UAM UNIVERSIDAD AUTONOMA DE MADRID

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

MultiDark Multimessenger Approach for Dark Matter Detection

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Cosmology With a Very Light $L_\mu - L_\tau$ Gauge Boson

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Dark Side of the Universe

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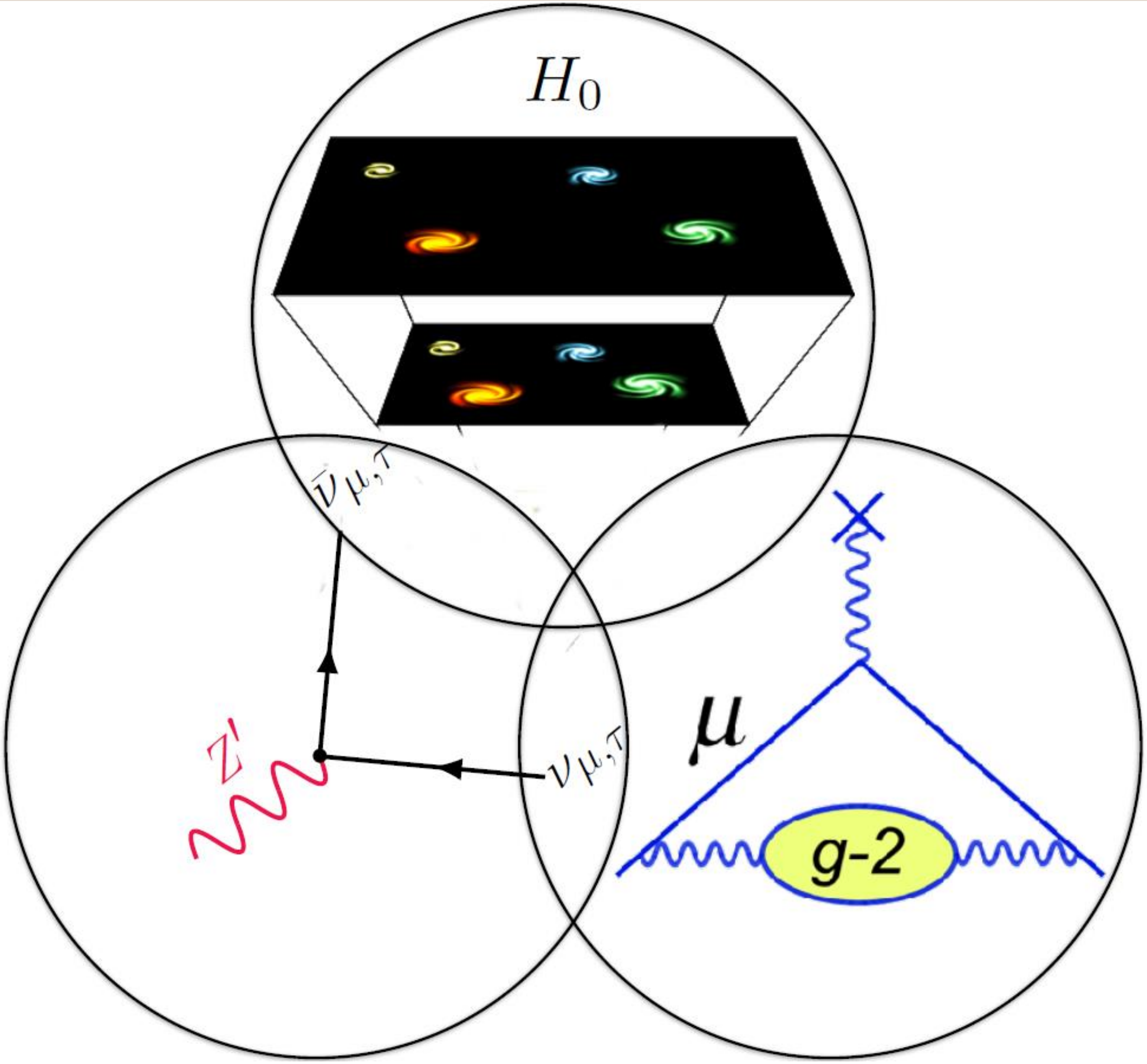
The 15th International Conference on the DARK SIDE OF THE UNIVERSE

Based on [1901.02010] with M. Escudero, D. Hooper & G. Krnjaic

Outline



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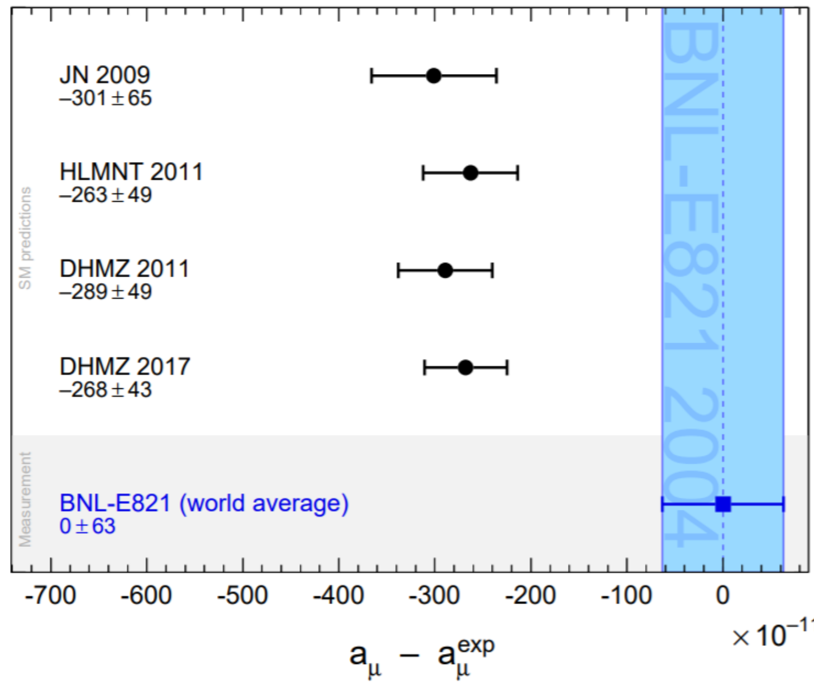
The $(g-2)_\mu$ anomaly

$$\vec{\mu}_\mu = g_\mu \frac{\sqrt{4\pi\alpha}}{2m_\mu}\vec{S}_\mu \qquad a_\mu \equiv \frac{g_\mu - 2}{2}$$



- Long standing ~**3.5σ** discrepancy

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 268(63)(43)\times 10^{-11}$$

[PDG]

- SM prediction very **robust**

[Blum et al. 1311.2198]

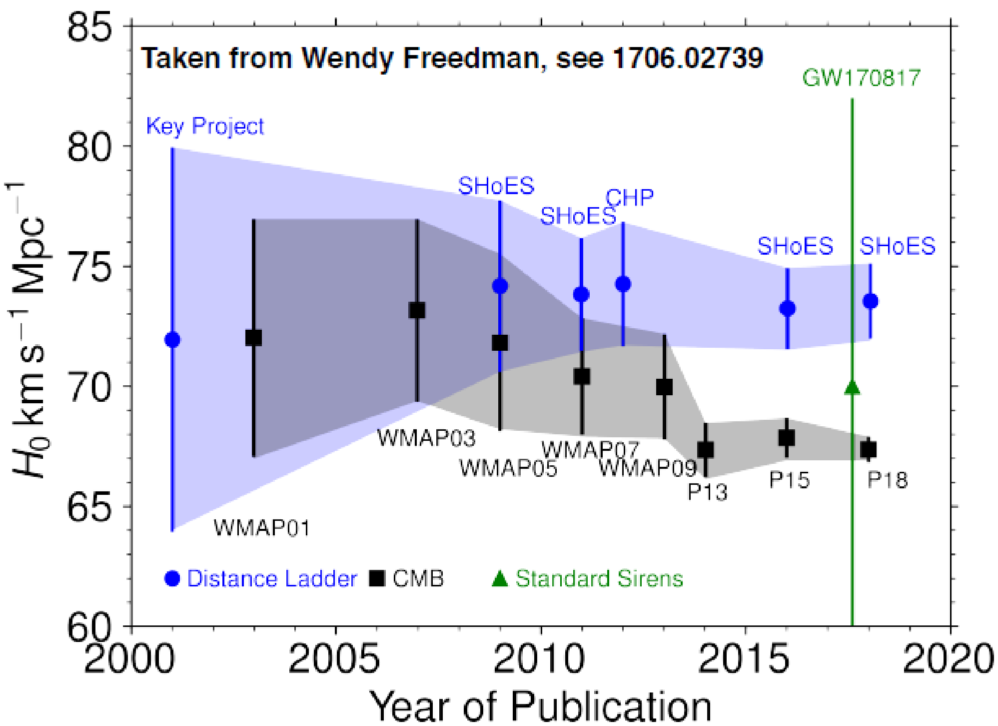
- Many BSM interpretations SUSY, extra Higgses and symmetries

[Lindner et al. 1610.06587]

- **Fermilab** should **redure error** by a **factor ~4** : early 2019?

- Experiment at **J-PARC** should reach same sensitivity

The Hubble tension



Riess *et al* 1801.01120, 1804.10655

$$H_0 = 73.45 \pm 1.66\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

3.5 σ tension!

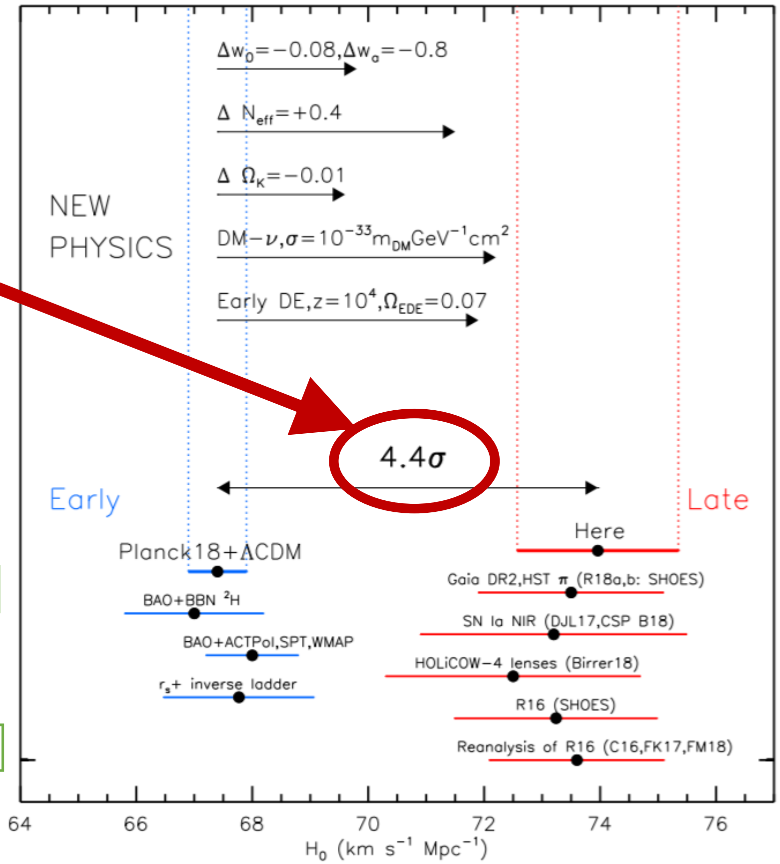
$$H_0 = 67.27 \pm 0.60\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Planck 2018 1807.06209

- Tension **unlikely** generated by **CMB systematics**
  [Verde et al. 1601.01701]
- Local measurement have been **checked against systematics**
  [Follin & Knox 1707.01175]
- Discrepancy **also present** with **BAO**
  [Addison 1707.06547]

The Hubble tension

- Latest determination of H_0 based on HST : $H_0 = 74.03 \pm 1.42$ km s^{-1} Mpc^{-1}



[Riess et al. 1903.07603]

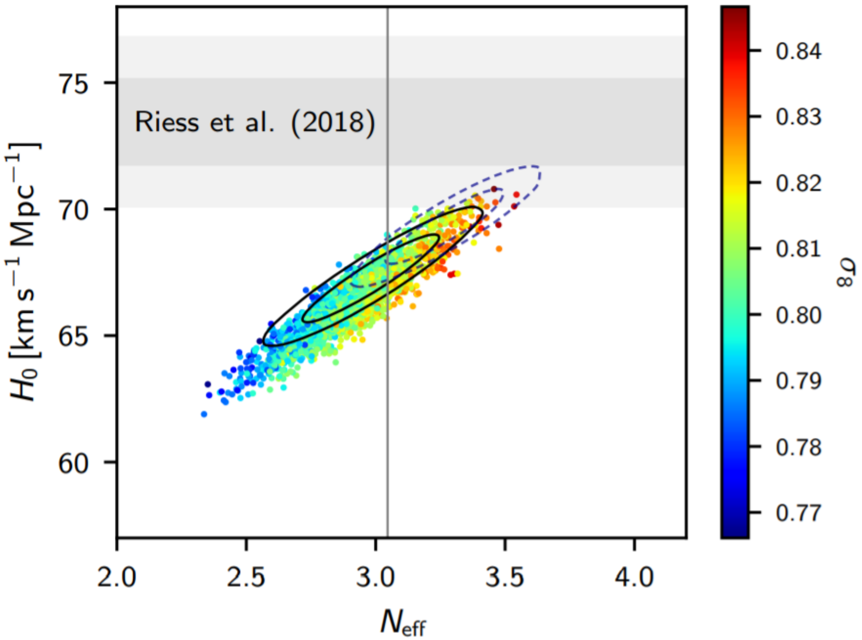
- **Possible solutions ?**
  - Early dark energy [Poulin et al. 1811.04083]
  - Decaying dark matter [Bringmann et al. 1803.03644]
  - Goldstones as dark radiation [Weinberg 1305.1971]
  - Non-zero curvature

- future Gaia data will **increase** precision on **local** determination of H_0

- **Stage-IV CMB experiment** expected to deliver $\sigma N_{\rm eff} \sim 0.03$

The Hubble tension : $\Delta N_{\rm eff} > 0$?

- Modifying $N_{\rm eff}$ before recombination changes the **sound horizon**, that can be **compensated** by a **larger** H_0 for keeping the **same acoustic angular scale**



- **Planck+BAO+RIESS18**

$$N_{\rm eff} = 3.27 \pm 0.15$$

$$H_0 = (69.32 \pm 0.97)\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

[Planck 1807.06209]

- $\Delta N_{\rm eff} < 0.53$ from Planck → sterile ν interpretation ?

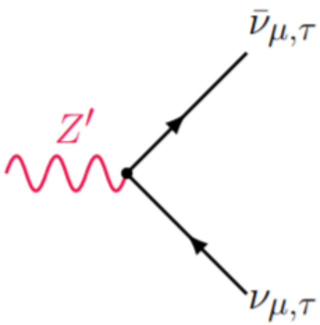
- $2.3 < N_{\rm eff} < 3.5$ from BBN [Cyburt et al. 1505.01076]

$\Delta N_{\rm eff} = 0.2 - 0.5$ alleviates the H_0 tension

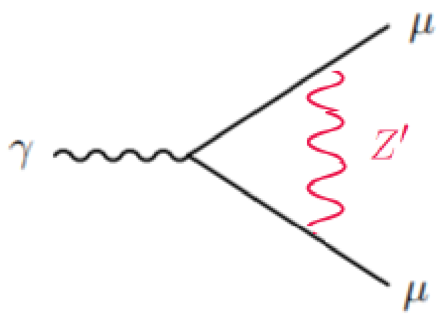
The main idea

Consider the generation of $\Delta N_{\text{eff}} > 0$ from interactions and decay of a light neutrophilic *Z'* gauge field

$$N_{\text{eff}} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\text{rad}} - \rho_\gamma}{\rho_\gamma}\right)$$



→ $T_\nu > T_\nu^{\text{SM}}$ → $\Delta N_{\text{eff}} > 0$



→ Δa_μ

$$\Delta N_{\text{eff}} > 0,\ N_\nu = 3,\ N_{\text{DR}} = 0,\ \ \Delta a_\mu$$

A light $L_\mu - L_\tau$ gauge boson

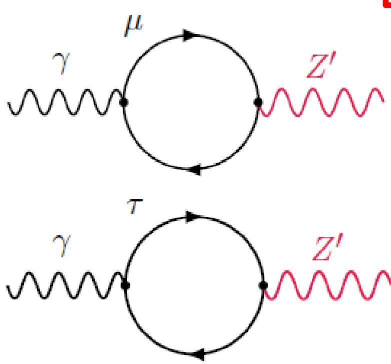
- Assuming a **local** U(1) gauged L_μ-L_τ number

$$\mathcal{L}_{\rm int} = g_{\mu-\tau} Z'_\alpha (\bar{\mu}\gamma^\alpha\mu + \bar{\nu}_\mu\gamma^\alpha P_L \nu_\mu - \bar{\tau}\gamma^\alpha\tau - \bar{\nu}_\tau\gamma^\alpha P_L\nu_\tau)$$

- Simple **anomaly-free** BSM extension : **2 parameters**

$$10^{-15} < g_{\mu-\tau} < 10^{-1} \qquad 1\,\mathrm{eV} < m_{Z'} < 2m_\mu$$

- **Kinetic mixing**

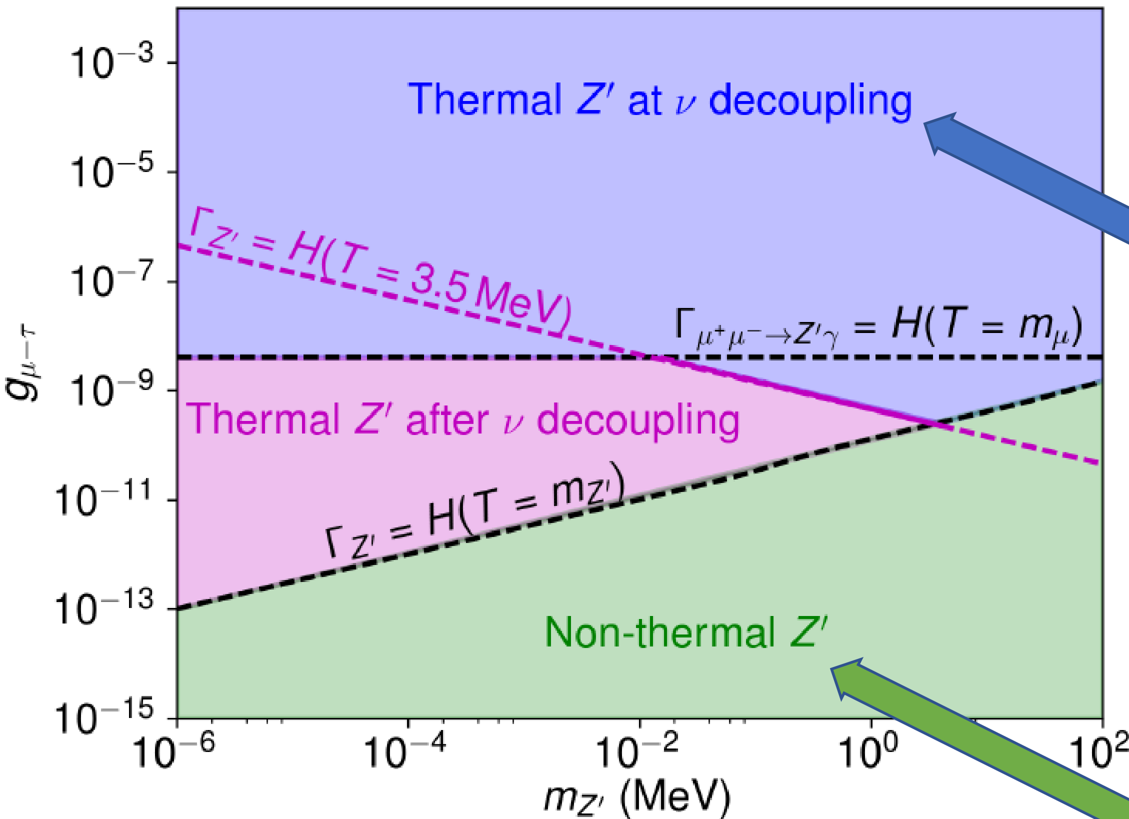


$$\epsilon = -\frac{e g_{\mu-\tau}}{12\pi^2}\log\frac{m_\tau^2}{m_\mu^2} = -\frac{g_{\mu-\tau}}{70}$$

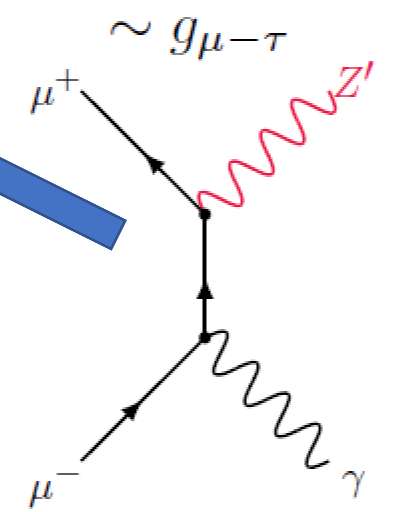
- **Neutrinophilic** $\Gamma_{Z'\to\bar{\nu}_i\nu_i} = \frac{g_{\mu-\tau}^2 m_{Z'}}{24\pi}$

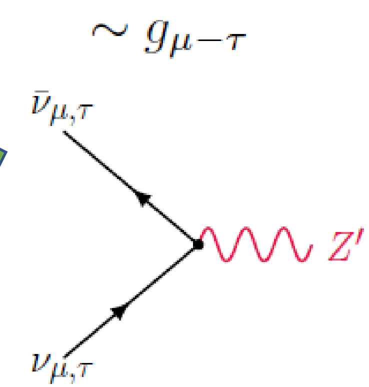
- Coupling to **electrons** $\mathrm{Br}_{Z'\to e^+e^-} \simeq 2\times 10^{-5}$

A light $L_\mu - L_\tau$ gauge boson



Key processes





3 regimes :

- Thermal Z' at ν decoupling
- Thermal Z' after ν decoupling
- Non-thermal Z'

The thermal regime

- *Z'* in thermal equilibrium with ν due to large coupling

$$T_{Z'} = T_\nu$$

- ν-oscillations are active at T ~ 3 MeV :

$$T_\nu \equiv T_{\nu_\mu} = T_{\nu_\tau} = T_{\nu_e}$$

- Need to solve

[Escudero 1812.05605]

$$\frac{dT_\nu}{dt} = -\left(4H\rho_\nu + 3H\left(\rho_{Z'} + p_{Z'}\right) - \frac{\delta\rho_\nu}{\delta t} - \frac{\delta\rho_{Z'}}{\delta t}\right)\left(\frac{\partial\rho_\nu}{\partial T_\nu} + \frac{\partial\rho_{Z'}}{\partial T_\nu}\right)^{-1}$$

$$\frac{dT_\gamma}{dt} = -\left(4H\rho_\gamma + 3H\left(\rho_e + p_e\right) + \frac{\delta\rho_\nu}{\delta t} + \frac{\delta\rho_{Z'}}{\delta t}\right)\left(\frac{\partial\rho_\gamma}{\partial T_\gamma} + \frac{\partial\rho_e}{\partial T_\gamma}\right)^{-1},$$

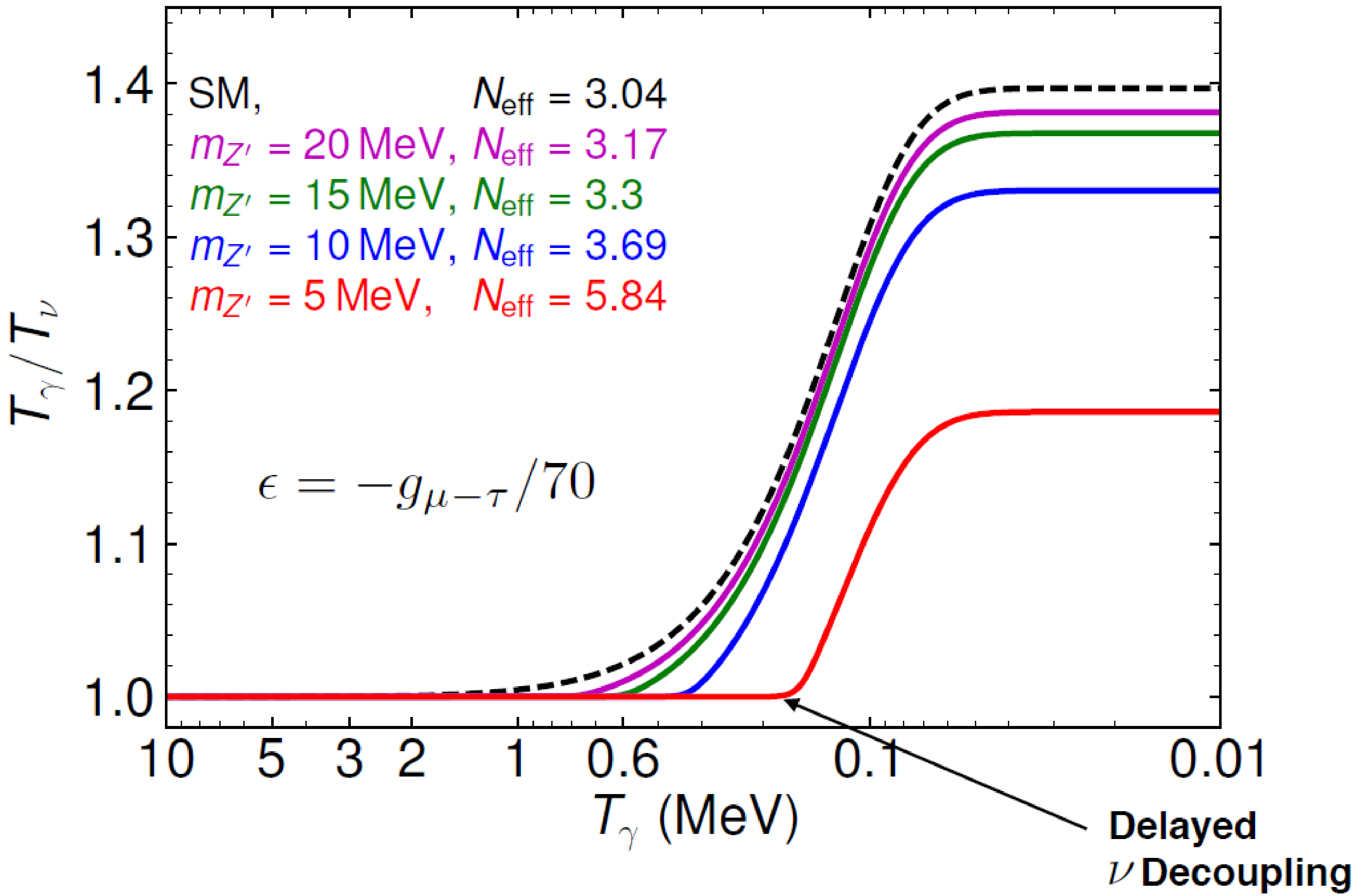
- Need to compute thermal averaged rates

$$e^+e^- \leftrightarrow \bar{\nu}\nu$$

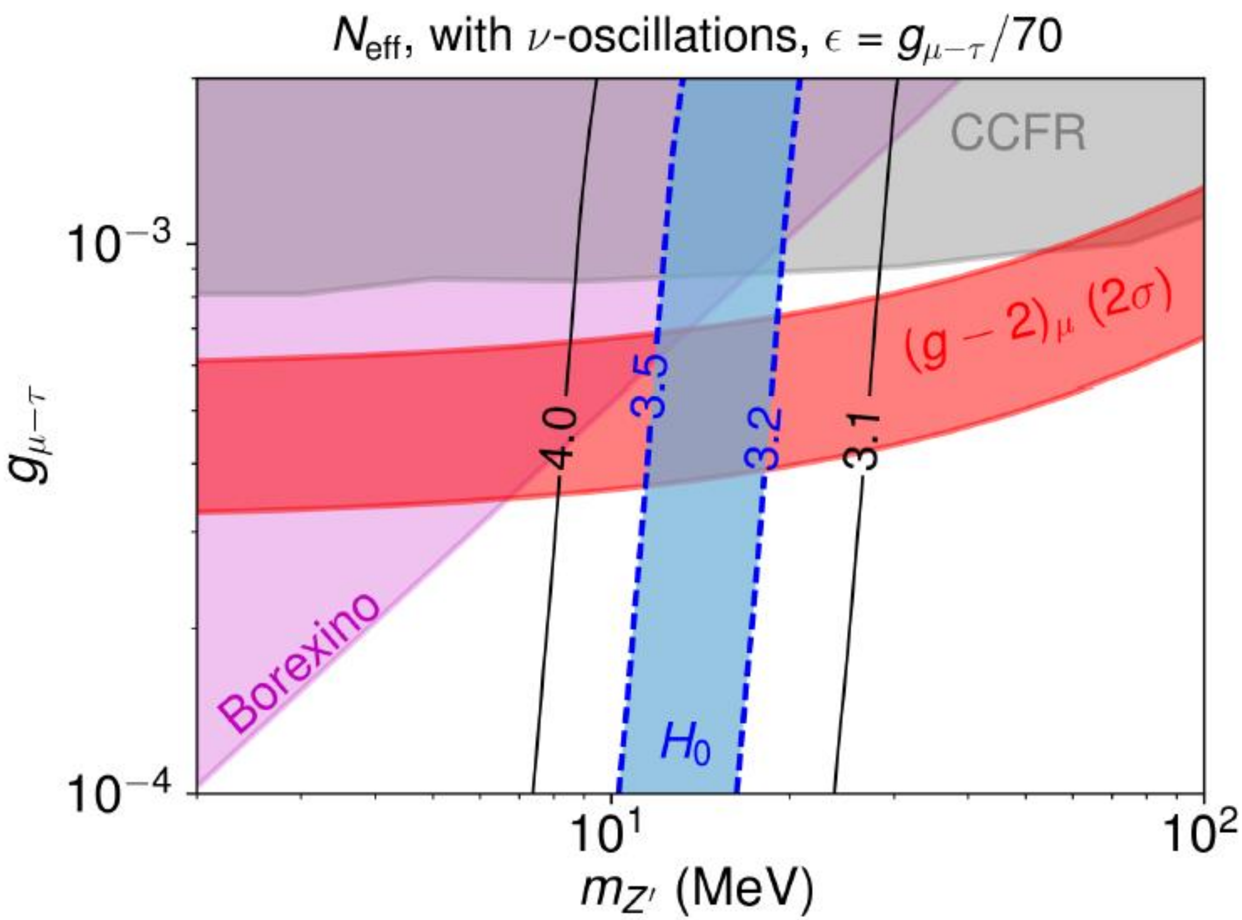
$$Z' \leftrightarrow e^+e^-$$

The thermal regime

$g_{\mu-\tau} = 4 \times 10^{-4} \simeq g_{\mu-\tau}|_{g-2}$



The thermal regime

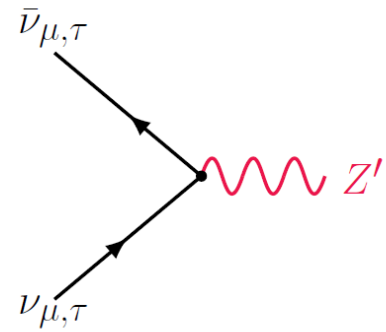


- **Compatible** with simultaneous H_0 and $(g-2)_\mu$!

$$m_{Z'} \simeq 10 - 20 \text{ MeV} \qquad g_{\mu-\tau} \simeq (4-8) \times 10^{-4}$$

Weakly coupled regime

- For **small couplings**, **no** early thermal Z'-SM equilibrium, only **one** relevant process



- **Non-thermal !** Need the full phase space distribution

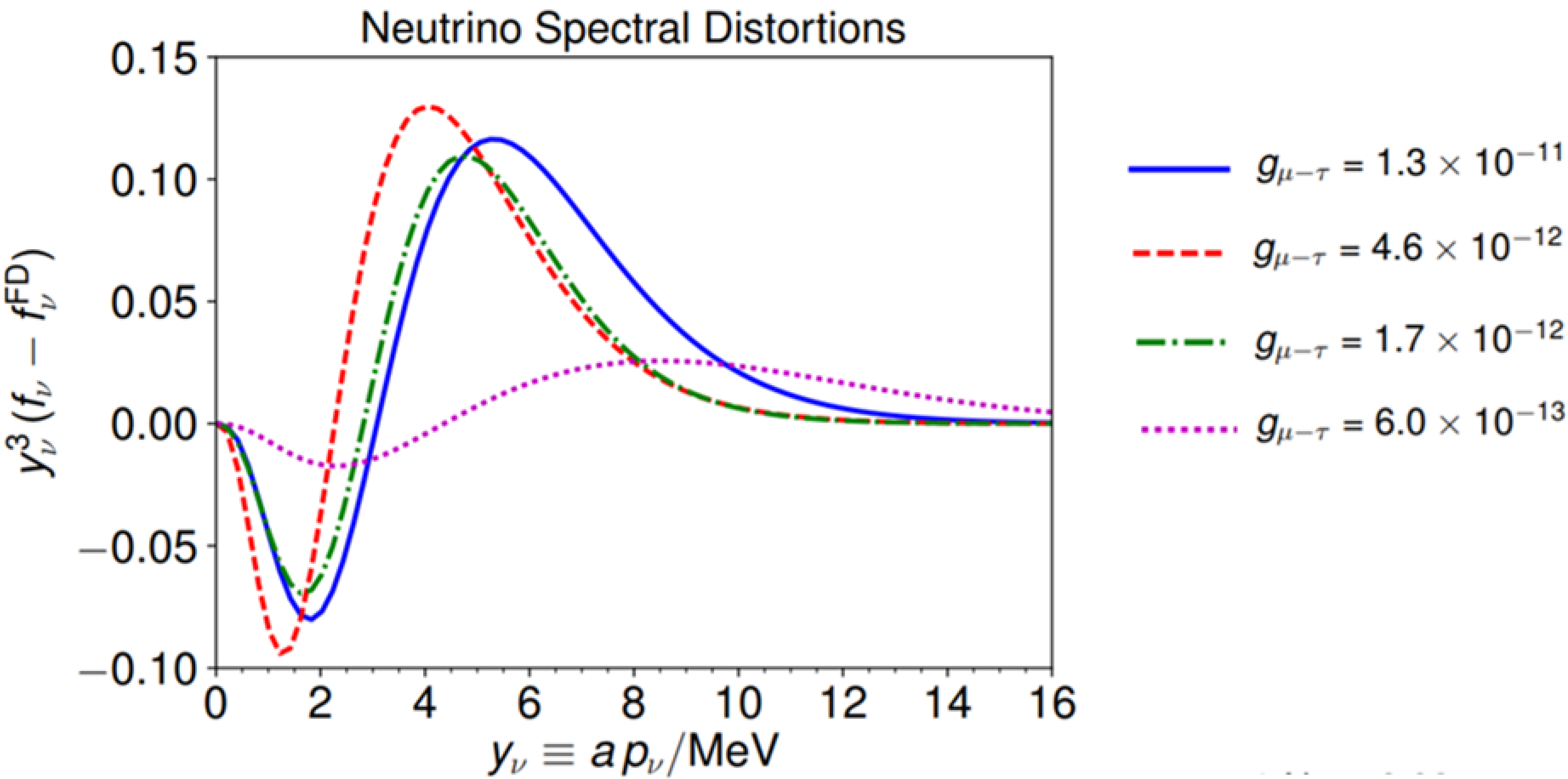
$$\frac{\partial f_{Z'}}{\partial t} - H p_{Z'} \frac{\partial f_{Z'}}{\partial p_{Z'}} = -\frac{m_{Z'} \Gamma_{Z'}}{E_{Z'} p_{Z'}} \int_{\frac{E_{Z'}-p_{Z'}}{2}}^{\frac{E_{Z'}+p_{Z'}}{2}} dE_\nu F_{\rm dec}\left(E_{Z'}, E_\nu, E_{Z'} - E_\nu\right) ,$$
$$\frac{\partial f_\nu}{\partial t} - H p_\nu \frac{\partial f_\nu}{\partial p_\nu} = \frac{m_{Z'} \Gamma_{Z'}}{E_\nu p_\nu} \int_{|(m_{Z'}^2/4p_\nu)-p_\nu|}^{\infty} \frac{dp_{Z'} p_{Z'}}{E_{Z'}} F_{\rm dec}\left(E_{Z'}, E_\nu, E_{Z'} - E_\nu\right)$$

with $F_{\rm dec}(E_{Z'}, E_{\nu_1}, E_{\nu_2}) = f_{Z'}(E_{Z'})\left[1 - f_\nu(E_{\nu_1})\right]\left[1 - f_\nu(E_{\nu_2})\right] - f_\nu(E_{\nu_1}) f_\nu(E_{\nu_2})\left[1 + f_{Z'}(E_{Z'})\right].$

- **Stiff** set of equations, solved for **100 bins** in comoving momentum for the Z' and ν distributions

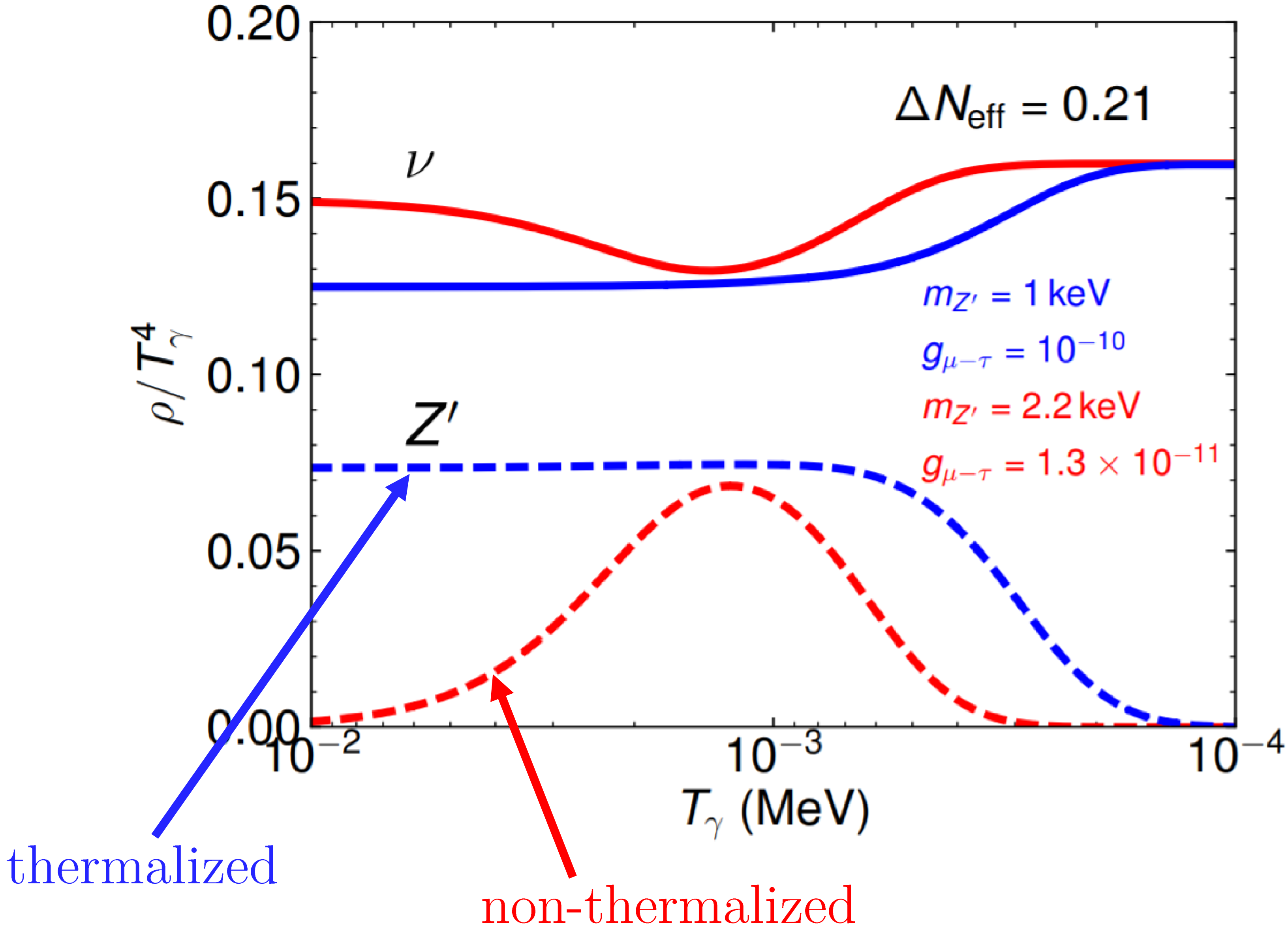
- Check **continuity equation** $$\frac{d\rho}{dt} = -3H\left(\rho + p\right)$$

The ν phase space distribution

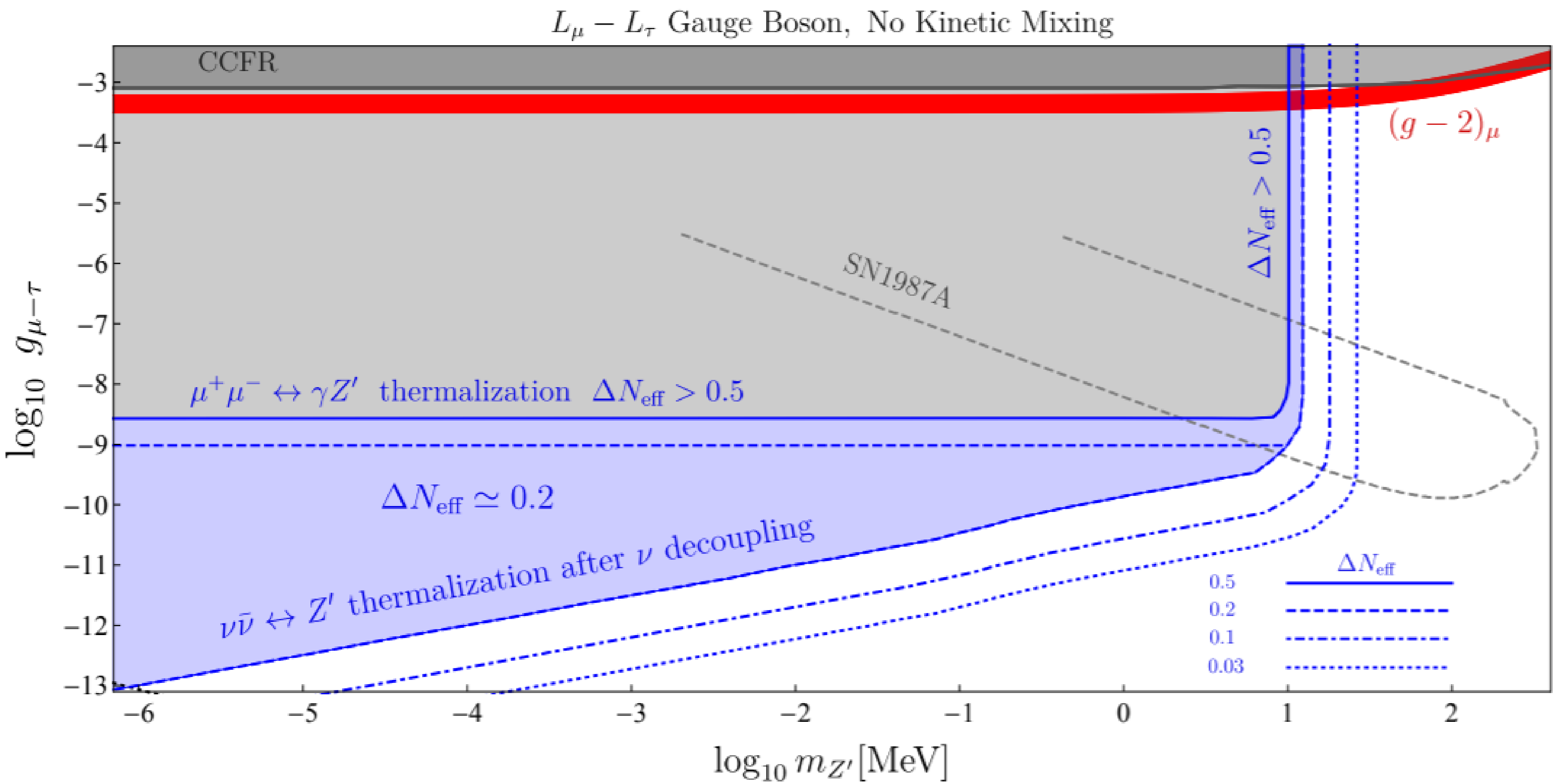


- **Non-thermal** distribution : our approach is justified !

Weakly coupled regime

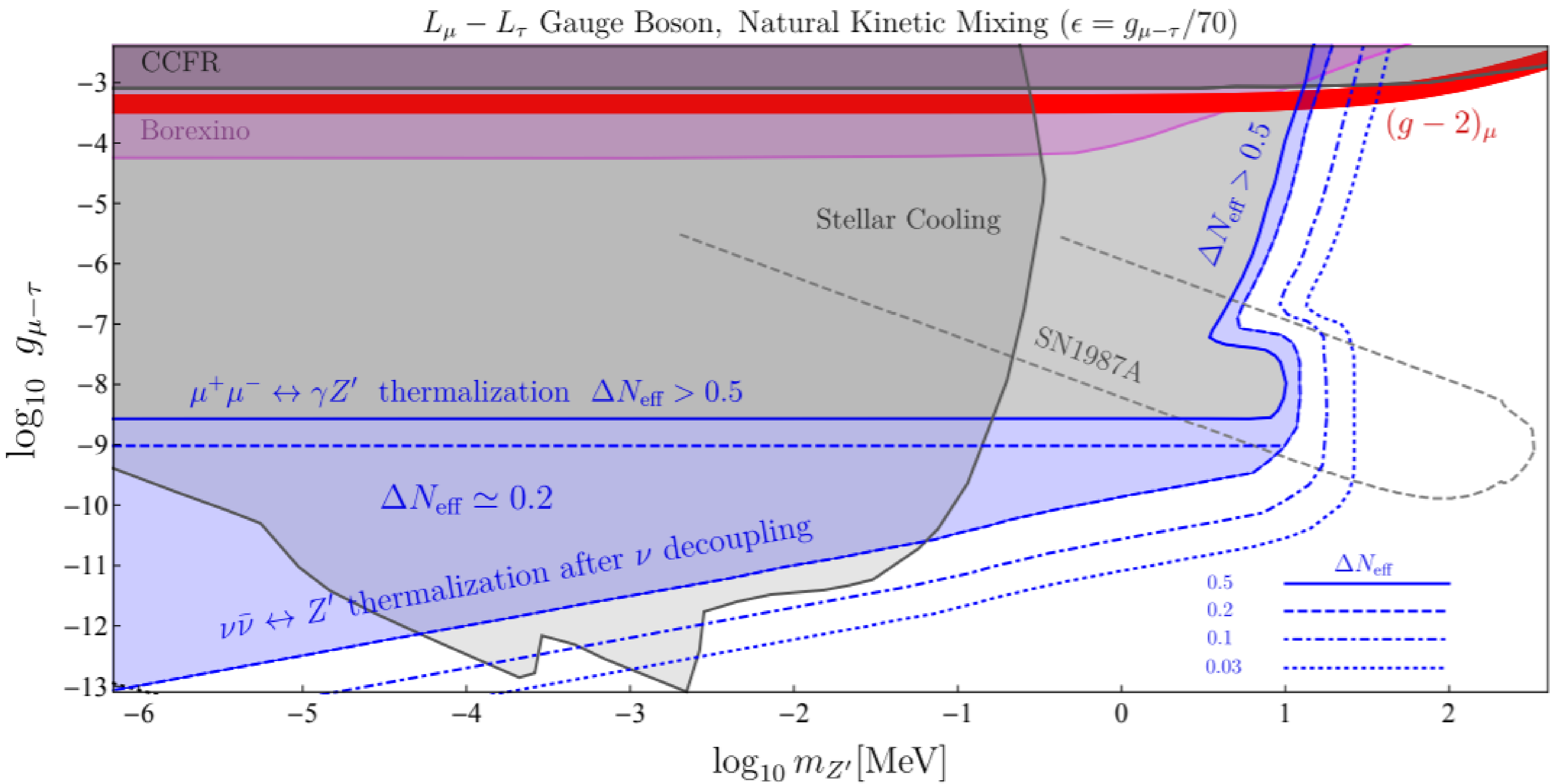


The results



- $\Delta N_{\rm eff} = 0.21$ over a **large plateau** of parameter space
- Due to **secluded ν-*Z'*** system after ν-decoupling and **out-of-equilibrium decay**

The results



- **Stellar cooling** important when **kinetic mixing** considered
- For $m_{Z'} < 100$ keV : $\Delta N_{\rm eff} = 0.21$ at CMB but $\Delta N_{\rm eff} = 0$ at BBN !

Take-home message

- The H_0 and $(g-2)_\mu$ **tensions** : physics **beyond** ΛCDM?

- H_0 and $(g-2)_\mu$ **tensions** can be simultaneously addressed for

$$m_{Z'} \simeq 10 - 20 \text{ MeV} \qquad g_{\mu-\tau} \simeq (4-8) \times 10^{-4}$$

- $\Delta N_{\rm eff} = 0.21$ a generic prediction of a light L_μ-L_τ gauge boson

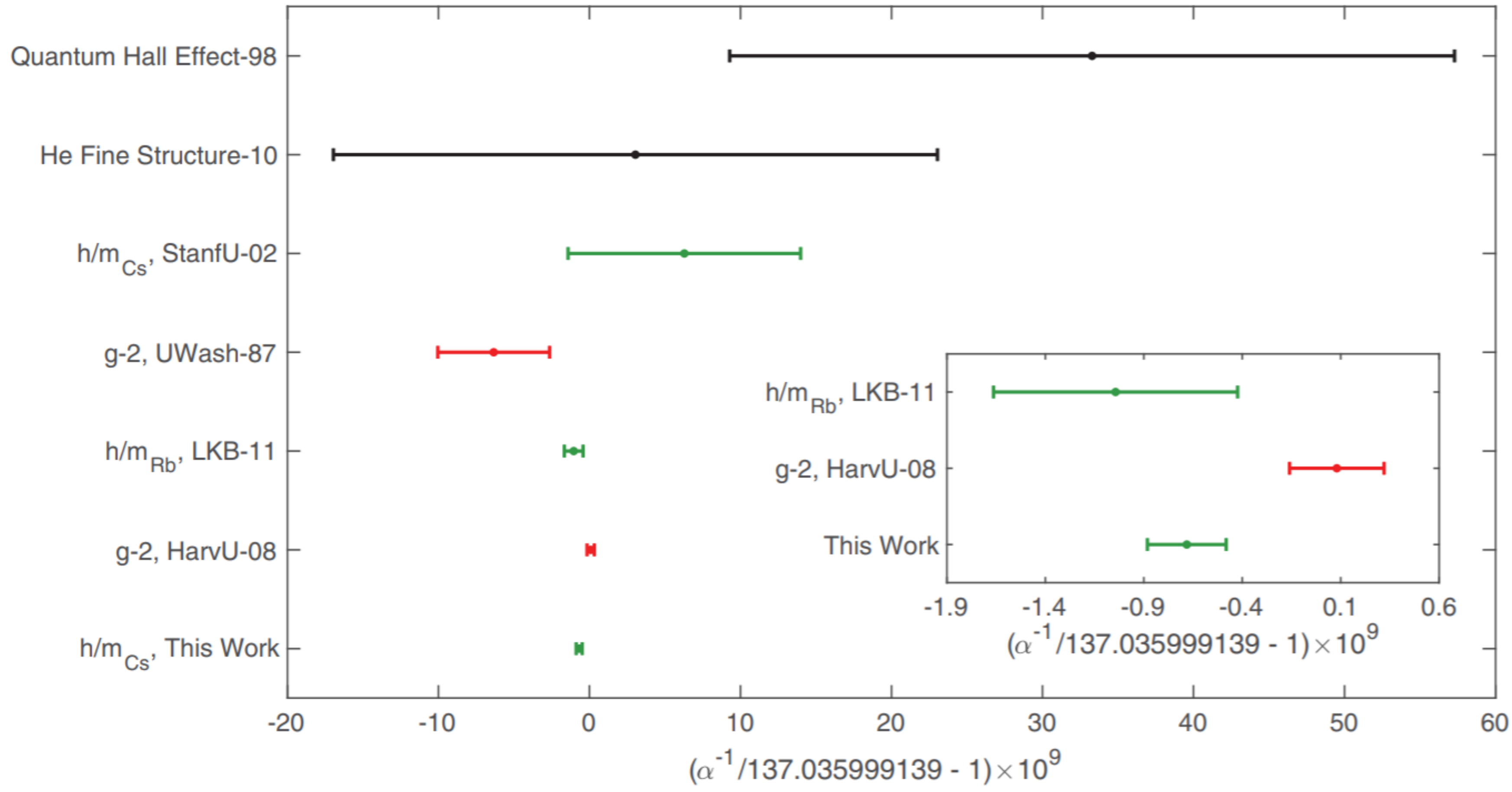
- **Local measurements** of H_0 expected to deliver a precision of ~ **1%** within the **next few years**

- The $\Delta N_{\rm eff} \sim 0.2$ - 0.5 hypothesis could be **tested** at **stage-IV** CMB experiments, expected to deliver $\sigma N_{\rm eff} \sim 0.03$

- Very reach interplay between particle physics and cosmology

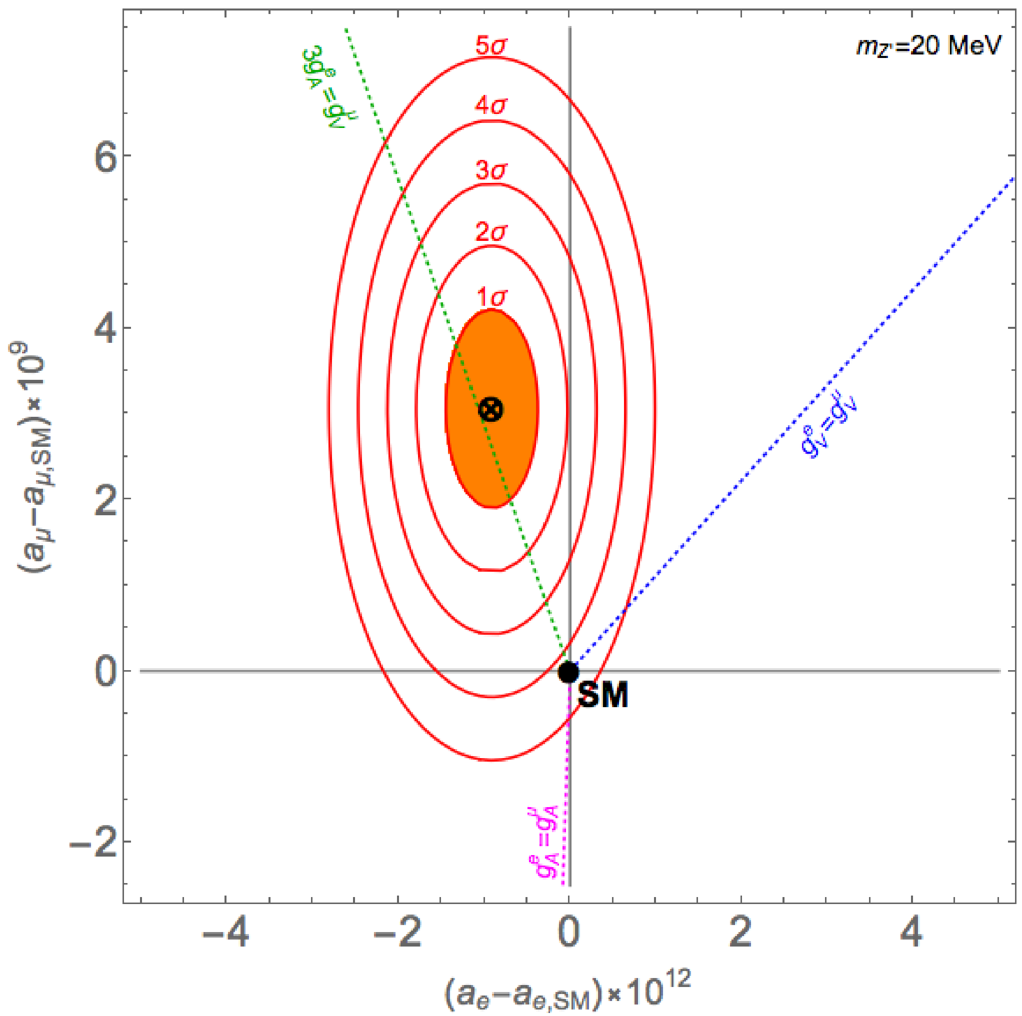
Back-up Slides

The $(g-2)_e$ anomaly



[Parker, R. H., Yu, C., Zhong, W., Estey, B., & Müller, H. (2018). *Measurement of the fine-structure constant as a test of the Standard Model.* Science, 360(6385), 191–195.]

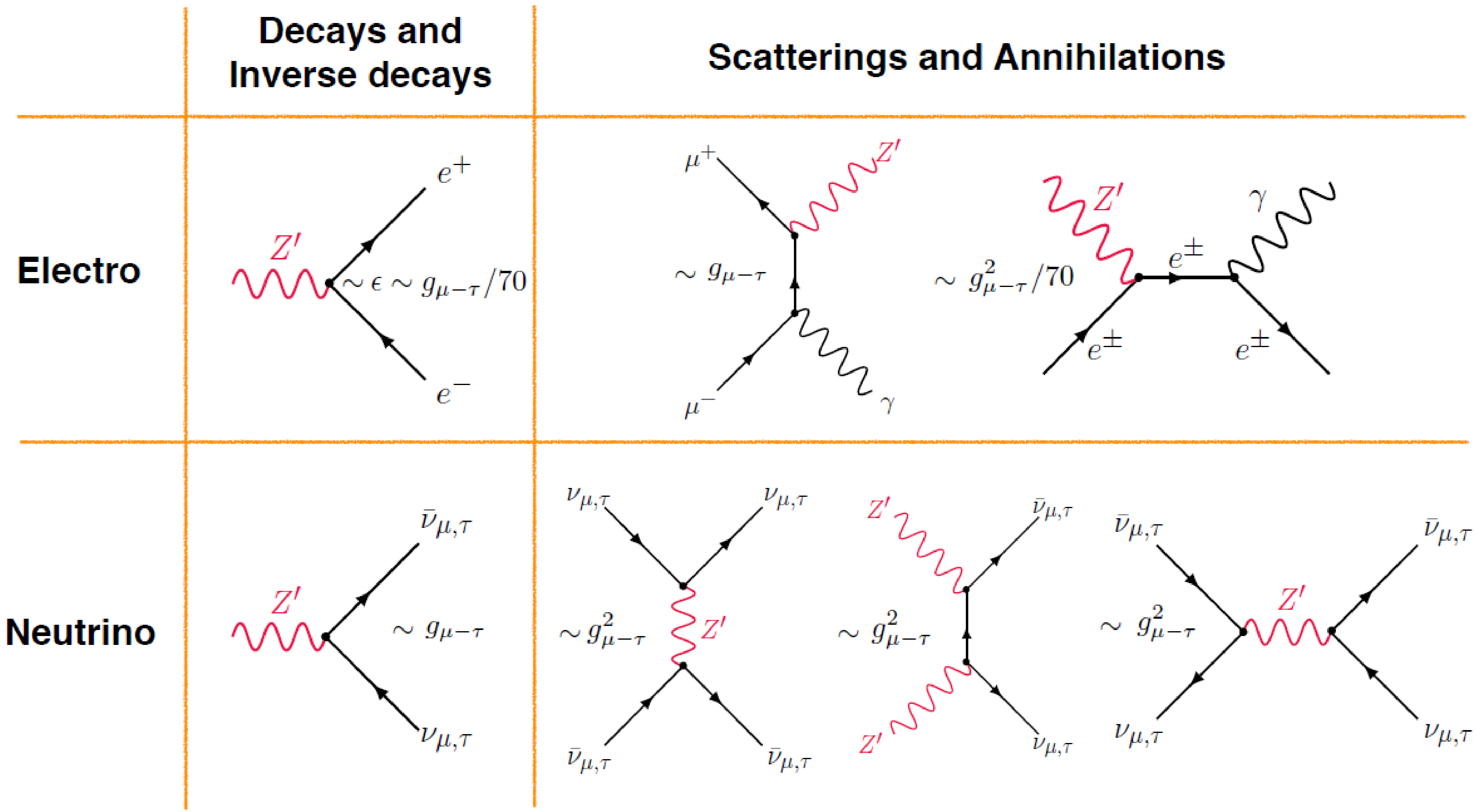
The $(g-2)_e$ anomaly



[Adam Falkowski's blog *Resonaances*]

A light $L_\mu - L_\tau$ gauge boson

- Z' in kinetic equilibrium with $e^\pm$, γ, ν ?

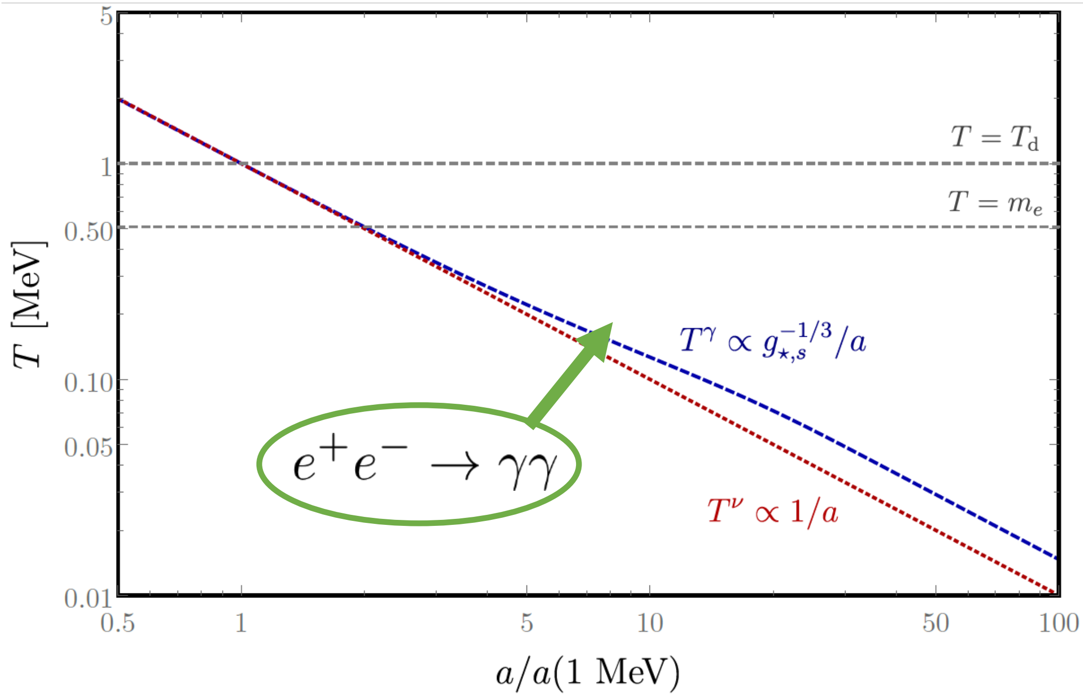


ν — decoupling and N_{eff}

- ν-decoupling T_{d} when $n_\nu \langle \sigma v \rangle \sim H$

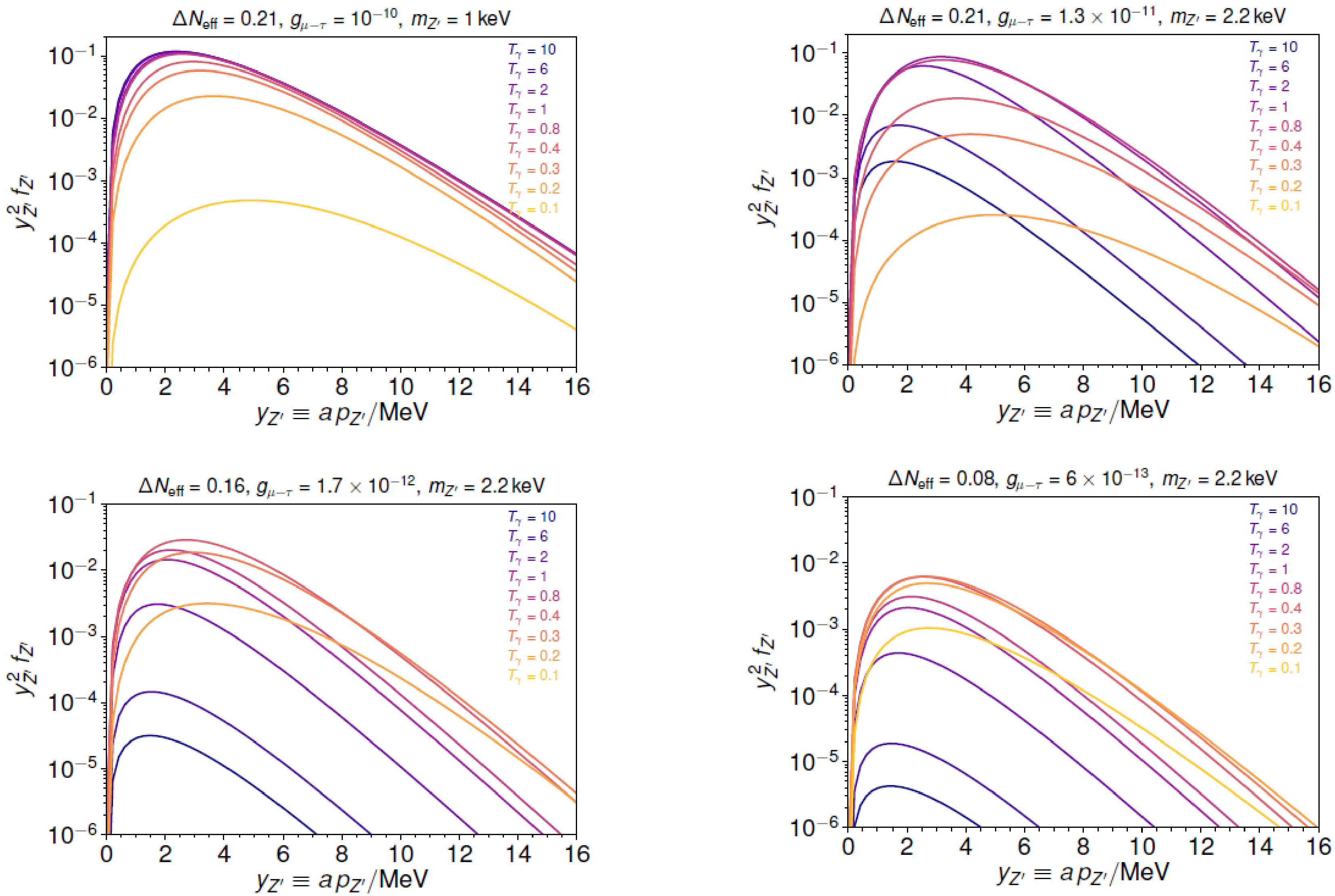
with $n_\nu \langle \sigma v \rangle \simeq G_F^2 T^5$

$T_{\mathrm{d}} \sim 1$ MeV



- $N_{\mathrm{eff}} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\mathrm{rad}} - \rho_\gamma}{\rho_\gamma}\right)$
- $N_{\mathrm{eff}} = 3\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_\nu}{T_\gamma}\right)^4$
- $N_{\mathrm{eff}}^{\mathrm{SM}} = 3.045$ [Salas & Pastor 1606.06986]
- Why $N_{\mathrm{eff}} \neq 3$? [Dolgov 0202122]
  - $T_{\mathrm{d}} \neq 1$ MeV
  - Non-instantaneous decoupling
  - ν-oscillations
  - QED finite temperature corrections

Phase space distribution



Constraints

Laboratory constraints

Neutrino Tridents	Relevant for large couplings and large masses
Kaon decays	Relevant if no kinetic mixing
B-factories	Relevant for the g-2 anomaly region
Beam dumps	Absent due to $\mathrm{Br}_{Z' \to e^+ e^-} \simeq 2 \times 10^{-5}$
Solar neutrino scatterings	Relevant for the g-2 anomaly region

Astrophysical constraints

SN1987A	Very important in a considerable portion of parameter space
Stellar Cooling	Very important in a considerable portion of parameter space

Cosmological constraints

Energy injection at the CMB	Absent due to $\mathrm{Br}_{Z' \to e^+ e^-} \simeq 2 \times 10^{-5}$
Energy injection during BBN	Absent due to $\mathrm{Br}_{Z' \to e^+ e^-} \simeq 2 \times 10^{-5}$

The $(g-2)_\mu$ anomaly

History of $(g-2)_e$

$$\vec{\mu}_e = g_e \frac{\sqrt{4\pi\alpha}}{2m_e} \vec{S}_e$$

- **1948 Schwinger** $(g-2)_e/2 \simeq \alpha/(2\pi)$

- **2008**

$$(g-2)_e^{\exp}/2 = 1\,159\,652\,180.73(28) \times 10^{-12}$$

[Hanneke et al. 0801.1134]

$$(g-2)_e^{\rm SM}/2 = 1\,159\,652\,181.61(23) \times 10^{-12}$$

[Aoyama et al. 1712.06060]

- **2018 : ~2σ discrepancy in $(g-2)_e$?**

[Parker et al. 1812.04130]

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