Open problems in particle physics

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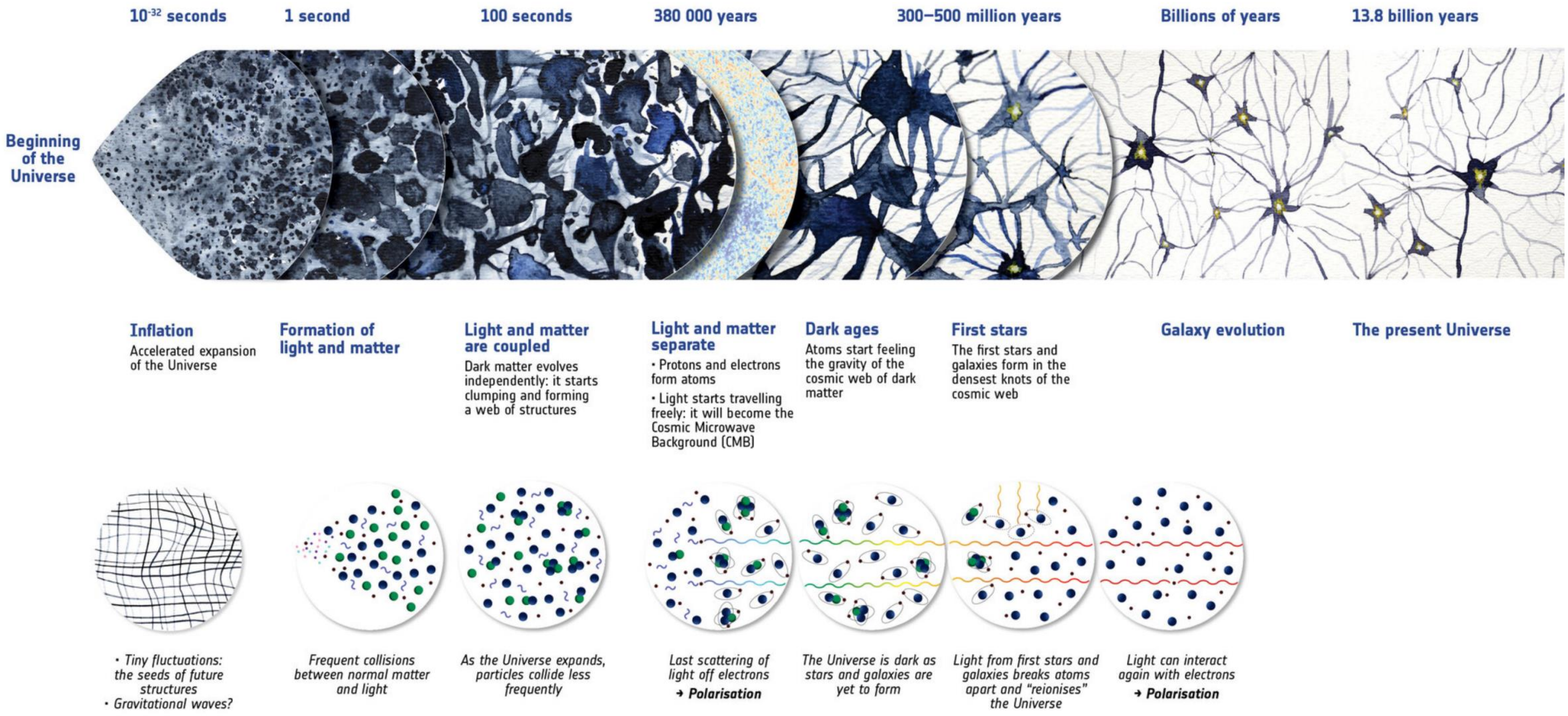
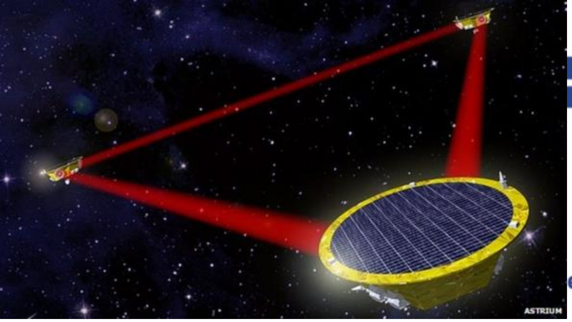
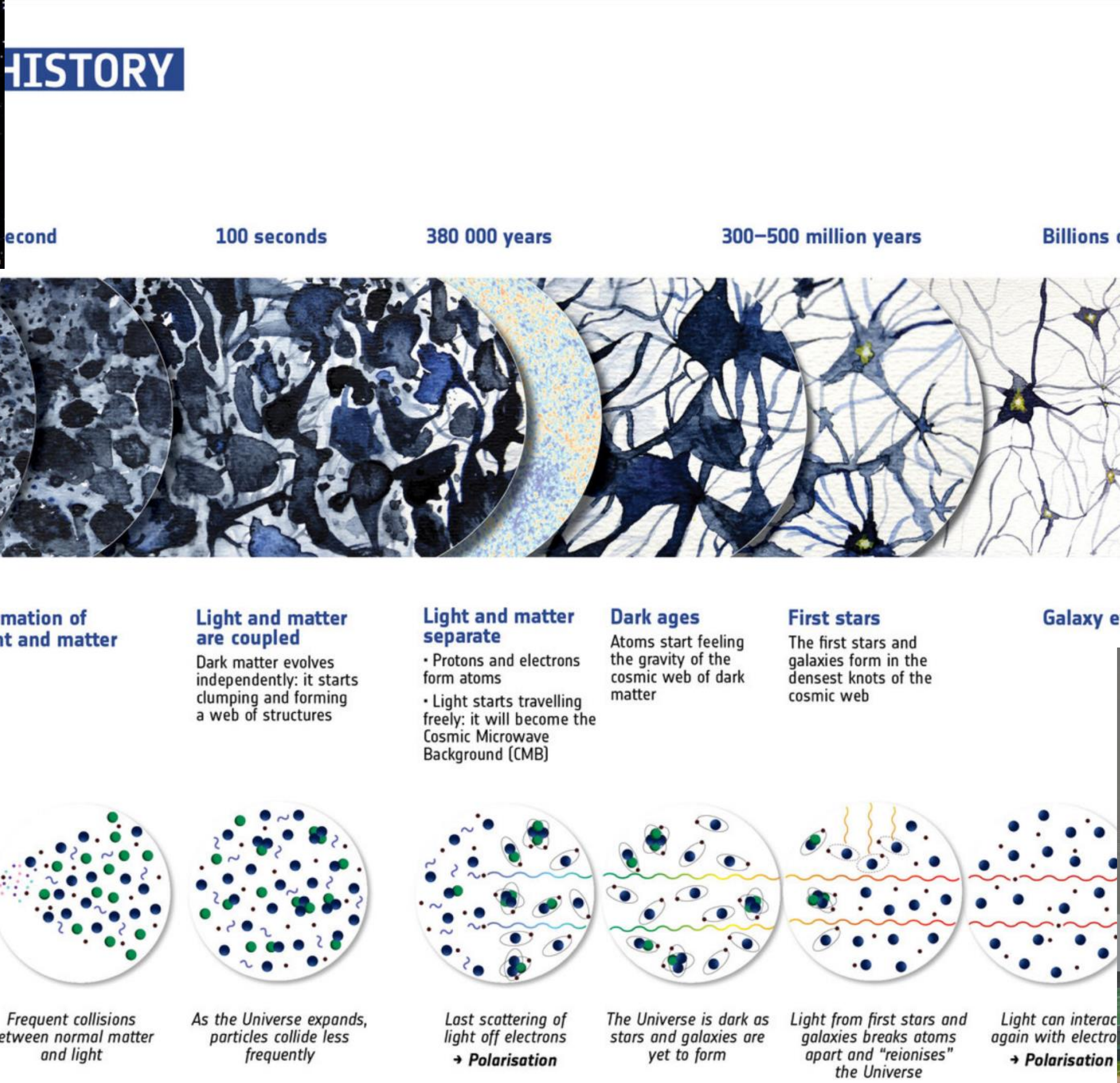
The Universe

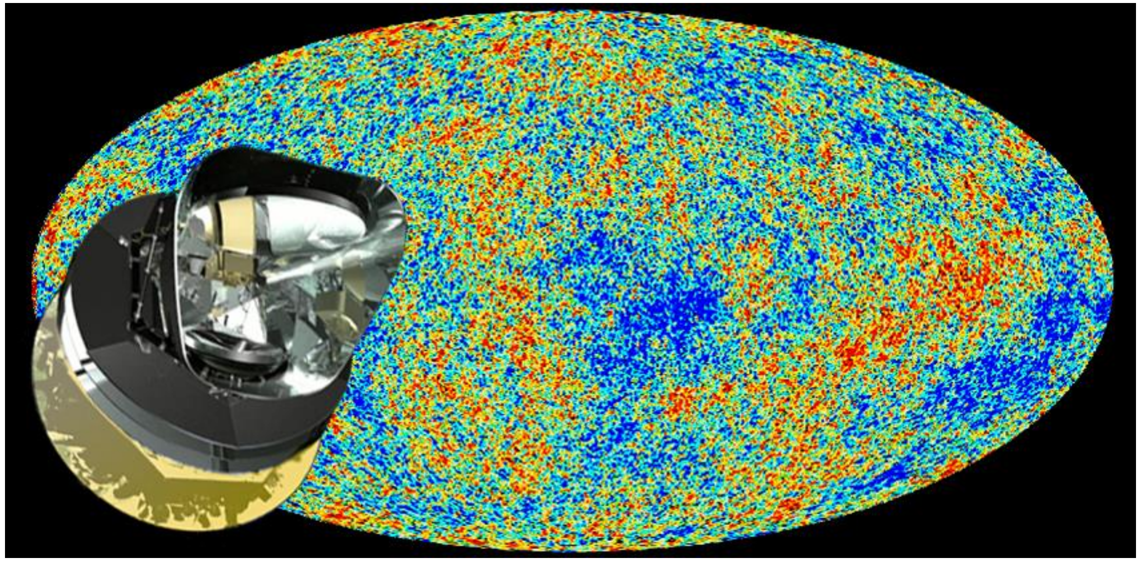
→ COSMIC HISTORY

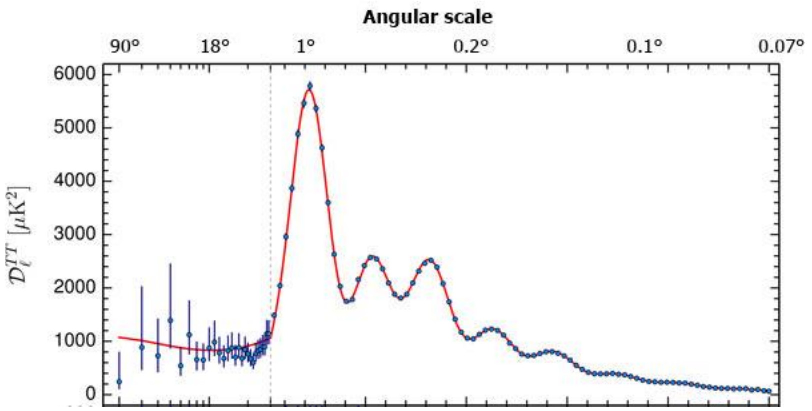


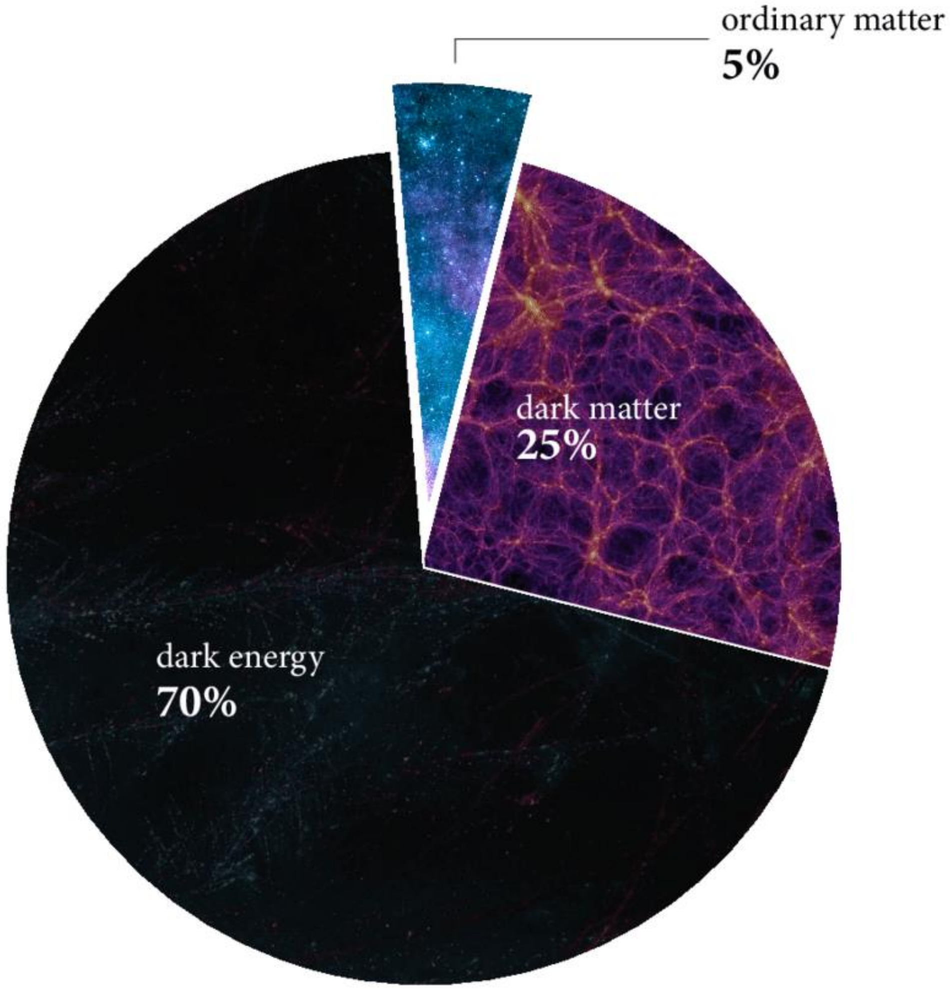



HISTORY
esa
econd
100 seconds
380 000 years
300–500 million years
Billions of years
13.8 billion years
Beginning of the Universe
Inflation
Accelerated expansion of the Universe
Formation of light and matter
Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures
Light and matter separate
• Protons and electrons form atoms
• Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)
Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter
First stars
The first stars and galaxies form in the densest knots of the cosmic web
Galaxy evolution
The present Universe
Frequent collisions between normal matter and light
As the Universe expands, particles collide less frequently
Last scattering of light off electrons
→ Polarisation
The Universe is dark as stars and galaxies are yet to form
Light from first stars and galaxies breaks atoms apart and "reionises" the Universe
→ Polarisation

The energy budget of the Universe







The whole Universe is a lab for fundamental physics

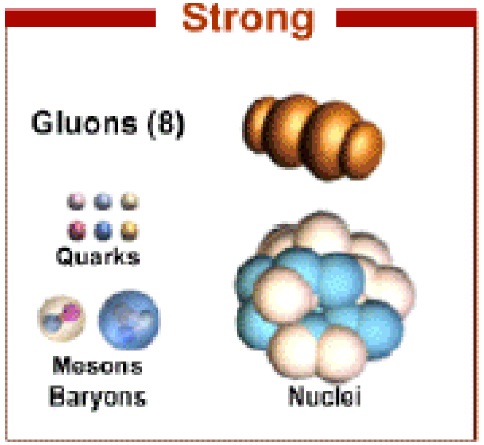
- To describe the Universe, we have 3 standard models:

1. The SM of particle physics, a gauge theory based on SU(3)xSU(2)xU(1)
2. The standard cosmological concordance model (ΛCDM), 6 parameters
3. General Relativity, a classical theory of gravity

The three models are not consistent and they complement each other

The Standard Model of particle physics

The SM is a gauge theory $SU(3)_C x SU(2)_L x U(1)_Y$



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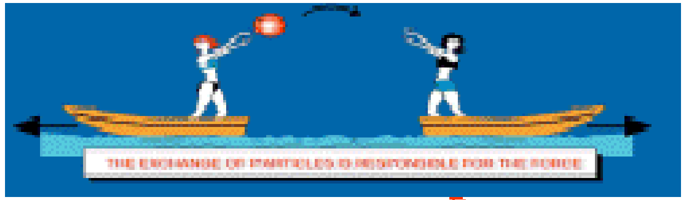
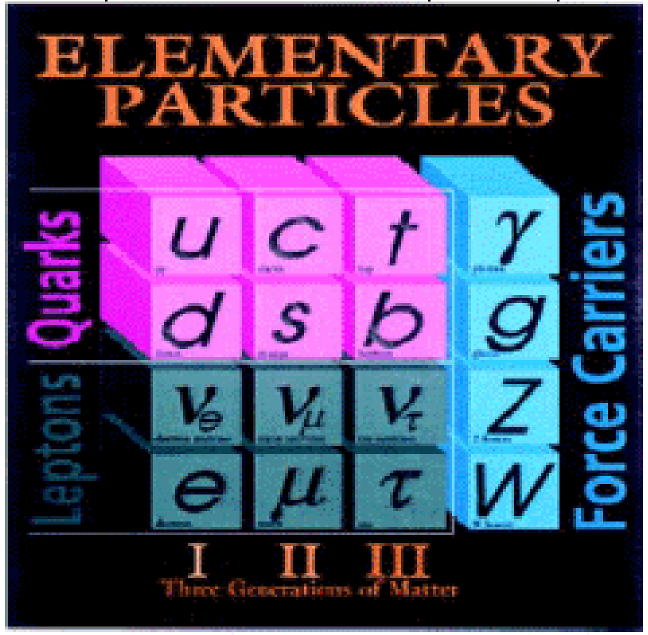


Matter
fermions

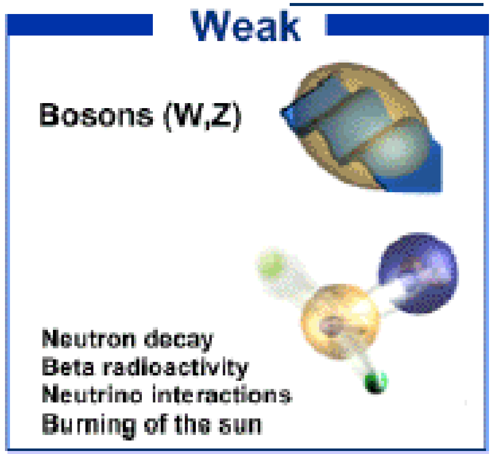
Force carriers
bosons



+ antiparticles

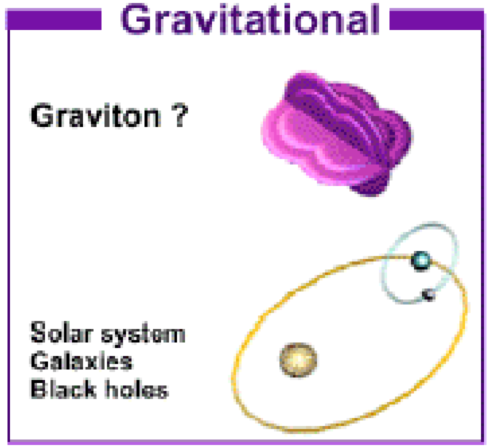
e.g: $p=uud$; $\Lambda^0=uds$; $\Lambda^0_b=udb$

$\pi^+=u\bar{d}$; $\psi=c\bar{c}$; $\Upsilon=b\bar{b}$

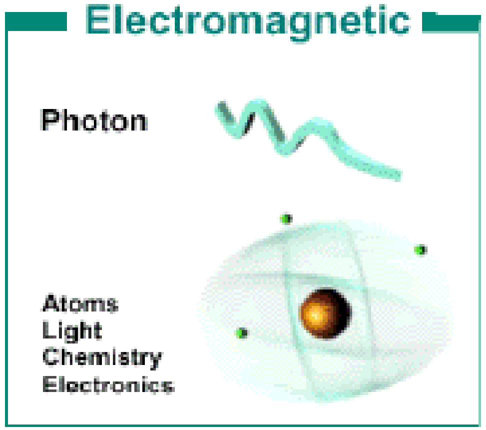


10^{-13}

10^{-38}

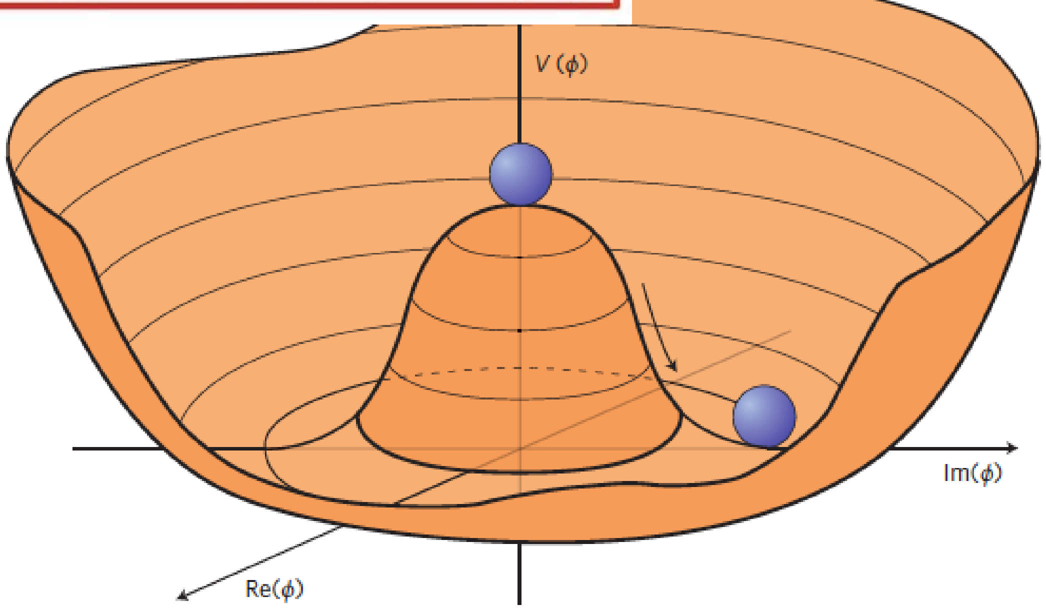


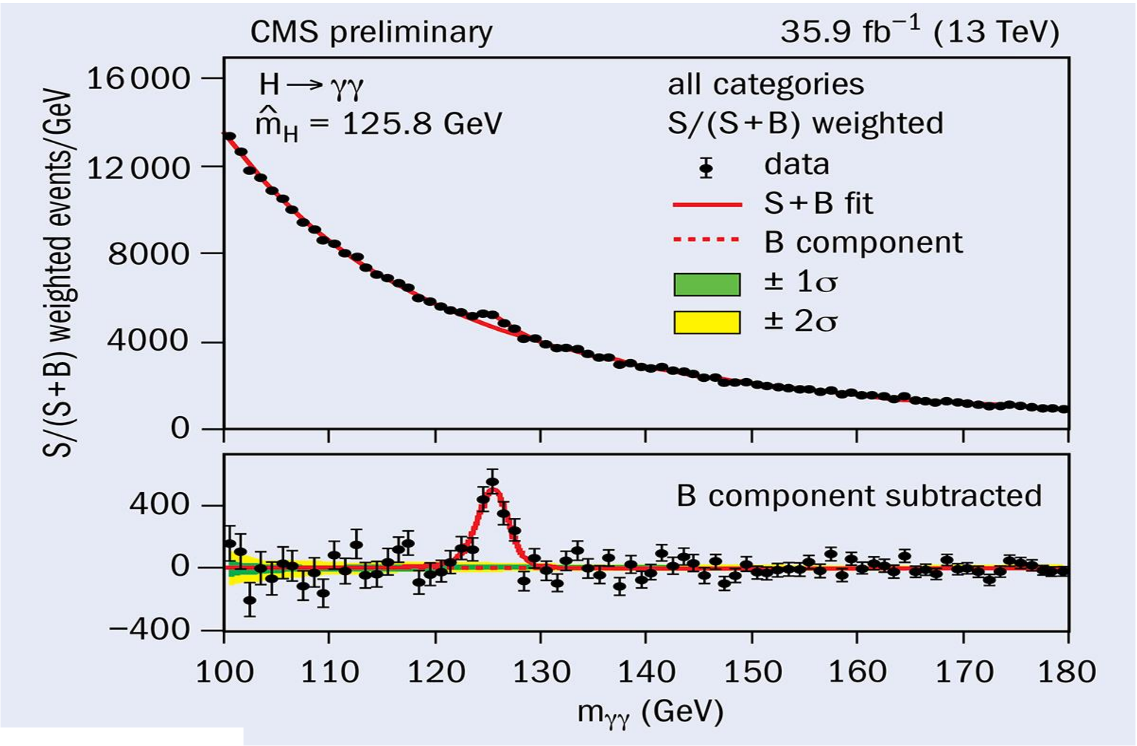
10^{-2}

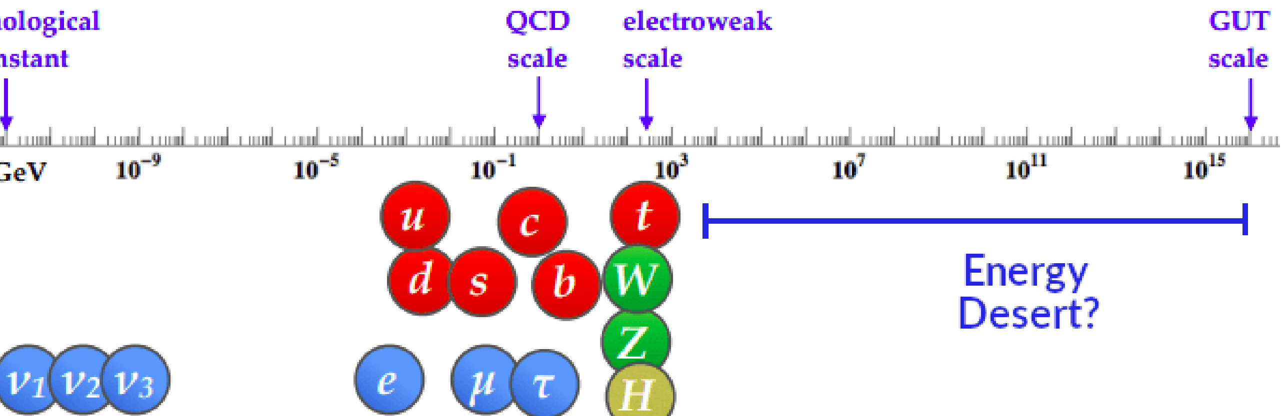


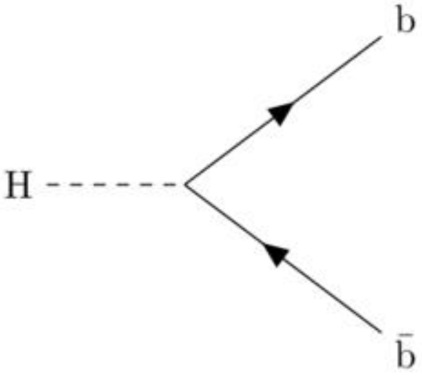
The Higgs mechanism

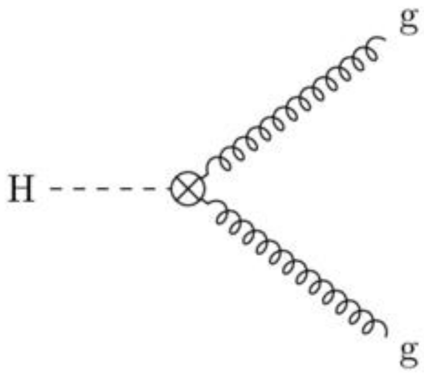
$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$







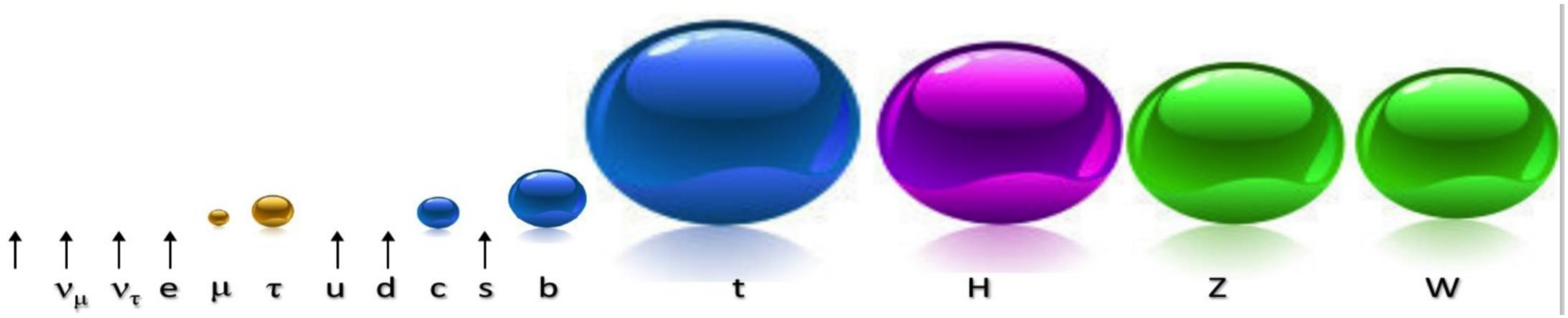


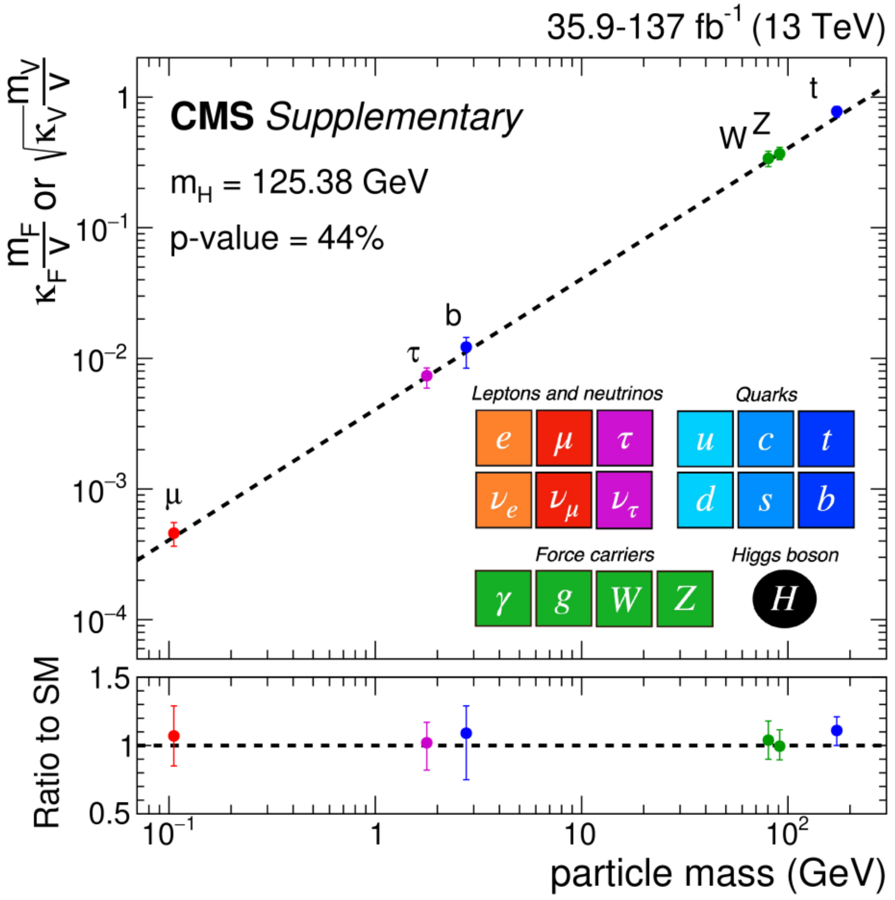


Higgs and the flavour problem

- In the SM flavour is described by Yukawa interact.

$$H\psi_L^i Y_{ij} \psi_R^j$$





- Yukawa couplings are hierarchical, up and down, quark and lepton sectors are all different
- No symmetry or other fundamental principle exist to describe them
- Despite of huge amount of data, we have no understanding of the origin of flavour physics

Dominant idea: the Froggatt-Nielsen mechanism

- Based on U(1) flavour symmetry and non-renormalizable operators of the form

$$\left(\frac{\phi}{M}\right)^2 H\psi_2\psi_2 + \left(\frac{\phi}{M}\right)^3 H\psi_1\psi_3 + \left(\frac{\phi}{M}\right)^4 H\psi_1\psi_2 +$$

- Choosing $\varepsilon = \frac{\langle\phi\rangle}{M}$ appropriate particle quantum numbers results in:
- Extendable to SU(2), SU(3) and discrete flavour symmetry groups
- Is this paradigm testable? Falsifiable?

$$Y = \begin{pmatrix} \varepsilon^6 & \varepsilon^4 & \varepsilon^3 \\ \varepsilon^4 & \varepsilon^2 & \varepsilon \\ \varepsilon^3 & \varepsilon & 1 \end{pmatrix}$$

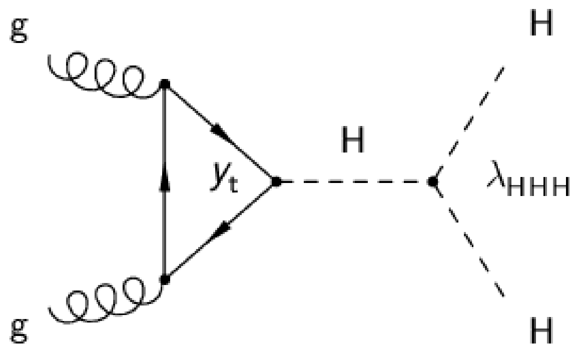
Have we tested the SM Higgs sector experimentally?

1. Yes, assuming the SM. In the SM there is a relation between the Higgs mass and self coupling λ

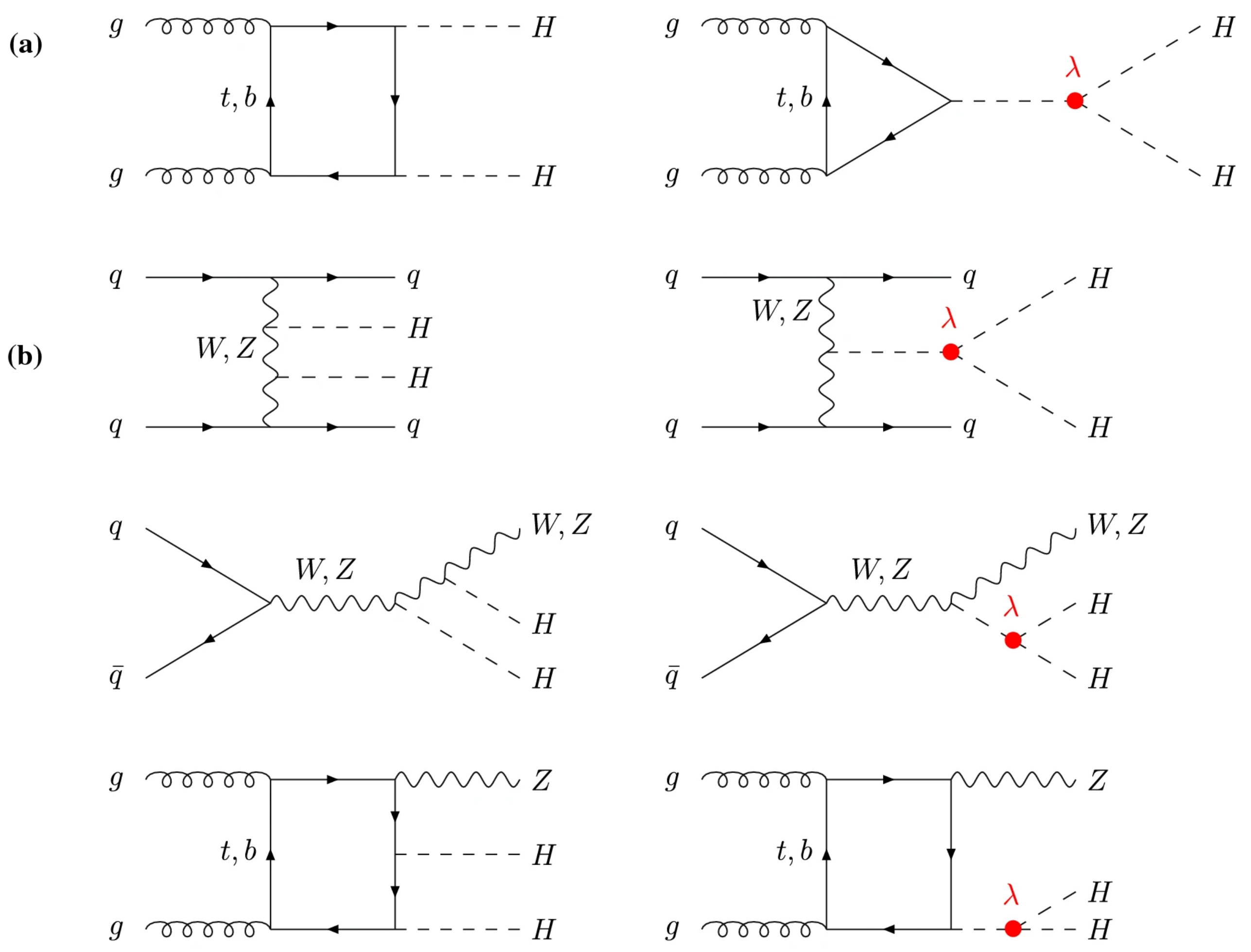
2. No, in general. Other EWSB scenarios are possible

3. One needs to measure the self coupling λ directly

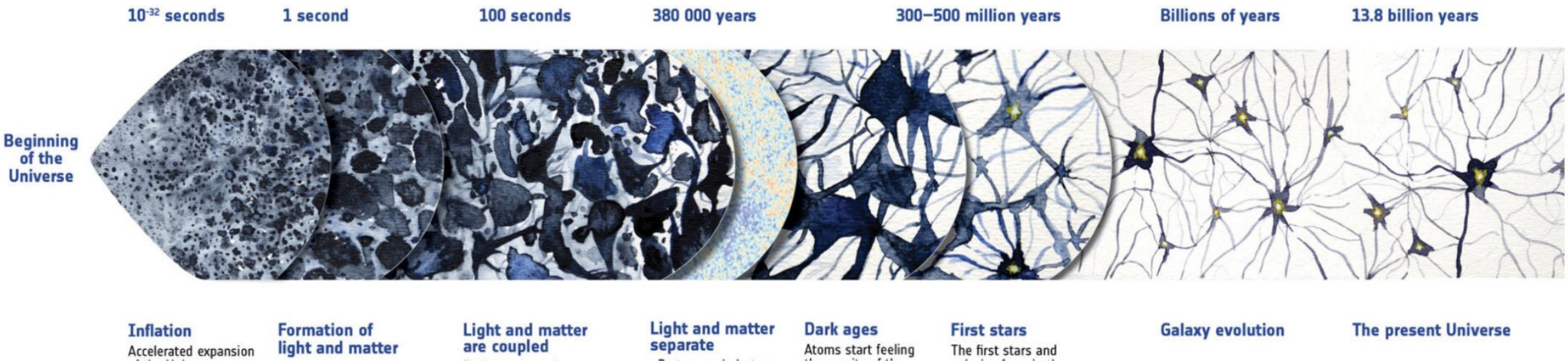
The idea:



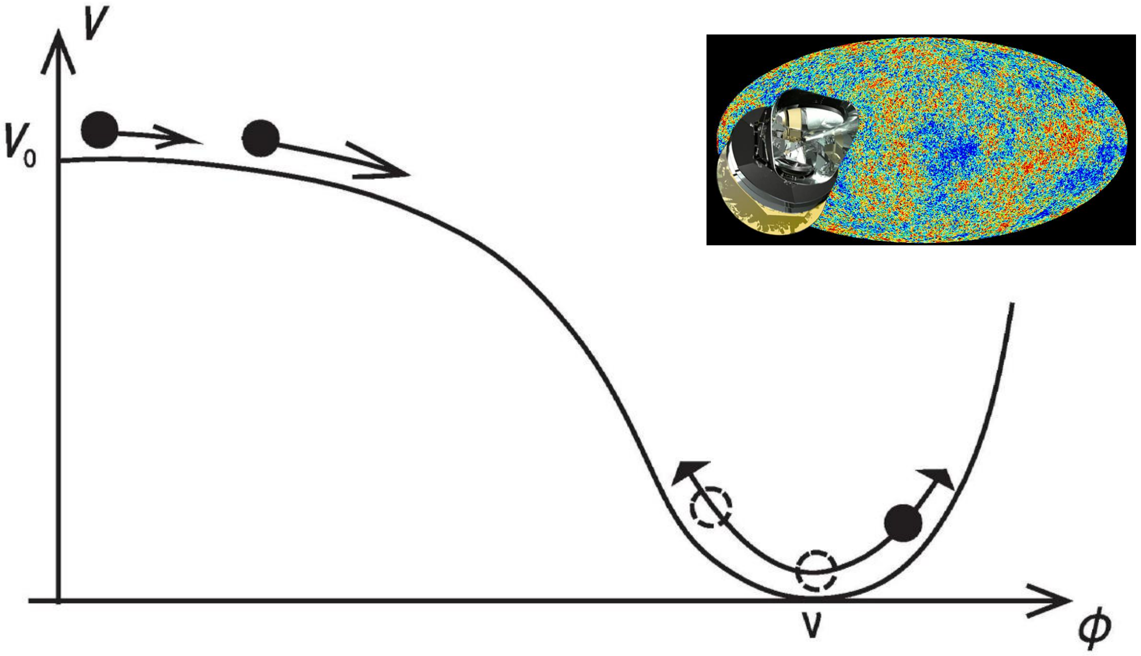
The reality:

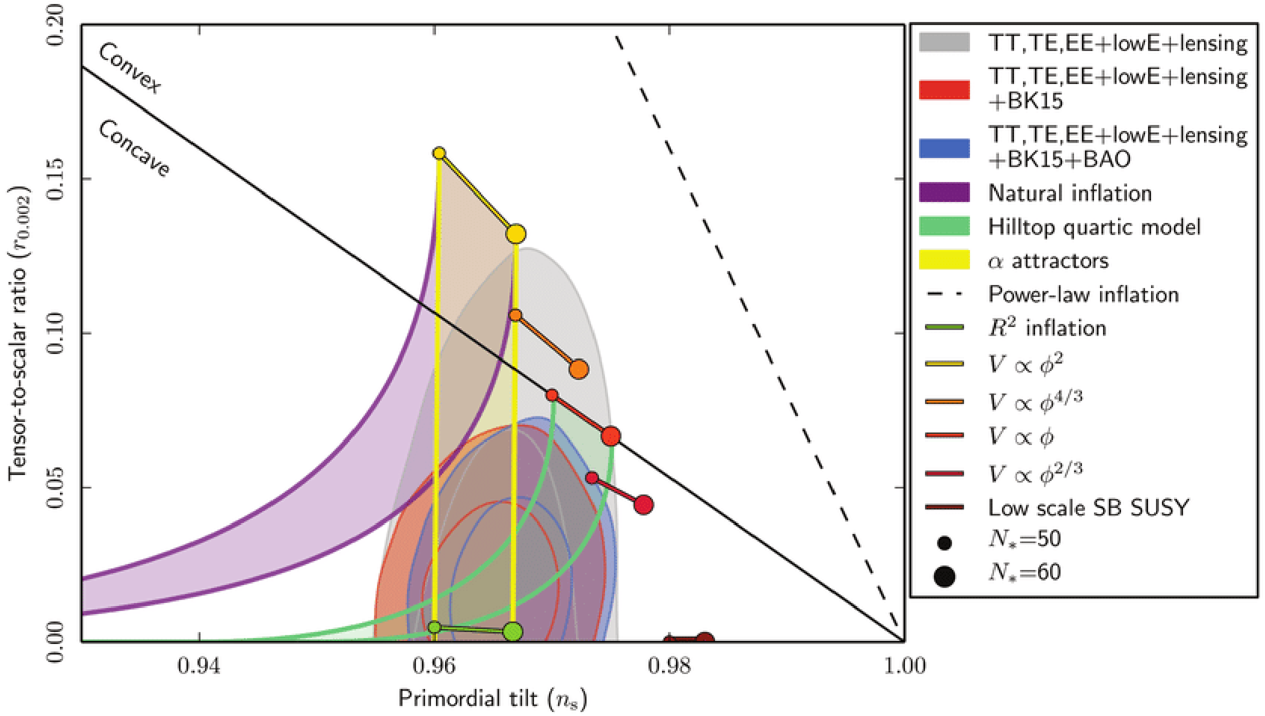


Open question: Inflation?



GR: vacuum energy expands space exponentially

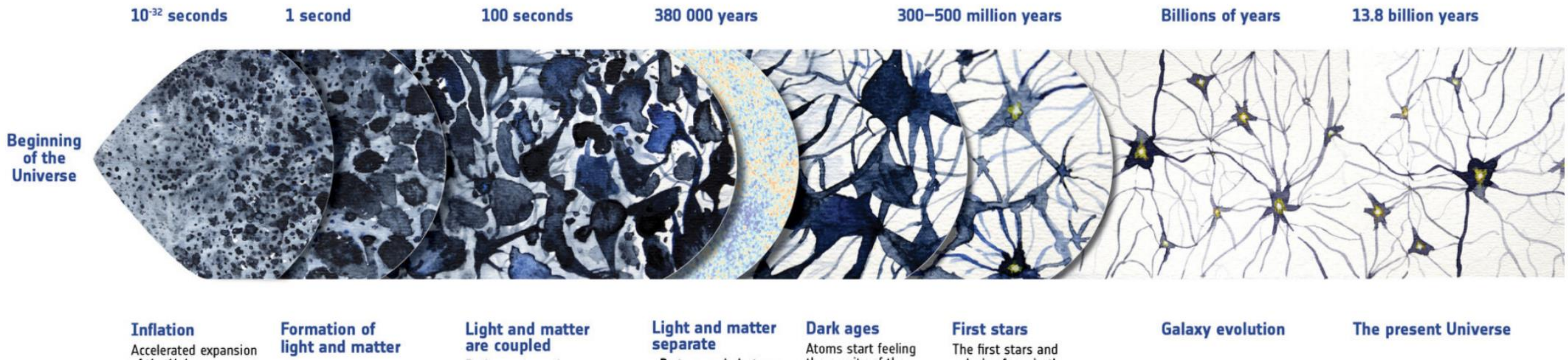




1. Flat potential: Inflation with almost const energy density
2. Oscillations: Reheating creates thermal plasma and matter

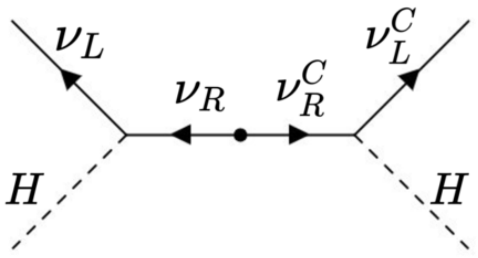
1. There are two measured quantities in inflation:
   a) Spectral index n_s measures tilt of the pot.
   b) Amplitude A of the spectrum gives the scale
2. Bounds on the tensor-to-scalar ratio r

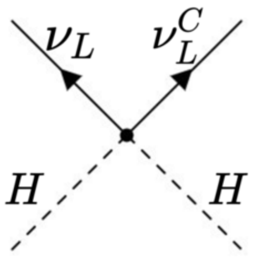
Open question: Baryon asymmetry?



Where is the antimatter?

- Sakharov conditions:
  1. B violation
  2. C and CP violation
  3. Out of equilibrium condition
  4. Sphalerons violate B-L, convert L to B





- Neutrinos are massive and may be Majorana particles: Lepton number violation

- Introduce heavy Majorana neutrinos N with

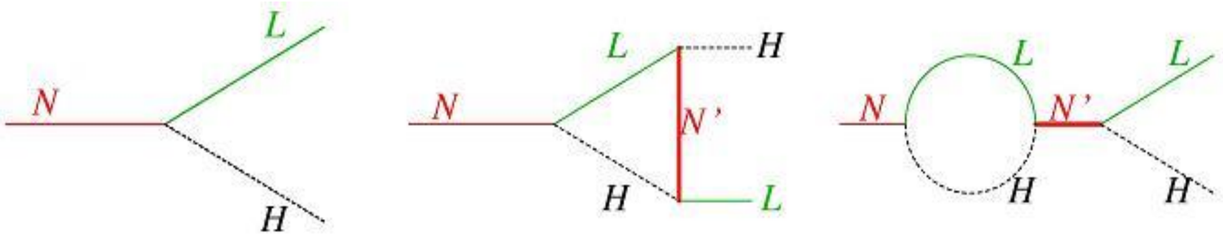
$$\tfrac{1}{2} M_N NN + L_i Y^{ij} N_j H$$

- The seesaw mechanism $\mathcal{M}_\nu = Y_\nu^T (M_N)^{-1} Y_\nu v^2 \sin^2 \beta$

- Leptogenesis in decays of N in the early Universe

CP asymmetry in N_1 decays

- $N_1 \Rightarrow L\,H$
- $N_1 \Rightarrow L^c H^\dagger$



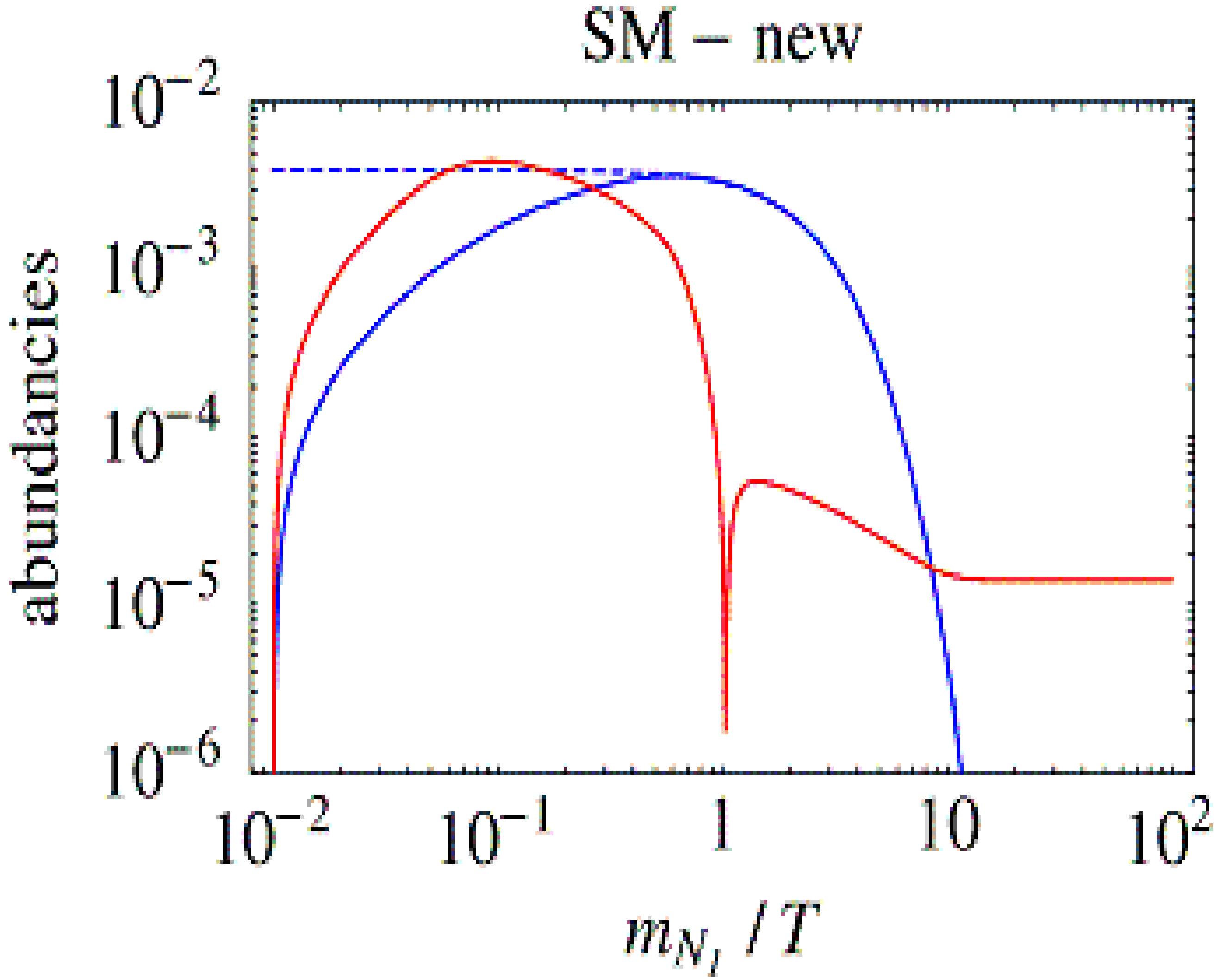
$$\epsilon_{N_1}(0) = \frac{1}{8\pi} \sum_{j\neq 1} \frac{\mathrm{Im}\left[(Y^\dagger Y)^2_{j1}\right]}{[Y^\dagger Y]_{11}} f\left(\frac{m^2_{N_j}}{m^2_{N_1}}\right)$$

$$f(x) = \sqrt{x}\left[\frac{x-2}{x-1} - (1+x)\ln\left(\frac{1+x}{x}\right)\right] \xrightarrow{x\gg 1} -\frac{3}{2\sqrt{x}}$$

$$|\epsilon_{N_1}| \leq \frac{3}{16\pi}\frac{m_{N_1}(m_3 - m_1)}{v^2} \qquad \frac{n_B}{n_\gamma} = 6.1^{+0.3}_{-0.2} \times 10^{-10}$$

CP violation requires at least 2 generations of N

Evolution of abundances for vanishing initial N abundance



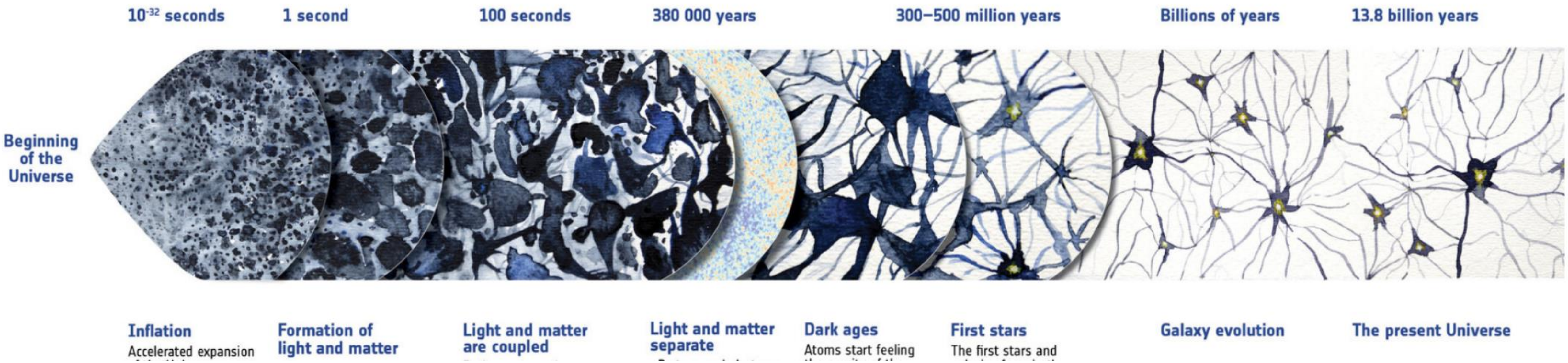
Additional supression factors:

1. Initial abunance of N in thermal plasma of order 0.01
2. Wash-out effects of order 0.001

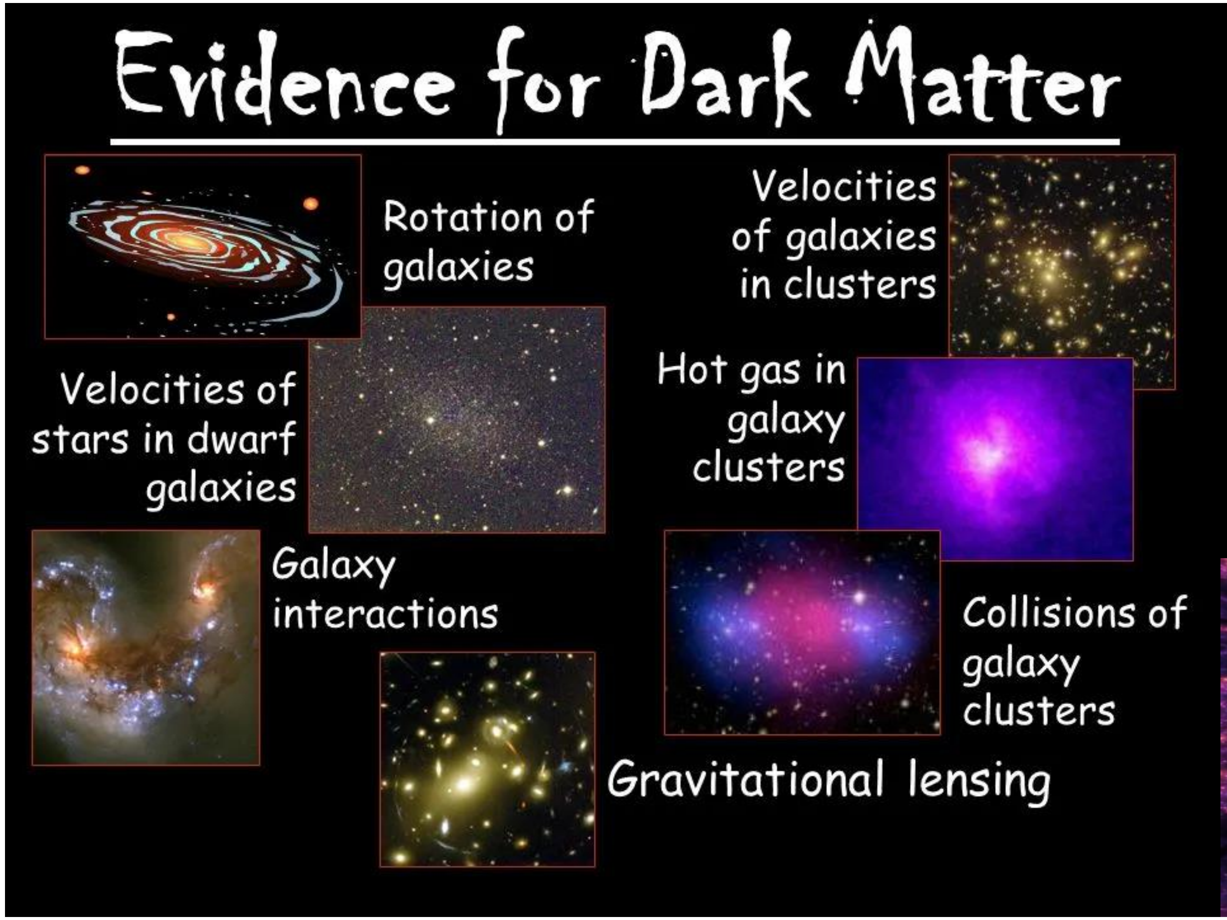
$$\frac{n_B}{n_\gamma} = 6.1^{+0.3}_{-0.2} \times 10^{-10}$$

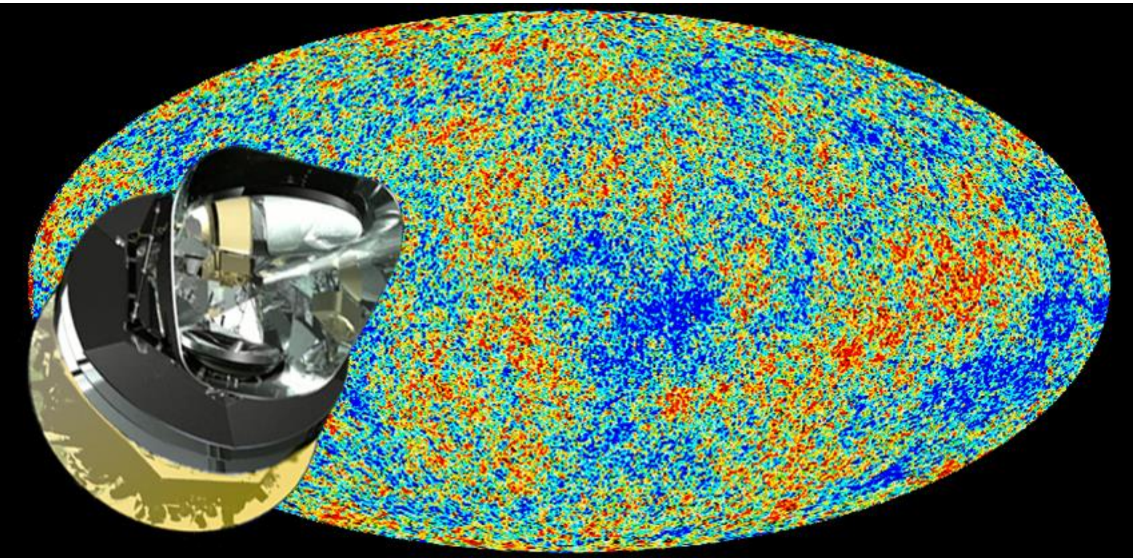
achievable

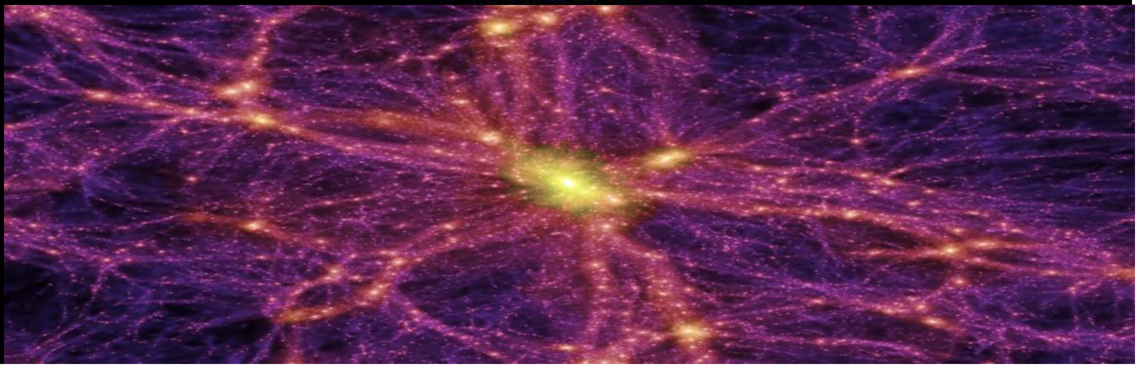
Open question: Dark Matter?



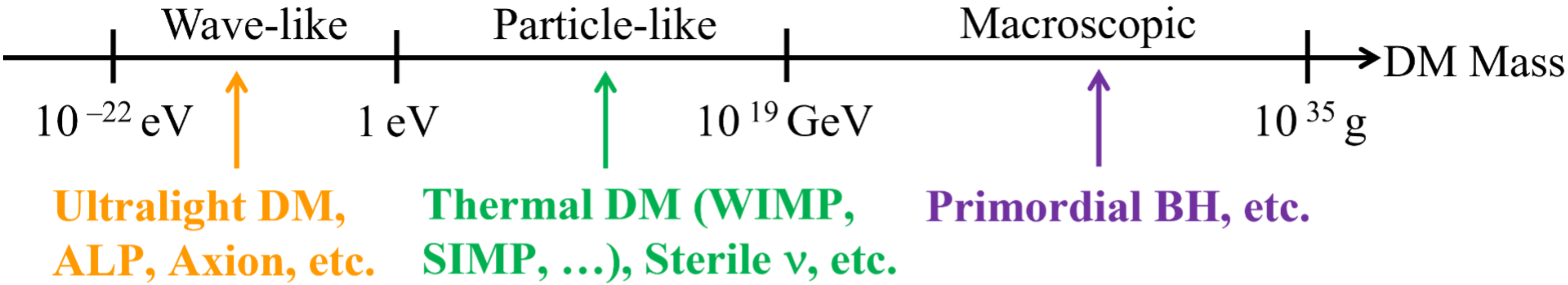
Dark Matter of the Universe



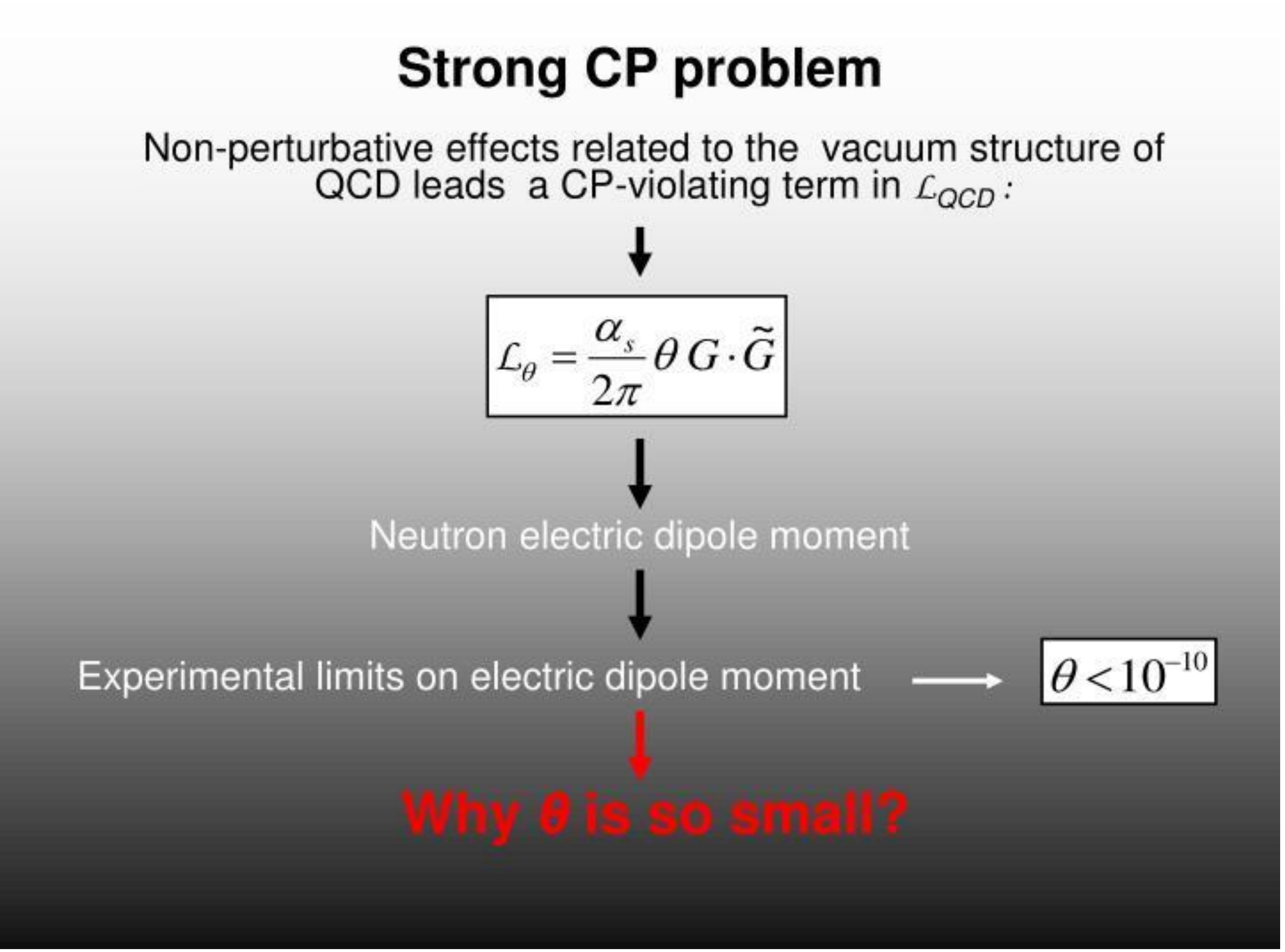




Dark Matter candidates and their masses

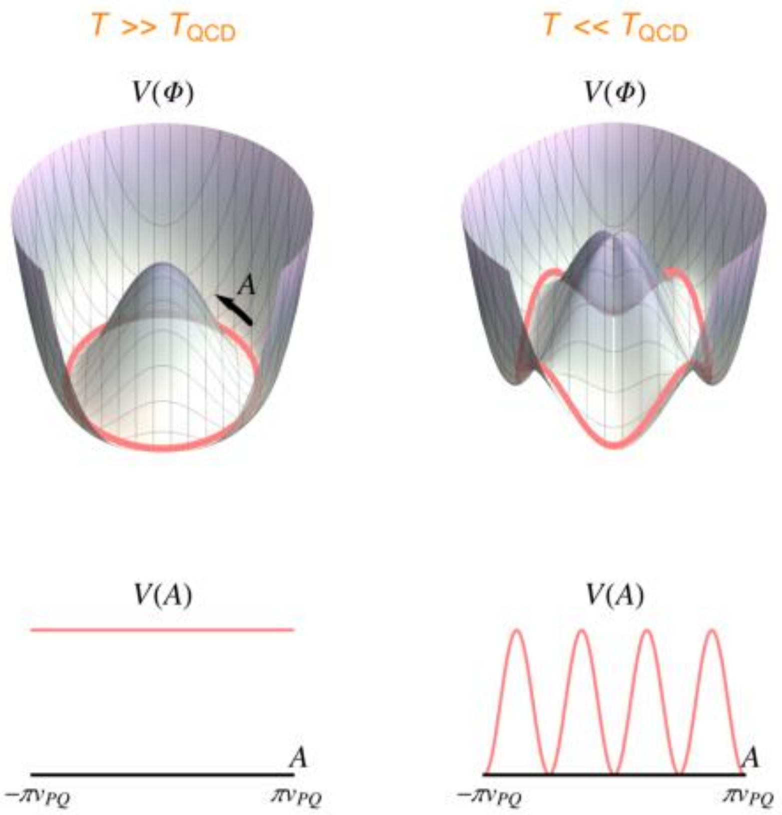


Axions and the strong CP problem



Possible solutions:

1. LR symmetry and P symmetry
2. Promote θ to a dynamical field



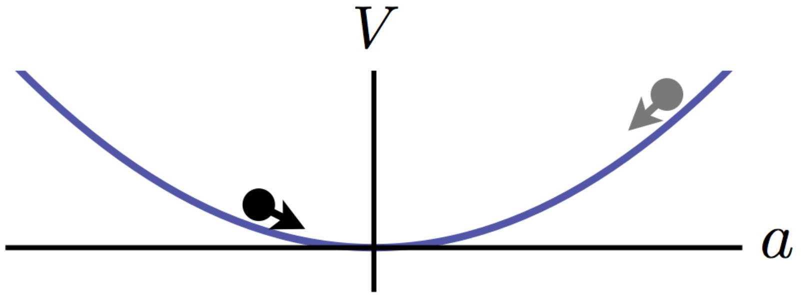
Ultralight oscillating scalars – DM candidate

- If scalar is light, its phase space density is high

$$\rho_{\rm DM} \approx 0.3\,\frac{\rm GeV}{\rm cm^3} \approx (0.04\,{\rm eV})^4 \qquad m \lesssim 0.01\,{\rm eV}$$

Such a DM should be described as a field

- To be viable DM, particles must be created at rest



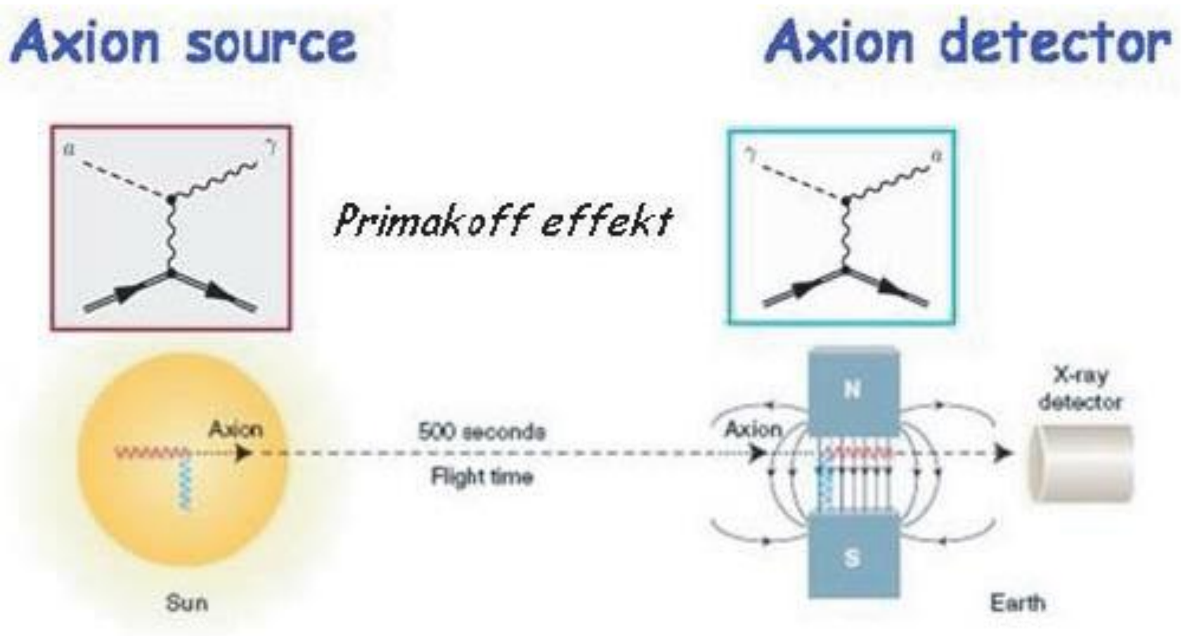
$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0 \qquad H \sim T^2/M_{\rm Pl}$$

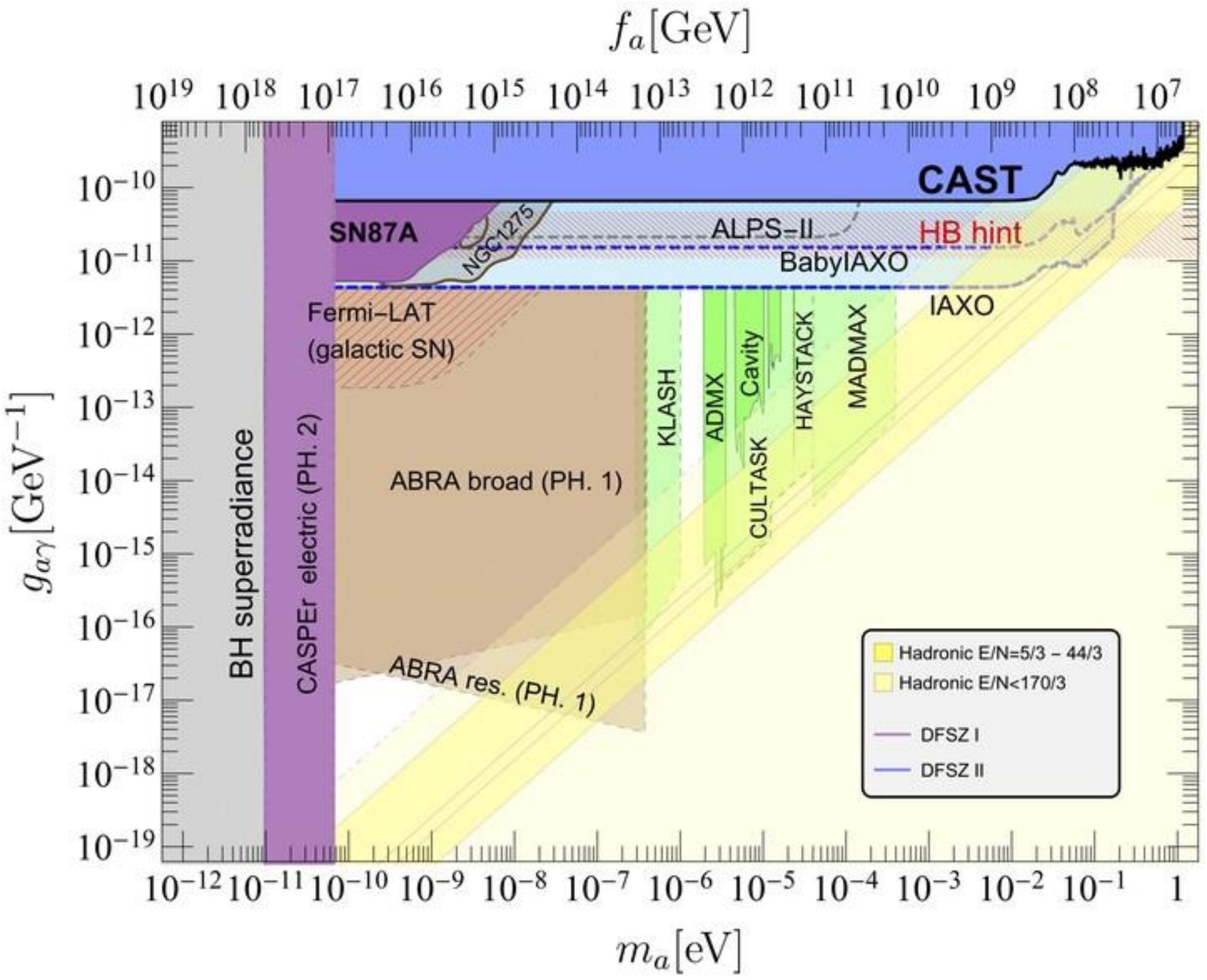
$$\phi = A\cos(m(t - t_*)) \qquad A \approx \phi_* \sqrt{\frac{a_*^3}{a^3}}$$

$$\Omega_{\rm DM} = \frac{\rho_\phi}{\rho_{\rm cr}} \sim \sqrt{\frac{m}{\rm eV}}\left(\frac{\phi_*}{10^{11}\,{\rm GeV}}\right)^2$$

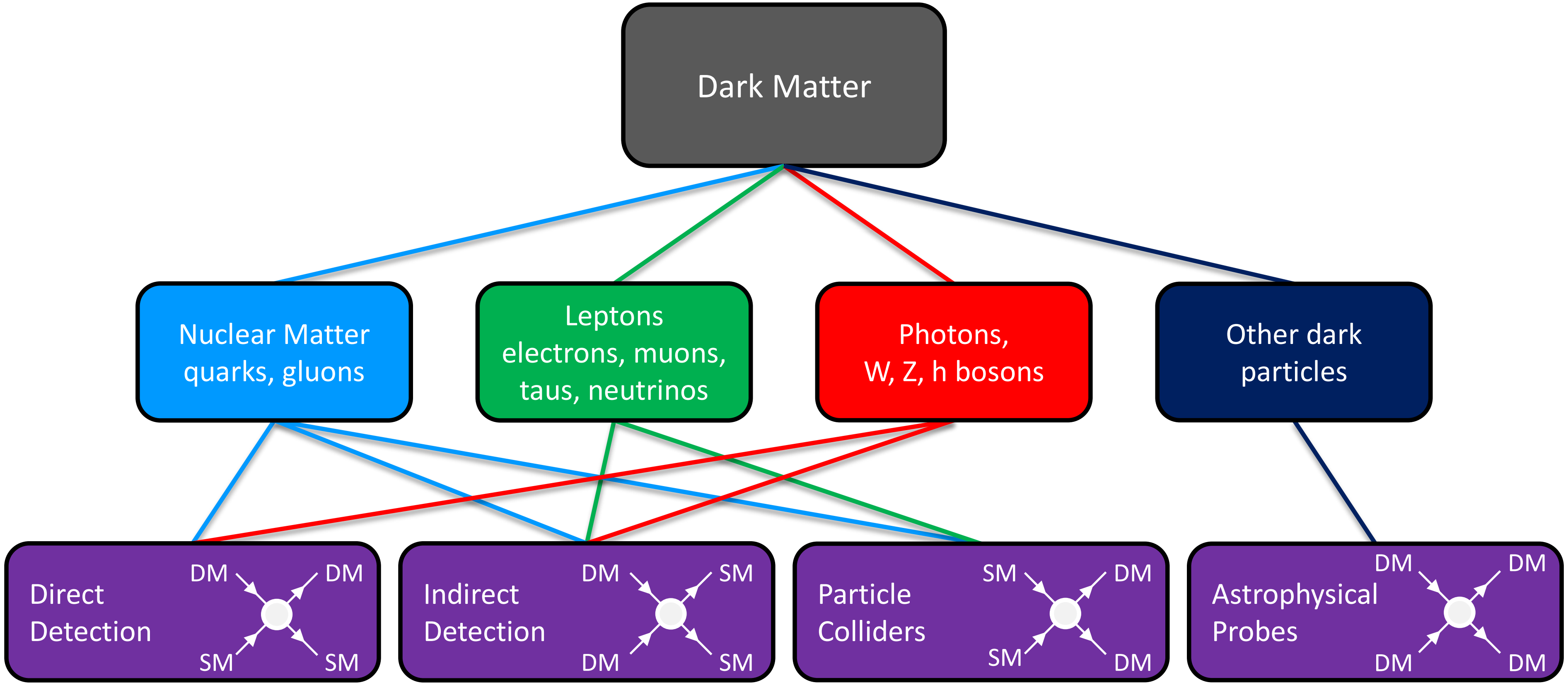
Initial misalignment mechanism

Oscillating QCD axion is a detectable DM candidate





Strategies for WIMP searches



Scattering off nuclei

Annihilation at freeze-out,
Annihilation today

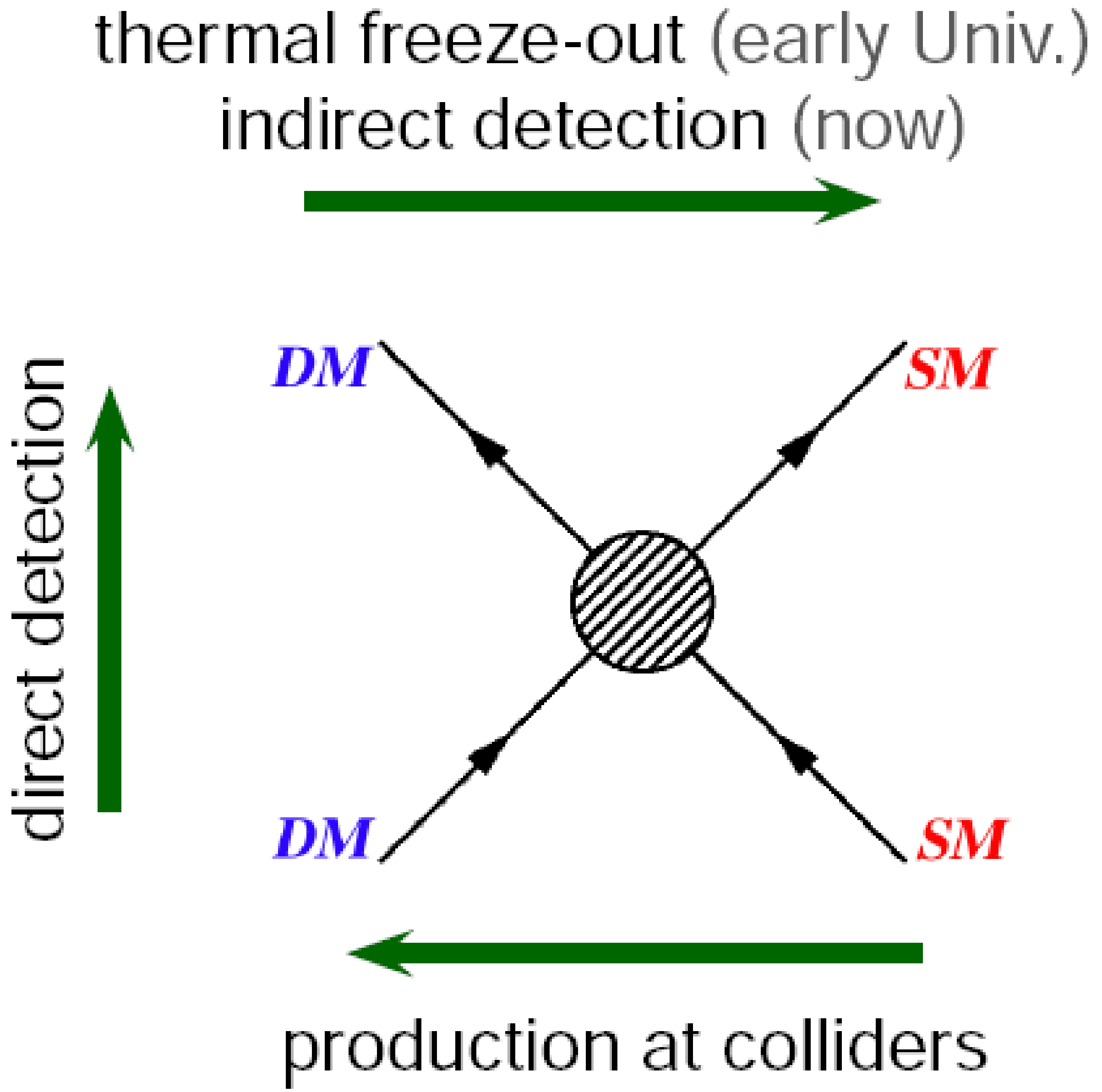
Bullet clusters,
DM halo profile,
Core vs cusp

Complementarity of DM experiments

DM velocity
dependence
s-wave, p-wave

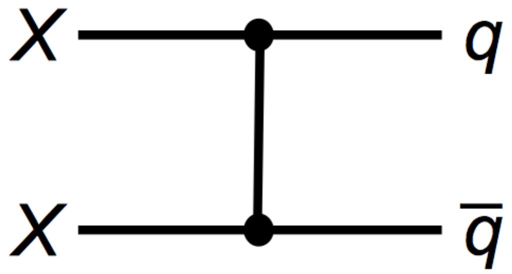
Warning!

Such a relation may be too naïve!



The WIMP miracle

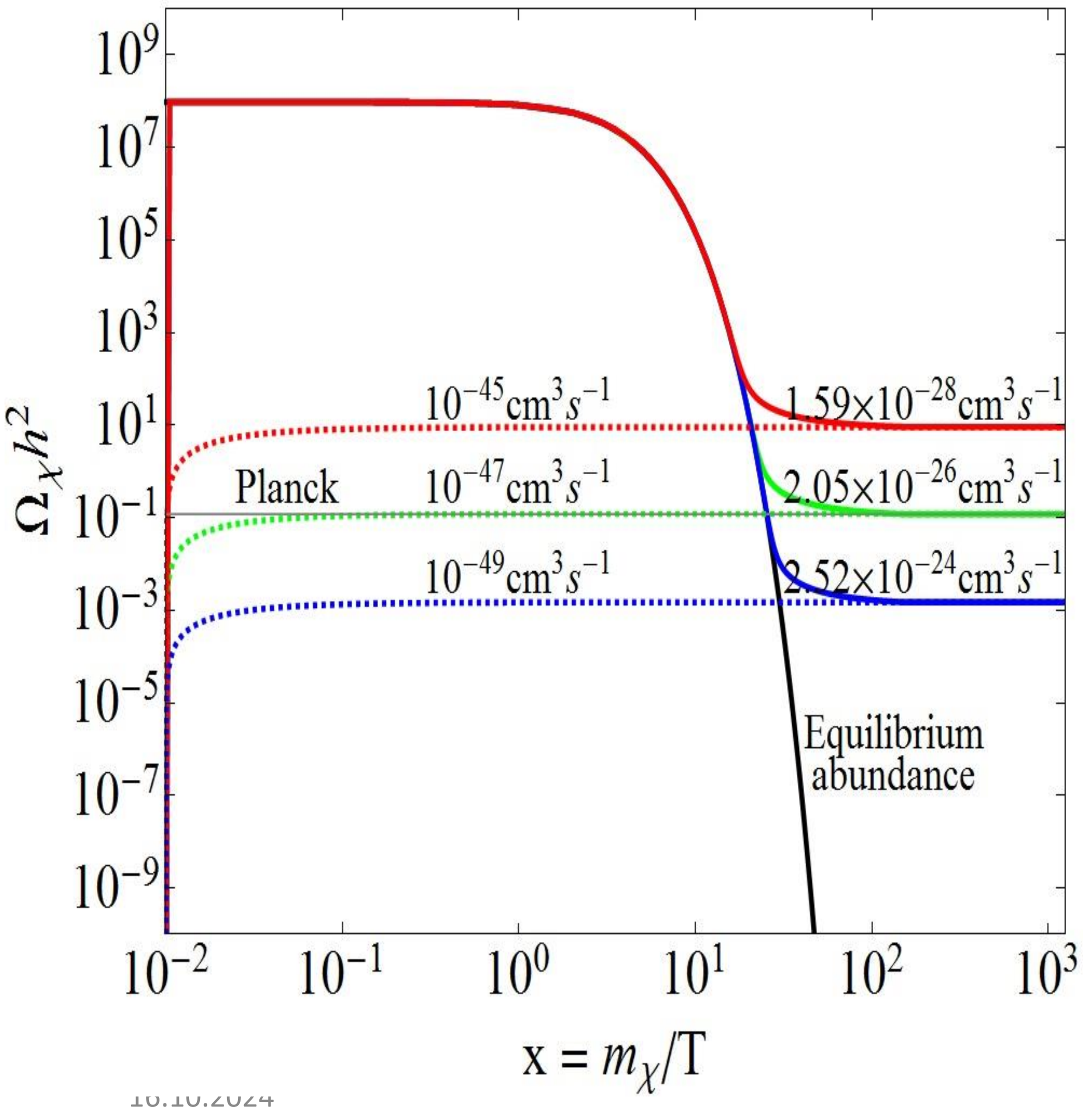
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



$m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

This mass scale has nothing to do with EWSB -- a miracle

DM as a thermal relic



$$n_{\rm DM} \propto \exp(-m/T)$$

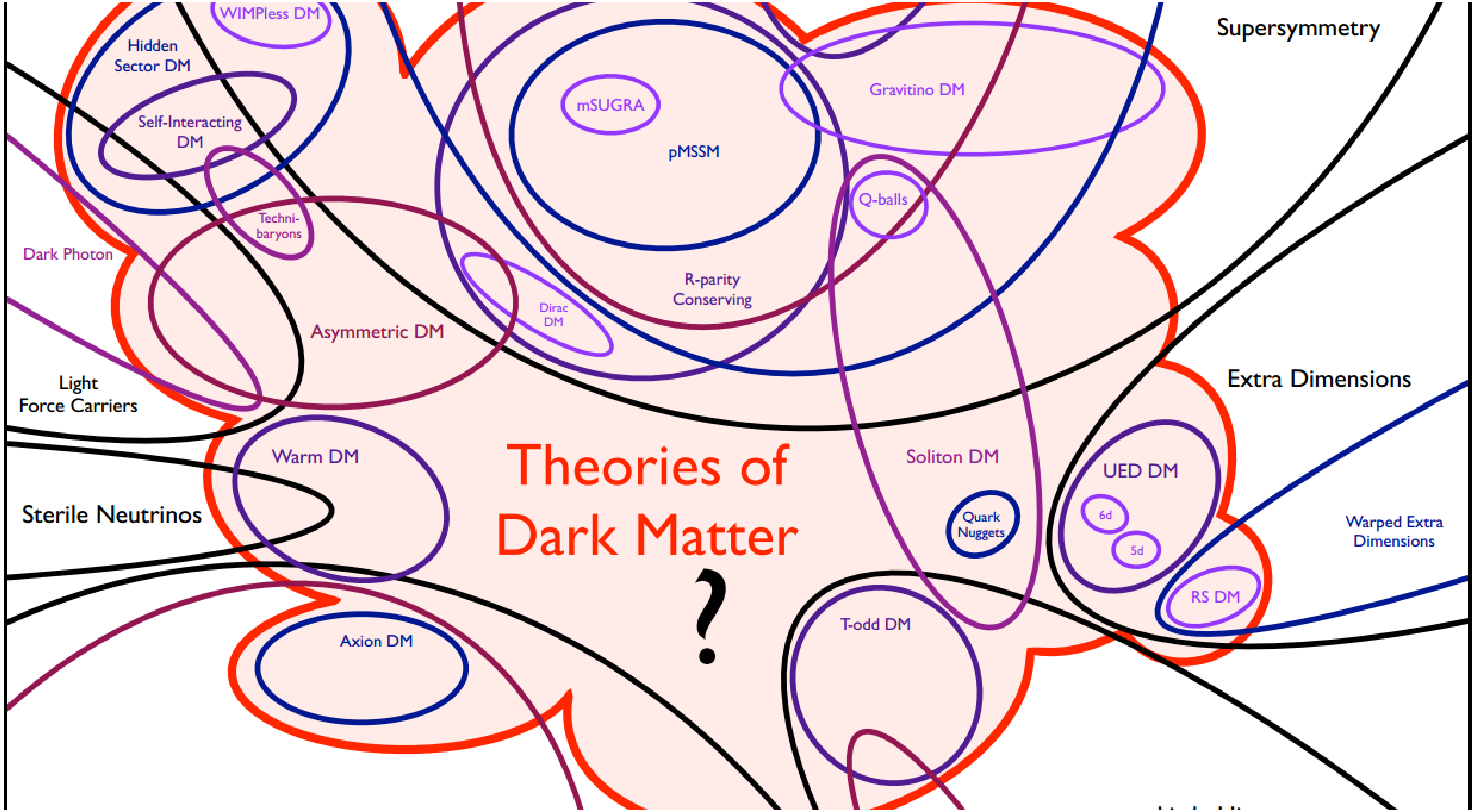
$$\Gamma \sim \langle n_{\rm DM}\sigma\rangle \lesssim H \sim T^2/M_{\rm Pl}$$

$$\frac{\rho_{\rm DM}}{\rho_\gamma} \sim \frac{m}{T_{\rm now}}\frac{n_{\rm DM}}{n_\gamma} \sim \frac{1}{M_{\rm Pl}\sigma T_{\rm now}}$$

$$\frac{M}{T_f} \approx \ln \frac{{\rm dof}_{\rm DM} M M_{\rm Pl}\sigma_0}{240\ g_{\rm SM}^{1/2}} \sim 26$$

$$\Omega h^2 \simeq 0.1 \times \left(\frac{\langle\sigma v\rangle_{\rm freeze}}{3\times10^{-26}\ {\rm cm^3s^{-1}}}\right)^{-1}$$

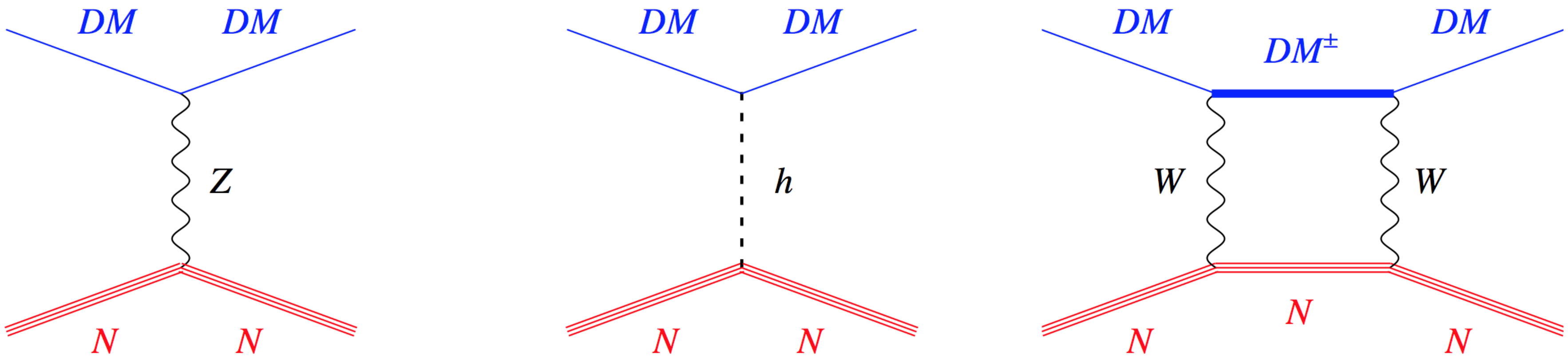
WIMP candidates



Dark Matter direct detection

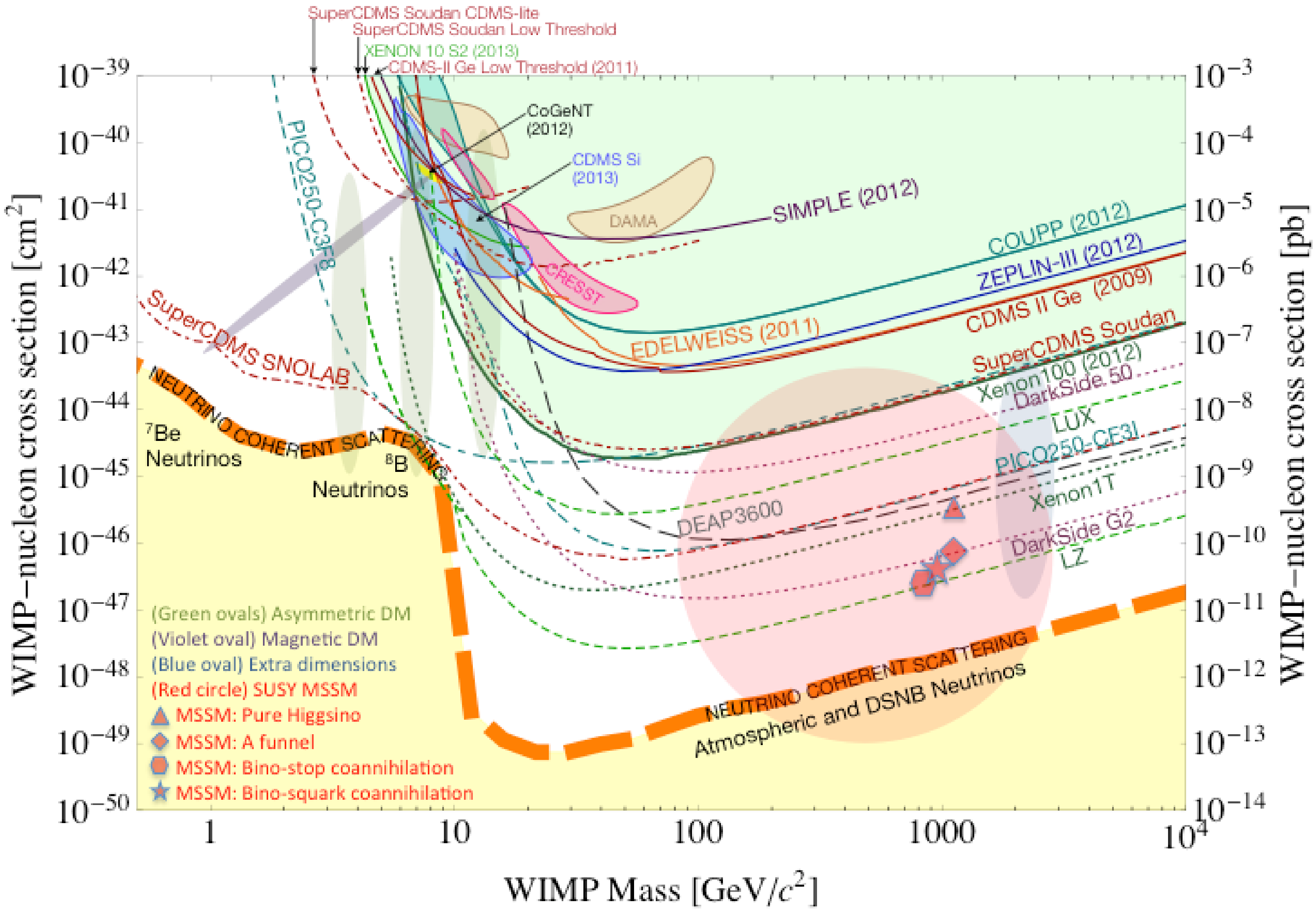
$\sigma_{\mathrm{SI}} =$ spin-independent DM-nucleon cross section

allows to compare experiments: DM/nucleus cross section $\sigma_{\mathcal{N}} = A^2 \sigma_{\mathrm{SI}}$.

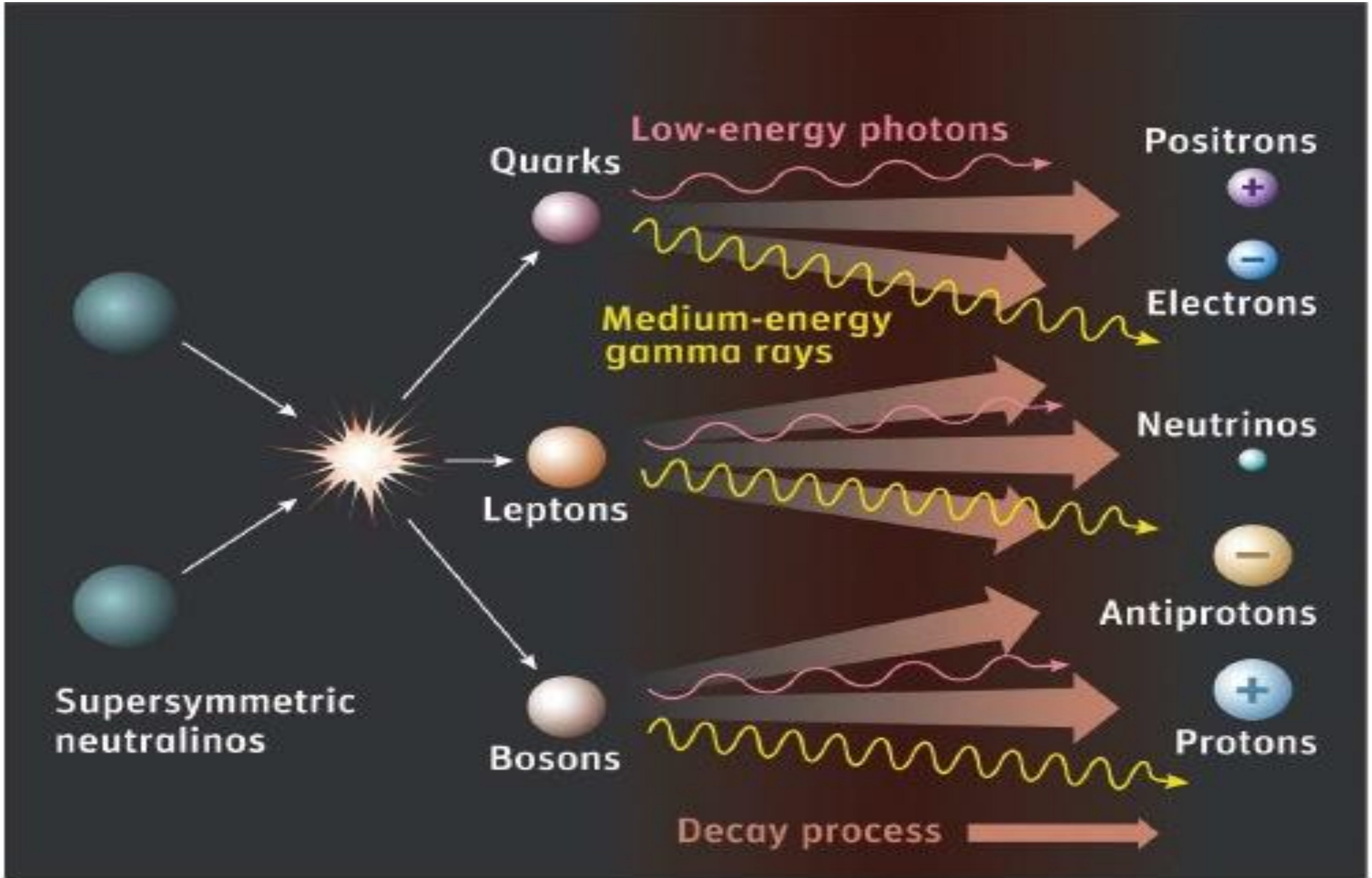


tree, vector	tree, scalar	loop
$\sigma_{\mathrm{SI}} \approx \dfrac{\alpha^2\, m_N^2}{M_Z^4}$	$\sigma_{\mathrm{SI}} \approx \dfrac{\alpha^2\, m_N^4}{M_h^6}$	$\sigma_{\mathrm{SI}} \approx \dfrac{\alpha^4\, m_N^4}{M_W^6}$

Experimental results



Dark Matter indirect detection

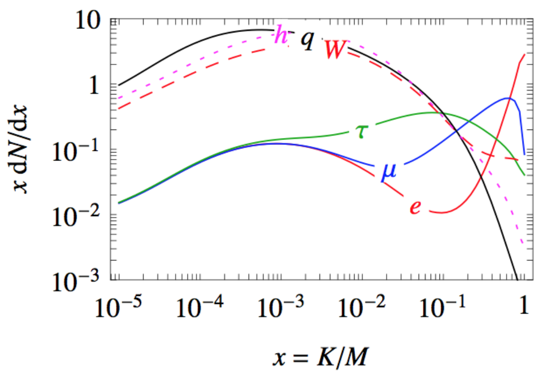


Strategy - injecting DM contribution to CR

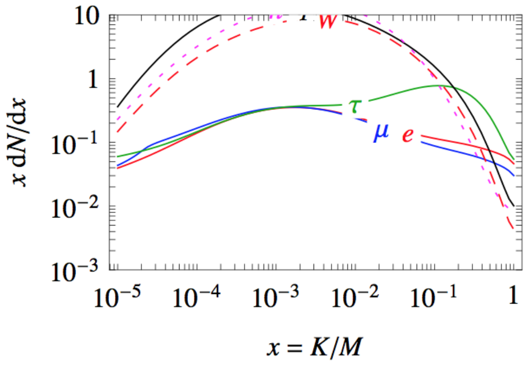
DM DM →

W^+W^-,	ZZ,	hh			EW sector
e^+e^-,	$\mu^+\mu^-$,	$\tau^+\tau^-$			Leptons
$t\bar{t}$,	$b\bar{b}$,	$q\bar{q}$	$\ldots$	gg	Hadrons

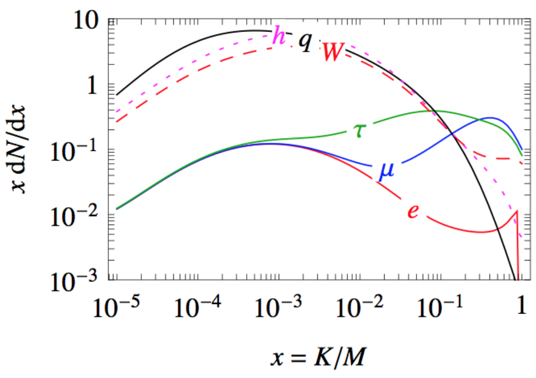
DM DM → electrons



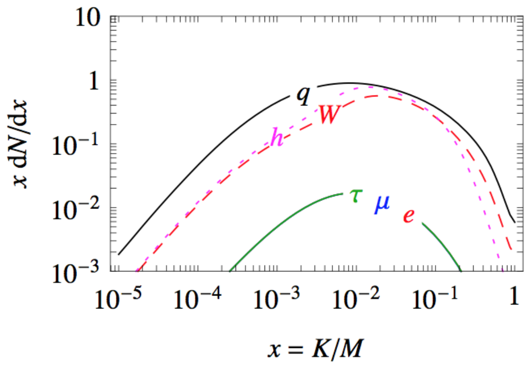
DM DM → photons



DM DM → neutrinos



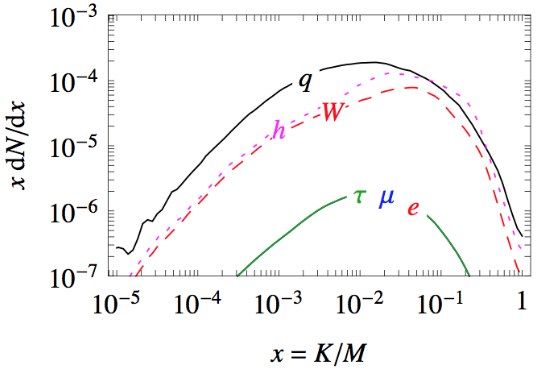
DM DM → protons



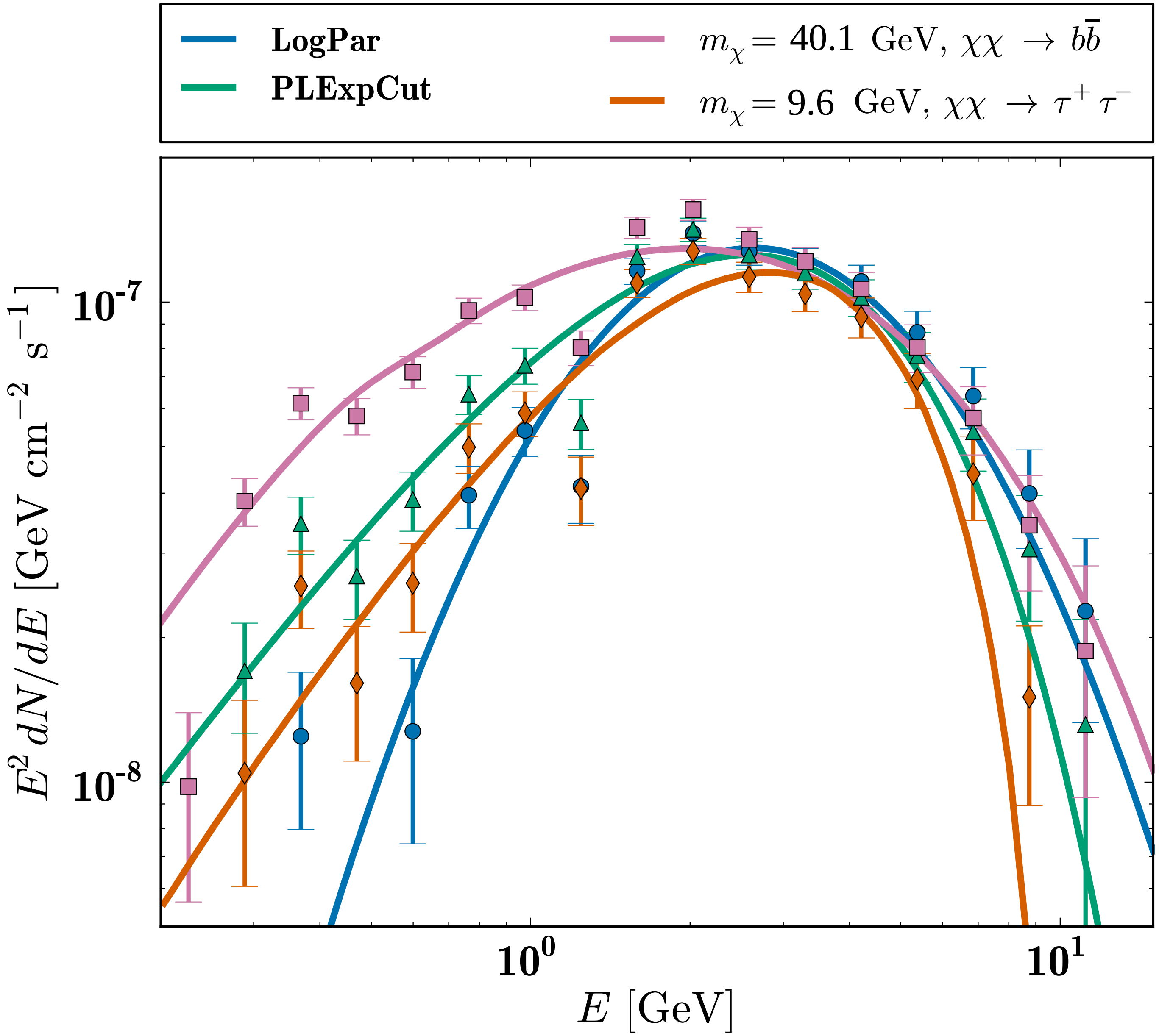
$$Q = \frac{1}{2}\left(\frac{\rho}{M}\right)^2 \langle \sigma v \rangle \frac{dN_e}{dE}$$

Energy spectra of
final state particles

DM DM → deuterium



DM interpretation of the GeV excess



1) Morphology of the signal is consistent with DM halo profile

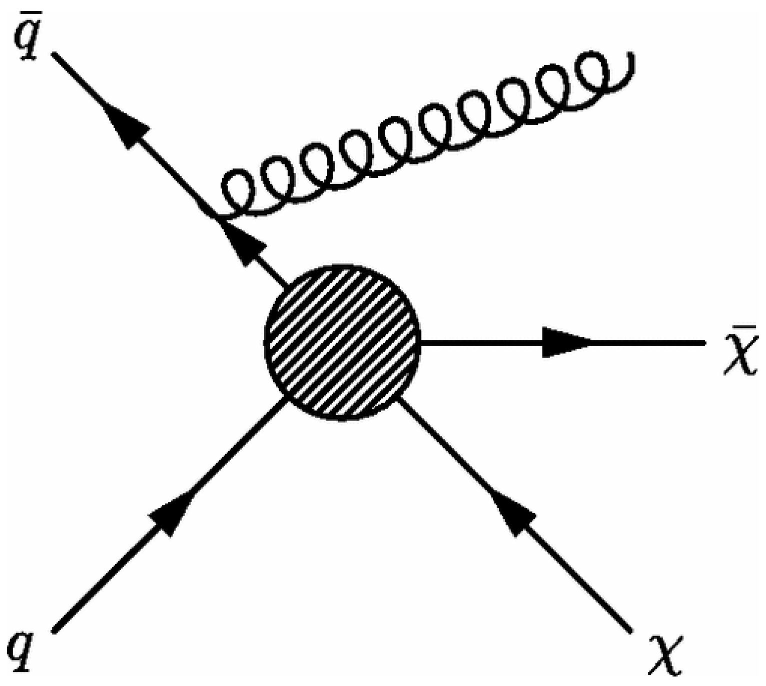
2) The ann. xs. is the thermal freeze-out xs

Triple coincidence?

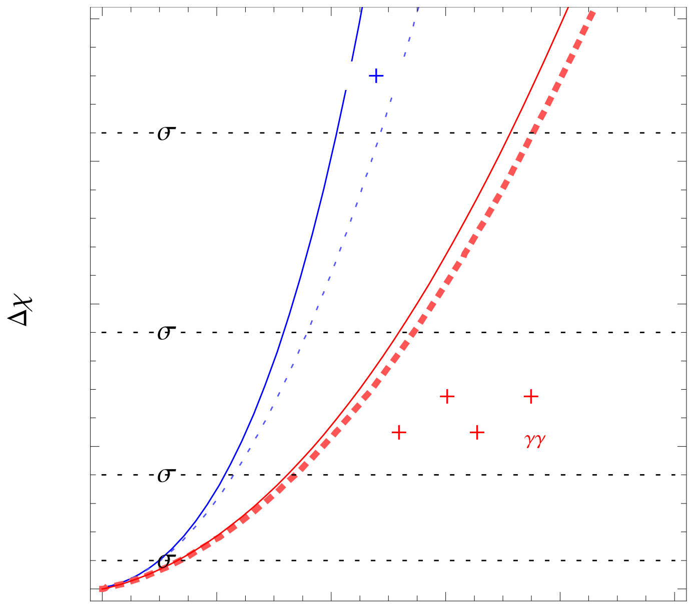
Or the first signal of DM?

Collider tests of DM

The experimental signature is a mono-jet or a single photon plus missing energy

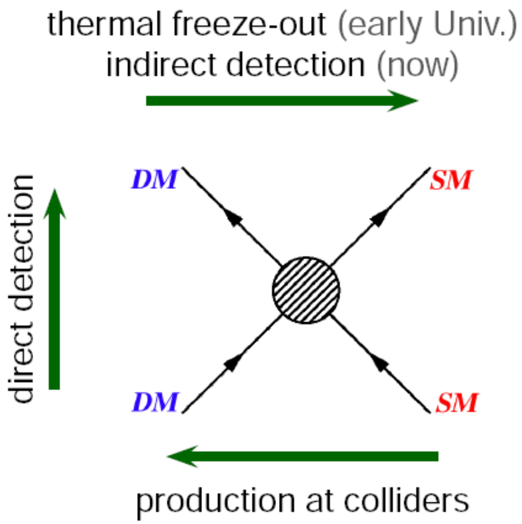


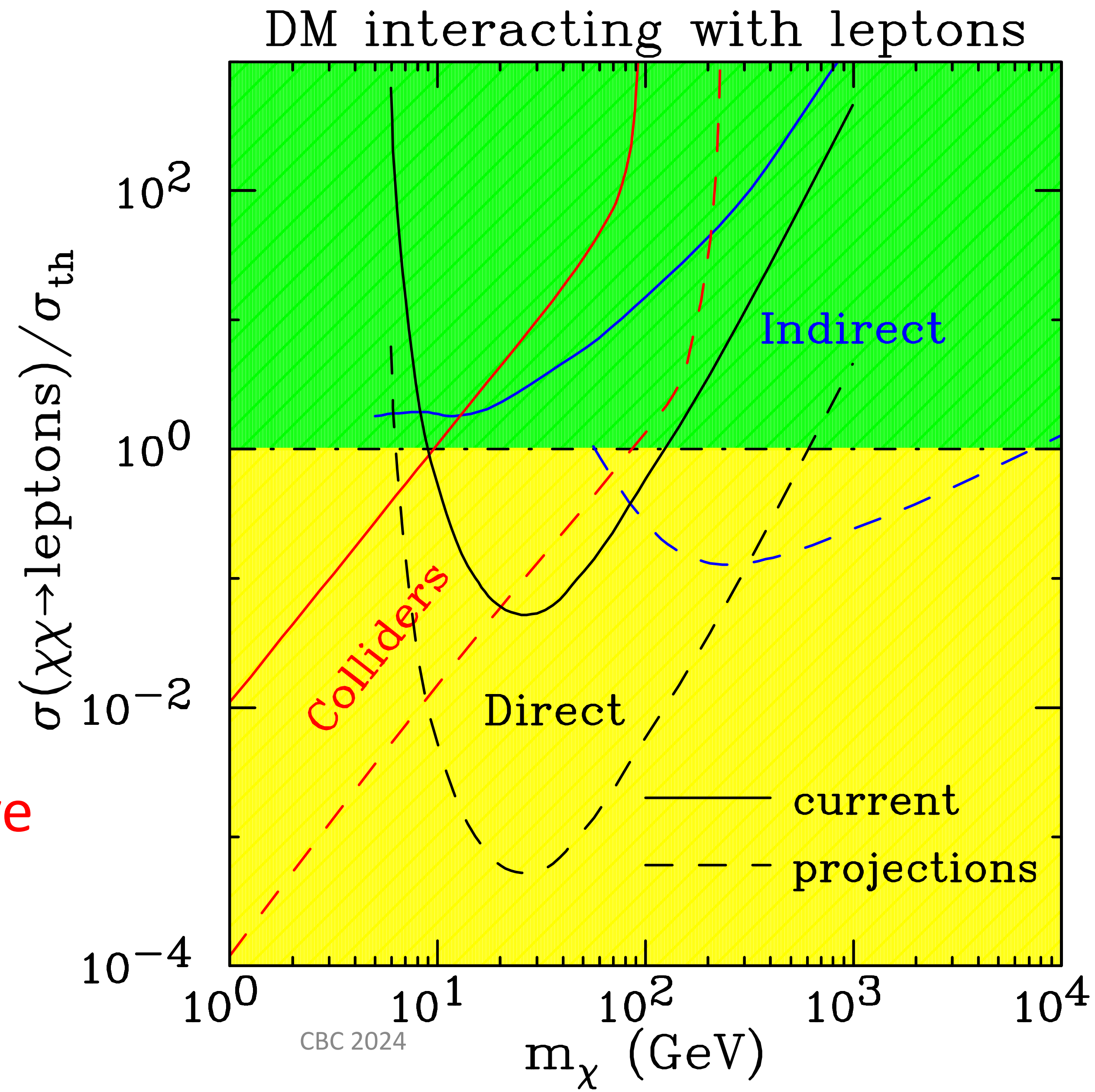
Higgs inv.decays



Only bounds on DM theories from the LHC

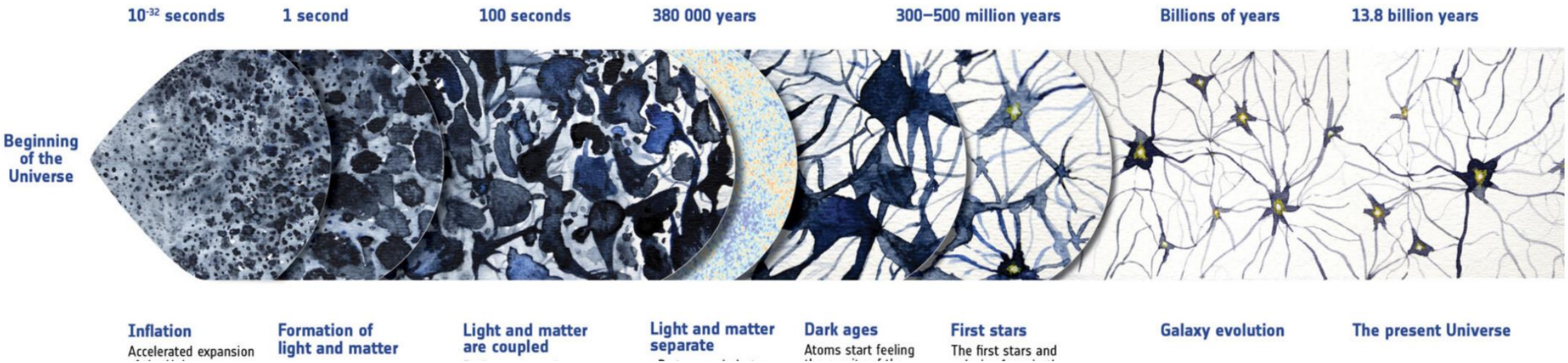
Complementarity of different DM tests





WARNING: likely too naive

Open question: Primordial Black Holes and other GW observables?



History of gravitational waves

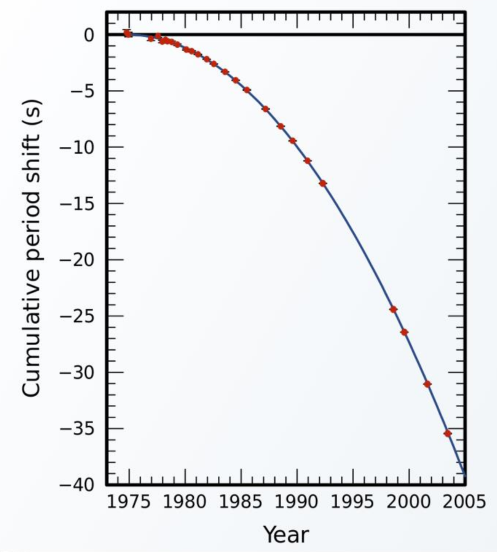
20TH CENTURY

1916: GWs predicted by Einstein

theoretical status uncertain until the second half of the 20th century

1970s: first indirect observation of GWs

orbital decay of the Hulse Taylor binary pulsar



21ST CENTURY

2015: first direct detection of GWs

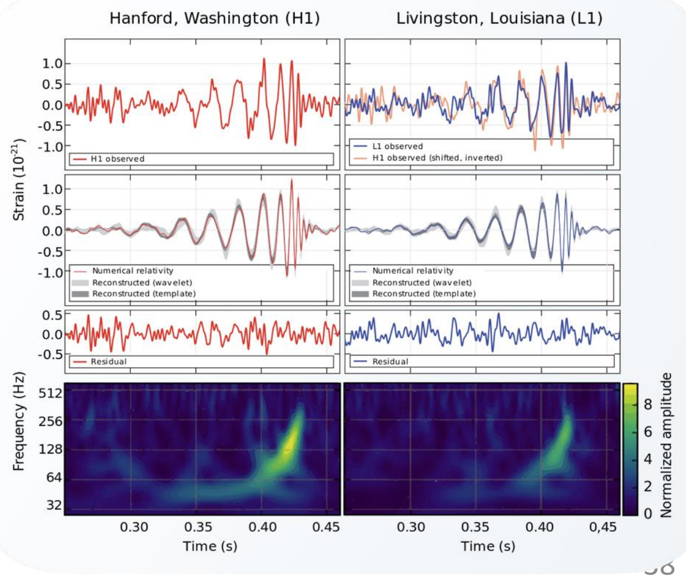
GW150914 - merger of $\mathcal{O}(30)$ solar mass BHs [LIGO]

2017: first merger of neutron stars

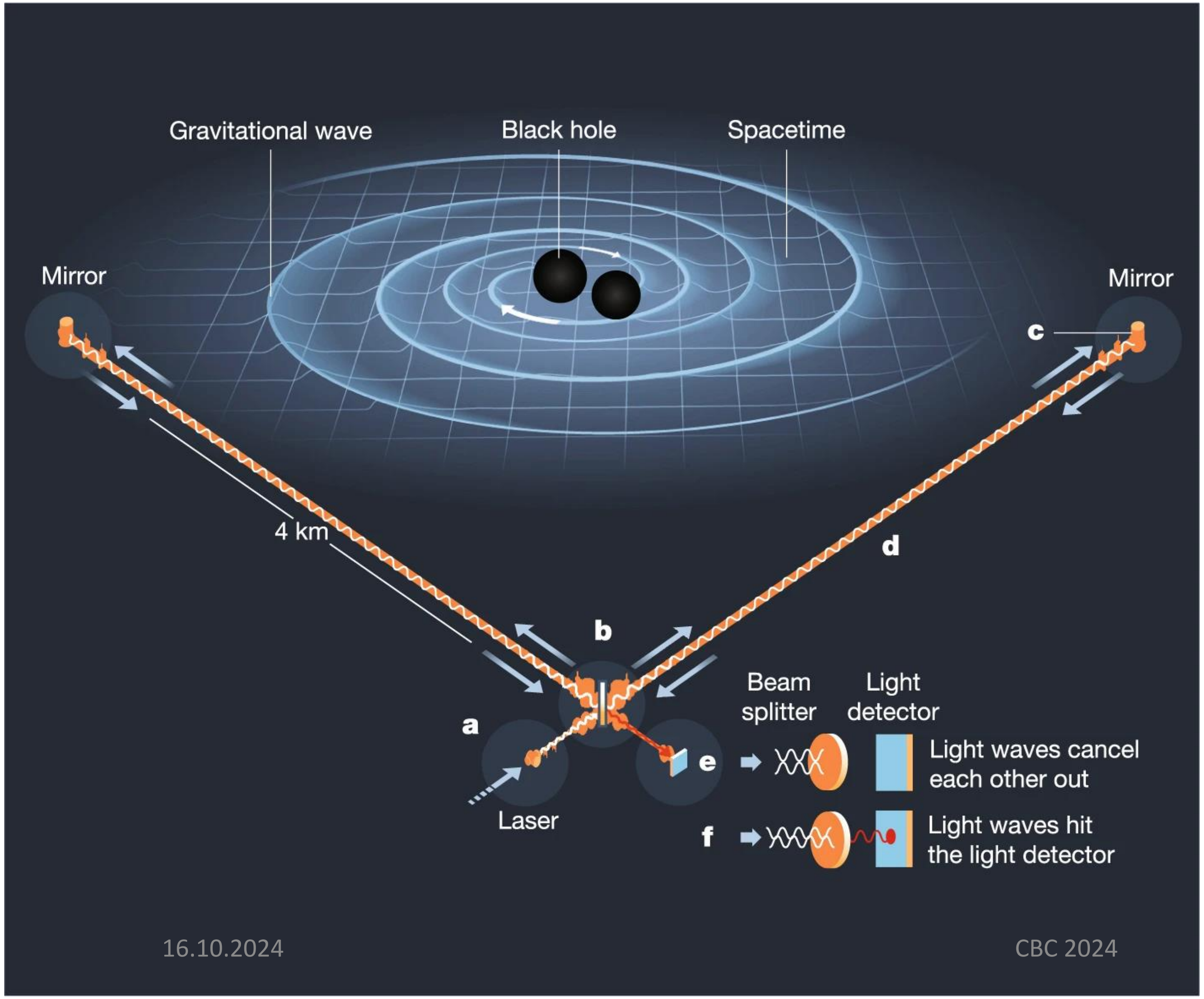
GW 170817

2023: first evidence for a GW background

pulsar timing array experiments [NANOGrav]

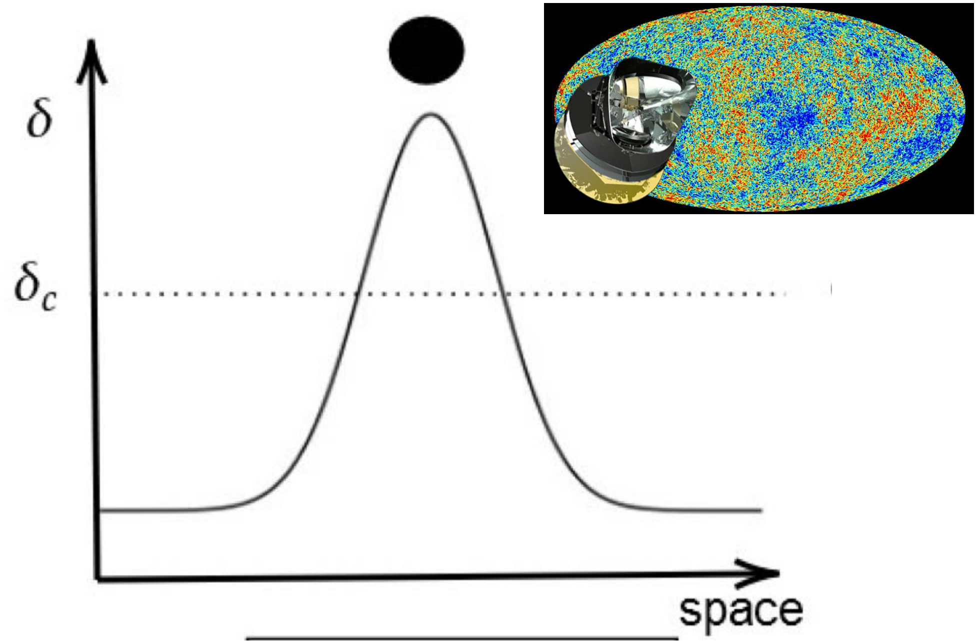


In 2015 the LIGO discovered GWs in BH merges



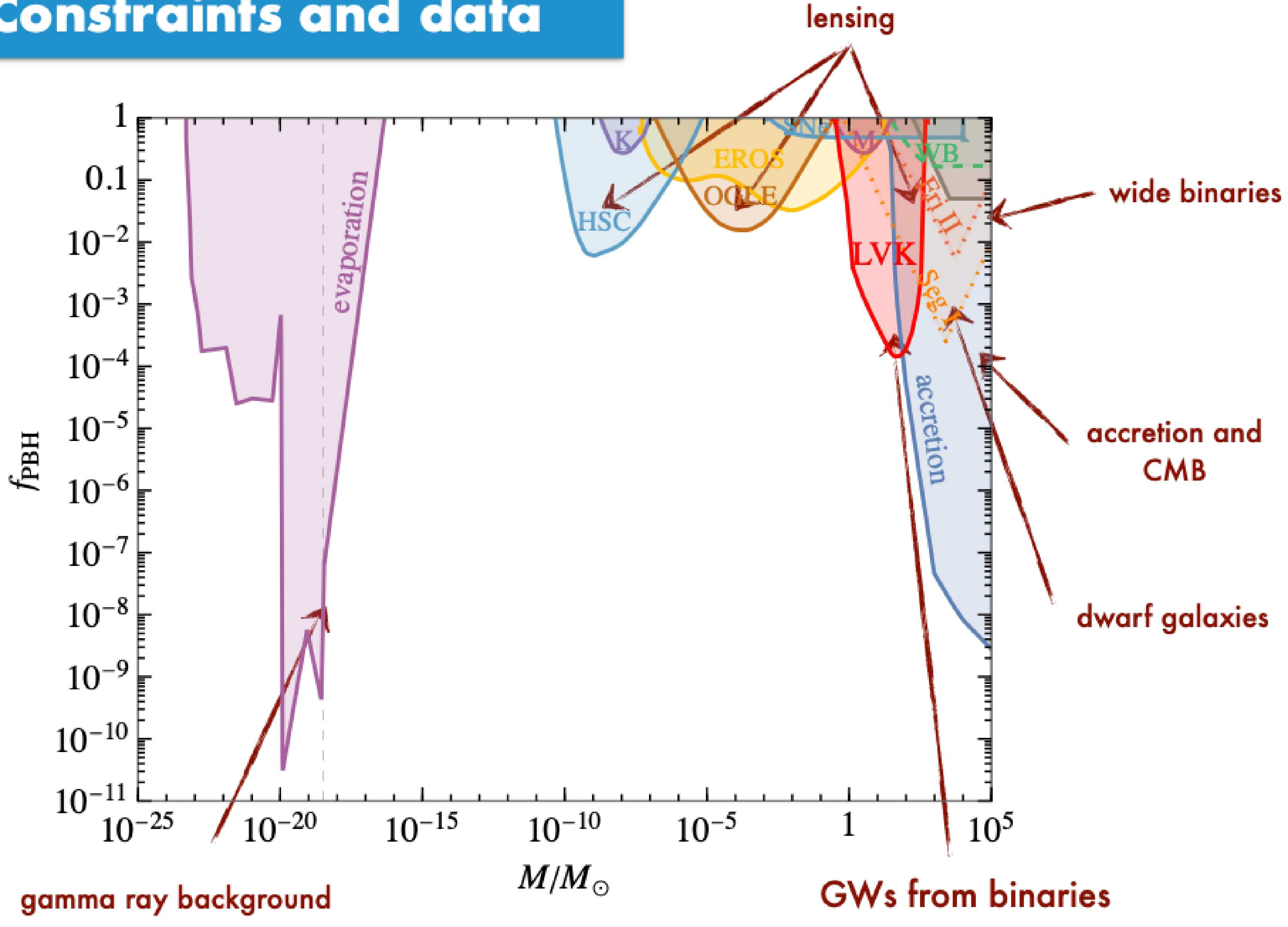
The observed BH masses where 30 M_{sol}, “too large” for astrophysical expectations

Did LIGO discover the DM in the form of PBHs?



Inflation creates large density fluctuations which Create PBHs when entering to the horizon

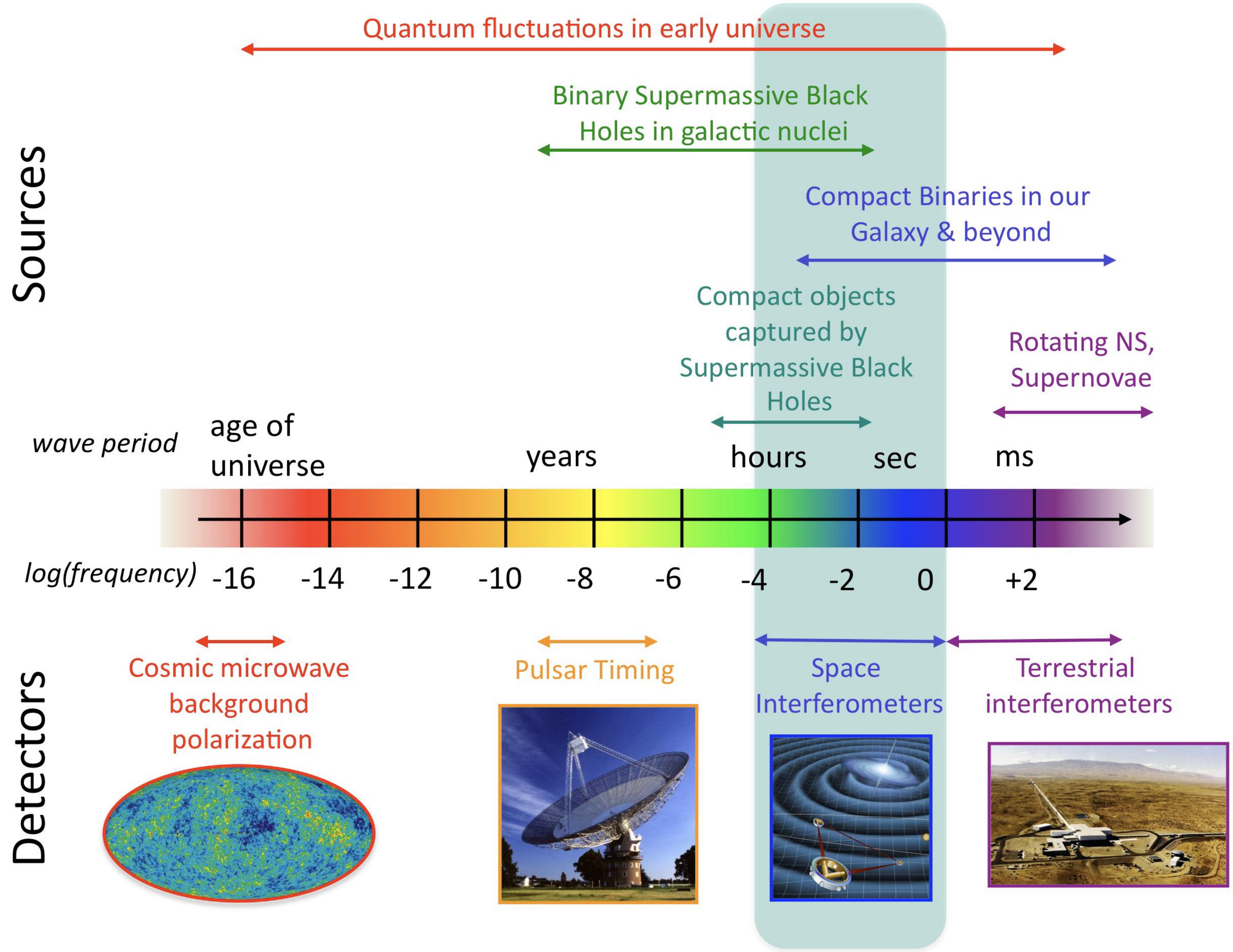
Constraints and data



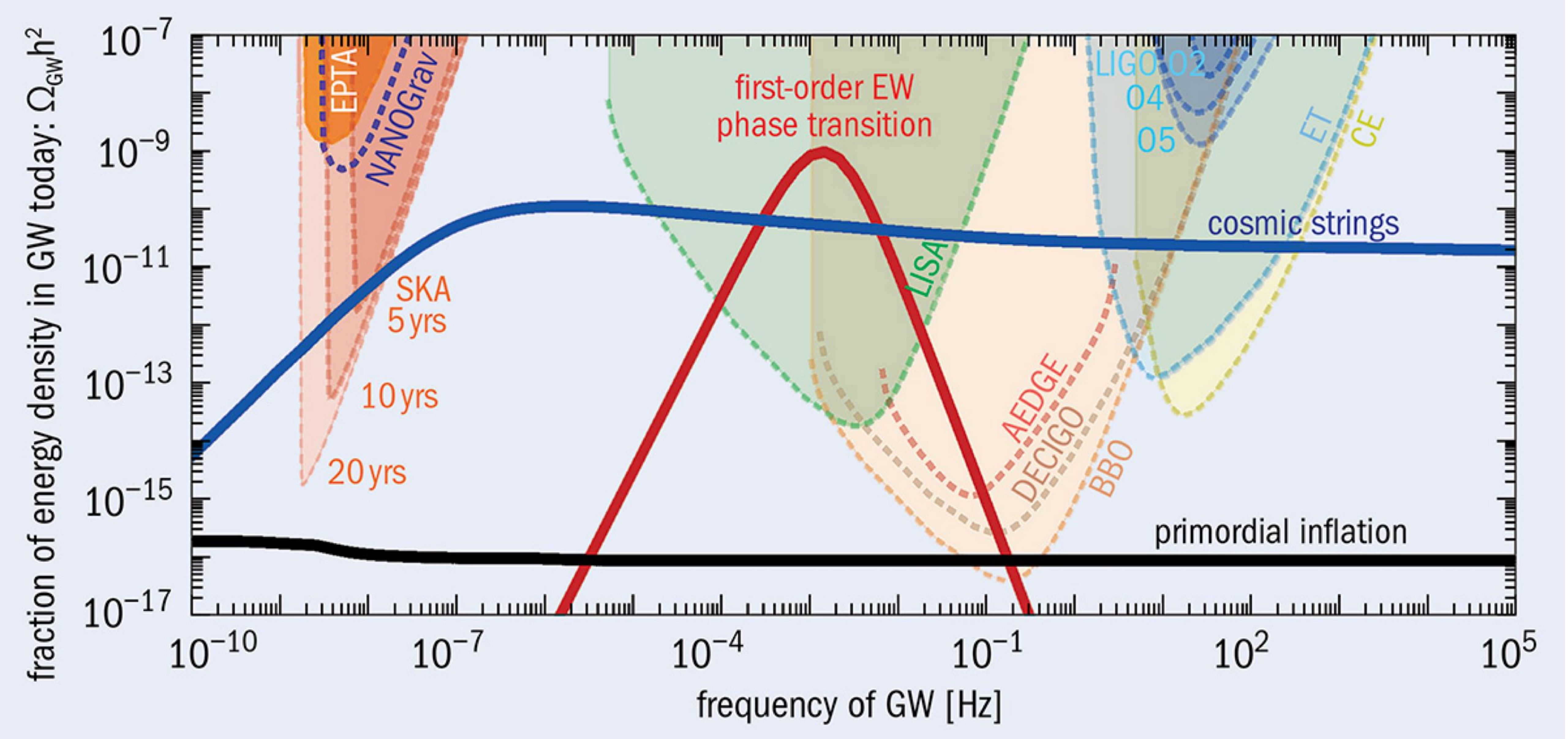
PBHs can be all of the DM in the asteroid mass window

Small PBH fraction at large masses can provide seeds for galaxies

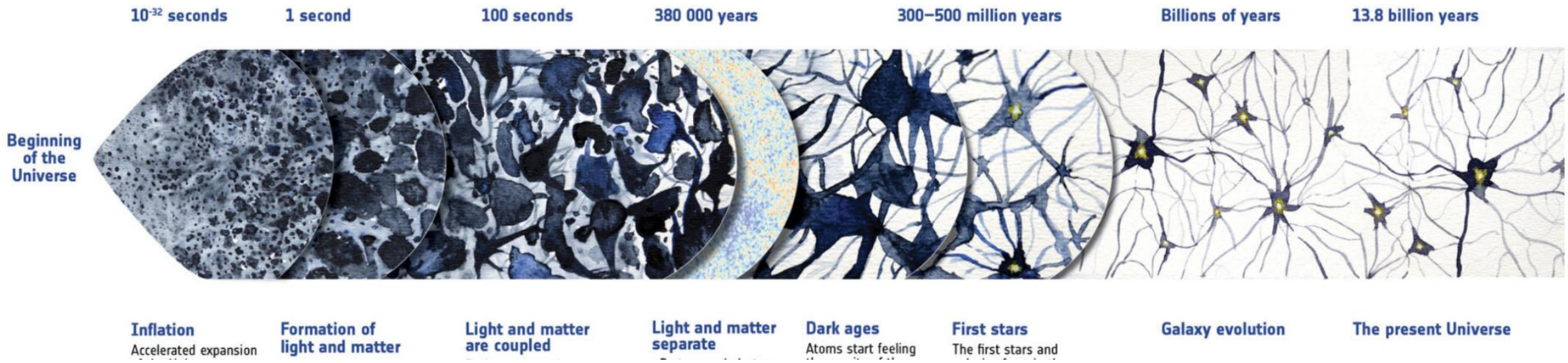
Very rich physics


Sources
Quantum fluctuations in early universe
Binary Supermassive Black Holes in galactic nuclei
Compact Binaries in our Galaxy & beyond
Compact objects captured by Supermassive Black Holes
Rotating NS, Supernovae
wave period
age of universe
years
hours
sec
ms
log(frequency)
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
Detectors
Cosmic microwave background polarization
Pulsar Timing
Space Interferometers
Terrestrial interferometers

Cosmic phase transitions and GW signals



Open question: Dark Energy?



Scenarios of Dark Energy are not predictive

Dark Energy is kind of slow inflation

1. Cosmological constant **Λ** of General Relativity
   a. Why the density is so small, 10^{-4} eV << M_{planck}?

2. Quintessence – small value of the scalar potential
   a. Analoguous to the inflation but at small scale

All DE explanations suffer from the hierarchy problem, why << M_{planck}?

Conclusions

- The SM of particle physics is not complete and must be extended
- Its extensions receive contributions from ΛCDM and GR
- The SM, ΛCDM and GR complement each other

The whole Universe is one big laboratory