Program

1) Why and how explore the TeV region

2) The hierarchy 'problems': Λ and m_{Higgs}.

3) Solutions to m_{Higgs} (both faces):
   - − Technicolor.
   - − Little-Higgs.
   - − Extra dimensions.
   - \+ Supersymmery.

4) Solutions to Λ:
   - −

5) Antrophic 'solutions' to all.

Alessandro Strumia, SNFT, Parma 2005

Status of high-energy physics

[Caution with over-enthusiast / over-pessimistic / politically-correct descriptions]

$\star$ SM proposed around 1970 (QCD after experiments, electroweak before).

- Since then **nothing** unexpected discovered at higher energies.

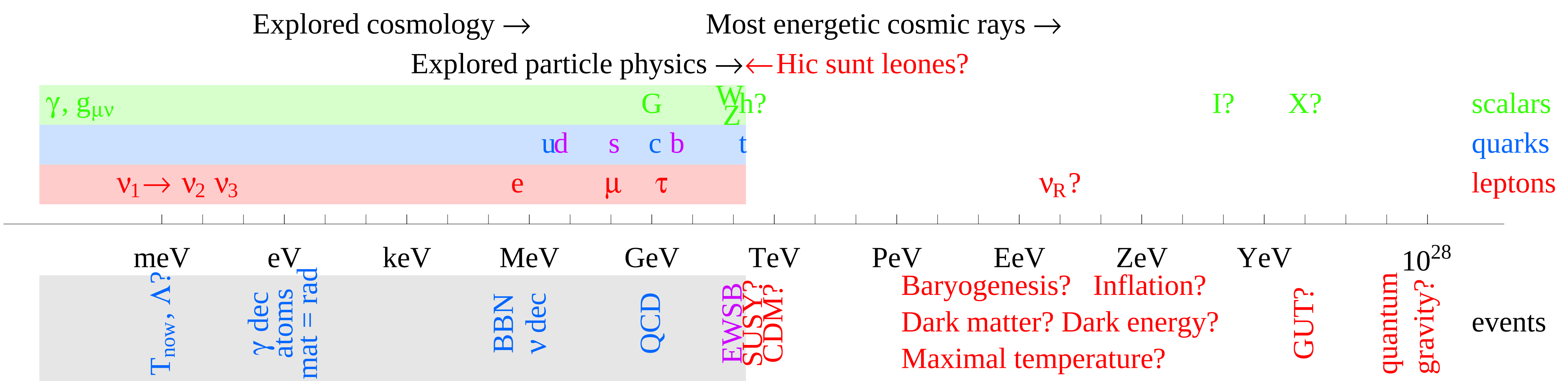
$\star$ But 2 **good** (=maybe right) reasons to theorize new physics at $E \sim$ TeV.

- But nothing seen just below it. Concrete proposals disfavored.

$\circ$ Working **hard**, colliders are **now** going to explore it.

Results will strongly impact theory and decide the future of the field

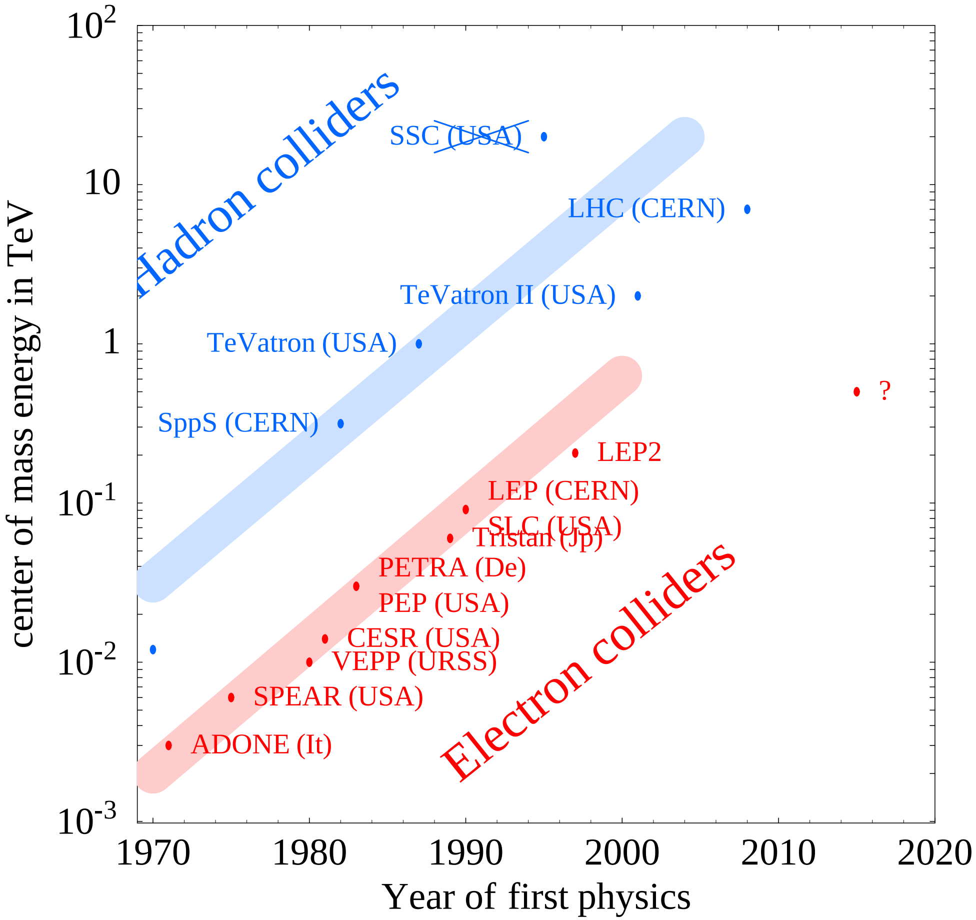
The energy scale



Goals of TeV experiments: (1) thermal dark matter,
(2) understand electroweak symmetry breaking.

Experiments

Towards the TeV



Divide energy of hadron colliders by a few to get their **mean** energy: p is composite of a few quarks.

Past exponential increase in energy achieved thanks to new technologies. E.g. first small hadron collider made obsolete big target experiments. Recently slower progress thanks to 30 km, 20 yr, few G€.

From LHC to ILC?

Higher energy need higher luminosity: LHC aims at $\mathcal{L} \sim$ few/nb $\cdot$ sec = bomb

$$\sigma \sim \frac{1}{E^2} = 0.4\,\mathrm{nb}\frac{\mathrm{TeV}^2}{E^2} \qquad \mathrm{nb} \equiv 10^{-33}\,\mathrm{cm}^2$$

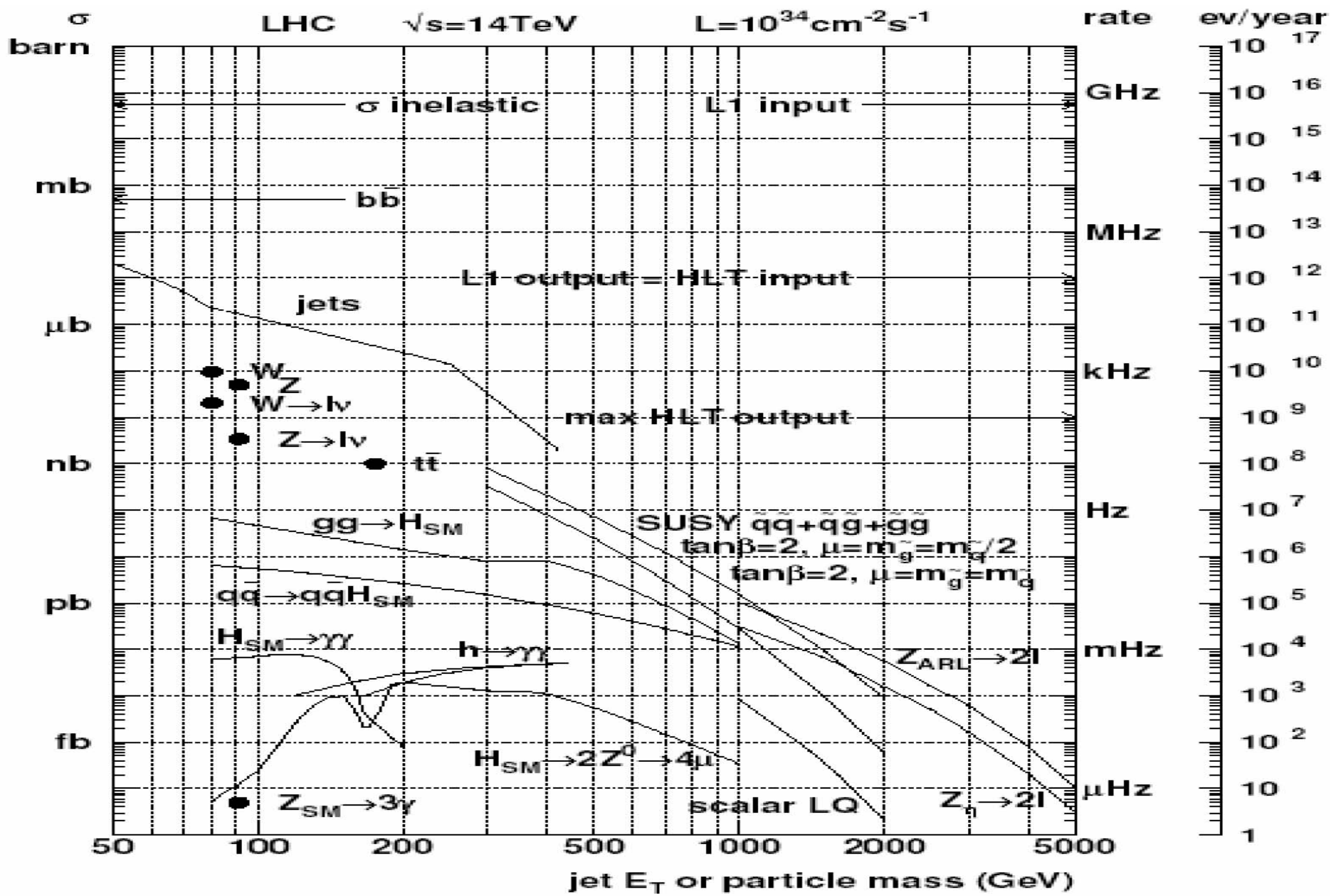
Proton size $\sigma \sim 1/m_p^2 \gg 1/E^2$ gives more junk that what computers can store:
(1) trash almost all data with fast triggers (keep missing $\not{E}_T$, energetic particles)
(2) remains a combination of everything. Analyze with grid of computers.
(3) if something discovered, to understand it a cleaner e^+e^- might be needed.

Circular e^+e^- colliders limited by radiation: Larmor $dE/dx = 2e^2\gamma^4\beta^3/3R^2$:

$$\frac{E_{\max}}{m_e} = \gamma_{\max} \approx \sqrt[4]{R^2 \cdot dE/dx|_{\max}} \sim 6\ 10^5\sqrt{\frac{R}{5\,\mathrm{km}}}\sqrt[4]{\frac{dE/dx|_{\max}}{m_e c^2/10\,\mathrm{cm}}}$$

The next project seems a **linear e^-e^+** collider at $\sqrt{s} \gtrsim 500\,\mathrm{GeV}$: needs $\sim 50\,\mathrm{km}$

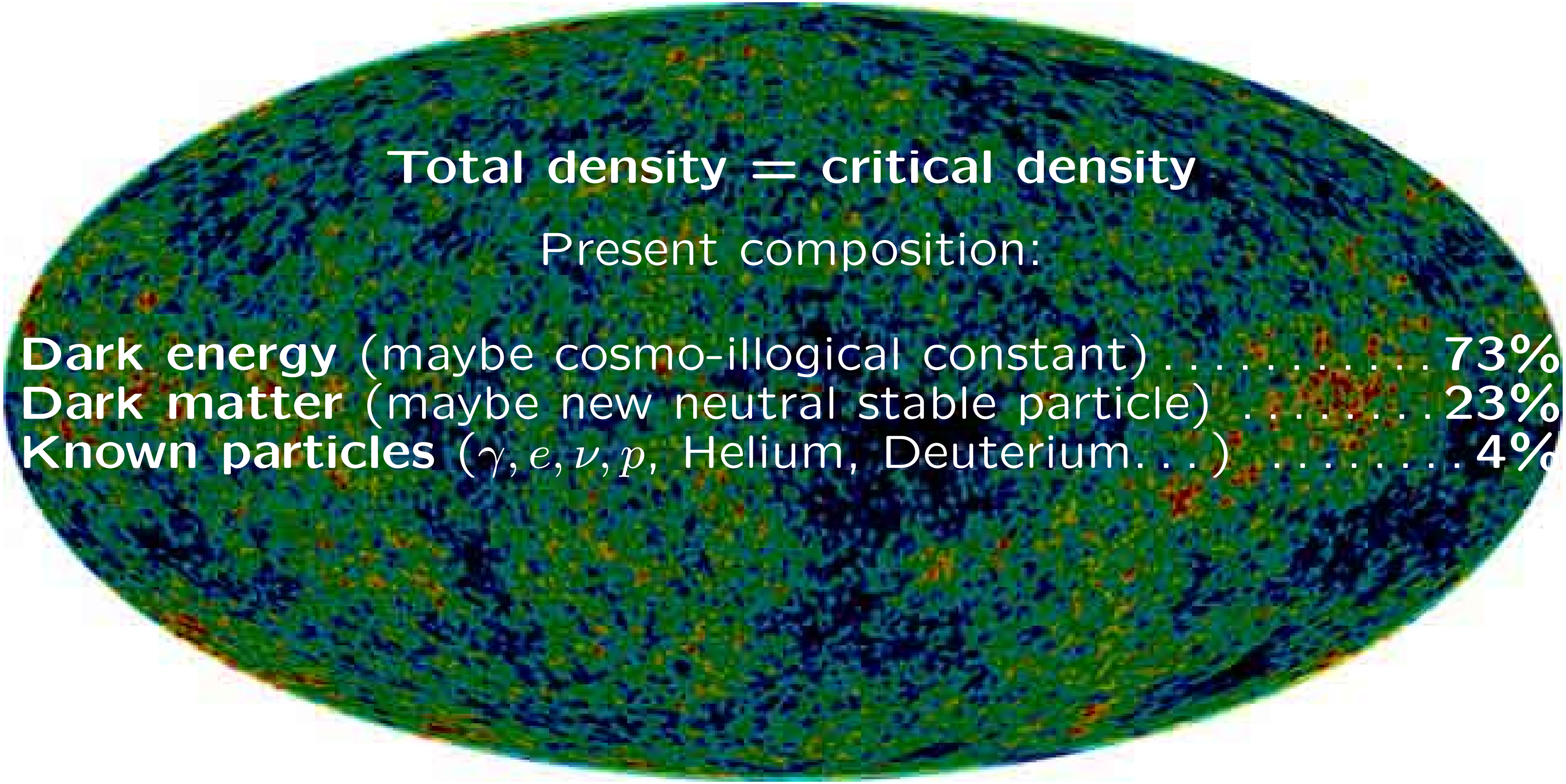
code	Optimistic name	Pessimistic joke
LHC	Large Hadron Collider	Last Hadron Collider
ILC	International Linear Collider	Imaginary Linear Collider



σ
barn
LHC
√s=14TeV
L=10^34 cm^-2 s^-1
rate
ev/year
σ inelastic
L1 input
GHz
mb
b b̄
MHz
L1 output = HLT input
jets
μb
W
Z
W→lν
Z→lν
kHz
max HLT output
nb
t t̄
gg→H_SM
Hz
SUSY q̃q̃+q̃g̃+g̃g̃
tanβ=2, μ=m_g̃=m_q̃/2
tanβ=2, μ=m_g̃=m_q̃
qq̄→qq̄H_SM
pb
H_SM→γγ
h→γγ
mHz
Z_ARL→2l
fb
H_SM→2Z^0→4μ
Z_SM→3γ
scalar LQ
Z_η→2l
μHz
50
100
200
500
1000
2000
5000
jet E_T or particle mass (GeV)
10^17
10^16
10^15
10^14
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1

Thermal dark matter

Inventory



Total density = critical density

Present composition:

Dark energy (maybe cosmo-illogical constant) **73%**
Dark matter (maybe new neutral stable particle) **23%**
Known particles (γ, e, ν, p, Helium, Deuterium. . .) **4%**

Big bang: $H \sim T^2/M_{\rm Pl}$

Homogeneous $\rho(t)$ expands according to Newton acceleration

$$\ddot{R} = -\frac{GM(r<R)}{R^2} = -\frac{4\pi G\rho(t)}{3}R$$

Get 'energy constant' k assuming non-relativistic matter: $\rho(t) \propto 1/R^3(t)$:

$$\frac{d}{dt}\left[\frac{1}{2}\dot{R}^2 - \frac{4\pi}{3}G\rho R^2\right] = 0 \qquad H^2 \equiv \frac{\dot{R}^2}{R^2} = \frac{8\pi G}{3}\rho - \frac{k}{R^2}$$

Critical case $k=0$: needs $\rho = 3H^2/8\pi G \equiv \rho_{\rm cr}$ and expands for free. Valid for all ρ in general relativity, where k is curvature; inflation smoothes $k \to 0$.

Matter in thermal equilibrium at temperature $T \gg m$ has density

$$n_{\rm eq} \sim T^3 \qquad \rho_{\rm eq} \sim T^4$$

one particle with energy $\sim T$ per de-Broglie wavelength $\sim 1/T$.
Non relativistic particles are Boltzmann-suppressed: $n_{\rm eq} \sim e^{-m/T}(mT)^{3/2}$.

PS: in units $\hbar = c = 1$ $G = 1/M_{\rm Pl}^2$ with $M_{\rm Pl} \sim 10^{19}$ GeV.

Dark matter as thermal relic

What happens to a stable particle at $T < m$?

Scatterings try to give thermal equilibrium

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

But at $T \lesssim m$ they become too slow:

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

Out-of-equilibrium relic abundancy:

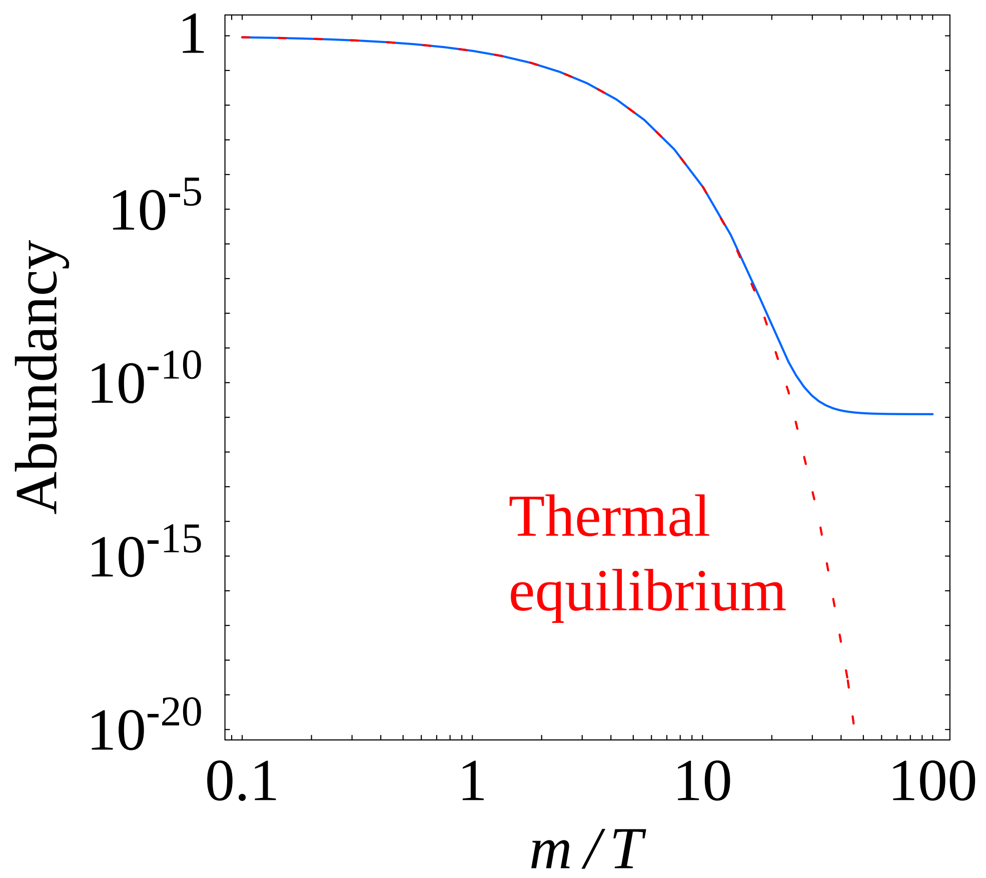
$$\frac{n_{\rm DM}}{n_\gamma} \sim \frac{T^2/M_{\rm Pl}\sigma}{T^3} \sim \frac{1}{M_{\rm Pl}\sigma m}$$

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

Inserting $\rho_{\rm DM} \sim \rho_\gamma$ and $\sigma \sim 1/m^2$ fixes

$$m \sim \sqrt{T_{\rm now}M_{\rm Pl}} \sim \text{TeV}$$

Directly produced at CERN 2008?



Cosmological constant

ρ_Λ = energy (and pressure) density of vacuum = Energy/Volume = Mass^4

$$\mathscr{L}_{\text{Einstein}} = \int d^4x \sqrt{g} \left[\frac{R}{16\pi G} - \rho_\Lambda\right]$$

$$R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu} \qquad \Lambda = 8\pi G \rho_\Lambda$$

Positive Λ makes expansion faster .

Theory

EW-breaking suggests $\rho_\Lambda \sim V_{\text{min}} = [V_0 - m^2 H^2 + \lambda H^4]_{\text{min}} \sim \lambda v^4 \sim 10^{55} \rho_\Lambda$.

GUT-breaking suggests $V_{\text{min}} \sim M^4_{\text{GUT}} \sim 10^{110} \rho_\Lambda$.

Quantum corrections to Λ seem $\mathcal{O}(\Lambda^4_{\text{UV}})$: 10^{120} too large if $\Lambda_{\text{UV}} \sim M_{\text{Pl}}$

QCD gives $V_{\text{QCD}} \sim \Lambda^4_{\text{QCD}} \sim 10^{35}\Lambda$.

Expectation was: some unknown mechanism sets $\Lambda = 0$

Experiment

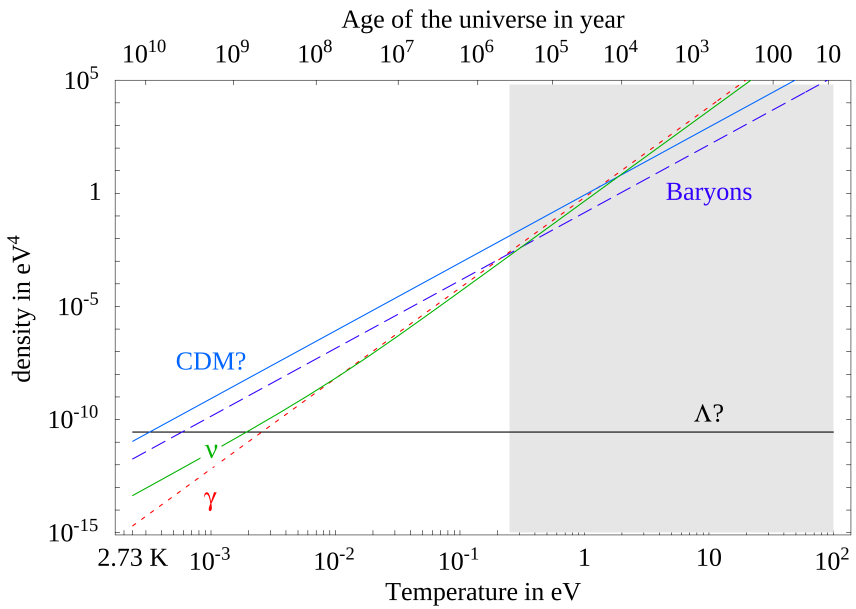
There are two ‘evidences’ for a small positive cosmological constant

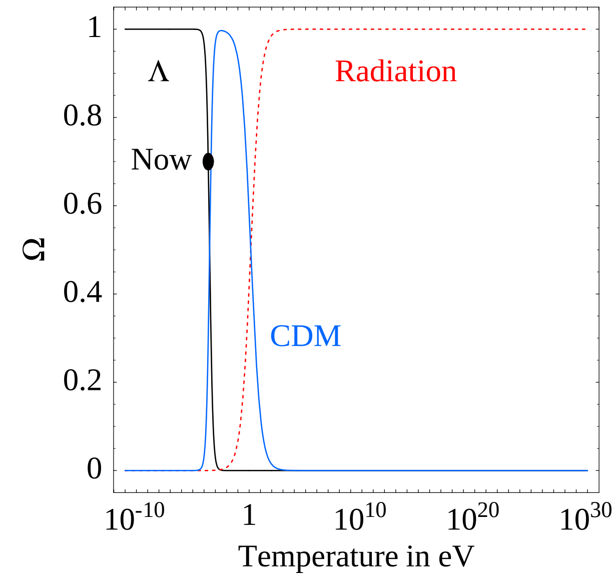
$$\rho_\Lambda \approx (2.3\ 10^{-3}\,\text{eV})^4 \sim 10^{-30}\text{g/cm}^3 \qquad \Lambda \sim H^2 \sim (10^{-33}\,\text{eV})^2$$

1. Older supernova explosions seem fainter [1998]: accelerated expansion.
2. CMB and LSS data suggest $\Omega_{\text{CDM}} = 0.3$, $\Omega_{\text{tot}} = 1$ [2002]: $\Omega_{\text{DE}} = 0.7$.

Cosmo-illogical constant

Evolution of the average energy densities of photons, neutrinos, baryons, Cold Dark Matter and cosmological constant Λ.





Why $\Omega_\Lambda \sim 1$ now?

The hierarchy ‘problems’

Continua su → www.cern.ch/astrumia/BSM.pdf