# Supernova constraints on Dark Flavored Sectors

A crossover between Flavor Physics* and Astrophysics

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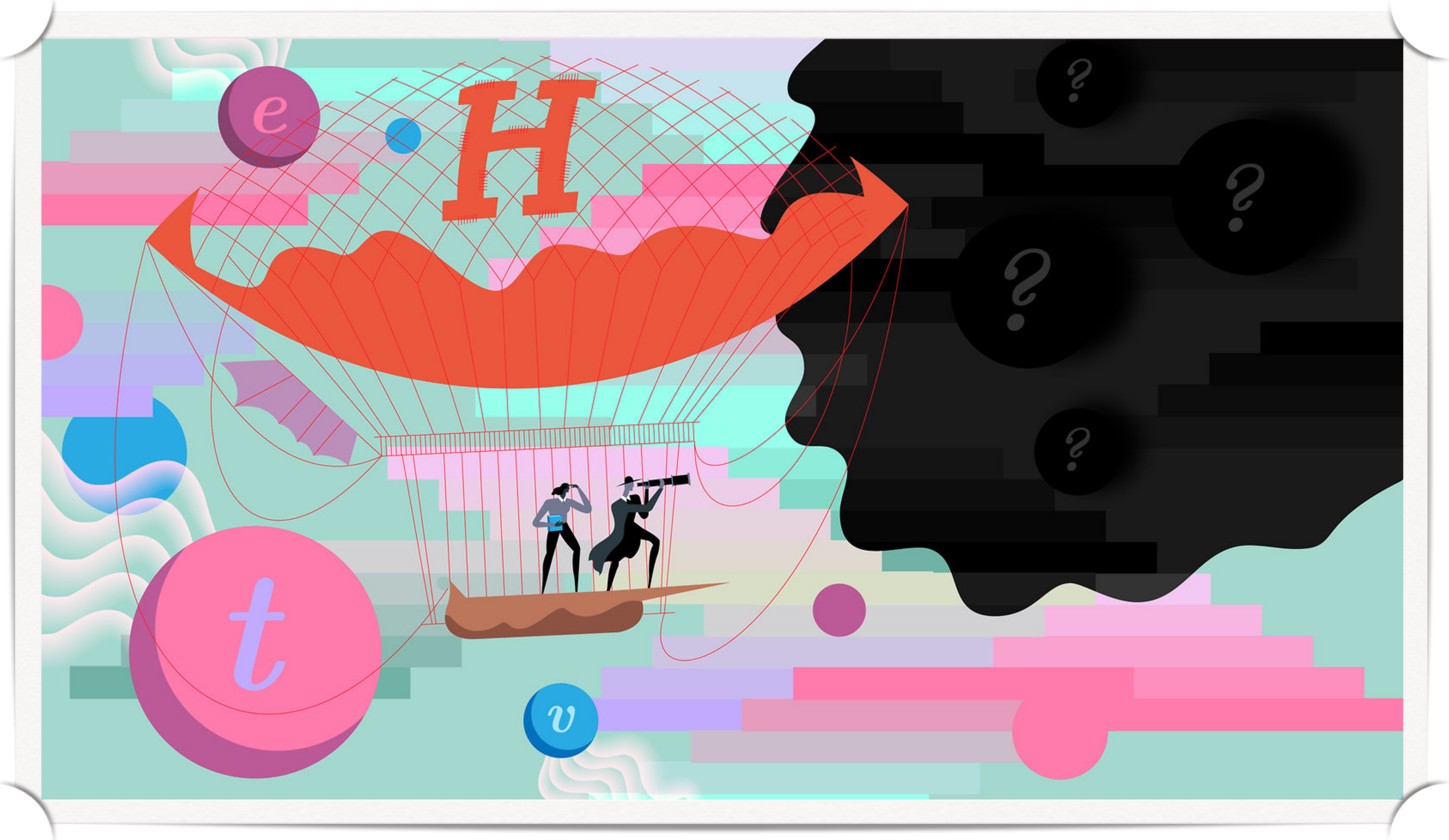
# Dark sectors

- **Null searches of WIMPs + Particle physicists imagination**

- Introduce **new particles** neutral under the SM
- Let them interact with the SM through "**portals**"
  - Higgs or neutrino portals, dark photon, $Z'$, axions, …
- The can solve **DM puzzle** but also other problems
  - Strong CP problem, baryogenesis, neutrino masses …
  - **Experimental anomalies?**




Dark sectors can be **complex** and they open up a wide range of possibilities and phenomenology

Dark

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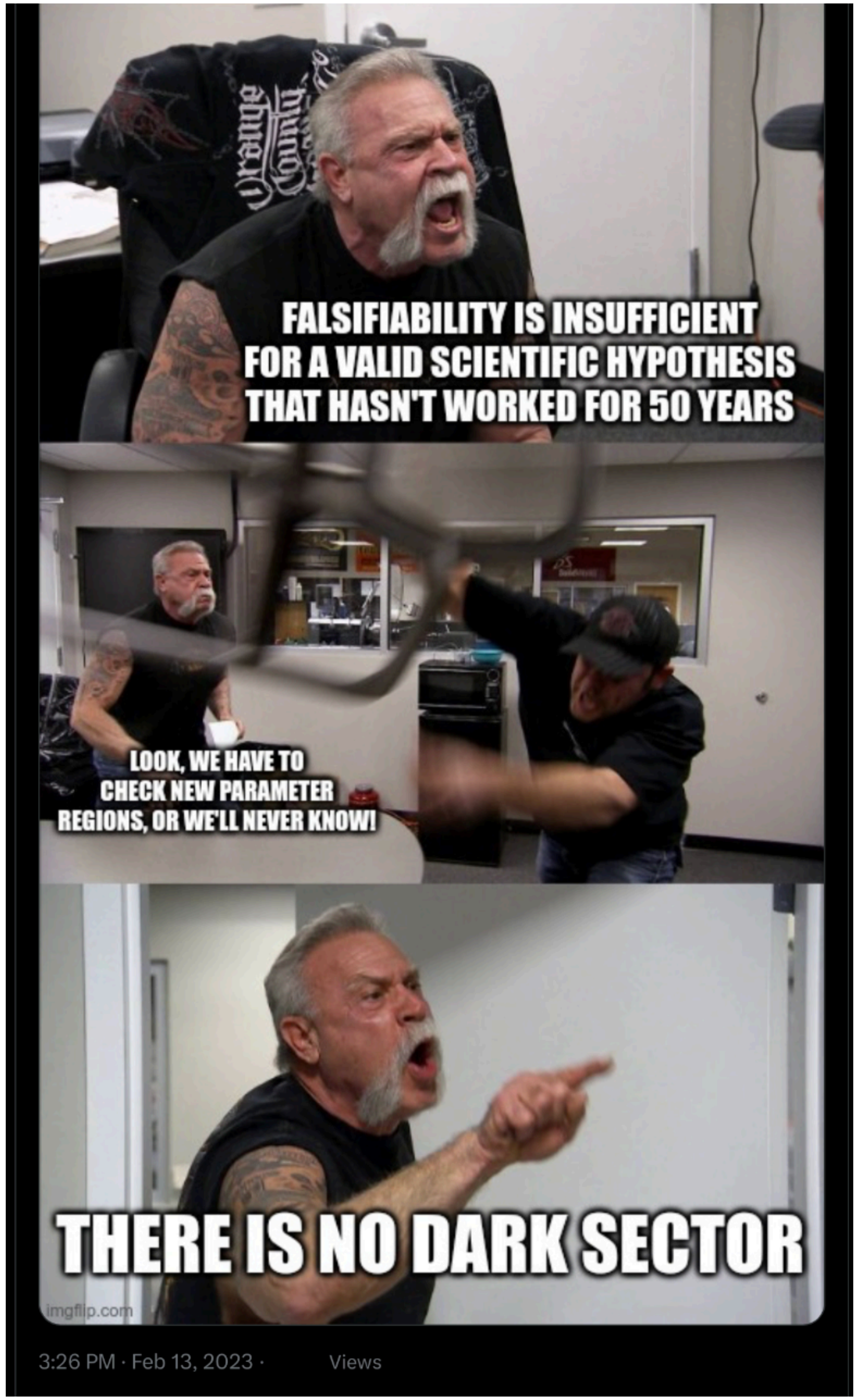
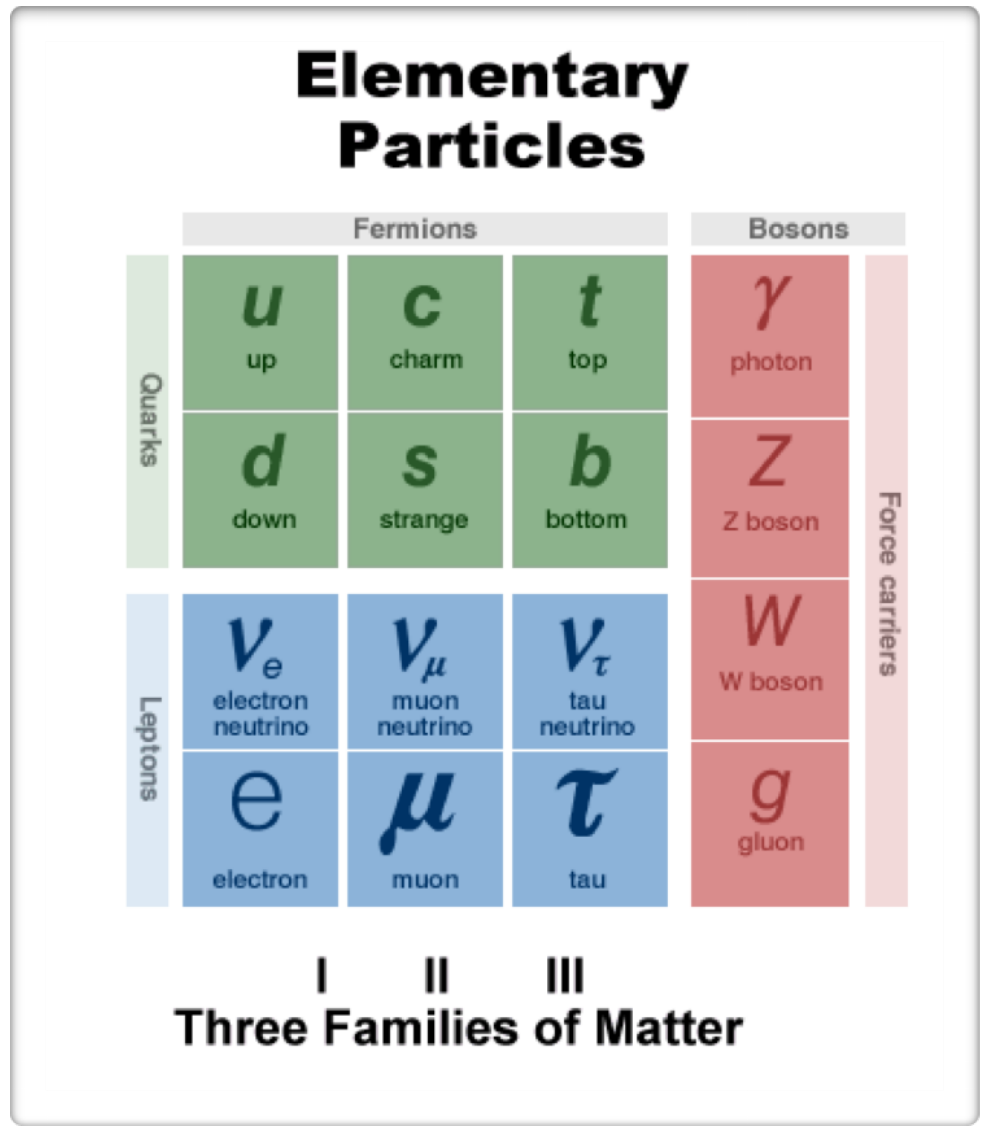
Dark sectors have been at the centre of a heated online controversy!

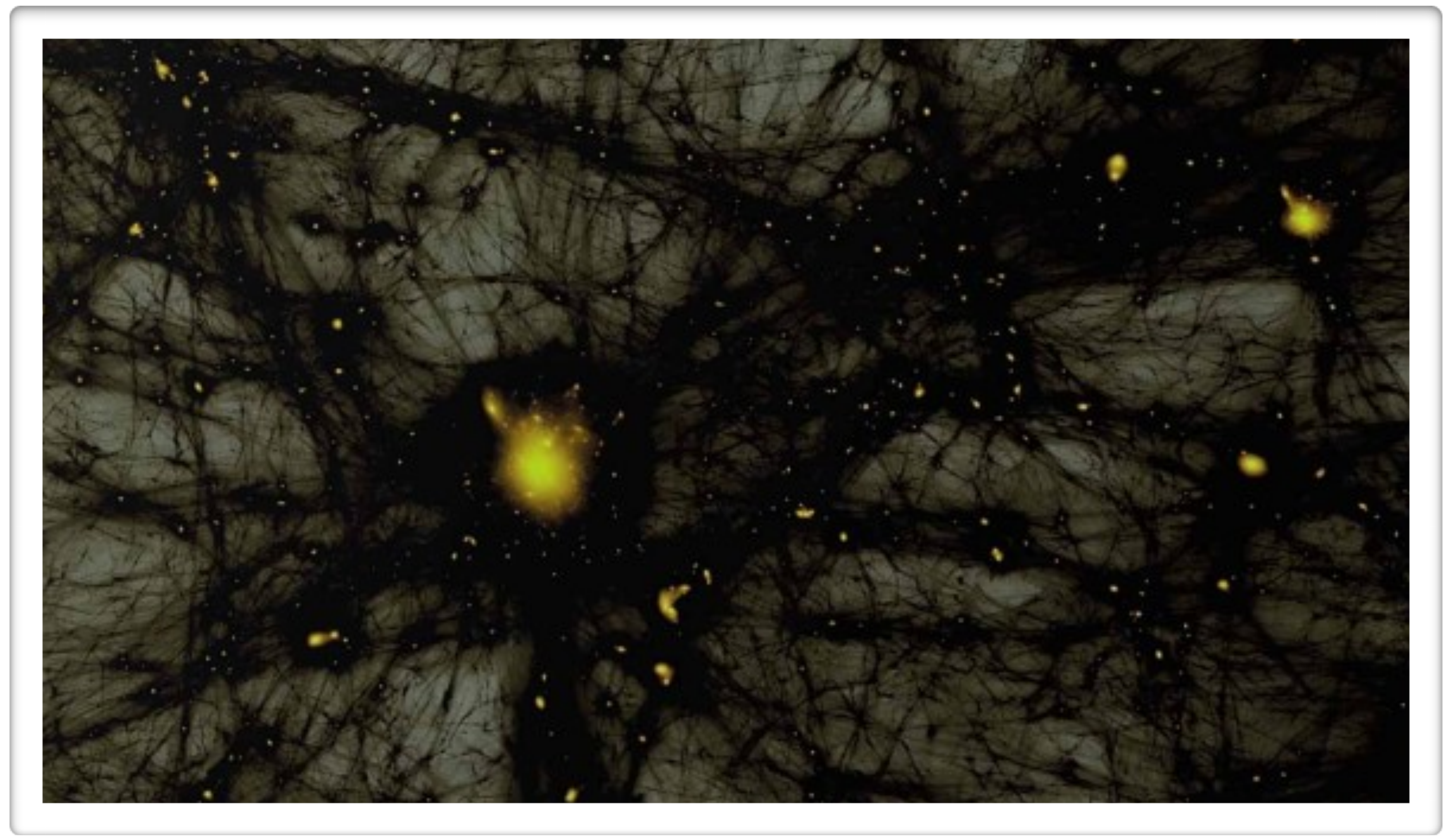

[@WKCosmo (Will Kinney)](@WKCosmo)

# Flavor physics and dark sectors

- Portals are often assumed to couple **universally** to fermions
  - Simplicity, avoid proliferation of parameters, **falsifiability** ...







- However, portals can have nontrivial flavor* interactions ... Why ...?
  - **Theoretical:** Flavor puzzle, baryogenesis, generality (EFT) ...
  - **Striking** flavor-violating signatures**:** Flavor factories & anomalies ...

* Quark flavor or charged-lepton flavor (no neutrinos)

# Theoretical motivation

- **Flavored axions** can appear in 3 contexts
  1. **Familons:** Spontaneously broken global flavor symmetries Wilczek+'82 Ema+'17 Ema+'17
  2. **General DFSZ axion models:** $U(1)_{\mathrm{PQ}}$ charges can be **flavor dependent** JMC+'21
  3. **Radiative Yukawa corrections in the SM** JMC+'21 Bauer+'21 Chala+'22
- **Flavored gauge bosons** can appear in 2 contexts
  1. ***Z'*:** IR relics gauged flavor symmetries e.g. $U(1)_{L_\mu - L_\tau}$ Grinstein+'10 Alonso+'17 Cline & JMC'17
  2. **Massless $\gamma'$:** Non-renormalizable couplings to matter Holdom+'86 Dobrescu+'05 Fabbrichesi+'20
- **Flavored dark baryons** can appear in 2 contexts
  1. **Mesogenesis:** Novel mechanism to explain DM & baryogenesis Elor+'19 Alonso-Álvarez+'21
  2. **Neutron lifetime anomaly:** Dark neutron decays Fornal+'18
- Other models in Snowmass document Goudzovski+'23

# Searching for dark sectors @ intensity frontier

- Many ongoing searches

Belle II

PHYSICAL REVIEW LETTERS **124**, 141801 (2020)

Editors' Suggestion | Featured in Physics

**Search for an Invisibly Decaying $Z'$ Boson at Belle II in $e^+e^- \to \mu^+\mu^-(e^\pm\mu^\mp)$ Plus Missing Energy Final States**

PHYSICAL REVIEW D **106**, 032015 (2022)

**Search for a light $Z'$ in the $L_\mu - L_\tau$ scenario with the NA64-$e$ experiment at CERN**

PHYSICAL REVIEW D **105**, L071101 (2022)

Letter

**Search for invisible decays of the $\Lambda$ baryon**

JHEP

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NA62

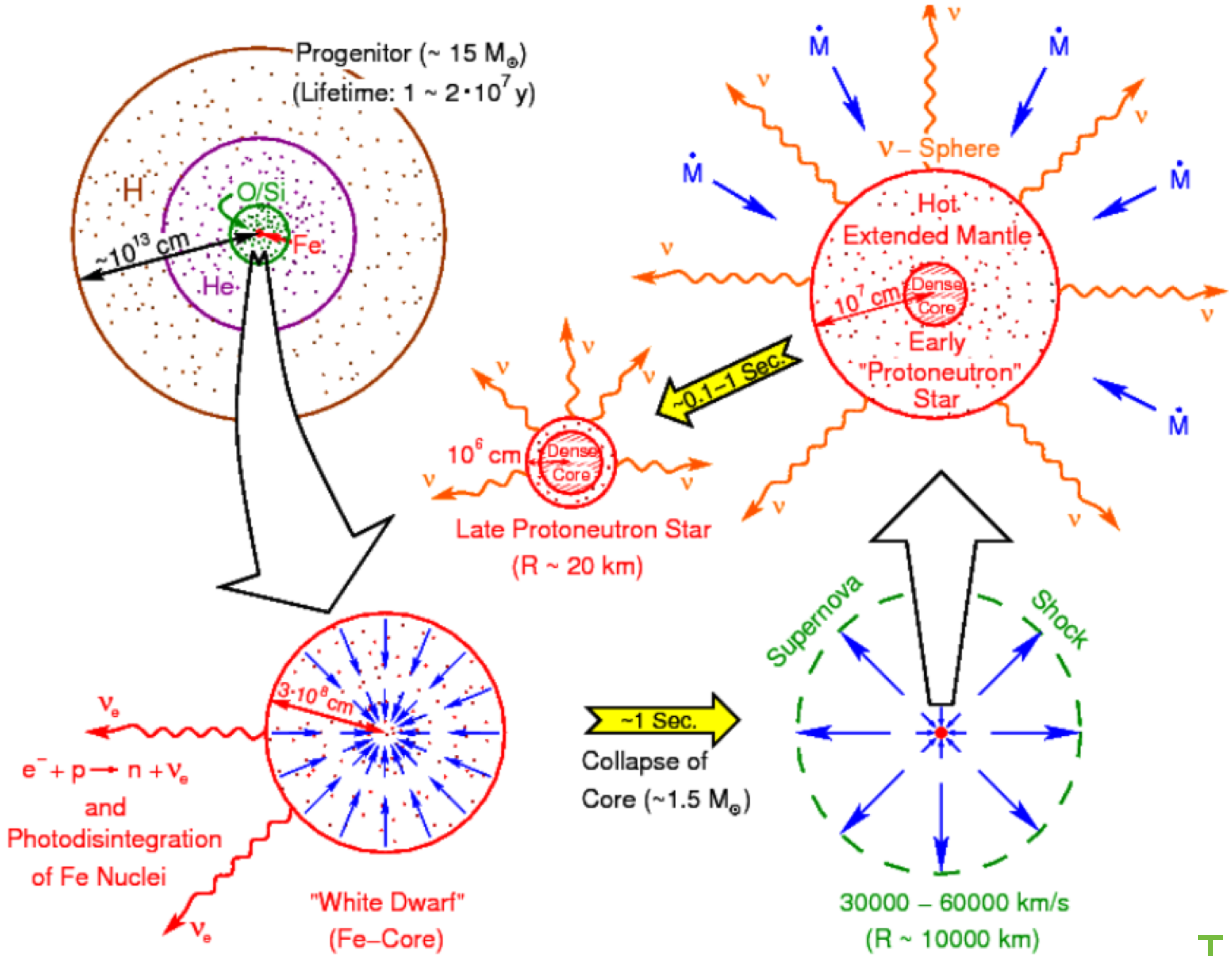
**Search for a feebly interacting particle $X$ in the decay $K^+ \to \pi^+ X$**

**Dark sectors in the sub-GeV range**

Are they affected by the SN 1987A bound?

# Type II supernovae (core collapse)

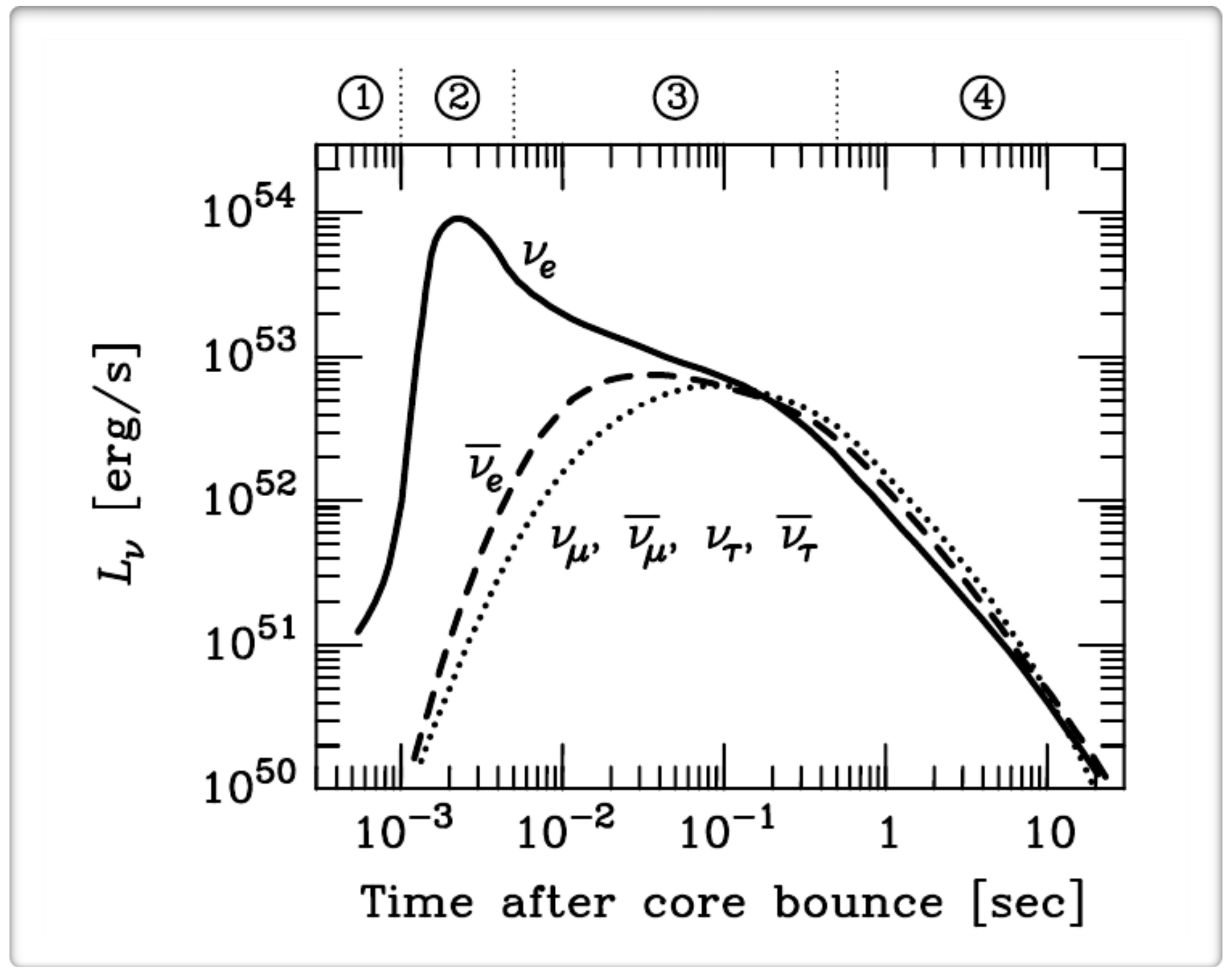
- Fate of massive stars $9\,M_\odot \sim 40\,M_\odot$




Burrows+'90

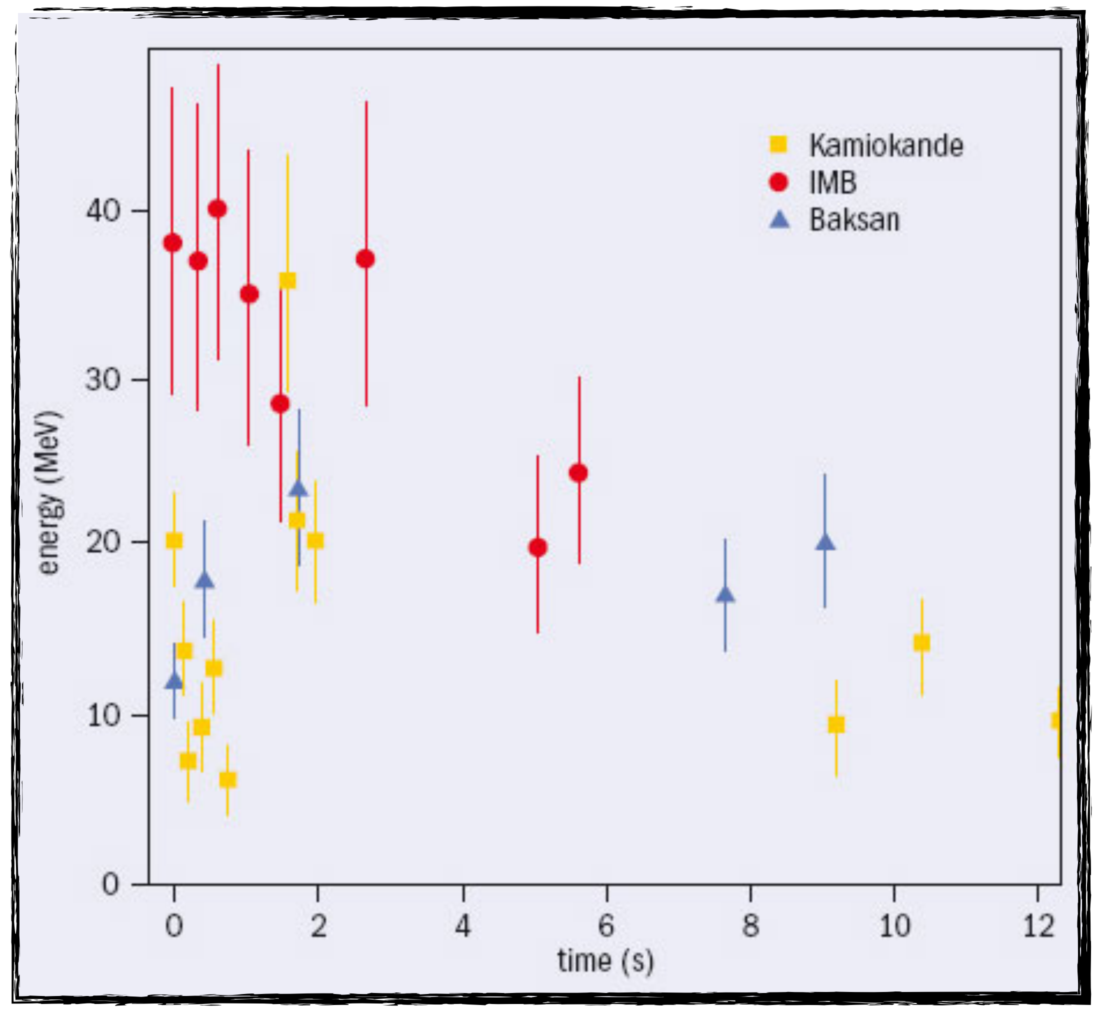
T. Janka Colloquium @ CERN

# SN 1987A and core-collapse theory

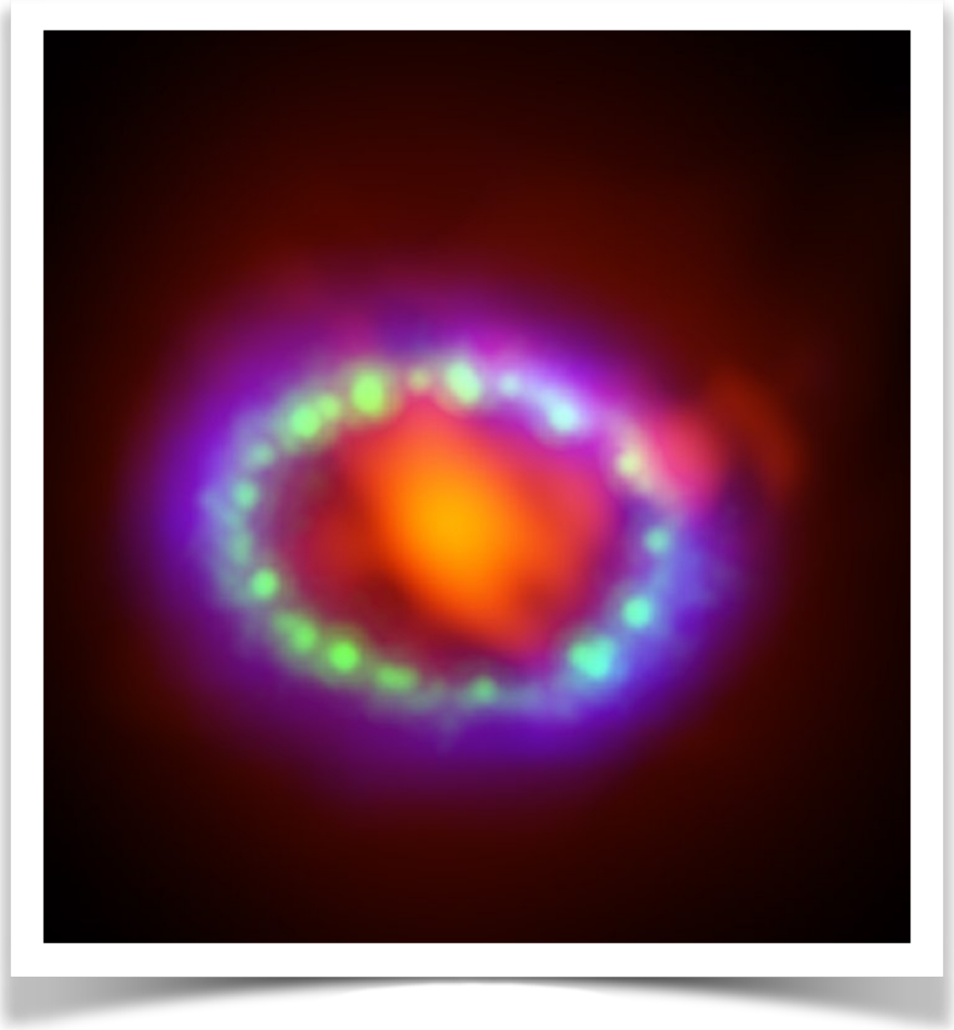



- **Expectations from theory** Raffelt'96, Janka'12
  - **Total Energy:** $3 \times 10^{53}$ erg
  - 99% energy carried away by $\nu$'s
  - **Thermal energy in the process:** $\langle E_\nu \rangle \simeq 10$ MeV
  - Duration of $\nu$ pulse $\approx 10$ s

- **Results from observations SN 1987A**
  - Total $\nu$ flux through Earth

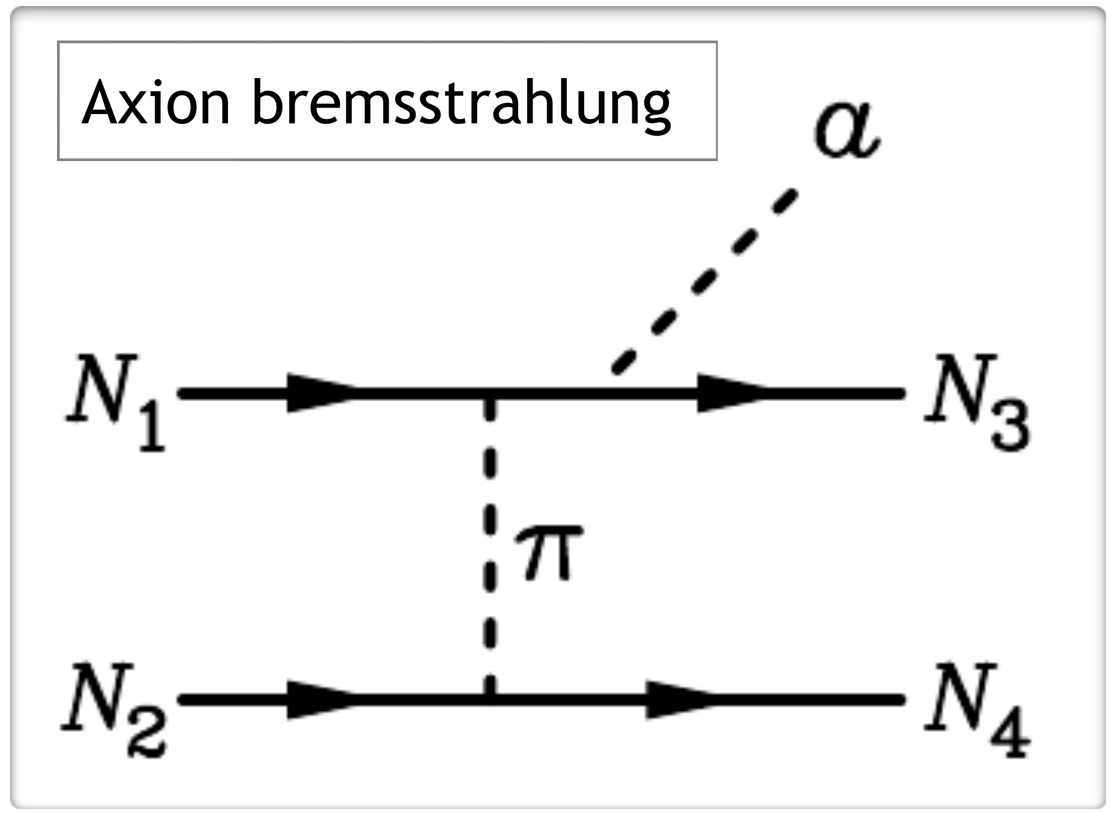


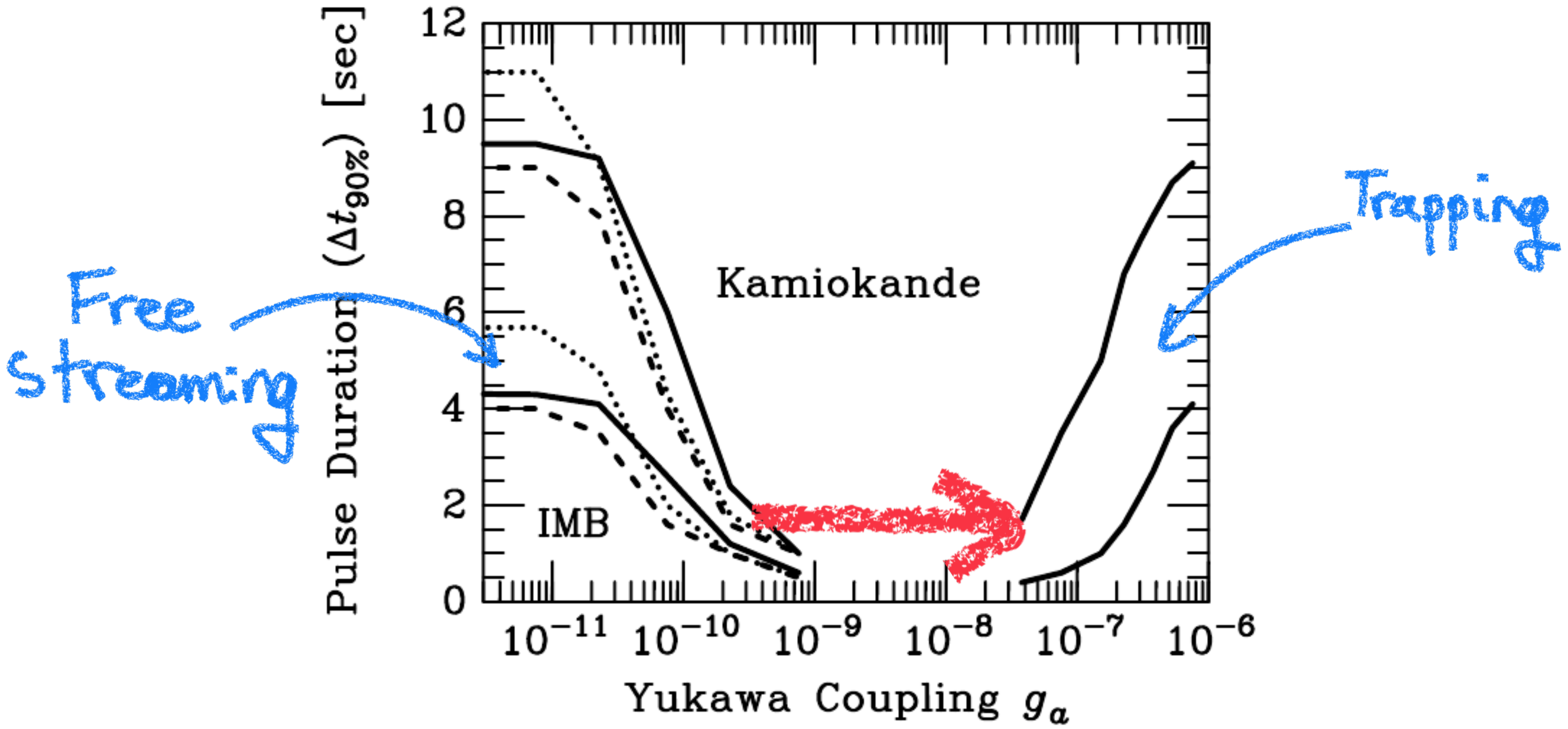

  - Hints for detection of **NS 1987A** by ALMA



# The SN 1987A bound on dark sectors

- **Exotic (BSM) cooling** ⇒ Shortening duration of neutrino signal Raffelt'96
  - Classical bound on **QCD axion**



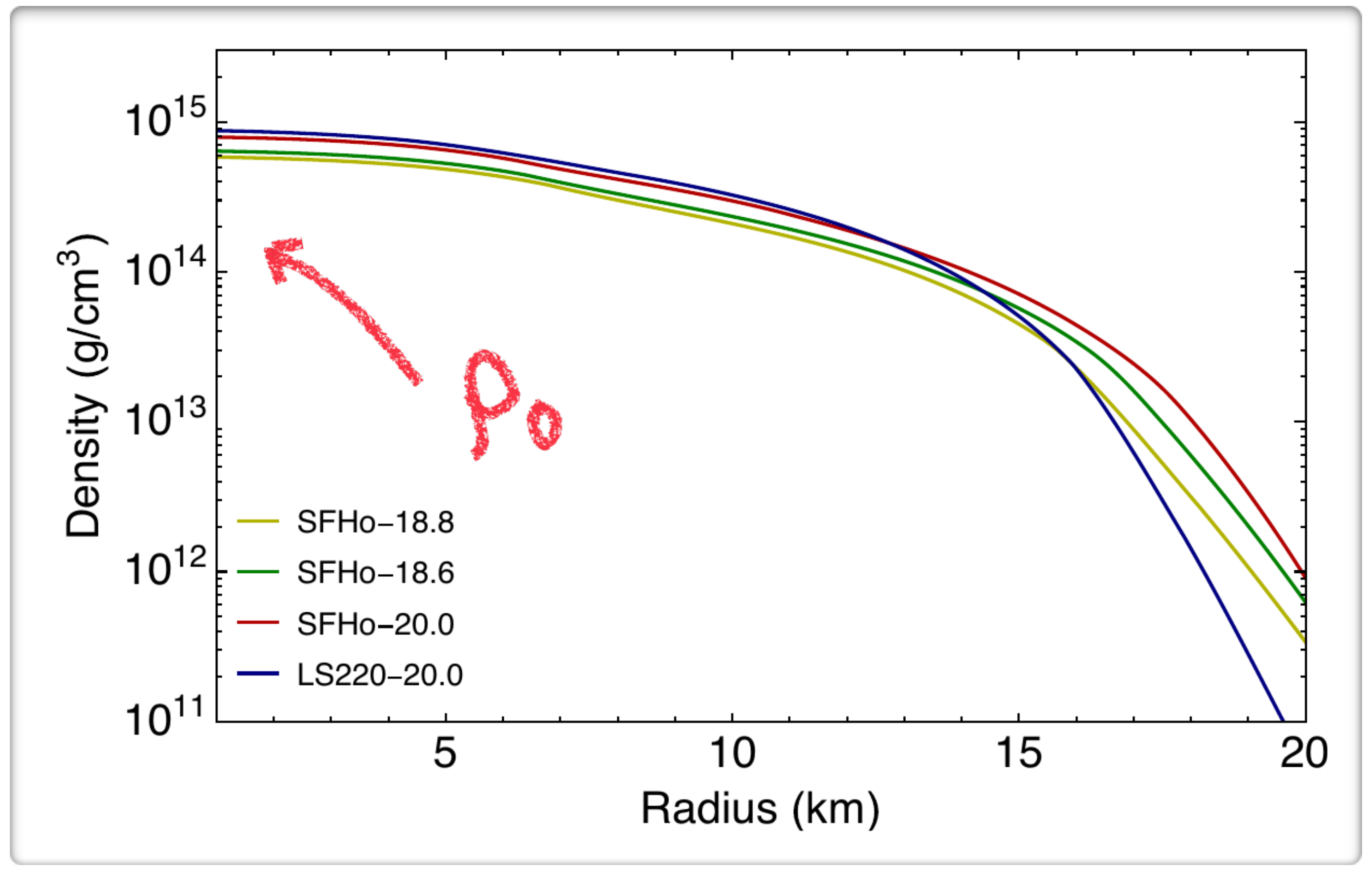




**SN criterion:** $L_{\rm dark} \lesssim L_\nu$ at 1s post-bounce

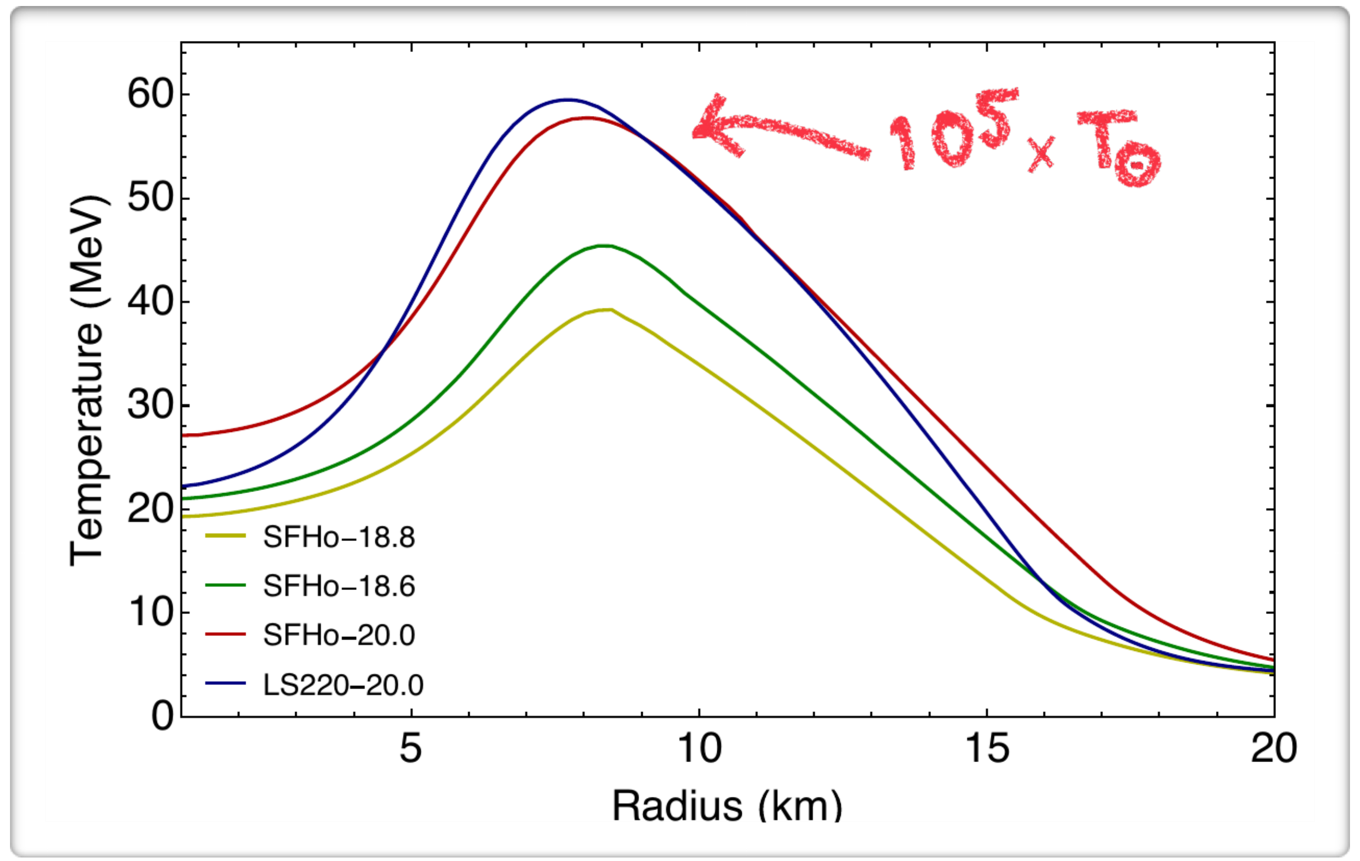
- SN cooling constraint is a "standard" in sub-GeV dark sector models
  - **Well established** buy not exempt from controversies, e.g. Bar+'20 T. Janka Colloquium @ CERN

# Heavy flavors in SN: Muons

- **Proto-neutron star at the centre** $\Rightarrow$ **Extreme environment** (SN sims from Bollig'20)
  - Extremely dense




  - Extremely hot

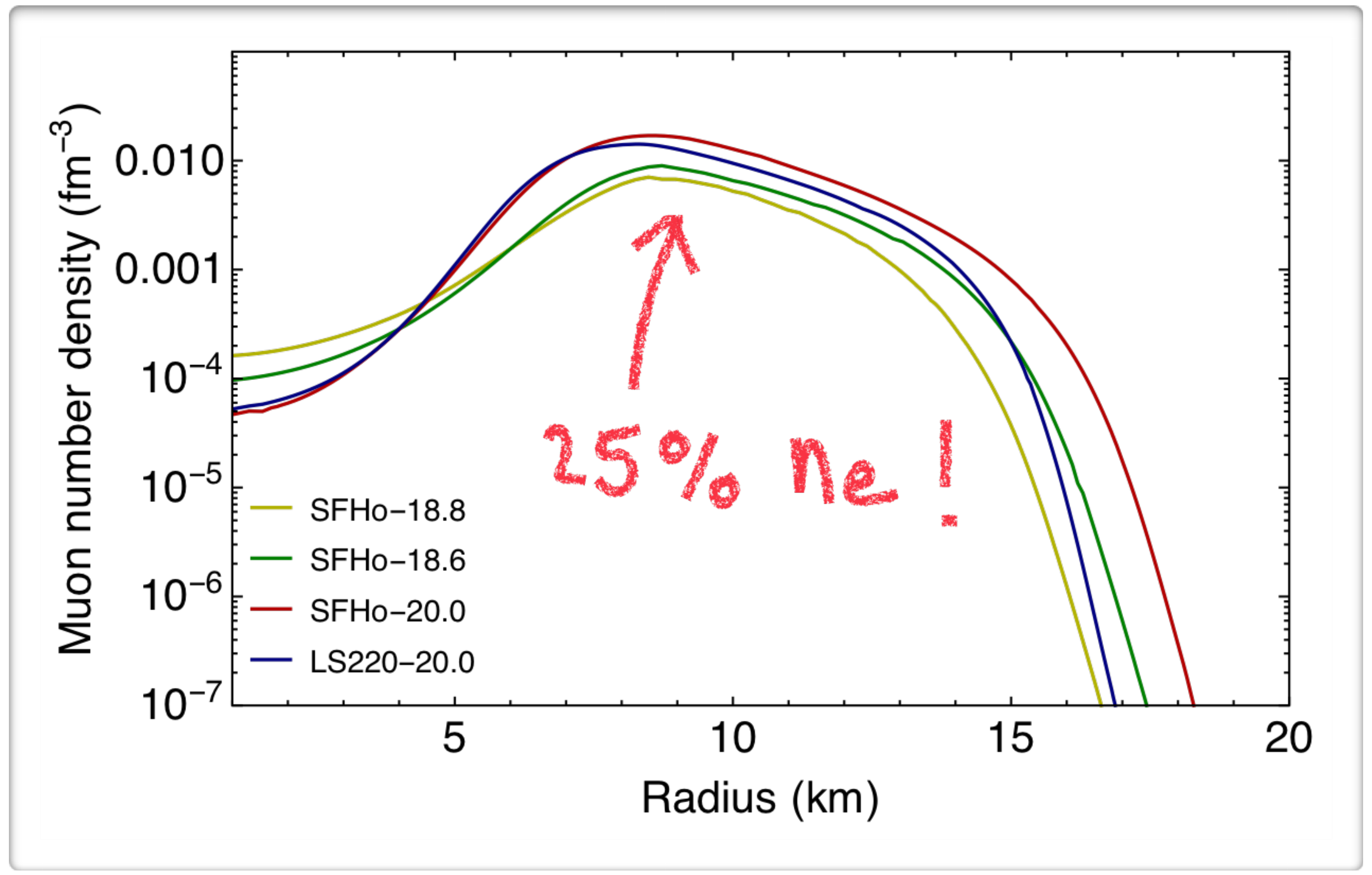



- **Thermal population of muons**

$$n_\mu \approx n_e e^{-m_\mu/T}$$

  - Enhanced by partial degeneracy ($e^-$ chemical pot.)
  - Produced and sustained by weak interactions

$$\bar{\nu}_e e^- \leftrightarrow \bar{\nu}_\mu \mu^-, \, \nu_\mu n \leftrightarrow \mu^- p, \, \ldots$$



# Muonic dark forces: EFT

To appear Manzari, JMC, Spinner, Ziegler

- **Muonic dark forces ⇒ SN limit applies** Bollig'20
  - Let' s start with **Effective Field Theory** between muons and dark fermions $\chi$

$$\mathscr{L}_{\rm EFT} = \frac{1}{\Lambda_\ell^2} \sum_{X,Y} C_{XY} \left(\bar{\chi}\,\Gamma_X\,\chi\right) \cdot \left(\bar{\ell}\,\Gamma_Y\,\ell\right), \quad \text{where } X, Y = S, P, V, A, T$$

  - There are several "microscopic" mechanisms at play

Free streaming — **Coupling** → Trapping

"dark sphere"

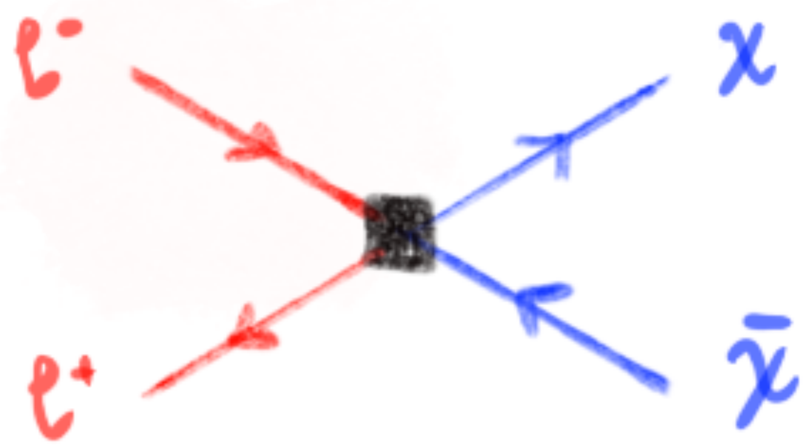
**Volume emission:**

$$\frac{dL_{\rm dark}}{dV} \approx n_a n_b \times E_\chi \times \langle \sigma v \rangle \times \prod_{i=1}^{n} F_{\rm deg}$$

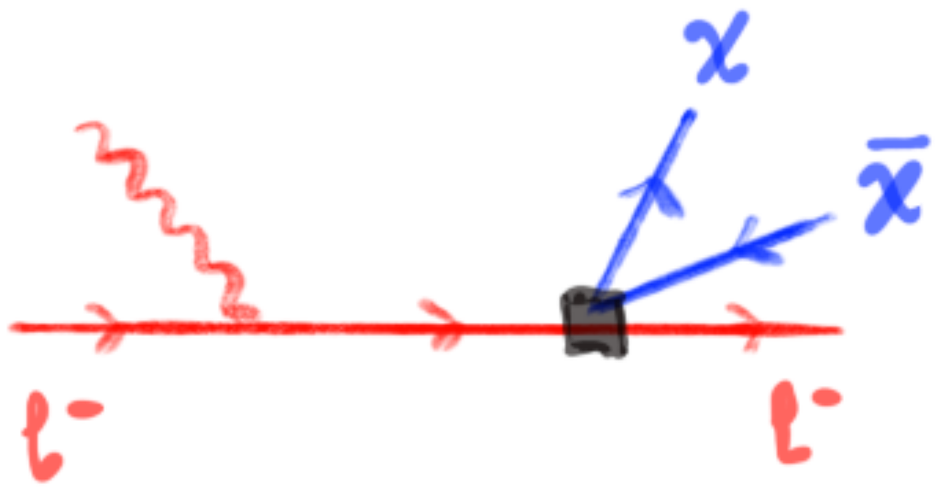
**Surface emission:**

$$L_{\rm dark} \approx \frac{2\pi^3}{15} R_{\rm dark}^2 T_{\rm dark}^4$$

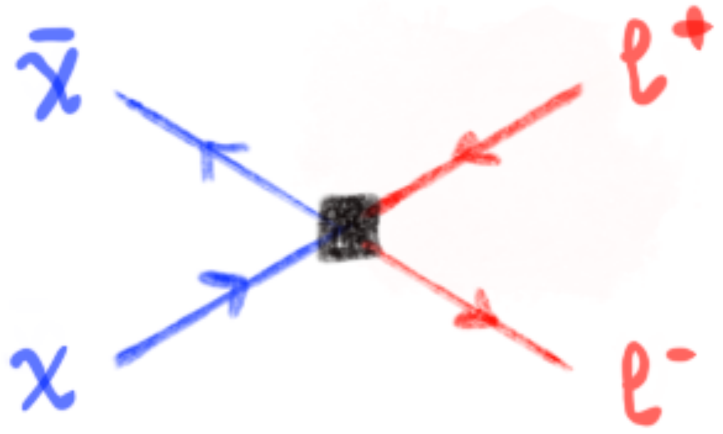
Annihilation



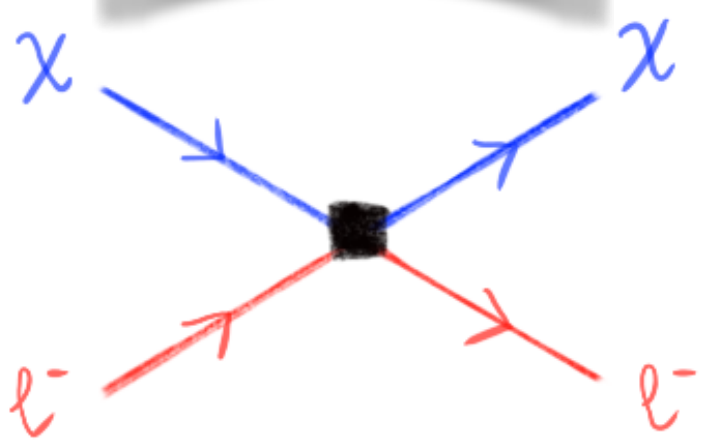

Semi-Compton




Inverse annihilation




Scattering

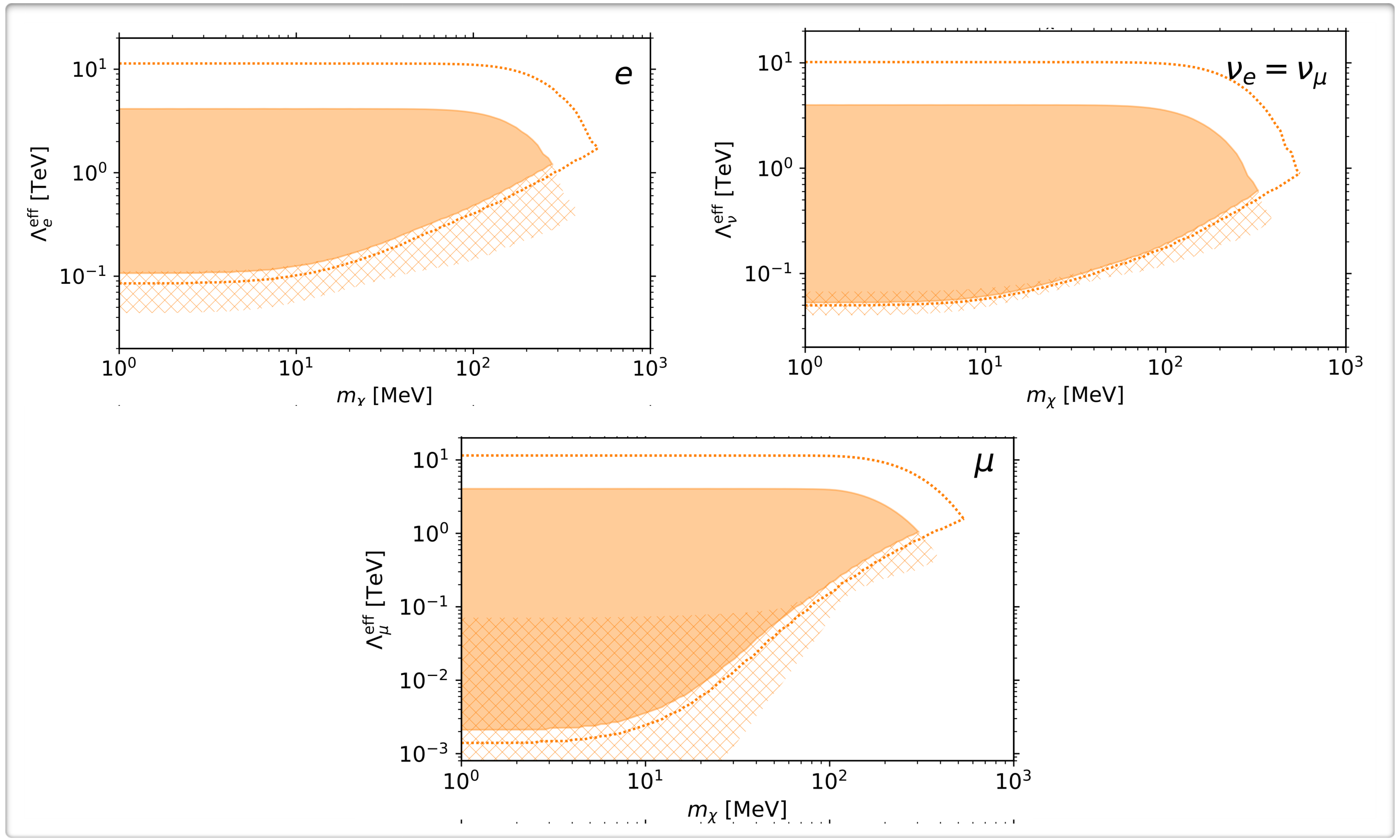


# SN 1987A bounds on the EFT

- For **massless** dark sector particles

| $X_\chi Y_\ell$ | $\Lambda_e^{\rm eff}$ [TeV] | $\Lambda_\mu^{\rm eff}$ [TeV] | $\Lambda_{\nu_\mu}^{\rm eff}$ [TeV] |
|---|---|---|---|
| $SS$ | $0.062 - 3.9$ | $0.0017 - 3.1$ | $0.046 - 4.5$ |
| $PS$ | $0.062 - 3.9$ | $0.00048 - 3.6$ | $0.046 - 4.5$ |
| $VV$ | $0.10 - 4.1$ | $0.0018 - 4.1$ | $0.062 - 4.8$ |
| $AV$ | $0.10 - 4.1$ | $0.0023 - 3.3$ | $0.062 - 4.8$ |
| $RR$ | $0.072 - 2.9$ | $0.0015 - 2.6$ | $0.044 - 3.4$ |
| $LV$ | $0.085 - 3.5$ | $0.0018 - 3.1$ | $0.052 - 4.0$ |
| $TT$ | $0.16 - 4.9$ | $0.0033 - 4.8$ | $0.095 - 5.7$ |

- For **massive** dark sector particles




- SN bounds on the EFT operators with dark sectors **can reach several TeV!**
  - Bounds valid for dark-sector particles **with masses up to ≈ 100 MeV**

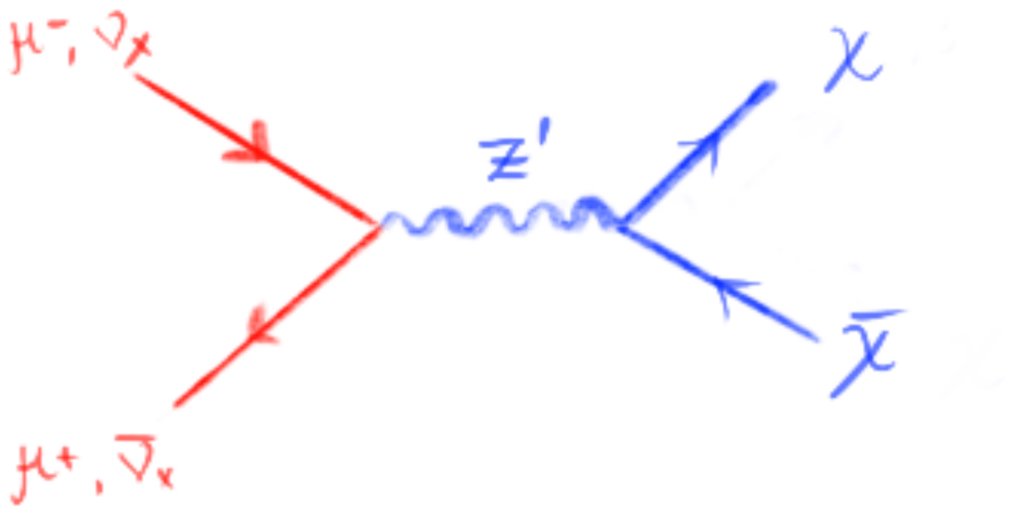
# Muonic portals: Z'  To appear **Manzari, JMC, Spinner, Ziegler**

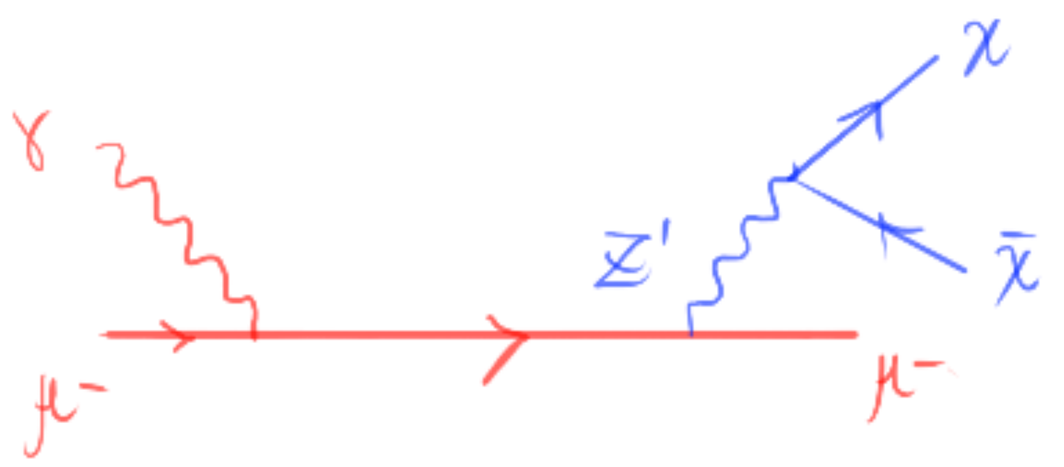
- Let's consider a gauged $U(1)_{L_\mu - L_\tau}$ with **dark fermions** charged under it

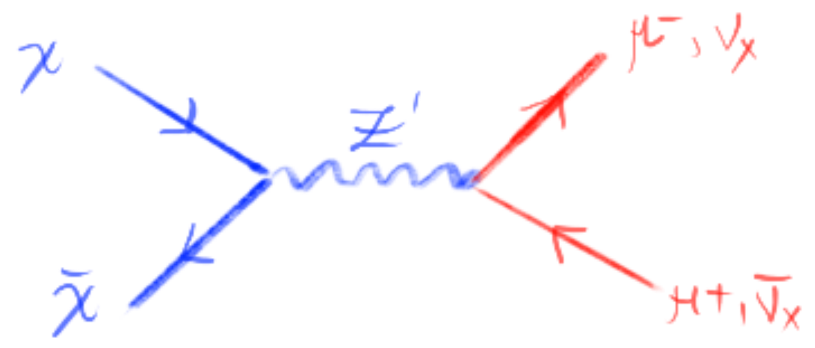
$$\mathscr{L}_{\rm int} = Z'_\mu \left( g_{\mu-\tau} \overbrace{\left(\bar\mu\gamma^\mu\mu + \bar\nu_\mu\gamma^\mu\nu_\mu - \bar\tau\gamma^\mu\tau - \bar\nu_\tau\gamma^\mu\nu_\tau\right)}^{j_\mu^{\rm SM}} + g_\chi \overbrace{\bar\chi\gamma^\mu\chi}^{j_\mu^{\rm Dark}} \right)$$

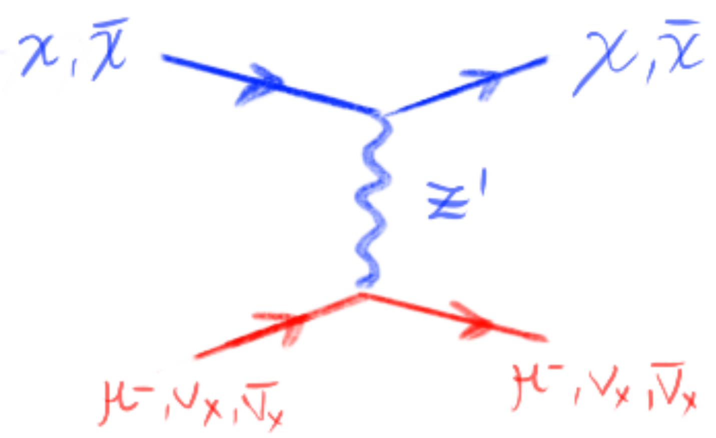
- Models aiming at explaining **DM**, $(g-2)_\mu$, $H_0$ **and more …** Foldenauer'20 Holst+'22
- **Experimental searches:** Belle II, NA64, proposed M3 experiment …

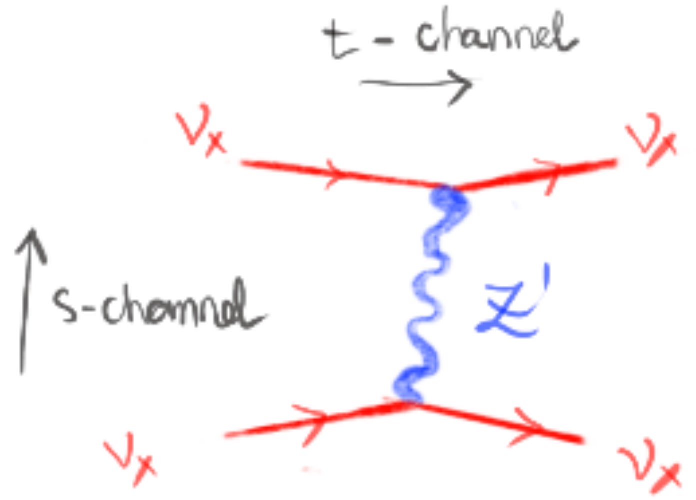
Free streaming → **Coupling** → Trapping



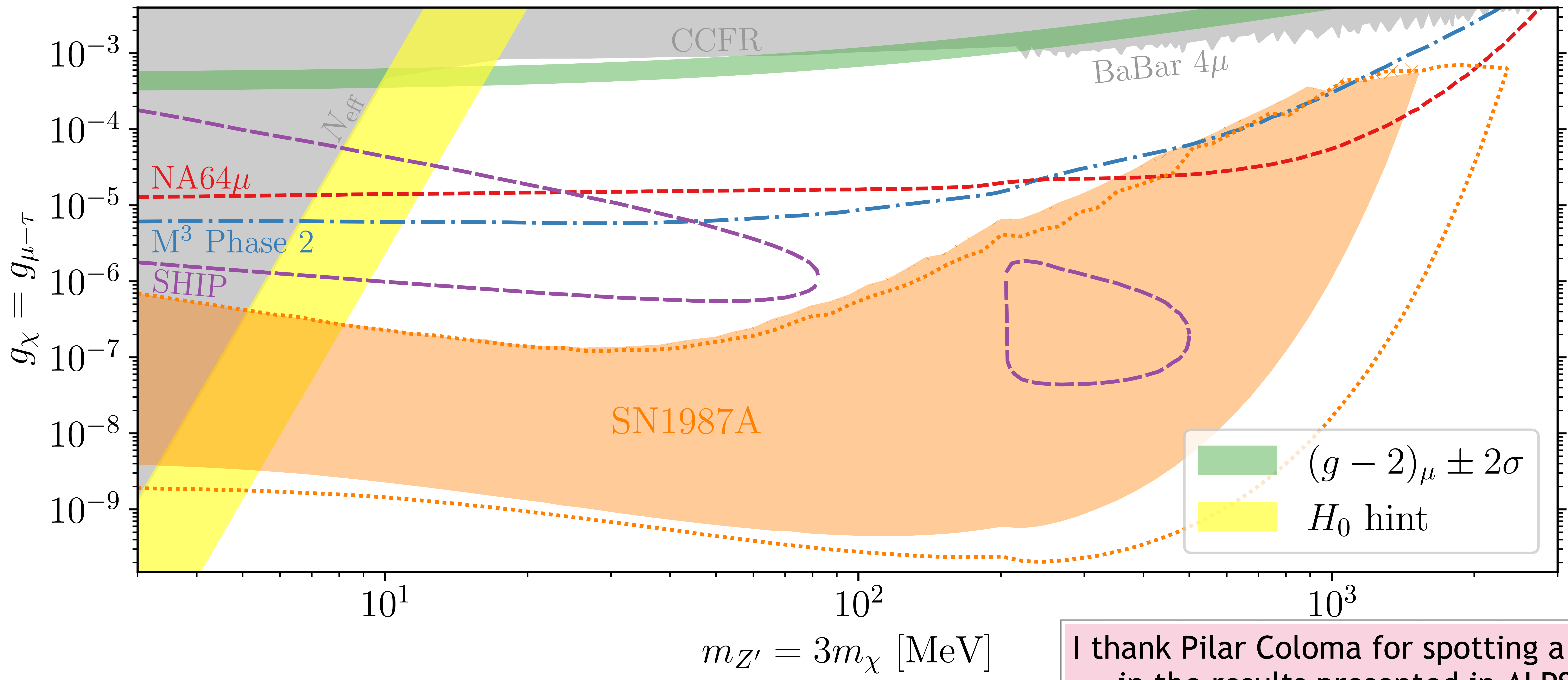




- **Neutrino self-interactions!**

# SN 1987A bound on $L_\mu - L_\tau$ dark sectors

- Set the benchmark to $g_{\mu-\tau} = g_\chi$ and $m_{Z'} = 3m_\chi$ and Z' - $\gamma$ mixing $\epsilon \sim g_{\mu-\tau}/70$ Holst+'22




I thank Pilar Coloma for spotting a mistake in the results presented in ALPS2023

- SN 1987A covers relevant parameter space of the model (consistent with Croon+'21).
- Neutrino and $\chi$ self interactions can lead to new constraints in the **trapping regime**

Manohar'87, Dicus+'88, Chang+'22

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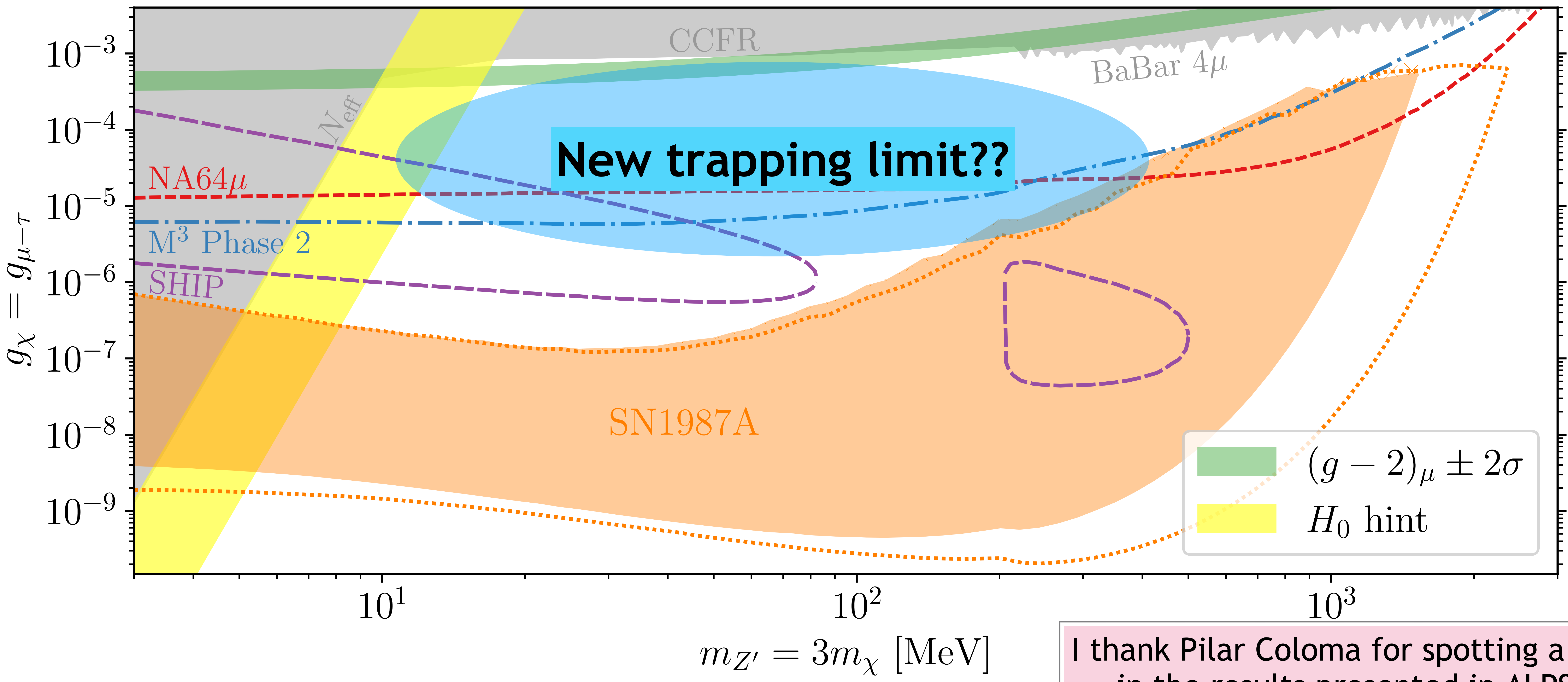


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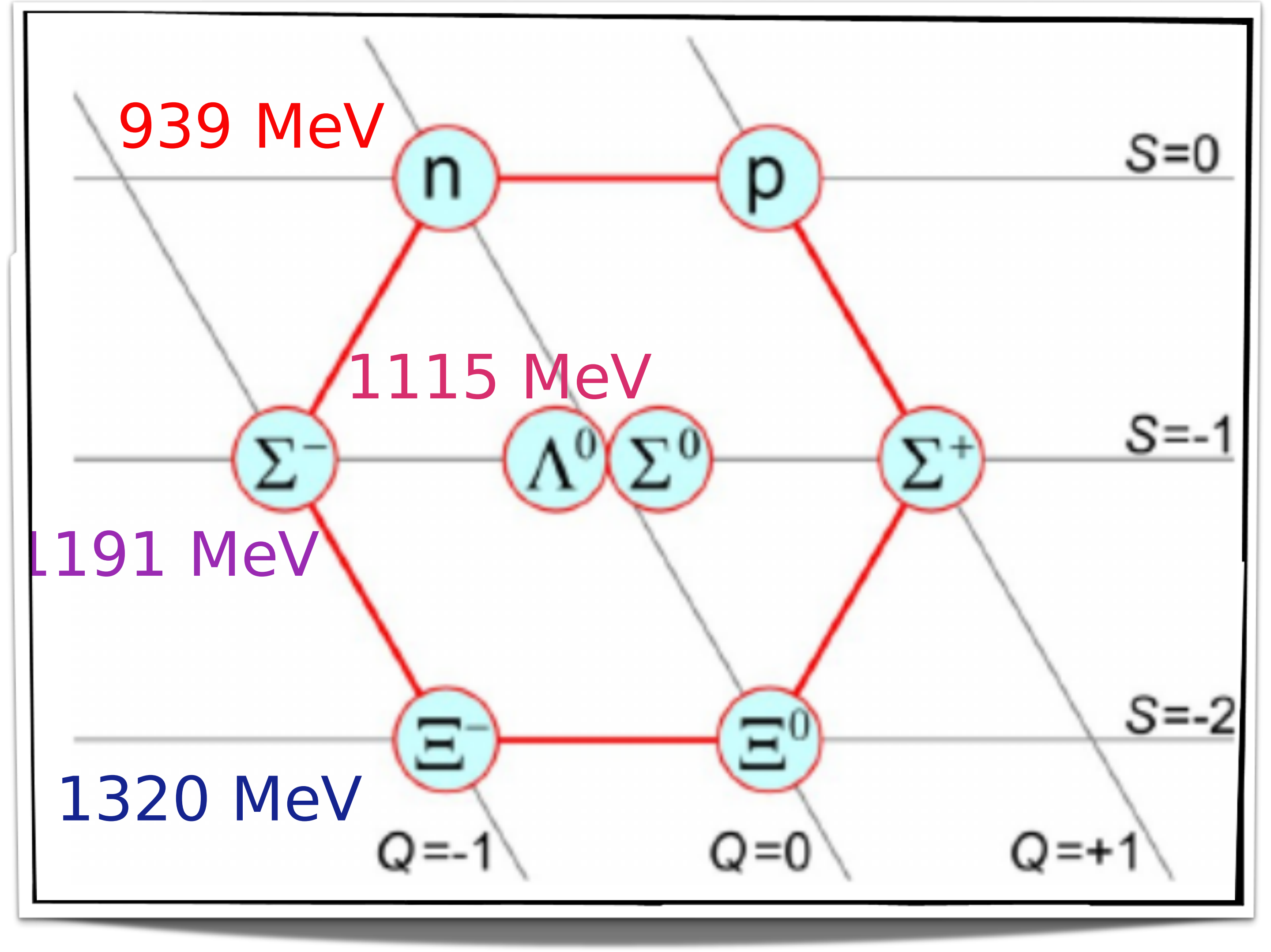
Manohar'87, Dicus+'88, Chang+'22

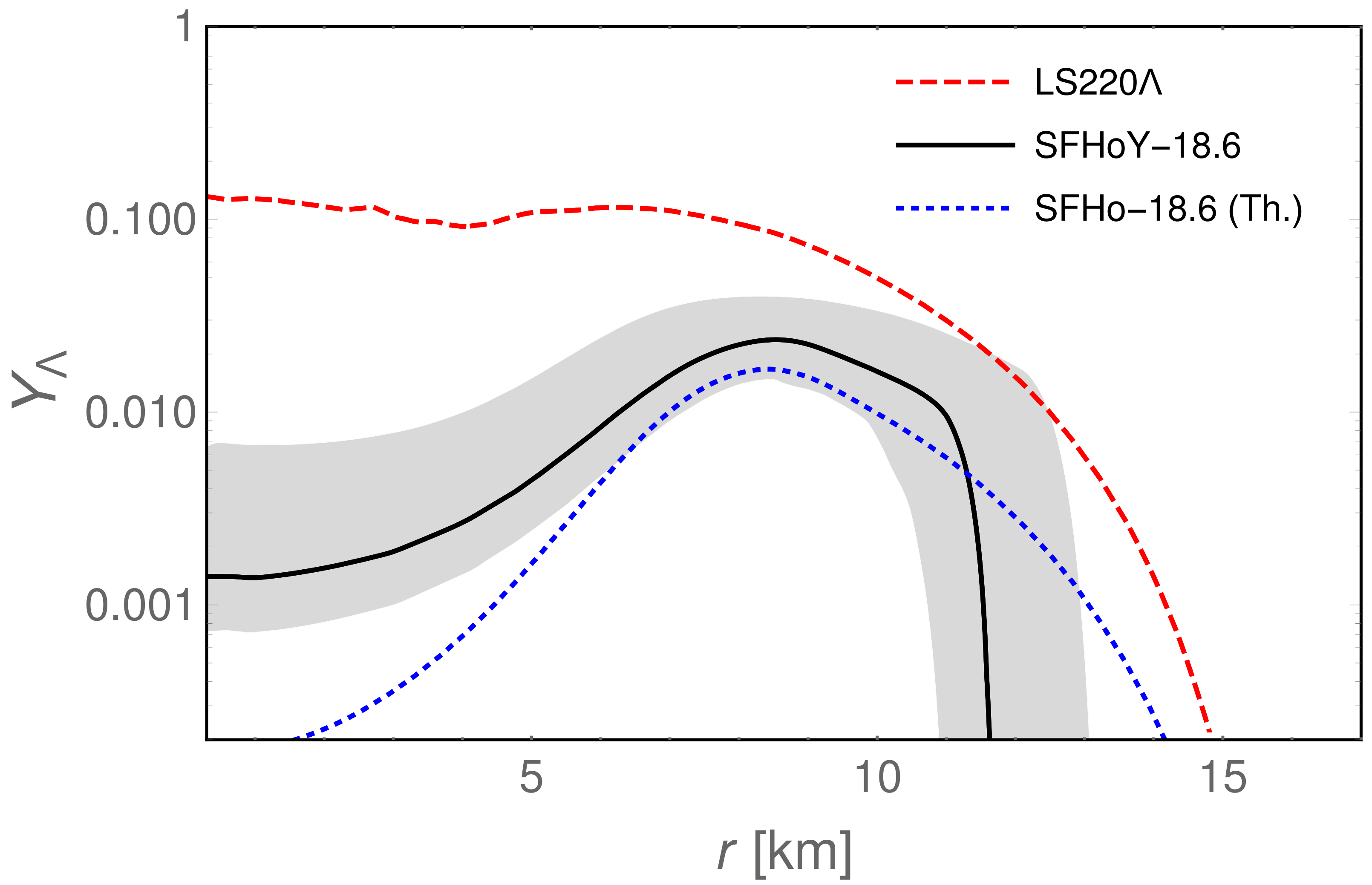
# Heavy flavors in SN: Hyperons JMC+'20

- **Supranuclear densities** (large neutron chemical potential) and **high temperatures**
  - **Hyperons:** $m_\Lambda - m_n = 175$ MeV




  - Thermal population of $\Lambda$ hyperons

$$e^- p \leftrightarrow \Lambda \nu_e,\ \Lambda \leftrightarrow p e^- \bar{\nu}_e\ , \ldots$$




- There are not SN simulations including hyperons
  - **Currently:** One matches the simulations to proper **hyperonic EoS** using compOSE data base
  - **Future:** Full-fledged SN simulations with muons and hyperons in SM and BSM

Collaboration Tobias Fisher (SN), Laura Tolos *et al*. (EoS), JMC & Jorge Terol-Calvo (particle physics)

# Strange dark forces: Dark bosons

- **SN limits on dark strangeness-changing transitions**

$$\mathscr{L}_{\text{strange}} = \overbrace{\frac{\partial_\mu a}{2f_a}\left(C_V^{sd}\bar{n}\gamma^\mu\Lambda + C_A^{sd}\bar{n}\gamma^\mu\gamma_5\Lambda\right)}^{\text{Axions}} + \overbrace{\frac{F'_{\mu\nu}}{\Lambda}\left(g_T^{sd}\bar{n}\sigma^{\mu\nu}\Lambda + g_{T5}^{sd}\bar{n}\sigma^{\mu\nu}\gamma_5\Lambda\right)}^{\text{Dark photons}}$$

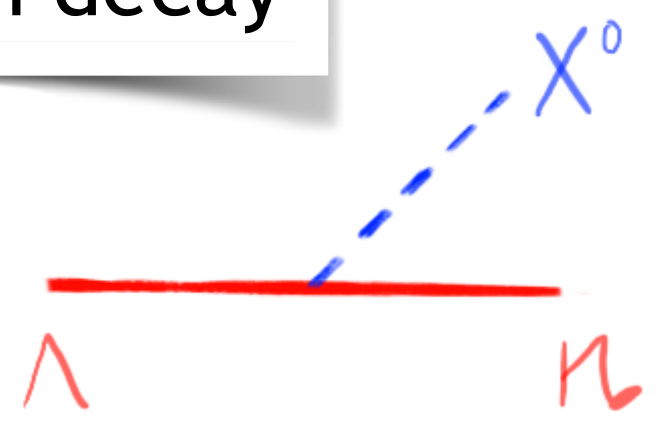
- Models leading to dark decays $\Lambda \to nX^0$ decay
- Complementary to $K^- \to \pi^- X^0$ in NA62 or $K^- \to \pi^-\pi^+ X^0$ Fabbrichesi+'20

Free streaming → **Coupling** → Trapping

$\Lambda \to n X^0$ rate

**Volume emission:** $\frac{dL_{\text{dark}}}{dV} \approx n_n(m_\Lambda - m_n)\Gamma_0 \times e^{-\frac{m_\Lambda - m_n}{T}}$

In-medium decay



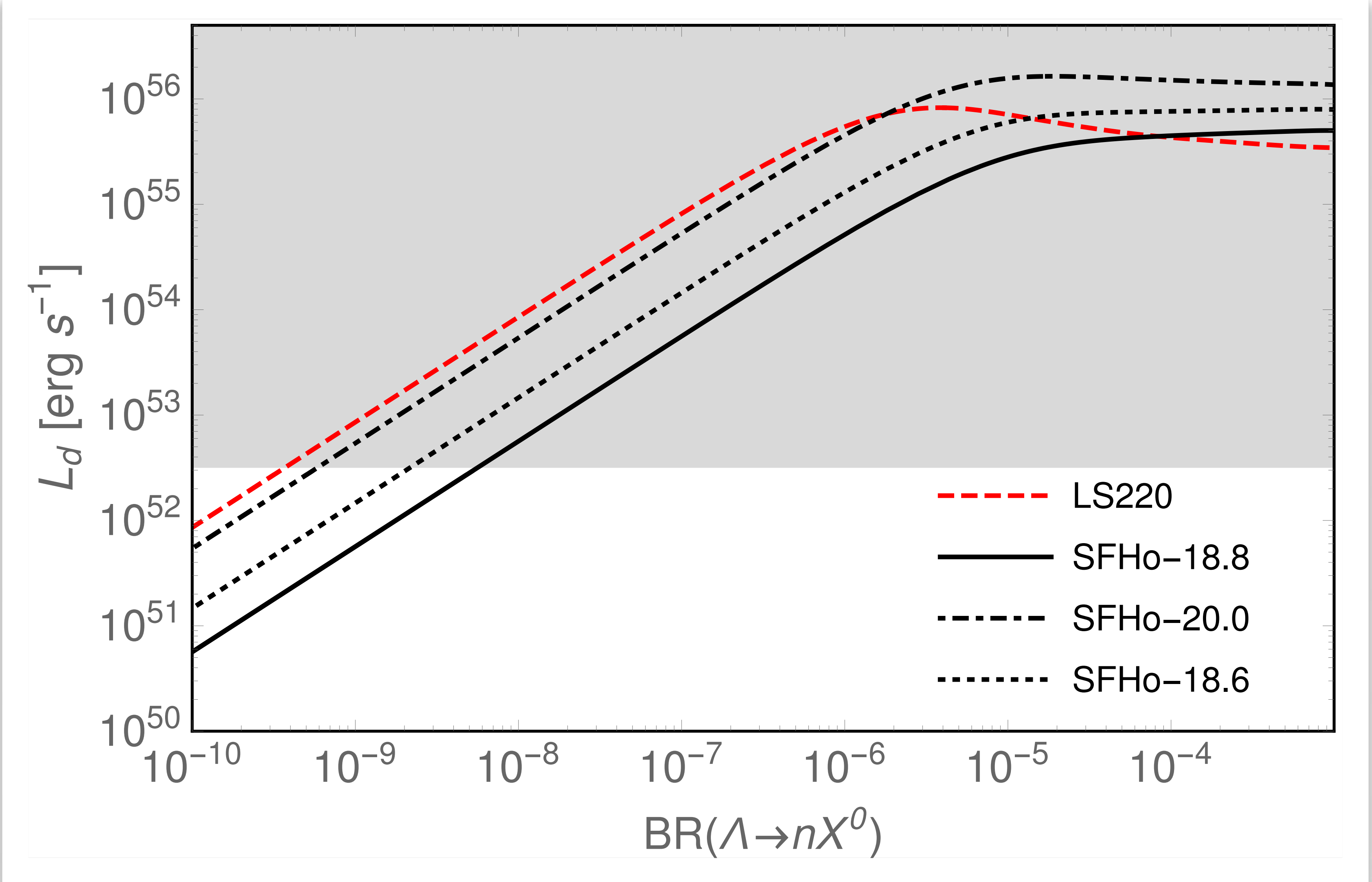

**Surface emission:** $L_{\text{dark}} \approx \frac{2\pi^3}{15} R_{\text{dark}}^2 T_{\text{dark}}^4$

Coalescence


**Ineffective:** Hyperons disappear in hot regions

# SN 1987A bound on strange dark bosons

- SN bound is established directly on the dark $\Lambda \to n$ **dark branching ratio**

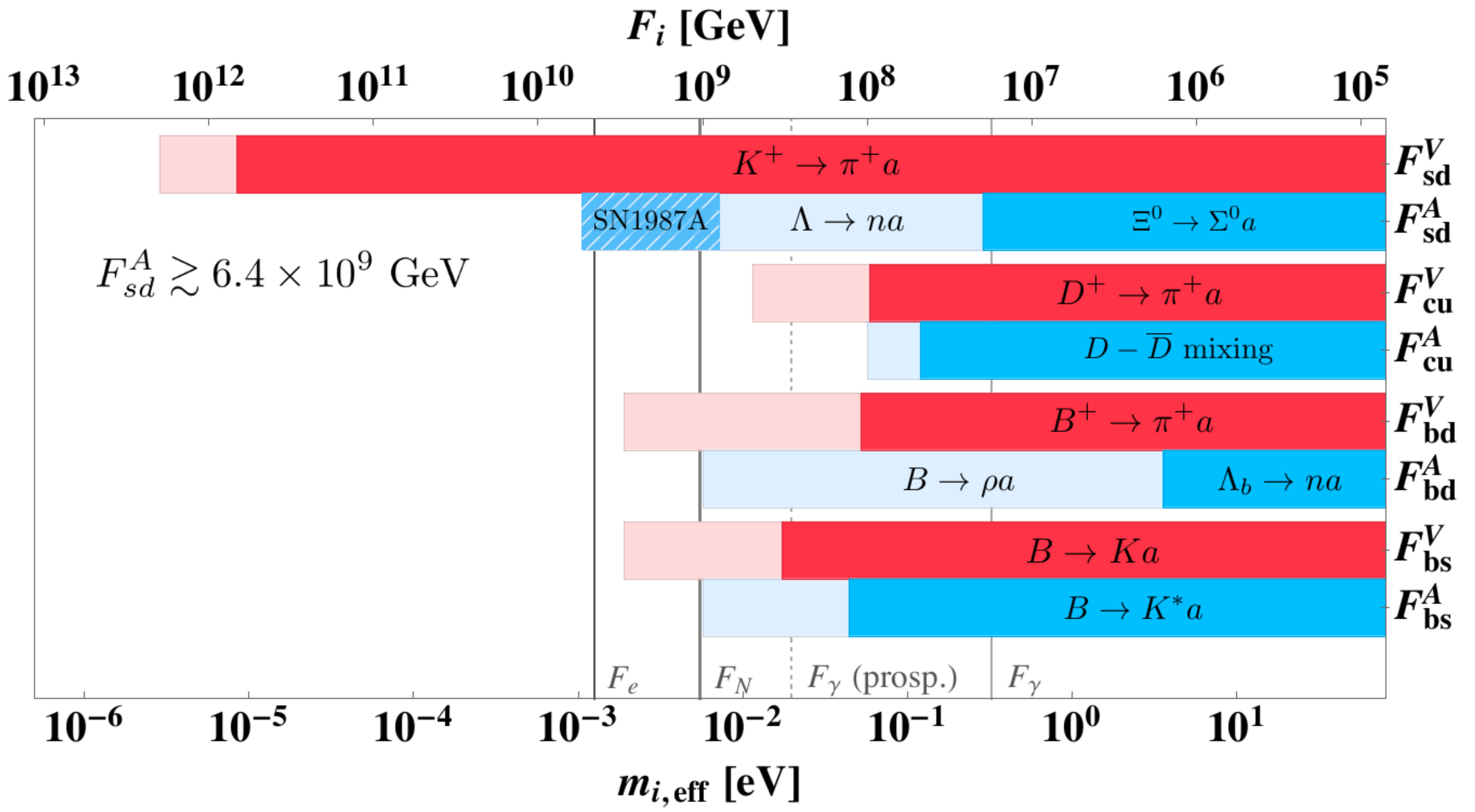



$$\mathrm{BR}(\Lambda \to n) \lesssim 8 \times 10^{-9}$$

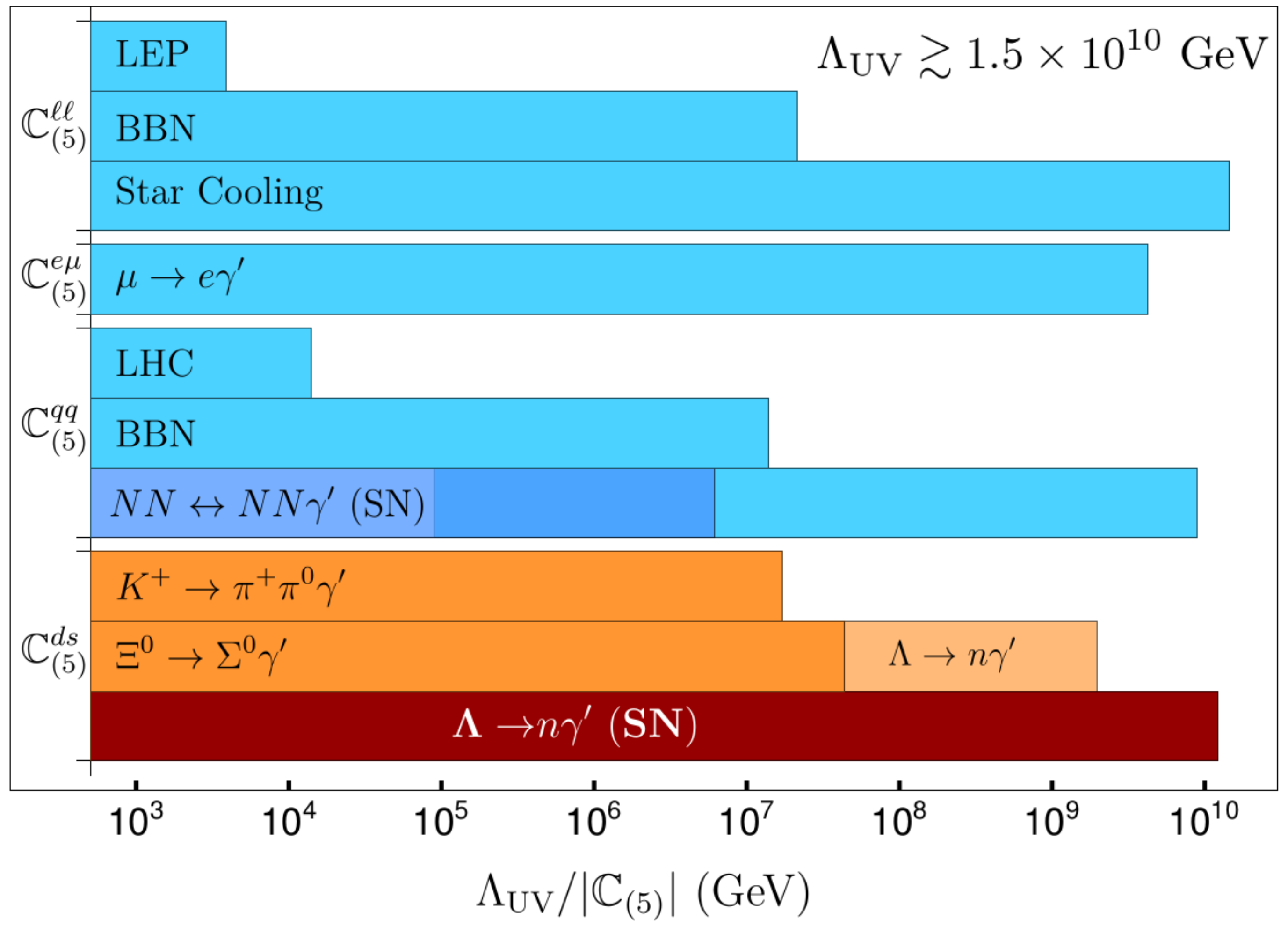
BR's in $10^{-10}$

| | SFHo-18.6 | SFHo-18.8 | SFHo-20.0 | LS220-20.0 |
|---|---|---|---|---|
| Thermal | 27 | 60 | 7 | 6 |
| EoS-App. | 20 | 46 | 6 | 2 |
| EoS | 36 | 92 | 10 | 4 |
| EoS* | 32 | 81 | 9 | 4 |
| $L_d^t$ [erg s$^{-1}$] | $1.1 \times 10^{55}$ | $6.5 \times 10^{54}$ | $1.7 \times 10^{55}$ | $1.7 \times 10^{54}$ |

- Best limit on **axion** axial **couplings** JMC+'21




- Best limit on **dim-5 dark photon couplings**




JMC+'20

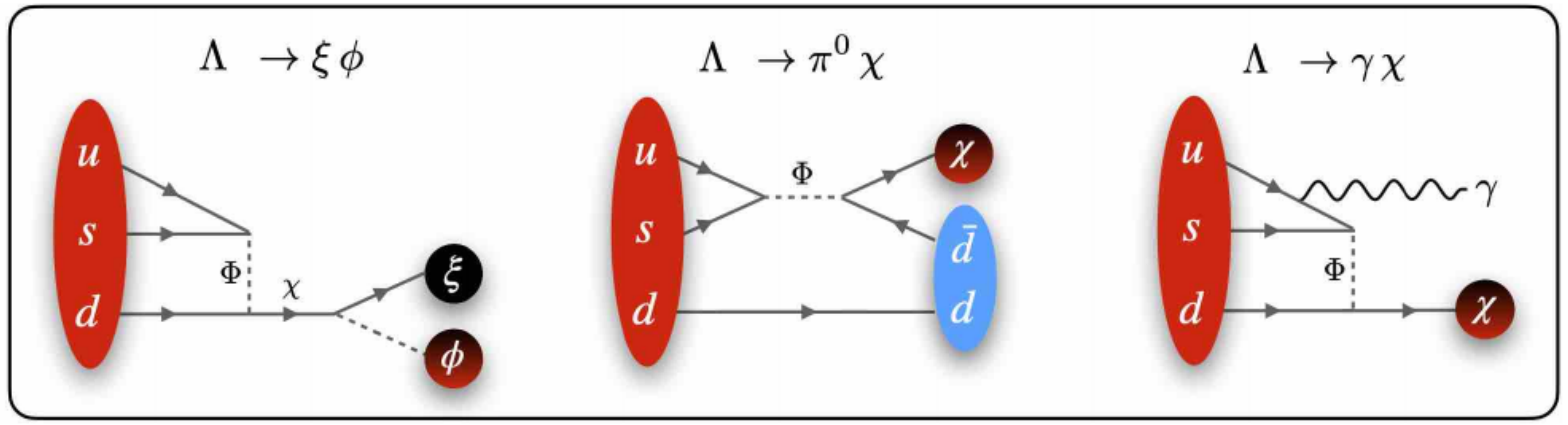
# SN 1987A bound on strange dark baryons Alonso-Álvarez (JMC)+'21

- **Mesogenesis and $\tau_n$ anomaly ($m_{\rm Dark} \gtrsim m_p$)**
  Most general EFT for different heavy mediators

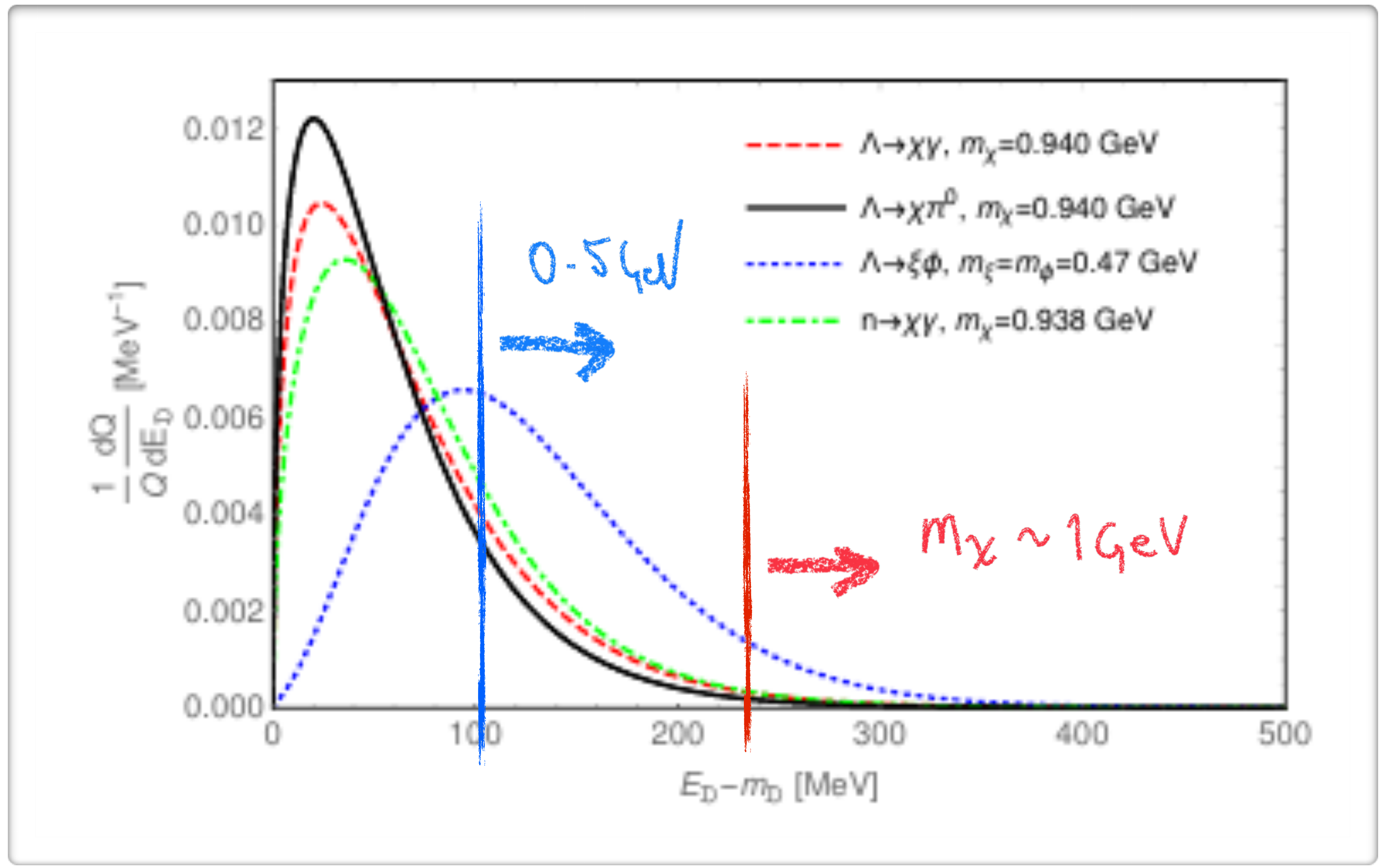
$$\mathscr{L}_{\rm EFT} = \frac{1}{M_\Phi^2}\left(C_{ab,c}\epsilon_{ijk}(u^i_{Ra}d^j_{Rb})(\chi_R d^k_{Rc}) + C'_{ab,c}\epsilon_{ijk}\epsilon_{\alpha\beta}(Q^{i\alpha}_{La}Q^{j\beta}_{Lb})(\chi_R d^k_{Rc})\right)$$

$\chi$ can be a fermionic portal $\chi \to \xi\phi$

- **Production: $\Lambda \to \mathrm{inv}$ or $\Lambda \to \pi^0 + \mathrm{inv}$**




- Dark baryons gravitationally trapped




- **Very strong bounds on BRs**

| Simulation | $\Lambda \to \chi\gamma$ | | $\Lambda \to \chi\pi^0$ | $\Lambda \to \xi\phi$ | |
|---|---|---|---|---|---|
| | $m_\chi$ [GeV] | | $m_\chi$ [GeV] | $(m_\xi, m_\phi)$ [GeV] | |
| | 0.94 | 1.05 | 0.94 | (0.94, 0) | (0.5, 0.5) |
| SFHo18.80 | $5.4 \cdot 10^{-8}$ | $\mathbf{1.6 \cdot 10^{-7}}$ | $1.1 \cdot 10^{-7}$ | $\mathbf{5.0 \cdot 10^{-9}}$ | $\mathbf{2.4 \cdot 10^{-9}}$ |

- $\Lambda \to \mathrm{inv}$ measured by BESIII

$$\mathrm{BR}(\Lambda \to \mathrm{inv})^{\rm exp} \leq 7.4 \times 10^{-5}$$

# Conclusions

- Increasing interest on dark flavored sectors
  1. **Powerful experiments:** Discovery potential and testability
  2. **Connections to BSM:** Anomalies, DM, baryogenesis, ...
- SN 1987A bound on dark flavor sectors
  1. **Heavy flavors** (muon & strange) are in equilibrium in PNS plasma
  2. **Strong bounds** from exotic-cooling arguments

> This may guide (but not completely discourage) experimental searches

- Prospects
  1. **SN bounds in other flavored dark-sector models:** See Snowmass doc Goudzovski+'23
  2. **Improve SN understanding:** Specifically, dark sectors in the trapping regime
  3. **SM astrophysics:** Role of hyperons in SN explosions