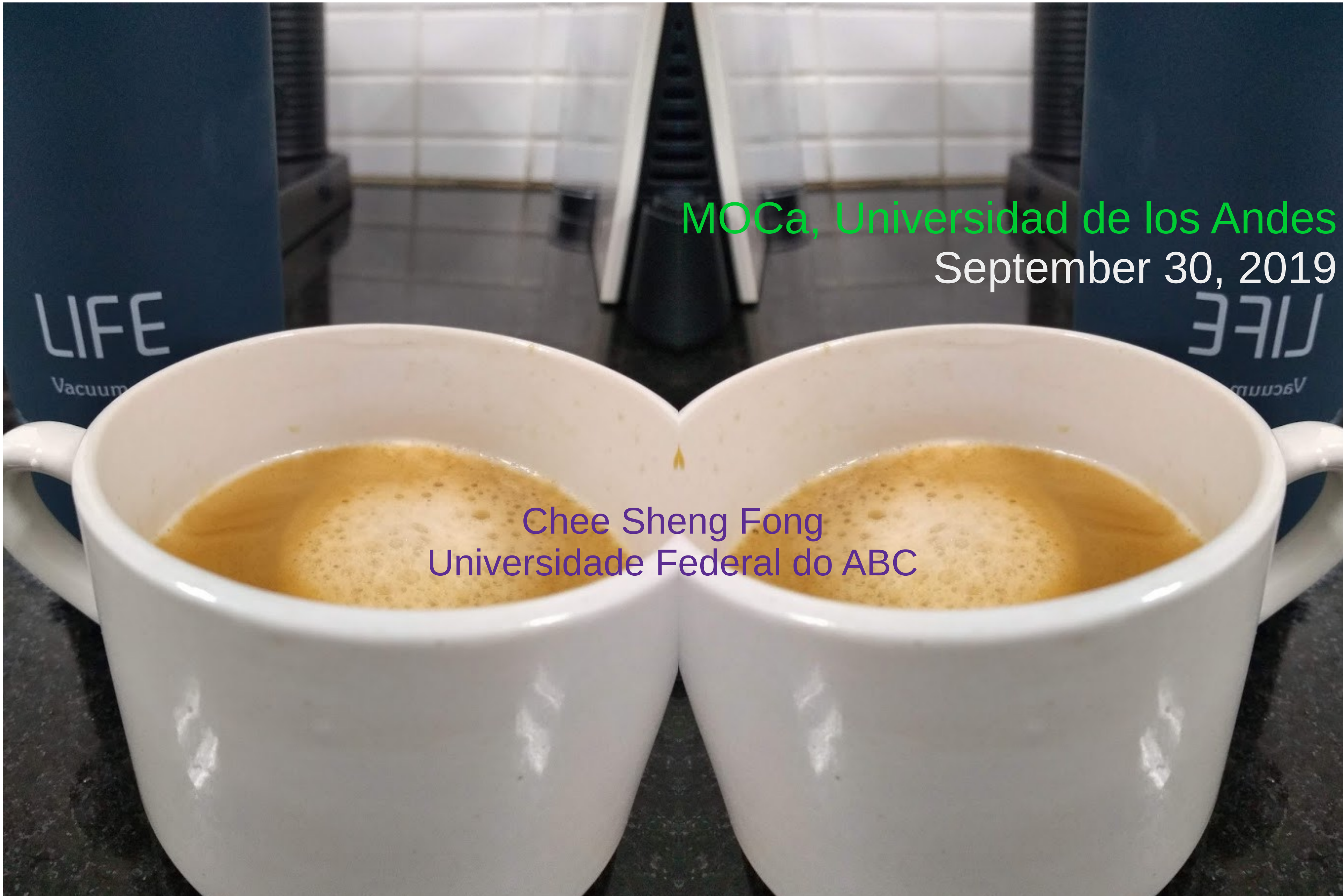
Dark Matter hinting to Mirror World?



MOCa, Universidad de los Andes
September 30, 2019

Chee Sheng Fong
Universidade Federal do ABC

Current understanding of the Universe

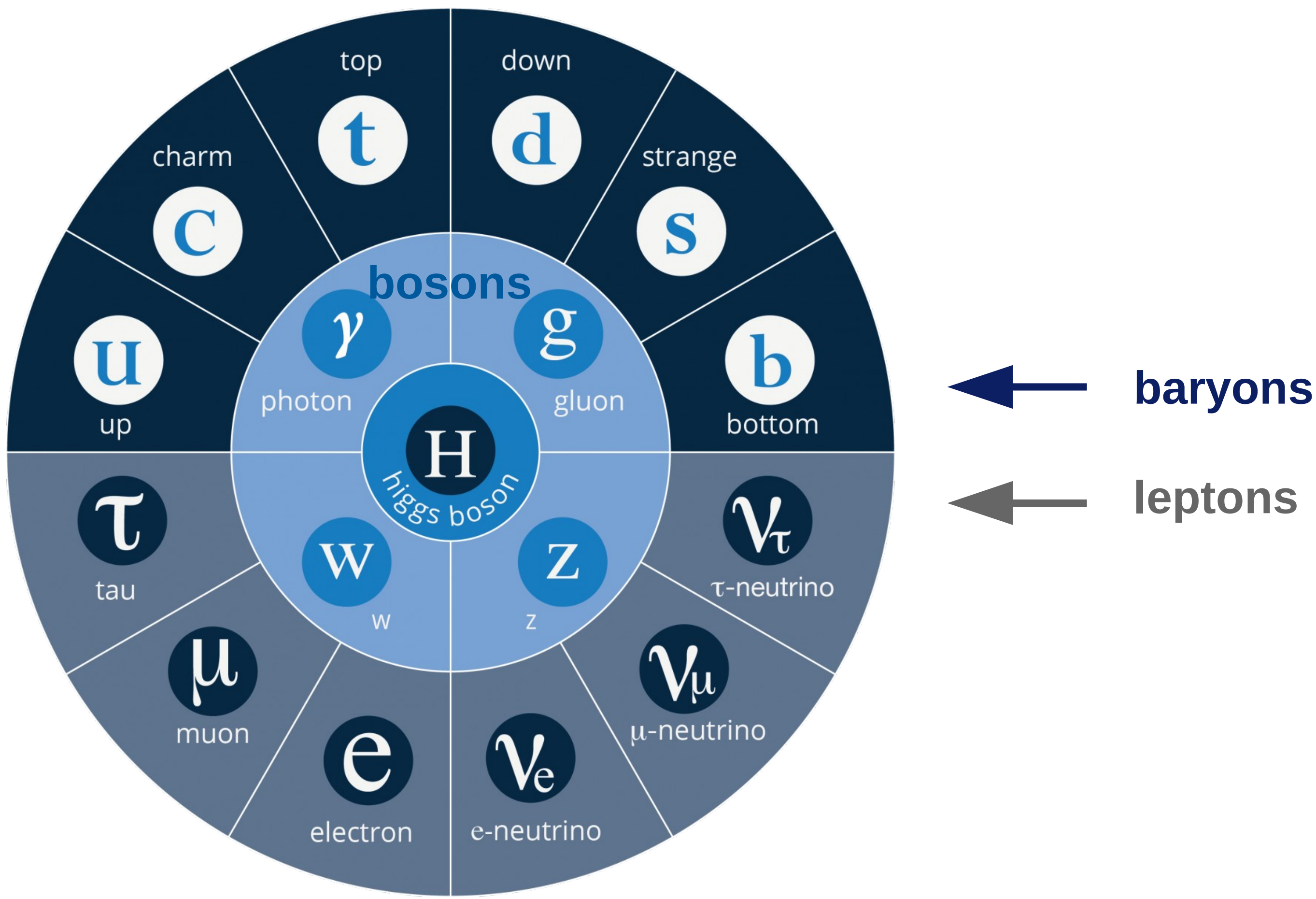
***Q**uantum* ***F**ield* ***T**heory*:
the **S**tandard **M**odel of particle physics **(SM)**

***G**eneral* ***R**elativity*:
the **Λ** **C**old **D**ark **M**atter model **(ΛCDM)**

The Standard Model

of particle physics

All charged particles (besides ɣ, g, H & Z) comes with the corresponding antiparticles



Since 2012, we have discovered all of them.

Source: https://atlas.cern/discover/physics

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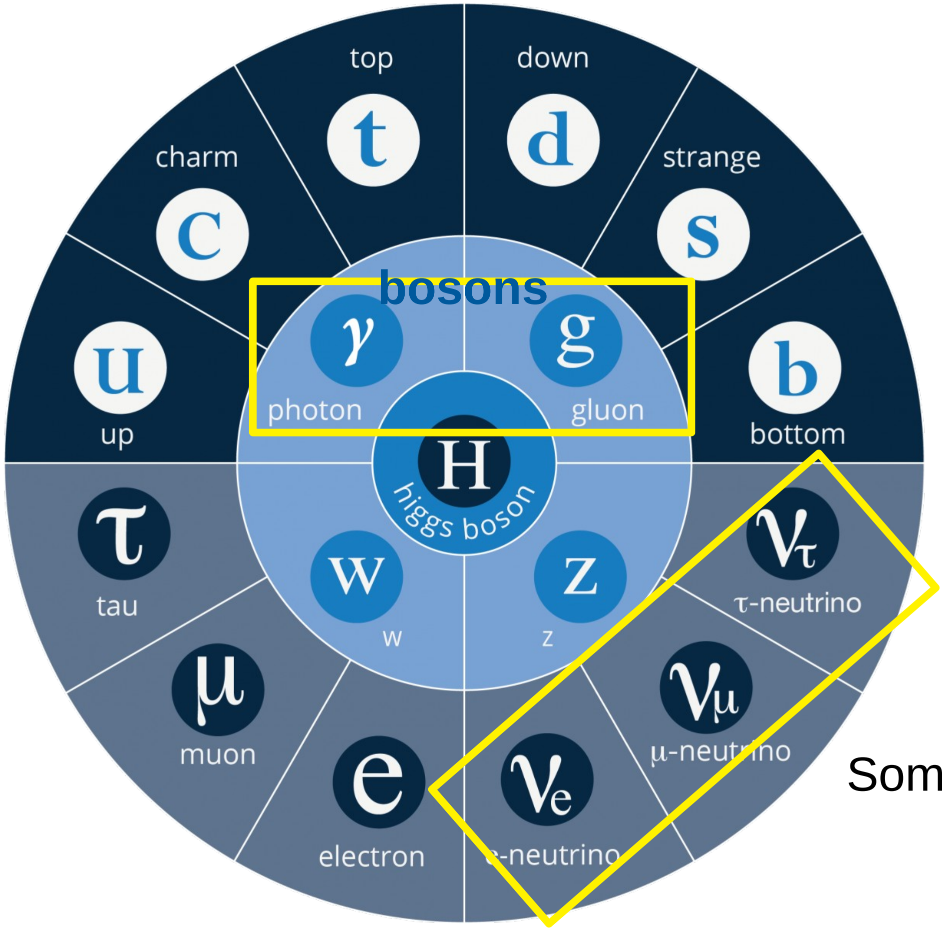

baryons

leptons

Some of them are massless!

Since 2012, we have discovered all of them.

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observationally ...

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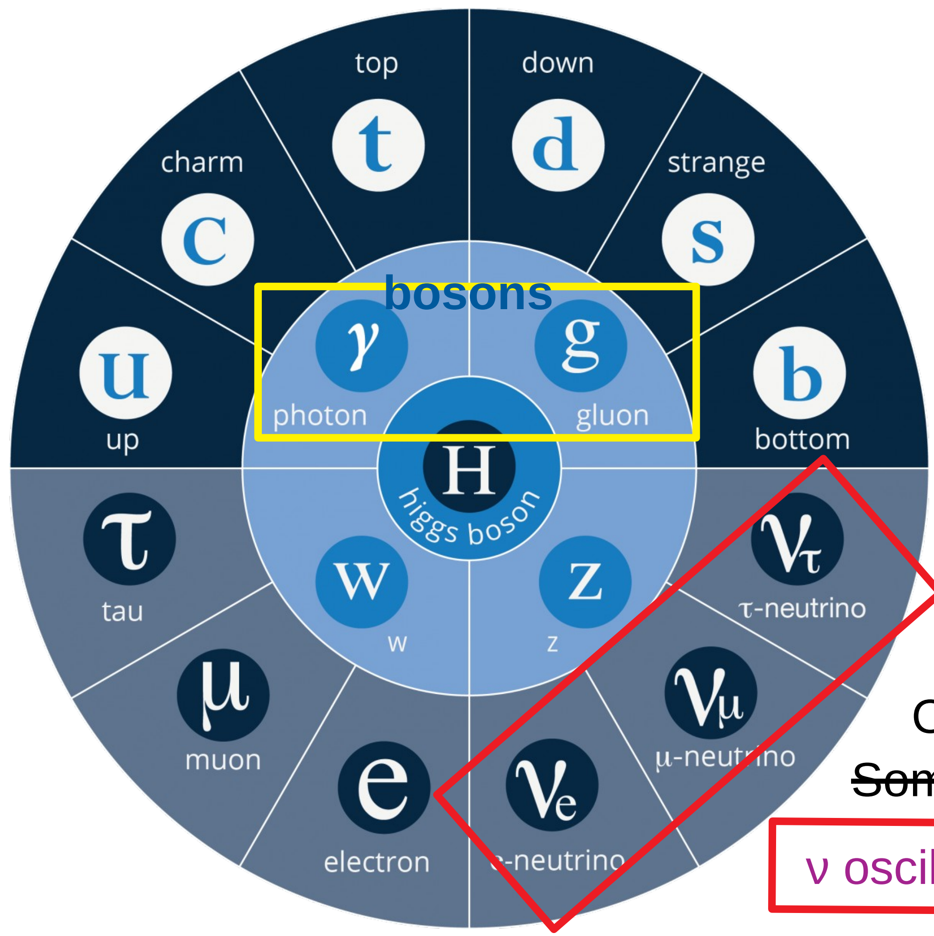

baryons

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Only γ, g
~~Some of them~~ are massless!

ν oscillations (1998): tiny $m_\nu \neq 0$

?

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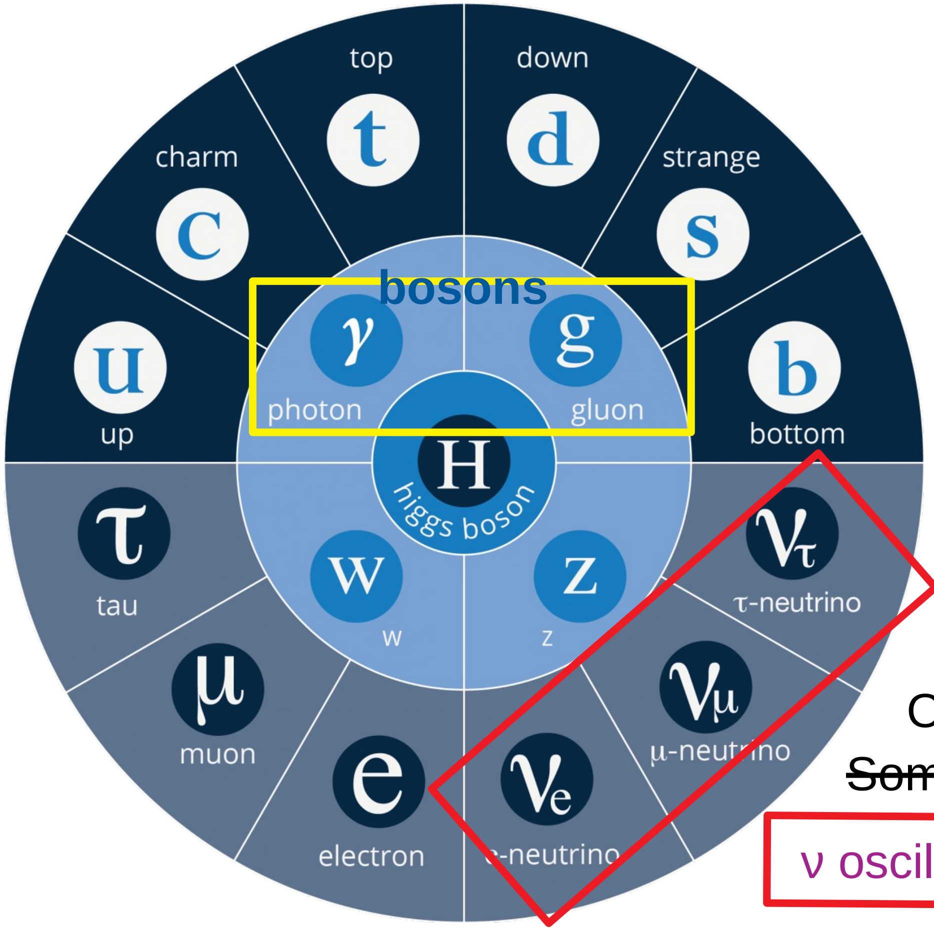
Universe is made of <u>only matter (particles)</u>

?



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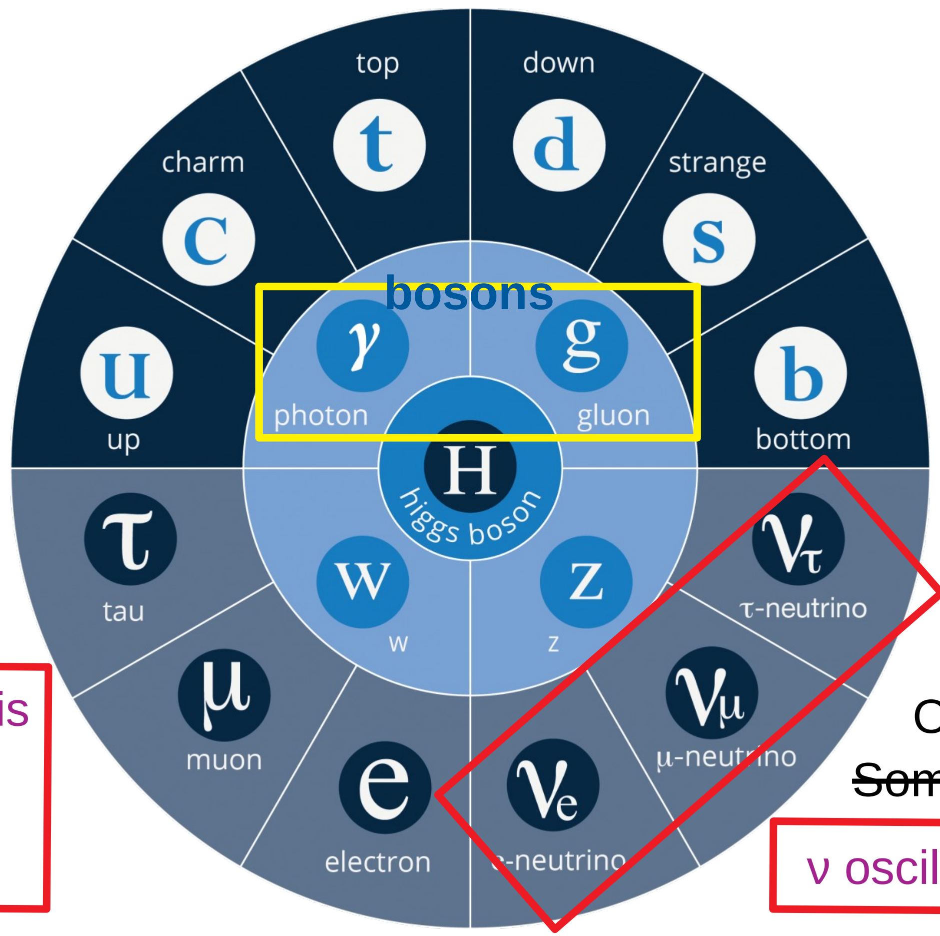

baryons

leptons

The matter we observe is only 5%! The rest: 20% unknown matter 75% unknown energy

?

Only ɣ, g ~~Some of them~~ are massless!

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observationally ...

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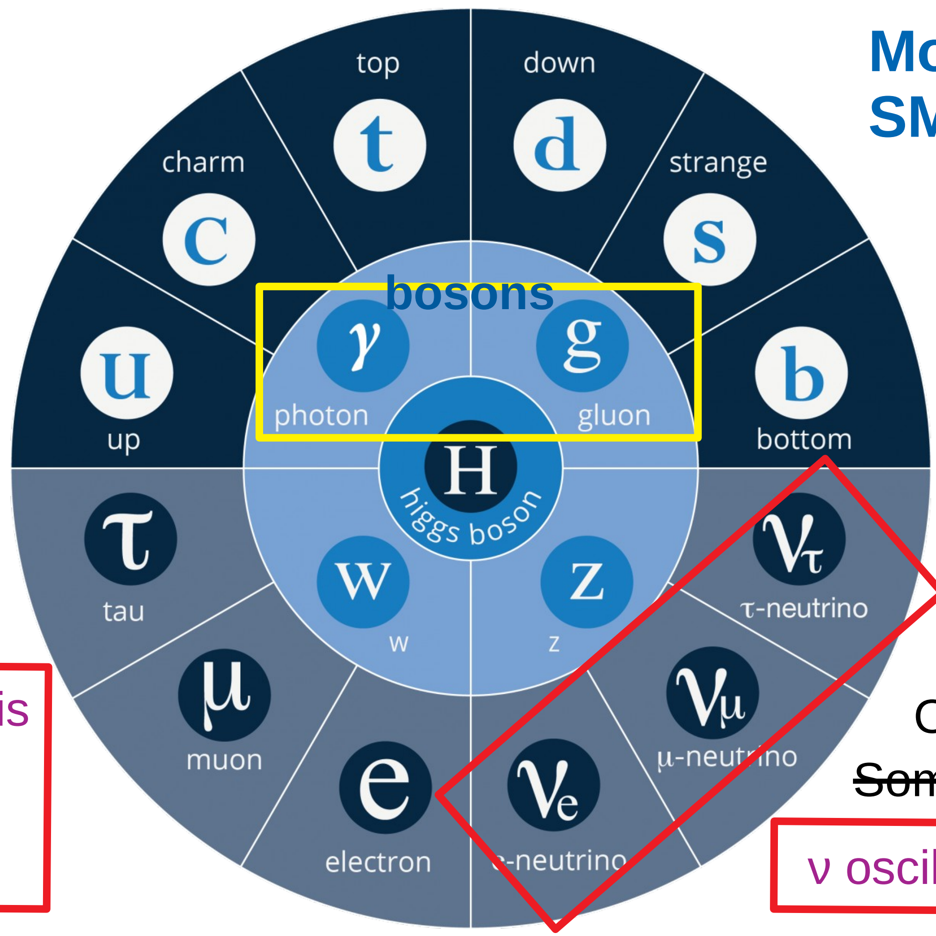
Modifications to the SM or GR or both?

Universe is made of only matter (particles)

?



baryons

leptons

The matter we observe is only 5%! The rest:
20% dark matter
75% dark energy

?

Only ɣ, g
~~Some of them~~ are massless!

ν oscillations (1998): tiny $m_\nu \neq 0$

?

Since 2012, we have discovered all of them.

Evidences only from gravitational effects

dark = unknown

Source: https://atlas.cern/discover/physics

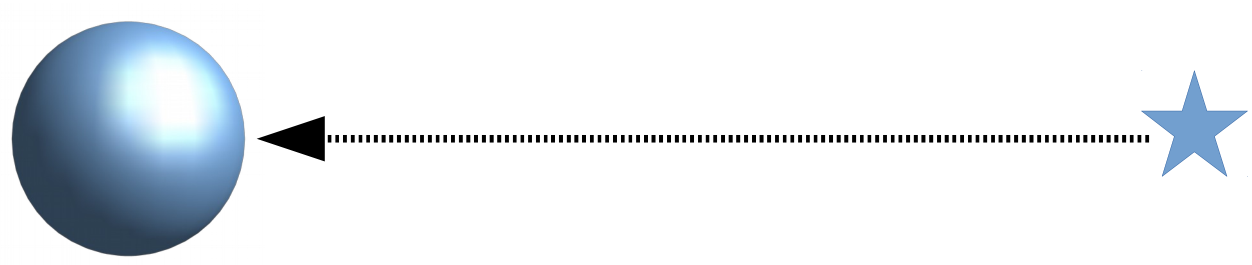
Outline

- How/What we know about dark matter?
- Dark matter = mirror universe?
- Higgs portal
- Kinetic mixing
- Neutrino portal

What is the cosmic energy content?

- Using Standard Candle: Type Ia supernovae

$$\ell(z) = \frac{L}{4\pi d_L(z)^2}$$

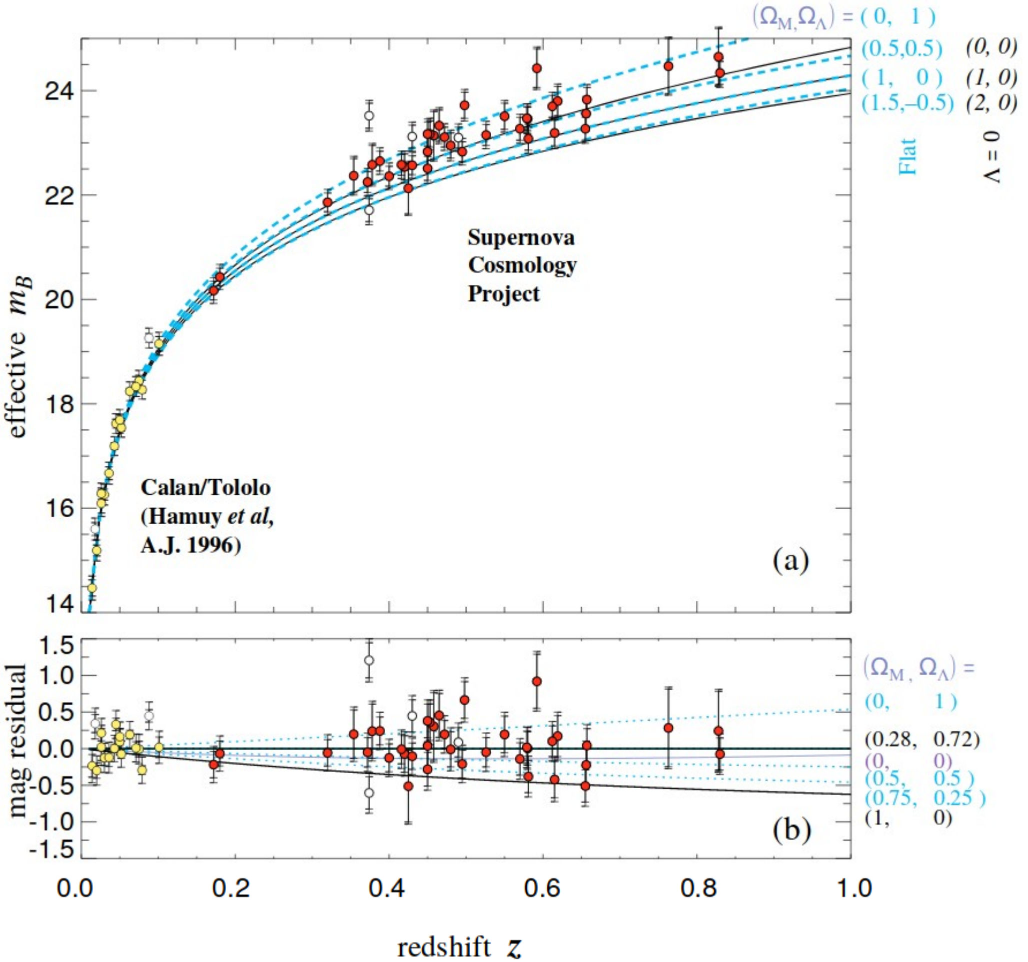


$$d_L = a(z) r (1+z)$$

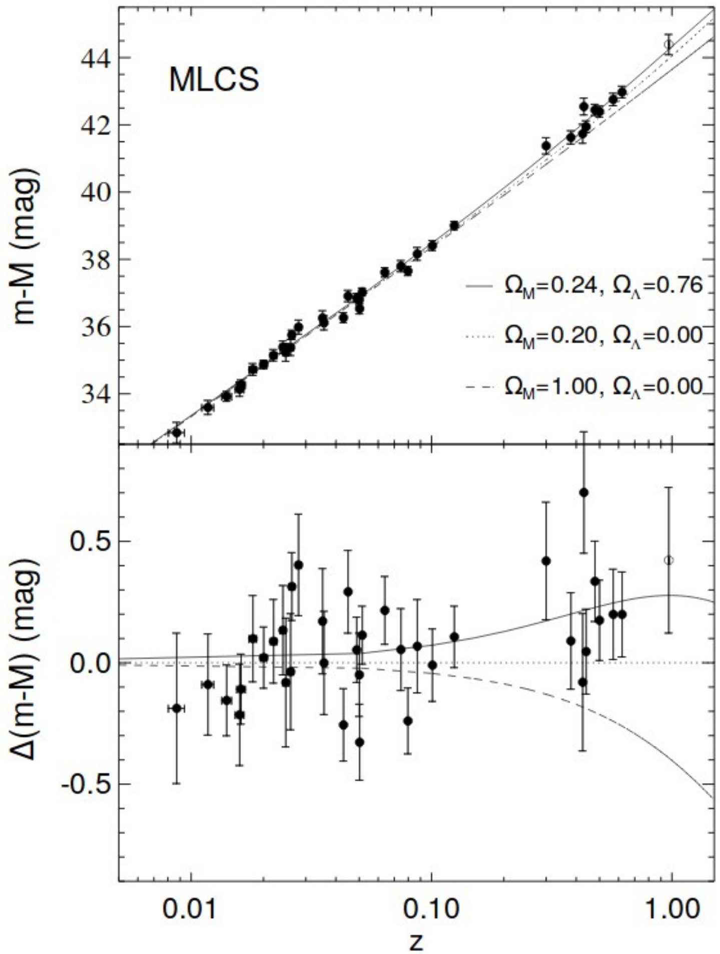
Depends on the cosmic energy content $\Omega_i \equiv \frac{\rho_i}{\rho_c}$

What is the cosmic energy content?

- Observations of Type Ia supernovae



[Permutter et al. astro-ph/9812133]



[Riess et al. astro-ph/9805201]

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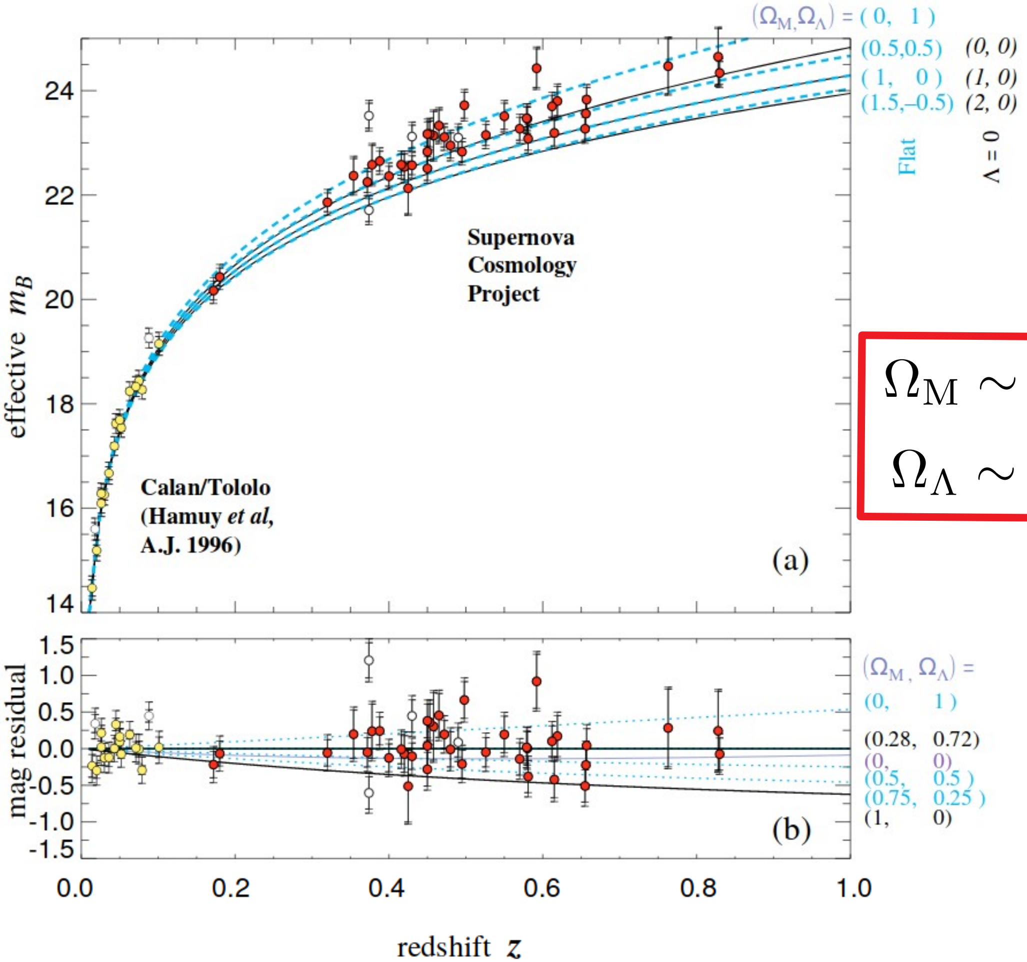
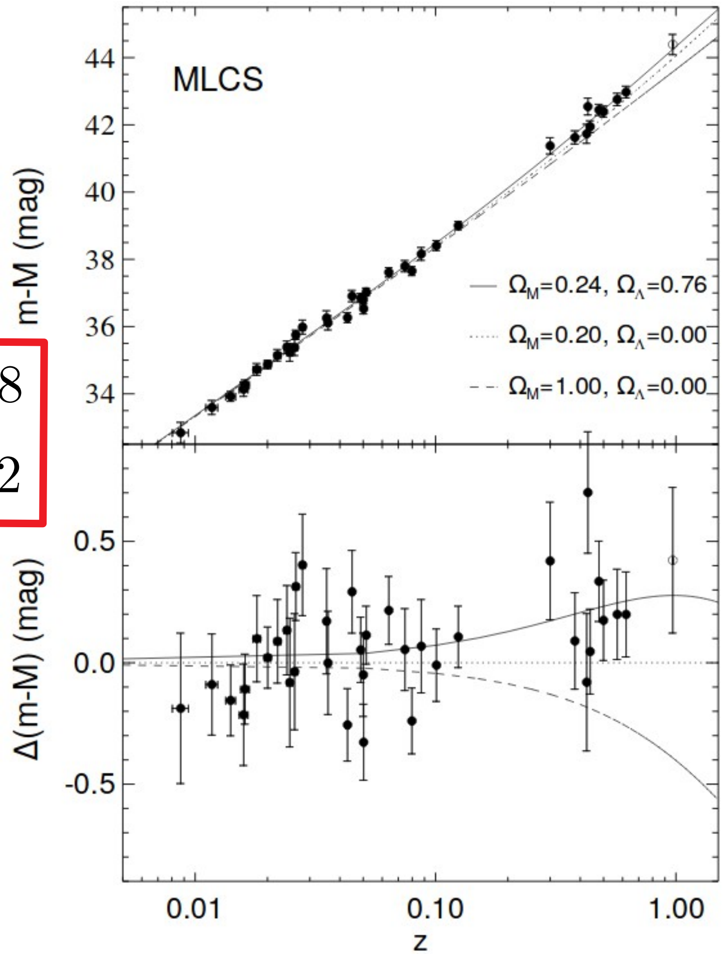


[Permutter et al. astro-ph/9812133]

$$\Omega_{\rm M} \sim 0.28$$

$$\Omega_\Lambda \sim 0.72$$



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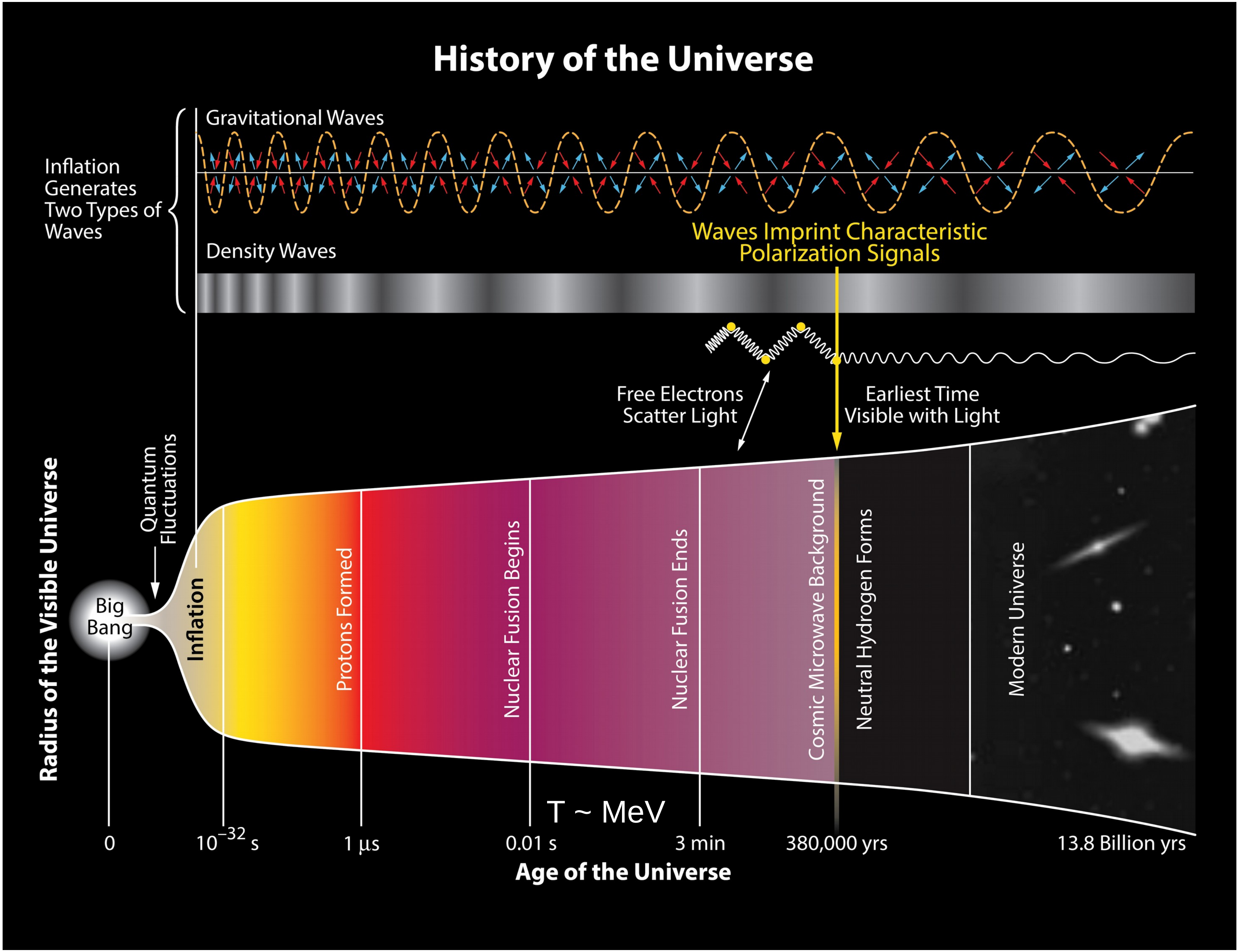
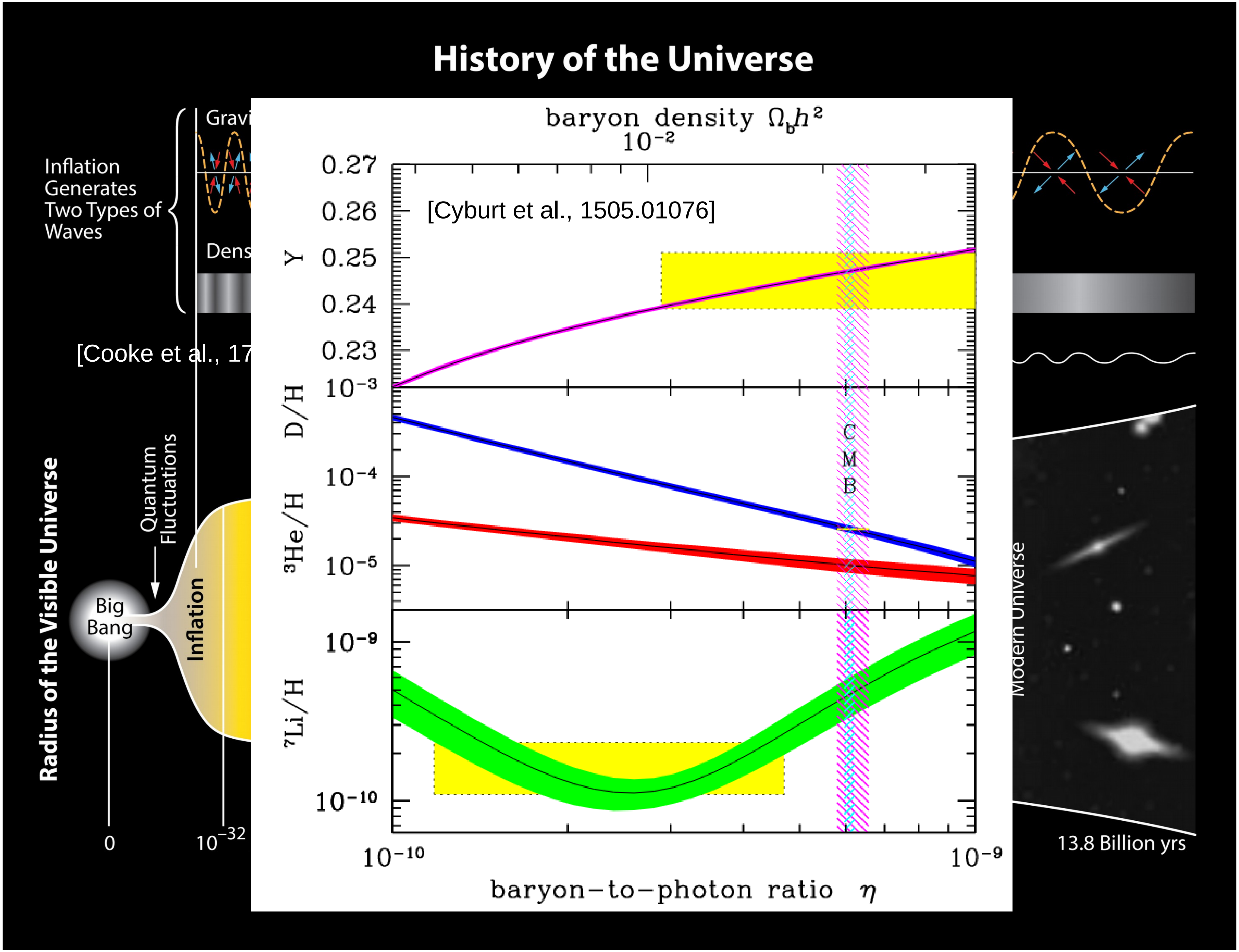


http://bicepkeck.org/visuals.html



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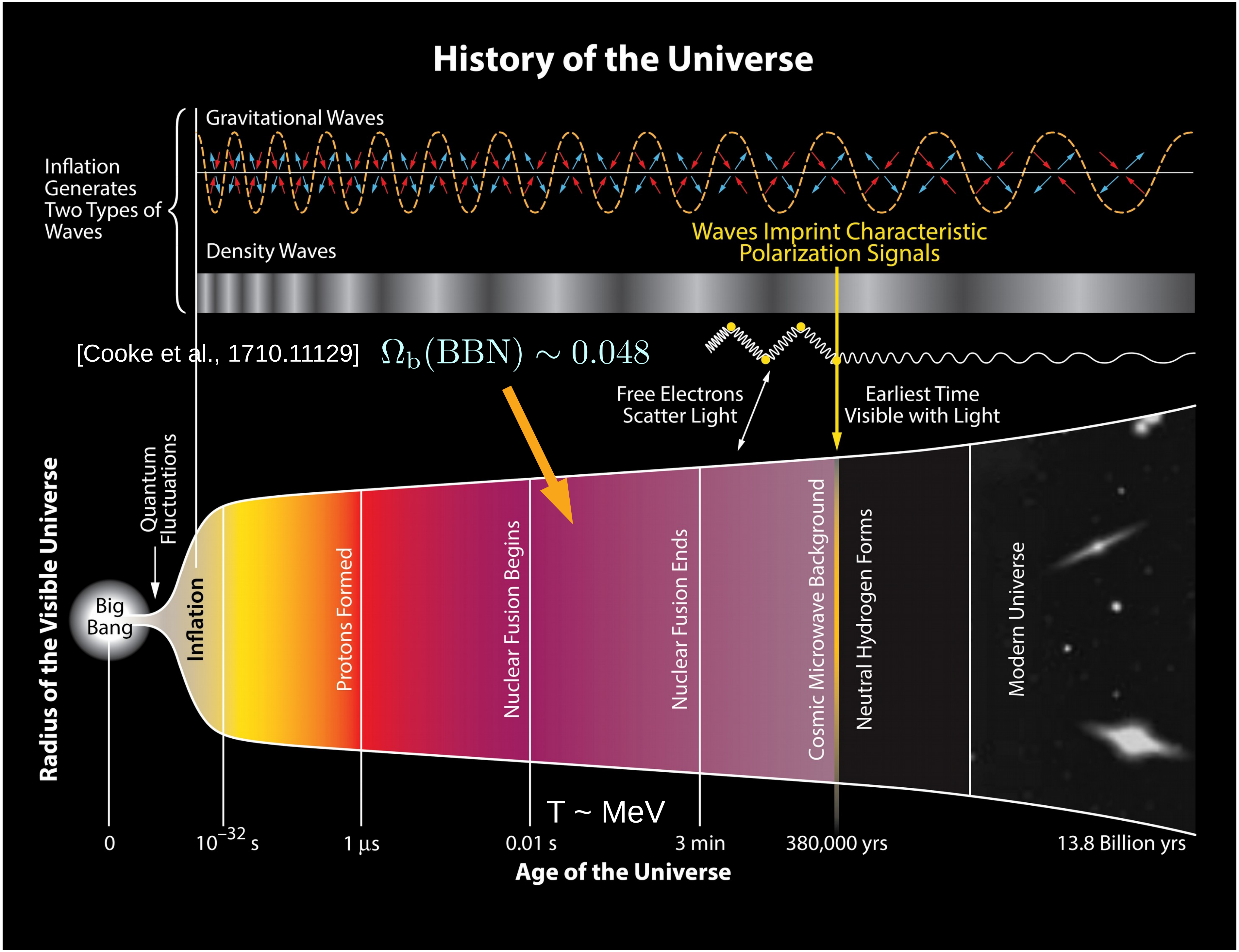

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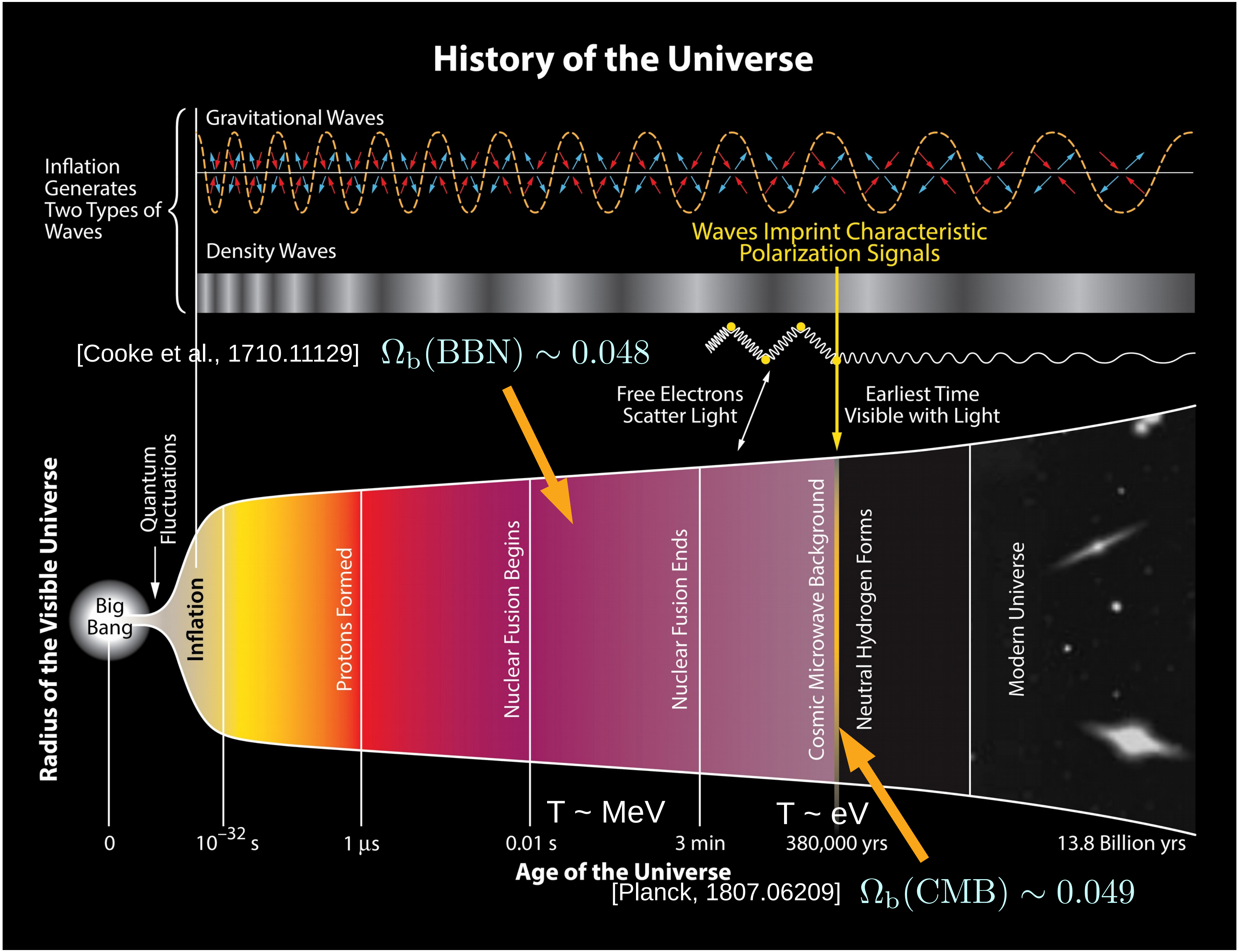

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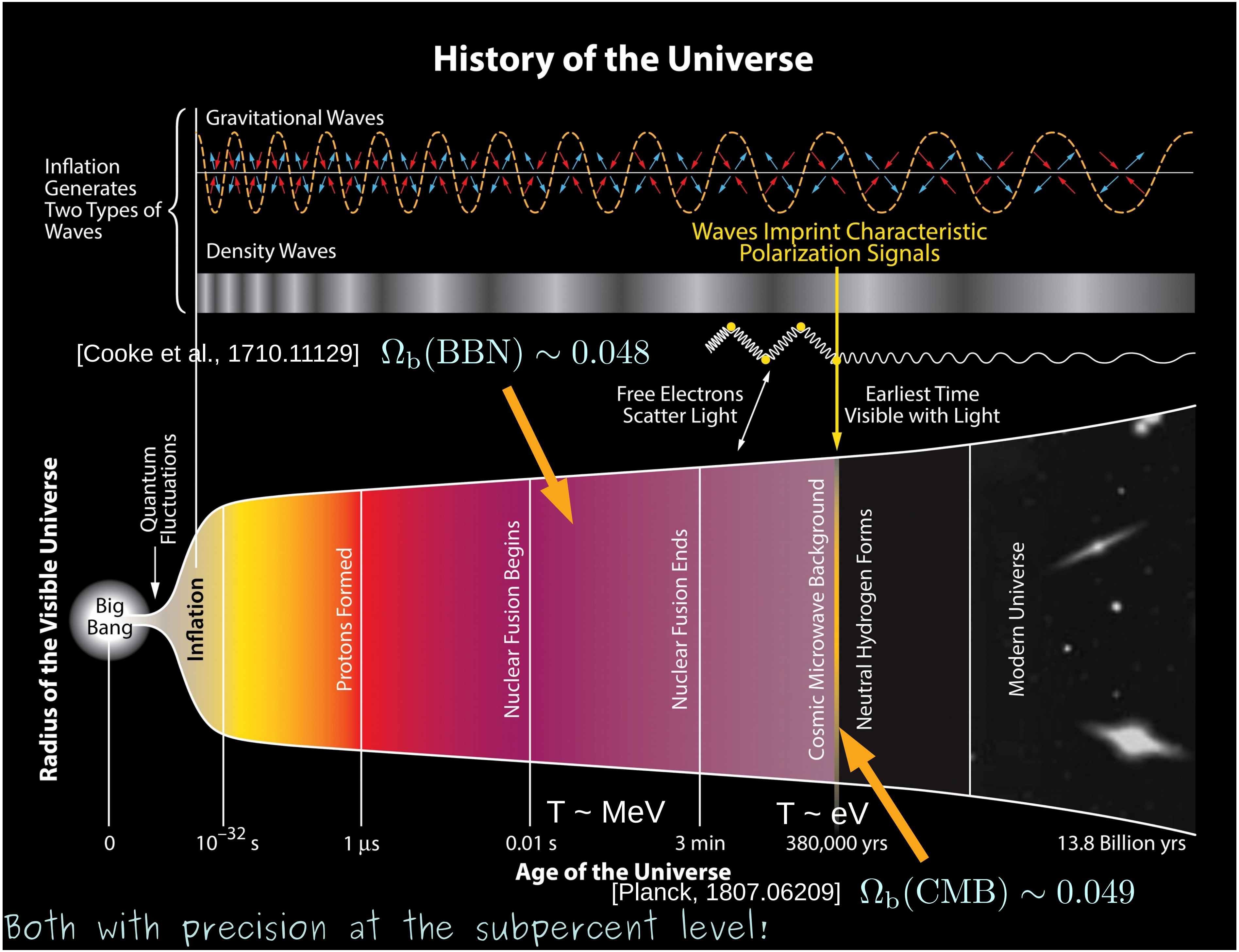

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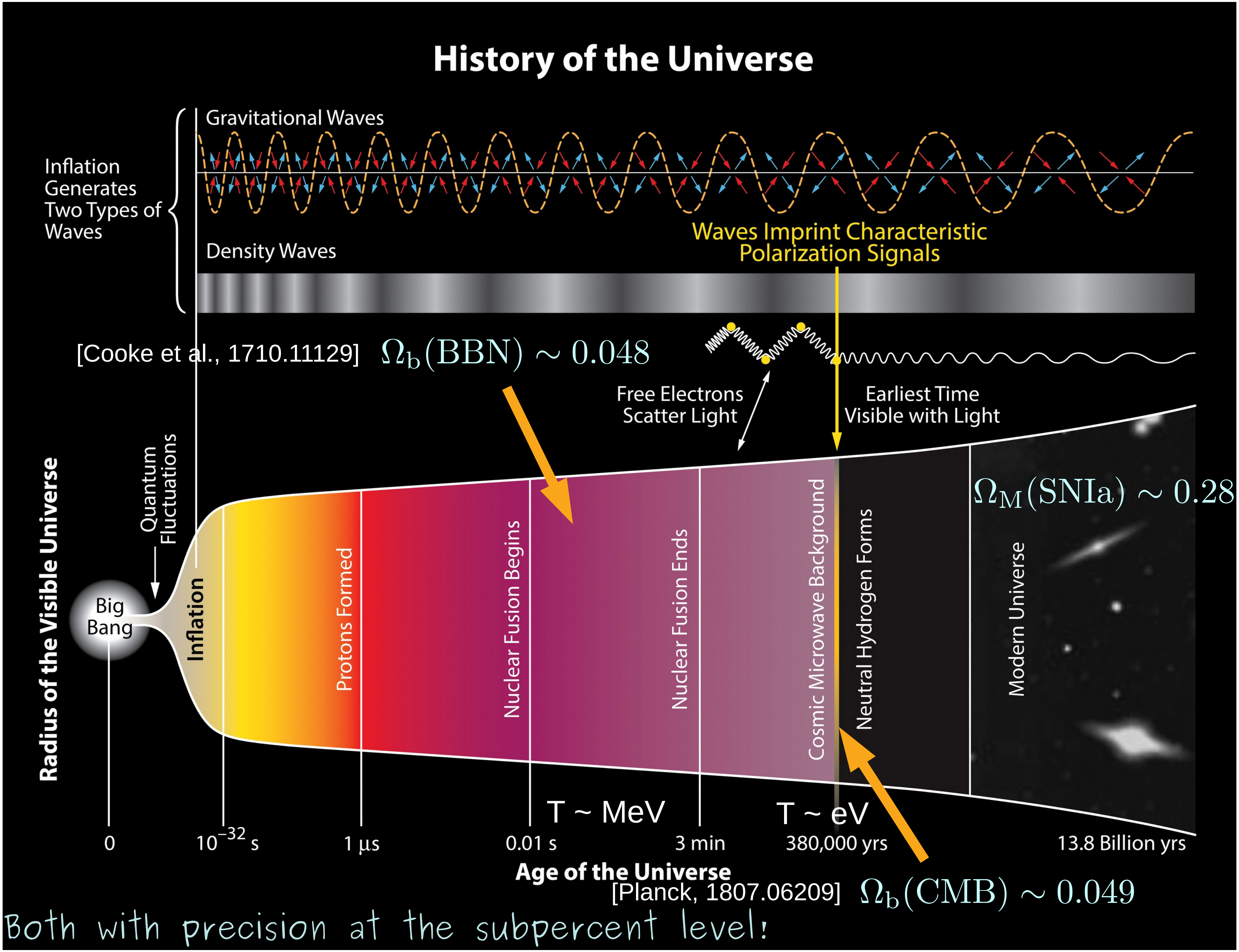

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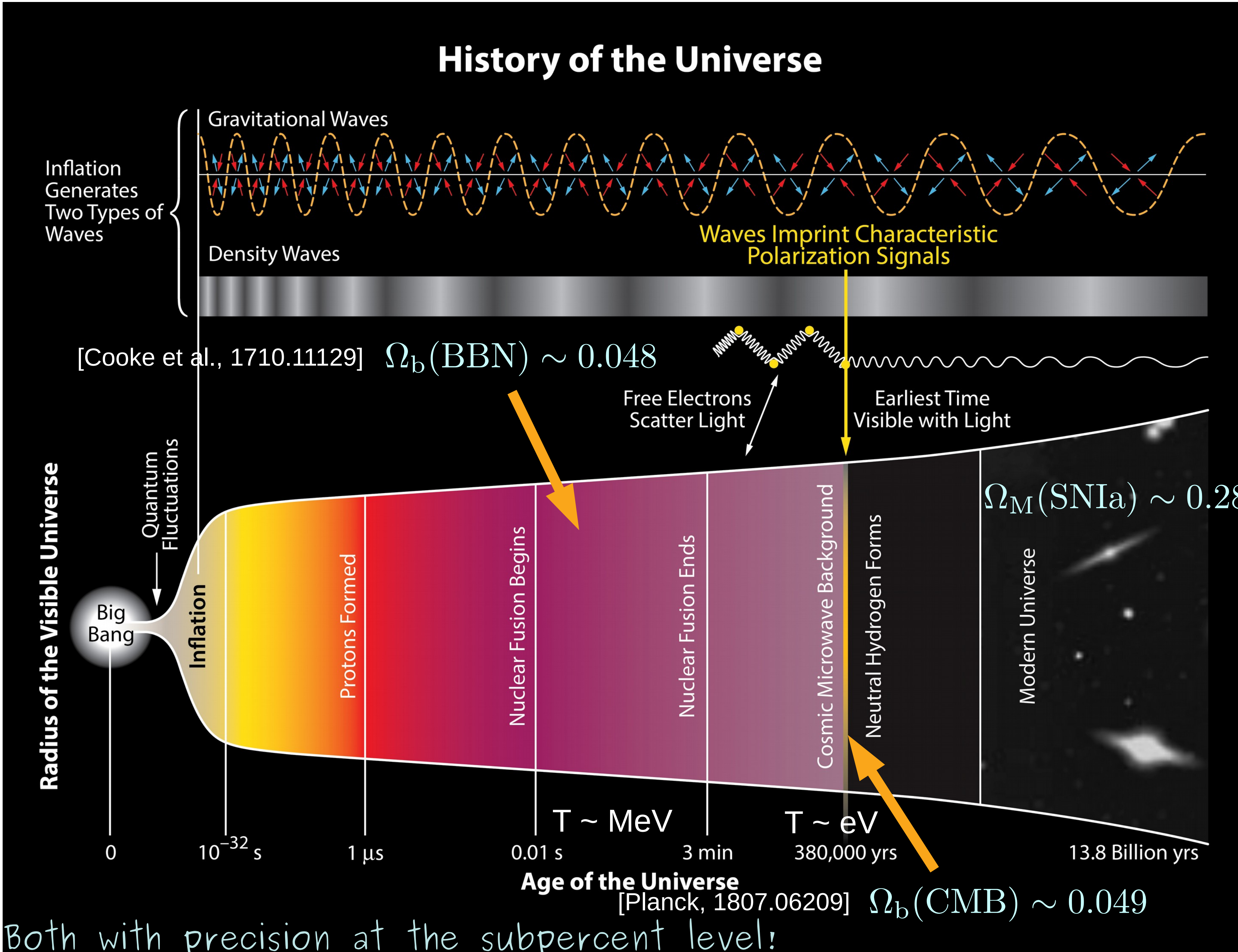
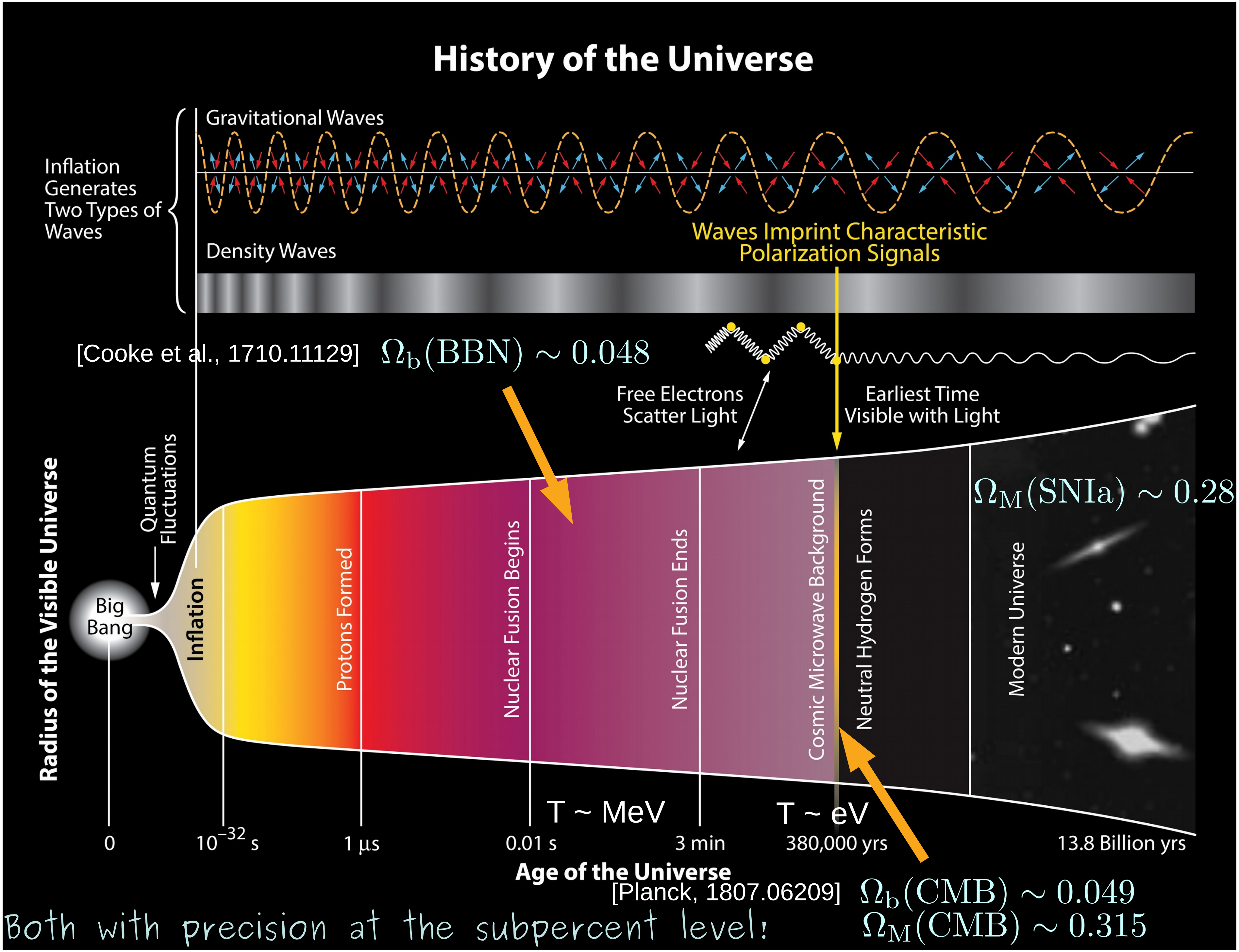


Dark Matter $\Omega_{\rm DM} = \Omega_{\rm M} - \Omega_{\rm b} \sim 0.23$

http://bicepkeck.org/visuals.html



Dark Matter $\Omega_{DM} = \Omega_M - \Omega_b \sim 0.26$

http://bicepkeck.org/visuals.html

What we know about dark matter?

- Matter power spectrum

$$\delta(\vec{x}) \equiv \frac{|\rho(\vec{x}) - \bar{\rho}|}{\bar{\rho}}$$

$\bar{\rho}$ Mean cosmic mass density

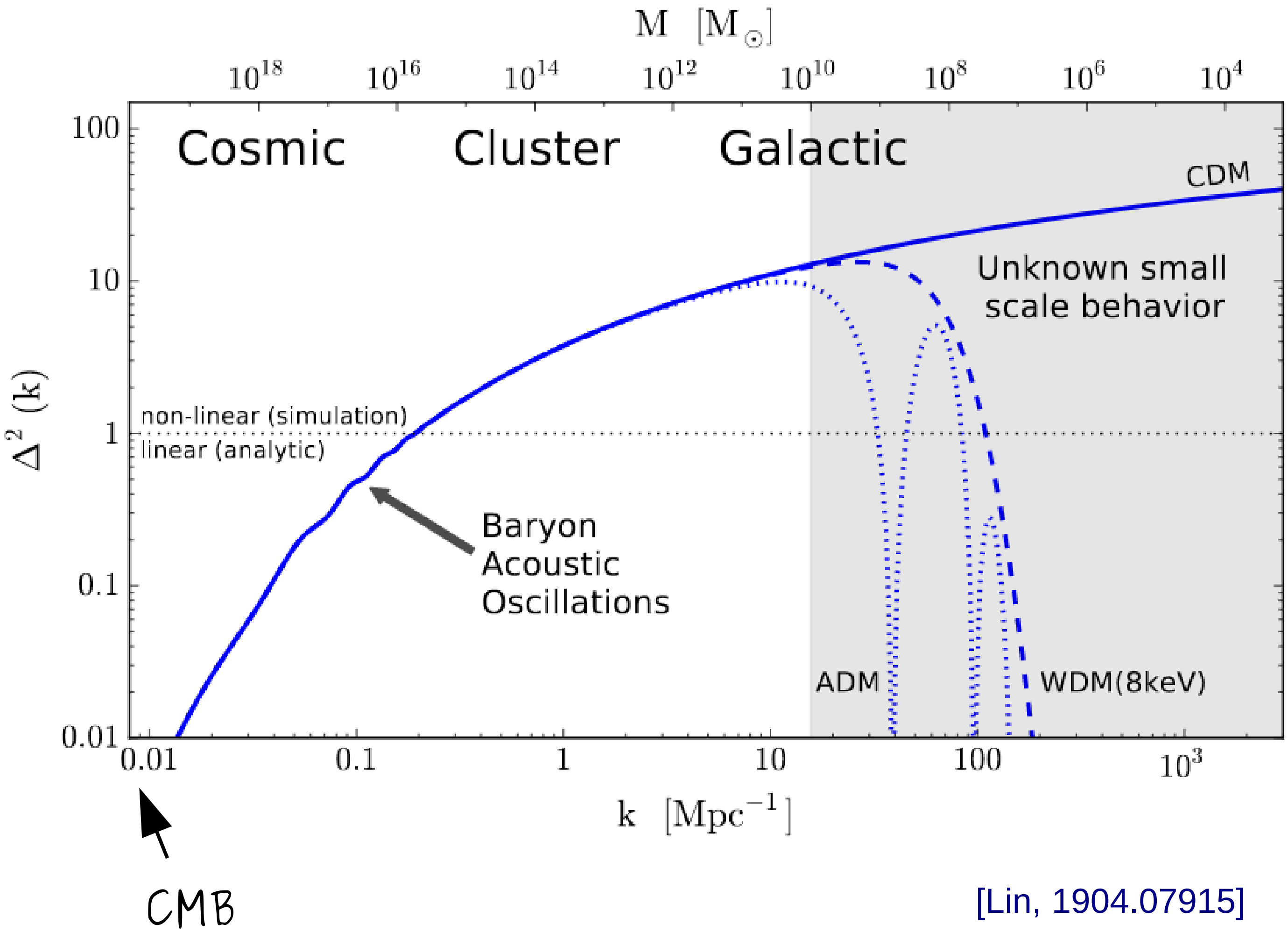
$$\left\langle \delta(\vec{k})\delta(\vec{k}') \right\rangle = (2\pi)^3 P(k)\delta(\vec{k} - \vec{k}')$$

$$\Delta^2(k) \equiv 4\pi \left(\frac{k}{2\pi}\right)^3 P(k)$$

$\Delta^2(k) \sim 1$ Order of one density fluctuations

What we know about dark matter?

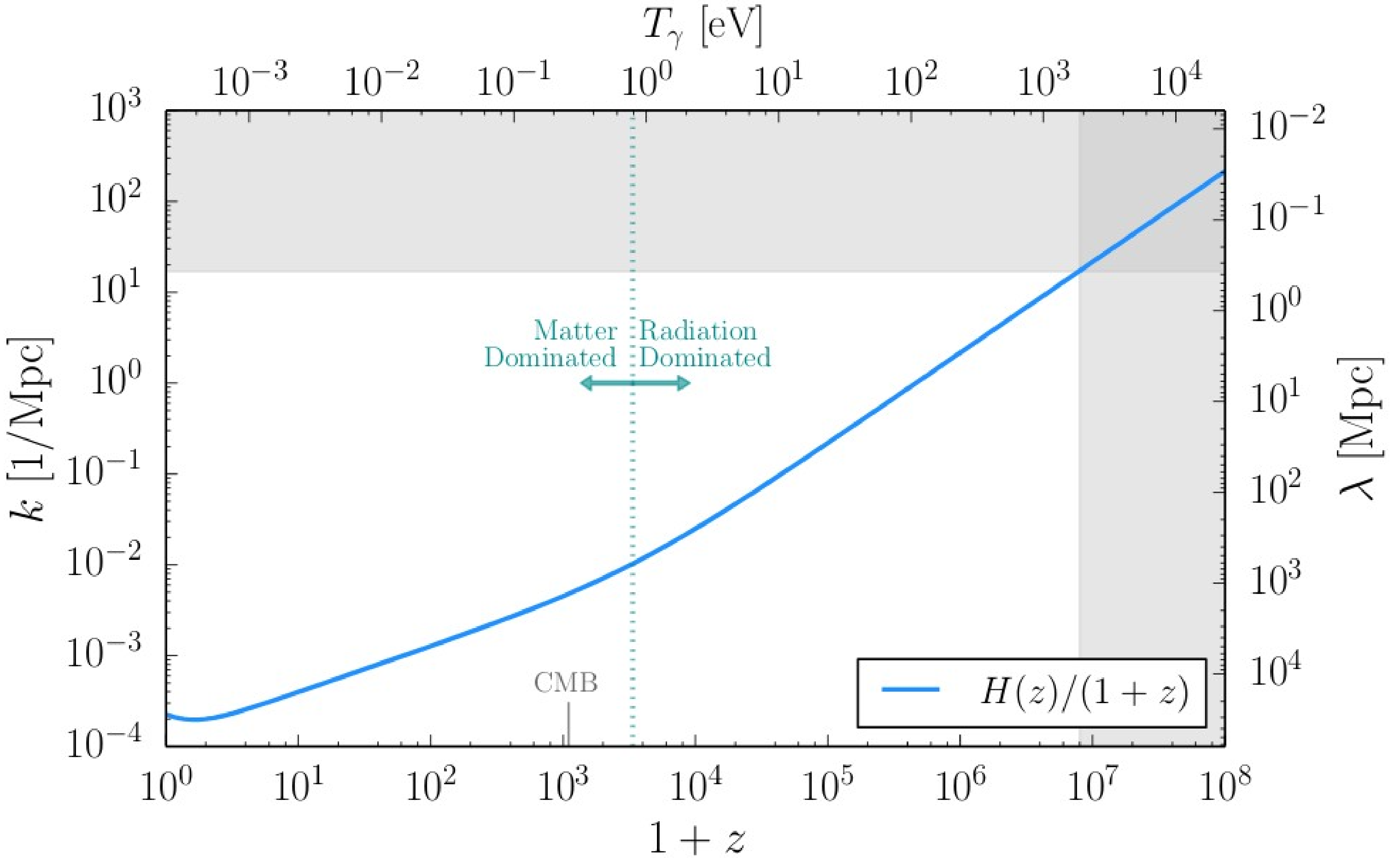
- Matter power spectrum



[Lin, 1904.07915]

What we know about dark matter?

- When the mode entered the horizon $k = \frac{H}{1+z}$



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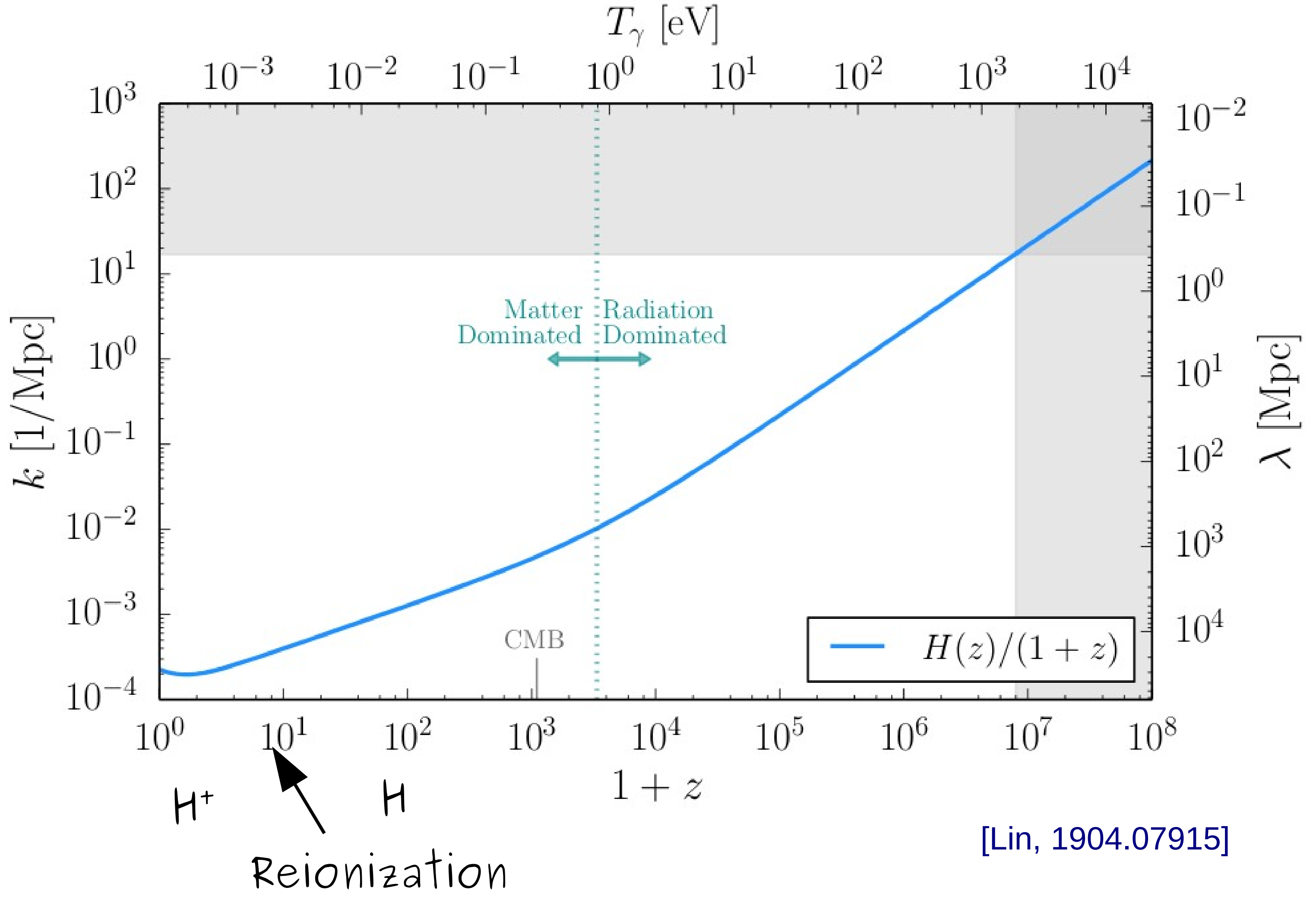
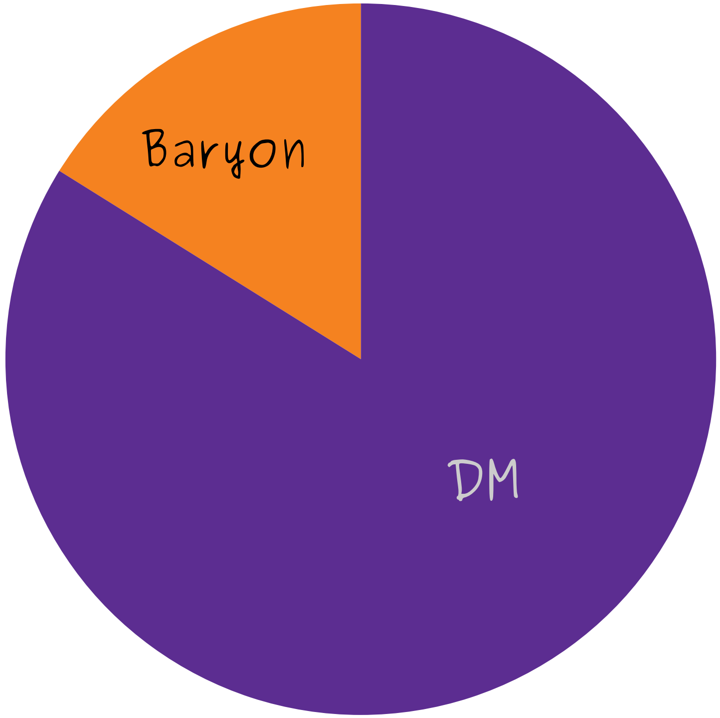


[Lin, 1904.07915]

What we know about dark matter?

- Couple weakly to the SM if any (nothing beyond gravitational is observed)
- BBN & CMB: energy density similar to that of baryon
- Form halos



$$\Omega_{\rm b} \sim 0.05$$

$$\Omega_{\rm DM} \sim 0.26$$

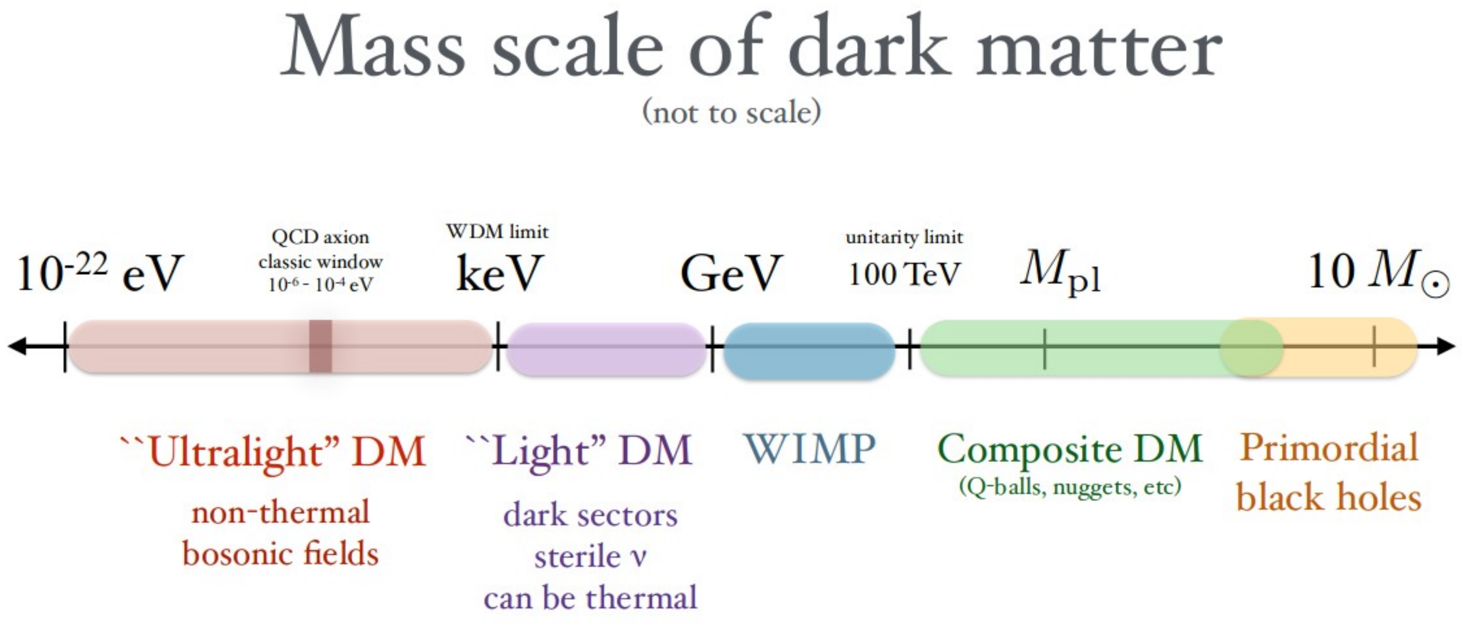
$$\rho_{\rm DM} \sim 5\rho_{\rm b}$$

Standard paradigm

- Cold dark matter (colisionless, dissipationless)
- However, some challenges at smaller scale:
  - Predict more peaked distribution at galactic center than observed
  - Predict more dwarf galaxies than observed
  - Observed dwarf galaxies seem to orbit in a plane

Types of dark matter

- Almost “anything”



[Lin, 1904.07915]

Coincidence of energy densities?

- From observations

$$\rho_{\rm DM} \sim 5\rho_{\rm b} \quad \begin{cases} \rho_{\rm b} = m_{\rm b} n_{\rm b} \\ \rho_{\rm DM} = m_{\rm DM} n_{\rm DM} \end{cases}$$

$m_{\rm b} \sim 1\,{\rm GeV}$ $\quad$ $n_{\rm b}/s \sim 10^{-10}$

$m_{\rm DM} \sim ?$ $\quad$ $n_{\rm DM}/s \sim ?$

Production mechanisms

- From freeze-out
- From freeze-in
- Axionlike
- Asymmetric
- Others

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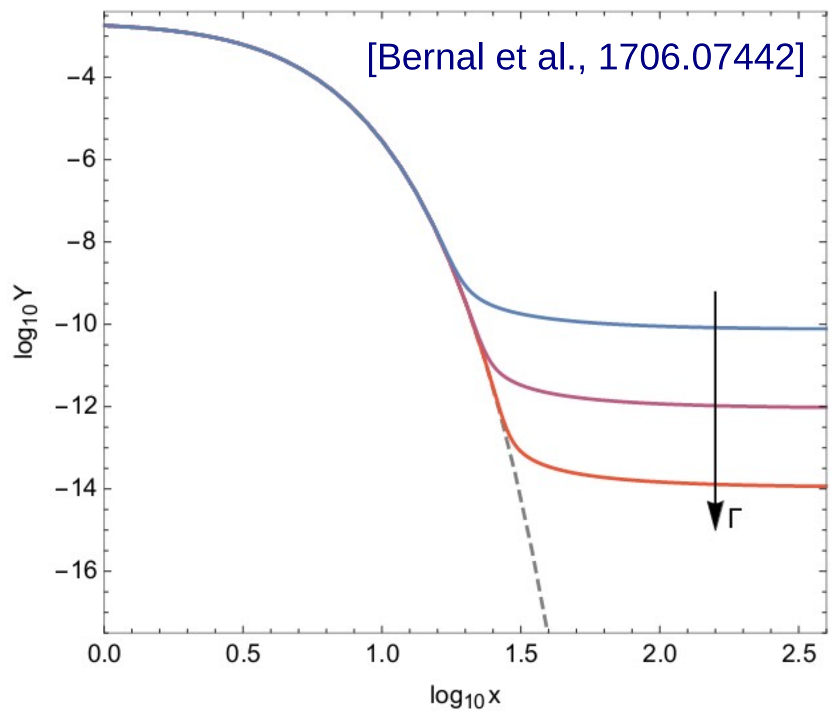

$$Y = \frac{n_{\rm DM}}{s}$$

$$\sim \frac{m_{\rm DM}}{g^2 M_{\rm Pl}}$$

$$x = \frac{m_{\rm DM}}{T}$$

$$\rho_{\rm DM} \sim 5\rho_{\rm b} \quad \begin{cases} \rho_{\rm b} = m_{\rm b} n_{\rm b} & m_{\rm b} \sim 1\,{\rm GeV} \quad n_{\rm b}/s \sim 10^{-10} \\ \rho_{\rm DM} = m_{\rm DM} n_{\rm DM} & m_{\rm DM} \sim {\rm TeV} \quad n_{\rm DM}/s \sim 10^{-13} \end{cases}$$

"Miracle": Weak mass scale & coupling

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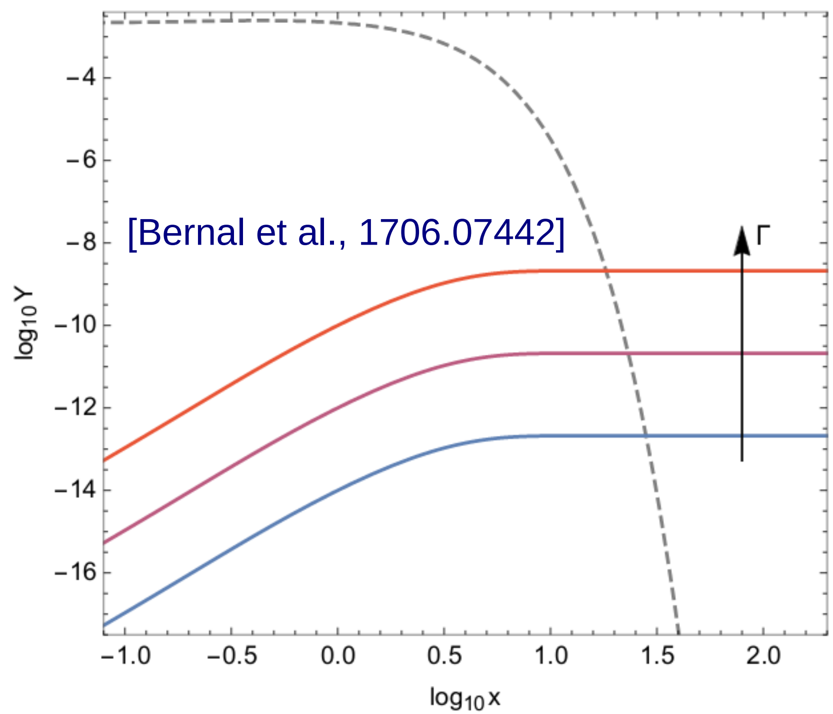

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Very weakly coupled, appear rather tuned

Production mechanisms

- From freeze-out
- From freeze-in
- Axionlike
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- Others

$$\Omega_{\rm DM} \sim \left(\frac{m_{\rm DM}}{10^{-3}\,{\rm eV}}\right)\left(\frac{f_A}{10^{12}\,{\rm GeV}}\right)\theta_i^2$$

$$\rho_{\rm DM} \sim 5\rho_{\rm b} \quad \begin{cases} \rho_{\rm b} = m_{\rm b} n_{\rm b} & m_{\rm b} \sim 1\,{\rm GeV} \quad n_{\rm b}/s \sim 10^{-10} \\ \rho_{\rm DM} = m_{\rm DM} n_{\rm DM} & m_{\rm DM} \sim 10^{-3}\,{\rm eV} \quad n_{\rm DM}/s \sim 100 \end{cases}$$

Small strong CP violation

Behaves like a classical field

Production mechanisms

- From freeze-out
- From freeze-in
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If dark interactions are fast enough to annihilate the symmetric component

$$n_{\rm DM} \sim n_{\rm b}$$

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Then why is $m_{\rm DM} \sim m_{\rm b}$?

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$m_{\rm DM} \sim m_{\rm b}$ $\quad n_{\rm DM}/s \sim n_{\rm b}/s$

Then why is $m_{\rm DM} \sim m_{\rm b}$?

Perhaps DM is very similar to baryon like … mirror baryon

Mirror world

- SM has a mirror SM' (restores parity)

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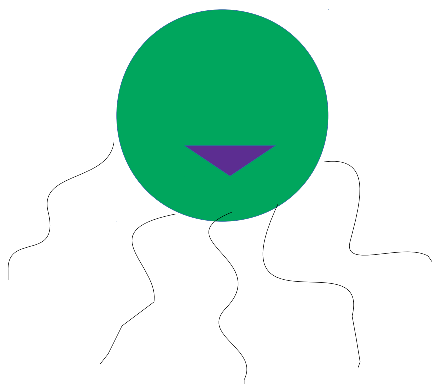

Mirror Einstein

right and the left. If such asymmetry is indeed found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry. If this is the case, it should be pointed out, there must exist two kinds of protons p_R and p_L, the right-handed one and the left-handed one. Furthermore, at the present

[Lee & Yang, Phys.Rev. 104 (1956) 254-258]

Mirror world

[Foot, Lew & Volkas, Phys.Lett. B272 (1991) 67-70]

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{SM'}} + \mathcal{L}_{\mathrm{mix}}$$

$$\mathcal{L}_{\mathrm{mix}} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \lambda H^\dagger H H'^\dagger H'$$

Interactions beyond gravity

Mirror world

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Interactions beyond gravity

- Mirror symmetry (conserved parity):

$$\psi_L \to \psi'_R,\ \psi_R \to \psi'_L,\ V \to V'$$

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- Most restrictive model: exact mirror

Special case of generic hidden sector DM

Only two additional parameters $\epsilon,\ \lambda$

$$\gamma',\; \nu',\; e' \quad \Longrightarrow \Delta N_\nu \simeq 6.14$$

Mirror world

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BBN

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Only two additional parameters ϵ, λ

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BBN

Broken mirror &/or Colder mirror

Mirror world

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Special case of generic hidden sector DM

Only two additional parameters $\epsilon,\ \lambda$

$$\gamma',\ \nu',\ e' \implies \Delta N_\nu \simeq 6.14$$

BBN $T'/T \lesssim 0.6$

CMB $T'/T \lesssim 0.3$

Broken mirror &/or Colder mirror

Higgs portal coupling

- The complete Higgs potential

$$V(H,H') = -\mu^2(H^\dagger H + H'^\dagger H') + \lambda_0\ (H^\dagger H)^2 + (H'^\dagger H')^2] + \lambda H^\dagger H H'^\dagger H'$$

Parity conserving vacuum $\lambda_0 > 0,\ |\lambda| < 2\lambda_0$

$$\langle H\rangle = \langle H'\rangle = v = \sqrt{\frac{\mu^2}{2\lambda_0 + \lambda}} \simeq 174\,\mathrm{GeV}$$

Mirror symmetry spontaneously broken $\lambda_0 > 0,\ \lambda > 2\lambda_0$

$$\langle H\rangle = v,\ \langle H'\rangle = 0$$

$$\text{QCD} \longrightarrow \langle H'\rangle \sim \frac{\Lambda^3_{\mathrm{QCD}}}{m^2_{H'}}$$

Next to minimal models $\langle H\rangle \ll \langle H'\rangle$ etc.

See review: [Foot, 1401.3965]

Higgs-mirror Higgs oscillation

[Foot, Kobakhidze & Volkas, 1109.0919]

- Parity conserving vacuum

$$H_1 = \frac{H_0 + H_0'}{\sqrt{2}}, \quad H_2 = \frac{H_0 - H_0'}{\sqrt{2}}$$

$$m_{H_1}^2 = 4v^2\left(\lambda_0 + \frac{\lambda}{2}\right), \quad m_{H_2}^2 = 4v^2\left(\lambda_0 - \frac{\lambda}{2}\right)$$

$$|m_{H_1} - m_{H_2}| \simeq \frac{|\lambda| v}{\sqrt{\lambda_0}} \qquad |\lambda| \ll \lambda_0$$

- Coherent Higgs production $|m_{H_1} - m_{H_2}| \lesssim \Gamma_H \simeq 4\,\mathrm{MeV}$

$$P(H_0 \to H_0') = \sin^2\left(\frac{t}{2t_{\mathrm{osc}}}\right) \qquad t_{\mathrm{osc}} = 1/|m_{H_1} - m_{H_2}|$$

Higgs-mirror Higgs oscillation

[Foot, Kobakhidze & Volkas, 1109.0919]

- Higgs invisible decay width

$$\langle P(H_0 \to H_0')\rangle = \Gamma_H \int_0^\infty dt e^{-\Gamma_H t} \sin^2\left(\frac{t}{2t_{\rm osc}}\right) = \frac{1}{2}\left(\frac{1}{1+\Gamma_H^2 t_{\rm osc}^2}\right)$$

- Cross-sections into visible channels are reduced by

$$f = 1 - \langle P(H_0 \to H_0')\rangle = \frac{1}{2} + \frac{1}{2}\left(\frac{\Gamma_H^2 t_{\rm osc}^2}{1+\Gamma_H^2 t_{\rm osc}^2}\right)$$

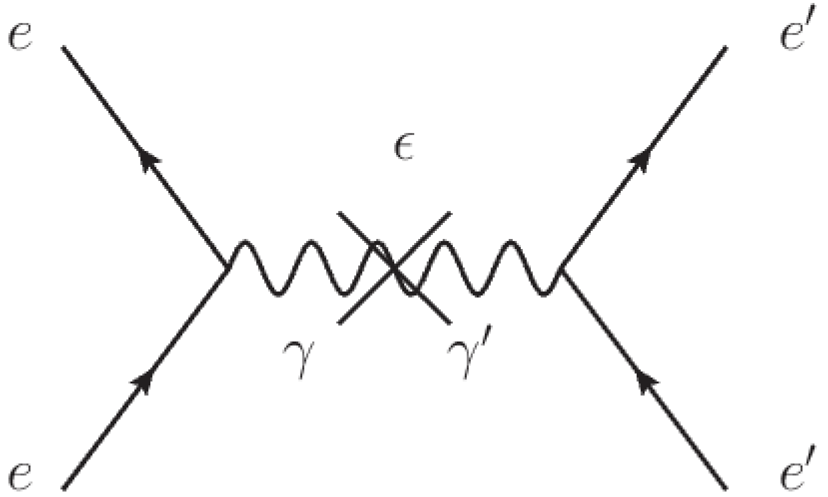
$$\mathrm{Br}(H \to \mathrm{inv}) < 0.23 \implies |\lambda| < 7.7 \times 10^{-6}$$

If reheatng is above 100 GeV, in order not to thermalize SM and the mirror sector through $HH \to H'H'$

$|\lambda| \lesssim 10^{-8}$ [Lew, hep-ph/9303252] [Ignatiev &Volkas, hep-ph/0005238]

Mirror world: kinetic mixing

- Even if we assume $T' \ll T$ after (asymmetric) reheating, the final temperature will depend on the kinetic mixing



Induced minicharge $\pm\epsilon e$ for mirror electron and mirror proton

[Ciarcelluti & Foot, 0809.4438]

$$\frac{(d\rho'/\rho)}{dT} = -\frac{2}{T}\frac{n_{e-}n_{e+}\langle\sigma v\rangle}{\rho H} \qquad \langle\sigma v\rangle = \frac{2\pi\alpha^2\epsilon^2}{3T}$$

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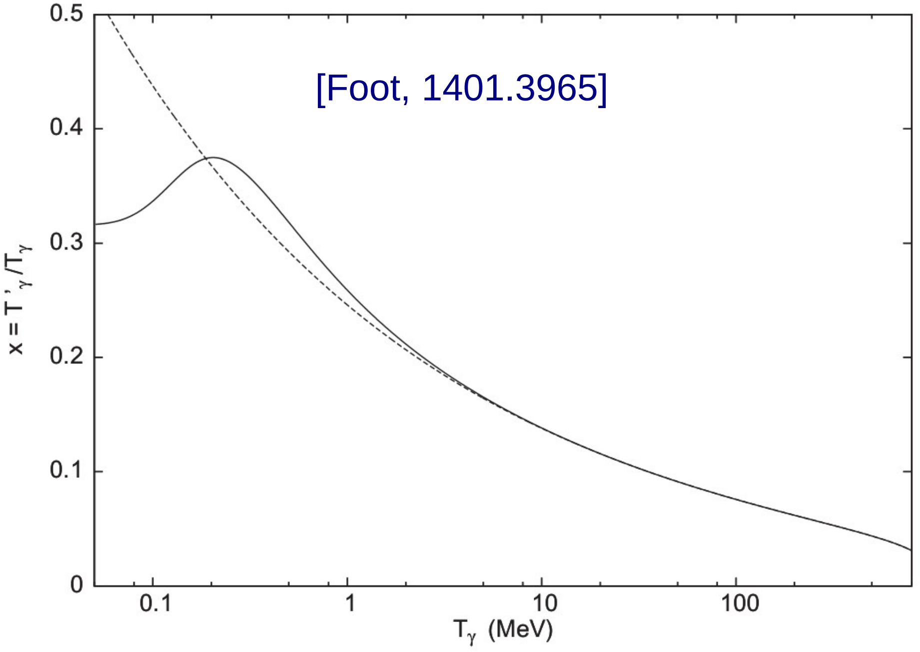


$$\frac{T'}{T} \simeq \frac{0.25}{(T/\mathrm{MeV})^{1/4}} \sqrt{\frac{\epsilon}{10^{-9}}}$$

$$\epsilon \simeq 10^{-9} \left(\frac{x_f}{0.3}\right)^2$$

[Ciarcelluti & Foot, 0809.4438]

$$\frac{(d\rho'/\rho)}{dT} = -\frac{2}{T} \frac{n_{e-} n_{e+} \langle \sigma v \rangle}{\rho H} \qquad \langle \sigma v \rangle = \frac{2\pi\alpha^2 \epsilon^2}{3T}$$

Mirror world: mirror BBN

[Ciarcelluti & Foot, 1003.0880]

- Assuming initial conditions $T' \ll T$
- Mirror neutrinos already decoupled, kinetic mixing only heat up mirror electron and mirror photon $T_{\nu'} \ll T'$ $T' = T_{\gamma'} \simeq T_{e'}$
- Relevant reactions

$$n' + e'^{+} \longrightarrow p' + \bar{\nu}' \qquad p' + e'^{-} \longrightarrow n' + \nu'$$

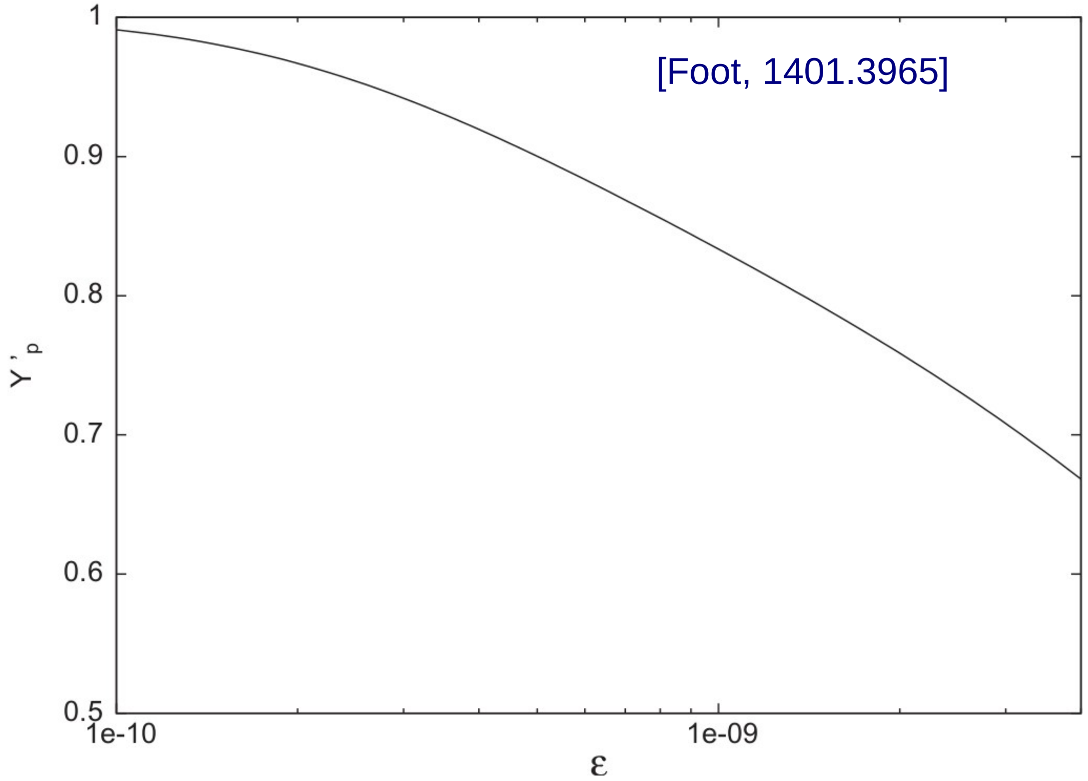
$n' \longrightarrow p' + e'^{-} + \bar{\nu}'$ Negligible since mirror BBN happens earlier when expansion is faster $T'_{\mathrm{freeze}} > T_{\mathrm{freeze}}$

$$\frac{dX'_n}{dt} = \lambda_{p' \to n'}(1 - X_{n'}) - \lambda_{n' \to p'} X_{n'} \qquad X_{n'} \equiv \frac{n_{n'}}{n_{n'} + n_{p'}}$$

Mirror world: mirror BBN

[Ciarcelluti & Foot, 1003.0880]

- Helium mass fraction $Y'_p \equiv \frac{n_{\mathrm{He}'} m_{\mathrm{He}}}{n_{\mathrm{He}'} m_{\mathrm{He}} + n_{\mathrm{H}'} m_{\mathrm{H}}}$
- All the neutrons go to Helium $Y'_p \simeq 2X_{n'}(\infty)$
- Large $Y'_p \approx 0.9$ for $\epsilon \sim 10^{-9}$



Mirror world: mirror BBN

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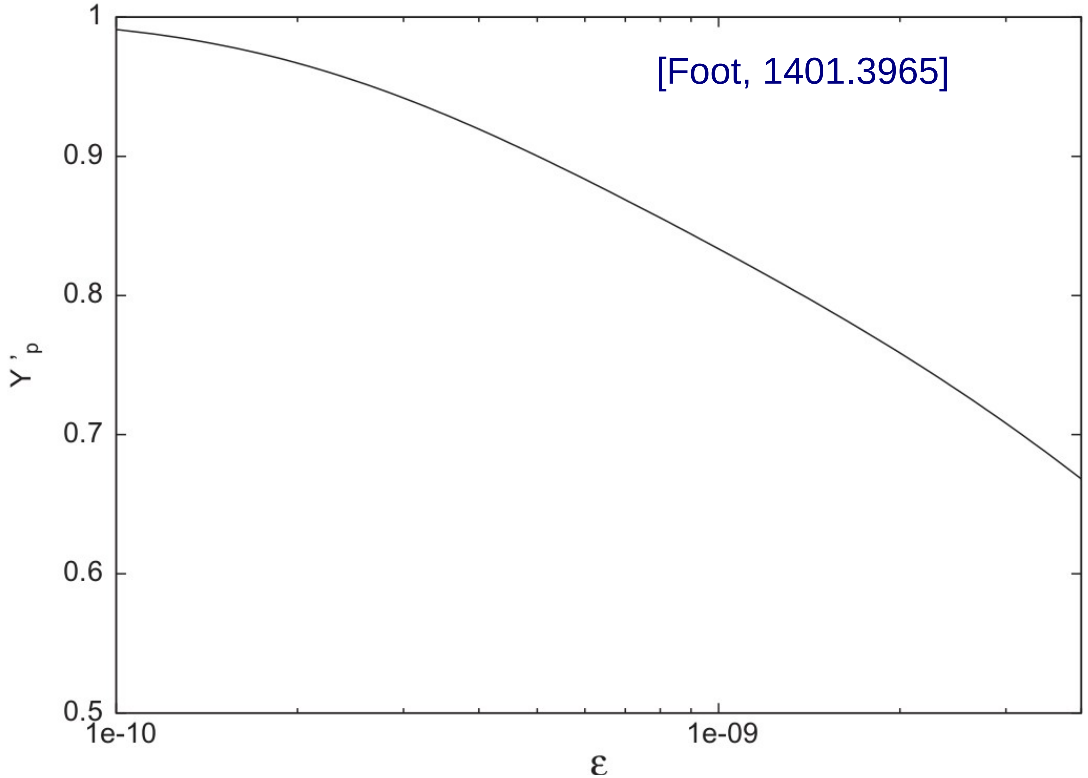

$$\bar{m} \equiv \frac{\sum n_{A'} m_{A'}}{\sum n_{A'}}$$

$$\simeq \frac{n_{\mathrm{He}'} m_{\mathrm{He}} + n_{\mathrm{H}'} m_p}{n_{\mathrm{He}'} + n_{\mathrm{H}'} + n_{e'}}$$

Mirror world: mirror BBN

[Ciarcelluti & Foot, 1003.0880]

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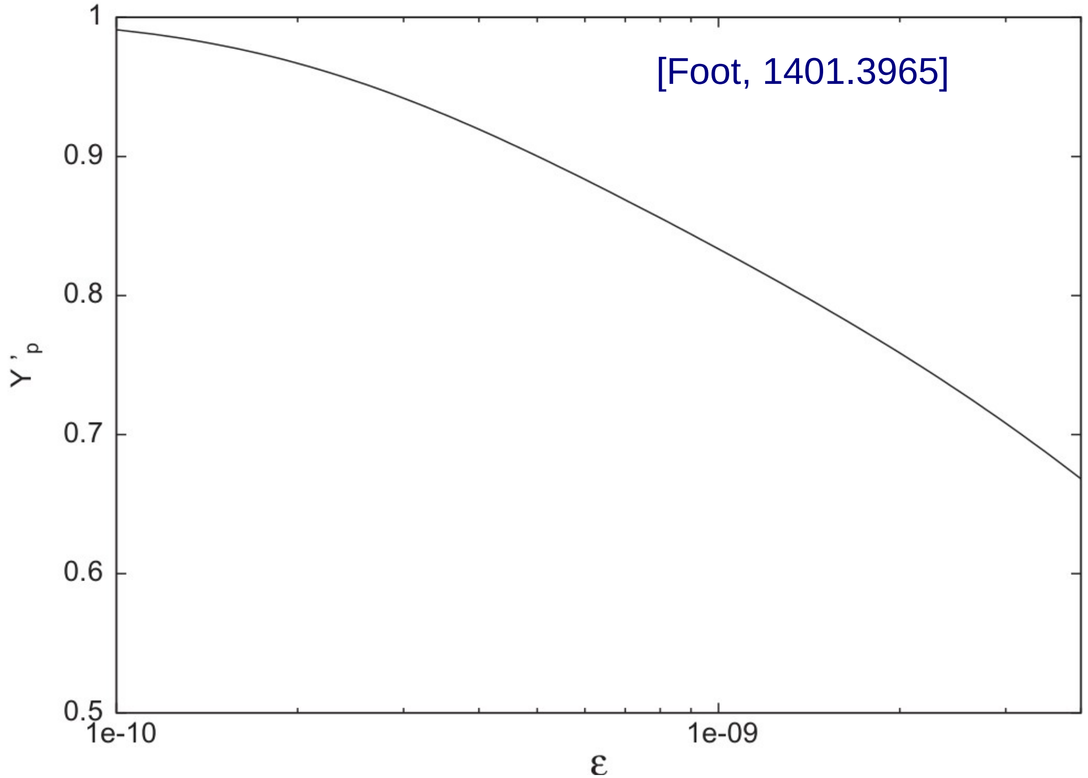

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$$\simeq \frac{n_{\mathrm{He}'} m_{\mathrm{He}} + n_{\mathrm{H}'} m_p}{n_{\mathrm{He}'} + n_{\mathrm{H}'} + n_{e'}}$$

$$\frac{\bar{m}}{m_p} \simeq \frac{1}{2 - \frac{5}{4} Y'_p}$$

$$Y'_p \approx 0.9 \implies \bar{m} \approx 1.1\,\mathrm{GeV}$$

Mirror matter halo

[Foot & Volkas, astro-ph/0407522]

- It is necessary for mirror matter to form spheroidal halos around spiral galaxies to explain the rotation curves
- For the mass of the halo dominated by Helium, it is estimated to be $T_{\rm halo} \approx 100\,{\rm eV}$
- So Helium is completely ionized since the ionization energy of the 2nd electron is ~55 eV.
- Interactions of mirror electrons with mirror ions will produce mirror photons which will escape the galaxy. All the energy will be removed in

$t_{\rm cool} \sim 0,3\,{\rm billion\ years}$ Too fast!

Mirror matter halo

[Foot & Volkas, astro-ph/0407522]

- The energy radiated from the halo

$$E_{\rm out} \sim 10^{44}\,{\rm erg/s} \sim 10^{51}\,{\rm erg/year}$$

- Galatic heating sources
  - Mirror supernovas $\sim 10^{51}\,{\rm erg/explosion}$ Ejected materials

    $\Longrightarrow 10^{51}\,{\rm erg/year}$ Rate two orders of magnitude higher than ordinary supernova

  - Ordinary supernovas

    $\sim 10^{51}\,{\rm erg/explosion}$ Ejected materials

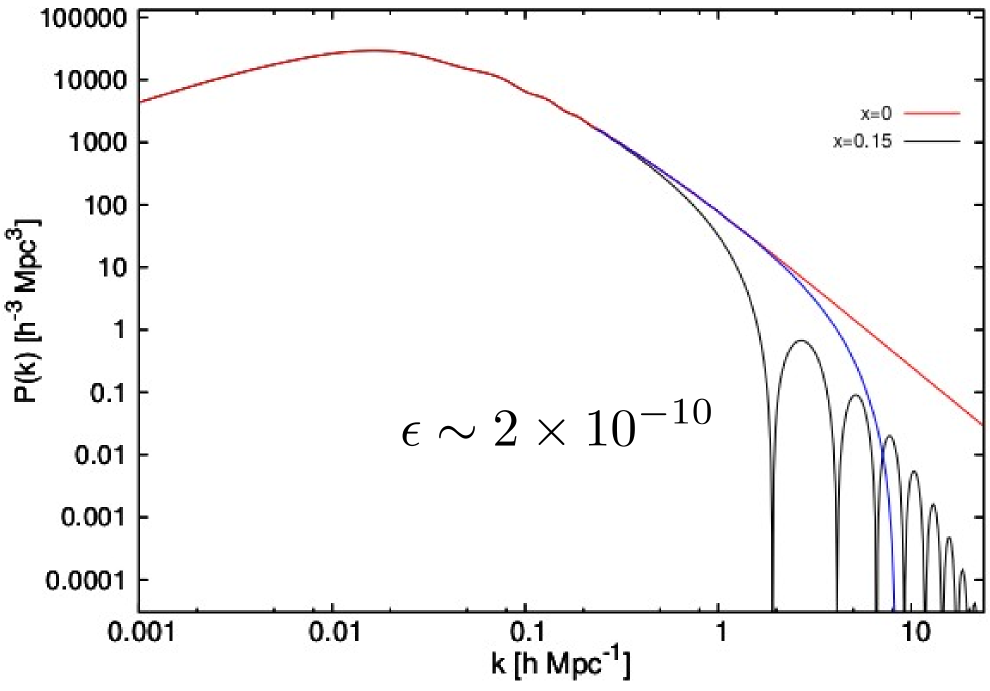
    $E_{\rm total} \sim 10^{53}\,{\rm erg/explosion}$ Mainly neutrinos in the SM

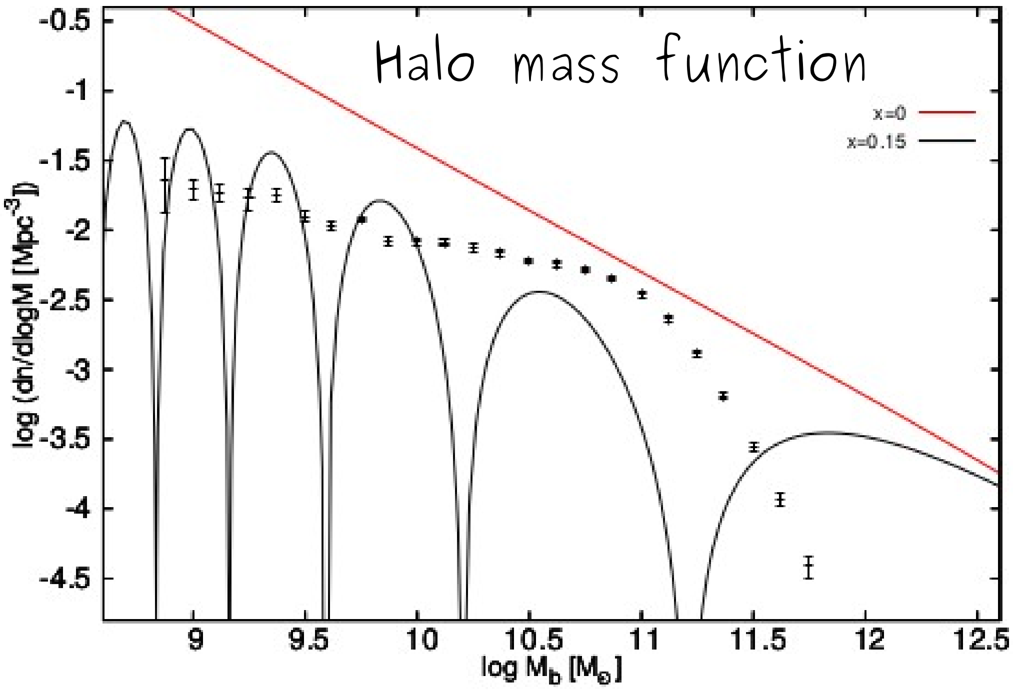
    $\epsilon \sim 10^{-9}$ $e^+e^- \to e'^+e'^-$ Escape the core as $e'^{\pm}, \gamma'$ and could be absorbed and heat up the halo

Mirror matter and structure

[Foot & Vagnozzi, 1602.02467]

- Dark recombination happens earlier due to colder temperature
  - Dark acoustic oscillation before dark recombination
  - Dark photon diffusion damping





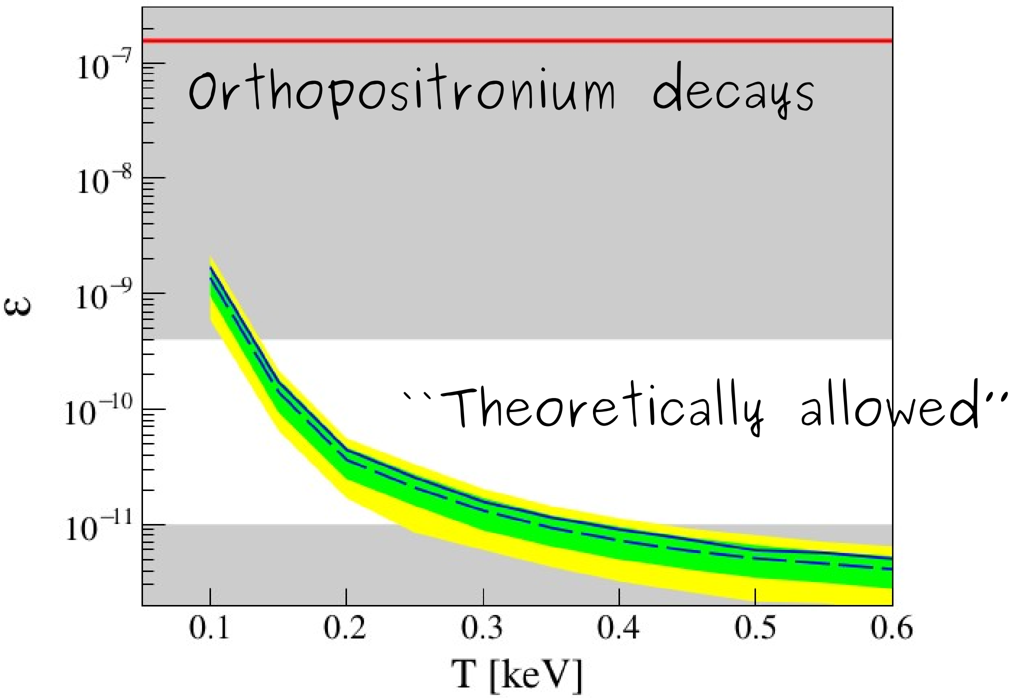
First direct detection constraint

[LUX Collaboration, 1908.03479]

- Liquid xenon time projection chamber
- Mirror halo is a completely ionized plasma with local mirror electron temperature $T \sim 0.3\,\mathrm{keV}$
- Mirror electron – electron Coulomb scattering

$$\frac{d\sigma}{dE_R} = \frac{2\pi\epsilon^2\alpha^2}{m_e E_R^2 v^2}$$

If positronium – mirror positronium mixing were to occur, decay to missing photons would leave a missing energy signal

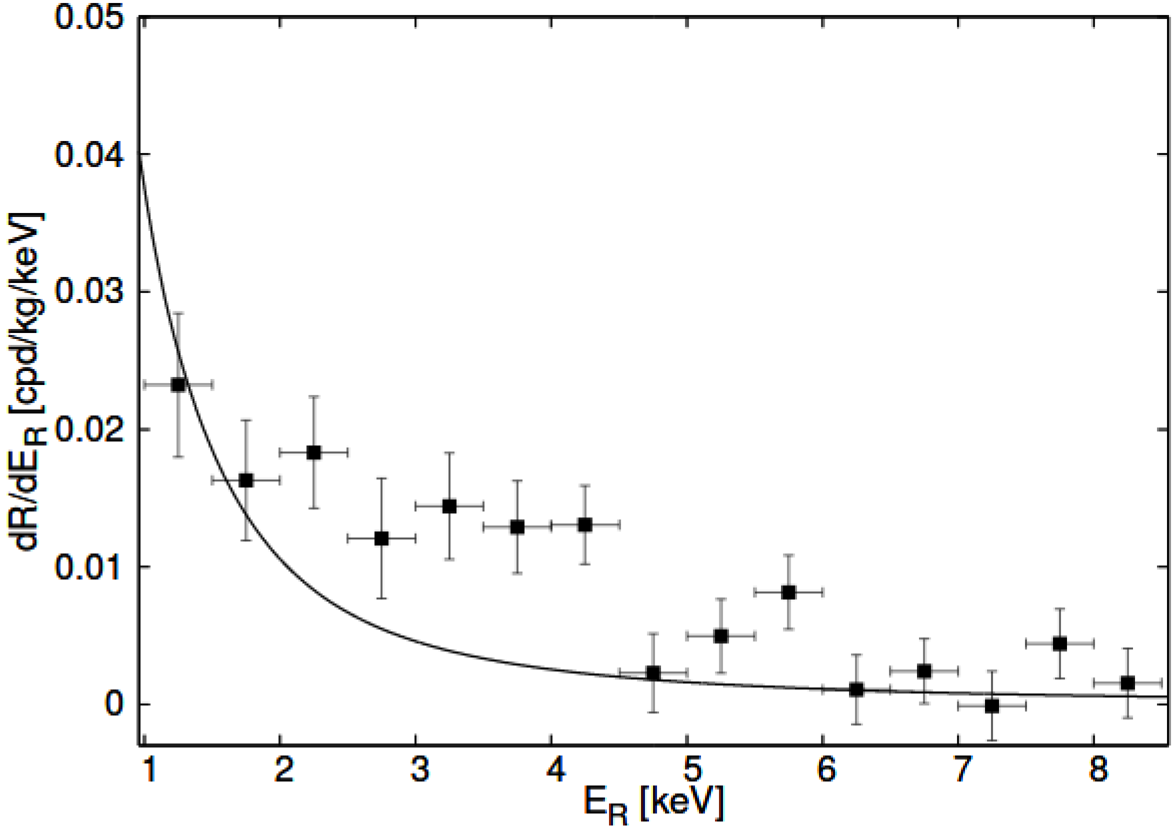


The only explaination of DAMA?

[Foot, 1804.11018]

- Mirror electron – electron Coulomb scattering

$$\frac{d\sigma}{dE_R} = \frac{2\pi\epsilon^2\alpha^2}{m_e E_R^2 v^2}$$



See however [Roberts & Flambaum, 1904.07127]

Neutrino mass

- To get nonzero neutrino mass, one can consider dimension five operators

[Akhmedov, Berezhiani & Senjanovic, hep-ph/9205230] [Foot & Volkas, hep-ph/9505359]
[Berezhiani & Mohapatra, hep-ph/9505385] [Barbieri, Hall & Harigaya, 1609.05589]

$$-\mathcal{L}_{\rm eff} = \frac{y_D}{\tilde{M}}(LH)^2 + \frac{y_D}{\tilde{M}}(L'H')^2 + \frac{y}{M}(LH)(L'H')$$

Neutrino portal

- After EW & EW' symmetry breaking

$$M = \begin{pmatrix} M_\nu & M_{\nu\nu'} \\ M_{\nu\nu'}^T & M_{\nu'} \end{pmatrix}$$

Parity conserving vacuum $\langle H \rangle = \langle H' \rangle \implies M_{\nu'} = M_\nu$

Neutrino mass

- Mostly Majorana $M \gg \tilde{M}$

$m_{\nu'} \simeq \left(\frac{v'}{v}\right) m_\nu$ $\quad$ $m_{\nu'} \simeq m_\nu$ Parity conserving vacuum

Neutrino–mirror neutrino mixing $|U_{\nu\nu'}| \sim \frac{M_{\nu\nu'}}{M_{\nu'}}$

- Mostly Dirac $\tilde{M} \gg M$

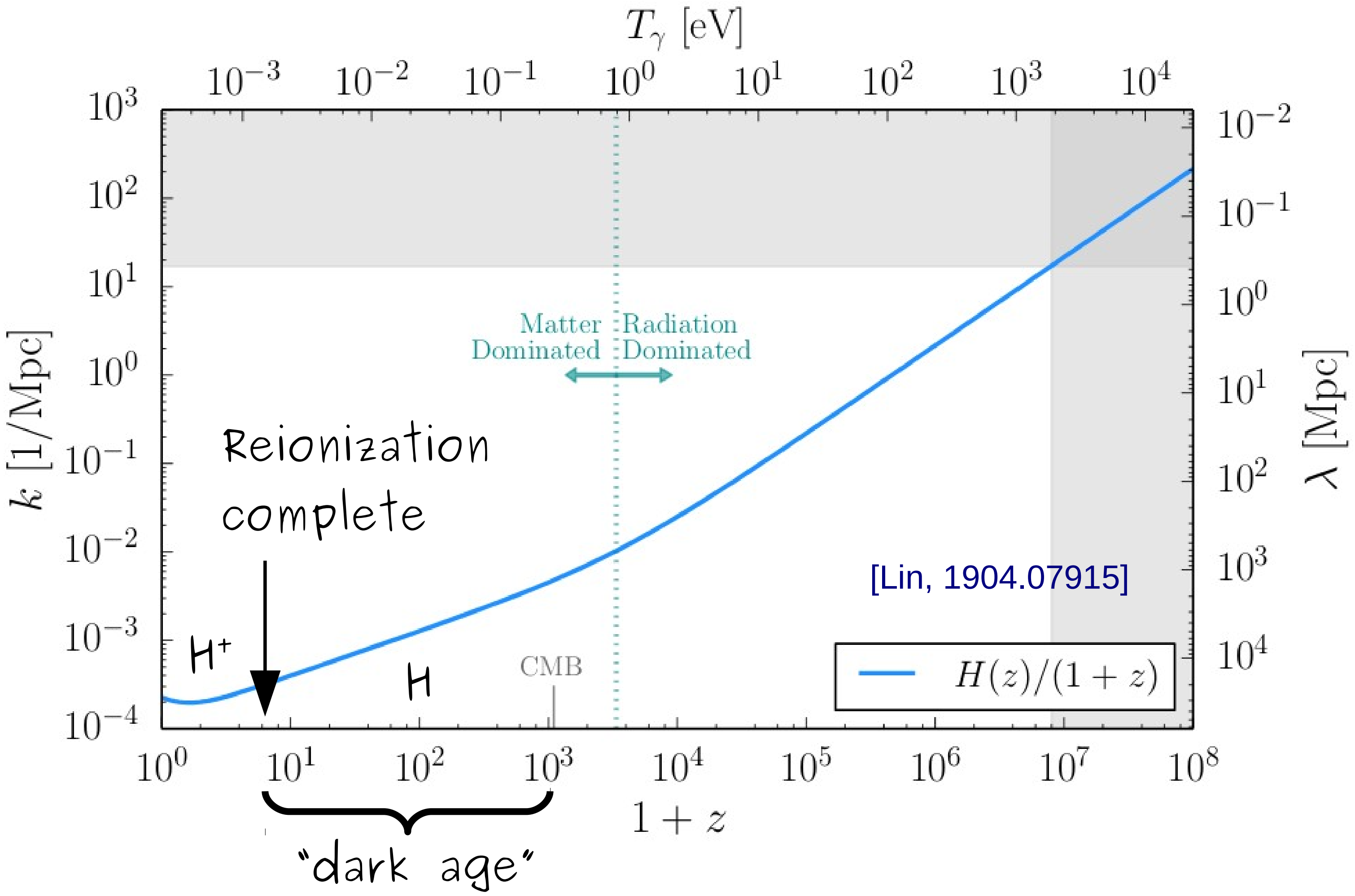
$m_{\nu'} \simeq m_\nu$ Parity conserving or violating vacuum

Mirror neutrinos are the right–handed partners

To be consistent, mass splitting should be very small $\Delta m \sim M_{\nu\nu'}$

21 cm line

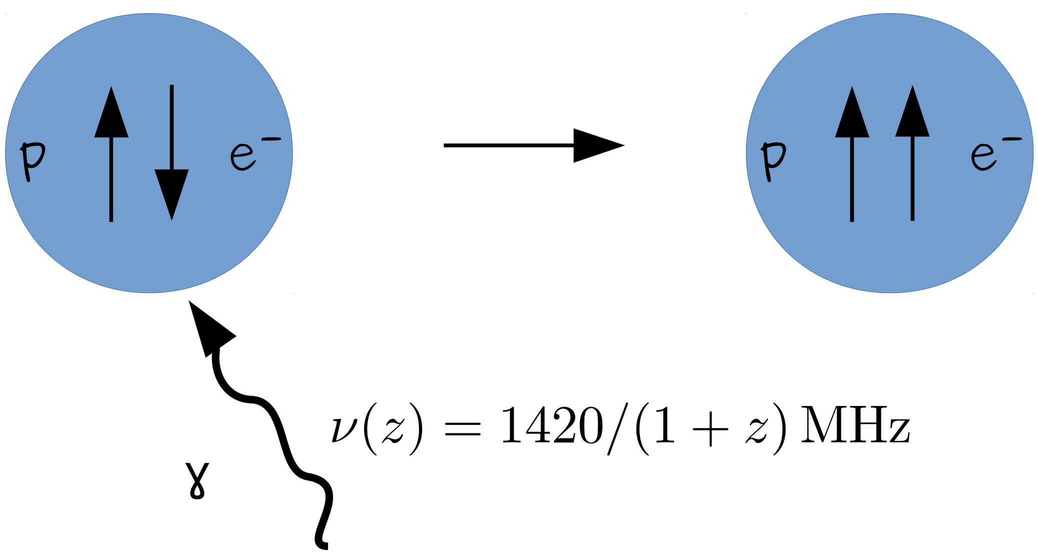
- During the “dark ages”, we have a unique probe of 21 cm line from atomic hydrogen



21 cm line

- During the “dark ages”, we have a unique probe of 21 cm line from atomic hydrogen

$$\nu = 1420\,\mathrm{MHz},\ \Delta E \simeq 5.9\,\mu\mathrm{eV}$$



$$\nu(z) = 1420/(1+z)\,\mathrm{MHz}$$

$T_s(z)$

Spin temperature defines the relative ppulation of triplet to singlet states

When CMB photon is hotter than the neutral hydrogan gas

This was observed by **EDGES**: Experiment to Detect the Global Epoch of Reionization Signature [Bowman et al., Nature 555, 67 (2018)]

21 cm line

- After recombination, remaining small ionization fraction $X_e = n_e/n$
- Compton scatterings keep baryonic gas and radiation at the same temperature until $z \sim 150$ when they decouple, the gas becomes colder
- When early stars formed, their photons couple the spin T_s and gas temperatures T_g

Onset of absorption $z \sim 20$

- The gas becomes hotter than the radiation $T_{\rm CMB}$

End of absorption $z \sim 15$

21 cm line

- The change in the brightness temperature is

$$T_{21} \simeq (23\,\mathrm{mK}) x_{\mathrm{HI}}(z) \left(\frac{0.15}{\Omega_m h^2}\right)^{1/2} \left(\frac{1+z}{10}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.02}\right) \left[1 - \frac{T_{\mathrm{CMB}}(z)}{T_s(z)}\right] .$$

- The evolution of the CMB and gas temperature are well calculated $T_{\mathrm{CMB}}(17) = 18 \times 2.7\,\mathrm{K} \simeq 49\,\mathrm{K}$

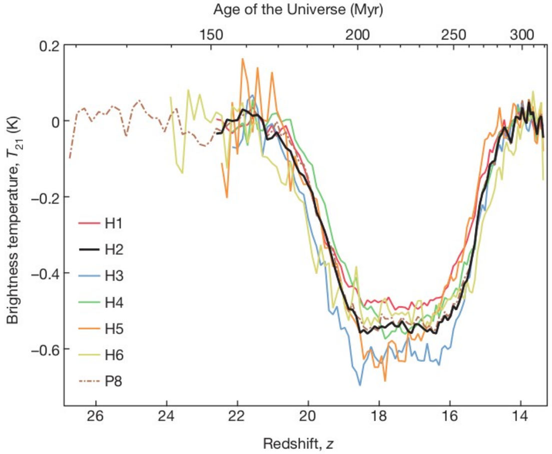
Conservatively $T_s(17) = T_{\mathrm{gas}}(17) \simeq 7\,\mathrm{K}$ $\Longrightarrow T_{21}(17) = -0.2\,\mathrm{K}$

- EDGES measured more absorption

$$T_{21}(17)_{\mathrm{EDGES}} = -0.5^{+0.2}_{-0.5}\,\mathrm{K}$$

3.8σ deviation

[Bowman et al., Nature 555, 67 (2018)]



Imprint from mirror neutrinos?

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- Possibilities
  - Higher T_{CMB}
  - Lower T_s and T_g
  - Others

} $\frac{T_{\mathrm{CMB}}}{T_s}$ Enhanced by a factor of 2

We consider the decay on neutrino to photons through magnetic & electric moment $\nu_j \to \nu_i + \gamma$

$$\mathcal{L}_{\mathrm{eff}} = \frac{1}{2} \bar{\nu}_i \sigma_{\mu\nu} \left(\mu_{ij} + \epsilon_{ij}\gamma_5\right) \nu_j F^{\mu\nu}$$

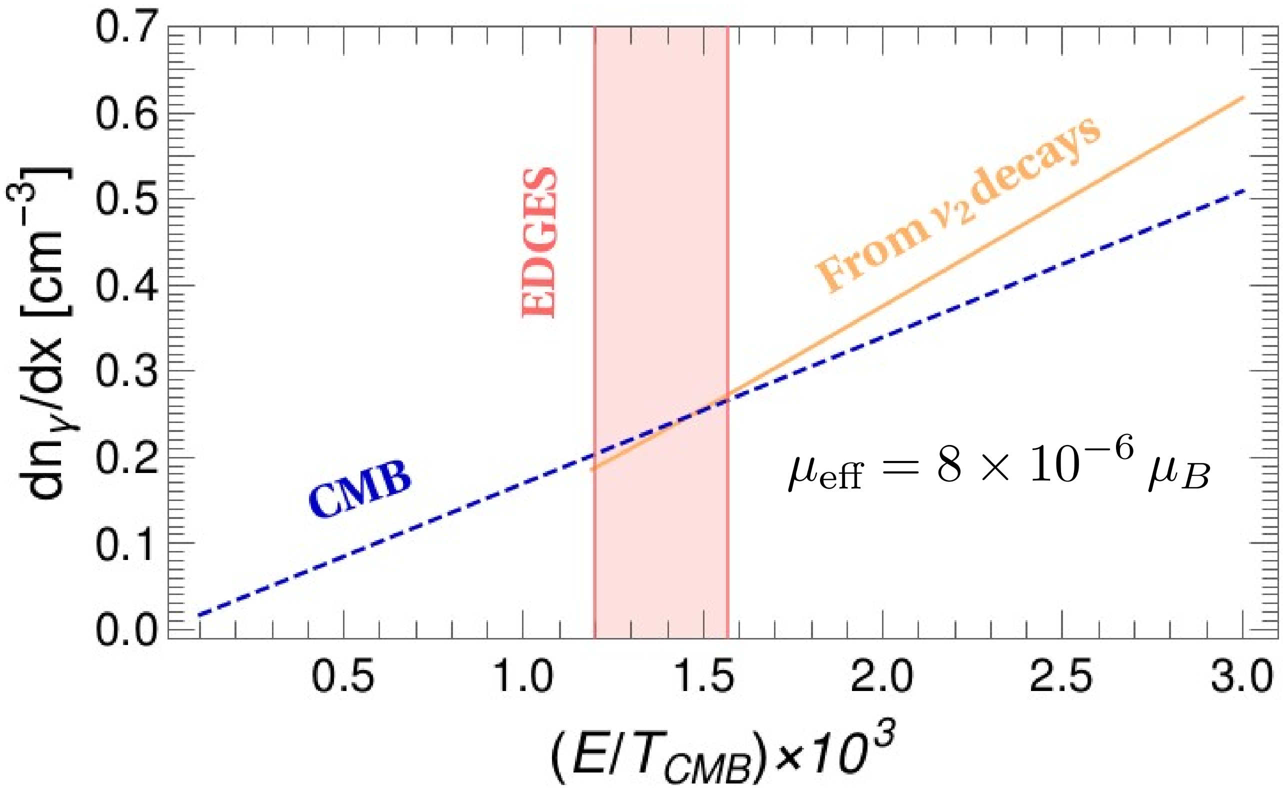
[Aristizabal Sierra & CSF, 1805.02685]

Imprint from mirror neutrinos?

[Aristizabal Sierra & CSF, 1805.02685]

- In conflict with astrophysical bound $\mu_{\rm eff} = \sqrt{|\mu|^2 + |\epsilon|^2}$

Astrophysical bounds from stars $\mu_{\rm eff} \lesssim 3.0 \times 10^{-12}\,\mu_B$



Imprint from mirror neutrinos?

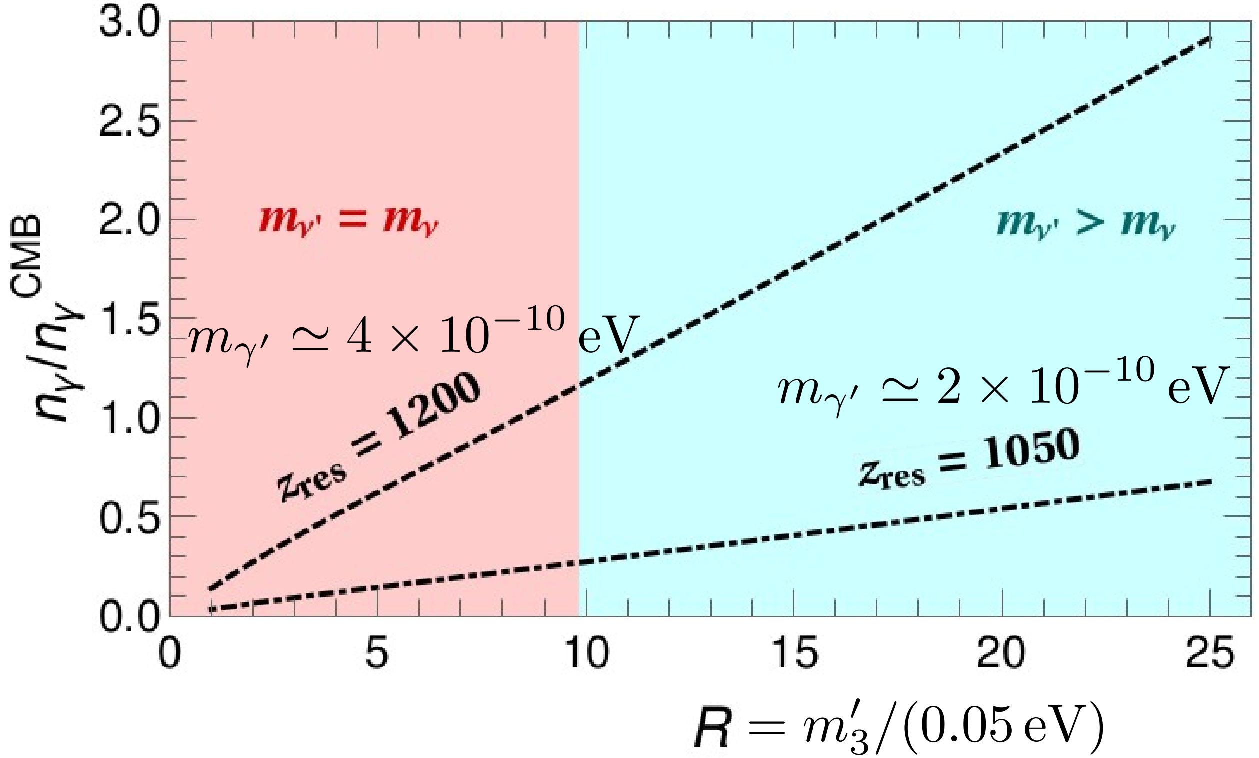
[Aristizabal Sierra & CSF, 1805.02685]

- Decay of mirror neutrinos $\mu'_{\rm eff} = \sqrt{|\mu'|^2 + |\epsilon'|^2}$

Astrophysical bounds from stars $\epsilon\mu'_{\rm eff} \lesssim 3.0 \times 10^{-12}\,\mu_B$

CMB $\epsilon \lesssim 10^{-6}$ $\sum_i m_i + \sum_i m'_i(n'_\nu/n_\nu) < 0.68\,\mathrm{eV}$

$\nu'_j \to \nu'_i + \gamma'$ $\gamma \to \gamma'$ resonant conversion



$T'/T = 0.4$

$\mu'_{\rm eff} = 3 \times 10^{-5}\mu_B$

$\epsilon = 10^{-7}$

Mirror symmetry breaking is required

SM and Mirror Genesis

- UV neutrino sector

$$\mathcal{L} = i\bar{N}_i \partial N_i - M_i \bar{N}_i N_i - y_{\alpha j} \bar{L}_\alpha \tilde{H} P_R N_j - y'_{\alpha j} \bar{L'}_\alpha \tilde{H}' P_R N_j^c + \mathrm{h.c.}$$

$\Longrightarrow \mathcal{L}_{\text{eff}} = -\frac{y}{M_2}(LH)(L'H')$ Dirac neutrinos Absence of $0\nu\beta\beta$

- Conserved $(B-L)-(B'-L')$

$\Longrightarrow Y_{B-L} = Y_{B'-L'}$ Dirac leptogenesis

  - From decay [Gu, 1209.4579] [Earl, CSF, Gregoire & Tonero, 1903.12192]
  - From scattering [Bento & Berezhiani, hep-ph/0107281]

$Y_B = Y_{B'}$ Exact mirror

$Y_B \neq Y_{B'}$ Broken mirror

SM and Mirror Genesis

- UV neutrino sector

$$\mathcal{L} = i\bar{N}_i \partial N_i - M_i \bar{N}_i N_i - y_{\alpha j} \bar{L}_\alpha \tilde{H} P_R N_j - y'_{\alpha j} \bar{L}'_\alpha \tilde{H}' P_R N_j^c + \text{h.c.}$$

$\Longrightarrow \mathcal{L}_{\text{eff}} = -\frac{y}{M}(LH)(L'H')$ Dirac neutrinos Absence of $0\nu\beta\beta$

- Conserved $(B-L)-(B'-L')$

$\Longrightarrow Y_{B-L} = Y_{B'-L'}$ Dirac leptogenesis

  - From decay $T_{\text{reheating}} > M_i$ [Gu, 1209.4579] [Earl, CSF, Gregoire & Tonero, 1903.12192]
  - From scattering $T_{\text{reheating}} < M_i$ [Bento & Berezhiani, hep-ph/0107281]

$Y_B = Y_{B'}$ Exact mirror

$Y_B \neq Y_{B'}$ Broken mirror

Outlook

- Existence of a whole zoo of hidden sector particles like mirror world is as exciting as ever
- Even the most restricted case of exact mirror (but colder) is quite complicated, might solve some puzzles and definitely not excluded (much work to be done)
- Perhaps mirror physicists are asking the same questions as we do