A la recherche de la Nouvelle Physique
(introduction et perspective théorique)

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1. motivation: puzzles, dreams, questions,...
   - NP exists (m_ν, DM,DE, asym B,$\frac{\delta}{\delta\rho}$...)
   - mais qui est-elle et ou la rencontrer?
2. lampposts for finding New Physics
3. what to do as a theorist?
   - précision vs rare — quels avantages?
   - measuring feeble cplings of ephemeral particles
   - from events to a model?

Lets suppose NP $=$ new particle/field ($+$ its interactions)

Motivations, “Science Drivers”(vocab. snowmass) for NP Searches

1. curiosity: push the limits/ explore the unknown
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2. (a bit more focused) (theory puzzles):
   - challenges of SM (a successful QFT): gravity **(Malbrunot)**, hierarchy, strong CP...

3. (a bit more focused) NP *exists*:
   - $\boldsymbol{m_\nu}$: how well do we know the neutrinos?
     How many?/Model for mass matrix?**(LFV:Carloganu)**/Is L # conserved? **($0\nu2\beta$:Kermaidic)**

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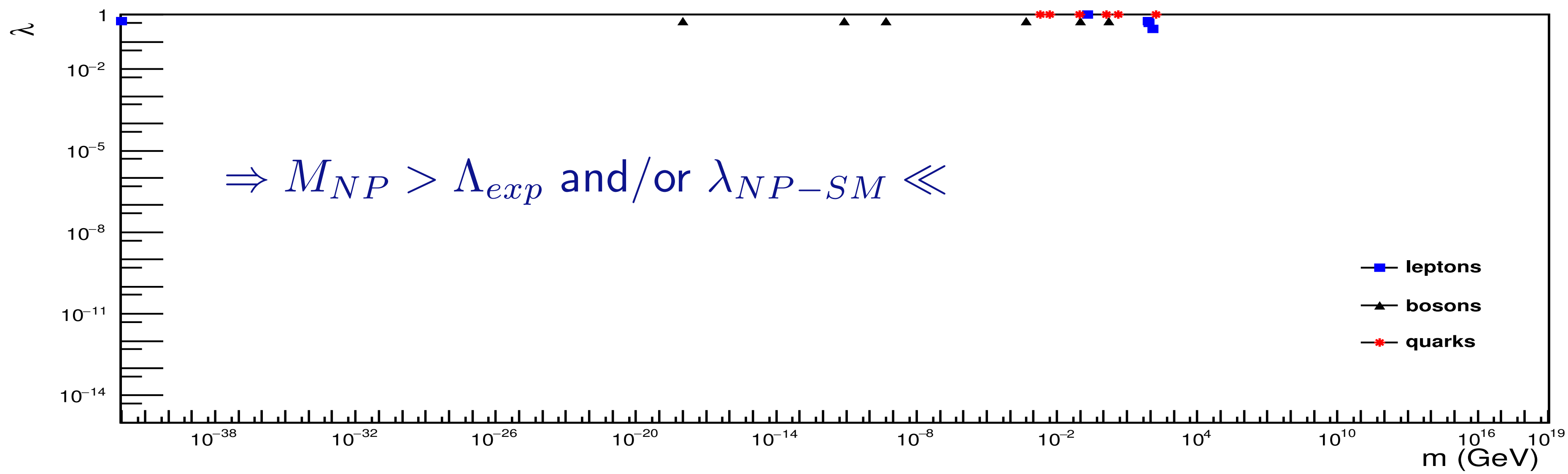
   - **DM** (+DE?) , $\boldsymbol{\delta\rho/\rho}$ and **matter excess**
     What is DM? **(Franco)**/Origin of matter? (CPV,B or L violn, $\boldsymbol{0\nu2\beta}$)/Who are DE and inflaton?

$\Rightarrow$ profound questions... *Why are we here?*

NP exists...but not found it yet...where to look?



★ brilliant model-builders on your corridor? Ask them where to look!★

...otherwise:*look everywhere* = under lampposts

Enlightening Lampposts (when one does not know where to look for what)

rare processes : *"peu d'exemplaires/peu fréquent"* (Larousse)
= less probable in the SM, than exptal sensitivity(ideally)
(**LFV, DM direct detection, CPV,** rare meson decays, ...)

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precision : *"qualité globale...donnant a peu près le meme résultat lorqu'on répète plusieurs fois la mesure"* (Larousse 3)
= processes that can be accurately calculated in the SM,
and accurately measured
$g - 2$, τ_n,...

each area/expt is a lamppost; role of theory to connect discoveries under different lampposts

Theory for unknown New Physics(no models)

1. $M_{NP} \gg \Lambda_{exp}$, NP cannot be on-shell/external leg.
   Can be exchanged among lighter particles $\Rightarrow$ contact interactions= operators.
   Effective Field Theory is QFT formalism allowing to construct all possible operators:

$$\mathcal{L} = \mathcal{L}_{light} + \sum_n \frac{1}{\Lambda_{NP}^n} \sum_J C_J \mathcal{O}_J$$

   $\star$ describes all $M_{NP} \gg \Lambda_{exp}$ models
   $\star$ elegant separation of known dynamics (SM) from unknown NP (heavy).
   So allows to account for SM loop effects between Λ_{exp} and Λ_{NP} ; calculate once and valid for all models! .

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2. for light NP with $\lambda_{NP-SM} \ll$:
   suppose is SM-gauge-singlet, classify by "portals" (talk to $H^\dagger H$, neutrinos or photon), and study representative models.

   $\star$ can be on-shell, could *discover* particles.

$(g-2)_\mu$ vs $\mu \to 3e$: polyvalent precision vs restrictive rare

Consider $\frac{(g-2)_\mu}{2} \equiv a \simeq \alpha_{em}/\pi\Big|_{SM}$. Measure via *Eqns of Motion* (QED *amplitude*):

(torque $\vec{\tau} = \vec{\mu} \times \vec{B}$; $\vec{\mu} = g\frac{e}{2m}\vec{S}$)

$$\Delta a \equiv a^{SM} - a^{exp} \simeq 3 \times 10^{-9}$$

Davier

$$\sim \frac{m_\mu^2}{16\pi^2 \Lambda_{NP}^2} \Rightarrow \Lambda_{NP} \lesssim m_t \text{ , any } \boldsymbol{NP} \text{ contributes}$$

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Davier

No $\mu \to 3e$ in SM; currently $BR(\mu \to 3e) \leq 10^{-12}$. Normalised to *weak* μ decay

$$BR(\mu \to e\bar{e}e) \equiv \frac{\Gamma(\mu \to e\bar{e}e)}{\Gamma(\mu \to e\bar{\nu}\nu)} \quad , \quad \Gamma(\mu \to e\bar{\nu}\nu) = \frac{G_F^2 m_\mu^5}{192\pi^3} = \frac{m_\mu^5}{1536\pi^3 v^4}$$

Carloganu

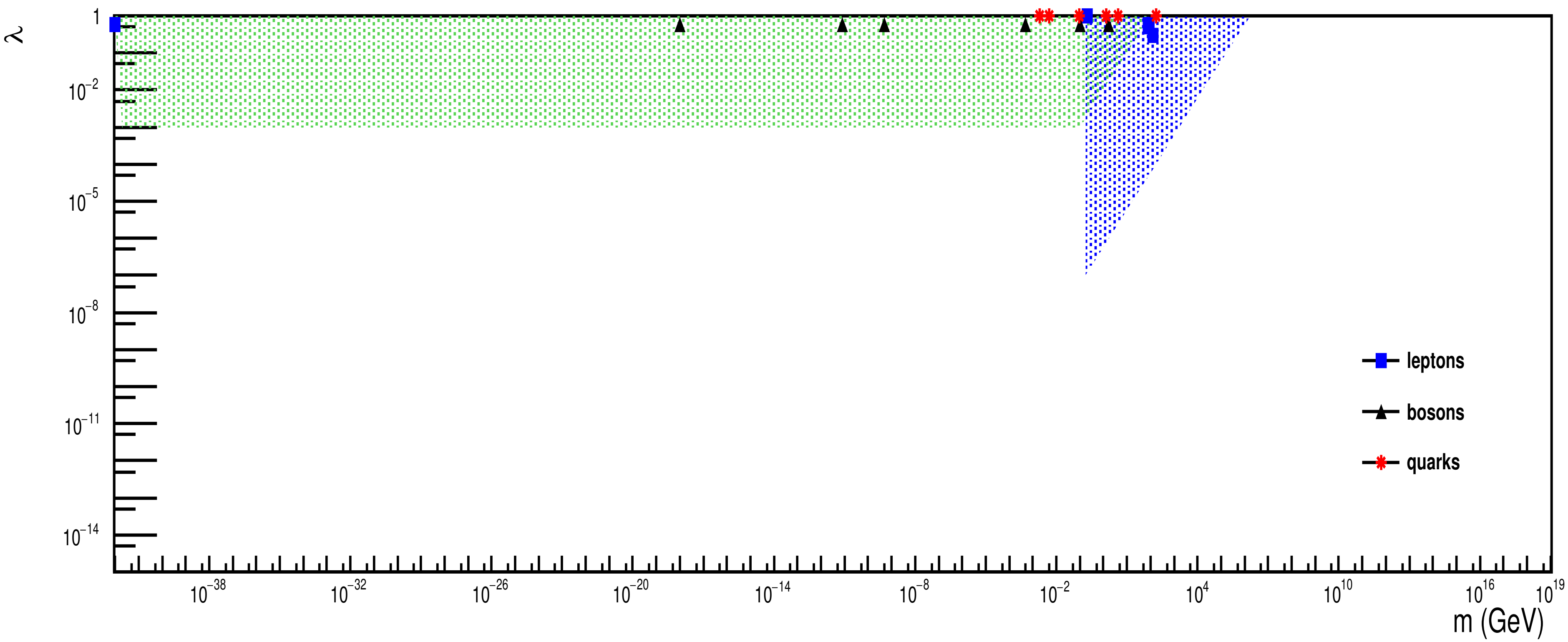
$$\text{...so if } \Gamma(\mu \to e\bar{e}e) \simeq \frac{m_\mu^5}{1536\pi^3 \Lambda_{LFV}^4} \quad \text{then} \quad BR \lesssim 10^{-12} \Rightarrow \boldsymbol{\Lambda_{LFV} \lesssim 200 \text{ TeV}}$$

rare searches have better sensitivity to selected interactions
precision searches sensitive to many types of NP, including light

Exploring NP parameter space...

$(g-2)_\mu$ sensitive to light NP with cpling $\gtrsim 10^{-(4\to 3)}$ to μ

current MEG bound $BR(\mu \to e\gamma) \leq 4.2 \times 10^{-13}$ excludes



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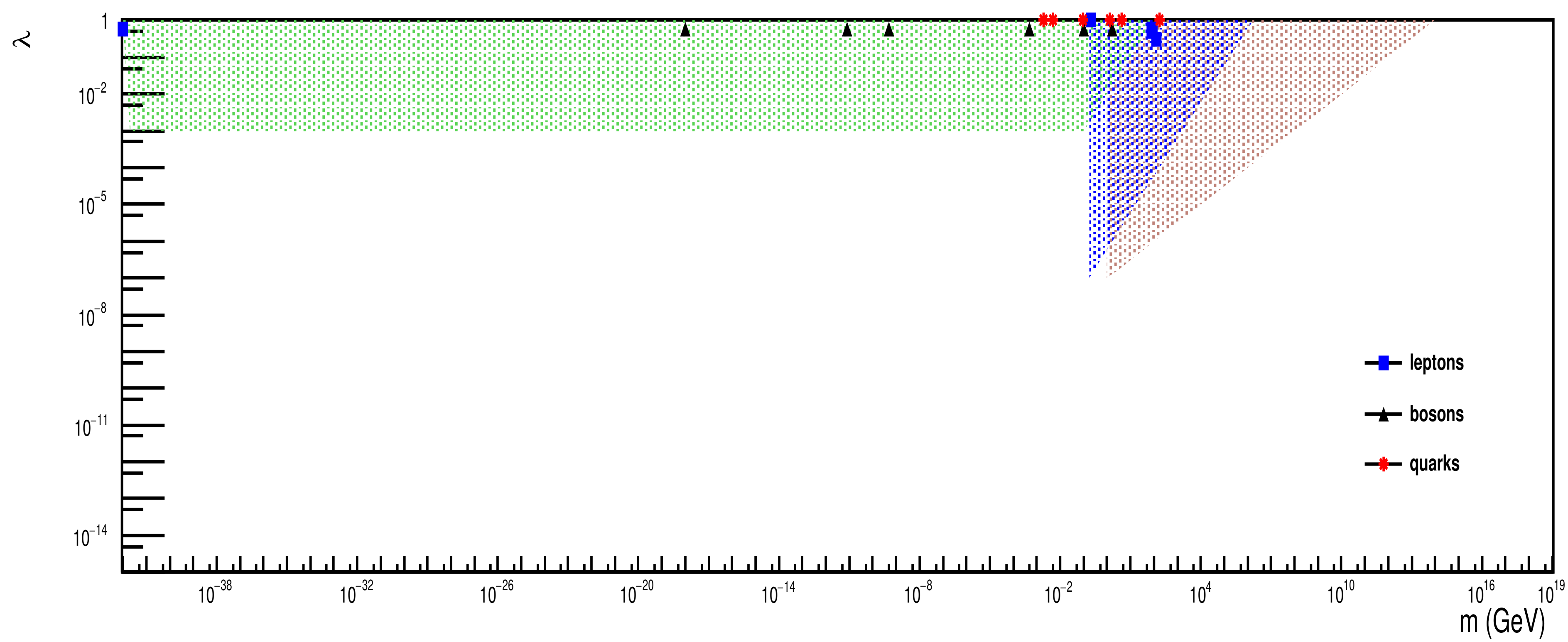
$0\nu 2\beta$ (dim5 m_ν) : $m_\nu \sim \lambda^2 v^2/M \lesssim 0.1$ eV



From events to a model: what to do as a theorist?

But there are many $\{\lambda_{NP \cdot SM}, \Lambda_{NP}\}$;
plot superposed bounds on inequivalent interactions : (
(model-dep whether mediated by same NP...)

	Λ_{NP} (GeV)
r_p	$\lesssim 1$
$(g-2)_\mu$	$\sim 10^2 \to 10^3$
$(g-2)_e$	$\sim 10 \to 10^3$
B anom.	$\sim 10^3$
e edm	$\gtrsim 10^5 \to 10^7$
μ edm	$\gtrsim 10^2$
n edm	$\gtrsim 10^x$
$\mu \leftrightarrow e$	$\gtrsim 10^5$
$\tau \leftrightarrow \ell$	$\gtrsim 10^3$
$0\nu 2\beta$	$\gtrsim 10^{14}$ (dim5)
p decay	$\gtrsim 10^{16}$

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Lets suppose NP heavy = can use EFT
(a plot per operator...)

1. if as many exptal observations as operators (ex=EW precision @ LHC, quark flavour), do fit, construct correlation matrix...

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Lets suppose NP heavy = can use EFT

1. if as many exptal observations as operators (ex=EW precision @ LHC, quark flavour), do fit, construct correlation matrix...

2. if few exptal searches vs many op.s, build op. basis corresponding to observables
(no physics is basis choice; good choice makes caln simple)

$\Leftrightarrow$ defines relevant subspace for comparing expt and models (disappears the dismaying crowd of distracting operators)

$\mu \to e$: 2010.00317

New interactions of decaying particles: looking for τ-LFV?

p-**decay** $\Rightarrow \Lambda_{NP} \gtrsim 10^{16}$ **GeV**, $\mu \to e \Rightarrow \Lambda_{NP} \gtrsim 10^{6}$ **GeV**, $\tau \to l \Rightarrow \Lambda_{NP} \gtrsim 10^{3}$ **GeV**

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$\Rightarrow$ why is **proton lifetime** ($\tau_{p \text{ decay}} \lesssim 10^{32}\text{yr}$) so sensitive?

($\mathcal{A}(0\nu2\beta) \propto 1/\Lambda_{NP}$, whereas $\mathcal{A}(p \to e\pi) \propto 1/\Lambda_{NP}^2$)

$\approx$ stable matter particle (τ_ν more difficult), Avogrado ($N_A \sim 6 \times 10^{23}$ nucleons/gr) big

$\Leftrightarrow$ watch many p long time:

$$\tau_{p \text{ decay}} \sim 100 \text{ tonnes} \times \frac{10^6 \text{ gr}}{\text{tonne}} \times \frac{3 \times 10^{23} p}{\text{gr}} \times 10 \text{ yrs} \simeq 10^{32} \text{ yrs} \sim \frac{\Lambda^4}{m_p^5} \Rightarrow \Lambda \gtrsim 10^{16} \text{ GeV}$$

(similarly excellent bds on feebly cpled light NP from watching many stars for long time)

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compare $\tau \to l$ decayss:

hard to make ($\sim 10^2$/sec @BelleII)+decay fast ($\tau_\tau \sim 3 \times 10^{-13}$ sec)

$$\frac{N_\tau}{\mathrm{yr}} \times \tau_{watch} \sim 10^9 \times \tau_\tau \approx \tau_{\tau \to l} \sim 10^9 \tau_\tau$$

$\tau \to \mu\pi$ vs $\mu + N \to \tau + X$?

μs : easier to make $\sim 10^{8\to 10}\mu/$ sec, 10^{-10} sec to traverse 3cm target

$$N_\mu/\mathrm{yr} \times \tau_{watch} \sim (10^{17}\ \mu/\text{yr})\ \times 10^{-10}\mathrm{sec}$$

$\Rightarrow$ sensitivity to $1/\Gamma(\mu + N \to \tau + X) \lesssim 10^7$sec

final state τ? : $\tau \to \mu\pi$ vs $\mu + N \to \tau + X$?

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$\Rightarrow$ compare rates for $\tau \to \mu\pi$,$\mu + N \to \tau + X$ (mediated by $\frac{1}{\Lambda^2}(\overline{\mu}\gamma^\alpha\tau)(\overline{u}\gamma^\alpha u)$)

$$\Gamma_{\mu+N\to\tau+X} \sim \sigma n_N \sim \frac{1}{\text{flux}}\overline{|\mathcal{M}|}^2 n_N \sim \frac{1}{s}\frac{s^2}{\Lambda^4}n_N \sim \frac{s}{\Lambda^4}n_N$$

$$\Gamma_{\tau\to\mu\pi} \sim \frac{1}{\text{flux}}\overline{|\mathcal{M}|}^2 \times \text{phase space} \sim \frac{1}{m_\tau^2}\frac{m_\tau^4}{\Lambda^4}m_\tau^3 \sim \frac{m_\tau^5}{\Lambda^4}$$

But $\quad n_N \quad \sim \quad \frac{N_A}{gr} \times \frac{gr}{cm^3} \times (2 \times 10^{-14}\mathrm{cmGeV})^3 \simeq 10^{-17}\mathrm{GeV}^3 \ll m_\tau^3$

final state phase space density $\gg$ density occupied states of matter

$$N_\tau/\mathrm{yr} \times \tau_\tau \times \Gamma(\tau \to \mu\pi) \gg N_\mu/\mathrm{yr} \times \tau_{watch} \times \Gamma(\mu + N \to \tau + X)$$

$\Rightarrow$? Look for τ decay

!! my estimates from 2019. See detailed study of $e \to \tau$ at ElectronIonCollider in 2102.06176

Summary

(il me parait que) New Physics could be found by observing excess events where the SM expectation is **rare**, or by observing an anomaly when the SM expectation is **precise**ly known.

We know that New Physics are there: observations require them (some theory suggestions too). We have several anomalies; maybe some of the New Physics is just around the corner?

What should we do when the NPs arrives?

BackUp

How well do we know neutrinos — peculiar spectral particles

- neutrinos are protoptyes for light, feebly interacting NP
  - we do not see them, but loose $(E, \vec{p})$ conservation if no ν (Pauli)
  - we hypothesize they are three, in SU(2) doublets with $\{e, \mu, \tau\}$
    (but some anomalies; are there more νs?)

- we hypothesize $m_\nu \neq 0$ — explains multitude of deficits and flavour-changes
  but not see kinematically $E^2 - |\vec{p}|^2 \neq 0$ (yet; Katrin)
  nor see gravitational mass (yet; cosmo)

- to write a mass in $\mathcal{L}$ for νs:
  - Dirac: require 3 additional light (gauge singlet) ν
  - Majorana: ν_L have mass with themselves $m\overline{\nu_L^c}\nu_L$
    but 'tis non-renorm in the SM, so requires adding heavy NP.
    NP is Lepton Flavour changing (COMET) and L Number changing ($0\nu 2\beta$)

How many ν? What is the origin of m_ν?
Is Lepton Number conserved?

Why are we here?

- (philosophical, religious aspects)
- we and stars made of matter, can be here because U contains matter excess. How to make U's excess?
  - requires $\not{B}$, $\not{C}\not{P}$, $\not{T}\not{E}$
  - generated after inflation; no known SM recipe (but not impossible)

  $\Rightarrow$ $\not{B}$: **proton decay, $0\nu2\beta$** (combined with SM B+L)

  $\Rightarrow$ $\not{C}\not{P}$: **edm, ν-oscillations, meson decays**

- we are hosted by planet, hosted by sun, hosted by galaxy. How do galaxies arise in our U?
  - galaxy seeds = large scale $\frac{\delta\rho}{\rho}$ from inflation
  - galaxies grew thanks to DM and DE in suitable quantities

  $\Rightarrow$ **who are DM, DE and the inflaton?**