Neutrinos in Cosmology

Little particles on the biggest scale

The Physics of Neutrinos: Progress and Puzzles

The 87th Compton Lecture Series

Enrico Fermi Institute, University of Chicago

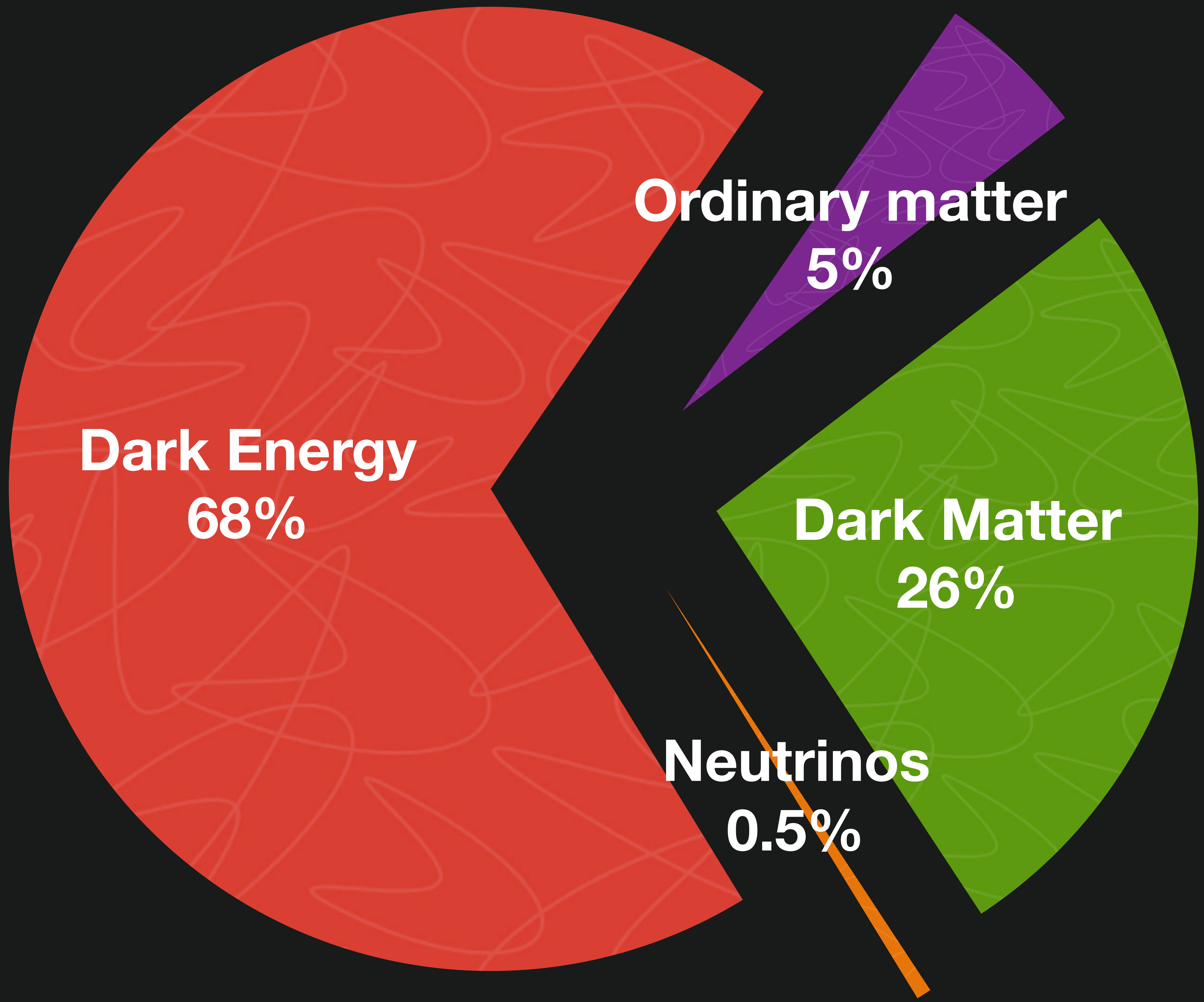
Marco Raveri

April 21, 2018

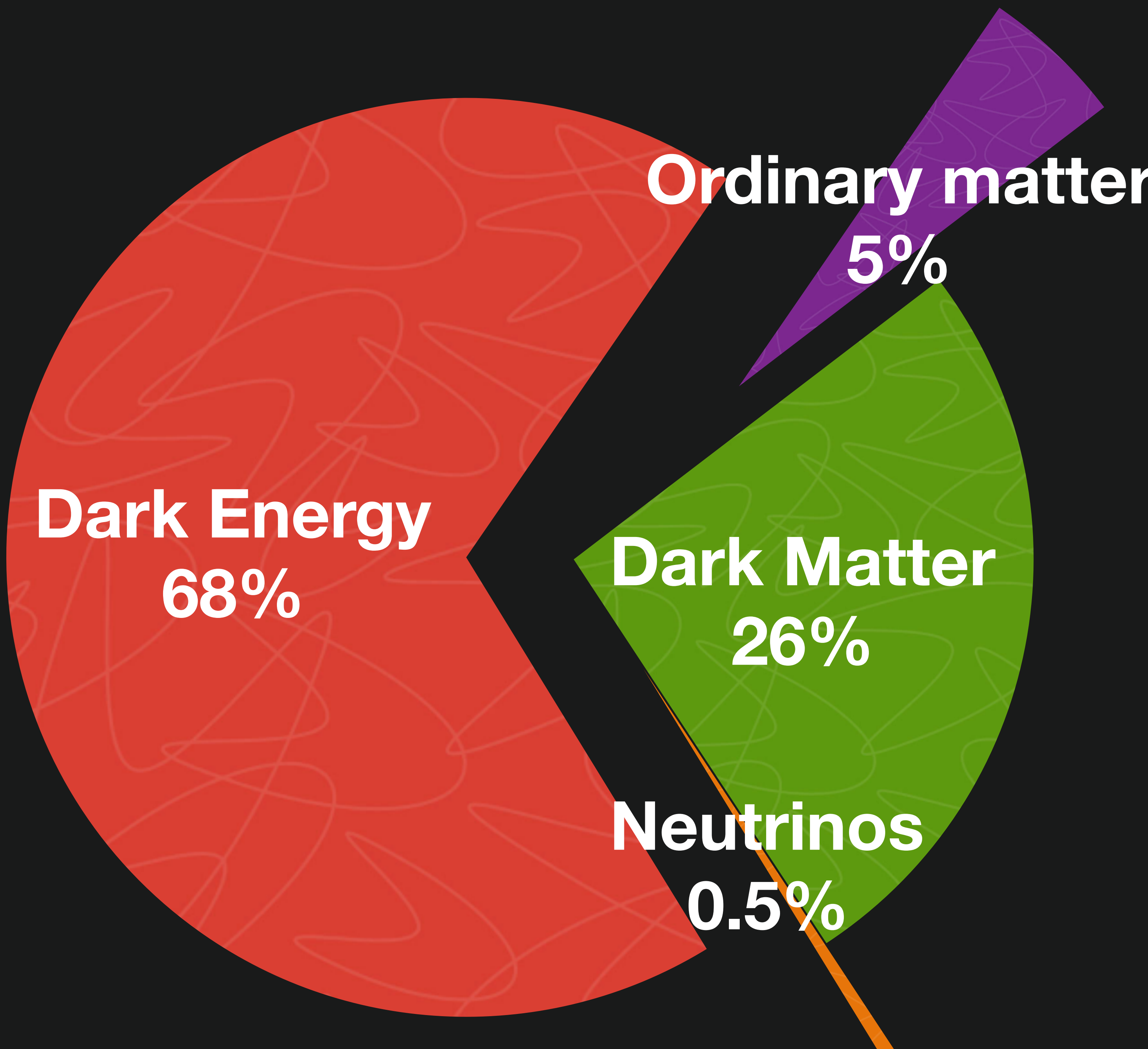
The Universe & Neutrinos

Image: logarithmic map of the observable universe, Pablo Carlos Budassi

The constituents of the Universe



The constituents of the Universe



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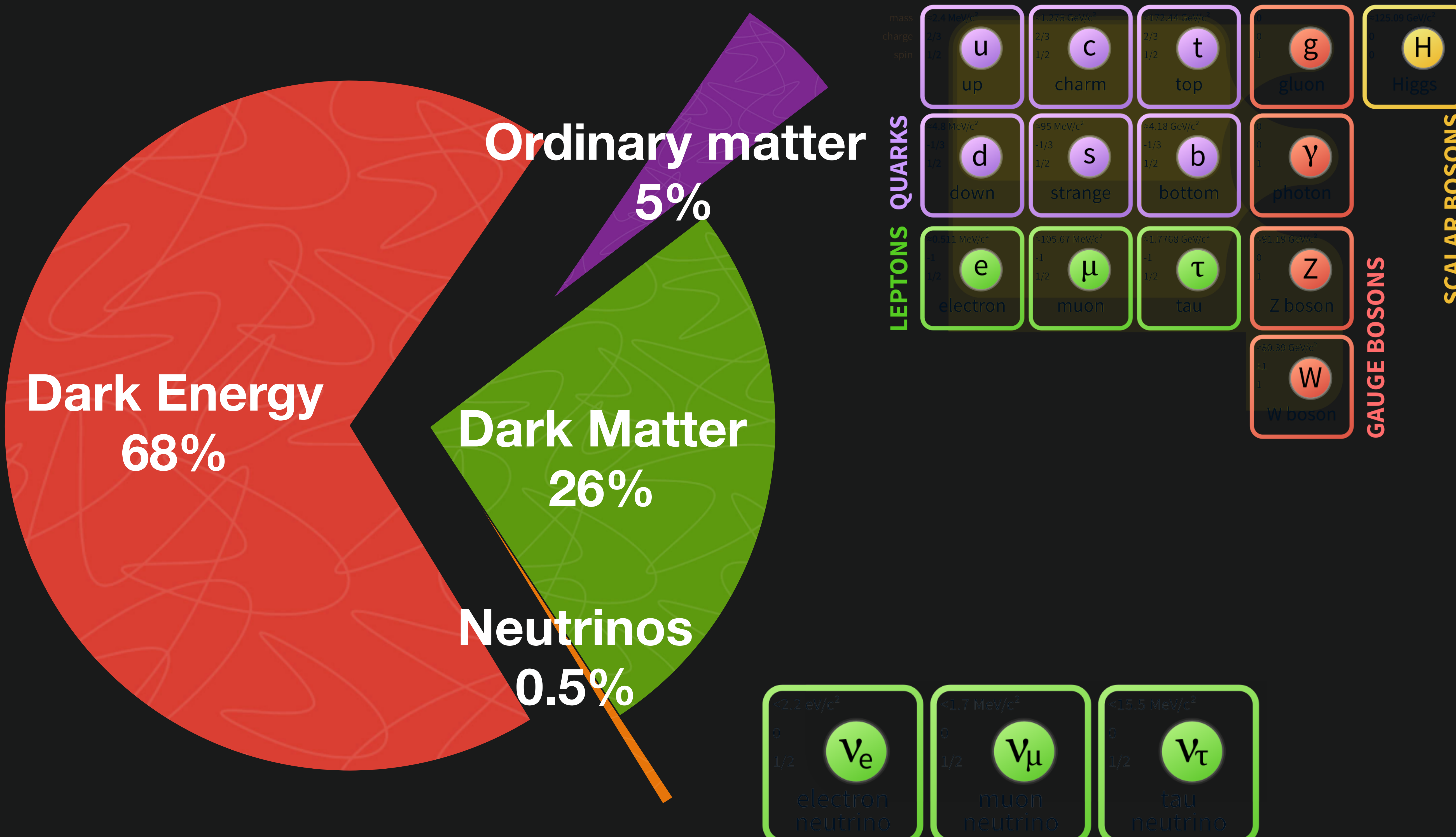
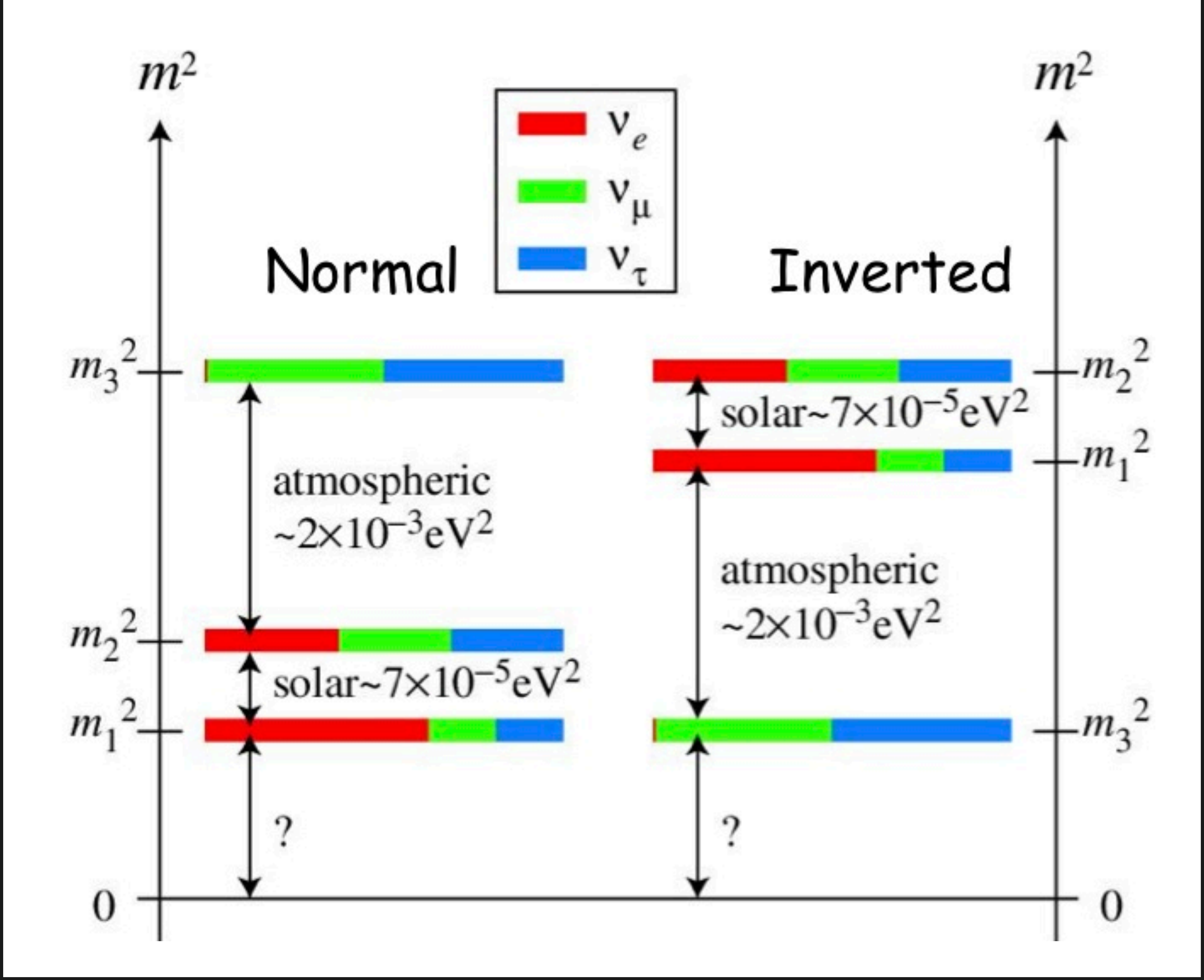


The missing piece



Tiny particle, big scale

The expansion of the Universe

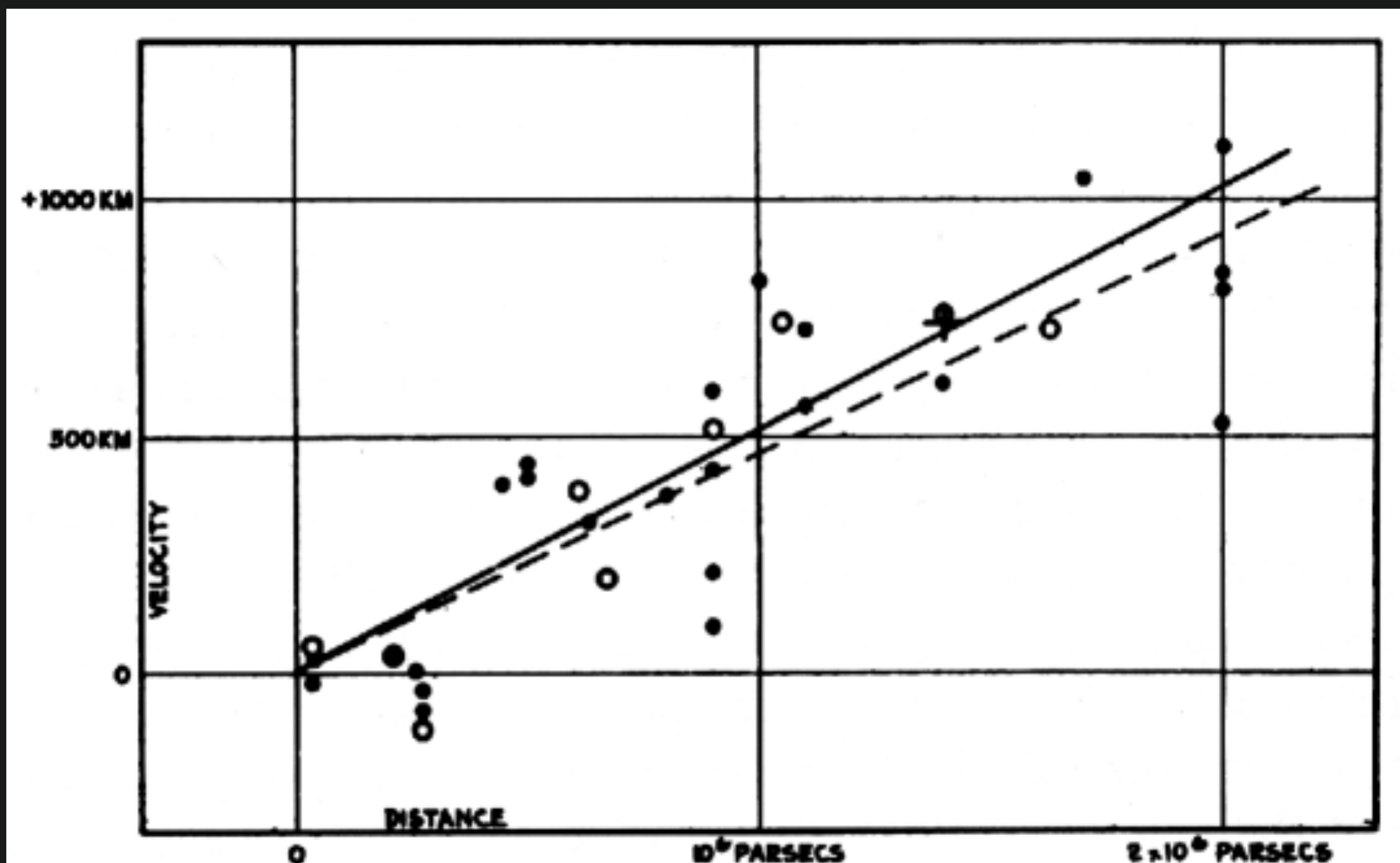


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

UChicago student

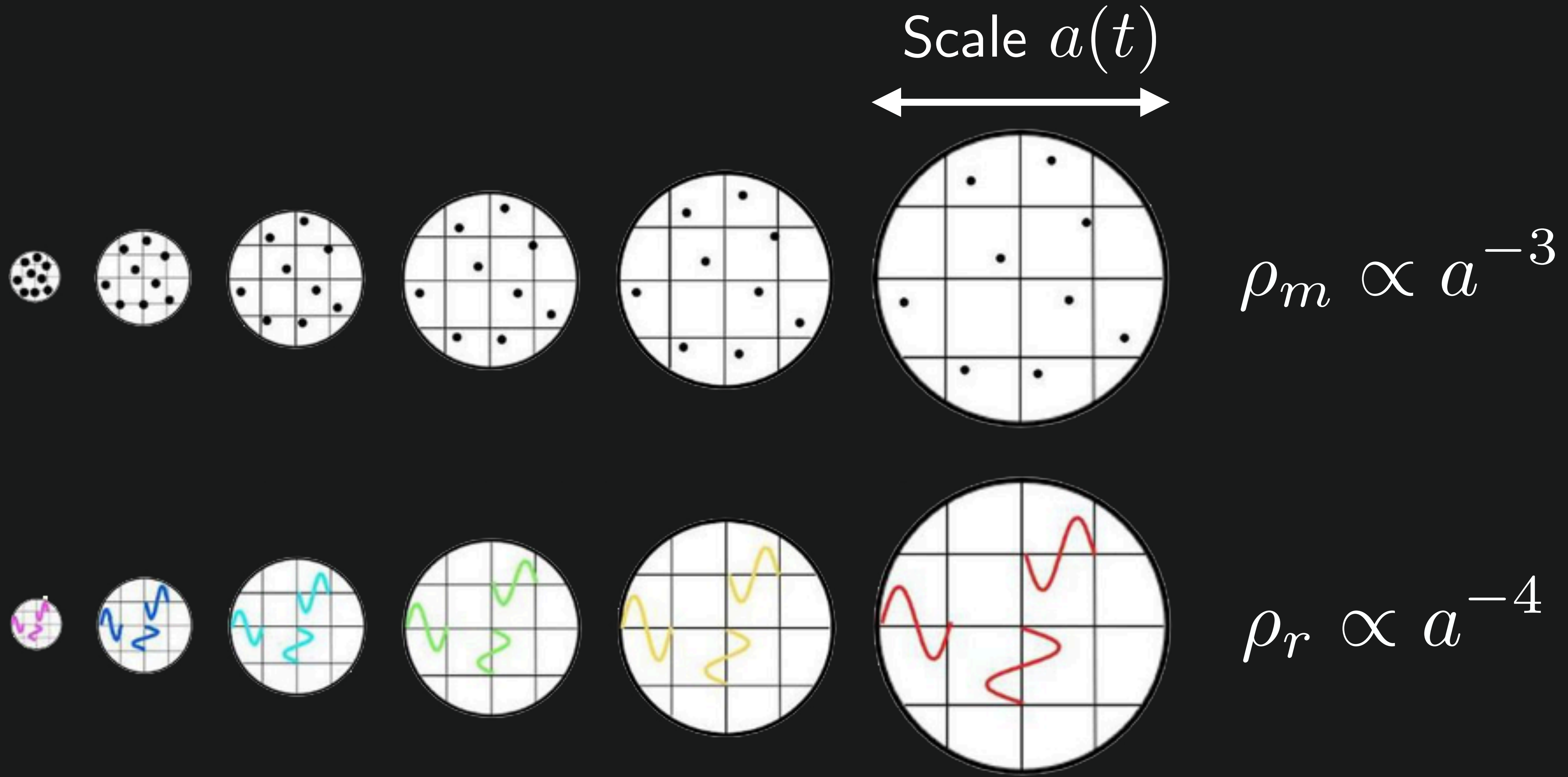
The recessional velocity of galaxies is proportional to their distance from us.

The universe expands.

Matter dilutes and cools as the Universe expands

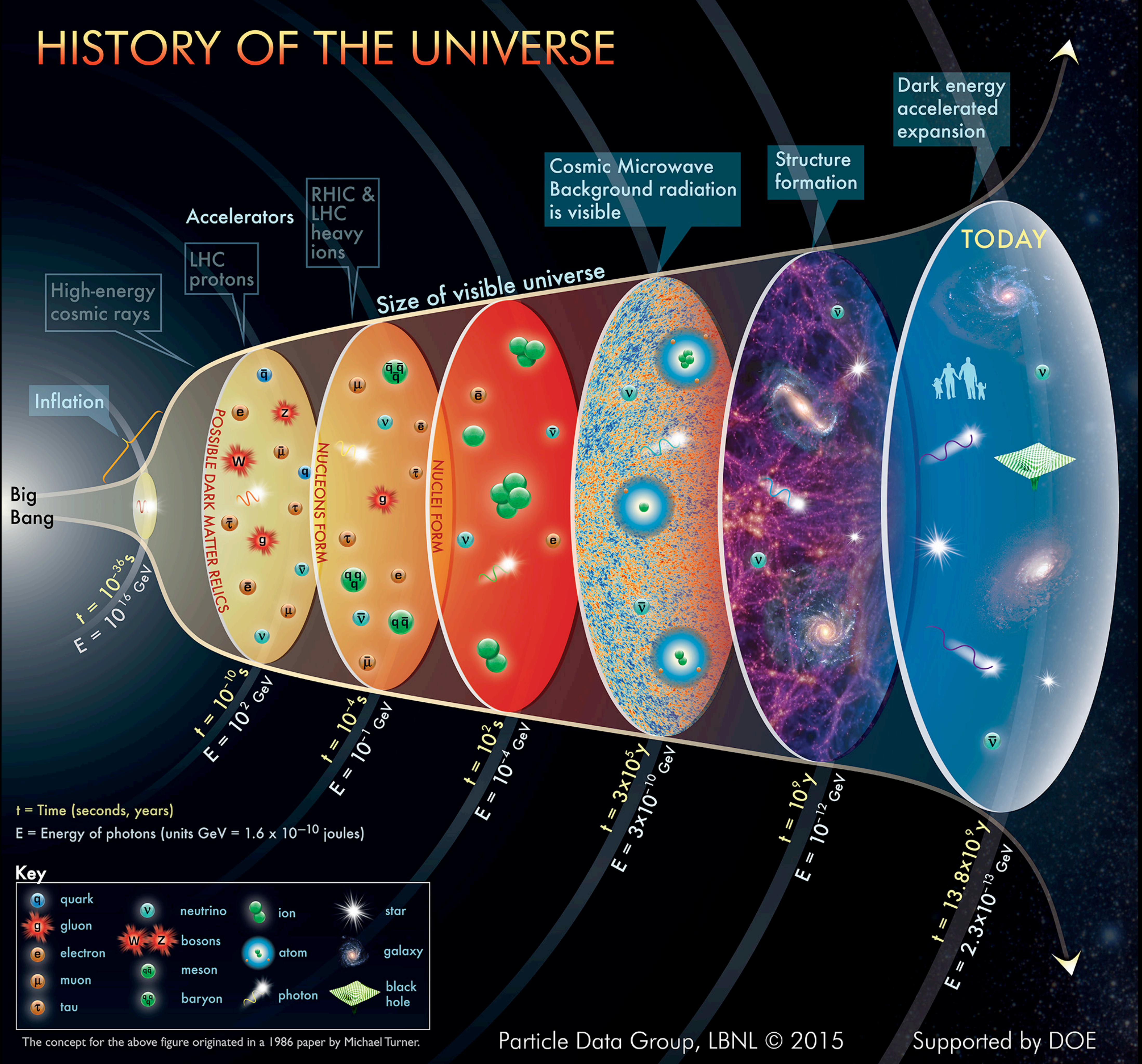
Image: Ethan Siegel

Matter dilutes and cools as the Universe expands

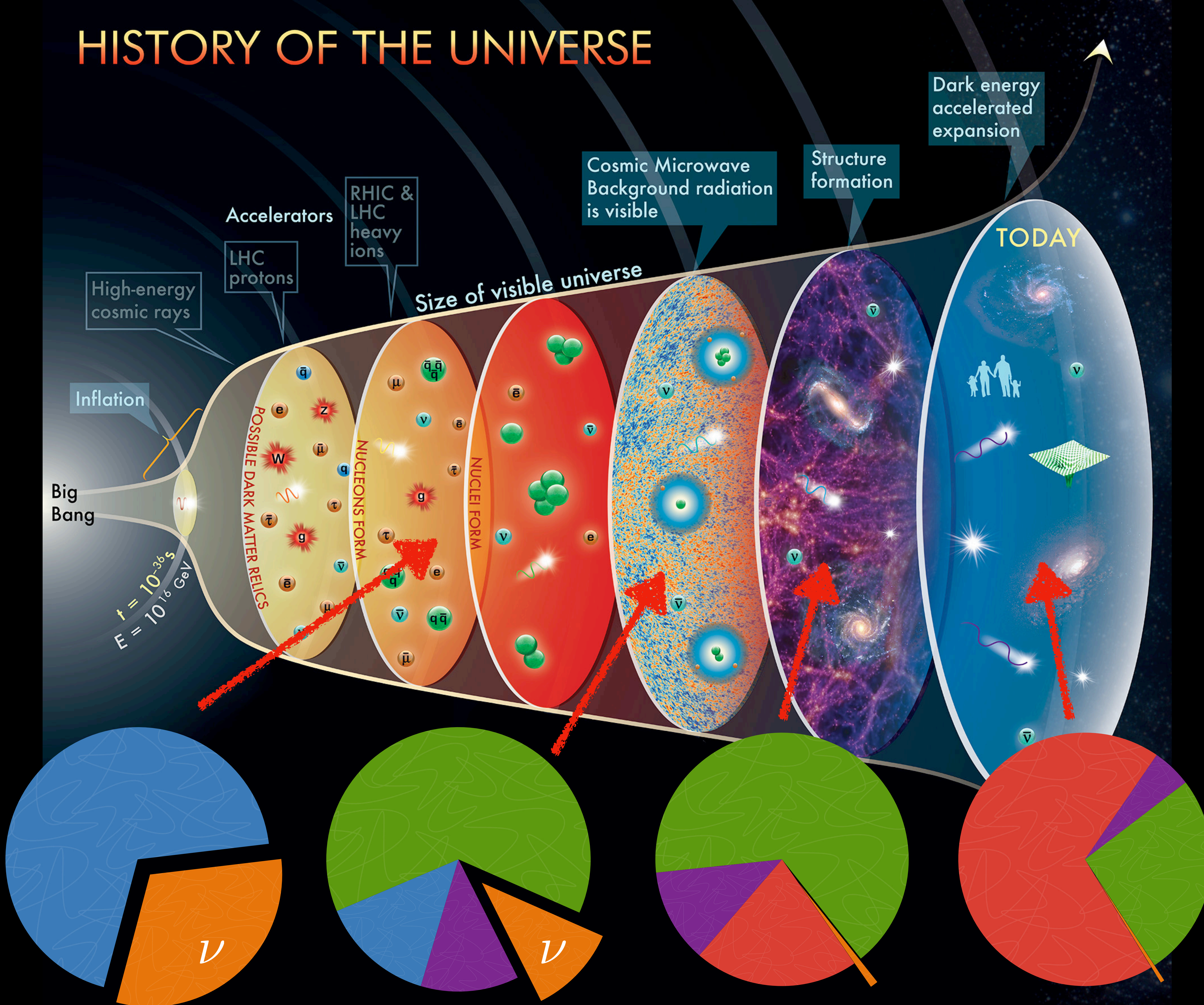


Radiation dilutes and redshifts as the Universe expands

Image: Ethan Siegel



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3\text{x}10^{5}$ y
$E = 3\text{x}10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8\text{x}10^{9}$ y
$E = 2.3\text{x}10^{-13}$ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE



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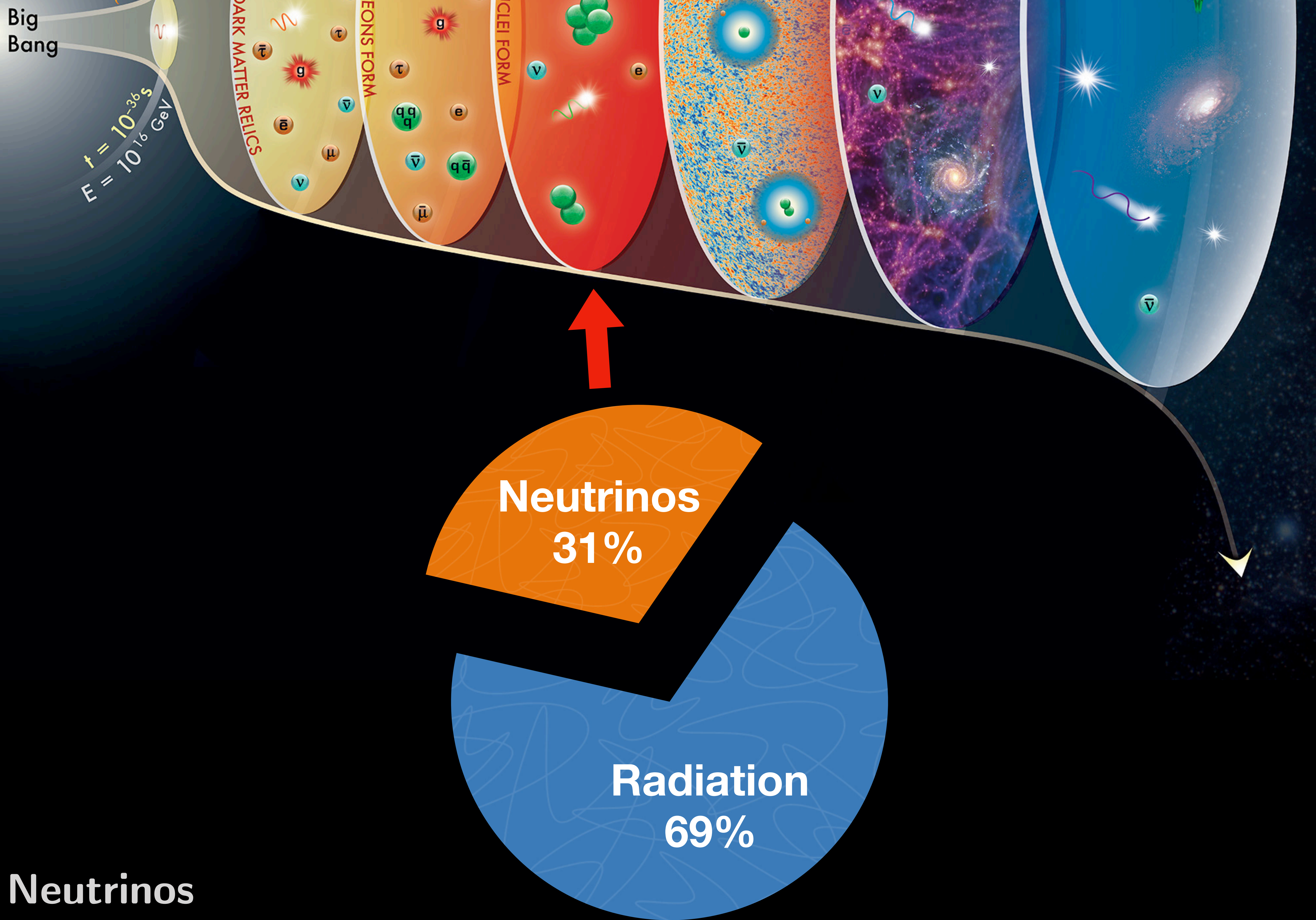
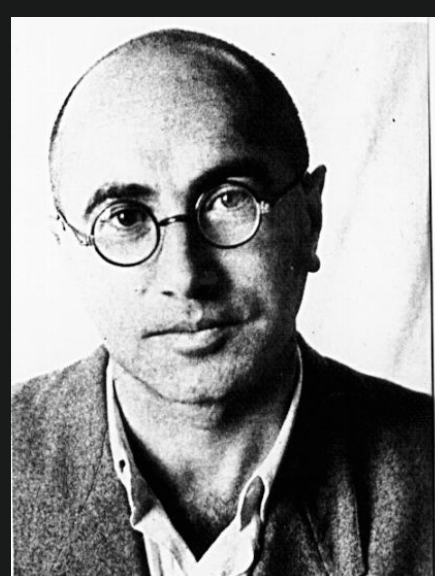


Neutrinos in the early universe

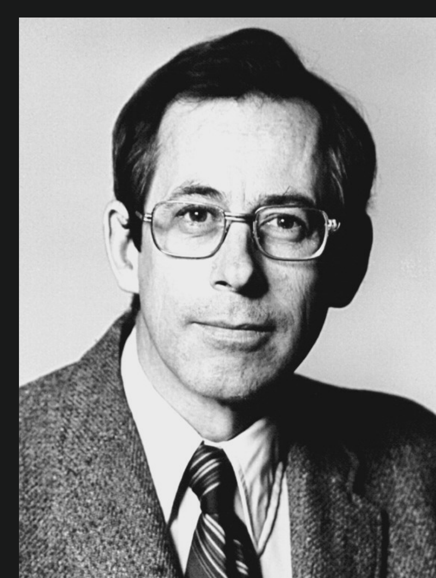
Alpher–Bethe–Gamow

“The Origin of Chemical Elements” (1948)

Ya. B. Zel'dovich



Jim Peebles



Fred Hoyle

The First Three Minutes: A Modern View of the Origin of the Universe, Steven Weinberg

Neutrino decoupling

$$\Gamma = n\langle\sigma v\rangle \qquad\qquad \Gamma = n\langle\sigma v\rangle \sim H$$

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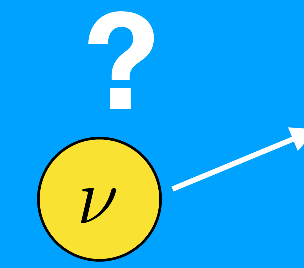
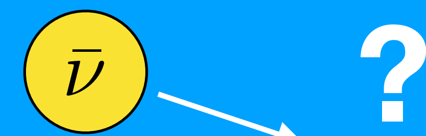
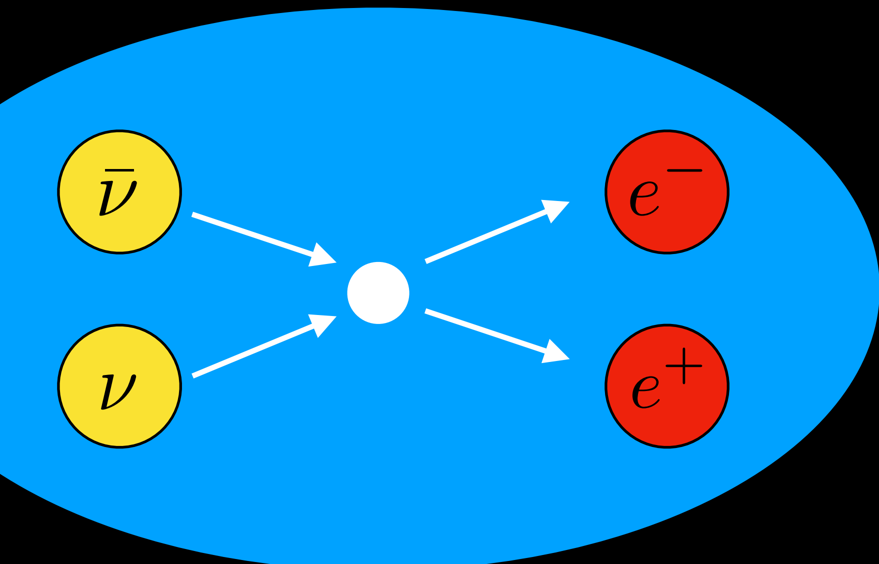




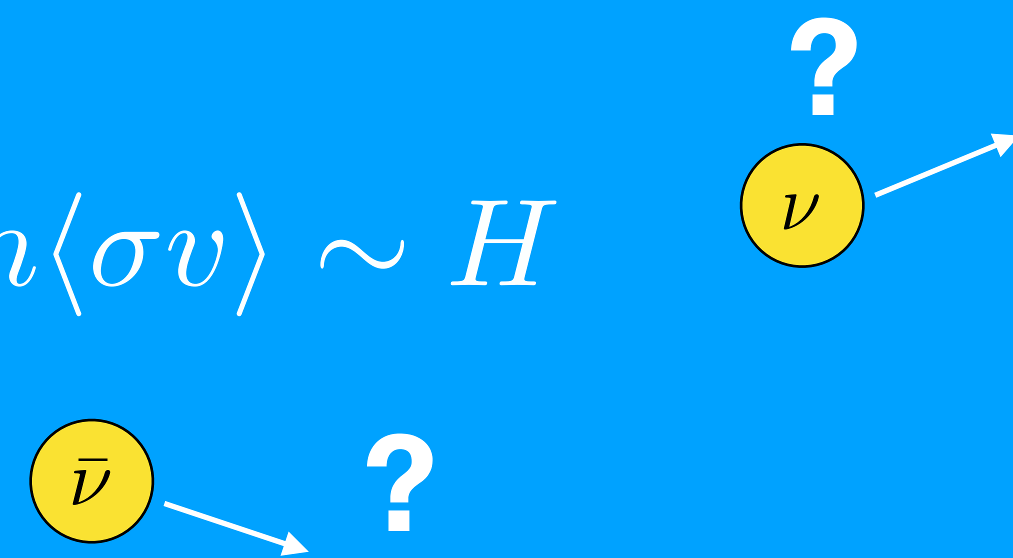


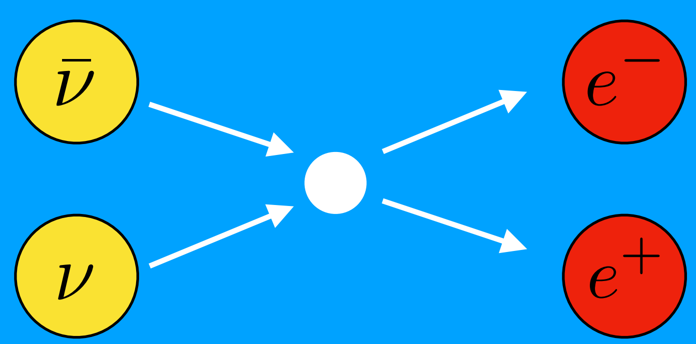
$$\nu_e + \bar{\nu}_e \longleftrightarrow e^- + e^+$$

Neutrino decoupling

$$\Gamma = n\langle\sigma v\rangle$$

$$\Gamma = n\langle\sigma v\rangle \sim H$$





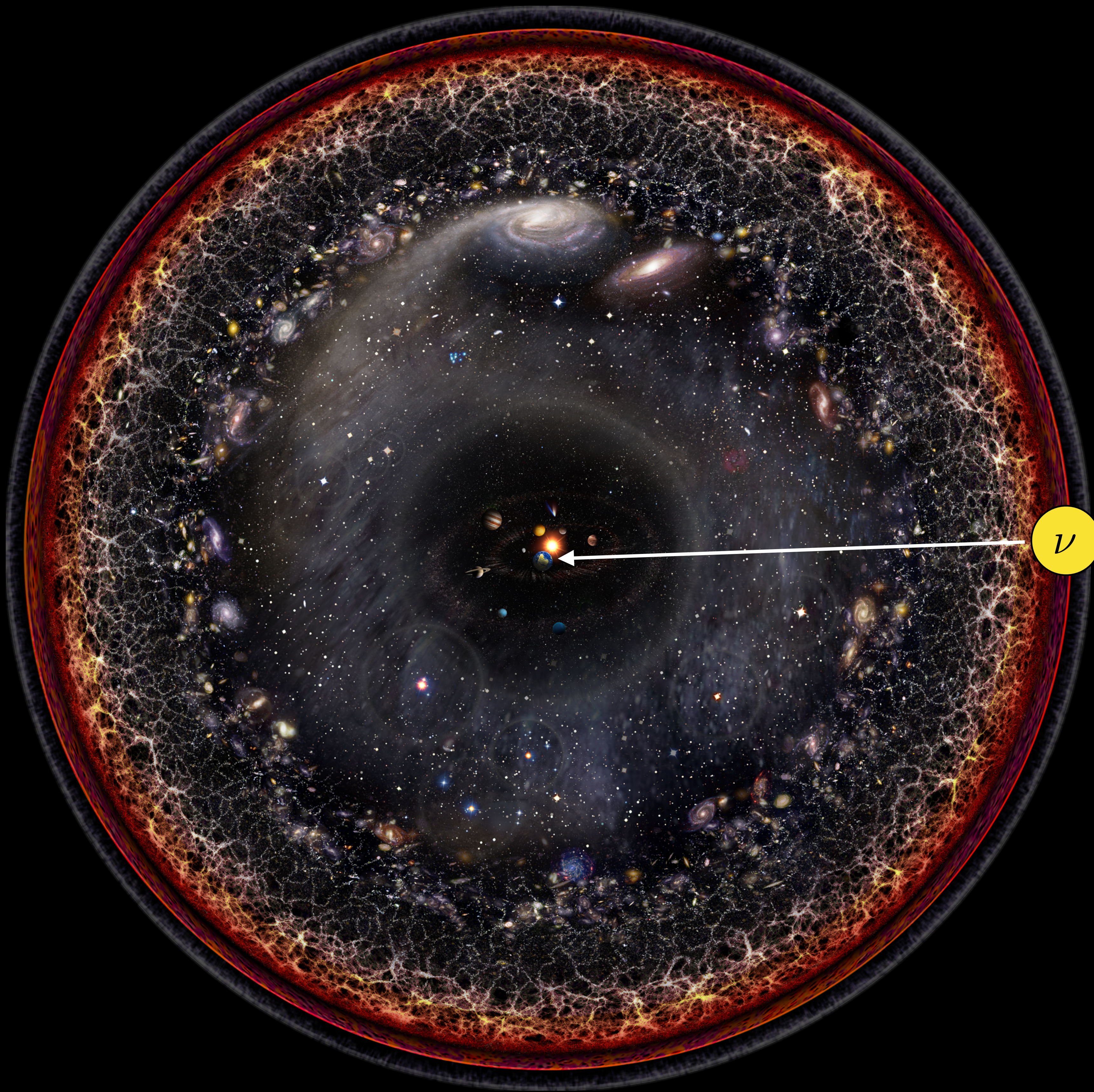
$$\nu_e + \bar{\nu}_e \longleftrightarrow e^- + e^+$$

$$\Gamma = n\langle\sigma v\rangle \sim G_F^2 T^5$$

$$\Gamma = n\langle\sigma v\rangle \sim H \sim \sqrt{GT^4}$$

$$T \sim \left(\frac{\sqrt{G}}{G_F^2}\right)^{1/3} \sim 1\ \mathrm{MeV} \sim 1\ \mathrm{s} \sim 10^{10}\ \mathrm{K}$$

Free streaming of neutrinos since decoupling



Relic neutrino density and number of neutrinos

$$e^+ + e^- \longrightarrow \gamma + \gamma$$

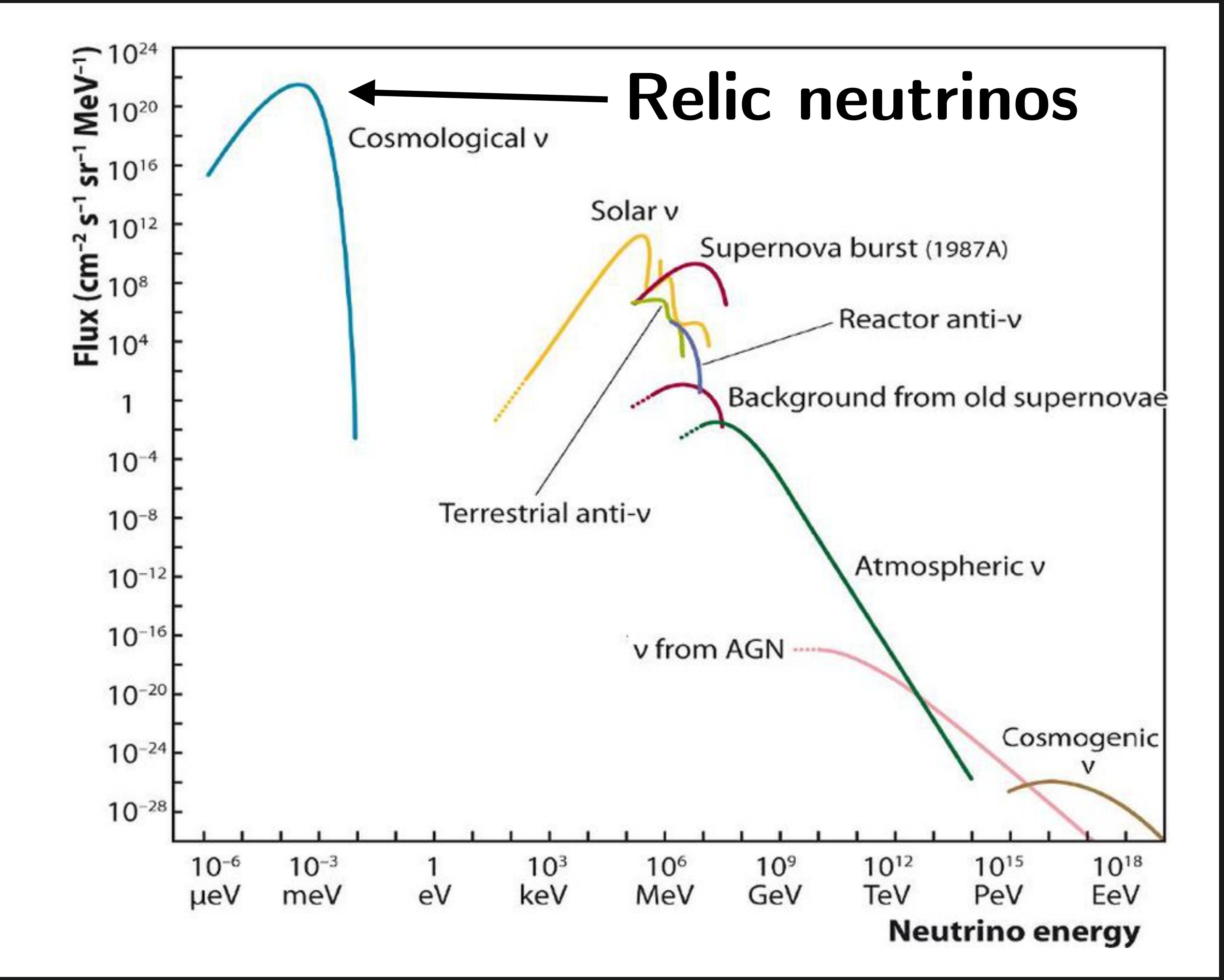
$$\frac{T_\gamma^{\mathrm{after}}}{T_\gamma^{\mathrm{before}}} = \frac{T_\gamma}{T_\nu} = \left(\frac{11}{4}\right)^{1/3}$$

$$\rho_\nu = \left[\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right]\rho_\gamma$$

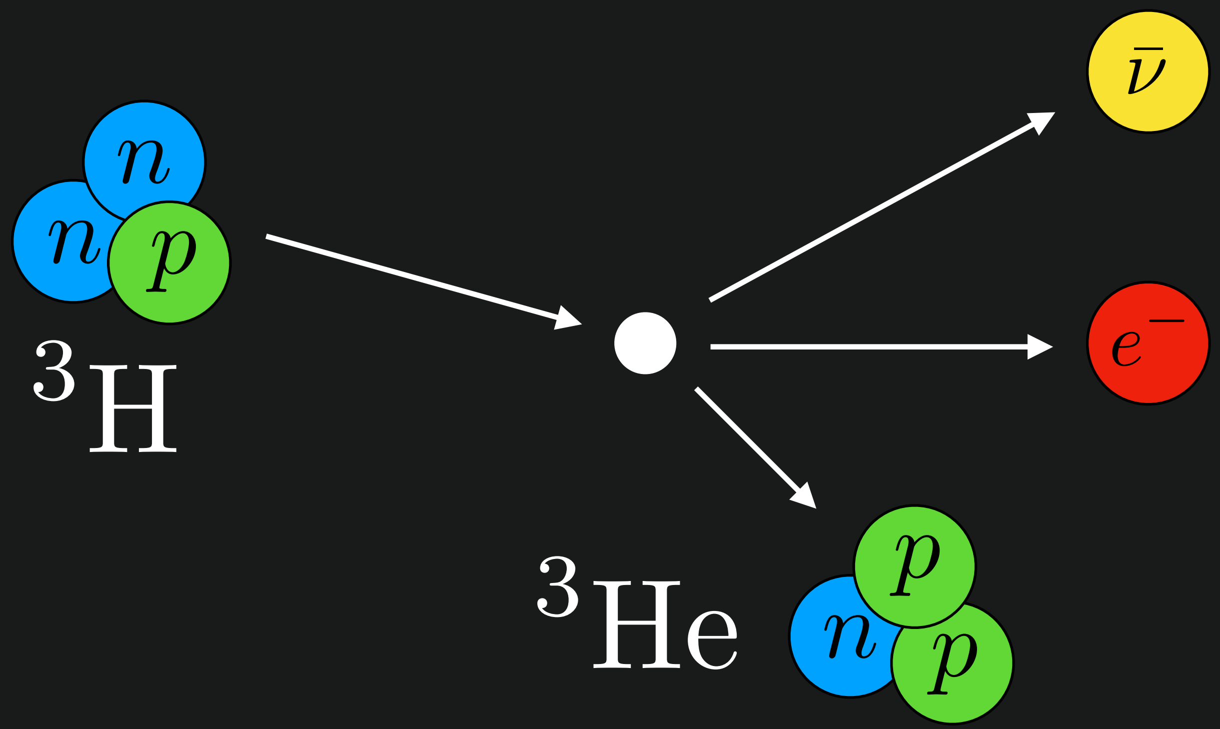
$$N_{\mathrm{eff}} = 3.046$$

Direct detection of the neutrino background

$$\rho_r \propto a^{-4}$$



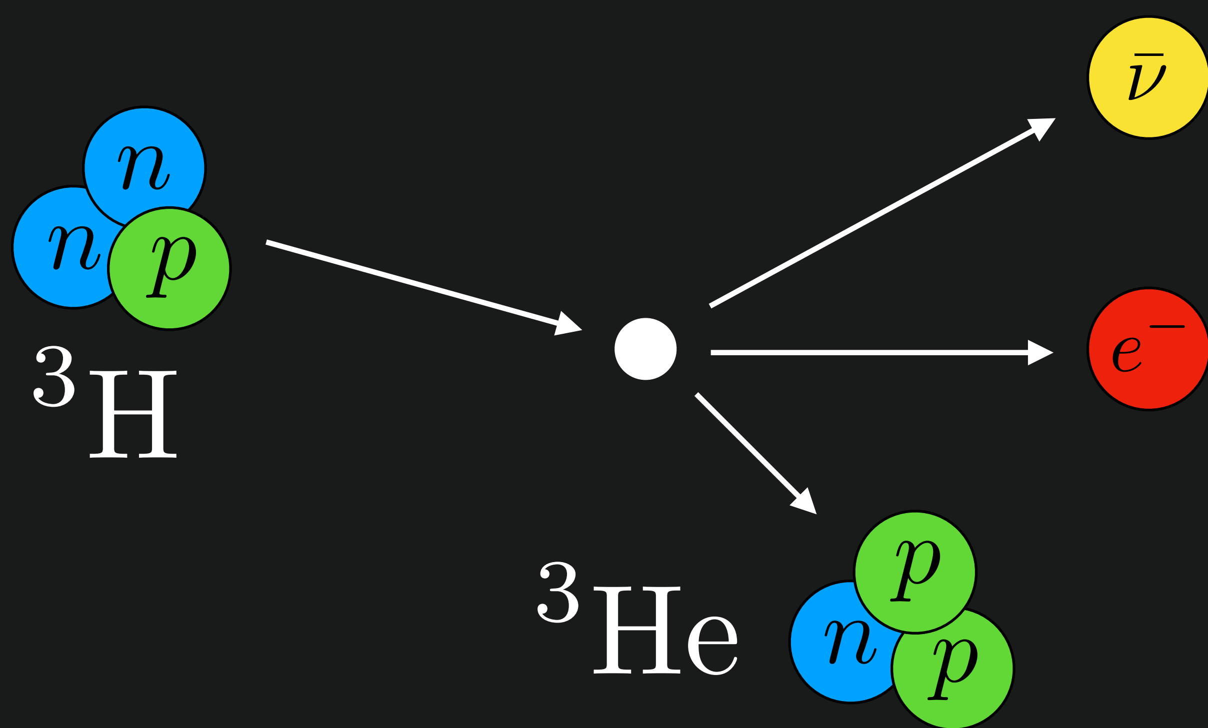
Tritium beta decay and capture



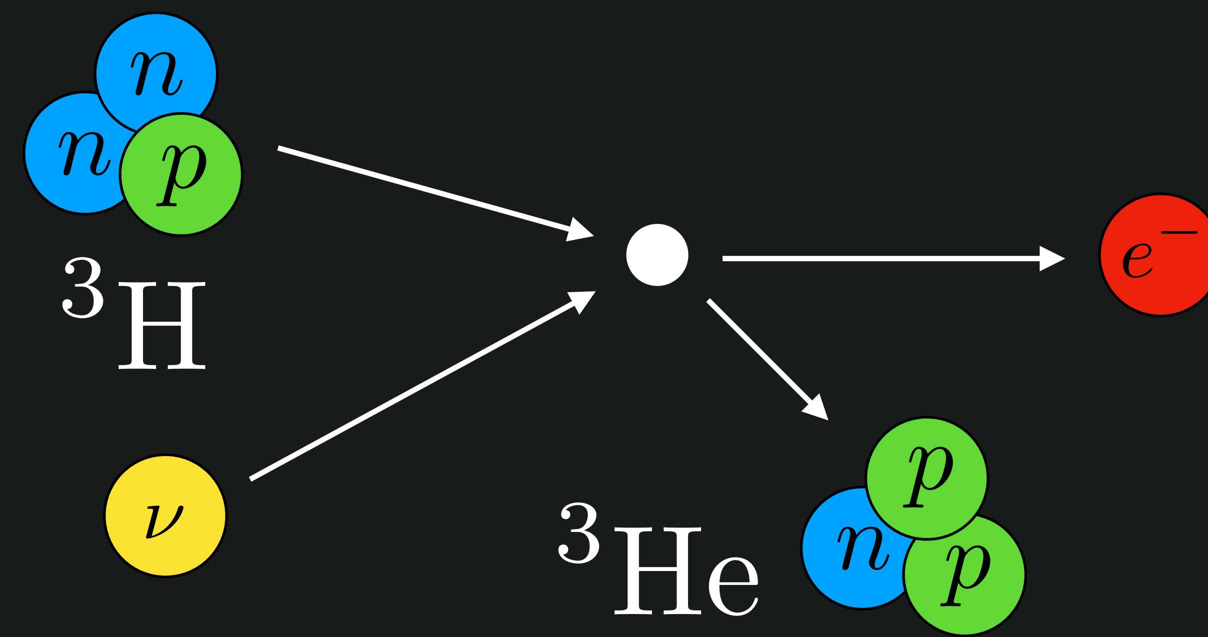
Tritium beta decay

e^+

Tritium beta decay and capture

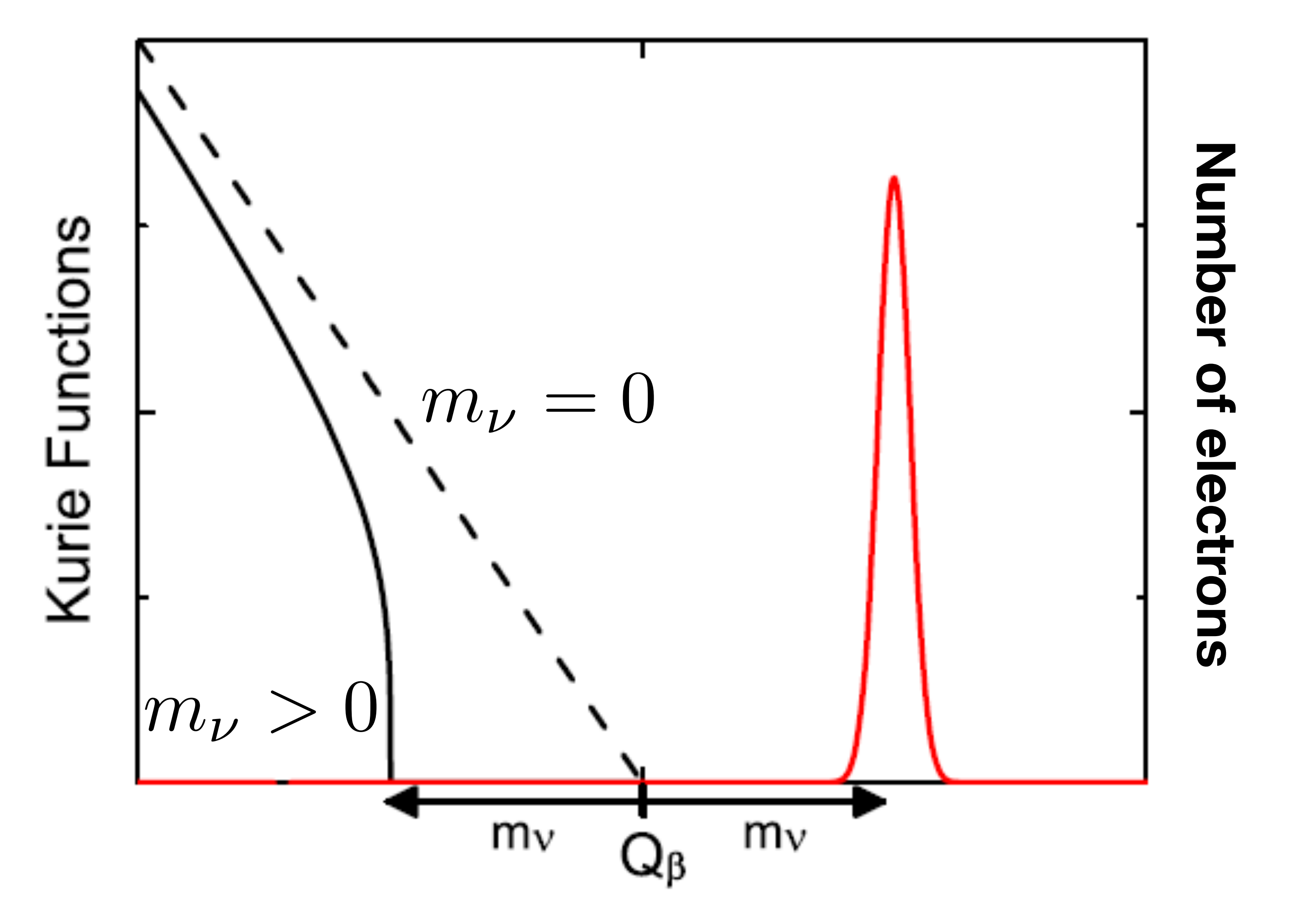


Tritium beta decay

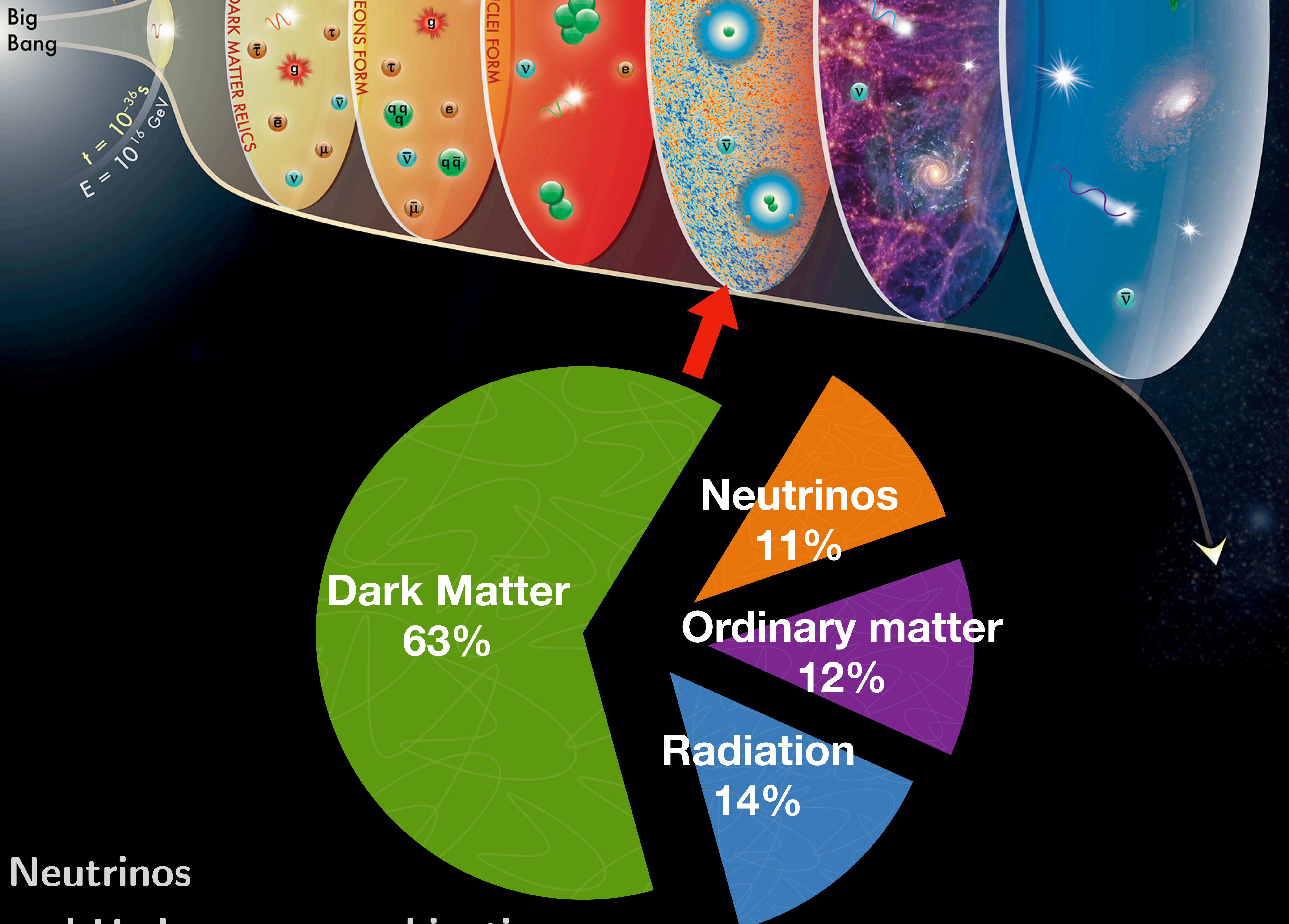


Neutrino capture on Tritium

e^{+}



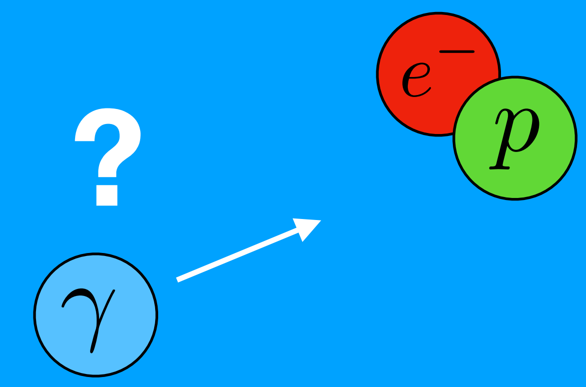
PTOLEMY
prototype

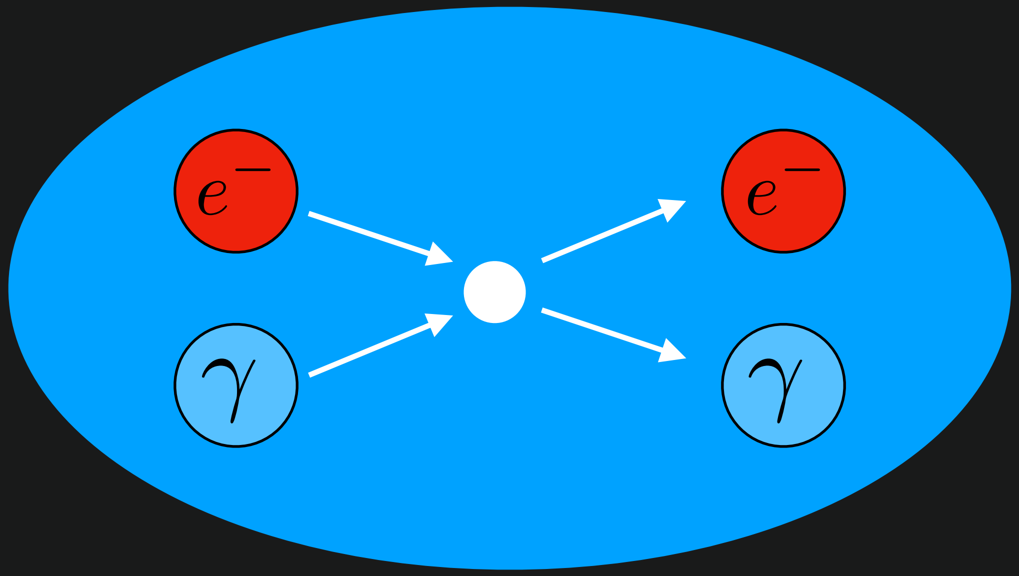


Neutrinos

and Hydrogen recombination

Hydrogen recombination



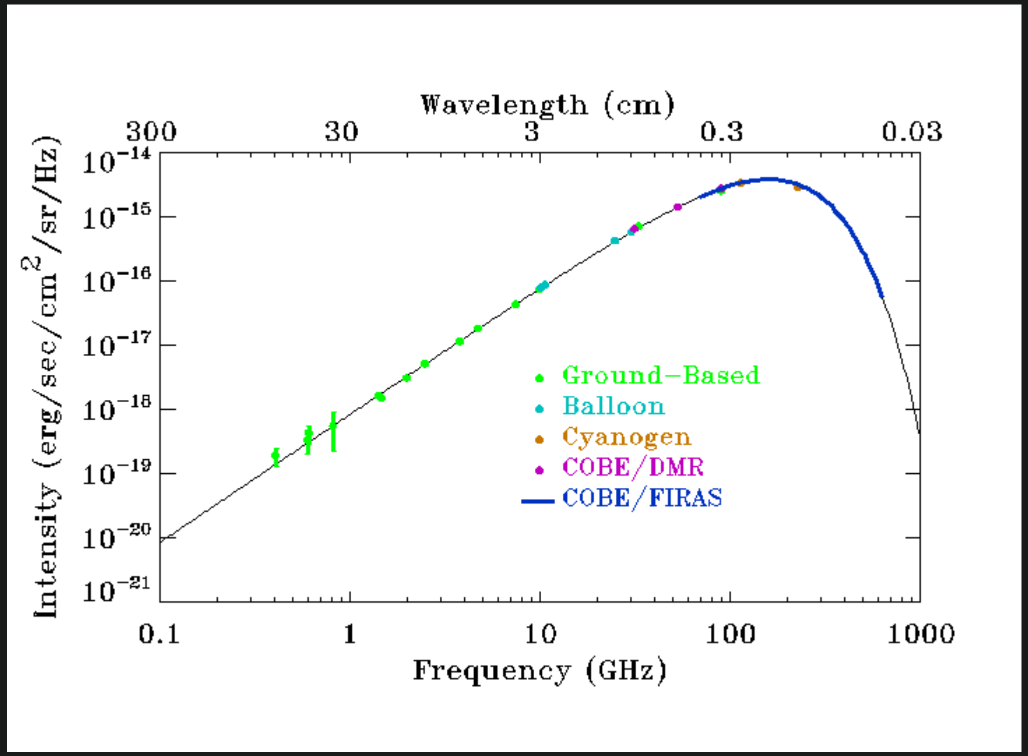


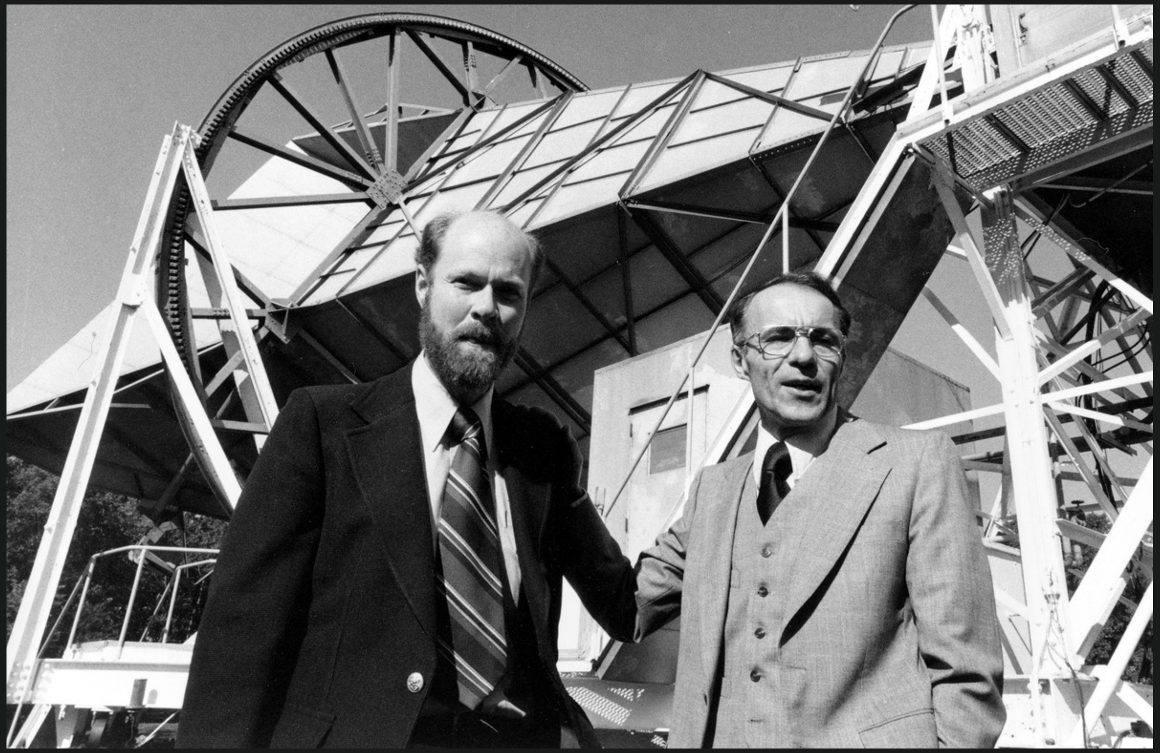
Thomson scattering

fewer photons have sufficient energy to break the binding energy of an electron in a neutral hydrogen atom

After their last scattering photons free stream to us

Penzias and Wilson (1964)

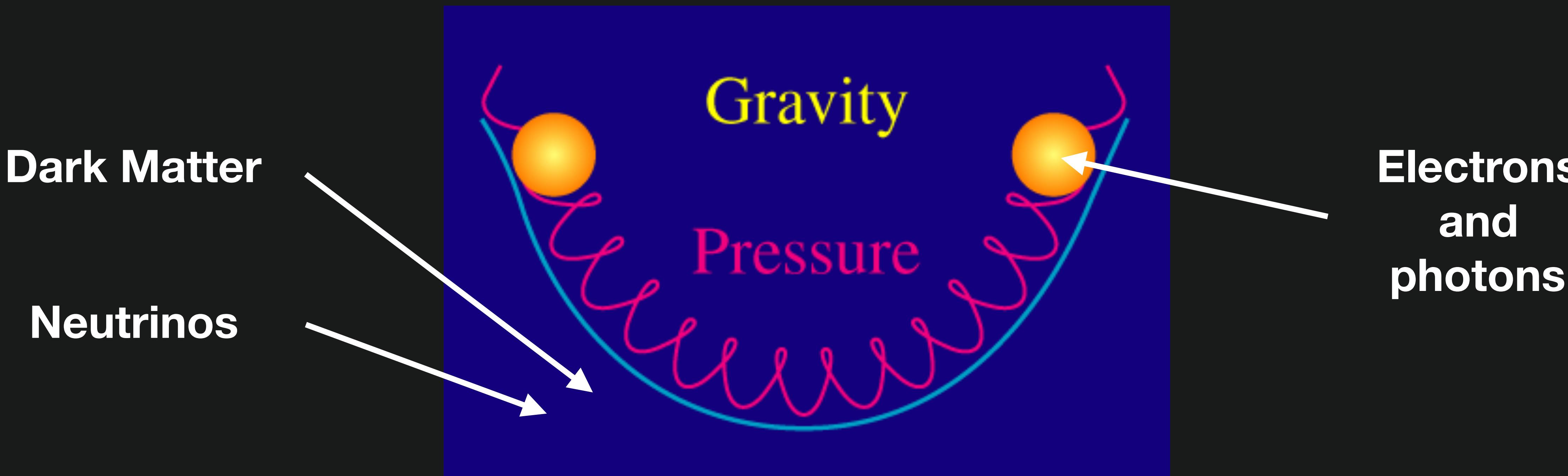




Cosmic Background Explorer (CoBE) satellite (1989-1993)

The First Three Minutes: A Modern View of the Origin of the Universe, Steven Weinberg

Fluctuations in the Microwave Background



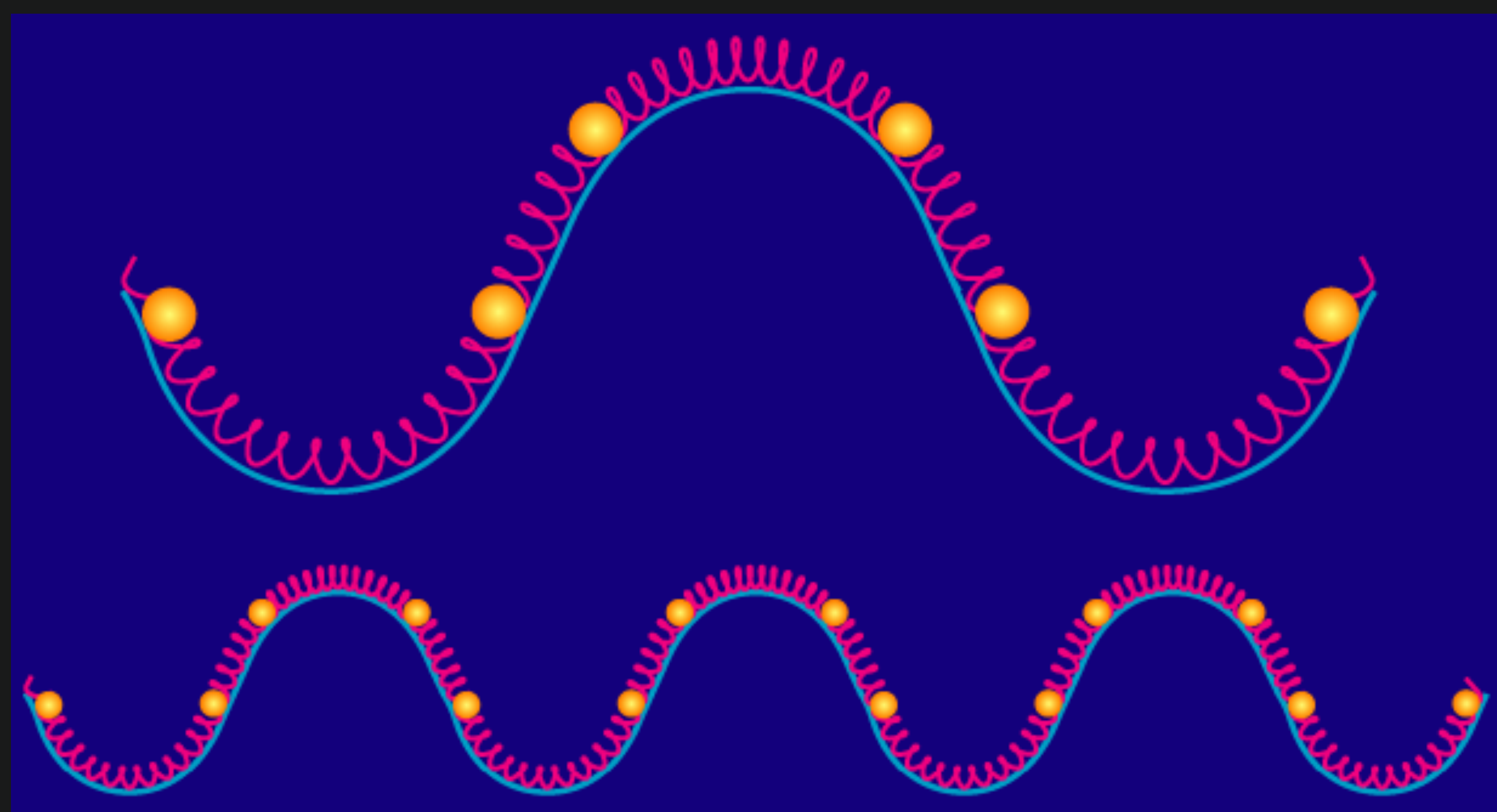
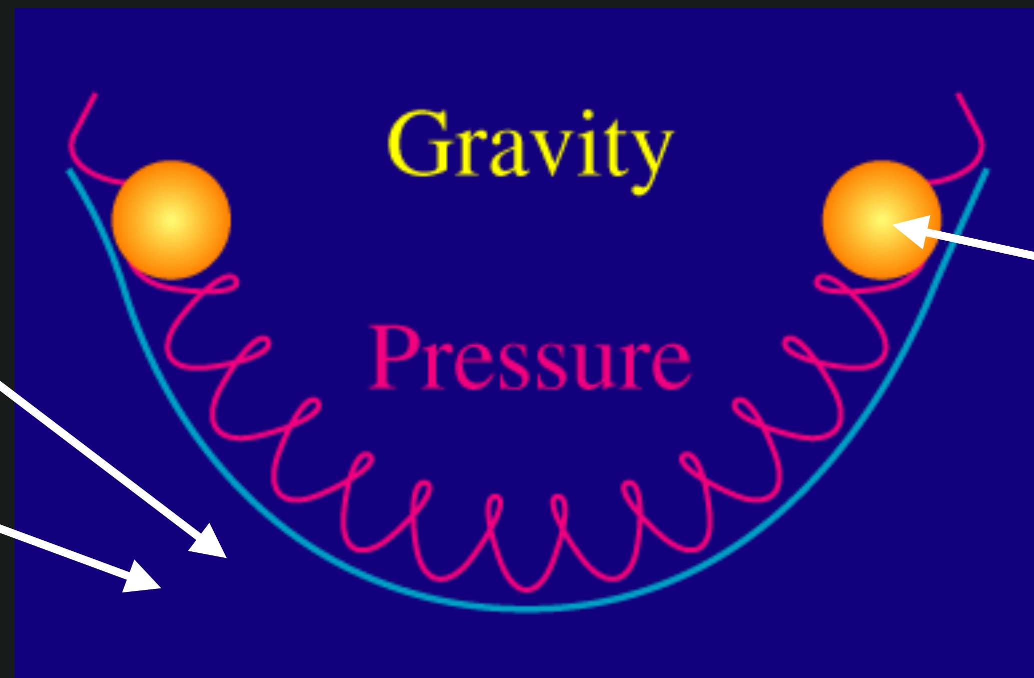


Image: Wayne Hu's CMB Tutorials

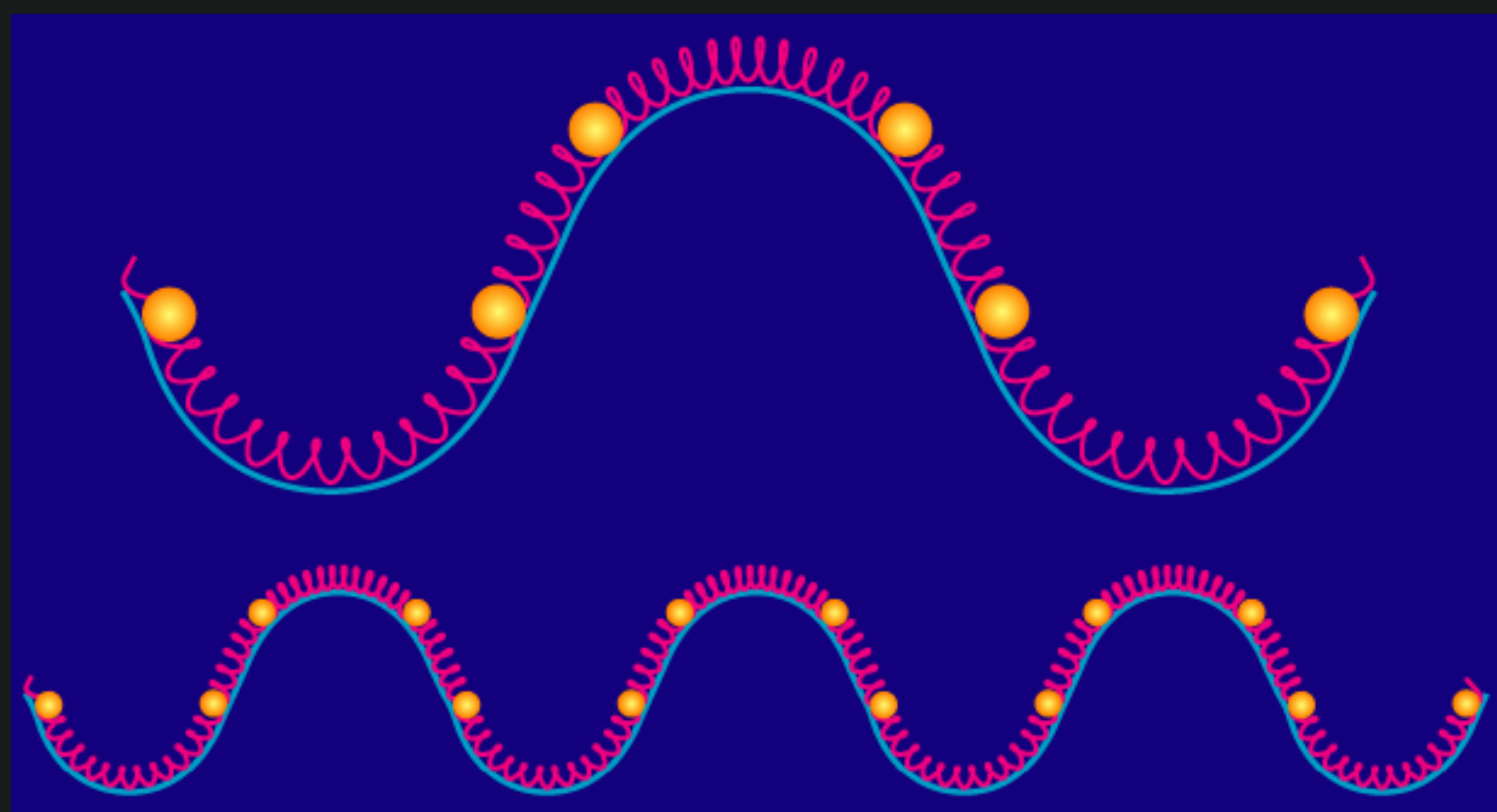
Fluctuations in the Microwave Background

Dark Matter

Neutrinos



Electrons and photons



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Fluctuations and last scattering

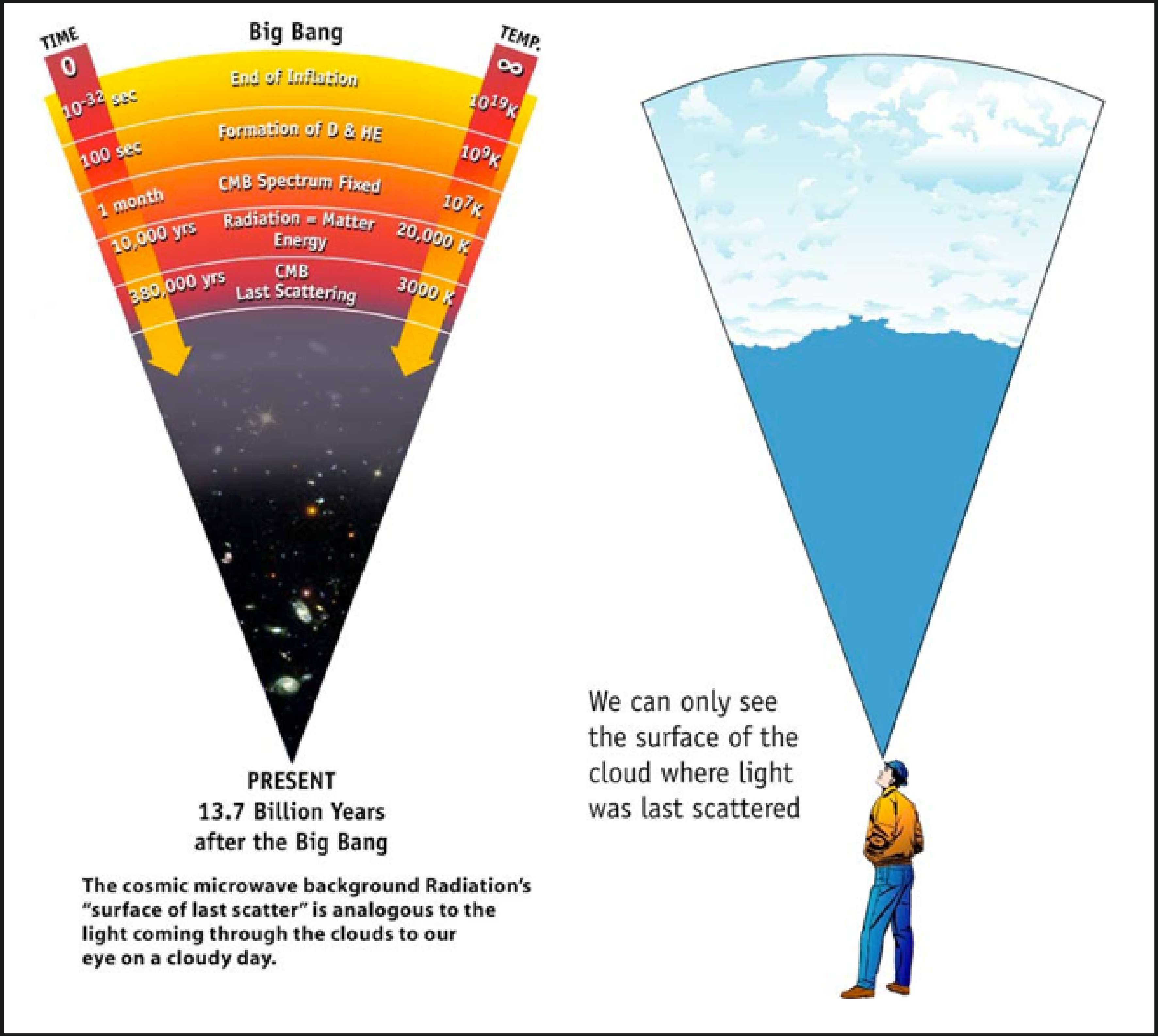


Image: Lambda website

WMAP and Planck

(2001 to 2010)

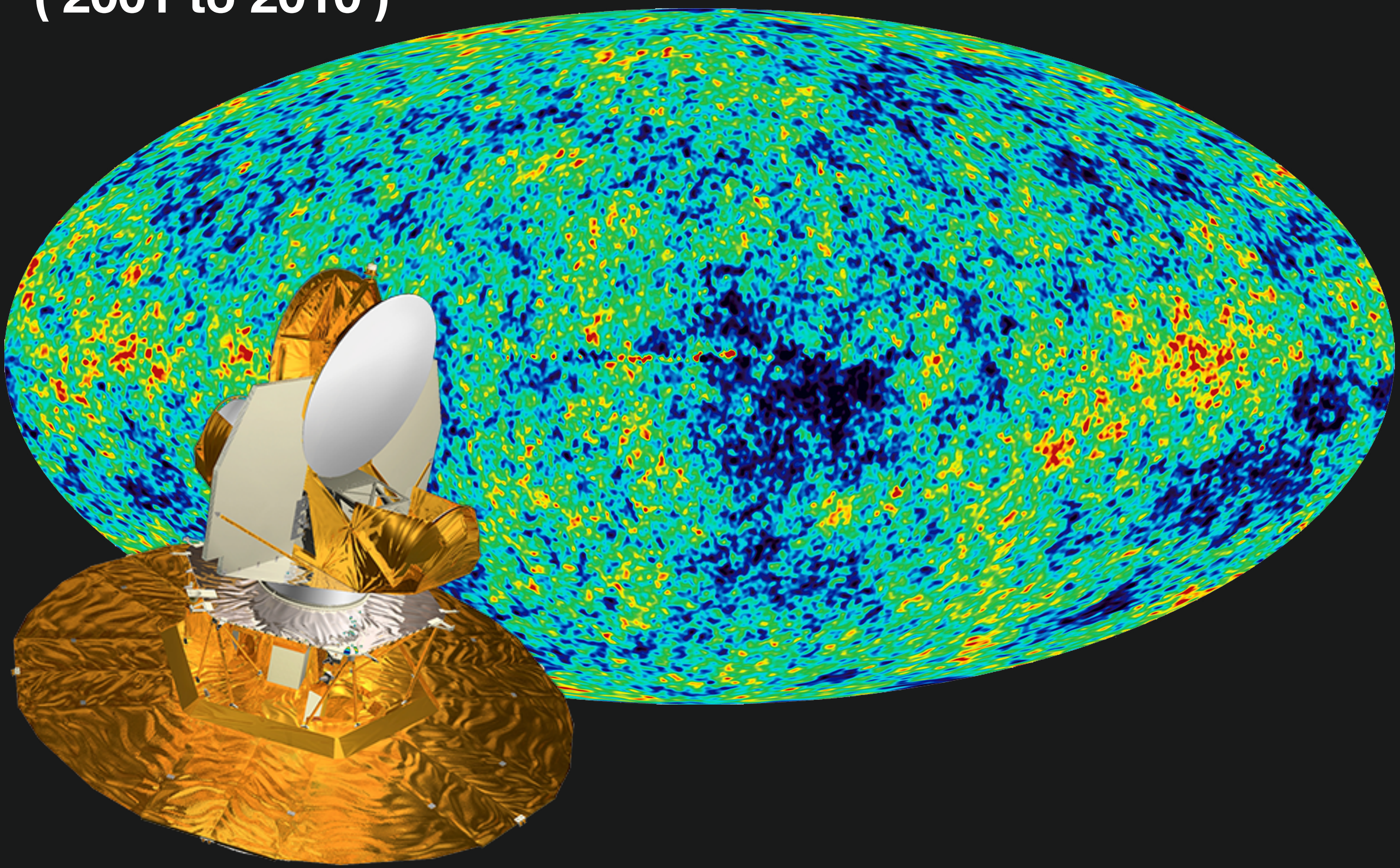
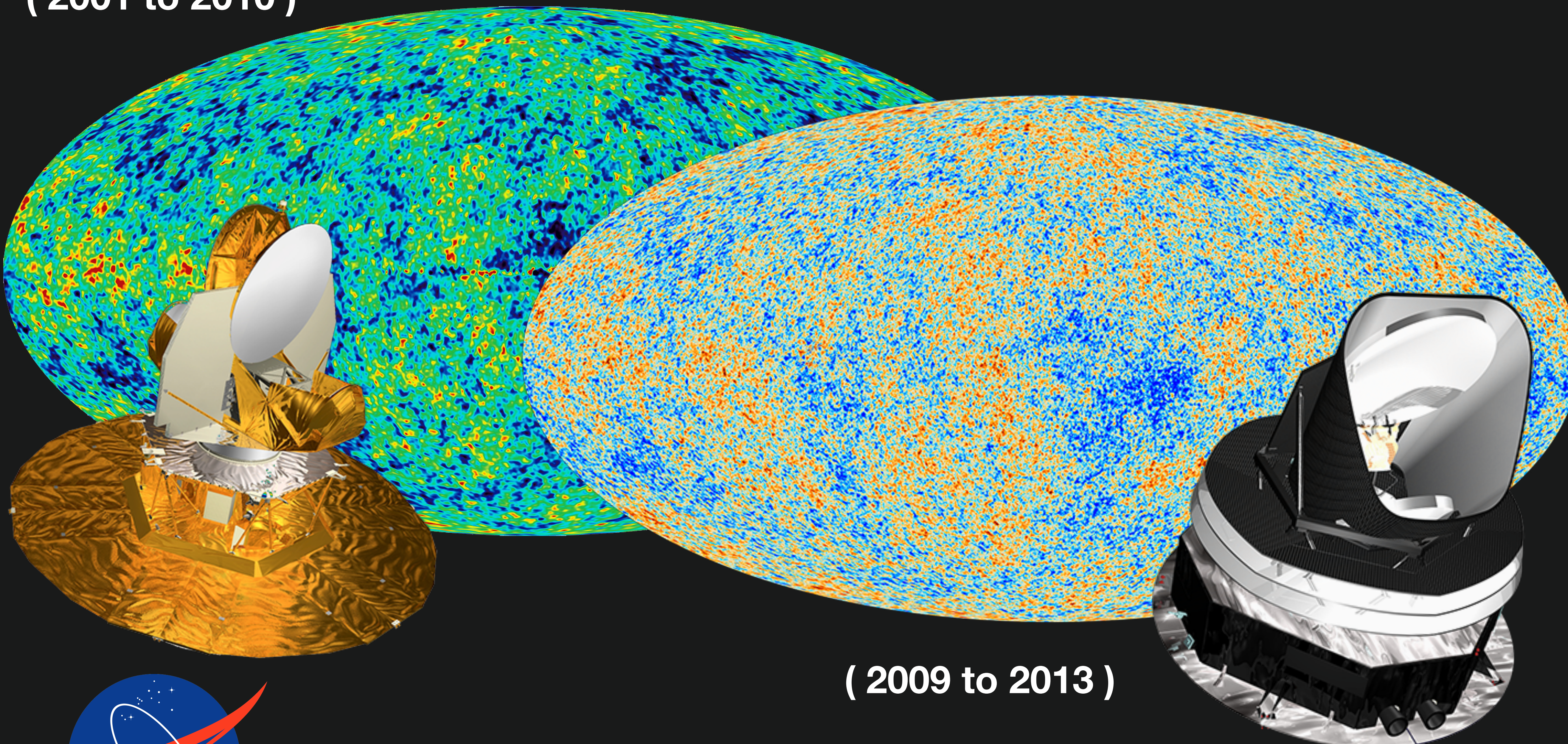


Image: ESA and NASA

WMAP and Planck

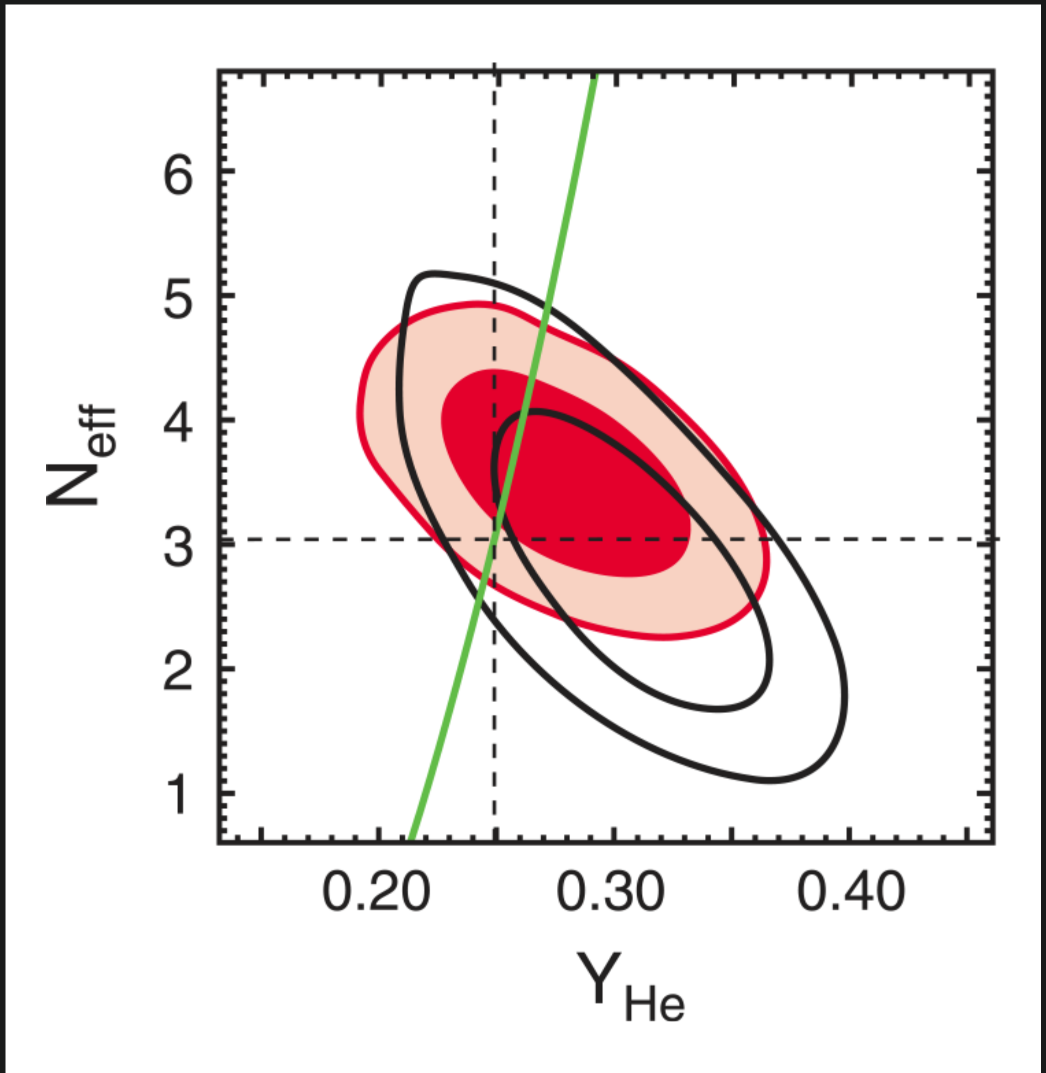
(2001 to 2010)

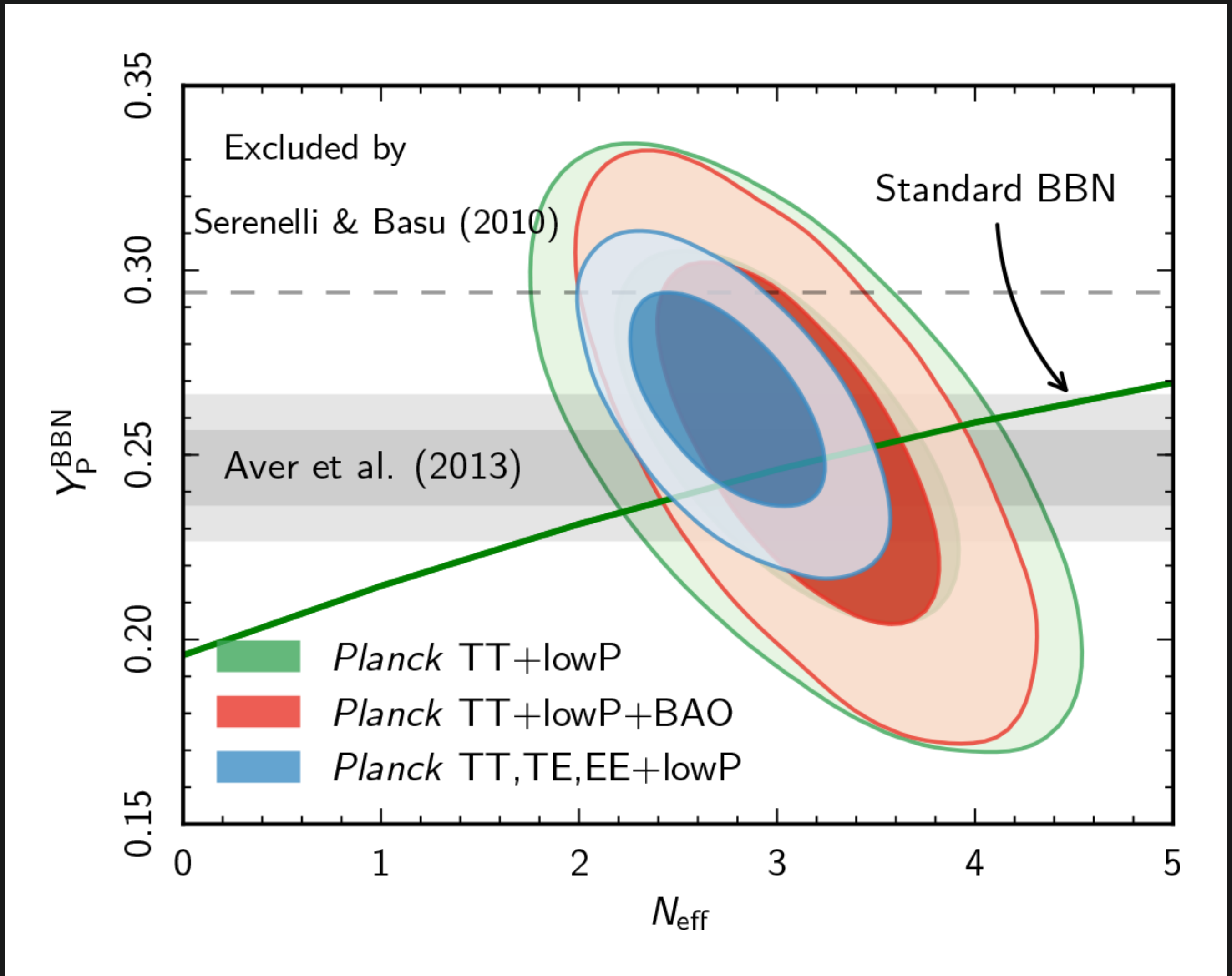


(2009 to 2013)

Image: ESA and NASA

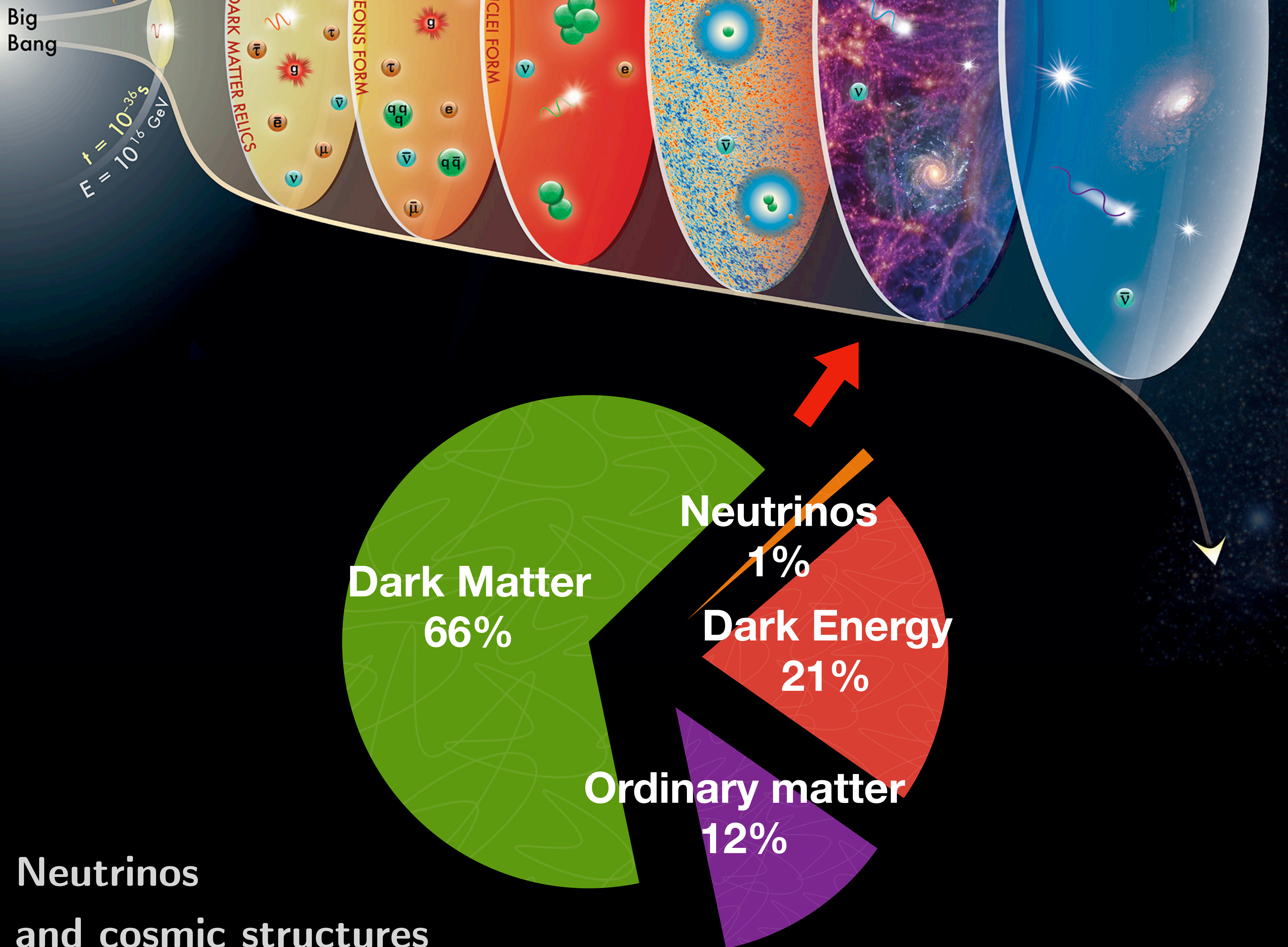
Indirect detection of the neutrino background



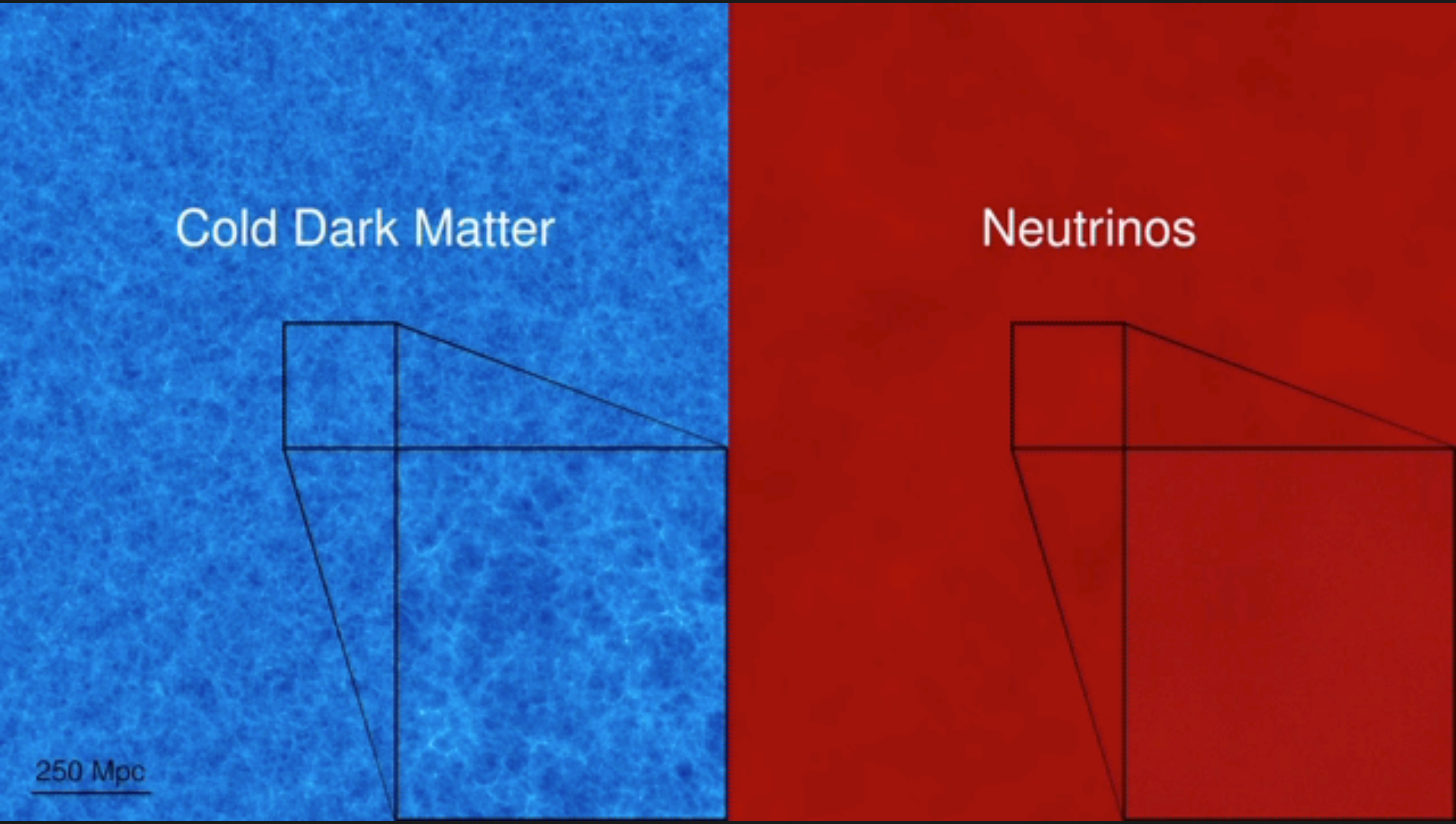


WMAP

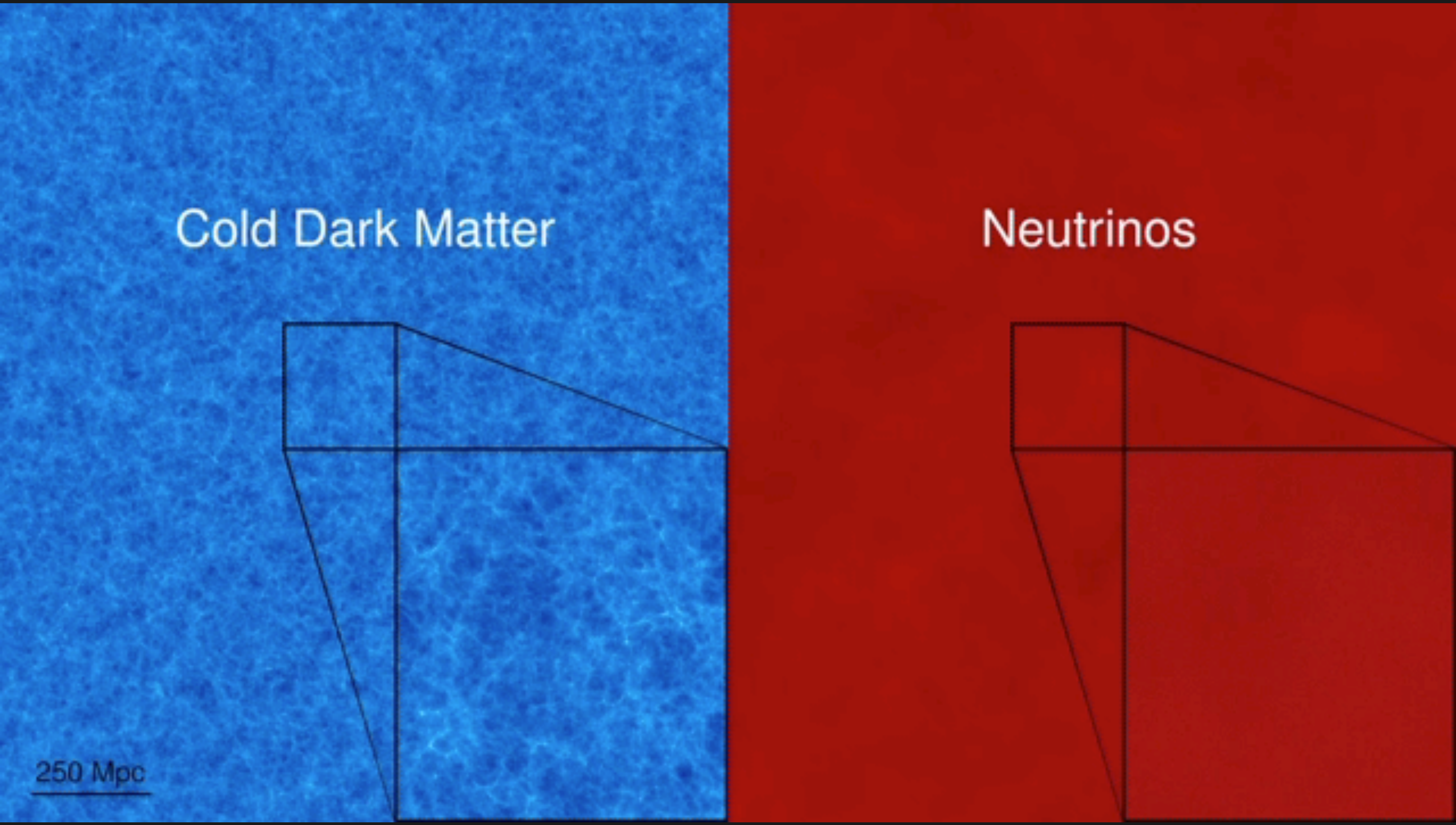
Planck



Neutrinos and cosmic structures



Video: TianNu Simulation Project Team



Video: TianNu Simulation Project Team

Massive neutrino free streaming

$$\lambda_{\mathrm{FS}}(t) \sim \frac{v_{\mathrm{th}}}{H}$$

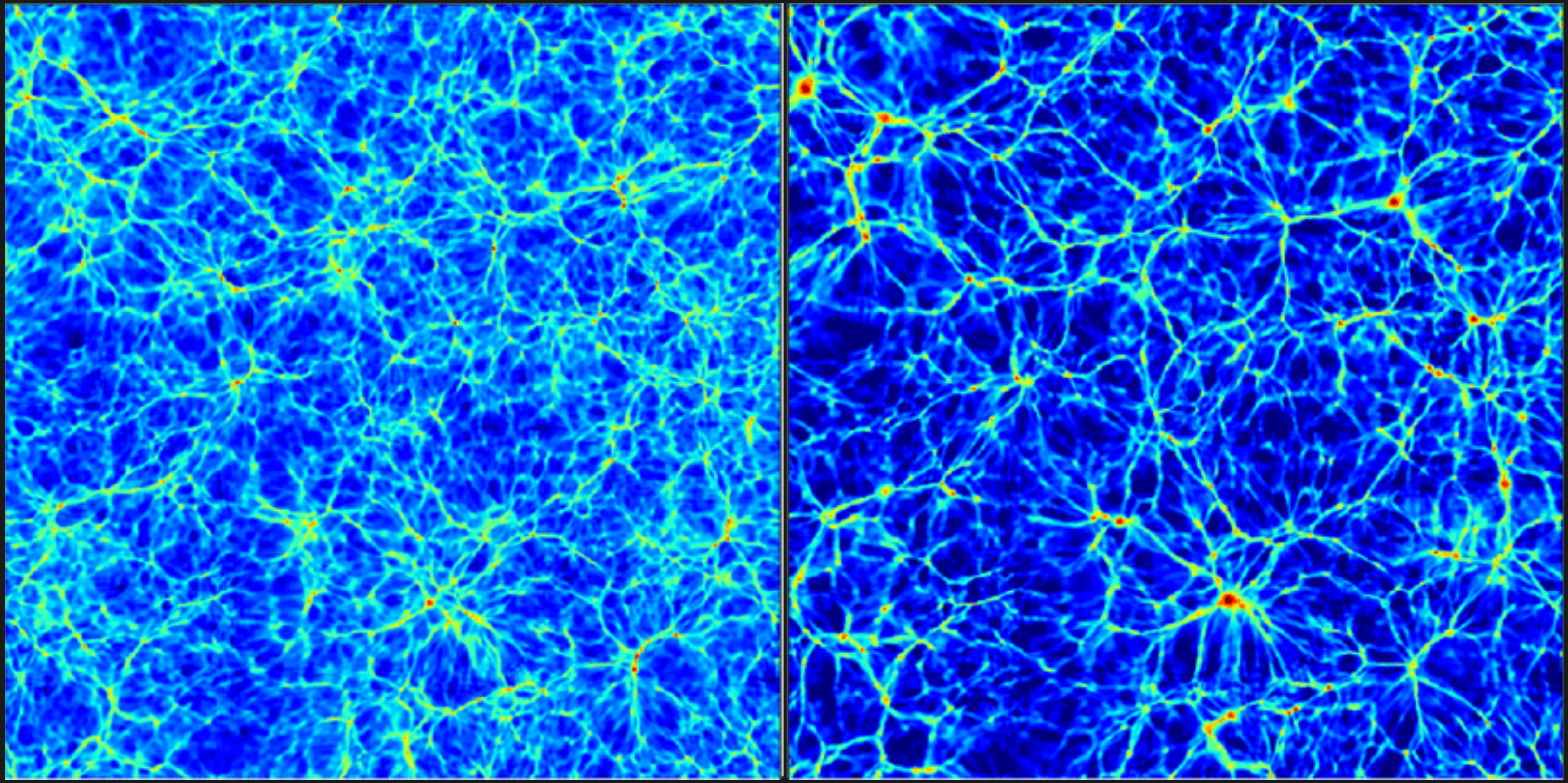
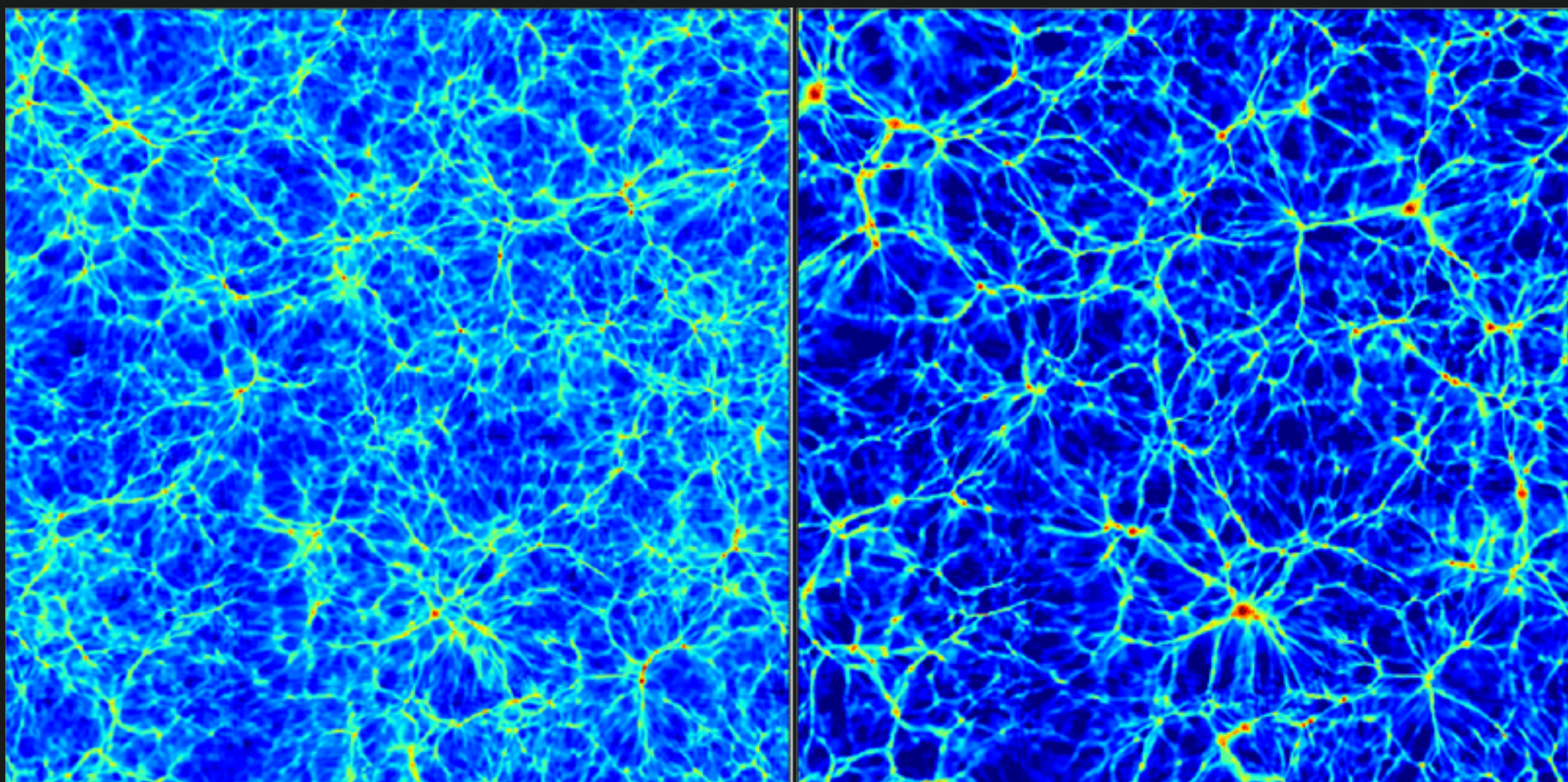


Image: Agarwal and Feldman

Massive neutrino free streaming

$$\lambda_{\mathrm{FS}}(t) \sim \frac{v_{\mathrm{th}}}{H}$$

with neutrinos **without neutrinos**



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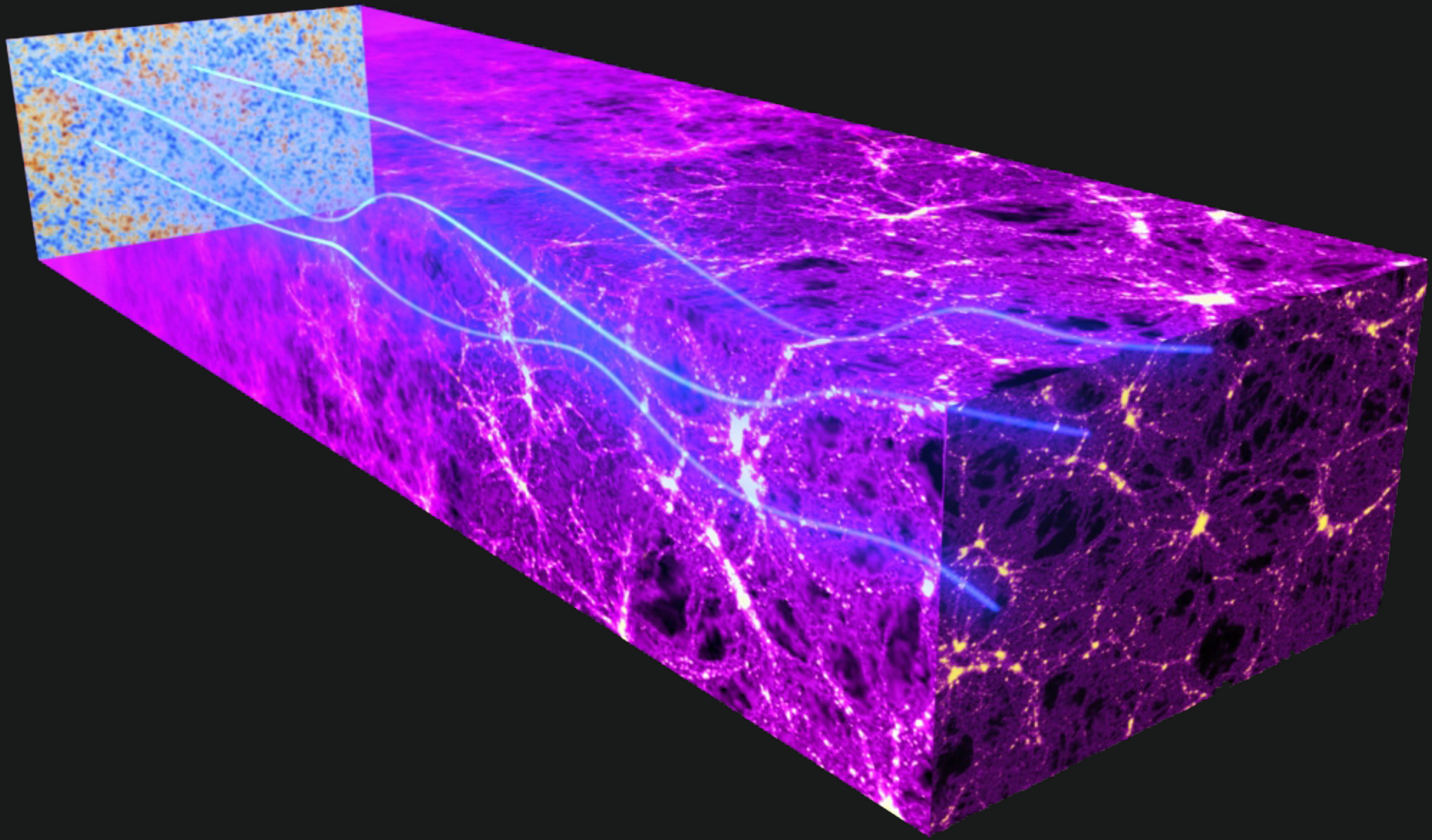
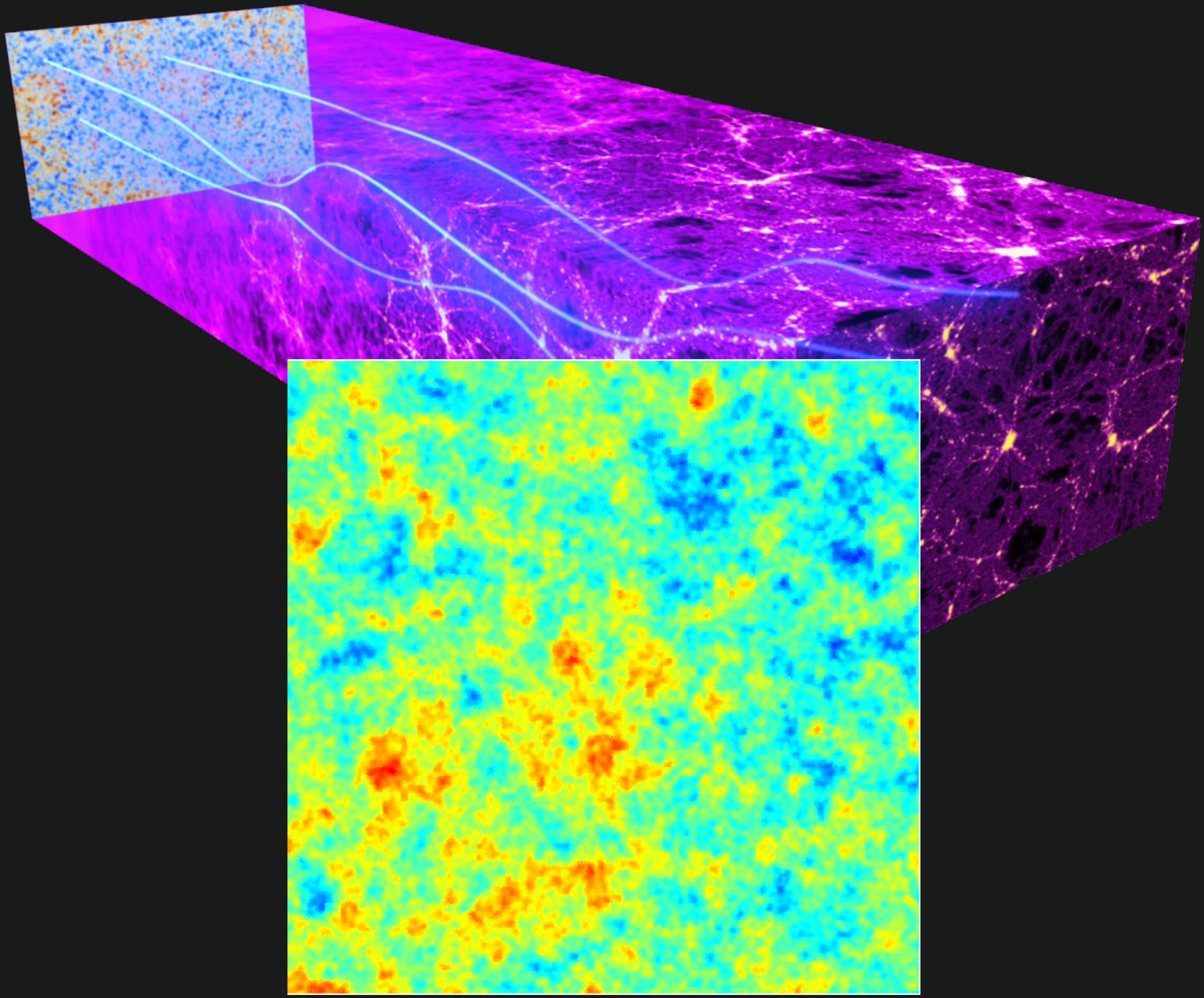


Image: ESA and Simulating weak lensing on CMB maps, S. Basak



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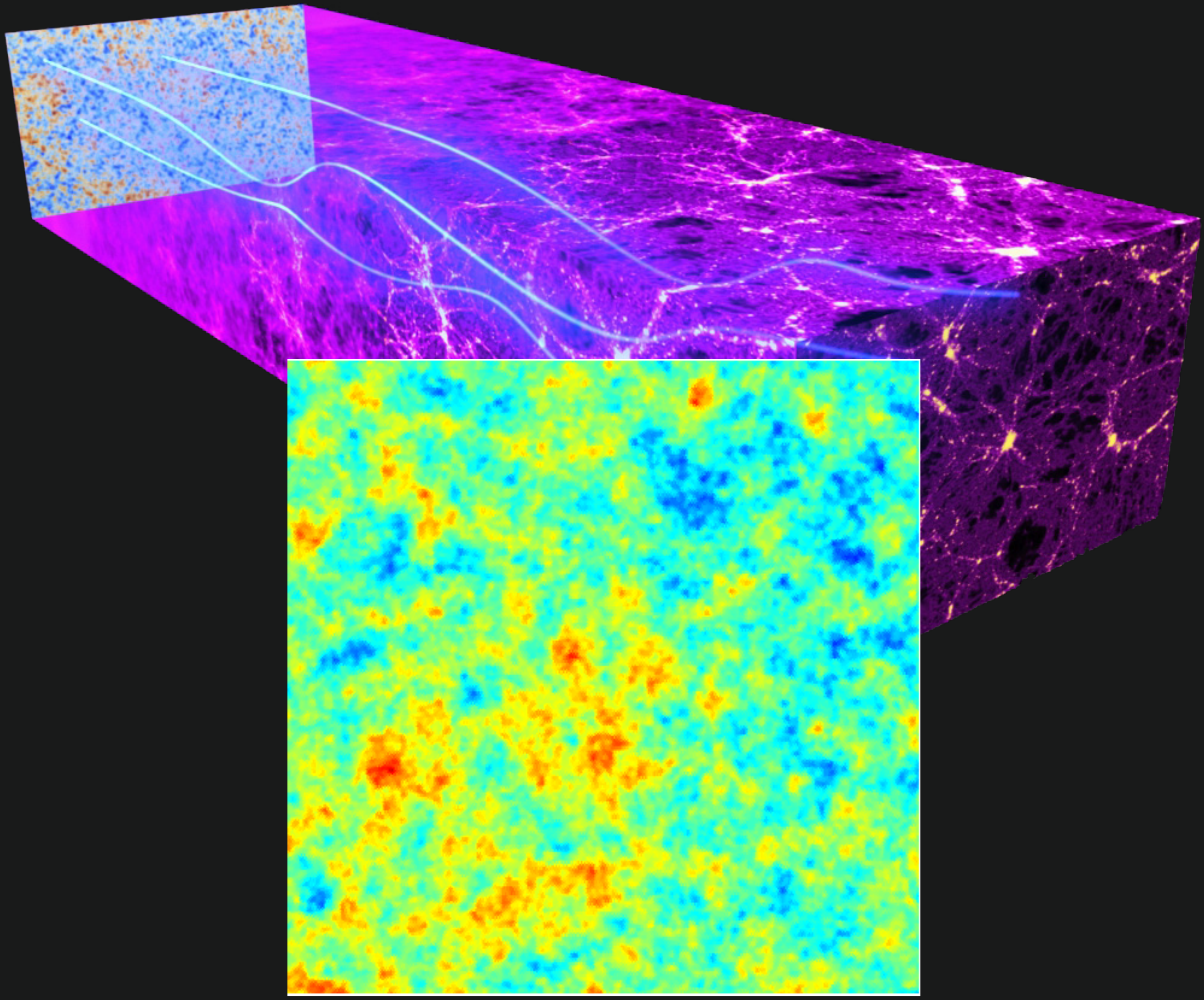

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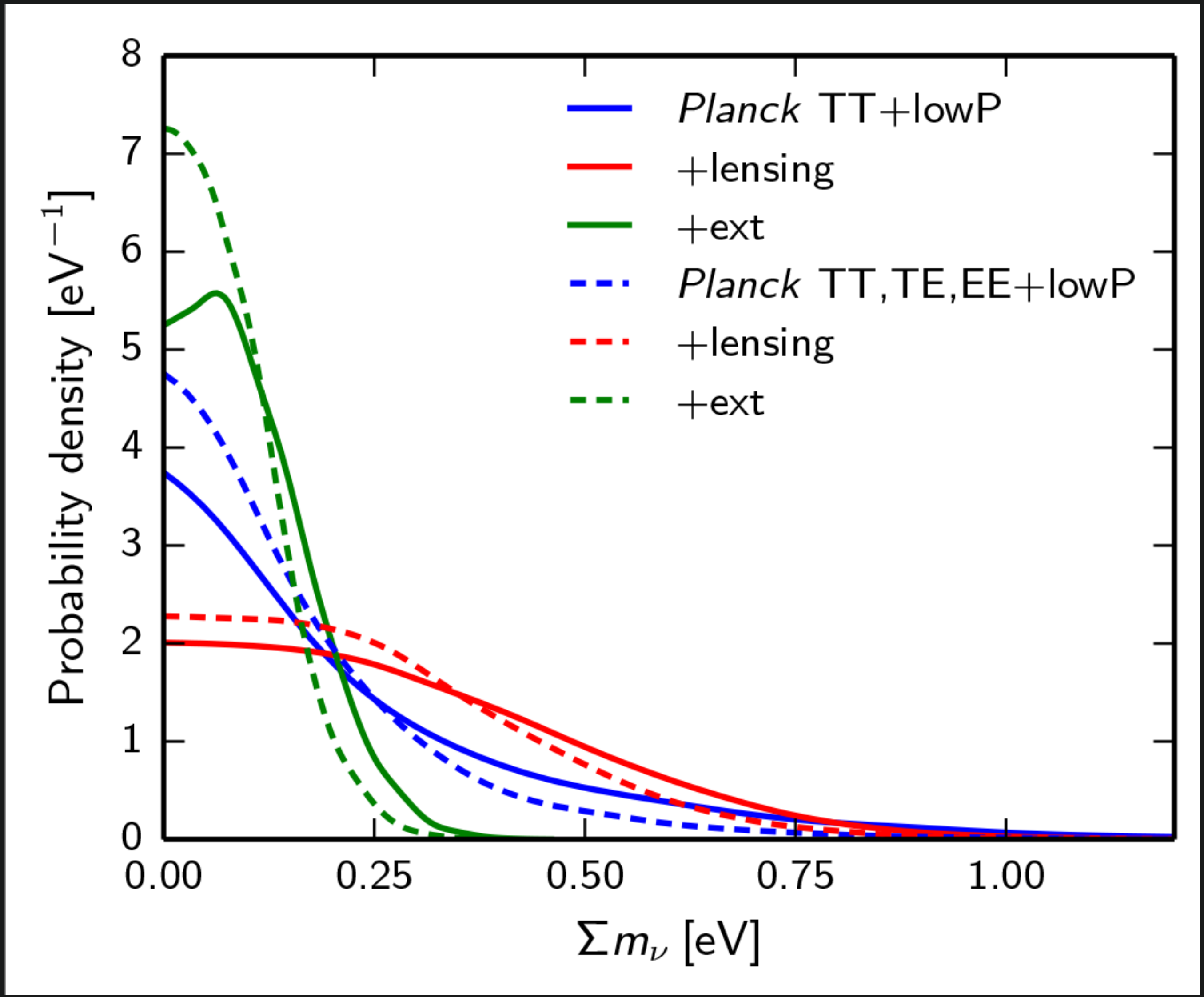
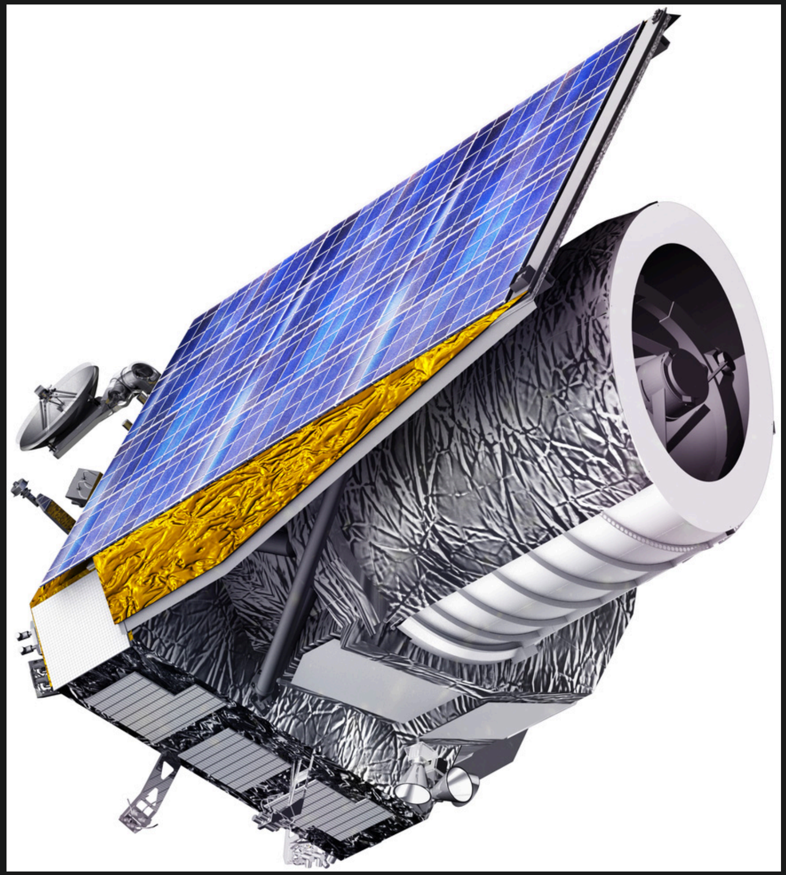
Constraints on the neutrino mass from Cosmology

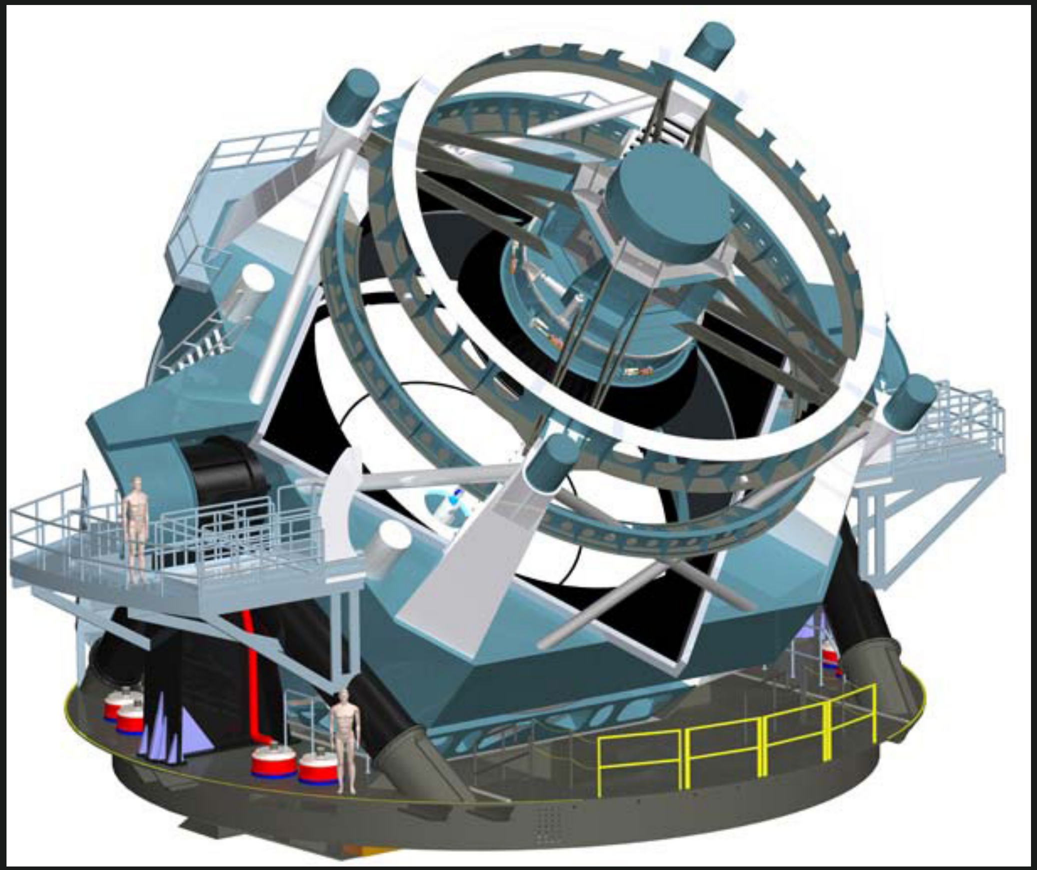


$$\Sigma_\nu m_\mu < 0.2 - 0.6 \text{ eV}$$

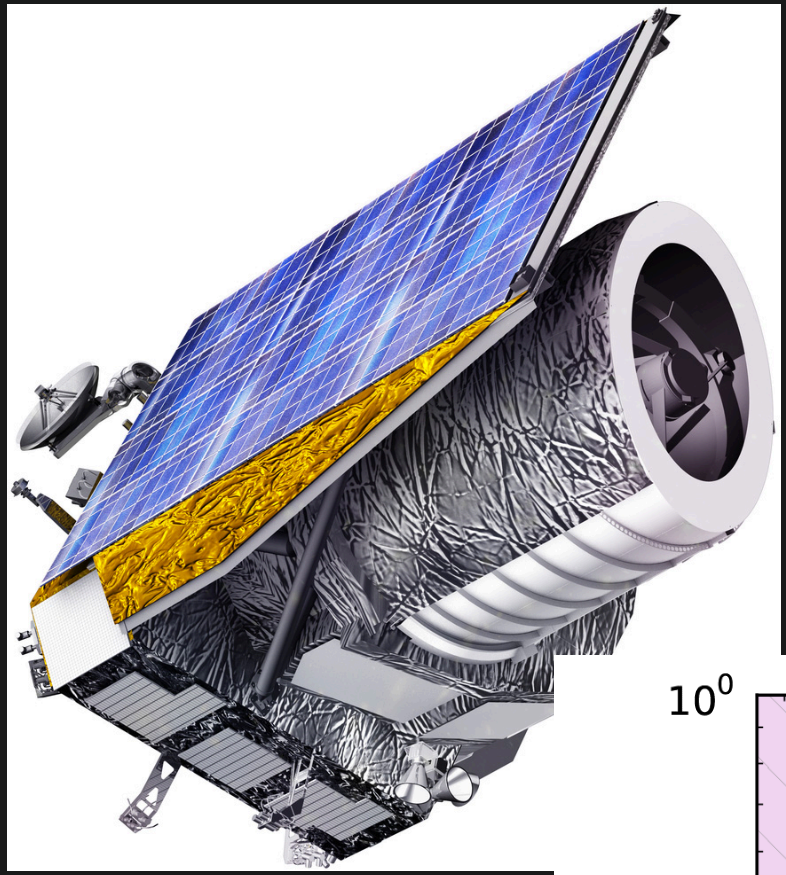
Image: Planck Satellite



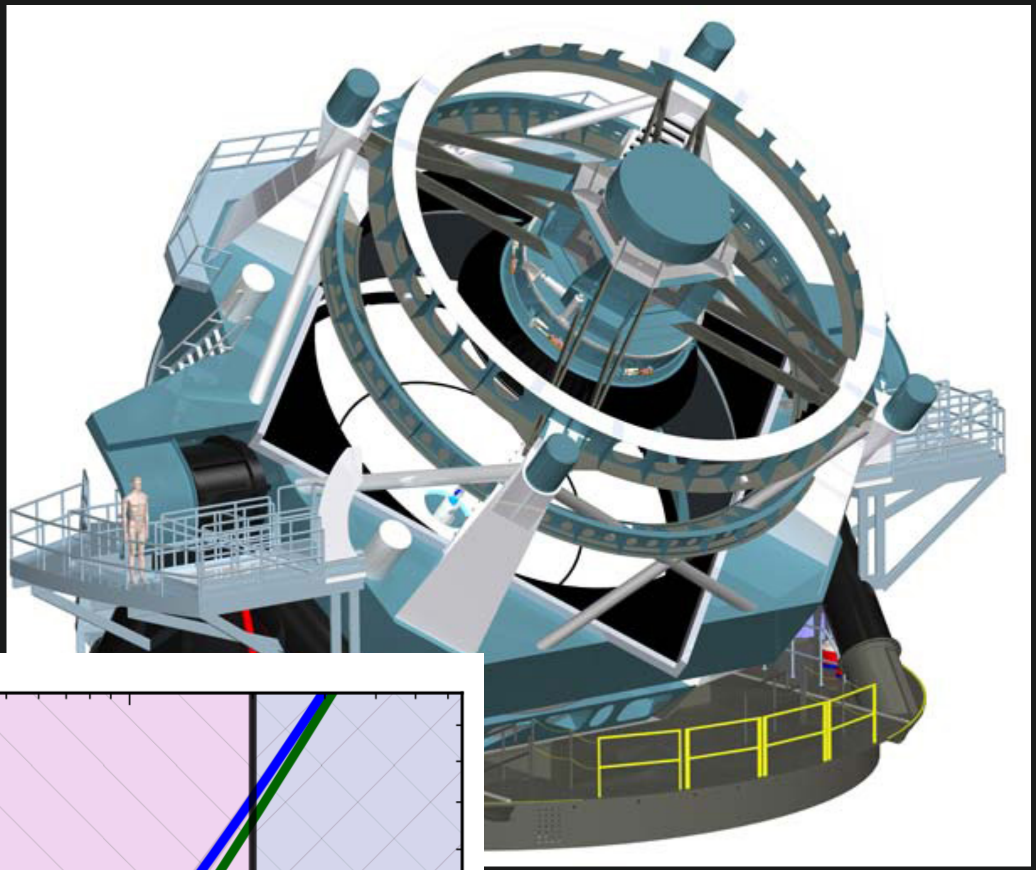
Euclid



LSST



Euclid



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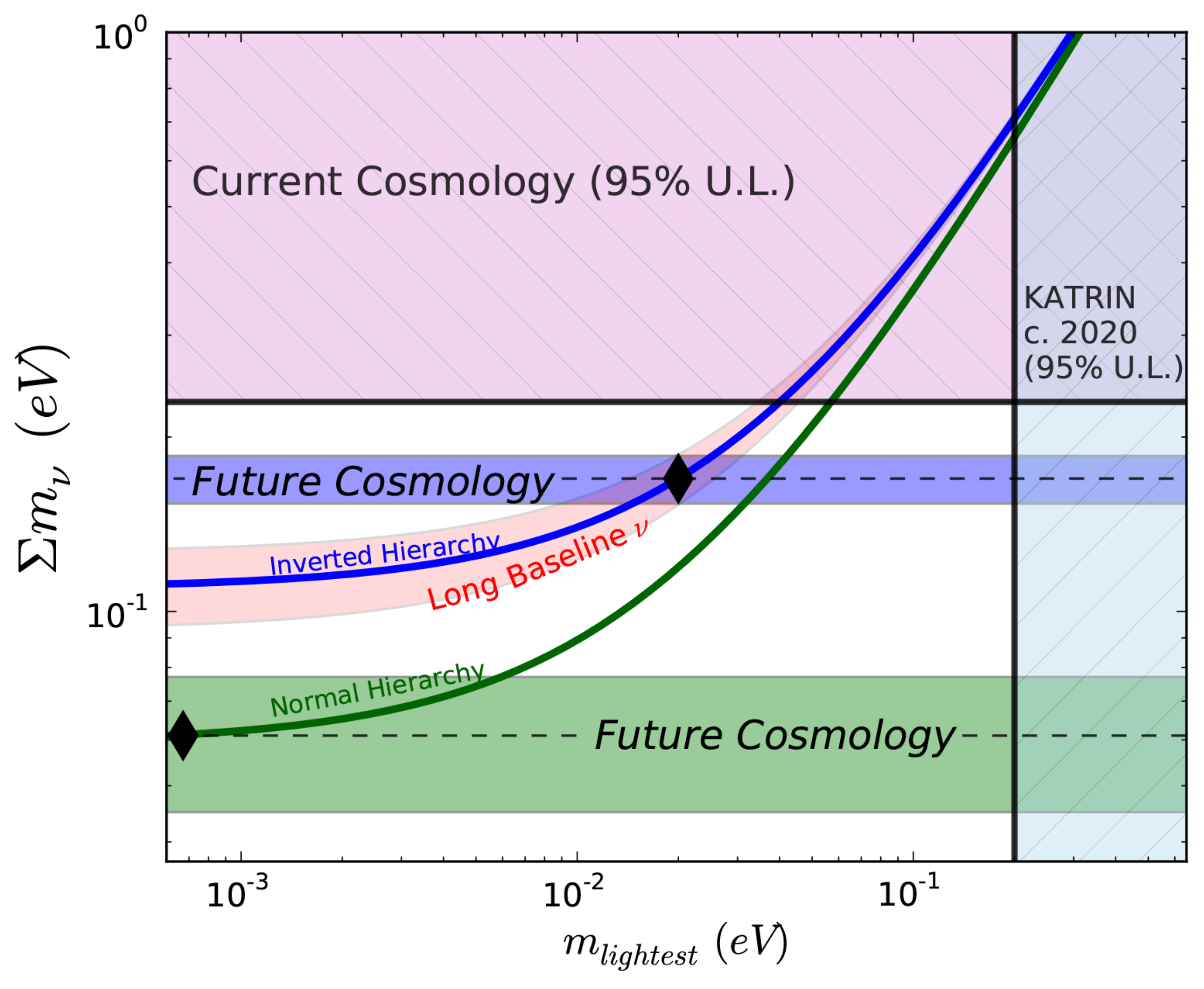

+ many others...

Image: Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure, K.N. Abazajian et al.

Thank You!

Image: Logarithmic map of the observable universe, Pablo Carlos Budassi