ELTE EÖTVÖS LORÁND UNIVERSITY

Beyond the Standard Model: Cosmology

Károly Seller

ELFT Particle Physics Summer School, 29th of May 2024.

The Standard Models

Particle physics

- Quantum Field Theory (QFT)
- $\mathbf{G_{SM}} = SU(3)_c \times SU(2)_L \times U(1)_Y$
- Particle content:
  - Quarks
  - Charged leptons
  - Neutrinos
  - Higgs boson
  - Gauge bosons

Cosmology

- **ΛCDM**: FLRW + SM + BSM
- General relativity (background)
- QFT (particle processes)

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Cosmology

- **ΛCDM**: FLRW + SM + BSM
- General relativity (background)
- QFT (particle processes)
- Energy content of Universe (Ω_i):
  - Relativistic matter ($\gamma + \nu$)
  - Non-relativistic matter (Baryonic matter + DM)
  - Dark energy (~~vacuum,~~ ???)

What do the numbers mean?

- **Framework:** fundamental constants (h, c, ...)
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  - Set (almost) all of them to 1 → natural units

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Need more planets close to the Sun **to explain** the orbit of Mercury!	**vs**	**Need more** types of matter **to explain** the evolution of the Universe!

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1. Cosmic Microwave Background
[*Planck Collab.* 2021.]

- From era of recombination
- Power spectrum of fluctuations
- 6 parameter fit (flat ΛCDM)
- Many more derived parameters

Λ, Ω_c, Ω_m, N_{eff}, Σm_ν, …

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- - - *Planck* 2018 6-parameter fit to flat ΛCDM cosmology - - -		
baryon density of the Universe	$\Omega_b = \rho_b/\rho_{crit}$	$^{\ddagger}0.02237(15)\,h^{-2} = {}^{\dagger}0.0493(6)$
cold dark matter density of the Universe	$\Omega_c = \rho_c/\rho_{crit}$	$^{\ddagger}0.1200(12)\,h^{-2} = {}^{\dagger}0.265(7)$
100 × approximation to r_*/D_A	$100 \times \theta_{MC}$	$^{\ddagger}1.04092(31)$
reionization optical depth	τ	$^{\ddagger}0.054(7)$
ln(power prim. curv. pert.) ($k_0 = 0.05\,\mathrm{Mpc}^{-1}$)	$\ln(10^{10}\Delta^2_{\mathcal{R}})$	$^{\ddagger}3.044(14)$
scalar spectral index	n_s	$^{\ddagger}0.965(4)$
pressureless matter parameter	$\Omega_m = \Omega_c + \Omega_b$	$^{\dagger}0.315(7)$
dark energy density parameter	Ω_Λ	$^{\dagger}0.685(7)$
energy density of dark energy	ρ_Λ	$^{\dagger}5.83(16) \times 10^{-30}\,\mathrm{g\,cm^{-3}}$
cosmological constant	Λ	$^{\dagger}1.088(30) \times 10^{-56}\,\mathrm{cm^{-2}}$
fluctuation amplitude at $8\,h^{-1}$ Mpc scale	σ_8	$^{\dagger}0.811(6)$

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2. Big Bang Nucleosynthesis
[E. Aver *et al.* 2020.]

- Abundances of light elements
- SM + FLRW = SBBN
  - very successful (Lithium?)
  - Experiment + Simulations

Y_p, η, N_{eff} ...

Hubble tension

Cosmological measurements (CMB) vs Local Universe Measurements

$H_0 = 67.66 \pm 0.42$ km s^{-1} Mpc^{-1}

$H_0 = 73.04 \pm 1.04$ km s^{-1} Mpc^{-1}

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Cosmic Microwave Background

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"Assuming base-ΛCDM cosmology, the inferred (model-dependent) late-Universe parameters are: ..."

"These results are highly model dependent and this needs to be borne in mind when comparing with other measurements..."

Local Universe (SH0ES)

[A. G. Riess *et al.* 2022.]

- Hubble Space Telescope
- 40+2 Type Ia SNe ($z \leq 0.01$)
- Cepheid variables
- Three-step distance ladder
- Determine: redshift + distance

Non-constant dark energy ($P_{\mathrm{de}} = w_{\mathrm{de}}\varepsilon_{\mathrm{de}}$)

Cosmic Microwave Background vs Dark Energy Spectroscopic Instrument (DESI)

$$w_{\mathrm{de}} = -1.028(31)$$
$$w_{\Lambda} = -1$$

$$w_{\mathrm{de}} = -0.997 \pm 0.025$$
$$w_{\mathrm{de}}(a) = (-0.827 \pm 0.063) - (0.75 \pm 0.29)(1 - a)$$

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$a \leq a_0 = 1$
scale factor

$w_0 > -1$
value today

$w_{\mathrm{de}}(a) \leq w_0$
value in past

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Cosmic Microwave Background

[*Planck Collab.* 2021.]

- Assumes so-called w CDM model
  - $w =$ EoS of dark energy
  - In ΛCDM, w_{Λ} = -1
  - Allow $w \neq -1$
  - Keep $w =$ const.
  - CMB: no info on changing w [E.V. Linder, 2007.]

DESI 2024.

[*DESI Collab.* 2024.]

- Based on BAO observations
- Redshift range: $0.1 < z < 4.2$
- 6 million extragalactic objects
- Combination with other measurements (CMB, BBN, SNe...)

Some other experiments to note

- Gravitational waves – peeking behind the curtain
  - LIGO (VIRGO): ground-based, high frequency (1-100 Hz)
  - LISA: space-based, intermediate frequency (10^{-5}-1 Hz)
    - Phase transition (first order) signatures expected here
    - Topological defects (domain walls, cosmic strings)…
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- **Ultra-high energy cosmic rays** – Auger Observatory, IceCube, TA…
  - Open questions: source and composition?

Cosmology

Back to theory...

- Focus on two of the most well-established unexplained observations

Dark matter

- CMB fit: $\Omega_c = 0.265(7)$
- Large scale structure
- Gravitational lensing
- Galaxy dynamics (rotation, collisions)

Baryon asymmetry

- BBN fit: $\eta = 6.14(19)\times10^{-10}$
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- Lack of anti-matter structures
- AMS–02 experiment

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Dark matter – What is it?

- Extending the SM with a massive and weakly interacting particle

Feels gravity

Avoided detection

Maybe not?

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- History – **Weakly Interacting Massive Particle** (WIMP)
  - WIMP "miracle" – EW scale mass with EW cross section size
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- Notable examples:
  - Heavy Neutral Leptons (HNL) or right-handed (sterile) neutrinos (RHN)
  - Axions and axion-like particles (ALPs)
  - Additional scalar fields (e.g. 2HDM) or massive gauge fields (e.g. dark photons)

Dark matter – Setting the scene

- Universe is filled with a hot rapidly interacting plasma
  - SM particles in equilibrium (kinetic + chemical ($\mu \approx 0$))
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Connection between SM and the "dark sector"

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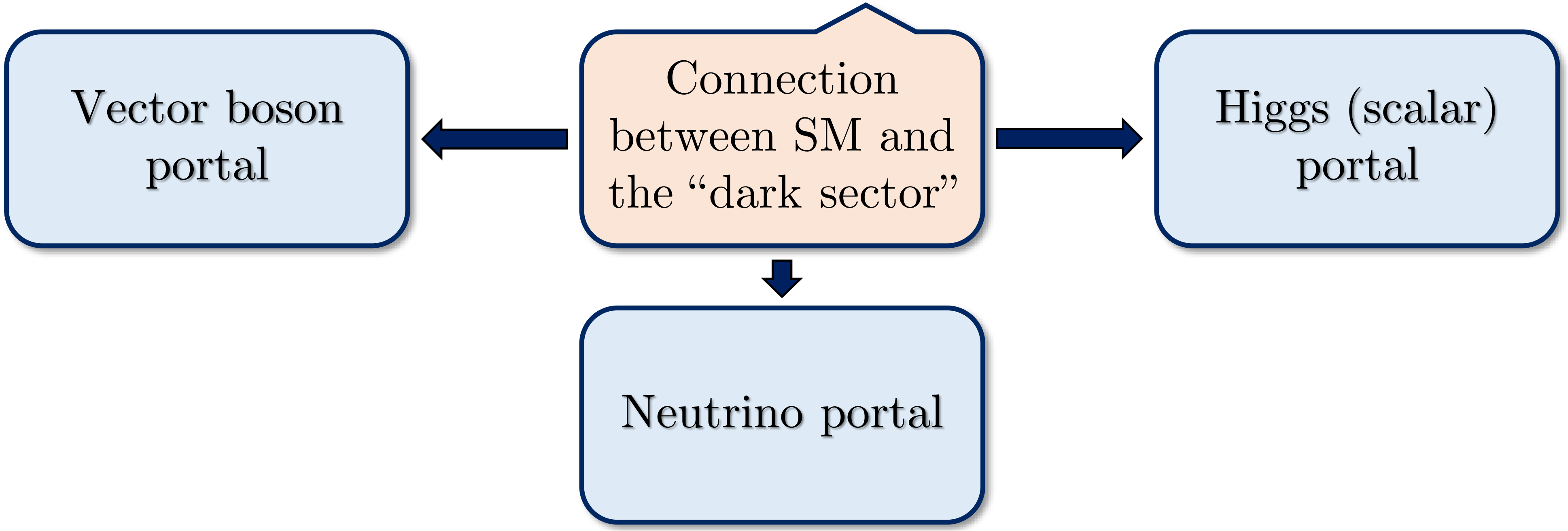

Dark matter – Thermal interaction rates

- Particle processes: heavy particle decays and scatterings/annihilations
  - Viewed from: cosmic rest frame (GR)
  - Particle energies have thermal distributions: FD or BE

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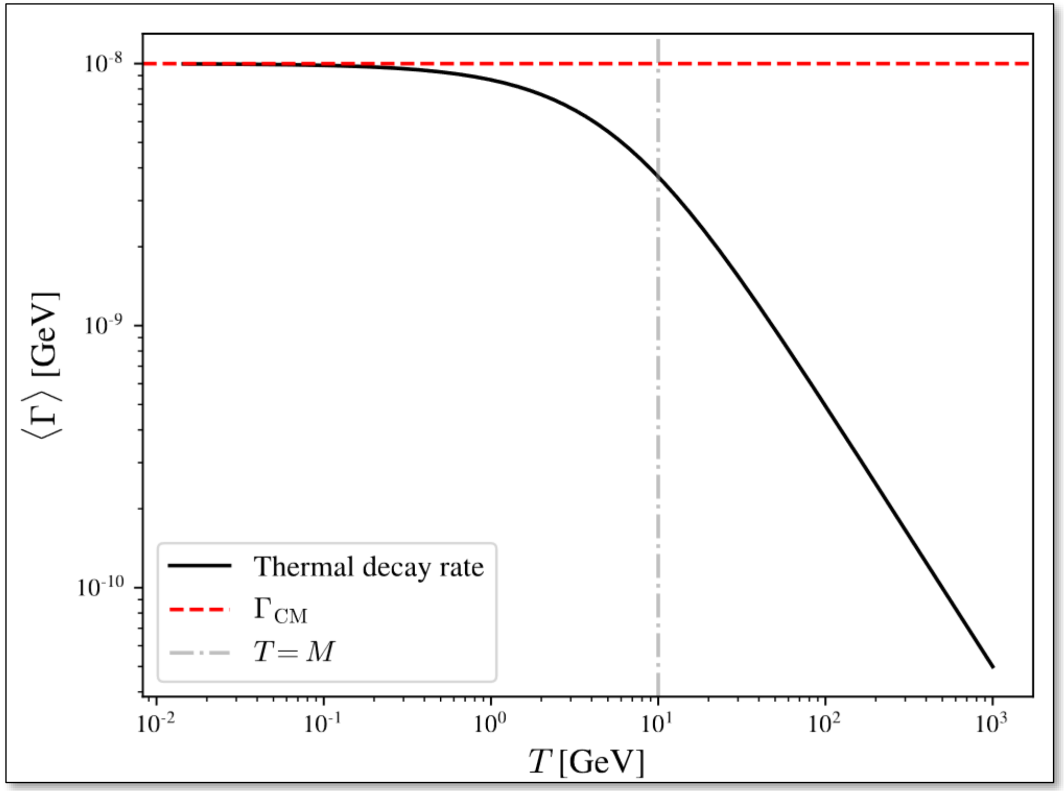

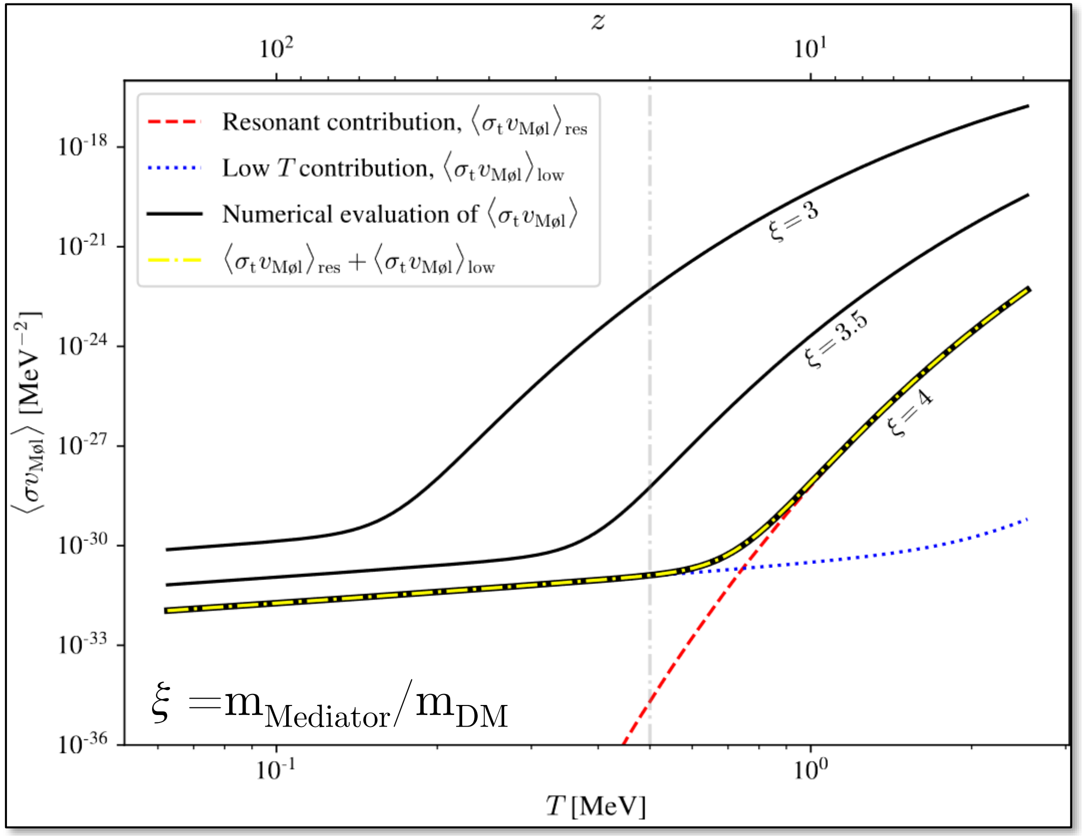

Dark matter – Production mechanisms

- **Dark matter**: has to decouple from the plasma early in the Universe

Stop interacting with SM and BSM

Before BBN, roughly at $T = 0.1M$

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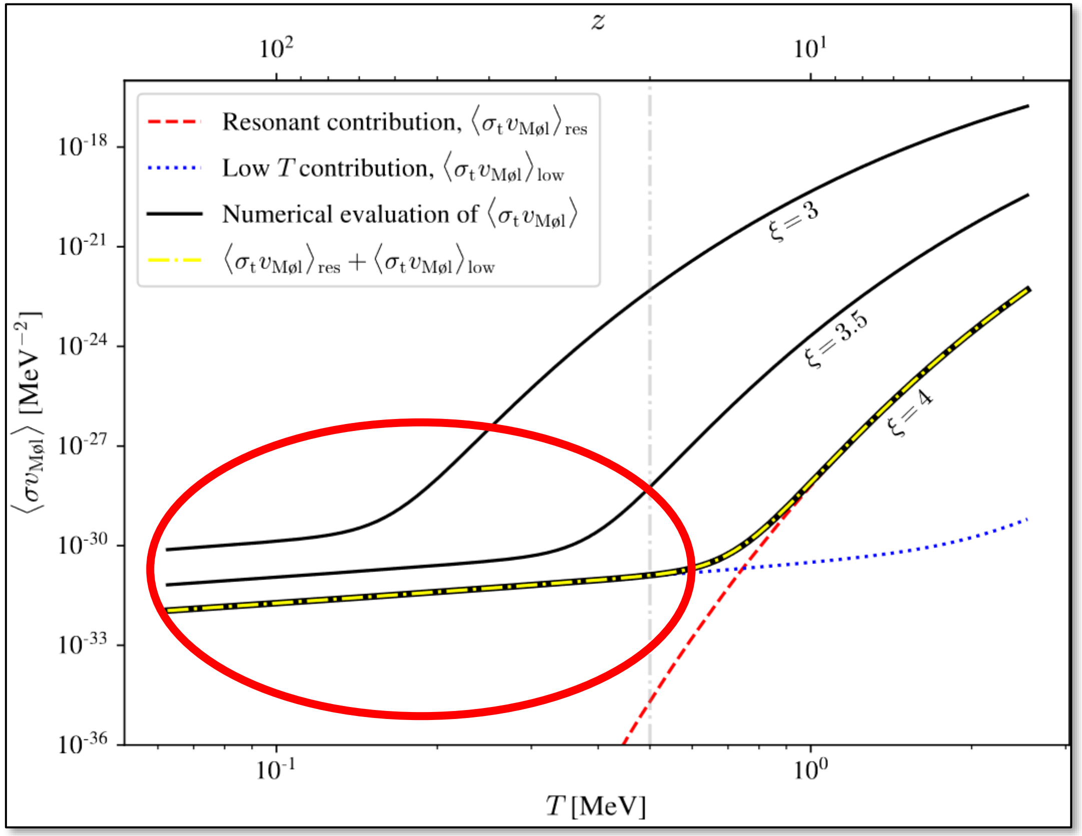

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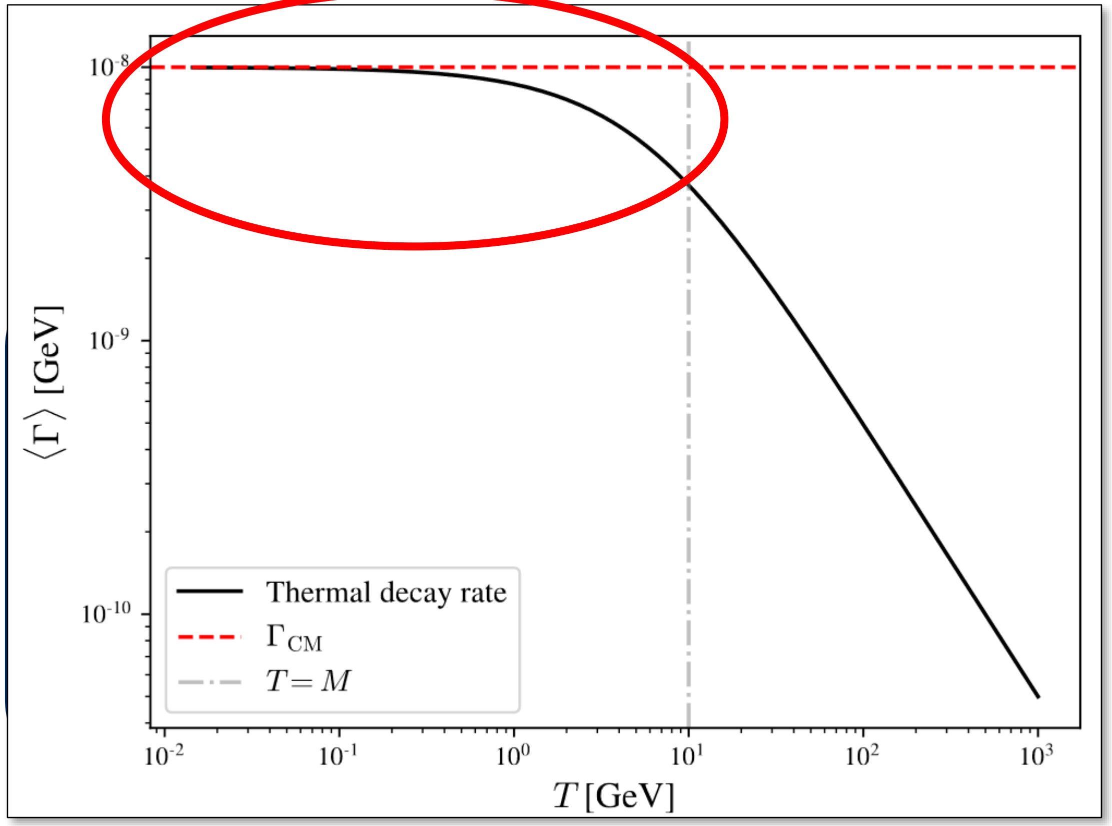

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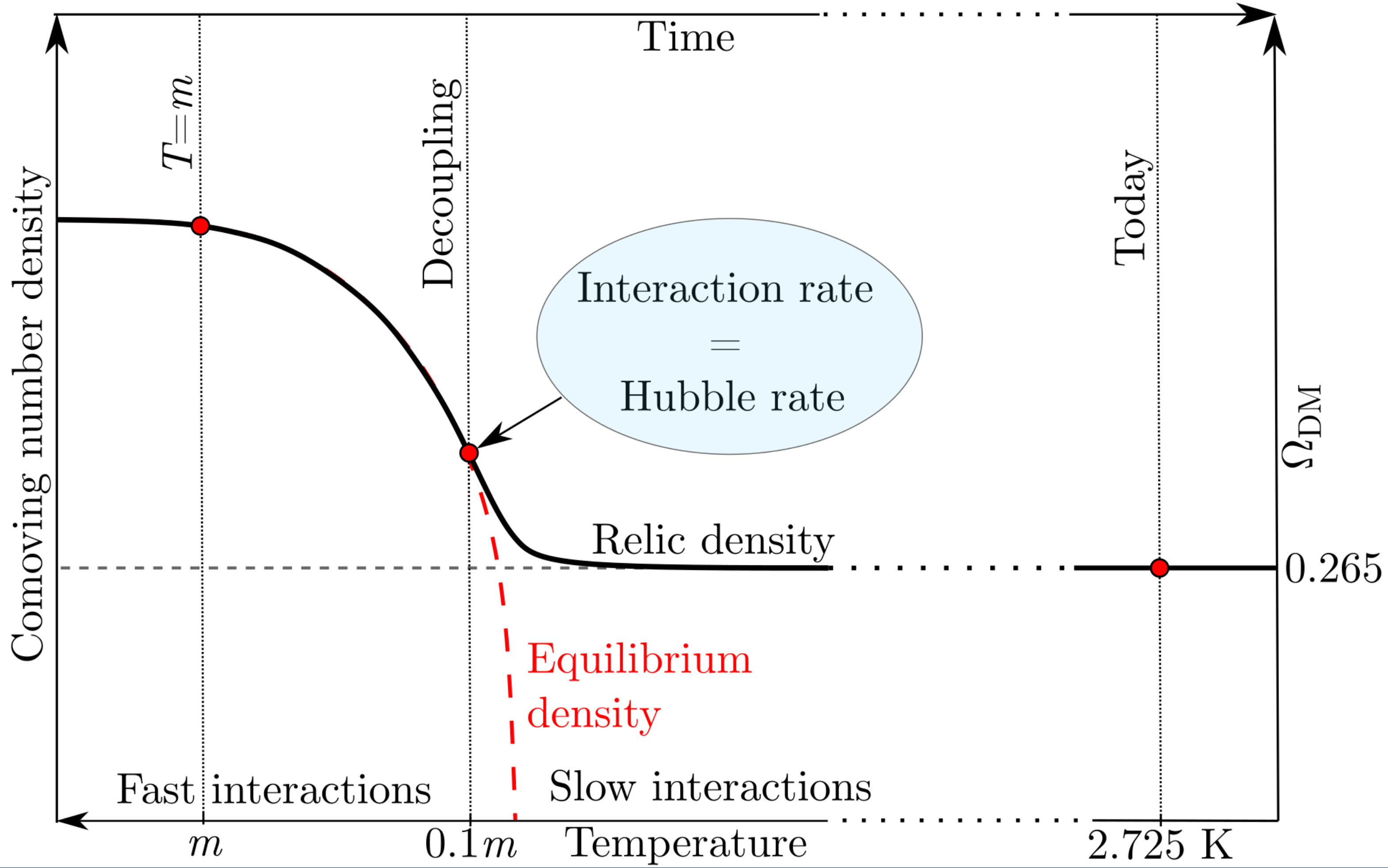
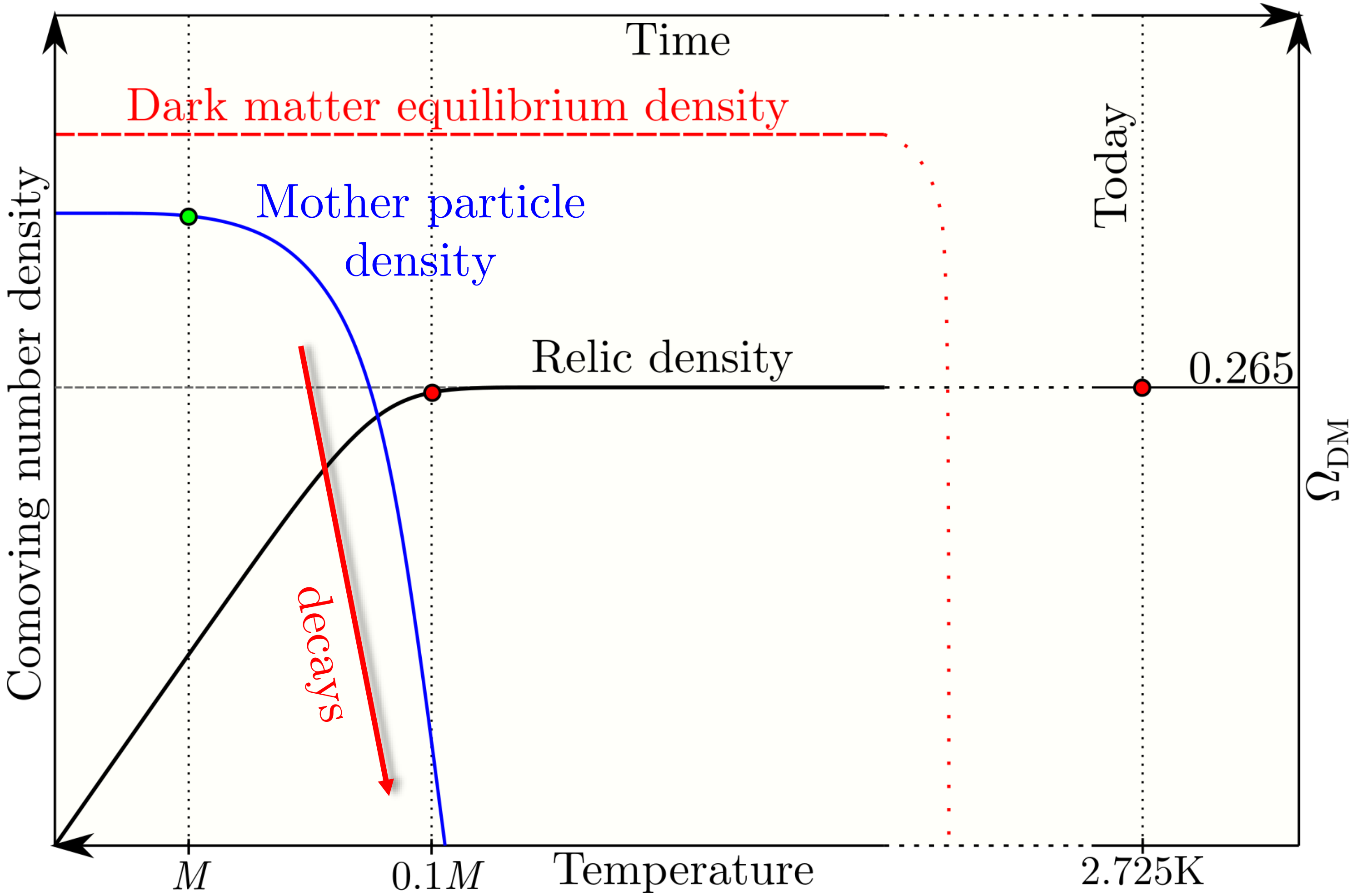


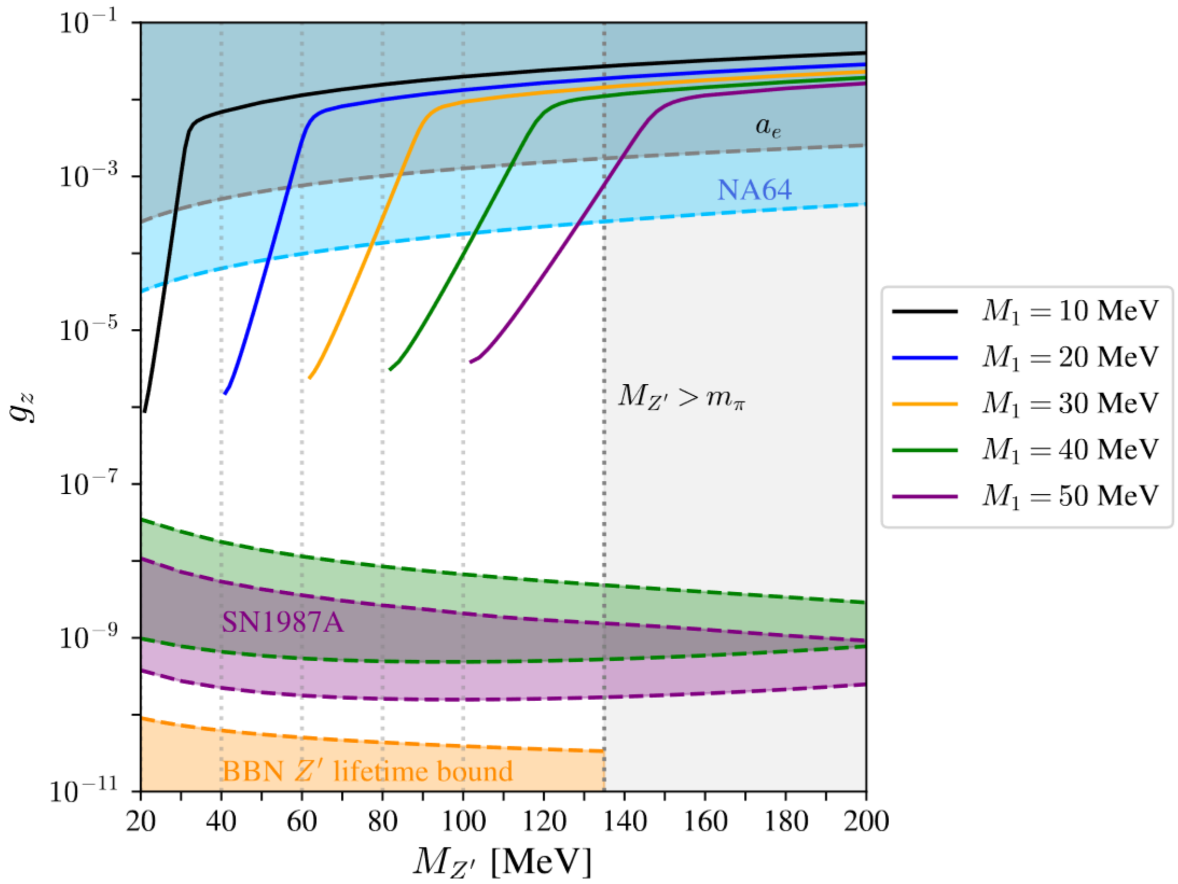
Dark matter – Freeze-in scenario



Dark matter example: SWSM + Freeze-out scenario

SWSM = G_{SM}×U(1)$_z$ [Z. Trócsányi, 2020.]

- Dark matter candidate: lightest RHN
- Dark matter portal: Z' boson portal
- Model parameters:
  - gauge coupling: g_z
  - Z' mass: $M_{Z'}$
  - RHN mass: M_1



Dark matter example: SWSM + Freeze-out scenario

Supernova constraints (SN1987A)

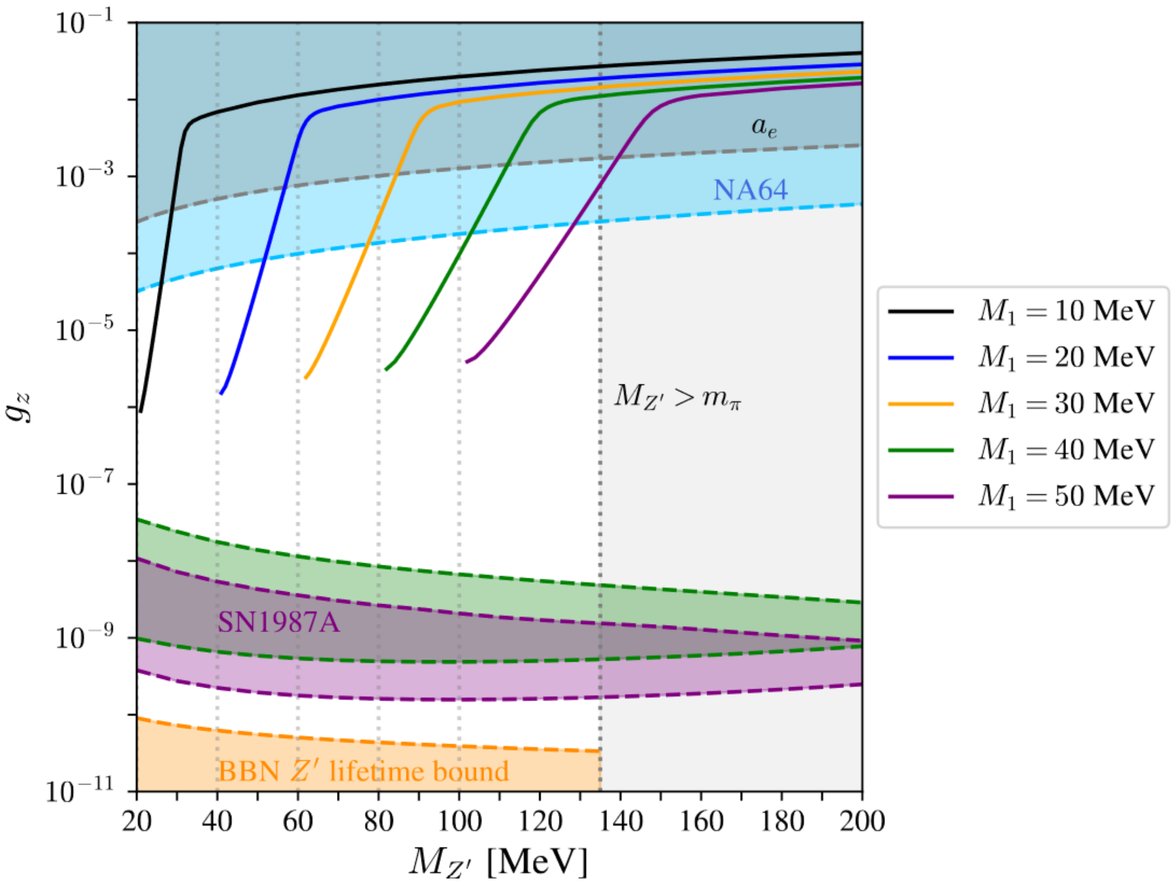
- Flux measured + simulations for SN
- BSM should not change cooling significantly

Big Bang Nucleosynthesis (BBN)

- Pion-enhanced p - n conversion
- Changing energetics around $T \approx 0.1$ MeV
- Changing degrees of freedom ($n_{eff} \approx 3$)

Particle physics experiments

- U(1) contribution to $g-2$
- NA64 experiment (dark photon)
- FASER, BELLE II, LDMX...



Matter-antimatter asymmetry – Sakharov conditions

- Baryon asymmetry generated and not pre-inflation relic

Through some B-violating processes

Inflation: Exponential dilution

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- Sakharov conditions: requirements for successful generation of asymmetry [A.D. Sakharov, 1967]

    1. Baryon number violation
    2. C and CP violation
    3. Deviation from equilibrium

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    1. Baryon number violation

        - Without it an initially symmetric Universe stays symmetric
        - SM conserves $B - L$ but violates $B + L$ through the sphaleron process

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    1. Baryon number violation → sphaleron process
    2. C and CP violation
        - If C or CP were conserved: reaction rates for q and $\bar{q}$ are equal
        - SM has CP violation in the CKM matrix

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1. Baryon number violation → sphaleron process
2. C and CP violation → CP violation in the CKM matrix
3. Deviation from equilibrium
   - In equilibrium (most symmetric state) asymmetry is washed out
   - Phase transitions can provide deviation (phase separation, bubbles)

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Electroweak baryogenesis possible?

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1. Baryon number violation → sphaleron process — This is OK
2. ~~C and CP violation → CP violation in the CKM matrix~~ — Not enough
3. ~~Deviation from equilibrium → Phase transitions~~ — Crossover

~~Electroweak baryogenesis possible?~~

Matter-antimatter asymmetry – Saving baryogenesis

- Fix conditions 2. and 3. → EW Baryogenesis still viable

2. C and CP violation:
   - Can use C and CP violating effective operators
     - Leads to EDMs → experimental constraints
     - Complicated non-equilibrium phenomena [Y. Li *et al.* 2024.]

3. Deviation from equilibrium:
   - Phase transition can be made first order with scalar extensions
     - With only one new scalar: already at tree level [J. R. Espinosa *et al.* 2012.]

Matter-antimatter asymmetry – Sakharov conditions

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1. Baryon number violation → sphaleron process — This is OK
2. C and CP violation → Effective operators — This is OK
3. Deviation from equilibrium → Extended scalar sector — This is OK

Electroweak baryogenesis possible? → Maybe, yes?

Matter-antimatter asymmetry – Leptogenesis

- **Idea:** Generate ΔL instead of ΔB → Use sphaleron processes to convert

> Through lepton number violating decays of HNLs

> Sphalerons violate $\Delta B + \Delta L$ but they conserve $\Delta B - \Delta L$

Matter-antimatter asymmetry – Leptogenesis

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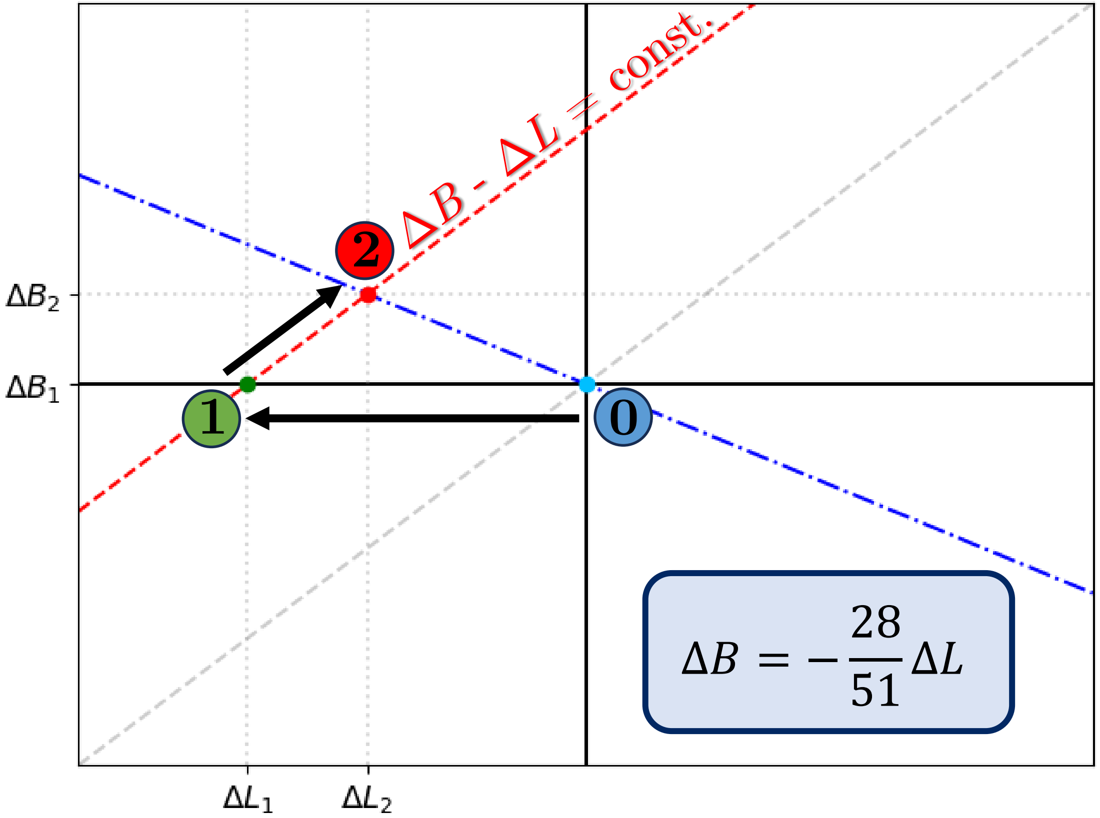


0 Symmetric state

HNL decays CP $\neq 0$

1 $\Delta L \neq 0,\ \Delta B = 0$

Sphaleron conversion

2 $\Delta L \neq 0,\ \Delta B \neq 0$

[J.A. Harvey and M.S. Turner, 1990.]

Matter-antimatter asymmetry – Sakharov conditions again

- Baryon asymmetry via leptogenesis
- Sakharov conditions:

    1. Baryon number violation → sphaleron process — This is OK
    2. C and CP violation → CP violation in HNL decays — This is OK
    3. Deviation from equilibrium → HNL production and decay — This is OK

SM+RHNs leptogenesis

Matter-antimatter asymmetry – Leptogenesis types

1. **Thermal leptogenesis** [M. Fukugita and T. Yanagida, 1986.] [W. Buchmüller *et al*, 2004.]
    - Standard leptogenesis with very massive HNLs ($M_{\text{HNL}} > 10^9$ GeV)

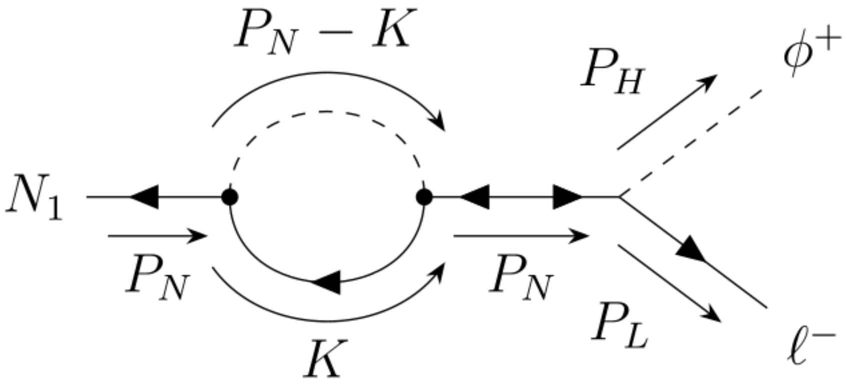
2. **Flavored leptogenesis** [A. Pilaftsis and T.E.J. Underwood, 2005.]
    - Individual lepton number converted to baryon number
    - Necessarily lepton flavor non-universal (constraints)

3. **Resonant leptogenesis** [A. Pilaftsis, 1997.]
    - Self energy diagram in the HNL decay is resonant when $M_1 \approx M_2$
    - CP violation is proportional to imaginary part of decay diagram
    - CP violation can be arbitrarily large with HNL mass fine tuning

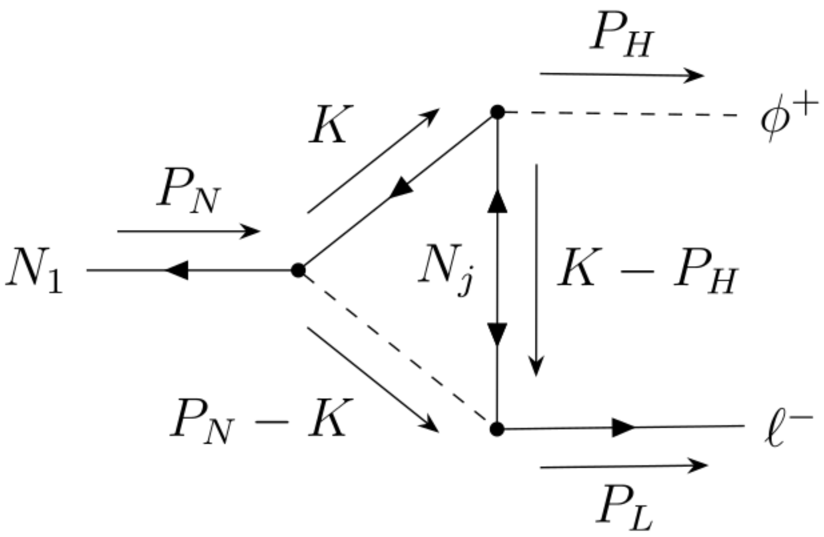
Matter-antimatter asymmetry – CP violation

CP violation proportional to the imaginary part of HNL decay diagrams:

Finite temperature cutting rules!



Resonant if $M_1 \approx M_2$



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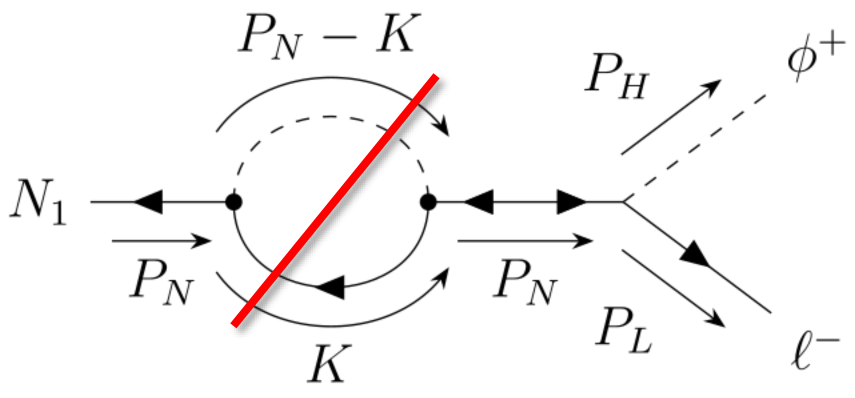

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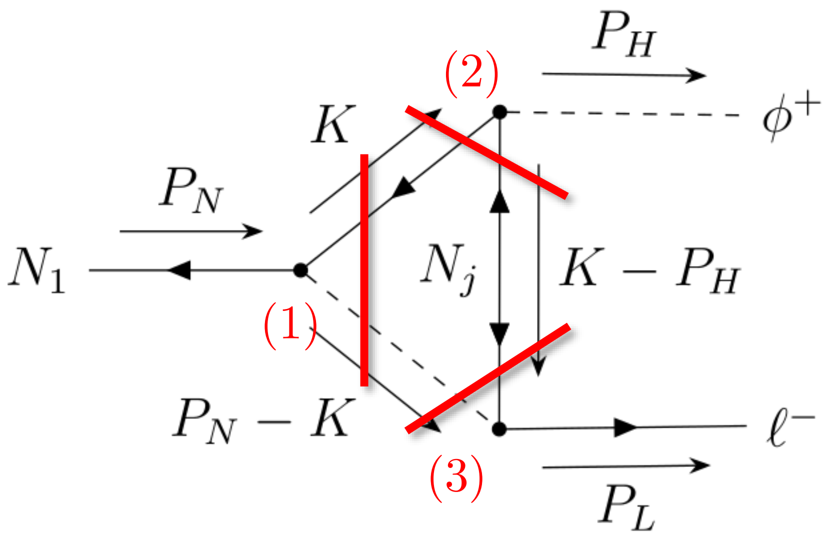
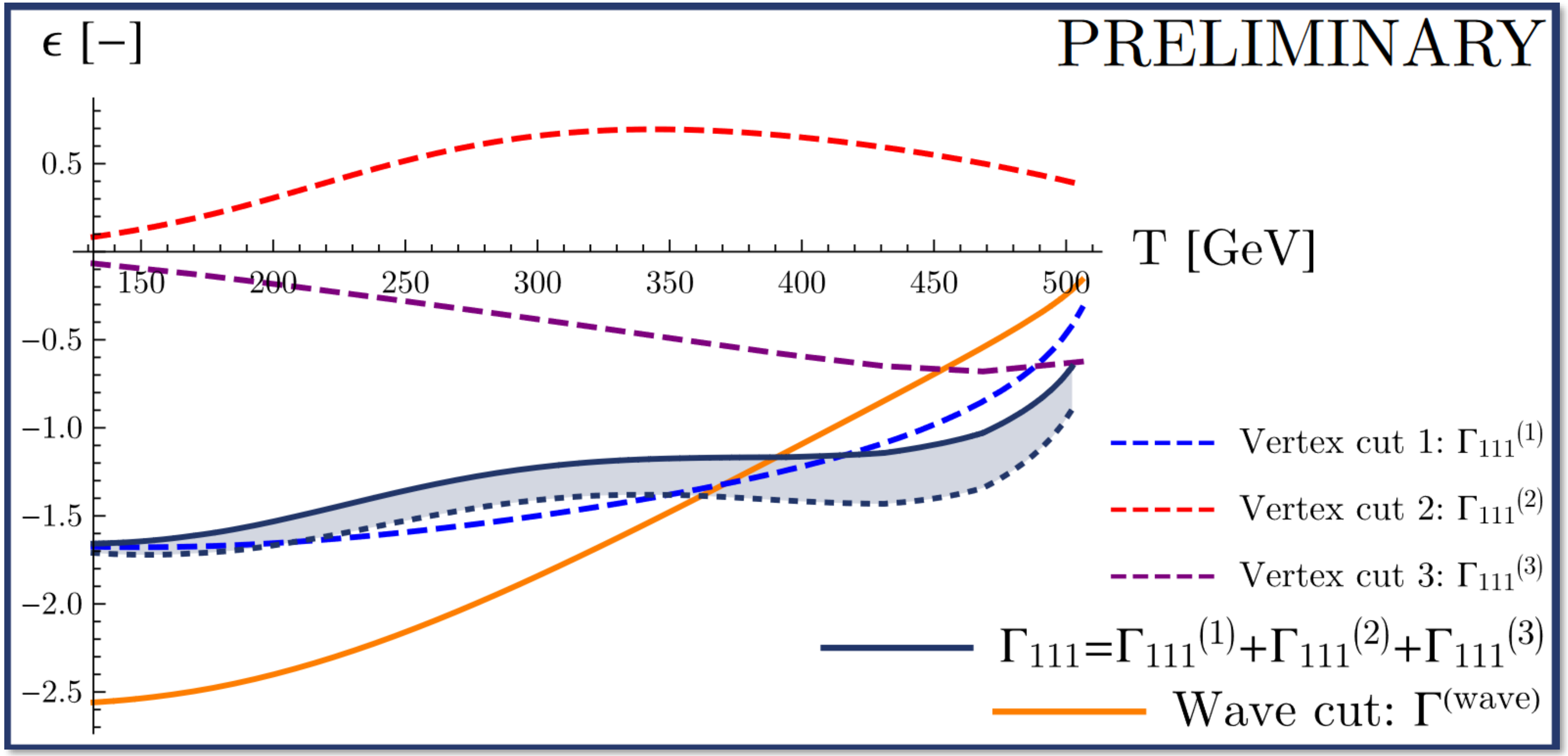


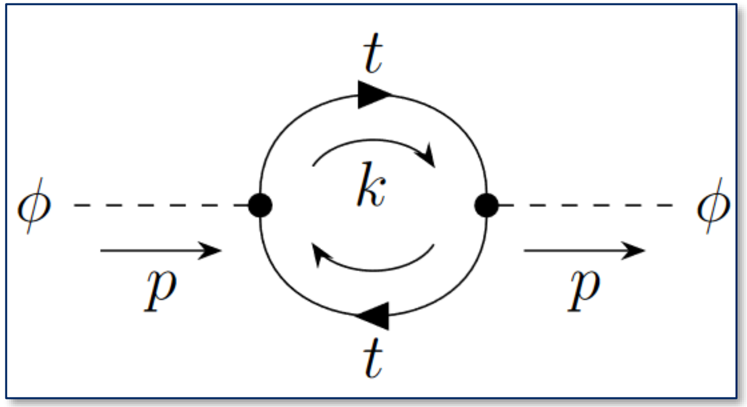
Matter-antimatter asymmetry – CP violation

CP violation proportional to the imaginary part of HNL decay diagrams



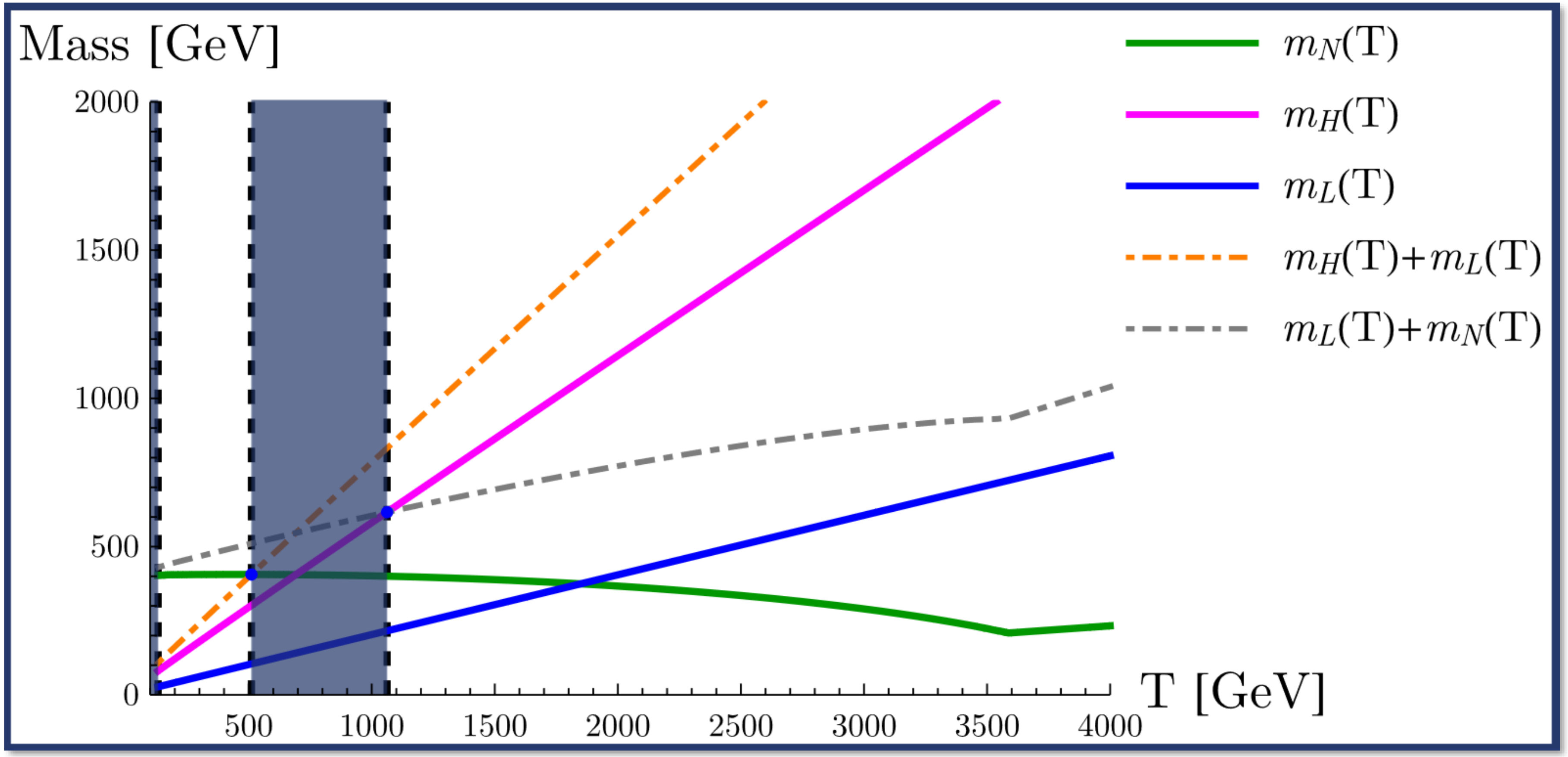
Matter-antimatter asymmetry – Thermal masses

- Universe filled with hot and rapidly interacting plasma
- Particles traversing the plasma get screened due to interactions
  - Particles gain an effective “thermal mass”
- Thermal mass proportional to coupling and temperature $M_{\mathrm{T}} \propto gT$
- Calculated from self energy diagrams in finite T field theory, e.g.:



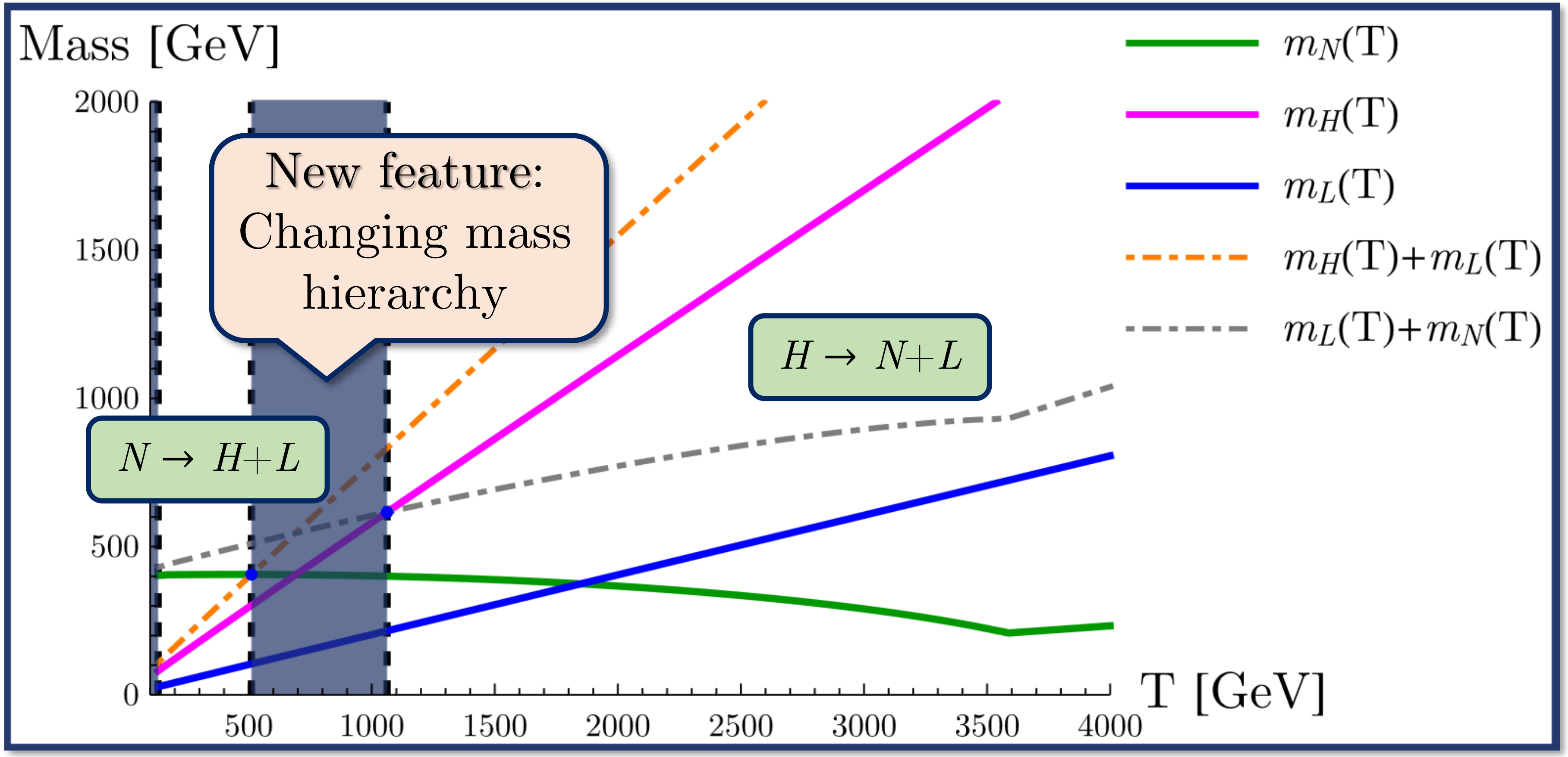
Matter-antimatter asymmetry – Thermal masses

Thermal mass proportional to coupling and temperature $M_{\mathrm{T}} \propto gT$



Matter-antimatter asymmetry – Thermal masses

Thermal mass proportional to coupling and temperature $M_{\mathrm{T}} \sim gT$



Matter-antimatter asymmetry – Boltzmann equations

Calculate the particle abundance in the expanding Universe in the presence of number changing particle interactions

1. HNLs out of equilibrium (Sakharov III.)
2. ΔL generated by out of equilibrium decays of HNLs

1. ∂_t(HNL abundance) = (HNL producing reactions)
2. ∂_t(ΔL abundance) = ε (HNL decay rate) – (ΔL washout by scatterings)

Matter-antimatter asymmetry – Boltzmann equations

Calculate the particle abundance in the expanding Universe in the presence of number changing particle interactions

1. HNLs out of equilibrium (Sakharov III.)
2. ΔL generated by out of equilibrium decays of HNLs

$$sHz\frac{\mathrm{d}\mathcal{Y}_{\Delta \mathrm{L}}}{\mathrm{d}z} \simeq \gamma_{\mathrm{D}}\left[\epsilon\left(\frac{\mathcal{Y}_N}{\mathcal{Y}_N^{\mathrm{eq}}}-1\right)-\frac{\mathcal{Y}_{\Delta \mathrm{L}}}{\mathcal{Y}_\ell^{\mathrm{eq}}}\right]-\frac{\mathcal{Y}_{\Delta \mathrm{L}}}{\mathcal{Y}_\ell^{\mathrm{eq}}}\left[2\gamma_{N,s}^{\mathrm{sub.}}+4\gamma_{N,t}+\gamma_{\phi,s}\frac{\mathcal{Y}_N}{\mathcal{Y}_N^{\mathrm{eq}}}+2\gamma_{\phi,t}\right]$$

washout

$$sHz\frac{\mathrm{d}\mathcal{Y}_N}{\mathrm{d}z} \simeq \left(1-\frac{\mathcal{Y}_N}{\mathcal{Y}_N^{\mathrm{eq}}}\right)\left(\gamma_\chi+\gamma_{\mathrm{D}}+2\gamma_{\phi,s}+4\gamma_{\phi,t}\right)$$

Summary

- Cosmology necessarily involves BSM physics
- Tensions between astrophysical and cosmological measurements point towards not well-understood underlying theory?
- Particle physics sees nothing while cosmology needs vast quantities of unknown matter/energy
- Advancements in experimental techniques allow us to probe the Universe closer and closer to the very beginning
- Dark matter + Leptogenesis both solvable by particle physics
    - Adding RHNs to SM can basically solve everything
- *We know an answer, but did we understand the question?*

Thank you for your attention!

References

[*Planck Collab.* 2021.] – https://inspirehep.net/literature/1682902

[E. Aver *et al.* 2020.] – https://inspirehep.net/literature/1822144

[A. G. Riess *et al.* 2022.] – https://inspirehep.net/literature/1986964

[*DESI Collab.* 2024.] – https://inspirehep.net/literature/2774167

[NANOGrav, 2023.] – https://inspirehep.net/literature/2672619

[FIPs 2022] – https://inspirehep.net/literature/2656339

[Z. Trócsányi, 2020.] – https://inspirehep.net/literature/1711779

[A.D. Sakharov, 1967] – https://inspirehep.net/literature/51345

[Y. Li *et al.* 2024.] – https://inspirehep.net/literature/2782239

[J. R. Espinosa *et al.* 2012.] – https://inspirehep.net/literature/920578

[J.A. Harvey and M.S. Turner, 1990.] – https://inspirehep.net/literature/296759

[M. Fukugita and T. Yanagida, 1986.] – https://inspirehep.net/literature/226949

[W. Buchmüller *et al.* 2004.] – https://inspirehep.net/literature/651434

[A. Pilaftsis and T.E.J. Underwood, 2005.] – https://inspirehep.net/literature/684638

[A. Pilaftsis, 1997.] – https://inspirehep.net/literature/440621