Neutrino fireworks and illumination

Heidelberg Castle illumination and fireworks

Image credit: Heidelberg Marketing

Eligio Lisi

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XXVIII International Conference on Neutrino Physics and Astrophysics (Heidelberg, Germany, 2018)

Watching fireworks and light shows is a joyful activity that attracts people of all ages and cultures

Preparing and setting off fireworks is also a professional activity that requires skills and discipline

Scorecard from an international festival:

- ☐ Sizing of the show, balance of firework sizes
- ☐ Overall design and artistry
- ☐ Shapes and structures (symmetry, patterns)
- ☐ New and novel effects, originality
- ☐ Synchronization, rythm, connection with sounds
- ☐ Use of colors, connections with light show
- ☐ Overall impression ("Wow" factor)

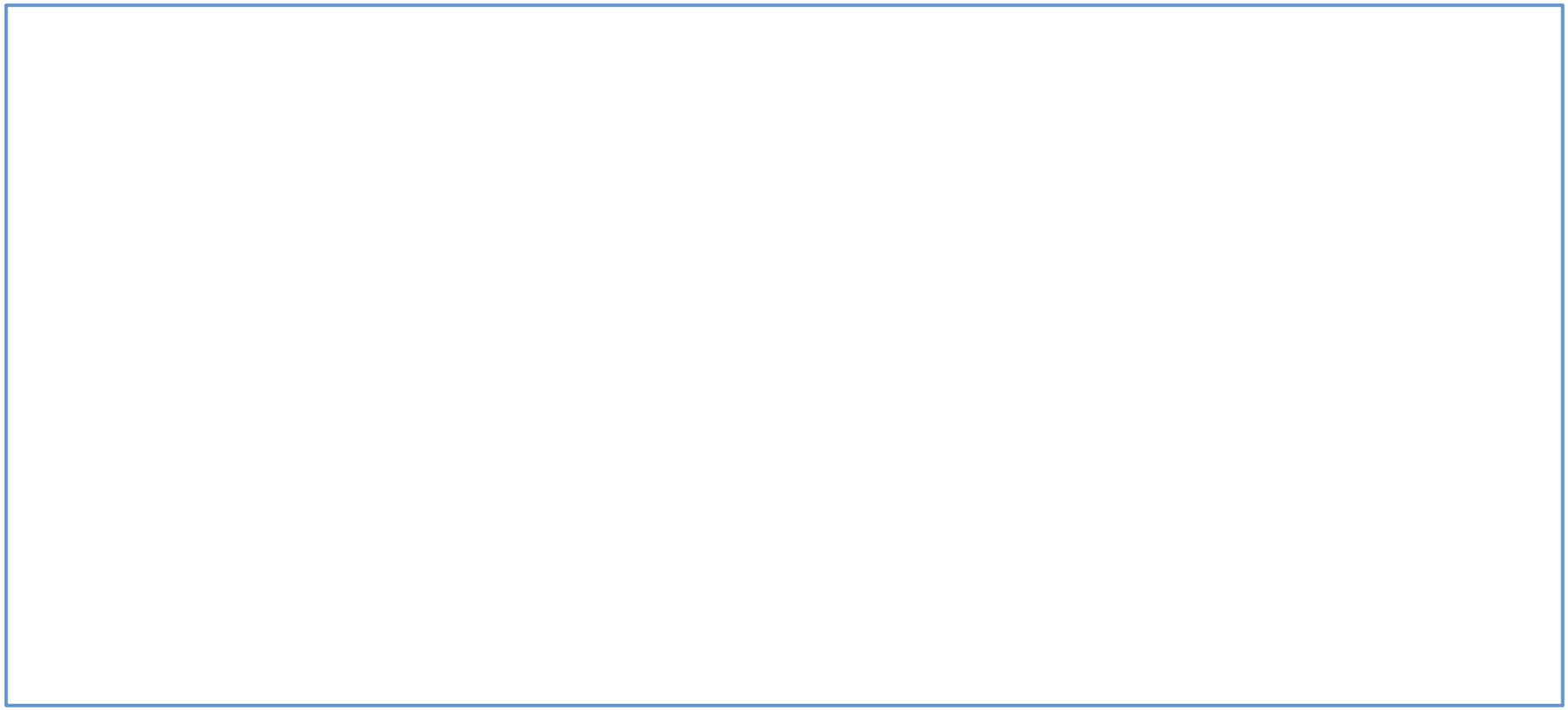
Success achieved through the synergy of many aspects...

We are going to enjoy similar synergies for a week, in the context of neutrino (astro)physics!

Image credit: Heidelberg Marketing

I shall use the **"ν firework metaphor"**
to convey the excitement for new results
and to link freely the different sessions

Neutrino Firework Session Chart 2018



Neutrino Firework Session Chart 2018

Size

When νs meet gravity and astrophysics

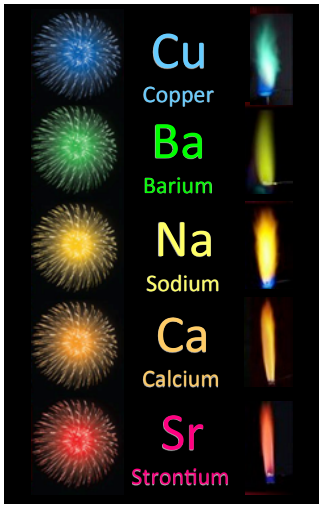
[Prologue]
Supernova ν
Gravit. waves
ν Astro/Cosmo

Neutrino Firework Session Chart 2018

Size

When νs meet gravity and astrophysics

Colors



When νs meet chromodynamics and nuclear physics

[Prologue]
Supernova ν
Gravit. waves
ν Astro/Cosmo

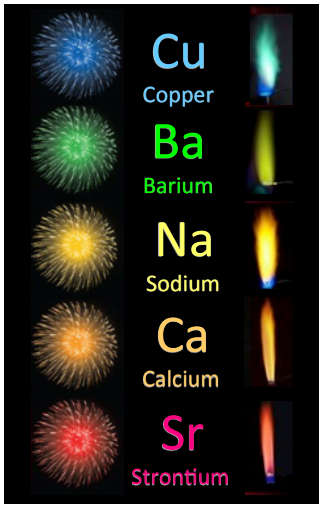
Coherent ν
New detectors
Cross sections
0ν double beta

Neutrino Firework Session Chart 2018

Size

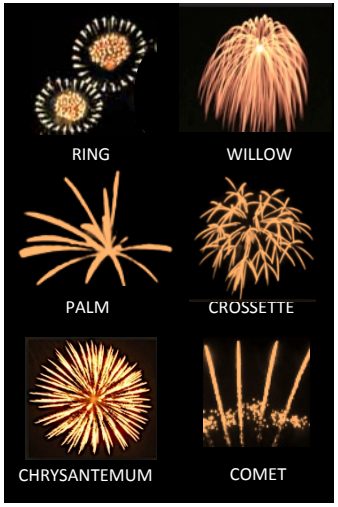
When νs meet gravity and astrophysics

Colors



When νs meet chromodynamics and nuclear physics

Shapes



When νs meet the many facets of particle physics

[Prologue]
Supernova ν
Gravit. waves
ν Astro/Cosmo

Coherent ν
New detectors
Cross sections
0ν double beta

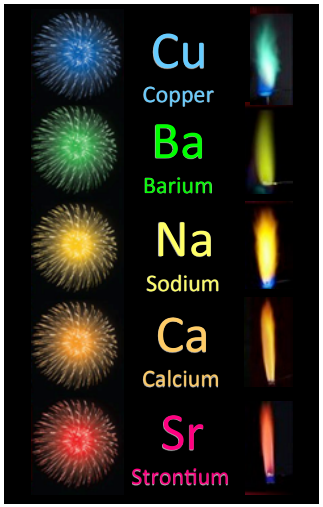
Solar, Atmos.
Reactor, Accel.
Lab. ν mass
Phenomenology

Neutrino Firework Session Chart 2018

Size

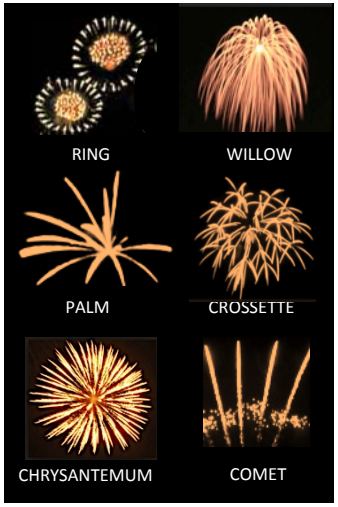
When ν's meet gravity and astrophysics

Colors



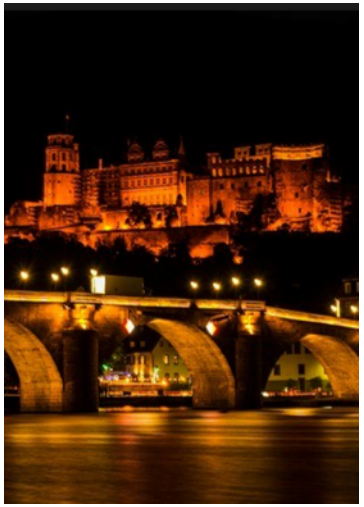
When ν's meet chromodynamics and nuclear physics

Shapes



When ν's meet the many facets of particle physics

Illumination



When ν's meet new physics and energy scales

[Prologue]
Supernova ν
Gravit. waves
ν Astro/Cosmo

Coherent ν
New detectors
Cross sections
0ν double beta

Solar, Atmos.
Reactor, Accel.
Lab. ν mass
Phenomenology

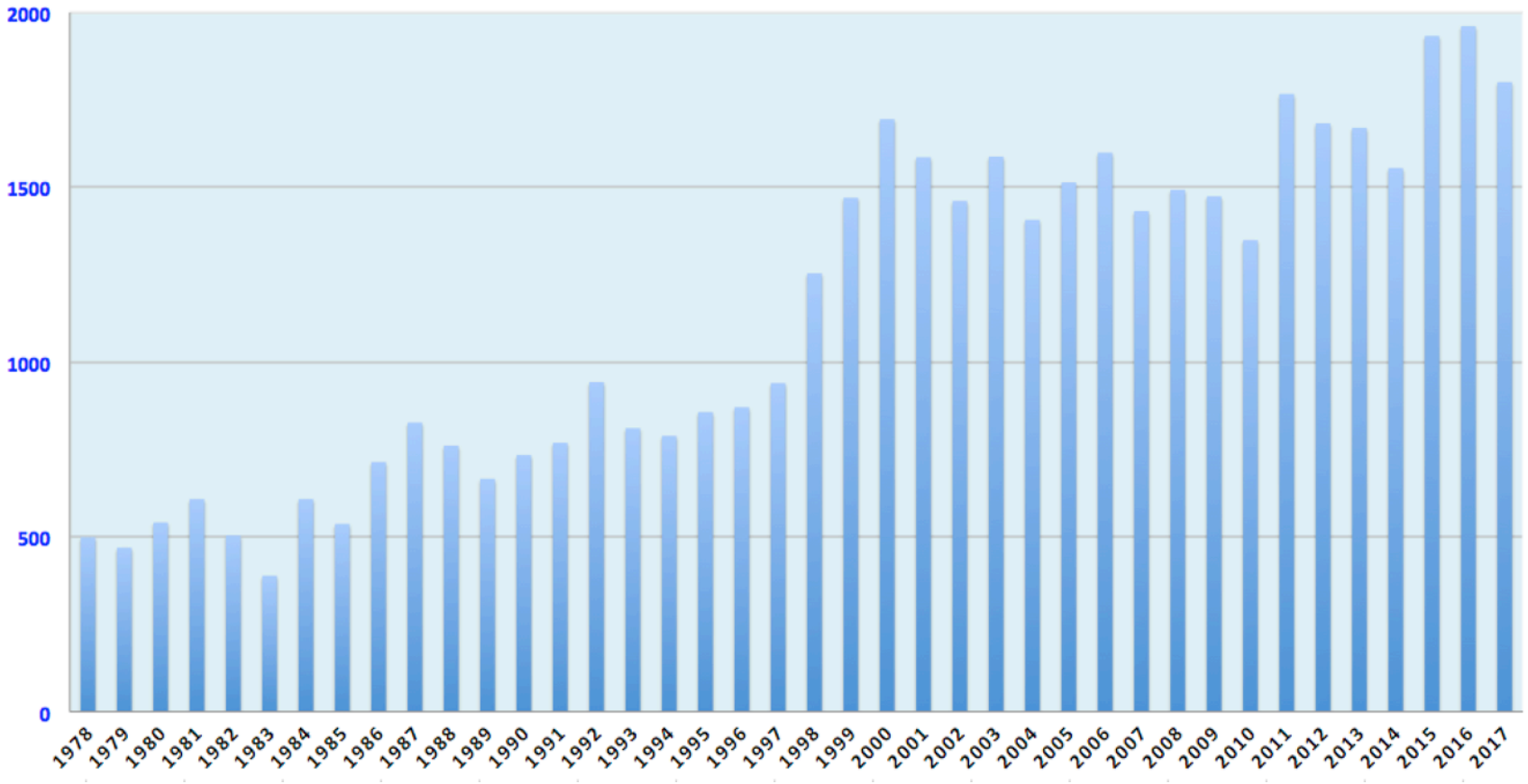
Theory
Sterile ν
Dark matter
[Epilogue]

Prologue:

Sizing our field

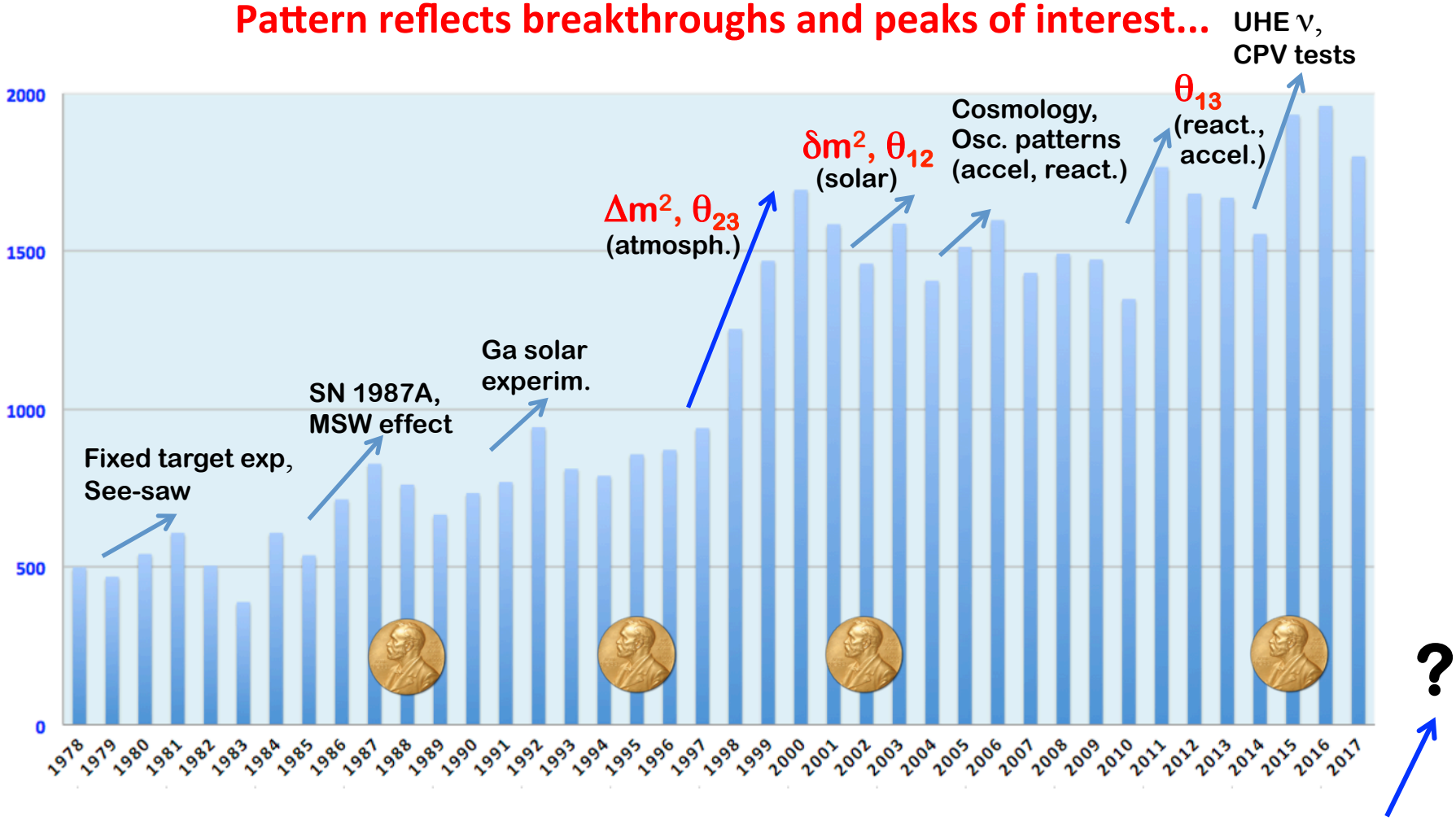
N. of #neutrino# preprints per year (1978-2018) from INSPIRE

A great field – in any respect! And is getting greater...



N. of #neutrino# preprints per year (1978-2018) from INSPIRE

Pattern reflects breakthroughs and peaks of interest...



... with more to come!

XL-size ν fireworks

When νs meet gravity and astrophysics

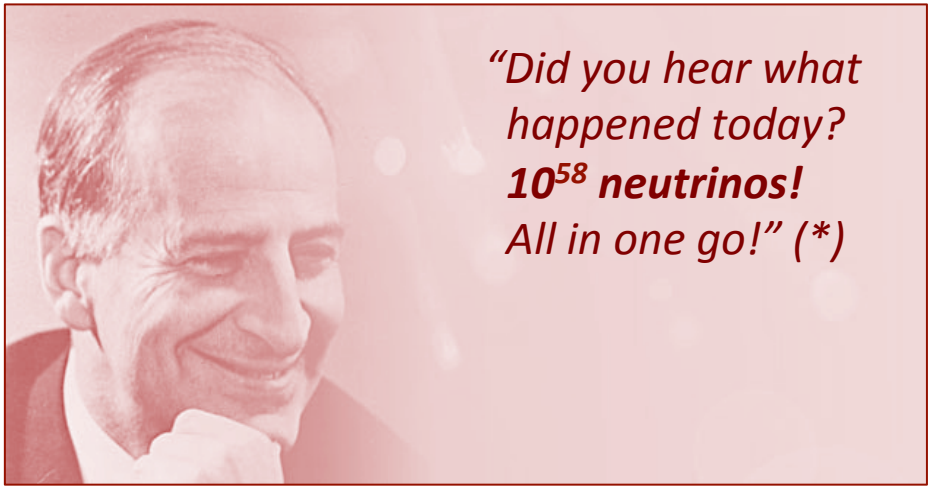
Supernova ν
Gravit. waves
ν Astronomy
ν Cosmology

The brightest: Supernovae

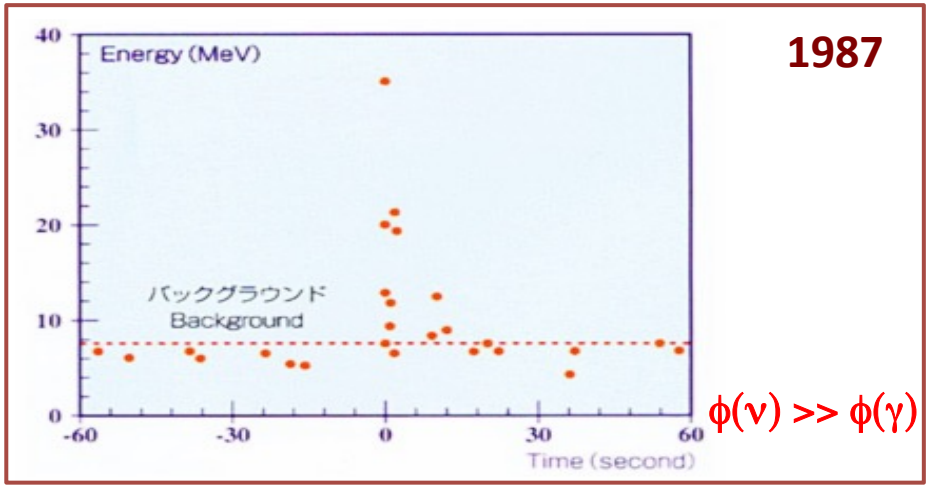
Bruno Pontecorvo, JETP 36, 1625, **1959**

❝ Therefore at a certain stage of the evolution of stars it may be that the energies sent into space in the forms of neutrinos and photons are comparable ❞

Early hypothesis on stellar ν *sources and their* ***multimessenger*** *signals:* $\phi(\nu) \sim \phi(\gamma)$



"Did you hear what happened today? ***10^{58} neutrinos!*** *All in one go!" (*)*



1987

$\phi(\nu) >> \phi(\gamma)$

(*) From Ludovico Pontecorvo's memories, as quoted in an interview by Frank Close (2013).

SN explosion: one the most challenging problems
Matter, νs, theory, computing... at the extreme!

Complex but unique multimessenger lab. for

particle (astro)physics
nuclear (astro)physics
general relativity

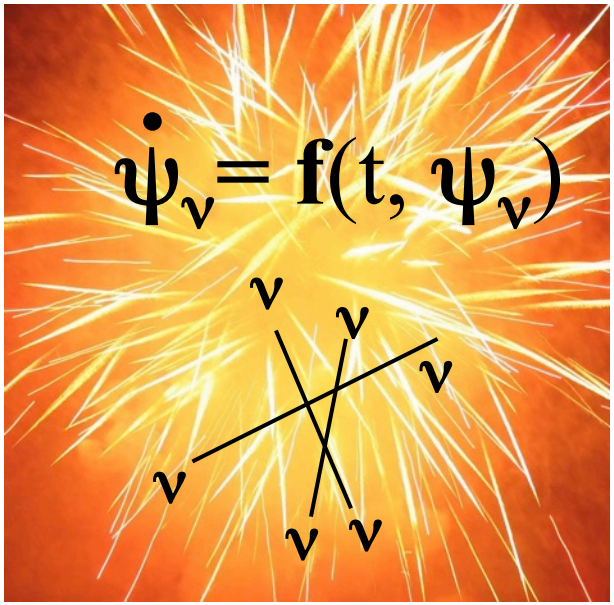
with feedback between matter and ν dynamics

ν–ν → strong-coupling effects of EW inter.

Highly nonlinear flavor evolution problem,
theoretical understanding in its infancy

The whole field will be boosted by:

Galactic core-collapse SN event
Observation of past SN fireworks' "glow"



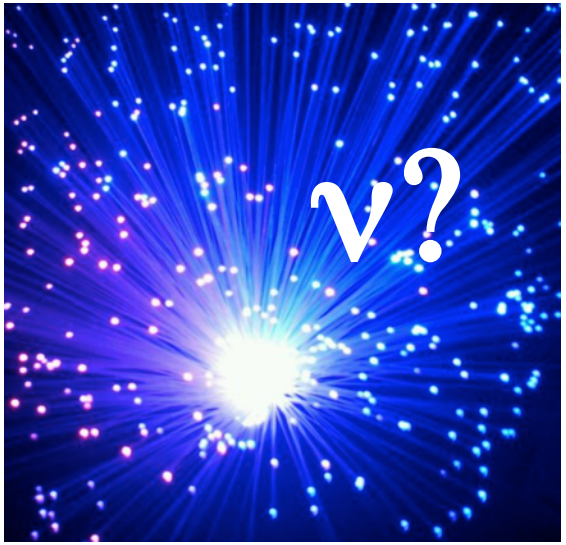
The loudest: GW170817 + EM signals

SN post-explosion physics (neutron stars + mergers): portal to amazing new phenomena...

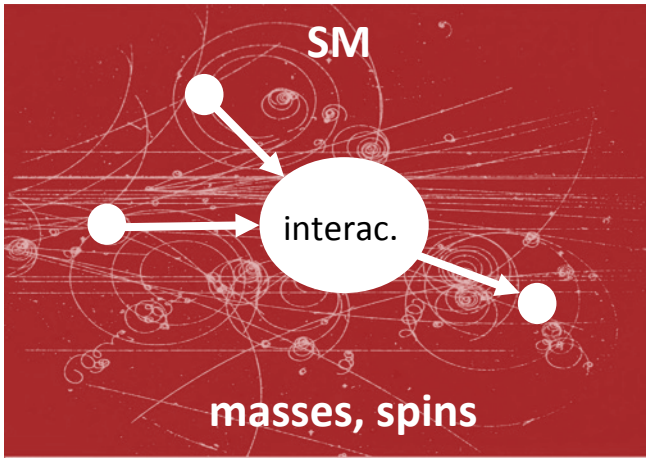
2017 neutron star merger event: first association of "GW sounds" and "EM light"

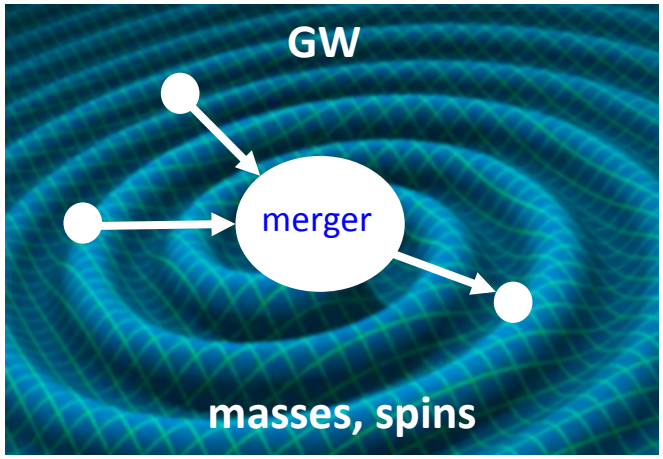
Present: Test of "known" physics in extreme conditions + new physics constraints:
neutron star properties and EoS, graviton properties, Hubble parameter,
EM emission mechanism, dark energy models, modified gravity, extra dimensions ...

Future: Joint signal by the three long-distance messengers (g, γ, ν) **?**



Suggestive analogies...





Catalog:
Particle Data Book
Current edition: ~2×10^3 pages

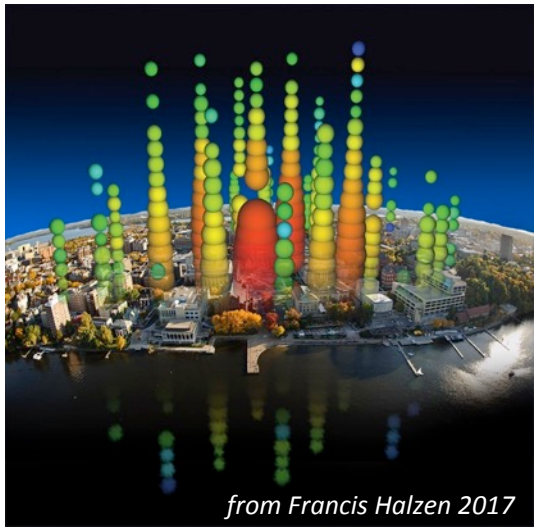
When it had 1 page (1936):
I. Rabi, μ: *Who ordered that?*
...many surprises followed!

Catalog:
"Compact Object Data Book"
Current edition: 1 page...

When it will have ~10^3 pages:
Likely to show objects/mergers
that no one ordered...

...we don't know what's in store!

The largest (on Earth): UHE ν

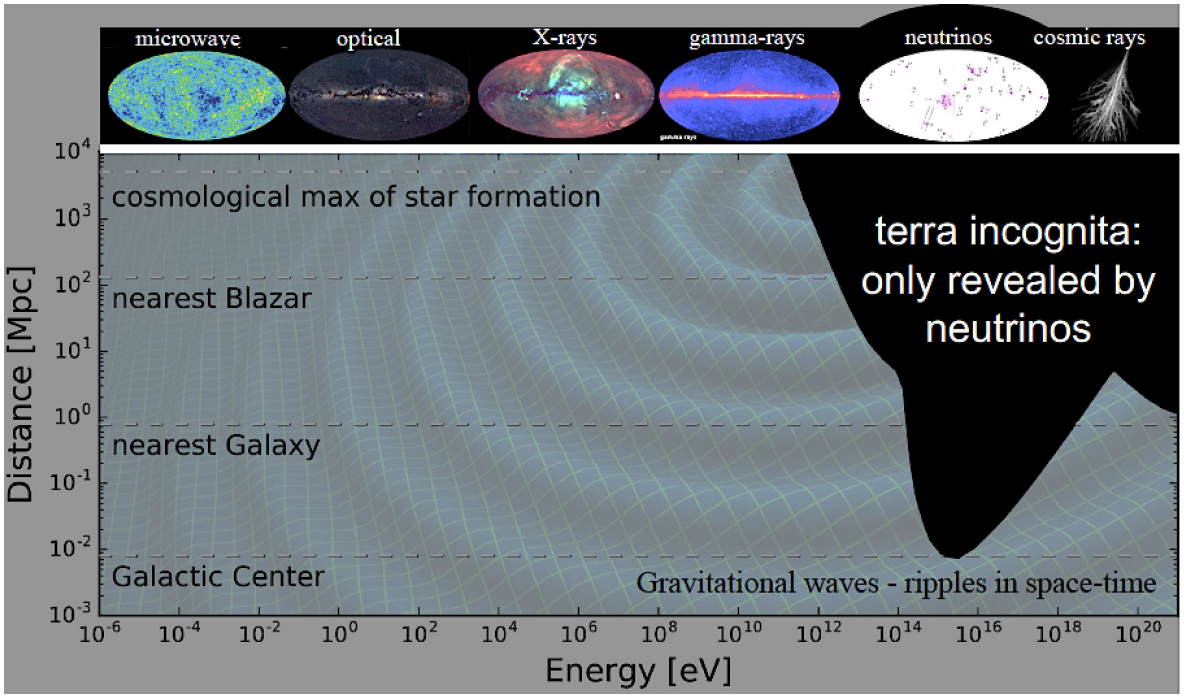


… ν's from cosmic distances …

New window opened, but landscape largely unknown!

Charting a new territory of the non-thermal universe

CMB Optical X-rays γ-rays **Neutrinos** CRs



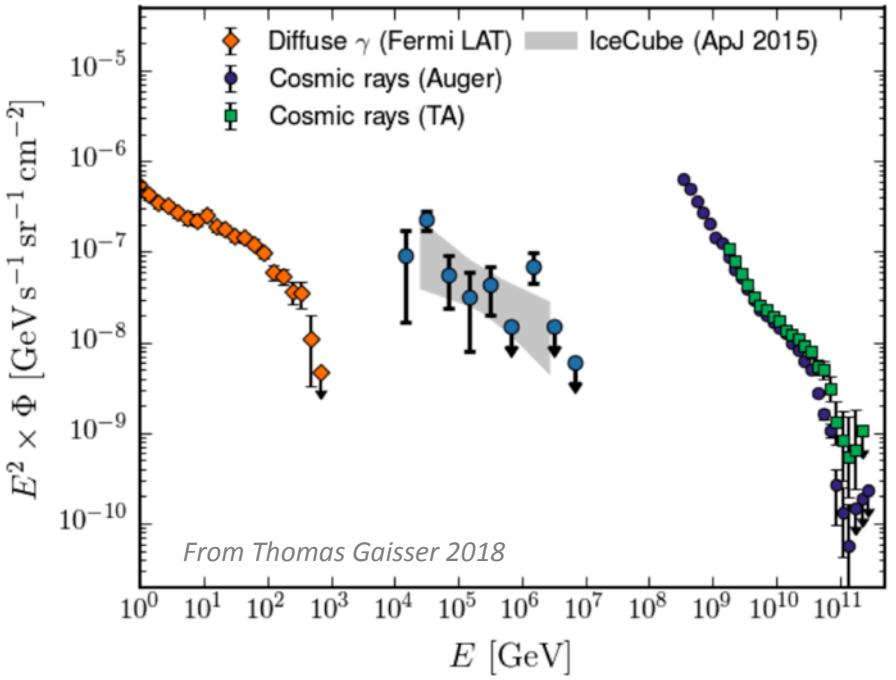
Unprecedented E, L may probe **new ν physics:**

nonstandard properties, coupling with DM, DE, anomalous dispersion or flavor evolution...

Need to understand sources first!

Goal: Understand UHE ν source distribution in

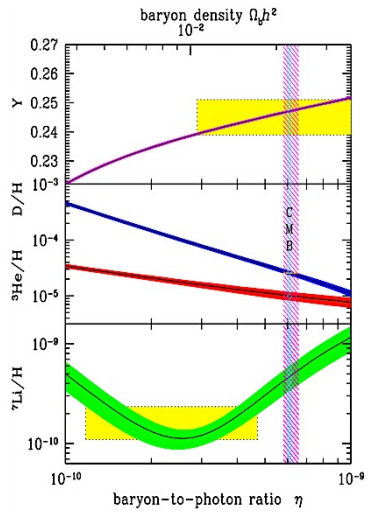
energy	*power law(s)*
angle	*pointlike vs diffuse*
flavor	$e : \mu : \tau$
distance	*galactic vs extragalactic*
type	*production mechanism*
time	*steady vs* ***transient***



γ and ν energy dens. comparable
("Pontecorvo-like"):
Hint of common origin?

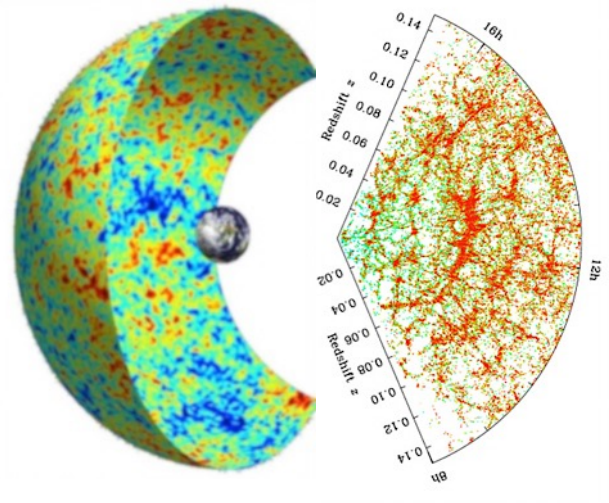
The largest (∞) firework*: Relic CνB

BBN (T~ MeV)



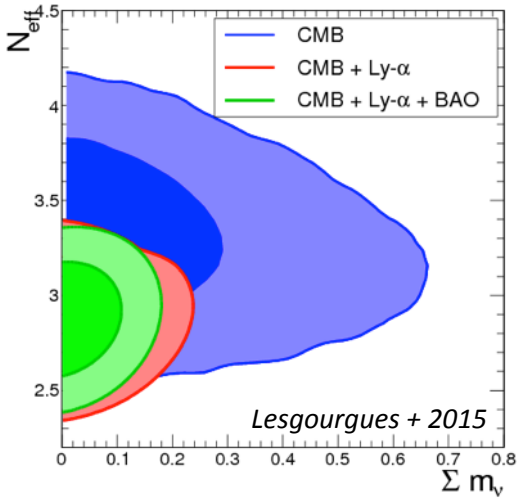
N_{eff}

CMB (T< eV) **LSS**



N_{eff} , Σm_ν

Within **ΛCDM** model:



Implications for sterile ν and mass ordering

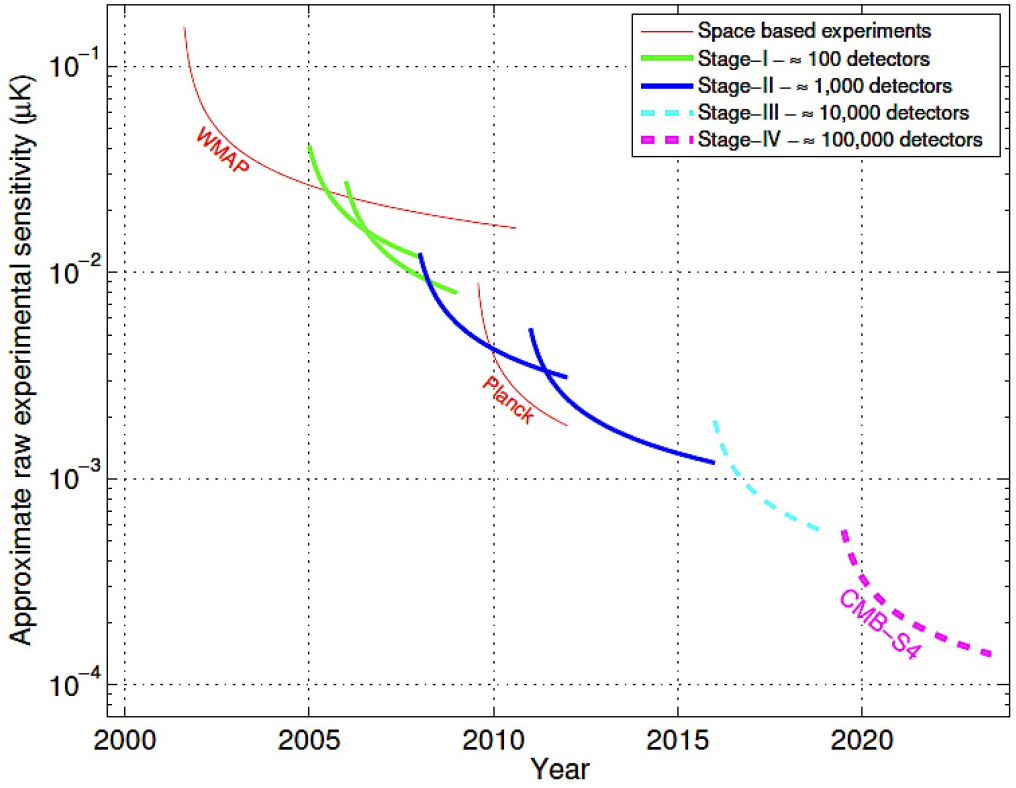
Cosmology: an amazing probe of (non)standard neutrino properties

Important complement (not replacement) to laboratory probes of ν...

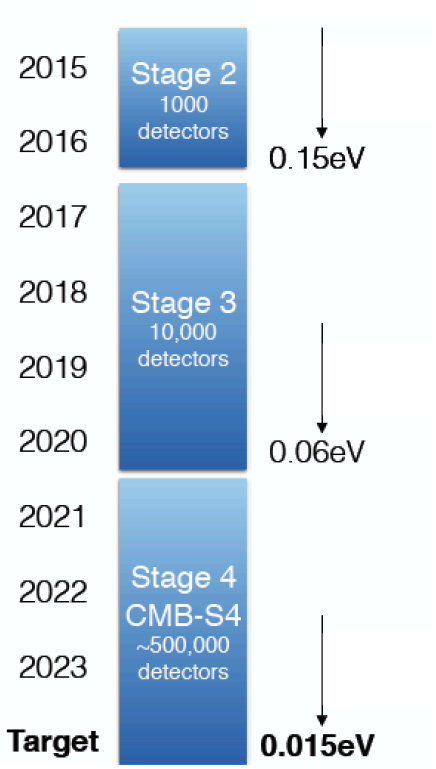
***Not necessarily the earliest: Preceded by Leptogenesis? An extremely important issue.**

...promising to access the absolute ν mass scale in the 20's of this century

Moore's law of CMB sensitivity in μK



...and expected error on Σm_ν

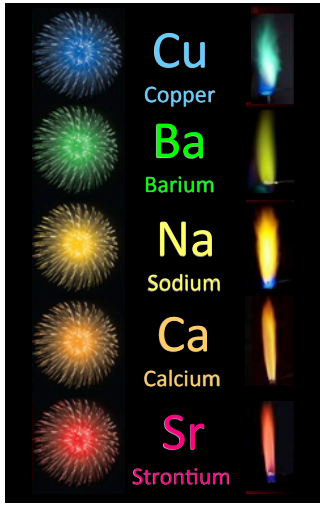


adapted from CMB-S4 Science Book

Will all data and Σm_ν converge within **ΛCDM** model?

Colors

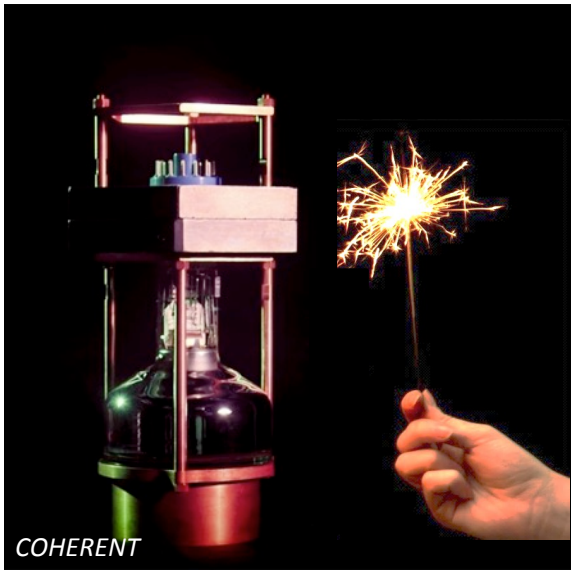
When νs meet chromodynamics and nuclear physics

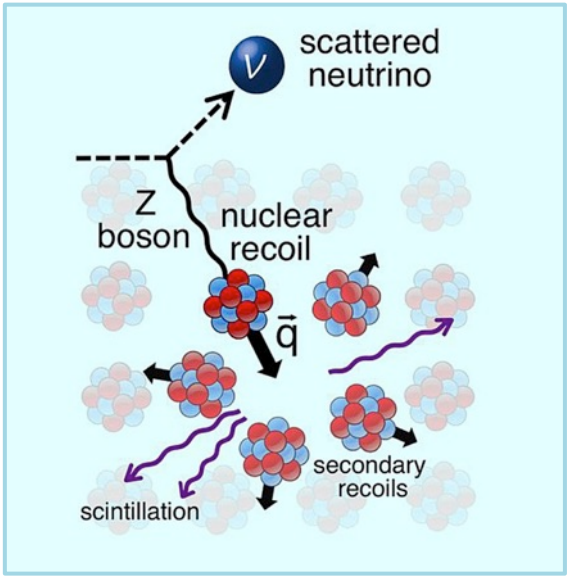


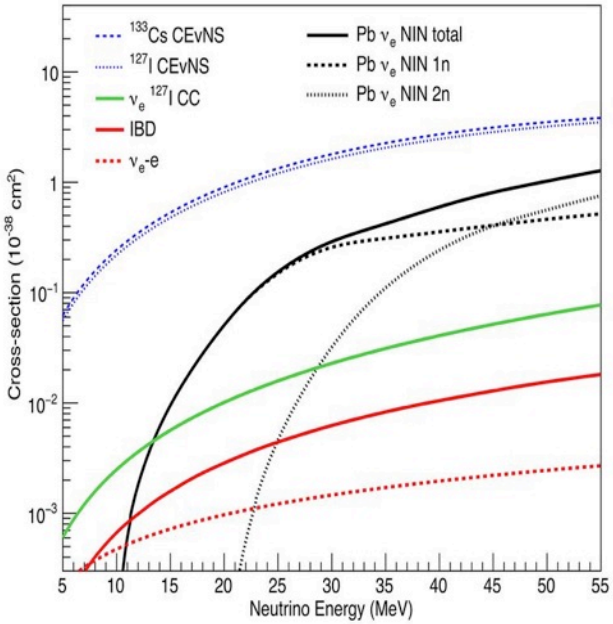
Coherent ν
New detectors
Cross sections
0ν double beta

After the largest... the smallest: Coherent Elastic ν Nucleus Scattering

Detector size ~ sparkler! ...probing **small** energies/recoils... but **large** cross sections







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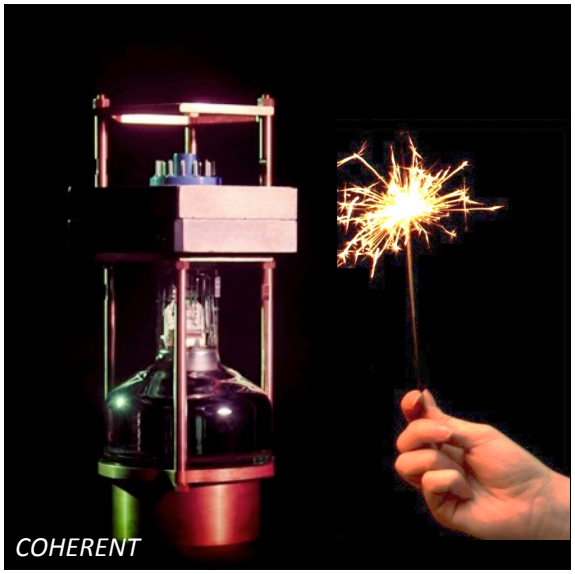
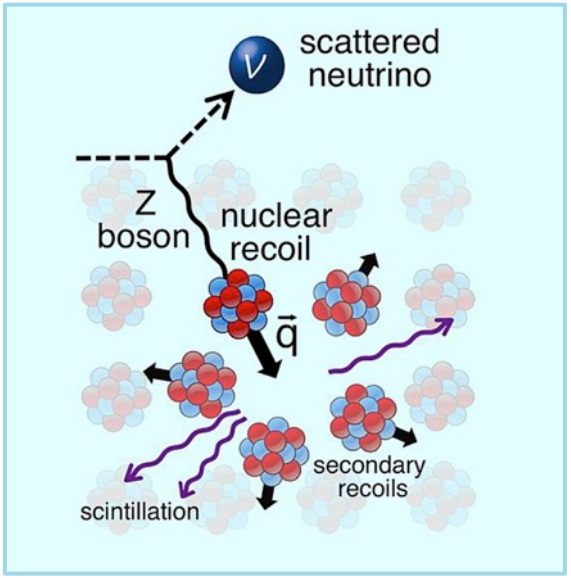
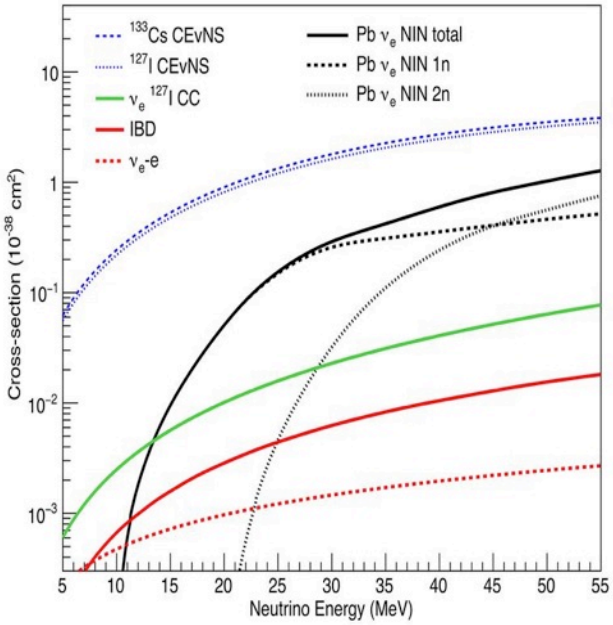
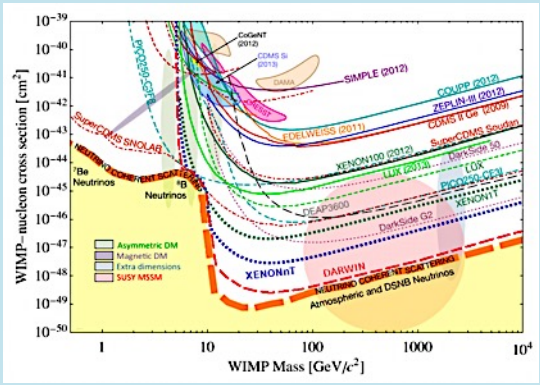






"Yesterday's discovery is today's calibration..."

(R. Feynman)

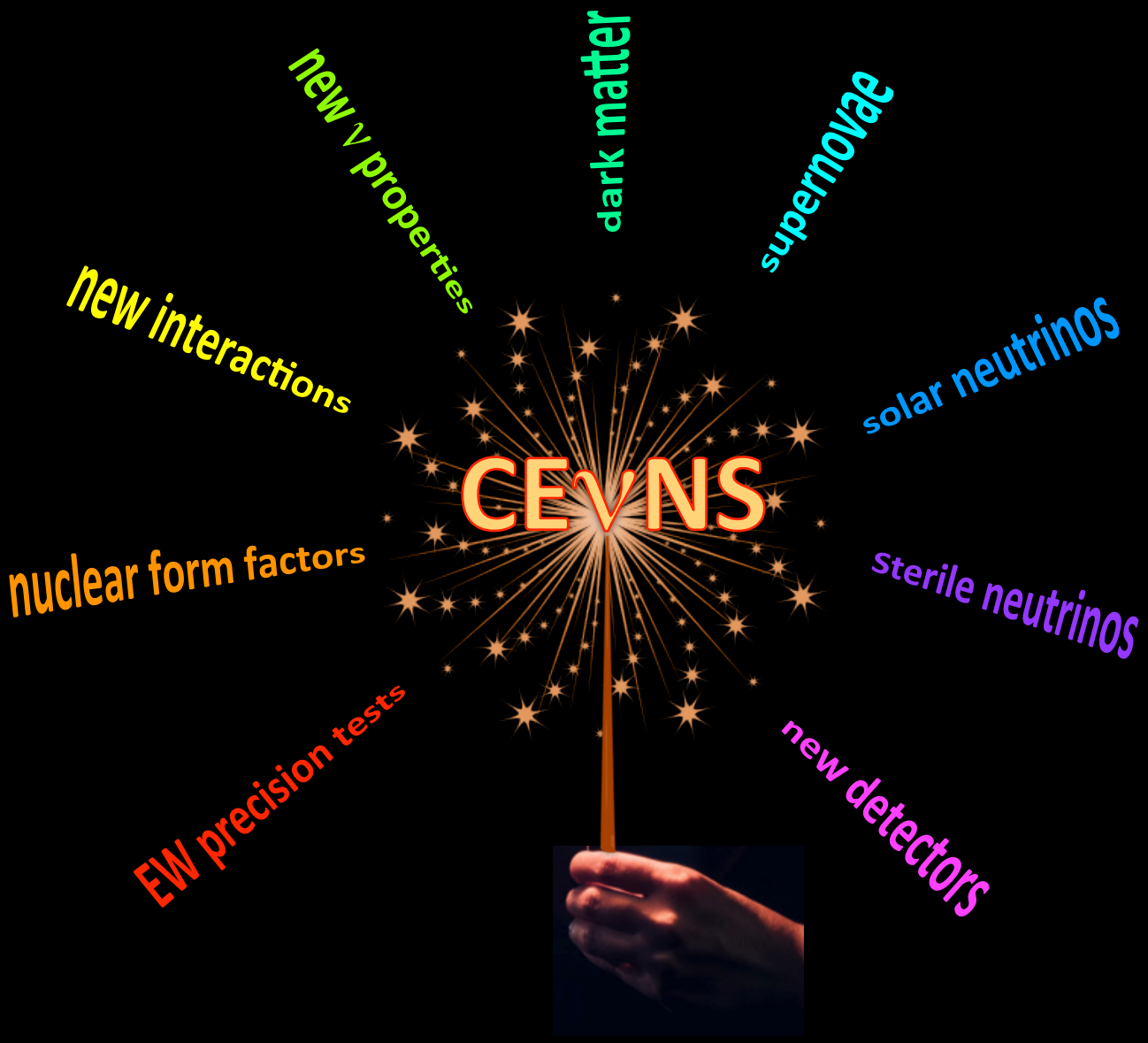


"...and tomorrow's background."

(V. Telegdi)

A new portal to (non)standard particle and nuclear physics

... small but multicolor !

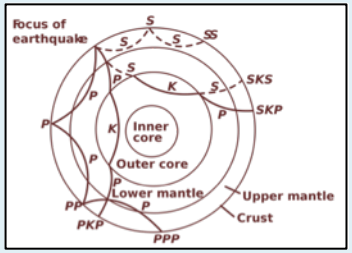


One way to reject background in DM searches:
directional sensitivity → **New detection techniques, e.g:**

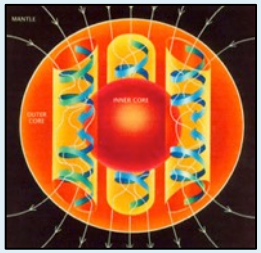
Great potential from new/improved concepts for liquid scintillators.

Among the many areas of interest: **improved geo-ν detection**
Irreplaceable **probe of the Earth** in a multimessenger approach!

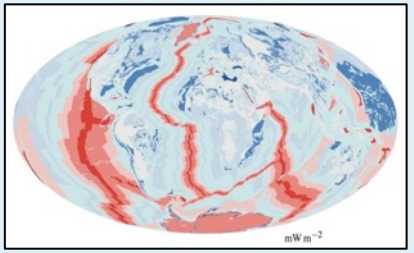
seismology



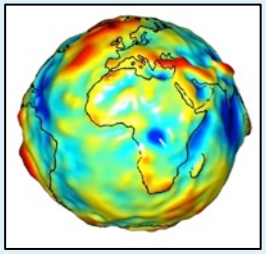
magnetism



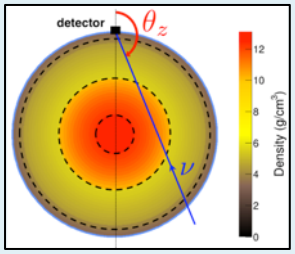
heat flow



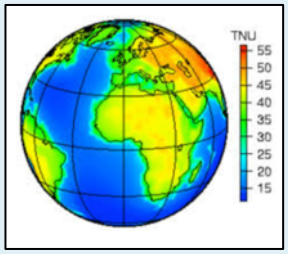
gravity



ν oscill/absor.



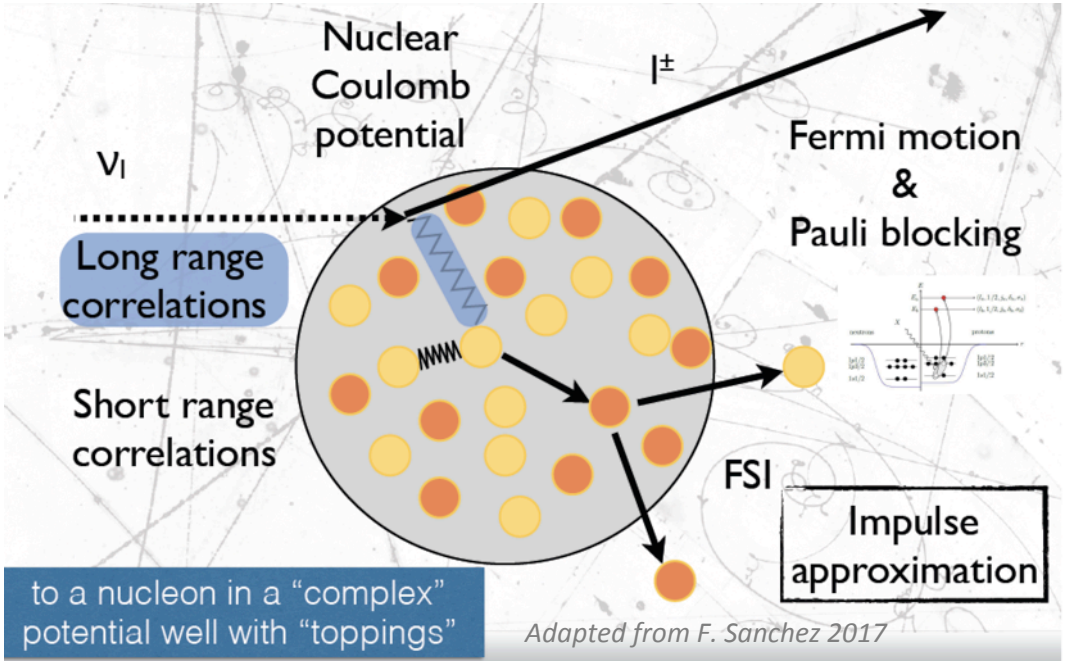
geo ν



From the nucleus as a whole to its inner part(on)s

Cross sections

A complex and interdisciplinary issue in ν physics, both expt and theo

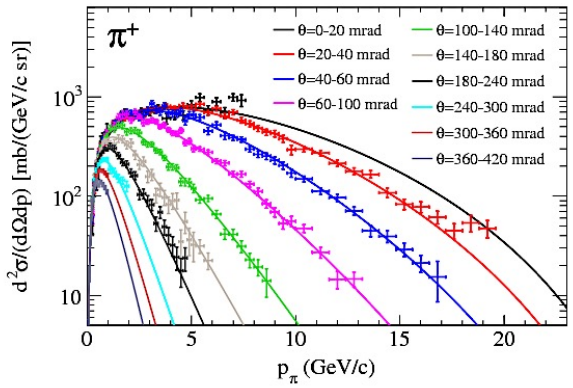


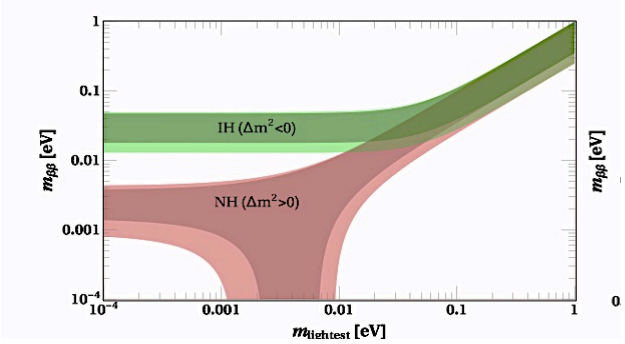
We have "standard models" for particle physics and for cosmology, but **but not yet for the nuclear response to electroweak probes**

Progress in this field crucial to get the most from many ν−related data

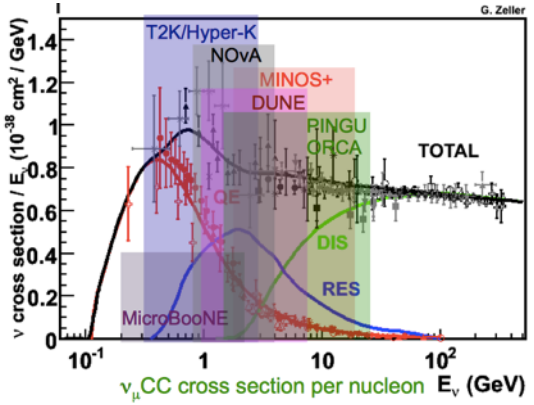
"Strong interaction" effects on "weak interaction" physics are ubiquitous...

Need hadron production data, e.g. pA → πX, +theory models to improve estimates of atm. and acceler. ν fluxes and errors





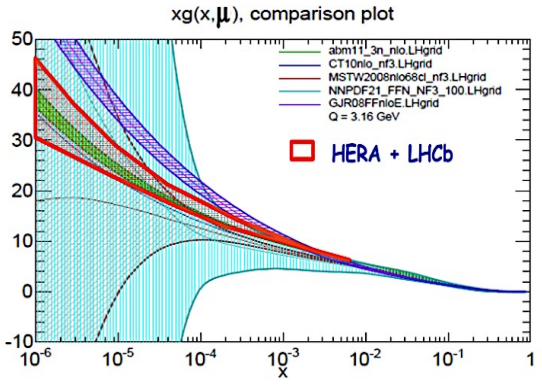
Current understanding of ν cross sections at O(GeV) does not match the needs of (next-generation) ν expts

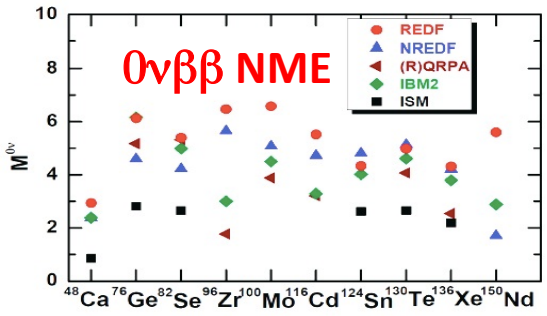


Better control of nuclear EW response (e.g., g_A) relevant to interpret 2β data and to connect them with other data

...

Improved PDFs at low-x via ~forward charm production at LHCb essential to constrain prompt component in UHE ν

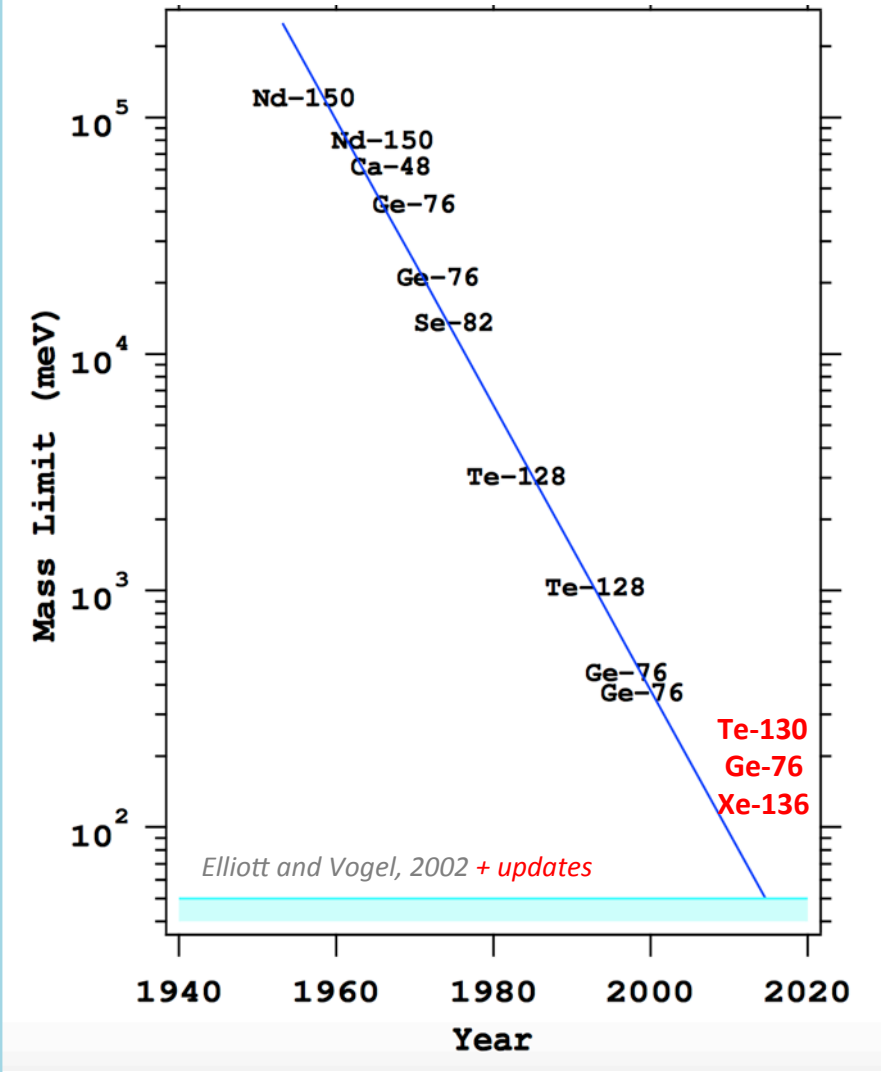


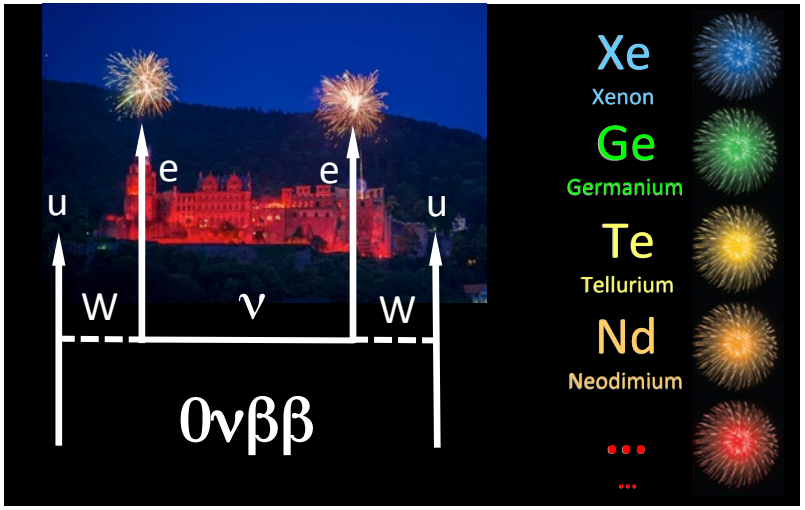


Progress requires joint contributions from different disciplines & communities

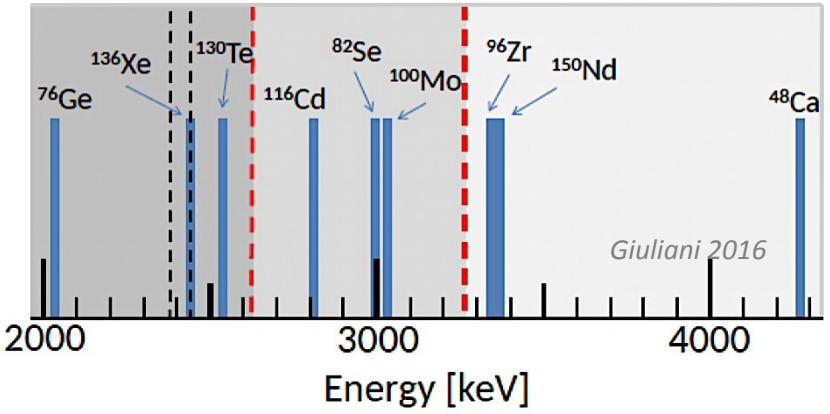
In the long-term: Lattice QCD? Recent calculations of axial coupling and form factor (g_A, m_A)

$0\nu\beta\beta$: Moore's law for the rare fireworks that we'd love to see, once in > $10^{25\text{-}26}$ years...



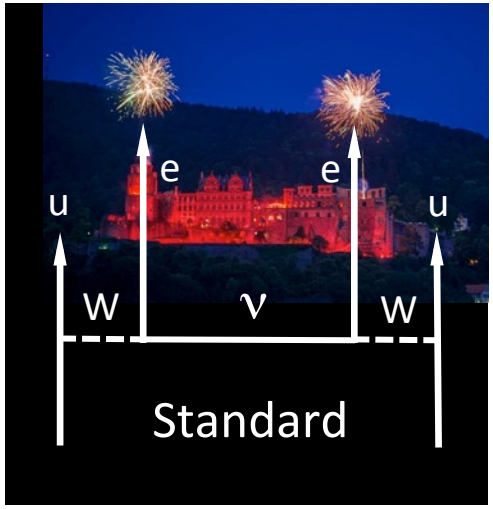


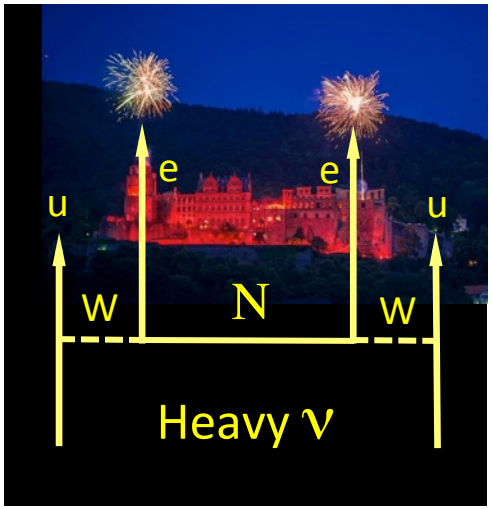
No "golden" isotope, search in a variety!

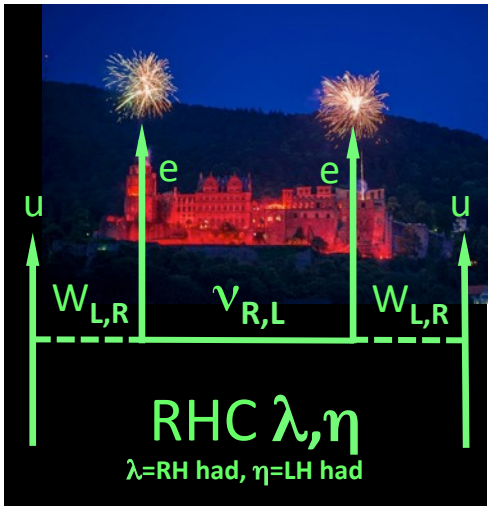


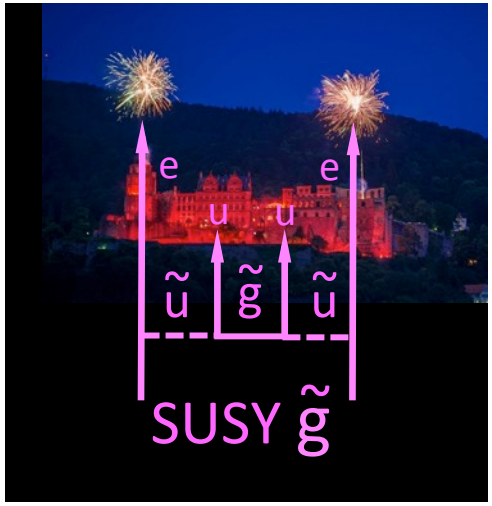
Heroic efforts! But... some fatigue? Extensive discussion about **new-generation expt's.**

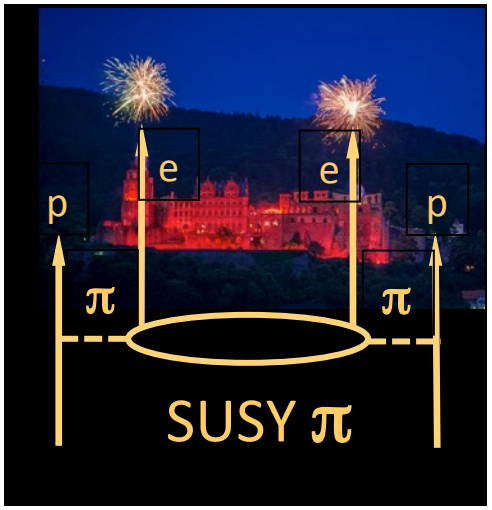
Warning: **don't stick to $m_{\beta\beta}$ metric, just go on with $T_{1/2}$!** Variety of $0\nu\beta\beta$ mechanisms:







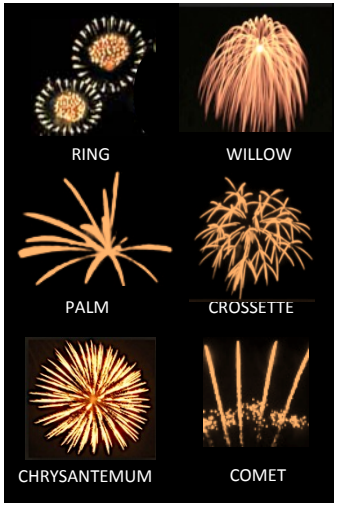




$0\nu\beta\beta$ from any mechanism → **Majorana nature of ν would be established anyway**

Shapes

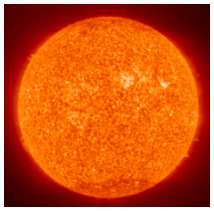
When νs meet the many facets of particle physics

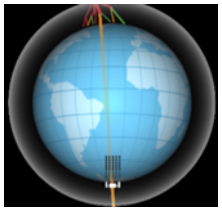


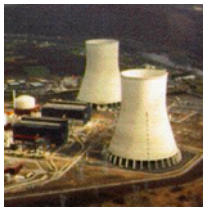
Solar, atmos.
Reactor, Accel.
Lab. ν mass
Phenomenology

Shapes of ν sources ...

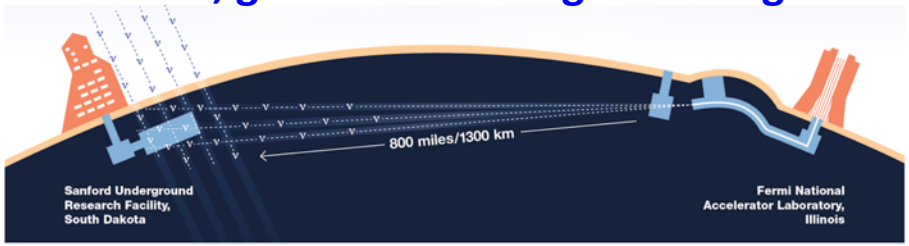
Only sources given to us for free can be 4π... (*)



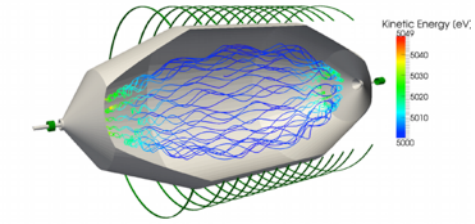


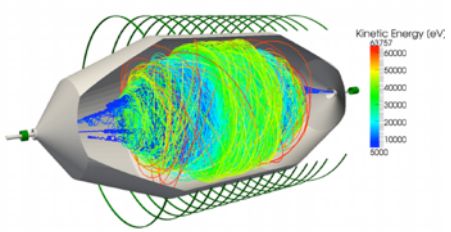


Otherwise, great skills to engineer long beams...



... and ingenious particle paths in the laboratory





(*) ... unless the source is small and the detector is 4π

Shaping particle physics via ν oscillation synergies...

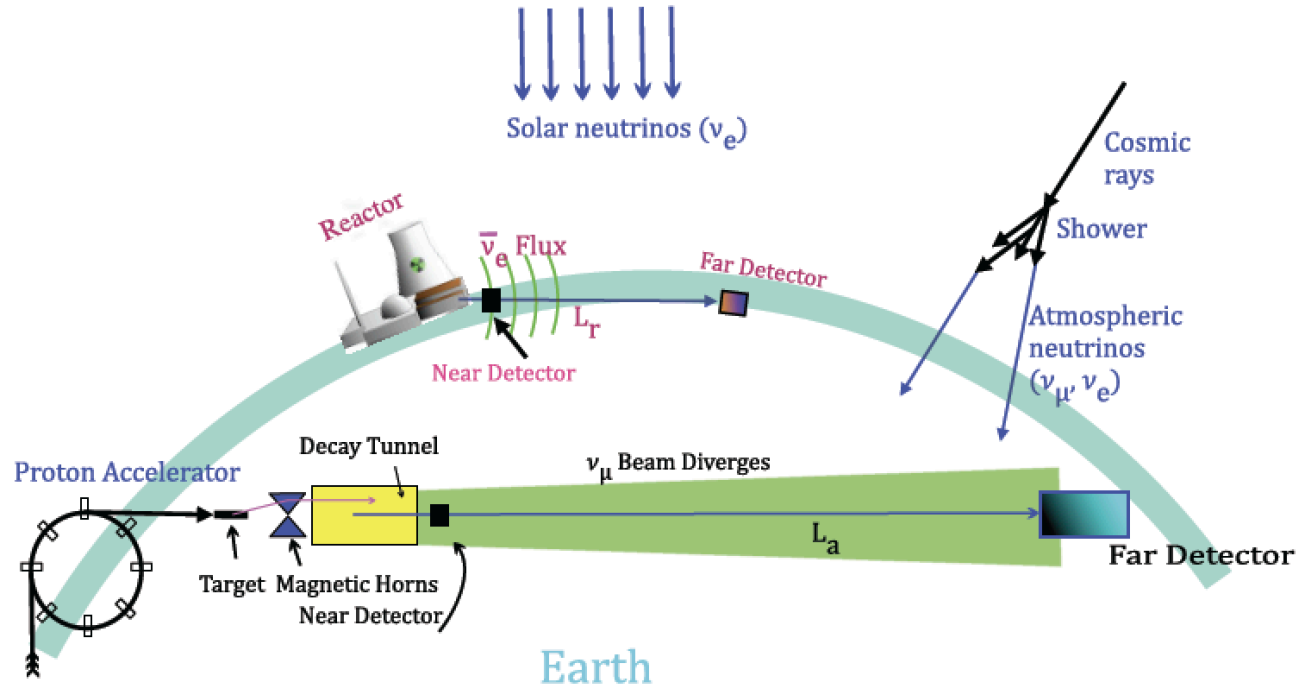


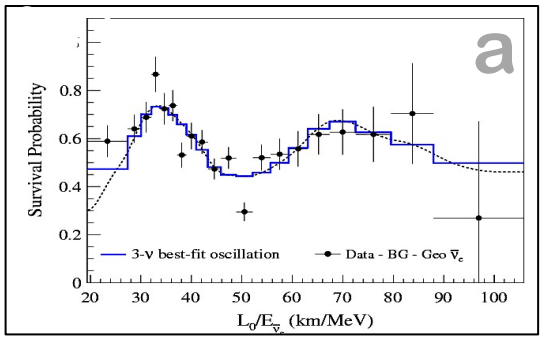
Figure 1: Schematic illustrating neutrino sources that have contributed to the current understanding of neutrino properties through neutrino oscillation experiments.

from Diwan+ 2016

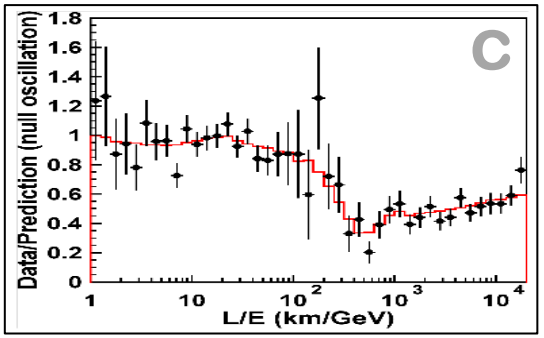
→ **emergence of a new PMNS 3ν paradigm in flavor physics, besides CKM**

Shapes and patterns in α → β channels in vacuum and matter...

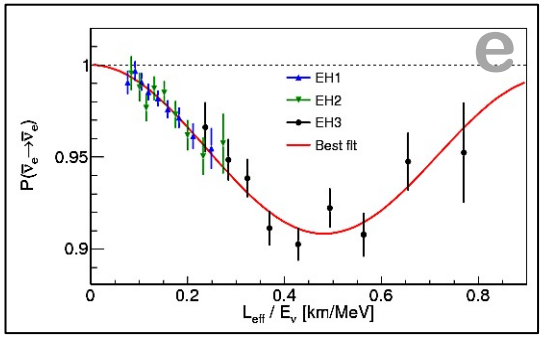
e→e (KamLAND)



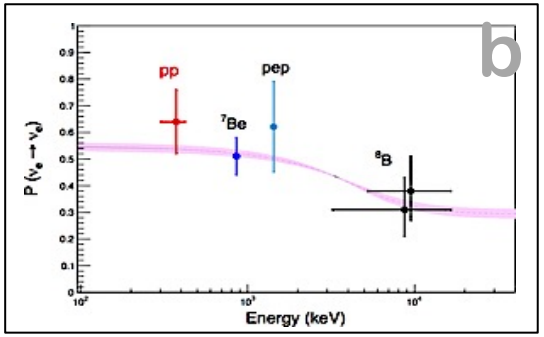
μ→μ (Atmospheric)



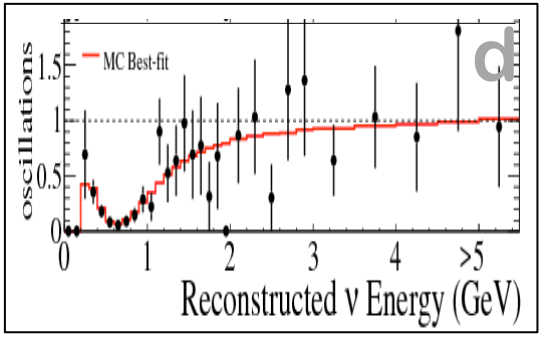
e→e (SBL Reac.)



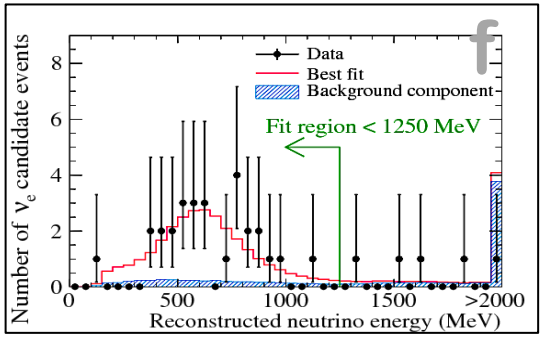
e→e (Solar)



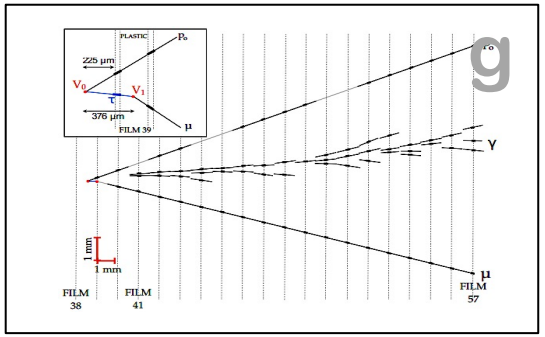
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK)

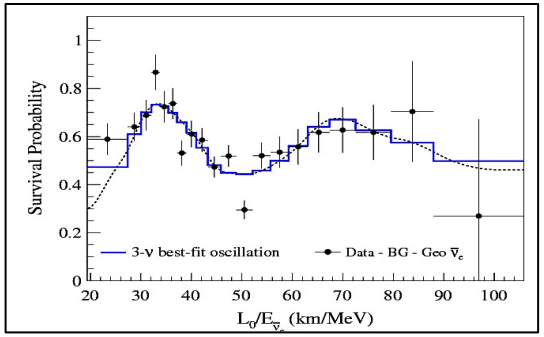


Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

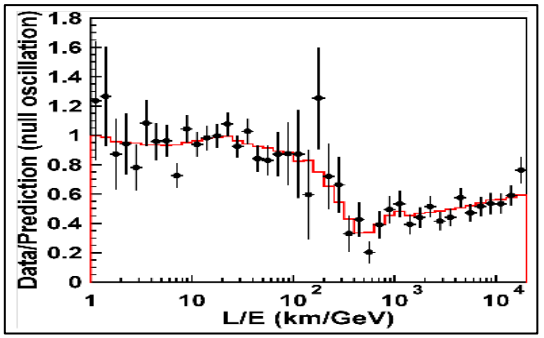
(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/ GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K atmospheric.

… successfully converging on known 3ν mass-mixing parameters…

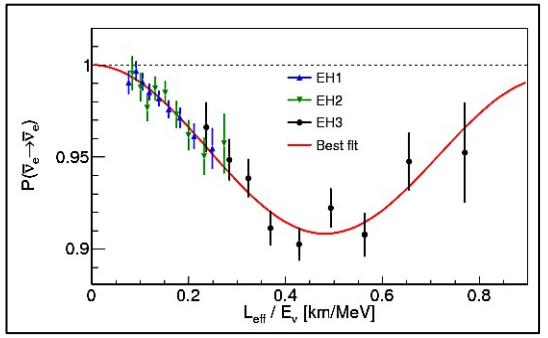
e→e (δm^2 , θ_{12})



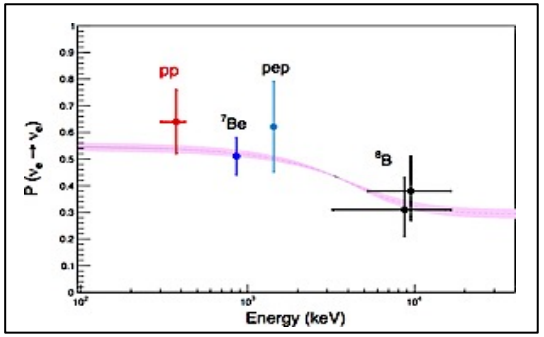
μ→μ (Δm^2 , θ_{23})



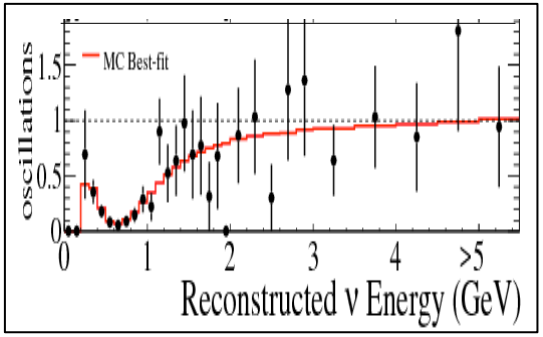
e→e (Δm^2 , θ_{13})



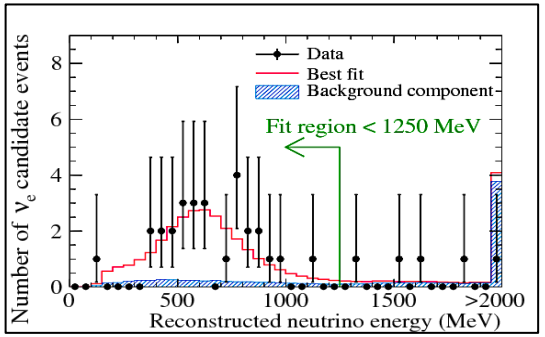
e→e (δm^2 , θ_{12})



μ→μ (Δm^2 , θ_{23})



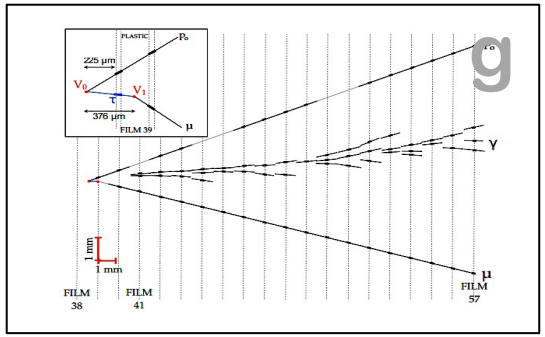
μ→e (Δm^2 , θ_{13} , θ_{23})



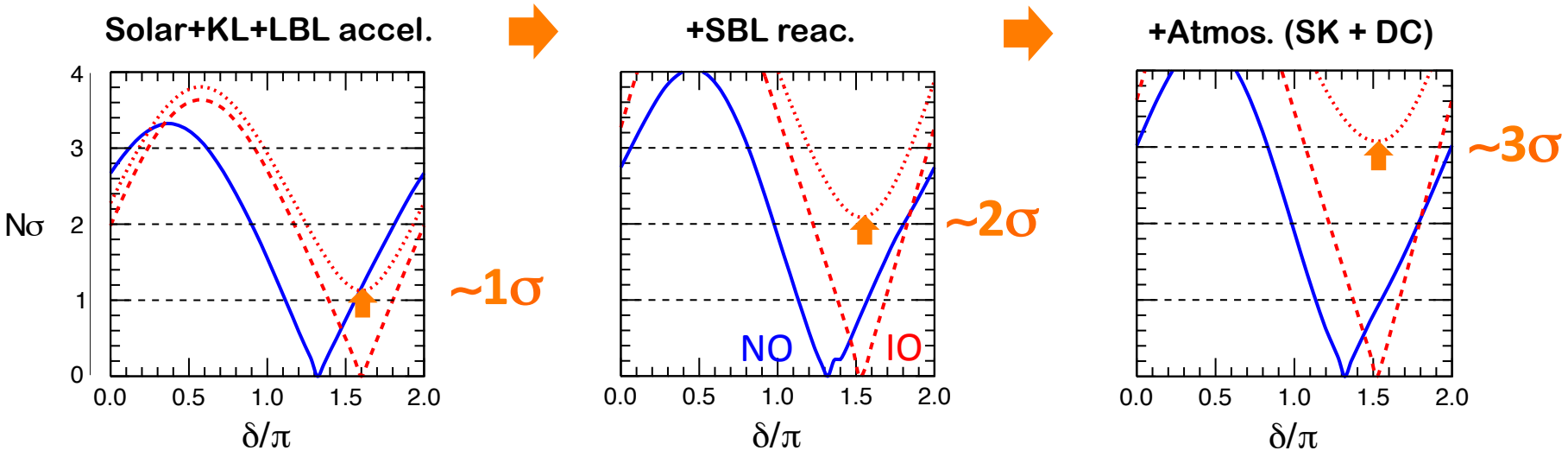
1σ uncertainty

Δm^2	1.4 %
δm^2	2.2 %
$\sin^2\theta_{13}$	3.8 %
$\sin^2\theta_{12}$	4.4 %
$\sin^2\theta_{23}$	~ 5 %

μ→τ (Δm^2 , θ_{23})



… providing hints on the unknown ones …



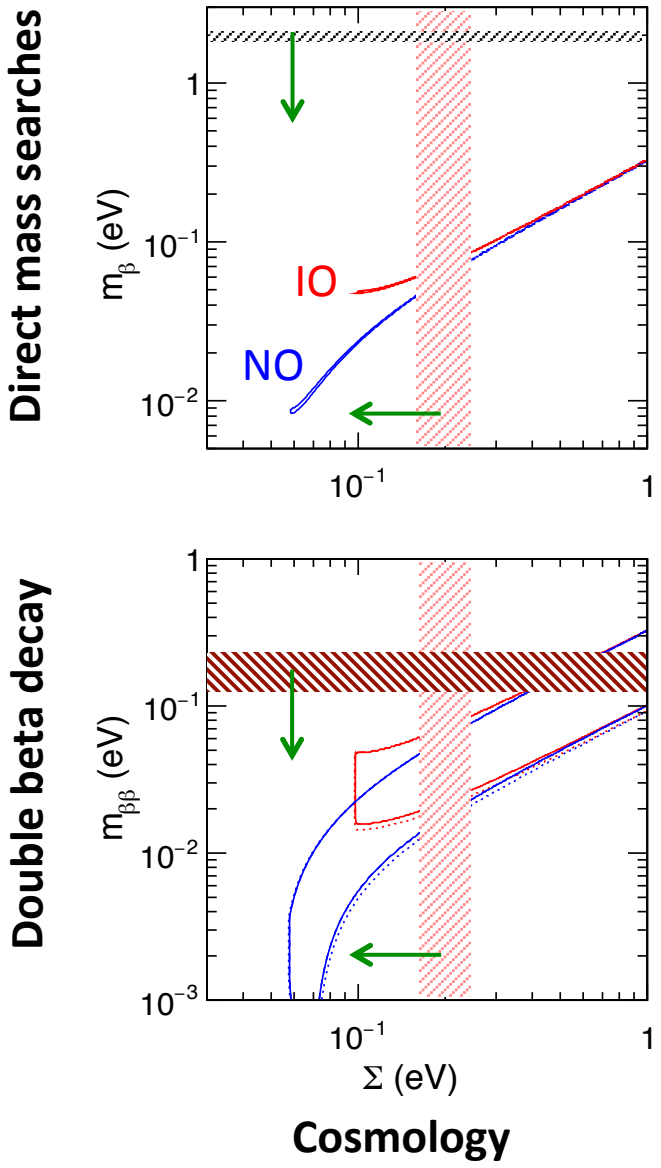
Capozzi+ arXiv:1804.09678

Inverted Ordering (IO) increasingly disfavored wrt Normal Ordering (NO)

CP phase constrained around $3\pi/2$ (maximal CPV), but $\sim\pi$ compatible at $\sim 2\sigma$

Will these hint survive the next talks by T2K+NOvA+….?
How well can they be tested by future dedicated experiments?

… and charting the 3ν phase space of non-oscillation searches



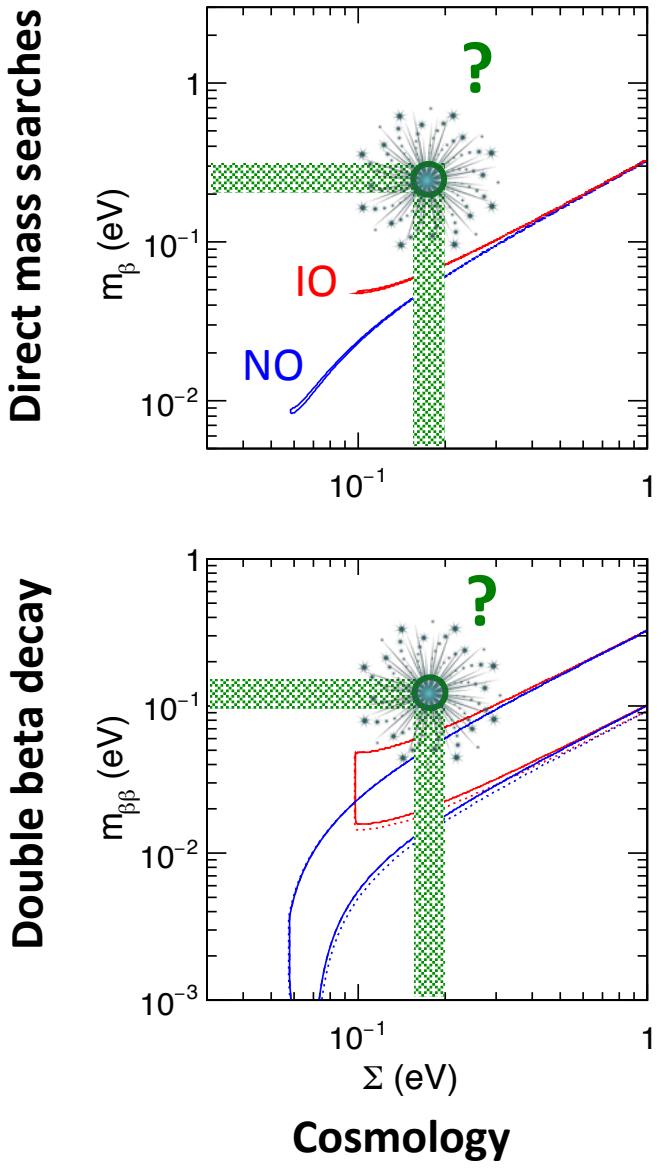
Great potential for breakthroughs in oscillation and nonoscill. searches!

Progress will benefit from advances on various **spectral shapes**:

- *Resolution, bkgd for (2)β decay*
- *Cosmological power spectra*
- *Reactor spectral features*
- *Accelerator energy spectra*
- *Bkgd spectra for solar CNO*
- *Atmosph. energy-angle spectra*
- *…*

Unprecedented **challenges** and opportunities for both **discovery and precision physics.**

… but data might well bring us beyond 3ν and re-shape the field!



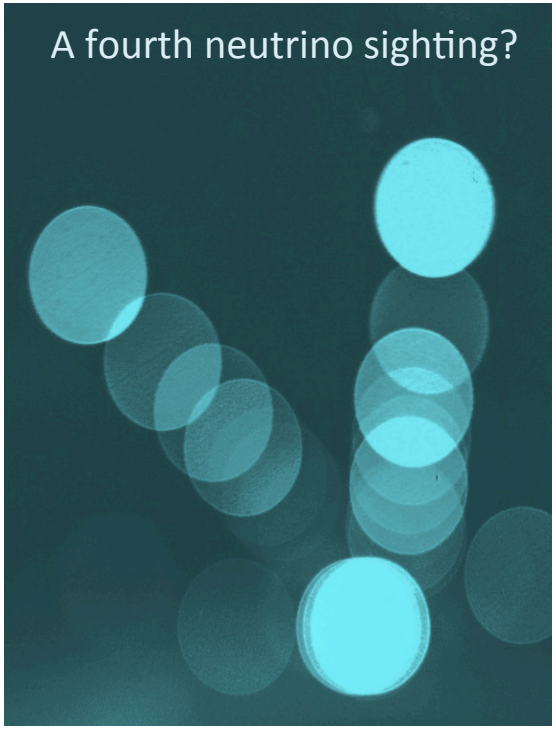
What if fireworks do not match?...

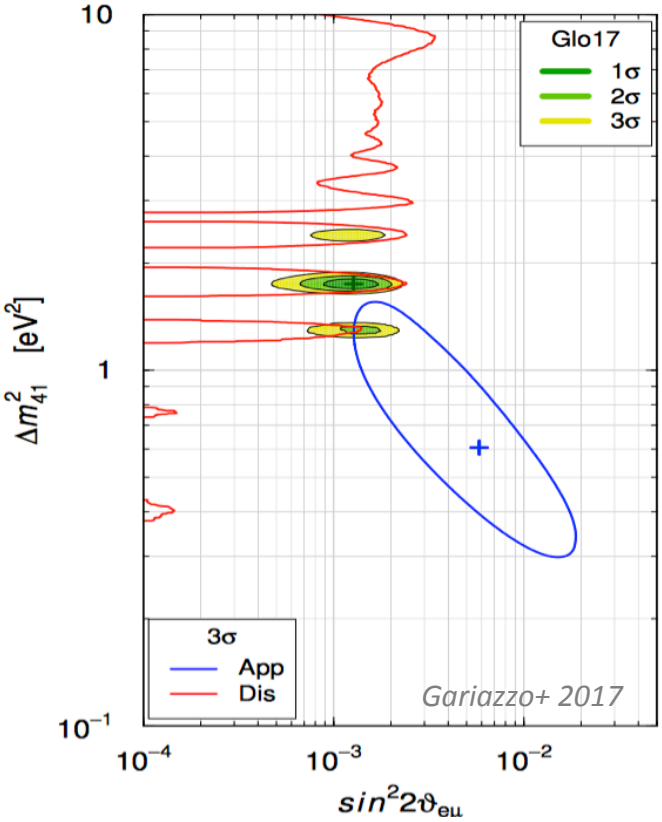
Lack of convergence within 3ν (barring expt mistakes) might point towards new possibilities:

- *Nonstandard $0\nu\beta\beta$ mechanisms*
- *Cosmology beyond ΛCDM*
- *New neutrino states*
- *New interactions*
- *Nonstandard ν properties*
- *New phenomena in propagation*
- *…*

Main contender in current ν physics:
Light sterile ν at O(eV) scale →

Still **unfocused images** (mirages?) of this creature,
despite a >20 yr hunt in a restricted territory,
where it seems to appear and disappear ...

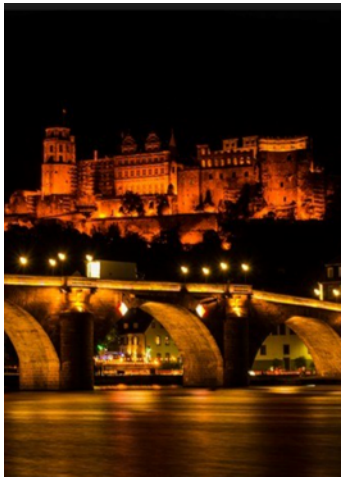




Enlightment from recent searches and analyses?

Illumination

When ν's meet new physics and energy scales



Theory
More on Sterile ν
Dark matter
[Epilogue]

Light in the dark... or the lack of it?

Different perspectives in [neutrino] physics

Subnuclear Physics: Past, Present and Future
Pontifical Academy of Sciences, Scripta Varia 119, Vatican City 2014
www.pas.va/content/dam/accademia/pdf/sv119/sv119-altarelli.pdf

The Mystery of Neutrino Mixing

Guido Altarelli

> Finally, one could have imagined that neutrinos would bring a decisive boost towards the formulation of a comprehensive understanding of fermion masses and mixings. In reality it is frustrating that no real illumination was sparked on the problem of flavour. We can reproduce in many different ways the observations, in a wide range that goes from anarchy to discrete flavour symmetries) but we have not yet been able to single out a unique and convincing baseline for the understanding of fermion masses and mixings.

Not yet… → Must remain open to a wide spectrum of options…

No organizing principle ("anarchy")	
Discrete family simmetries ("geometry")	linear relations between $\theta_{13}\cos\delta$ and θ_{12}, θ_{23}
Continuous flavor simmetries ("dynamics")	links between neutrino masses/angles/phases
Common quark/lepton features ("complementarity")	links between θ_{13} and θ_C

… which will benefit from more accurate or new data, e.g. on masses and possible breakthroughs in related areas (e.g., charged LFV)

But even if the flavor sector remains to be largely understood…

...time-honored ideas continue to illuminate the path forward!

perspective

NATURE PHYSICS | VOL 14 | FEBRUARY 2018

Symmetry and emergence

[**Edward Witten**, arXiv:1710.01791]

In a modern understanding of particle physics, global symmetries are approximate and gauge symmetries may be emergent. This view, which has echoes in condensed-matter physics, is supported by a variety of arguments from experiment and theory.

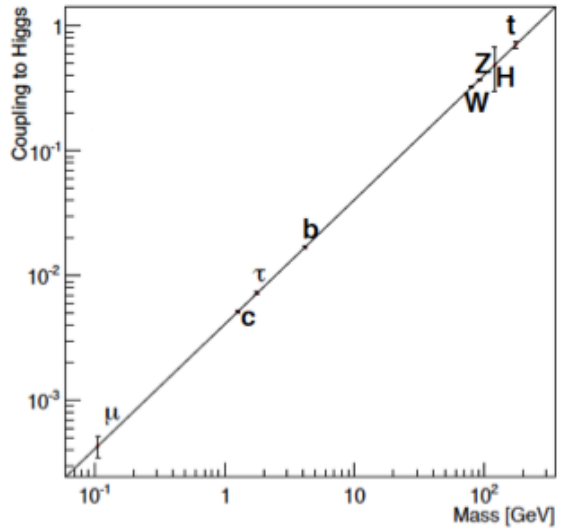
No reason for global symmetries to be exact, from different theoretical perspectives.

No global lepton number conservation	$\mathcal{L}_1 = \frac{1}{M} HHLL$	**Majorana neutrinos**
No global baryon number conservation	$\mathcal{L}_2 = \frac{1}{M^2} QQQL$	**Proton decay**
No a priori CP conservation in QCD	$\mathcal{L}_3 = \frac{a}{M'} \varepsilon^{\mu\nu\alpha\beta} \mathrm{tr}\, F_{\mu\nu} F_{\alpha\beta}$	**Axion**

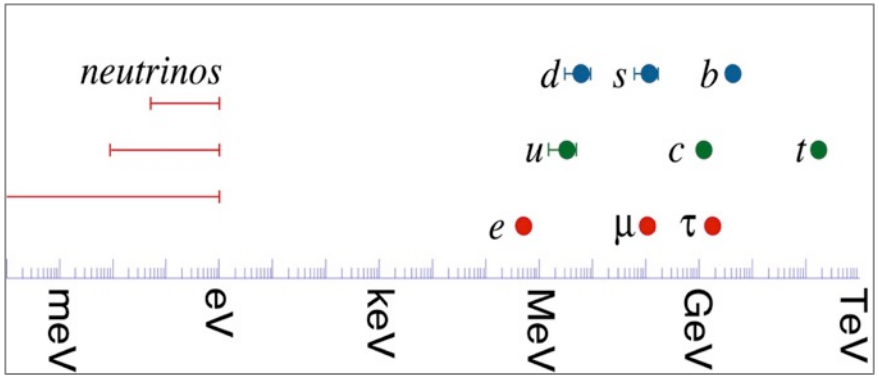
General arguments, not weakened by absence of new physics at the LHC scale...

Bridging two physics programs in collider and ν physics

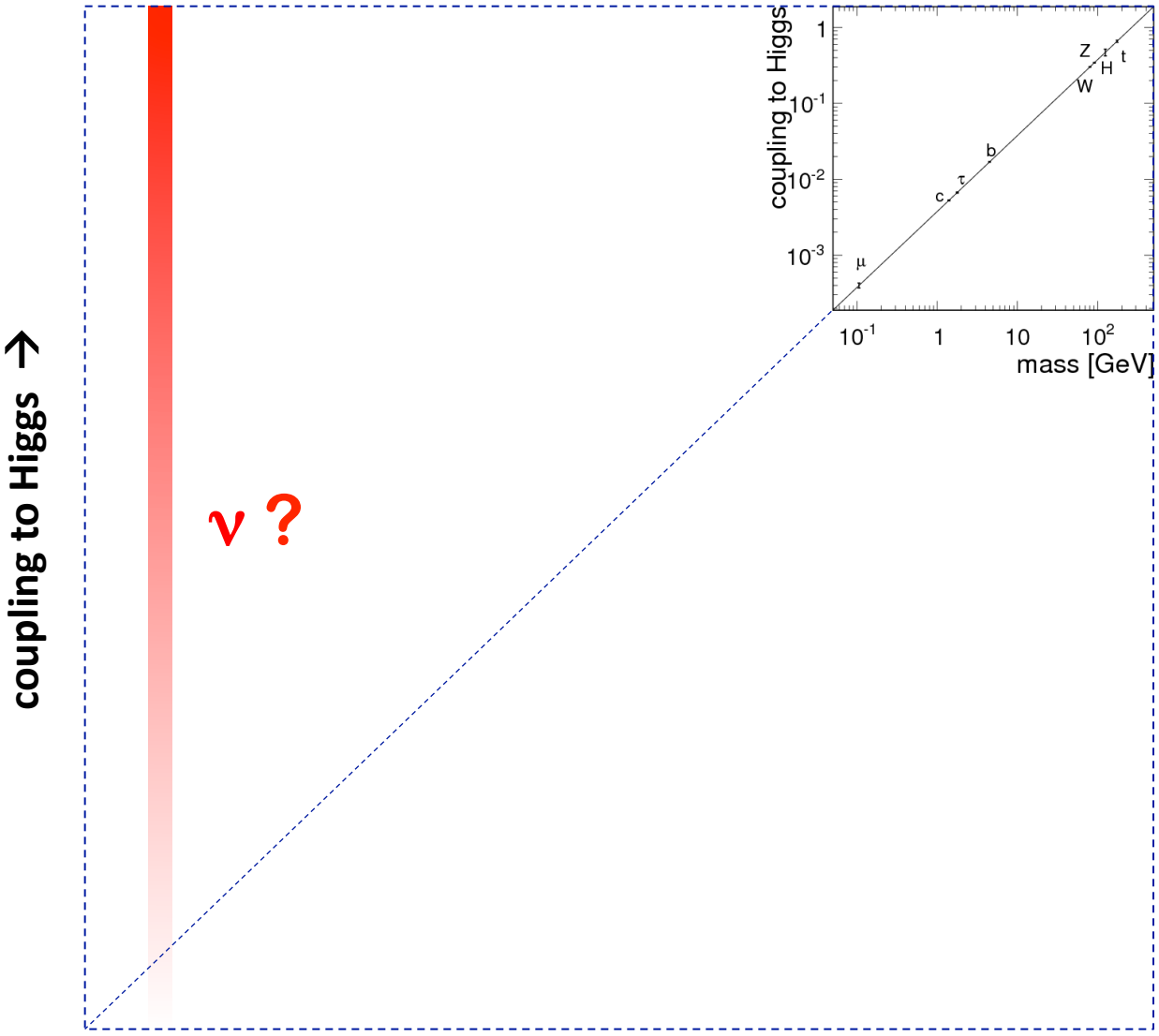
1. Test Higgs and SSB



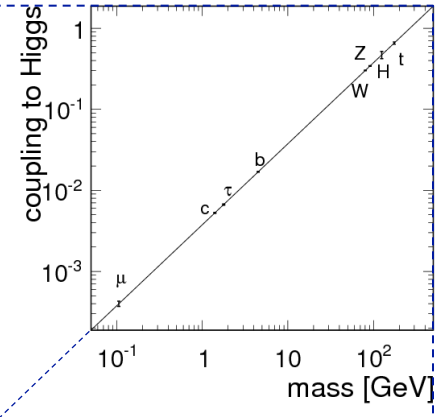
2. Find ν masses



1 + 2 **Where are the ν's on this plot? Why are they so light?**



Option I



coupling to Higgs →

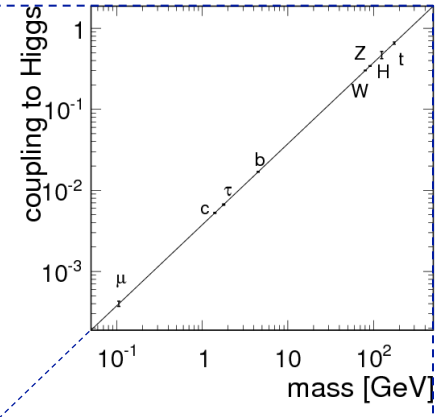
Dirac: neutrinos "talk" very weakly to the Higgs boson, **$y < 10^{-12}$** for unknown reasons...

ν

< 1 eV

particle mass →

Option II



ν

coupling to Higgs →

Majorana: neutrinos talk "normally" to the Higgs, but also to other (much) **higher scale(s) M** --> suppression factor

$y \rightarrow y\, M_H/M$ (see-saw)

< 1 eV

particle mass →

Neutrinos masses may offer
a great opportunity to jump
beyond the EW framework
via the see-saw mechanism...

... and to address fundamental physics issues, such as:

- new sources of CP violation at low and high energies
- lepton number violation and associated phenomena
- matter-antimatter asymmetry of the universe ...

M ~ GUT scale

CP-violating decays of heavy neutrinos at scale M may generate lepton asymmetry (leptogenesis):
Discovery of leptonic CP violation and of Majorana nature (+ proton decay?) would be important steps towards this scenario.

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M ~ low scale

At the other end of the spectrum, low-scale (e.g. EW) see-saw may also generate (at the price of fine-tuning) additional interesting phenomenology: dark matter candidates, di-lepton and heavy lepton events in HEP

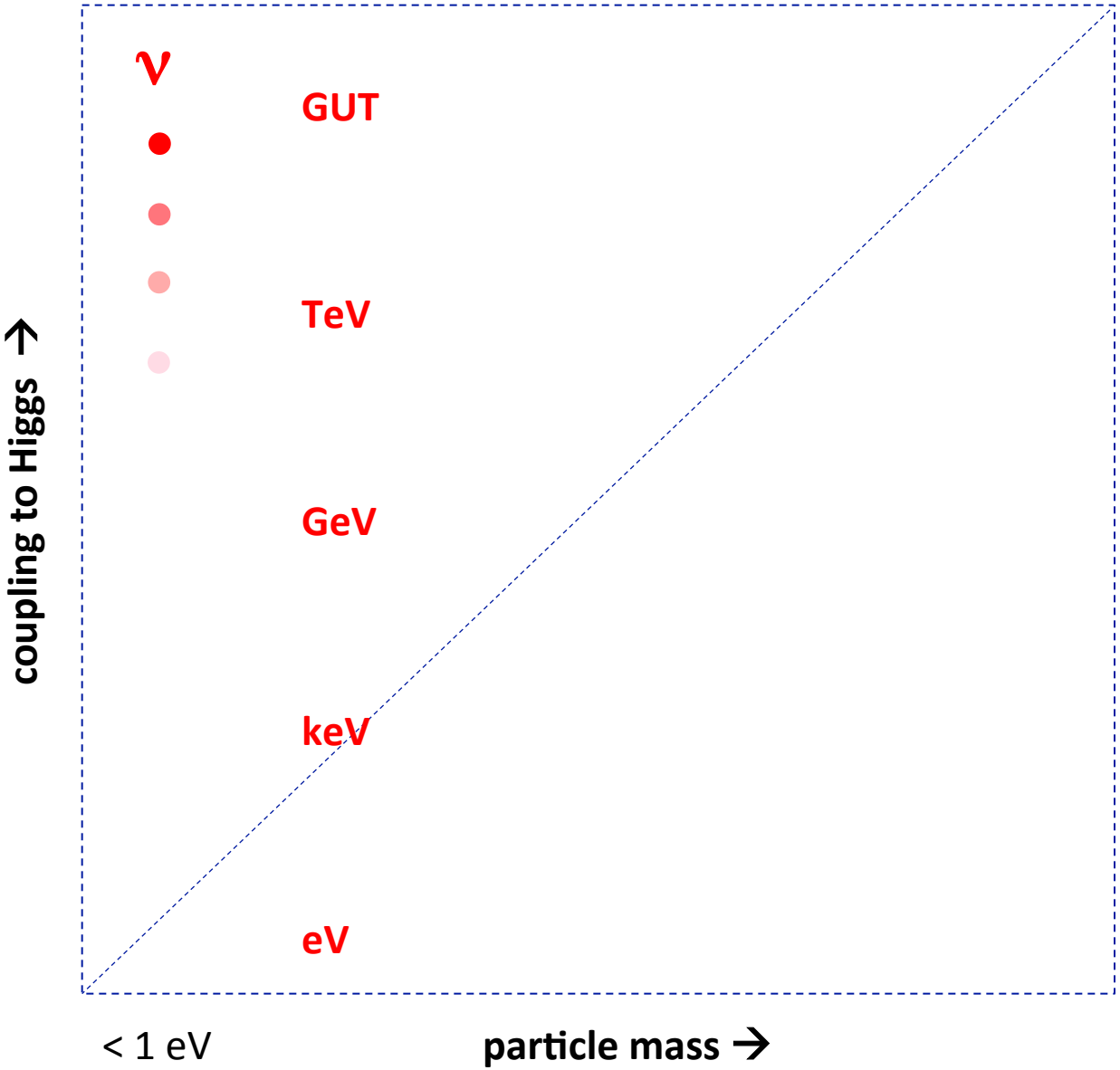
CP-violating decays of heavy neutrinos at scale M may generate lepton asymmetry (leptogenesis). Discovery of leptonic CP violation and of Majorana nature (+ proton decay?) would be important steps towards this scenario.

At the other end of the spectrum, low-scale (e.g. EW) see-saw may also generate (at the price of fine-tuning) additional interesting phenomenology: dark matter candidates, di-lepton and heavy lepton events in HEP

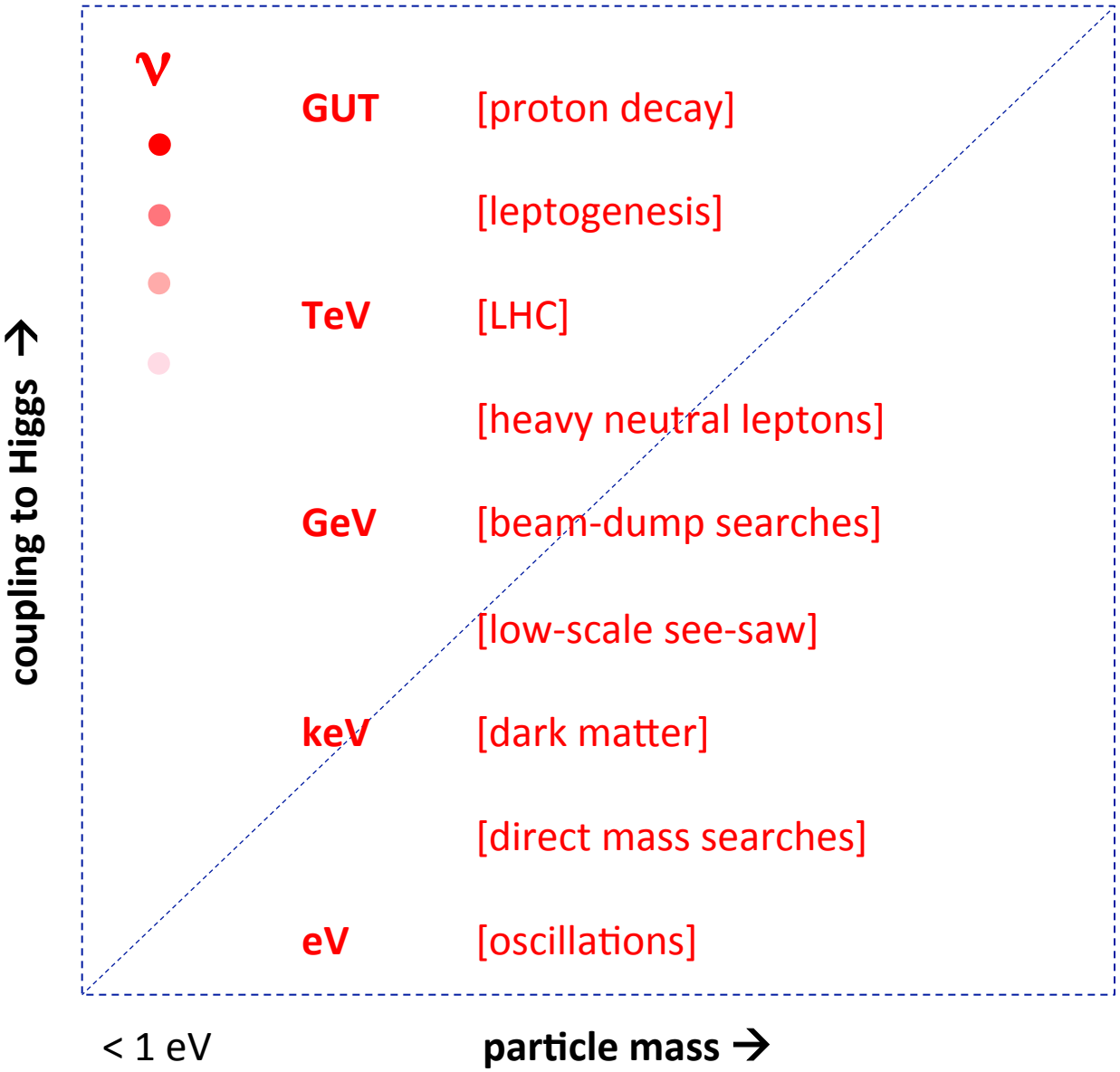
In principle, several sterile states might even be split among widely different energy scales, and affect various phenomena in (astro)particle physics.

EPILOGUE... Let us remain open-minded...

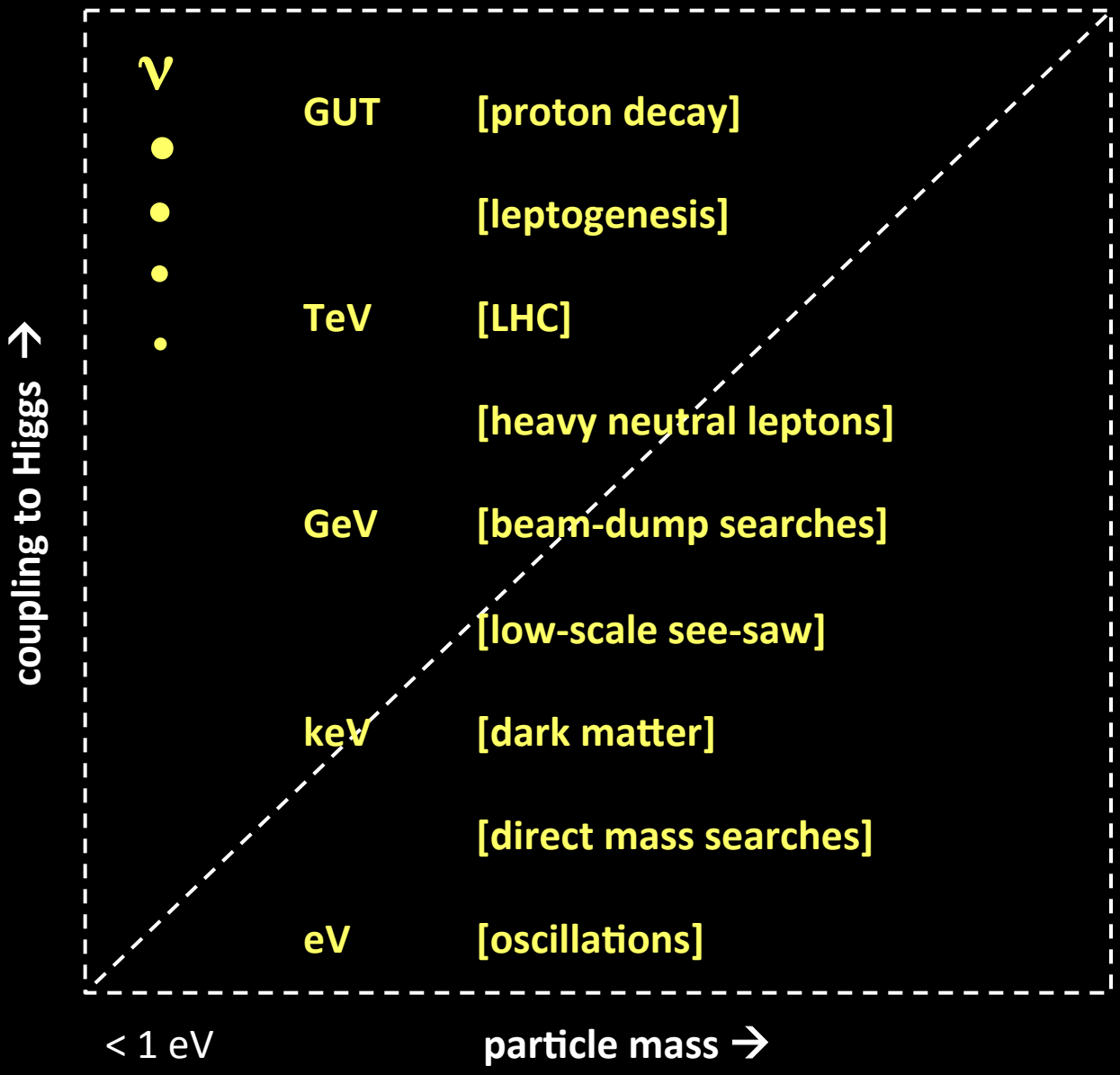
...neutrino physics can be linked to several new physics scales...



... and to a very rich phenomenology...

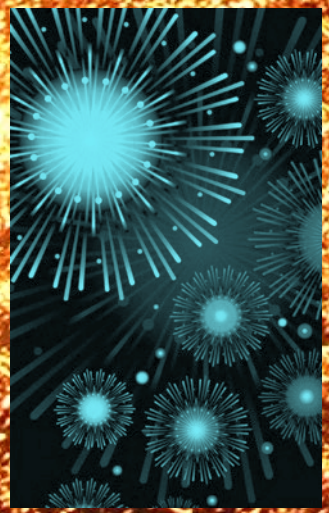


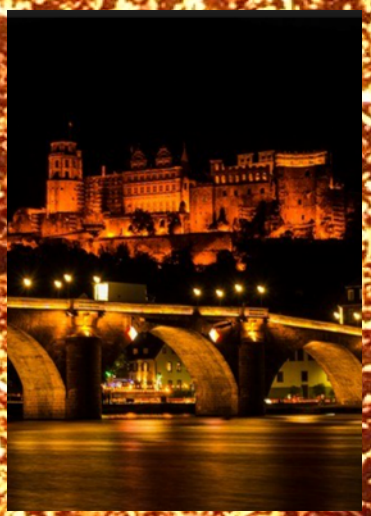
… from which we expect new light…



Background image credit: Wikimedia Commons

...with surprising fireworks!





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