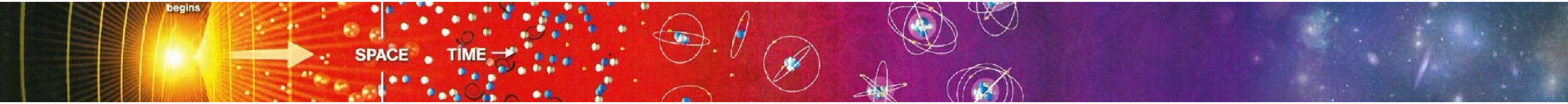
Charting the Landscape of the Early Universe



Julia Harz

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August 6th 2024
PSI Particle Physics Summer School, Lyceum Alpinum Zuoz

Outline

I. The Early Universe in a nutshell

II. From the Cosmos to the lab: Dark Matter and Baryogenesis

III. Gravitational Waves as Window to the Early Universe

I The Early Universe in a Nutshell

credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA), CC BY 4.0

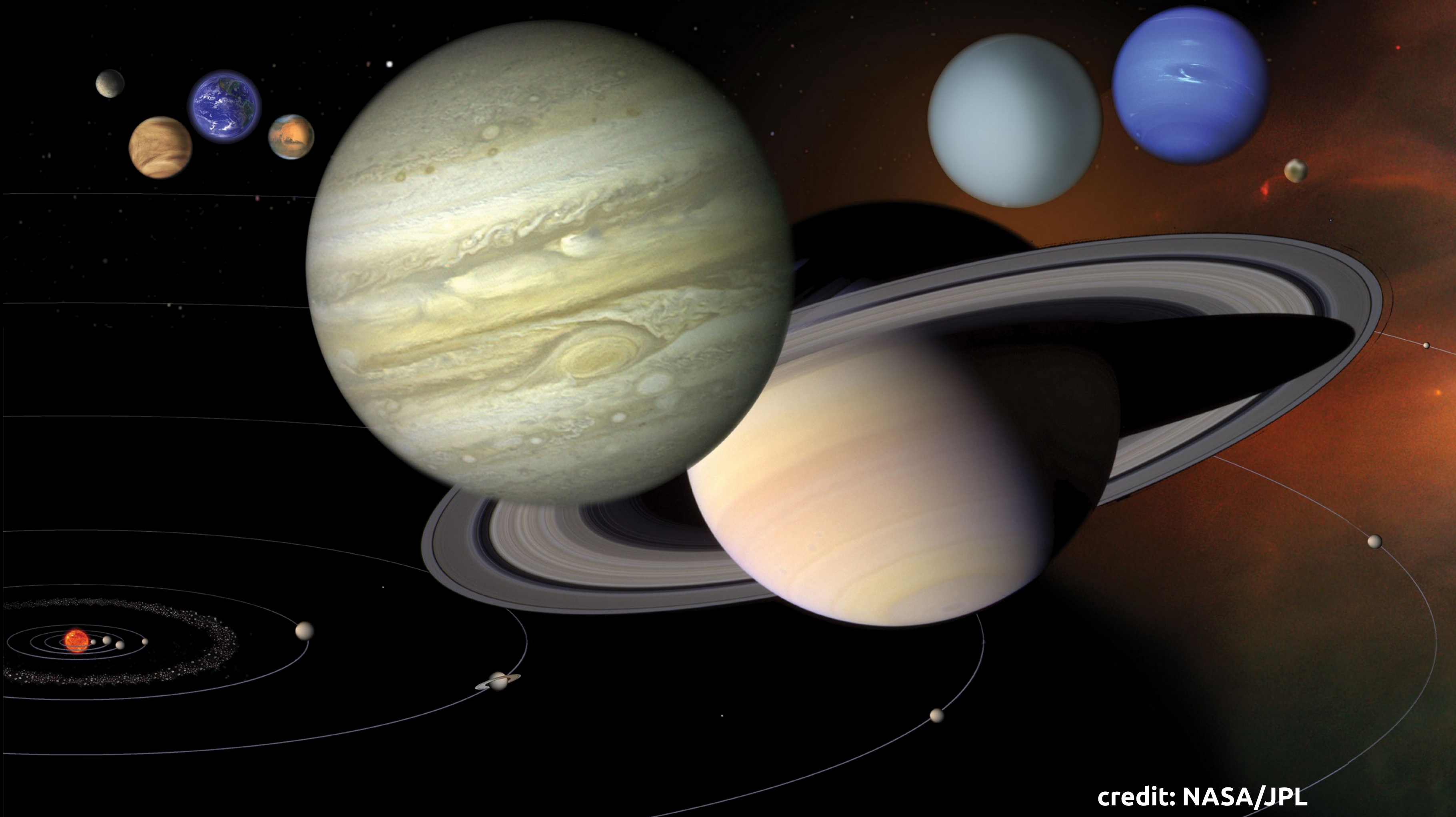
What is our Universe made of?

credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA), CC BY 4.0

Galaxies

credit: NASA, ESA, and B. Holwerda (University of Louisville), CC BY 4.0

Our solar system



credit: NASA/JPL

Our earth

credit: NASA/JPL

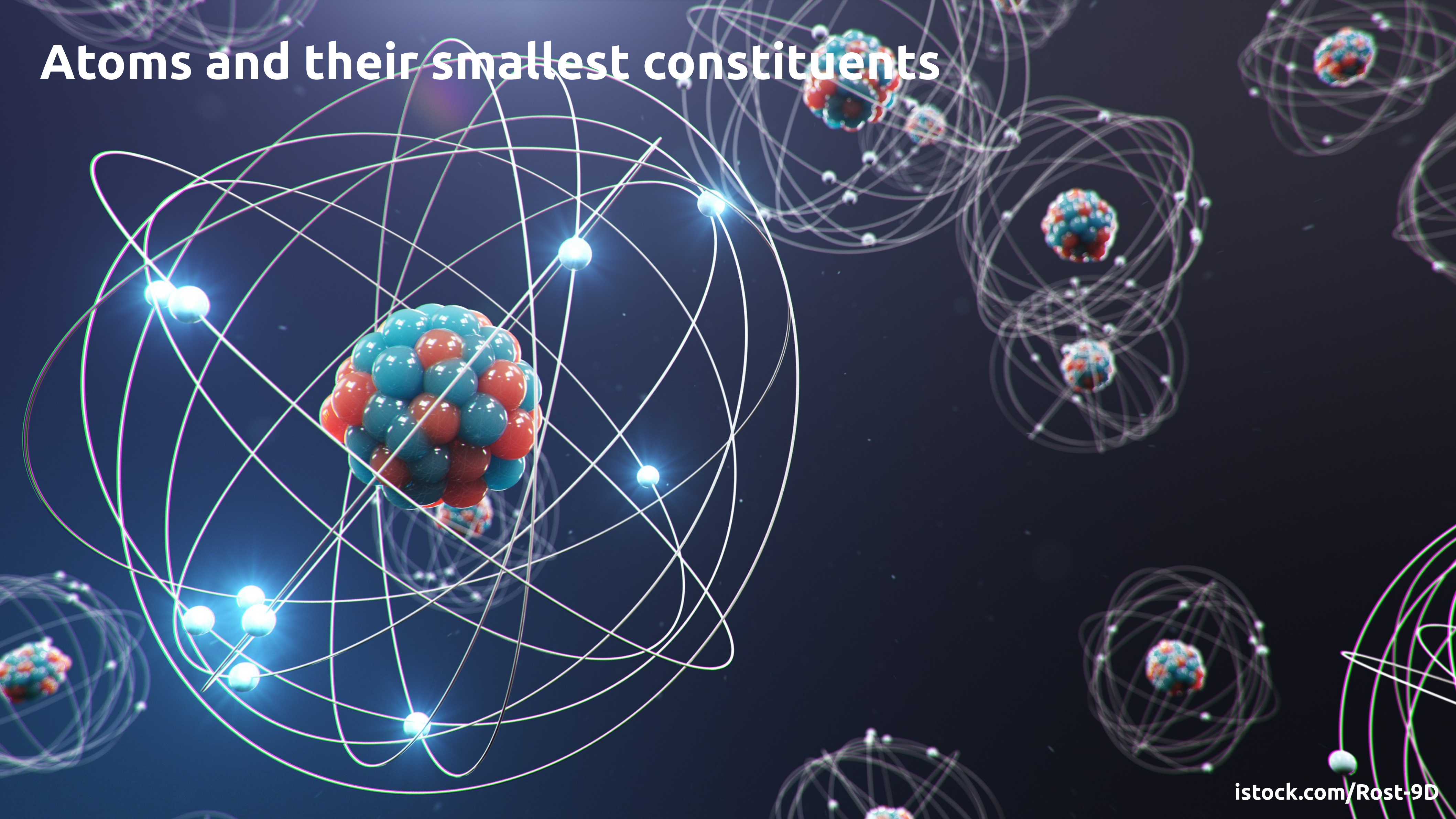
Structure in our vicinity

credit: Rosino, CC-BY-SA-2.0 (Ausschnitt)

Molecules

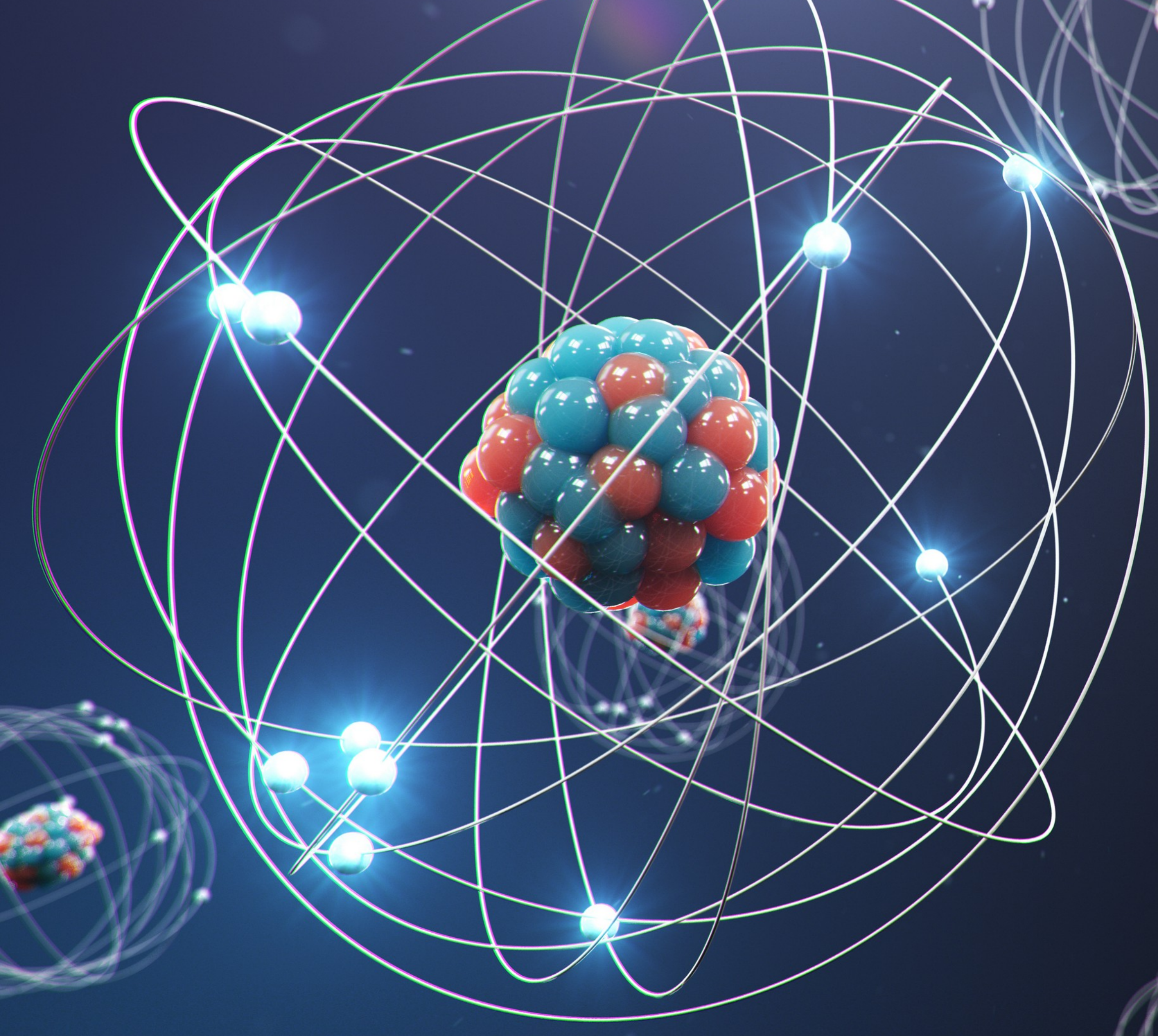
- credit: allispossible.org.uk, CC BY 2.0

Atoms and their smallest constituents



istock.com/Rost-9D

Atoms and their smallest constituents



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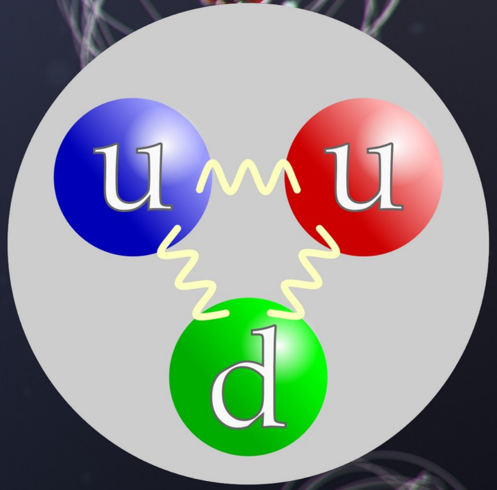
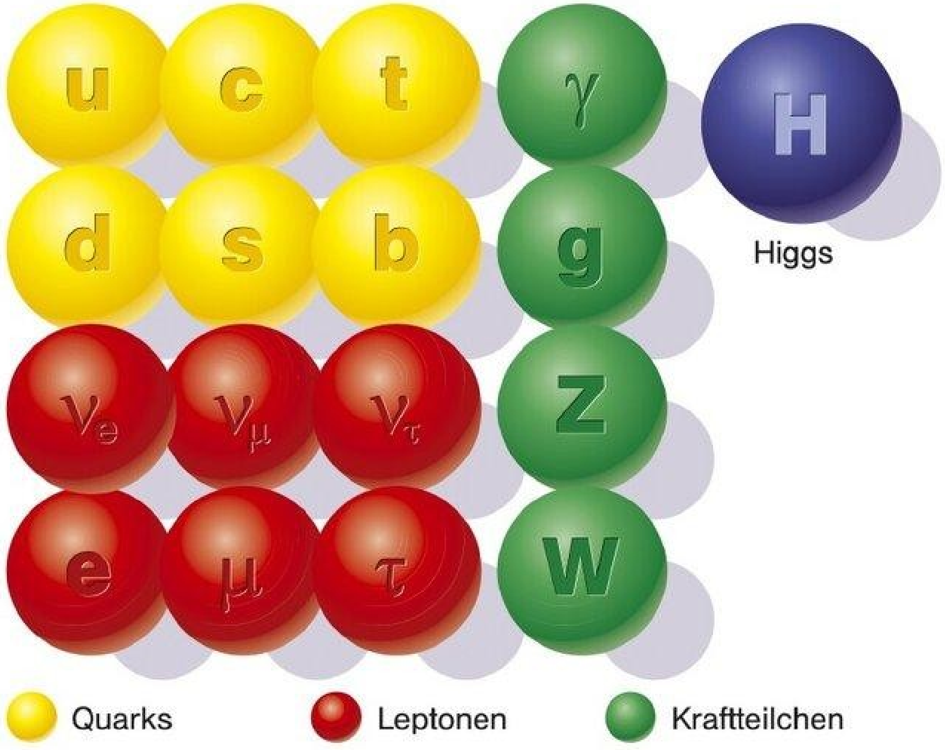


Quelle: Arpad Horvath, CC BY-SA 2.5

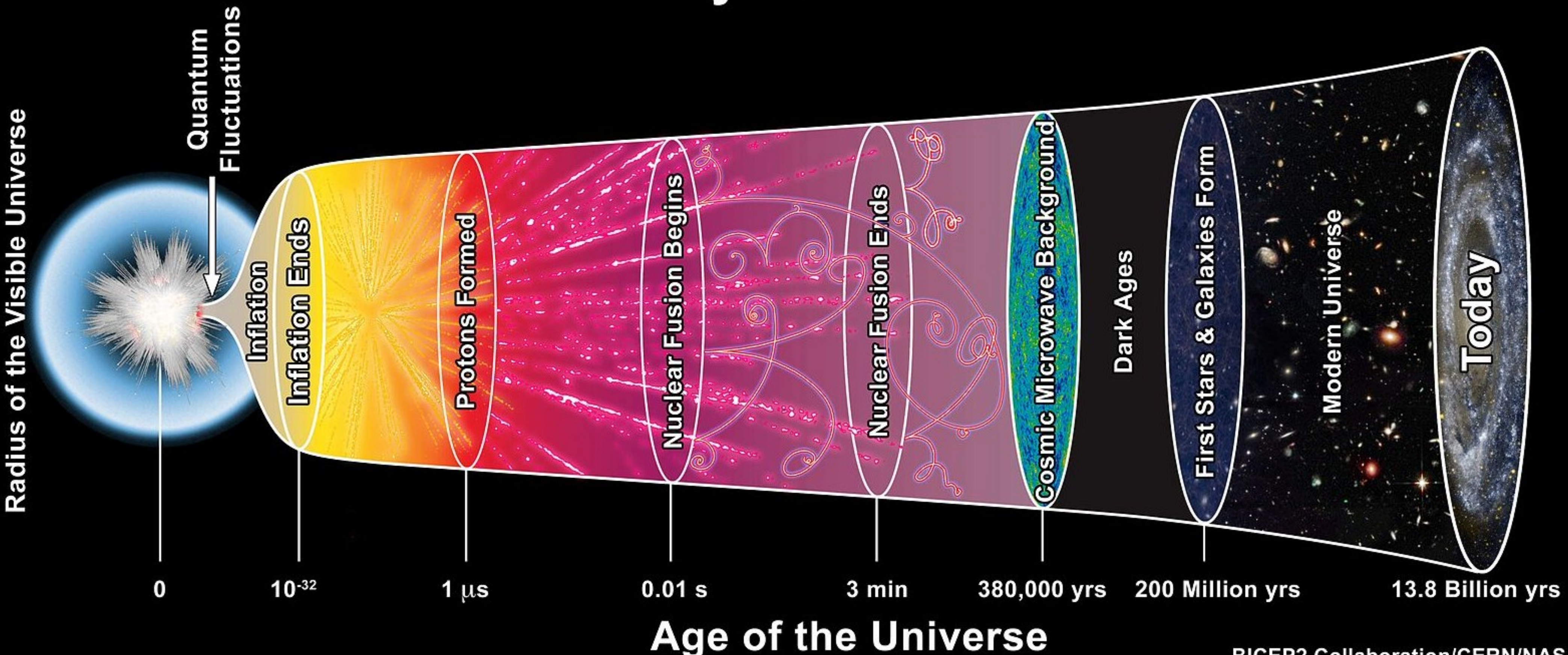
The Standard Model (SM) of particle physics



source: Welt der Physik / DESY

How did this all evolve?

History of the Universe



BICEP2 Collaboration/CERN/NASA

The homogeneous and isotropic Universe

At large scales

- **Homogeneous** (same at every point, translational invariance)
- **Isotropic** (same in all directions, rotational invariance)

Experimental evidence: cosmic microwave background, galaxy distribution

Described by **Friedmann-Robertson-Lemaitre-Walker (FRLW)** metric

$$ds^2 = dt^2 - a^2(t)[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + sin^2\theta d\phi^2)]$$

k= +1 spatially curved (spherical)

k= 0 spatially flat (euclidean)

k= -1 spatially curved (hyperbolic)

Scale factor a(t)

The expanding Universe

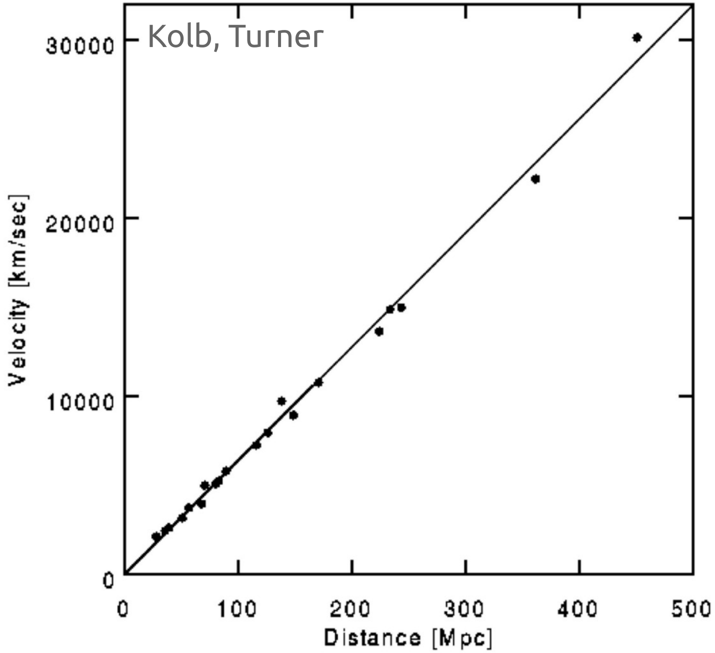
- For k=0, choose normalization (today): **$a(t_0)=a_0=1$**
- **Hubble parameter** as measure of the shrinking / expansion of the Universe

$$H = \frac{\dot{a}}{a}, H_0 \equiv \dot{a}(t_0)$$

- **Physical distances** can be described as

$$R = a(t) \cdot r$$

- **Hubble's law:** $v \simeq H_0 d$



Galaxies are receding away from us with a velocity that is proportional to their distance to us:

→ **Universe is expanding!** $v \propto \dot{a}(t)d$

Matter & Energy Content of the Universe

Dynamics of the scale factor a(t) depends on matter and energy content of the Universe

- Einstein equation: $G_{\mu\nu} = 8\pi G T_{\mu\nu}$
- Perfect fluid (homogeneous and isotropic): $T_{\mu\nu} = (\rho + p) U_\mu U_\nu - p g_{\mu\nu}$

$$U^\mu = (1, 0, 0, 0)$$

$$g_{\mu\nu} = (1, -a^2, -a^2, -a^2)$$

$$T_{\mu\nu} = \begin{pmatrix} \rho & 0 \\ 0 & -p g_{ij} \end{pmatrix}$$

Friedmann equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3}\rho - \frac{k}{a^2}$$

expansion

$$H^2 + \dot{H} = \frac{\ddot{a}}{a} = -\frac{1}{6}(\rho + 3p)$$

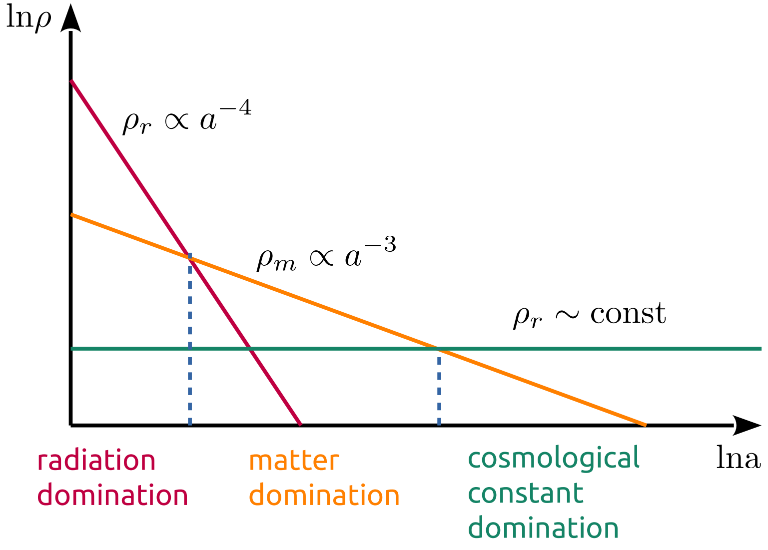
acceleration

Evolution of the Matter & Energy Content

Evolution in terms of equation of state parameter $\omega = \frac{p}{\rho}$

$$\frac{d\rho}{dt} + 3H(\rho + p) = 0$$

$$\rho(a) \propto a(t)^{-3(1+\omega)}$$



Energy content of the early Universe

radiation	$\rho_r \propto a^{-4}$	$p_r = 1/3\rho_r$	$\omega_r = \frac{1}{3}$
matter	$\rho_m \propto a^{-3}$	$p_m = 0$	$\omega_m = 0$
cosmological constant	$\rho_\Lambda \sim \mathrm{const}$	$p_\Lambda = -\rho_\Lambda$	$\omega_\Lambda = -1$

Matter & Energy Content of today's Universe

Connecting to observable parameters

$$H^2 = \frac{1}{3}\rho - \frac{k}{a^2}$$

$$\frac{\rho^{\rm tot}}{3H^2} - 1 = \frac{k}{a^2 H^2}$$

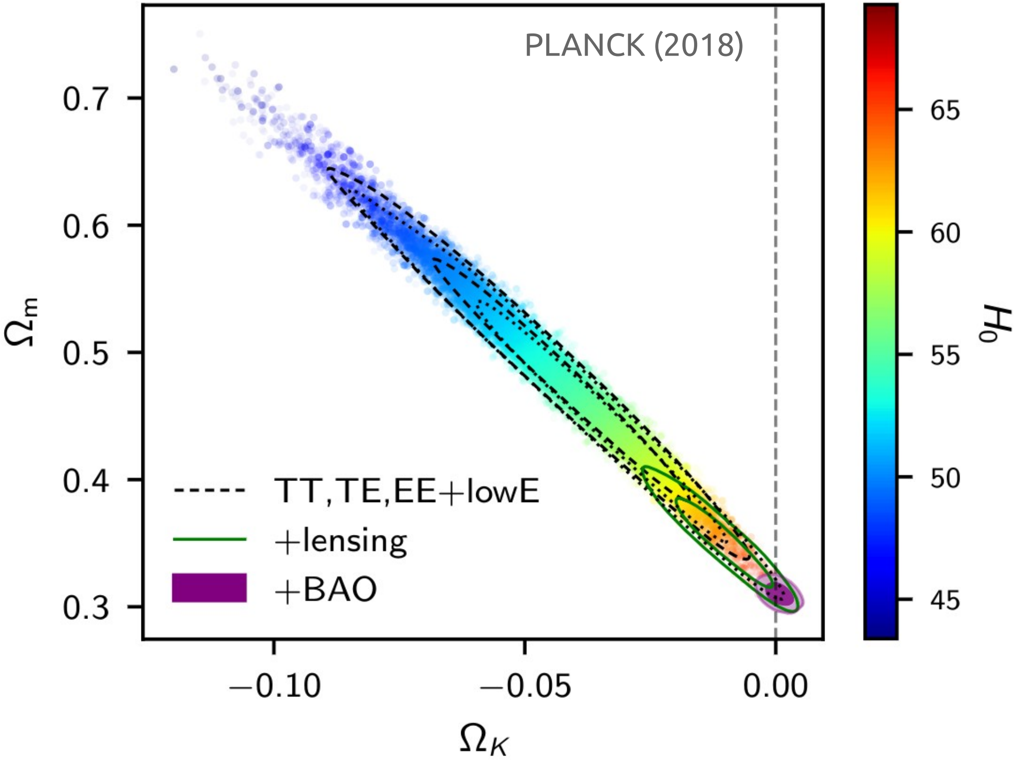
$$\frac{\sum_i \rho_i}{\rho_{\rm crit}} - 1 = \frac{k}{a^2 H^2}$$

Energy density parameter:

$$\Omega_i(t_0) \equiv \frac{\rho_i(t_0)}{\rho_{\rm crit}(t_0)}$$

Consistency relation (today):

$$\sum_i \Omega_i^0 + \Omega_k^0 = 1$$



The Flatness Problem

Evolution of flatness parameter

$$\frac{d}{dt}(\Omega_k) = -2\frac{\ddot{a}}{\dot{a}}\Omega_k$$

$\ddot{a} < 0$ for radiation and matter domination

Today's Universe flat to a very good accuracy $|\Omega_k(t_0)| \leq 0.0007$

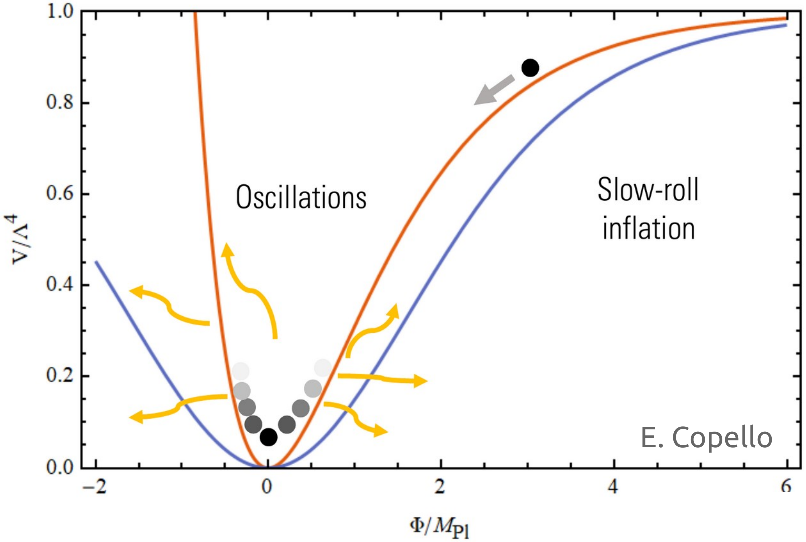
For radiation and matter domination this would imply $|\Omega_k(t_{\mathrm{Pl}})| \leq 10^{-60}$

→ **why is the Universe so flat? Extreme fine-tuning would have been required!**

However, if $\ddot{a} > 0$, small values would be approached dynamically

→ **accelerated expansion via inflation!**

Concept of Inflation



Introduce **scalar inflaton** **field with**

$$\rho_\Phi = \frac{1}{2}\dot{\Phi}^2 + V(\Phi) \qquad p_\Phi = \frac{1}{2}\dot{\Phi}^2 - V(\Phi)$$

Flatness and horizon problem is solved, when

$$H^2 + \dot{H} = \frac{\ddot{a}}{a} = -\frac{1}{6}(\rho + 3p) > 0$$

$$p < -\frac{1}{3}\rho$$

This is fulfilled when the potential energy dominates over the kinetic energy: **slow roll inflation**

$$V(\Phi) \gg \dot{\Phi}^2$$

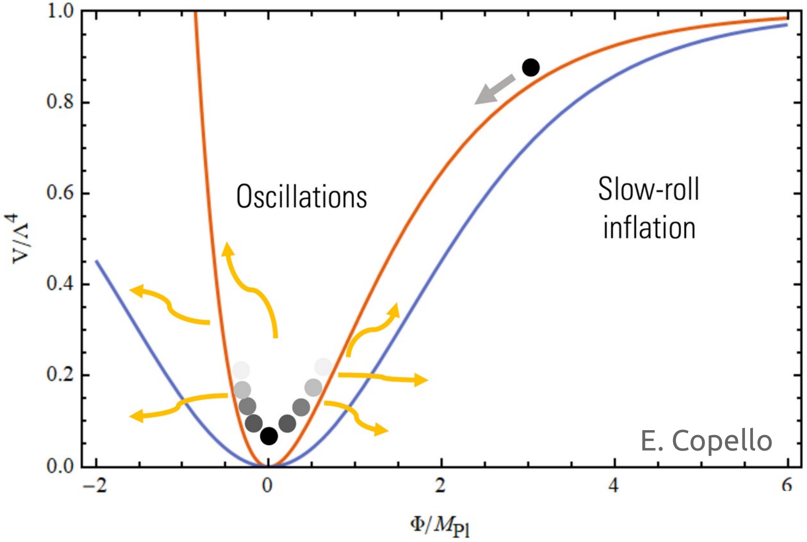
$$\omega = \frac{p_\Phi}{\rho_\Phi} = -1$$

Slow roll approximation for Inflation

Slow-roll parameters define the end of inflation:

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = -\frac{3\dot{\phi}^2}{2\rho} < 1 \qquad |\eta| \equiv \left|\frac{\dot{\epsilon}}{\epsilon H}\right| < 1$$

$$\epsilon_V \equiv \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 < 1 \qquad \eta_V \equiv M_{\rm Pl}^2\left(\frac{V''}{V}\right) < 1$$



Length of inflation measured by numbers of efolds:

$$N(\Phi) = \int_{t_i}^{t_{\rm end}} H\,dt$$

Linking to observables and cosmological data

Tensor-to-scalar ratio

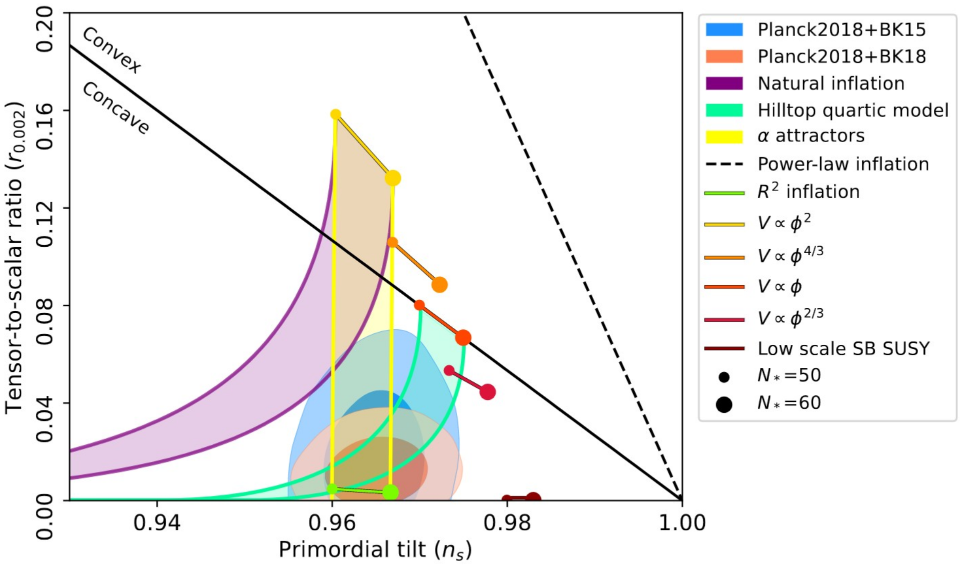
describes ratio between gravitational and density fluctuations

Experimental constraints can be evaluated by

$$r = 16\epsilon_V$$

$$n_s = 1 - 6\epsilon_V + 2\eta_V$$

$$A_{s,\star} = \frac{V}{24\pi^2 \epsilon_V M_{\mathrm{Pl}}^4}$$



Spectral index

describes dependence of the amplitude of the density perturbations on their wave length

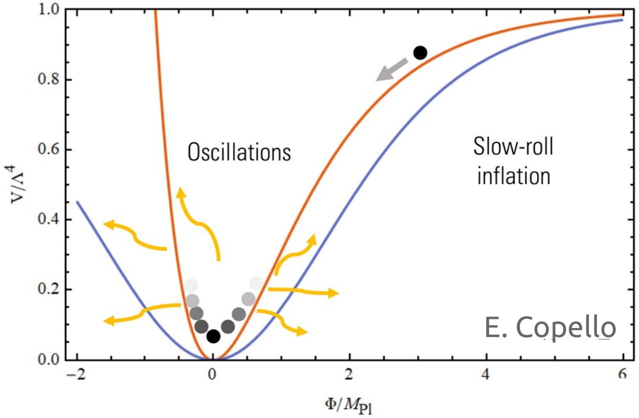
and compared with

$$A_{s,\star} = (2.1 \pm 0.1) \times 10^{-9} \qquad n_s = 0.9659 \pm 0.0040 \qquad r_{0.05} < 0.035, \qquad 95\%\,\mathrm{C.L.}$$

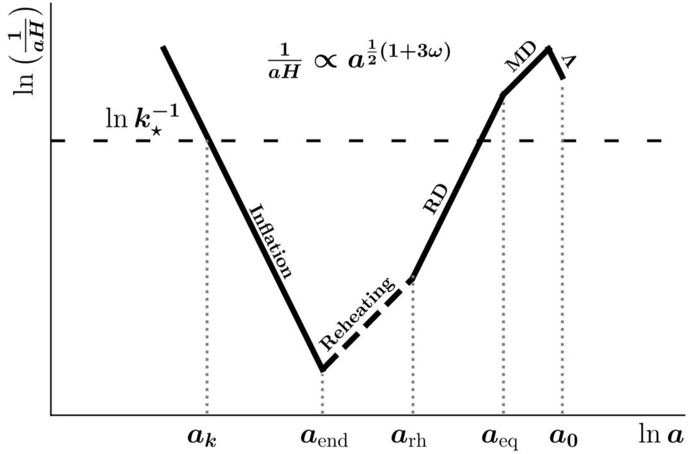
Reheating

At end of inflation, inflaton oscillates and transmits energy to SM particles = reheating

$$\langle \dot{\rho}_\Phi \rangle + 3H \langle \rho_\Phi \rangle = -\Gamma_\Phi \langle \rho_\Phi \rangle$$



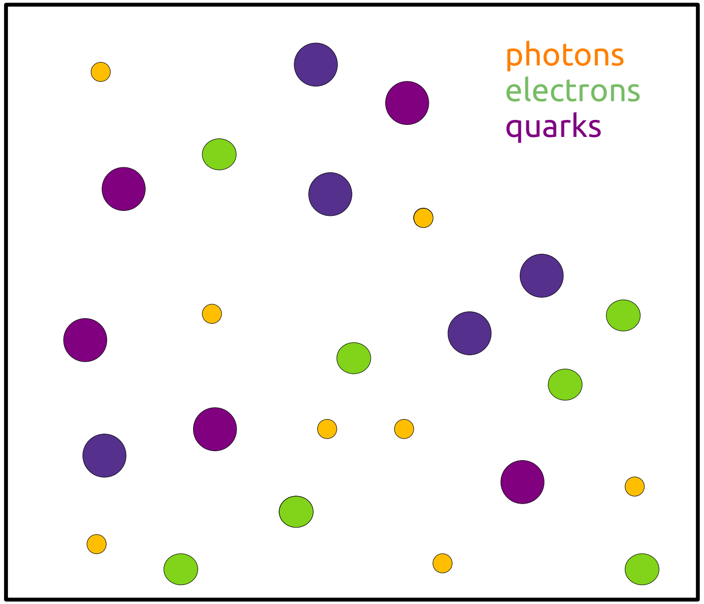
$$\Gamma_{\Phi \to F\bar{F}} = \frac{y^2}{8\pi} m_\Phi \qquad \Gamma_{\Phi \to XX^\dagger} = \frac{g^2}{8\pi m_\Phi}$$



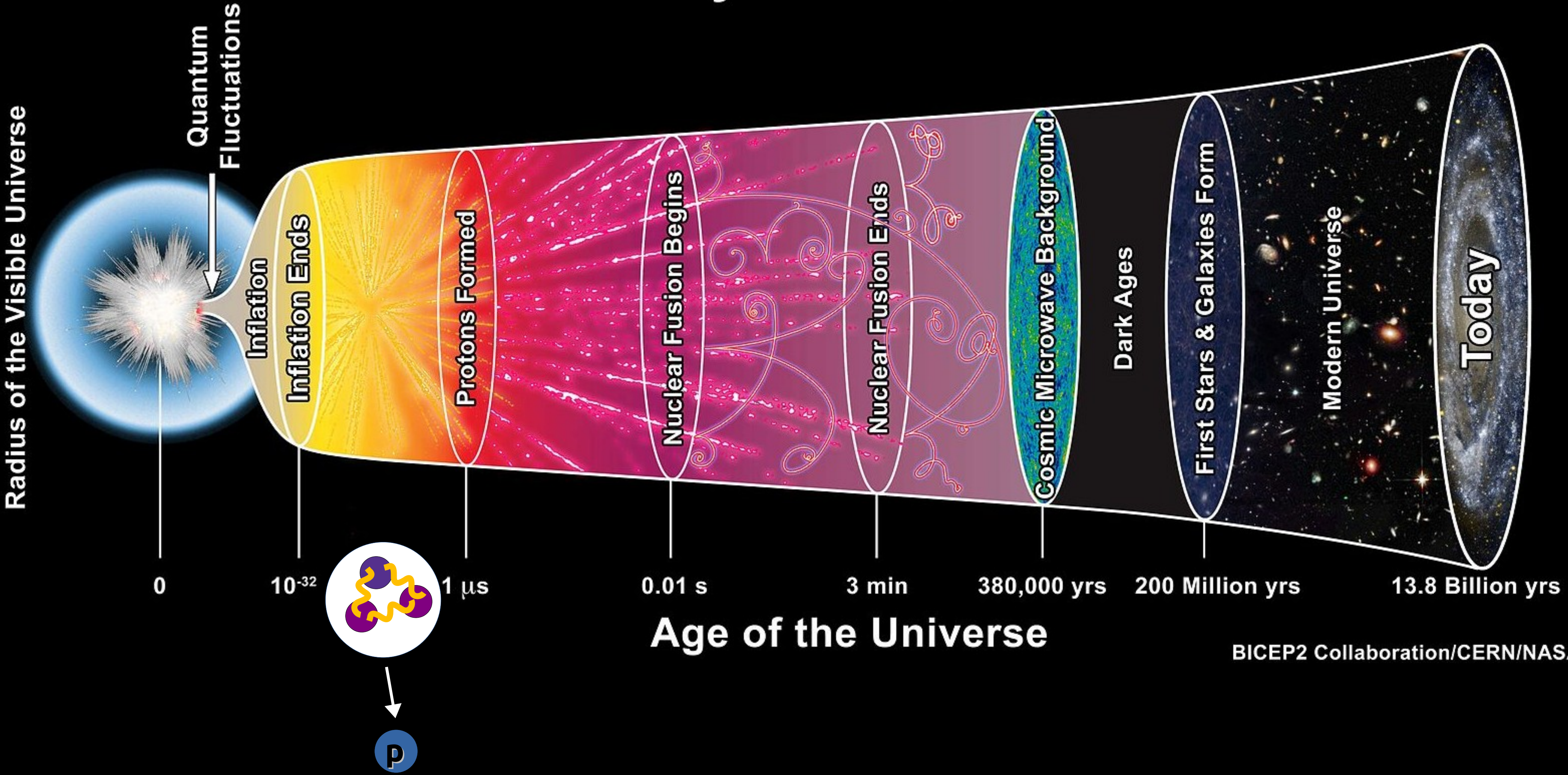
The **reheating temperature T_{rh}** **is defined as** $\rho_\Phi(a_{\rm rh}) = \rho_R(a_{\rm rh})$

Inflation

- Accelerated expansion of the Universe
- New physics (particle) needed
- New particle will decay into standard model particles
- Hot plasma of standard model particles



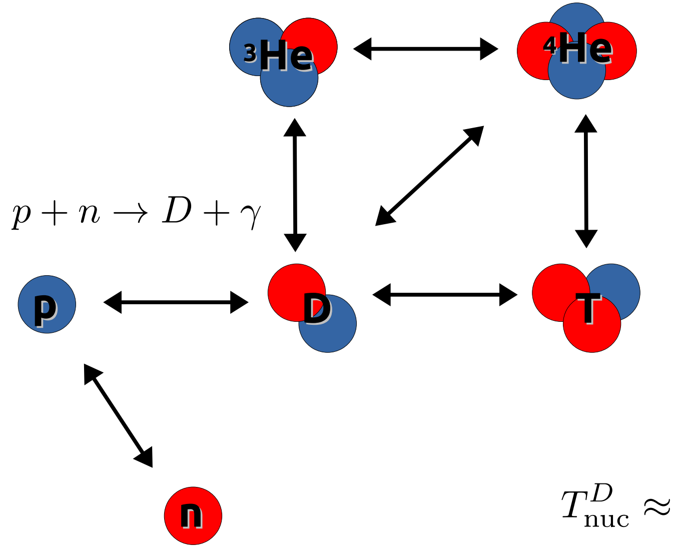
History of the Universe



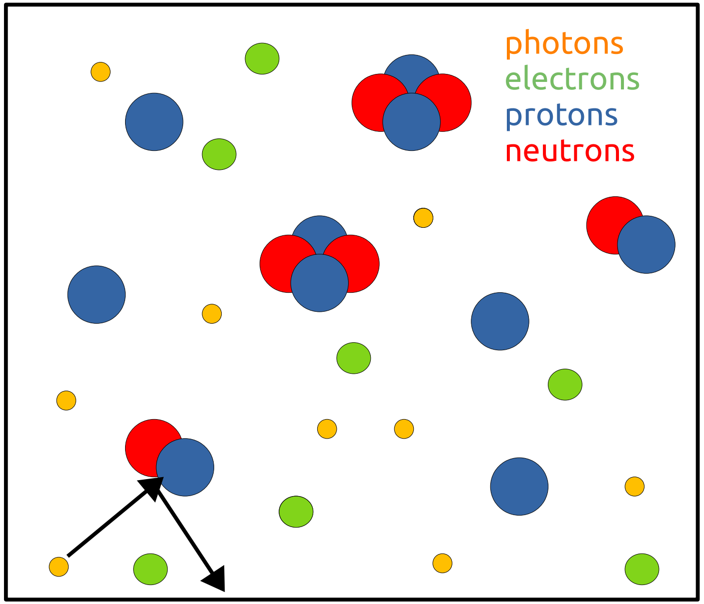
BICEP2 Collaboration/CERN/NASA

Big Bang Nucleosynthesis

- Forming of heavy nuclei
- Irreversible as soon as photons are not able to break up deuterium again



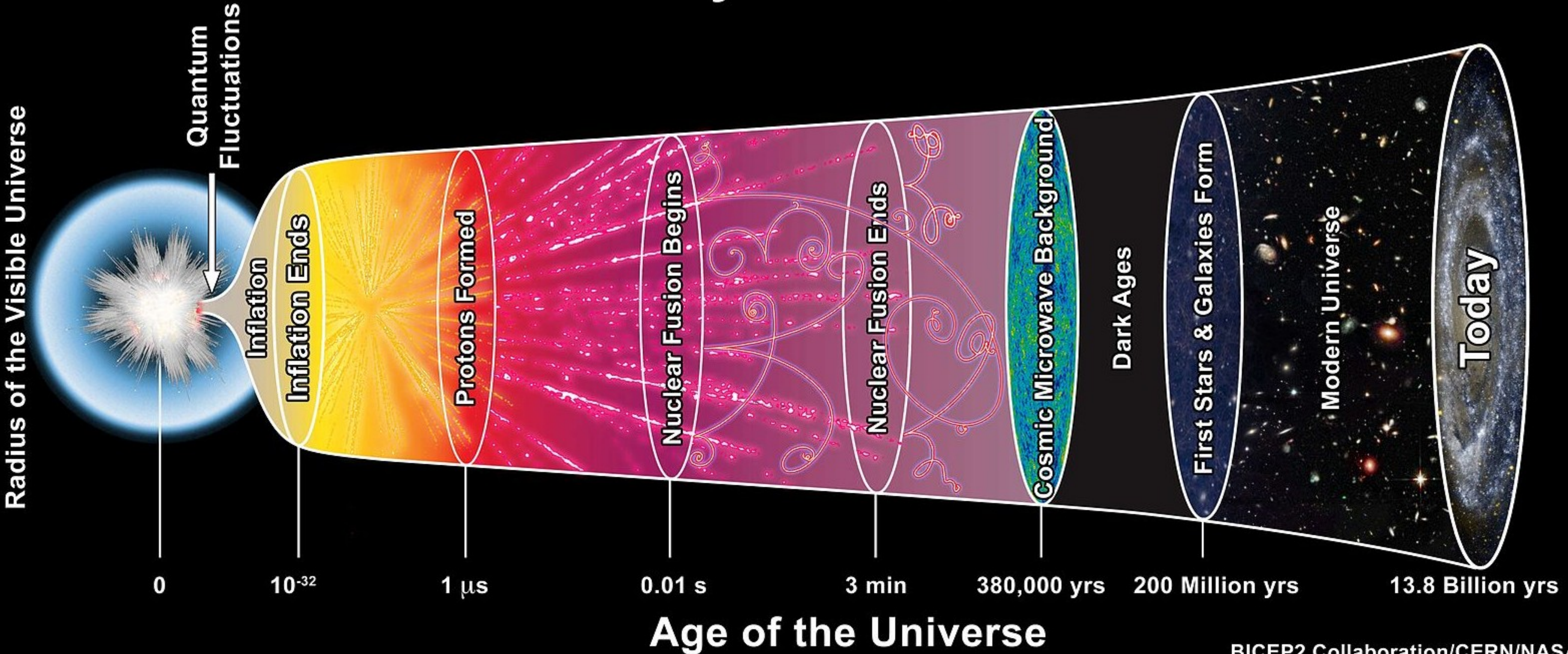
$$p + n \to D + \gamma$$



$$\eta_B^{\mathrm{obs}} = (6.143 \pm 0.190) \times 10^{-10}$$

$$T_{\mathrm{nuc}}^D \approx \frac{B_D}{\log {\eta_B}^{-1}}$$

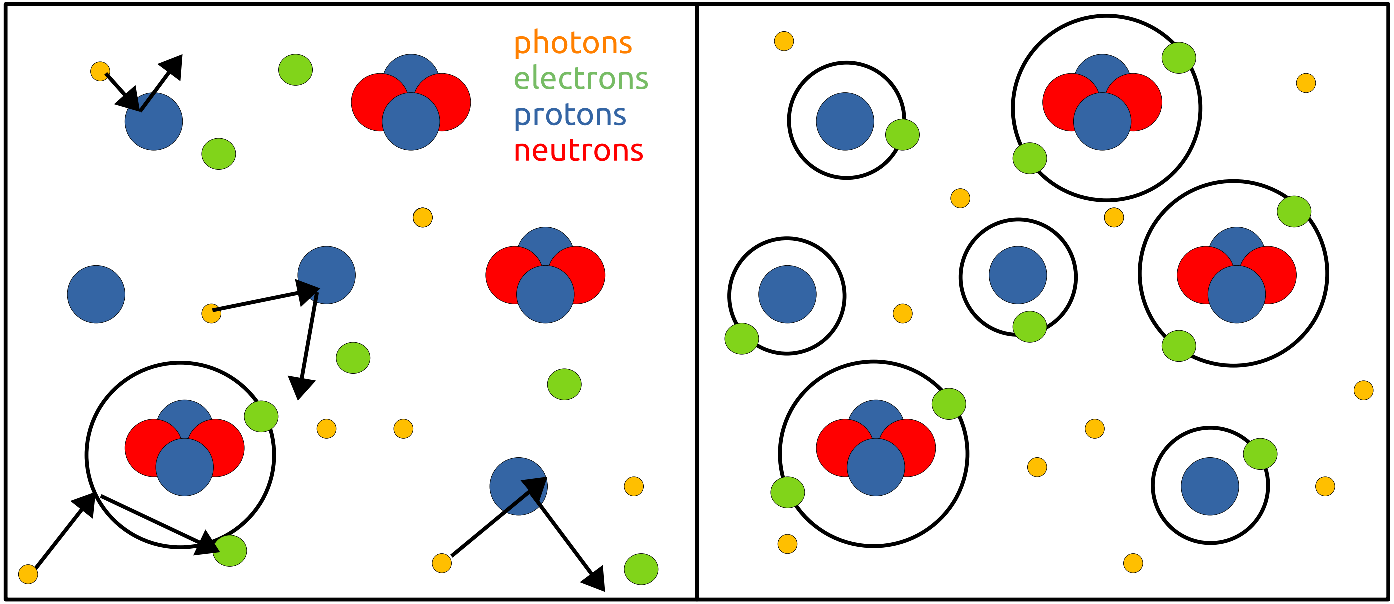
History of the Universe



BICEP2 Collaboration/CERN/NASA

The cosmic microwave background

- **Recombination** indicates the moment when stable atoms are formed and photons can freely move
- The **cosmic microwave background** consists out of these photons

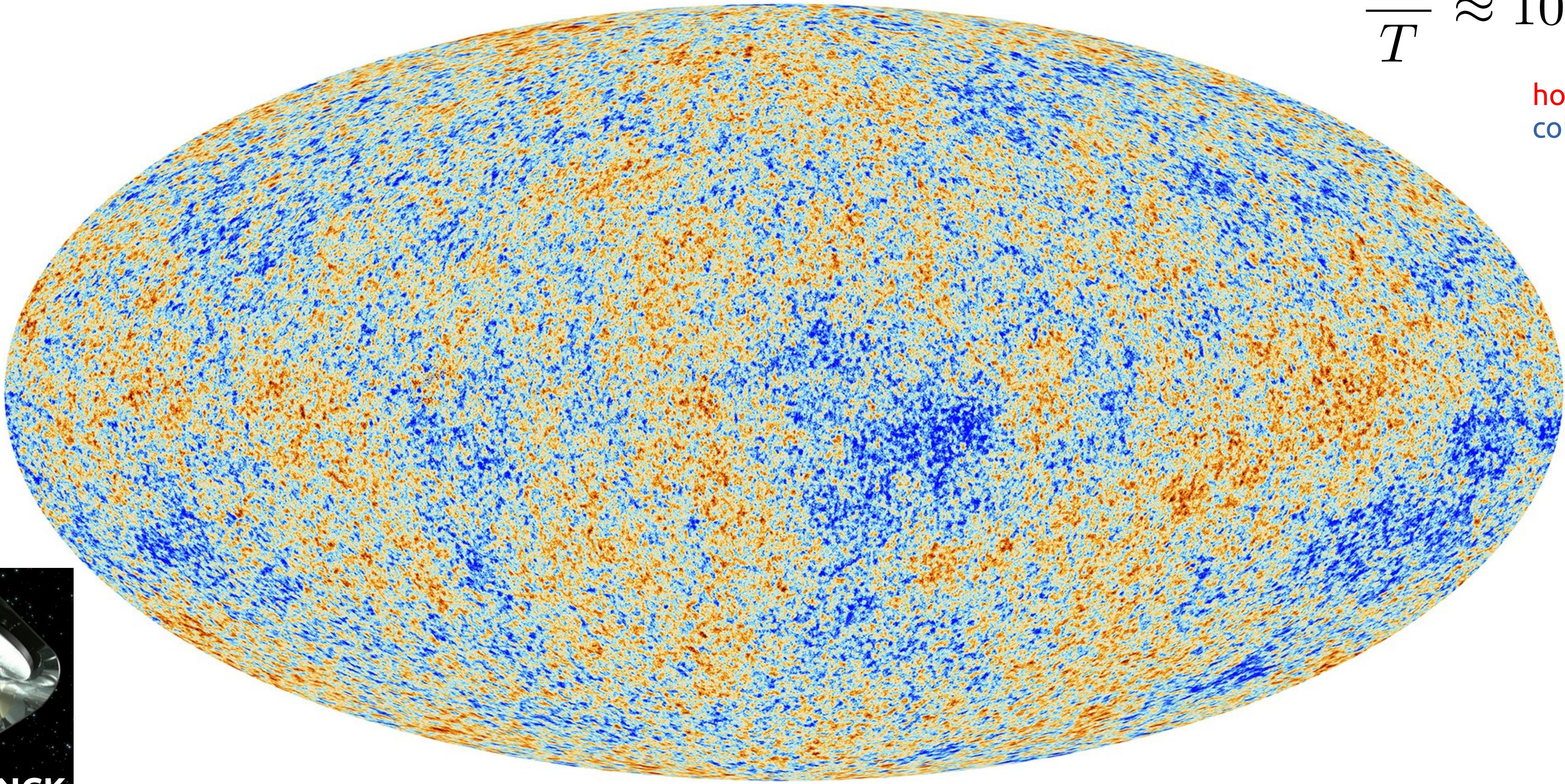


before recombination

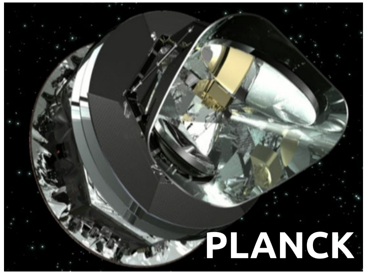
after recombination

The cosmic microwave background

$$\frac{\delta T}{T} \approx 10^{-5}$$

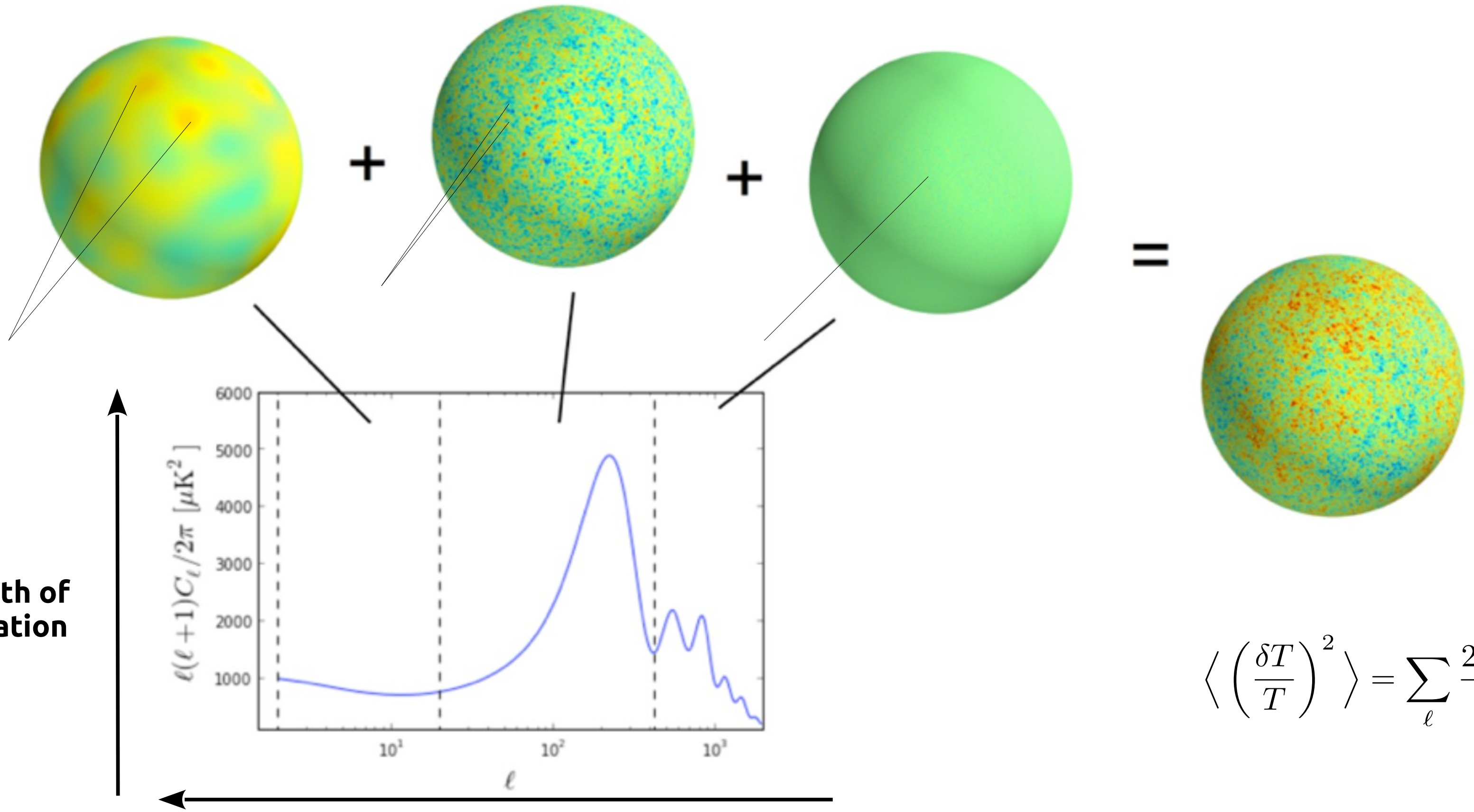


hot
cold



credit: ESA/PLANCK collaboration

The cosmic microwave background



strength of fluctuation

large angles

small angles

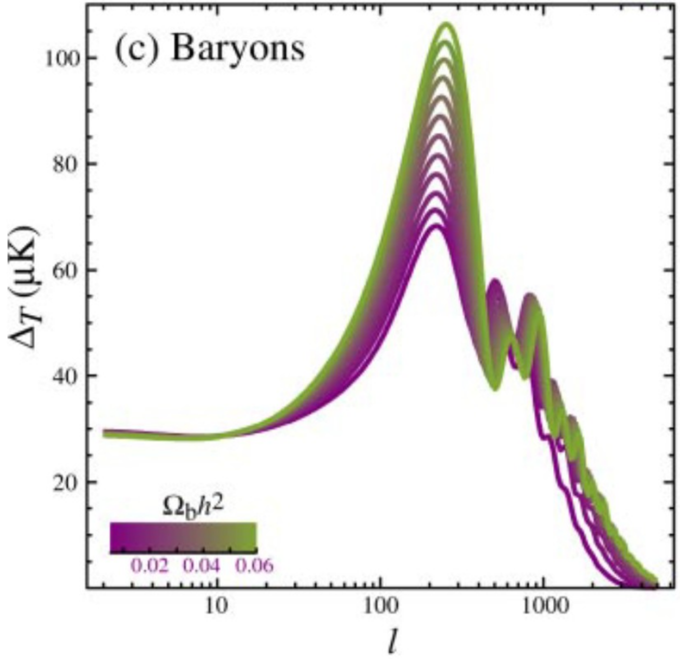
$$\left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle = \sum_\ell \frac{2\ell+1}{4\pi} C_\ell$$

credit: Olivier Doré, Caltech 2017, adapted

The cosmic microwave background

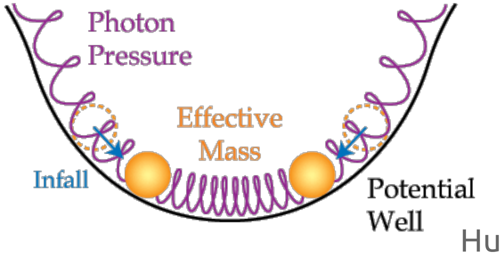
Hu, Dodelson (2002)

strength of fluctuation



large angles

small angles



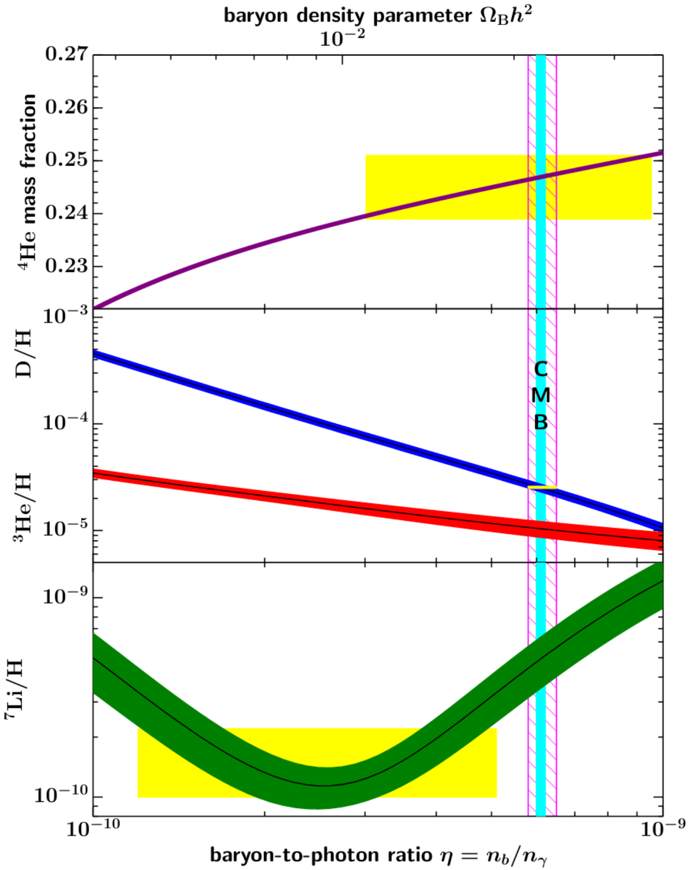
Hu

$$\Omega_B h^2 = 0.02230 \pm 0.00020$$

Contribution of baryons to today's total energy density

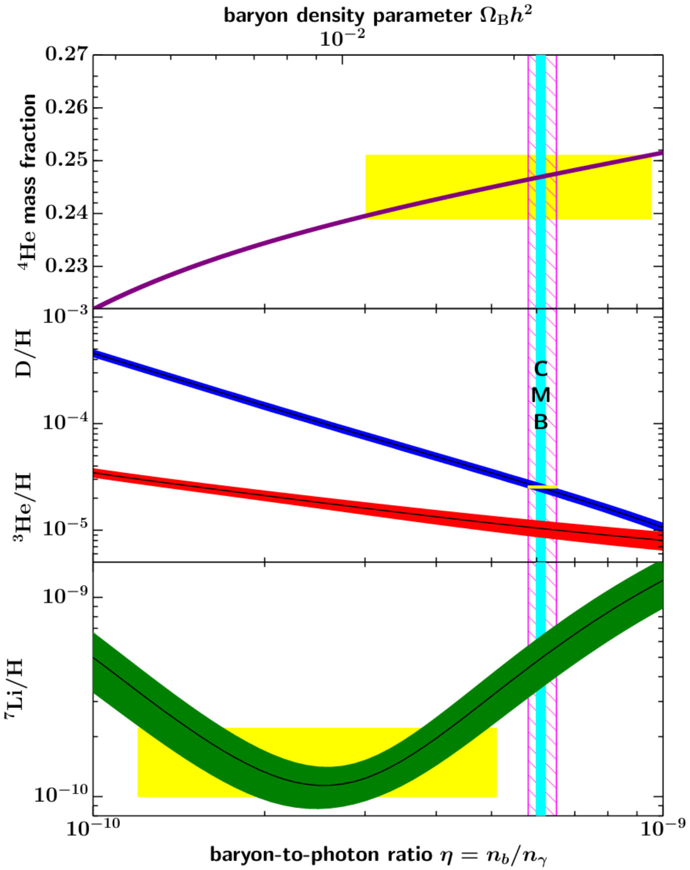
$$\Omega_B = 0.05$$

The Baryon Asymmetry – combining BBN and CMB



Baryon asymmetry confirmed by *two* independent measurements from *different* times of the early Universe

The Baryon Asymmetry – combining BBN and CMB



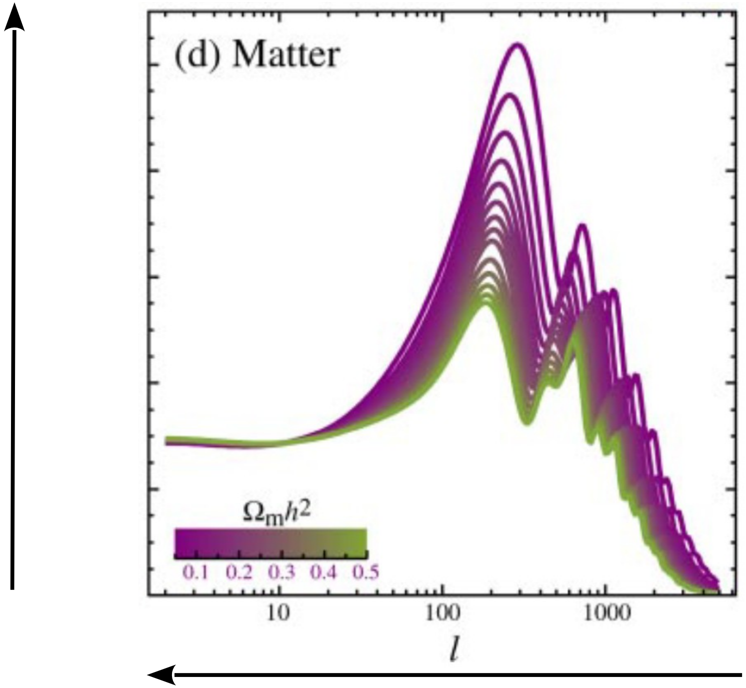
Baryon asymmetry confirmed by *two* independent measurements from *different* times of the early Universe

How was the baryon asymmetry generated?

The Puzzle of Dark Matter

Hu, Dodelson (2002)

strength of fluctuation



large angles

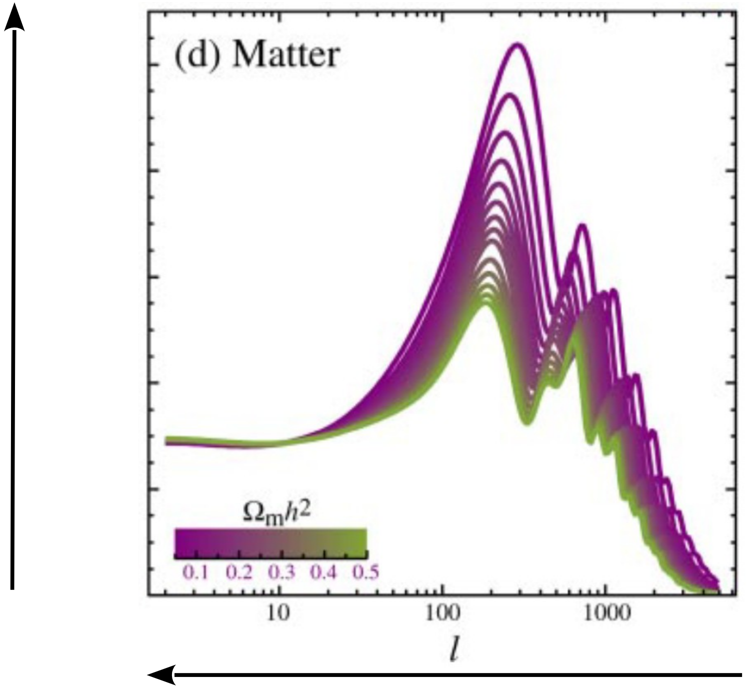
small angles

$$\Omega_{\rm CDM}h^2 = 0.120 \pm 0.001$$

Contribution of dark matter to today's total energy density

$$\Omega_{\rm CDM} = 0.26$$

The Puzzle of Dark Matter



Hu, Dodelson (2002)

strength of fluctuation

large angles

small angles

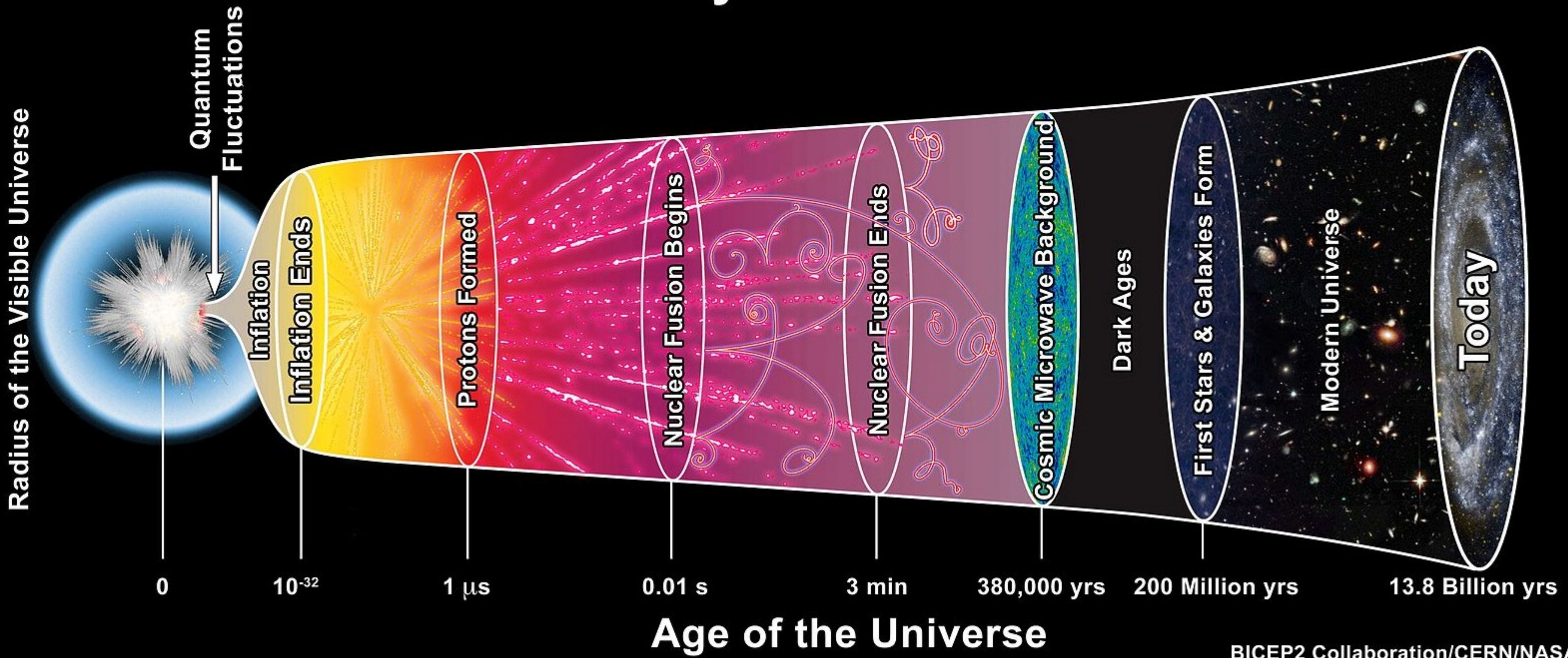
$$\Omega_{\mathrm{CDM}} h^2 = 0.120 \pm 0.001$$

Contribution of dark matter to today's total energy density

$$\Omega_{\mathrm{CDM}} = 0.26$$

What is dark matter?

History of the Universe



BICEP2 Collaboration/CERN/NASA

Take-home messages I

→ we can describe the evolution of the early Universe with the Friedmann equations

→ flatness and horizon problem point towards inflation

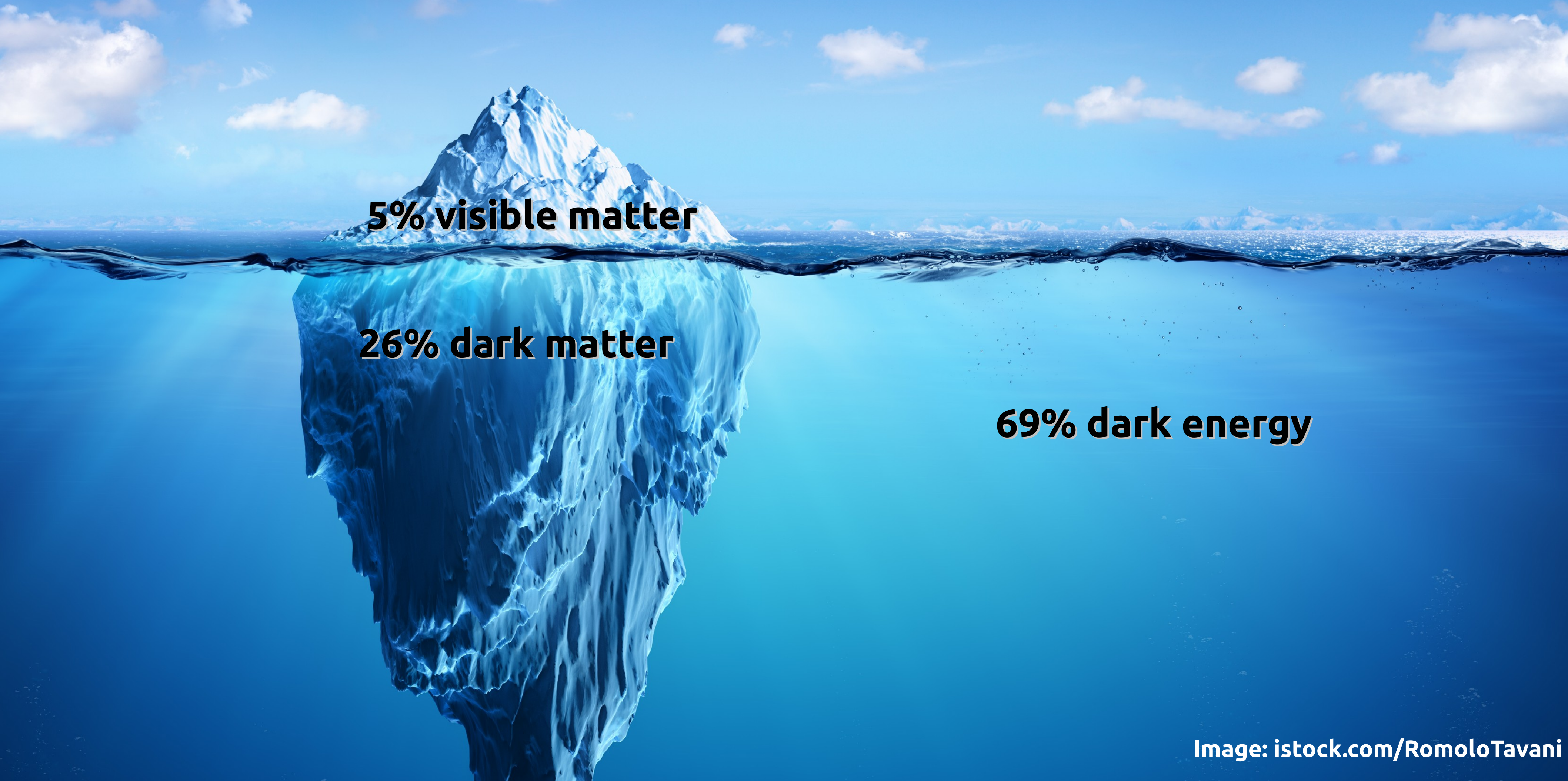
→ CMB + BBN determines precisely the baryon asymmetry

→ CMB determines accurately the DM abundance

$\Big\}$ Open puzzles
→ requires new physics

II From the Cosmos to the Lab: Dark Matter and Baryogenesis

Visible Matter – the tip of the iceberg



5% visible matter

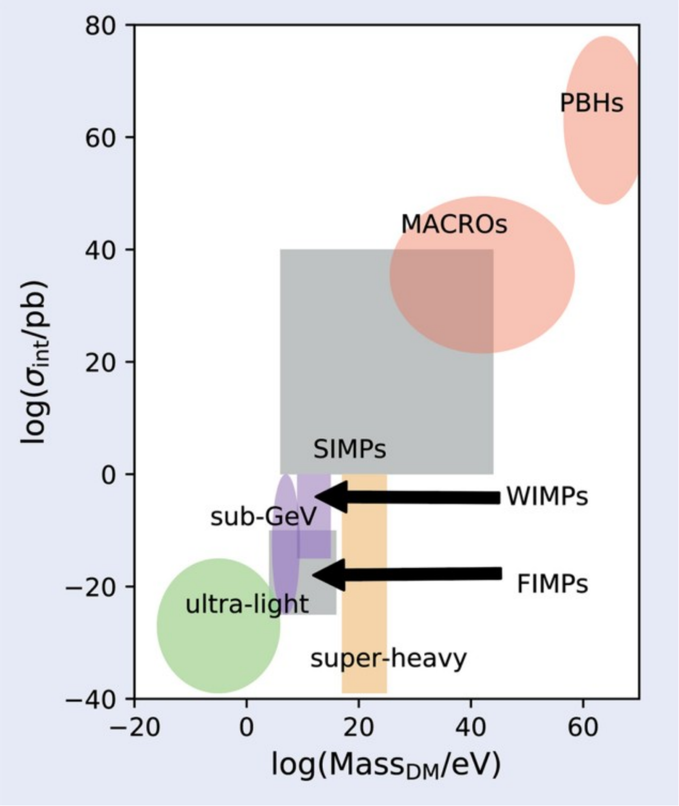
26% dark matter

69% dark energy

Image: istock.com/RomoloTavani

Landscape of dark matter candidates

Interaction strength of dark matter



mass of dark matter

C. Arina, CERN Courier, 4 March 2021

The “WIMP miracle”

WIMP – the **W**eakly **i**nteracting **m**assive **p**article

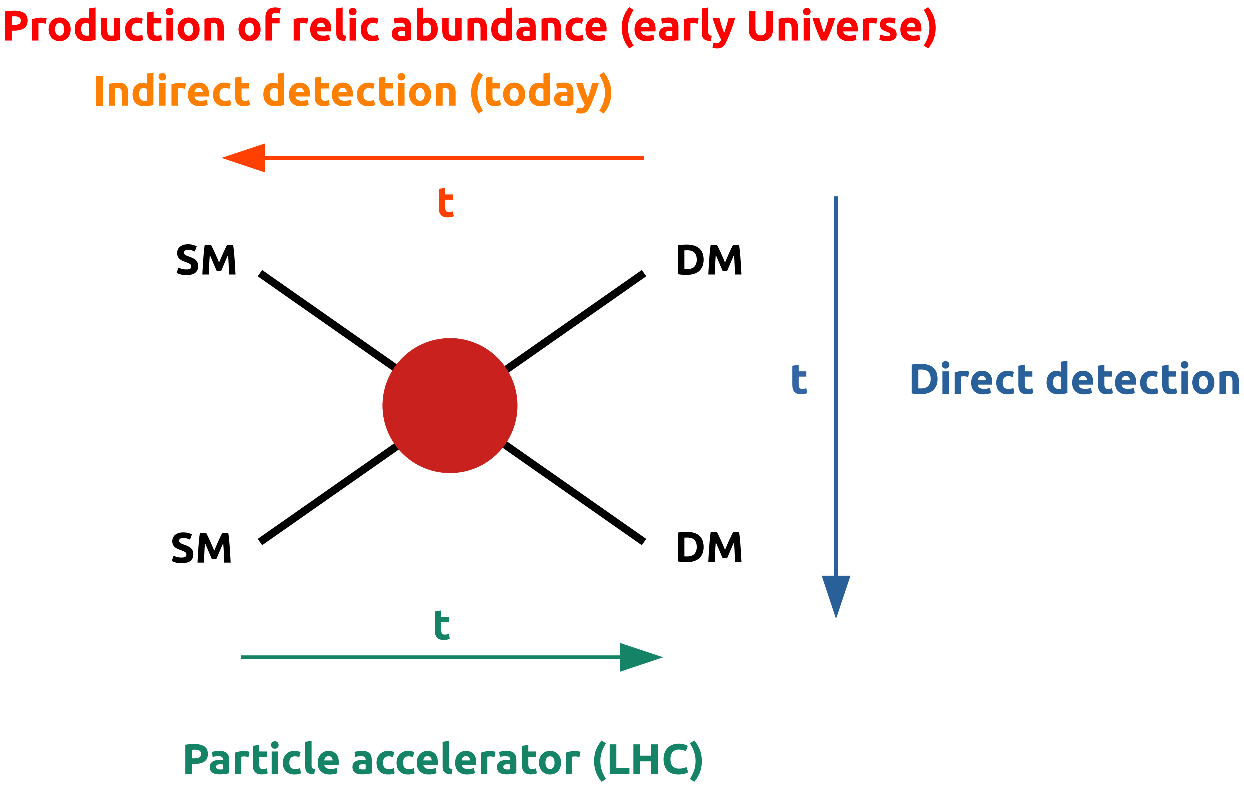
dark matter mass

$$\Omega \sim \frac{m_\chi^2}{g^4} \times 10^{-10}\mathrm{GeV}^{-2} \sim 0.26$$

interaction strength of dark matter

!?

The hunt for the WIMP



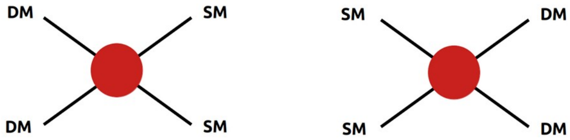
Theoretical prediction of the dark matter abundance

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\mathrm{eff}} v \rangle (n^2 - n_{\mathrm{eq}}^2)$$

temporal change of the number density of DM

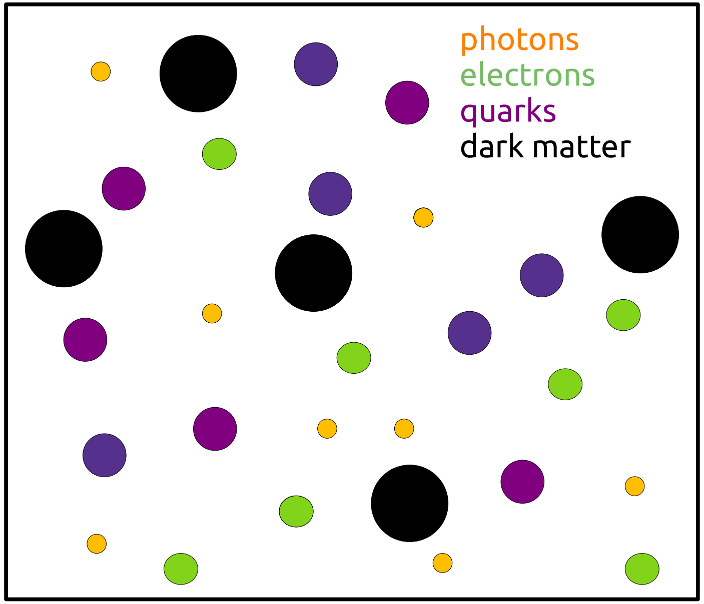
expansion of the Universe

interaction with other particles



Freeze-out of dark matter

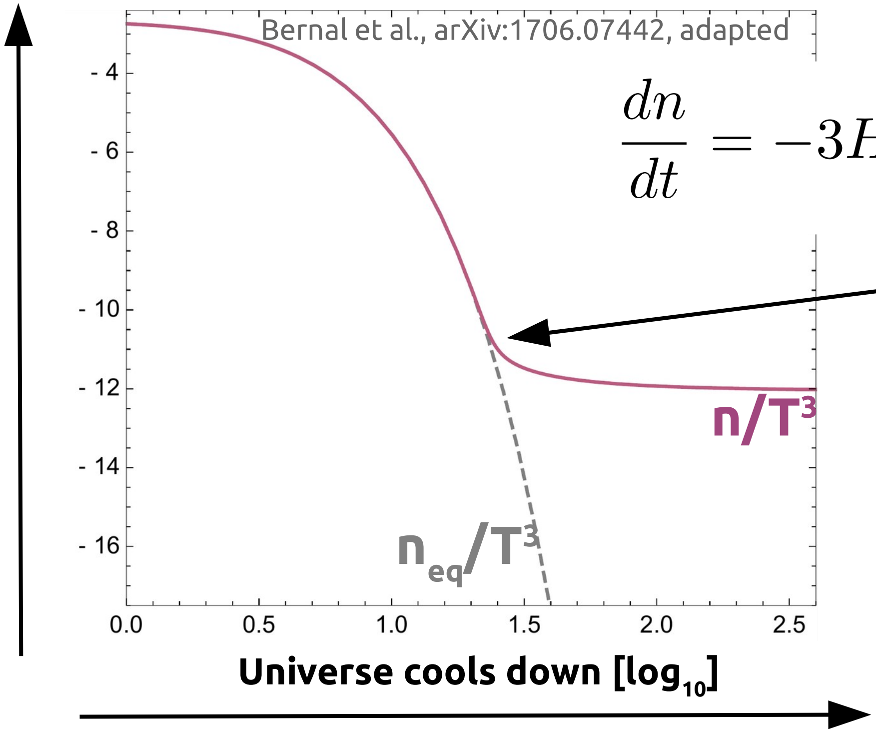
- Dark matter is in contact with the hot thermal bath of the standard model from the beginning (“in equilibrium”)



Freeze-out of dark matter

- **Assumption**: WIMP as DM candidate is due to its interaction rate in thermal equilibrium with the standard model bath

Normalized number density of Dark Matter $[\log_{10}]$

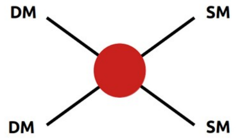


Bernal et al., arXiv:1706.07442, adapted

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\mathrm{eff}} v \rangle (n^2 - n_{\mathrm{eq}}^2)$$

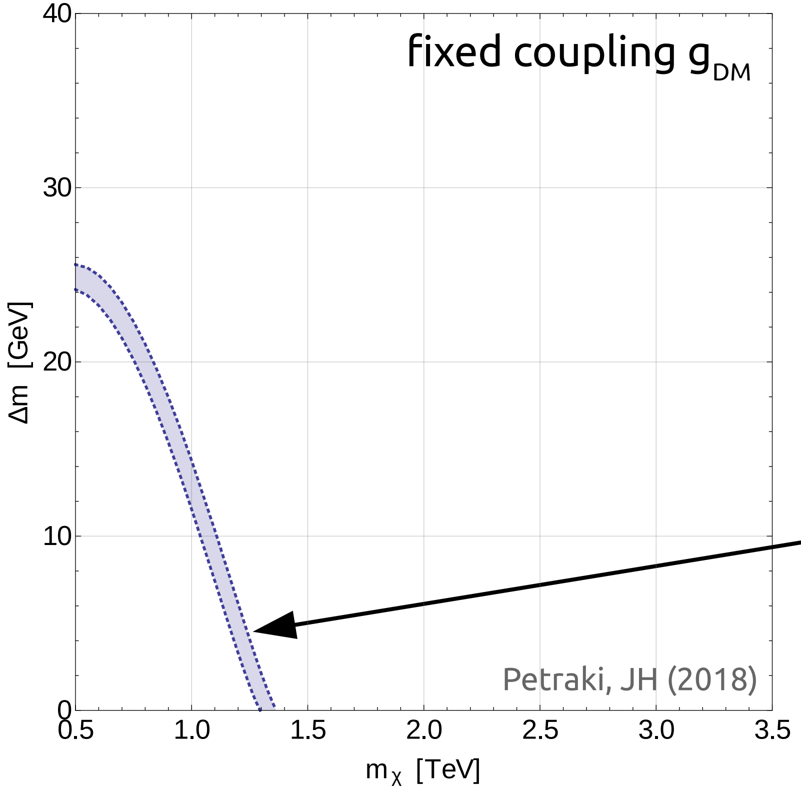
Expansion faster than interaction rate of dark matter ("freeze-out")

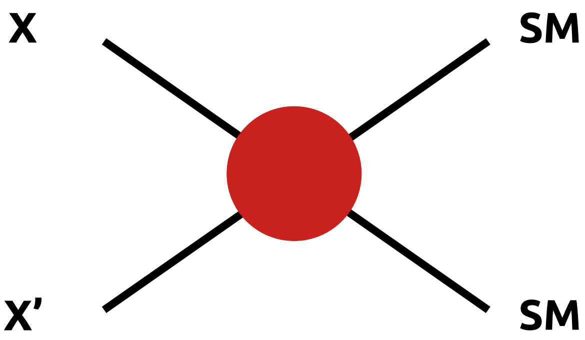
Universe cools down $[\log_{10}]$



Linking to PLANCK data

- **Example**: Two, new dark particles with mass difference Δm





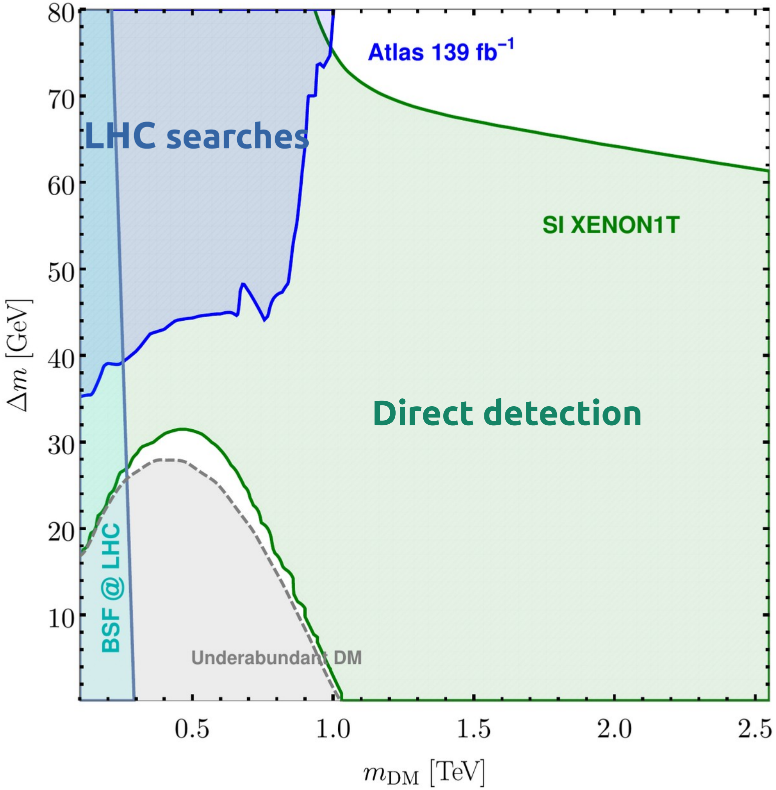
Relic abundance according to PLANCK

$$\Omega_{\mathrm{CDM}} = 0.264 \pm 0.002$$

Interplay of theory and experiment

- **Exclusion** of parameter space via (1) experimental data and (2) preventing DM overproduction

  (→ limit on g_{DM})

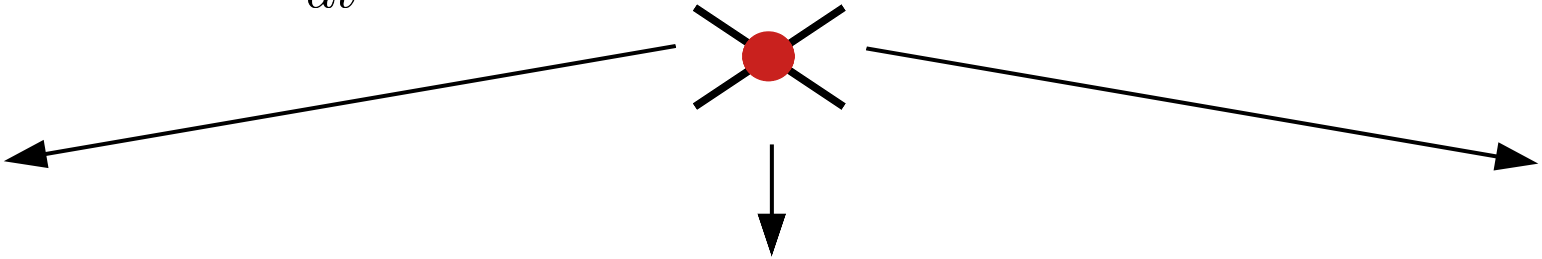


Becker, Copello, JH, Mohan, Sengupta (2022)

Towards new standards for the DM abundance prediction

- Improving precision of cross sections crucial for DM abundance calculation

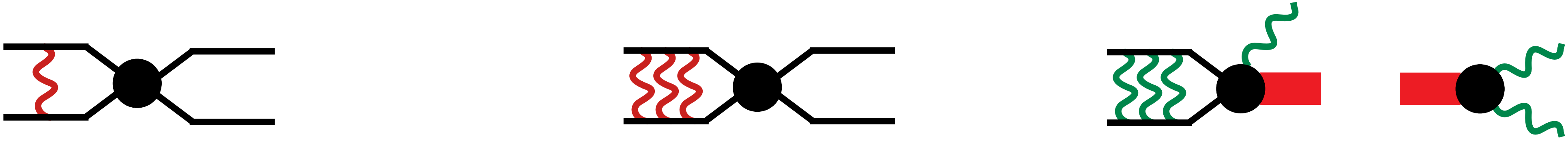
$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)$$



Higher order corrections

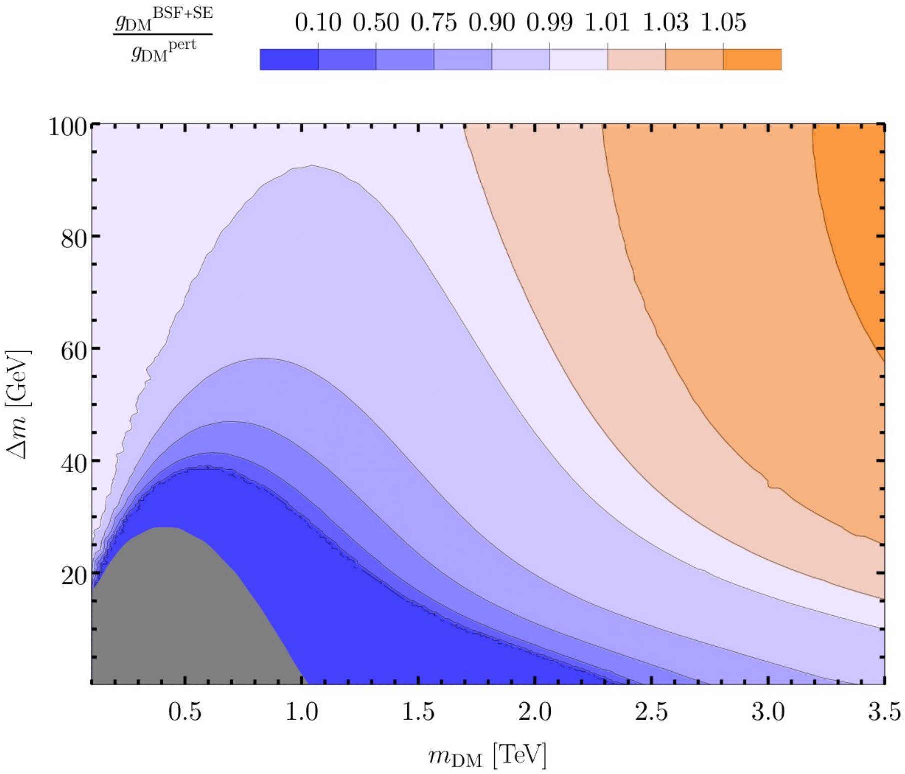
Sommerfeld effect

Bound states



Impact on minimal dark matter coupling strength

Identify lower bound on g_{DM} in order not to overproduce DM

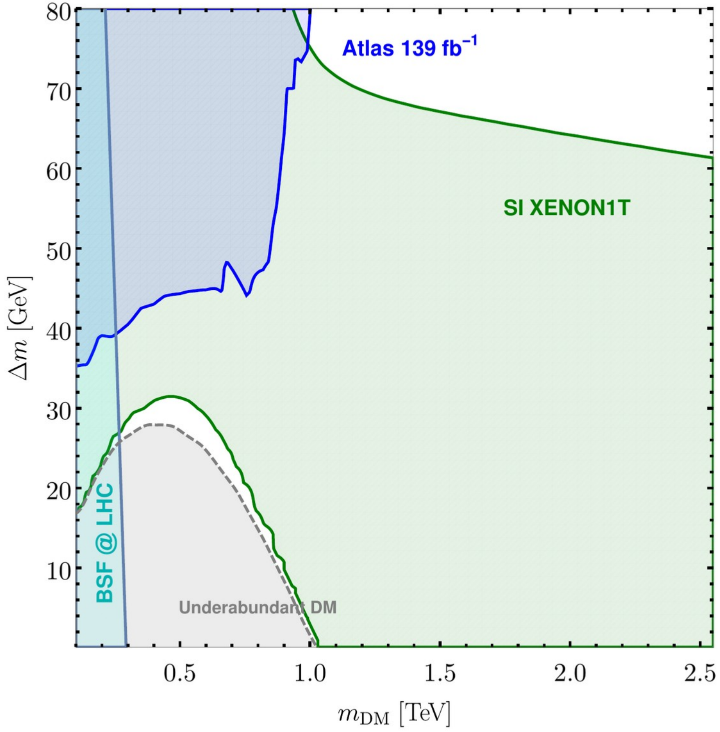


- **Non-perturbative effects result in corrections on minimal g_{DM}**
- **Depending on parameter space: positive or negative correction**

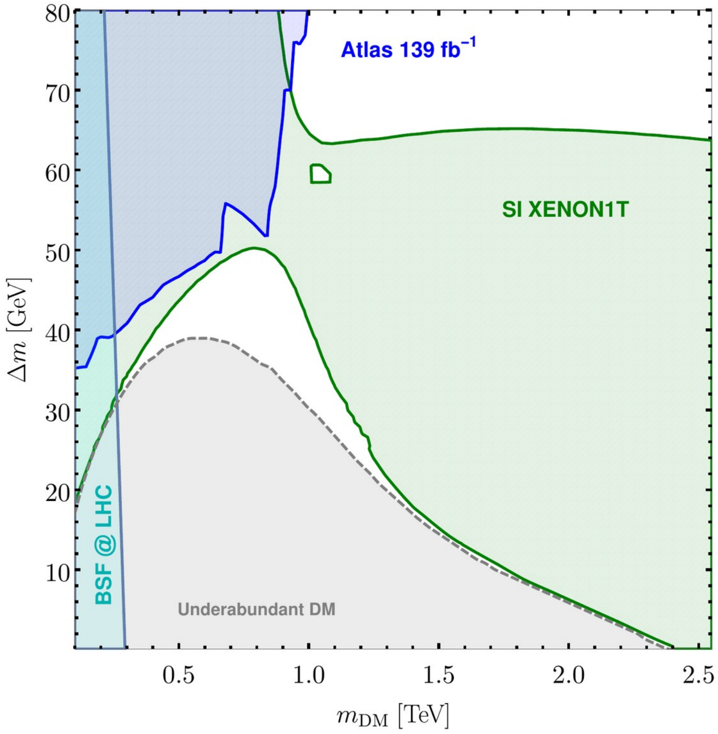
Becker, Copello, JH, Mohan, Sengupta (2022)

Impact on the interpretation of experimental results

Without SE and BSF



With SE and BSF



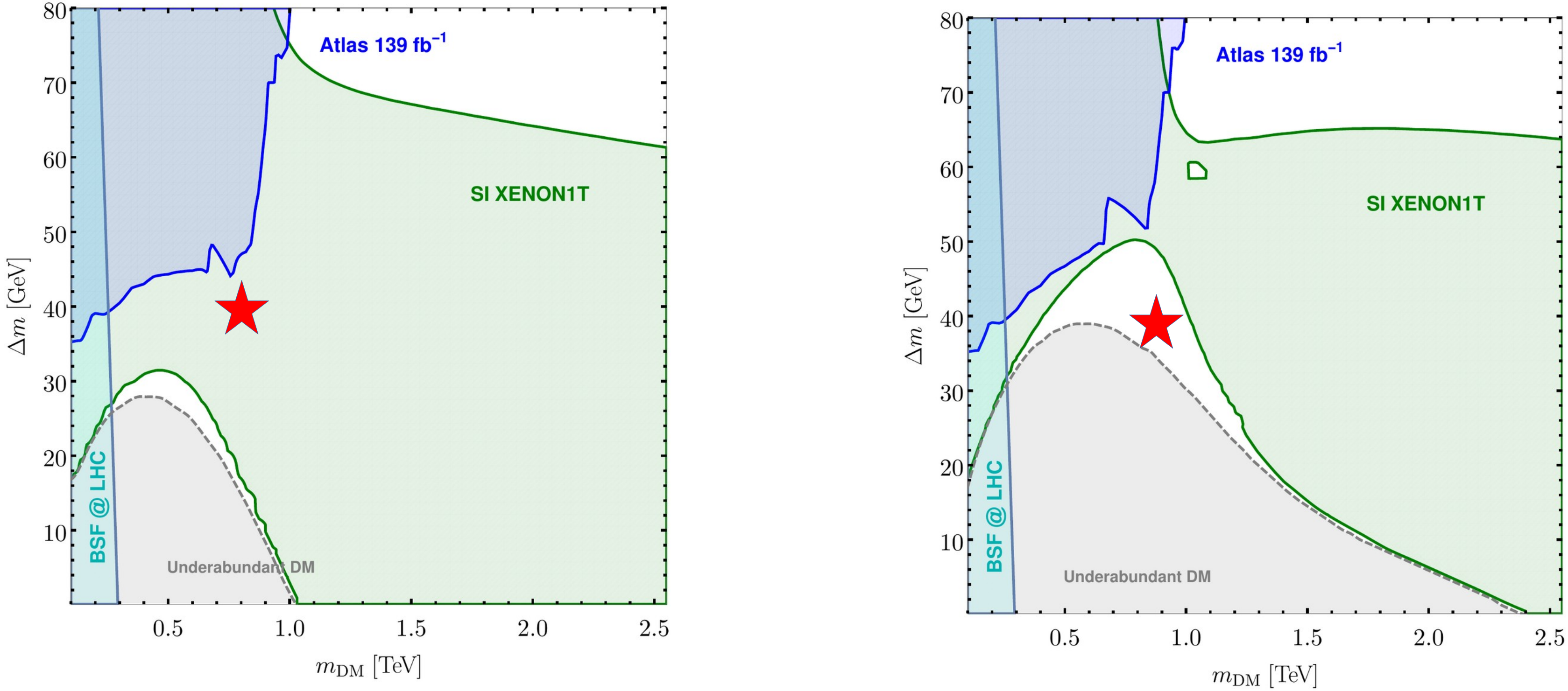
Previously excluded parameter space is NOT yet excluded!

Becker, Copello, JH, Mohan, Sengupta (2022)

Impact on the interpretation of experimental results

Without SE and BSF

With SE and BSF

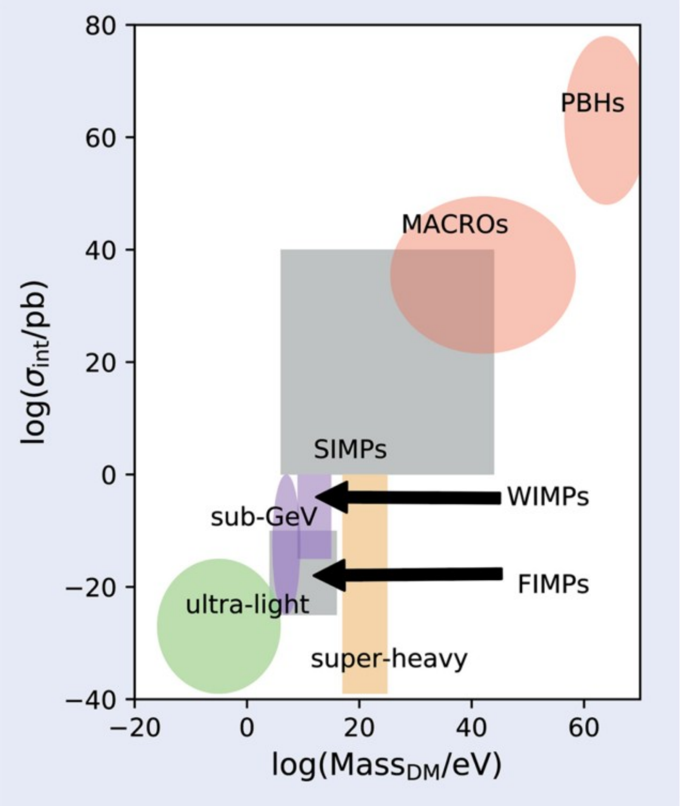


Previously excluded parameter space is NOT yet excluded!

Becker, Copello, JH, Mohan, Sengupta (2022)

Landscape of dark matter candidates

Interaction strength of dark matter



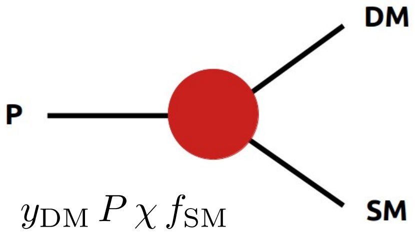
mass of dark matter

C. Arina, CERN Courier, 4 March 2021

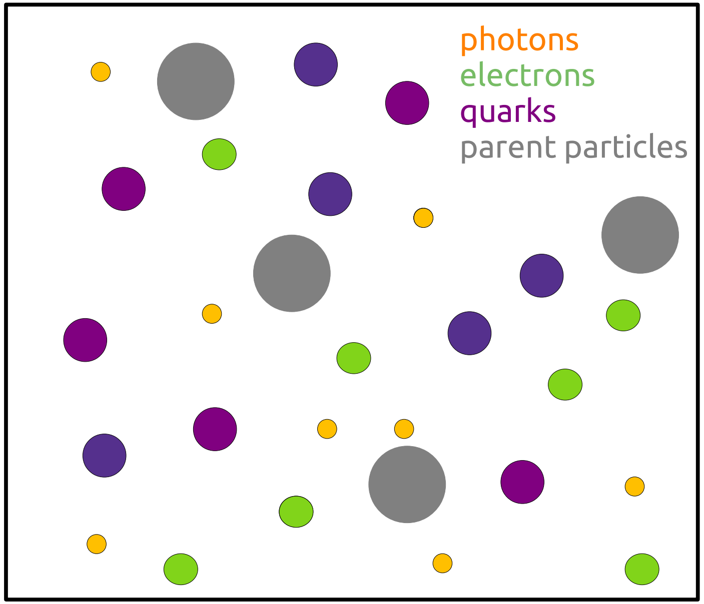
The FIMP

- **Assumption**: FIMP as DM candidate due to its very small interaction rate not in thermal equilibrium with the standard model bath

- **BUT:** DM produced via decay of parent particle

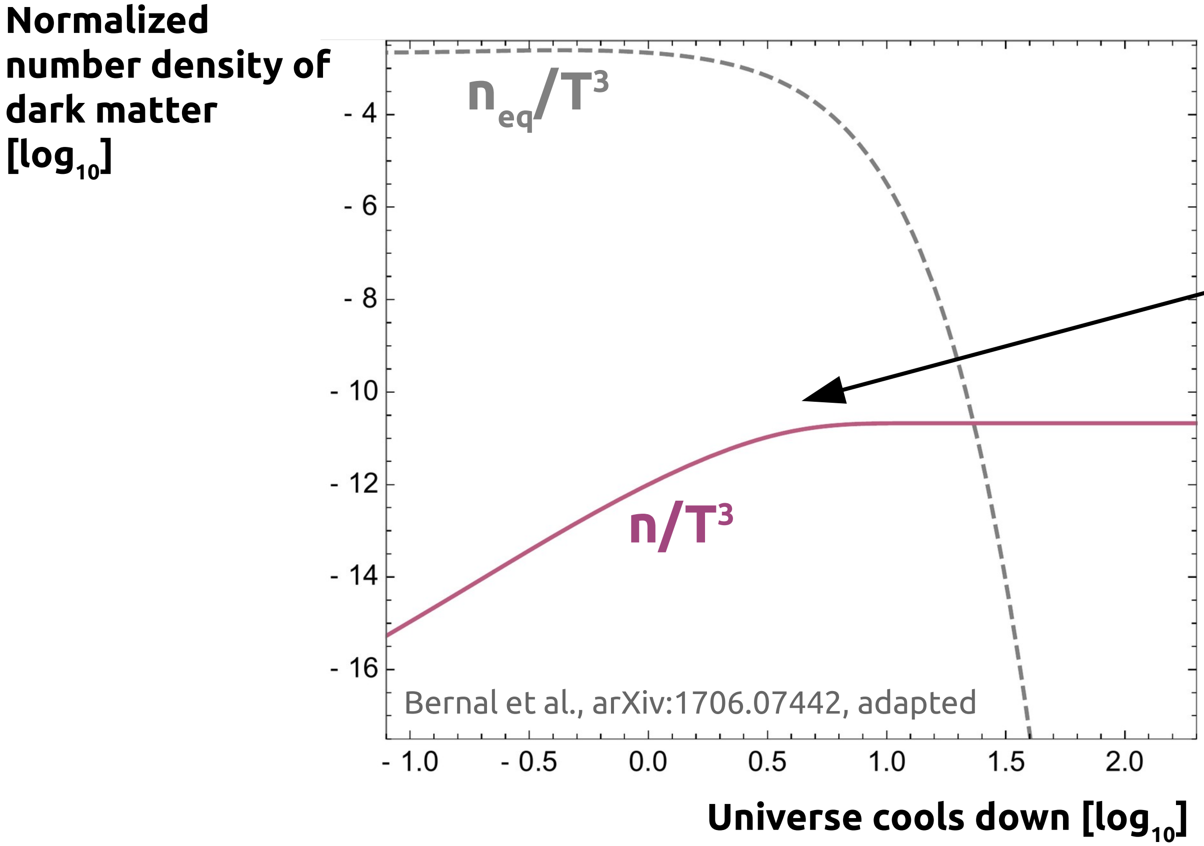


$y_{\mathrm{DM}}\, P\, \chi\, f_{\mathrm{SM}}$



Feeble interaction between parent particle and standard model particles!

The FIMP – freeze-in of dark matter

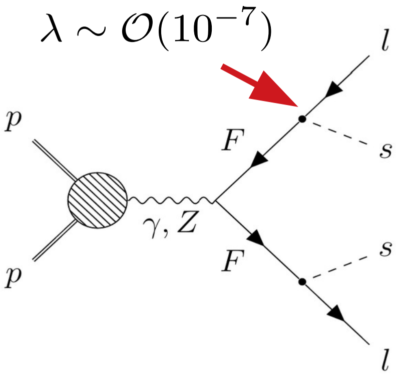


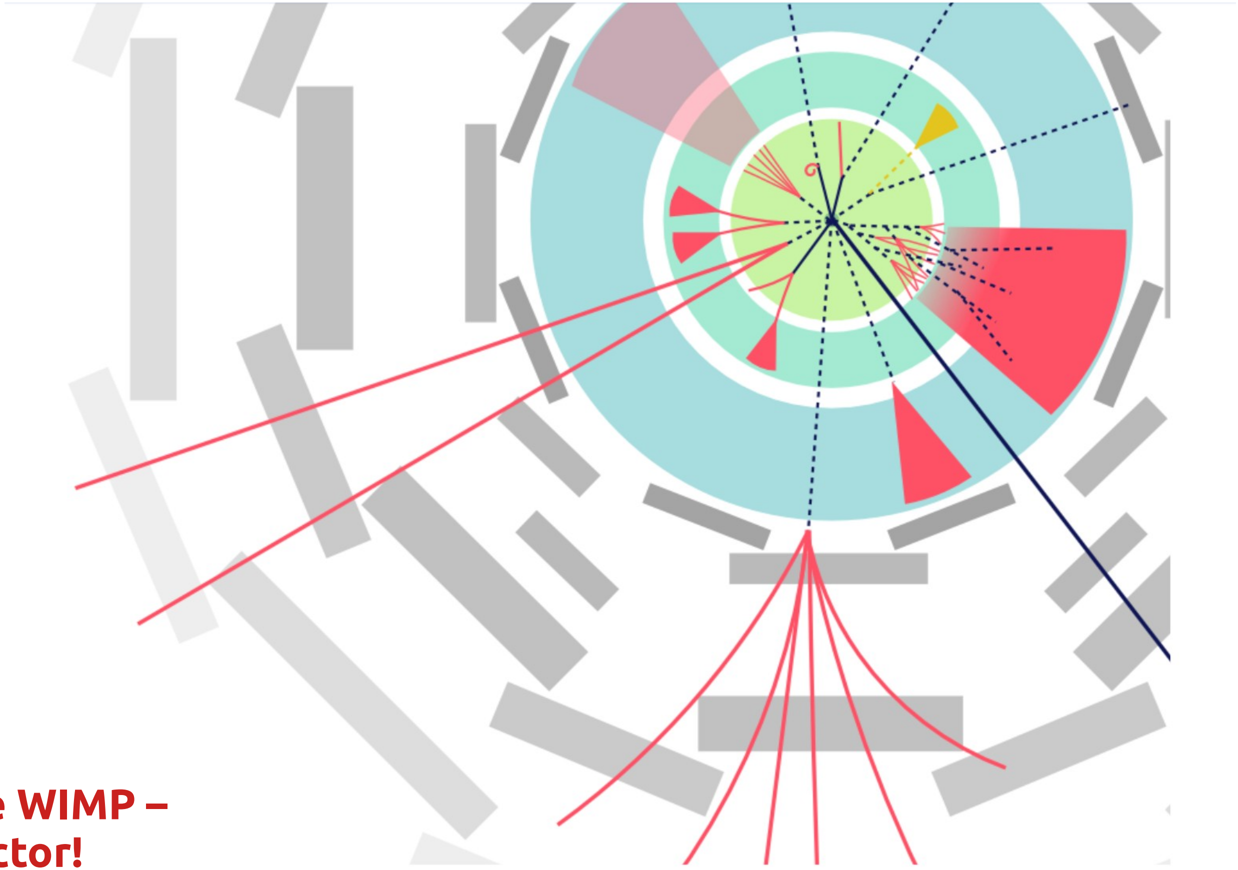
Bernal et al., arXiv:1706.07442, adapted

Expansion faster than production rate of DM ("Freeze-in")

Characteristic signatures at the LHC

- Feeble interactions lead to **long life time** of the parent particle

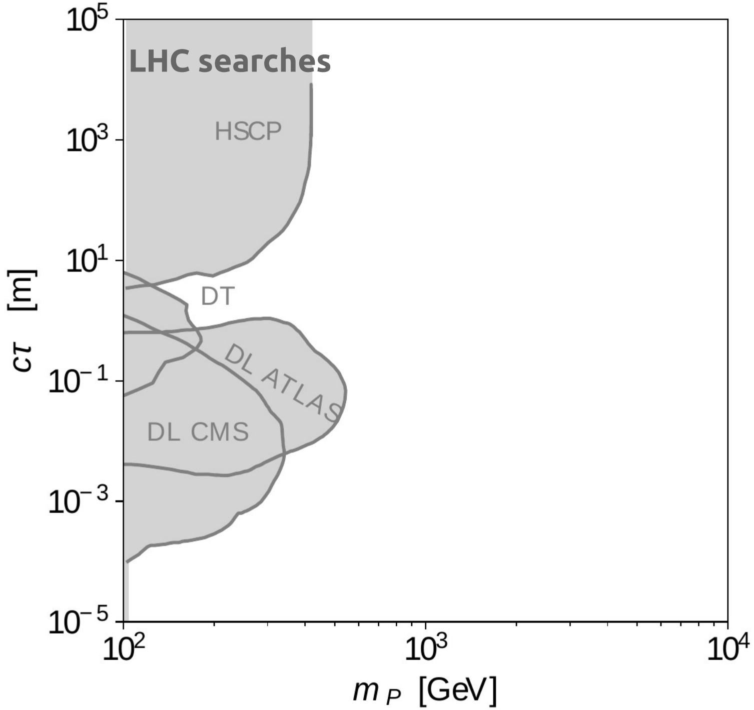


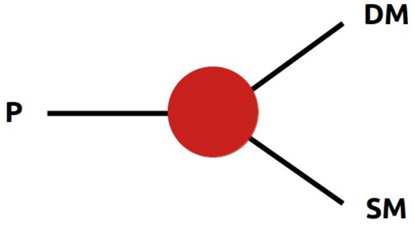


credit: Heather Russell, McGill University 2017

Long life times lead – contrary to the WIMP – to a late or no decay within the detector!

Linking the early Universe with physics in the lab





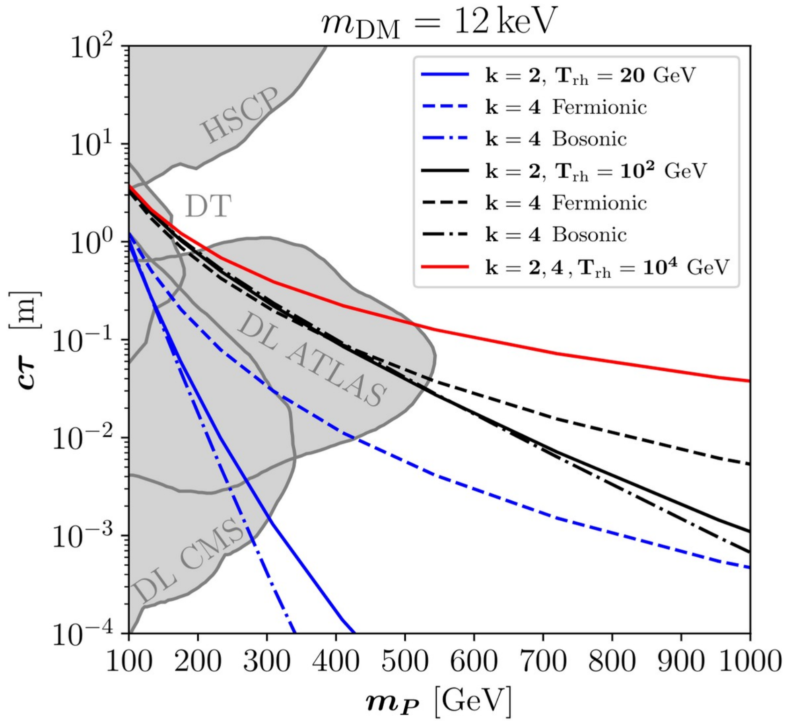
Becker, Copello, JH, Lang, Xu (2023)

Constraints from LLP searches at the LHC

Example: Muonphilic Majorana DM model

$$\frac{\Omega_{\rm DM}h^2}{0.12} \simeq \left(\frac{1.5\,{\rm m}}{c\tau}\right)\left(\frac{106.75}{g_s}\right)^{3/2}\left(\frac{m_{\rm DM}}{100\,{\rm keV}}\right)\left(\frac{200\,{\rm GeV}}{m_P}\right)^2 \times \begin{cases} \frac{2k+4}{3}\left(\frac{T_{\rm rh}}{m_P}\right)^{4k-1}\mathcal{I}_{\rm rh,b}+\mathcal{I}^0_{\rm RD} & \text{in BR} \\ \frac{2k+4}{3k-3}\left(\frac{T_{\rm rh}}{m_P}\right)^{\frac{9-k}{k-1}}\mathcal{I}_{\rm rh,f}+\mathcal{I}^0_{\rm RD} & \text{in FR} \end{cases},$$

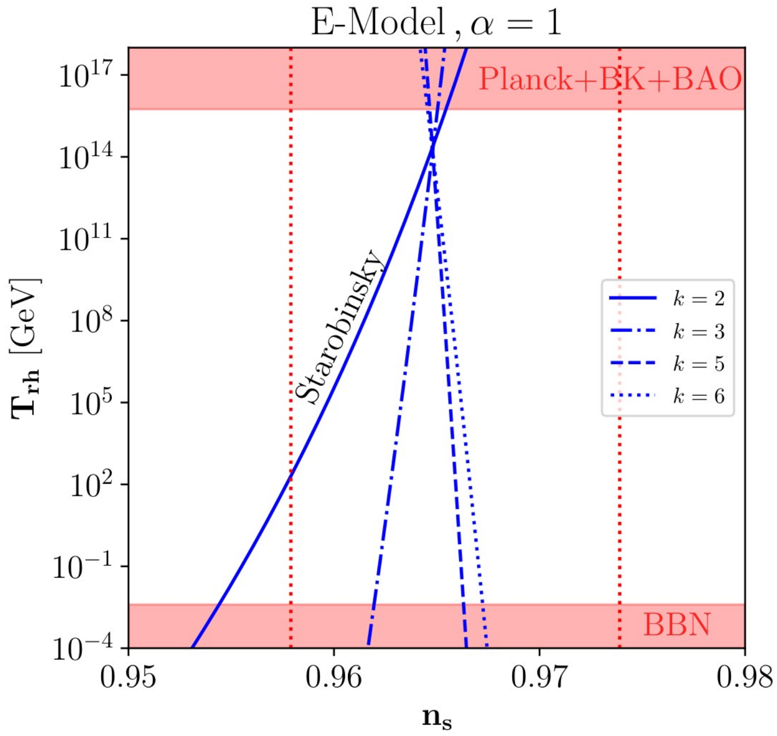
$$V(\Phi) = \lambda\frac{|\Phi|^k}{M^{k-4}}$$



→ **Dependence on reheating temperature of the Universe!**

Becker, Copello, JH, Lang, Xu (2023)

Constraints on the reheating temperature from inflation

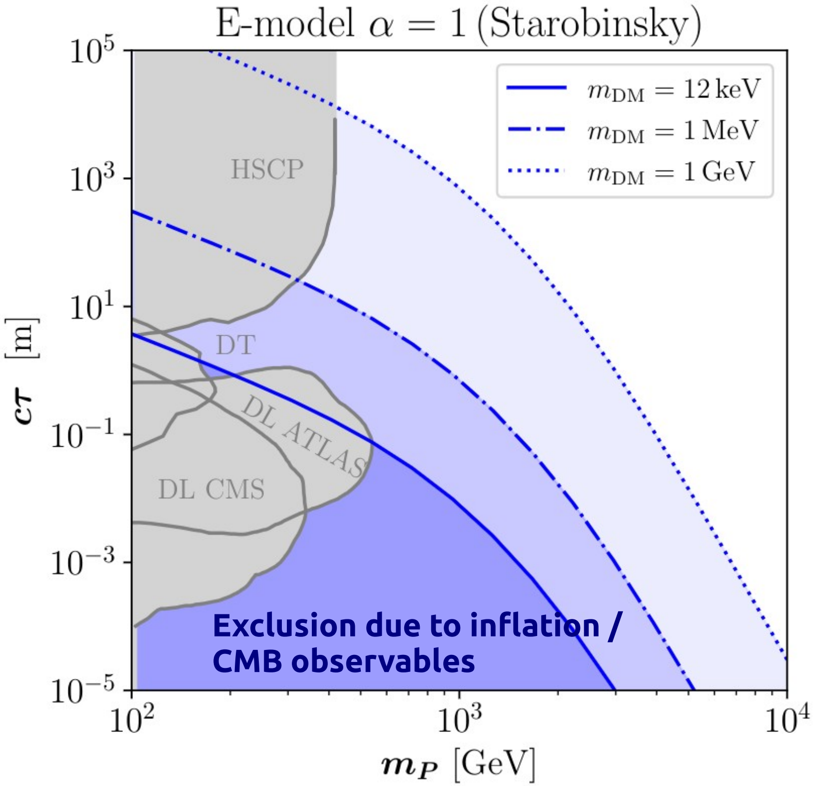


$$V(\Phi) = \lambda \frac{|\Phi|^k}{M^{k-4}}$$

→ **spectral index sets lower limit on T_{rh}**

Becker, Copello, JH, Lang, Xu (2023)

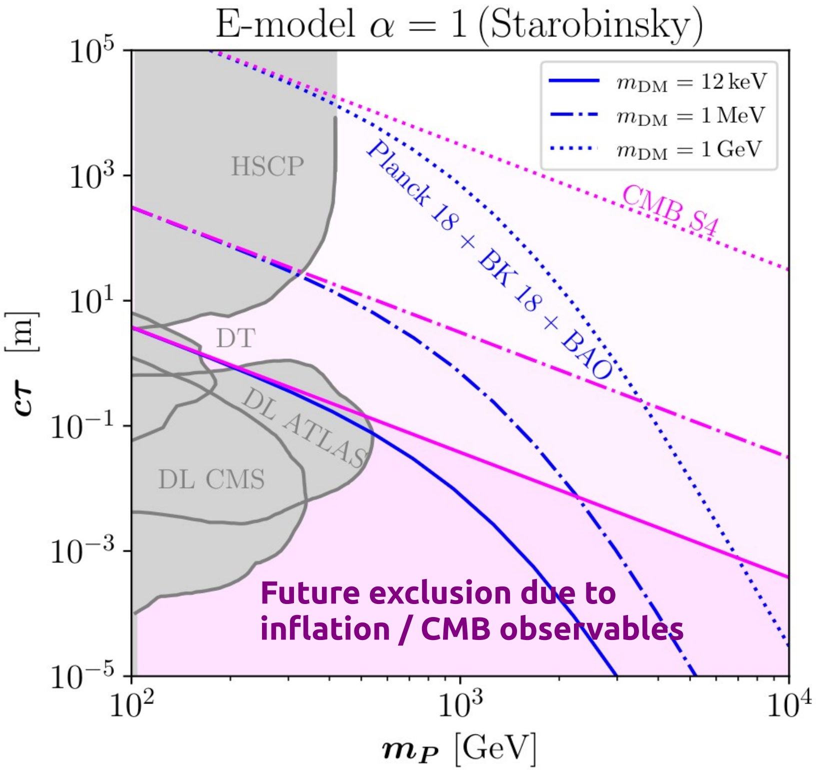
Linking the early Universe with physics in the lab



Exclusion due to inflation / CMB observables

Becker, Copello, JH, Lang, Xu (2023)

Linking the early Universe with physics in the lab



Future exclusion due to inflation / CMB observables

Becker, Copello, JH, Lang, Xu (2023)

Take-home messages II

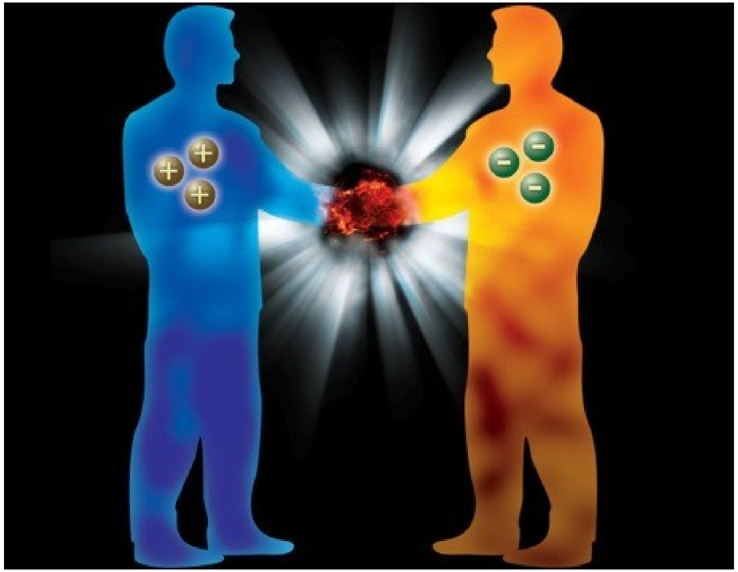
→ DM can span a large range of masses and interaction strengths

→ WIMP not yet dead

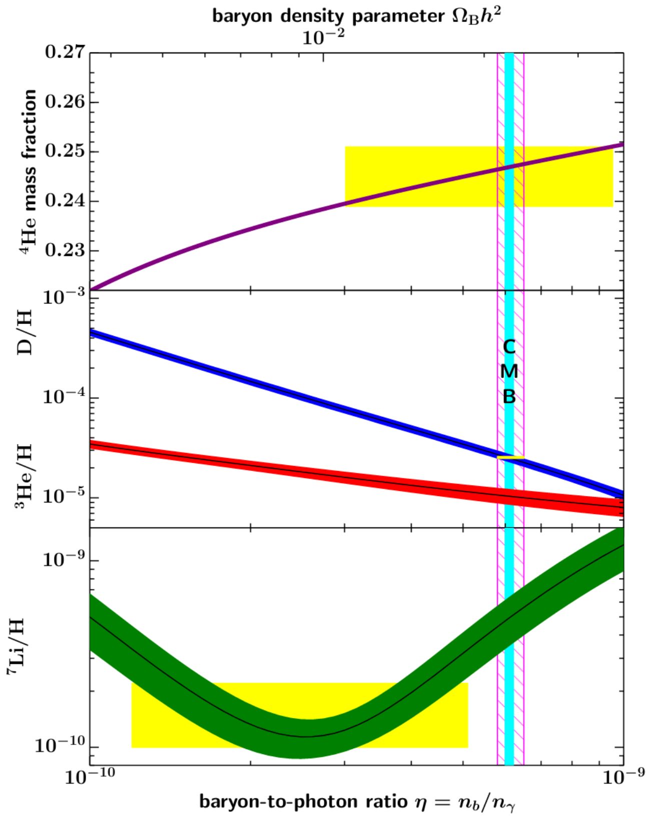
→ non-perturbative effects can crucially impact our interpretation of experimental limits

→ FIMPs feature interesting links between collider physics and cosmology (holistic approach!)

→ ask me about effects from the thermal plasma on dark matter production, in case of interest ;-)



Why do we exist?

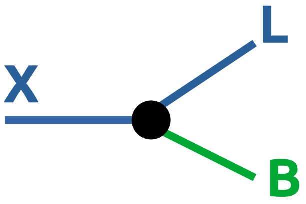


Why is there more matter than antimatter?

Why do we need new physics?

Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

☐ baryon number violation



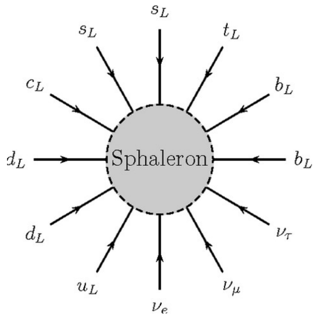
Why do we need new physics?

Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

SM?

☐ baryon number violation

SM sphaleron interactions



$$\Delta L = \Delta B = 3$$

highly active above T_{EW}

$$\partial_\mu (J^{B\mu} - J^{L\mu}) = 0$$ **B-L conserved**

$$\partial_\mu (J^{B\mu} + J^{L\mu}) \neq 0$$ **B+L violated**

$$\frac{\Gamma^b_{\rm SM}}{V} \sim \exp\left(-\frac{4\pi}{g_w}\frac{v_c}{T}\right)$$ **in broken phase suppressed**

$$\frac{\Gamma^s_{\rm SM}}{V} \sim \alpha_w^5 T^4$$ **in symmetric phase active**

Why do we need new physics?

Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

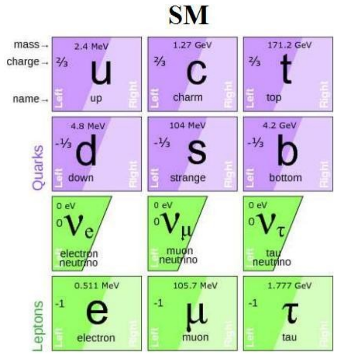
SM?

☑ baryon number violation

☐ C and CP violation

Charge conservation:

$$\Gamma(X \to AB) = \Gamma(\overline{X} \to \overline{A}\ \overline{B})$$



Requirement of charge violation:

$$\frac{dY_B}{dt} \approx \Gamma(X \to AB) - \Gamma(\overline{X} \to \overline{A}\ \overline{B})$$

Why do we need new physics?

Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

SM?

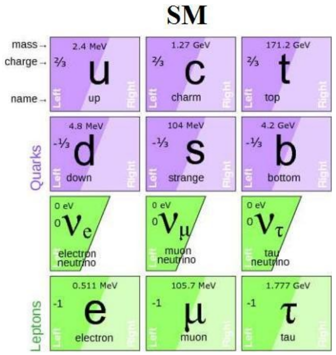
☑ baryon number violation

☐ C and CP violation

Charge and parity conservation:

$$\Gamma(X \to q_L q_L) = \Gamma(\overline{X} \to \bar{q}_R\, \bar{q}_R)$$

$$\Gamma(X \to q_R q_R) = \Gamma(\overline{X} \to \bar{q}_L\, \bar{q}_L)$$



Requirement of charge and parity violation:

$$\frac{dY_B}{dt} \approx \left[\left(\Gamma(\overline{X} \to \bar{q}_R\, \bar{q}_R) + \Gamma(\overline{X} \to \bar{q}_L\, \bar{q}_L)\right) - \left(\Gamma(X \to q_R q_R) + \Gamma(X \to q_L q_L)\right)\right]$$

Why do we need new physics?

Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

SM?

☑ baryon number violation

☒ C and CP violation

Quark sector exhibits CP violation (CPV)

$$|K_S^0\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_1^0\rangle + \epsilon\,|\bar{K}_2^0\rangle\right)$$

$$|K_L^0\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_2^0\rangle + \epsilon\,|\bar{K}_1^0\rangle\right)$$

$$\frac{J_{CP}}{T_C^{12}} \approx 10^{-20} \longleftrightarrow \mathcal{O}(10^{-10})$$

not enough CP violation within SM!

Why do we need new physics?

Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

SM?

☑ baryon number violation

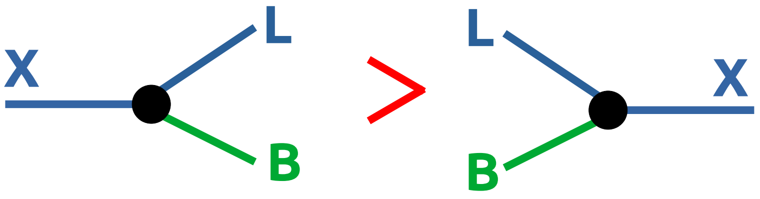
☒ C and CP violation

☐ departure from thermal equilibrium

$$\langle B\rangle_T = \mathrm{Tr}[e^{-\beta H}B] = \mathrm{Tr}[(CPT)(CPT)^{-1}e^{-\beta H}B]$$
$$= \mathrm{Tr}[e^{-\beta H}(CPT)^{-1}B(CPT)] = -\langle B\rangle_T$$

Departure from thermal equilibrium:

- First order phase transition (FOPT)
- Out-of-equilibrium decays



Why do we need new physics?

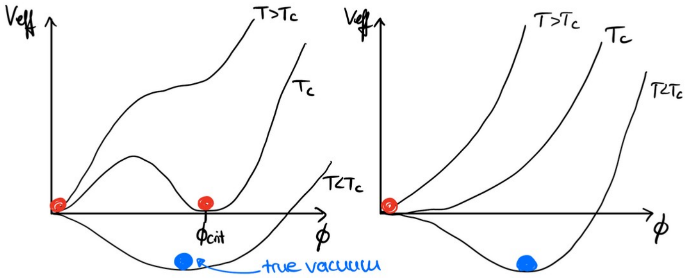
Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

SM?

☑ baryon number violation

☒ C and CP violation

☒ departure from thermal equilibrium



Strong FOPT during EWSB:

$$\frac{v_c}{T_c} \simeq \frac{3g^3v^2}{32\pi^2 m_h^2} \geq 1$$

$$m_h \leq 32\text{GeV}$$

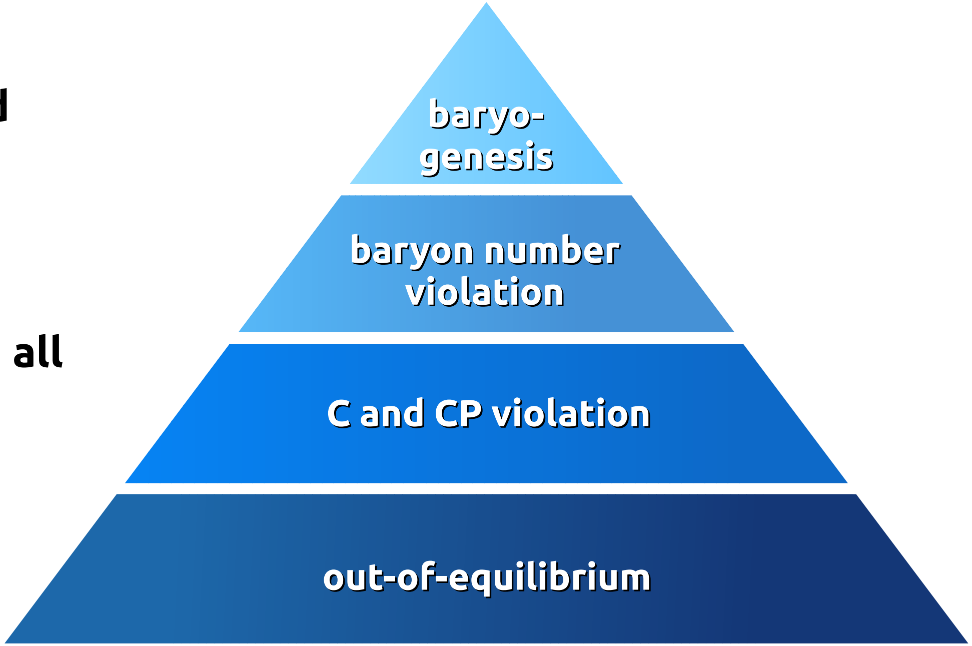
→ **Higgs too heavy for first order phase transition**

Why do we need new physics?

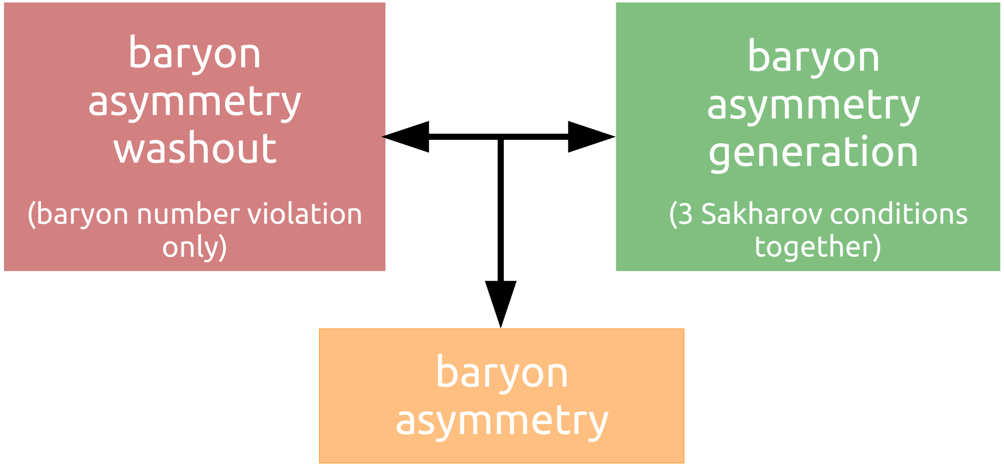
- **Three theoretical conditions** have to be fulfilled ("Sakharov conditions")

- The Standard Model cannot accommodate them all

→ **guarantee for new physics!**



Basic principle of baryogenesis



baryon asymmetry washout

(baryon number violation only)

baryon asymmetry generation

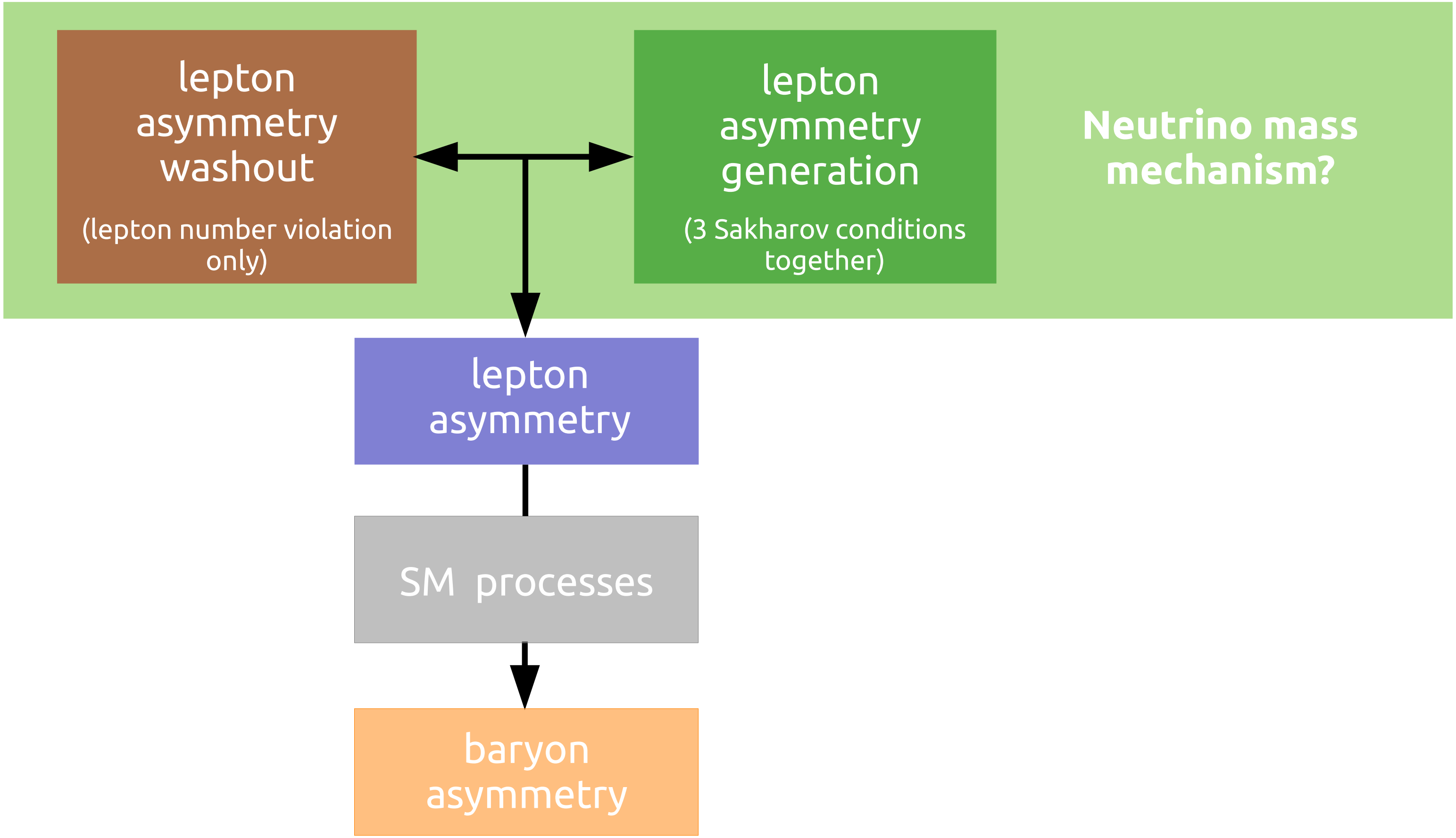
(3 Sakharov conditions together)

baryon asymmetry

Two complementary strategies to scientifically progress:

- **searching for new physics sourcing baryon asymmetry (identifying promising models)**
- **finding new physics depleting asymmetry (exclusion of models)**

Basic principle of leptogenesis



lepton asymmetry washout

(lepton number violation only)

lepton asymmetry generation

(3 Sakharov conditions together)

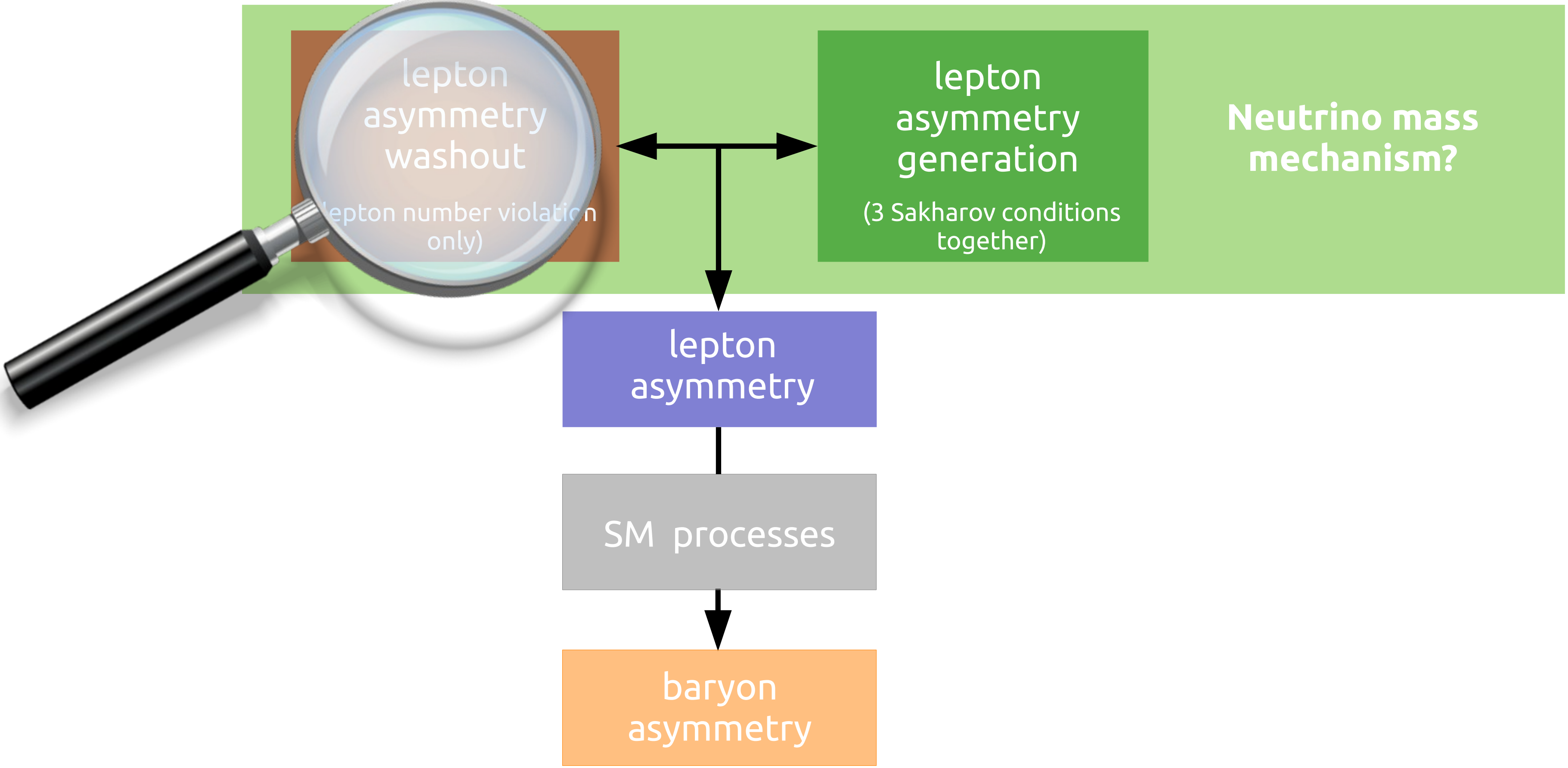
Neutrino mass mechanism?

lepton asymmetry

SM processes

baryon asymmetry

Basic principle of leptogenesis



lepton asymmetry washout

(lepton number violation only)

lepton asymmetry generation

(3 Sakharov conditions together)

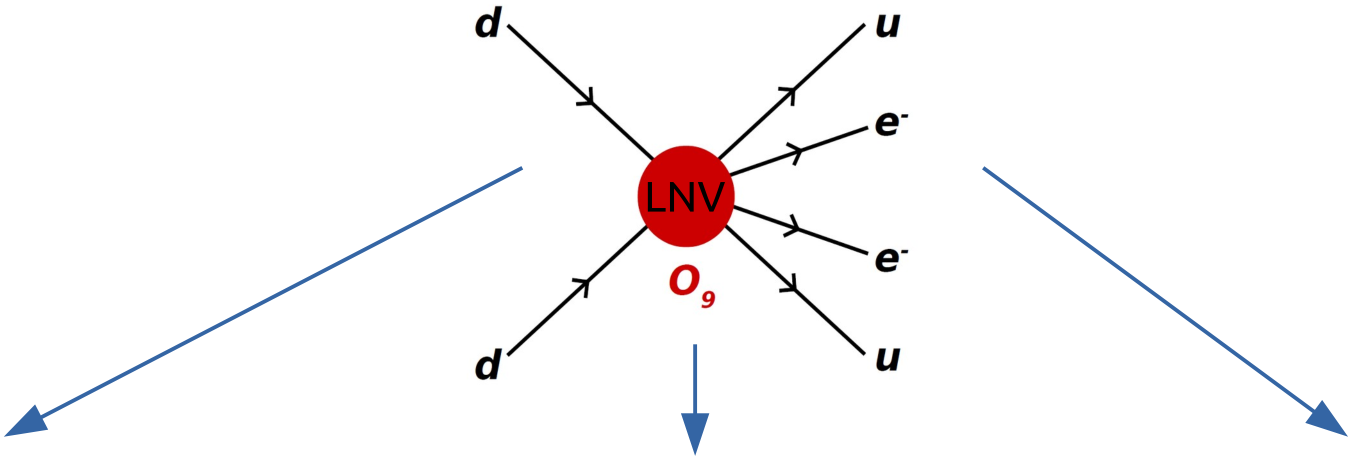
Neutrino mass mechanism?

lepton asymmetry

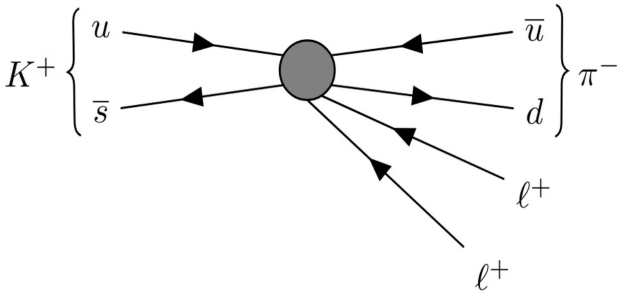
SM processes

baryon asymmetry

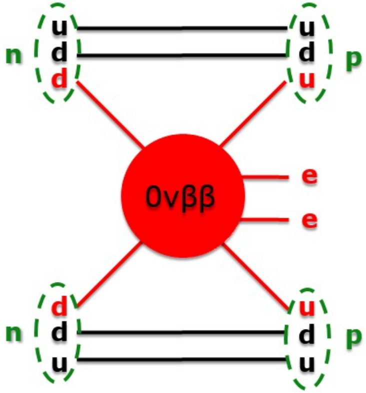
Probing LNV interactions



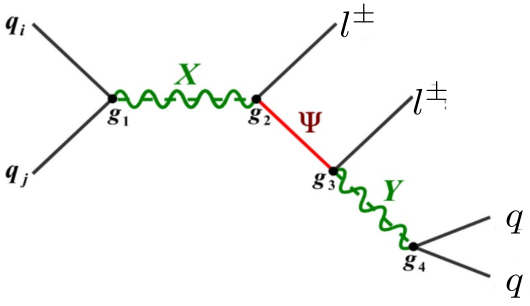
rare meson decays



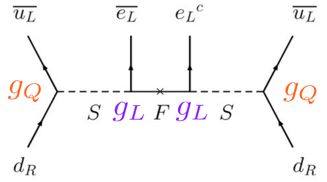
neutrinoless double beta decay

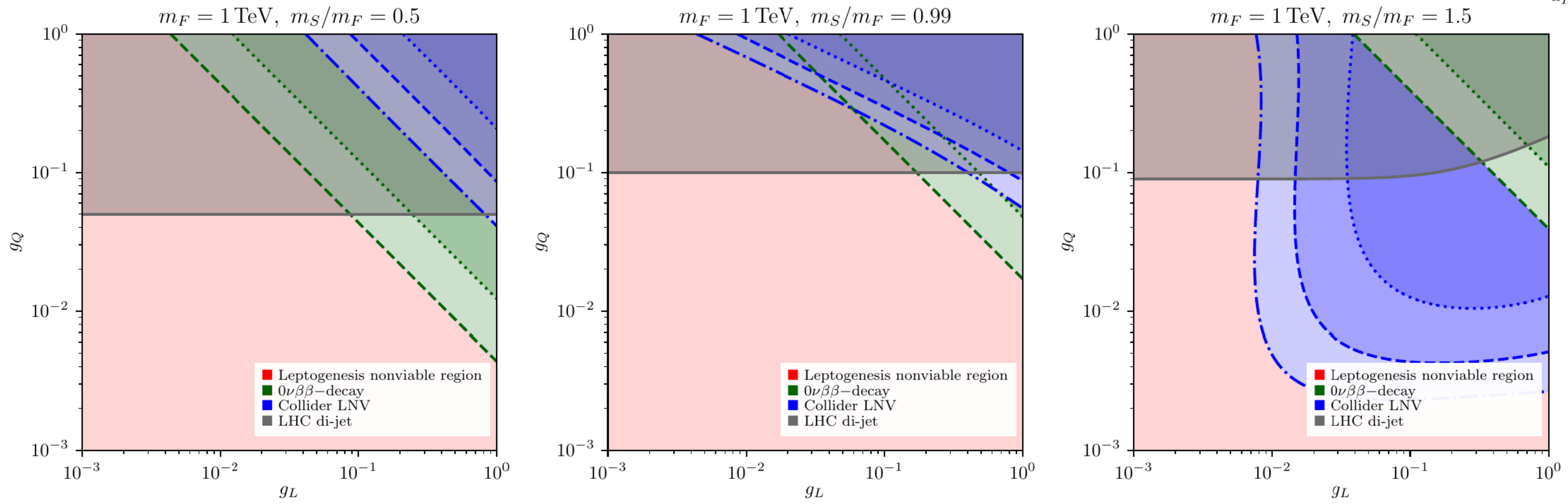


colliders



Probing Leptogenesis with LHC & 0νββ decay





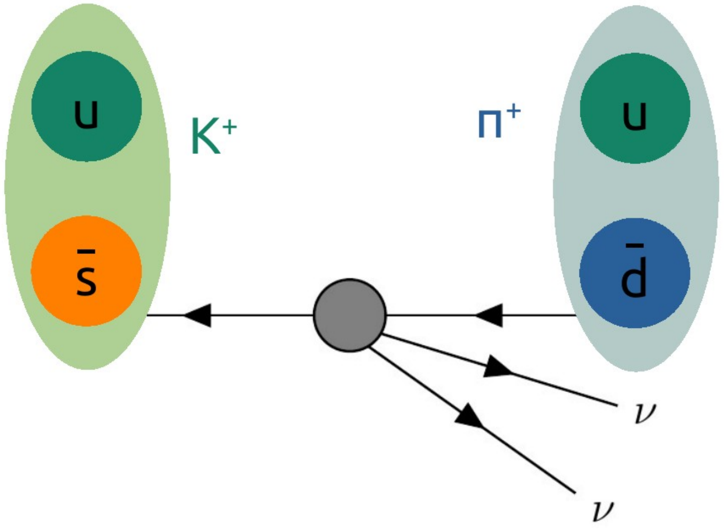
→ **Important complementarity between collider and 0νββ decay reach**

→ **Observation of TeV LNV would falsify standard thermal LG !**

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Probing LNV with invisible Meson Decays

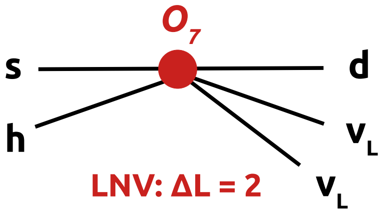
“Golden channel”



$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{SM}} = \left(8.5^{+1.0}_{-1.2}\right) \times 10^{-11}$$

Buras, Buttazzo, Girrbach-Noe, Knegjens (2015)

NA62 experiment aims for SM precision!



LNV: ΔL = 2

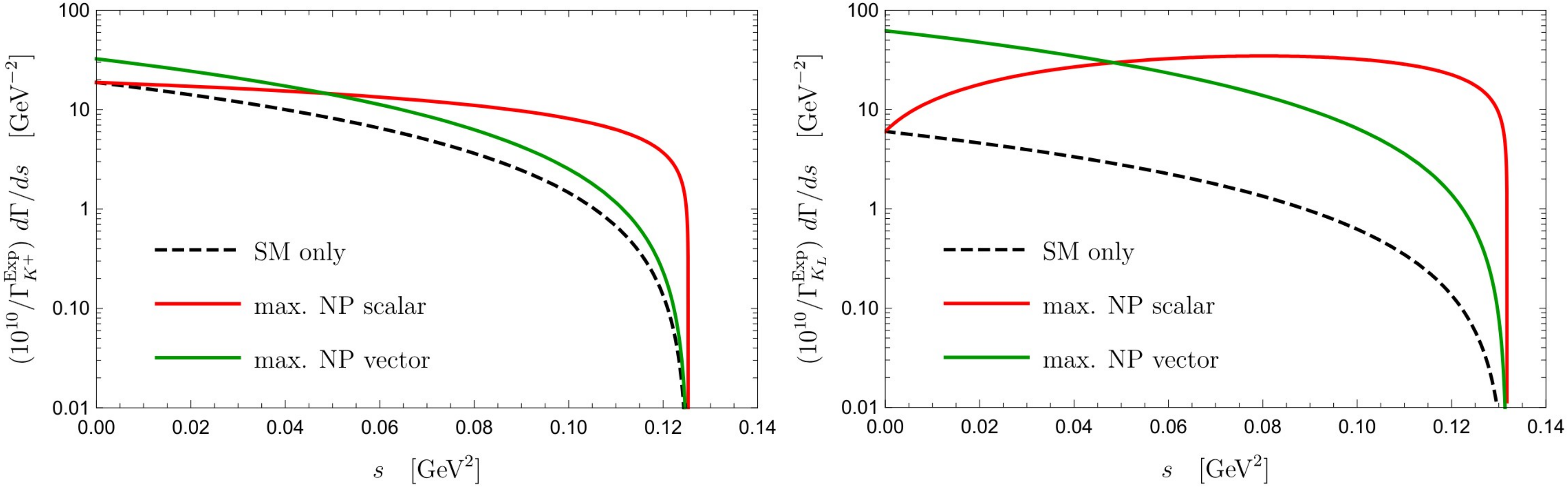
What if experiments point towards a deviation from the SM expectation?

As neutrinos are not explicitly measured, a new physics contribution could also be lepton number violating!

Probing LNV with invisible Meson decays

Allow for a NP scalar or vector contribution additionally to the SM such that the experimental upper bound

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.55 \times 10^{-10}$ **is saturated.**



→ NP scalar contribution leads to a striking difference in the distribution when comparing to vector only

→ ask me about our analysis for invisible B decays, in case of interest ;-)

Buras, JH, Mojahed (2024)
Deppisch, Fridell, JH (2020)

Take-home messages III

→ Sakharov conditions to be fulfilled to generate baryon asymmetry

→ direct tests possible for low-scale BG, only indirect tests for high-scale BG

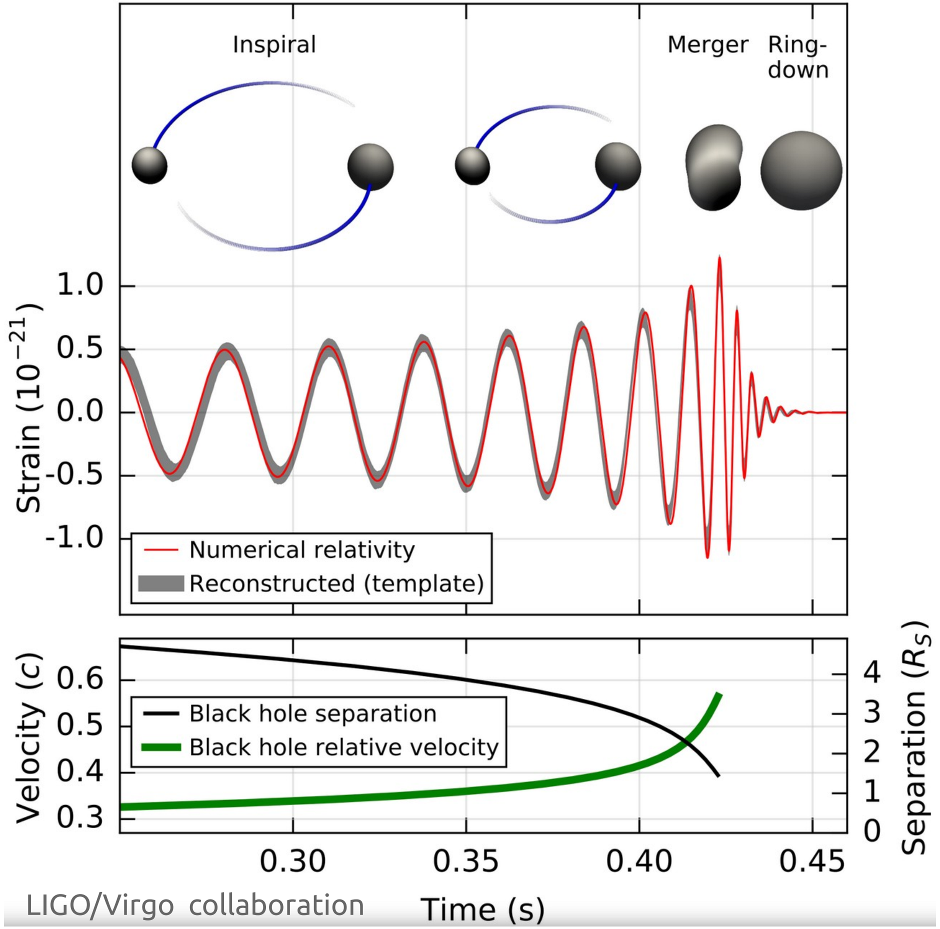
→ 0vbb decay, LHC, meson decays relevant for high-scale leptogenesis

→ even meson decays into invisible final state can be useful (but not alone)

→ ask me about the impact of n-nbar-oscillations, LHC, meson oscillations relevant for high-scale baryogenesis, in case of interest ;-)

III Gravitational Waves as Window to the Early Universe

New era of physics - first direct GW observation



LIGO/Virgo collaboration

On 14^{th} of September 2015, first direct observation (GW150914) of a GW by LIGO Hanford and Livingston observatories.

Signal vs stochastic gravitational wave background

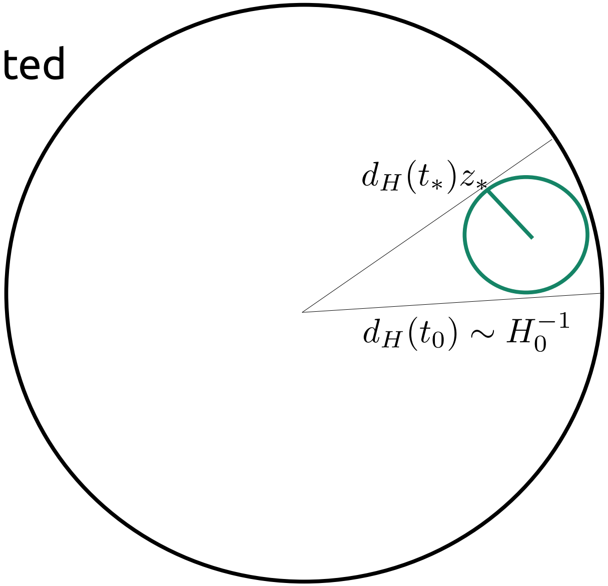
Can we directly observe sources from the early Universe?

The signal of a GW source at time t_* cannot produce a signal with correlated length / time scales larger than the causal horizon at that time

$$\ell_* \leq H_*^{-1}$$

Angular resolution needed for correlated GW signal at t_*

$$\theta = 360^\circ \cdot \left(\frac{2\pi d_H(t_0)}{2 d_H(t_*) z_*} \right)^{-1}$$



GW detector with angular resolution of 10 deg can only resolve events up to z_* < 20!
→ *Stochastic* Gravitational Wave Background (SGWB)

GW opens up new window to the early Universe

Tensor perturbations from early Universe events lead to gravitational wave imprints

$$ds^2 = -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j$$

$$\partial_i h_{ij} = h_{ii} = 0$$

$$\ddot{h_{ij}}(\mathbf{x},t) + 3H\dot{h}_{ij}(\mathbf{x},t) - \frac{\nabla^2}{a^2}h_{ij}(\mathbf{x},t) = 16\pi G \Pi_{ij}(\mathbf{x},t)$$

What can source a SGWB?

Inflation

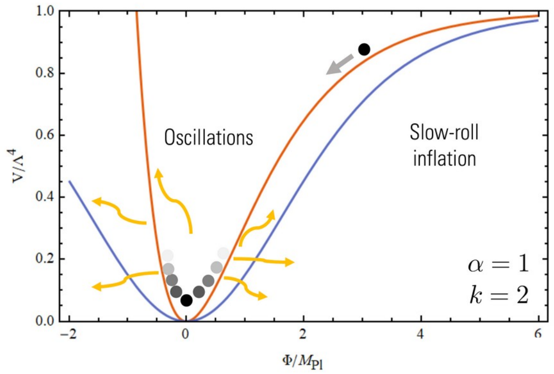
Temperature Fluctuations

First Order Phase Transition

Reheating (particle production)

Topological Defects (e.g. cosmic strings)

Example: Inflation



$$\ddot{h}_{ij}(\mathbf{x},t) + 3H\dot{h}_{ij}(\mathbf{x},t) - \frac{\nabla^2}{a^2}h_{ij}(\mathbf{x},t) = 0$$

So far we assumed "classical" scalar field without quantum fluctuations

$$\phi(\mathbf{x},t) = \overline{\phi}(t) + \delta\phi(\mathbf{x},t)$$

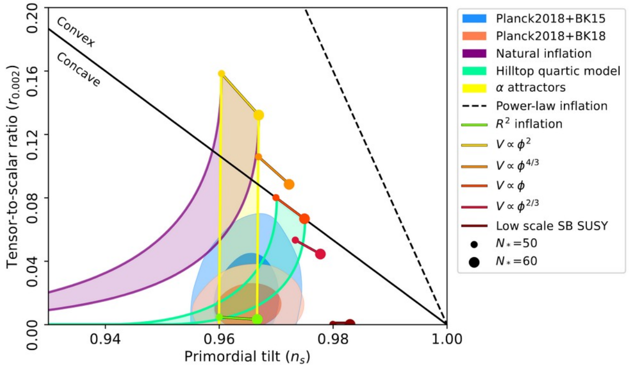
$$g_{\mu\nu}(\mathbf{x},t) = \overline{g}_{\mu\nu}(t) + h_{\mu\nu}(\mathbf{x},t)$$

Power spectrum of scalar (density fluctuations) and tensor (GWs) perturbations

$$\langle \mathcal{R}_{\mathbf{k}}\mathcal{R}_{\mathbf{k}'}\rangle = (2\pi)^3\delta(\mathbf{k}+\mathbf{k}')P_{\mathcal{R}}(k) \qquad \Delta_s^2 = \frac{k^3}{2\pi^2}P_{\mathcal{R}}(k)$$

$$\langle h_{\mathbf{k}}h_{\mathbf{k}'}\rangle = (2\pi)^3\delta(\mathbf{k}+\mathbf{k}')P_h(k) \qquad \Delta_t^2 = 2\frac{k^3}{2\pi^2}P_h(k)$$

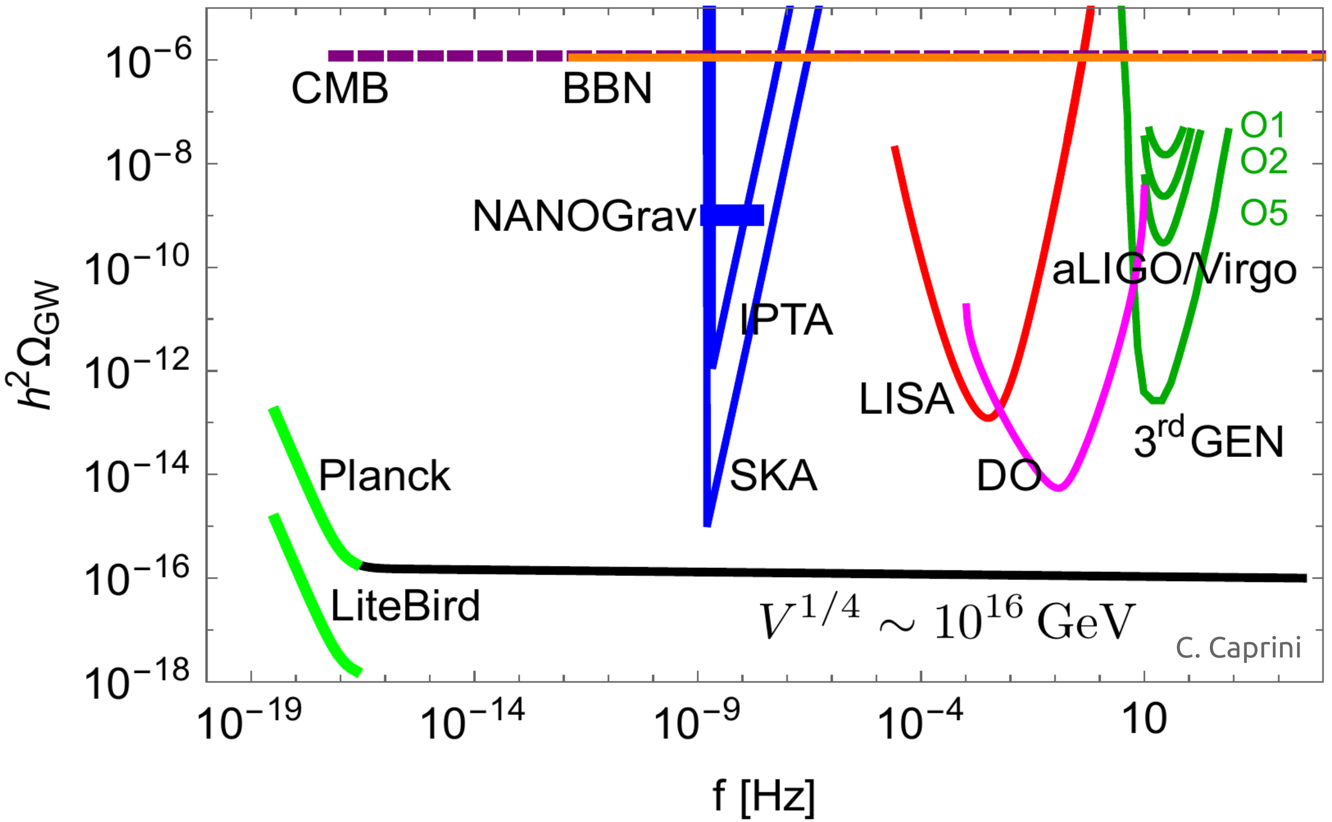
$$\left.\begin{matrix} \Delta_s^2 \\ \Delta_t^2 \end{matrix}\right\} \quad r = \frac{\Delta_s^2}{\Delta_t^2}$$



$$\Omega_{GW}(k,\tau_0) = \frac{[T'(k,\tau_0)]^2}{12a_0^2H_0^2}P_h(k)$$

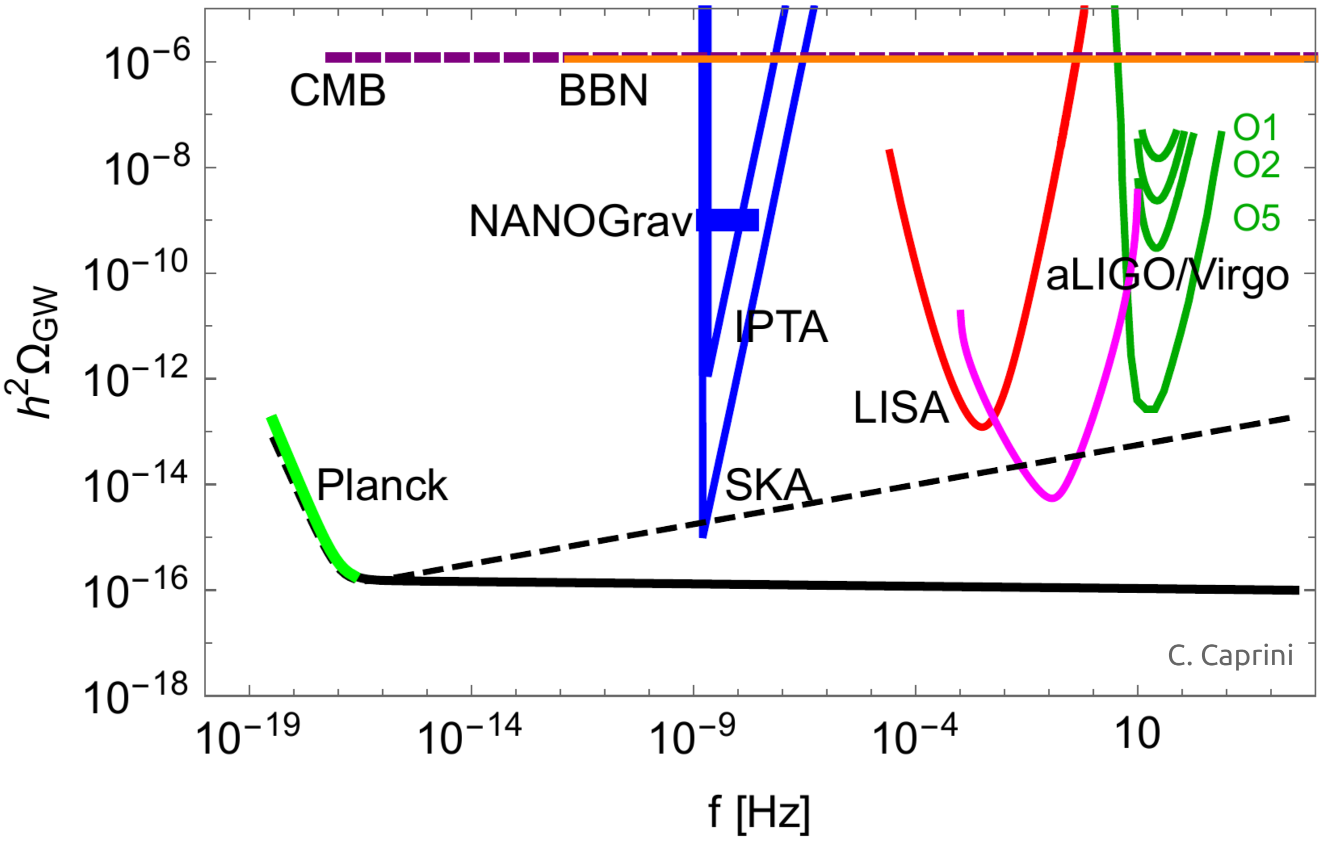
$$\Omega_{GW}(f) = \frac{33}{128}\Omega_{rad}\, r\, P_{\mathcal{R}}^*\left(\frac{f}{f_*}\right)^{n_T}\left[\frac{1}{2}\left(\frac{f_{eq}}{f}\right)^2 + \frac{16}{9}\right]$$

Example: Inflation



$\Pi_{ij}(\mathbf{x}, t) = 0$

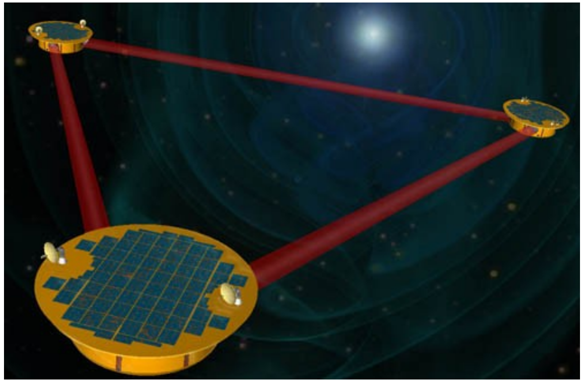
Example: Inflation



$\Pi_{ij}(\mathbf{x},t) \neq 0$

$\Pi_{ij}(\mathbf{x},t) = 0$

Plethora of GW experiments



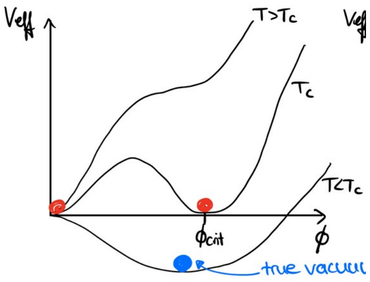
Pulsar Timing Arrays
(e.g. NanoGrav, ...)

Space based interferometers
(e.g. LISA, ...)

Earth based interferometers
(e.g. LIGO/Virgo,...)

nHz mHz kHz

Example: First order phase transition

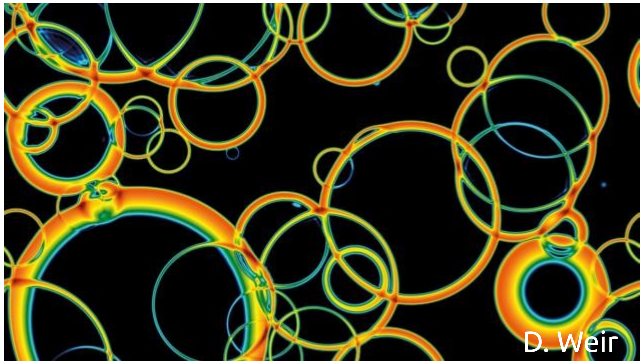


$$\ddot{h}_{ij}(\mathbf{x},t) + 3H\dot{h}_{ij}(\mathbf{x},t) - \frac{\nabla^2}{a^2}h_{ij}(\mathbf{x},t) = 16\pi G \Pi_{ij}(\mathbf{x},t)$$

Bubble wall collisions: $\Pi_{ij} \sim [\partial\phi_i \partial\phi_j]^{TT}$

Sound waves and turbulence: $\Pi_{ij} \sim [\gamma^2(\rho+p)v_i v_j]^{TT}$

Primordial magnetic fields (MHD turbulence): $\Pi_{ij} \sim [-E_i E_j - B_i B_j]^{TT}$


D. Weir

Example: First order phase transition

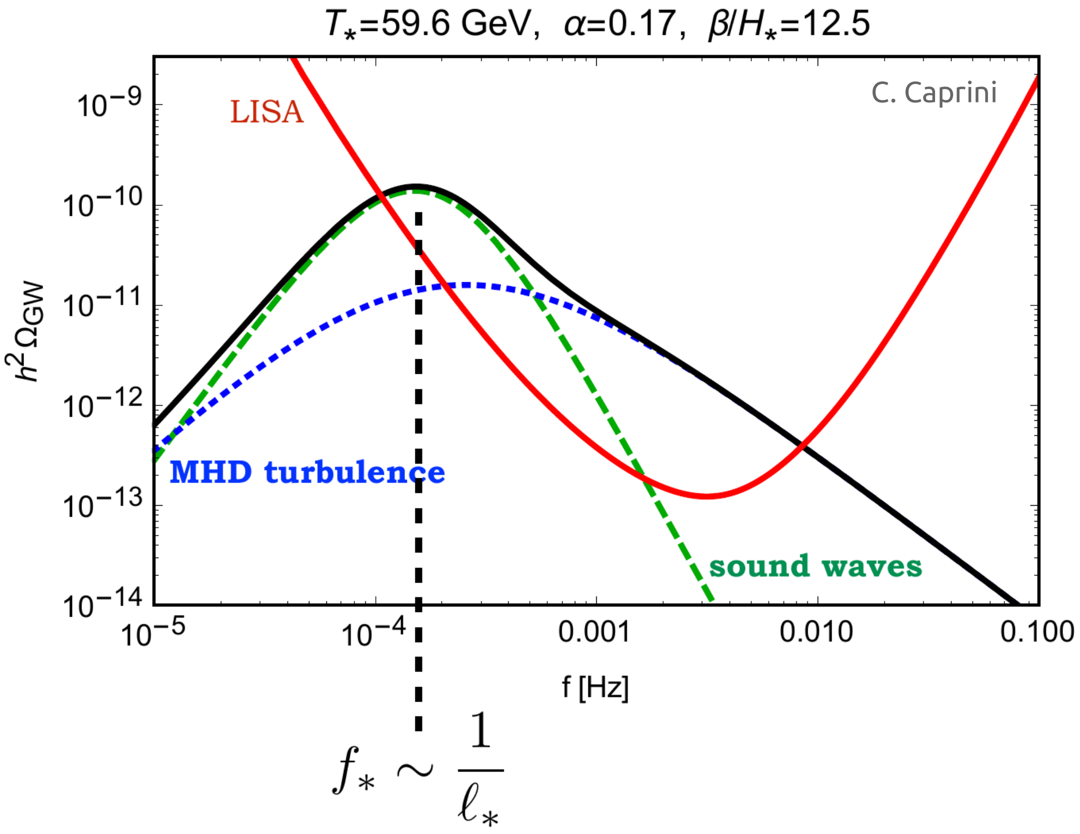
Characteristic frequency connected to bubble size:

$$f = f_* \frac{a_*}{a_0} = \frac{1.65 \times 10^{-7}}{\ell_* H_*} \left(\frac{g(T_*)}{100}\right)^{1/6} \frac{T_*}{\mathrm{GeV}} \mathrm{Hz}$$

Implications on detectability:

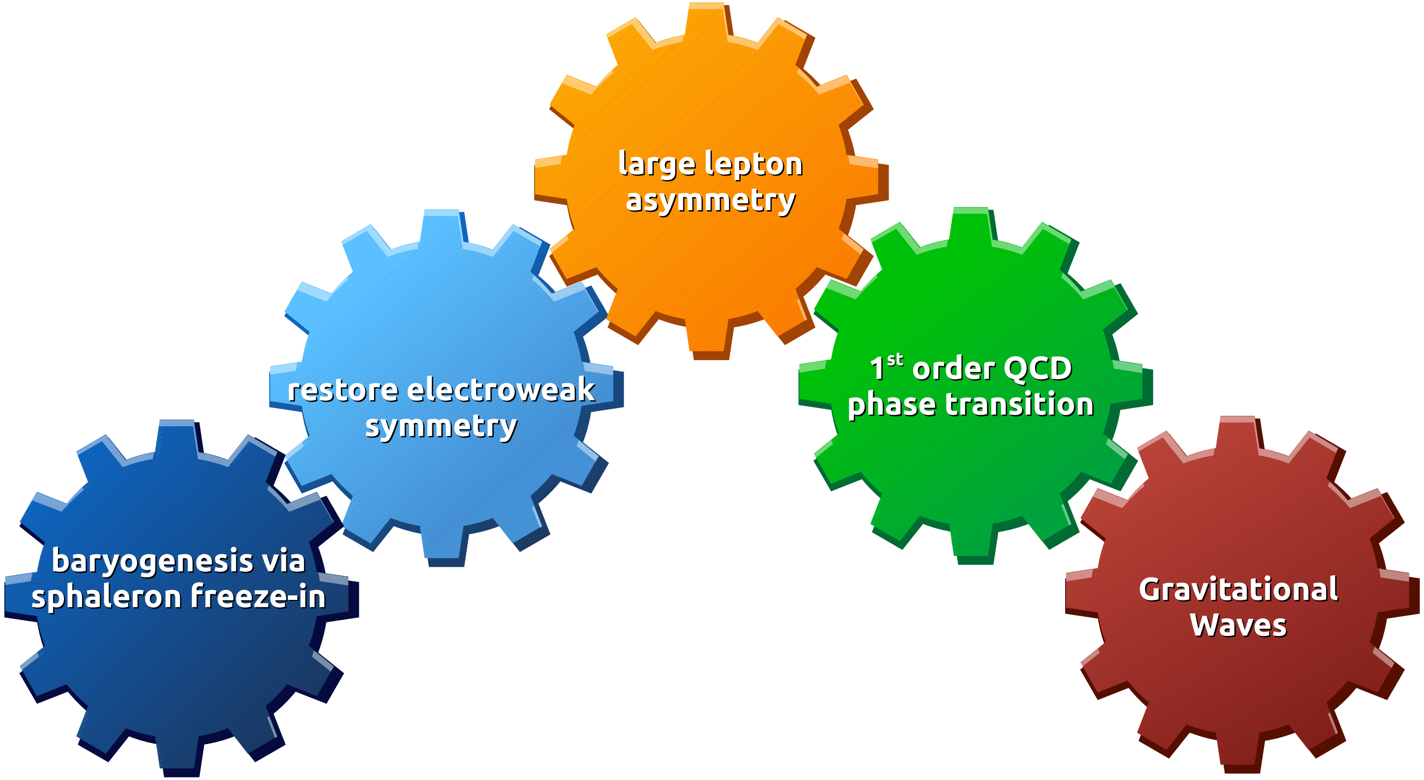
$T_{\mathrm{EW}} \sim 100\mathrm{GeV}$ $\quad \ell_* H_* \simeq 0.01 \Longrightarrow f \sim \mathrm{mHz}$ LISA

$T_* \sim 0.1\mathrm{GeV}$ $\quad \ell_* H_* \simeq 0.1 \Longrightarrow f \sim 10\mathrm{nHz}$ PTA



$$f_* \sim \frac{1}{\ell_*}$$

Sphaleron freeze-in BG with GWs from QCD transition



baryogenesis via sphaleron freeze-in

restore electroweak symmetry

large lepton asymmetry

1st order QCD phase transition

Gravitational Waves

Gao, Harz, Hati, Lu, Oldengott, White (2024)

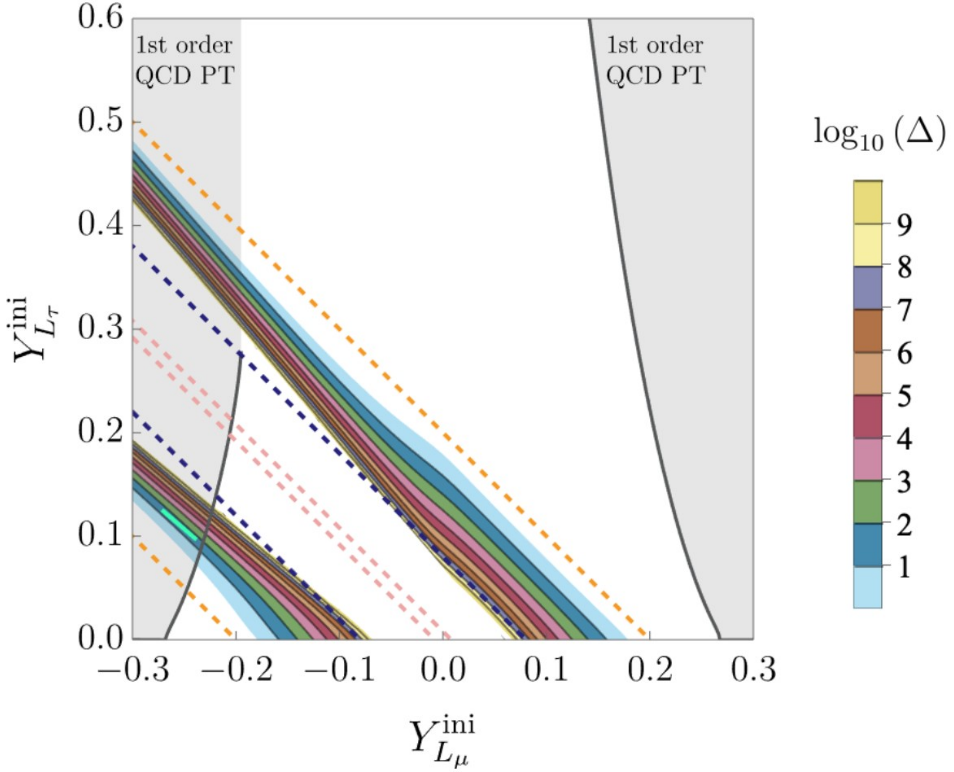
Sphaleron freeze-in BG with GWs from QCD transition

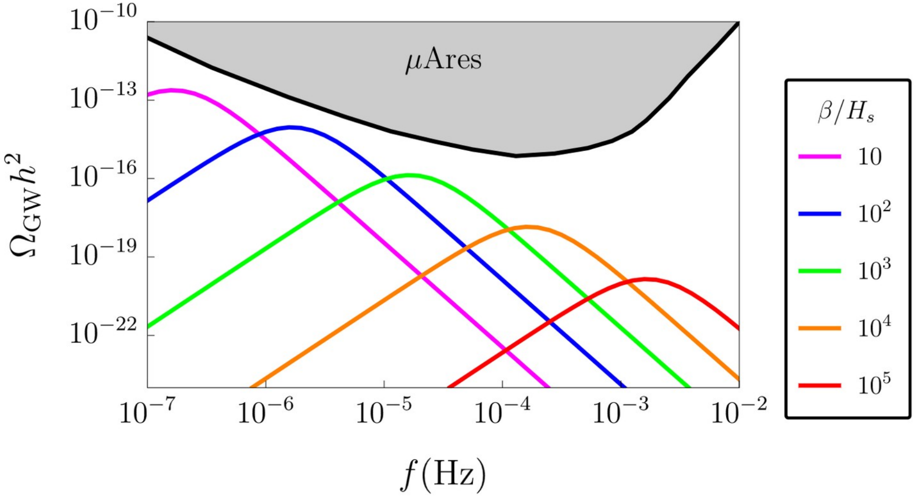
Idea: Large Lepton asymmetry restores EW symmetry and can lead to first order QCD transition

- **Large lepton asymmetry** leads to **restoration of EW symmetry** at large temperatures
- restoration of EW symmetry renders **sphaleron transitions inefficient** and slowly translate large lepton asymmetry into a baryon asymmetry
- Constraints on large lepton asymmetry from CMB and BBN and neutrino oscillations (flavour equilibrations): due to charge neutrality, **asymmetry must "hide" in neutrino sector**
- **Correct baryon asymmetry** only possible with additional **entropy dilution**
- Large lepton asymmetry can lead to f**irst order QCD phase transition**
- First order QCD phase transition can lead to **GWs**

Gao, Harz, Hati, Lu, Oldengott, White (2024)

Sphaleron freeze-in BG with GWs from QCD transition





Gao, Harz, Hati, Lu, Oldengott, White (2024)

Take-home messages IV

→ SGWB is a window to early Universe physics
(inflation, reheating, phase transitions, topological defects,...)

→ earth based and space based experiments cover different frequencies

→ exciting new complementary possibilities ahead

Conclusions

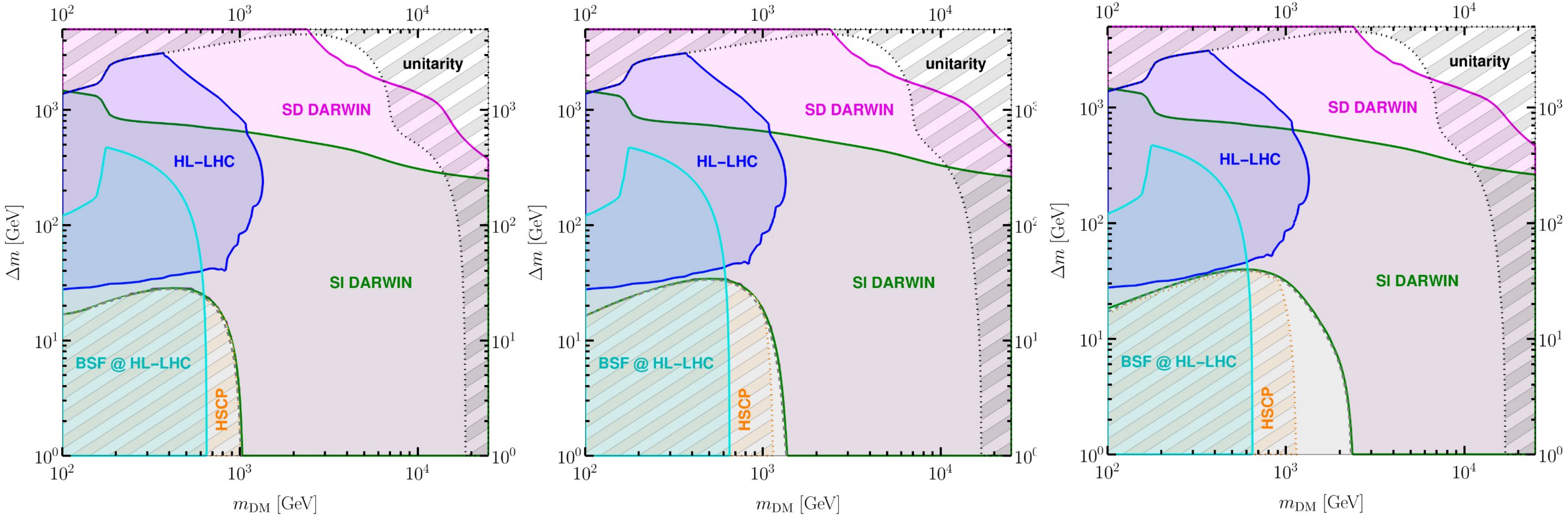
- Inflation, dark matter, the baryon asmmetry and neutrinos are four of the biggest puzzles of modern (astro)particle physics
- Novel theoretical strategies needed to discover new physics
- Cutting-edge methods needed for accurate theory predictions and correct experimental interpretation
- Crucial interplay with experiments not to leave any stone unturned

Exciting complementary insights from the early Universe and laboratory experiments!

Thank you for your attention!

NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)

Future prospects



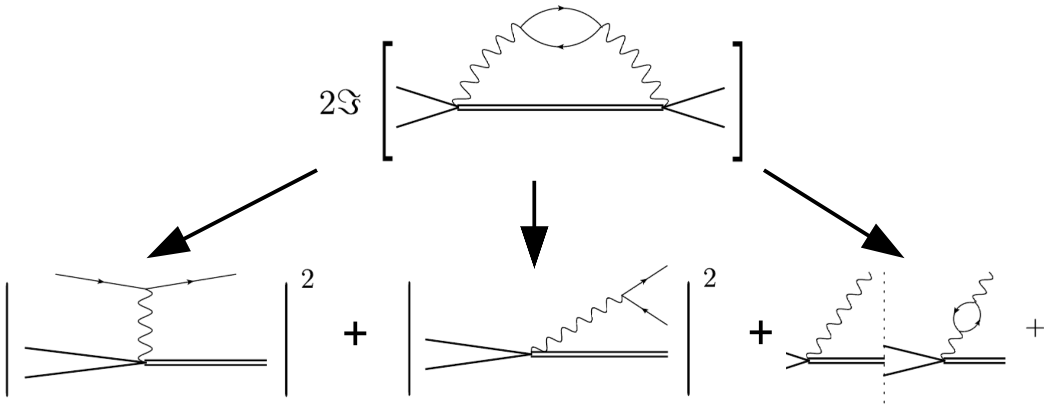
- **HSPC not strict exclusion limit (BSF@LHC is!)**
- **Highly testable: parameter space can be almost entirely probed**
- **BSF effects enlarge parameter range that still needs to be tested**

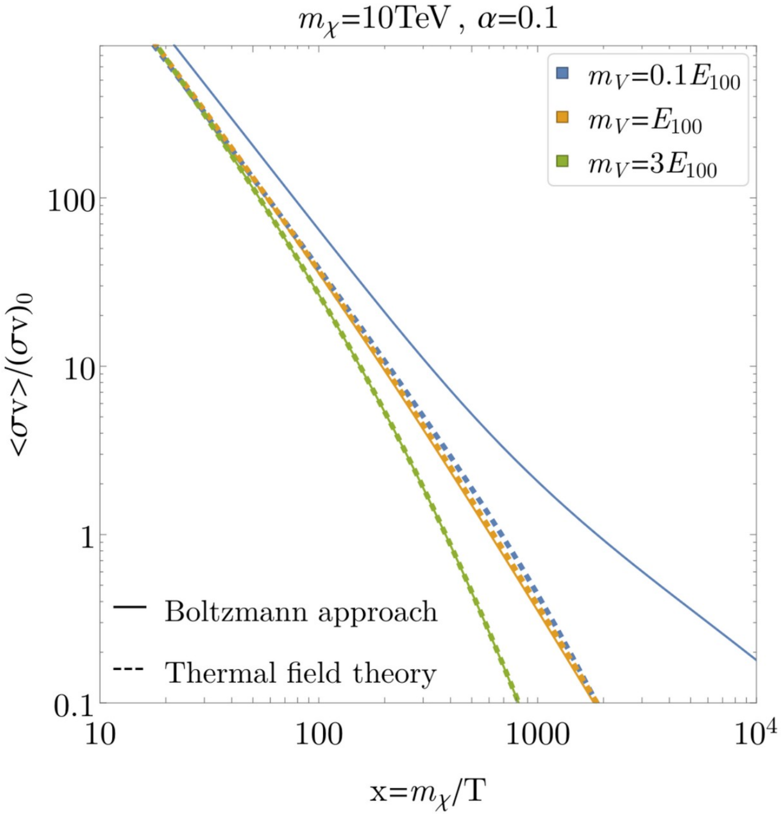
Becker, Copello, JH, Mohan, Sengupta (2022)

Towards new standards for the DM abundance

→ **first thermal description at NLO** of bound state formation beyond ionisation equilibrium in the WIMP paradigm

→ **improves** the unphysical log-enhanced Boltzmann approach **for massless mediators**

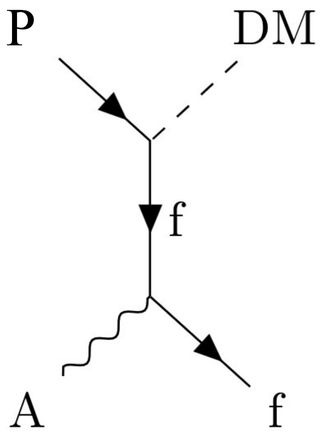




Binder, Blobel, **JH**, Mukaida (2020)

State-of-the art

- **Different treatments can be found in the literature**
    - Boltzmann approach with decays in vacuum only
    - Boltzmann approach with decays only including thermal masses
    - Boltzmann approach with decays and scattering including thermal masses
    - Non-equilibrium approach with tree-level propagators
    - Non-equilibrium approach with HTL approximated propagators



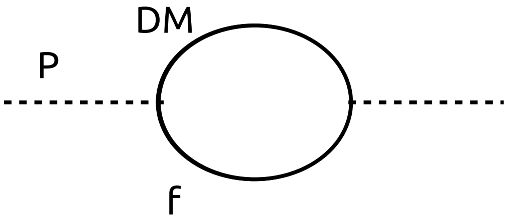
→ How do different treatments in the literature compare?

→ What is the *correct* result?

Advancing methods: calculation from first principles

- **Calculate freeze-in within non-equilibrium framework (closed time path formalism) with 1PI-resummed propagators at LO in the loop expansion of 2PI effective action**

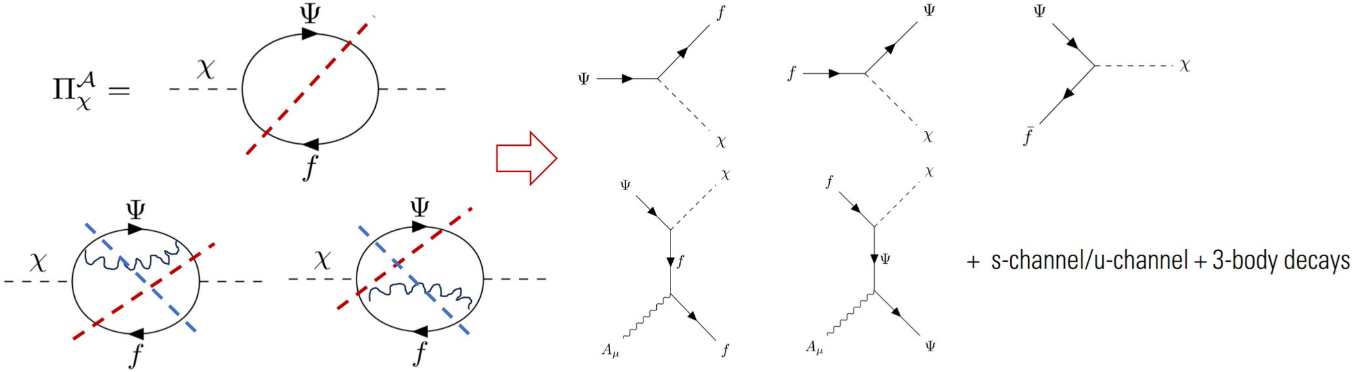
$$\dot{n}_{\mathrm{DM}}(t) + 3Hn_{\mathrm{DM}} = \frac{1}{2\pi^2}\int d|\vec{p}|\,\frac{|\vec{p}|^2}{E_{\mathrm{DM}}}\,\Pi^A_{\mathrm{DM}}(E_{\mathrm{DM}},|\vec{p}|)\,f_{\mathrm{DM}}(E_{\mathrm{DM}})$$



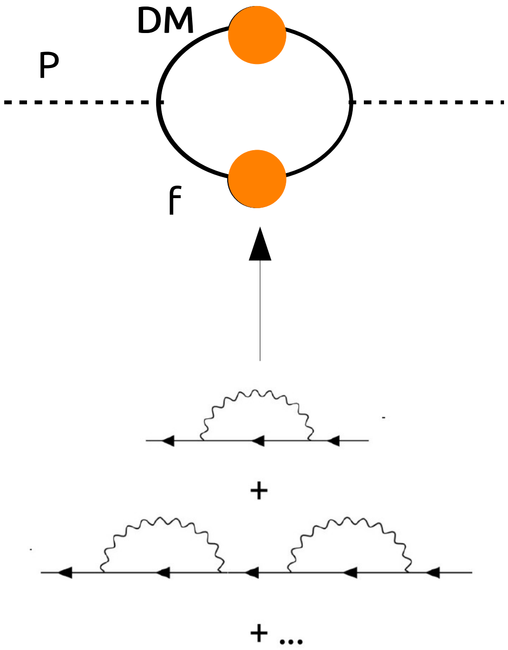
Becker, Copello, JH, Tamarit (2023)

Advancing methods: calculation from first principles

- **Calculate freeze-in within non-equilibrium framework (closed time path formalism) with 1PI-resummed propagators at LO in the loop expansion of 2PI effective action**

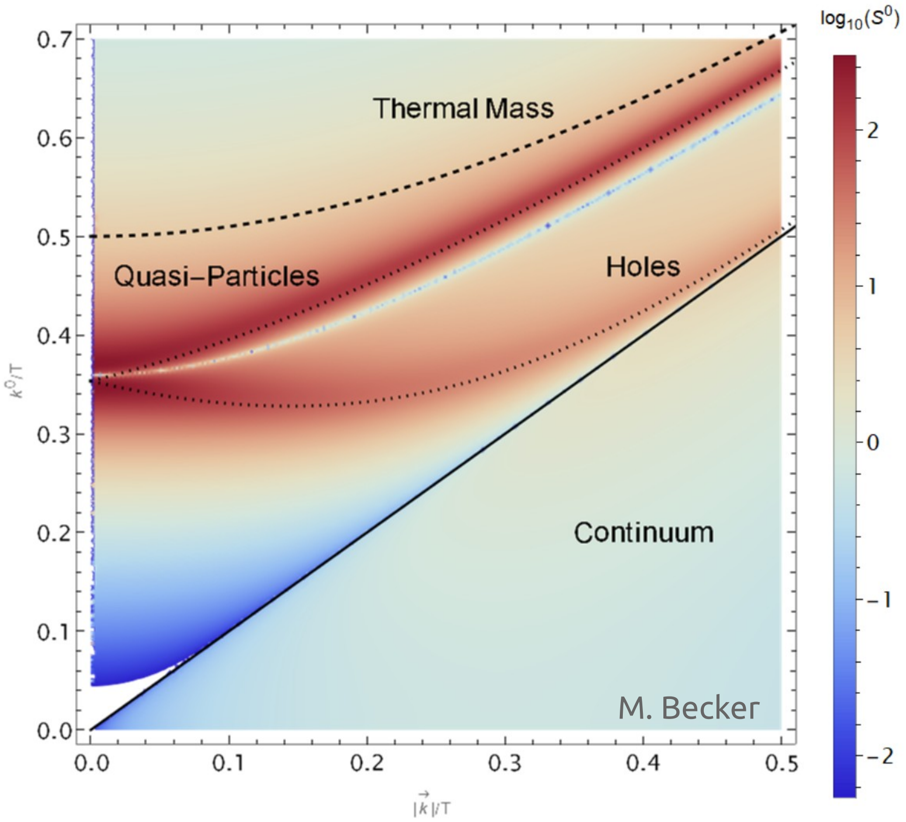


E. Copello



- With generic coupling G: F-A-A $G = Y^2 g_1^2 + C_2\left(\mathcal{R}_2\right) g_2^2 + C_2\left(\mathcal{R}_3\right) g_3^2$

Advancing methods: thermal corrections



$S^{\mathcal{A}} \sim$

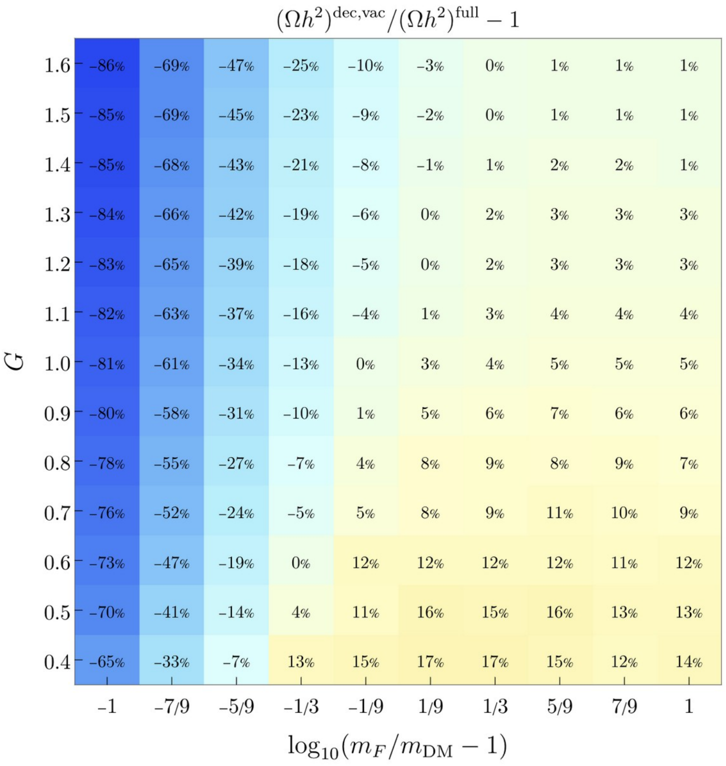
- **In vacuum** $\delta(k^2 - m_0^2)$
- **With thermal masses** $\delta(k^2 - m_{\mathrm{th}}^2)$
- **HTL approximation** $\delta(k^2 - \Sigma^{\mathcal{H}}(k)) + \mathcal{S}^{\mathcal{A}}_{\mathrm{cont.}}$
- **1PI resummed**

$$(k - \Sigma^{\mathcal{H}}(k))\frac{\Gamma(k)}{\Omega^2(k) + \Gamma^2(k)} - \Sigma^{\mathcal{A}}(k)\frac{\Omega(k)}{\Omega^2(k) + \Gamma^2(k)}$$

Impact of thermal corrections on freeze-in DM production

Compared to vacuum decay only

interaction strength of
P with the SM bath



G	-1	-7/9	-5/9	-1/3	-1/9	1/9	1/3	5/9	7/9	1
1.6	-86%	-69%	-47%	-25%	-10%	-3%	0%	1%	1%	1%
1.5	-85%	-69%	-45%	-23%	-9%	-2%	0%	1%	1%	1%
1.4	-85%	-68%	-43%	-21%	-8%	-1%	1%	2%	2%	1%
1.3	-84%	-66%	-42%	-19%	-6%	0%	2%	3%	3%	3%
1.2	-83%	-65%	-39%	-18%	-5%	0%	2%	3%	3%	3%
1.1	-82%	-63%	-37%	-16%	-4%	1%	3%	4%	4%	4%
1.0	-81%	-61%	-34%	-13%	0%	3%	4%	5%	5%	5%
0.9	-80%	-58%	-31%	-10%	1%	5%	6%	7%	6%	6%
0.8	-78%	-55%	-27%	-7%	4%	8%	9%	8%	9%	7%
0.7	-76%	-52%	-24%	-5%	5%	8%	9%	11%	10%	9%
0.6	-73%	-47%	-19%	0%	12%	12%	12%	12%	11%	12%
0.5	-70%	-41%	-14%	4%	11%	16%	15%	16%	13%	13%
0.4	-65%	-33%	-7%	13%	15%	17%	17%	15%	12%	14%

Normalized relative mass difference between P and DM

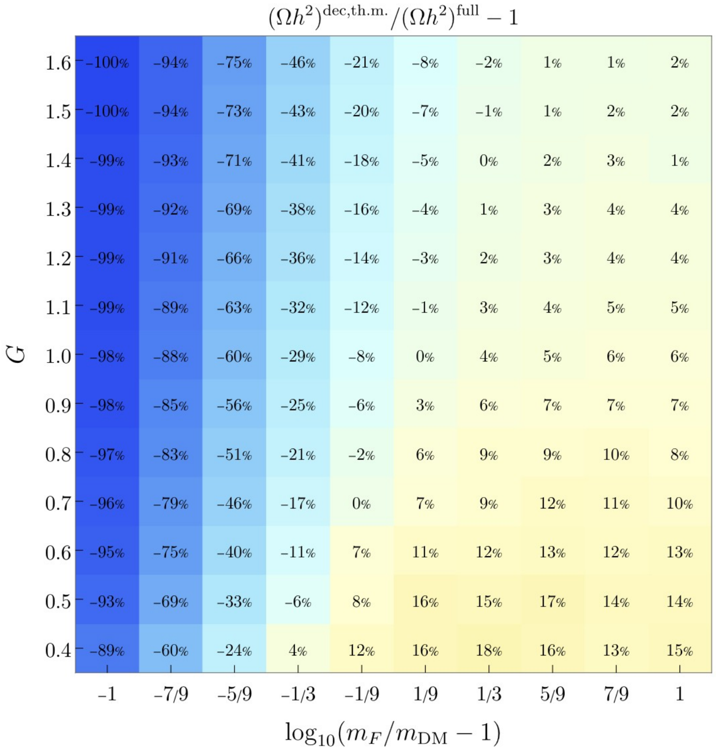
- $\Omega_{\rm DM}$ strongly underestimated for small mass splittings
- $\Omega_{\rm DM}$ (accidentally) correct for larger mass splittings

Becker, Copello, JH, Tamarit (2023)

Impact of thermal corrections on freeze-in DM production

Compared to decays with thermal masses

interaction strength of
P with the SM bath



G	−1	−7/9	−5/9	−1/3	−1/9	1/9	1/3	5/9	7/9	1
1.6	−100%	−94%	−75%	−46%	−21%	−8%	−2%	1%	1%	2%
1.5	−100%	−94%	−73%	−43%	−20%	−7%	−1%	1%	2%	2%
1.4	−99%	−93%	−71%	−41%	−18%	−5%	0%	2%	3%	1%
1.3	−99%	−92%	−69%	−38%	−16%	−4%	1%	3%	4%	4%
1.2	−99%	−91%	−66%	−36%	−14%	−3%	2%	3%	4%	4%
1.1	−99%	−89%	−63%	−32%	−12%	−1%	3%	4%	5%	5%
1.0	−98%	−88%	−60%	−29%	−8%	0%	4%	5%	6%	6%
0.9	−98%	−85%	−56%	−25%	−6%	3%	6%	7%	7%	7%
0.8	−97%	−83%	−51%	−21%	−2%	6%	9%	9%	10%	8%
0.7	−96%	−79%	−46%	−17%	0%	7%	9%	12%	11%	10%
0.6	−95%	−75%	−40%	−11%	7%	11%	12%	13%	12%	13%
0.5	−93%	−69%	−33%	−6%	8%	16%	15%	17%	14%	14%
0.4	−89%	−60%	−24%	4%	12%	16%	18%	16%	13%	15%

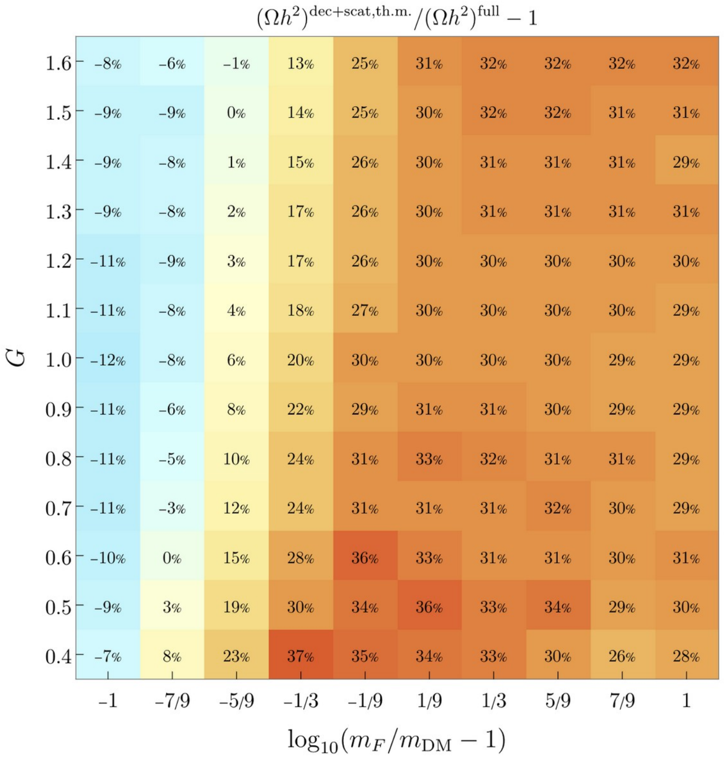
Normalized relative mass difference between P and DM

- Ω_{DM} strongly underestimated for small mass splittings
- Ω_{DM} (accidentally) correct for larger mass splittings
- **Thermal masses increase the deviation**

Becker, Copello, JH, Tamarit (2023)

Impact of thermal corrections on freeze-in DM production

Compared to decays and scattering with thermal masses



G	−1	−7/9	−5/9	−1/3	−1/9	1/9	1/3	5/9	7/9	1
1.6	−8%	−6%	−1%	13%	25%	31%	32%	32%	32%	32%
1.5	−9%	−9%	0%	14%	25%	30%	32%	32%	31%	31%
1.4	−9%	−8%	1%	15%	26%	30%	31%	31%	31%	29%
1.3	−9%	−8%	2%	17%	26%	30%	31%	31%	31%	31%
1.2	−11%	−9%	3%	17%	26%	30%	30%	30%	30%	30%
1.1	−11%	−8%	4%	18%	27%	30%	30%	30%	30%	29%
1.0	−12%	−8%	6%	20%	30%	30%	30%	30%	29%	29%
0.9	−11%	−6%	8%	22%	29%	31%	31%	30%	29%	29%
0.8	−11%	−5%	10%	24%	31%	33%	32%	31%	31%	29%
0.7	−11%	−3%	12%	24%	31%	31%	31%	32%	30%	29%
0.6	−10%	0%	15%	28%	36%	33%	31%	31%	30%	31%
0.5	−9%	3%	19%	30%	34%	36%	33%	34%	29%	30%
0.4	−7%	8%	23%	37%	35%	34%	33%	30%	26%	28%

interaction strength of
P with the SM bath

Normalized relative mass difference between P and DM

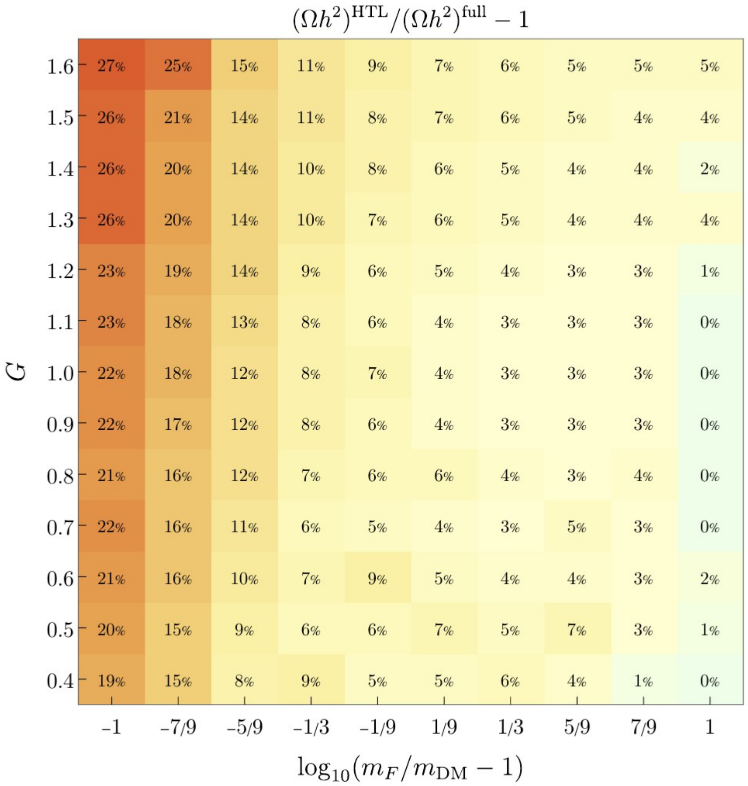
- Ω_{DM} underestimated for small mass splittings
- Ω_{DM} strongly overestimated for large mass splittings
- **When including Fermi-Dirac / Bose-Einstein statistics in semi-classical BEQ, deviation reduced by approx. 50%**

Becker, Copello, JH, Tamarit (2023)

Impact of thermal corrections on freeze-in DM production

Compared to HTL approximation

interaction strength of P with the SM bath



G	−1	−7/9	−5/9	−1/3	−1/9	1/9	1/3	5/9	7/9	1
1.6	27%	25%	15%	11%	9%	7%	6%	5%	5%	5%
1.5	26%	21%	14%	11%	8%	7%	6%	5%	4%	4%
1.4	26%	20%	14%	10%	8%	6%	5%	4%	4%	2%
1.3	26%	20%	14%	10%	7%	6%	5%	4%	4%	4%
1.2	23%	19%	14%	9%	6%	5%	4%	3%	3%	1%
1.1	23%	18%	13%	8%	6%	4%	3%	3%	3%	0%
1.0	22%	18%	12%	8%	7%	4%	3%	3%	3%	0%
0.9	22%	17%	12%	8%	6%	4%	3%	3%	3%	0%
0.8	21%	16%	12%	7%	6%	6%	4%	3%	4%	0%
0.7	22%	16%	11%	6%	5%	4%	3%	5%	3%	0%
0.6	21%	16%	10%	7%	9%	5%	4%	4%	3%	2%
0.5	20%	15%	9%	6%	6%	7%	5%	7%	3%	1%
0.4	19%	15%	8%	9%	5%	5%	6%	4%	1%	0%

Normalized relative mass difference between P and DM

- Ω_{DM} strongly overestimated for small mass splittings
- Ω_{DM} at percent level correct for large mass splittings
- Larger deviations for larger G

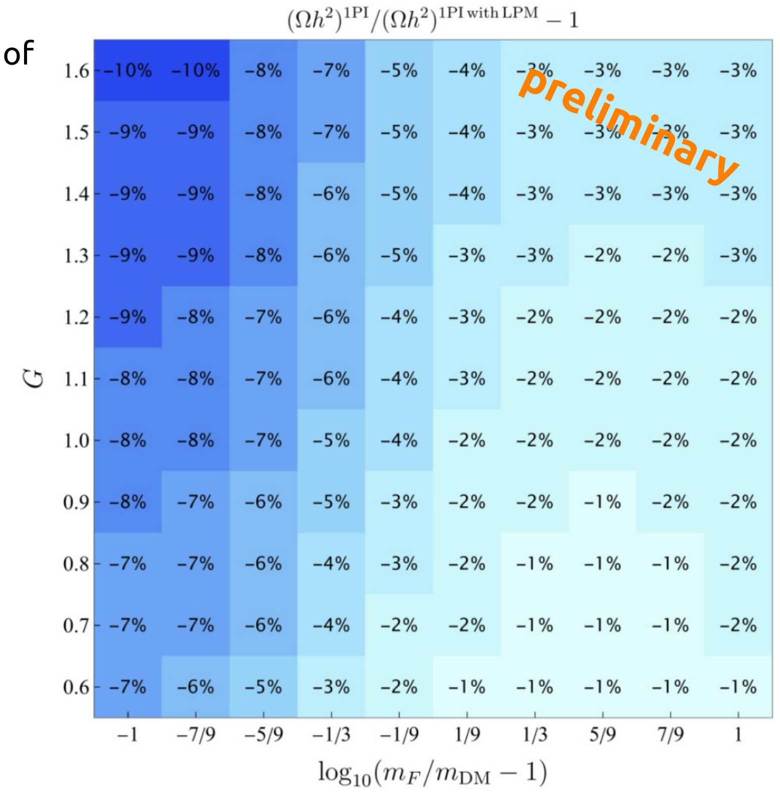
- **first consistent thermal calculation valid throughout all the relevant freeze-in regime**
- **significant corrections on Ω_{DM} dependent on mass splitting and gauge coupling G**

Becker, Copello, JH, Tamarit (2023)

Impact of thermal corrections on freeze-in DM production

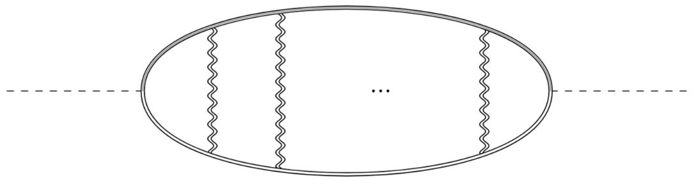
Including Landau-Pomeranchuk-Migdal (LPM) effect

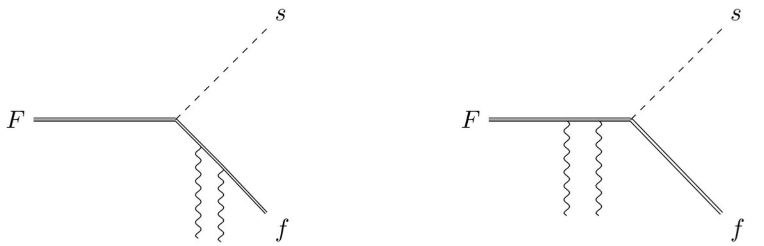
interaction strength of
P with the SM bath



G	−1	−7/9	−5/9	−1/3	−1/9	1/9	1/3	5/9	7/9	1
1.6	−10%	−10%	−8%	−7%	−5%	−4%	−3%	−3%	−3%	−3%
1.5	−9%	−9%	−8%	−7%	−5%	−4%	−3%	−3%	−3%	−3%
1.4	−9%	−9%	−8%	−6%	−5%	−4%	−3%	−3%	−3%	−3%
1.3	−9%	−9%	−8%	−6%	−5%	−3%	−3%	−2%	−2%	−3%
1.2	−9%	−8%	−7%	−6%	−4%	−3%	−2%	−2%	−2%	−2%
1.1	−8%	−8%	−7%	−6%	−4%	−3%	−2%	−2%	−2%	−2%
1.0	−8%	−8%	−7%	−5%	−4%	−2%	−2%	−2%	−2%	−2%
0.9	−8%	−7%	−6%	−5%	−3%	−2%	−2%	−1%	−2%	−2%
0.8	−7%	−7%	−6%	−4%	−3%	−2%	−1%	−1%	−1%	−2%
0.7	−7%	−7%	−6%	−4%	−2%	−2%	−1%	−1%	−1%	−2%
0.6	−7%	−6%	−5%	−3%	−2%	−1%	−1%	−1%	−1%	−1%

Normalized relative mass difference between P and DM



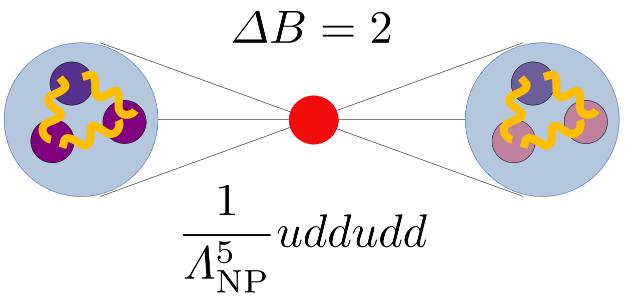


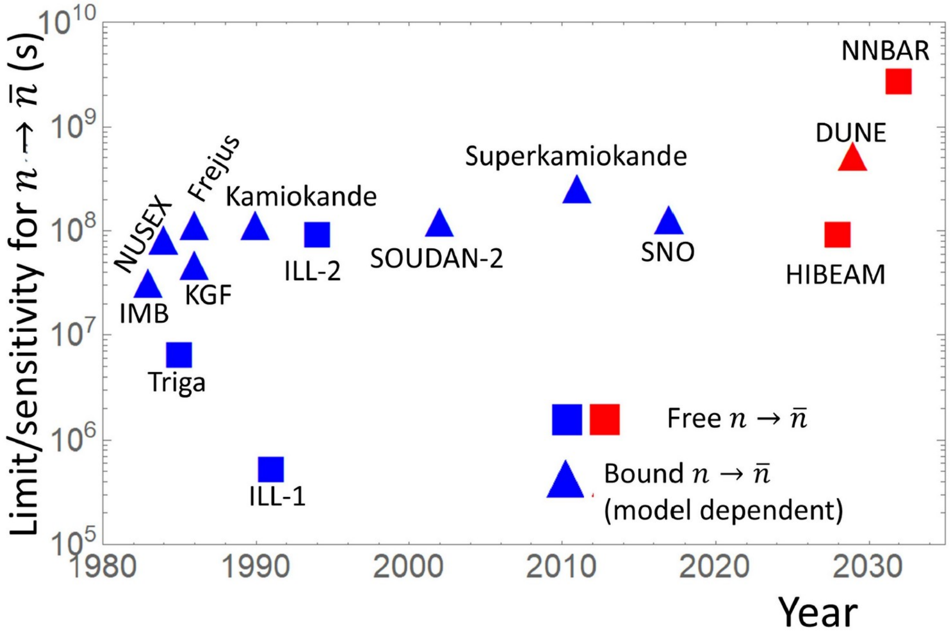
JH, Fernandez Lozano, in preparation (2024)

Probing baryogenesis

- **Goal**: Search for washout processes,

  e.g. (CP-conserving) neutron-antineutron oscillations





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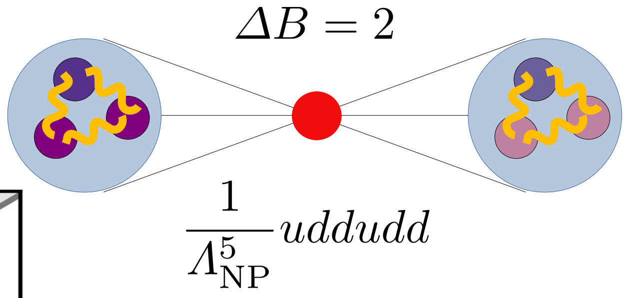
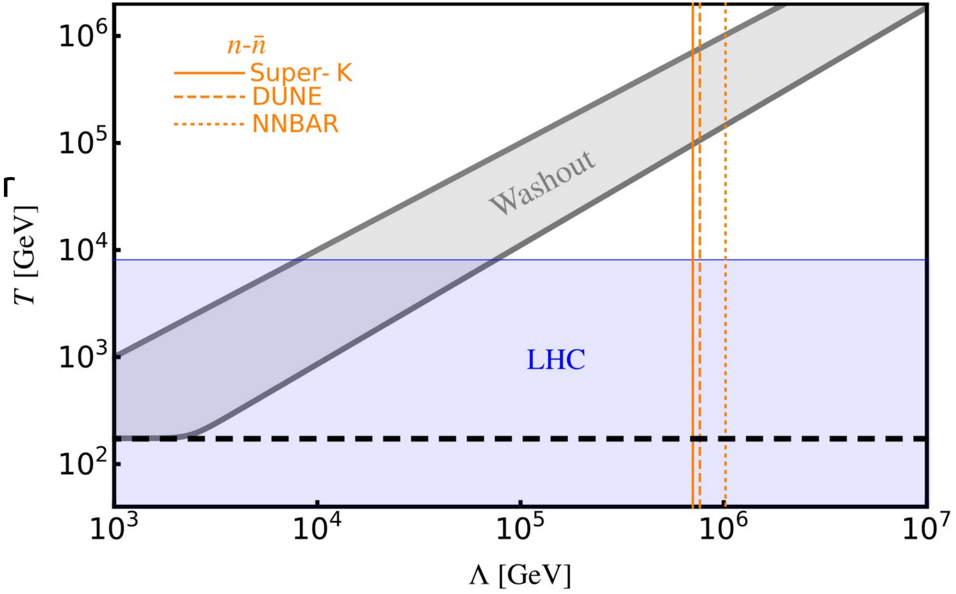


remaining energy scale for successful baryogenesis

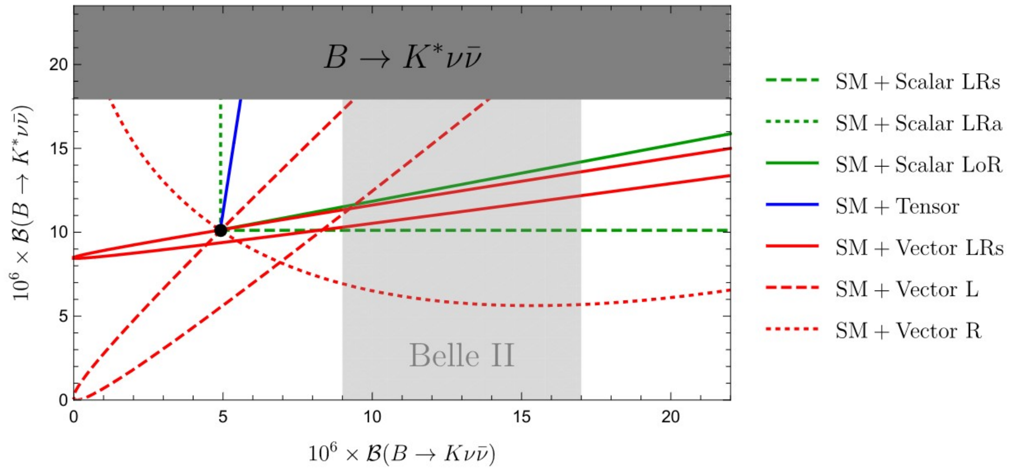


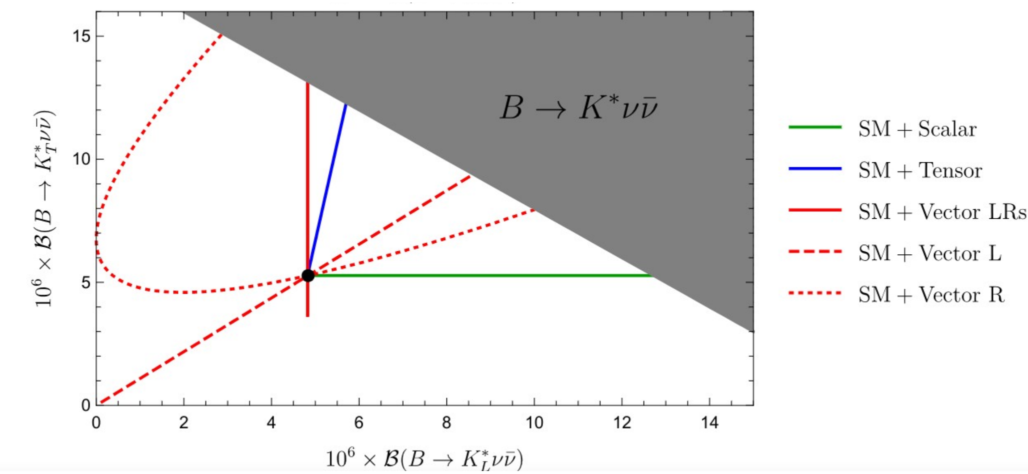
Associated energy scale of observed nnbar process

If observed, narrows down significantly range of possible baryogenesis

Fridell, JH, Hati (2021)

Probing LNV with invisible Meson decays





→ **A NP scalar contribution additionally to the SM leads to a striking difference in the distribution when comparing to a vector contribution only.**

Buras, JH, Mojahed (2024)