14-15 October 2024
SOUP School - Bertinoro

Dark Matter
evidences and candidates

Marco Cirelli
(LPTHE Jussieu CNRS Paris)

LPTHE LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES
cnrs dépasser les frontières
SORBONNE UNIVERSITÉ CRÉATEURS DE FUTURS DEPUIS 1257

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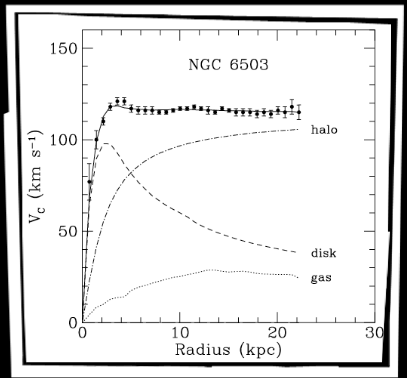
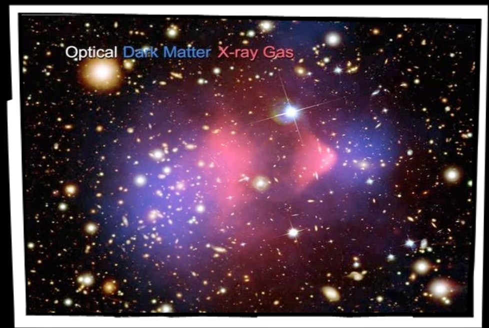
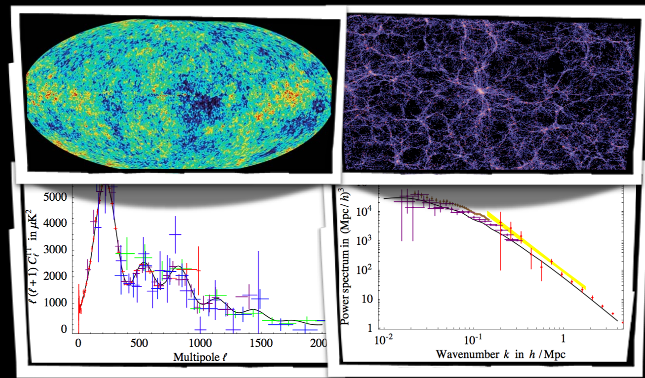


galactic rotation curves



weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

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Planck 2015, 1502.01589 (tab.4)

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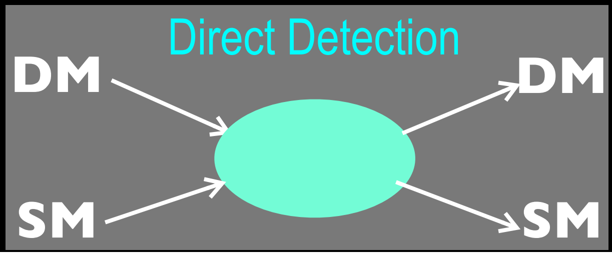

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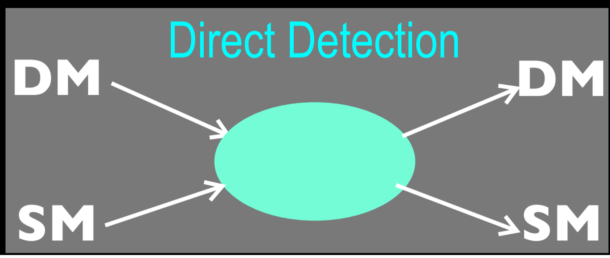

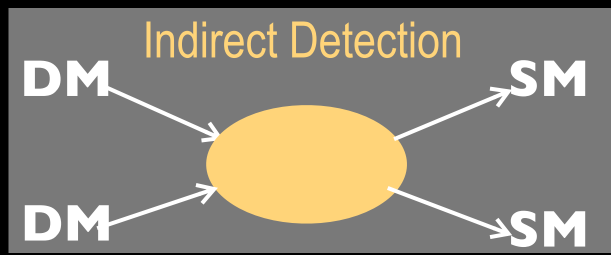

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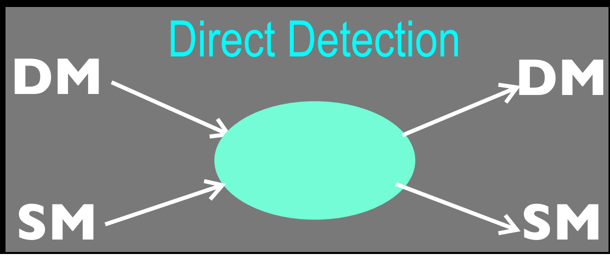
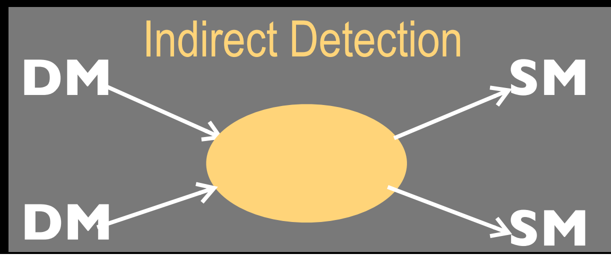
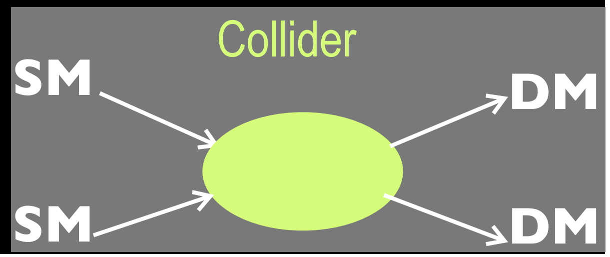
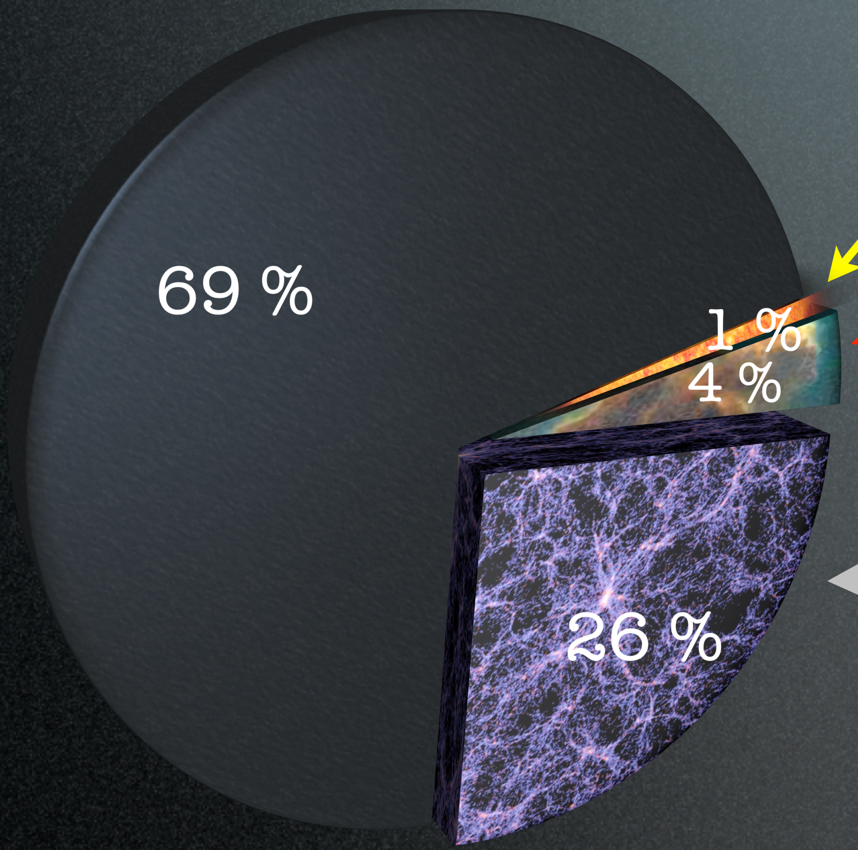






The cosmic inventory

Most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$

$\Omega_{\rm b} \simeq 0.040 \pm 0.005$

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

$\Omega_{\rm de} \sim 0.69$

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what's the difference
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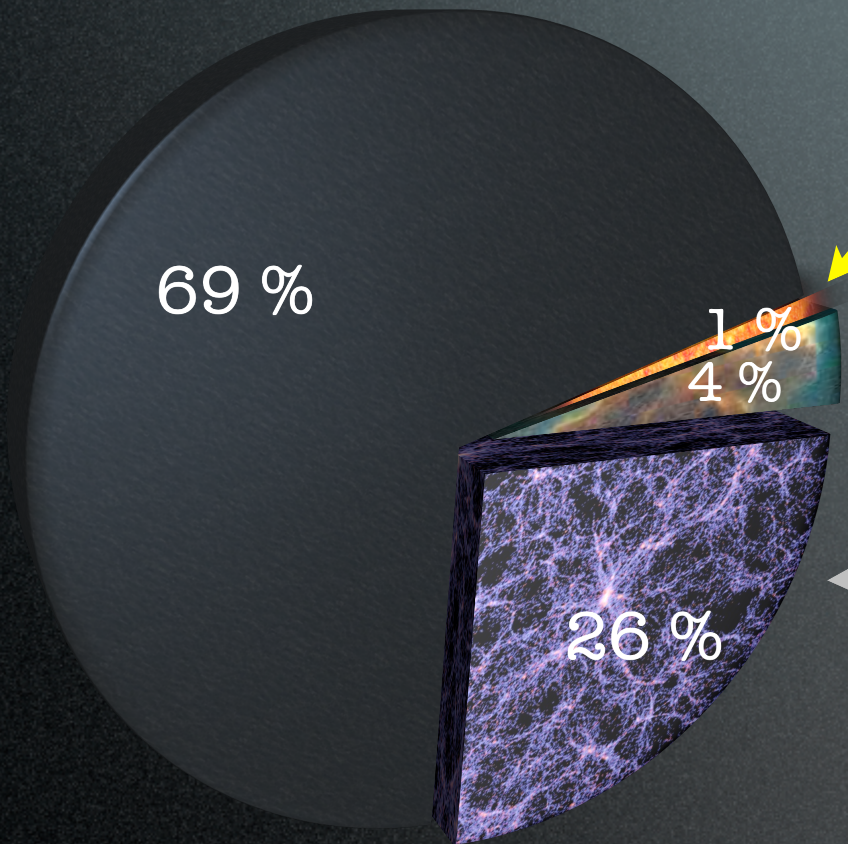

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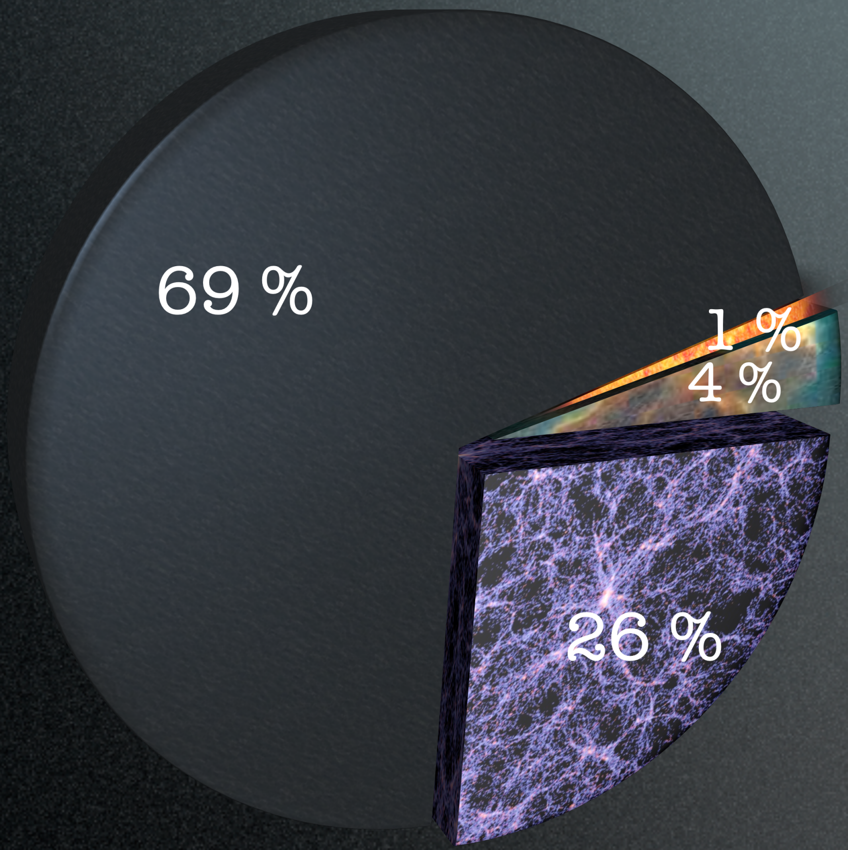

FAvgQ: what's the difference between DM and DE?

DM behaves like matter

- overall it dilutes as volume expands
- clusters gravitationally on small scales
- $w = P/\rho = 0$ (NR matter)
  (radiation has $w = -1/3$)

DE behaves like a constant

- it does not dilute
- does not cluster, it is prob homogeneous
- $w = P/\rho \simeq -1$
- pulls the acceleration, FRW eq. $\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3}(1+3w)\rho$

Evolution of the components of the Universe

NB: Log-Log scale

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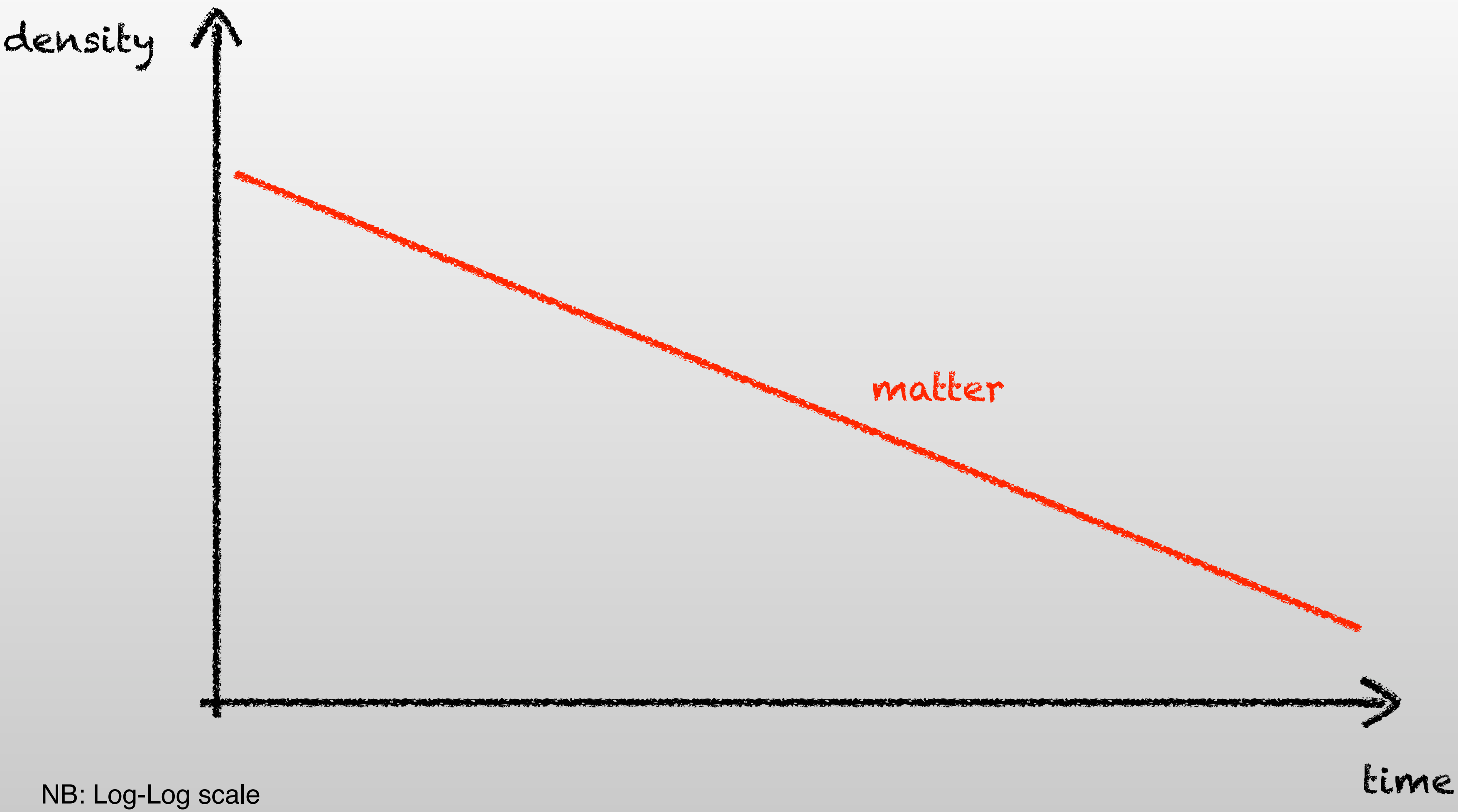

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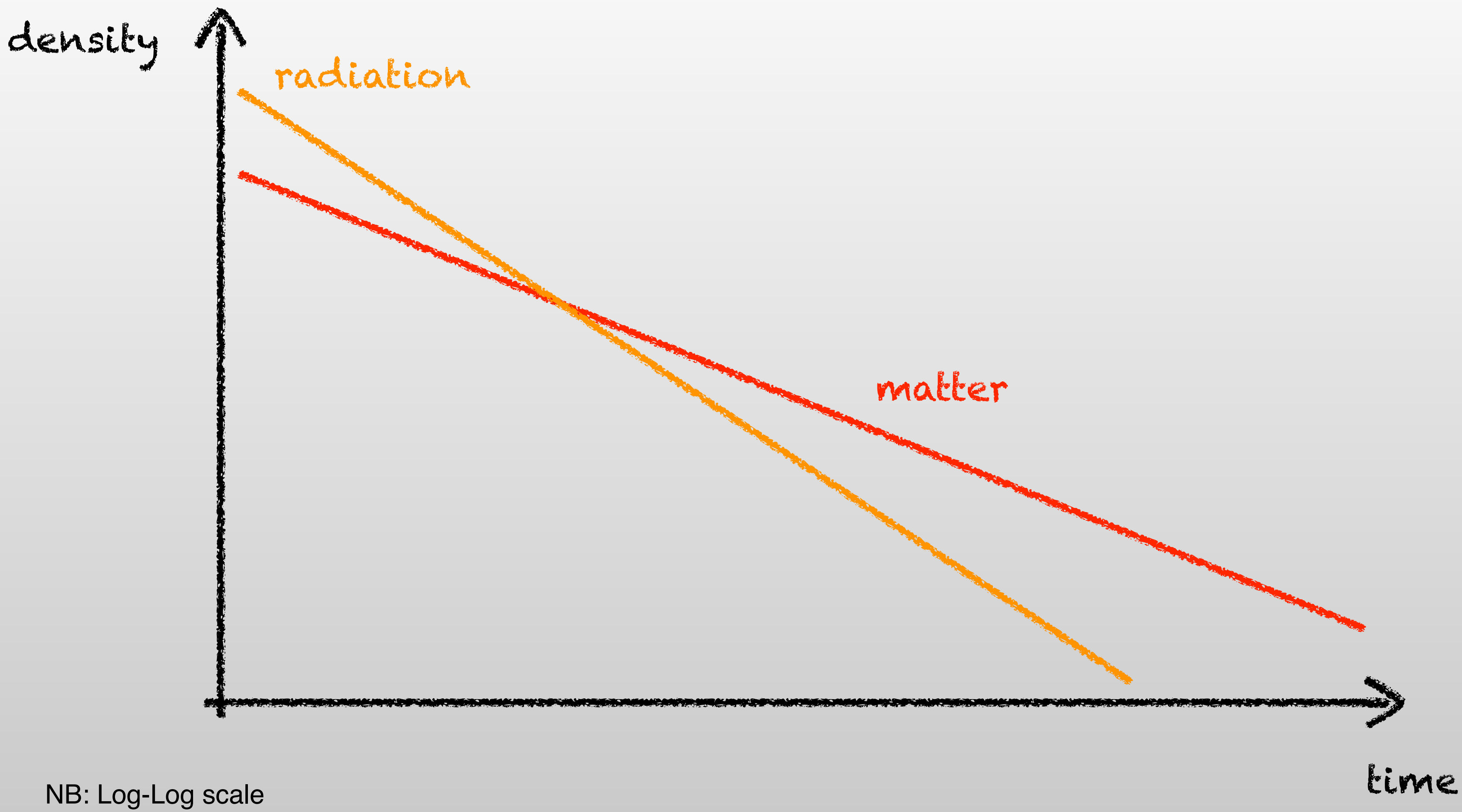

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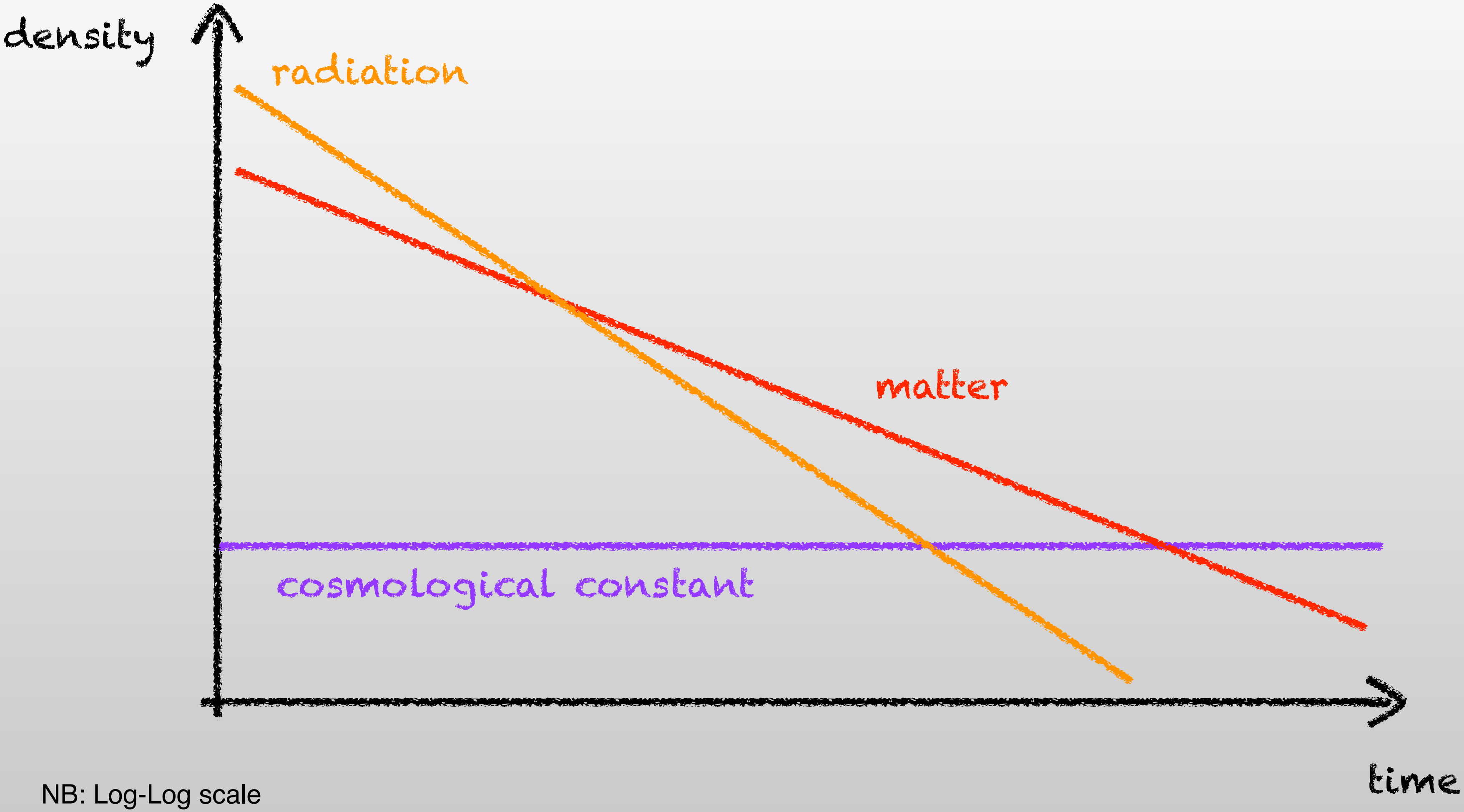

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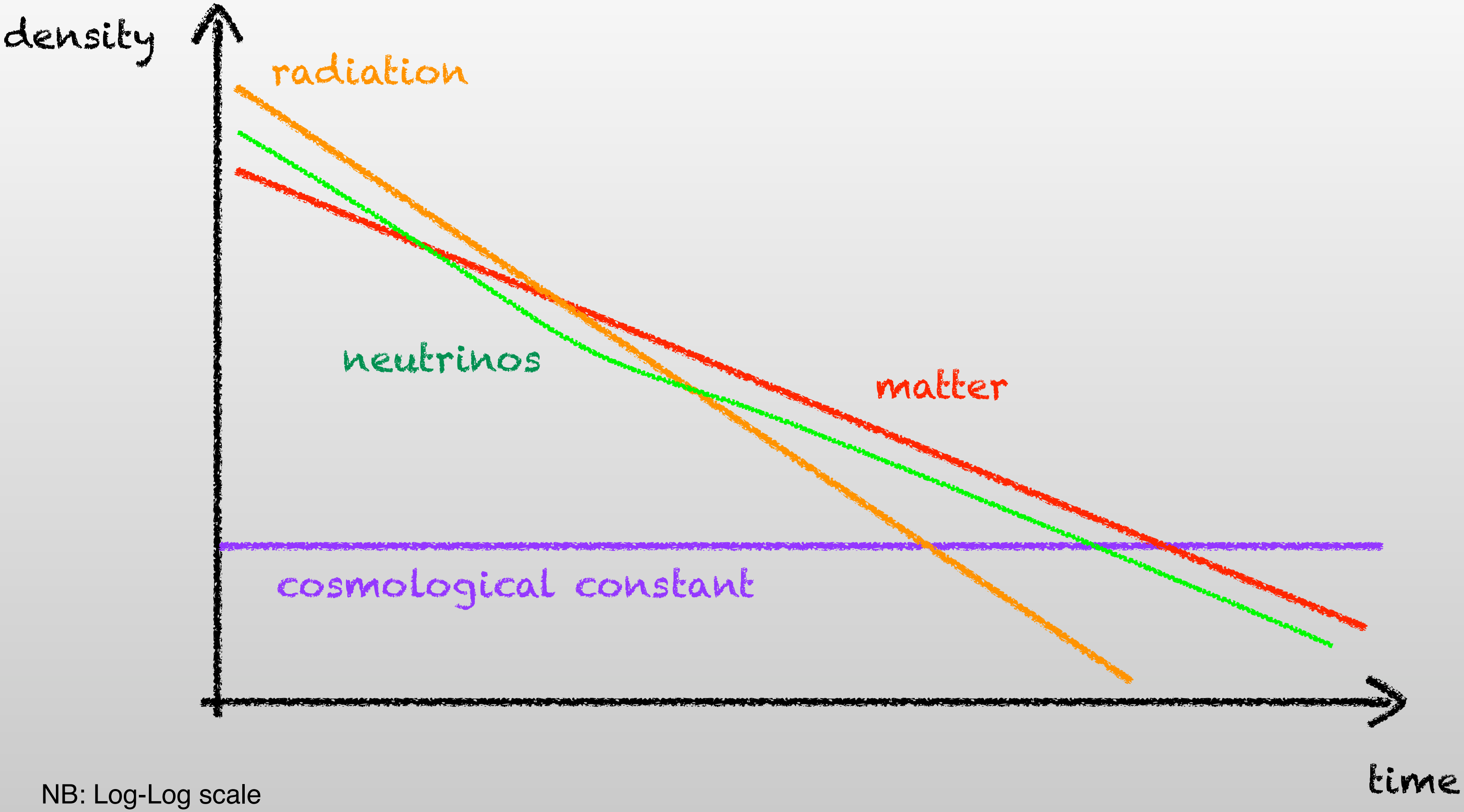

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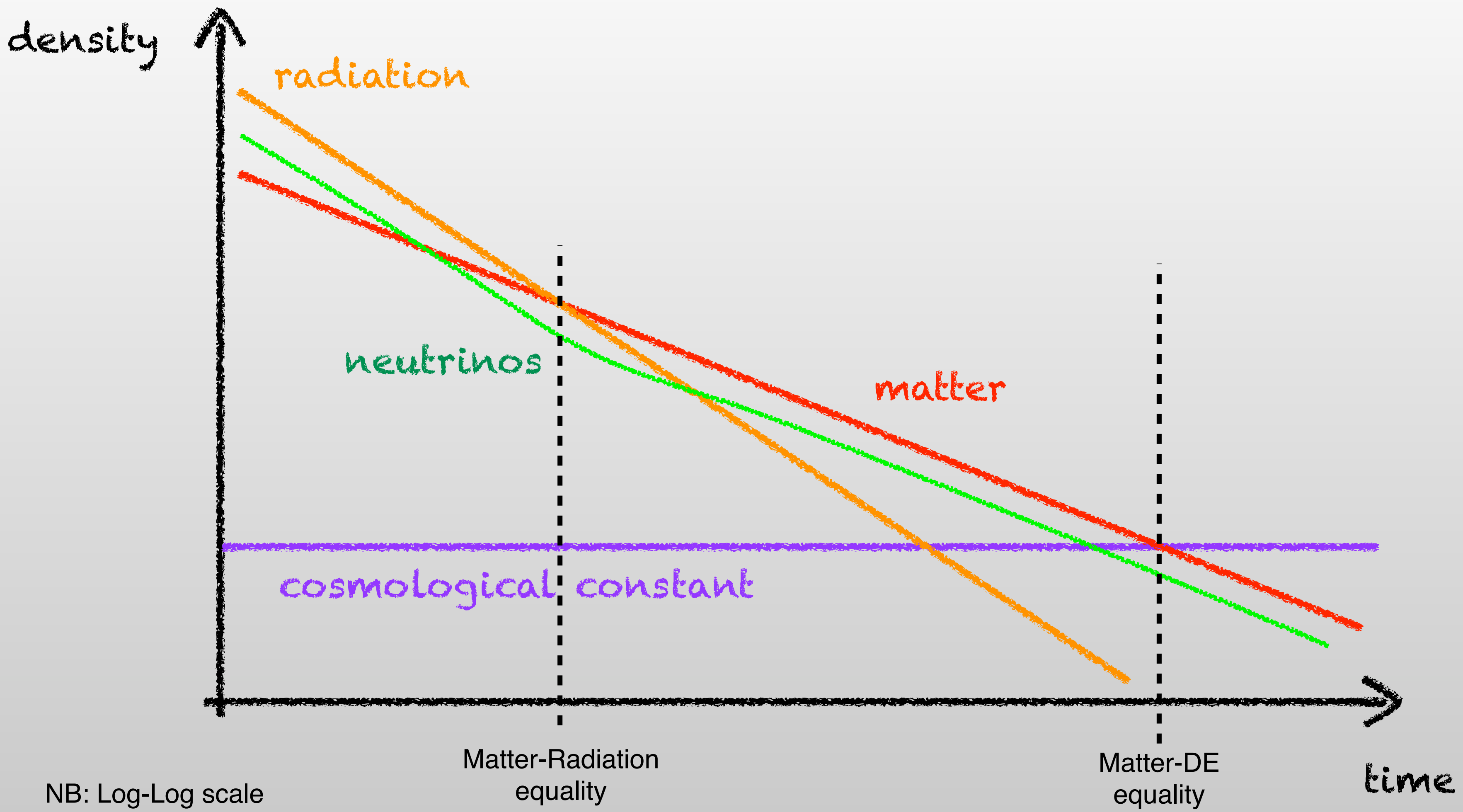

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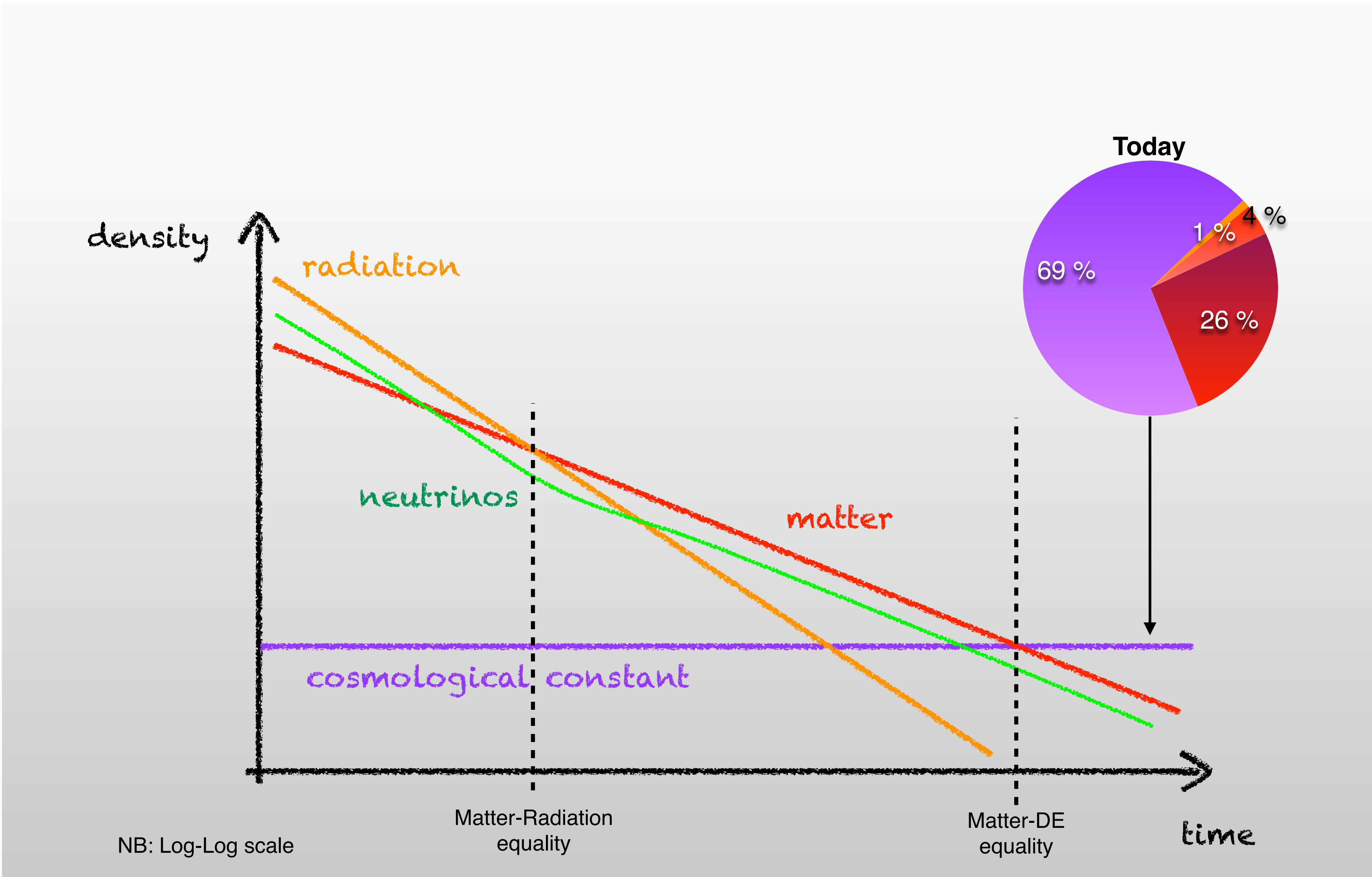

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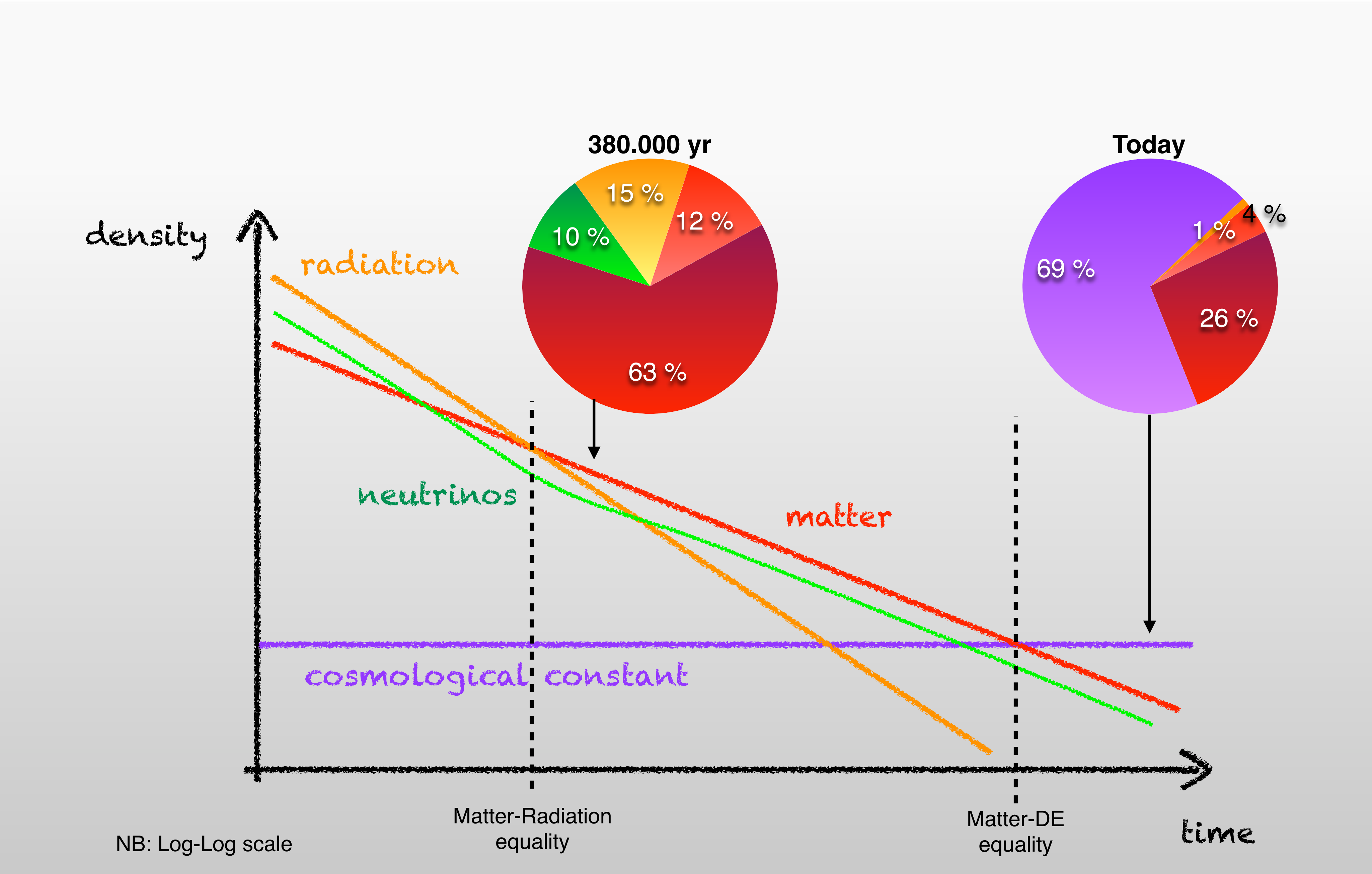

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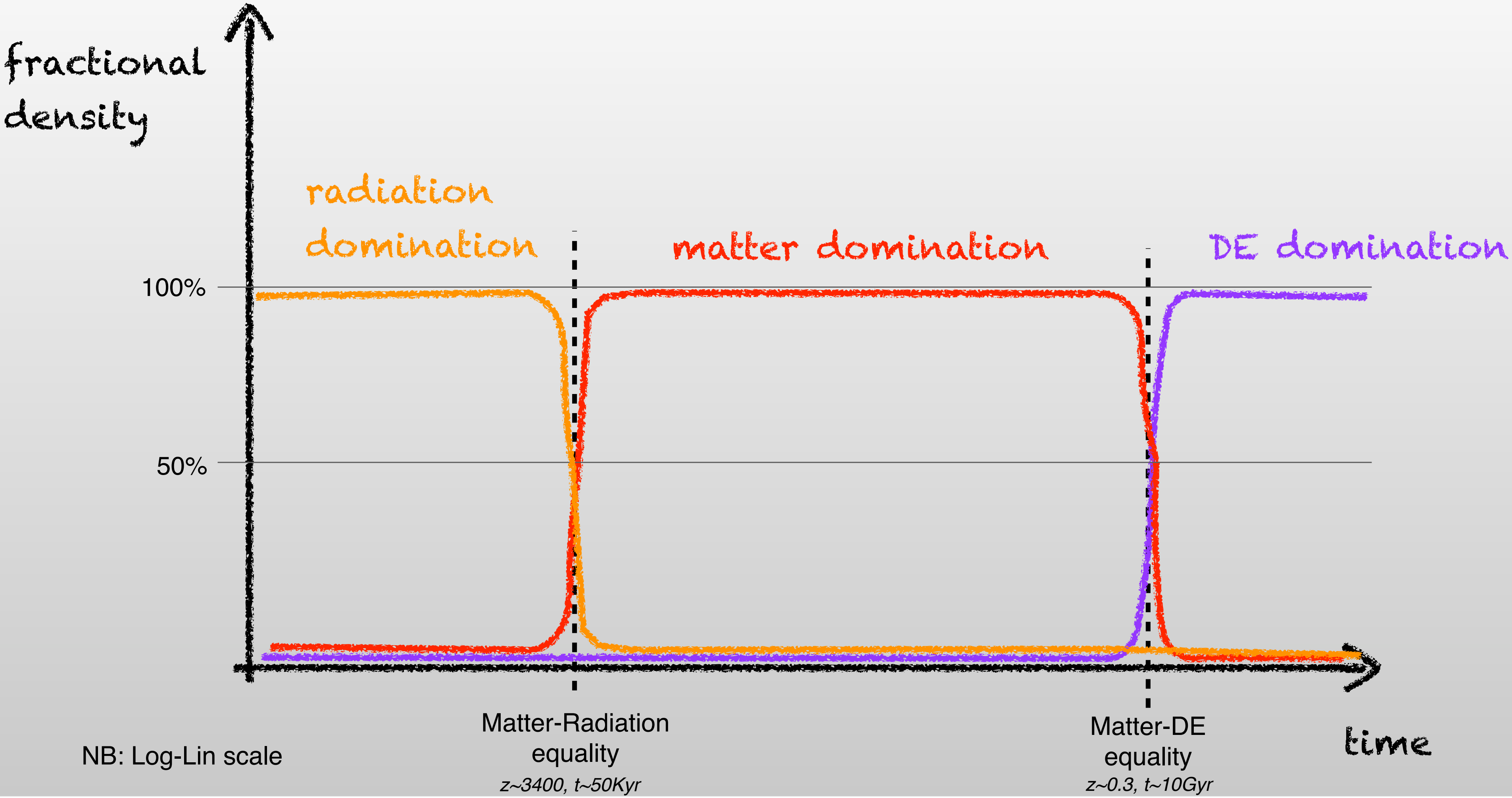

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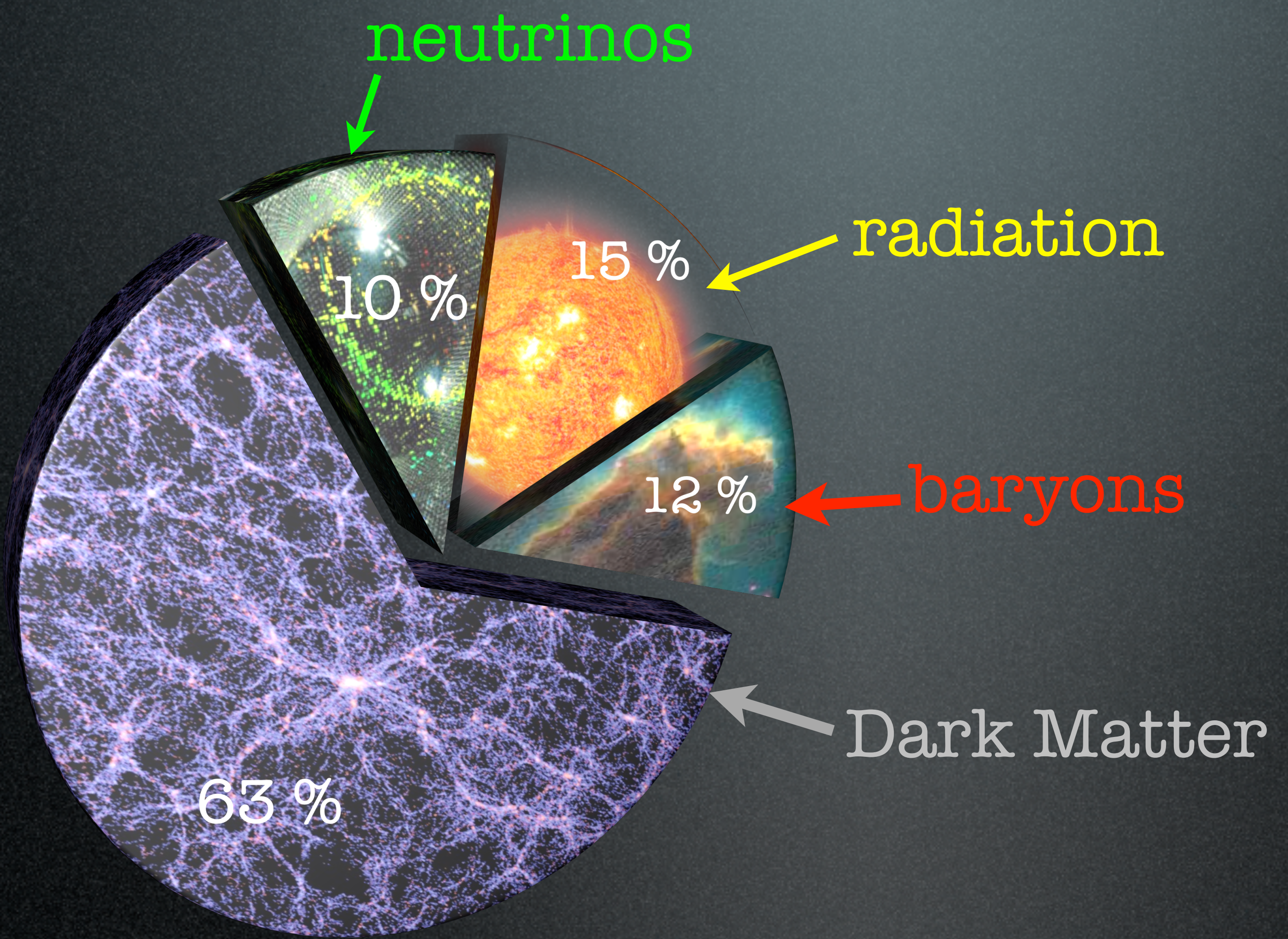

At the time of CMB formation (380 Ky)

How do we know that Dark Matter is out there?

The Evidence for DM

1) galaxy rotation curves

2) clusters of galaxies

3) ‘precision cosmology’

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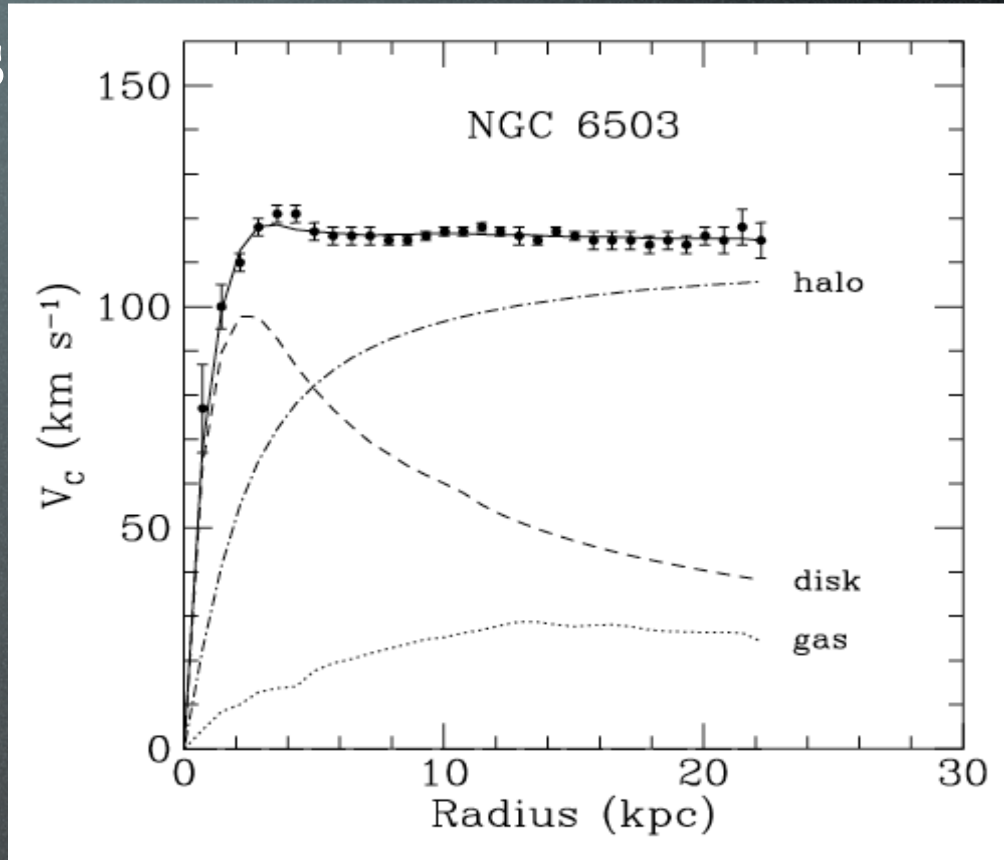
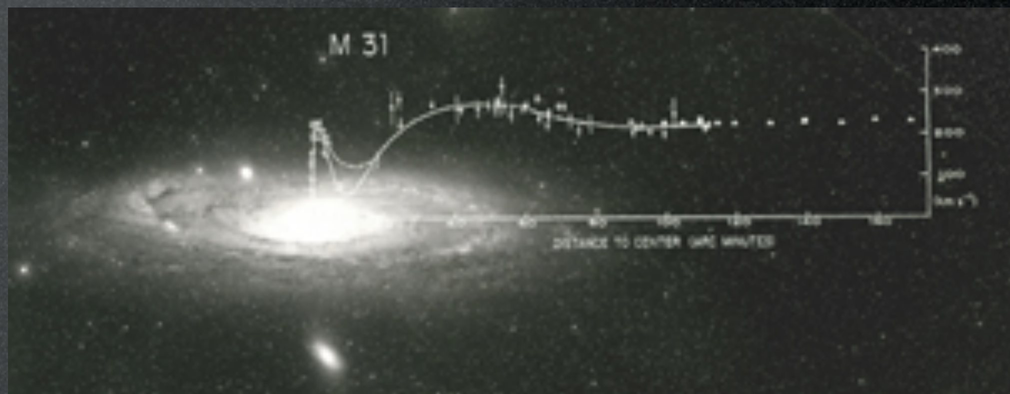


Begeman et al., MNRAS 249 (1991)



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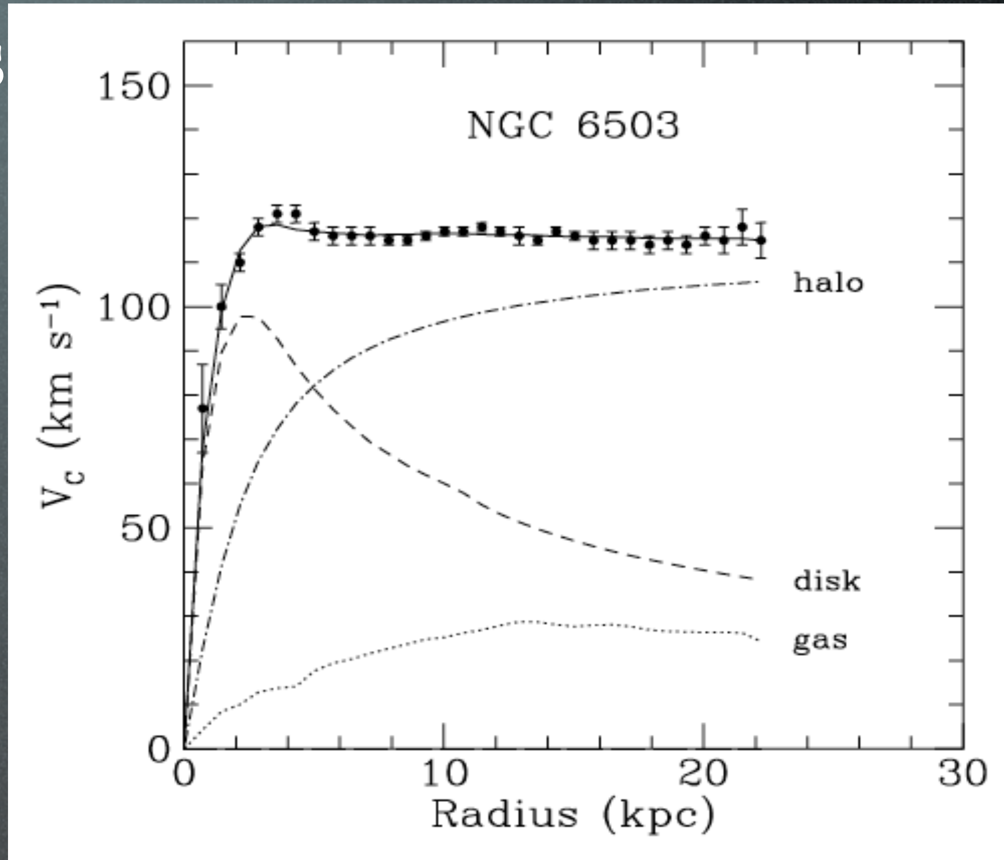
'centrifugal' 'centripetal'



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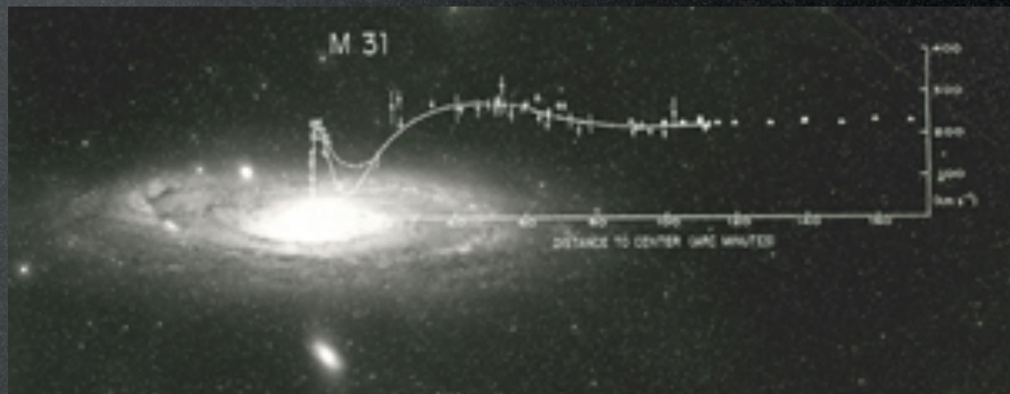

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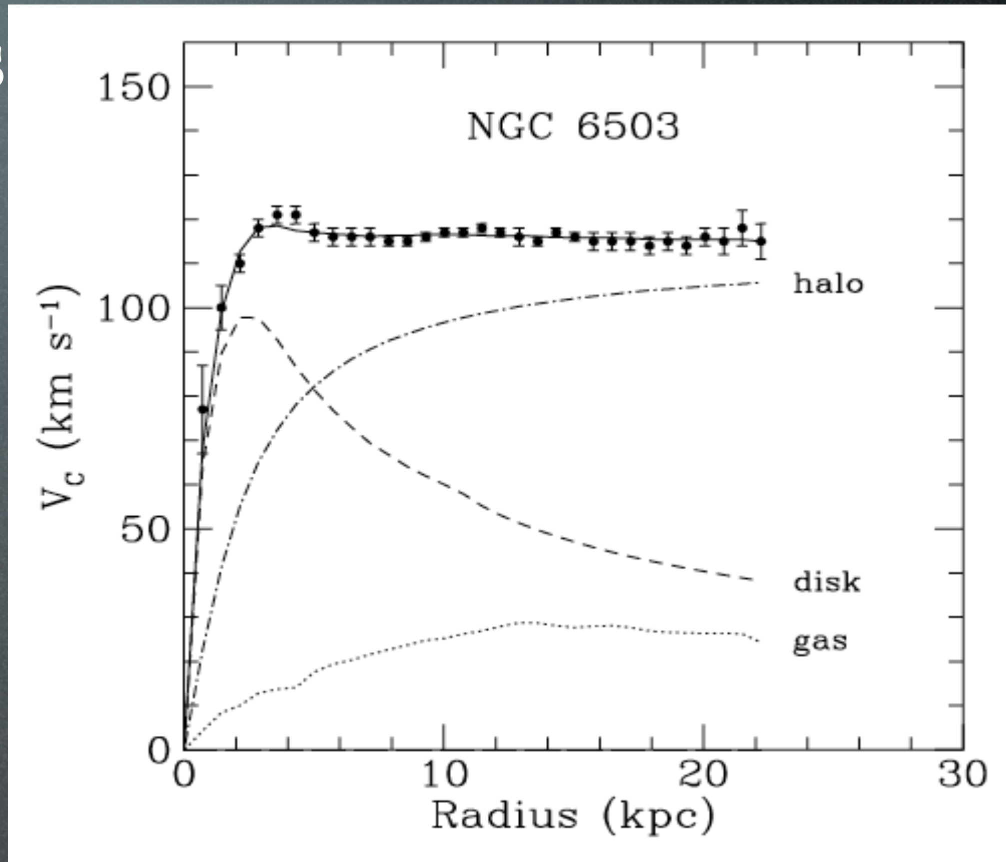
with $M(r) = 4\pi \int \rho(r)\, r^2 dr$

$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$

and indeed a 'gas' of non-interacting particles distributes like $1/r^2$



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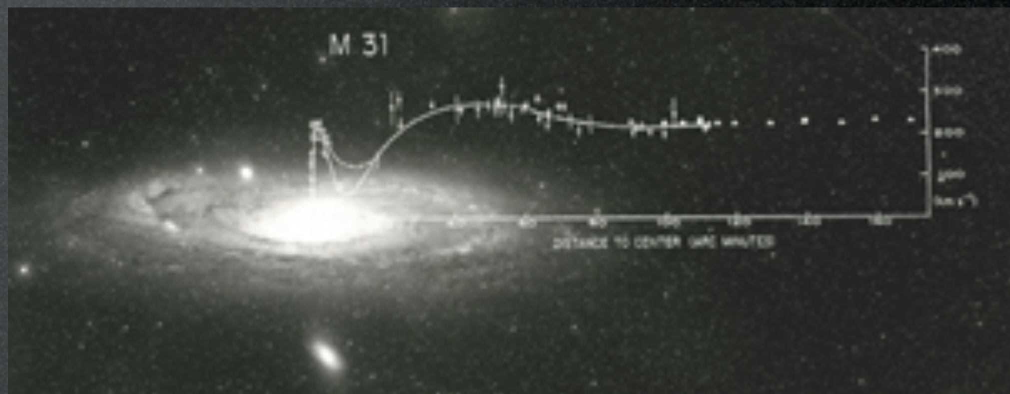

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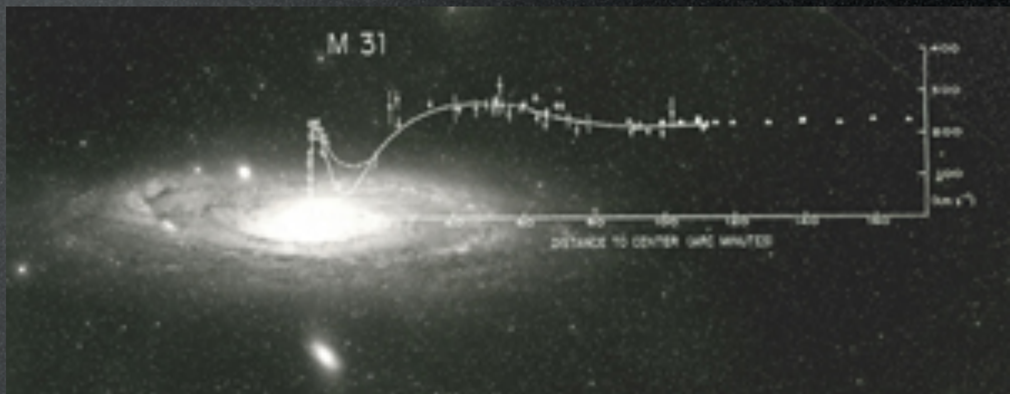
Caveat:

this treatment is over-simplified and is mostly a 'negative proof': visible matter with standard gravity can **not** reproduce the observed non-rapidly falling rotation curves, something else is needed.

Then, details are complex: curves are not exactly flat (so not necessarily $1/r^2$) and there are non-universal parametrs to tweak in each galaxy...



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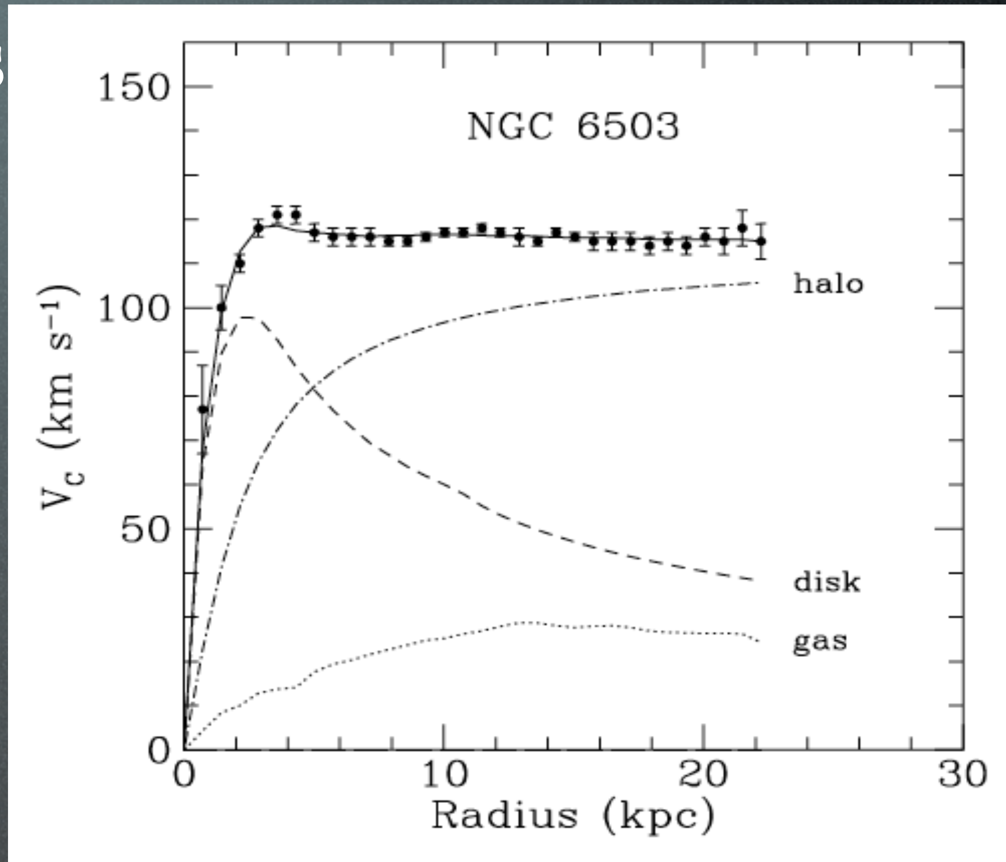

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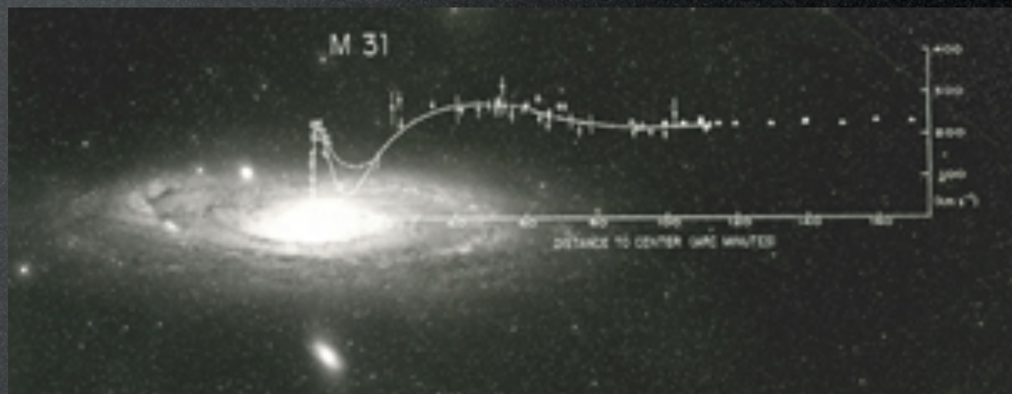

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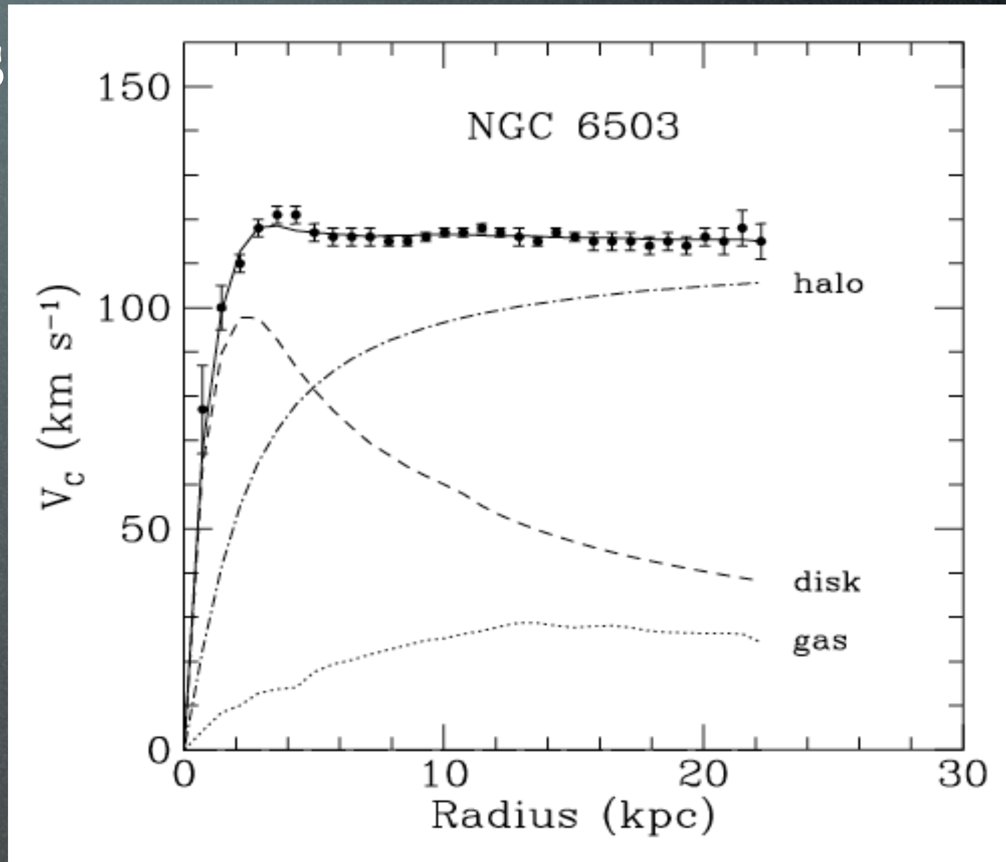

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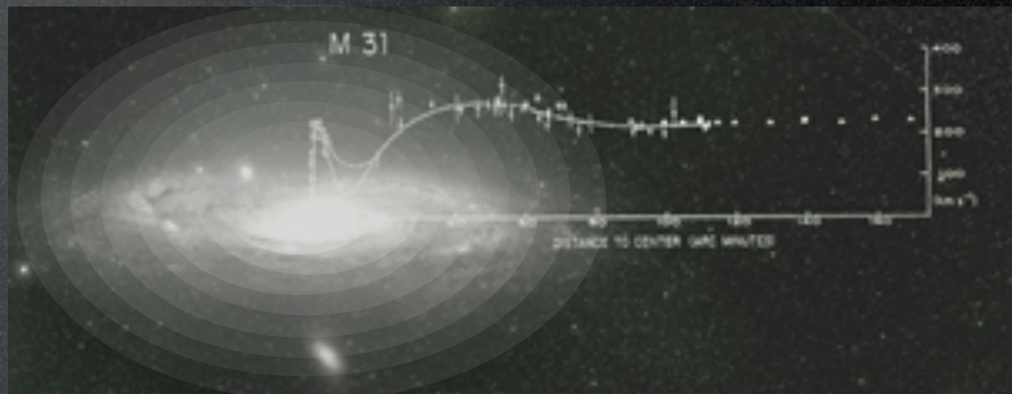

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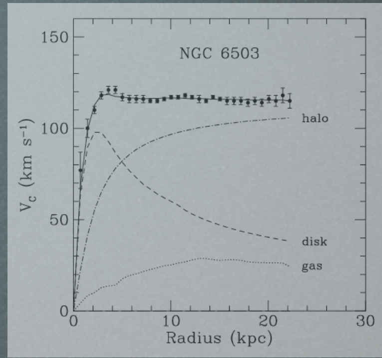

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- "rotation curves"
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"bullet cluster" - NASA
astro-ph/0608247
[further developments]

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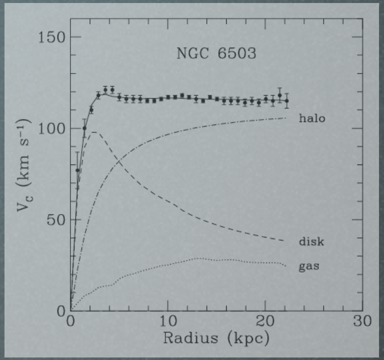

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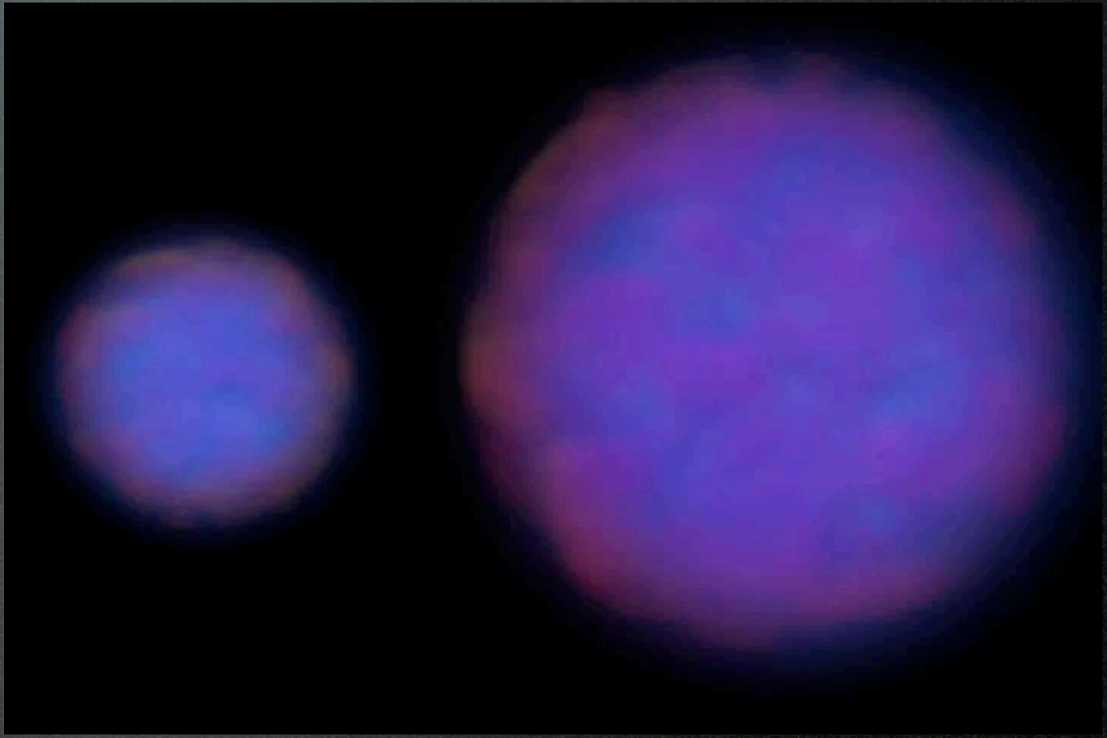

chandra.harvard.edu

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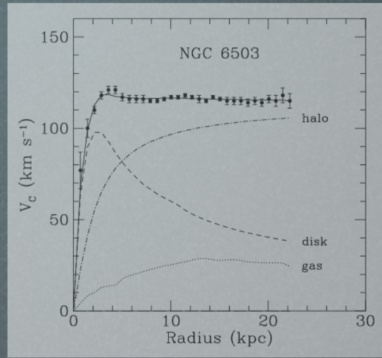

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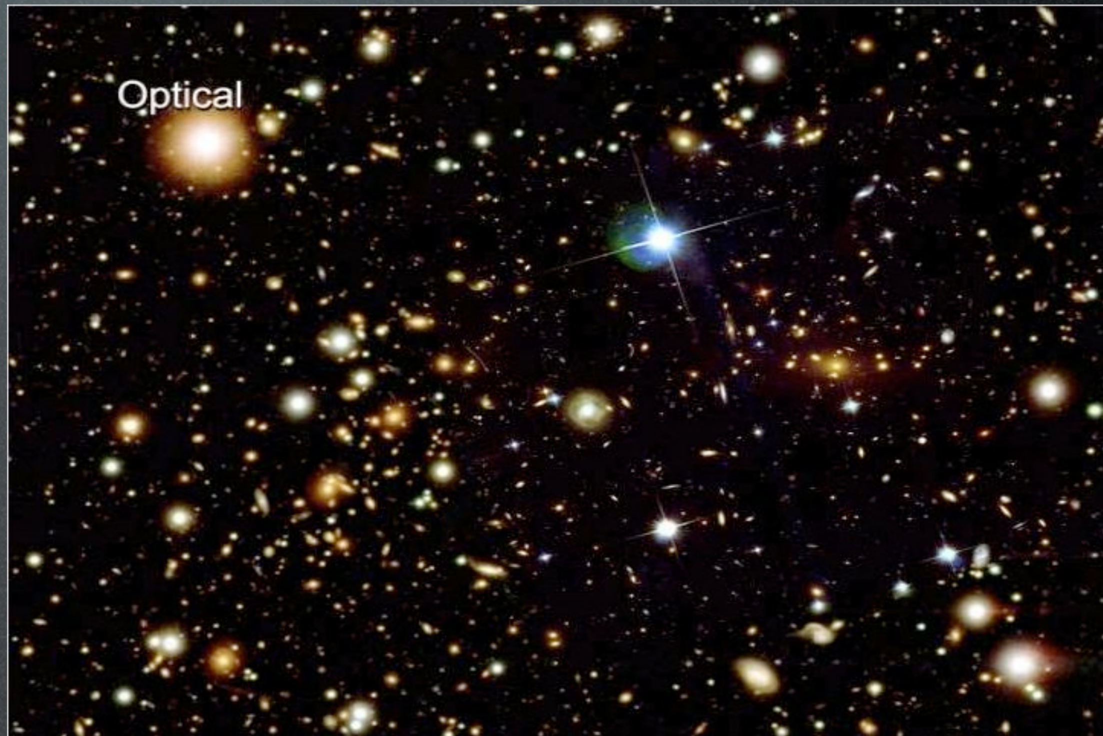

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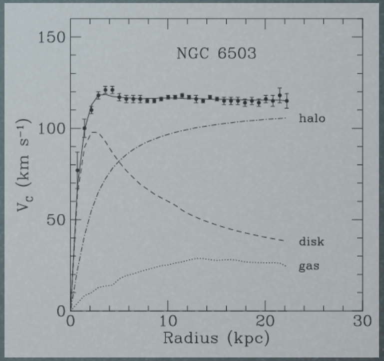

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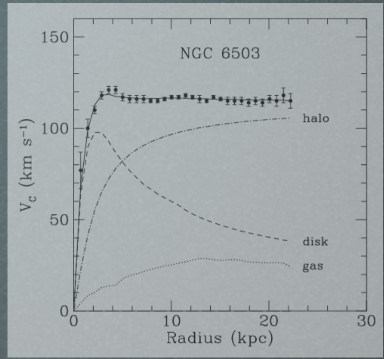

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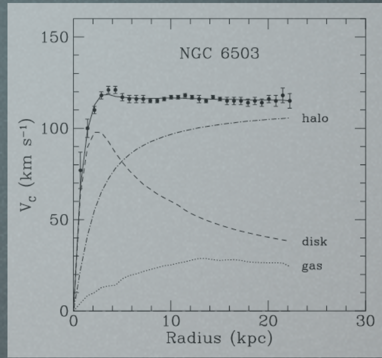

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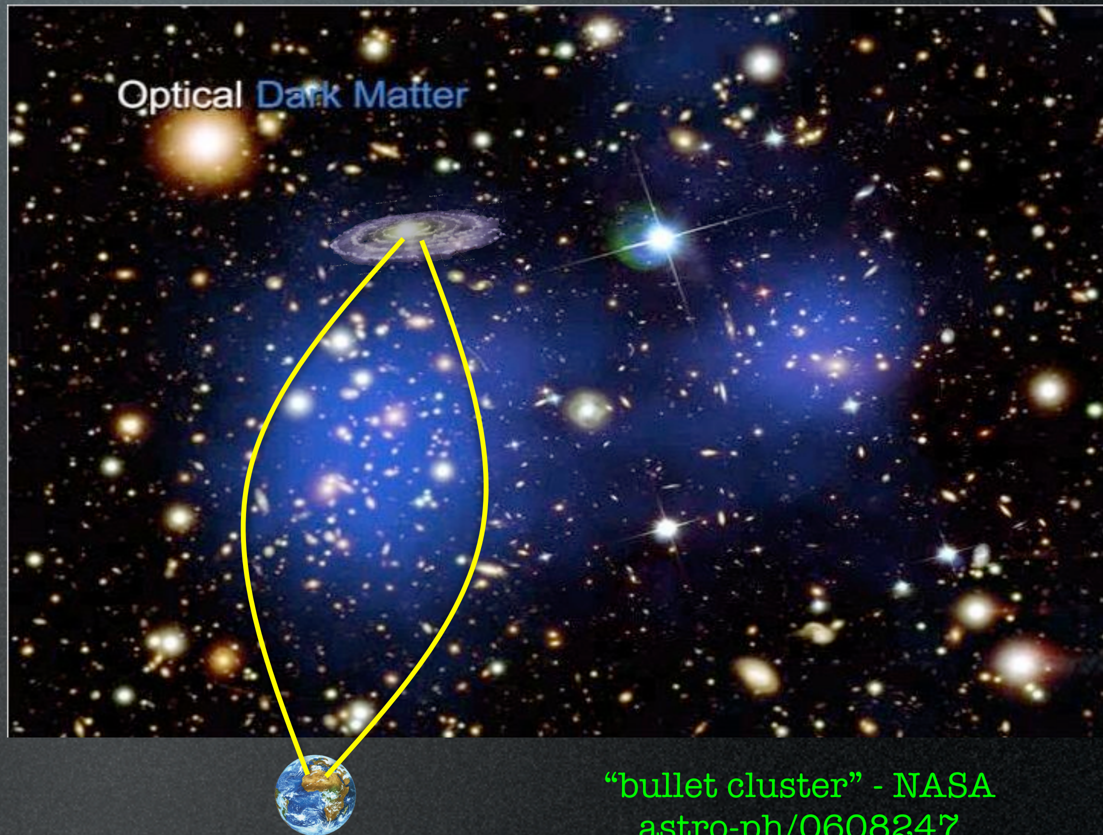
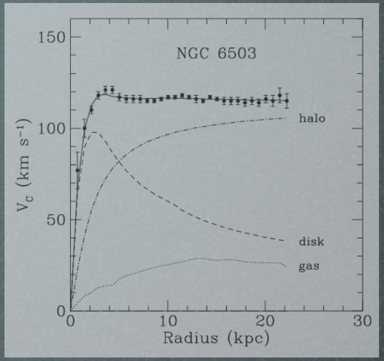


"bullet cluster" - NASA
astro-ph/0608247
[further developments]

The Evidence for DM

1) galaxy rotation curves



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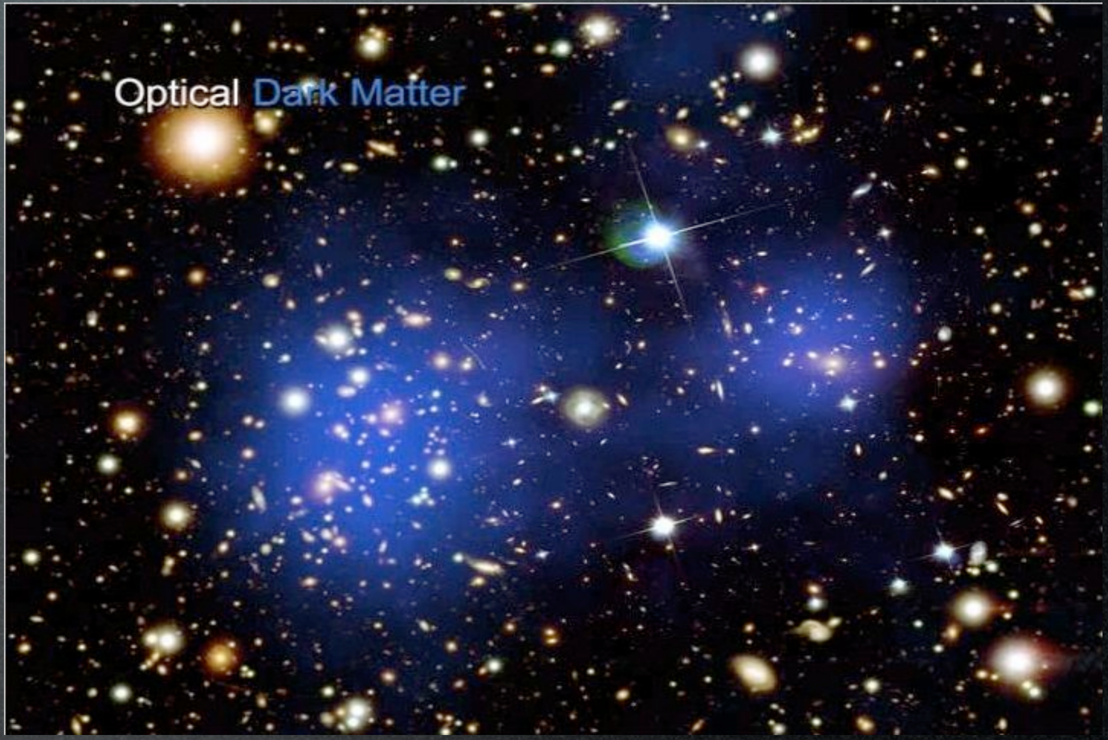

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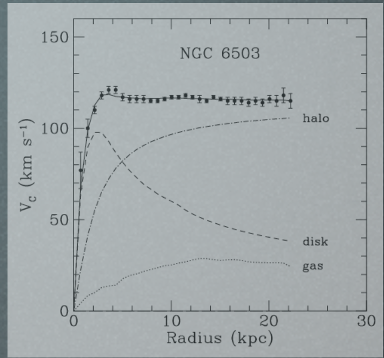

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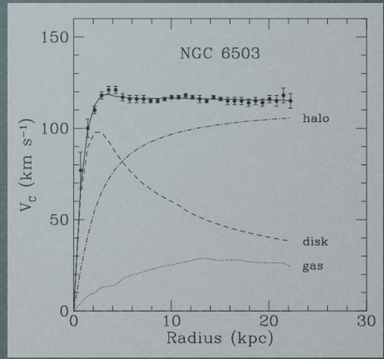

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ring of Dark Matter (2007)

The Evidence for DM

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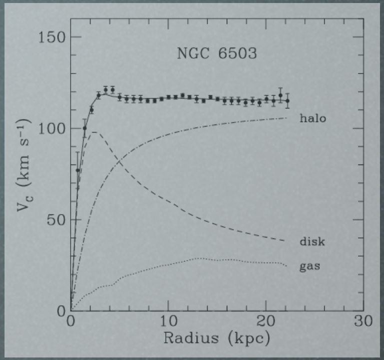

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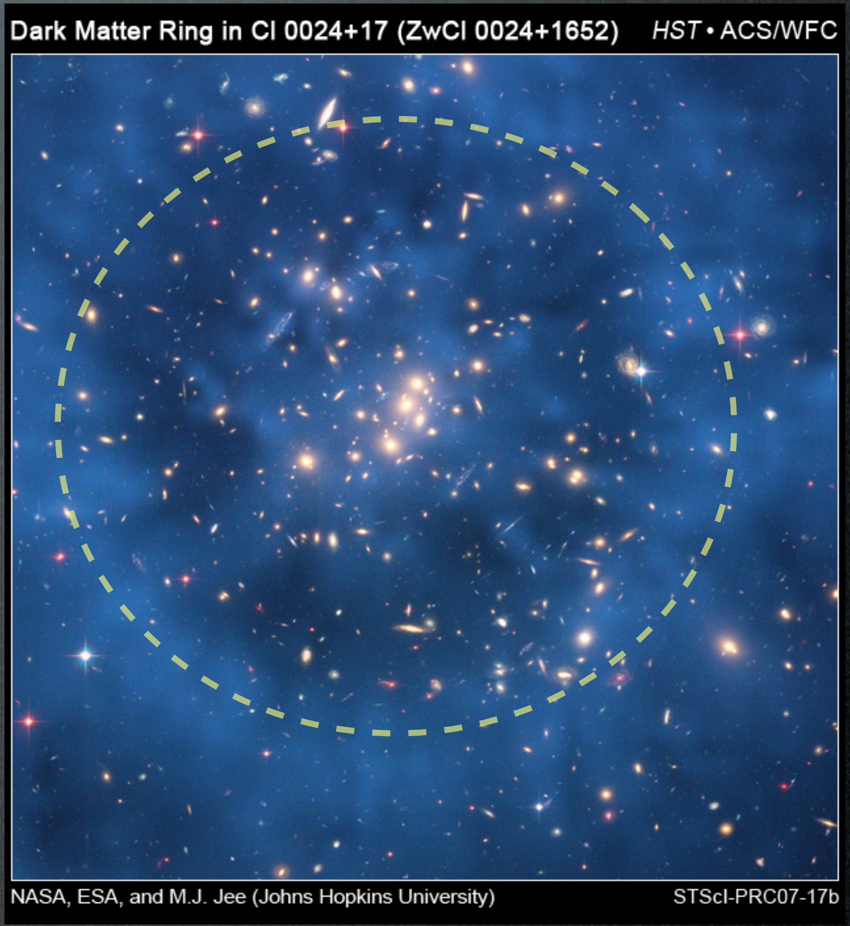

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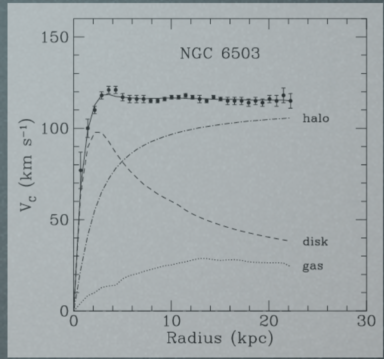
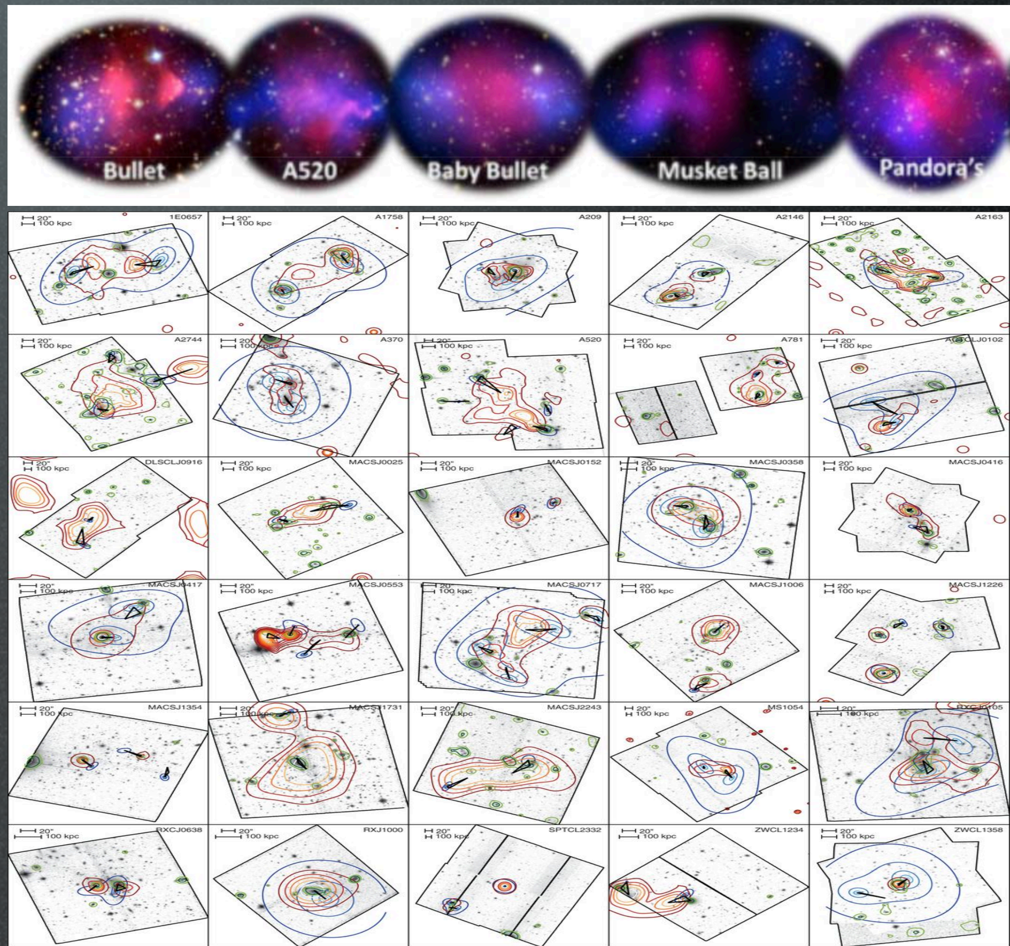
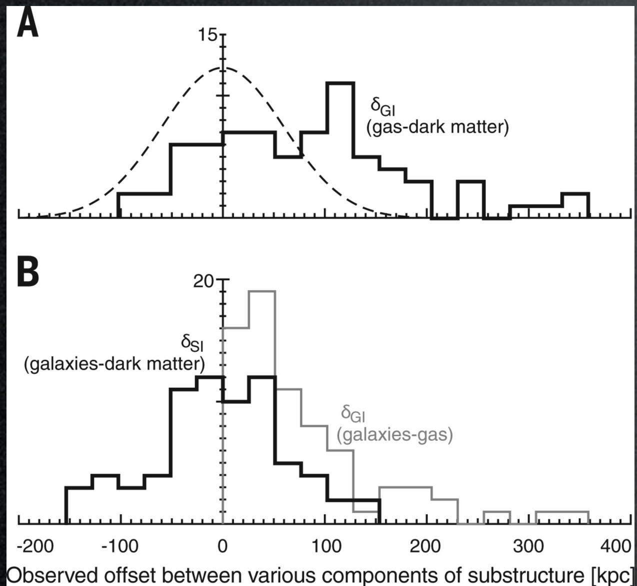


2) clusters of galaxies

72 more collisions:



quantitative study of drag:



'evidence for DM at 7.6σ'

Harvey et al., Science, 1503.07675

The Evidence for DM

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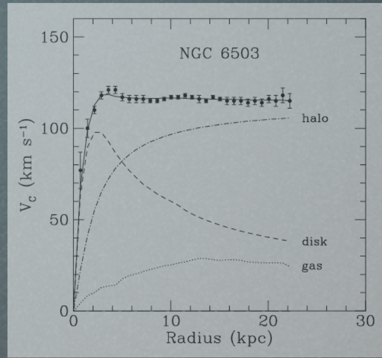
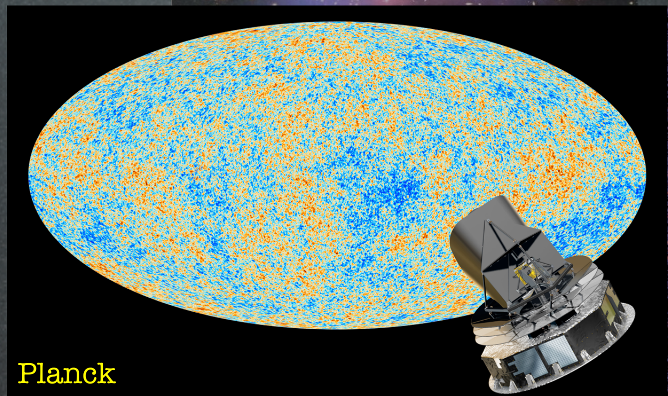
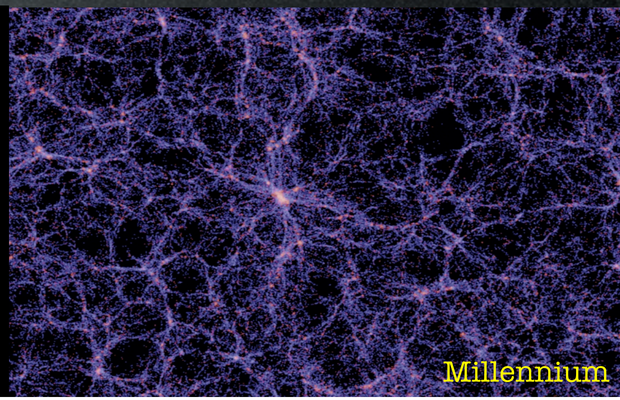
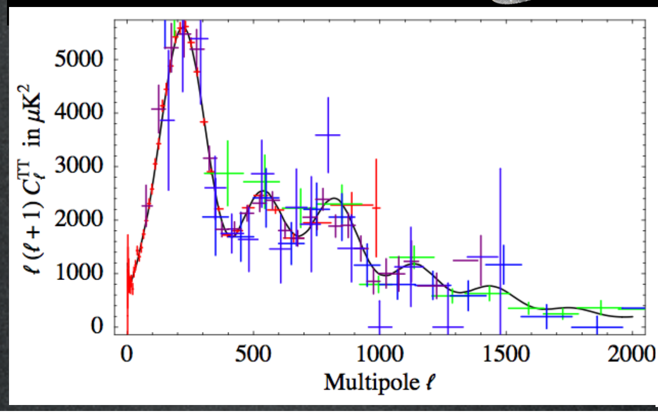


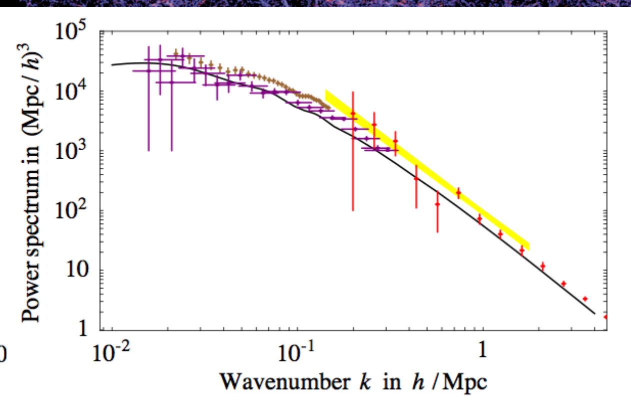
2) clusters of galaxies

3) ‘precision cosmology’



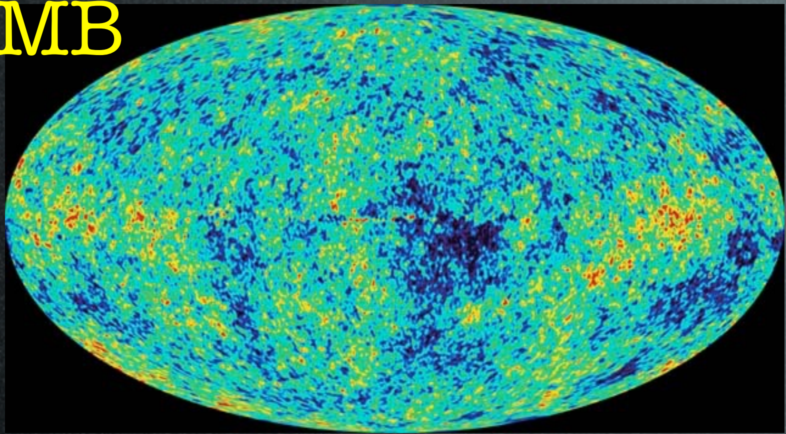




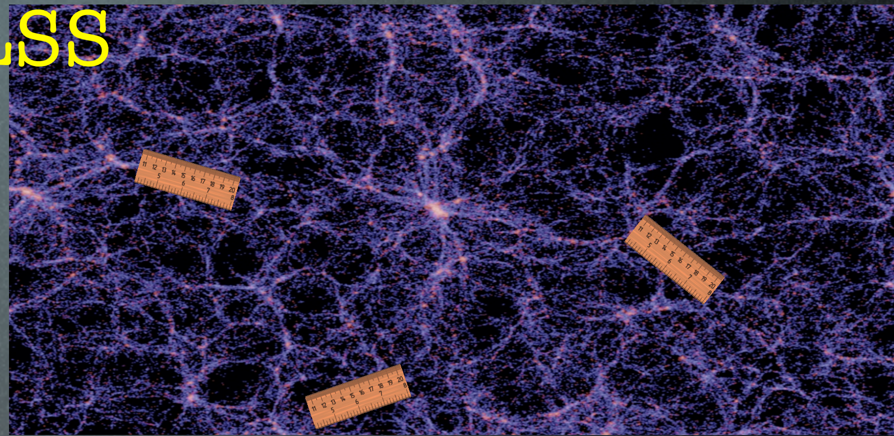


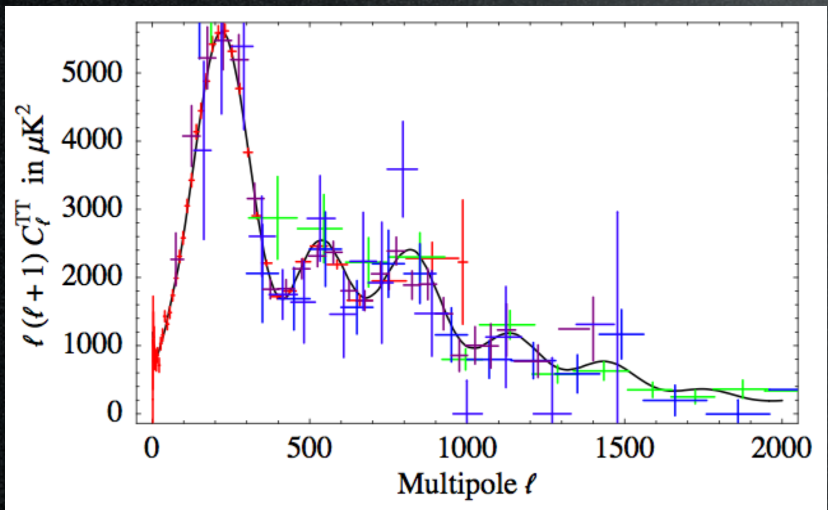
CMB & Large Scale Structure

CMB

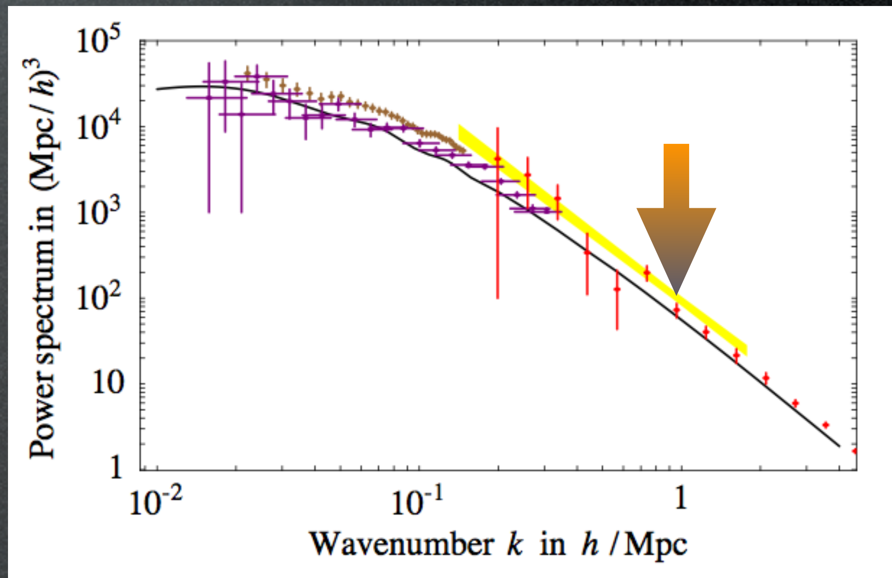


LSS





LSS matter power spectrum



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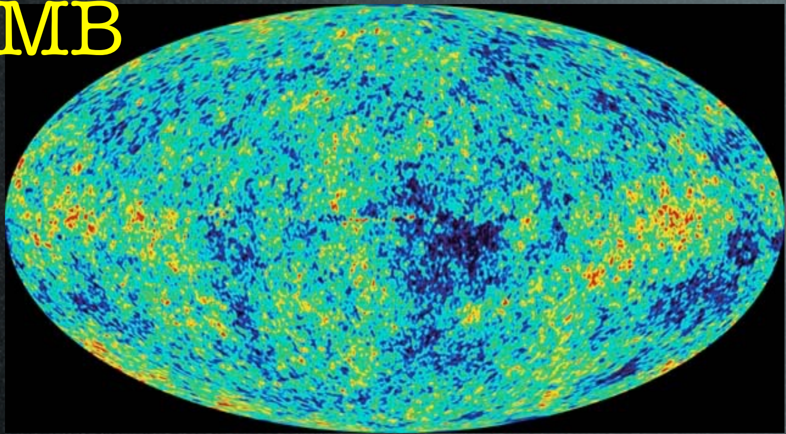

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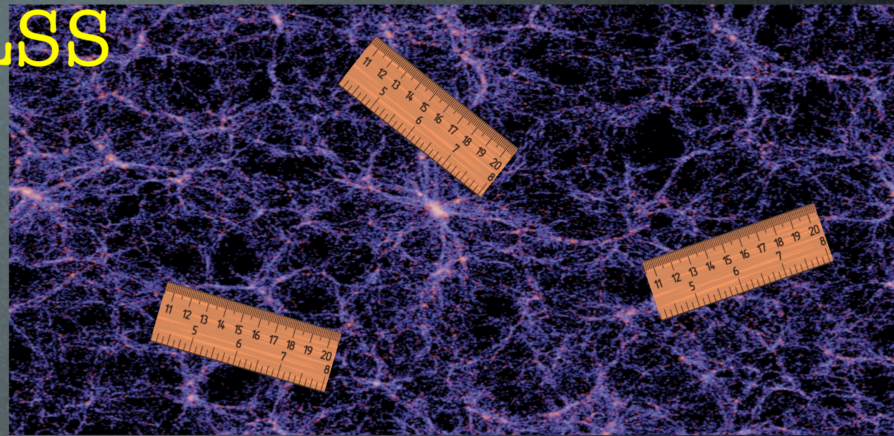

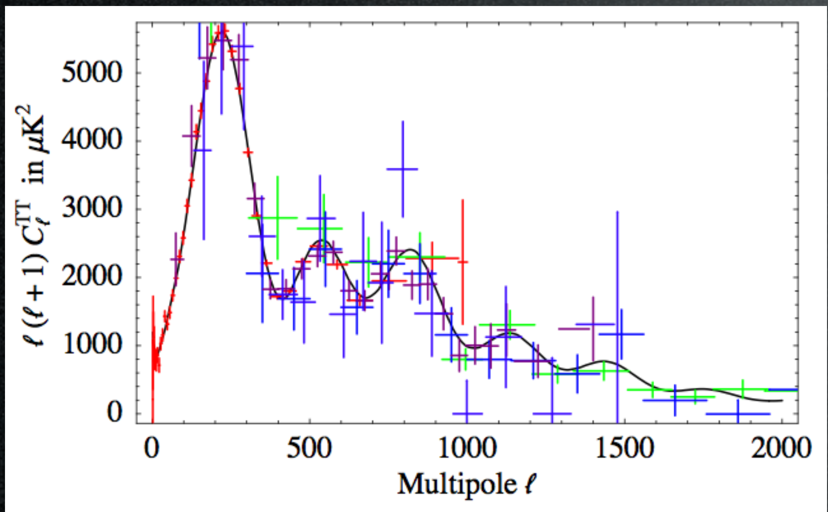

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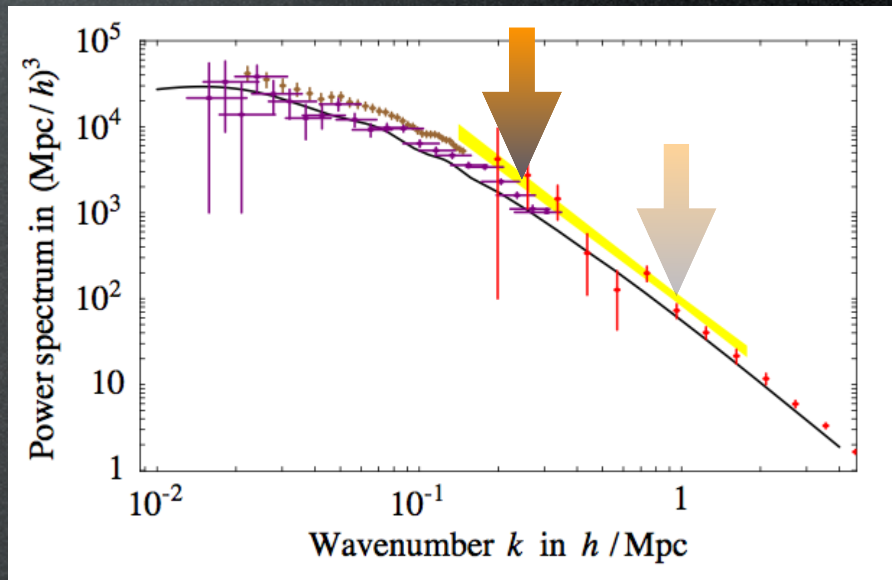

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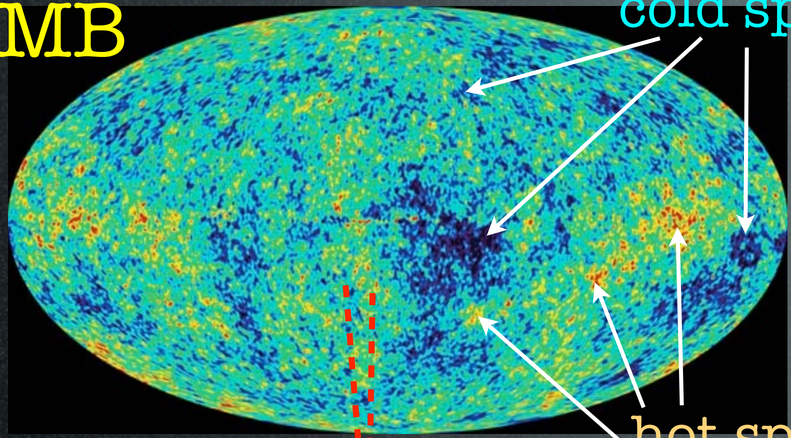

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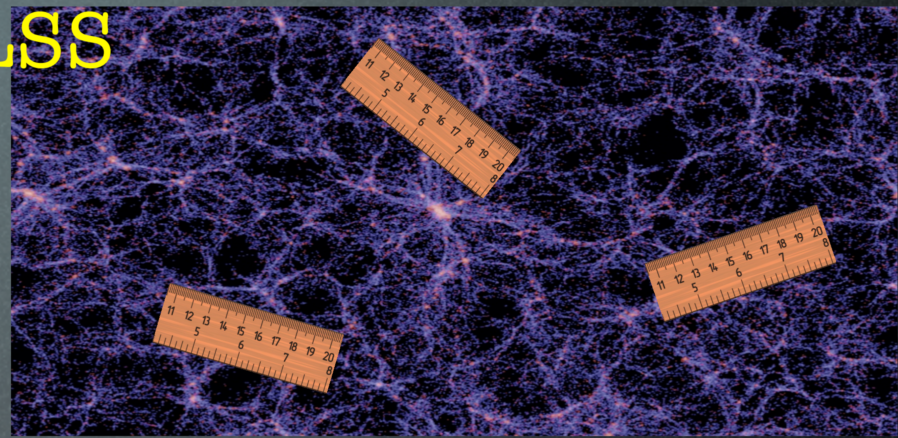
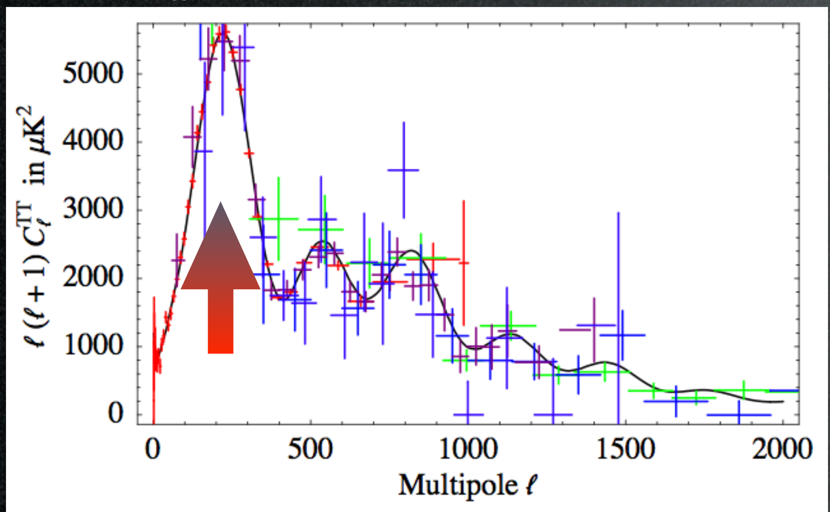


$T = 2.725° K$

$\frac{\delta T}{T} \sim 10^{-5}$

$1°$

CMB spectrum



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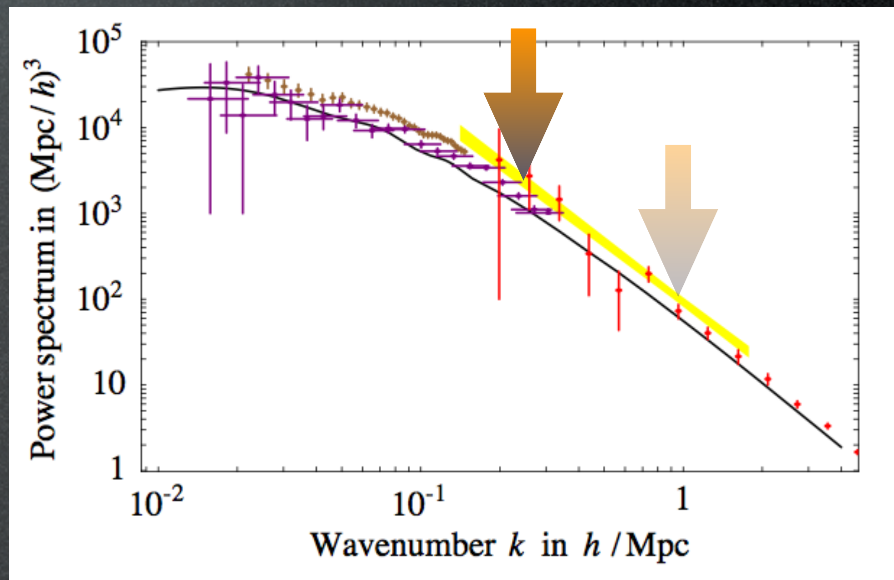
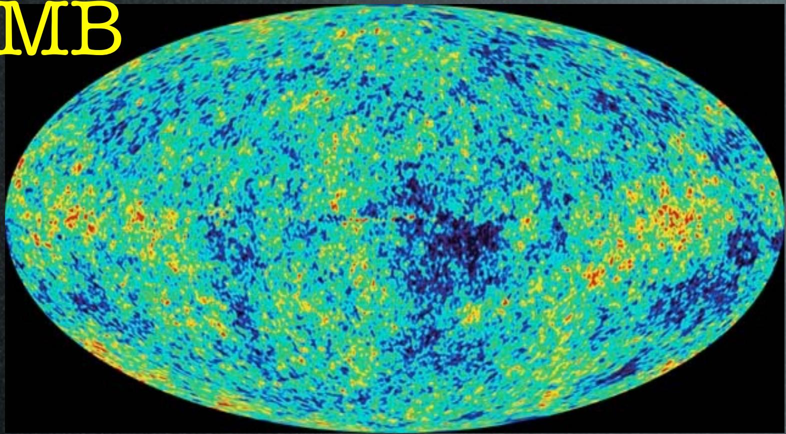


The Evidence for DM

CMB



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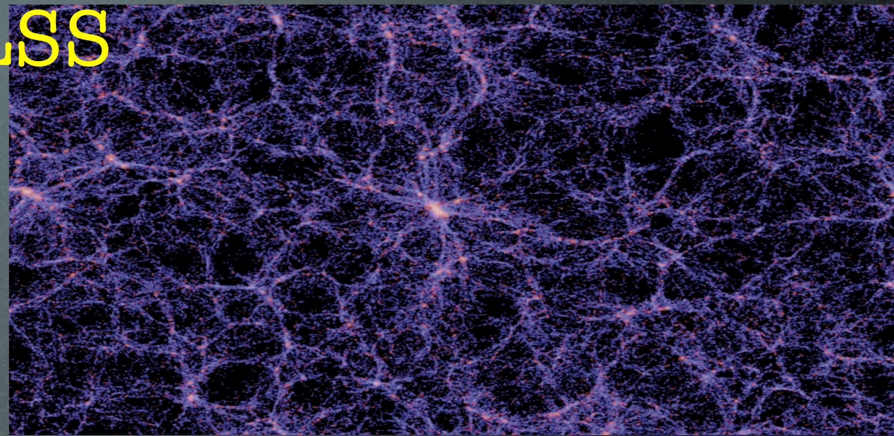
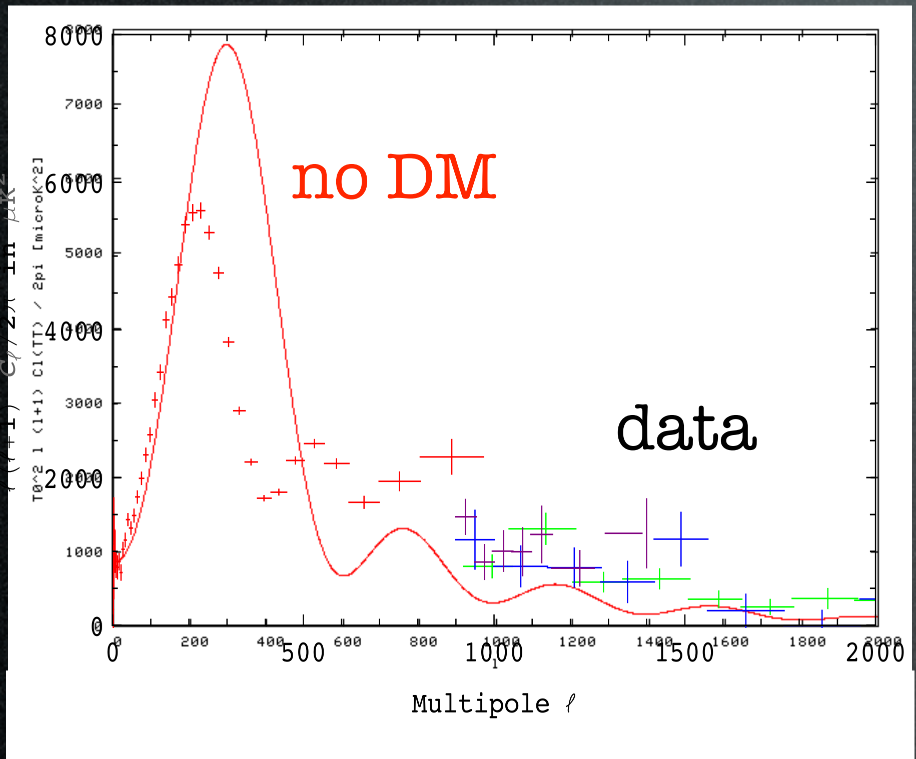
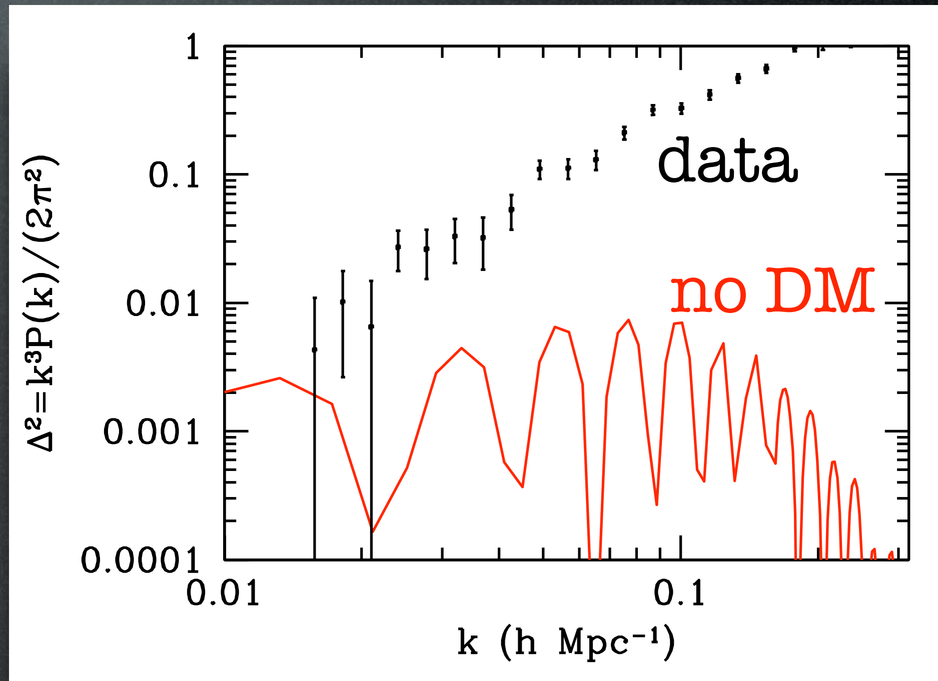


How would the power spectra be without DM? (and no other extra ingredient)



CAMB online

(in particular: no DM => no 3rd peak!)



Dodelson, Liguori 2006

(you need DM to gravitationally "catalyse" structure formation)


DETOUR

MOND? TeVeS?

Instead of adding matter, modify Newton or GR.

$$F = m\,a \longrightarrow F = m\,a \cdot \mu(a) \quad \text{with} \quad \mu(a) = \begin{cases} 1 & a > a_0 \\ a/a_0 & a \sim a_0 \end{cases}$$

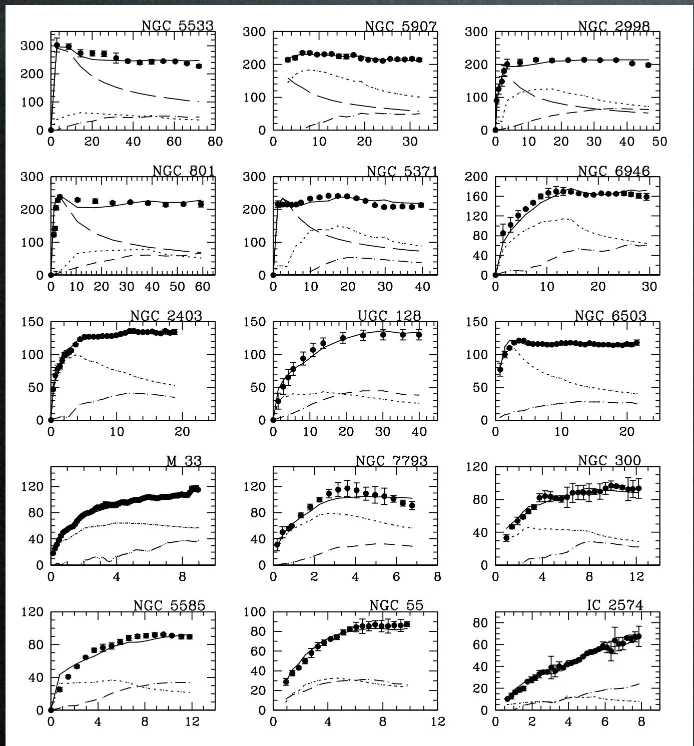
$$a_0 = 1.2 \cdot 10^{-10} m/s^2$$

$$F = m\,\frac{a^2}{a_0} = \frac{GMm}{r^2} \Rightarrow a = \frac{\sqrt{GMa_0}}{r} = \frac{v^2}{r} \Rightarrow v = (GMa_0)^{1/4} = \text{const}$$

force balance

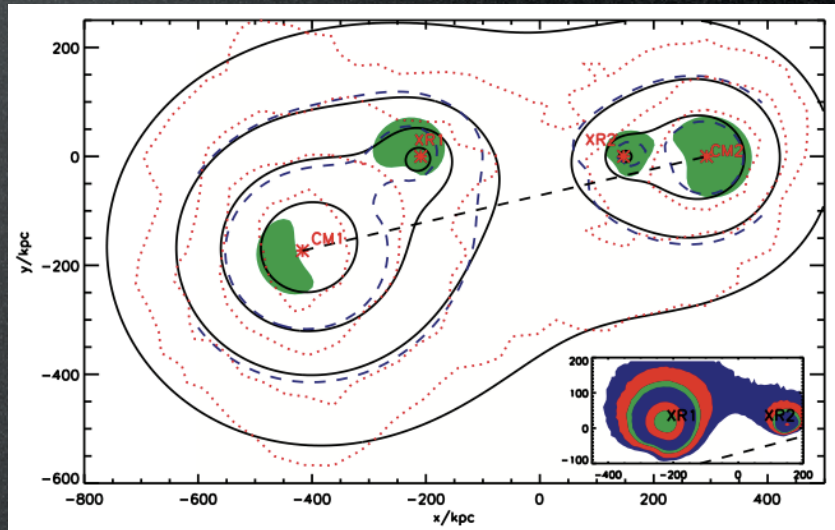
tangential acceleration

fits rotation curves very well



Sanders, McGaugh, Ann. Rev. AA, 2002

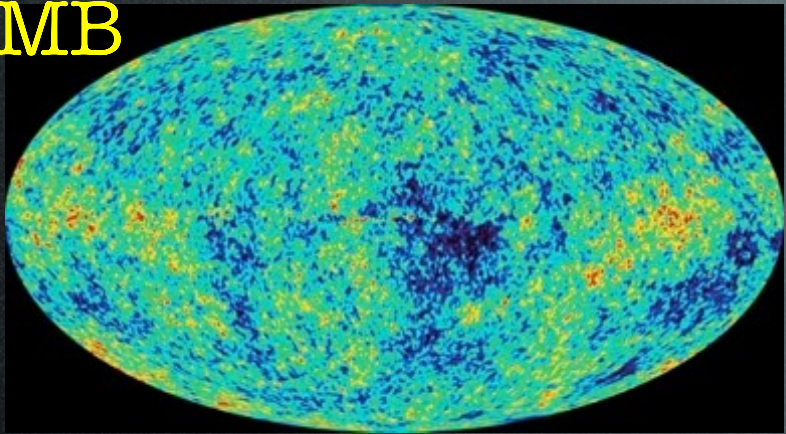
can fit (bullet) cluster if adding 2 eV neutrinos...



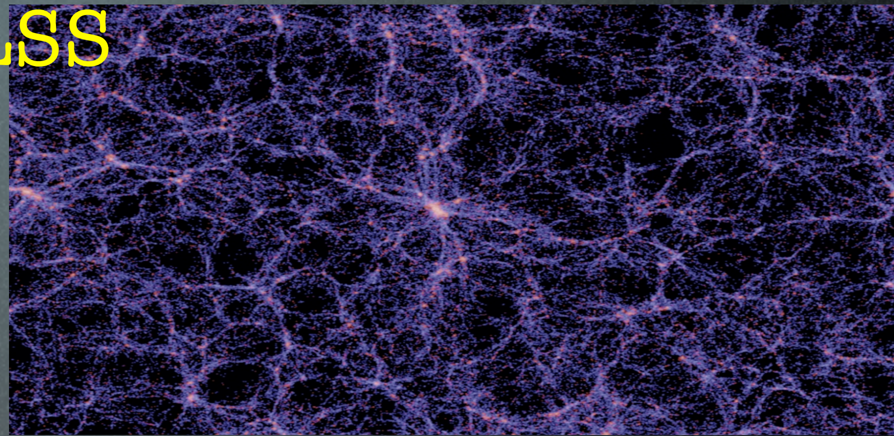
Angus et al., astro-ph/0609125

MOND? TeVeS?

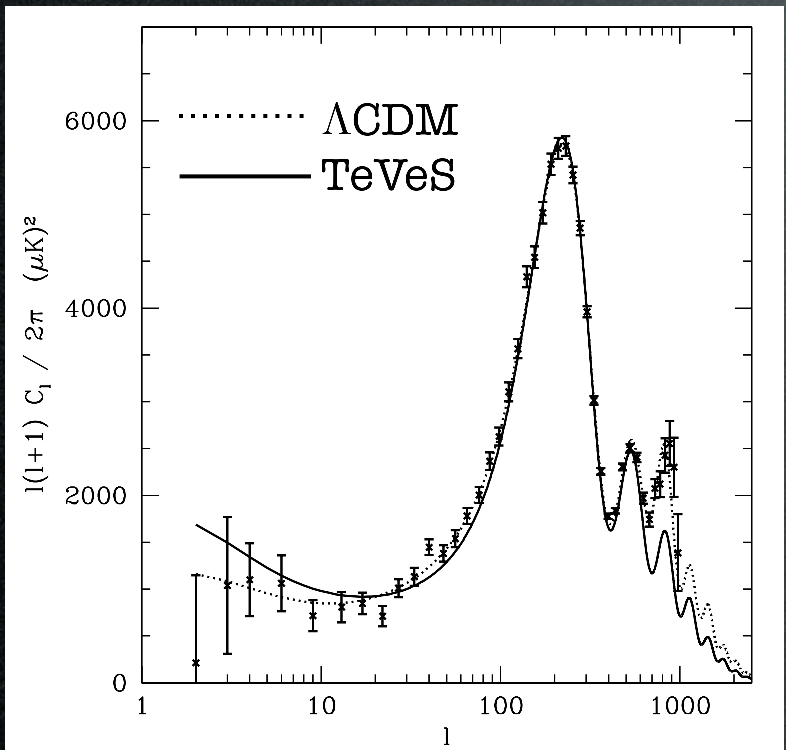
CMB



LSS

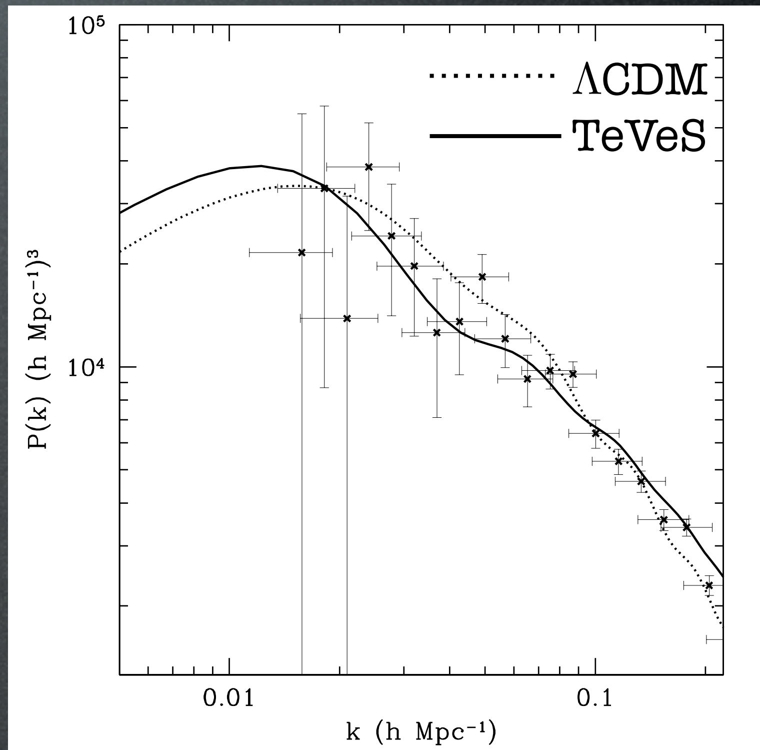


How would the power spectra be in MOND/TeVeS, without DM ?



C.Skordis, Review, 0903.3602

(in particular: no DM => no 3rd peak!)



C.Skordis, Review, 0903.3602

(here you can make it)


DETOUR

Introduction

- DM exists
- it's a new, unknown corpuscle — *no SM particle can fulfil* — *dilutes as $1/a^3$ with universe expansion*
- makes up 26% of total energy
  84% of total matter — $\Omega_{\rm DM} h^2 = 0.1188 \pm 0.0010$ *(notice error!)*
- neutral particle *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*
- very feebly interacting — *-with itself* *-with ordinary matter ('collisionless')*
- stable or very long lived — $\tau_{\rm DM} \gg 10^{17} {\rm sec}$
- possibly a relic from the EU

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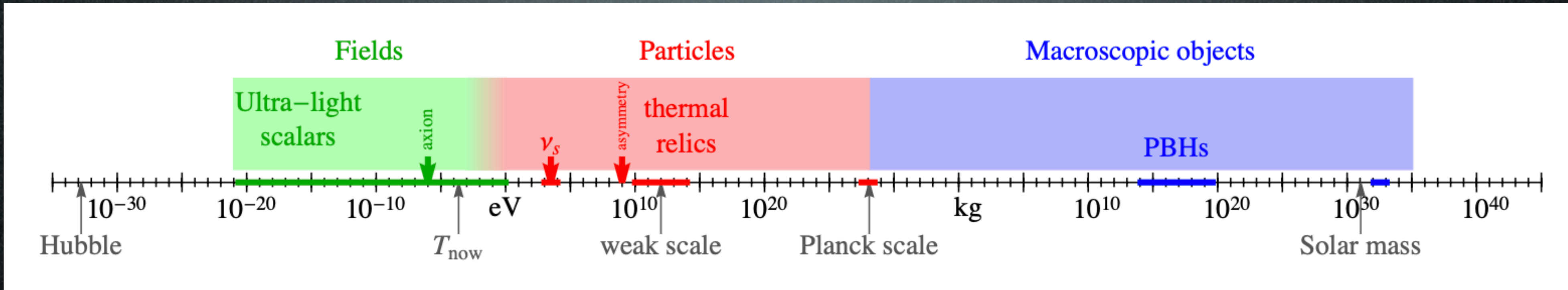
mass ???

interactions ???

Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

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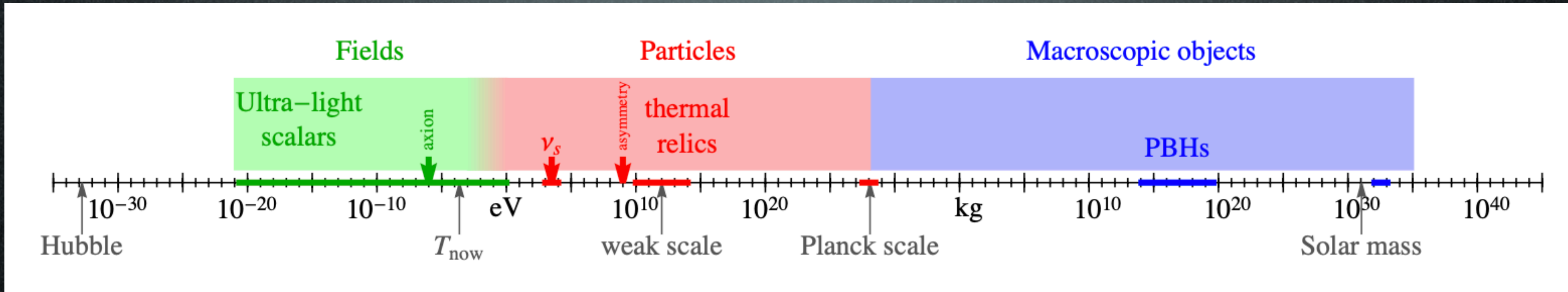

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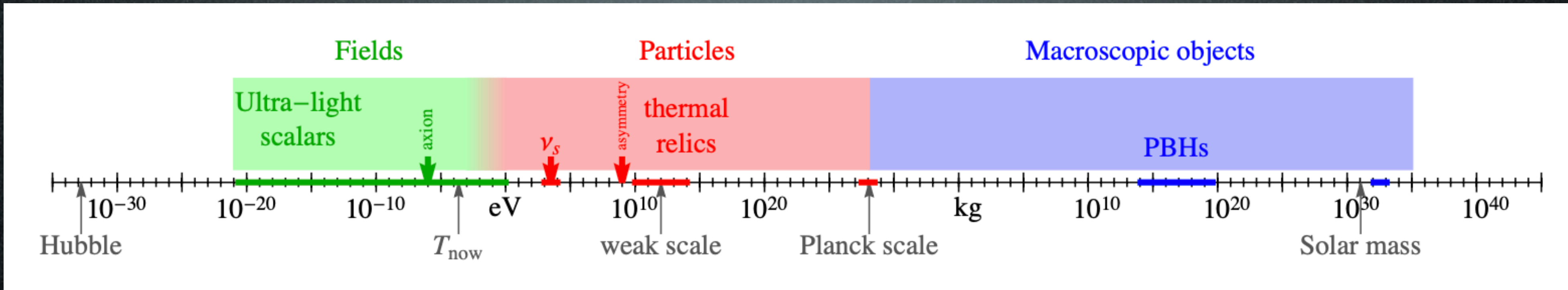
DM can be made
by a huge number of very light ‘particles’
or
a tiny number of very heavy ‘particles’
as long as it is:
neutral, cold, stable and feebly interacting

Candidates

A matter of perspective: plausible mass ranges



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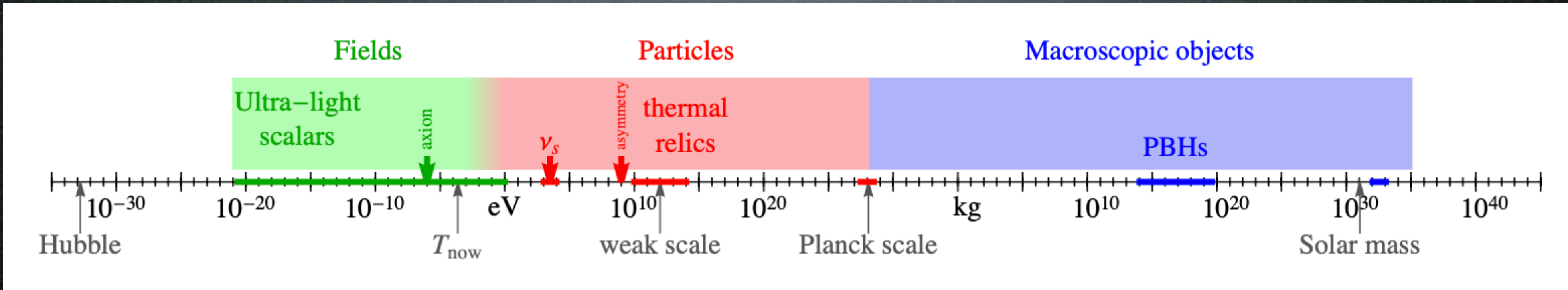

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cold ☐
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feebly int. ☐

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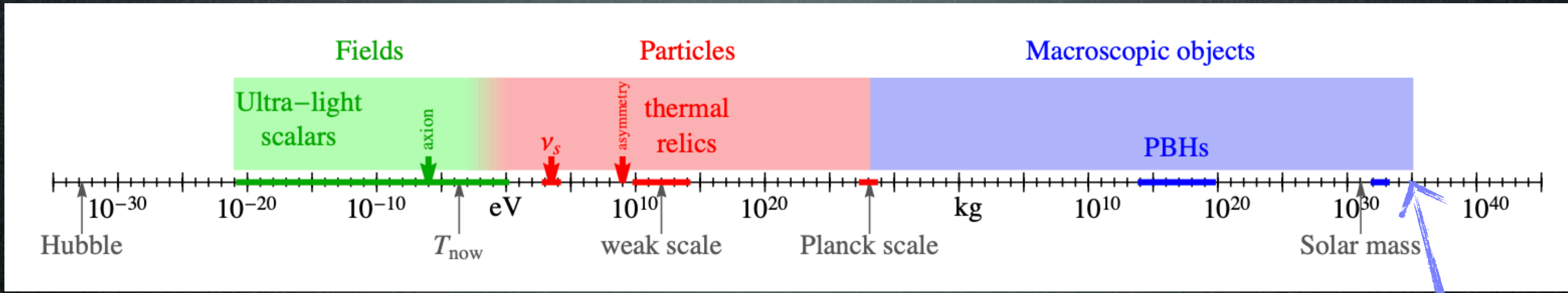

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as big as a dwarf galaxy

DM mass

$M \lesssim 10^4\ M_\odot$

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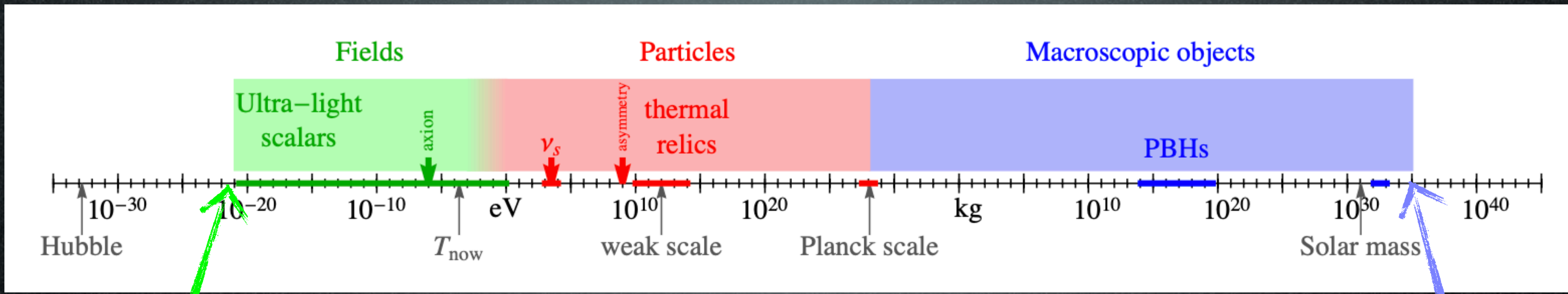

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DM de Broglie wavelength

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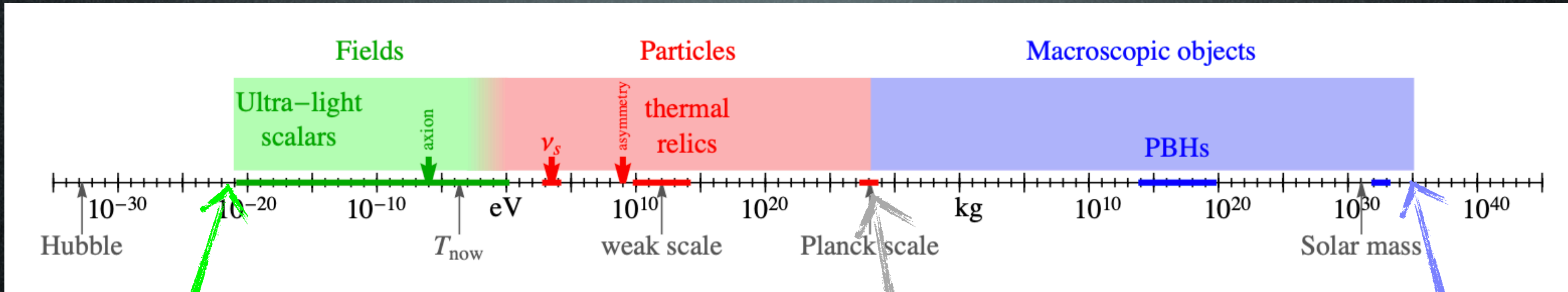

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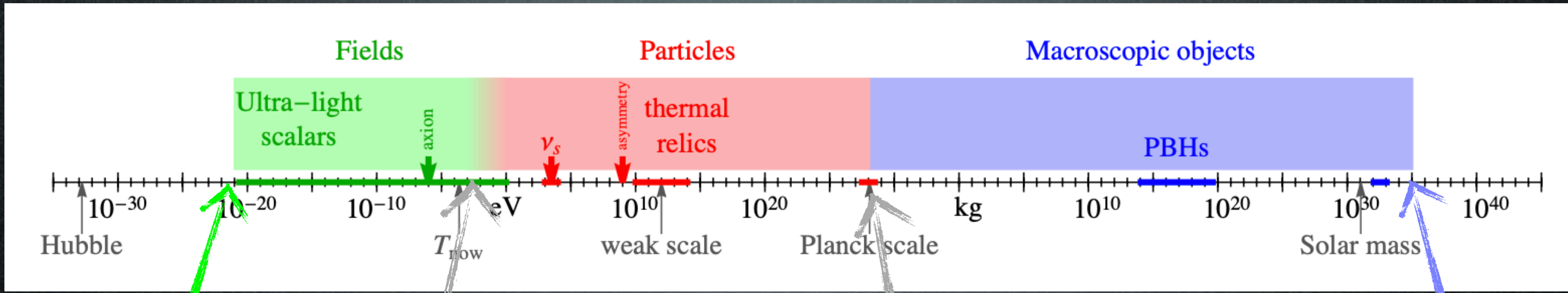

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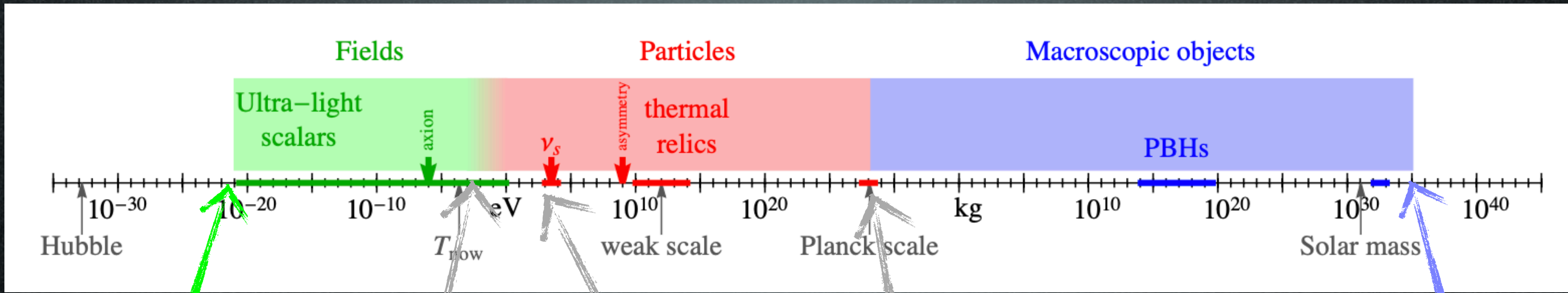

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occupation number

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$M \lesssim 0.1\,\mathrm{keV}$ necessarily *bosonic* | $M \gtrsim 0.1\,\mathrm{keV}$ *bosonic* or *fermionic*

Overview of Particle Physics candidates for Dark Matter

Candidates

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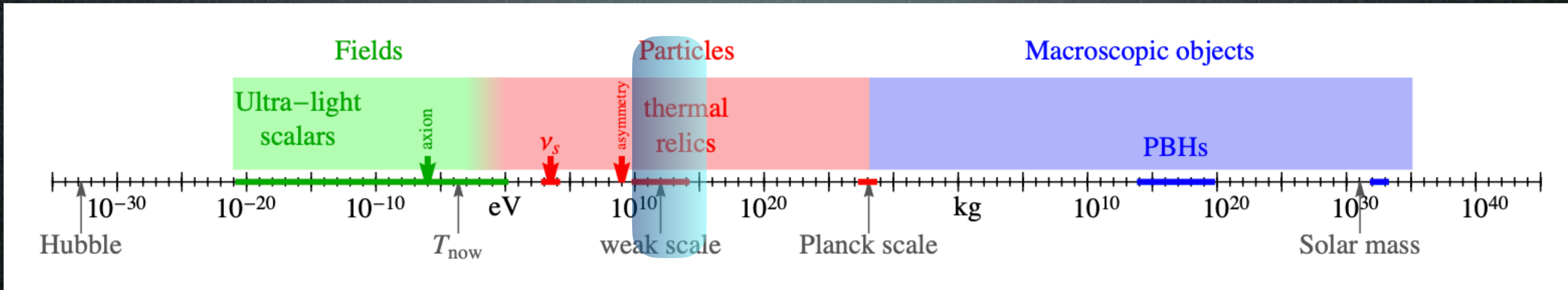

Thermal DM

DM as a thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.26$ for

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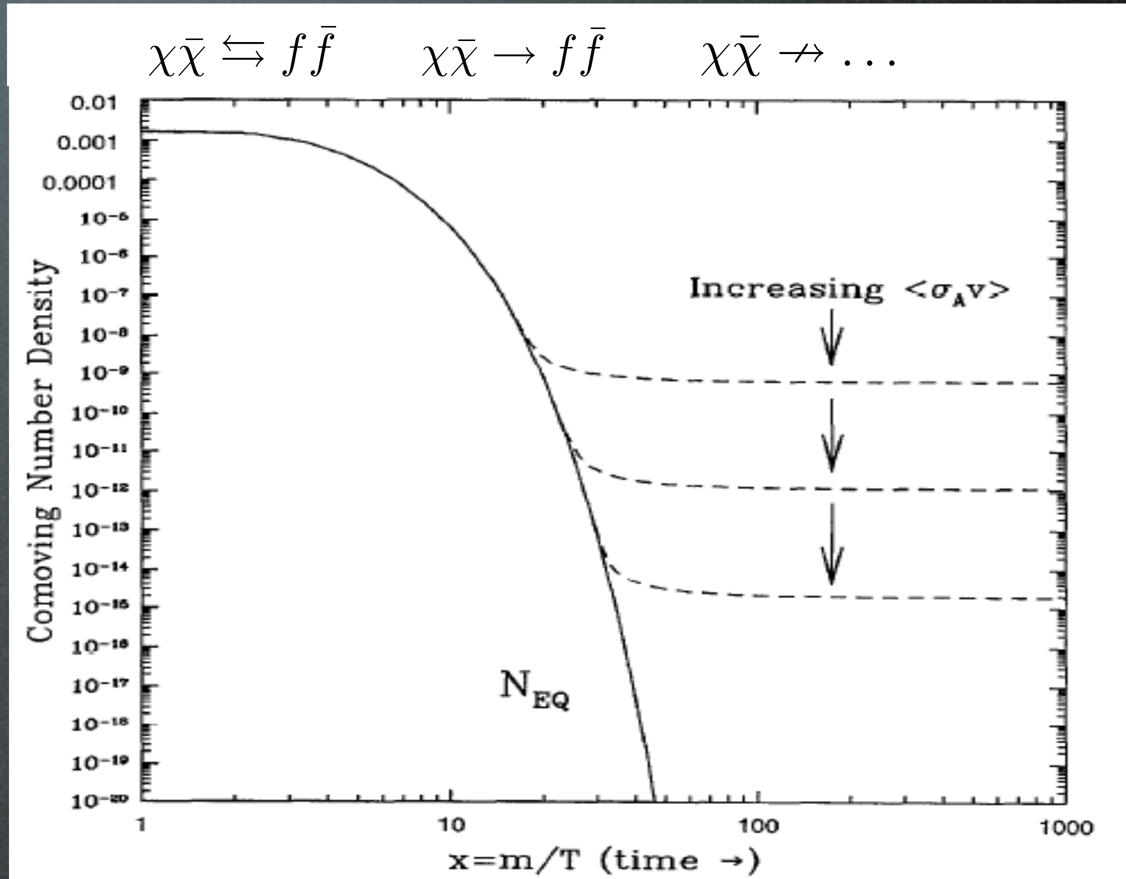

Kolb,Turner, The Early Universe, 1995

Weak cross section:

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(WIMP)

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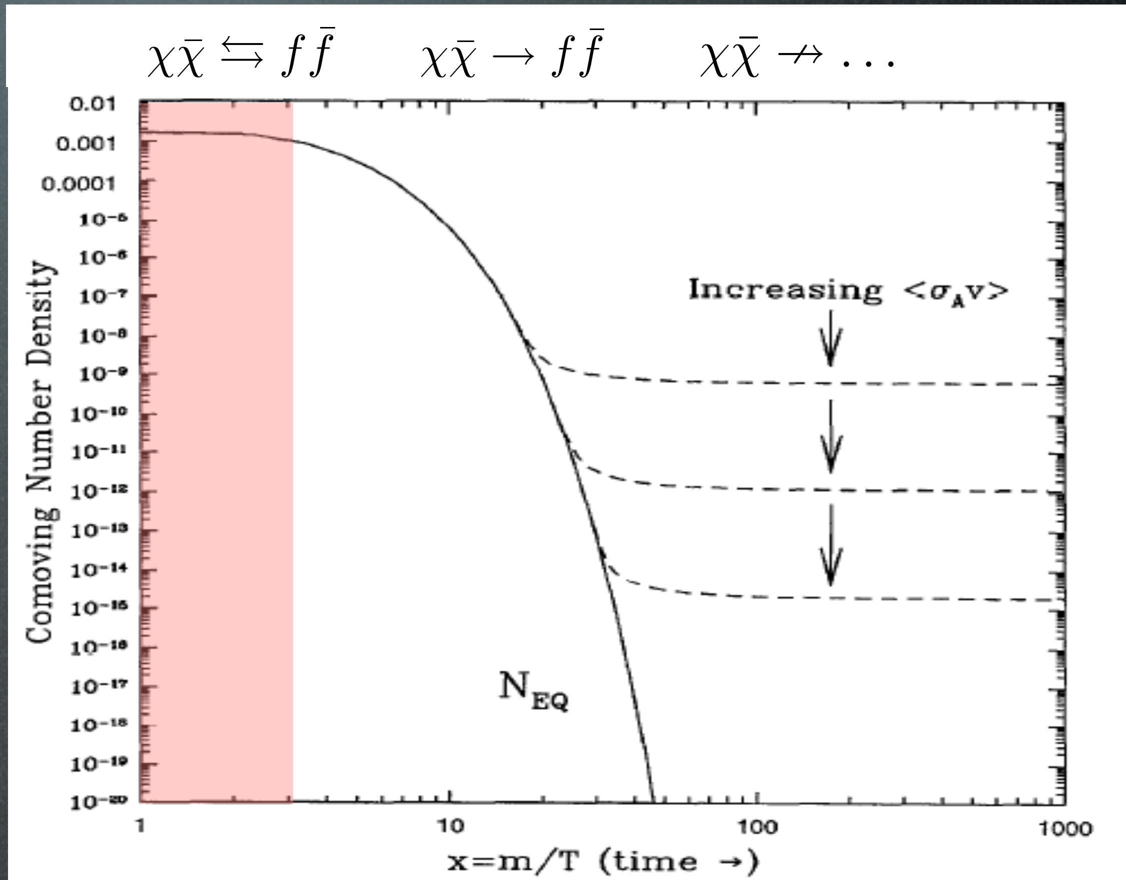

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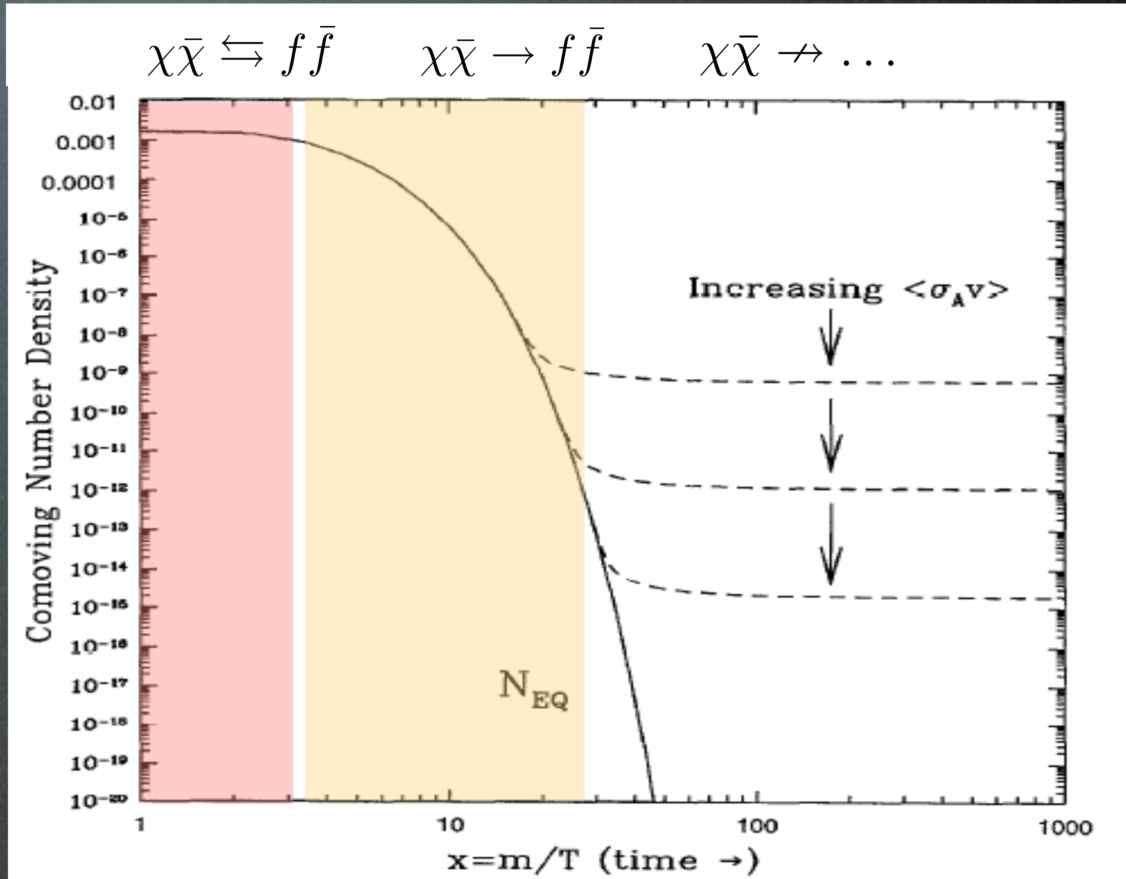

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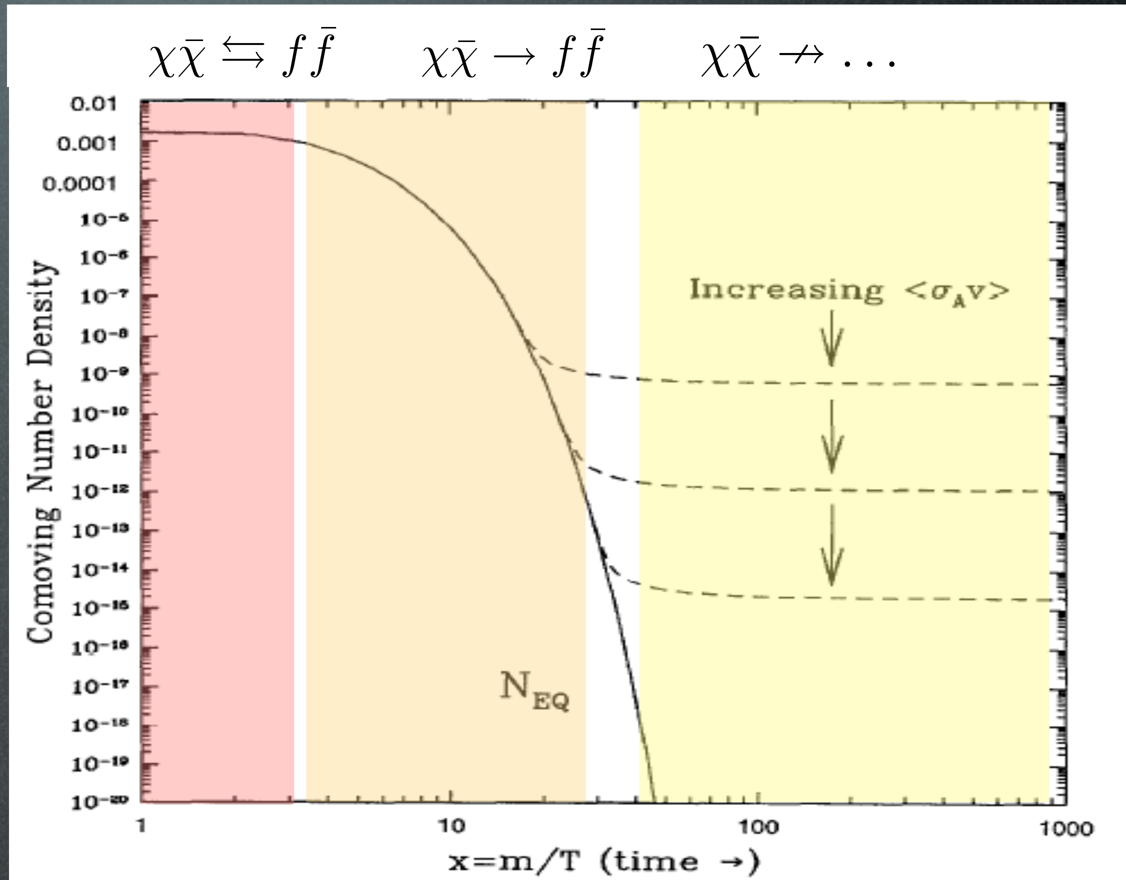

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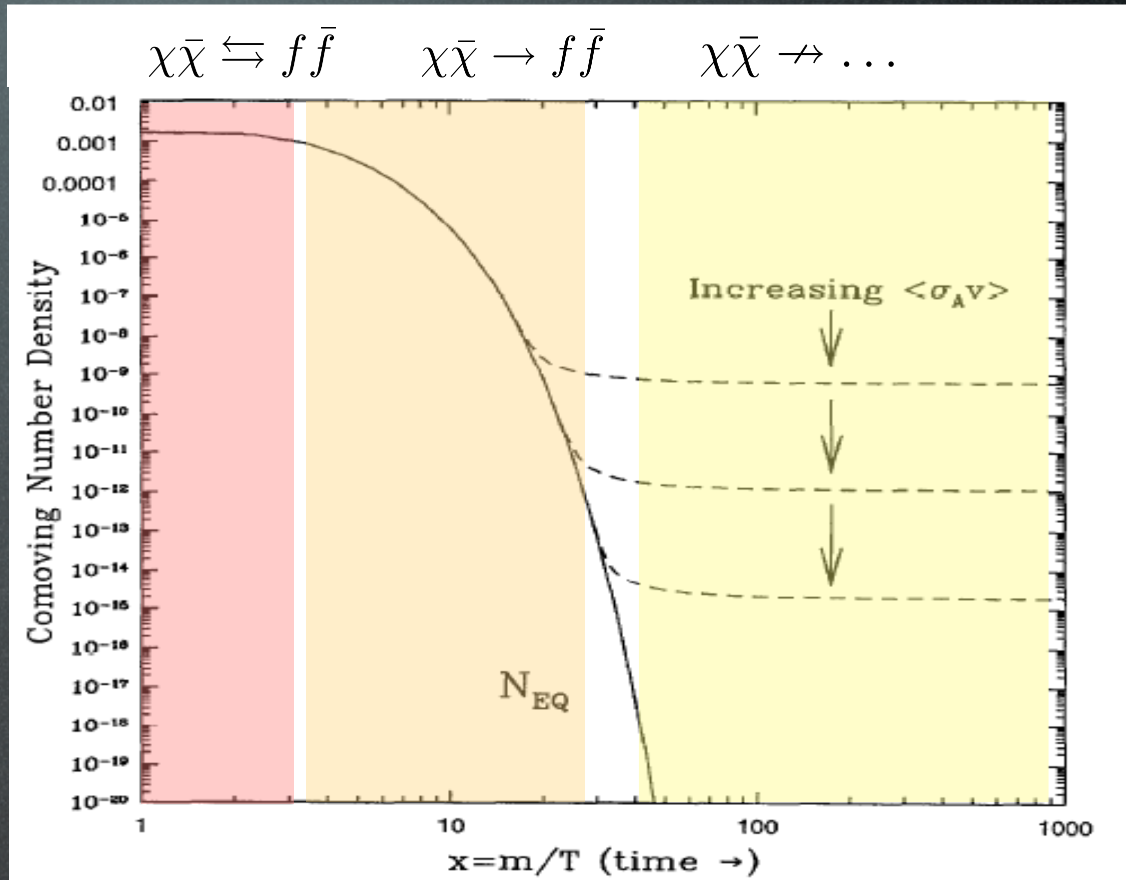
Relic $\Omega_{\rm DM} \simeq 0.26$ for

$$\langle \sigma_{\rm ann} v \rangle = 3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{sec}$$



Kolb,Turner, The Early Universe, 1995

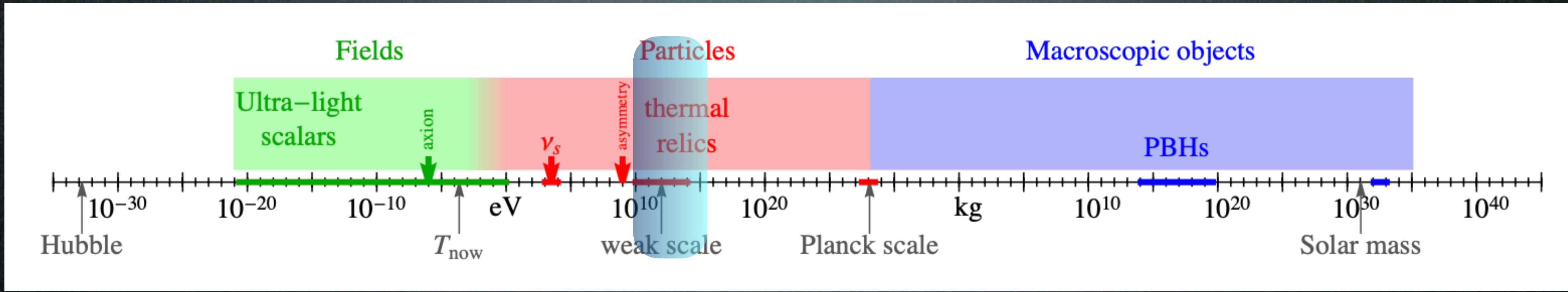
Weak cross section:

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\ TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

Weakly
Interacting
Massive
Particles

Candidates

A matter of perspective: plausible mass ranges



Thermal DM

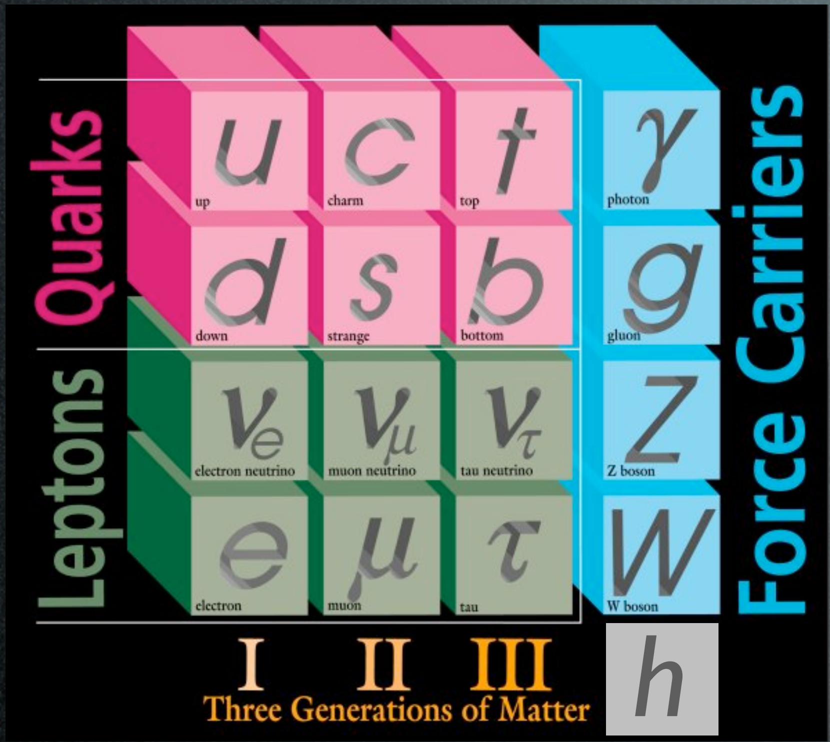
Candidates

A matter of perspective:

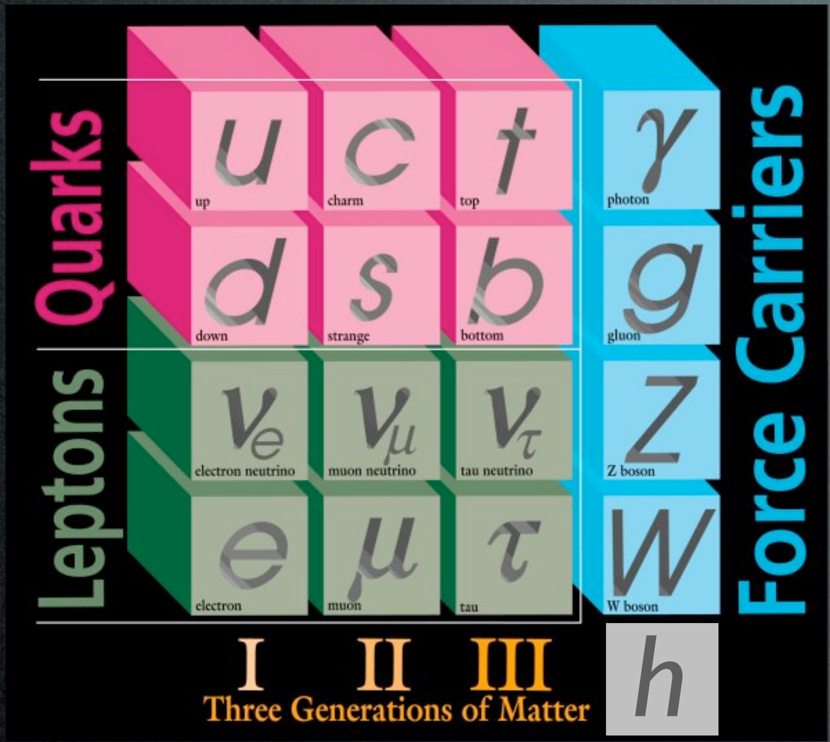
SuSy neutralino

other exotic candi- dates

SuSy DM in 2 minutes

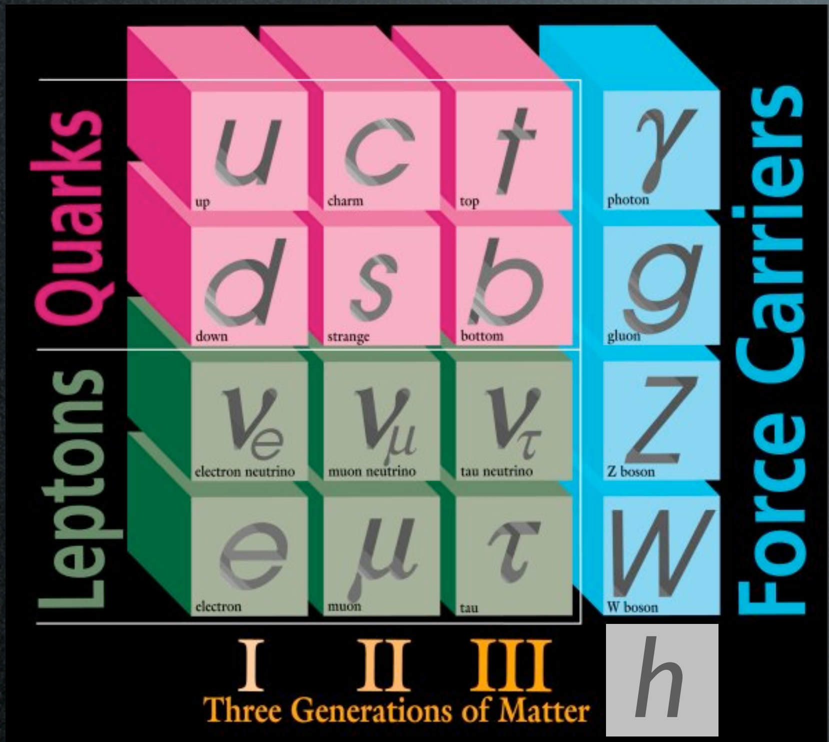


SuSy DM in 2 minutes

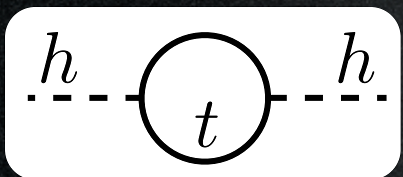


$m_{\mathrm{h}} \simeq 125\ \mathrm{GeV}$

SuSy DM in 2 minutes

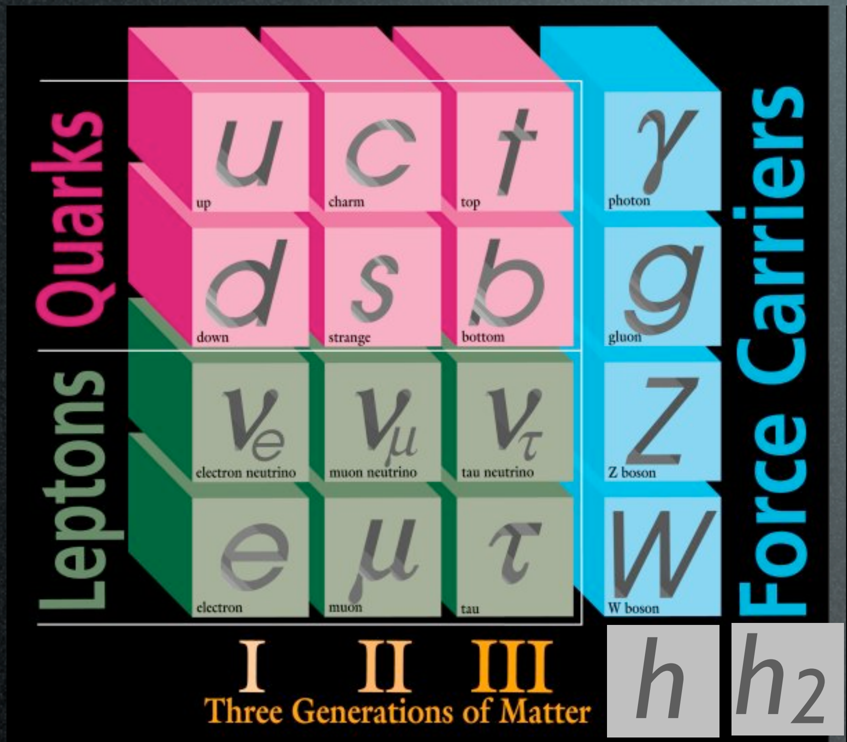


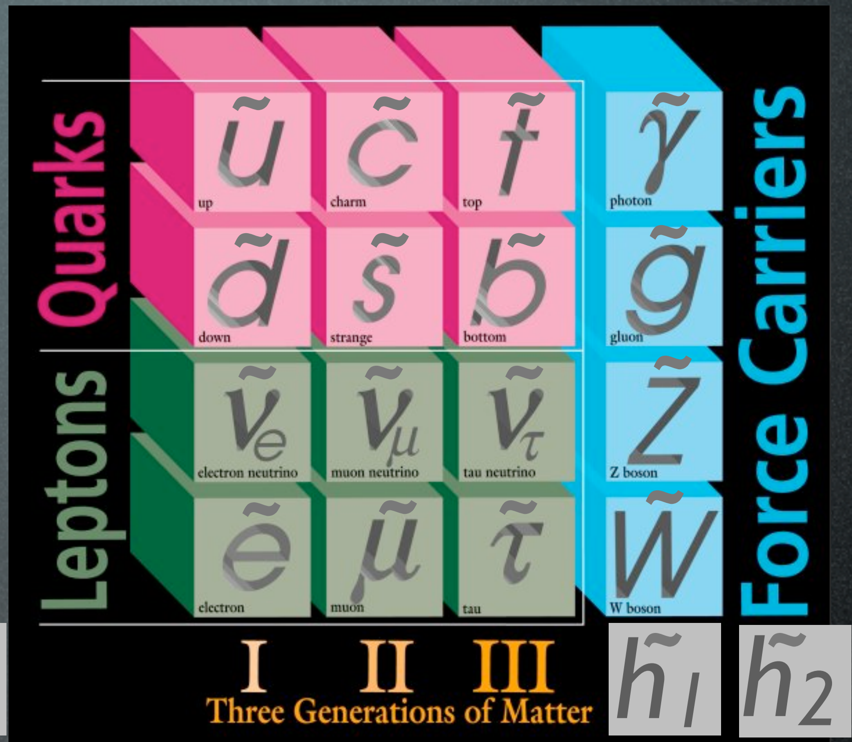
$m_{\rm h} \simeq 125$ GeV



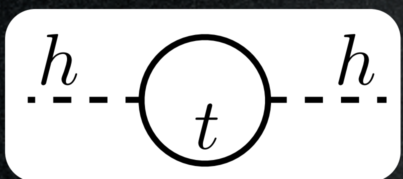
$\Delta m_{\rm h} \propto 10^{19}$ GeV

SuSy DM in 2 minutes

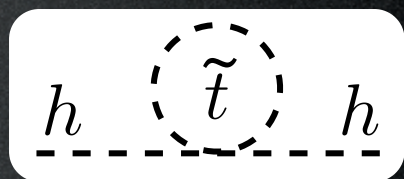




$m_{\rm h} \simeq 125$ GeV

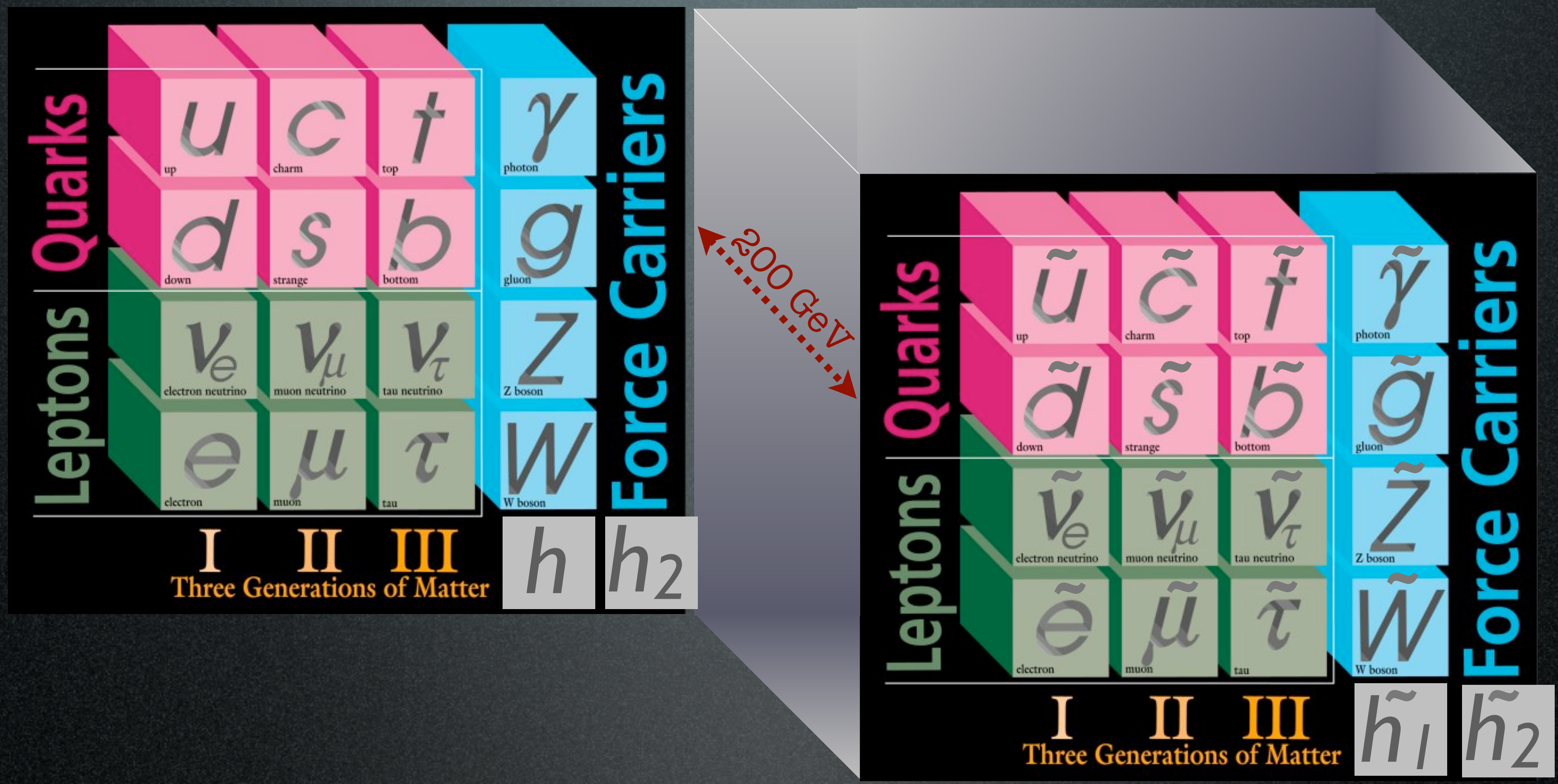


$\Delta m_{\rm h} \propto 10^{19}$ GeV

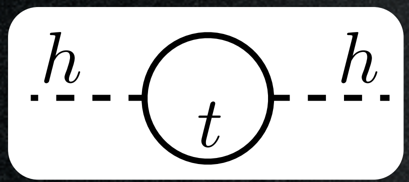


$\Delta m_{\rm h} \propto -10^{19}$ GeV

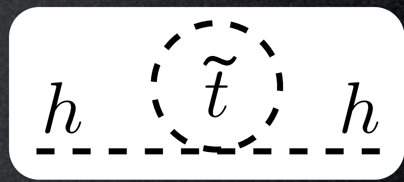
SuSy DM in 2 minutes



$m_{\rm h} \simeq 125$ GeV

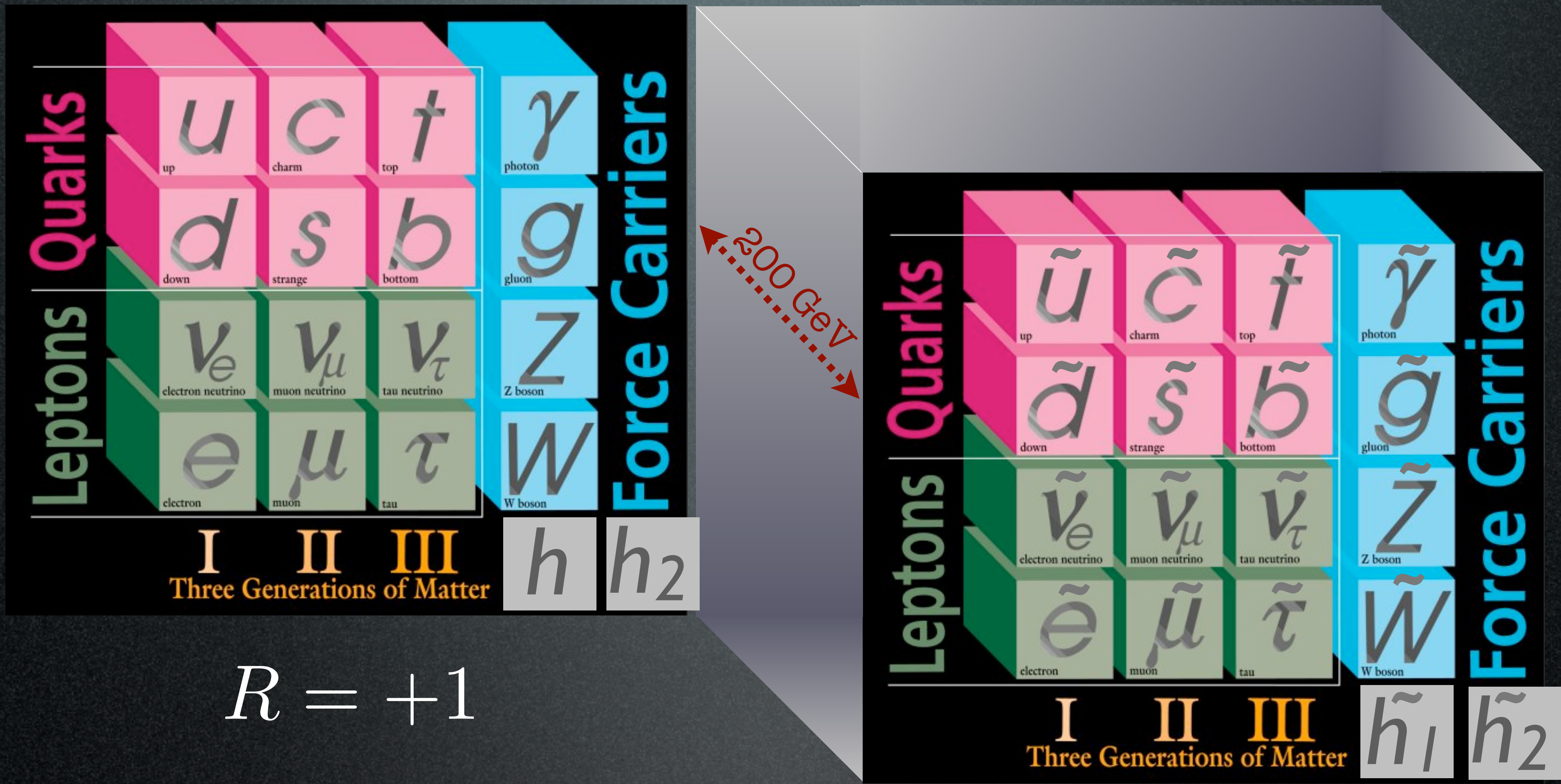


$\Delta m_{\rm h} \propto 10^{19}$ GeV



$\Delta m_{\rm h} \propto -10^{19}$ GeV

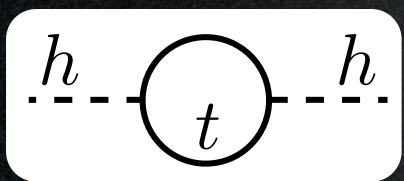
SuSy DM in 2 minutes



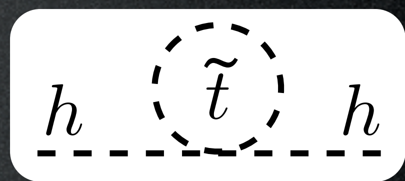
$$R = +1$$

$$R = -1$$

$m_{\rm h} \simeq 125$ GeV

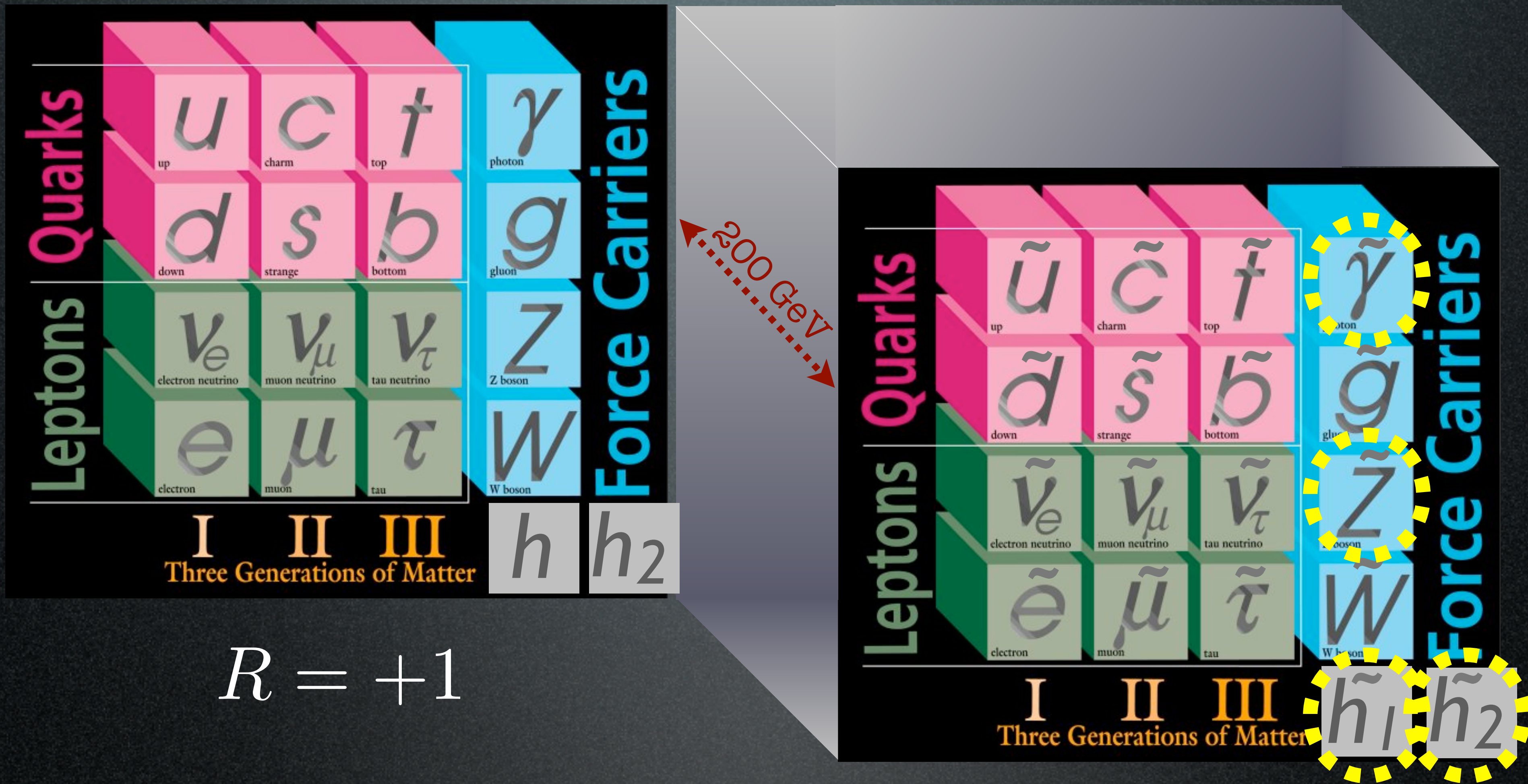


$\Delta m_{\rm h} \propto 10^{19}$ GeV



$\Delta m_{\rm h} \propto -10^{19}$ GeV

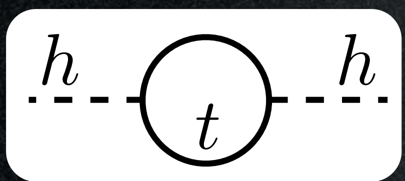
SuSy DM in 2 minutes



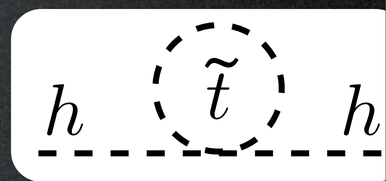
$R = +1$

$R = -1$

$m_h \simeq 125$ GeV

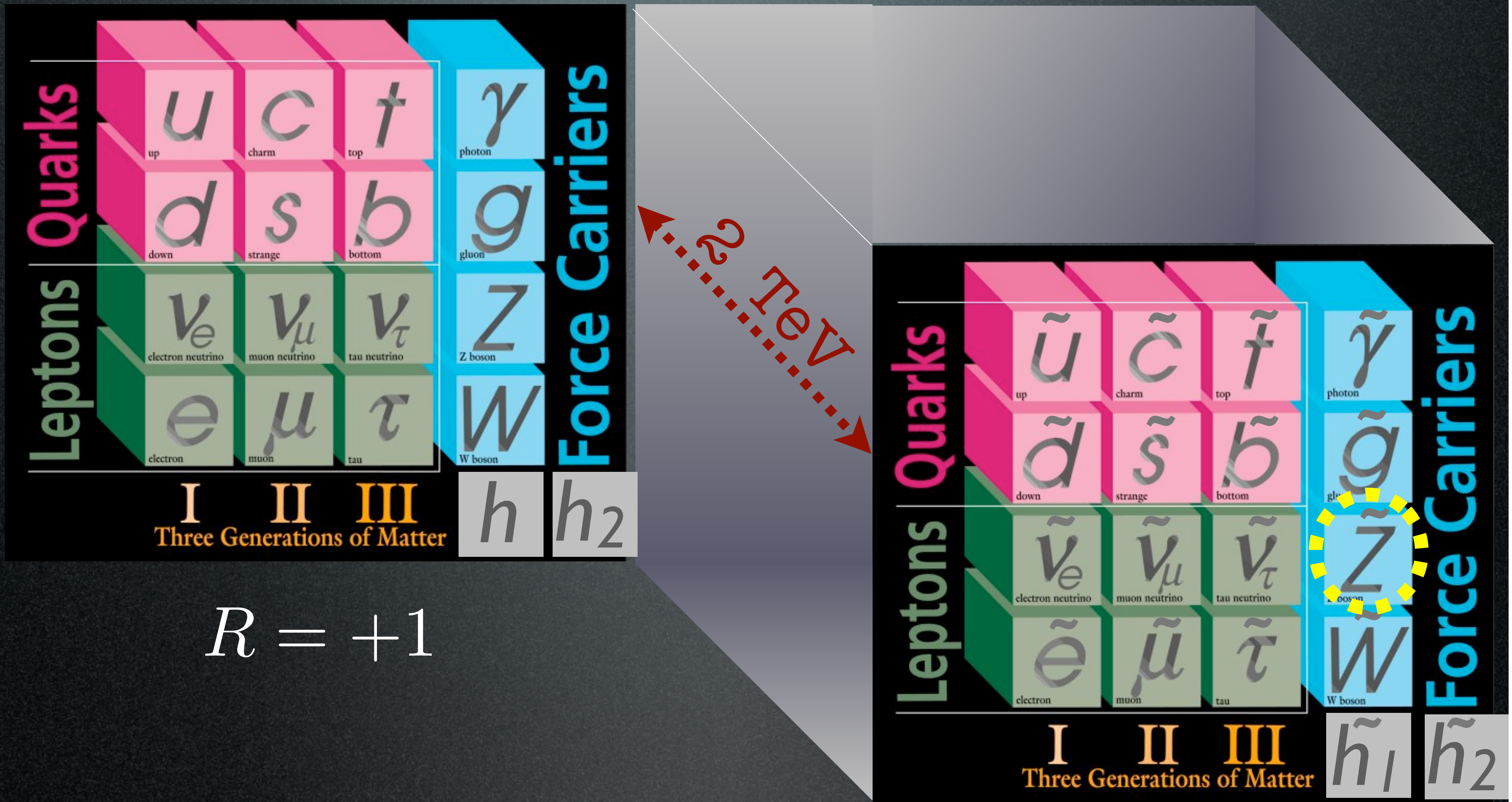


$\Delta m_h \propto 10^{19}$ GeV



- neutral ☑
- cold ☑
- stable ☑
- feebly int. ☑

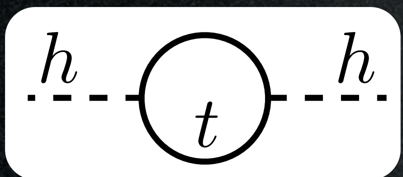
SuSy DM in 2 minutes



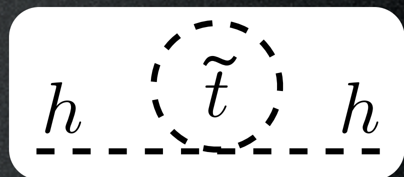
$$R = +1$$

$$R = -1$$

$$m_{\rm h} \simeq 125 \text{ GeV}$$



$\Delta m_{\rm h} \propto 10^{19}$ GeV



$\Delta m_{\rm h} \propto -10^{19}$ GeV

Candidates

A matter of perspective:

SuSy neutralino

other exotic candi-dates

Candidate

Excentric DM
...inuum ...M
graviballs DM
Large Nightmare DM
...omeopathic DM
Bouncing DM
...pectato... DM
Undulating DM
Puffy DM
...teal... DM
Ballistic DM
Fuzzy DM
...mbie DM
Minimal DM
Impede... DM
Cannibal DM
Scalar singl...
Anapol... DM
Indalo DM
...ino
dipolar DM
Little ...iggs ...M
Asym-metric ...
ELDER DM
SusY neutralin...
self-...estructing DM
SIM...
Regurgitated DM
Fluff... D...
Saturon DM
...yleig... DM
eXciting
...-inter...
foamy DM
ISPy DM
Tech... baryon
...atal ...M
SPartAcous DM
...IT... ...M
WIMPzillas
Dichrom... DM
Recycled DM
...xio...
STUMP DM
...rr... ...atte...
charming DM
Vector DM
...andemic DM
...idden ...
Leptobary... DM
WIMPless DM
Relentless DM
...eor... DM
...ncentrated DM
heav... higgs DM
Sterile Neutrino
Luminous DM
Geometric DM
...luza ...ein ...M
Gravitino
Elko DM
MeV DM
Q-balls
quark ...uggets
Fluorescent DM
dark photon
Imperfect DM
Magnetic inelasti... DM
Higgs ploding DM
Mimetic DM