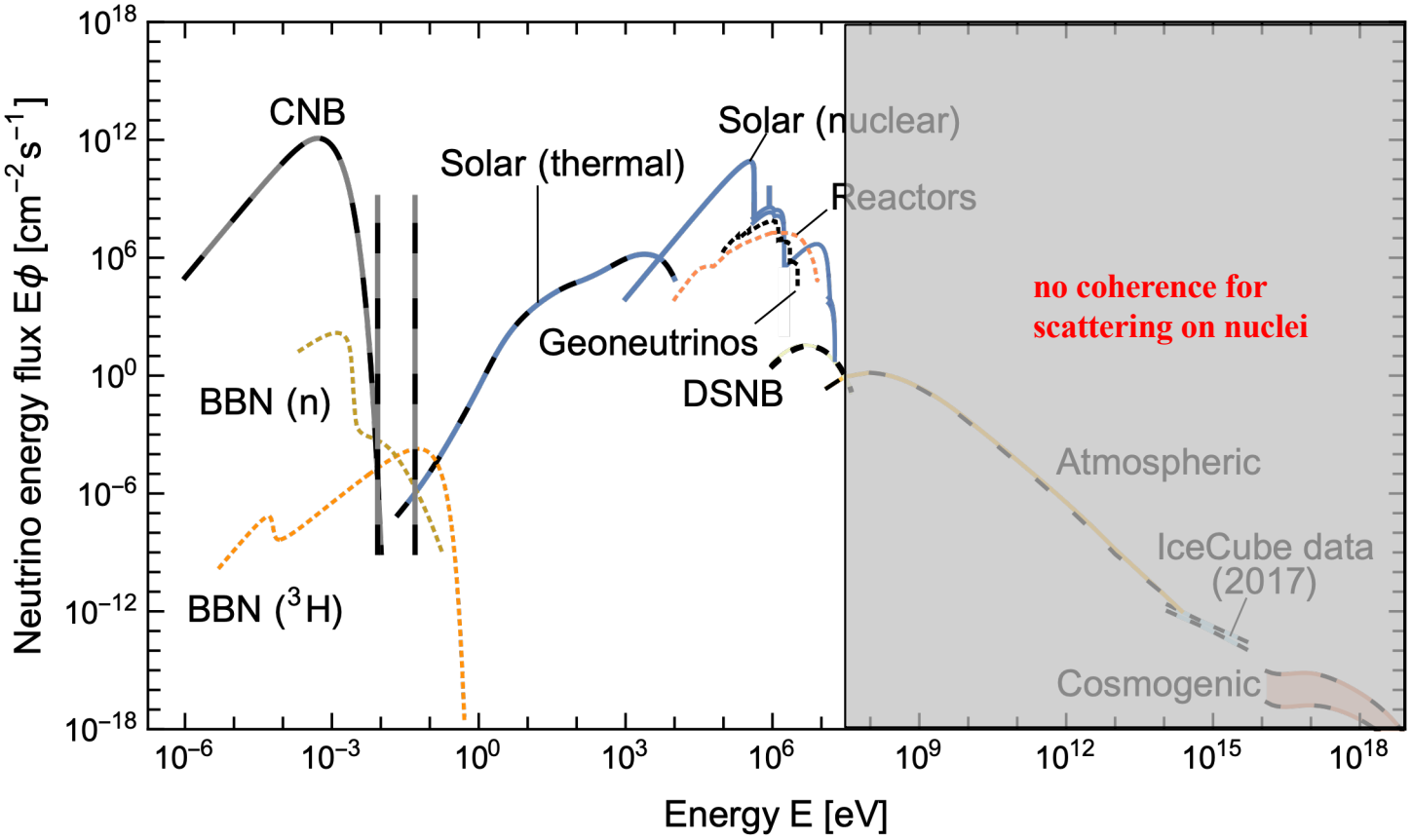
millicharges
neutrino magnetic moments

modified low E running of $\sin^2\theta_W$
$\sigma \sim N - [(1 - 4*\sin^2\theta_W)\, Z\,]^2$
←→ light dark sectors

dark matter candidates
g-2
...



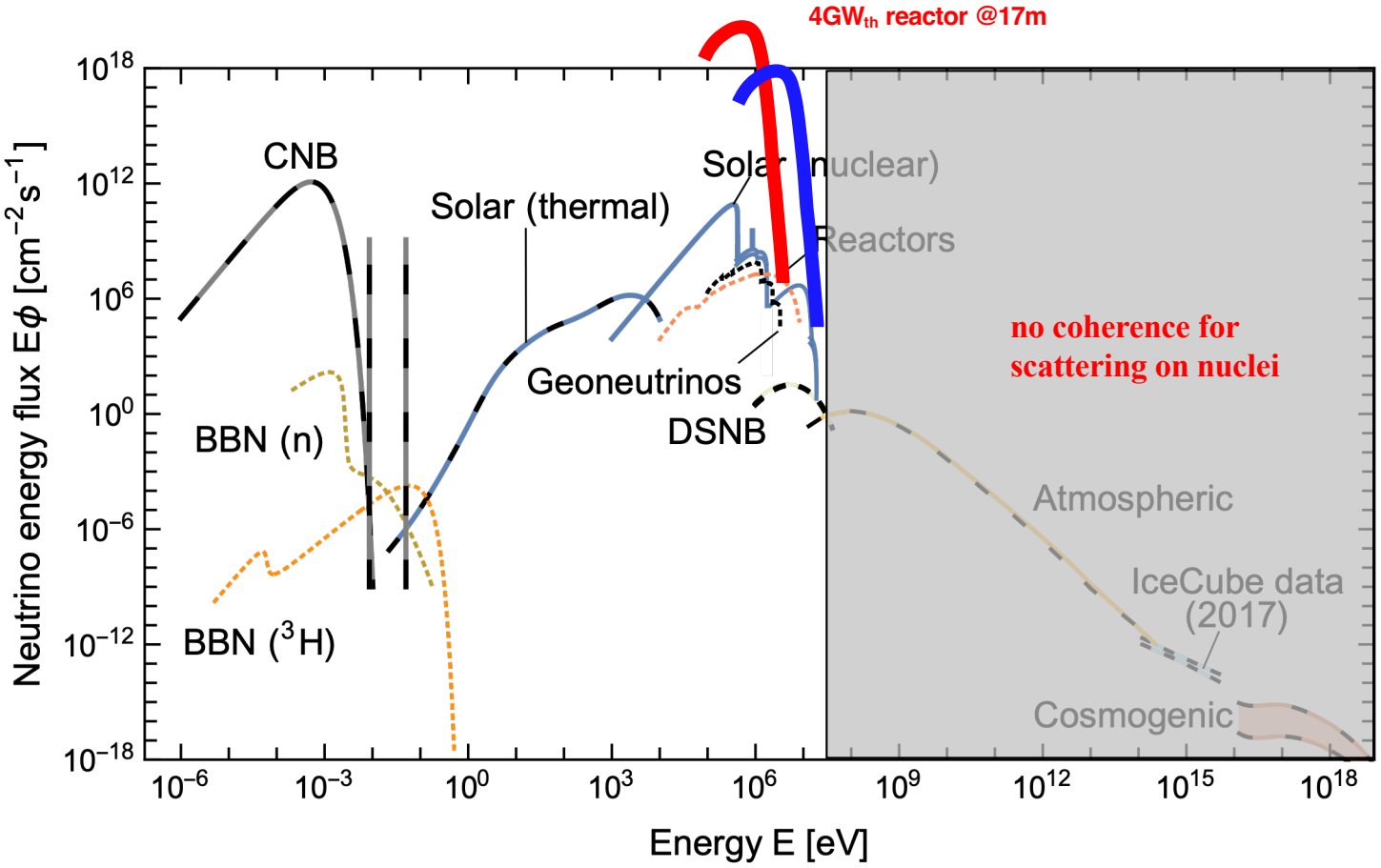
Neutrino Sources: Flux ⊗ Energy



Vitagliano, Tamborra, Raffelt
Rev.Mod.Phys. 92 (2020) 45006
arXiv:1910.11878

Neutrino Sources: Flux ⊗ Energy

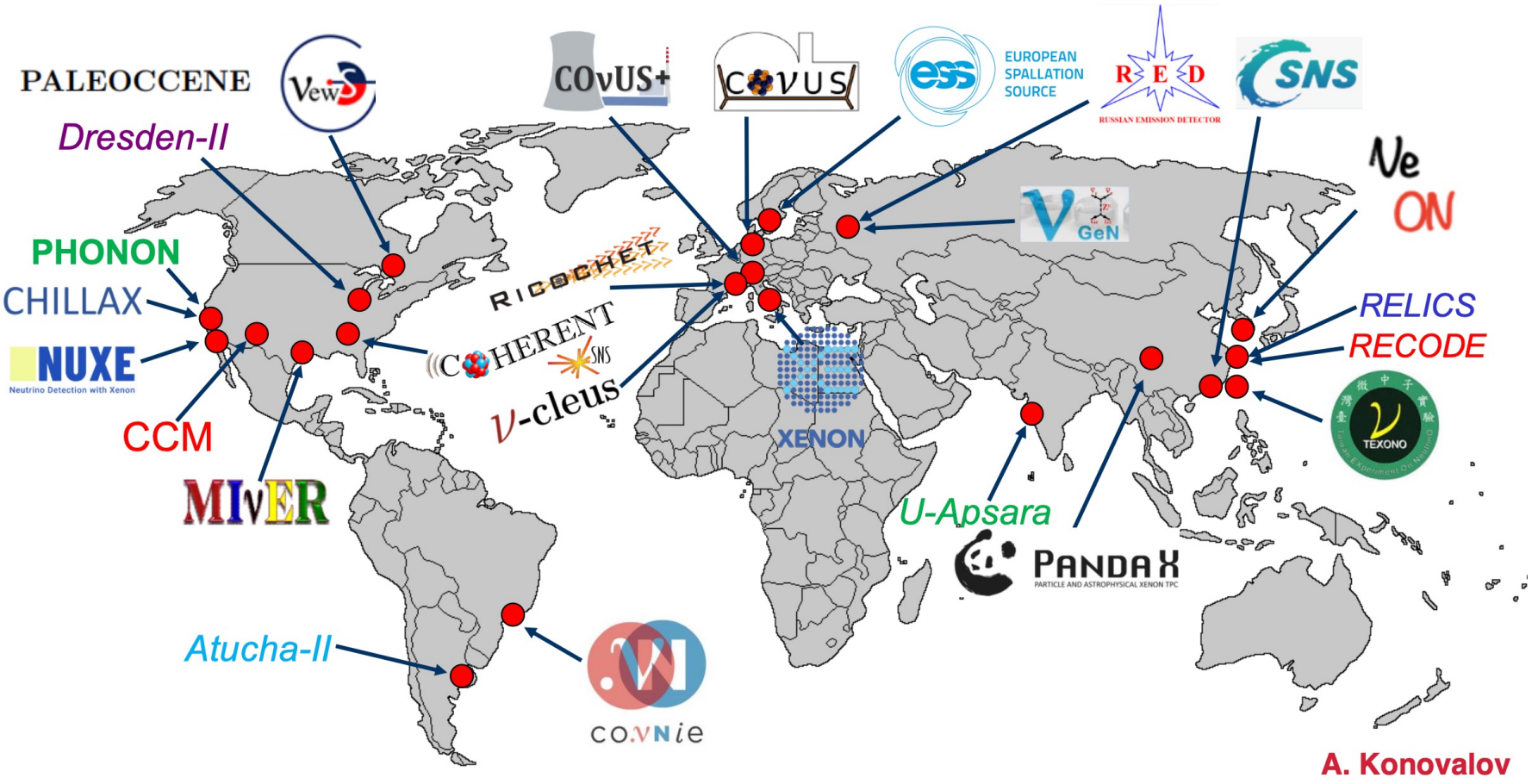
➔ very different close to a nuclear power reactor and in a stopped π-beam or a supernova



Vitagliano, Tamborra, Raffelt
Rev.Mod.Phys. 92 (2020) 45006
arXiv:1910.11878

➔ event rates: neutrino flux ⊗ detector size ←➔ backgrounds

The CEvNS World



1974 – prediction by D. Freedman

...

2017 – 1st observation by COHERENT in stopped π-beams ←→ F(q^2) - not fully coherent

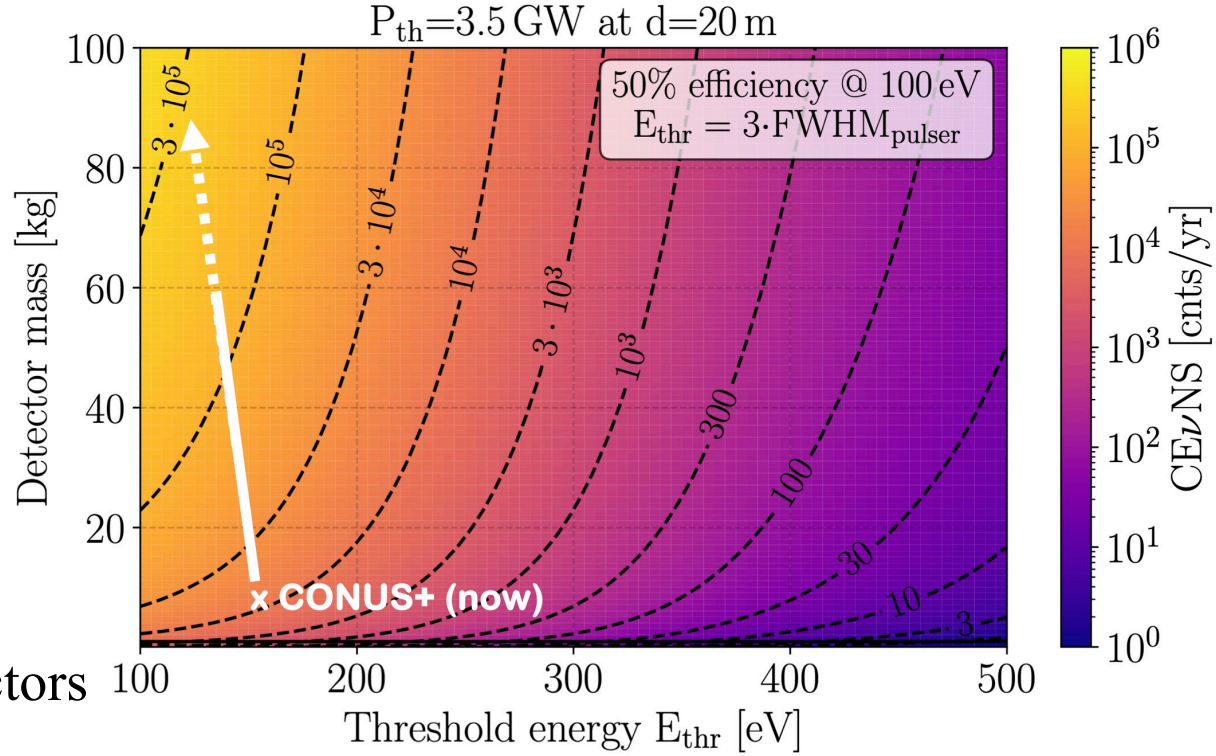
2024 – 1st with solar neutrinos by XENONnT and PandaX, later also LZ

2025 – 1st with reactor neutrinos by CONUS+ ➔ 2026: CONUS+ new result with 10.2 σ

Future CEνNS Prospects

CONUS+ technology for moderate size high statistics experiments established:

- O(100kg) Ge possible
- 100 eV threshold feasible



➔ 500.000 events in 5y

➔ scoping for something like CONUS100 on-going...

➔ ➔ other technologies @reactors

in addition:

- upgrades of COHERENT
- next generation LXe dark matter (XLZD, ...)

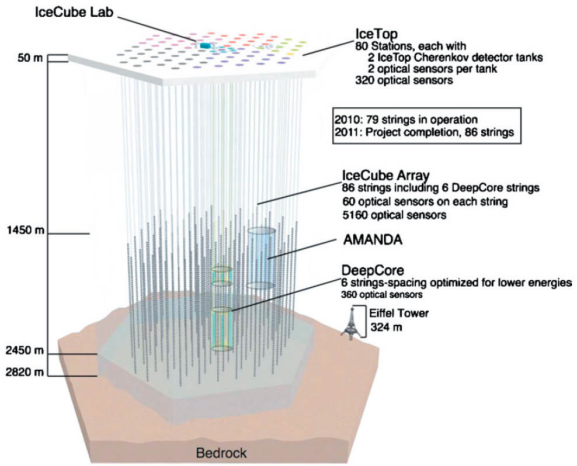
ML, T. Rink, M. Sen, JHEP 08 (2024) 171

➔ precision CEνNS physics with excellent potential within a few years...

Big versus small Experiments

neutrinos interact very weakly ➔ huge experiments

IceCube: km^3

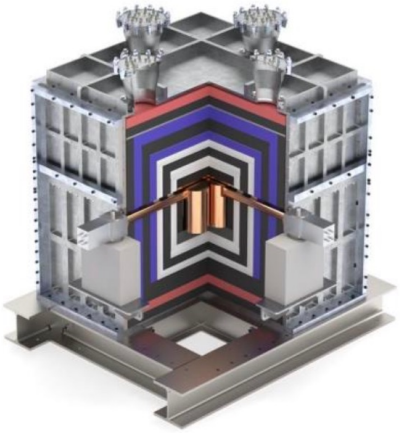


SuperKamiokande:
50.000 tons of water



CONUS+

- **σ~N^2 + huge flux**
- **size ~2m^3**
- **active mass: few kg**



big versus small experiments

- **cost**
- **time to new results**
- **physics potential: broad vs. scoping**
- **attracting students, broad training, ...**
- **changing world: focus of societies, politics, ...**

➔ aim at a good mixture of big and small!

Summary

- neutrinos have mass
  → **1st solid evidence for BSM physics → SM+**
- many reasons for more new physics in particle physics & cosmology
- so far everything described by SM+ and ΛCDM
- in next years we will learn more about new physics with neutrinos:
  - precision 3ν → origin of flavour, unitarity, steriles, ...
    →very well motivated → so far limits → where is the new physics?
  - preference for NH and Σm_ν from cosmology → exciting next years
    → implications for 0νββ and sources of L-violation
  - leptogenesis & BAU... many BAU mechanisms, even for Dirac ν's
  - next galactic supernova: neutrinos + light + gravitational waves
  - CEvNS: new results on excellent potential (beimg small helps)

→ neutrinos may have the best change for next discoveries