IJS

Univerza *v Ljubljani*
Fakulteta za *matematiko in fiziko*

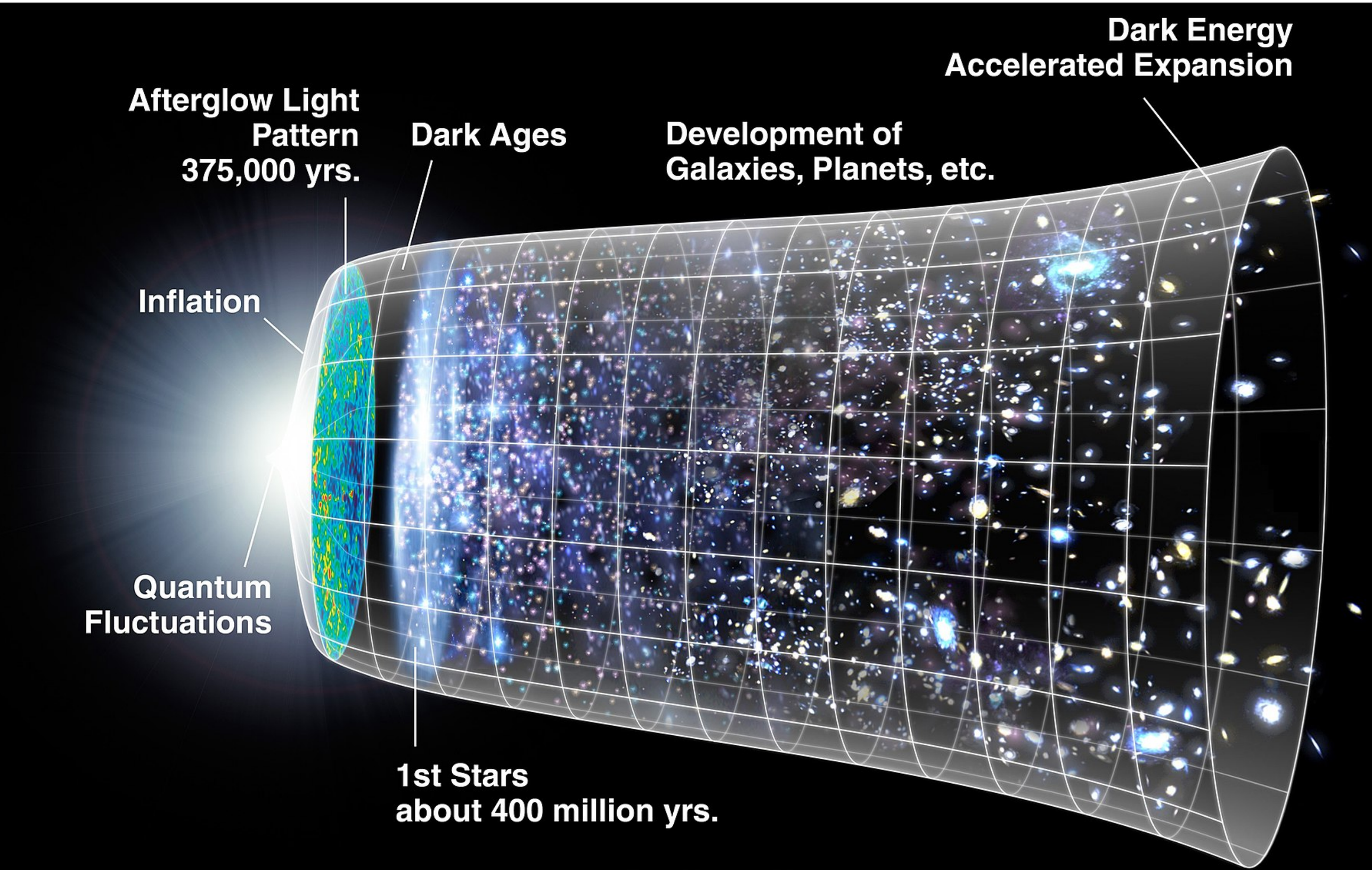
Zgodnje vesolje in Temna snov

Miha Nemevšek
(IJS & FMF)

CERN Slovenian Teacher Programme

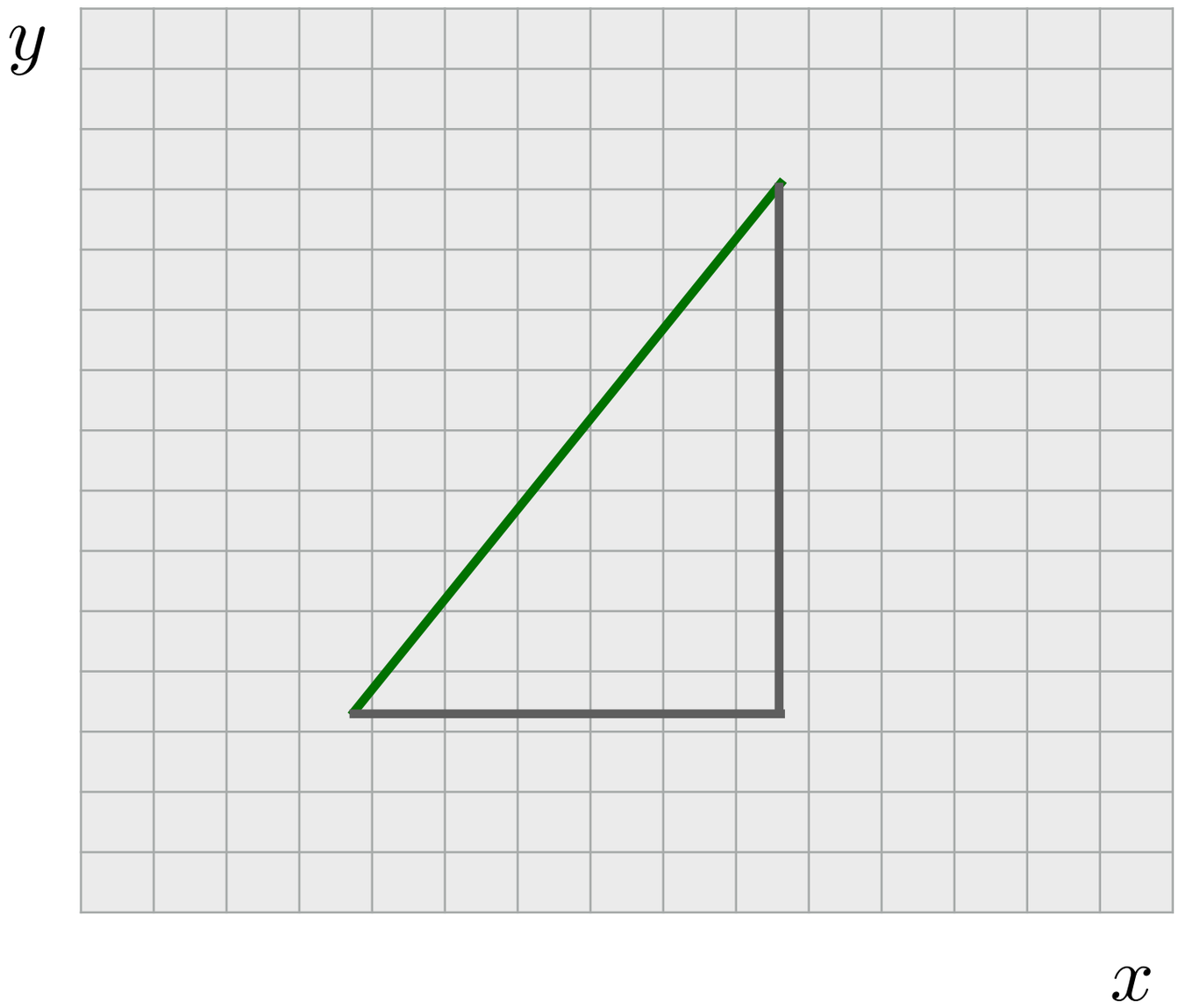
CERN, 5th October 2023

Zgodovina vesolja



Prostor

Navaden (Evklidski) prostor



Klasična mehanika

$$2D \quad d^2 = x^2 + y^2$$

$$3D \quad d^2 = x^2 + y^2 + z^2$$

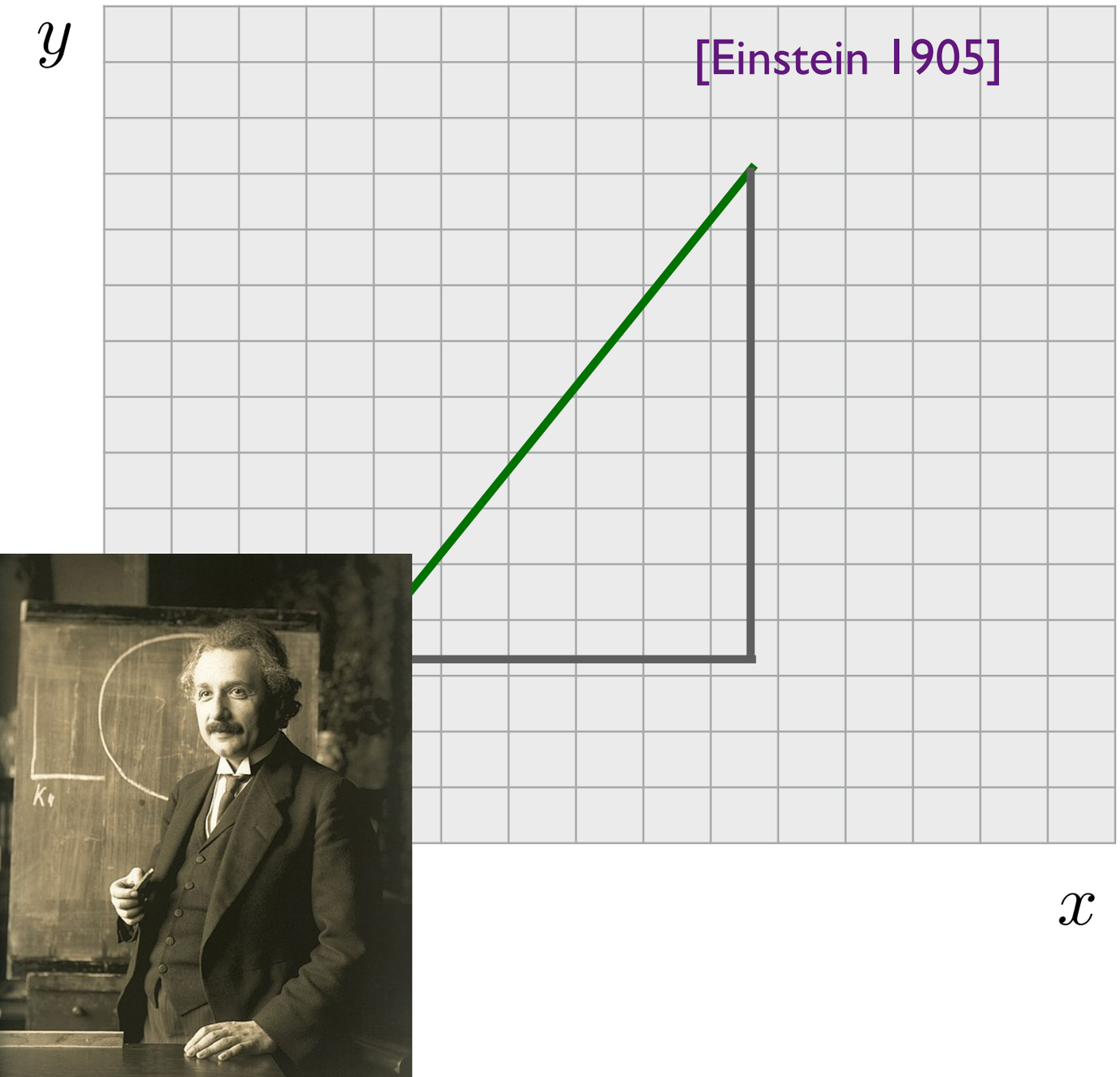
Hitrosti se seštevajo

$$\vec{v} = \vec{v}_1 + \vec{v}_2$$

Prostor se ne spreminja

Prostor-čas

Manj-navaden (Minkowski) prostor



Posebna teorija relativnosti

$$2D \quad d^2 = x^2 + y^2$$

$$3D \quad d^2 = x^2 + y^2 + z^2$$

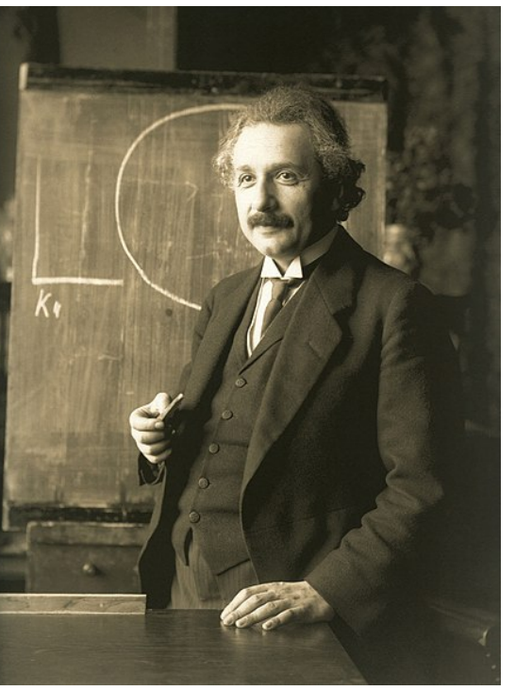
$$3 + 1D$$

$$d^2 = ct^2 - (x^2 + y^2 + z^2)$$

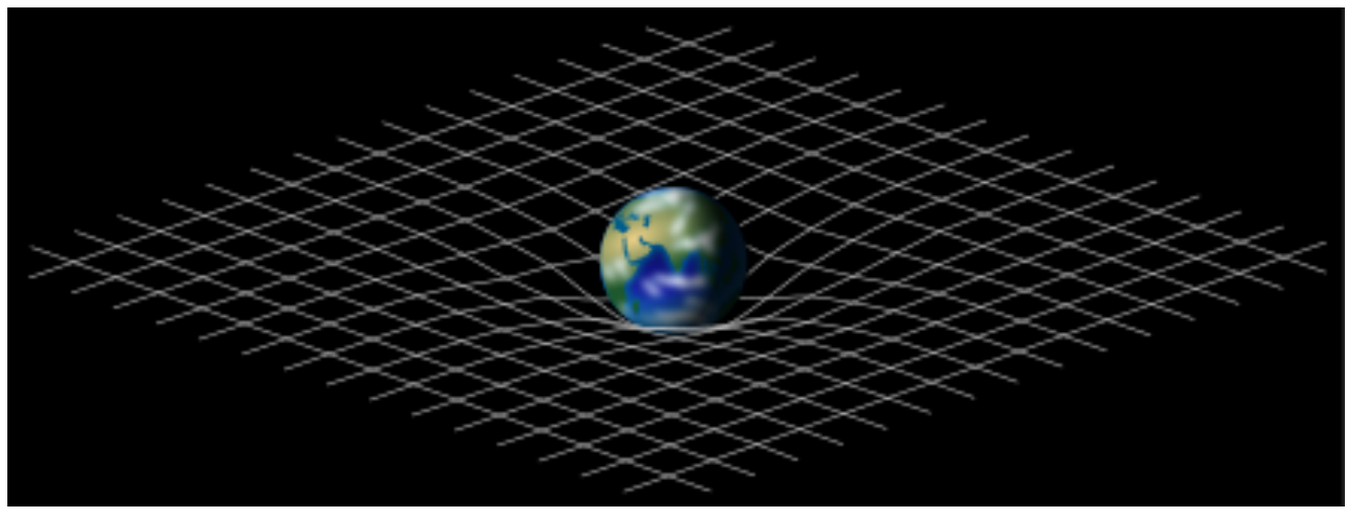
Hitrost svetlobe konstanta in maksimalna

Prostor se ne spreminja, je raven

Dinamičen prostor-čas



Splošna teorija relativnosti [Einstein 1915]



$$d^2 = f(ct, x, y, z)$$

Prostor in čas so prepleteni (planeti, črne luknje…)

Kako to vpliva na razumevanje našega celotnega vesolja? [FLRW 20-30s]

$$ds^2 = dt^2 - a(t)^2 \left(dx^2 + dy^2 + dz^2\right)$$

Širjenje vesolja

Friedman-Lemaitre-Robertson-Walker

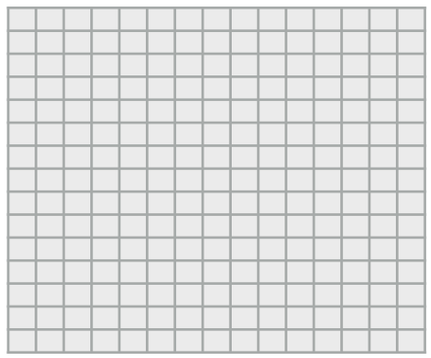
$$ds^2 = dt^2 - a(t)^2 \left(dx^2 + dy^2 + dz^2\right)$$

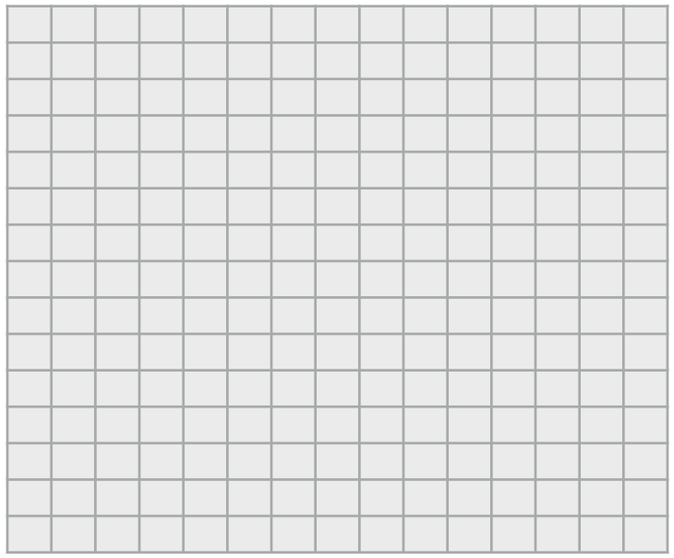
$a(t)$ skalirni faktor

Homogeno in izotropno vesolje na velikih skalah > Mpc

[FLRW 20-30s]

zgodnje vesolje





$a(t \ll t_0) \ll 1$

$a(t < t_0) < 1$

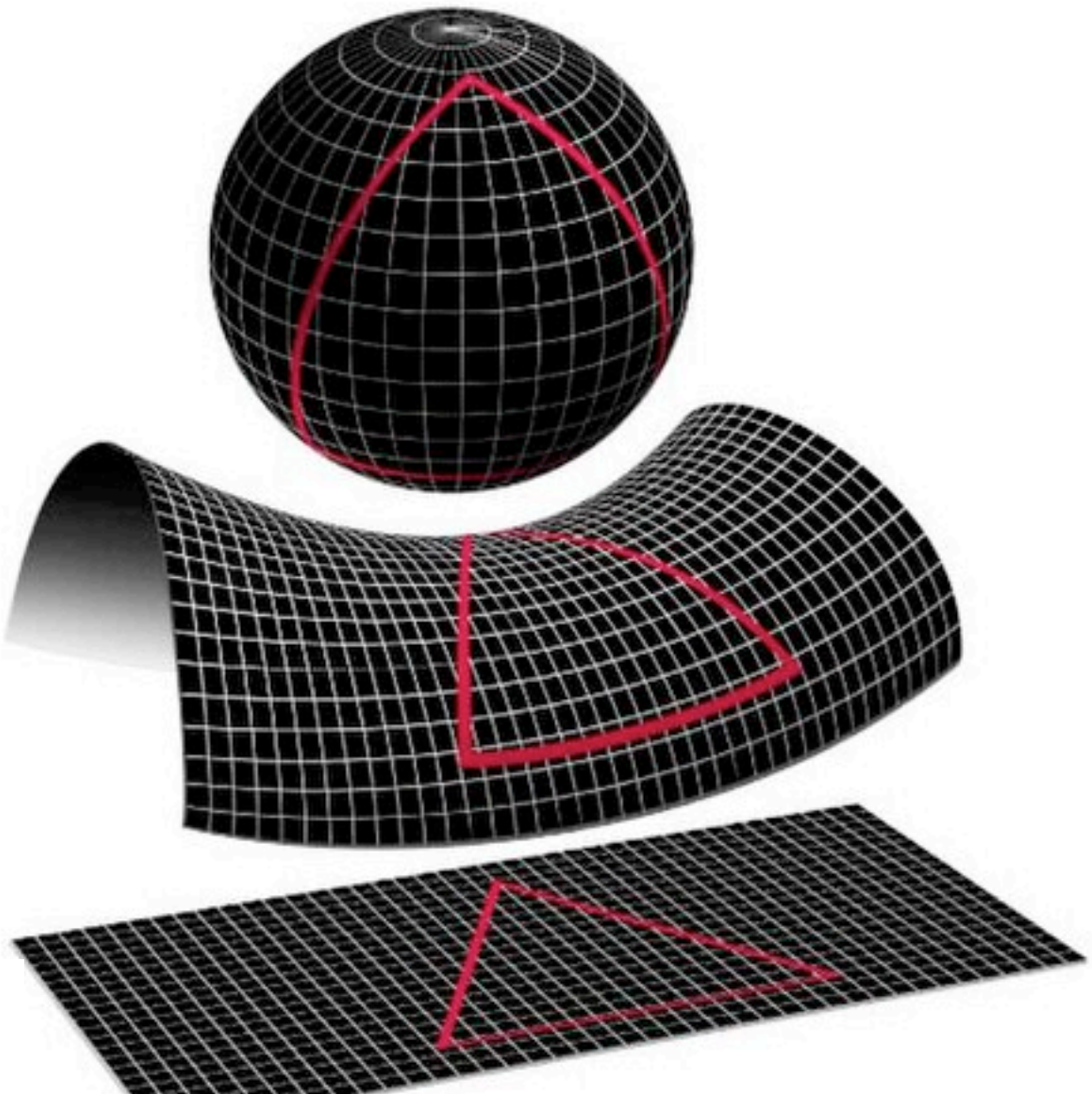
$a(t_0) = a_0 = 1$

Širjenje vesolja

Ukrivljenost vesolja [FLRW 20-30s]

$$ds^2 = dt^2 - a(t)^2 \left(dx^2 + dy^2 + dz^2\right)$$

$$= dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2\right)$$



Zaprto $k > 0$

Odprto $k < 0$

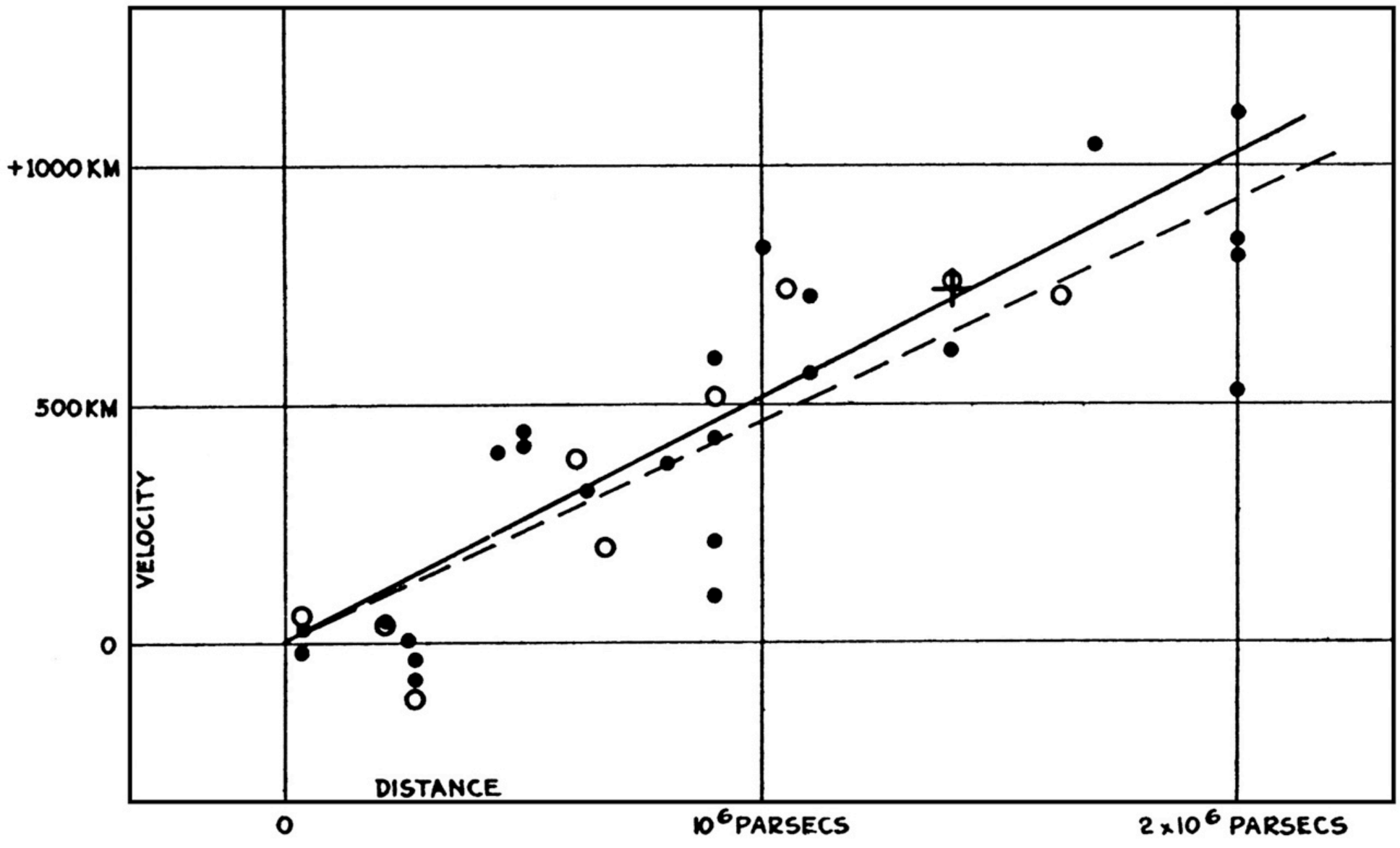
Ravno $k = 0$

Meritve

Hubblov diagram

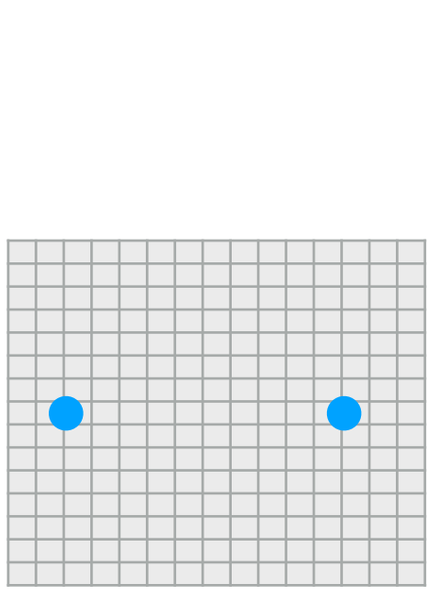
Širjenje vesolja [Hubble ’29]

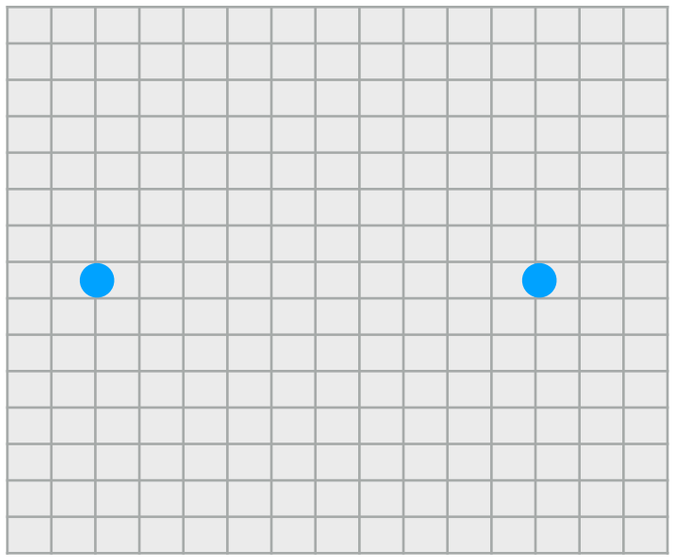
Hubblov parameter $$H = \frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{\dot{a}}{a}$$

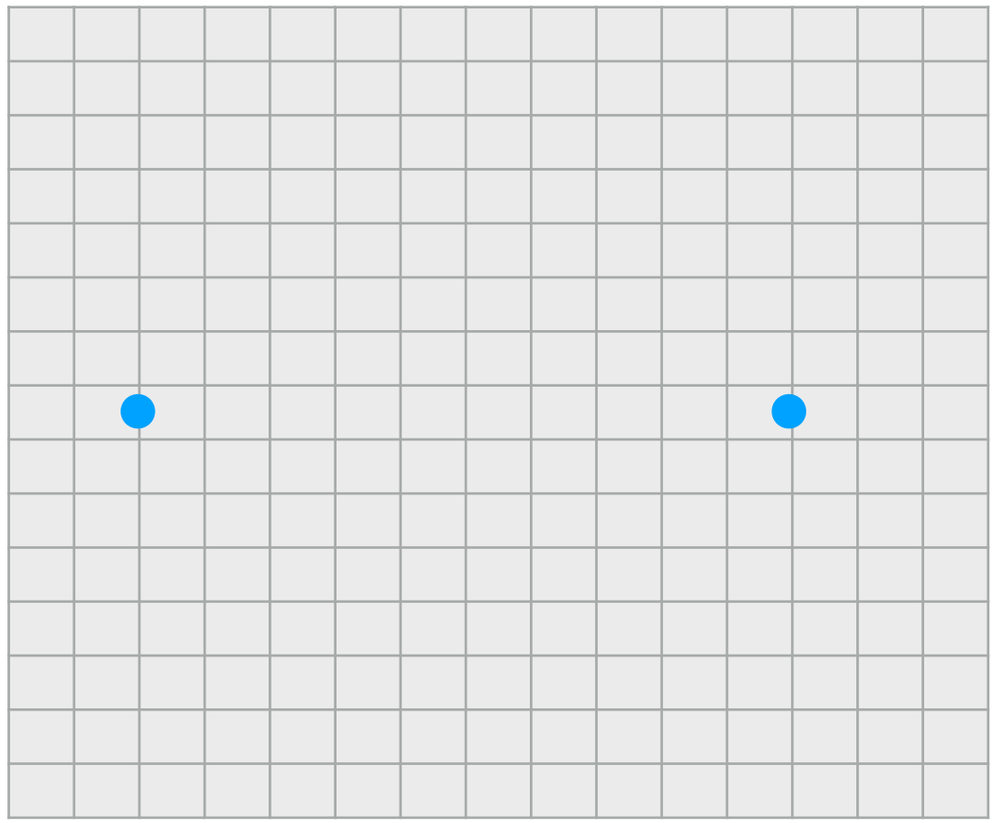


Hubblov parameter

Hitrost zvezd (redshift) je sorazmerna razdalji $v = H_0\, d$



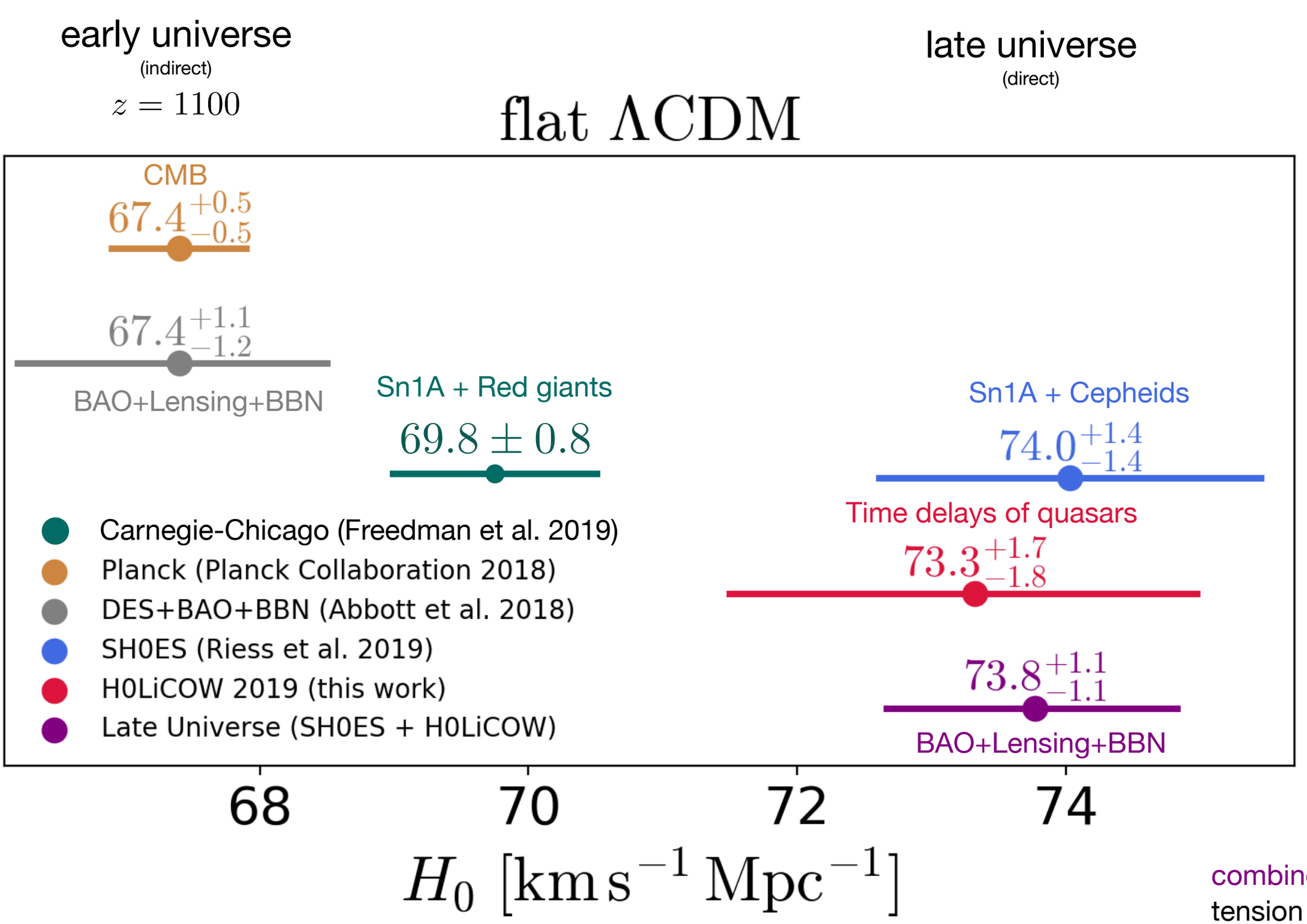




Hubblova konstanta danes

$$H_0 = [68 - 74]\,\frac{\mathrm{km}}{\mathrm{s}}\,\frac{1}{\mathrm{Mpc}} = h \times 100\,\frac{\mathrm{km}}{\mathrm{s}}\,\frac{1}{\mathrm{Mpc}}$$

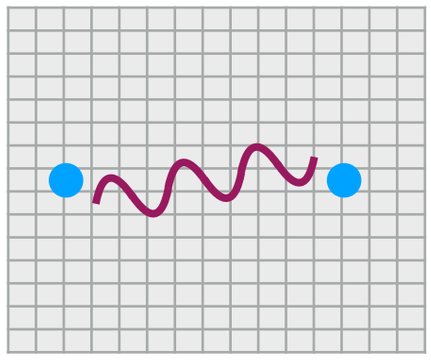
Hubblov parameter

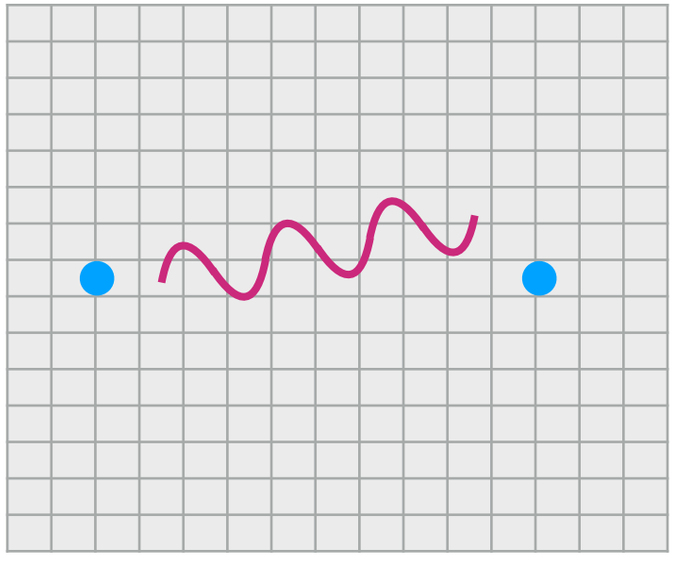


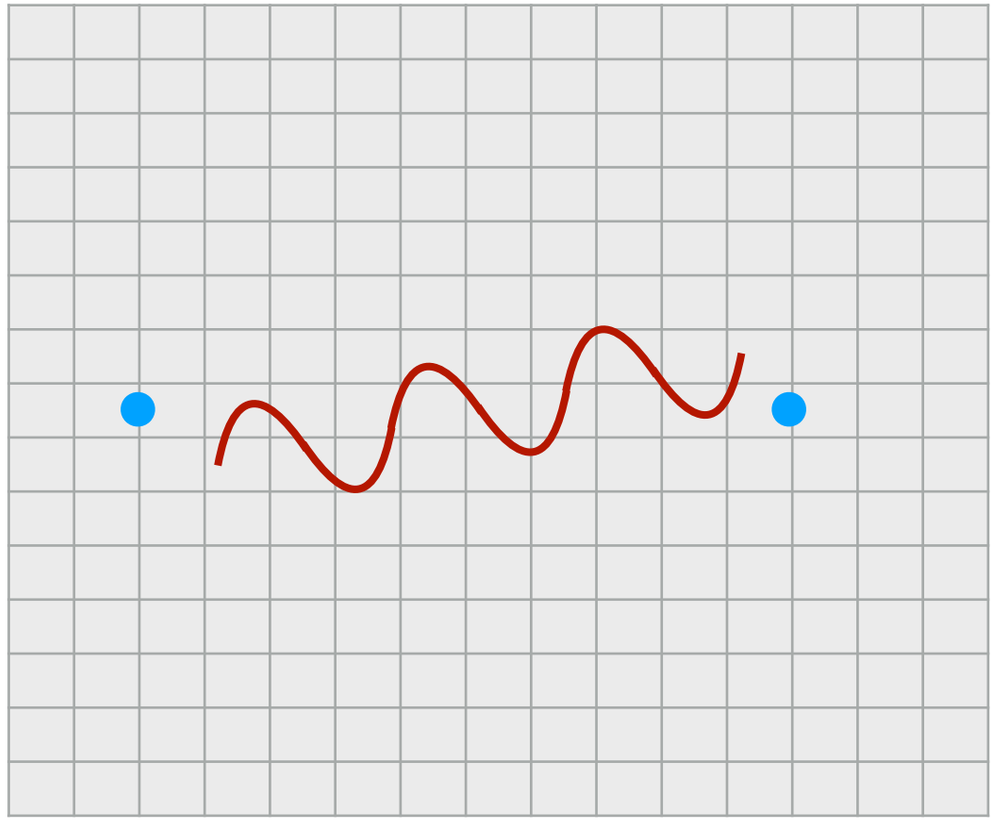
combined in 5.3 sigma tension with Planck

Rdeči premik

Valovna dolžina se raztegne (redshift), premik v rdeči IR del spektra





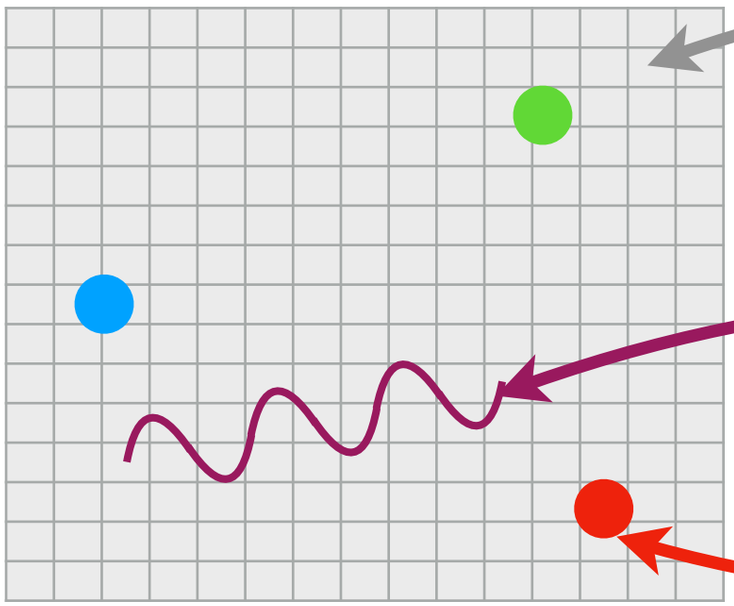


$$a(t) = \frac{1}{1+z} = \frac{\lambda'}{\lambda}$$

Svetloba (npr. zvezd) se razteza in energija se manjša, valovna dolžina se veča

Einsteinova enačba

Prostor-čas in vsebina vesolja so povezani



Prostor-čas opisuje metrika (FLRW) $G_{\mu\nu}$

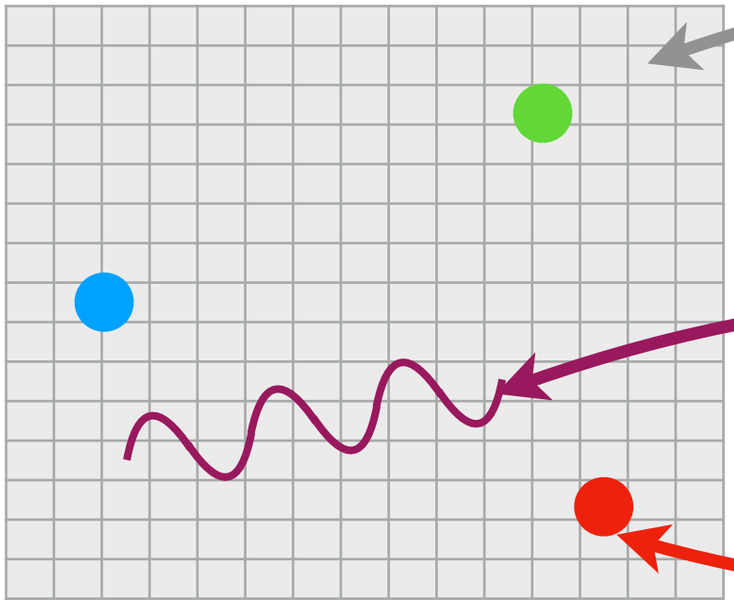
Vsebino vesolja opiše tenzor energije $T_{\mu\nu}$

$$G_{\mu\nu} = 8\pi\, G_N T_{\mu\nu}$$

John Wheeler: "Spacetime tells matter how to move; matter tells spacetime how to curve."

Einsteinova enačba

Prostor-čas in vsebina vesolja so povezani



Prostor-čas opisuje metrika (FLRW) $G_{\mu\nu}$

Vsebino vesolja opiše tenzor energije $T_{\mu\nu}$

$$T^{\mu\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

$\rho \ldots$ gostota energije

$p \ldots$ pritisk

Tip snovi

Materija

Sevanje

+ eksotika

Kozmološka konstanta

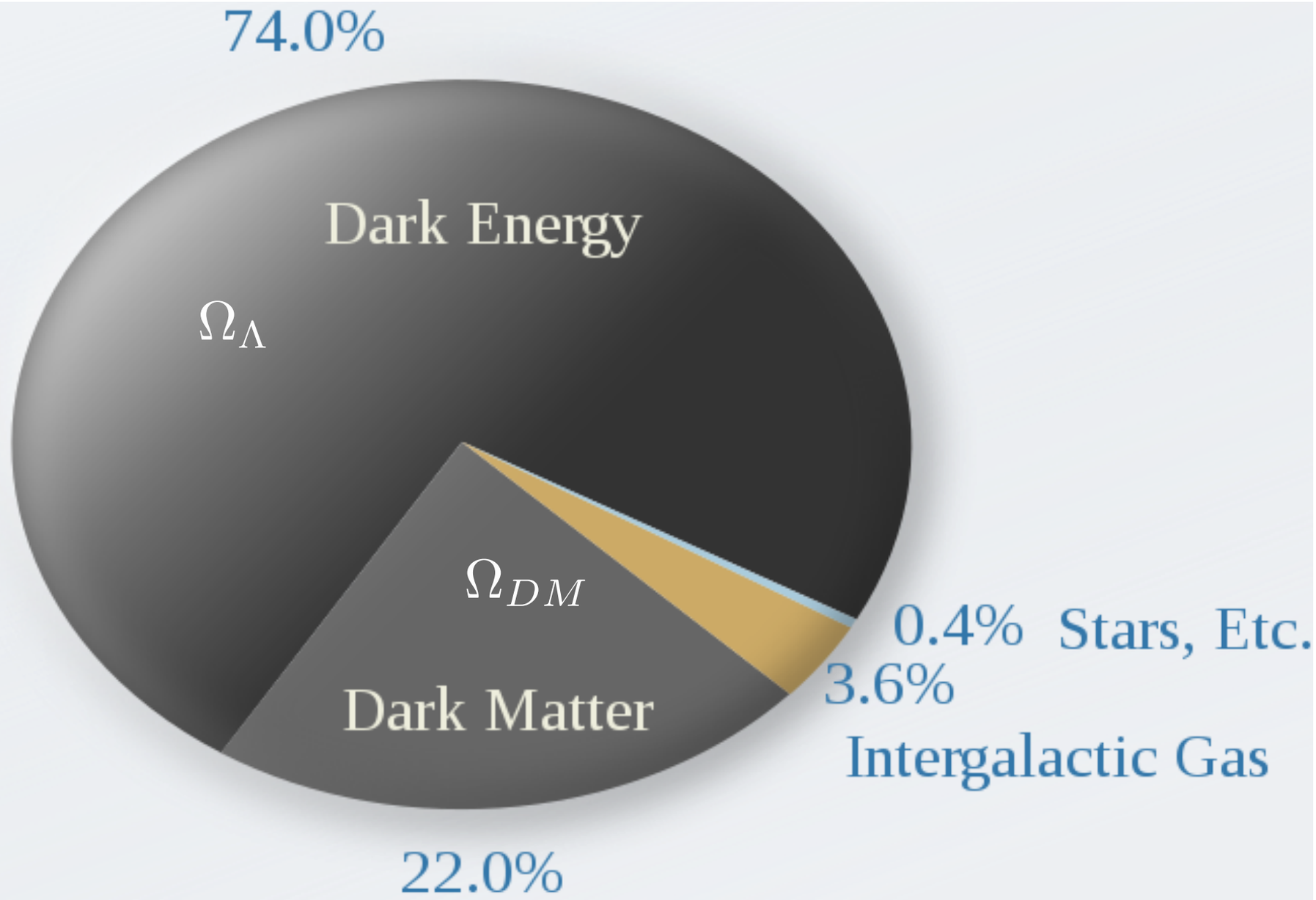
Energija vesolja

$$\Omega_x = \frac{\rho_x}{\rho_{\rm crit}}$$

$$\Omega_{\rm tot} = \Omega_\Lambda + \Omega_m + \Omega_\gamma + \dots$$

Za ravno vesolje, k=0

$$\Omega_{\rm tot}^{\rm exp} \simeq 1$$



Sevanje

$$\Omega_\gamma = 5 \times 10^{-5}$$

Nevtrini

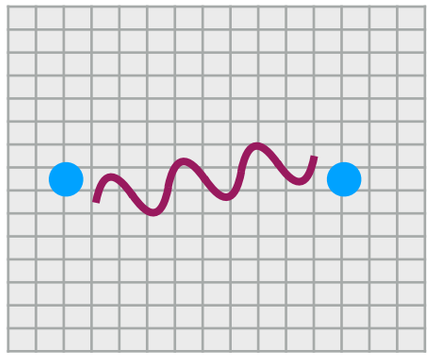
$$\Omega_{C\nu B} \simeq 1.3 \times 10^{-5}$$

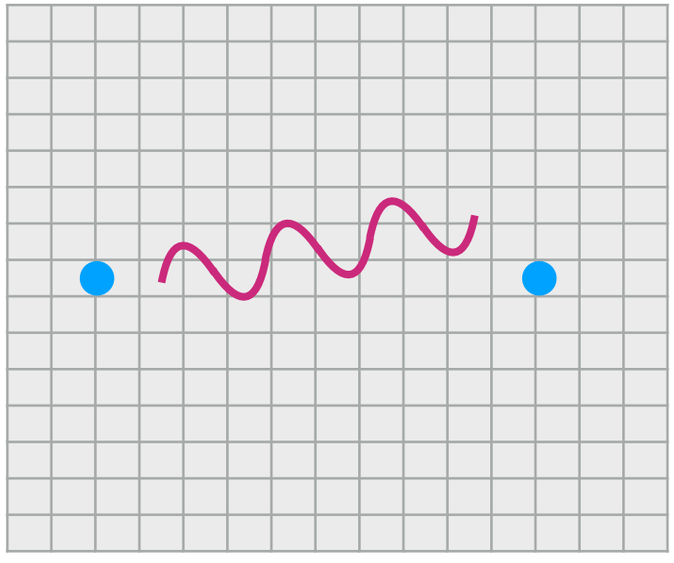
Gravitacijski valovi

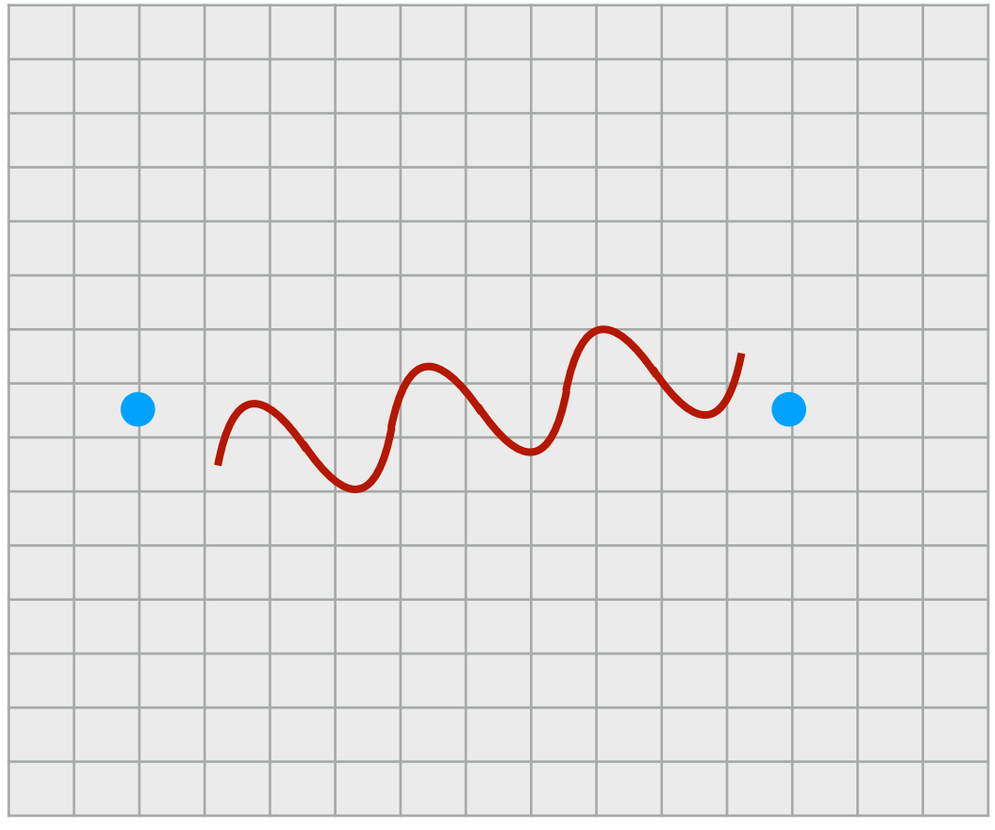
$$\Omega_{GW} \lesssim 10^{-11}$$

Vroče vesolje

Zavrtimo čas nazaj, vesolje se krči in energija fotonov se veča







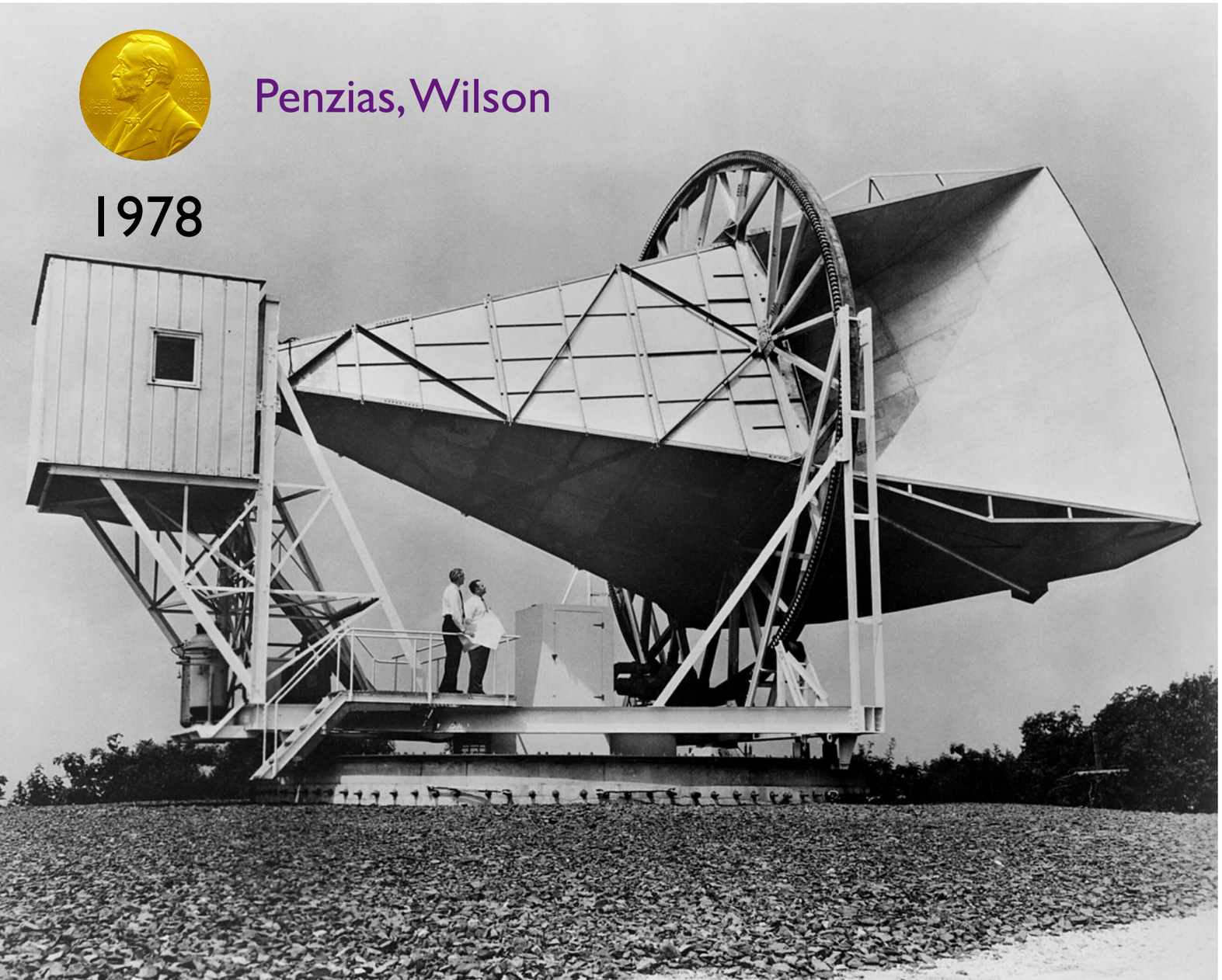
Fotoni so bili nekoč del plazme delcev, tesno sklopljeni z ostalimi

Kozmično mikrovalovno ozadje = Big bang

CMB - zgodovina

Kozmično mikrovalovno ozadje = Big bang

Nepojasjen šum na mikrovalovni dolžini (golobi?) [Penzias, Wilson '64]



Penzias, Wilson

1978

Stohastičen šum

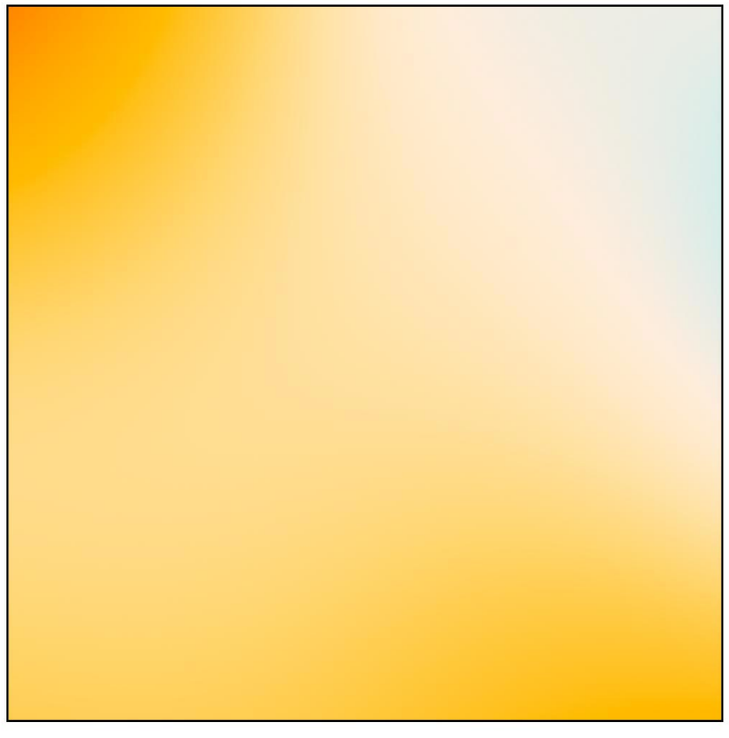
Prisoten na celem nebu,
100x močnejši od ozadja

V skladu z Big bangom

[Gamow; Dicke, Peebles, Wilkinson]

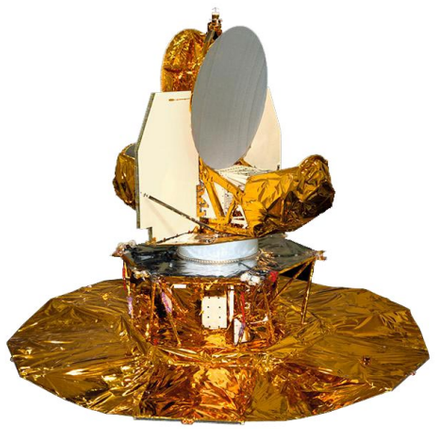
'Rojstvo' moderne kozmologije

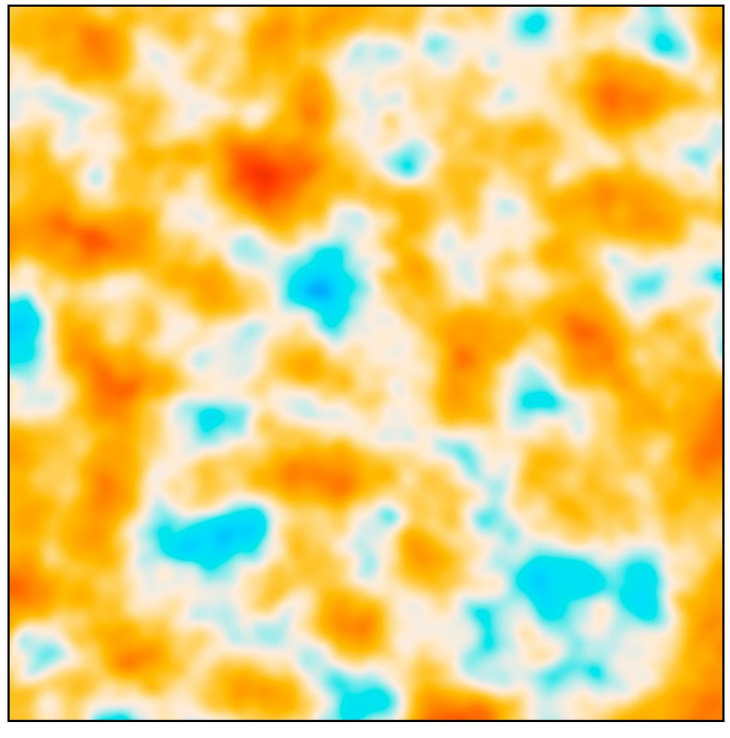
CMB - sateliti



COBE

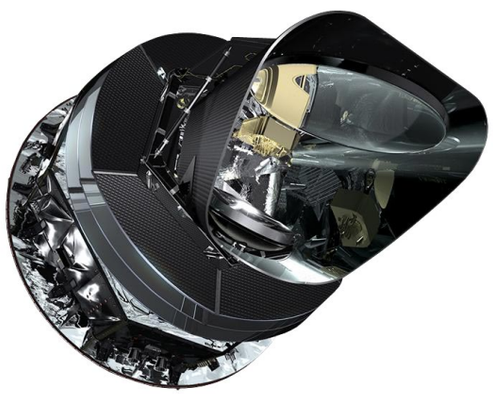
[1989-1993]

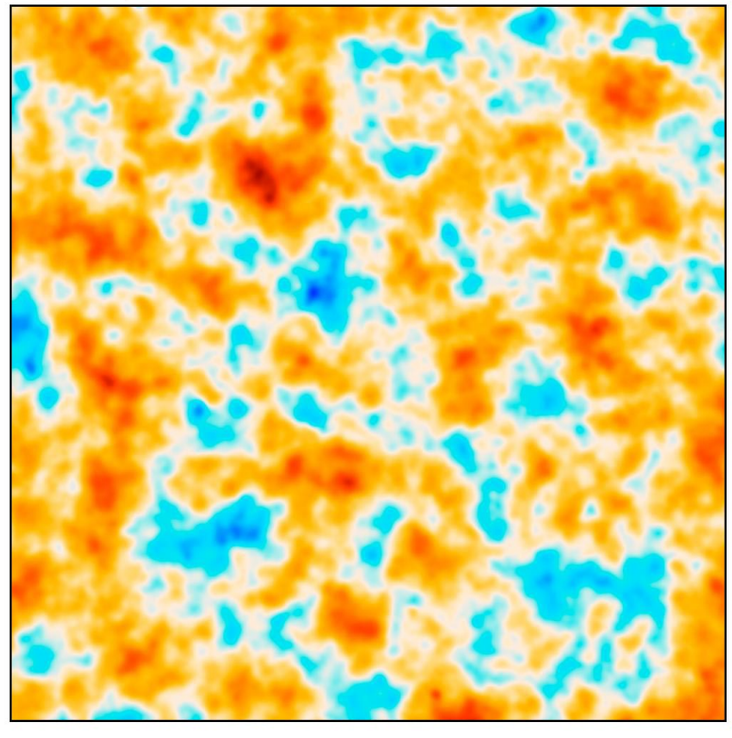




WMAP

[2001-2010]



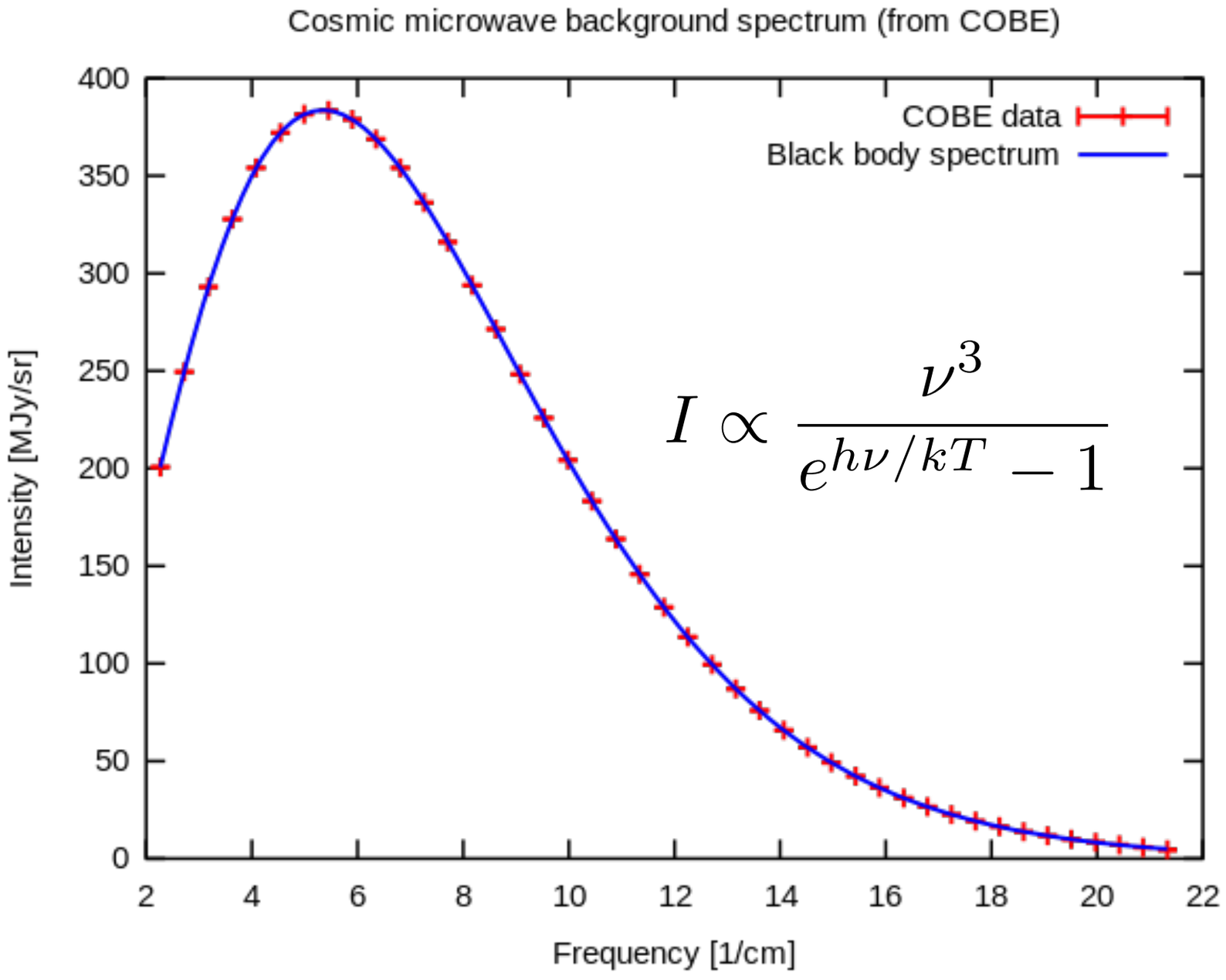


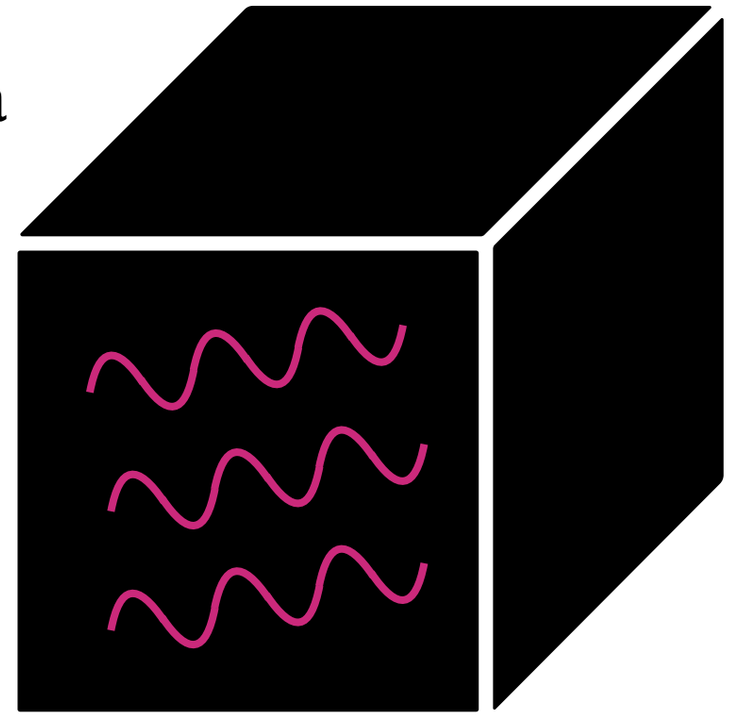
Planck

[2009-2013]

CMB - meritve

Meritve ustrezajo spektru popolnega črnega telesa





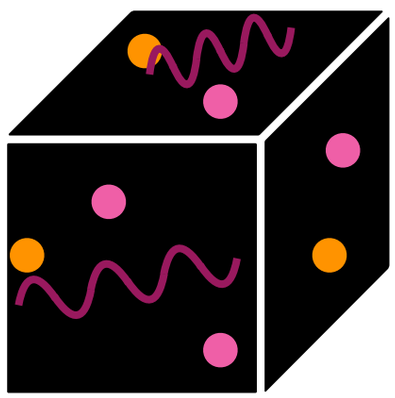
Svetloba ‘ujeta’ v plazmo

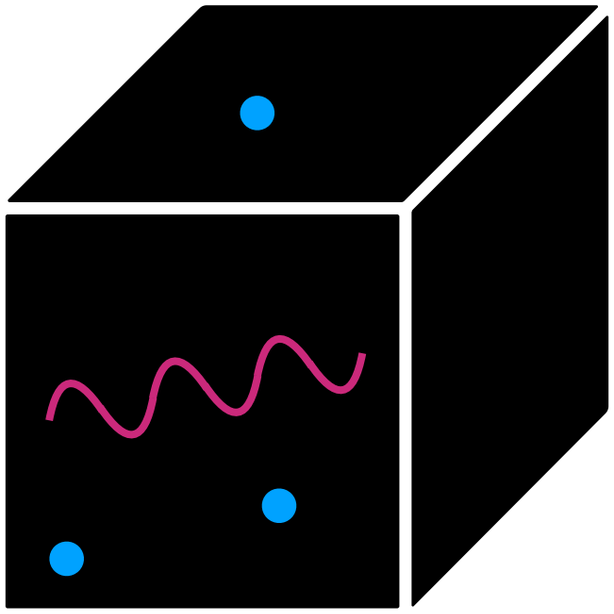
$$T_{\mathrm{CMB}} = 2.725\ \mathrm{K}$$

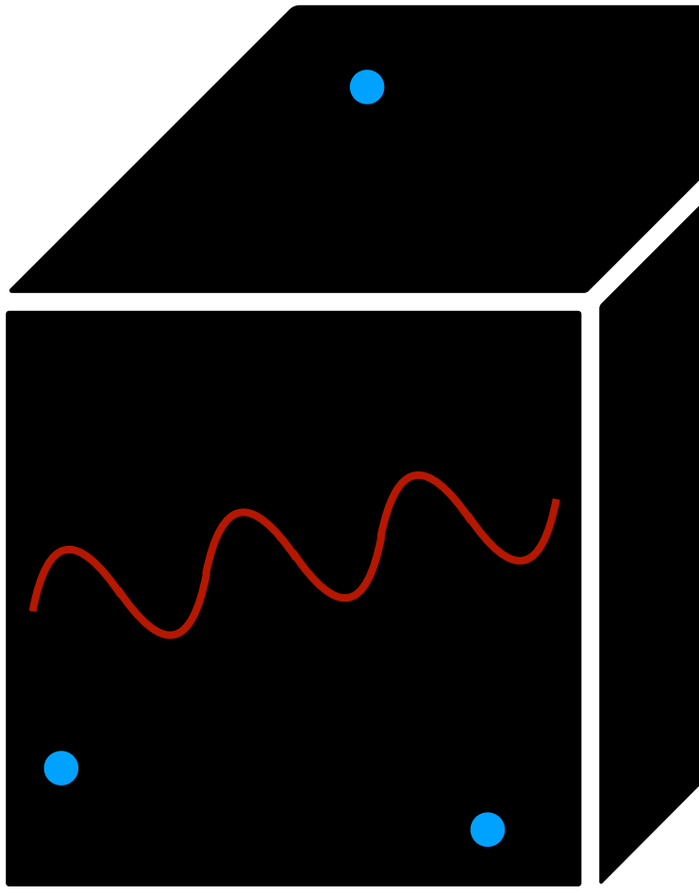
‘Orodje’ za kozmologijo

Big bang

CMB je dokaz, da je bilo vesolje nekoč v termičnem ravnovesju







Γ Interakcijska stopnja

H

Velikost vesolja - Hubblov parameter

$\Gamma > H$

v ravnovesju

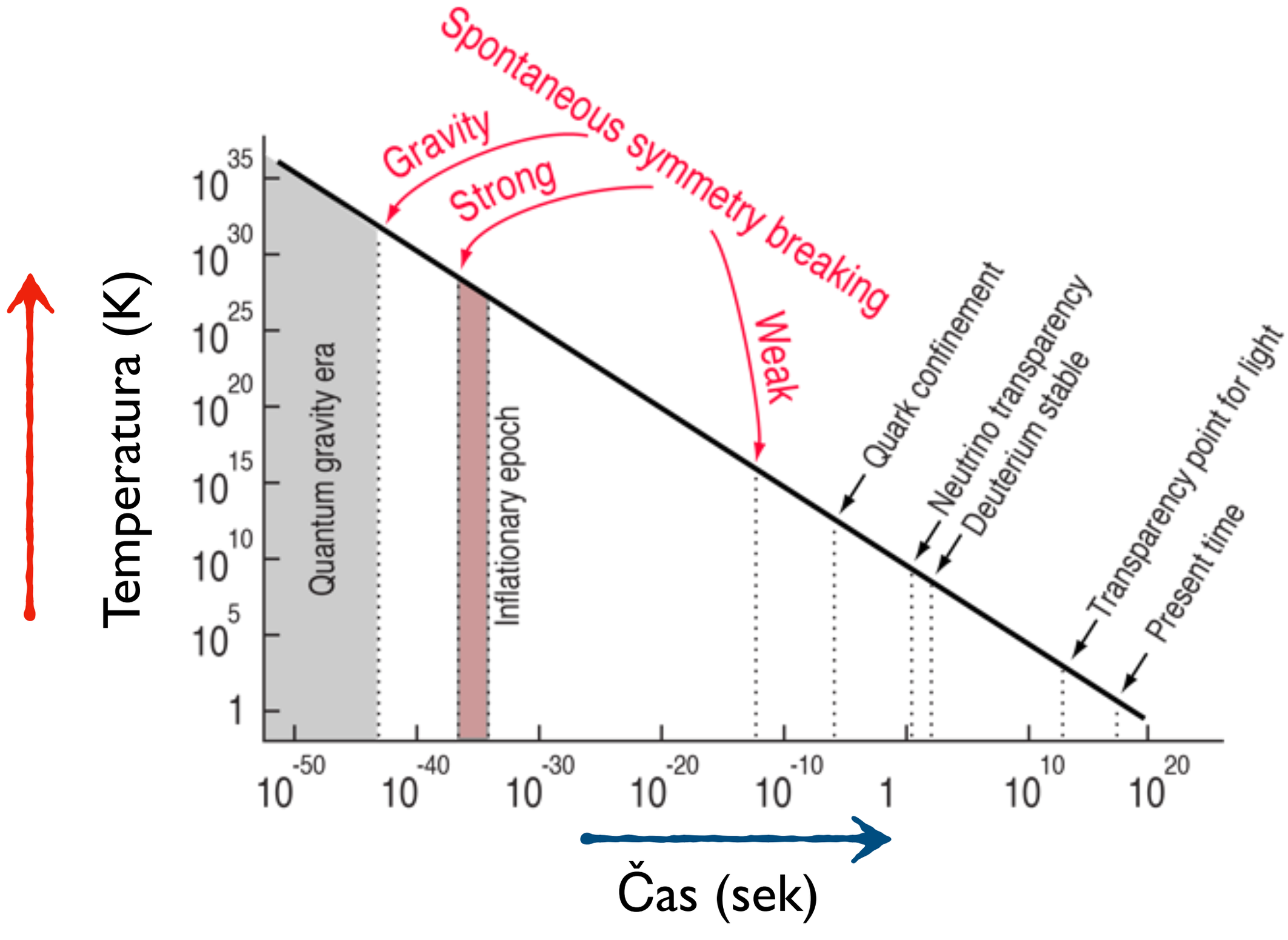
$\Gamma \simeq H$

na robu

$\Gamma < H$

izven ravnovesja

Big bang

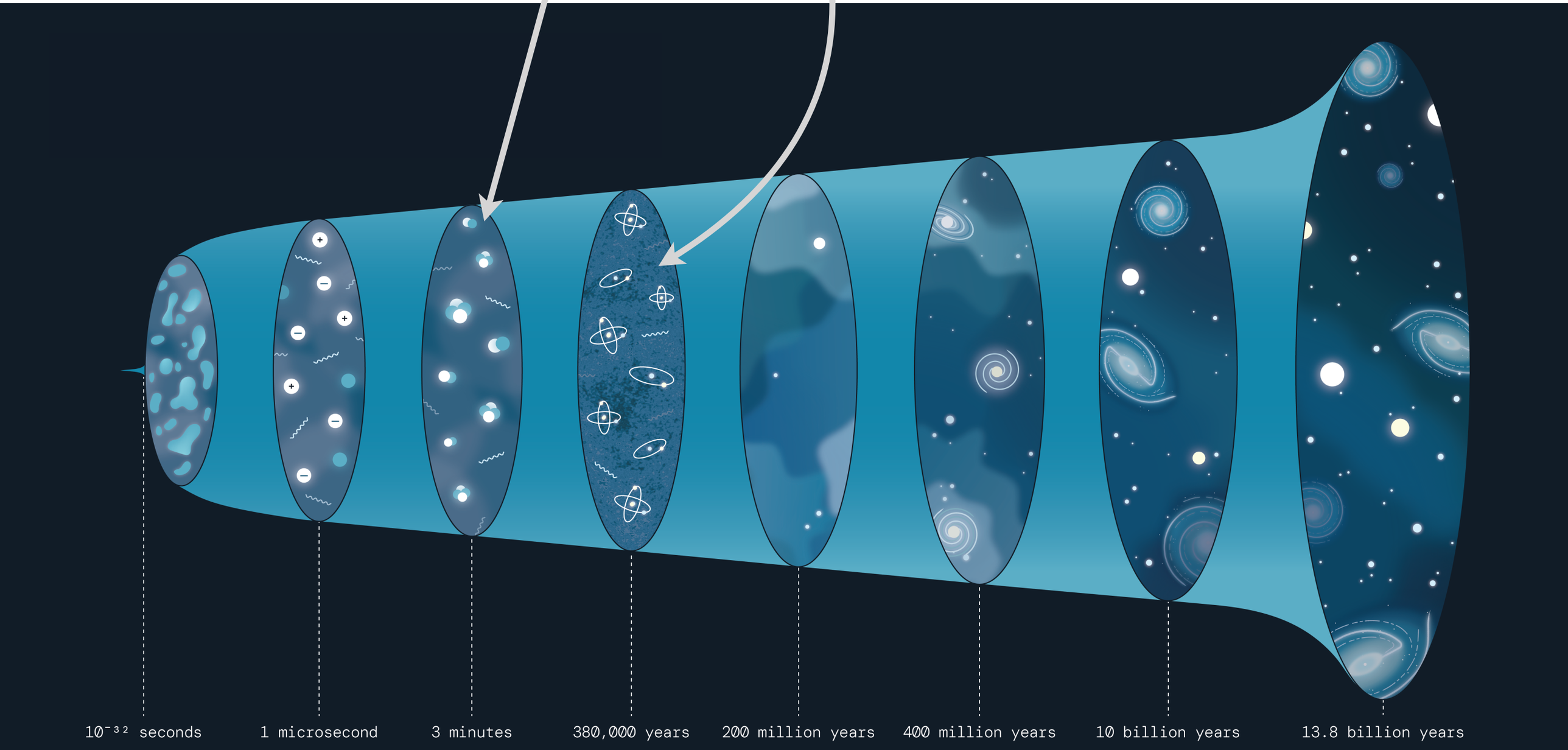

Spontaneous symmetry breaking
Gravity
Strong
Weak
Quantum gravity era
Inflationary epoch
Quark confinement
Neutrino transparency
Deuterium stable
Transparency point for light
Present time
Temperatura (K)
10^35
10^30
10^25
10^20
10^15
10^10
10^5
1
10^-50
10^-40
10^-30
10^-20
10^-10
1
10^10
10^20
Čas (sek)

Big bang

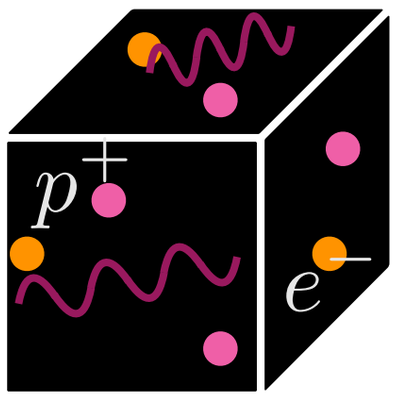
Fazni prehodi?

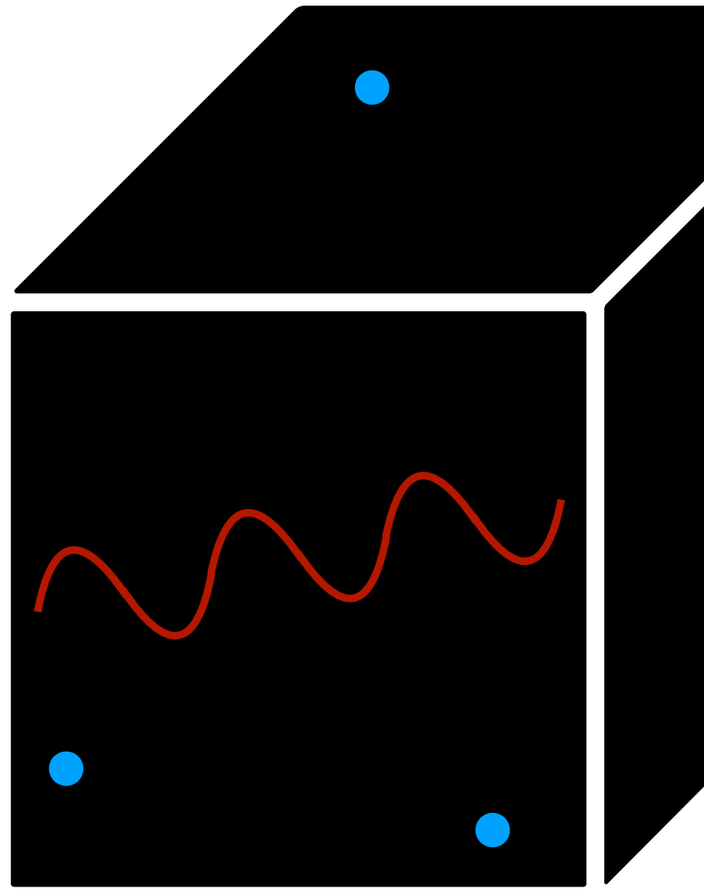
Temna snov?

Nevtrini Nukleosinteza Rekombinacija

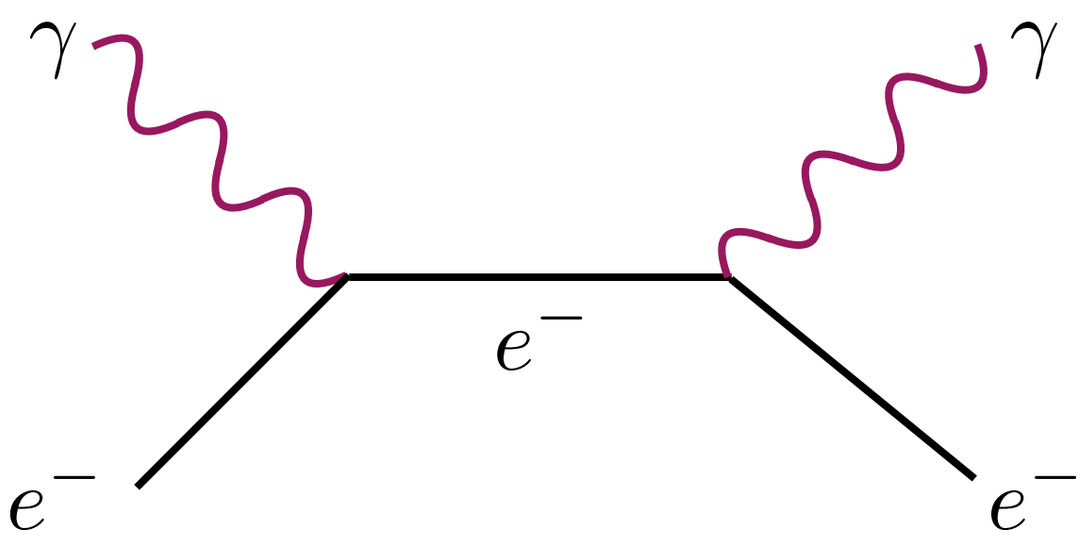


Rekombinacija





Elektroni in protoni trkajo s fotoni



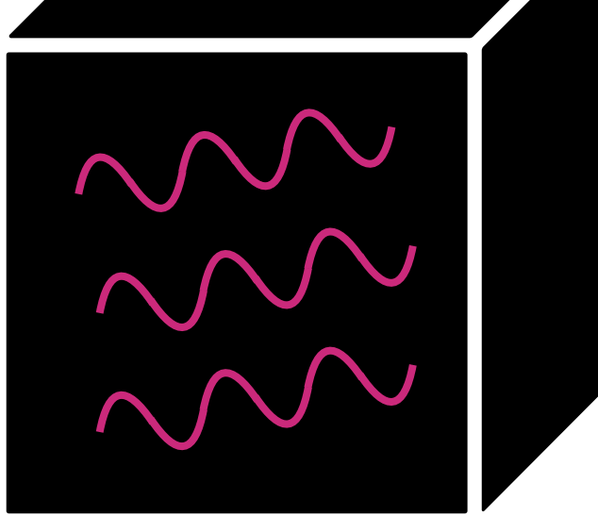
- $k_B T_\gamma \simeq E_{\mathrm{Ry}} = 13{,}6\ \mathrm{eV}$

Nabita plazma se spoji v nevtralen vodik

Fotoni se ohladijo, vodik ostaja

Elektroni izginejo in tik za tem vesolje
postane prozorno, nastane CMB

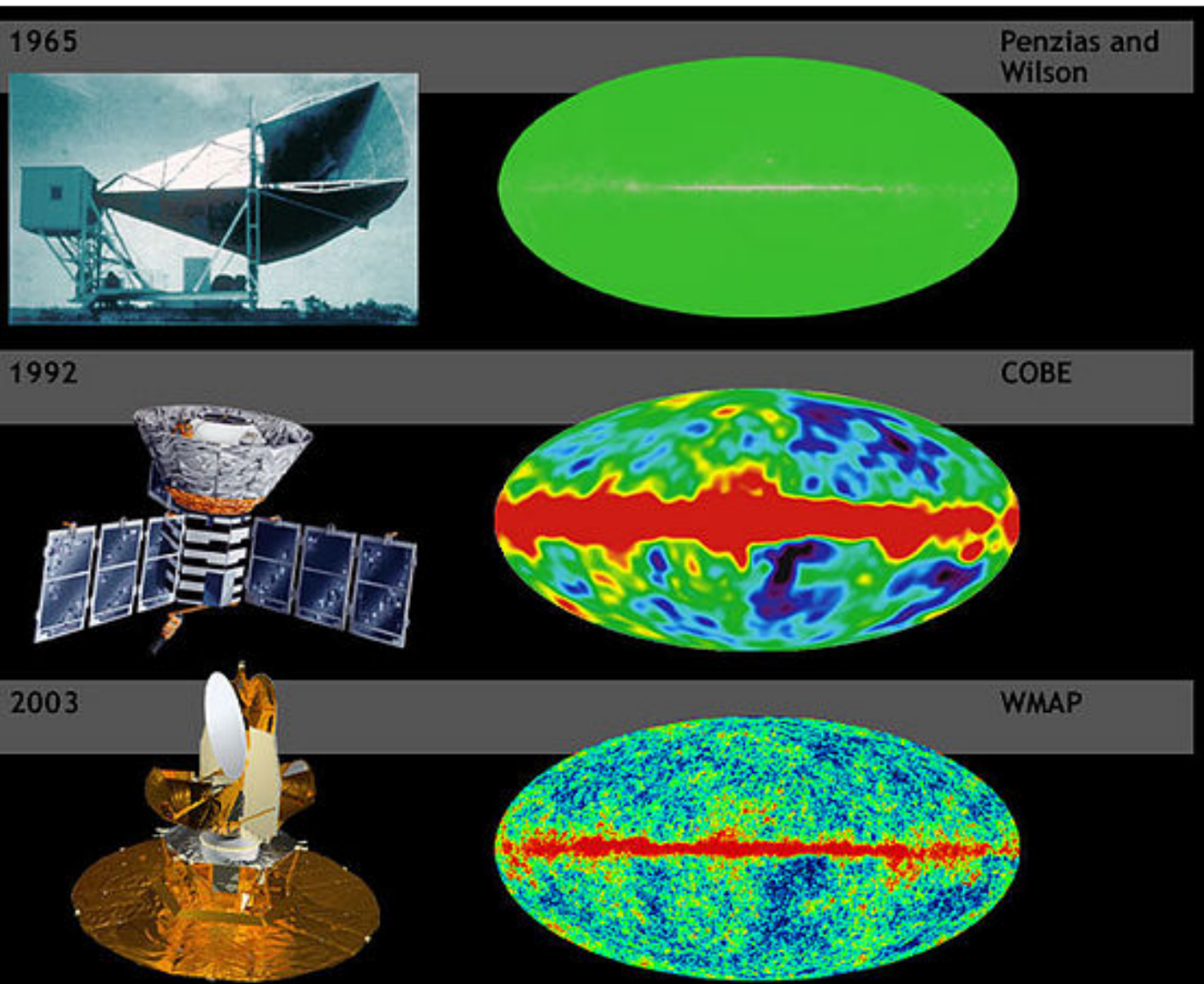
CMB - meritve

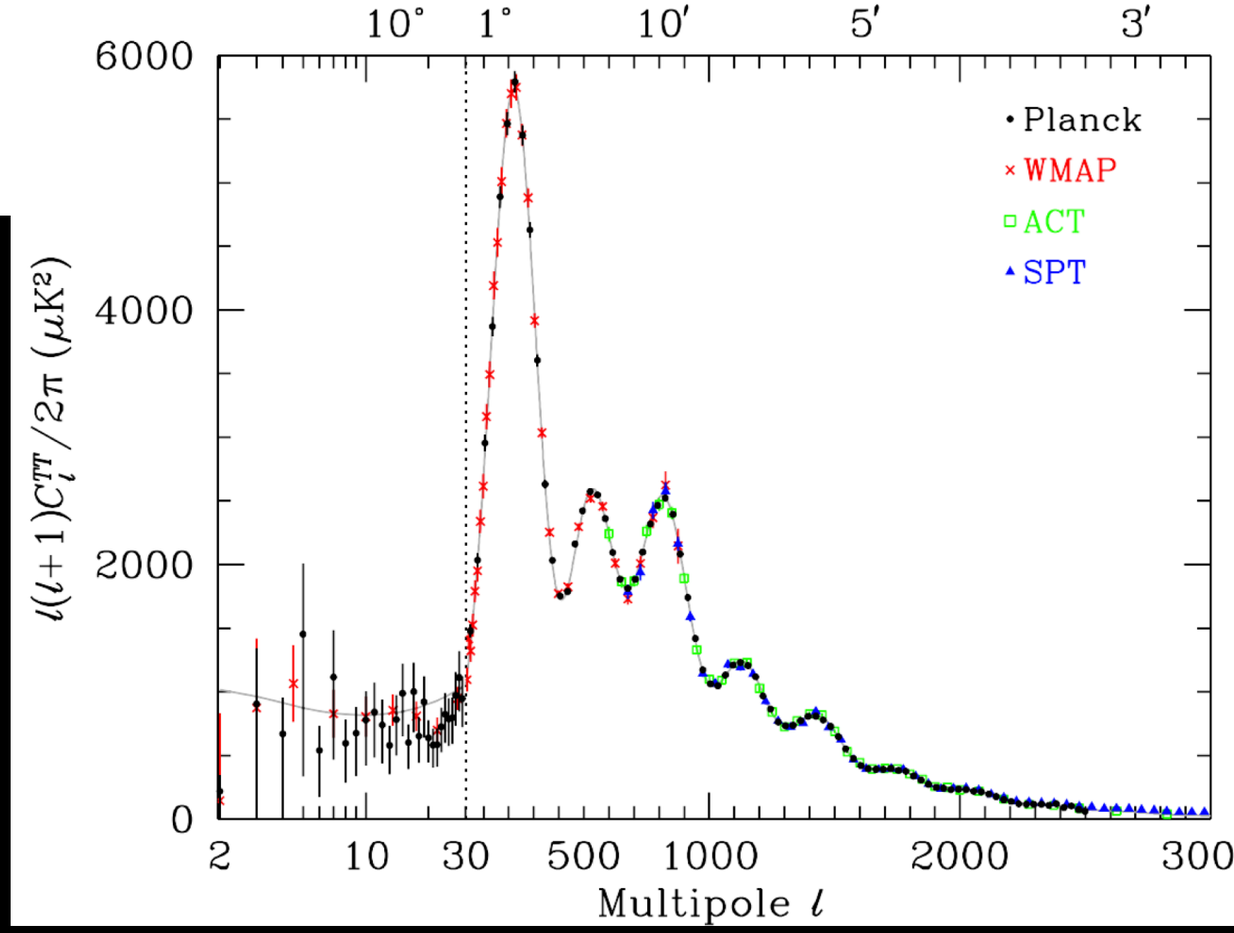


Zelo natančne meritve izmerijo majhna odstopanja

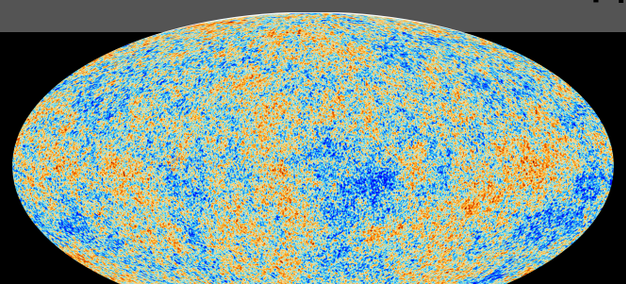
Dekompozicija v sferične harmonike, multipoli

Euclid in prihajajoče misije

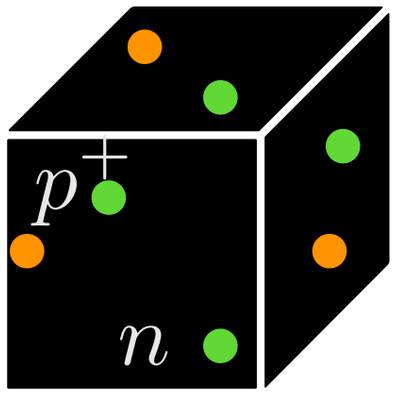


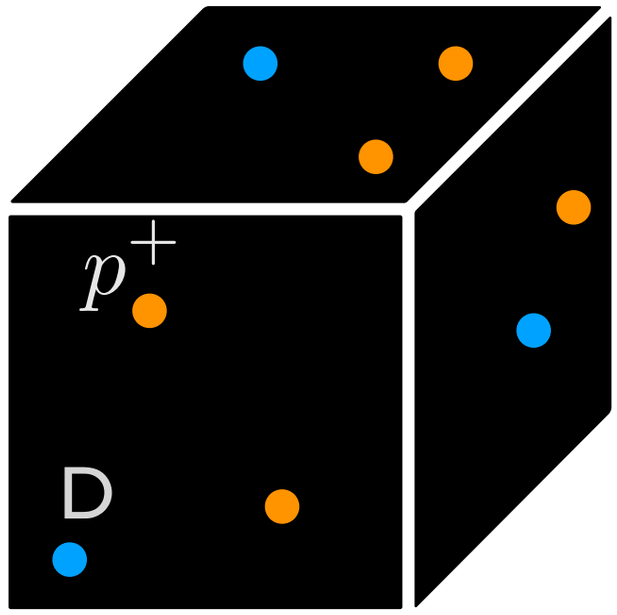


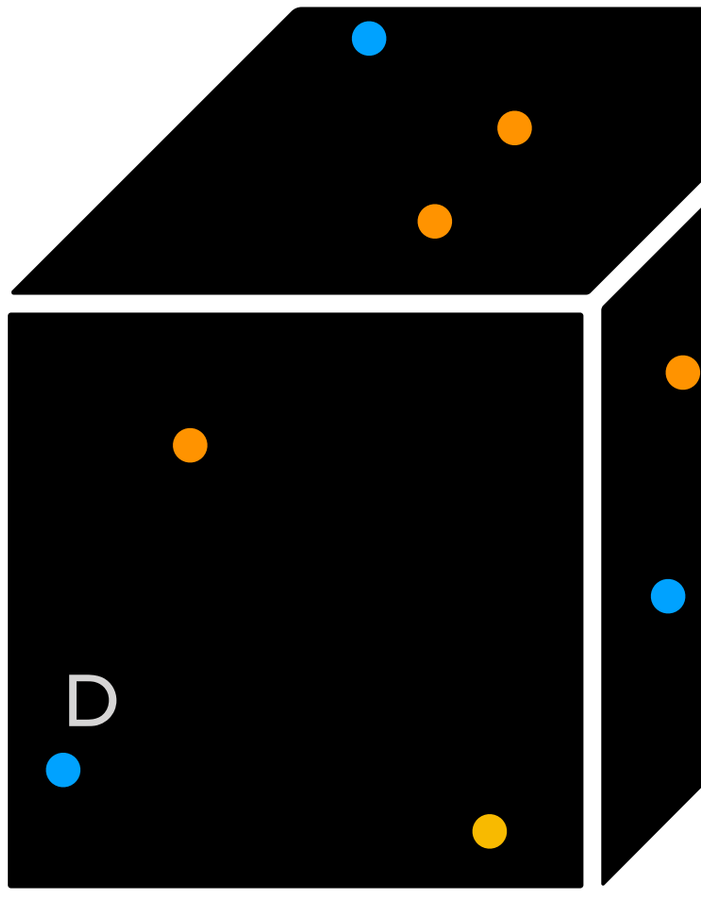
Planck



Nukleosinteza





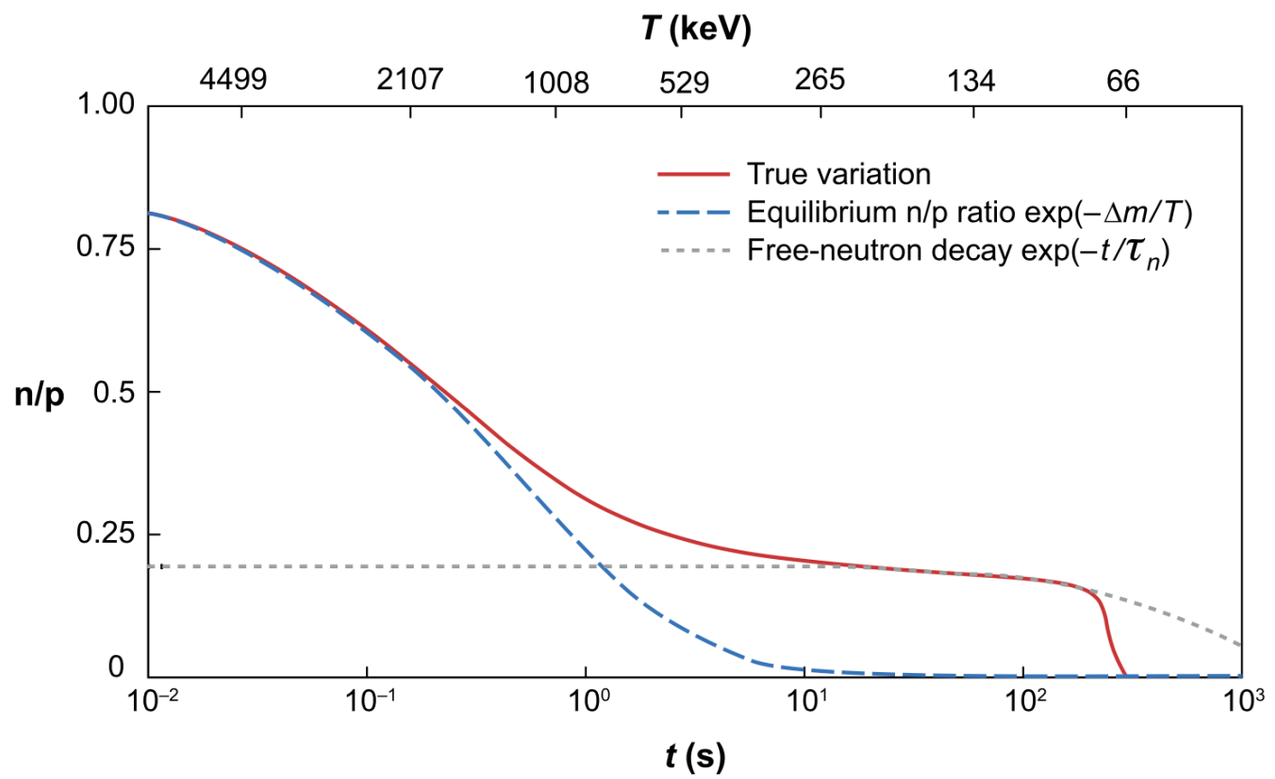


Zgodnje vesolje $T \gtrsim \mathrm{MeV}$

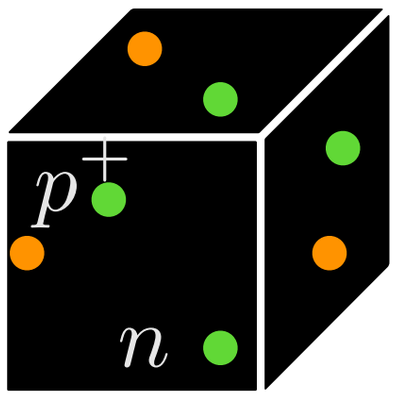
Mase nukleonov dajo številske gostote

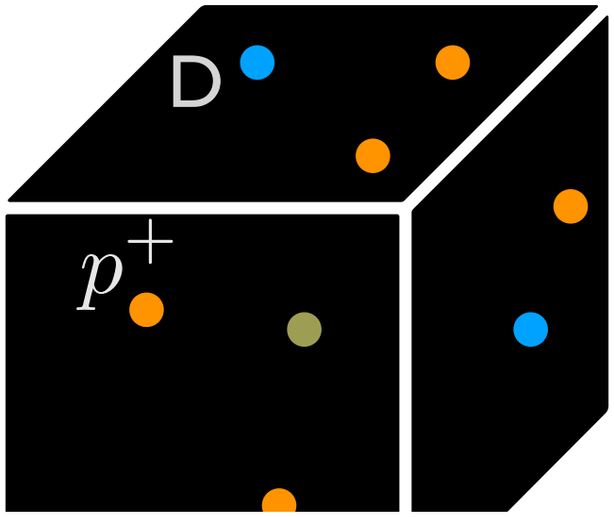
$$\frac{n_p}{n_n} = e^{(m_n - m_p)c^2/k_B T}$$

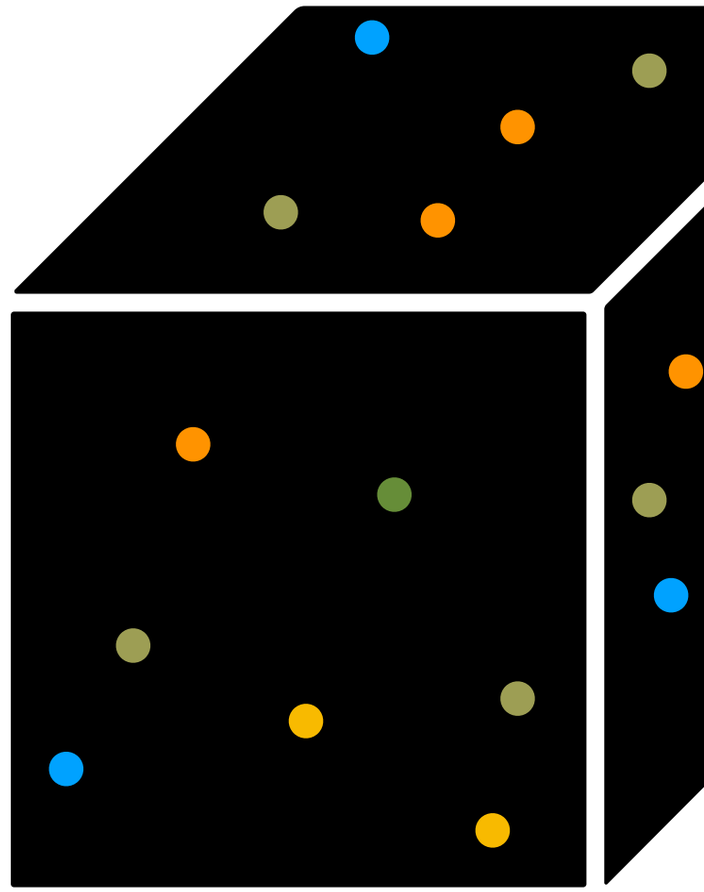
Prosti nevtroni razpadejo

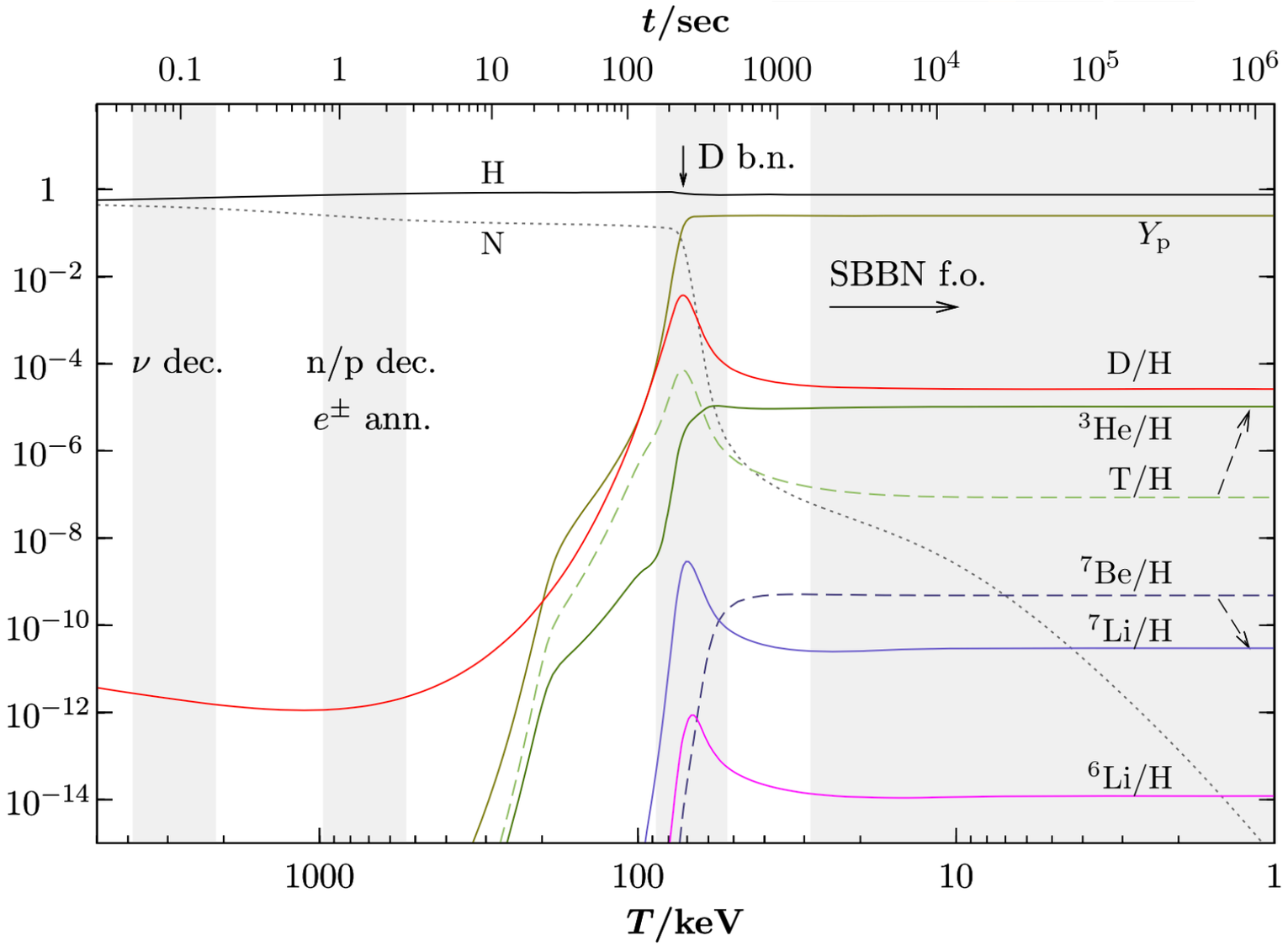


Nukleosinteza









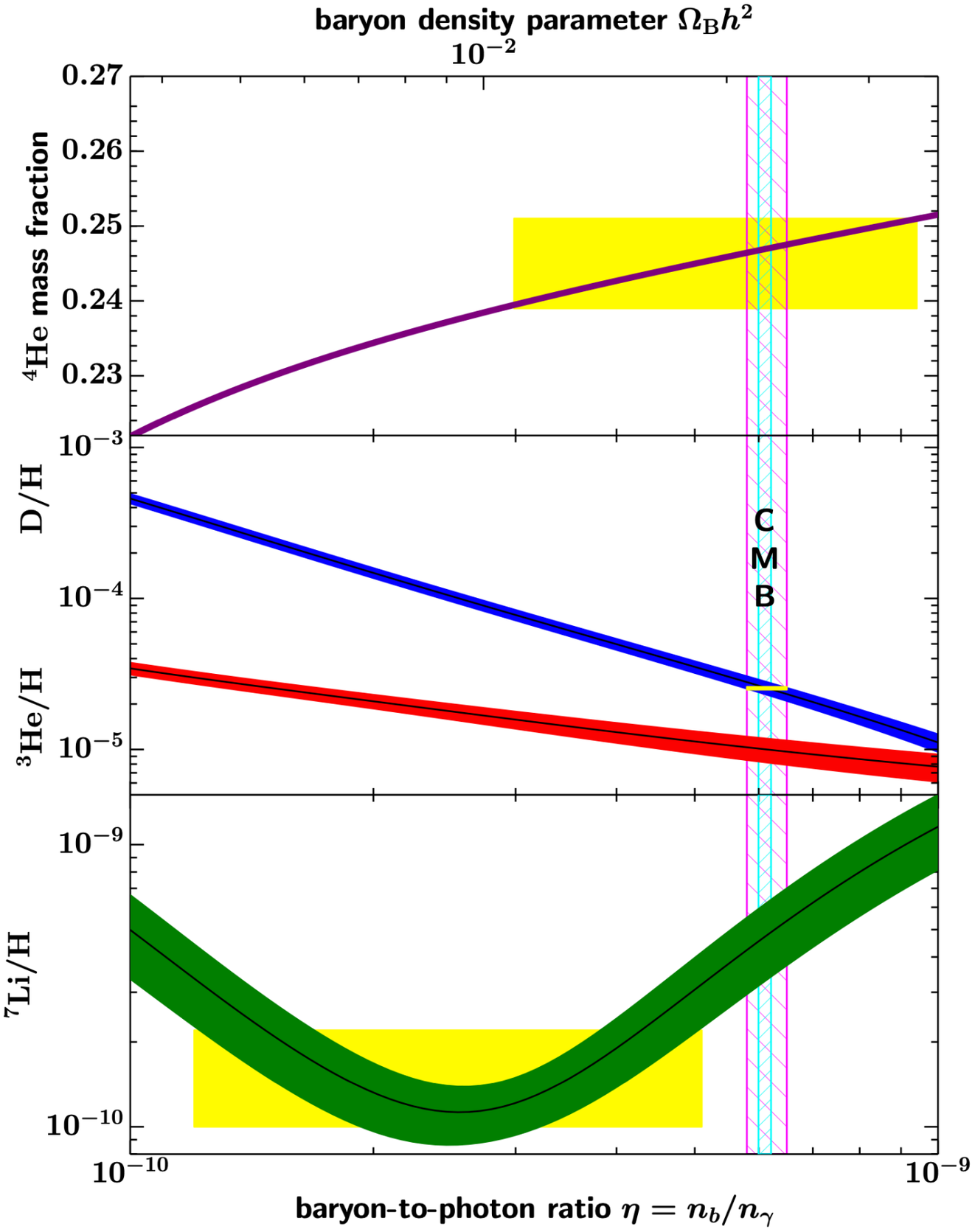
Tvorijo se lažja jedra

Devterij, Helij, Tricij*

Litij, Berilij*

Meritve potrjujejo to sliko

Nukleosinteza



Medgalaktični plini lahkih elementov

V skladu z CMB meritvami, Li problem

Odvisno od količine barionov

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

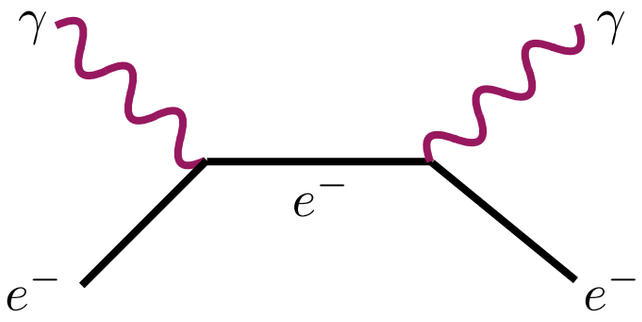
snov > anti-snov

?

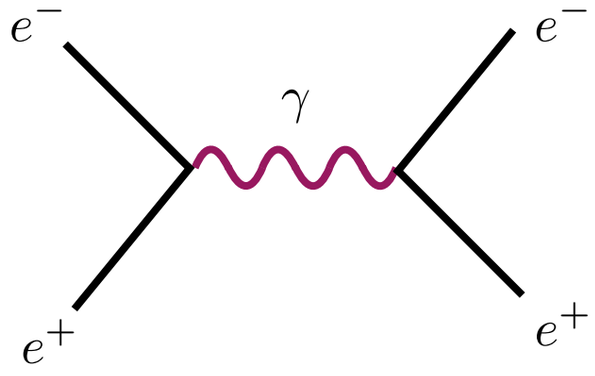
Težji elementi nastanejo v zvezdah

Nevtrini

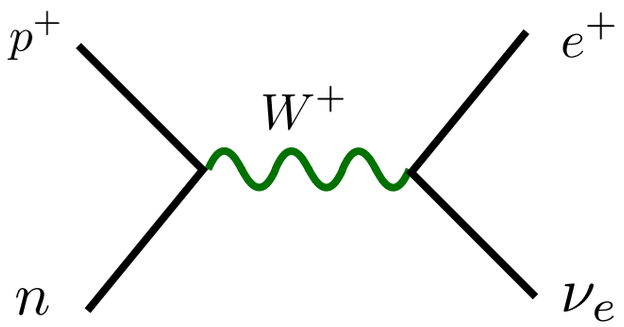
Big bang napove kozmično ozadje fotonov CMB



$$\Gamma_{QED} > H$$



Pri dovolj visokih temperaturah je tudi šibka interakcija v ravnovesju

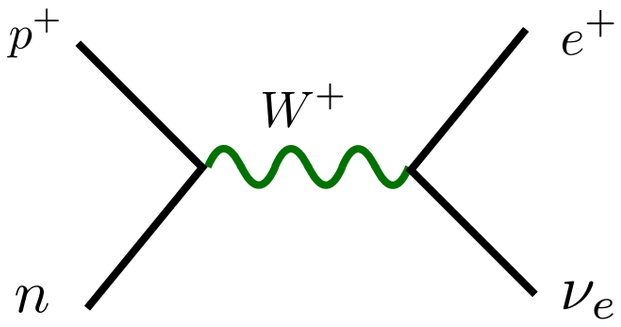


$$\Gamma_{\mathrm{EW}} > H \qquad\qquad T_\gamma = T_e = T_\nu$$

Vesolje je plazma z nevtrini

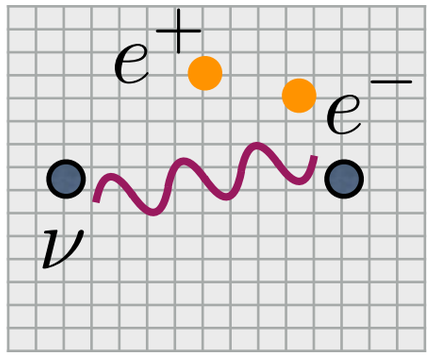
Nevtrini

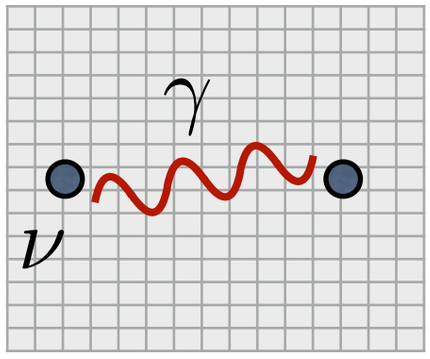
Pri ohlajanju se nevtrini odklopijo, vesolje postane prozorno zanje

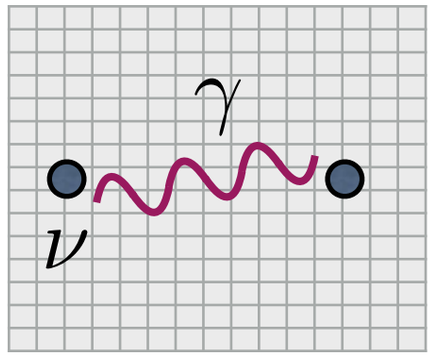


$$\Gamma_{\rm EW} \simeq H \qquad T_\nu^{\rm dec} \simeq 1.5\ {\rm MeV}$$

Big bang napove kozmično ozadje nevtrinov CνB







$$T_\gamma = T_e = T_\nu \qquad T_\gamma > T_\nu \qquad T_\nu = \sqrt[3]{\frac{4}{11}}\, T_\gamma$$

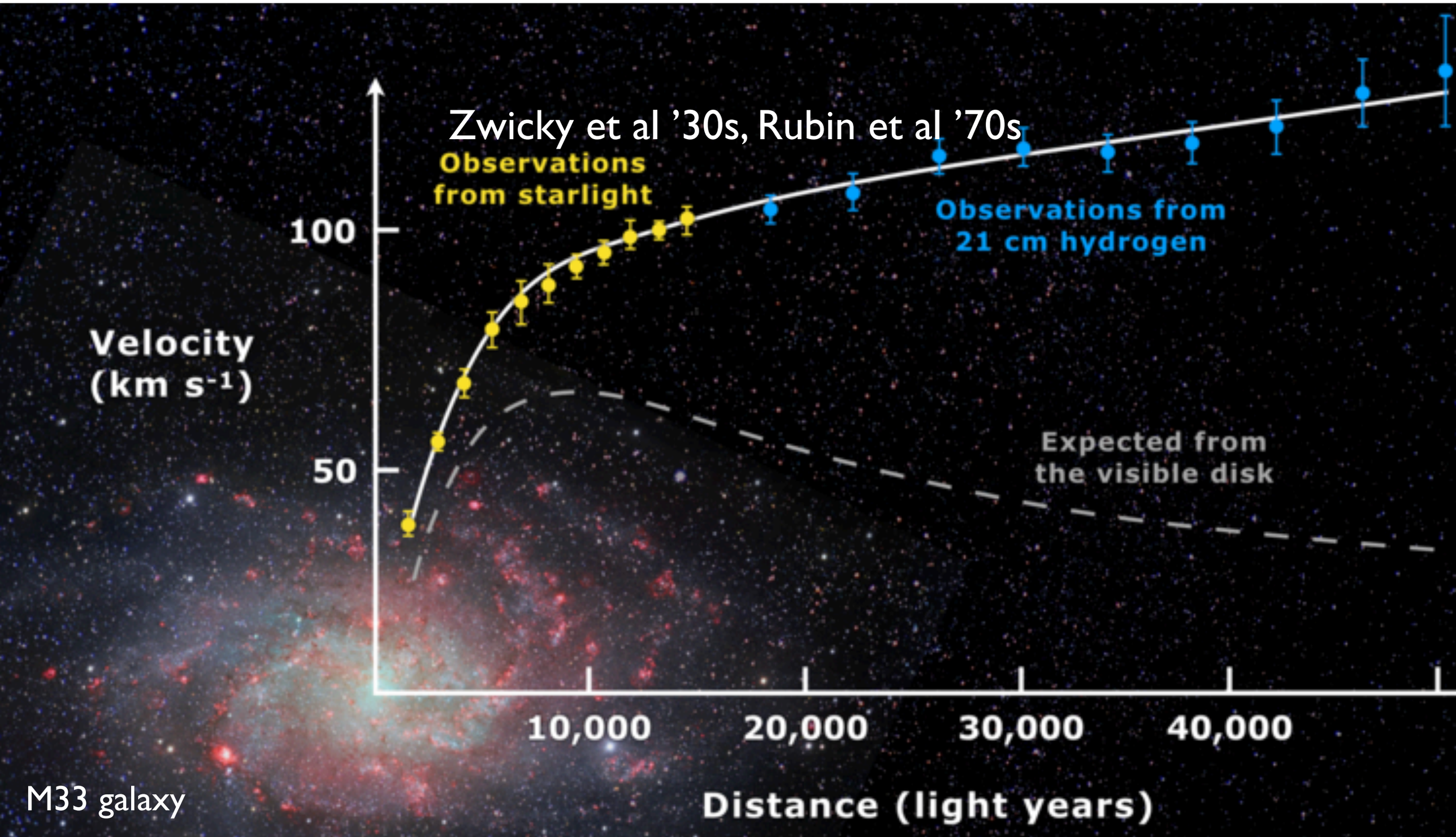
$T_\nu = 1.95K \simeq {\rm meV}$ = izziv (Majorana)

Danes (entropija)

Temna snov

Astrofizika

Rotacijske krivulje galaksij



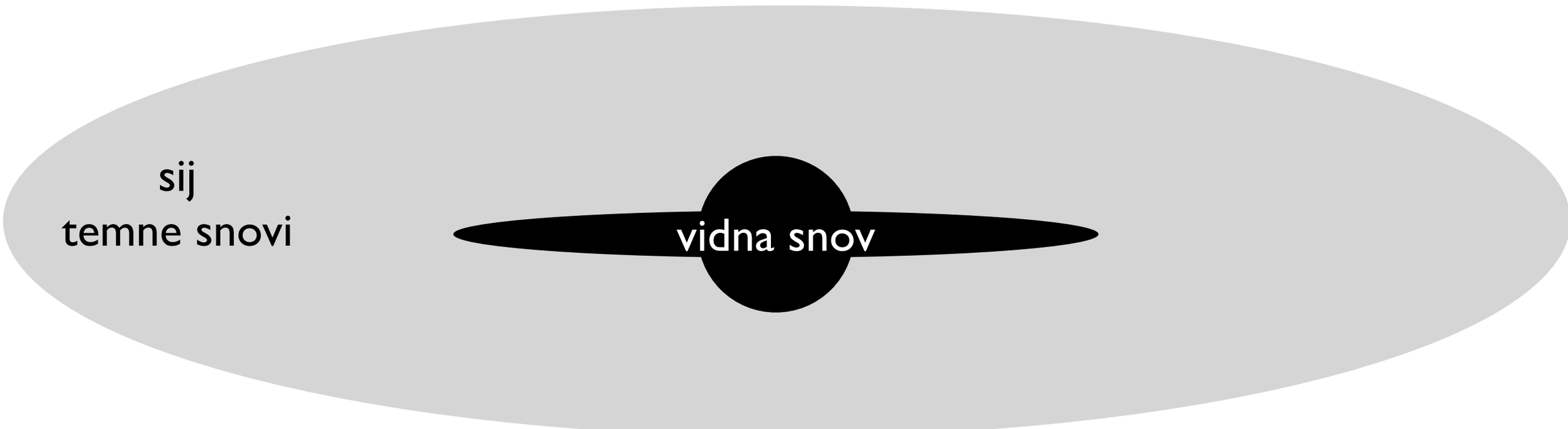
Astrofizika

Rotacijske krivulje galaksij

$$F_c = F_g$$

$$\frac{\cancel{m} v_c^2}{R} = \frac{G_N \cancel{m} M}{R^2} \quad \Rightarrow \quad v_c = \sqrt{\frac{G_N M}{R}} \simeq \text{konst.}$$

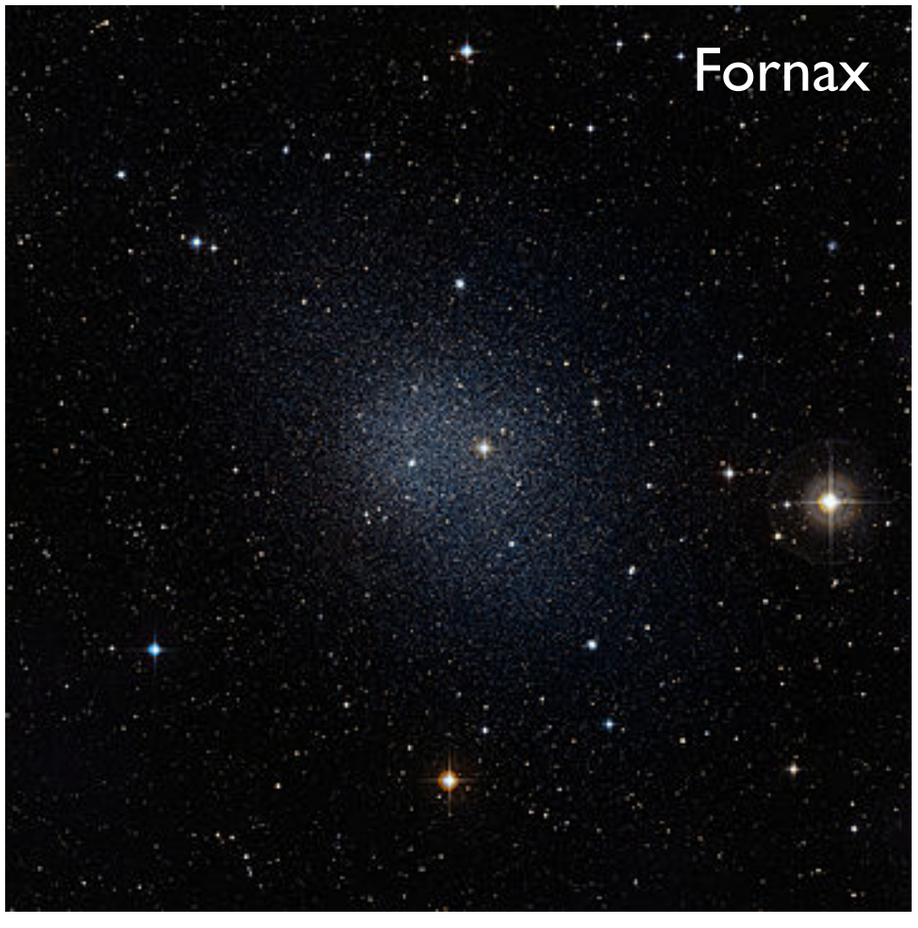
$$M = M_{\text{halo}} \propto R \qquad M_{\text{halo}} = \int d^3x \, \rho_{DM} = 4\pi \int_0^R dr \, r^2 \rho_{DM}(r)$$



Lastnosti

Nerelativistična

$$v_{DM} \simeq \sqrt{\frac{G_N M_{\rm dSph}}{R_{\rm dSph}}} \sim 10^{-5}$$



$R_{\rm dSph} \sim$ kpc

$M_{\rm dSPh} \gtrsim 10^7 M_\odot$

Spodnja meja na maso

Fermioni	$m^F_{\rm DM} \gtrsim 0.4$ keV	Pauli
Bozoni	$m^B_{\rm DM} \gtrsim 10^{-22}$ eV	De Broglie

Lastnosti

Elektromagnetni naboj: temna snov ne sveti, ne sije $Q(e) = 1$

omejitve iz CMB!

$m_{DM} <$ GeV

$$Q_{DM} < 4 \times 10^{-7} \left(\frac{m_{DM}}{\mathrm{GeV}}\right)^{0.35}$$

$m_{DM} >$ GeV

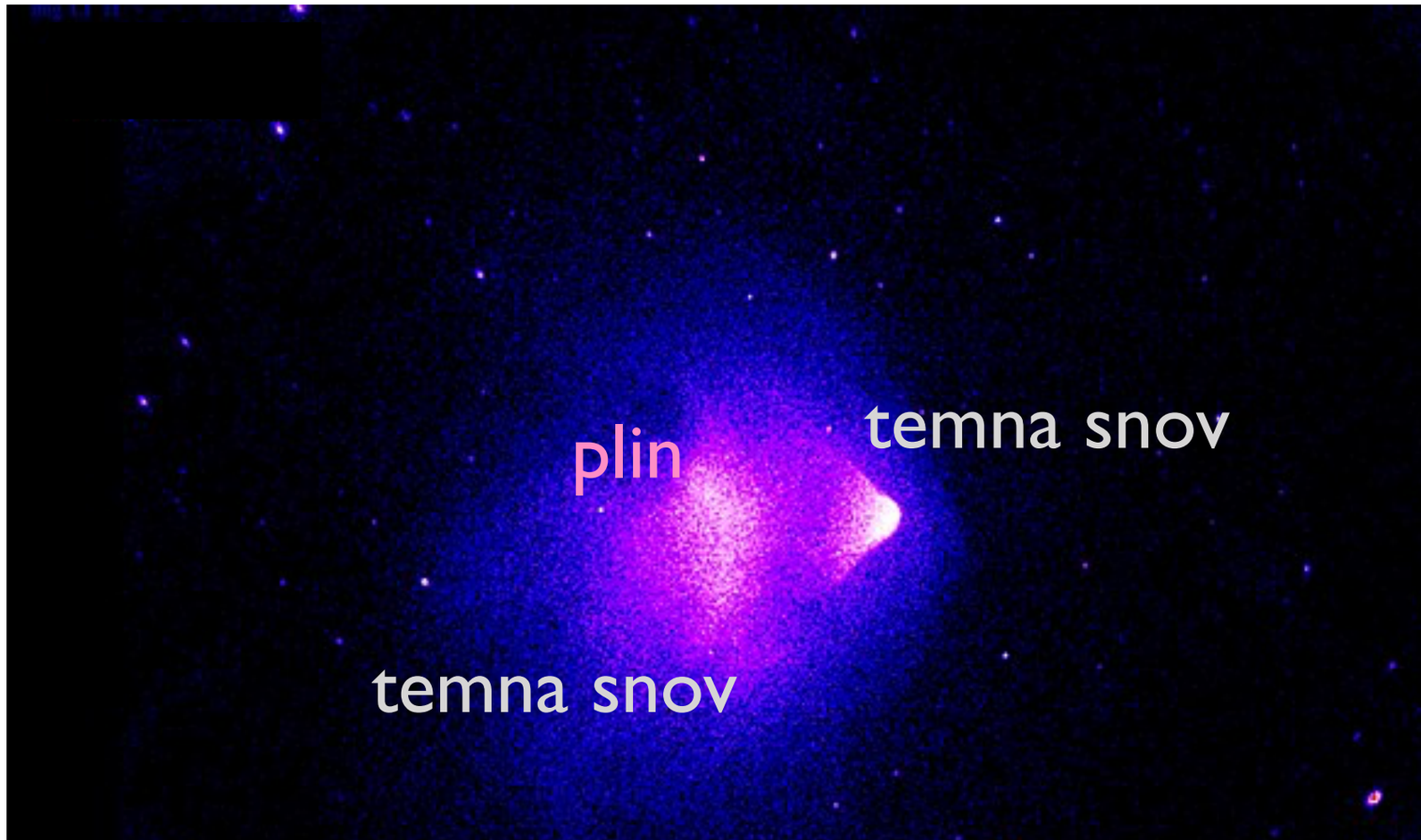
$$Q_{DM} < 3.5 \times 10^{-7} \left(\frac{m_{DM}}{\mathrm{GeV}}\right)^{0.58}$$

Interakcija DM-DM

$$\frac{\sigma_{\text{DM-DM}}}{m_{\text{DM}}} < 0.8 \frac{\text{barn}}{\text{GeV}}$$

Nukleoni

$$\frac{\sigma_{n-n}}{m_n} \sim \frac{\text{nekaj barnov}}{\text{GeV}}$$



Kandidati

WIMPi

SUSY - MSSM & razširitve

Singleti, dodatni multipleti (Inertni Higgsov dublet)

Razširjene/skrite interakcije (Levo-Desno, Dvojni sektorji, temna QCD, ...)

Ekstra dimenzije, Kaluza-Klein stolpi

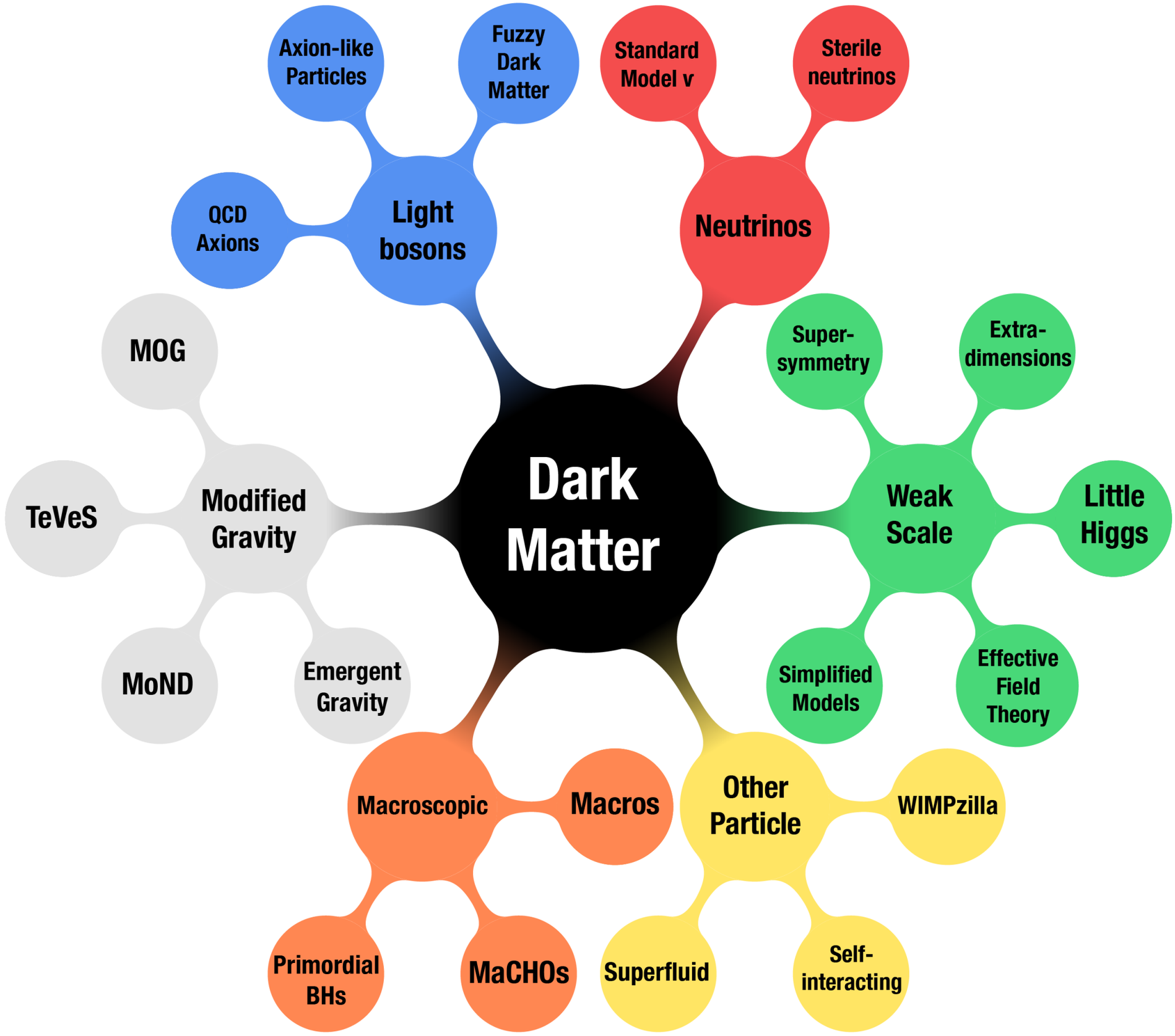
Desno-ročni/sterilni nevtrini

Axioni

Dodatni kandidati…

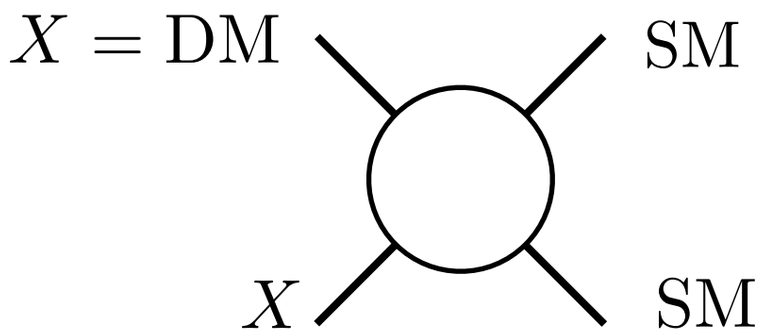
Primordialne črne luknje

Kandidati

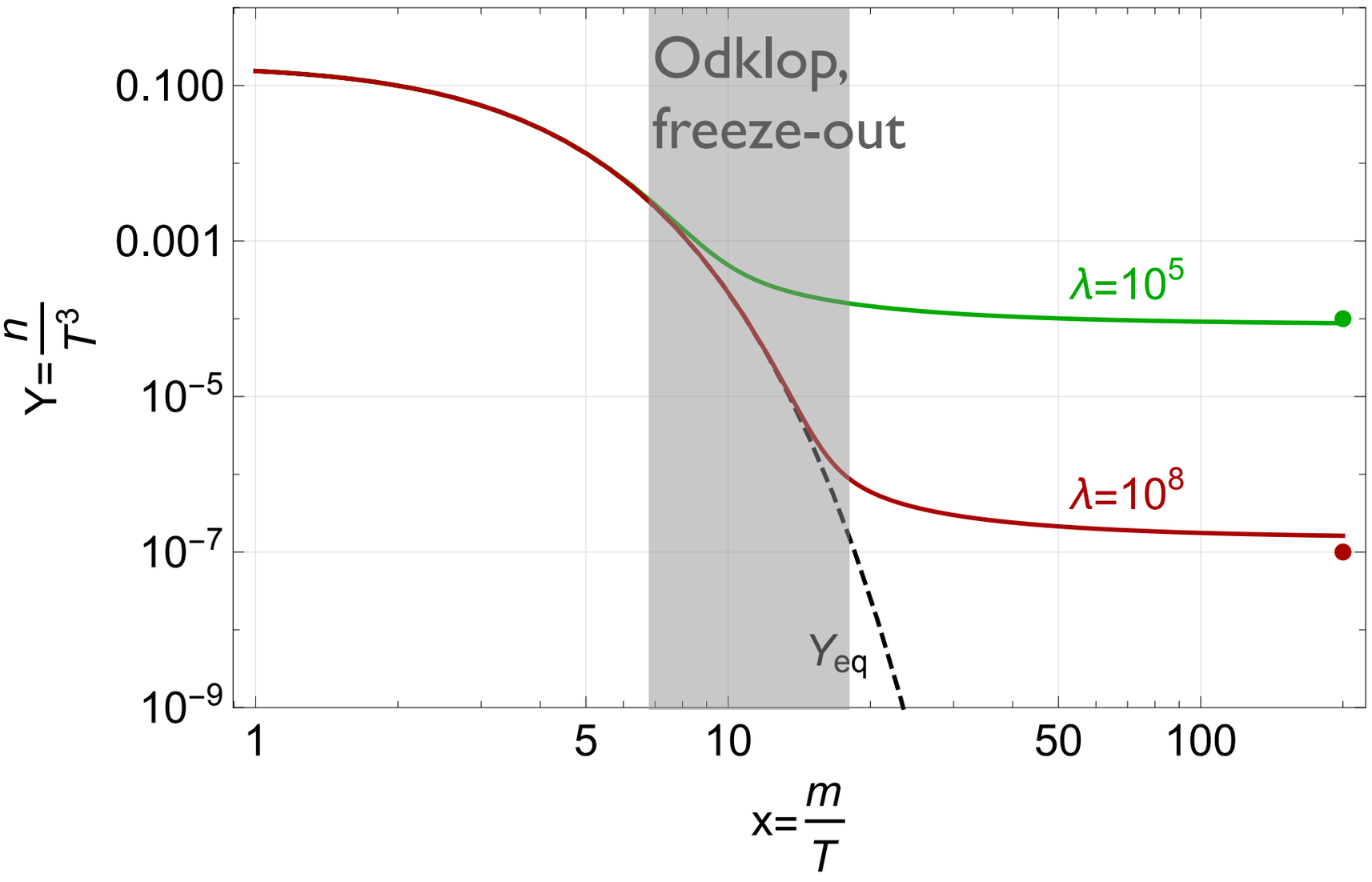

Axion-like Particles
Fuzzy Dark Matter
Standard Model ν
Sterile neutrinos
QCD Axions
Light bosons
Neutrinos
MOG
Super-symmetry
Extra-dimensions
Dark Matter
TeVeS
Modified Gravity
Weak Scale
Little Higgs
MoND
Emergent Gravity
Simplified Models
Effective Field Theory
Macroscopic
Macros
Other Particle
WIMPzilla
Primordial BHs
MaCHOs
Superfluid
Self-interacting

WIMP

V zgodnjem vesolju je bila temna snov v ravnovesju



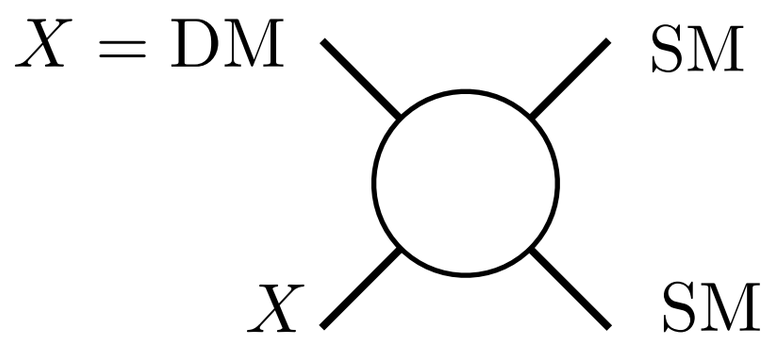
Veliko temne snovi

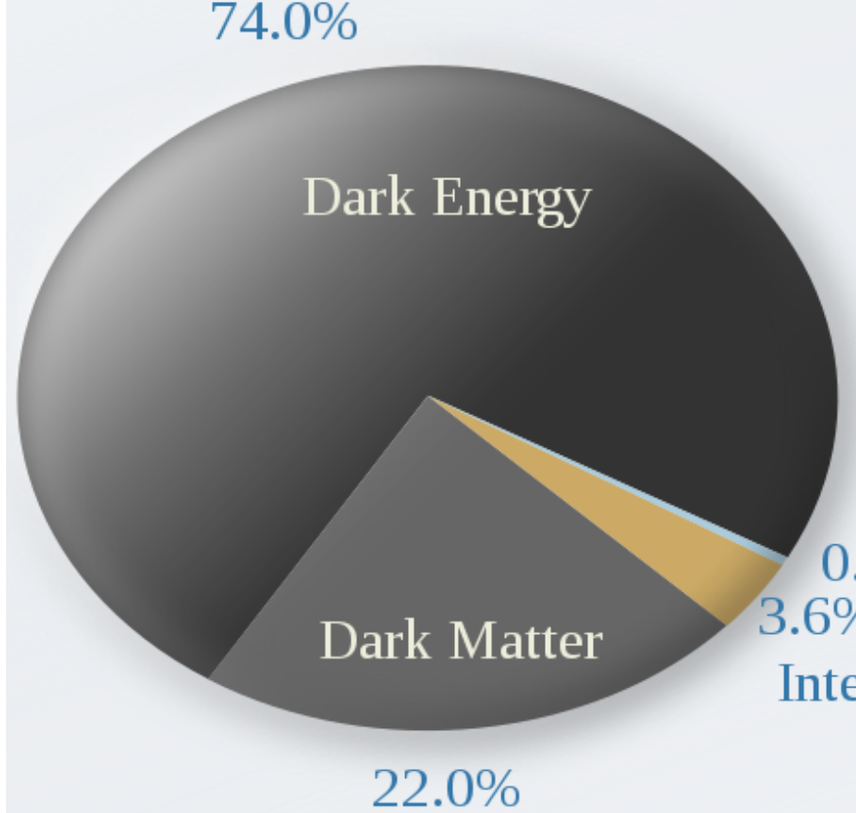


Več interakcije, več anihilacije, manj temne snovi

WIMP

WIMP 'miracle'

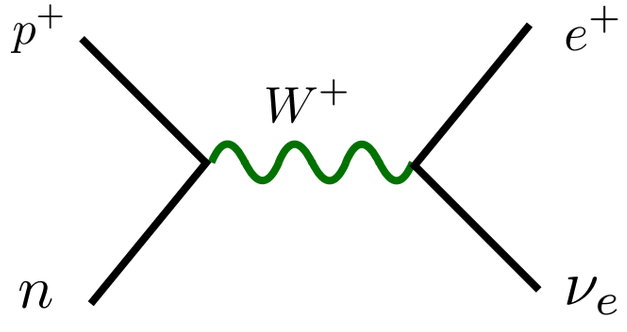




$$\Omega_{DM} \simeq 0.3\, h^{-2} \left(\frac{x_f}{10}\right) \left(\frac{g_*}{100}\right)^{1/2} \frac{10^{-39}\ \mathrm{cm}^2}{\langle \sigma v \rangle}$$

Brez nastavljanja parametrov $\langle \sigma v \rangle \sim 10^{-39}\ \mathrm{cm}^2$

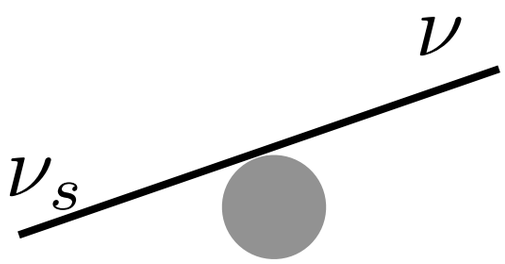
Ista številka kot za tipični šibki proces/sipanje



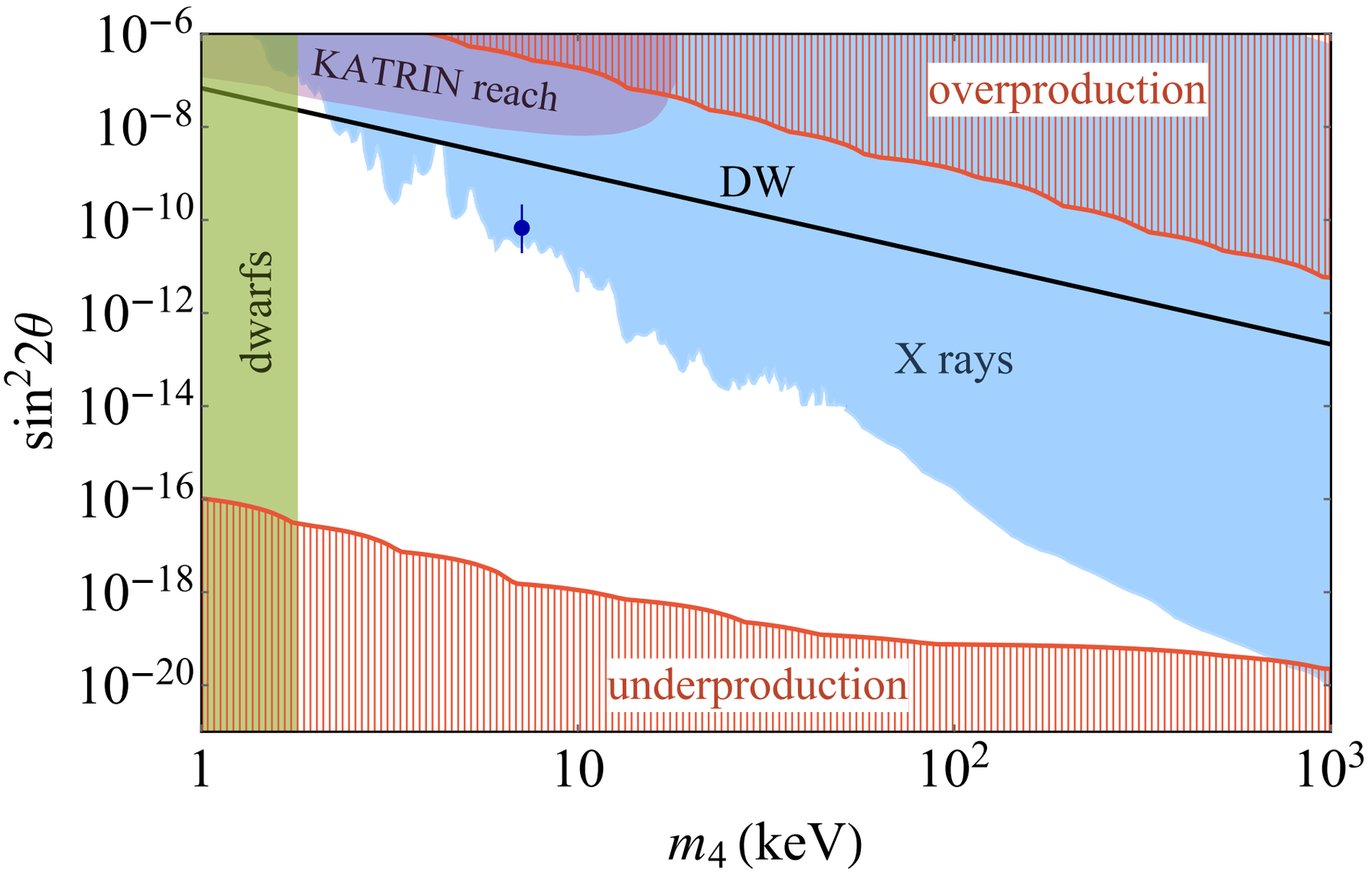
$\langle \sigma v \rangle \sim 10^{-39}\ \mathrm{cm}^2$

Sterilni nevtrini

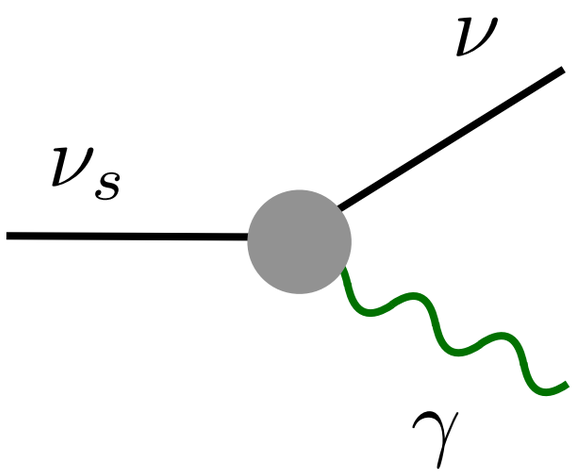
Masivni nevtrini in gugalnični mehanizem



mešanje $\theta \simeq \sqrt{\frac{m_\nu}{m_{\nu_s}}}$

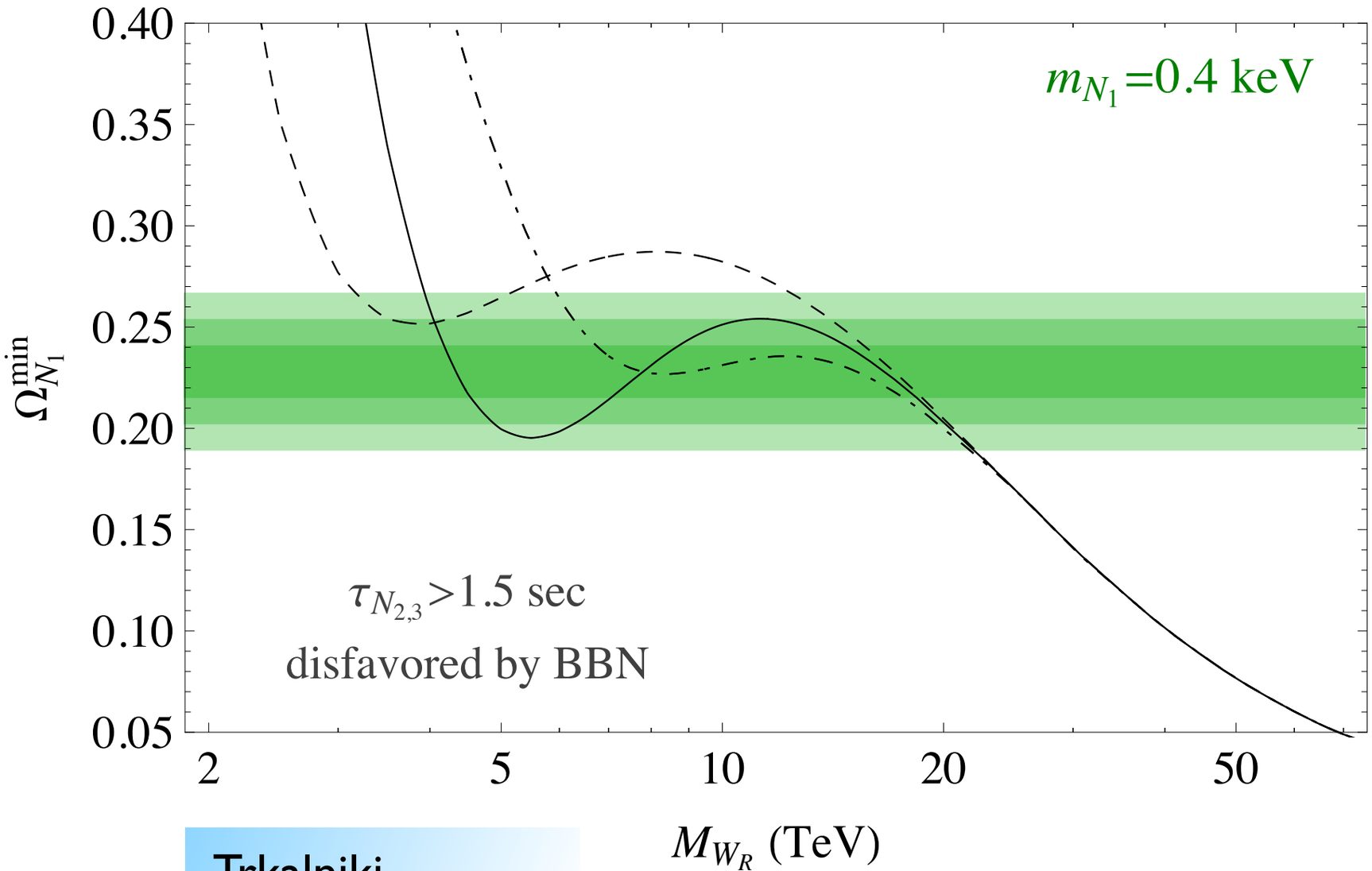


Omejitev X-žarki



Desno-ročni nevtrini in Levo-desno simetrija

Bogata fenomenologija, povezava z ostalimi iskanji in kozmologijo



Trkalniki

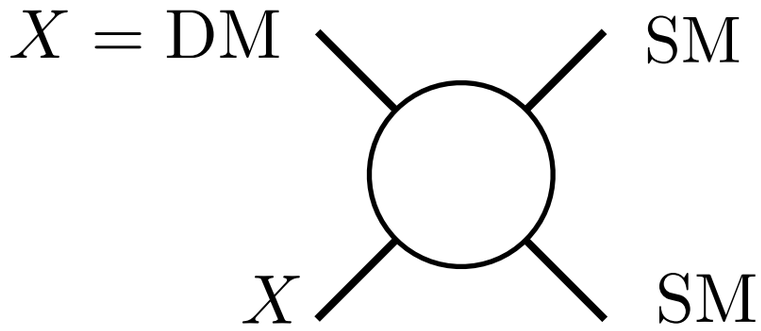
LSS (novo)

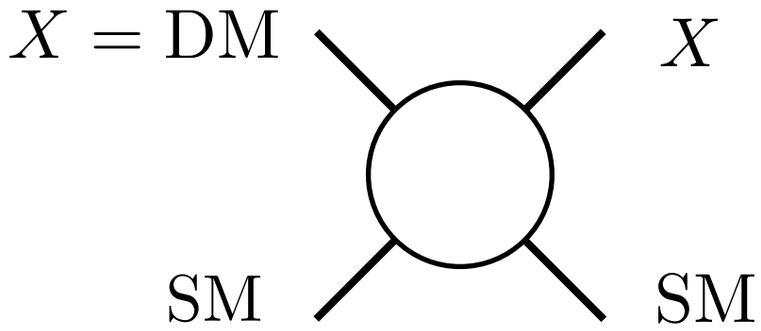
neutrino-less dvojni beta

EDMs

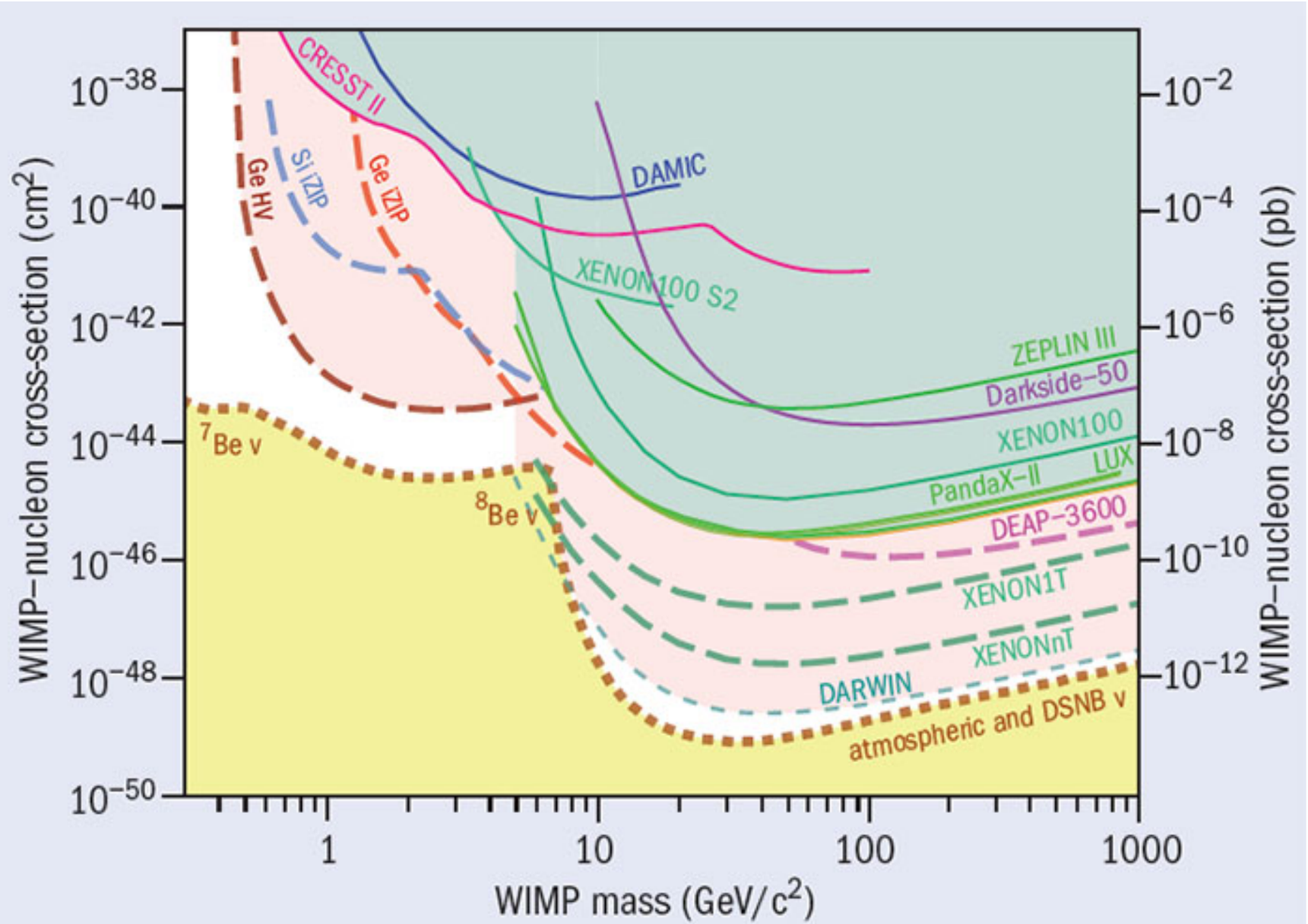
Direktna detekcija

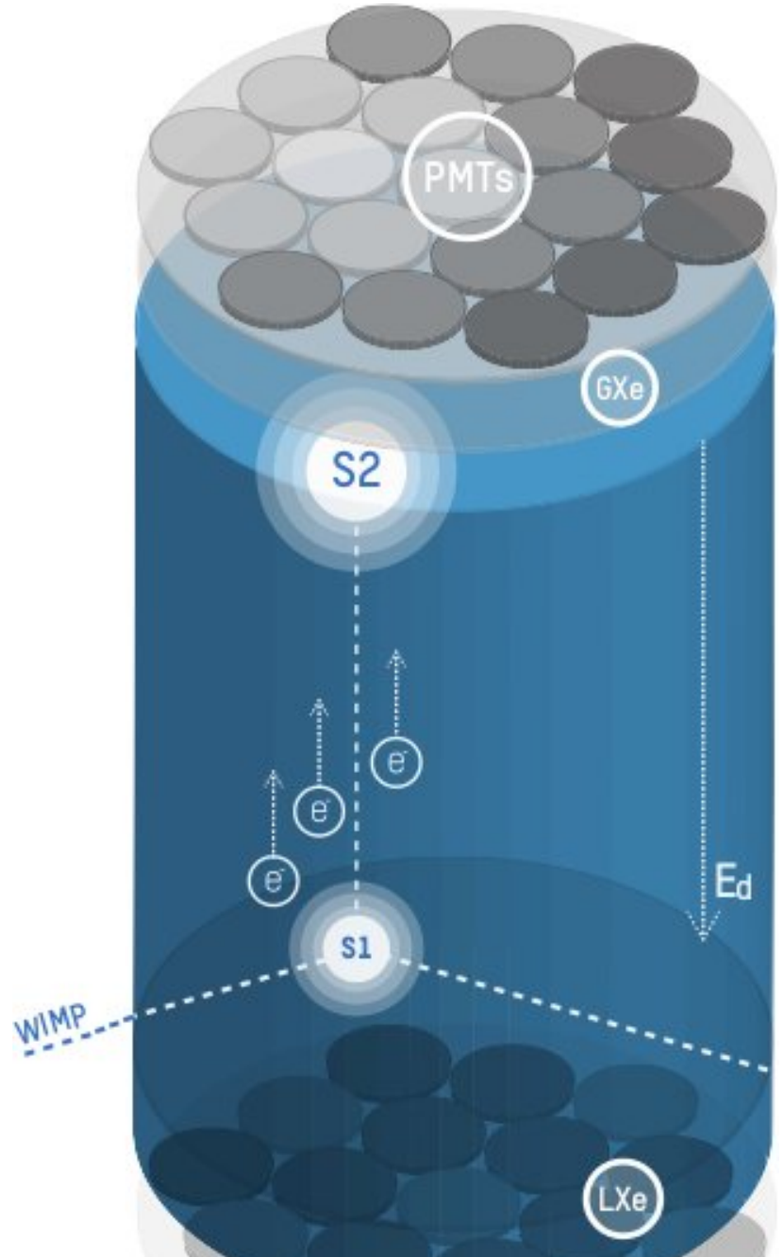
Zgodnje vesolje, plazma





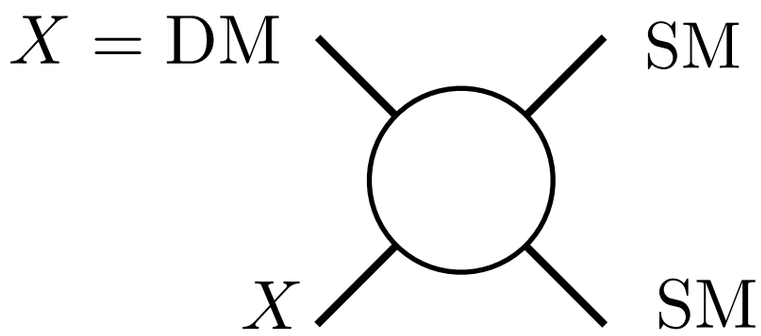
Lab., tarča

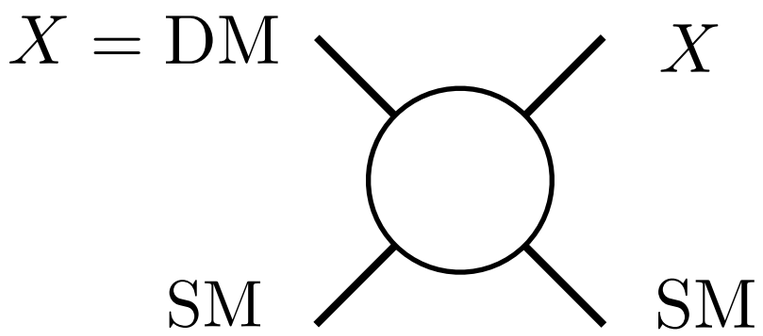




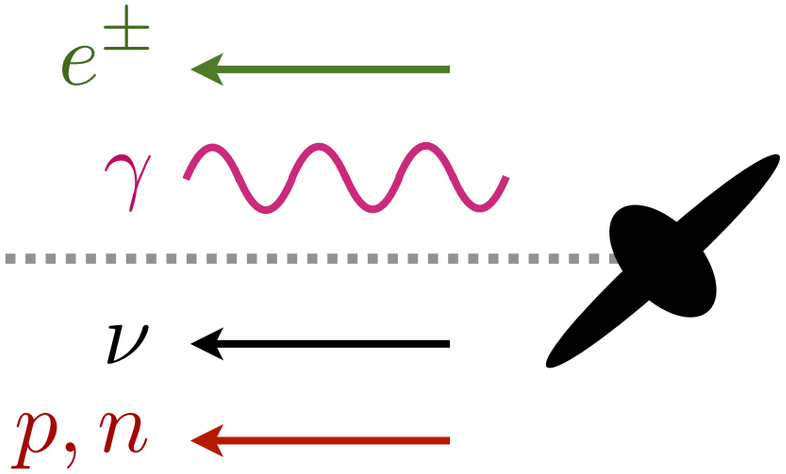
Indirektni signali

Zgodnje vesolje, plazma





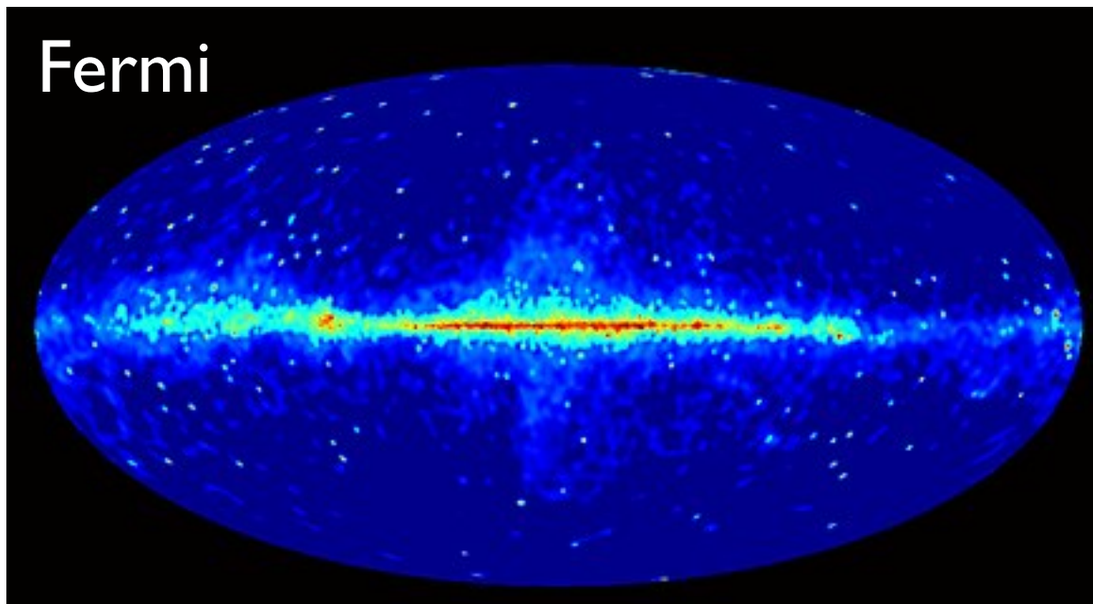
Zvezde



Anihilacija $\phi \propto n^2 \times \langle \sigma v \rangle$

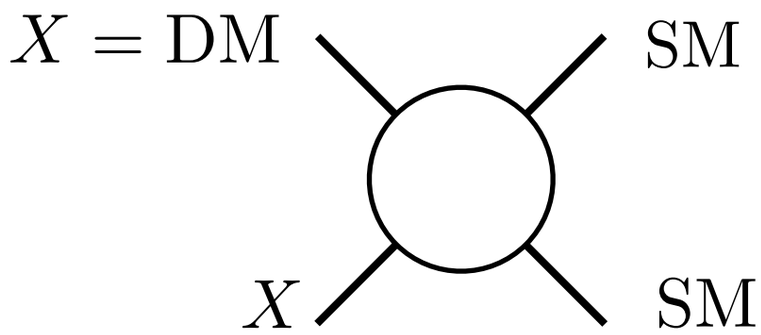
Razpad $\phi \propto \dfrac{n}{\tau_{\mathrm{DM}}}$

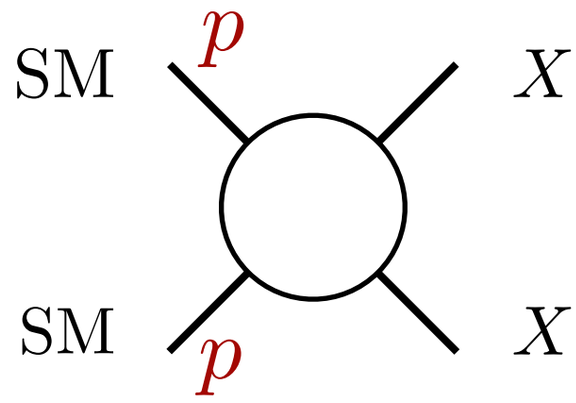
(7.5 keV črta)



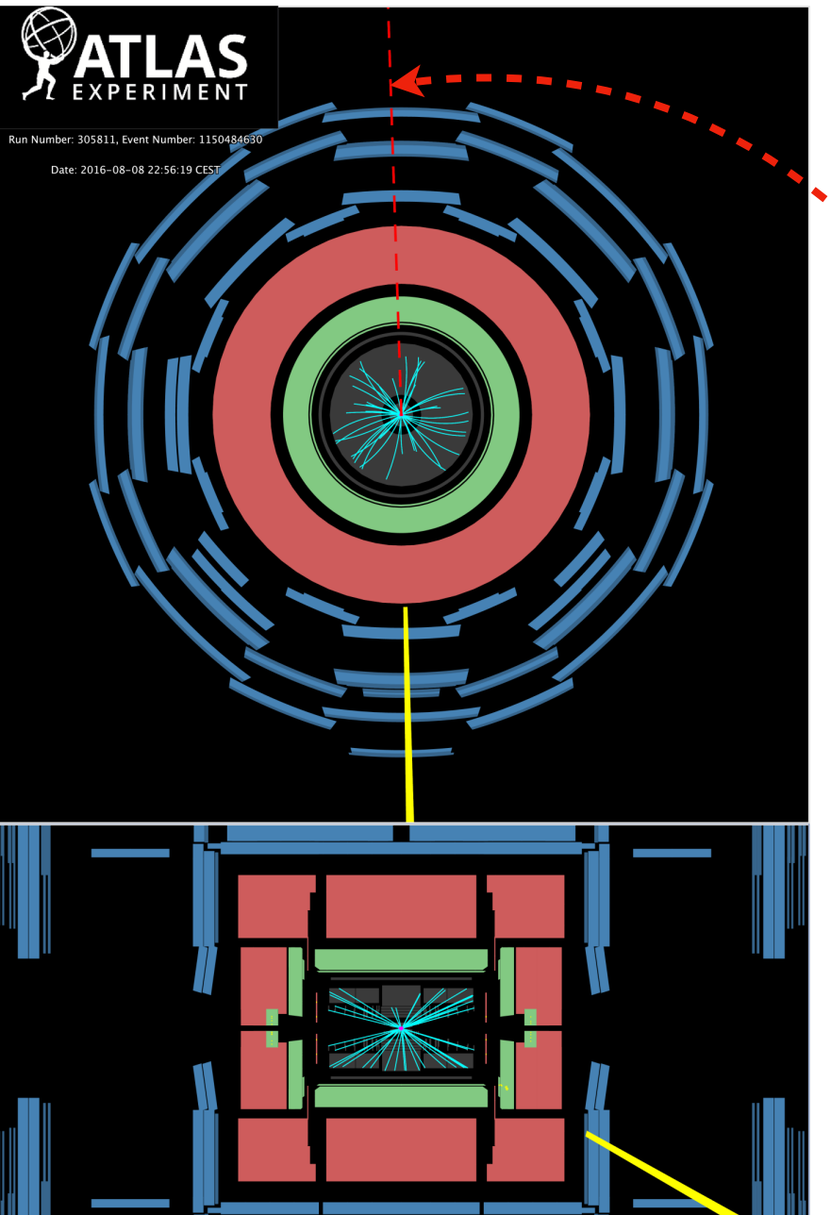
Temna snov in LHC

Zgodnje vesolje, plazma





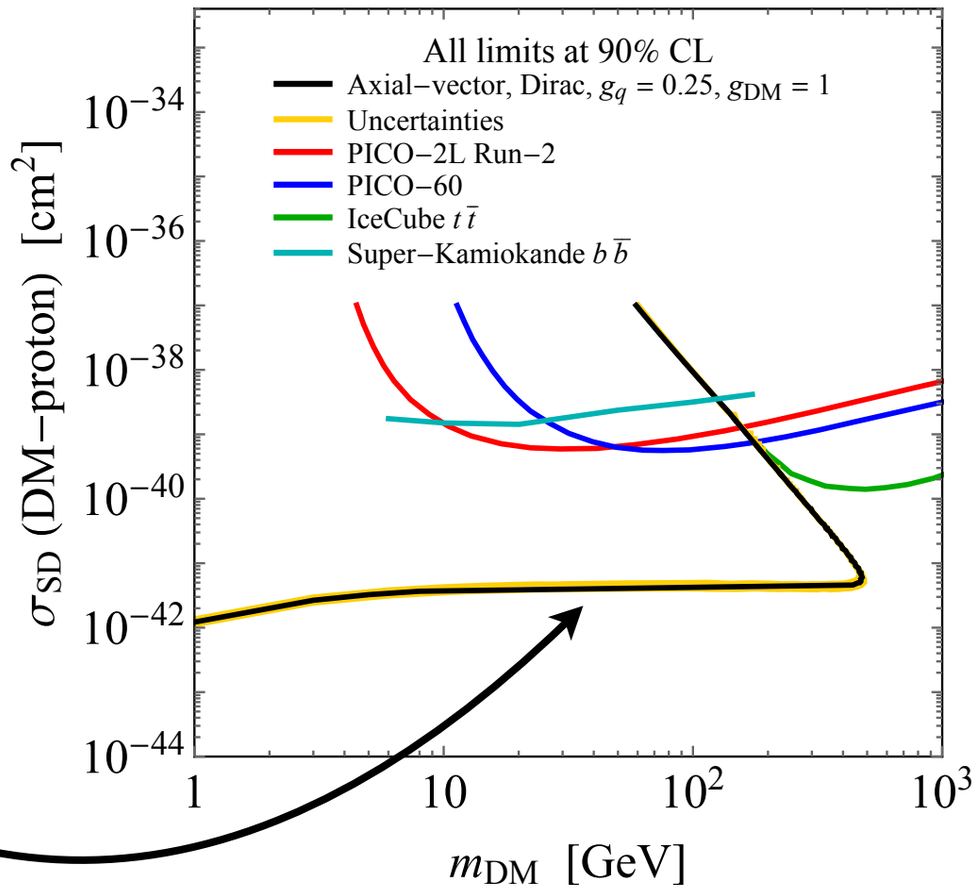
Trkalniki



Veliko iskanj na LHC: "DM working group"
SUSY, X-dim, generični skalarji, sterilni nevtrini, …

Signal = nekaj + manjkajoča E

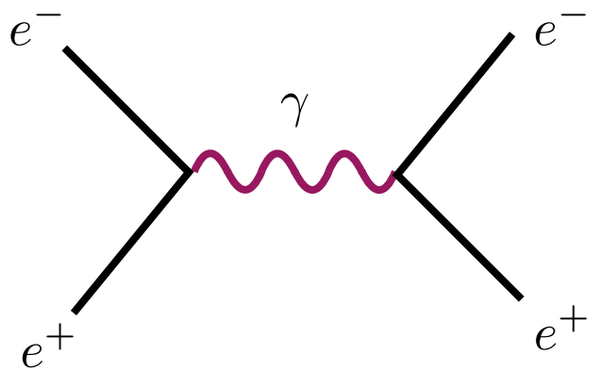
Komplementarno ostalim iskanjem



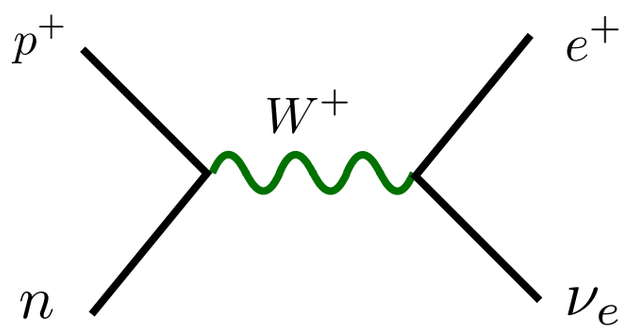
Aksioni

Teoretična motivacija: CP simetrija močne interakcije

QED



EW



QCD

$$\mathcal{L}_{\mathrm{QCD}} \ni \overline{\theta}\, G\tilde{G}$$

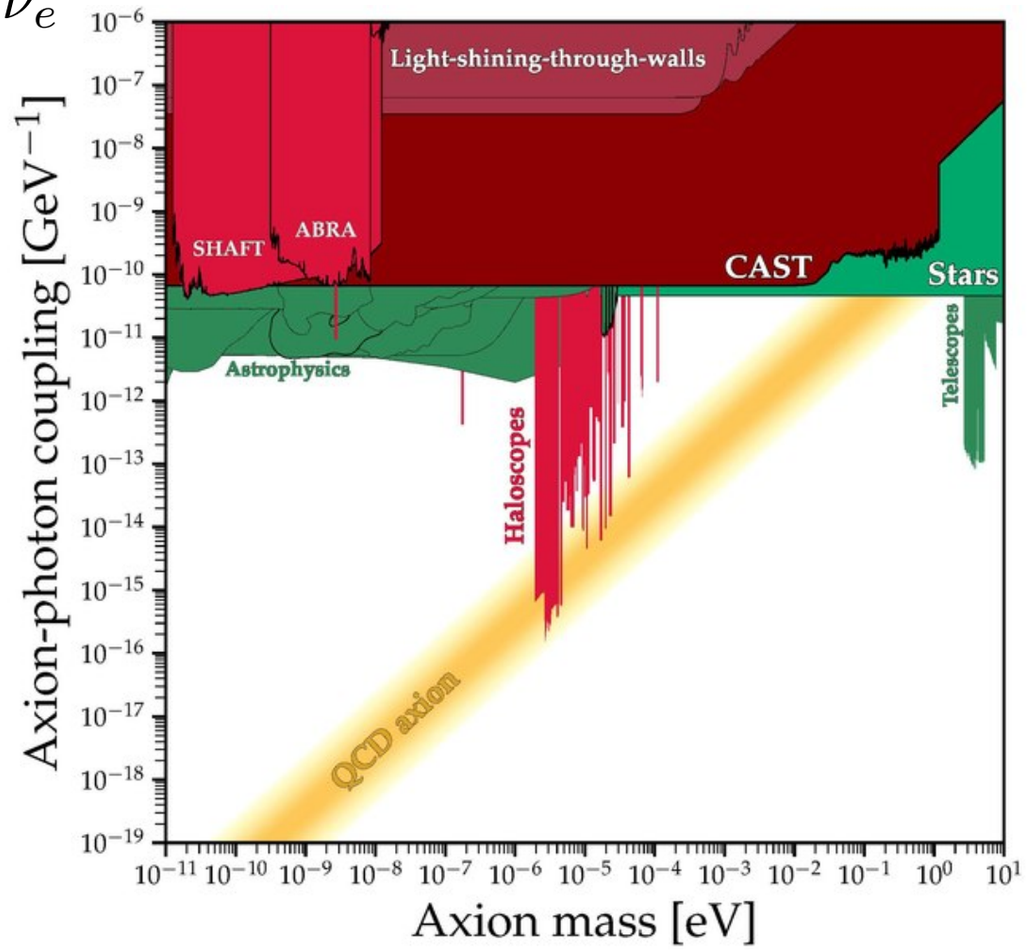
nEDM $\overline{\theta} < 10^{-10}$

Dinamična razlaga: aksion

$$\mathcal{L}_{\mathrm{PQ}} \ni \left(\overline{\theta} - a\right) G\tilde{G}$$

Številna iskanja $\mathcal{L}_{\mathrm{PQ}} \ni a\, F\tilde{F}$

Kandidat za temno snov, klasično polje

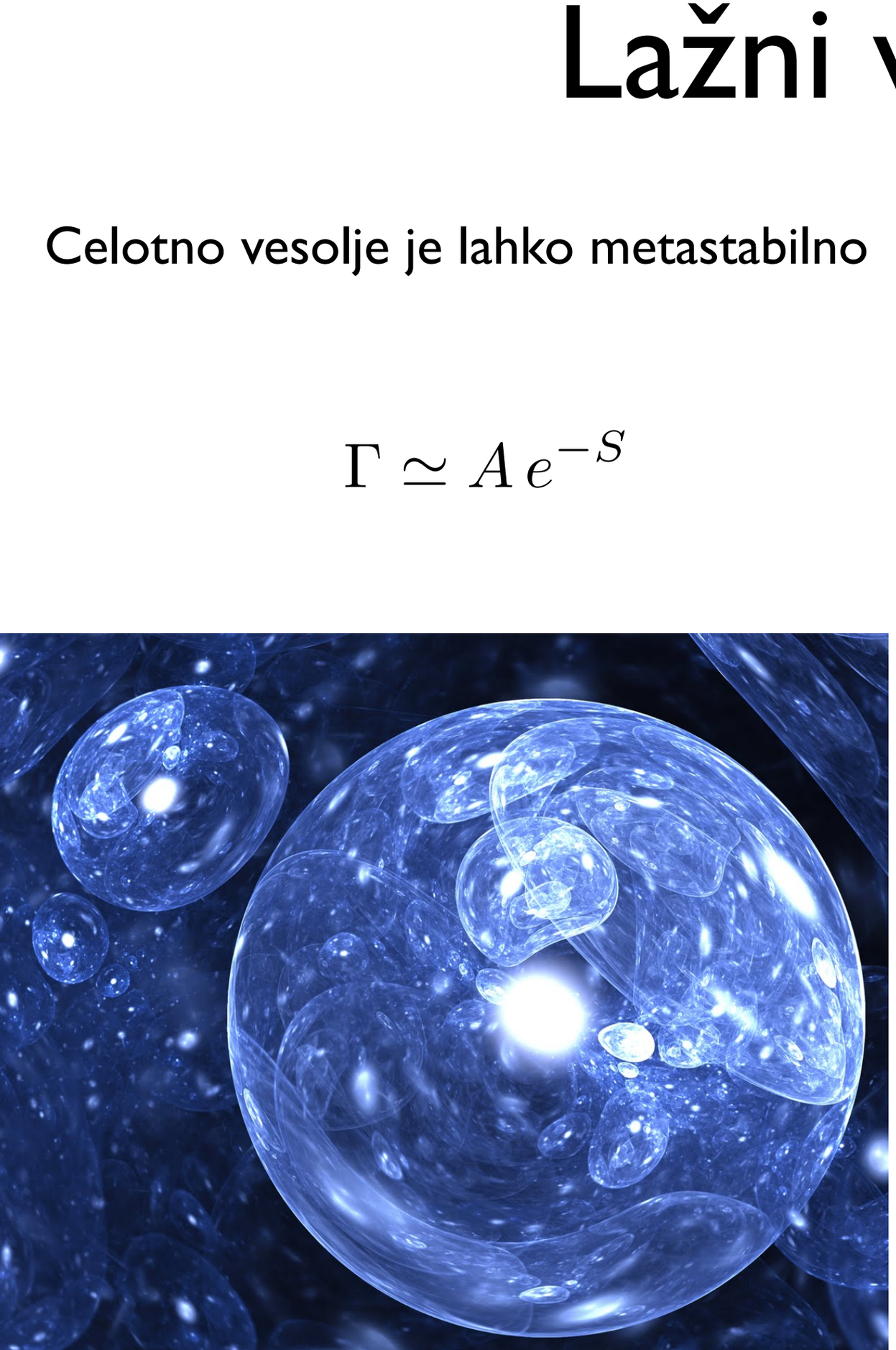


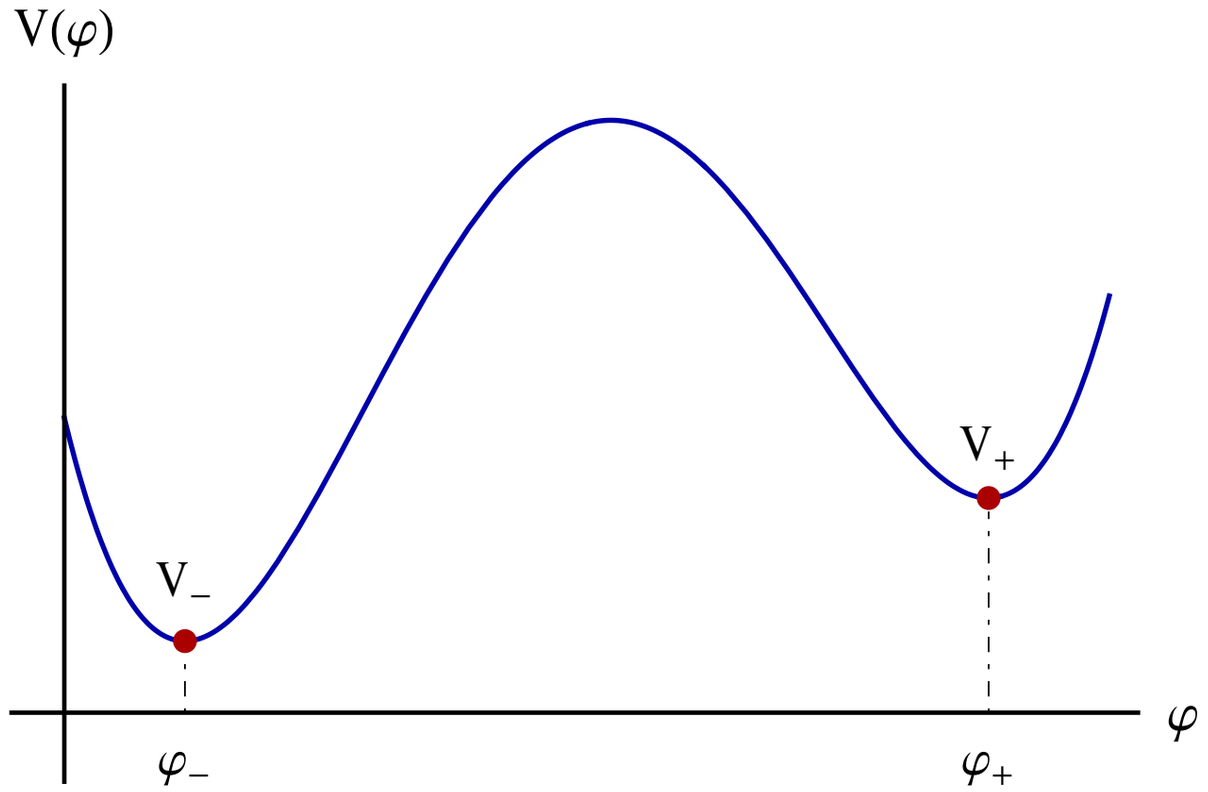
Fazni prehodi

Lažni vakuum

Celotno vesolje je lahko metastabilno

$$\Gamma \simeq A\, e^{-S}$$





Kvantne fluktuacije

$$T = 0\,, \qquad D = 4$$

Termične fluktuacije

$$T > 0\,, \qquad D = 3$$

Gravitacijski valovi

Zvočni valovi

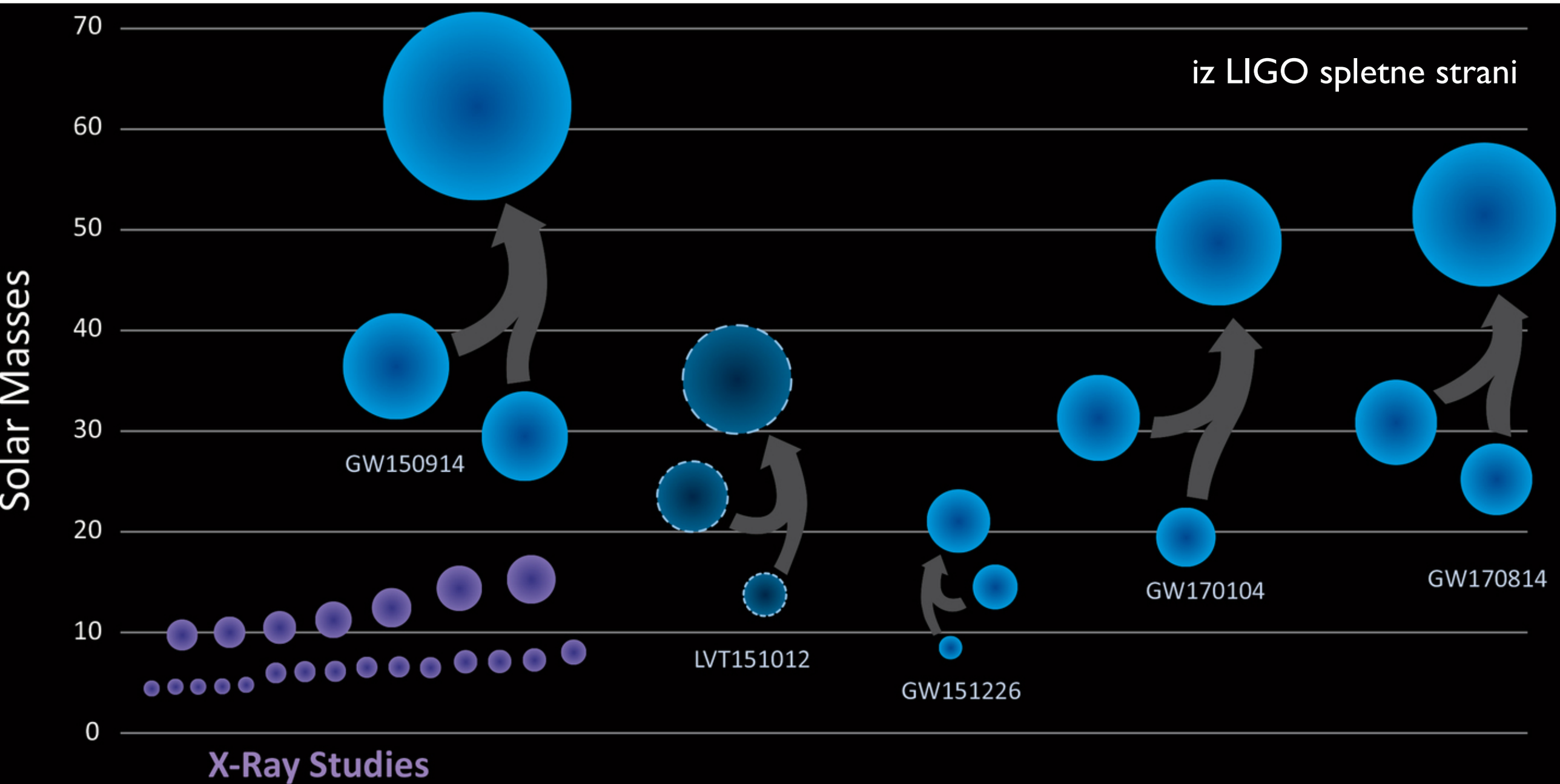
Trki mehurčkov

Turbulenca

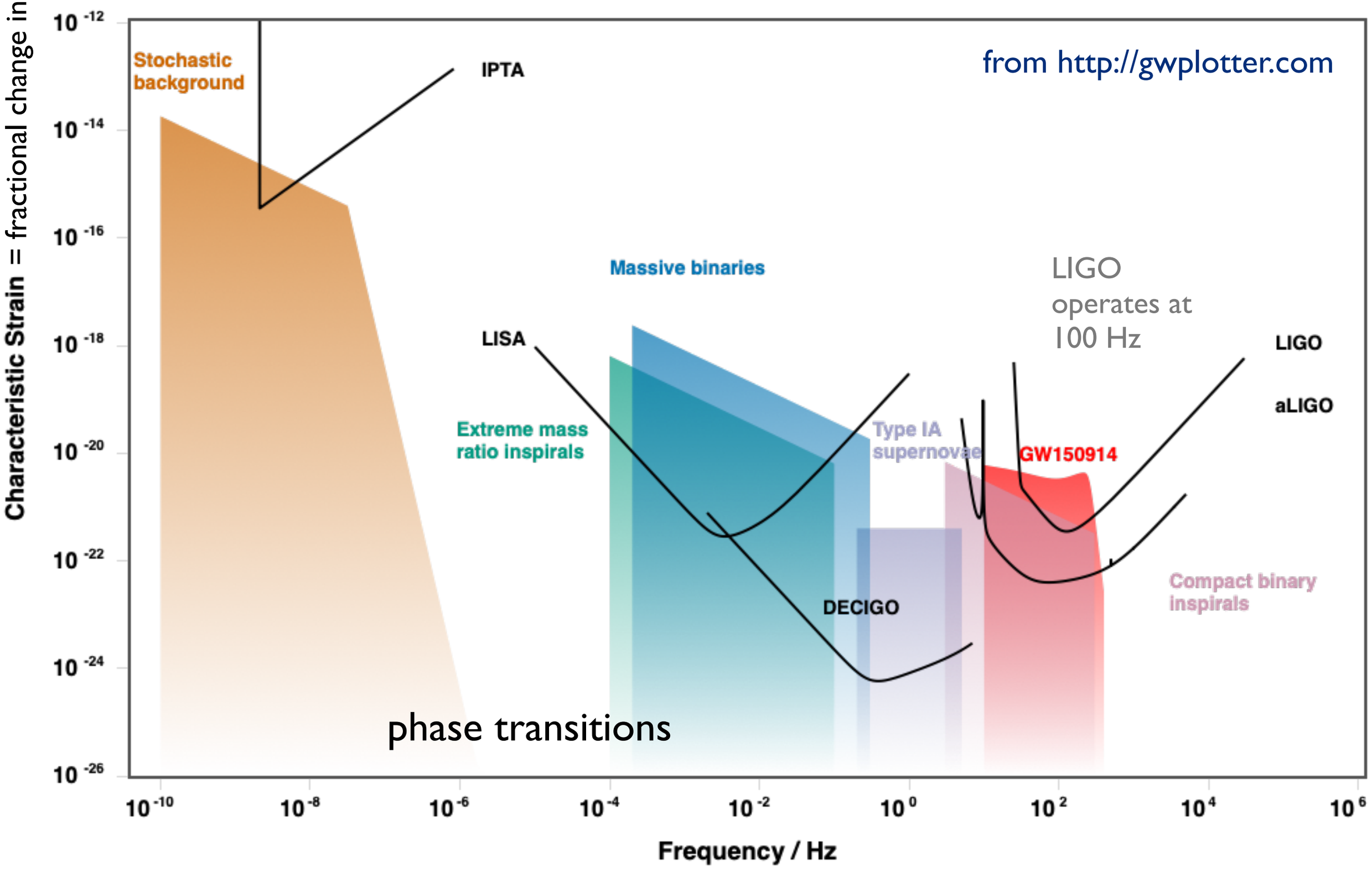
Gravitacijski valovi

Trenutni ‘točkasti izvori’ LIGO/VIRGO dogodki

združevanje črnih lukenj z O(10) sončevih mas, nevtronske zvezde



GW eksperimenti



IJS

Univerza *v Ljubljani*
Fakulteta za *matematiko in fiziko*

Hvala