23 September 2024

ISAPP School - Bad Liebenzell

Dark Matter
evidences and candidates

Marco Cirelli

(LPTHE Jussieu CNRS Paris)

Reviews/books on Dark Matter:

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2021 Les Houches Summer School on Dark Matter: https://indico.cern.ch/event/949654/

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Introduction

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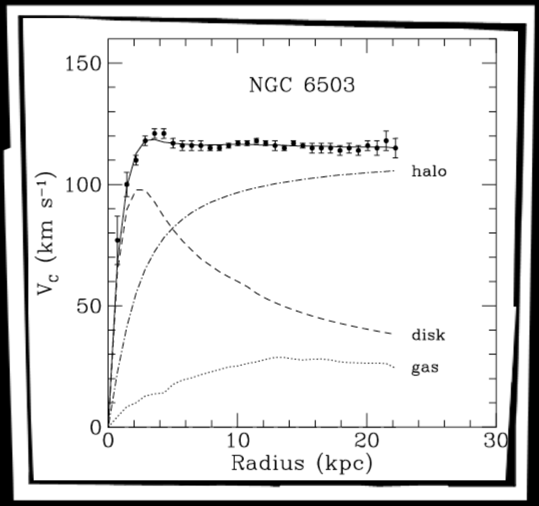
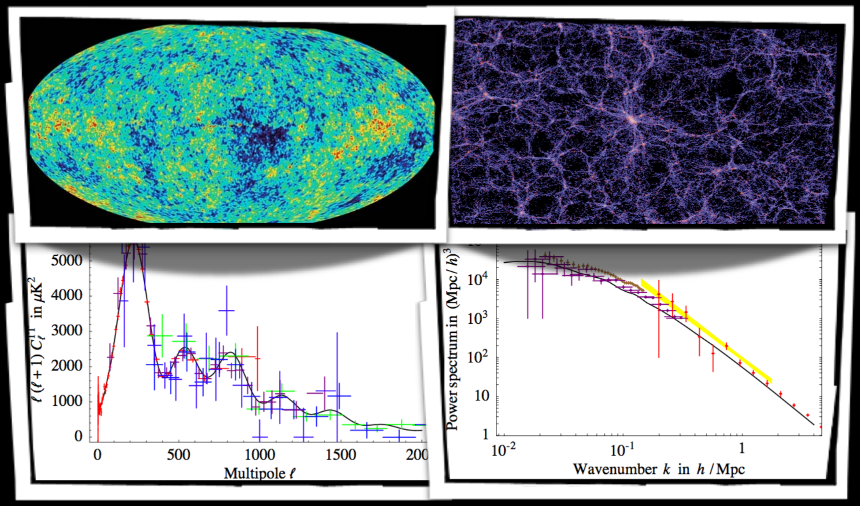


galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

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- it's a new, unknown corpuscle

no SM particle can fulfil

dilutes as $1/a^3$ with universe expansion

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  84% of total matter

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(notice error!)

Planck 2015, 1502.01589 (tab.4)

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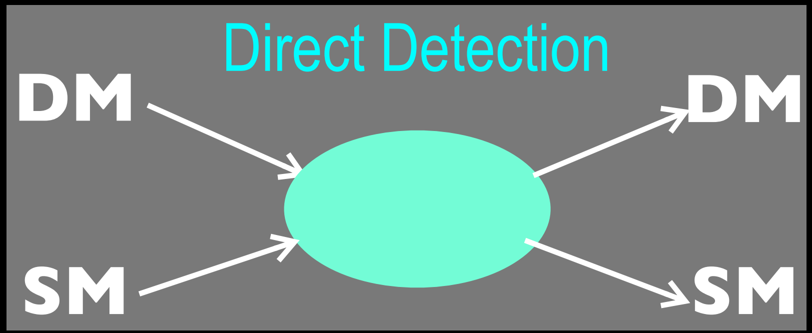

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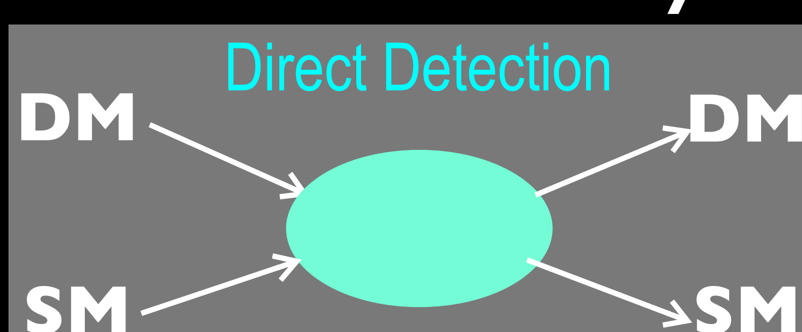

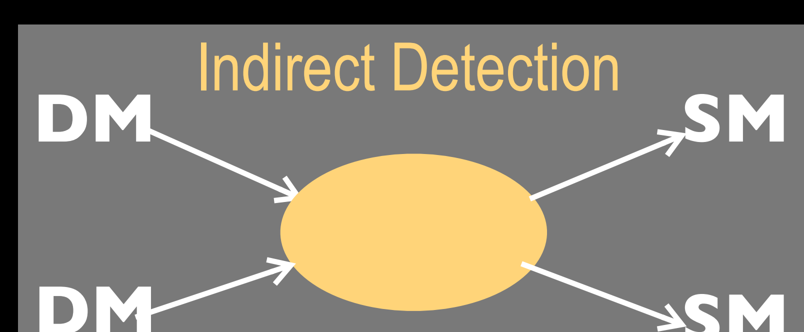

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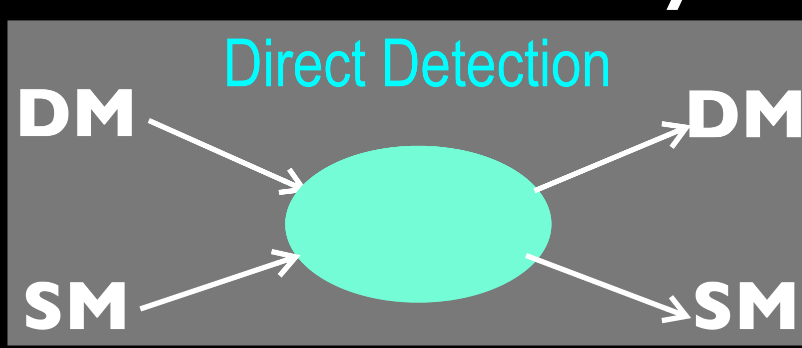
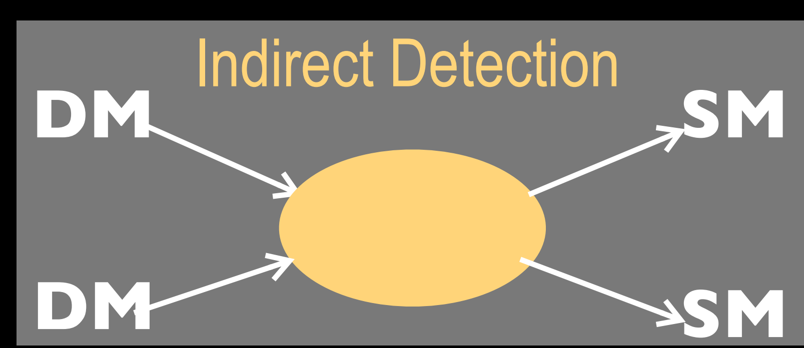
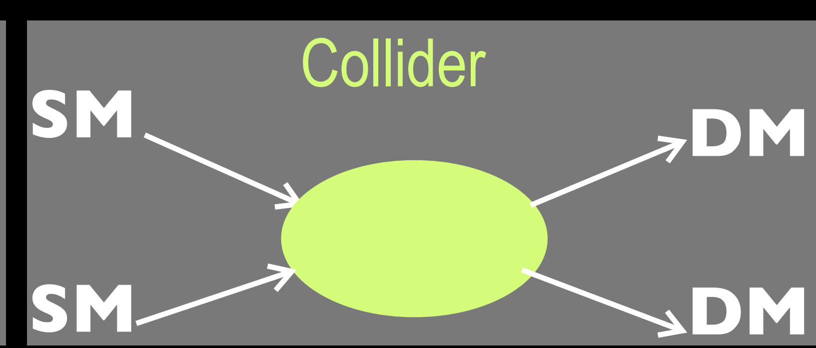
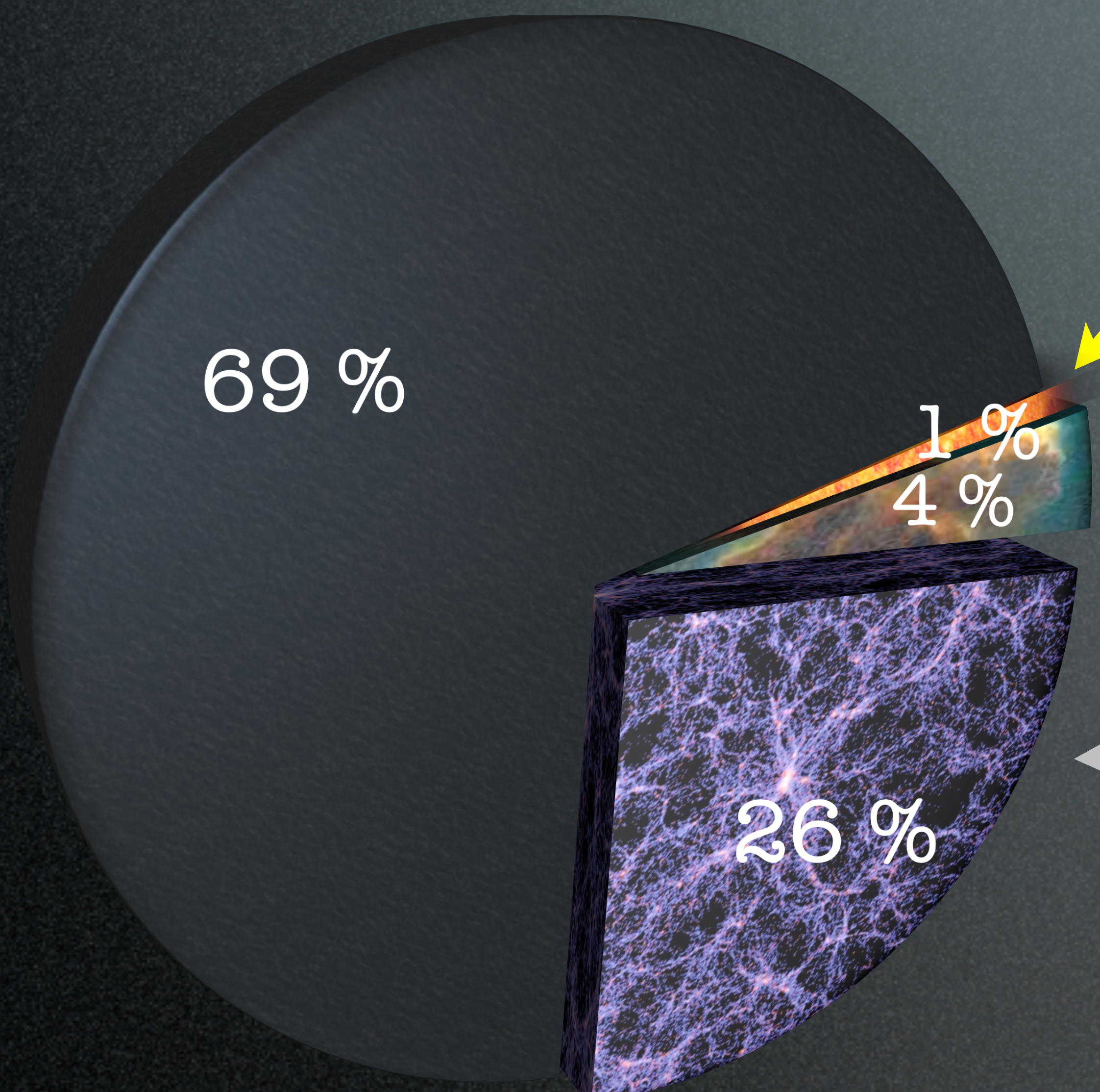






The cosmic inventory

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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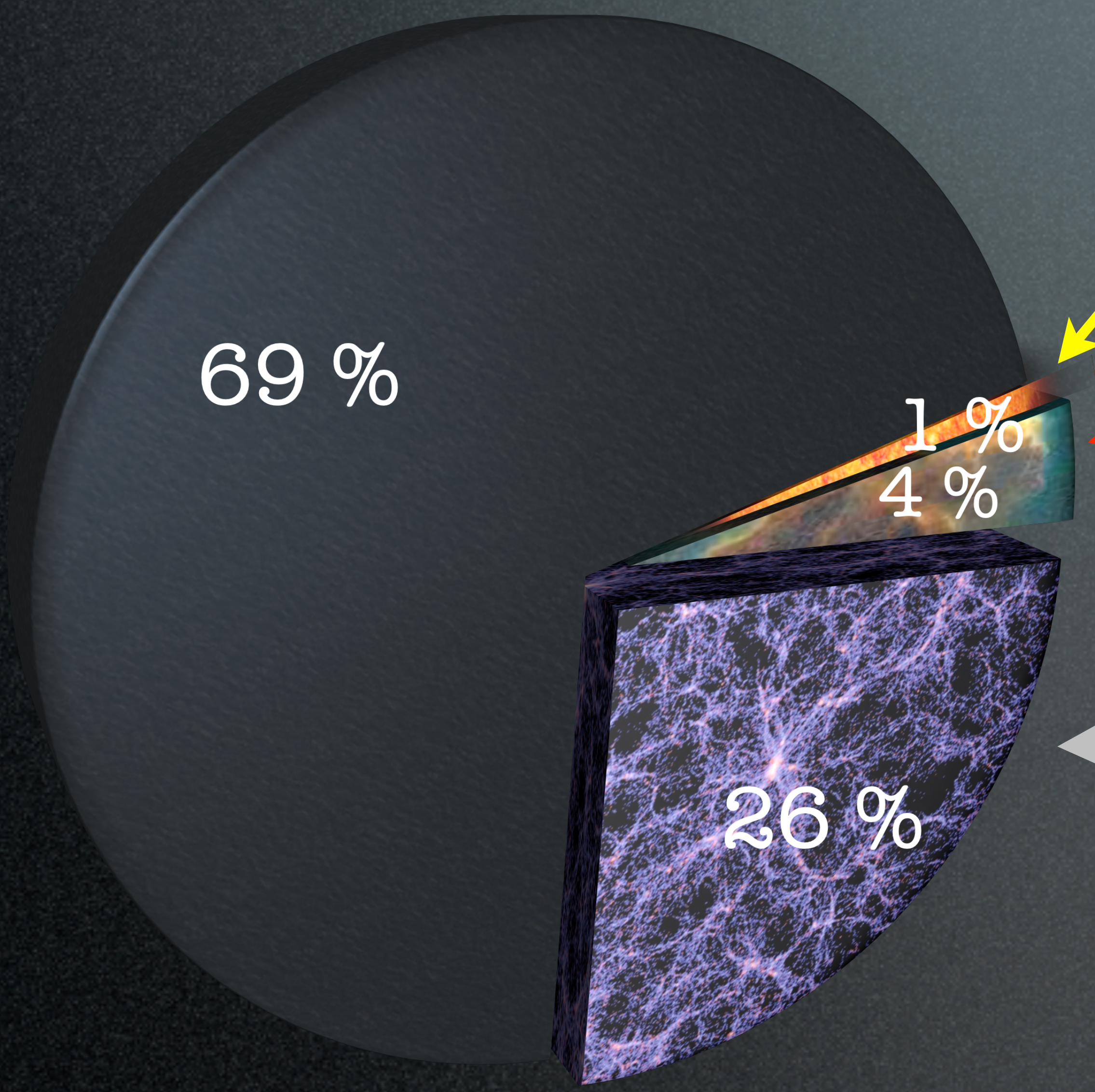

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particle physics $\cap$ cosmology

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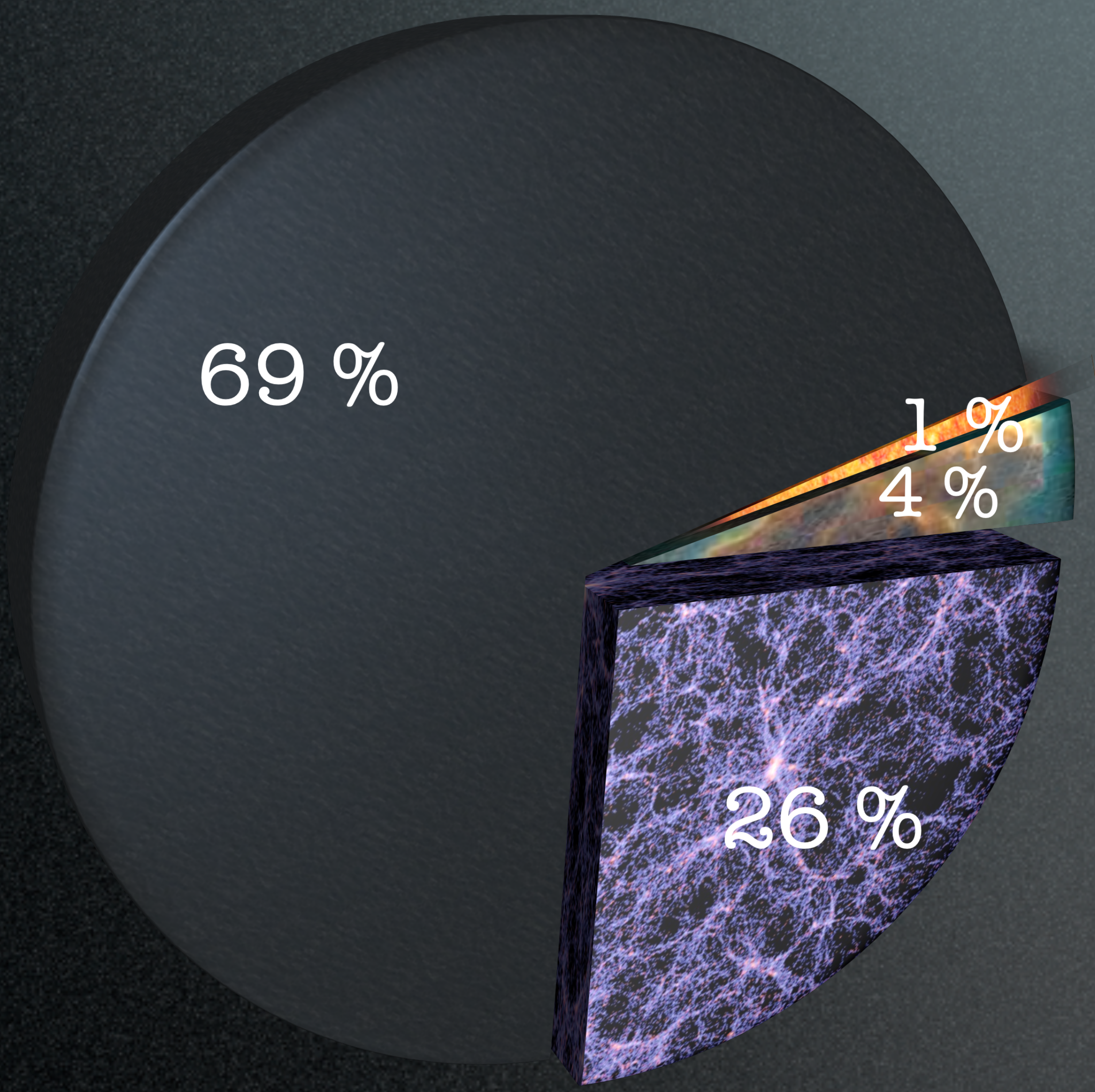


FAvgQ: what's the difference between DM and DE?

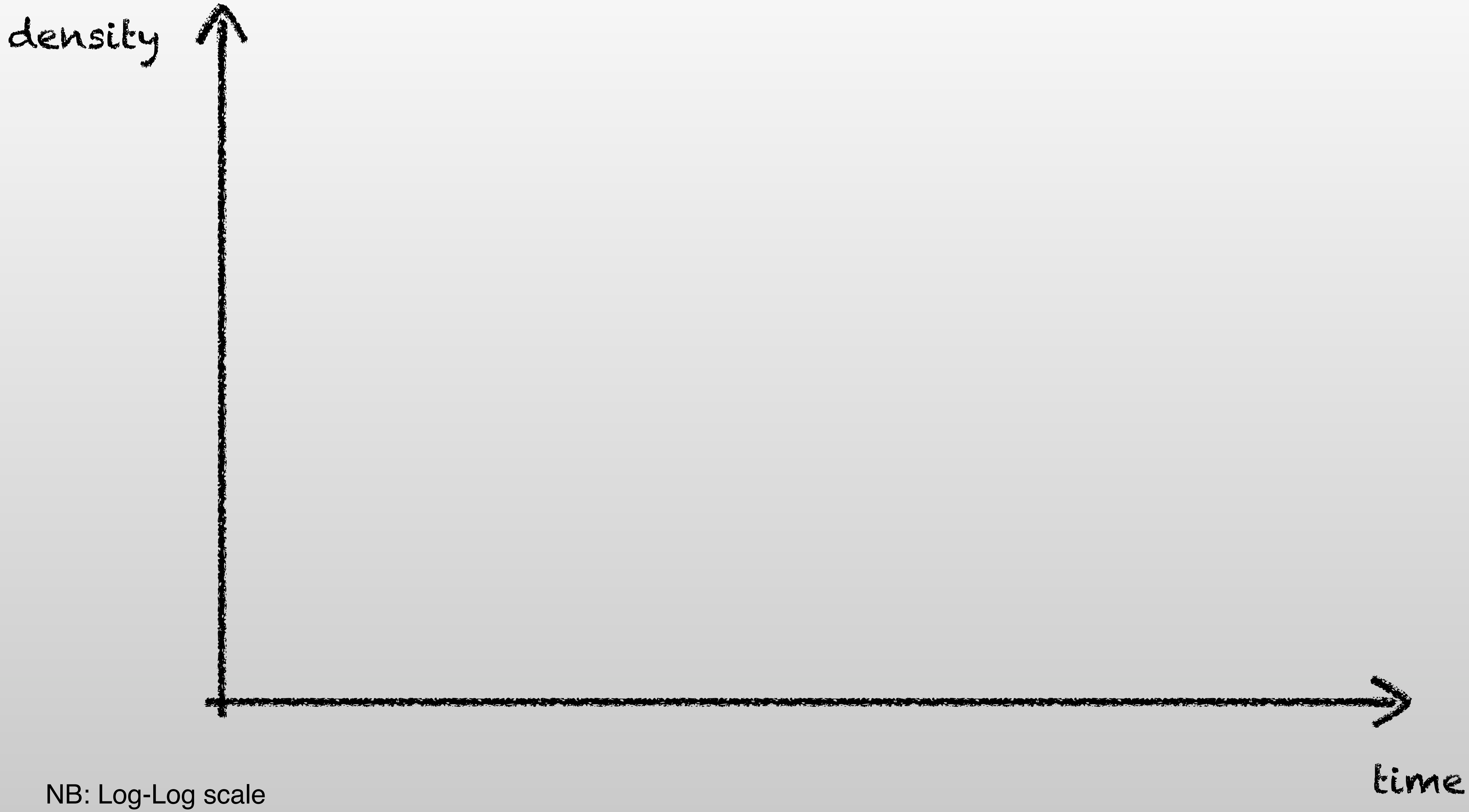
DM behaves like matter

- 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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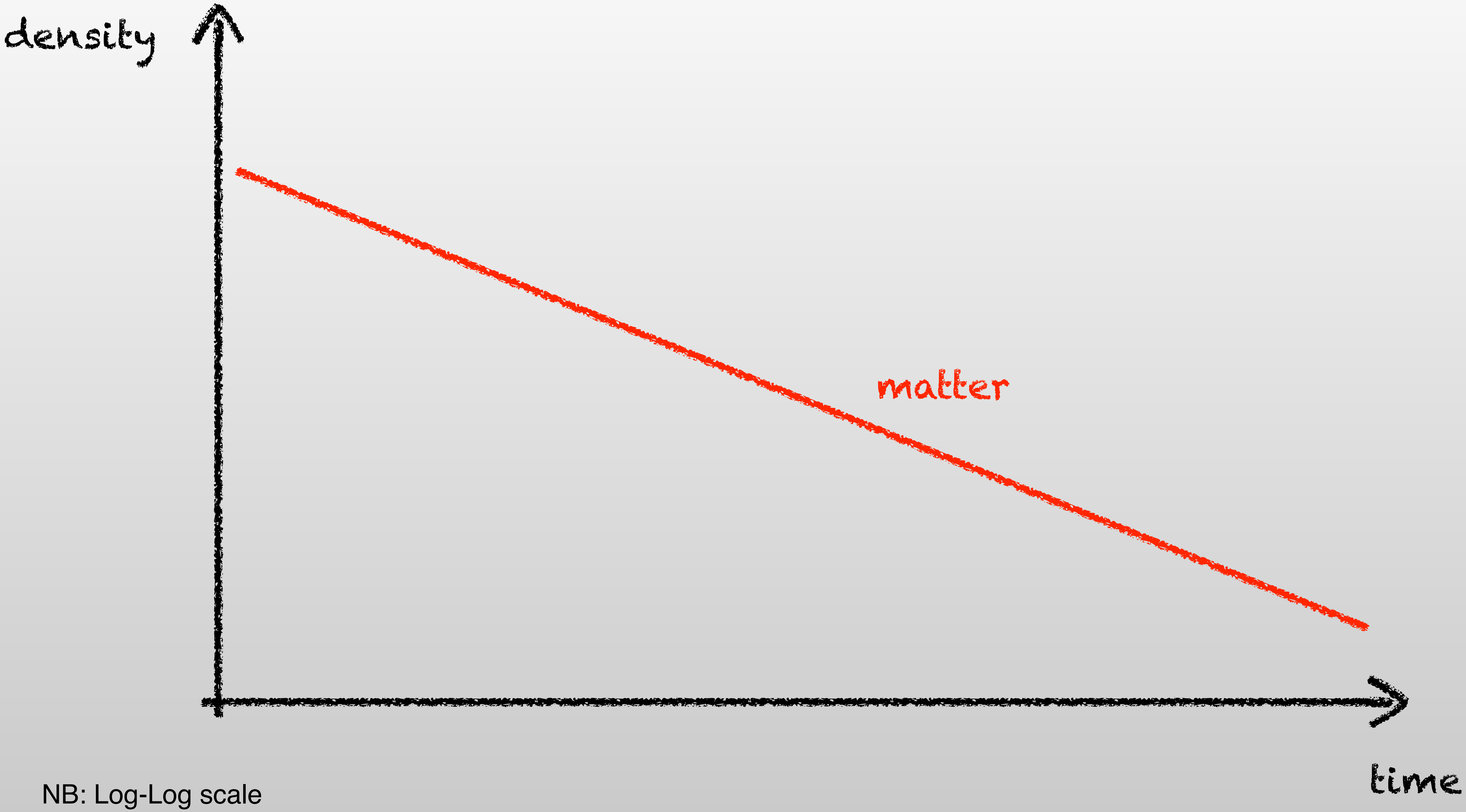

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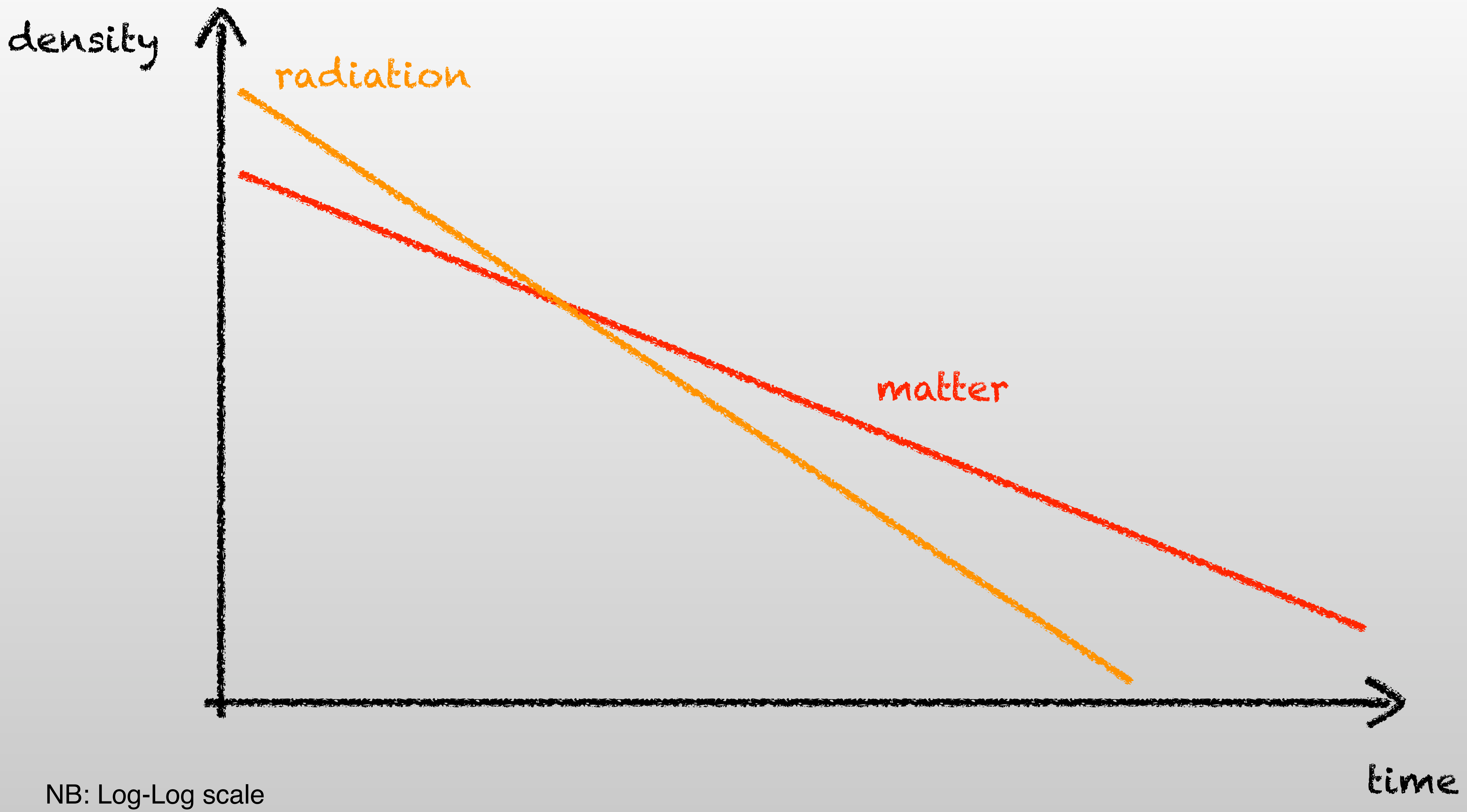

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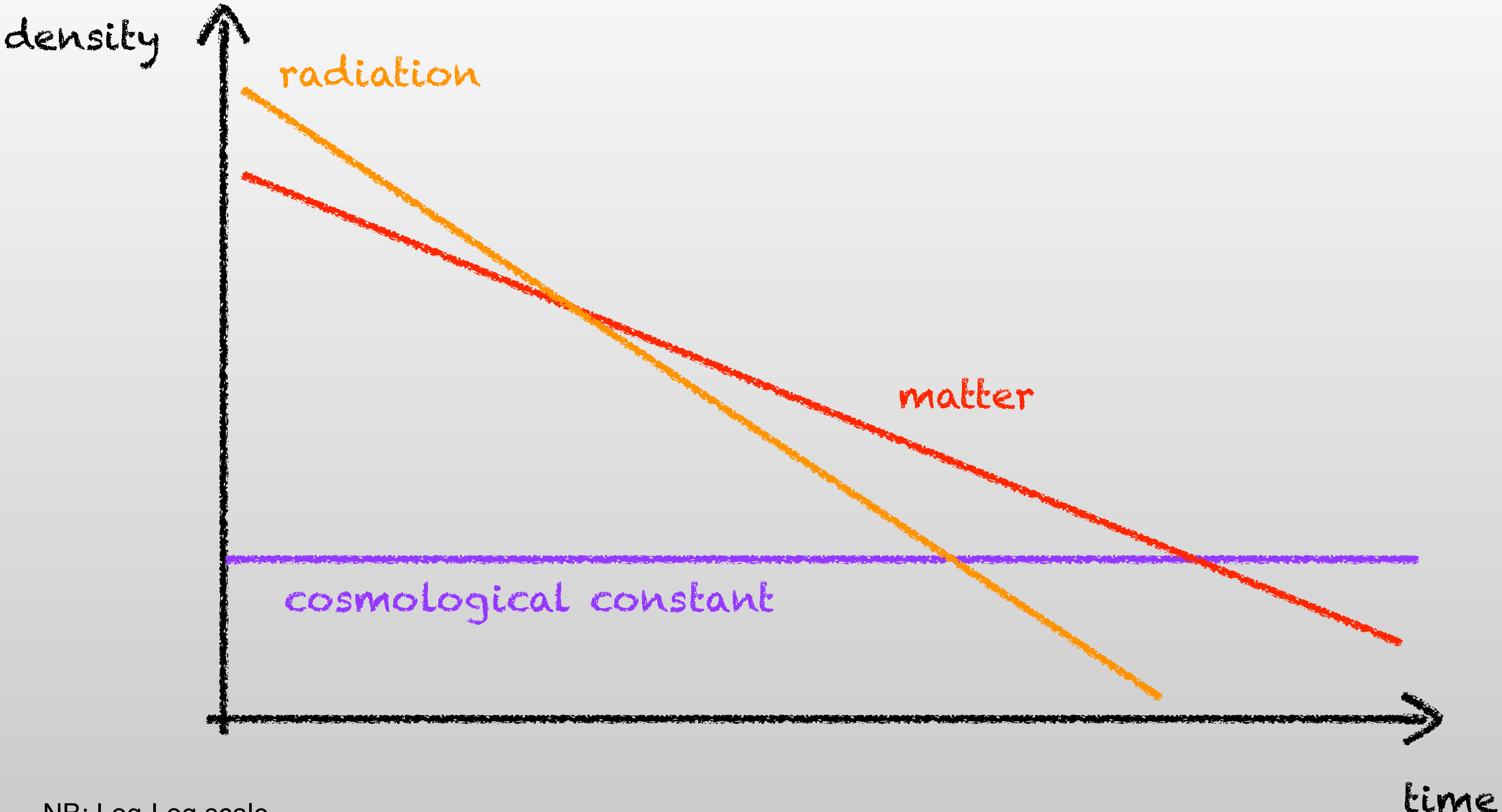

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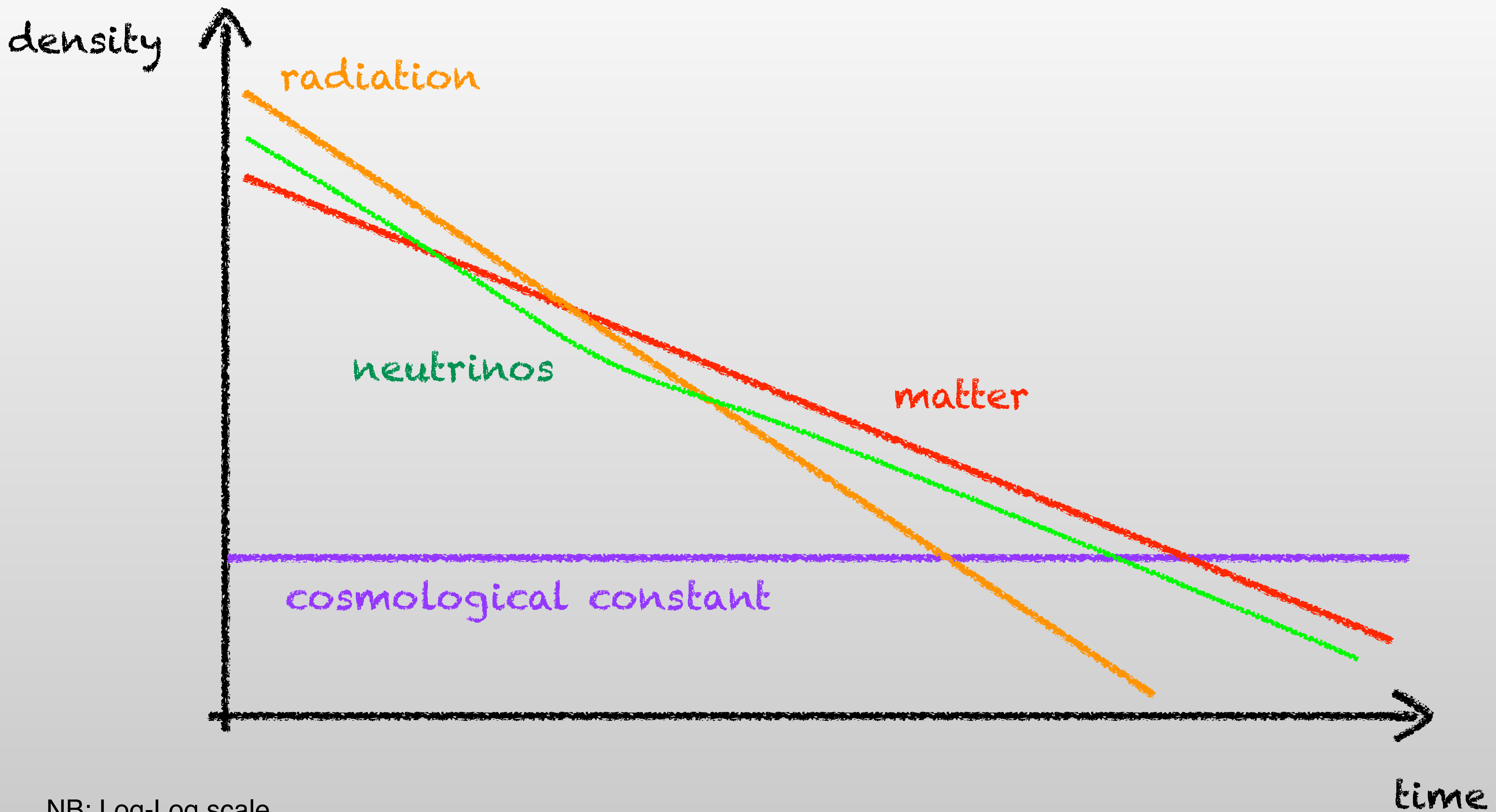

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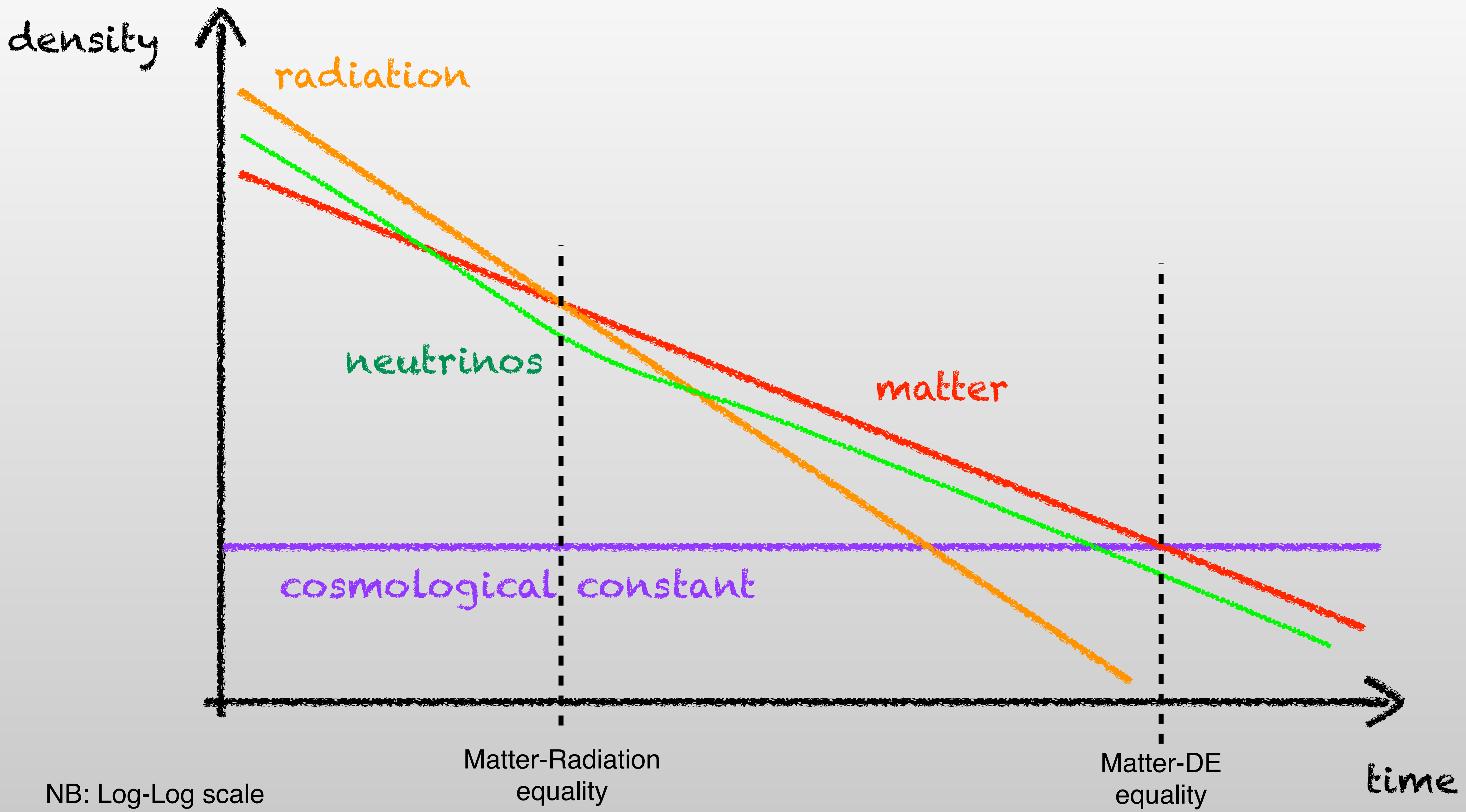

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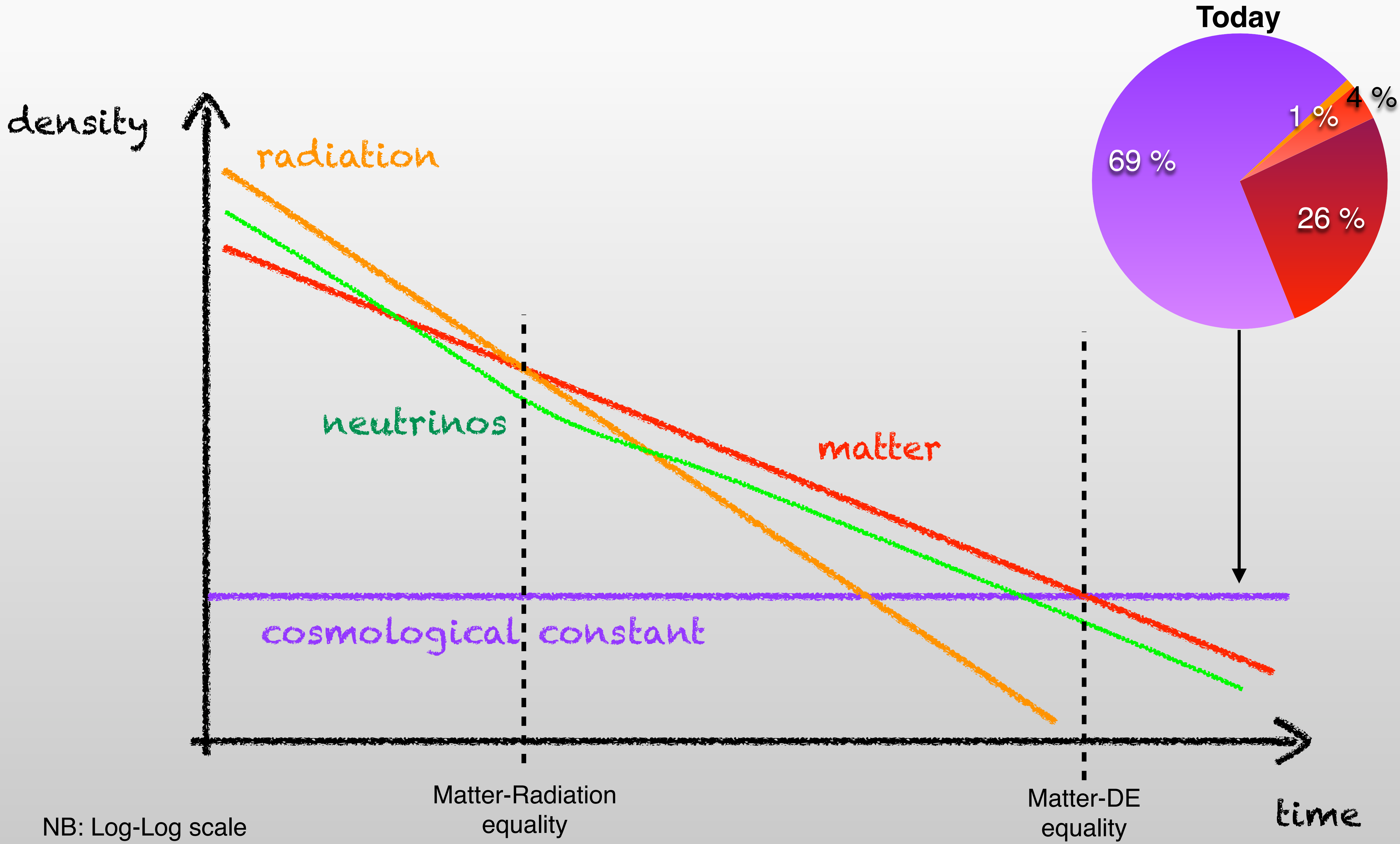

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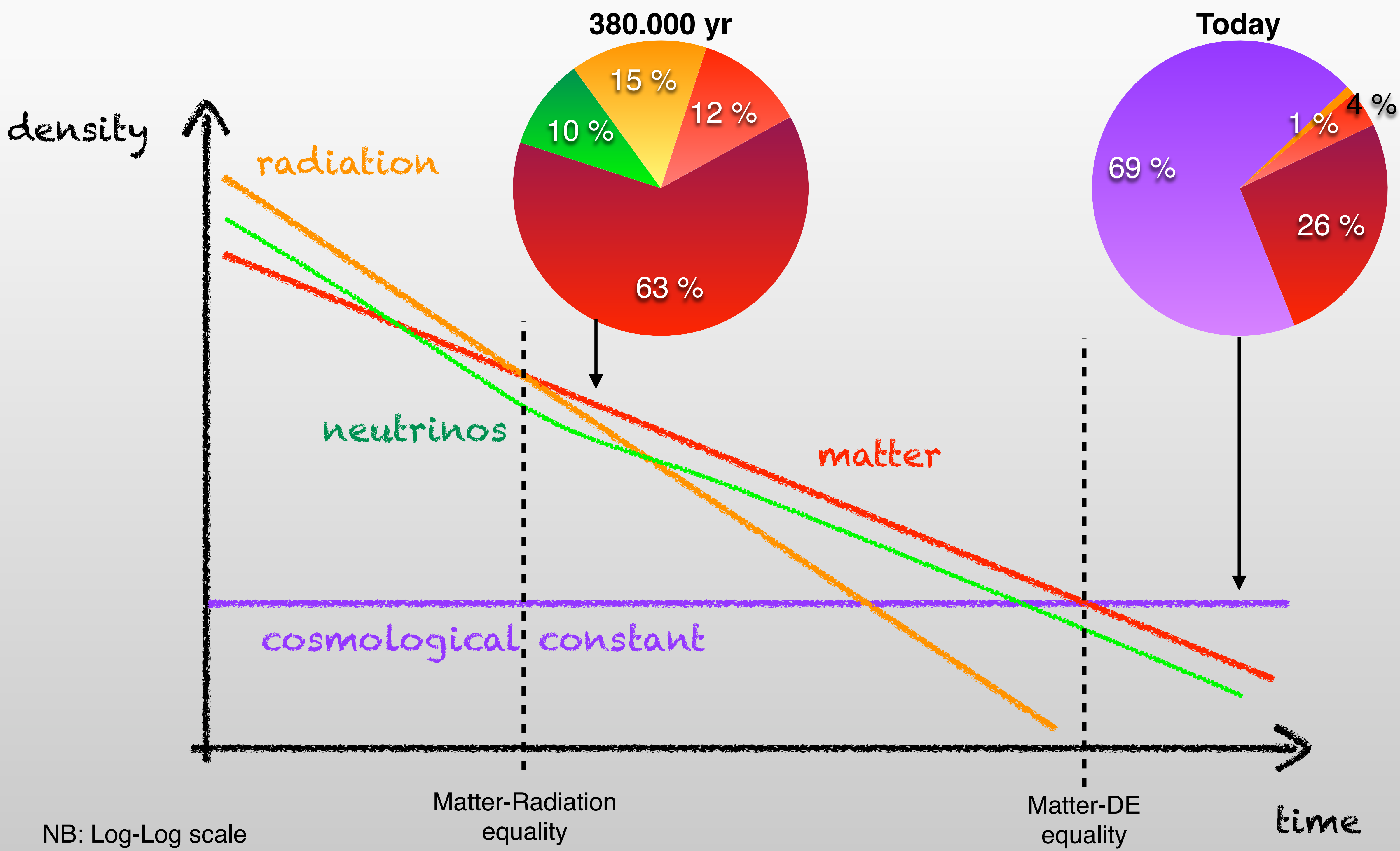

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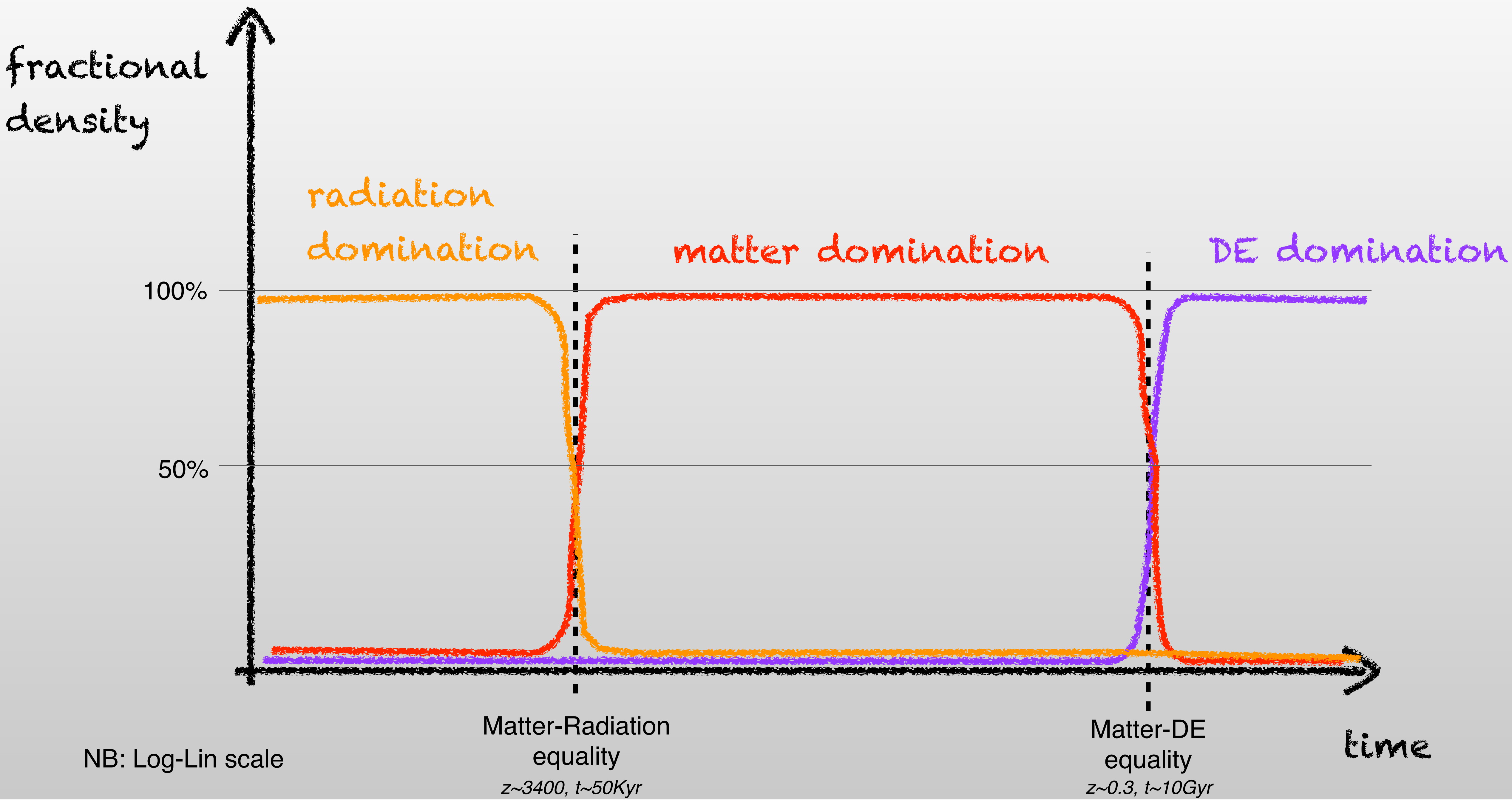

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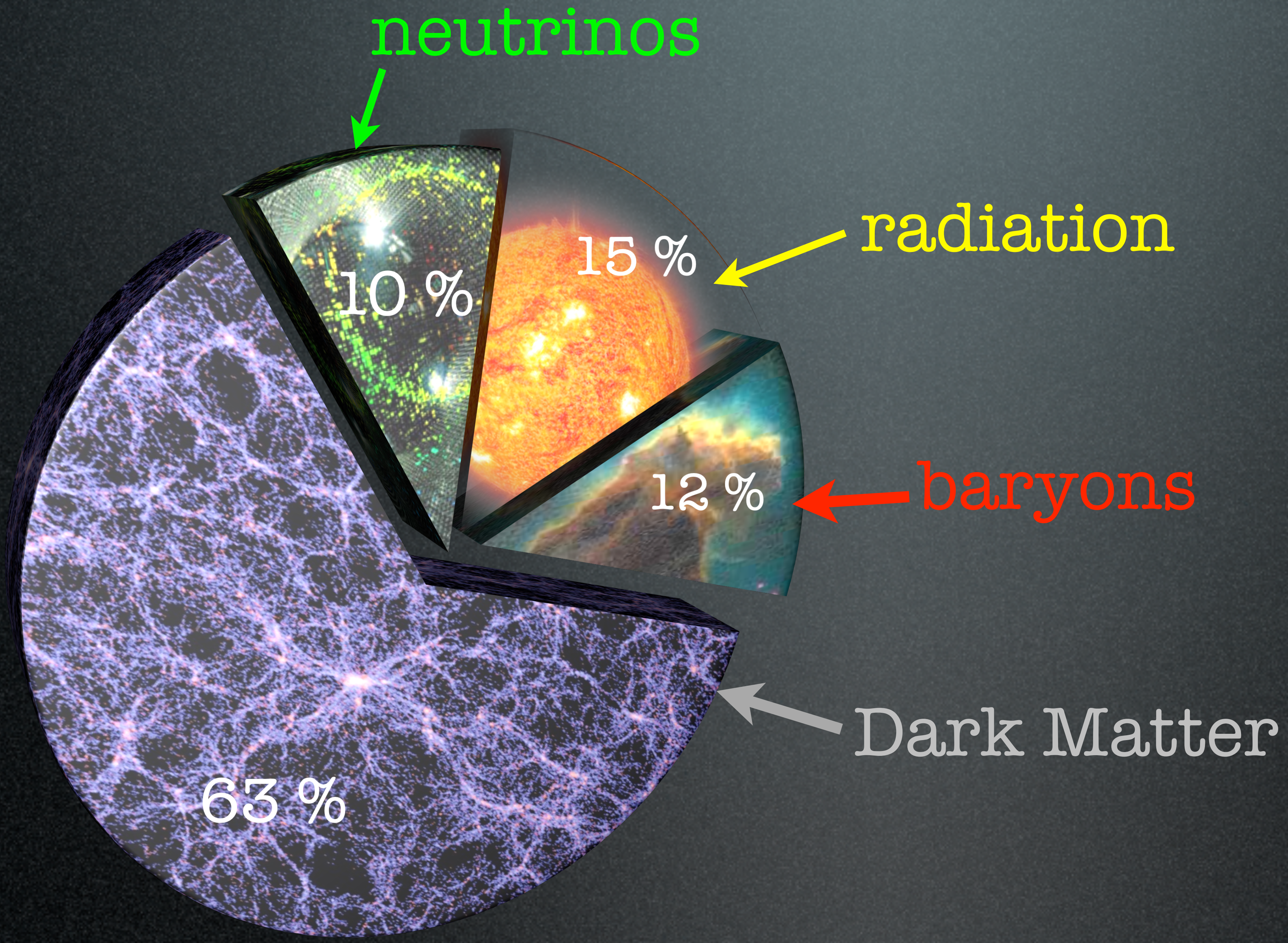

At the time of CMB formation (380 Ky)

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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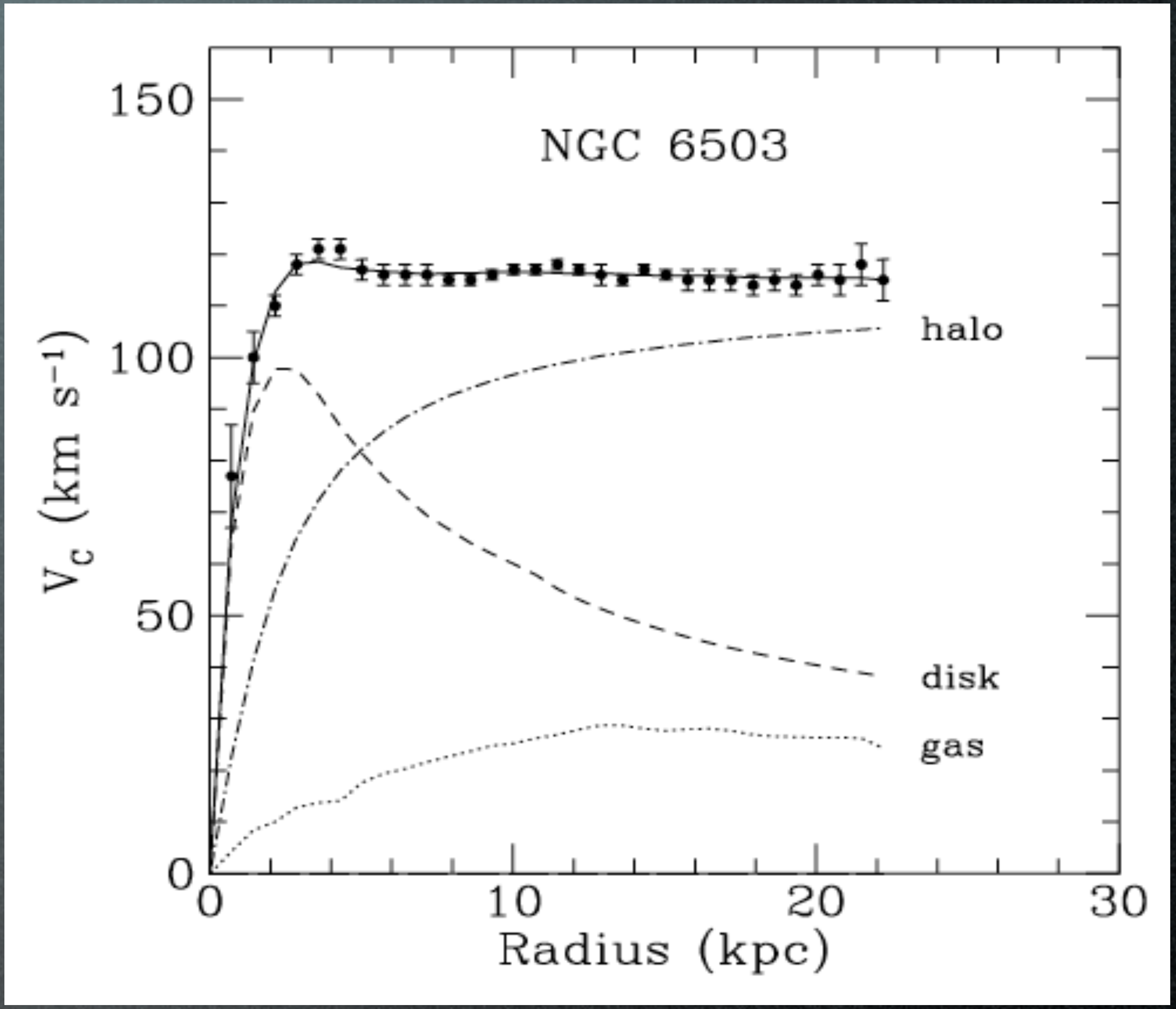
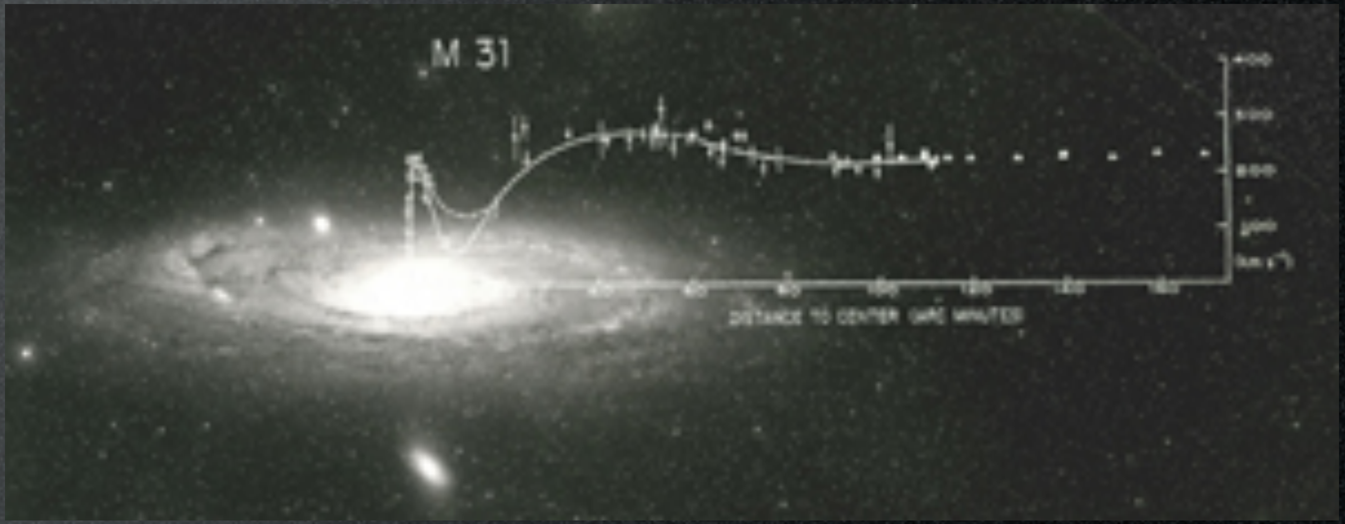


Begeman et al., MNRAS 249 (1991)



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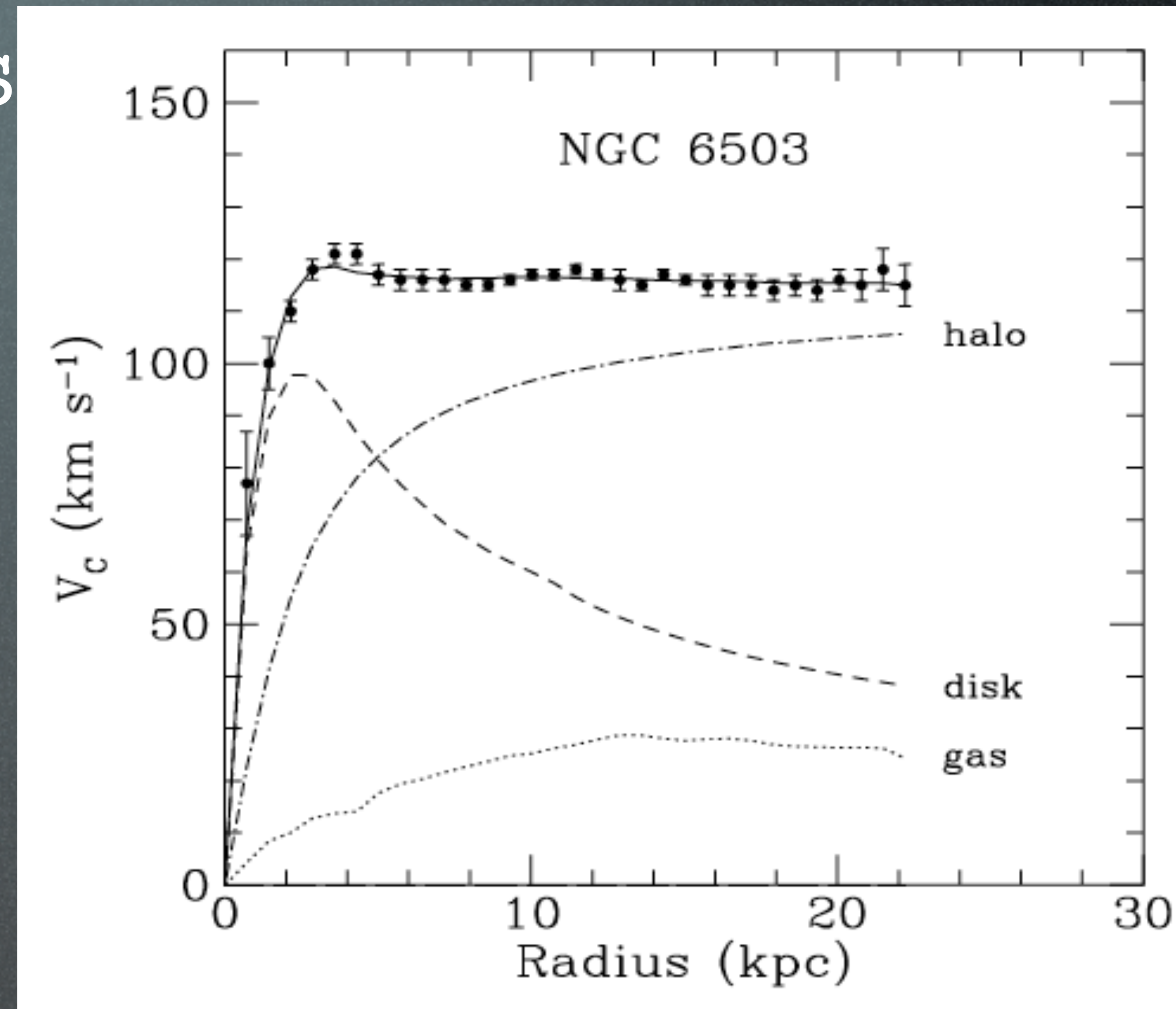
$$m\frac{v_c^2(r)}{r} = \frac{G_N m M(r)}{r^2}$$

'centrifugal' 'centripetal'



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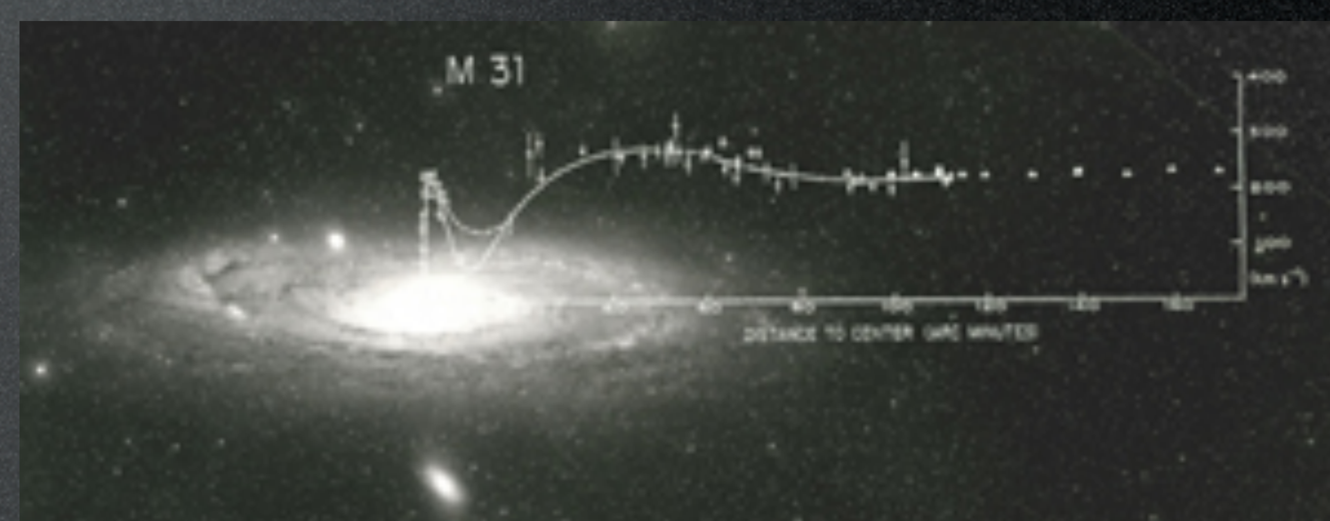

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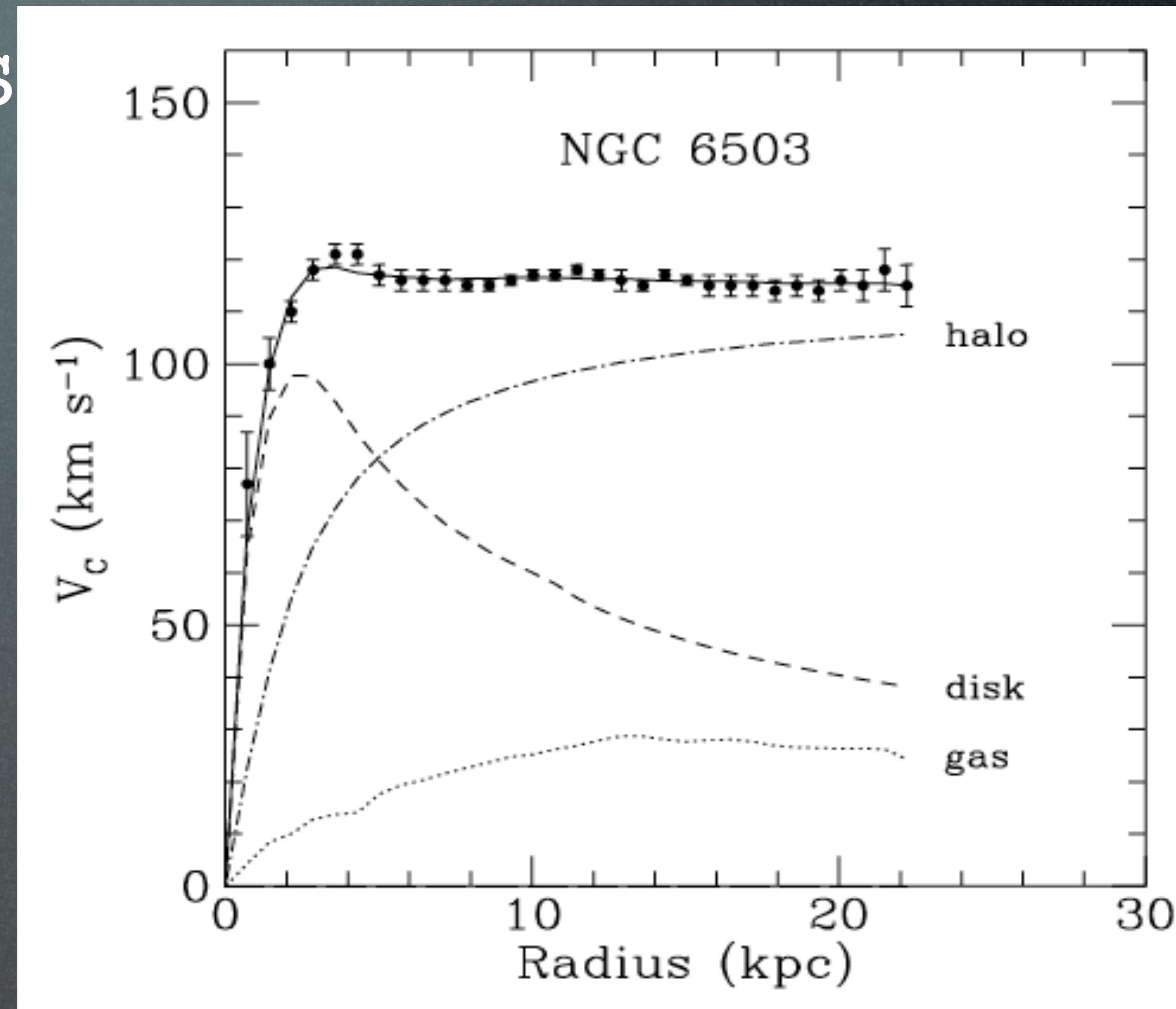
with $M(r) = 4\pi \int \rho(r)\, r^2 dr$

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

and indeed a ‘gas’ of non-interacting particles distributes like 1/r²



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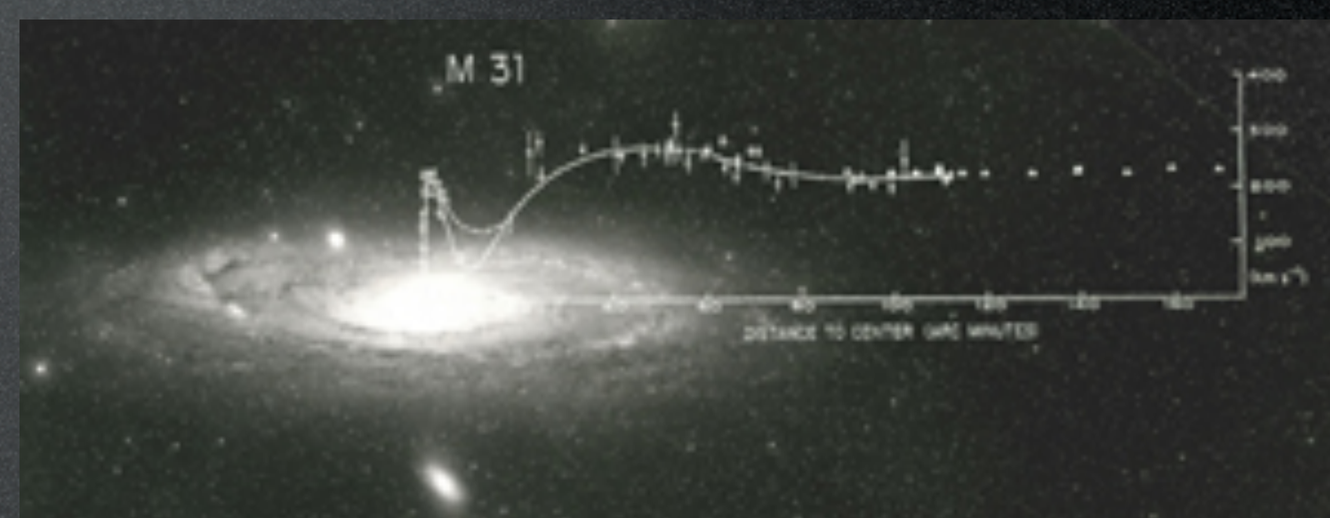

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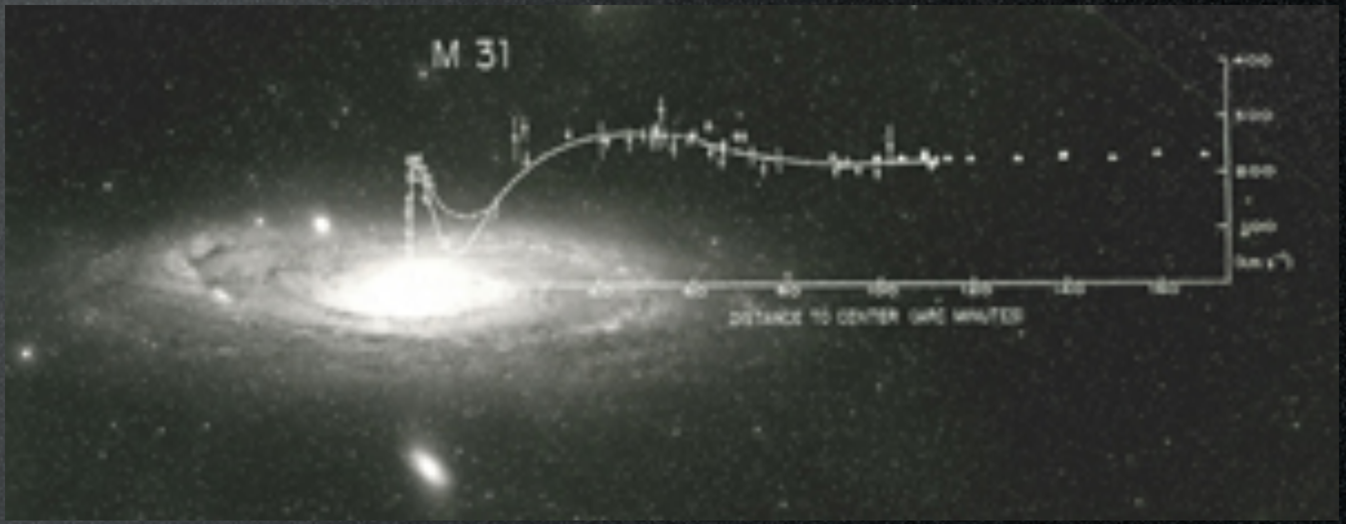
Caveat:

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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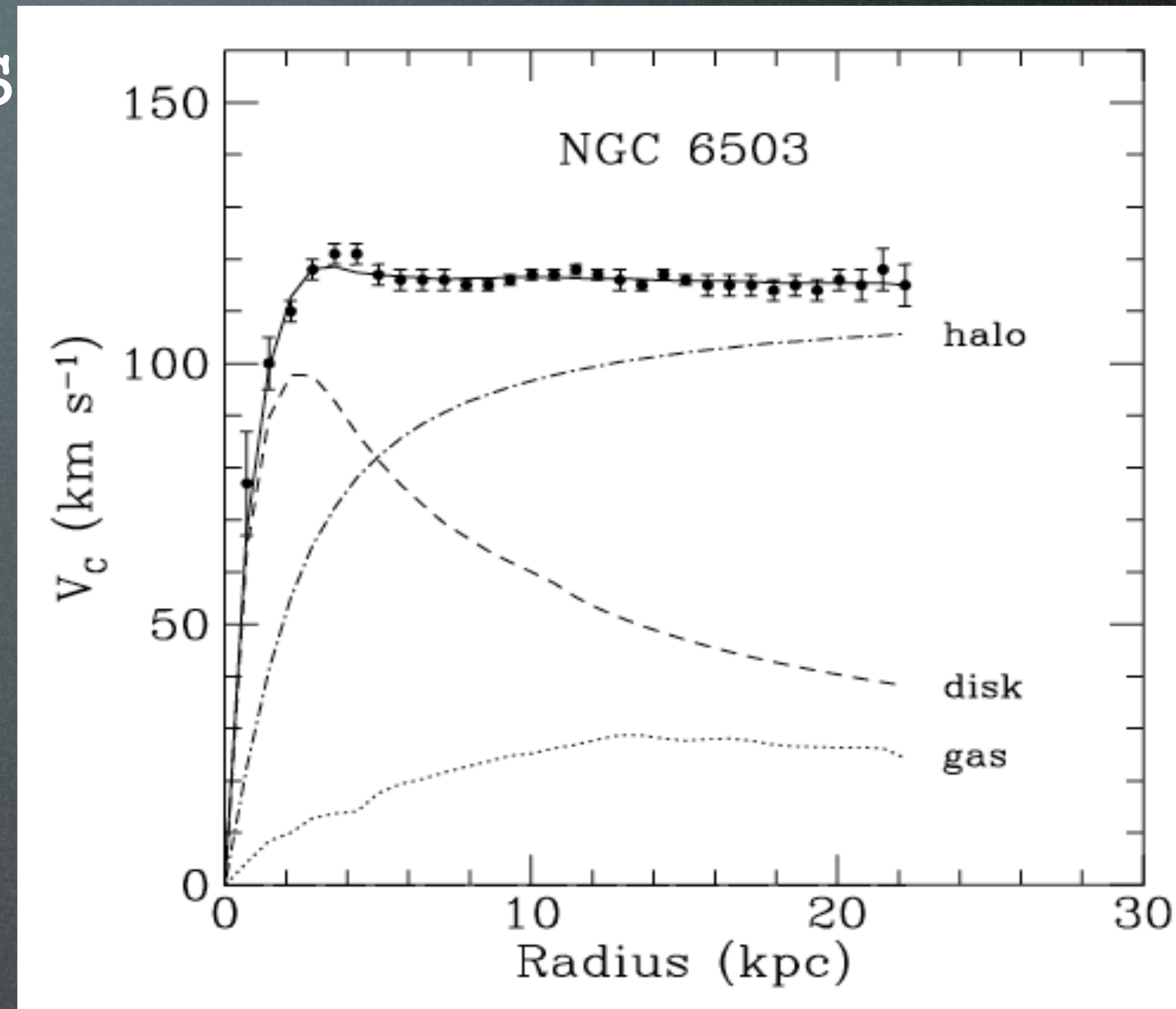

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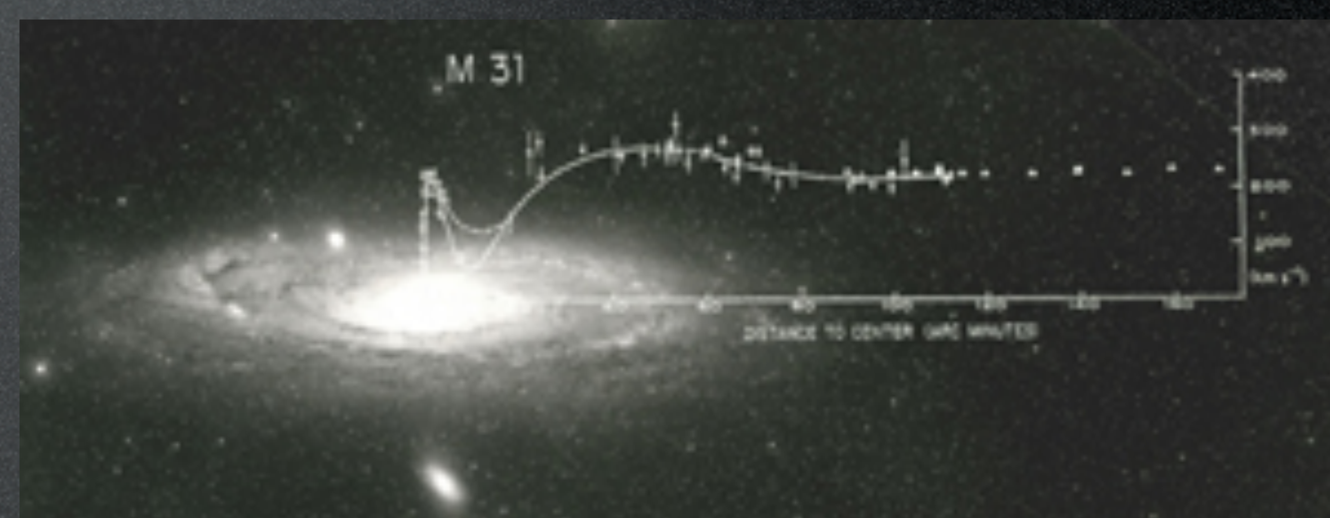

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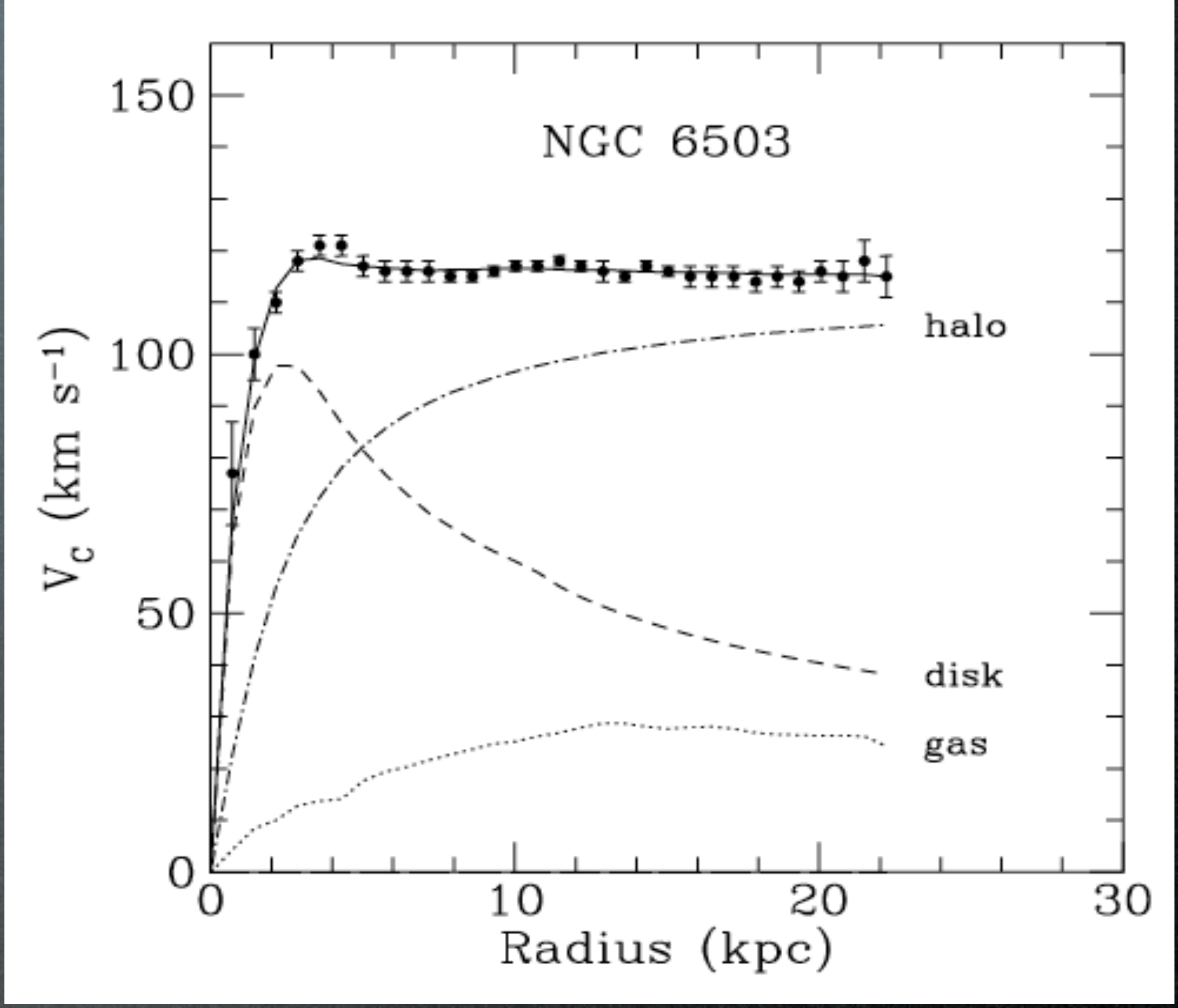

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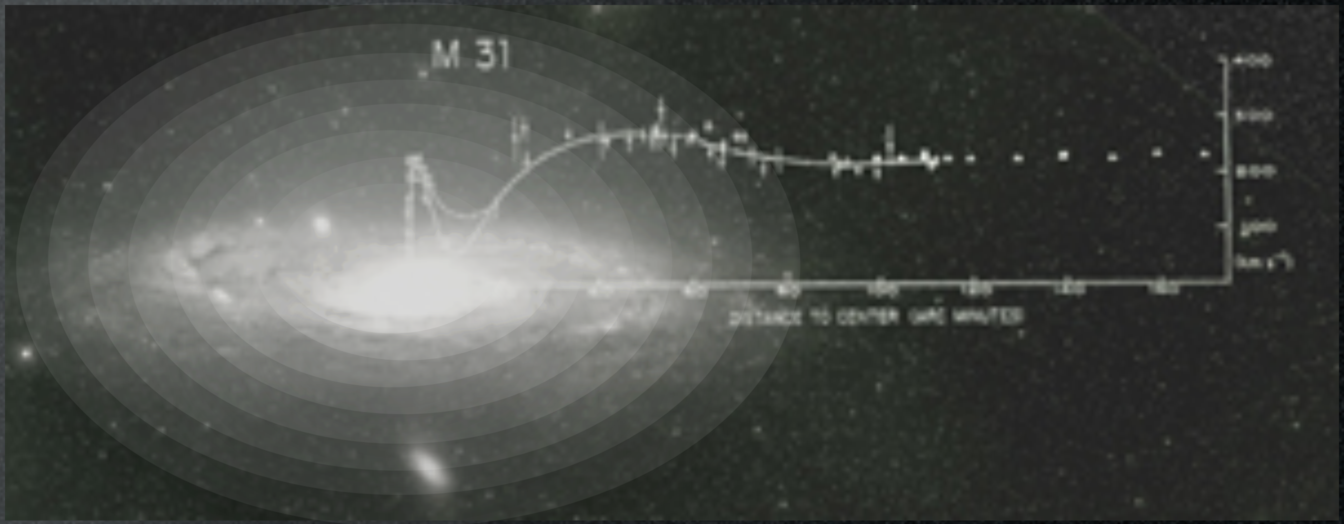

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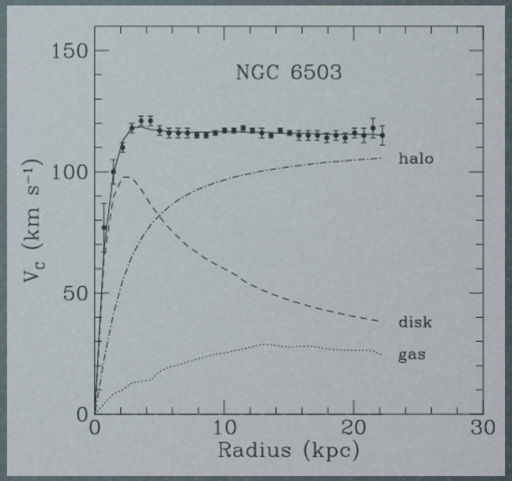

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- "rotation curves"
- gravitational lensing

"bullet cluster" - NASA
astro-ph/0608247

[further developments]

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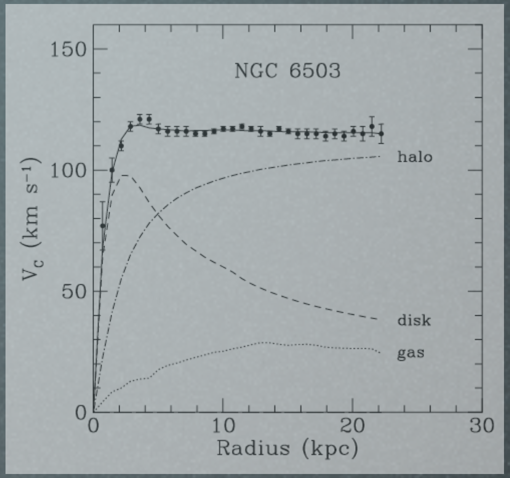

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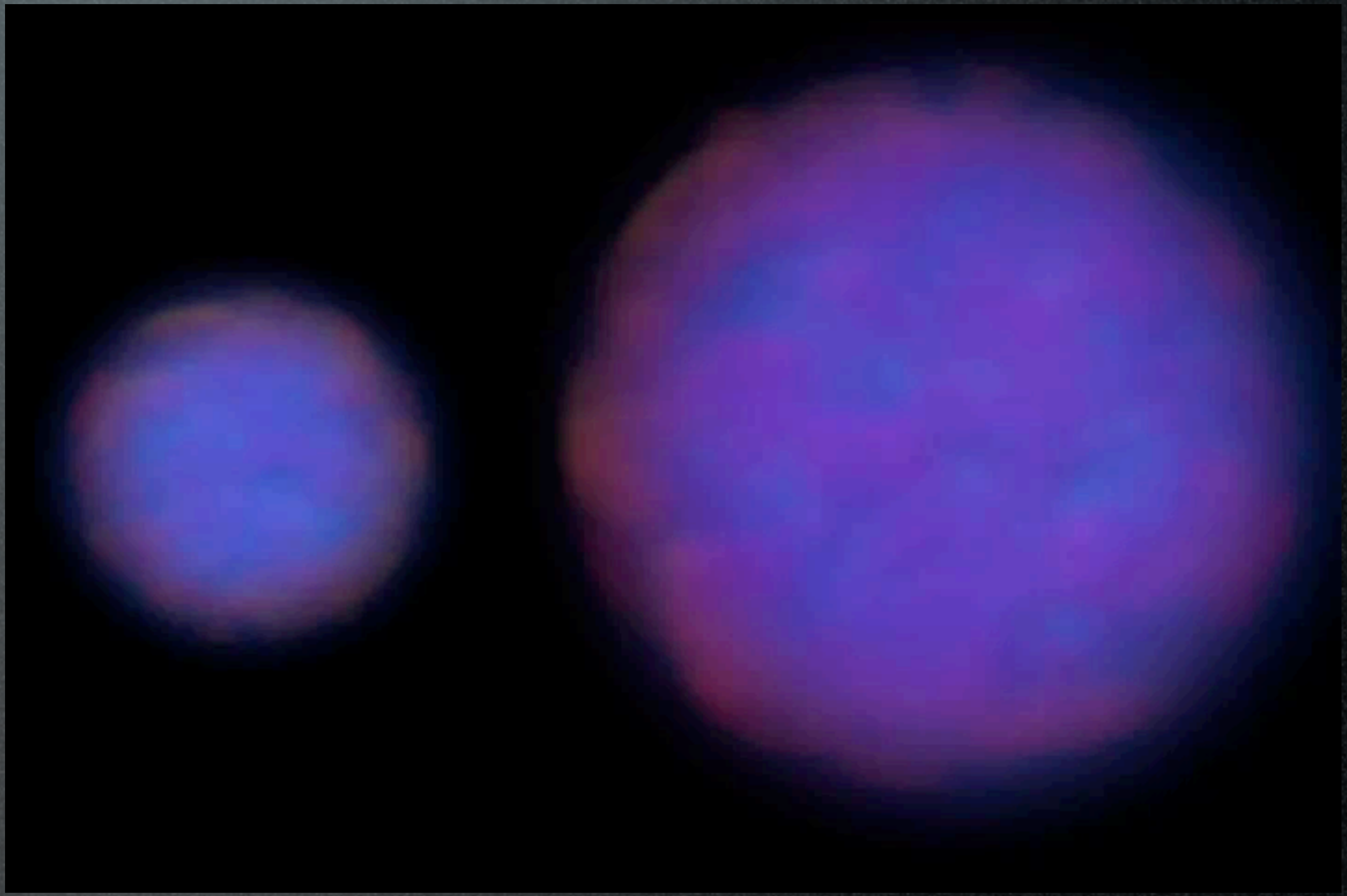

chandra.harvard.edu

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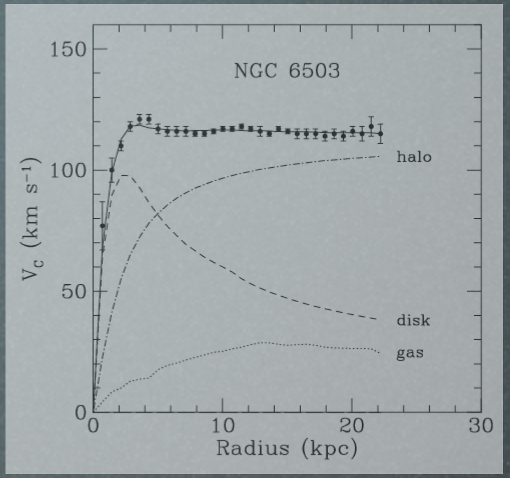

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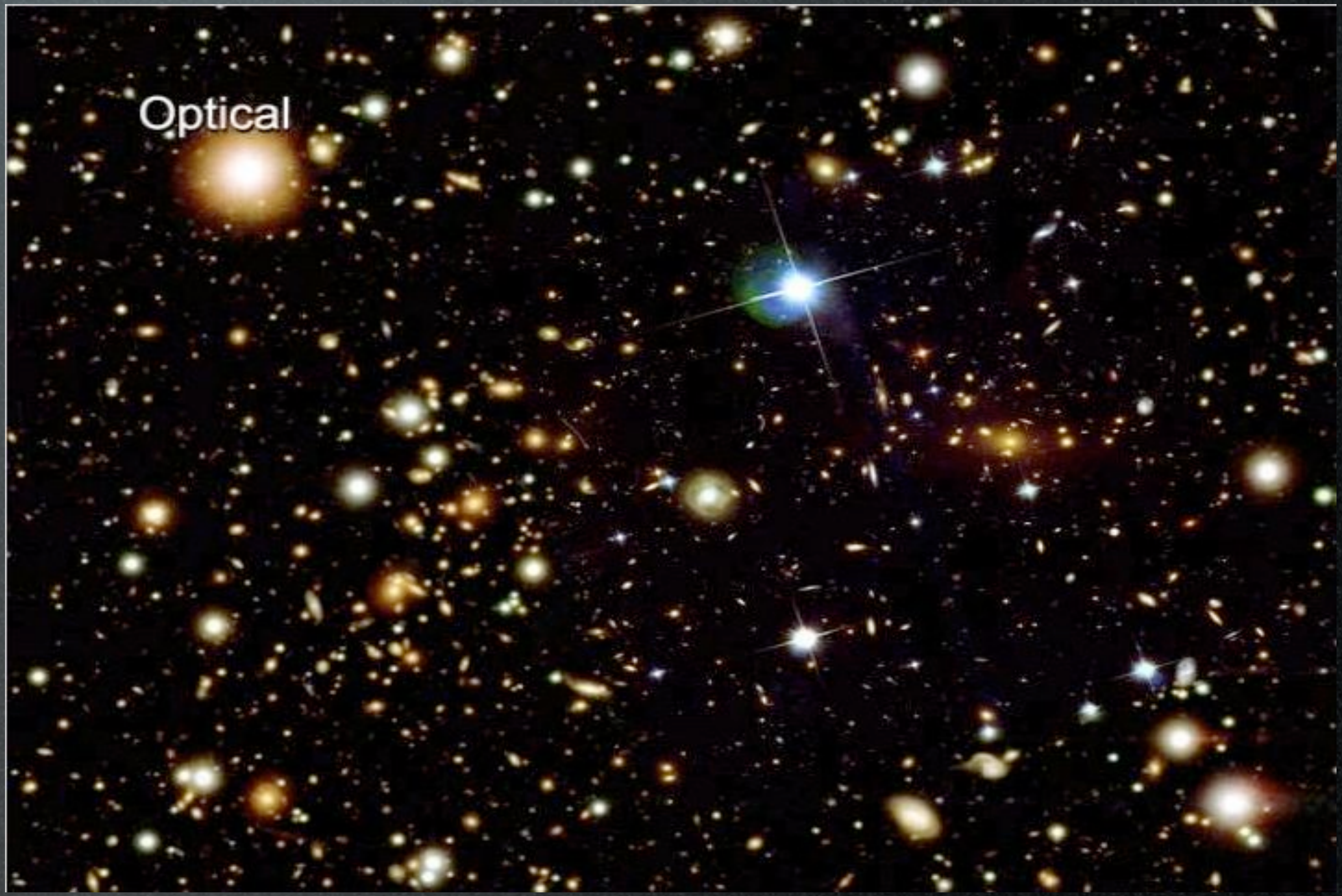

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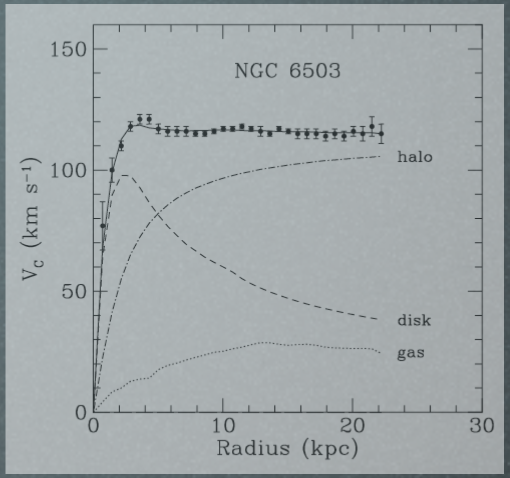

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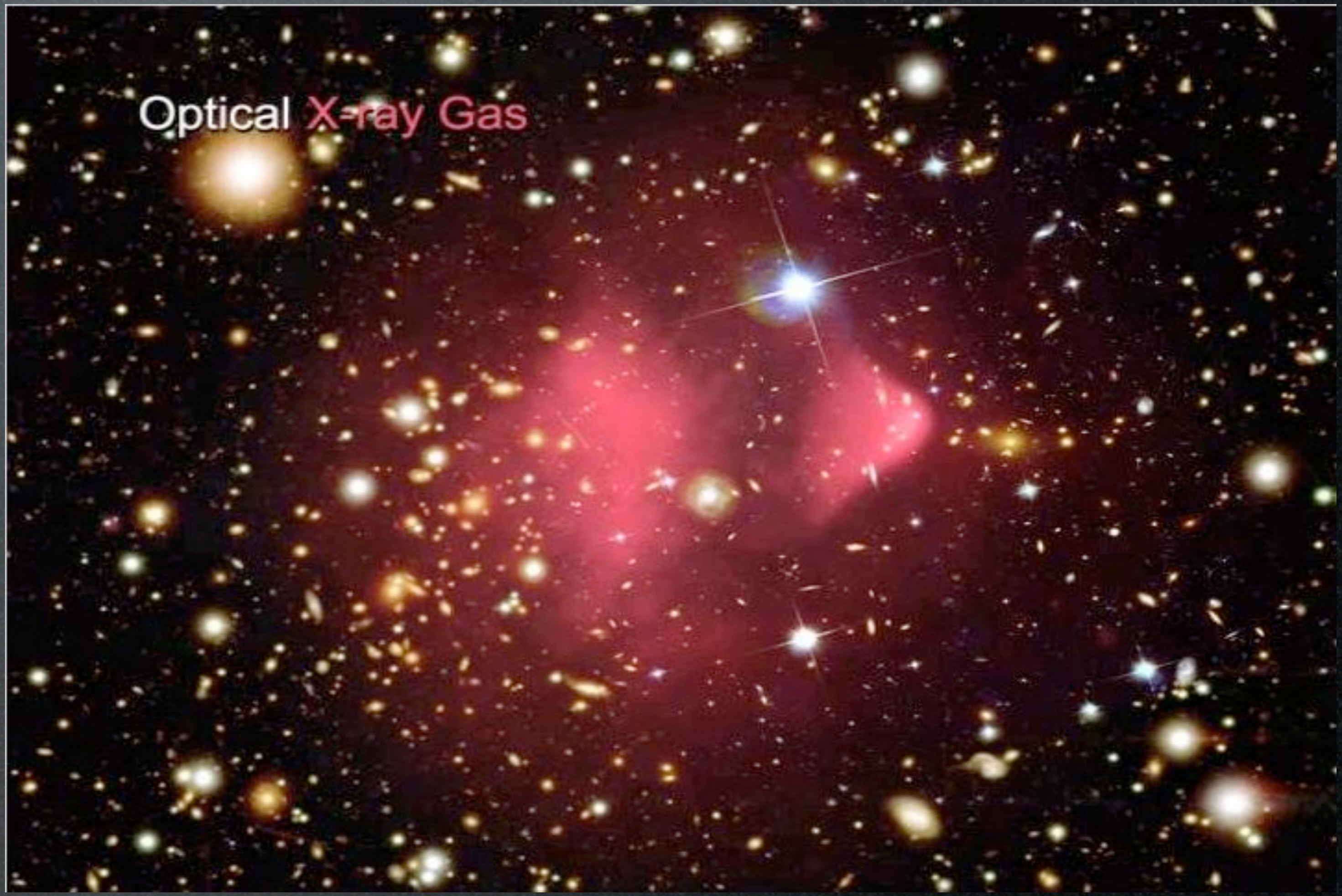

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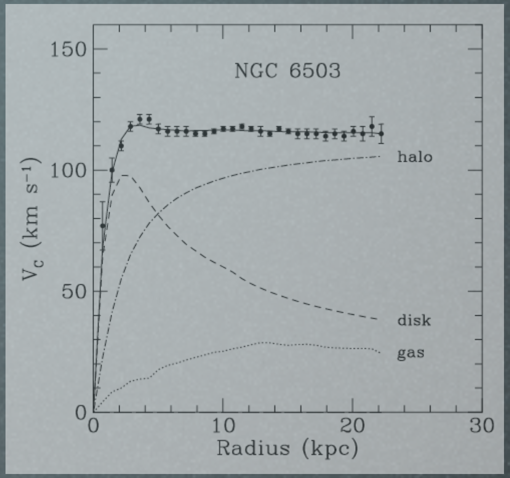

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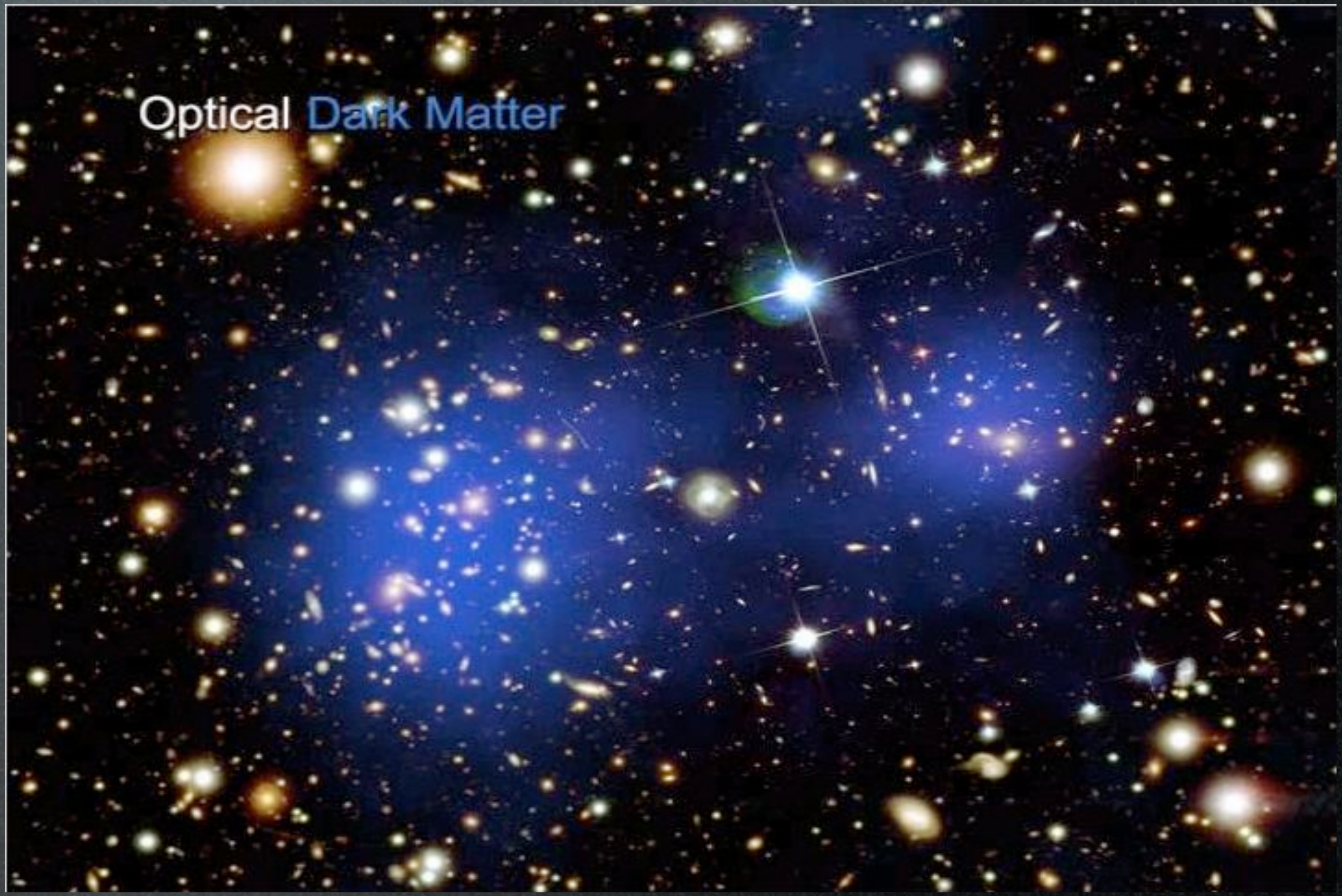

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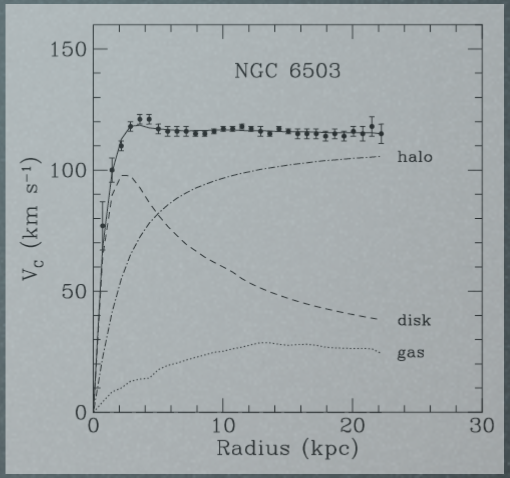
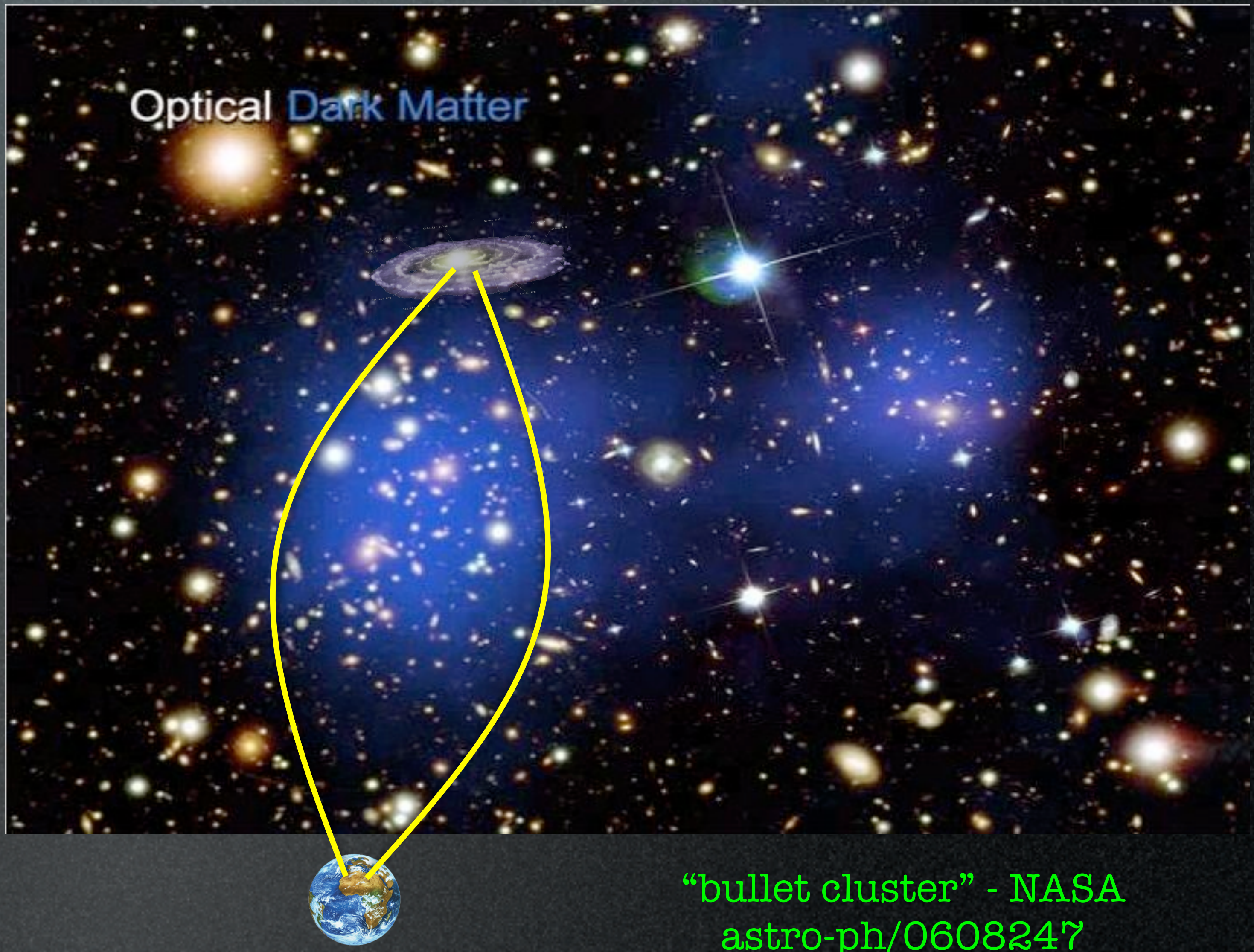


2) clusters of galaxies

- "rotation curves"
- gravitational lensing



"bullet cluster" - NASA
astro-ph/0608247

[further developments]

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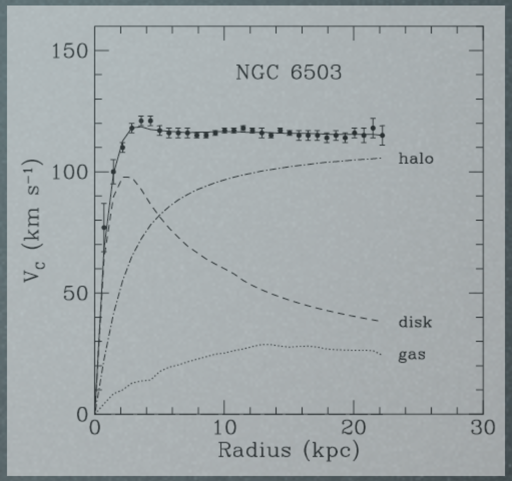

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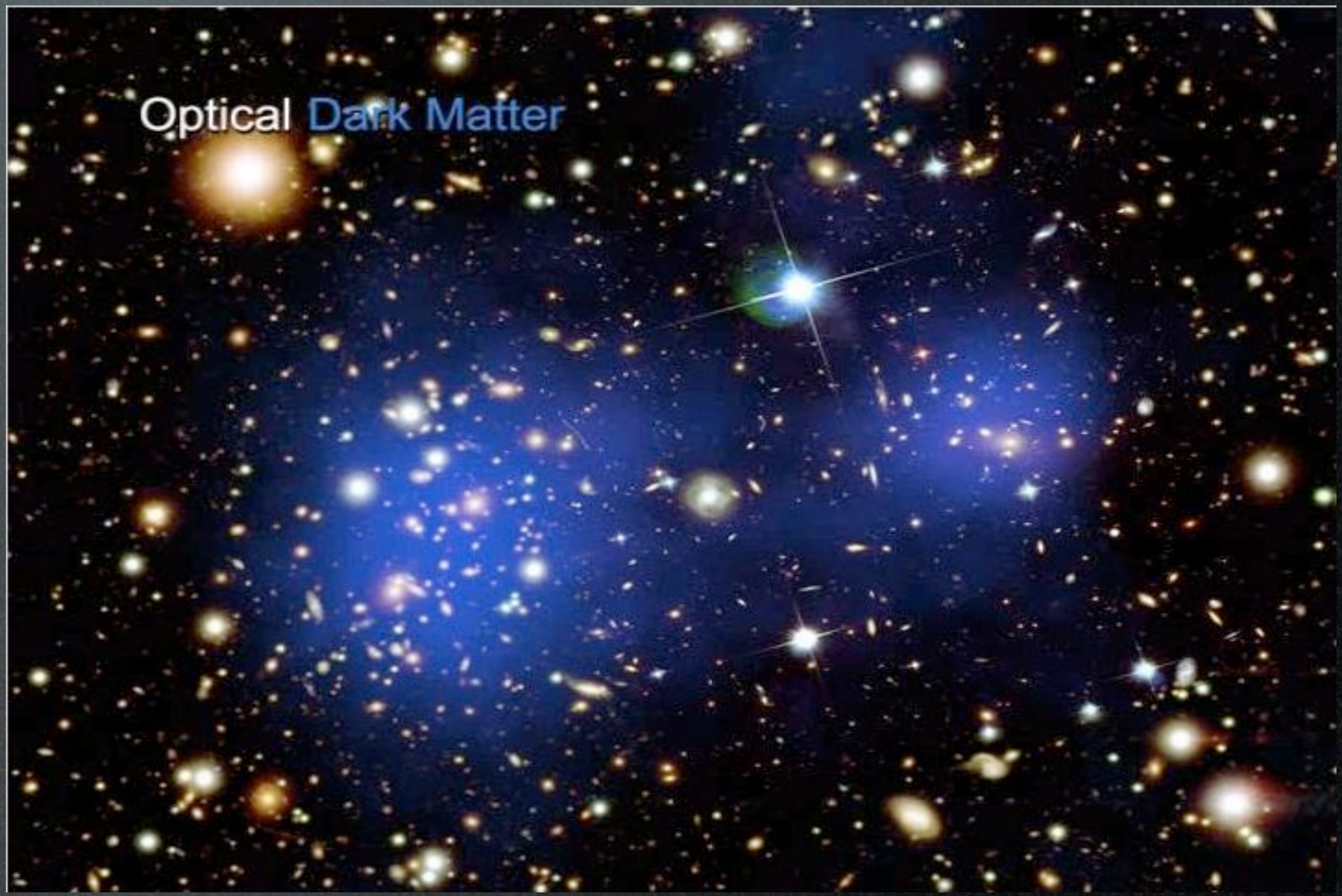

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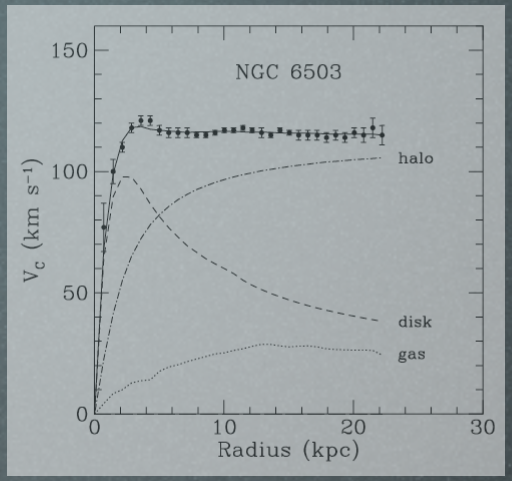

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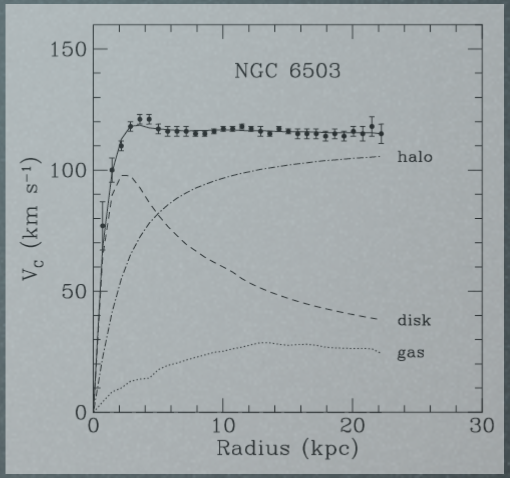

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ring of Dark Matter (2007)

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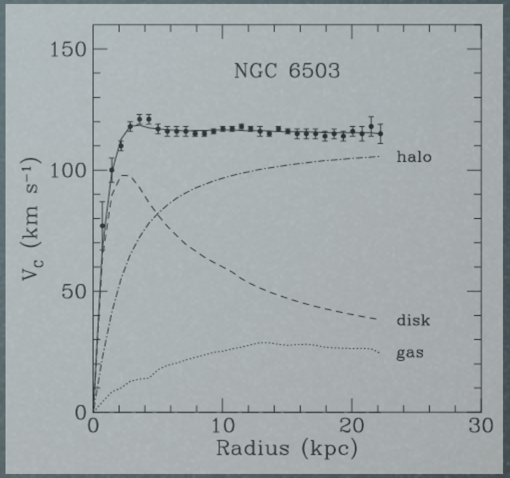

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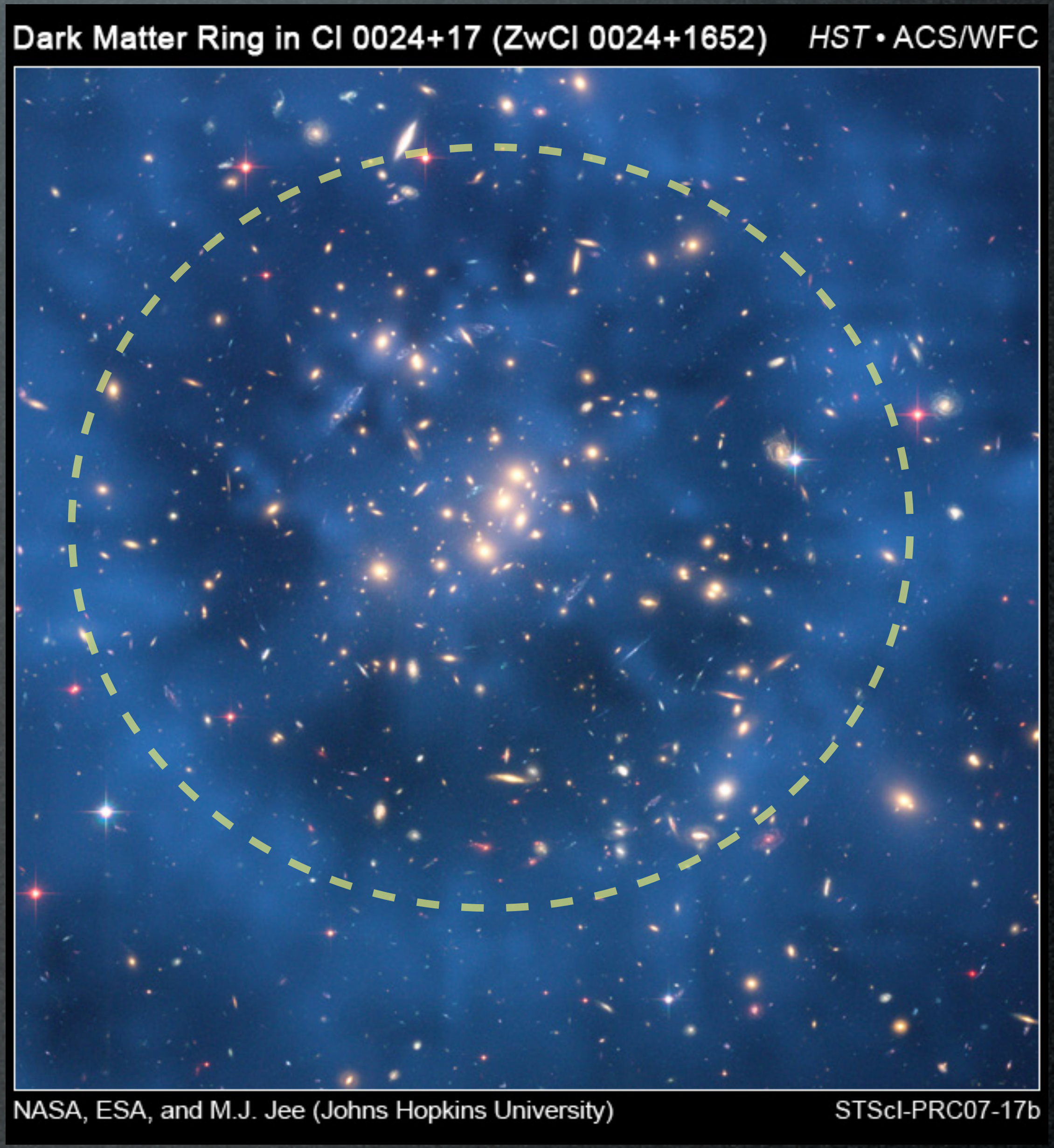

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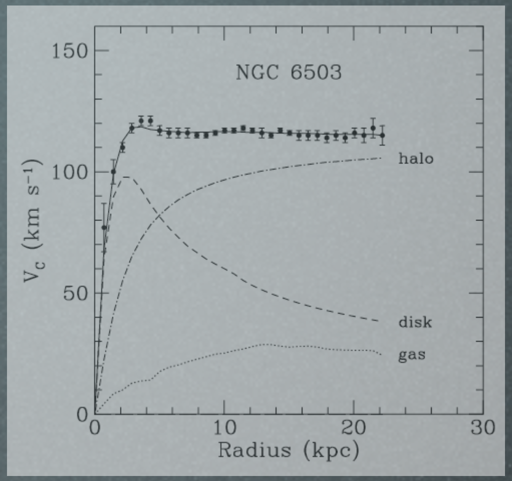
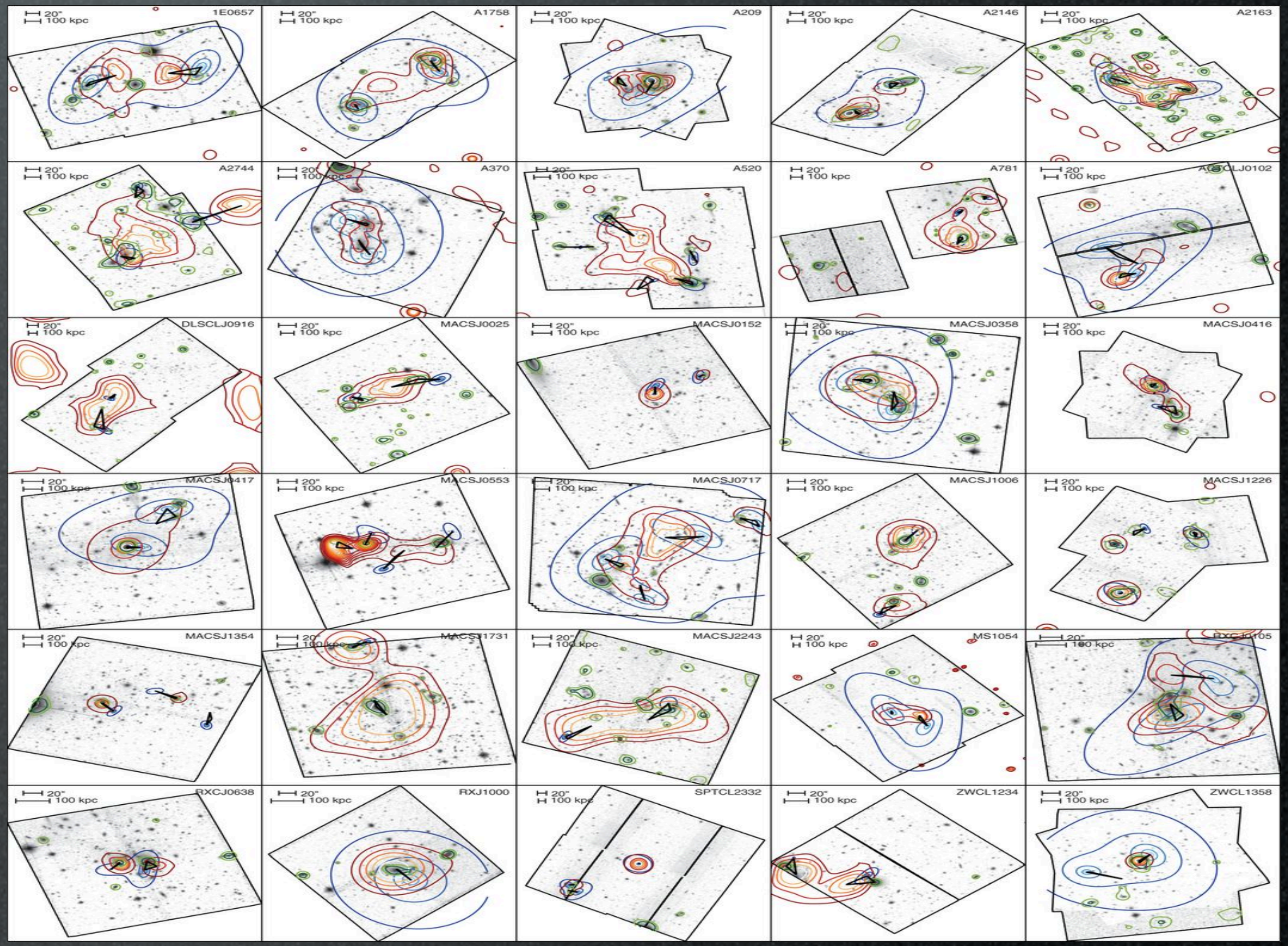
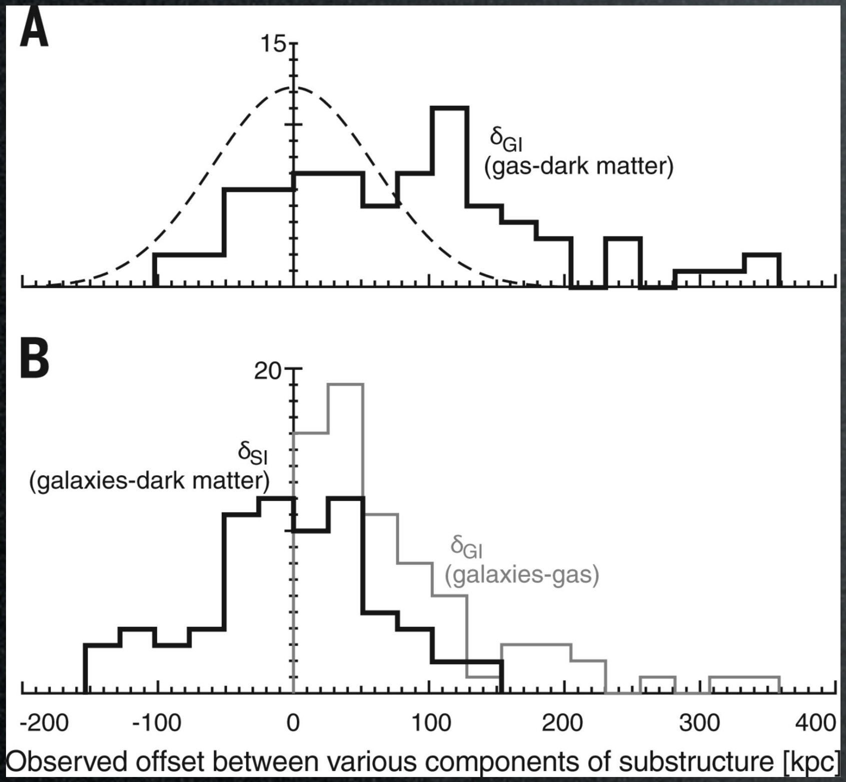


2) clusters of galaxies

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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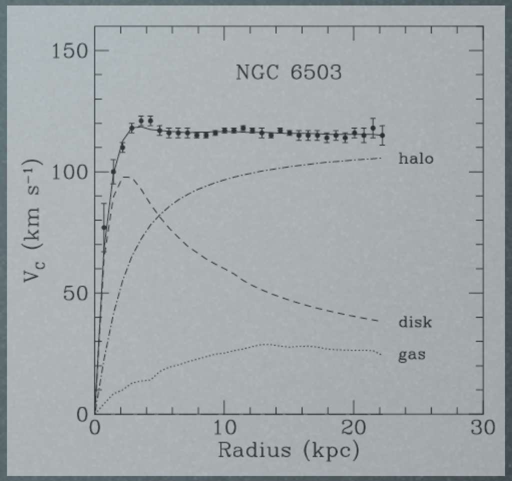
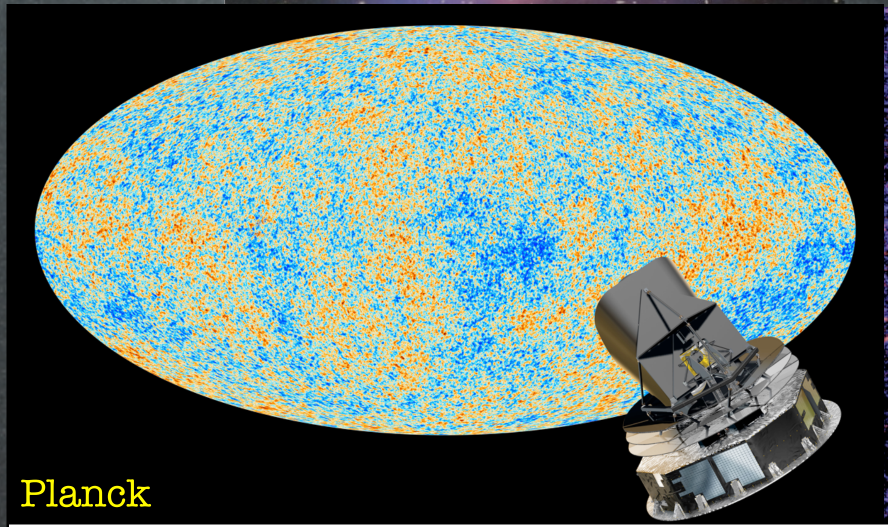
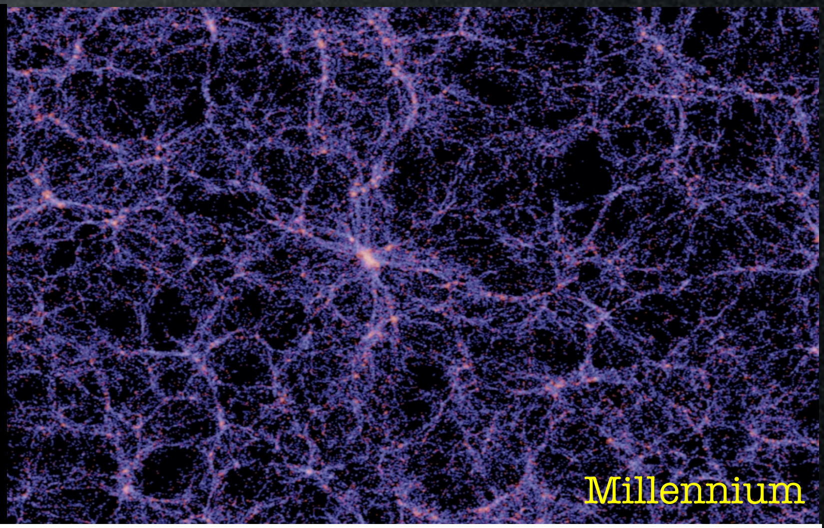
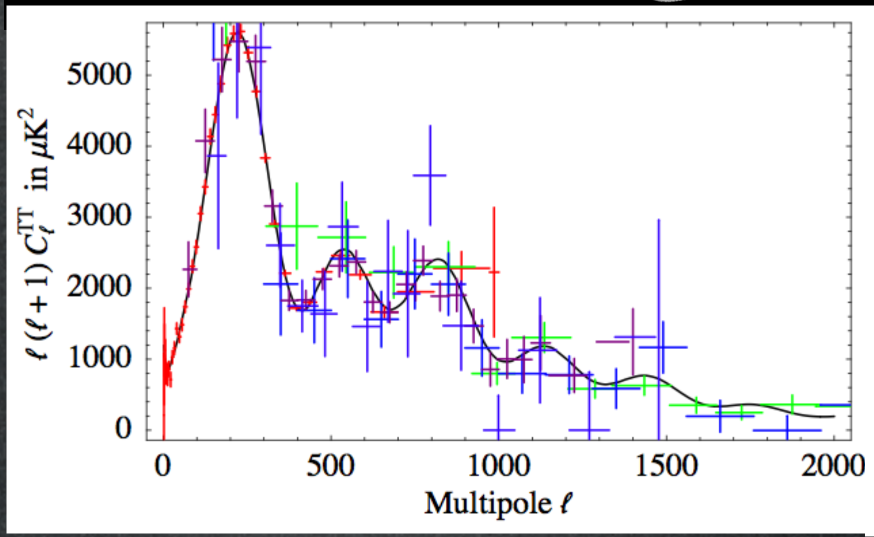


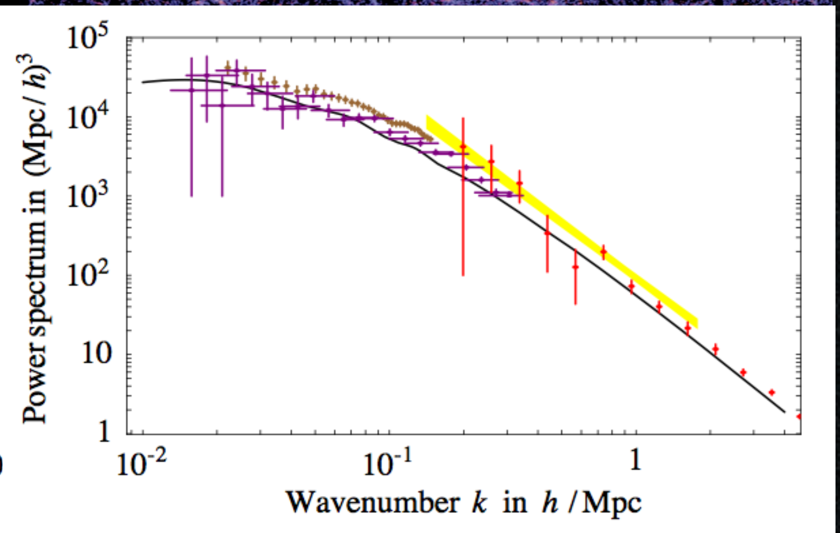
2) clusters of galaxies

3) 'precision cosmology'



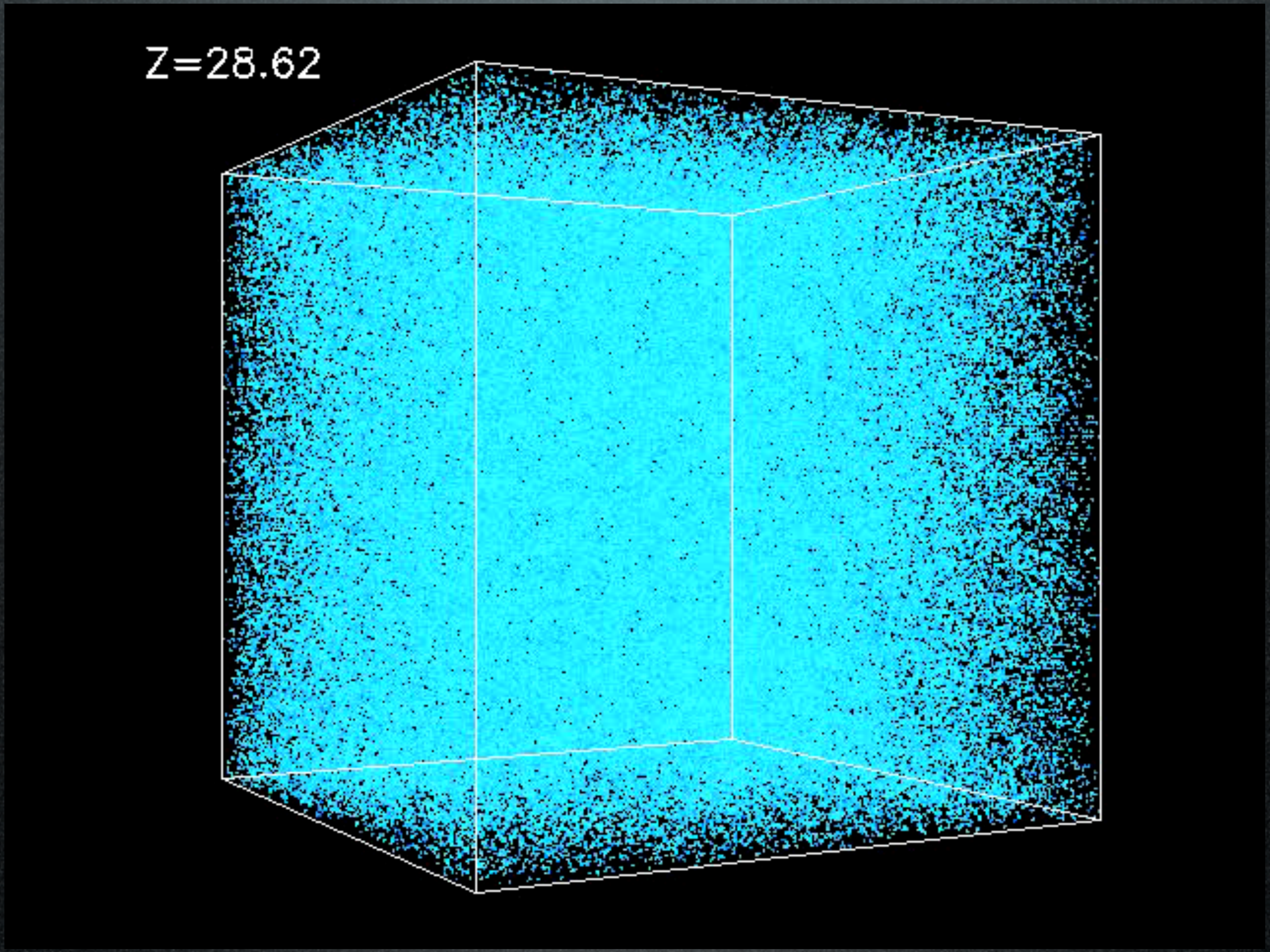






DM N-body simulations

2 10^6 CDM particles, 43 Mpc cubic box

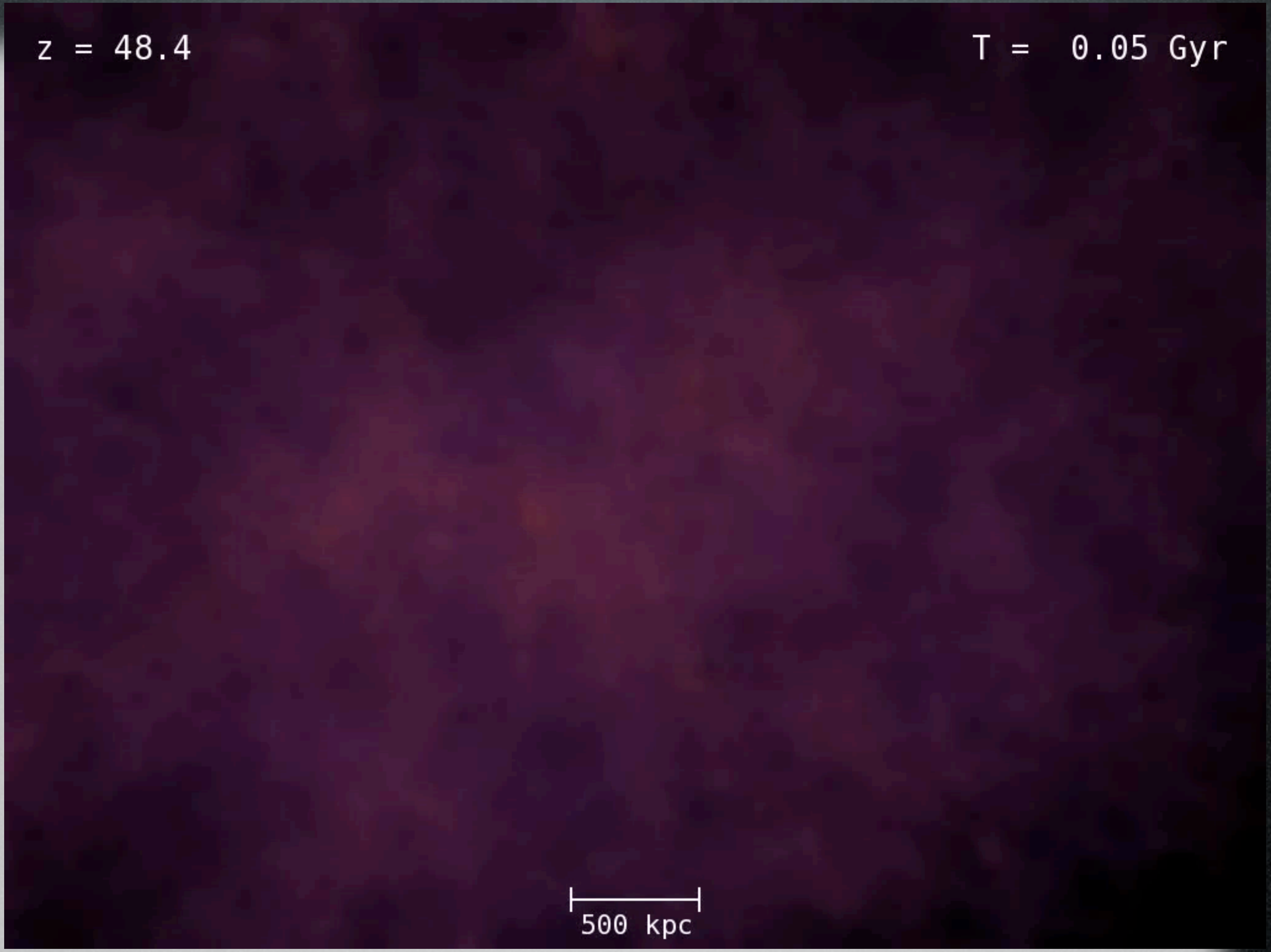


Andrey Kravtsov, cosmicweb.uchicago.edu

[back]

DM N-body simulations

Aquarius project of the VIRGO coll.:
1.5 10^9 CDM particles, single galactic halo

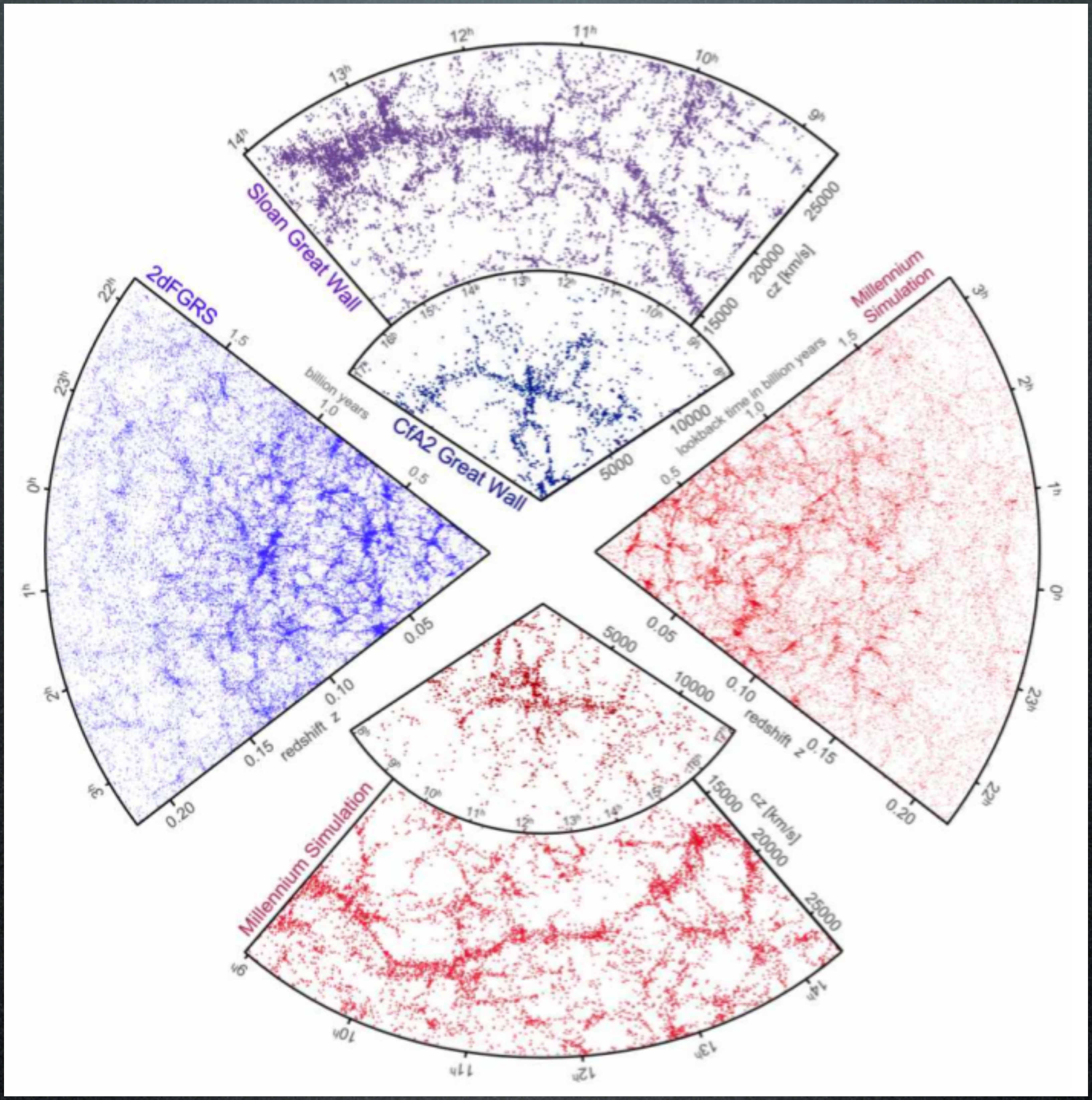


VIRGO coll., Aquarius project, www.mpa-garching.mpg.de/aquarius/ [back]

DM N-body simulations

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies,
2 billion lyr



Springel, Frenk, White, Nature 440 (2006)

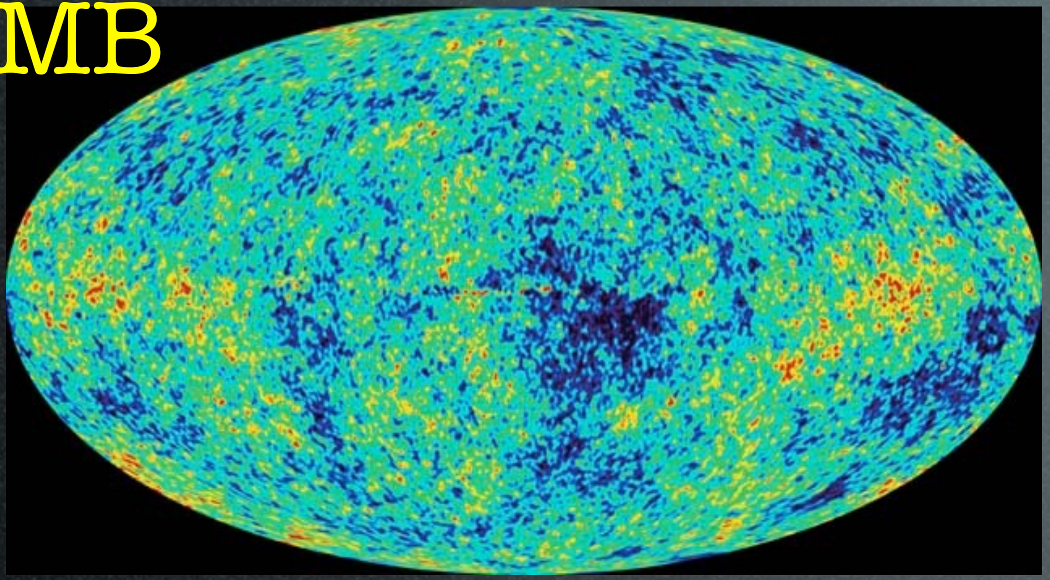
Of course, you have to infer galaxies within the DM simulation

Millennium:
10^{10} particles,
500 h^{-1} Mpc

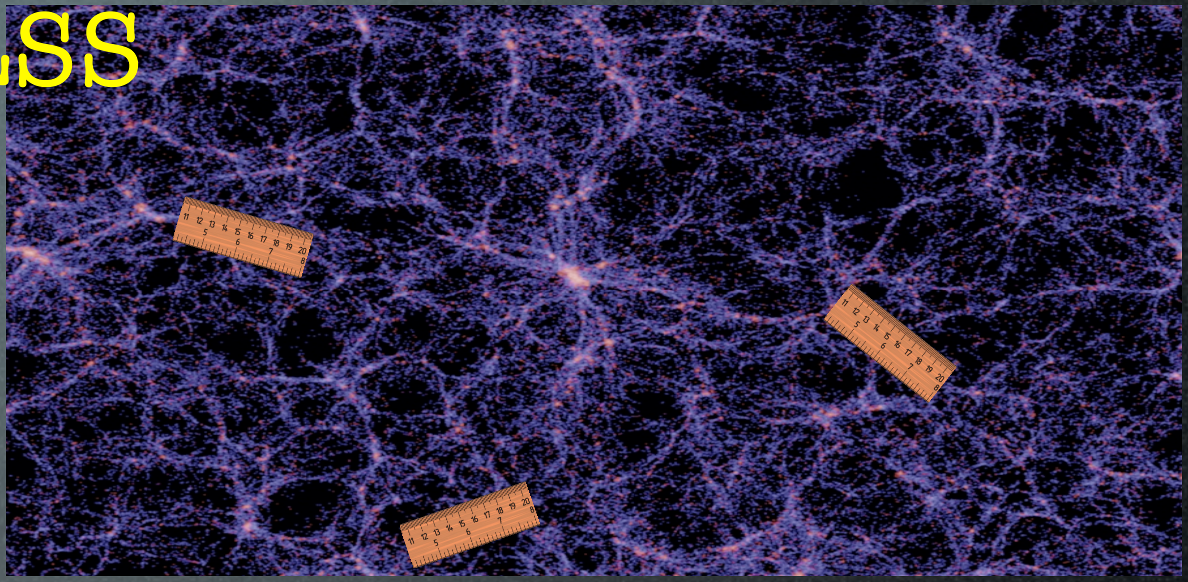
[back]

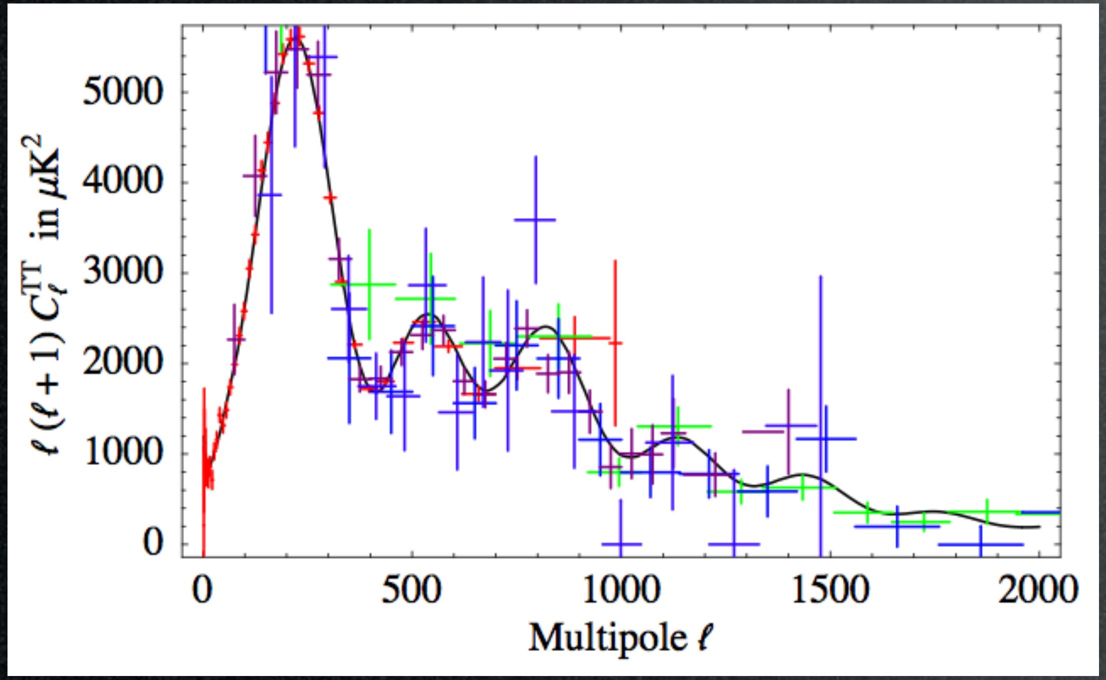
CMB & Large Scale Structure

CMB

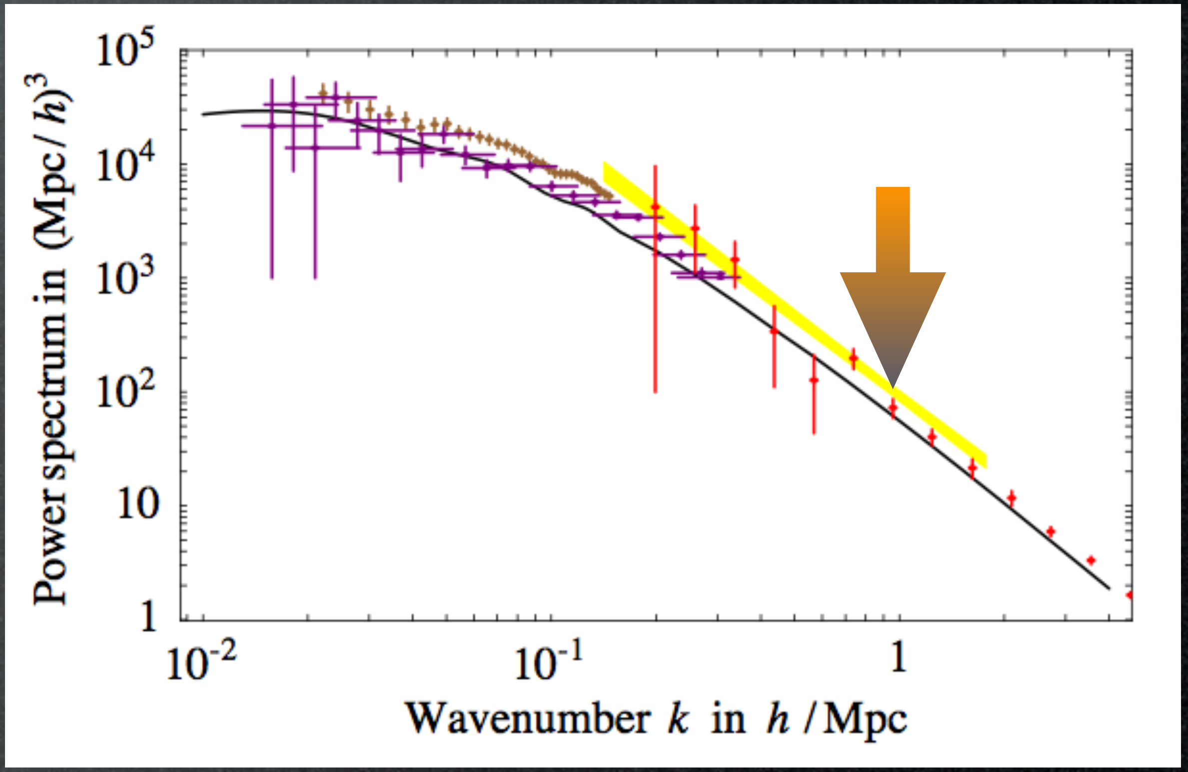


LSS





LSS matter power spectrum



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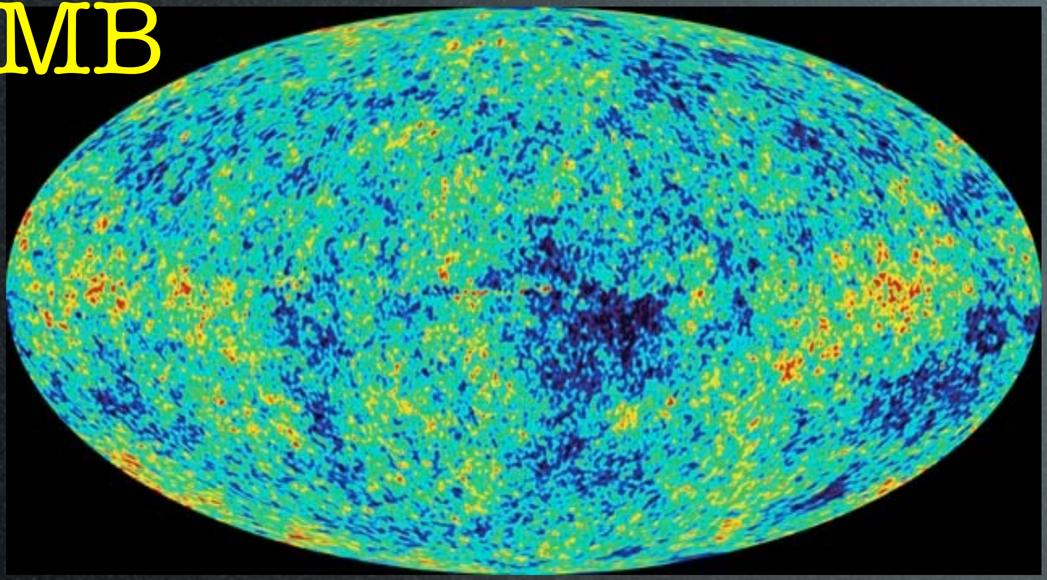

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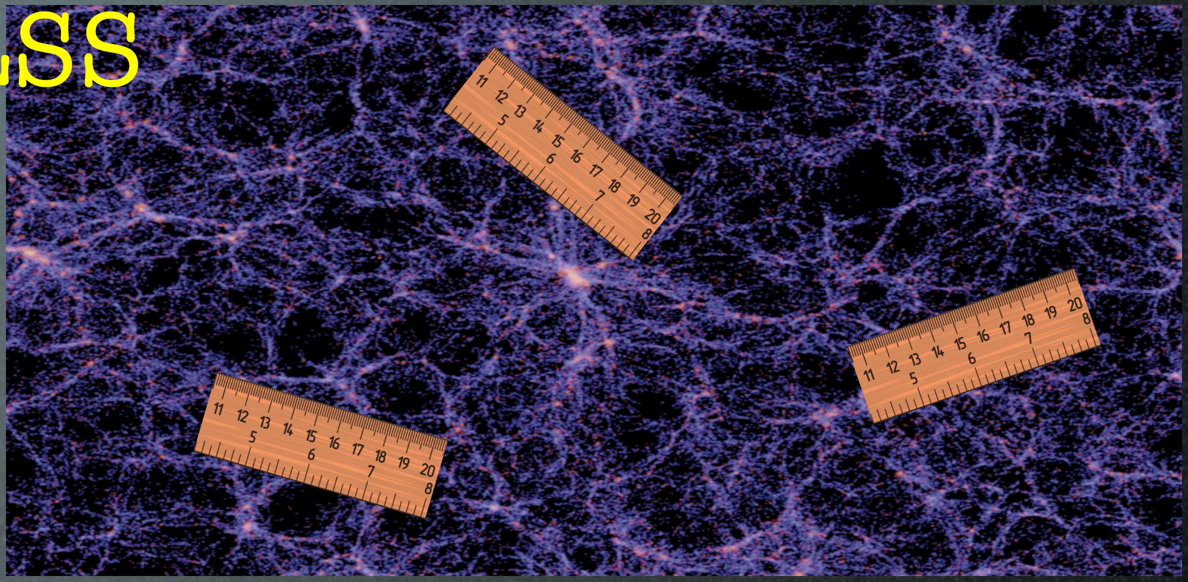

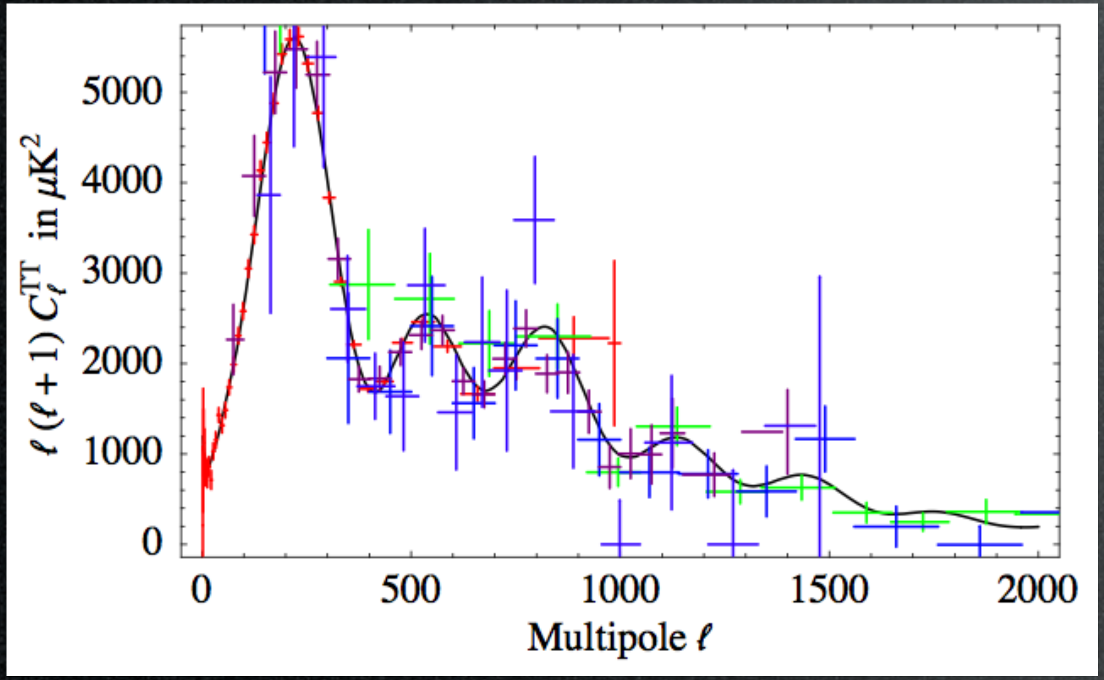

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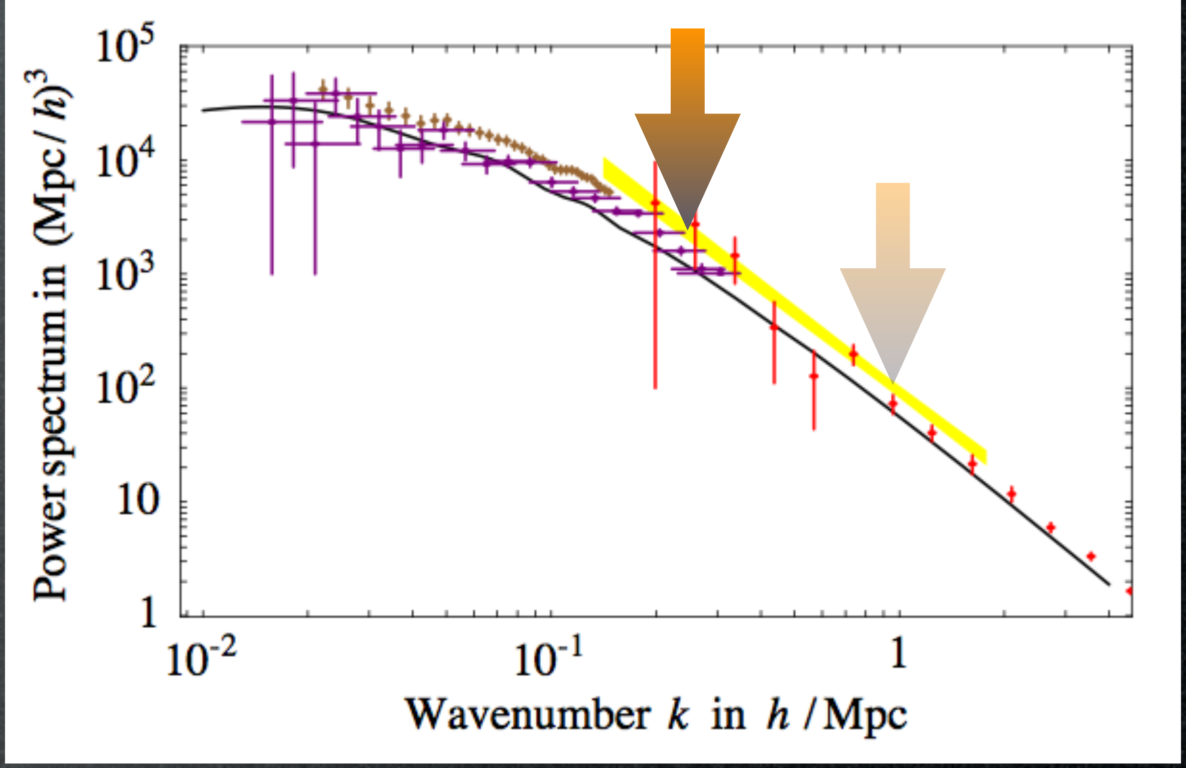

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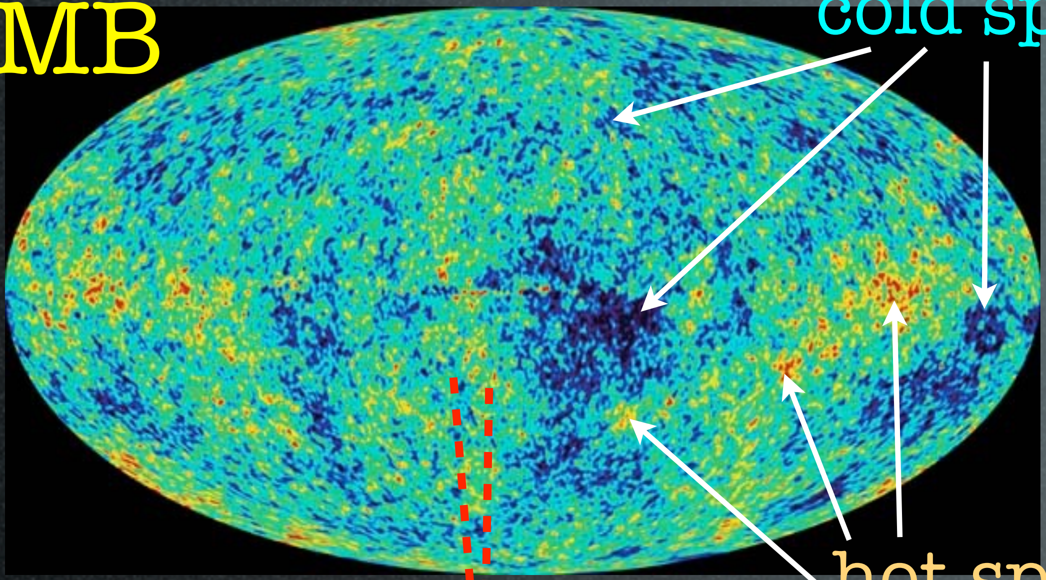
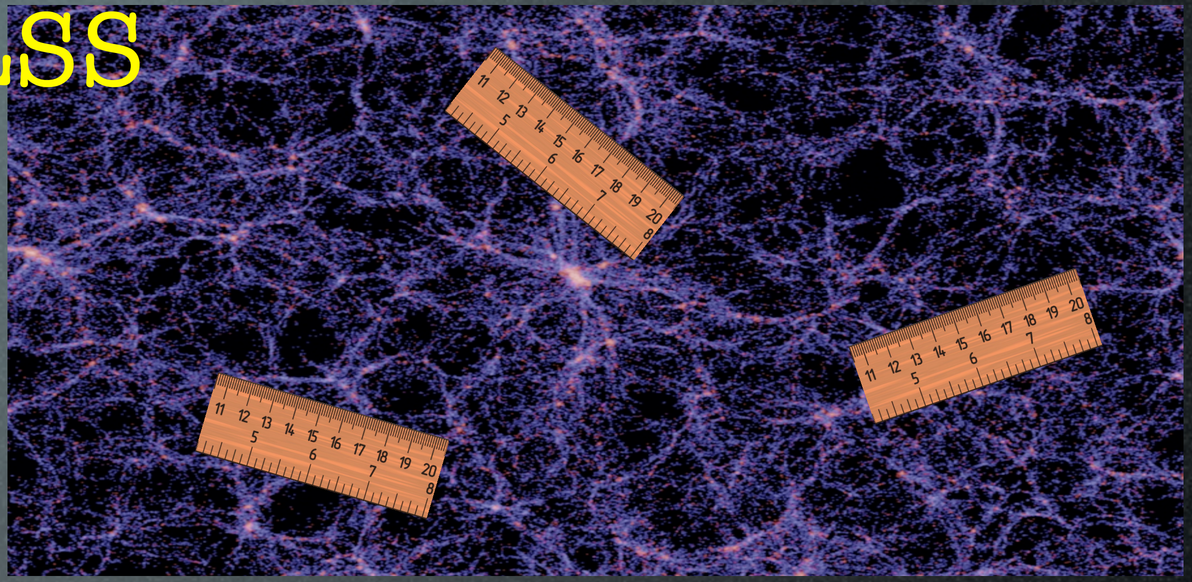


$T = 2.725^\circ K$

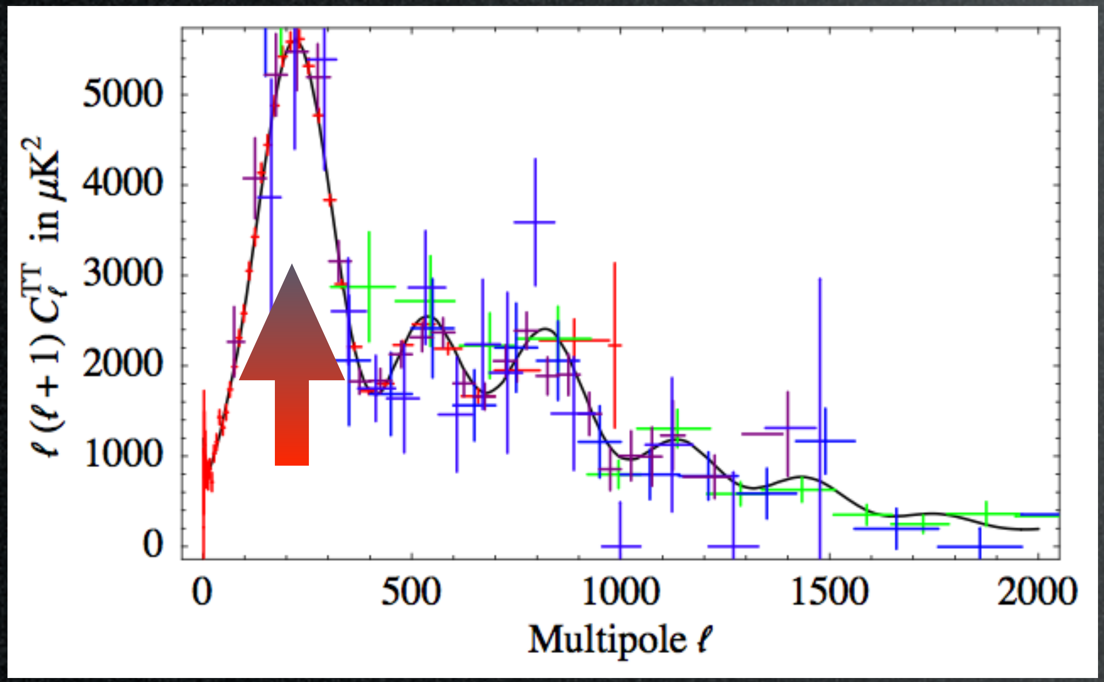
$\frac{\delta T}{T} \sim 10^{-5}$

1°

LSS



CMB spectrum



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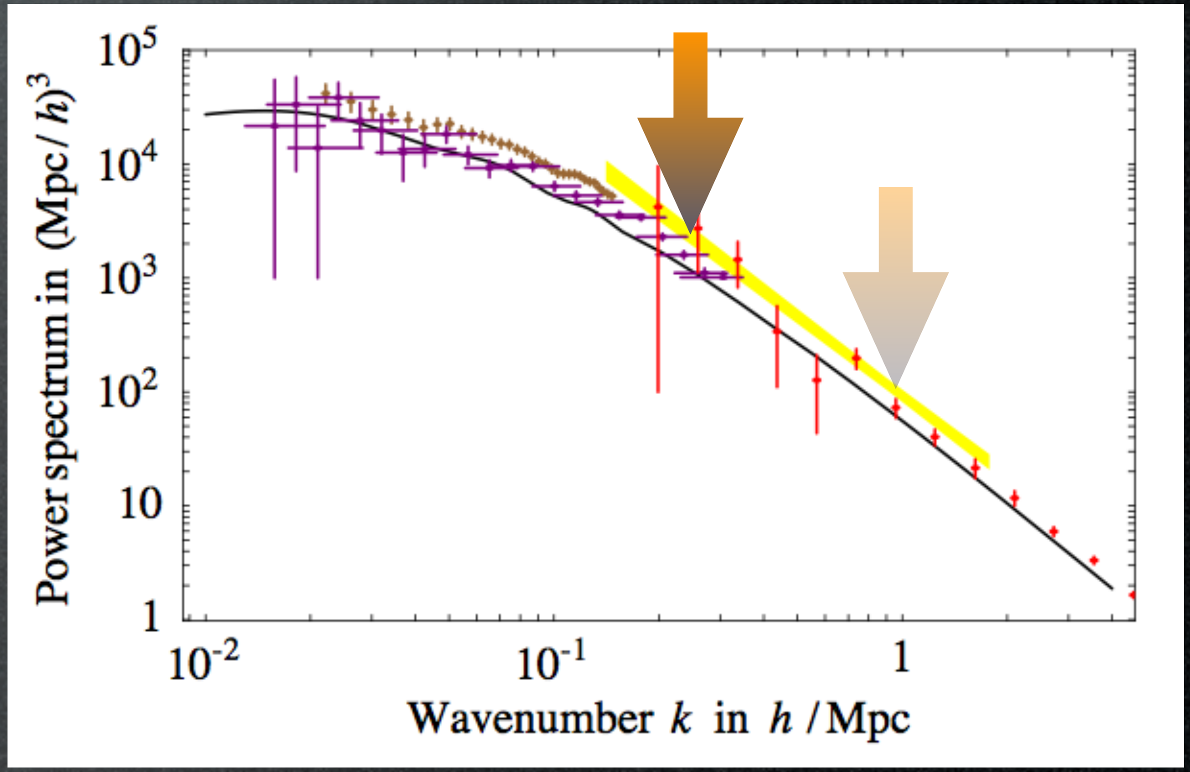
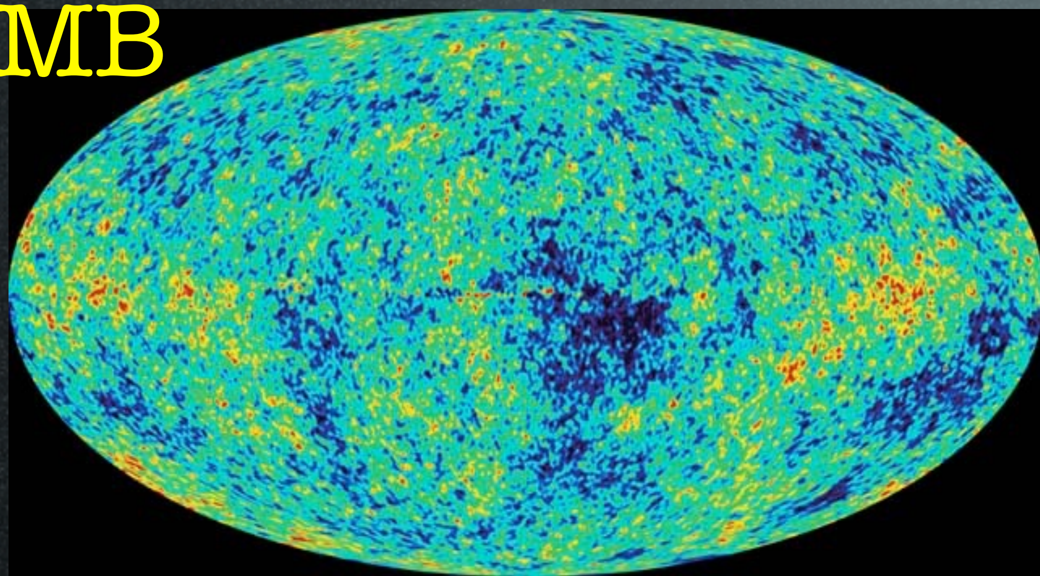


The Evidence for DM

CMB



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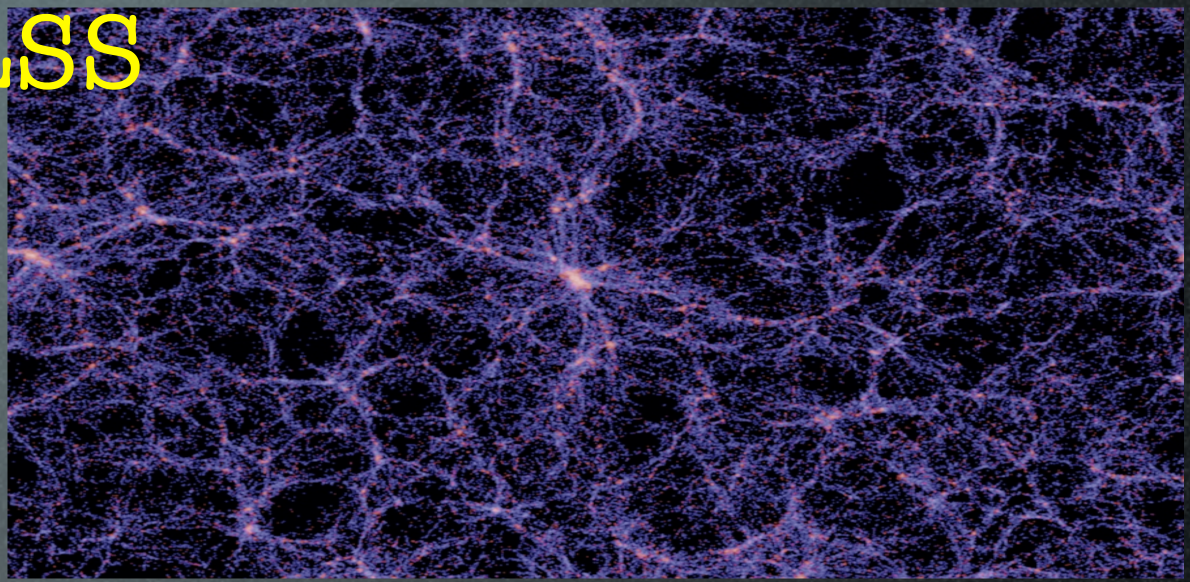
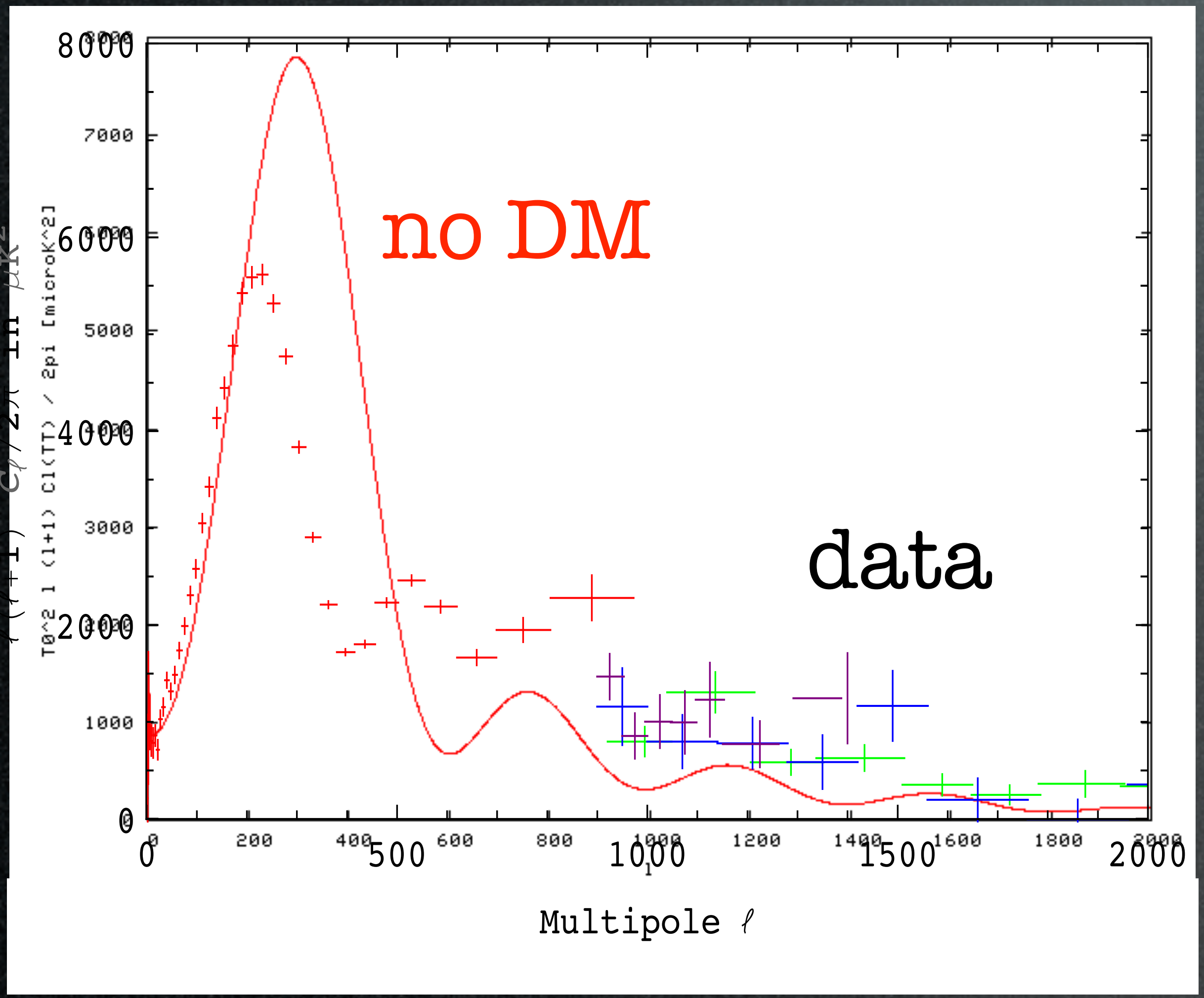
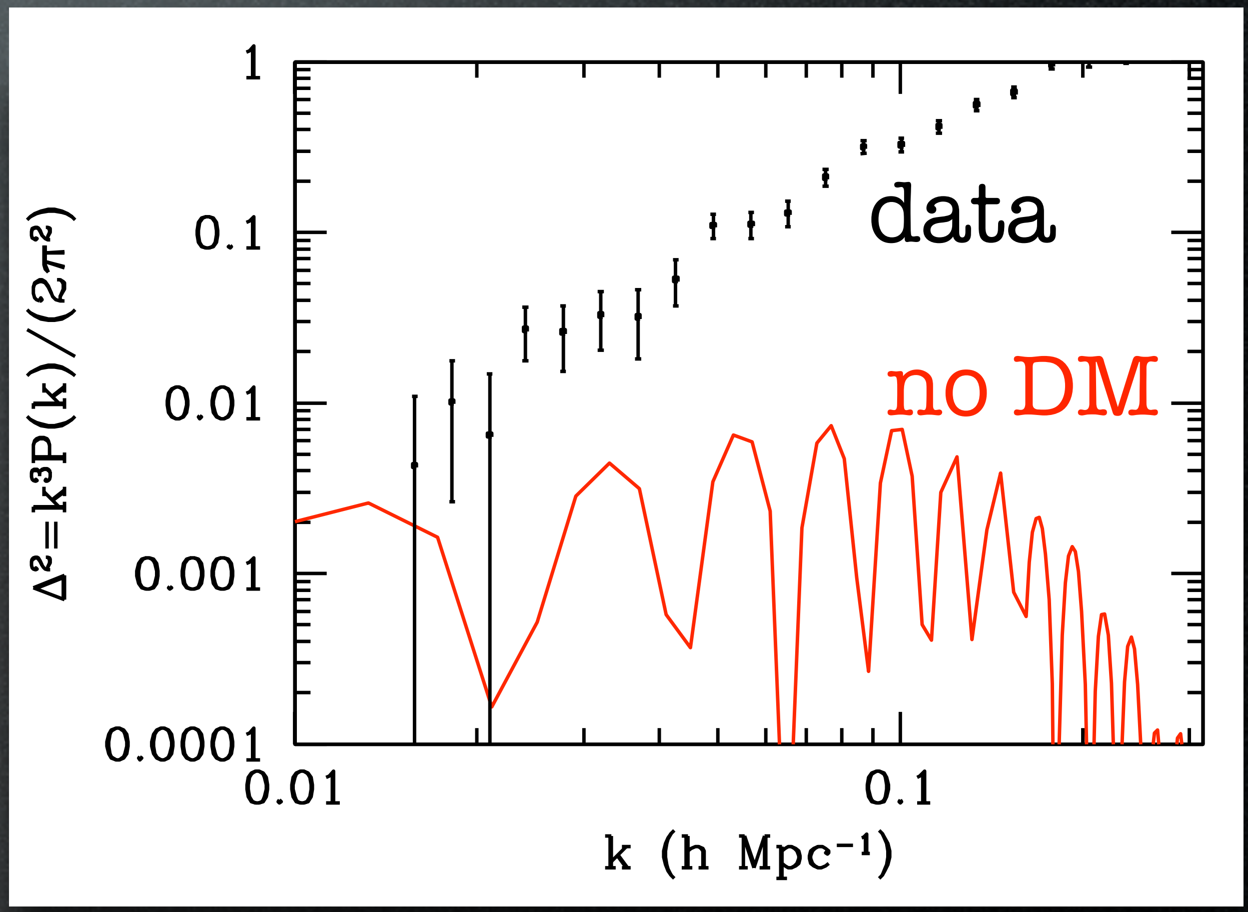


How would the power spectra be without DM? (and no other extra ingredient)



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.

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

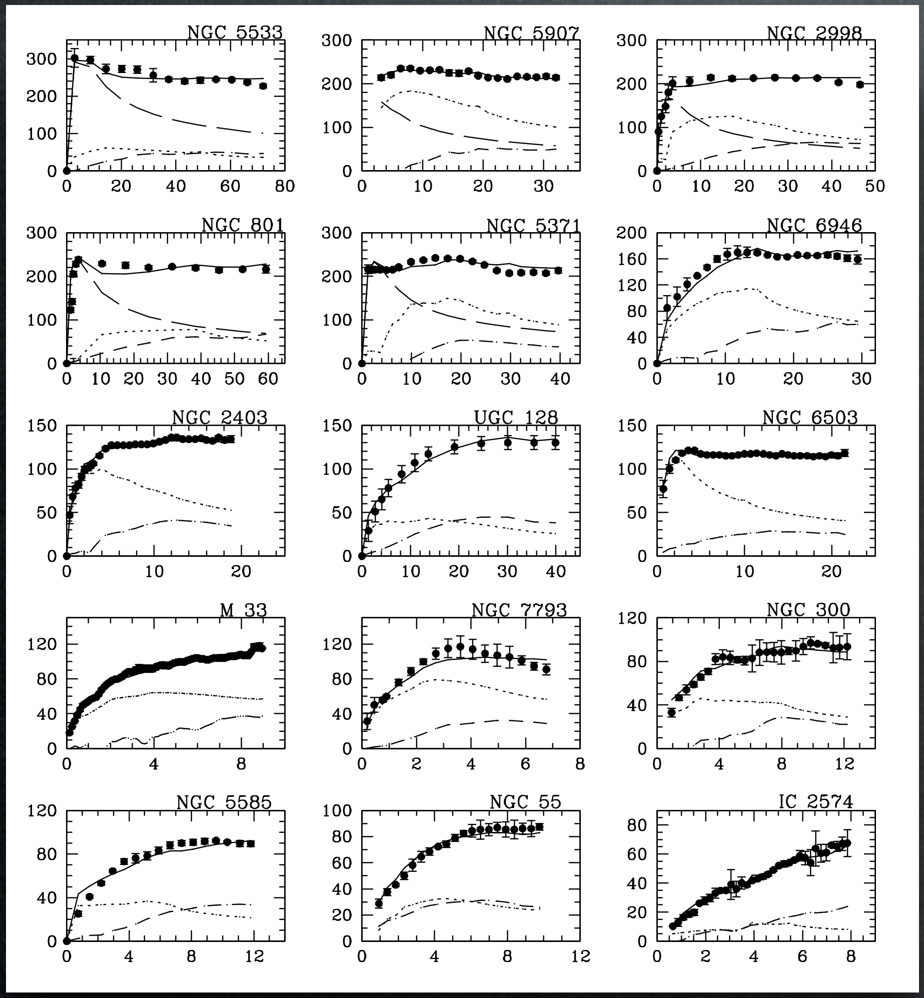
$$a_0 = 1.2 \cdot 10^{-10} m/s^2$$

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

force balance

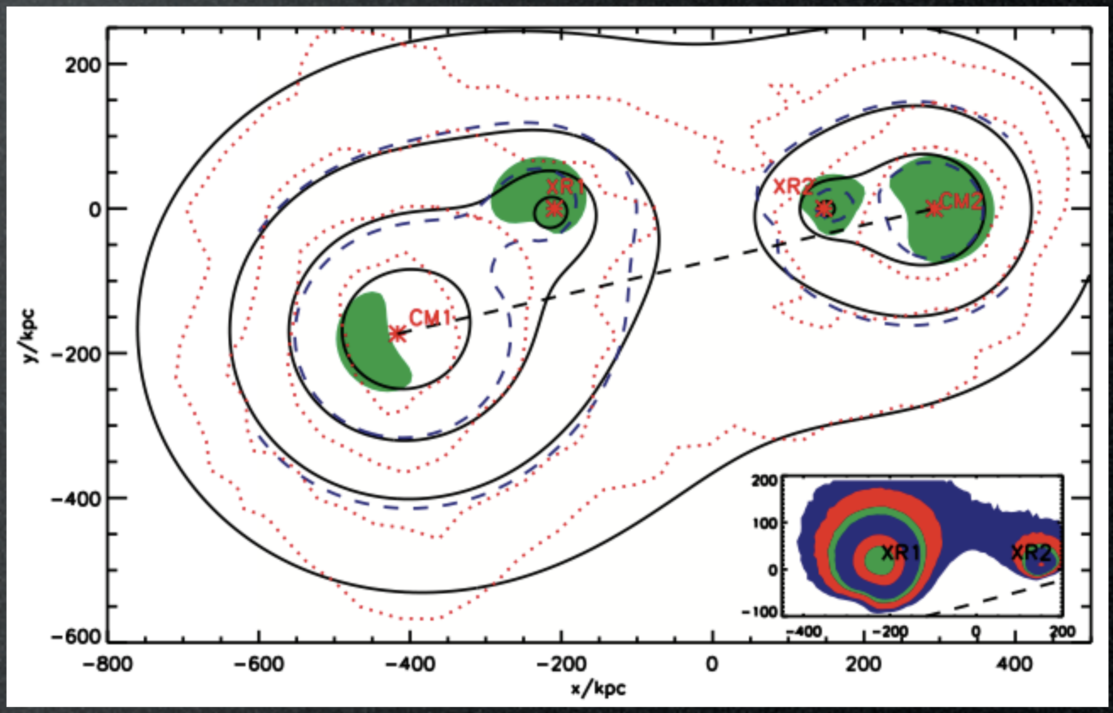
tangential acceleration

fits rotation curves very well



Sanders, McGaugh, Ann. Rev. AA, 2002

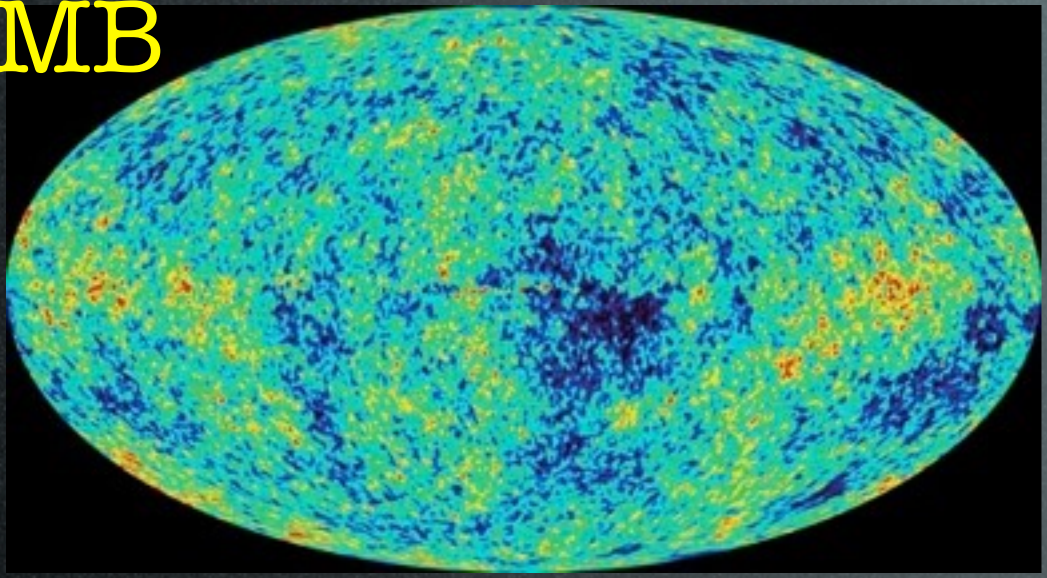
can fit (bullet) cluster if adding 2 eV neutrinos...



Angus et al., astro-ph/0609125

MOND? TeVeS?

CMB



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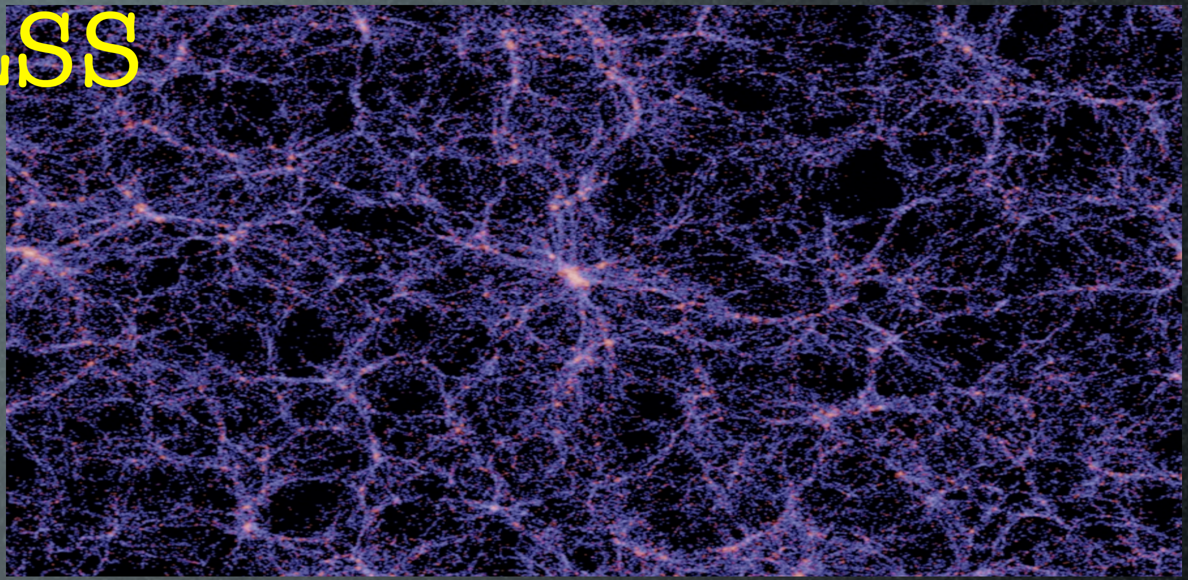
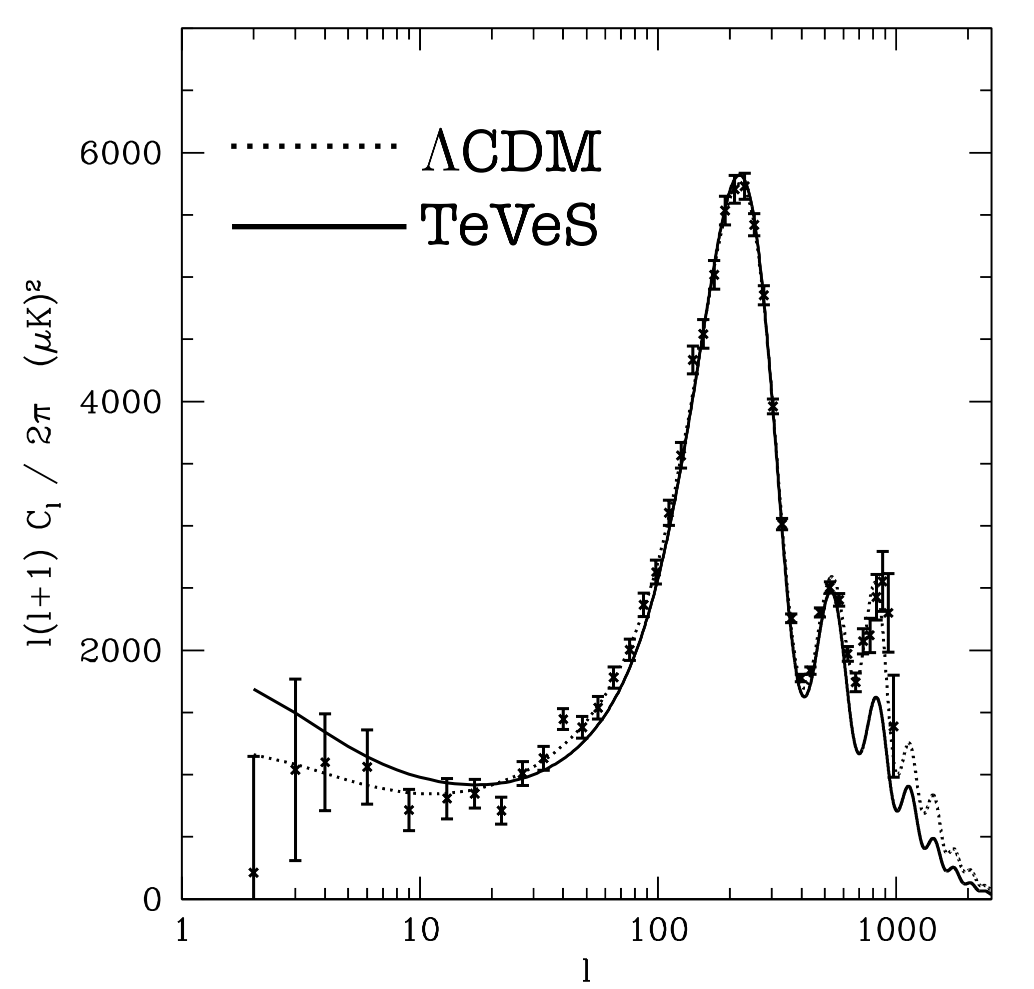
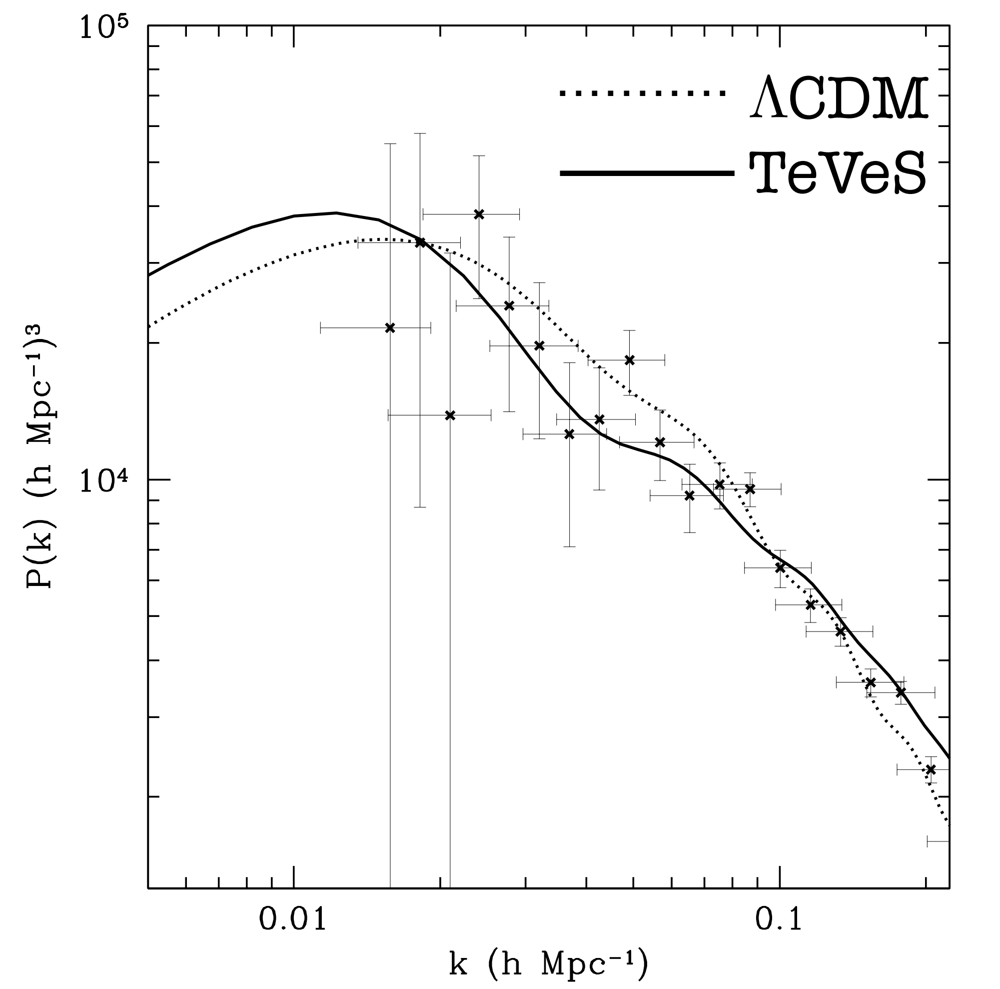


How would the power spectra be in MOND/TeVeS, without DM ?



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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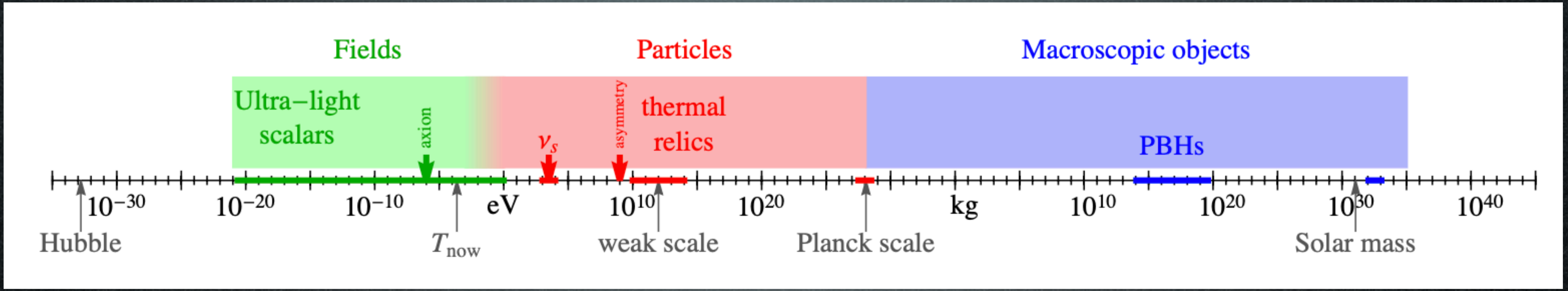
mass ???   interactions ???

Candidates

A matter of perspective: plausible mass ranges



90 orders of magnitude!

Candidates

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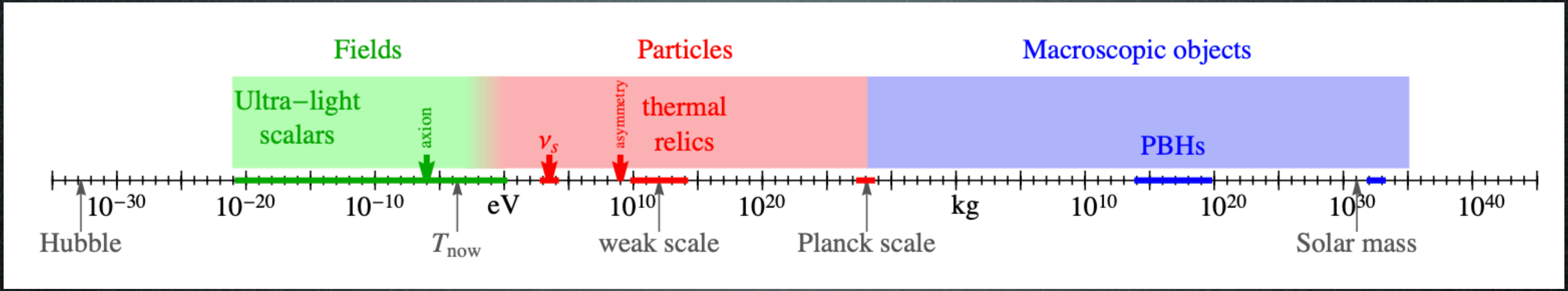

90 orders of magnitude!

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

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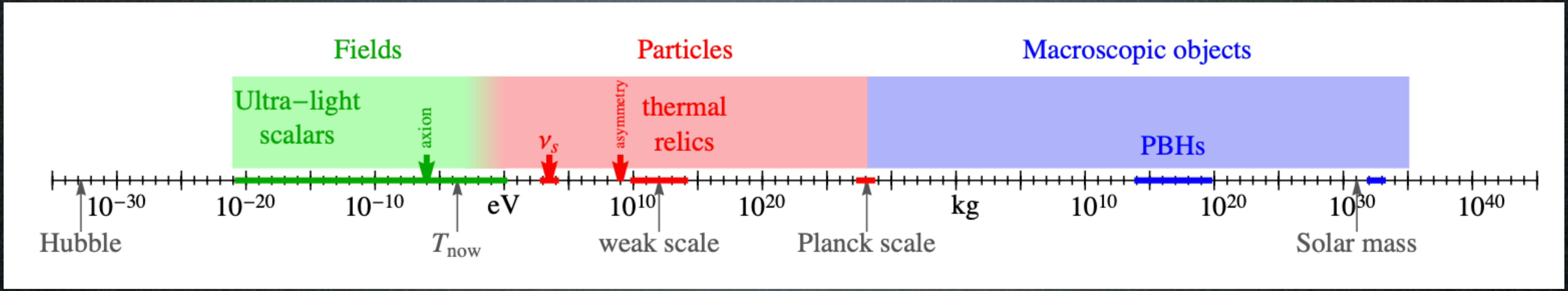

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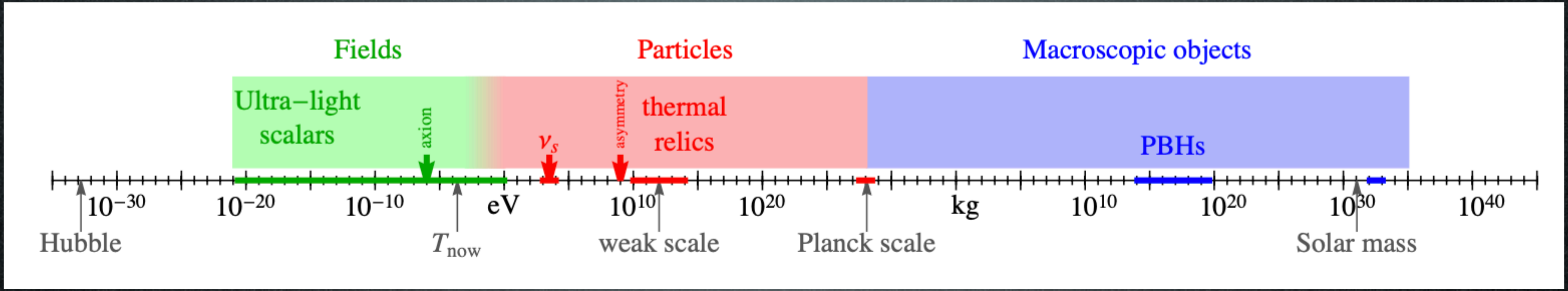

90 orders of magnitude!

neutral ☐
cold ☐
stable ☐
feebly int. ☐

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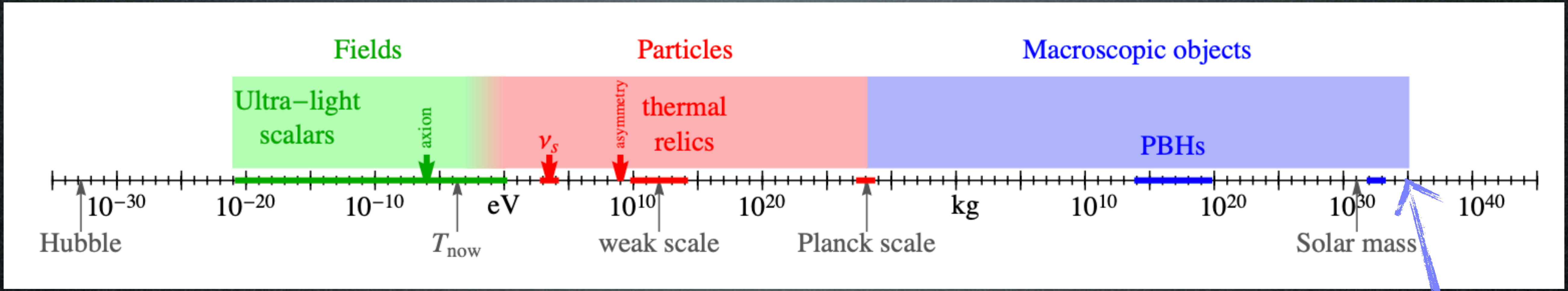

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as big as a dwarf galaxy

DM mass

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

Candidates

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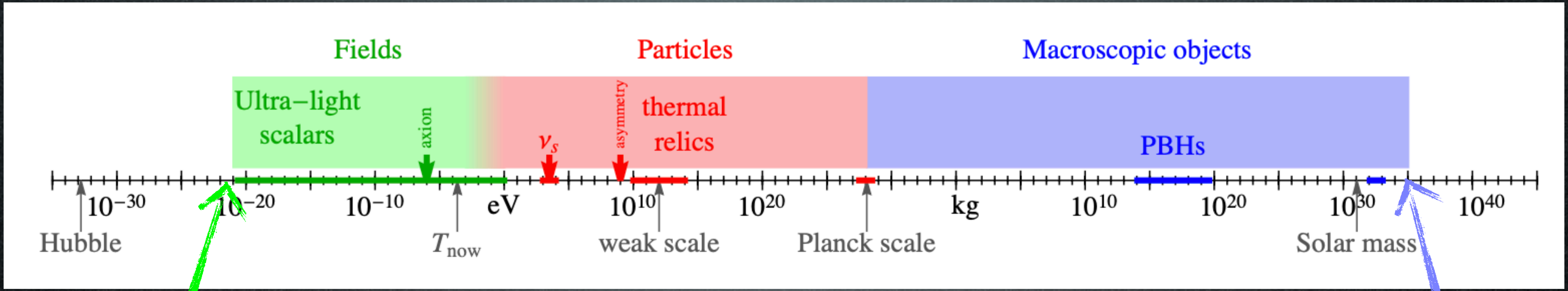

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DM de Broglie wavelength

$$\lambda = 2\pi/Mv \lesssim 1\ \mathrm{kpc}$$

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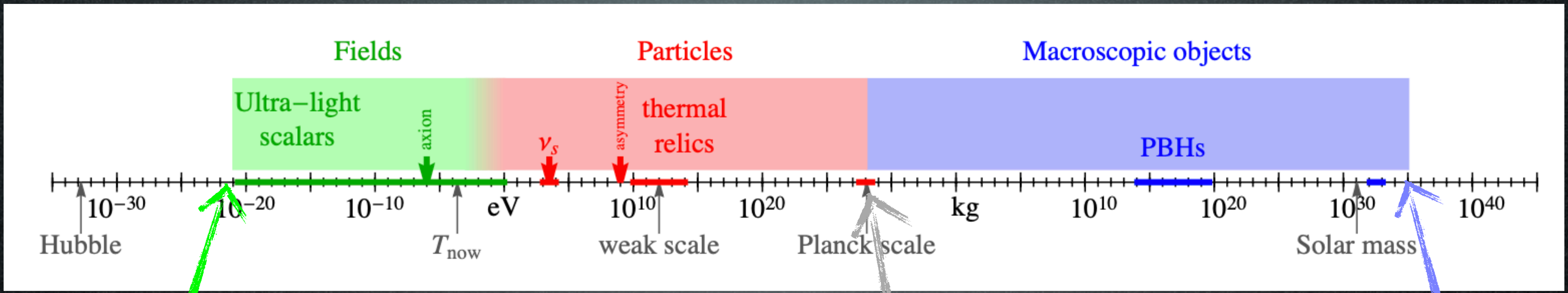

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as diffuse as a dwarf galaxy

most likely elementary | most likely composite

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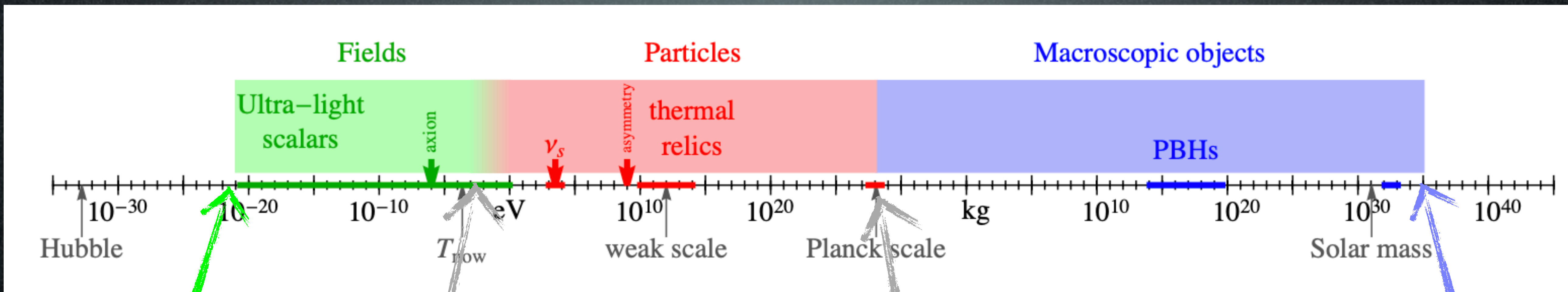

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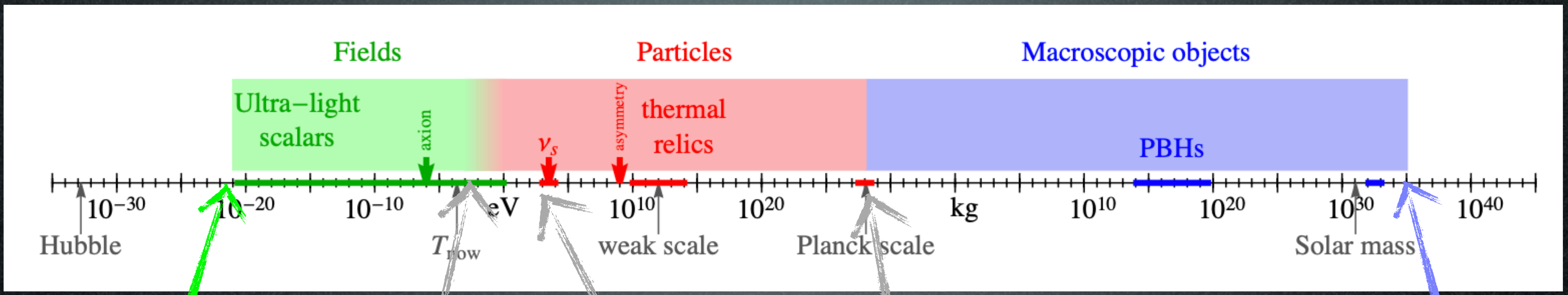

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occupation number

$$N \simeq \frac{\rho}{M/\lambda^3}$$

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

as big as a dwarf galaxy

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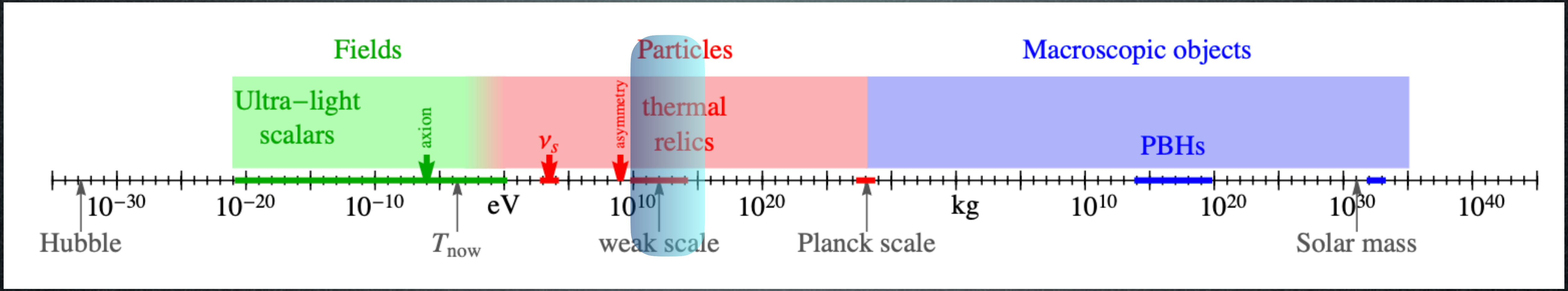
Overview of Particle Physics candidates for Dark Matter

Candidates

A matter of perspective: plausible mass ranges



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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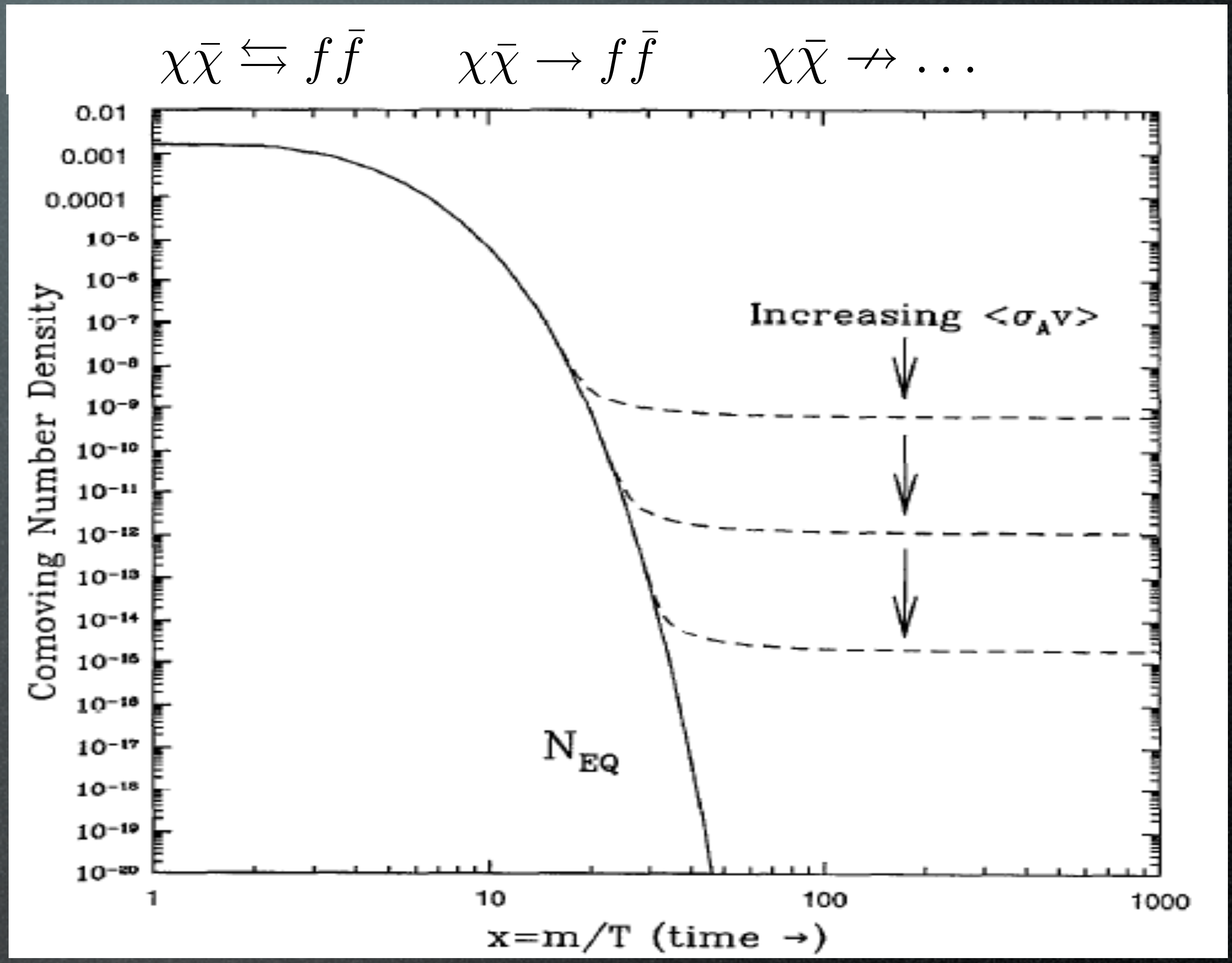

Kolb,Turner, The Early Universe, 1995

Weak cross section:

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

(WIMP)

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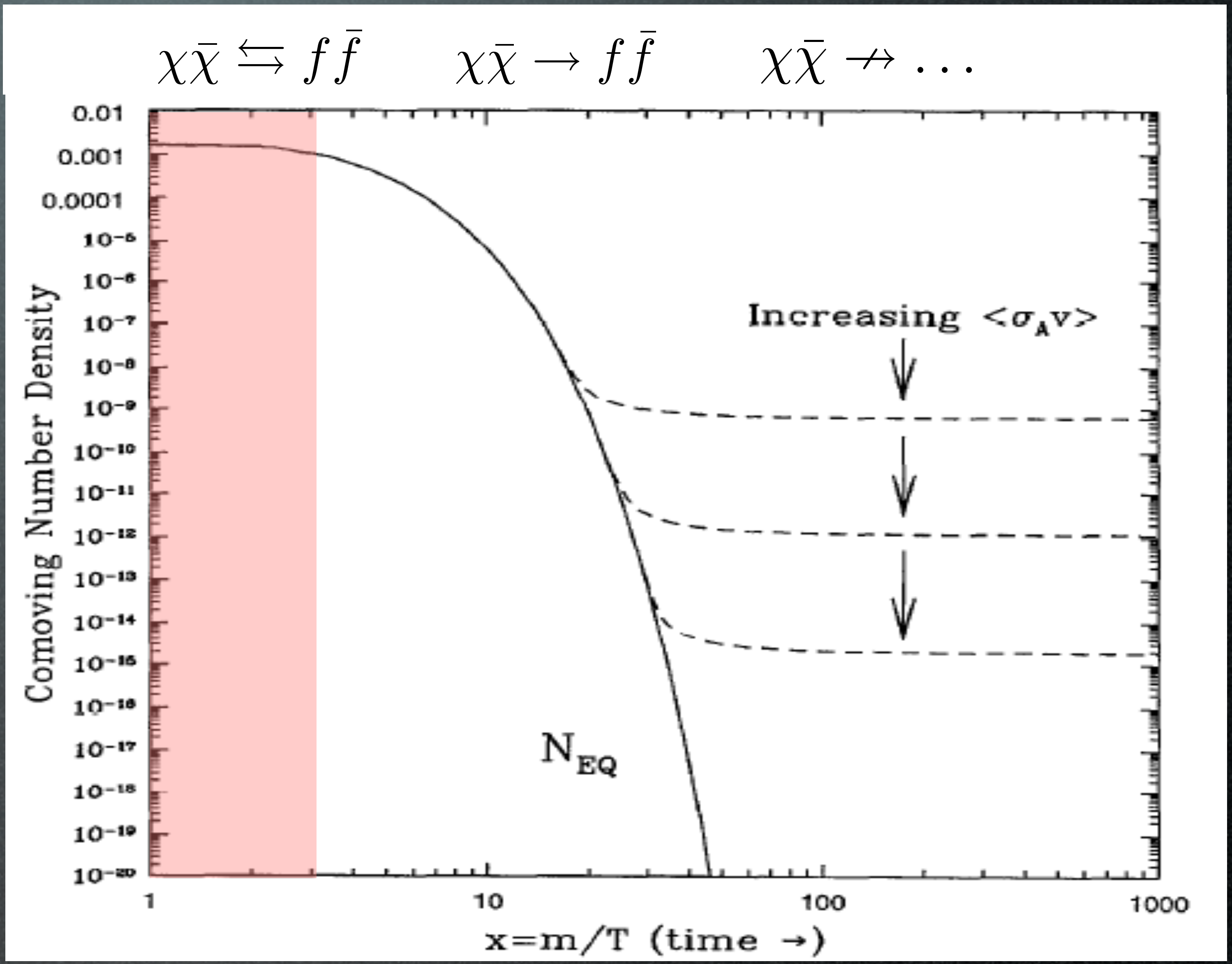

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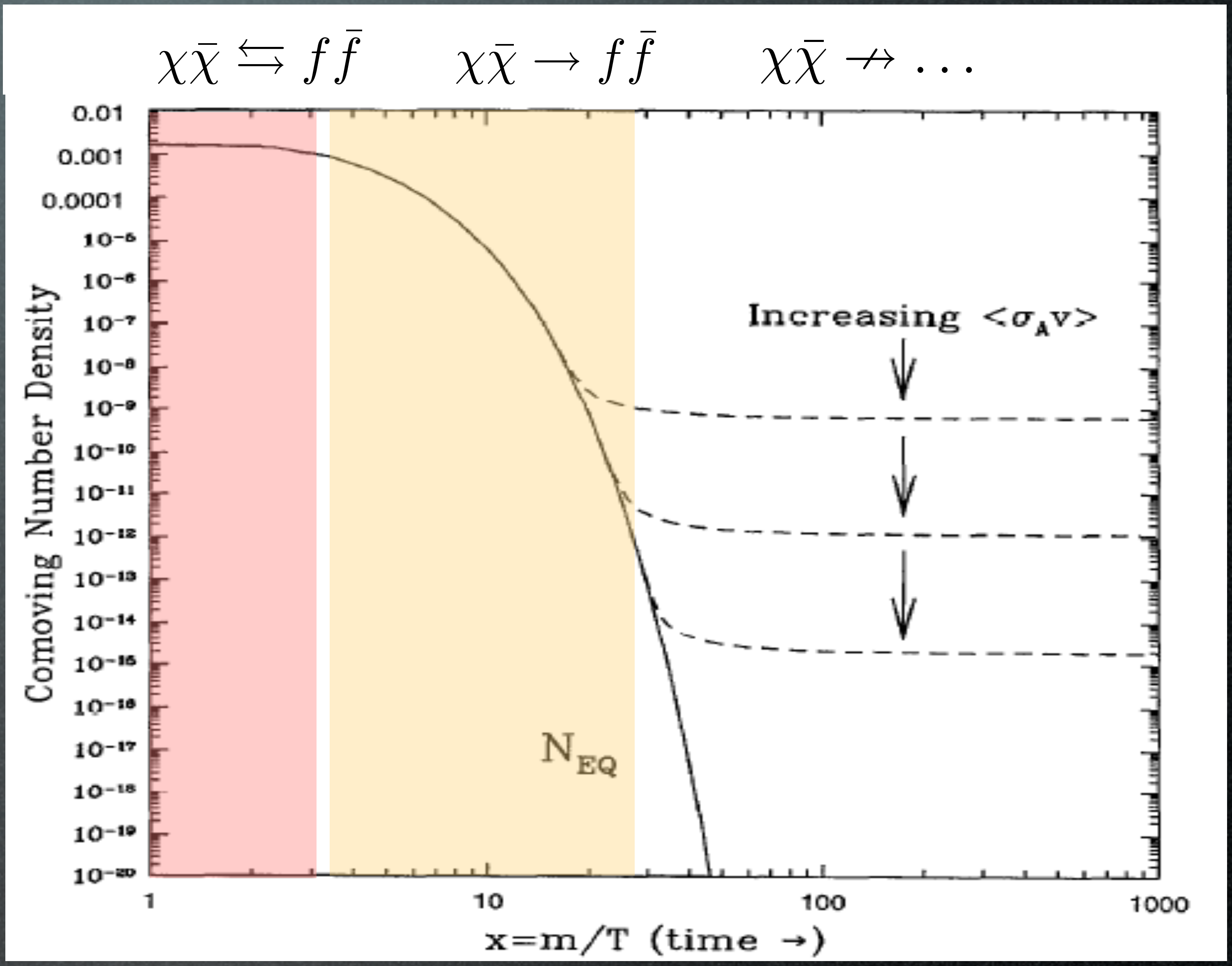
$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

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

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



Kolb,Turner, The Early Universe, 1995

Weak cross section:

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

(WIMP)

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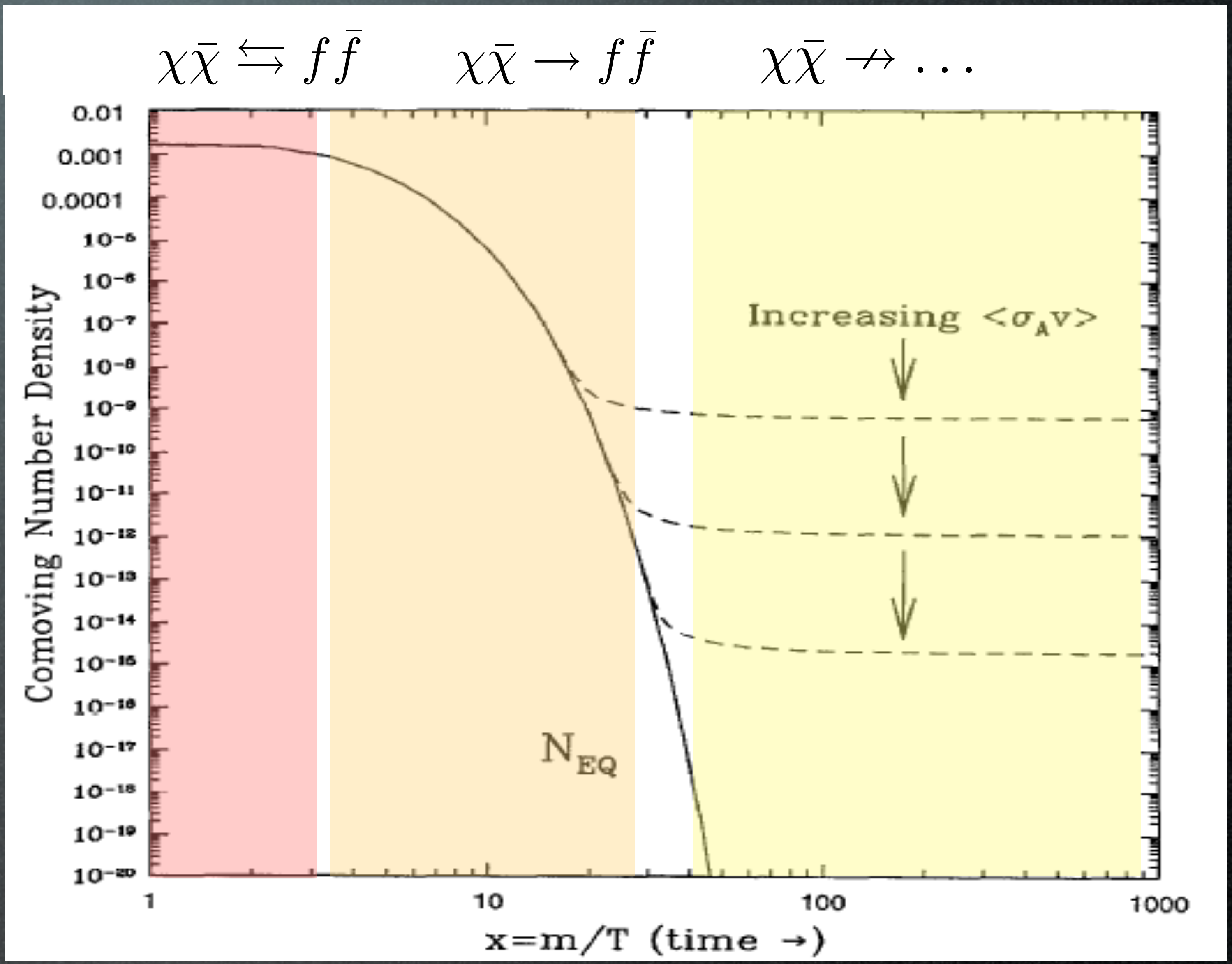

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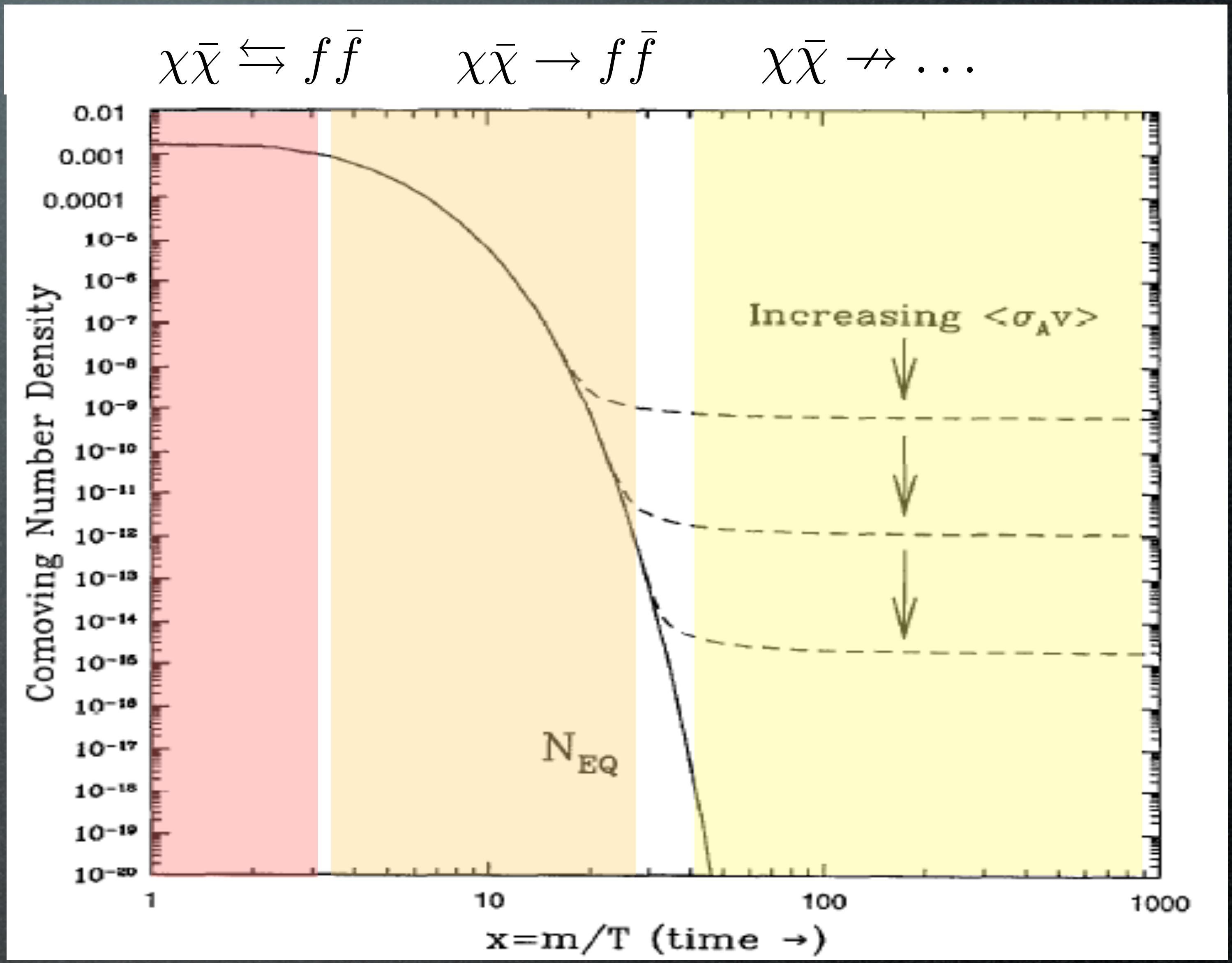

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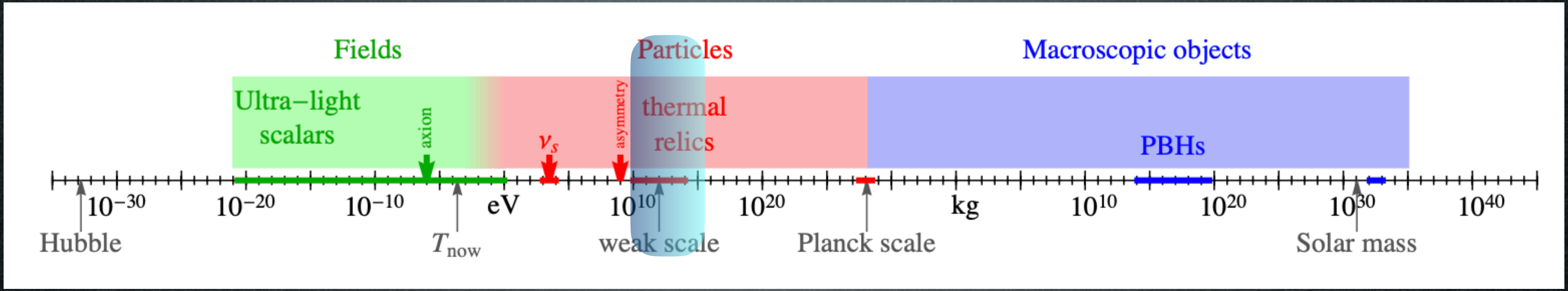
Weakly
Interacting
Massive
Particles

Candidates

A matter of perspective: plausible mass ranges



Thermal DM

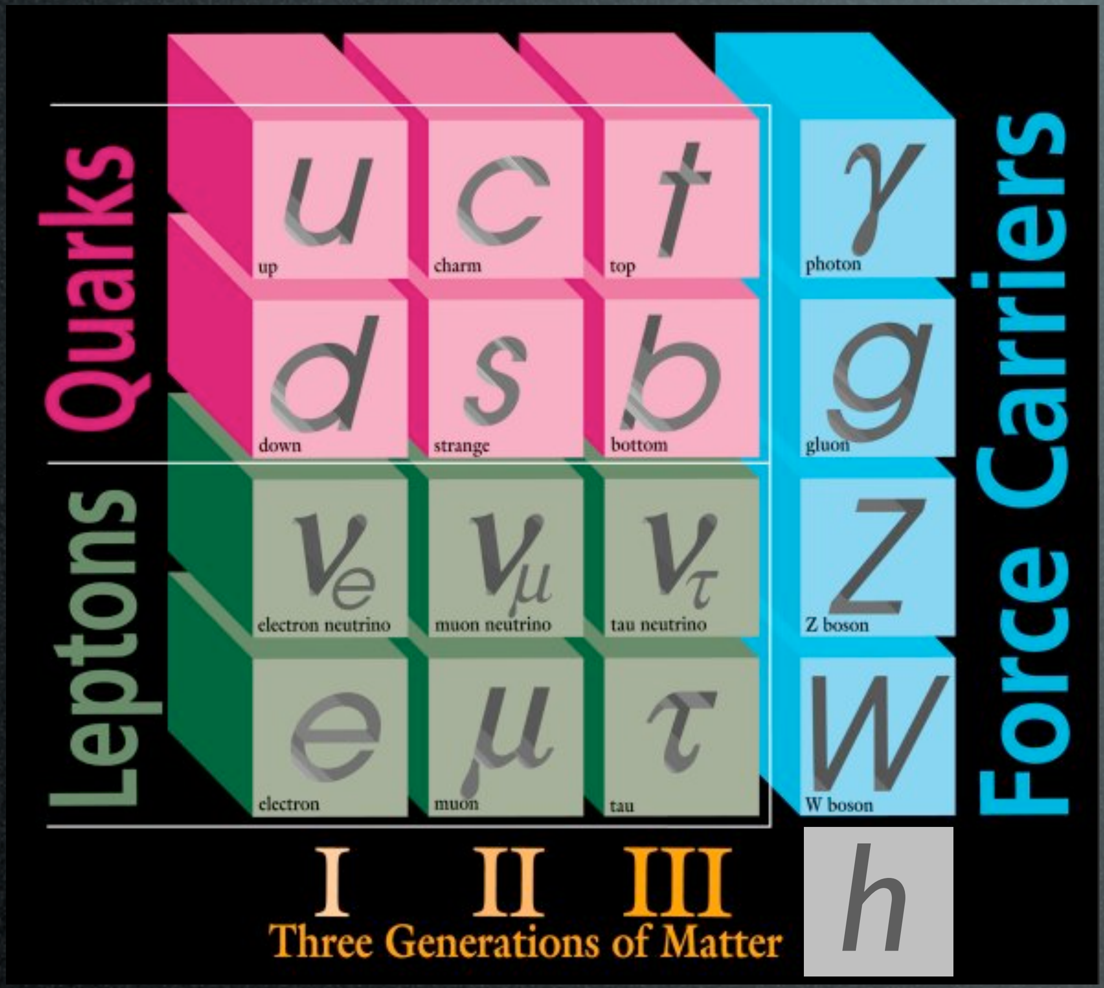
Candidates

A matter of perspective:

SuSy neutralino

other exotic candi-dates

SuSy DM in 2 minutes



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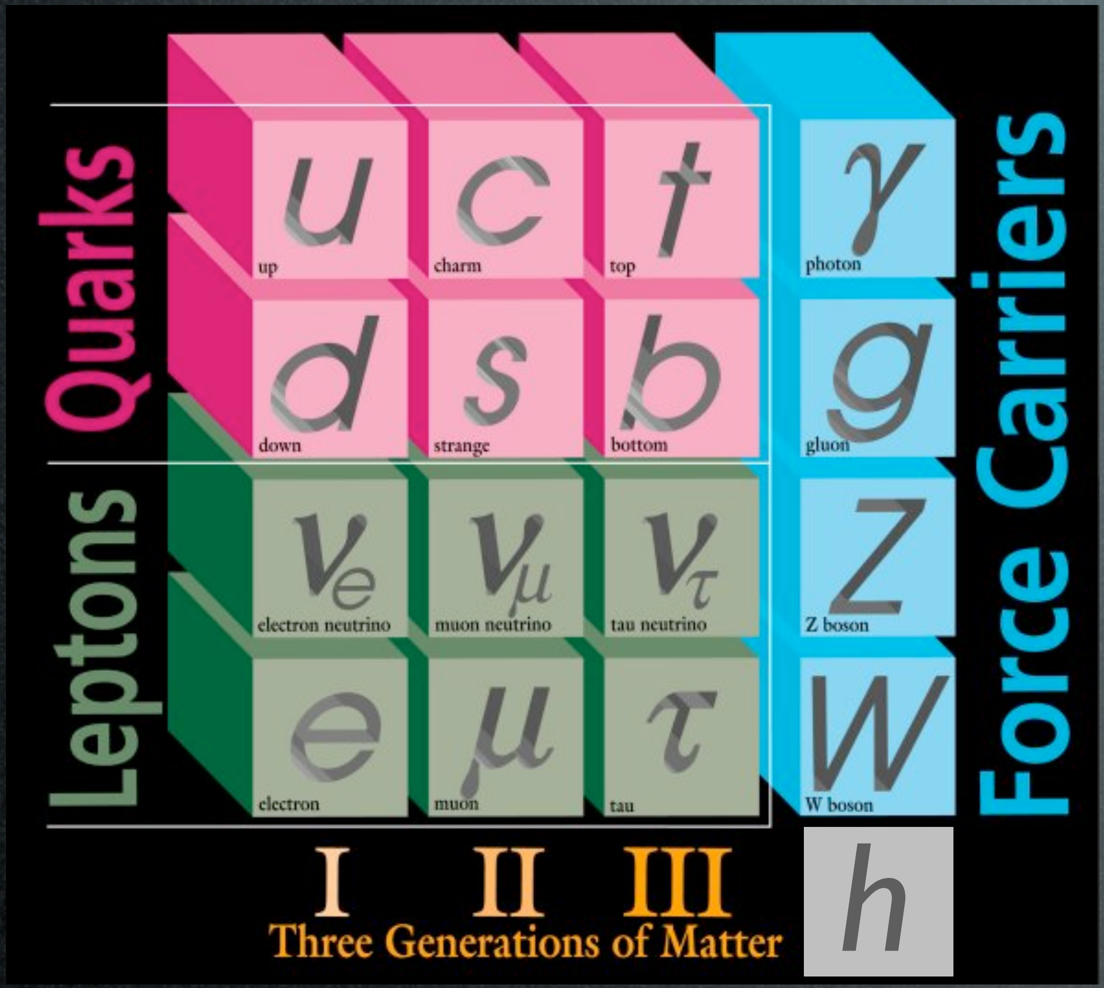

$m_{\rm h} \simeq 125~\rm GeV$

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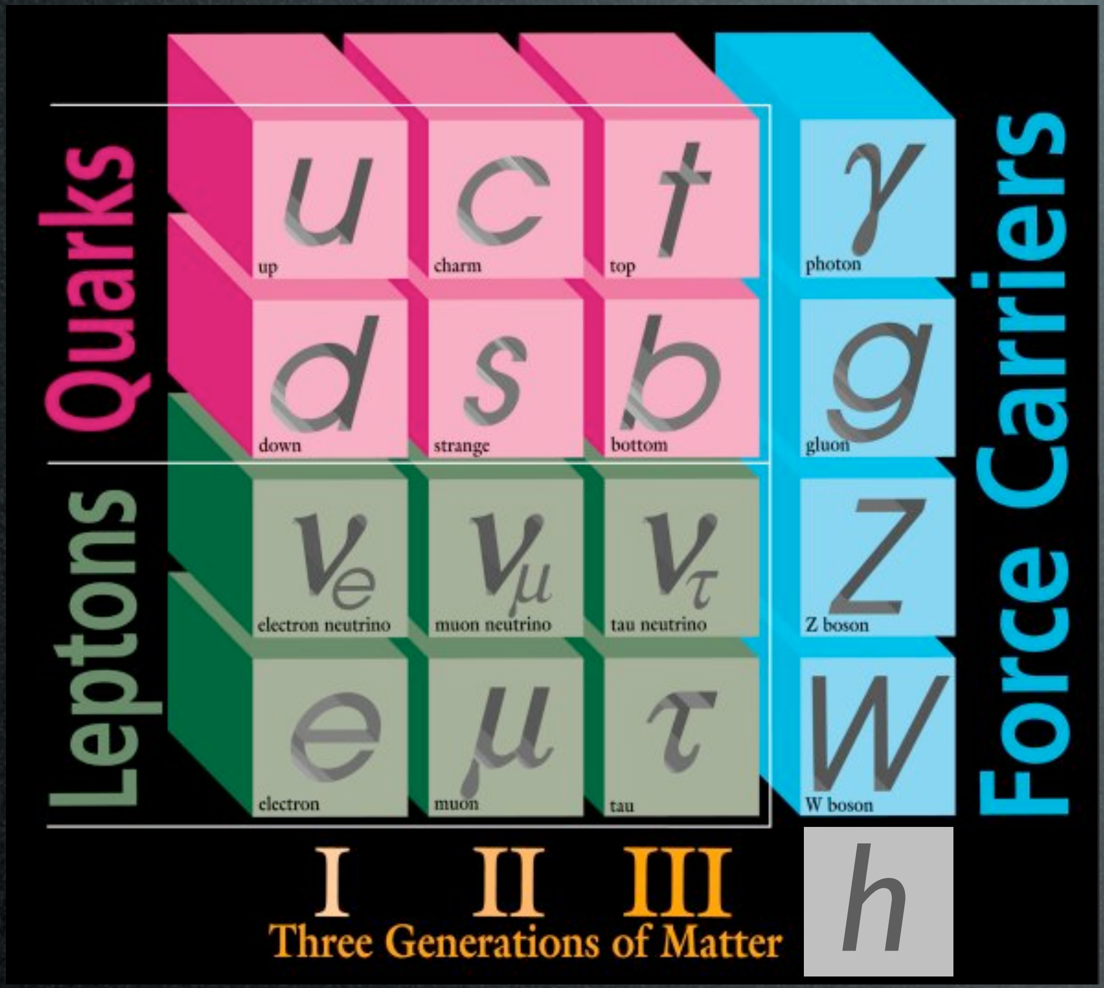

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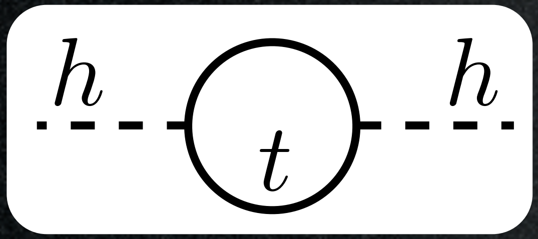

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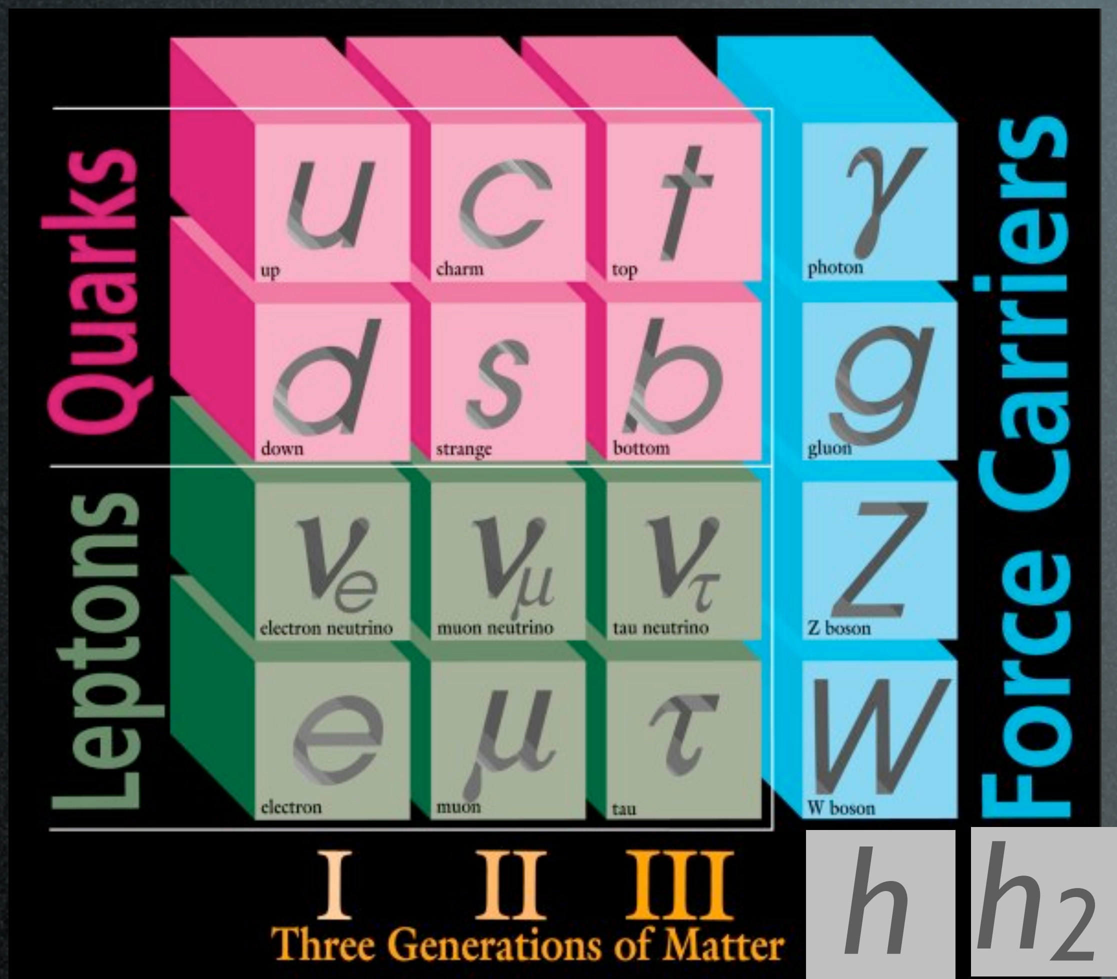

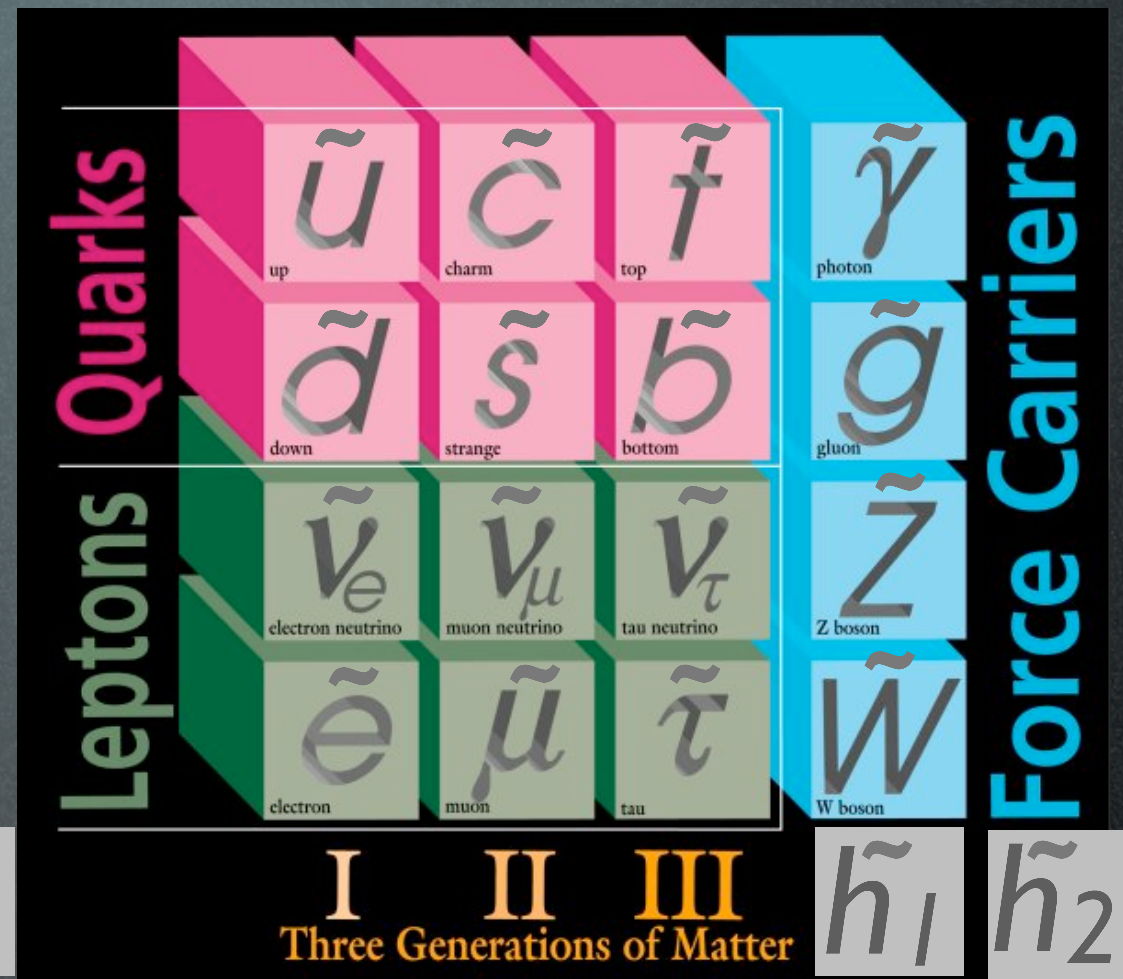

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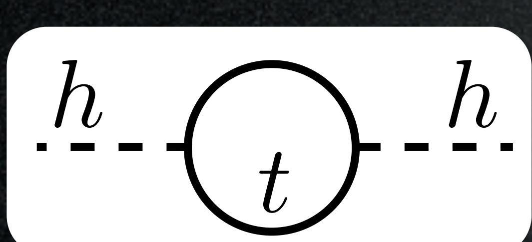

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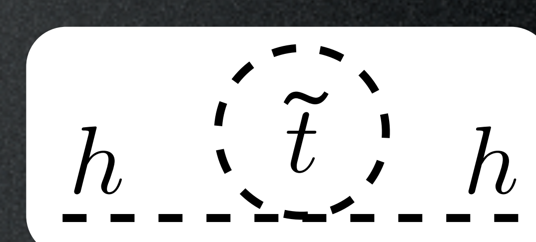

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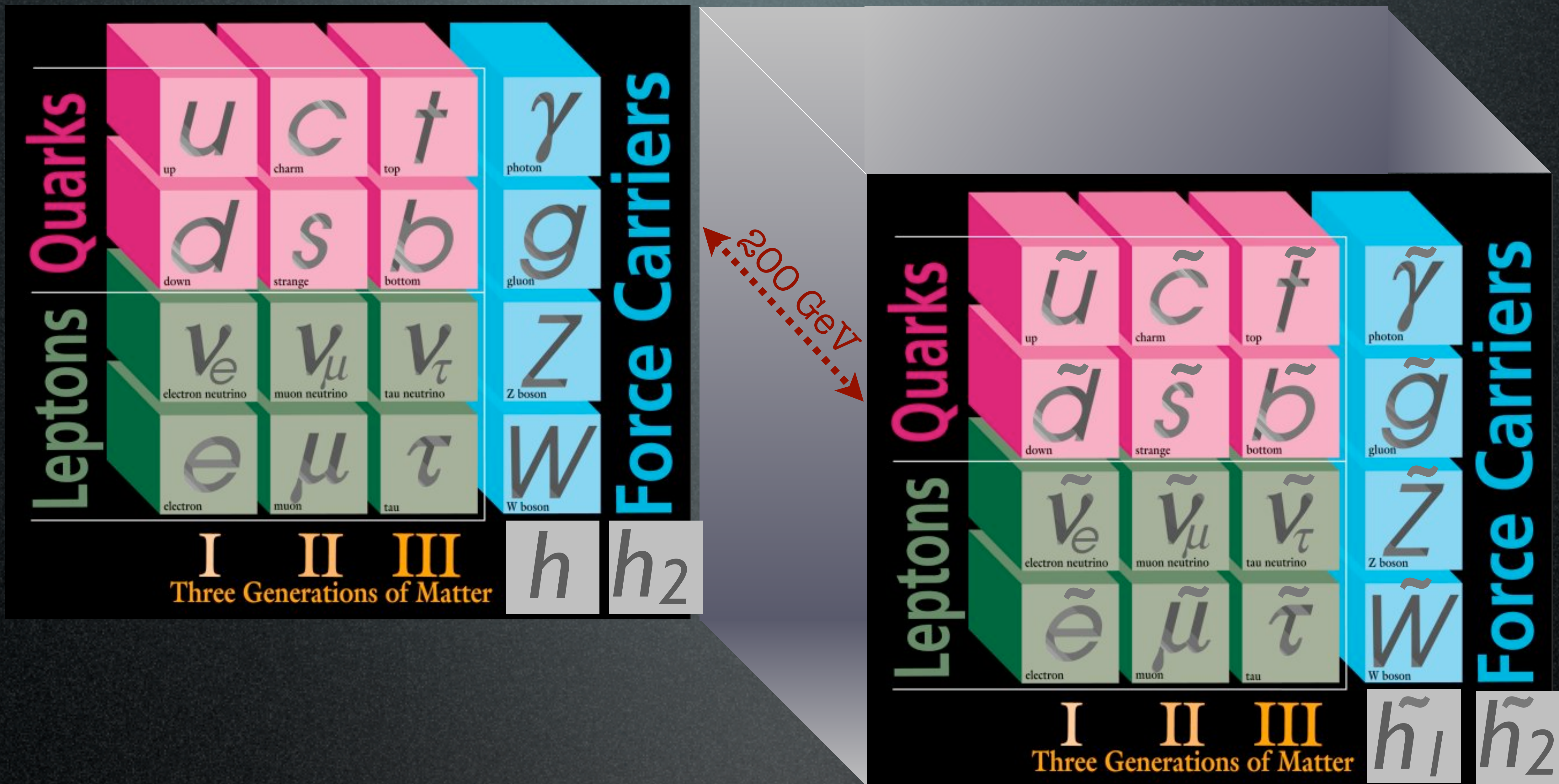

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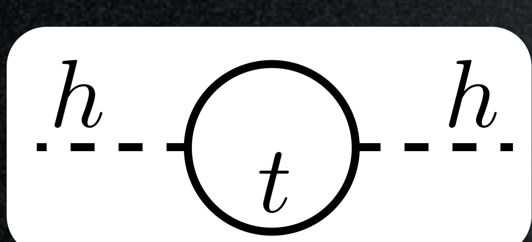

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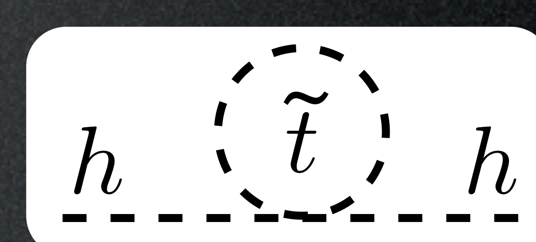

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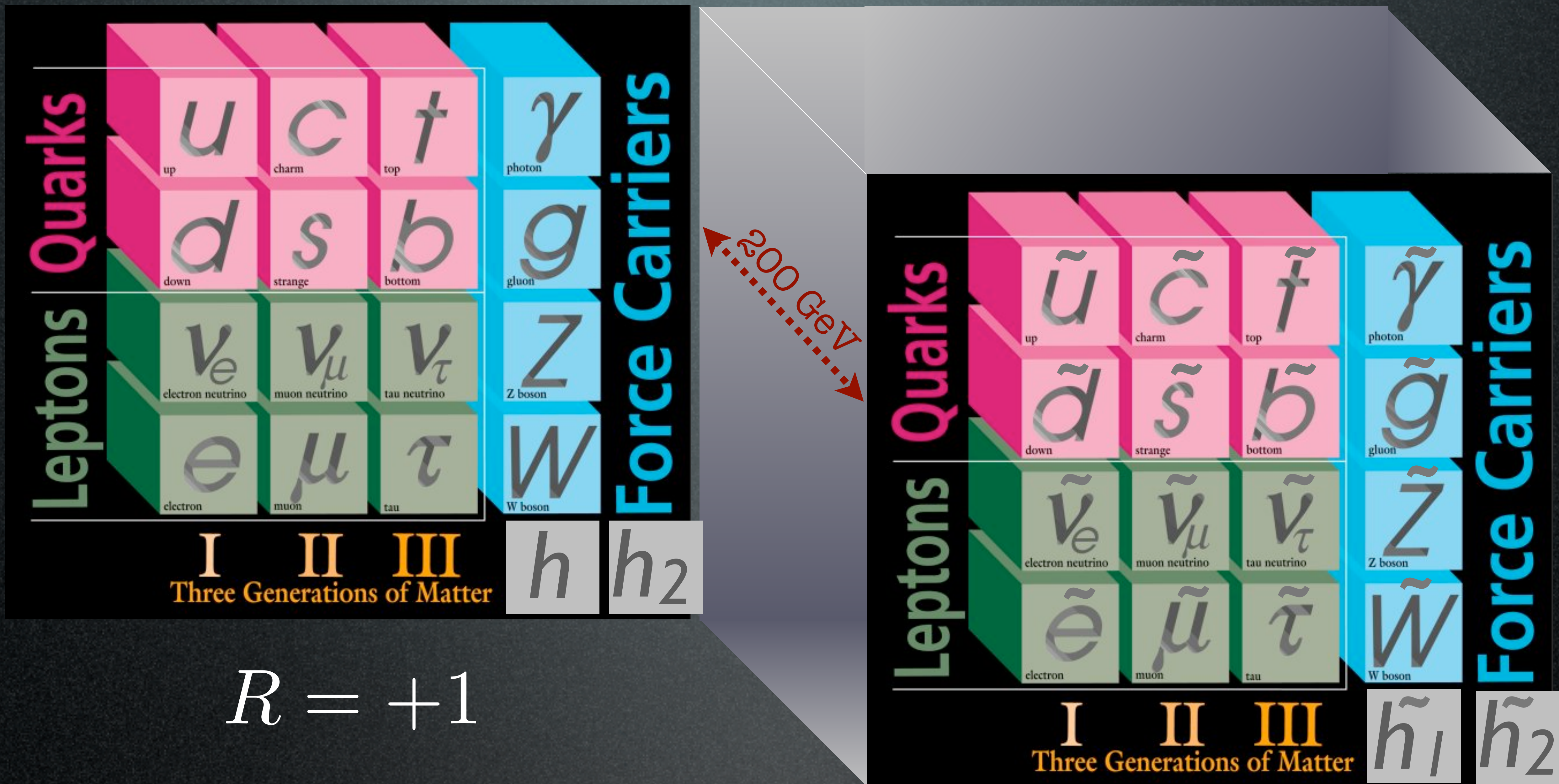
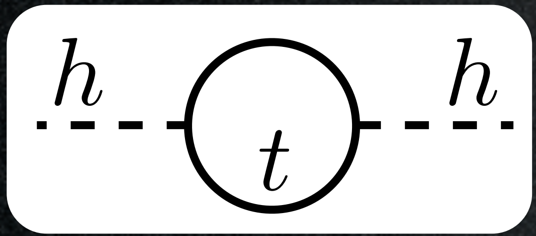


$$R = +1$$

$$R = -1$$

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



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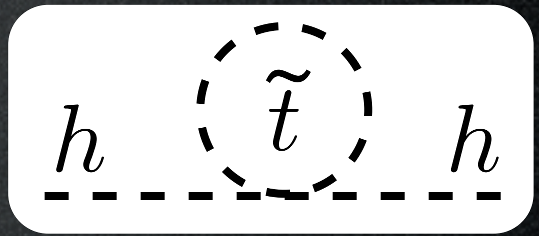

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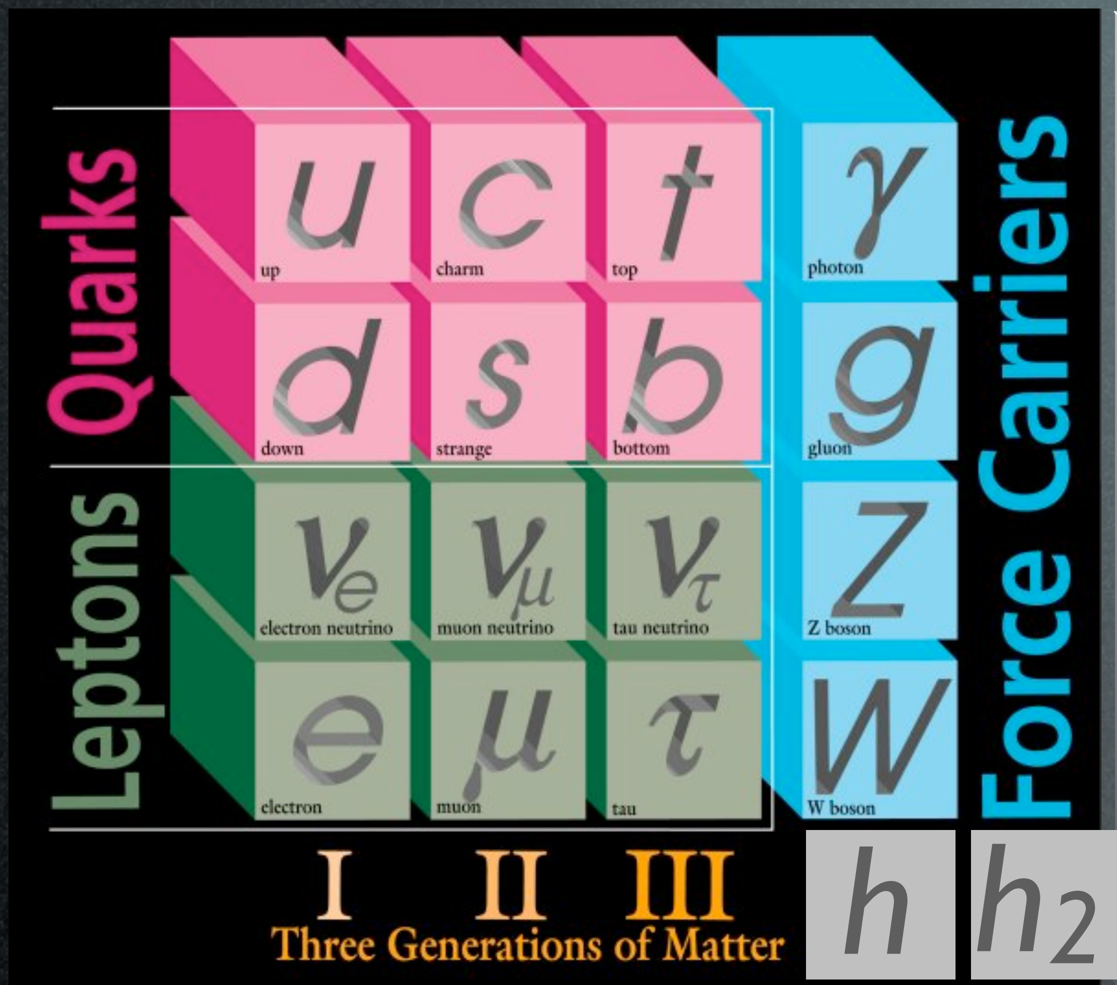

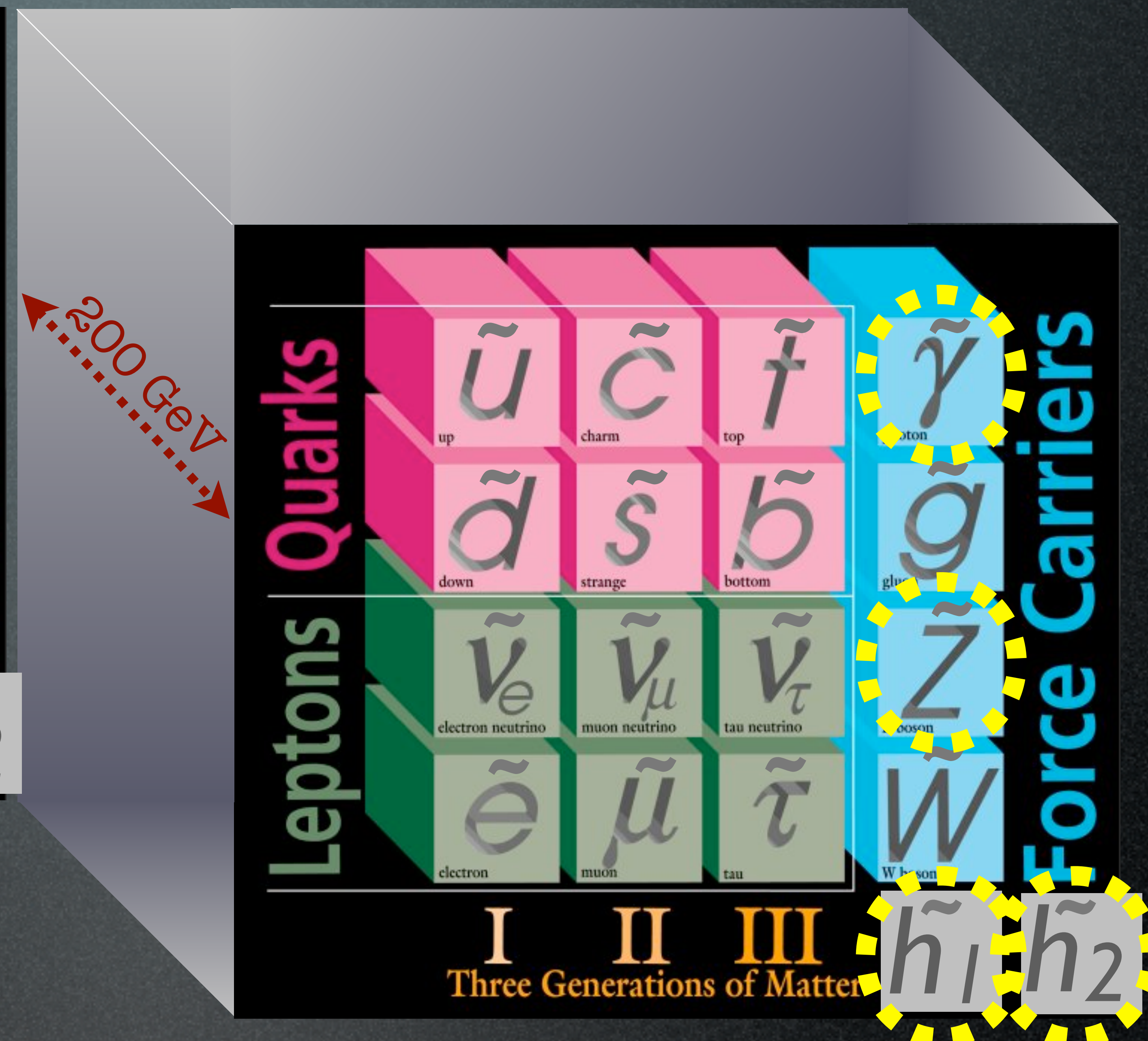

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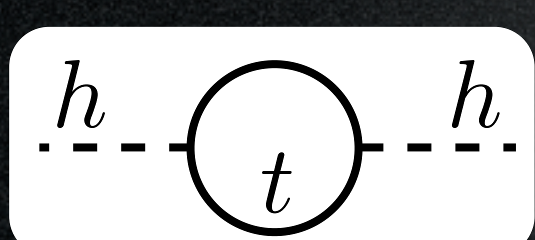

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neutral ✓
cold ✓
stable ✓
feebly int. ✓

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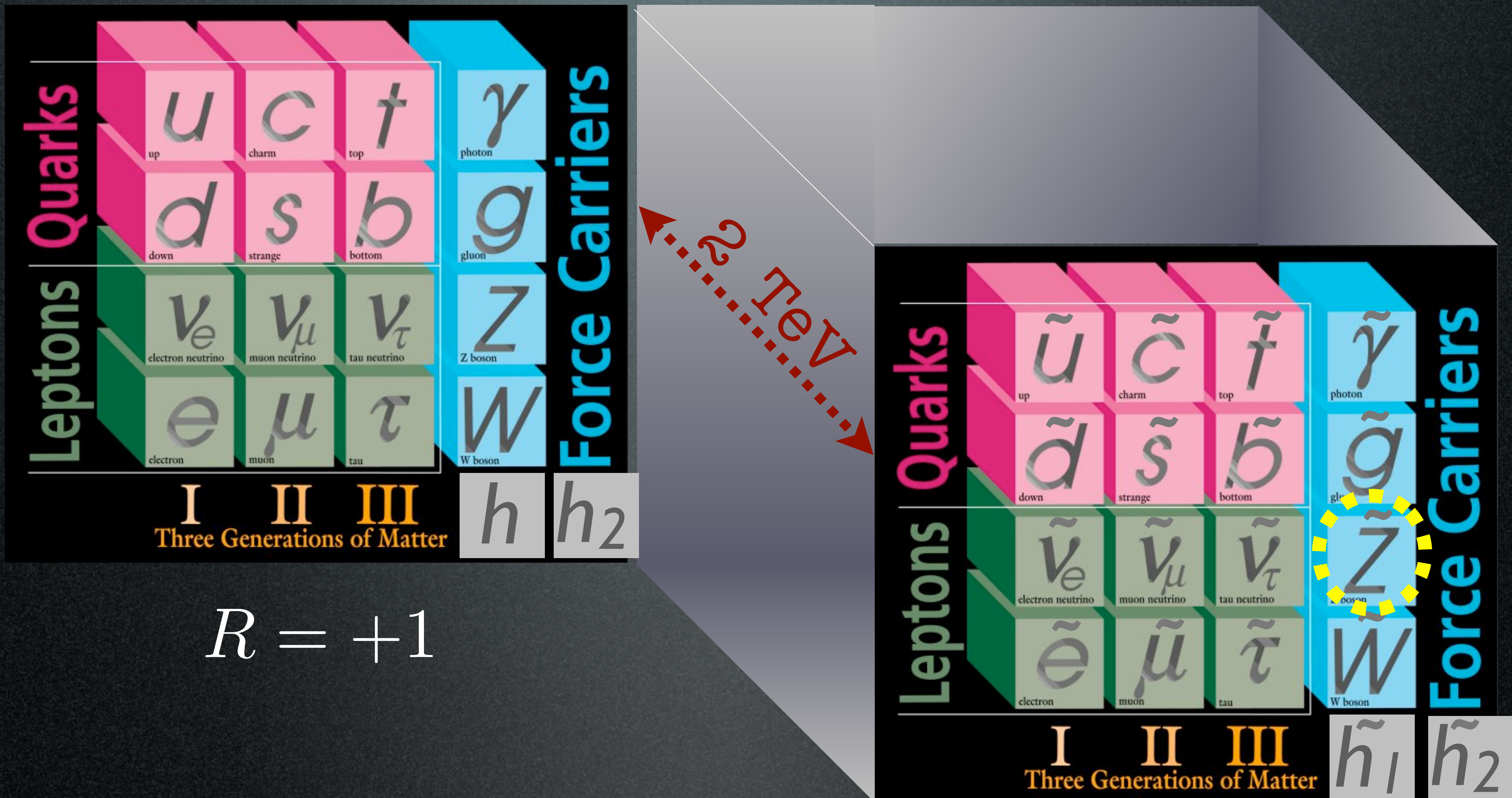

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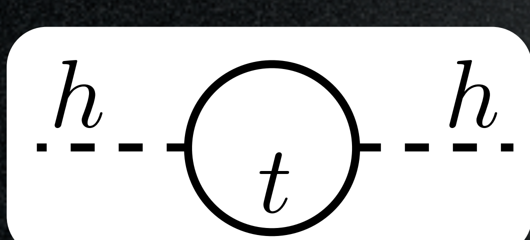

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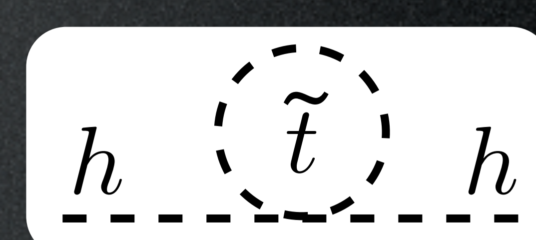

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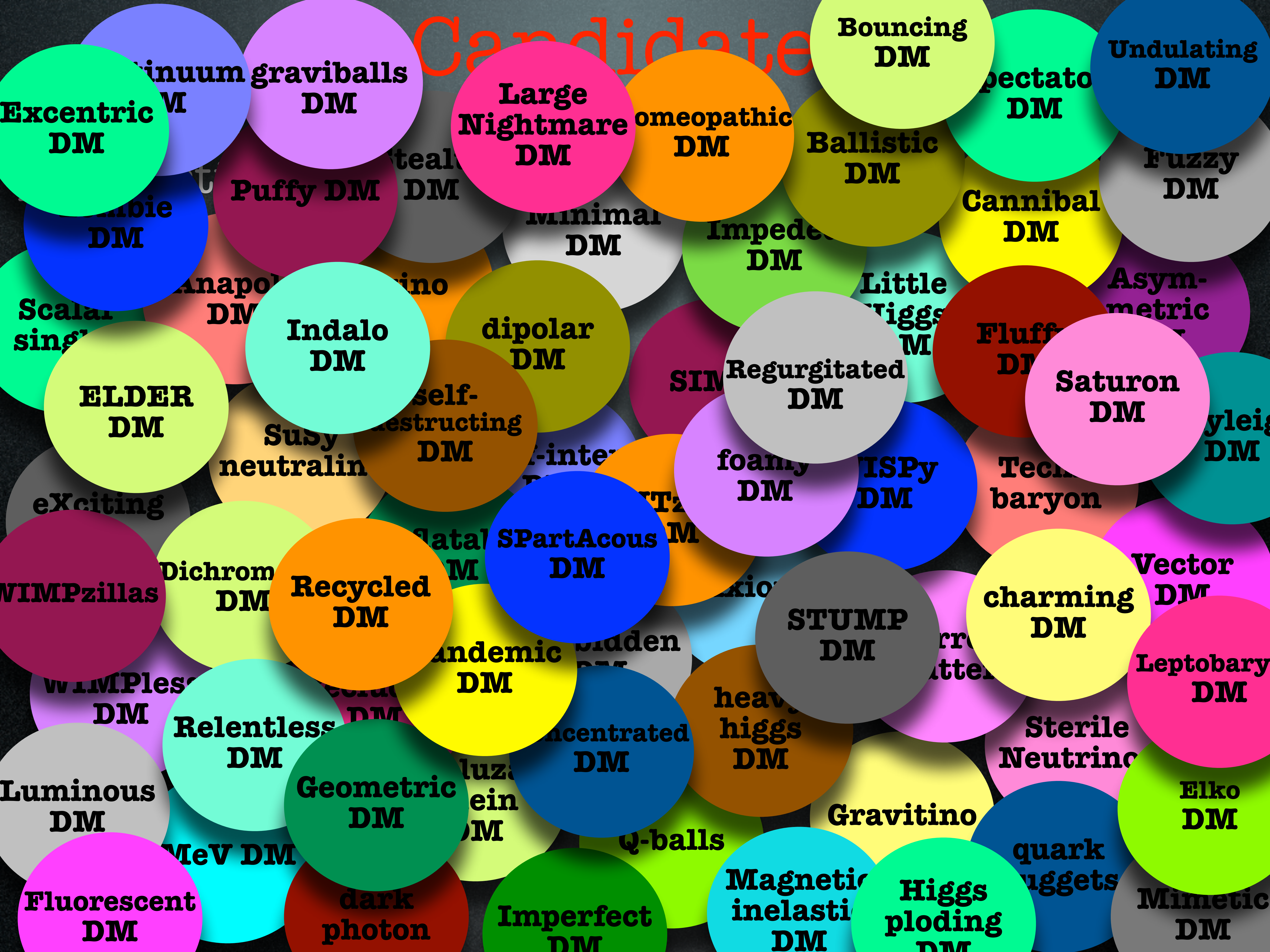
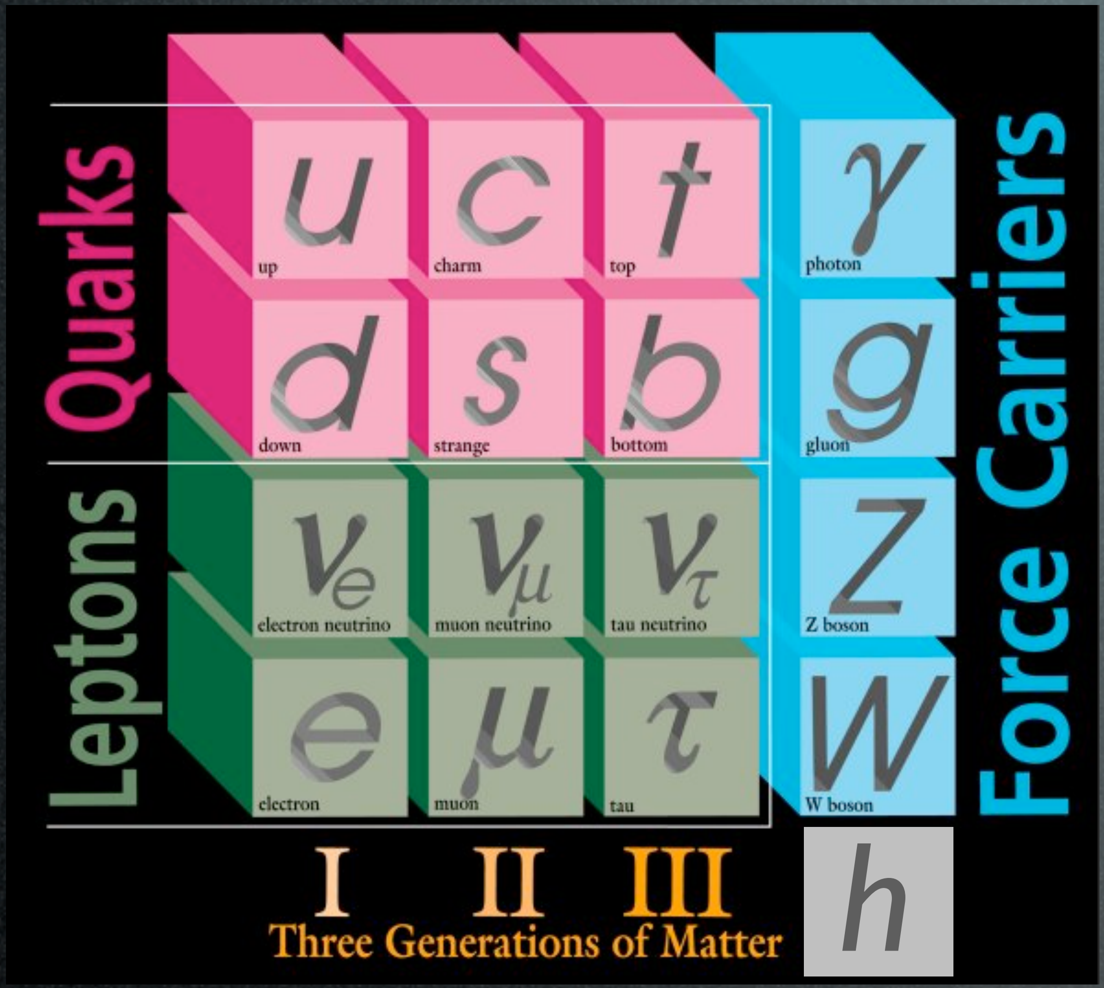
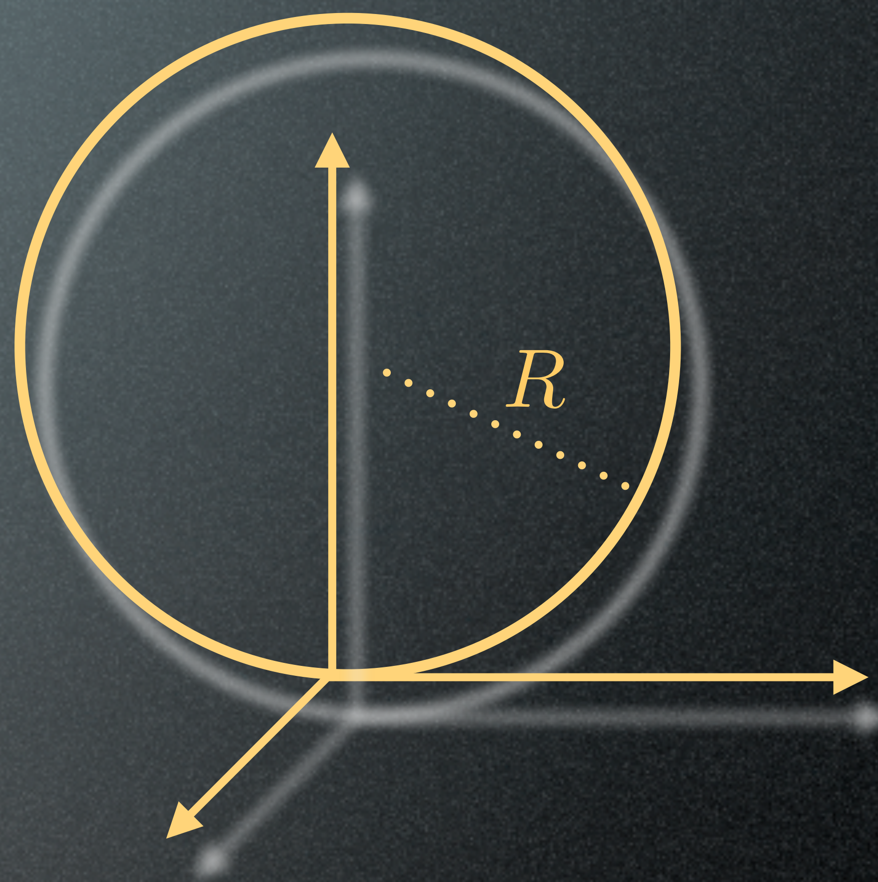

Bouncing DM
Undulating DM
Excentric DM
graviballs DM
Large Nightmare DM
Ballistic DM
Fuzzy DM
Puffy DM
Cannibal DM
Indalo DM
dipolar DM
Regurgitated DM
Saturon DM
ELDER DM
SPartAcous DM
Recycled DM
STUMP DM
charming DM
Vector DM
Relentless DM
Geometric DM
Luminous DM
Fluorescent DM
Gravitino
Q-balls
Elko DM
Imperfect DM

ExDim DM in 2 minutes





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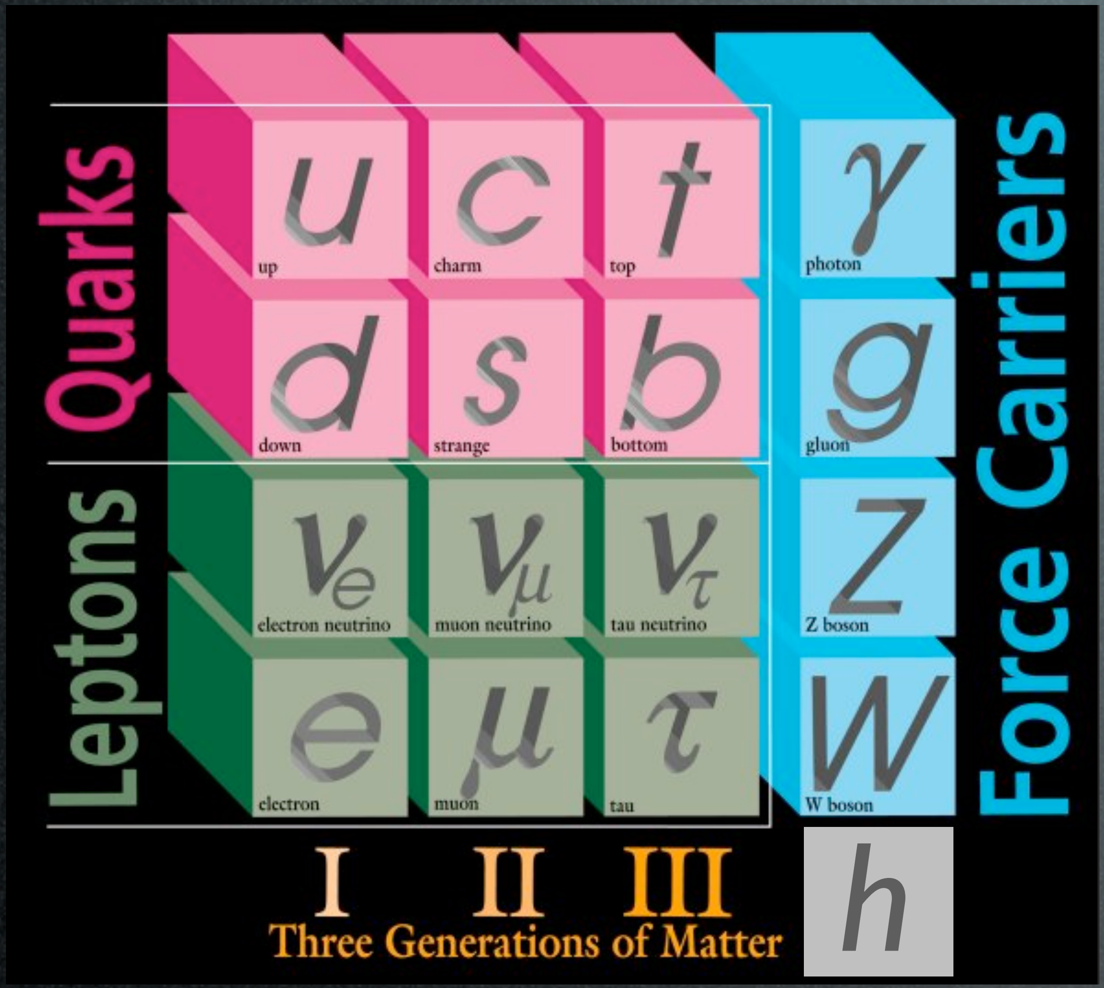
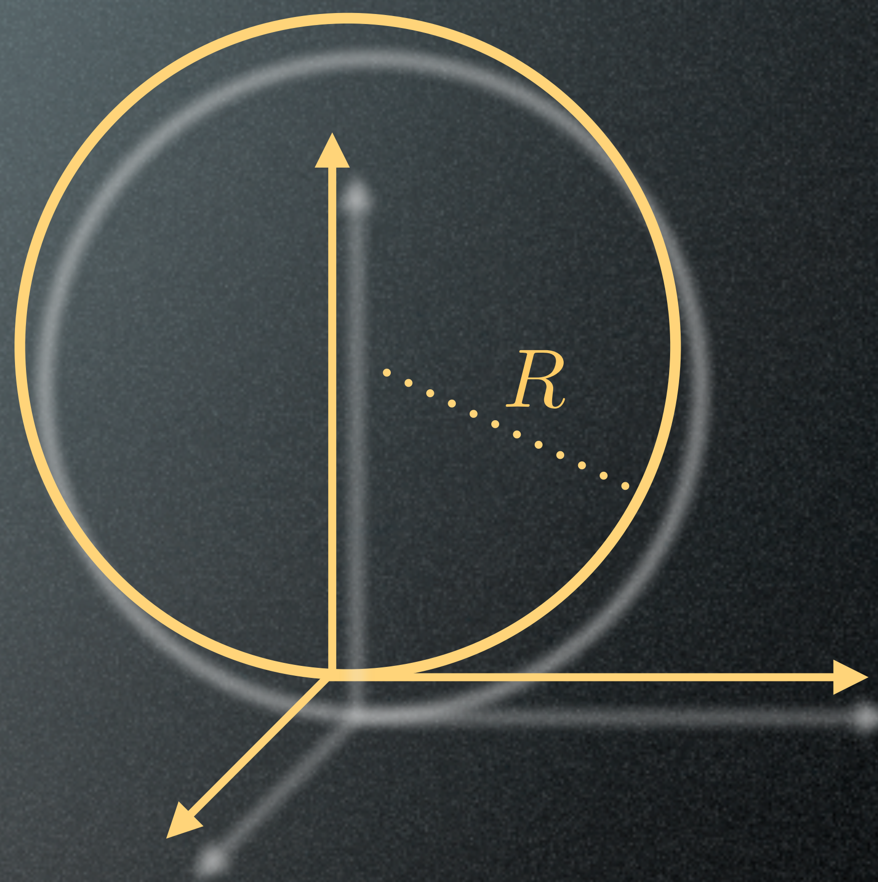




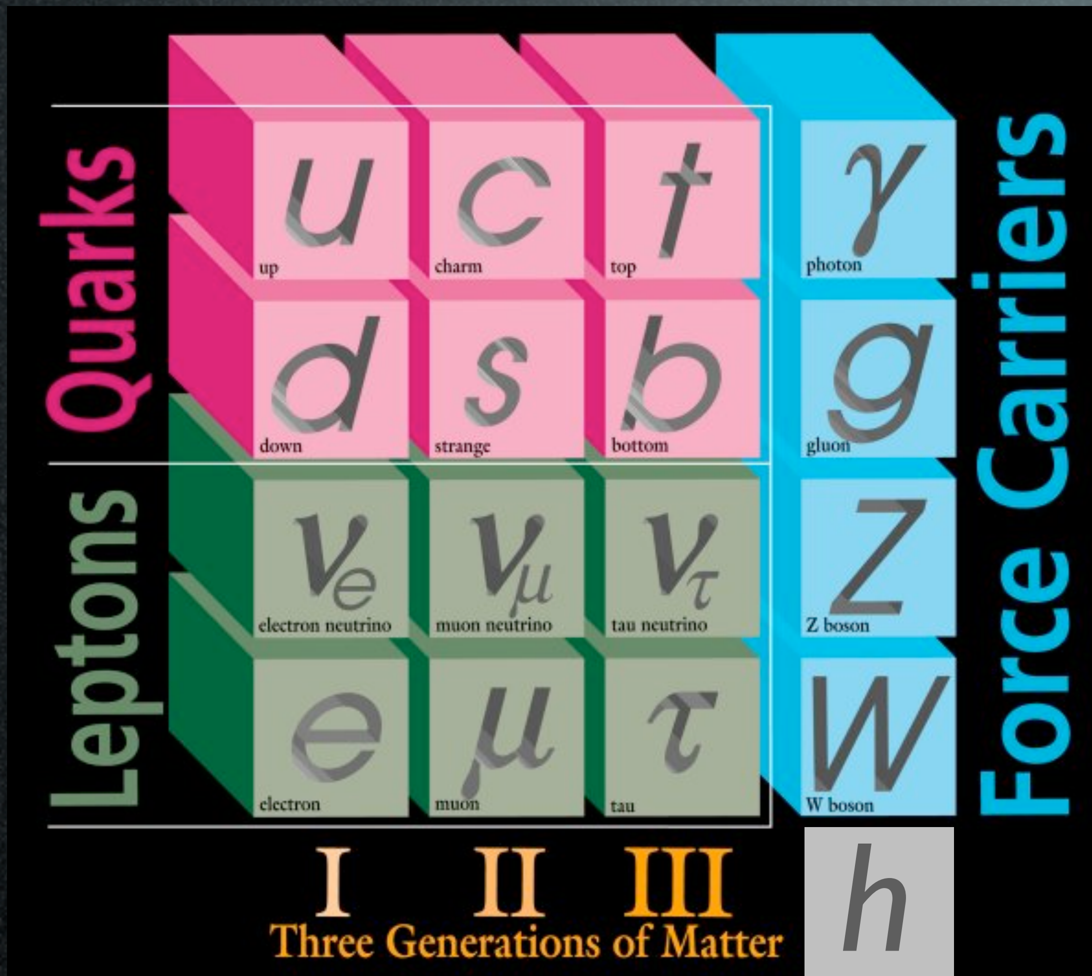
Original motivation:

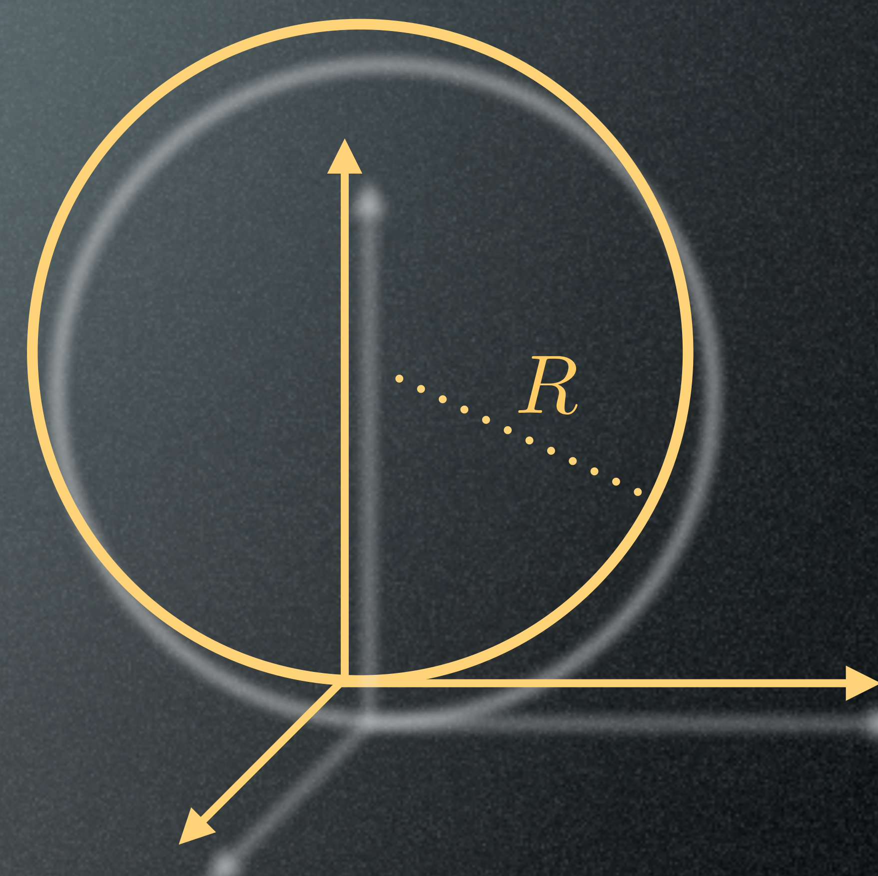
gravity in the ExDims, hierarchy problem

$$M_{Pl}^2 \sim M_{Pl(4+n)}^{2+n} R^n.$$

Arkani-Hamed, Dimopoulos, Dvali hep-ph/9803315

ExDim DM in 2 minutes



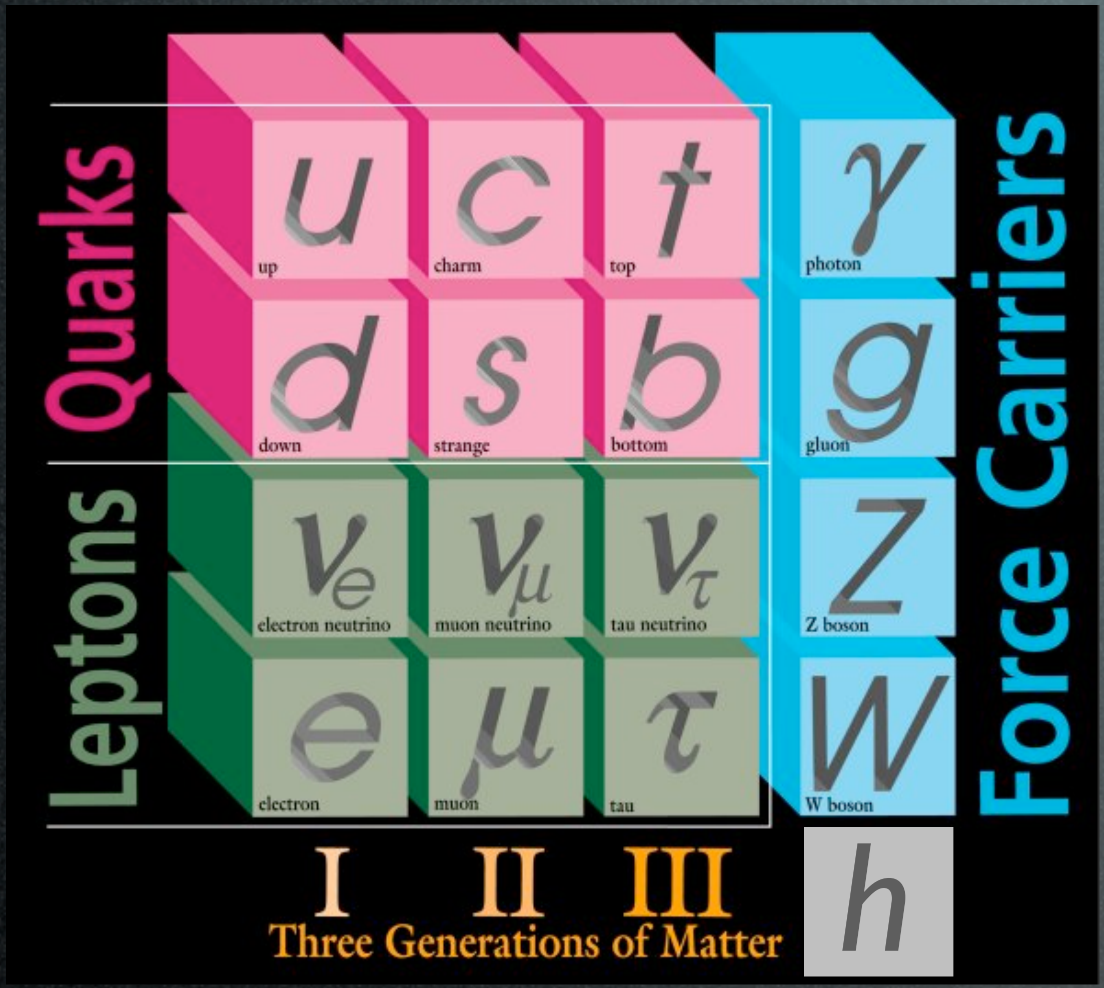


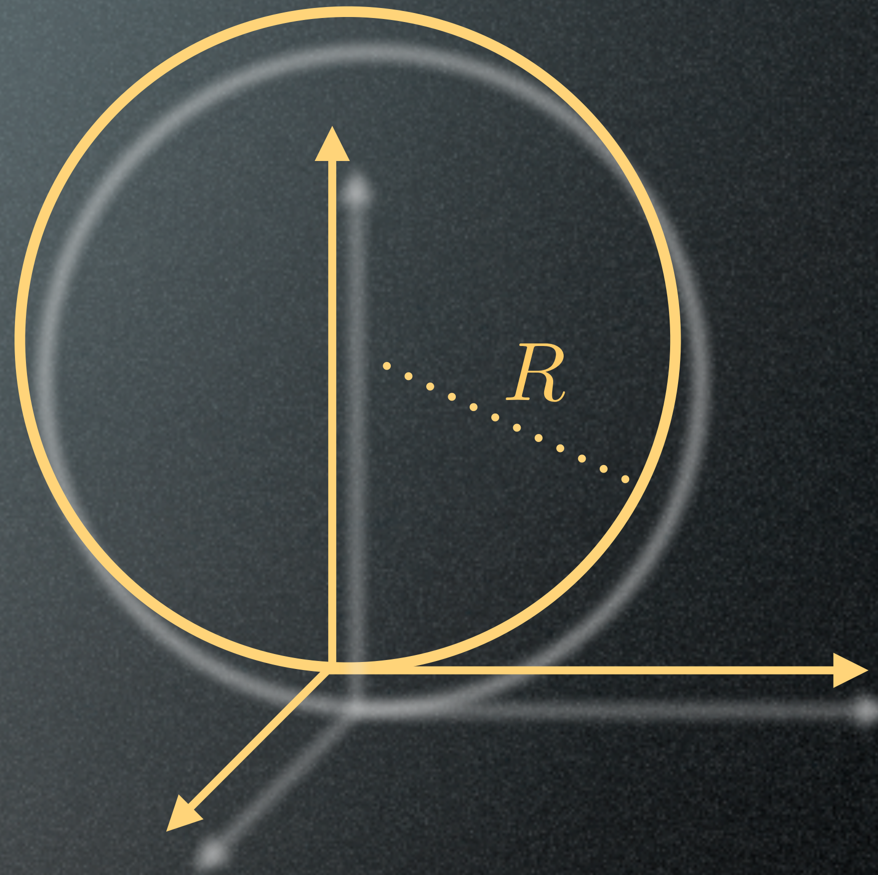
Evolution:

'universal ExDims', the SM in 5D

$$R \sim 1 \text{ TeV}^{-1}$$

ExDim DM in 2 minutes





any field in the compact 5th dimension:

$$\phi(y) = \phi(y + 2\pi R)$$

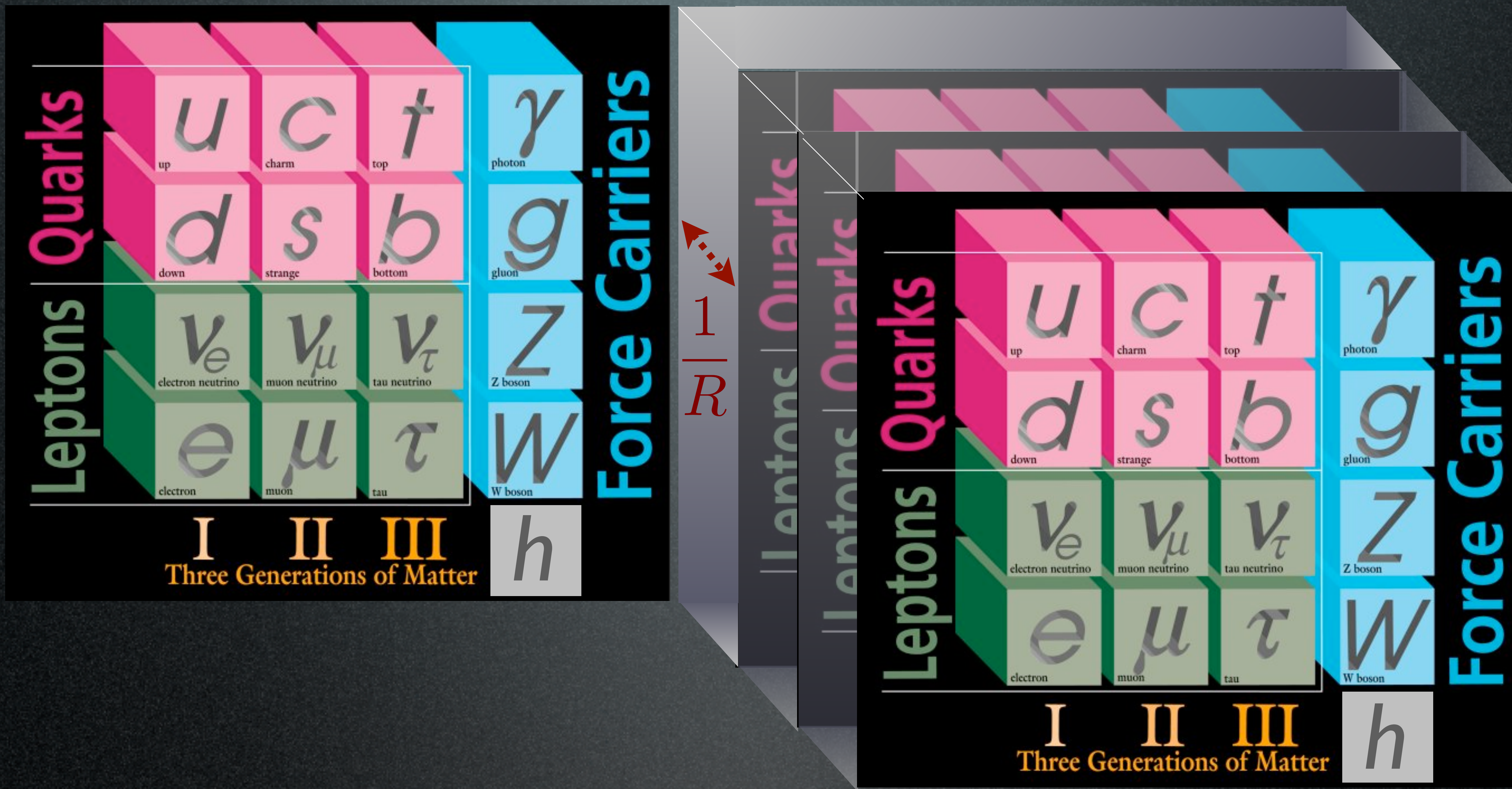
hence (Fourier) decomposition:

$$\phi(x,y) = \frac{1}{\sqrt{2\pi R}}\phi_0(x) + \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi R}} \left[\phi_n(x)\cos\left(\frac{ny}{R}\right) + \phi'_n(x)\sin\left(\frac{ny}{R}\right)\right]$$

i.e. states (indexed by *n*) with mass

$$M_n^2 = m^2 + \frac{n^2}{R^2}$$

ExDim DM in 2 minutes



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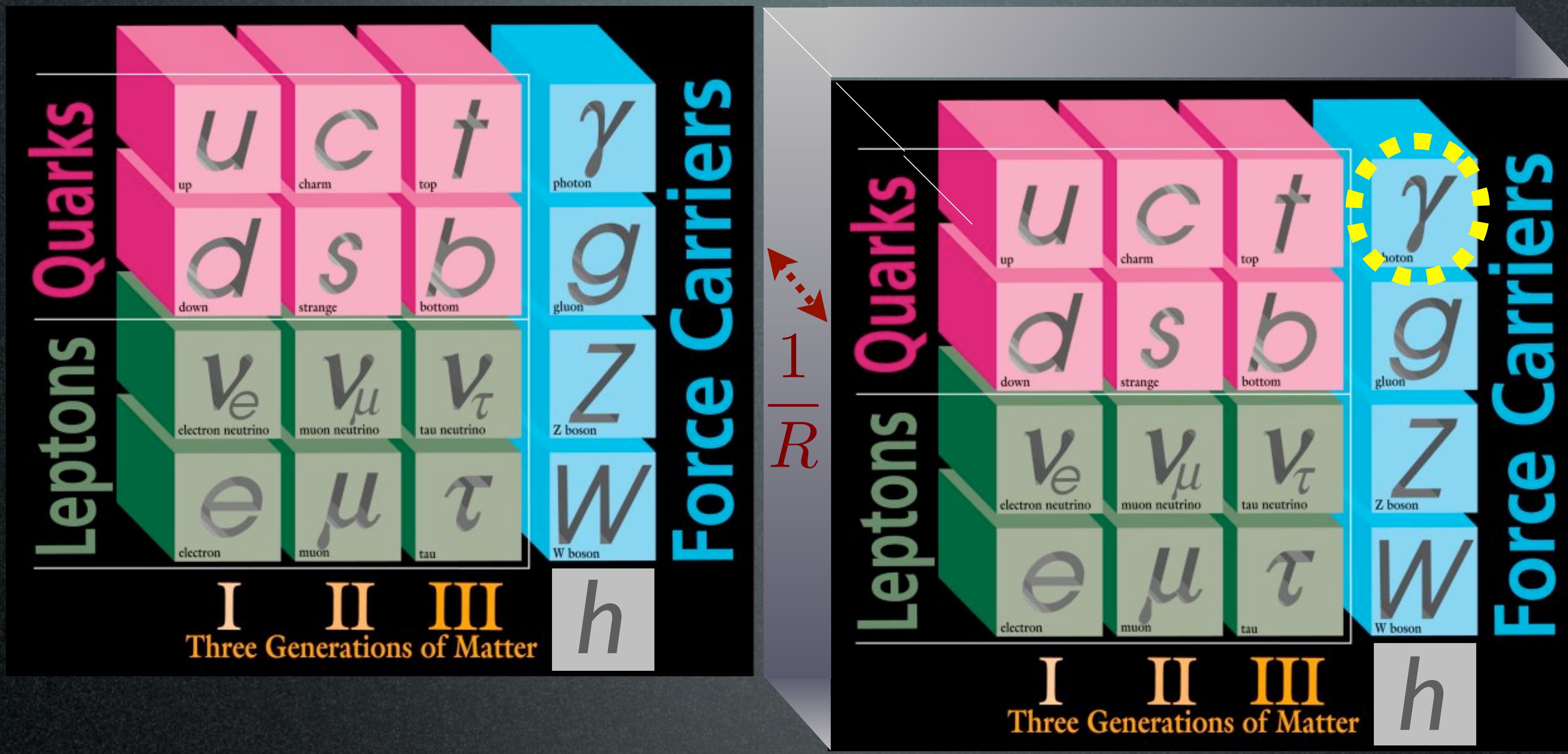

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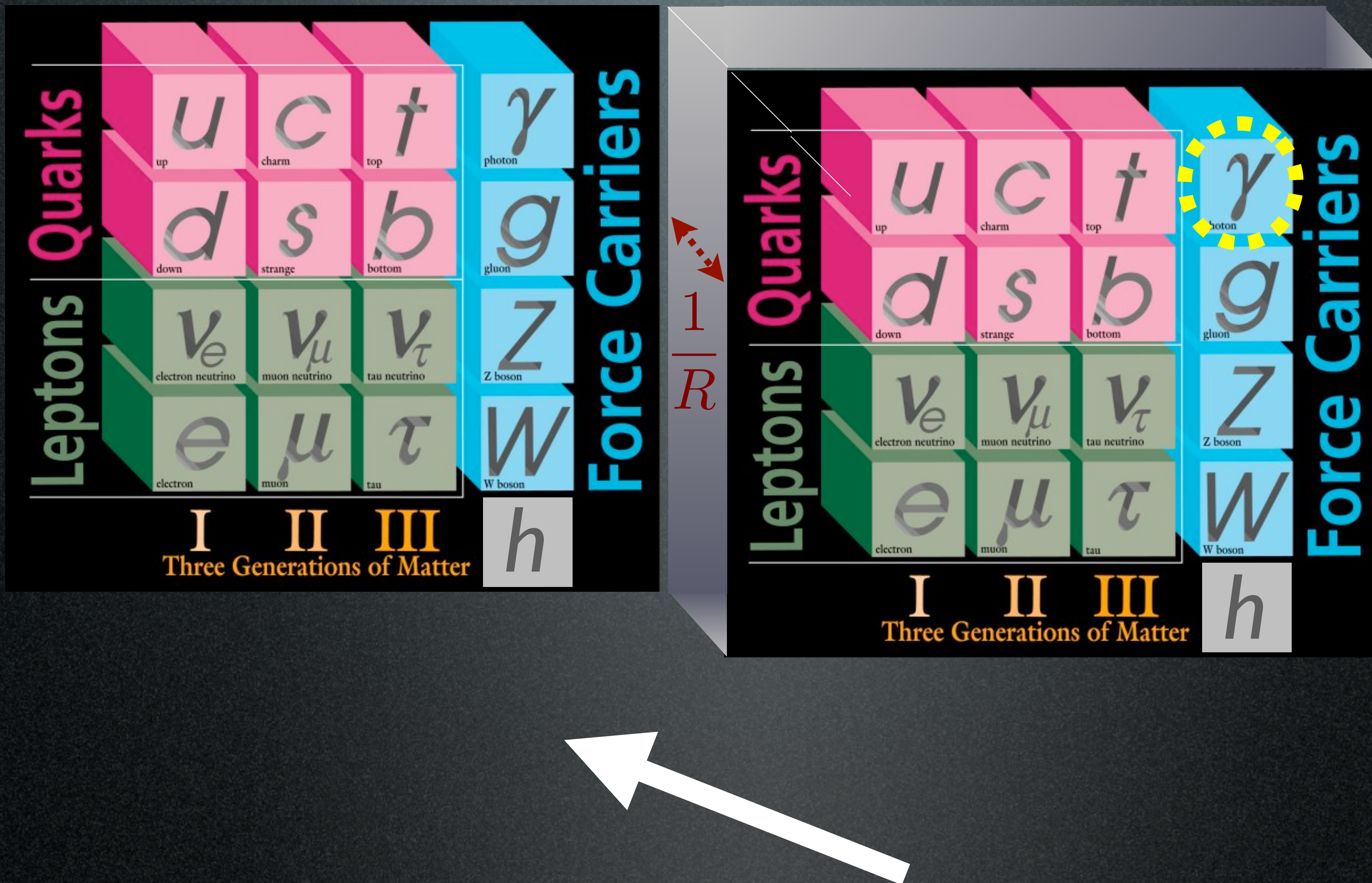

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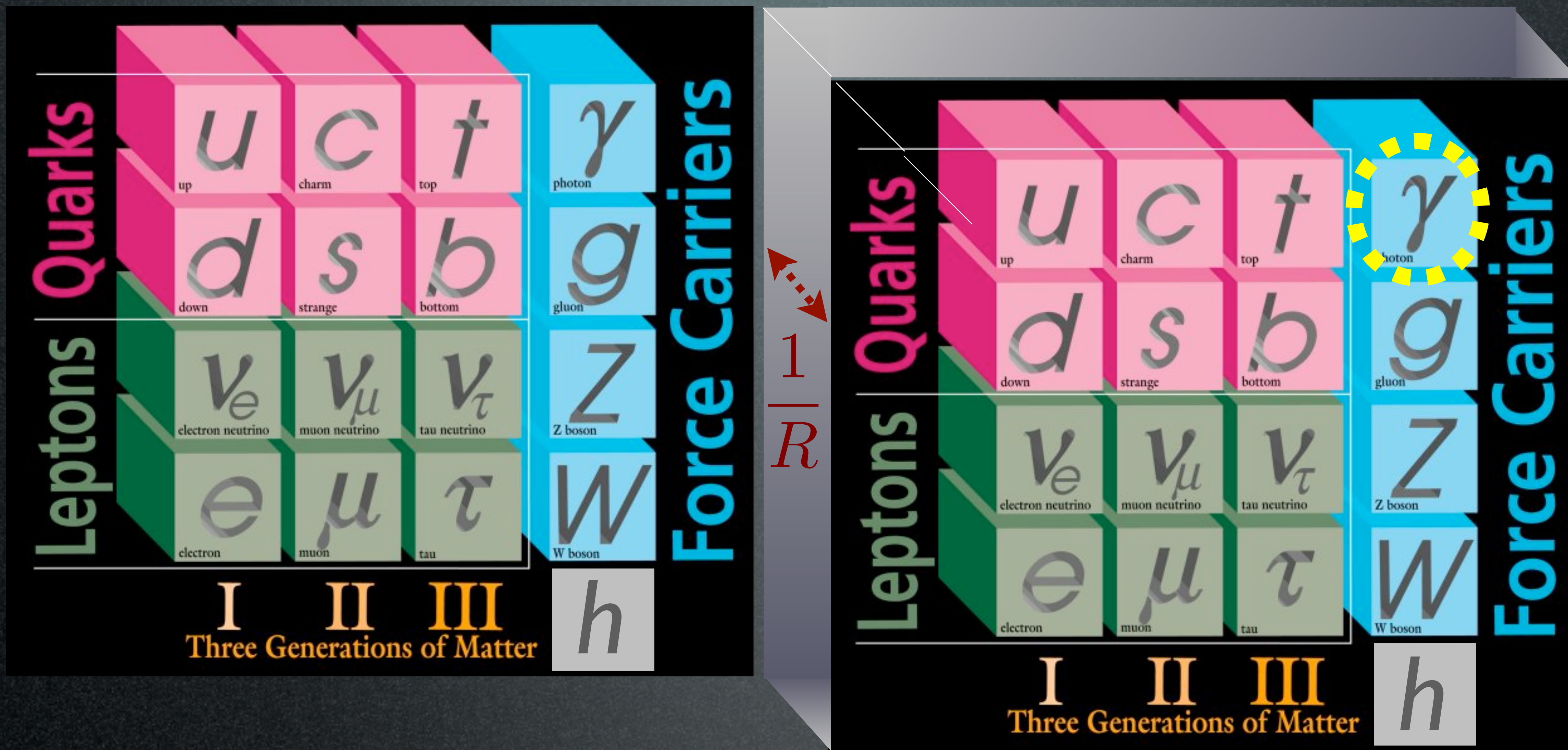

conservation of 5D momentum

(on orbifold boundary conditions, needed to have chiral SM fermions)

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

Scalar singlet DM

On top of the SM, add one extra scalar singlet S
and a symmetry $S \to -S$

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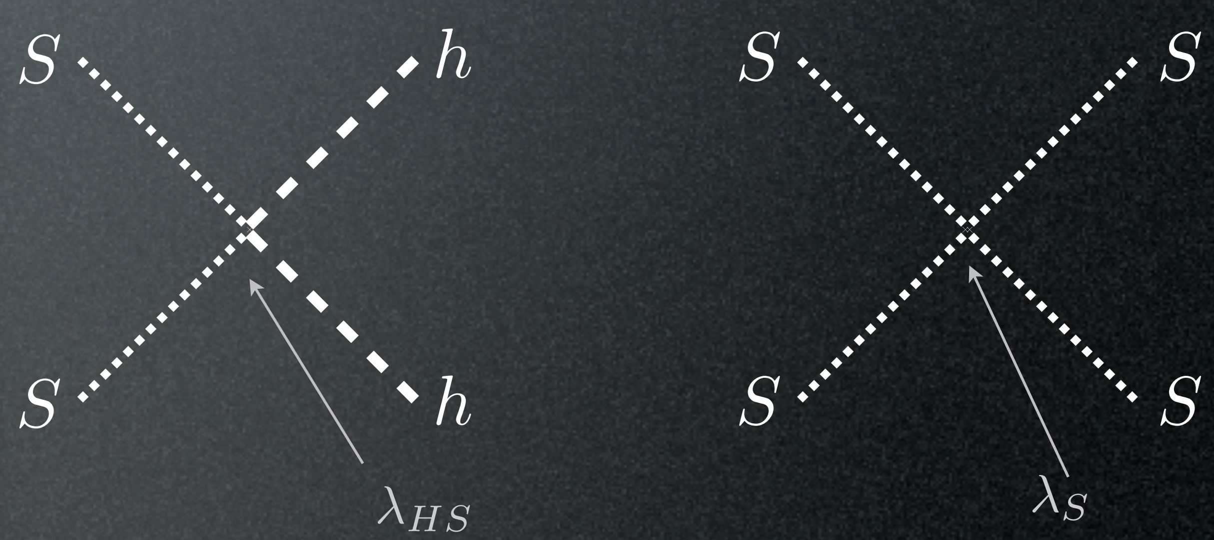
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{|\partial_\mu S|^2}{2} - \frac{m_S^2}{2} S^2 - \lambda_{HS} S^2 |H|^2 - \frac{\lambda_S}{4} S^4$$

parameters are: $m_S, \lambda_{HS}, (\lambda_S)$



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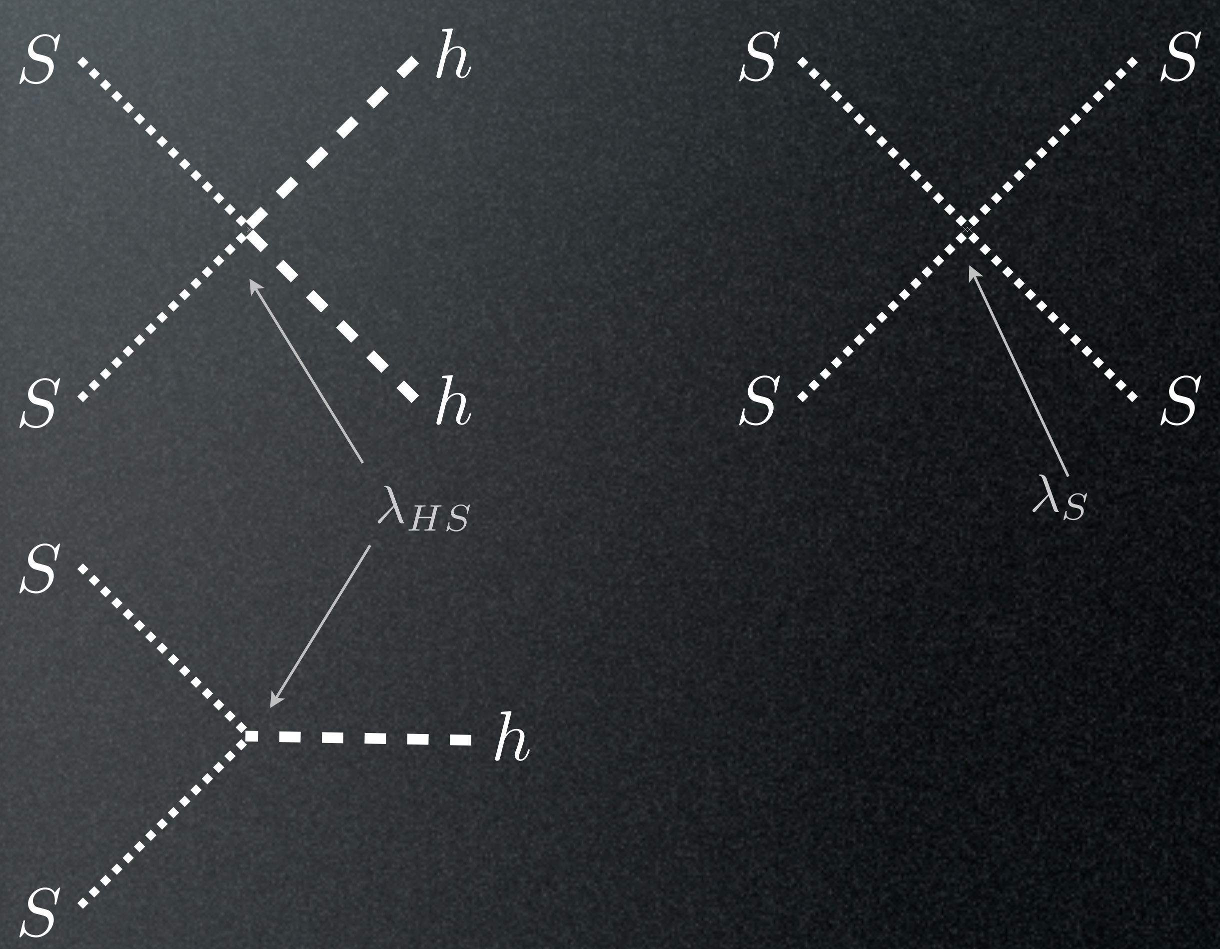

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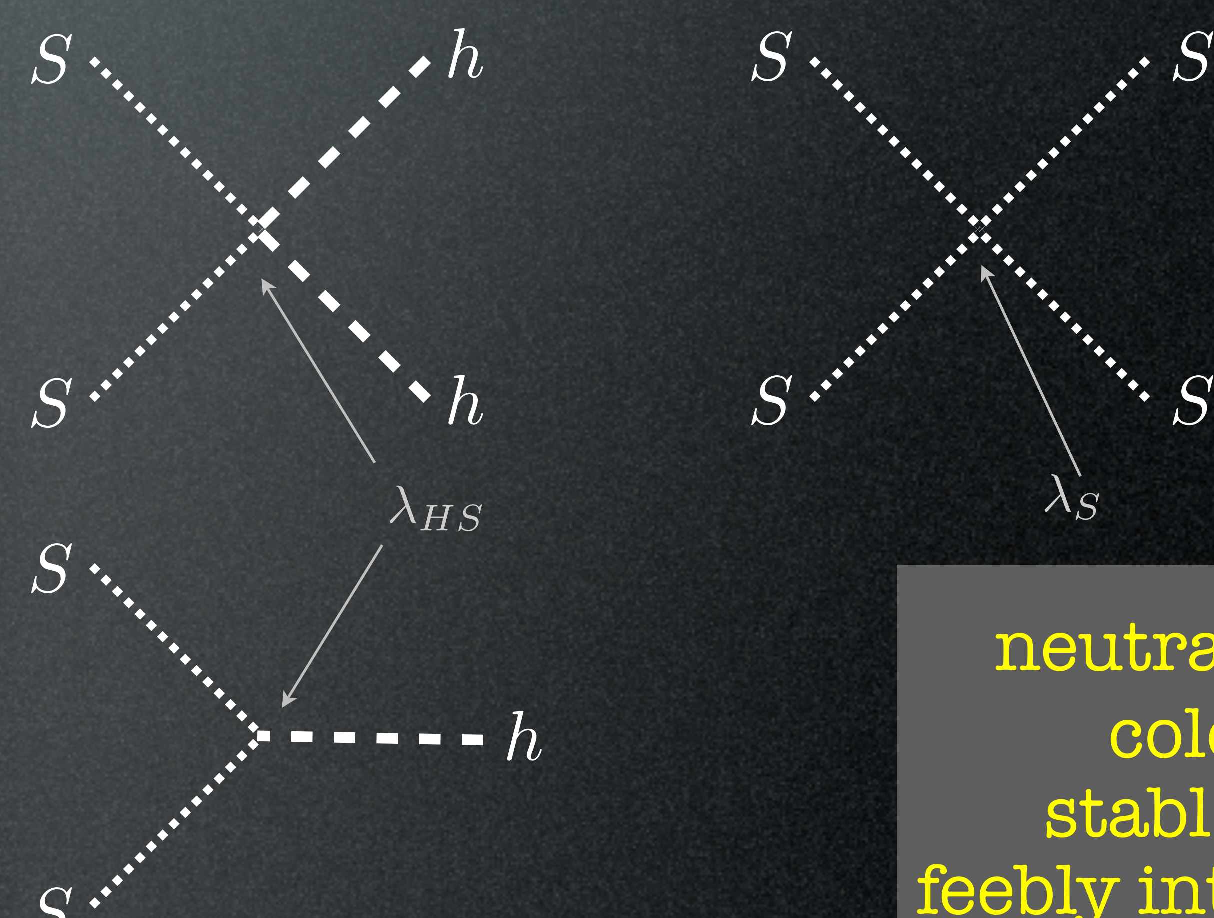

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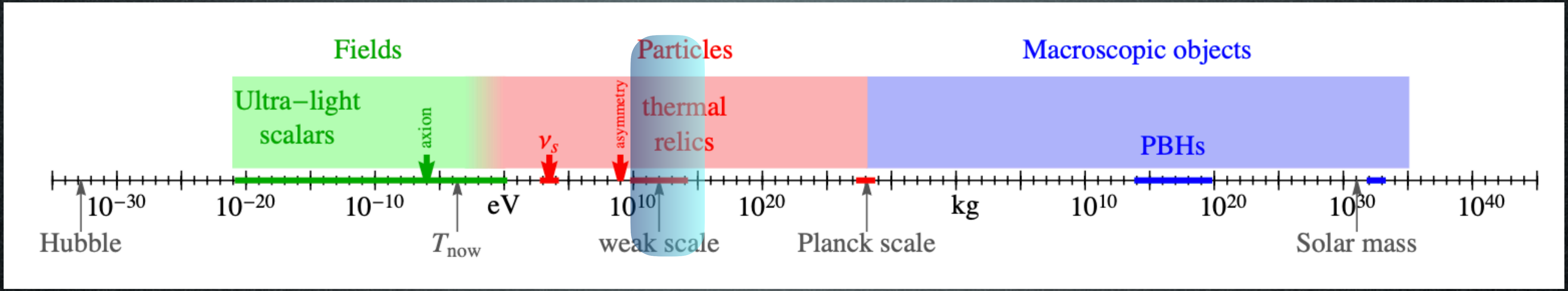
Candidates

A matter of perspective: plausible mass ranges



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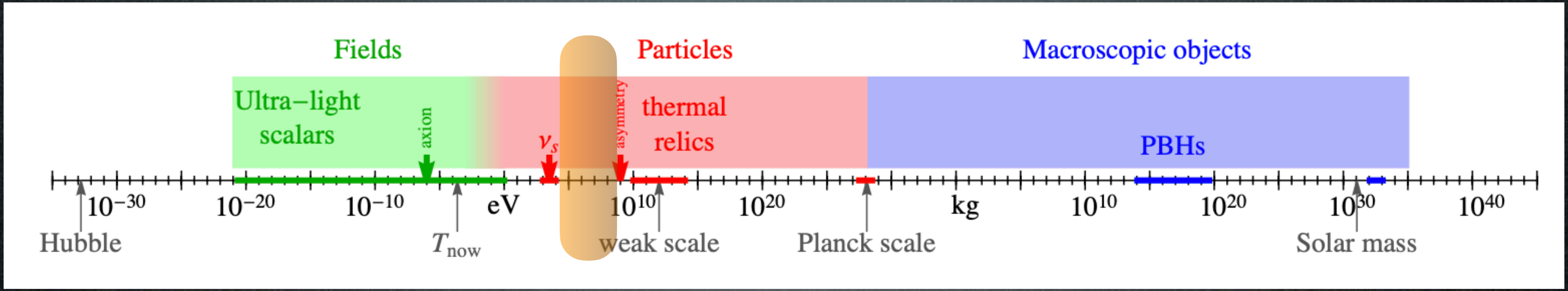

Sub-GeV DM?

Theory

Sub-GeV DM

- 'MeV (scalar) DM'

Boehm & Fayet hep-ph/0305261

In conclusion, scalar Dark Matter particles can be significantly lighter than a few GeV's (thus evading the generalisation of the Lee-Weinberg limit for weakly-interacting neutral fermions) if they are coupled to a new (light) gauge boson or to new heavy fermions F (through non chiral couplings and poten-

Theory

Sub-GeV DM

- WIMPless Dark Matter

Feng & Kumar 0803.4196

a.k.a. hidden sector DM
$\sim$ secluded DM

Theory

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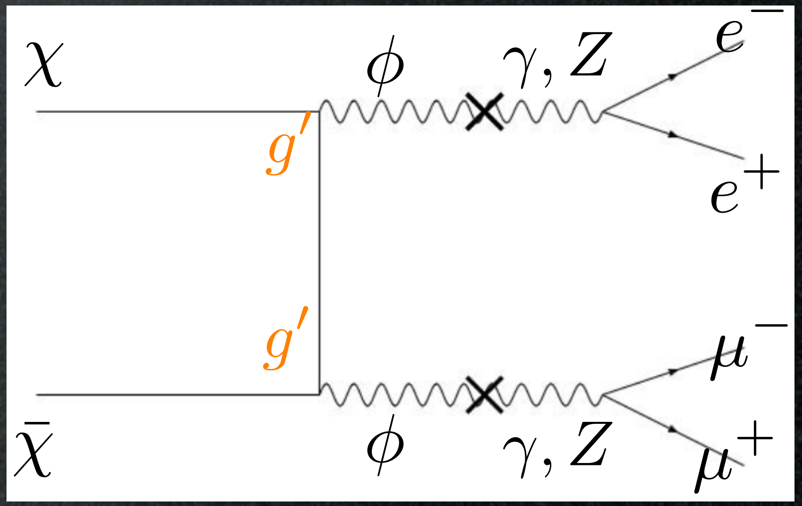
$$\langle\sigma_{\rm ann}v\rangle \approx \frac{\alpha_x^2}{m^2}$$

if g_x is small,
m 'naturally' small
(but nothing points to a precise value)



Production mechanism:
just thermal freeze-out
of these annihilations

Theory

Sub-GeV DM

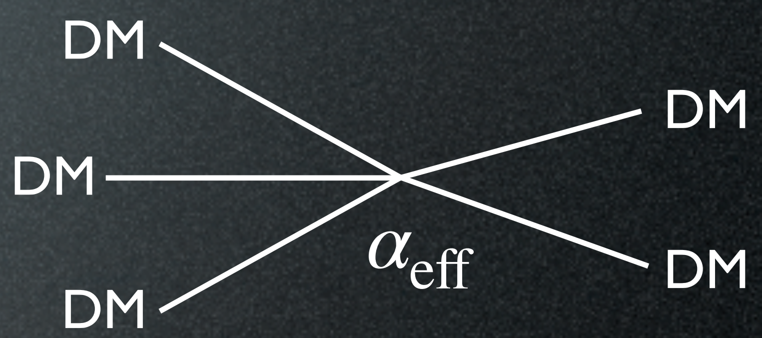
- ‘SIMP miracle’:

scalar DM with relic abundance set by 3 -> 2 processes

points to

$$m_{\rm DM} \sim \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100 \text{ MeV}$$

Hochberg et al 1402.5143



‘naturally realized’ in a dark-QCD-like setup

$$\alpha_{\rm eff} = \mathcal{O}(1) \quad \text{i.e.} \quad g_x \sim 4\pi$$

Theory

Sub-GeV DM?

- WIMPless Dark Matter
- ‘SIMP miracle’
- Asymmetric DM
- ‘MeV (scalar) DM’ (Integral 511 KeV excess)
- ‘simplified (light) DM models’
- …

Theory

Sub-GeV DM?

Why not!

- WIMPless Dark Matter
- 'SIMP miracle'
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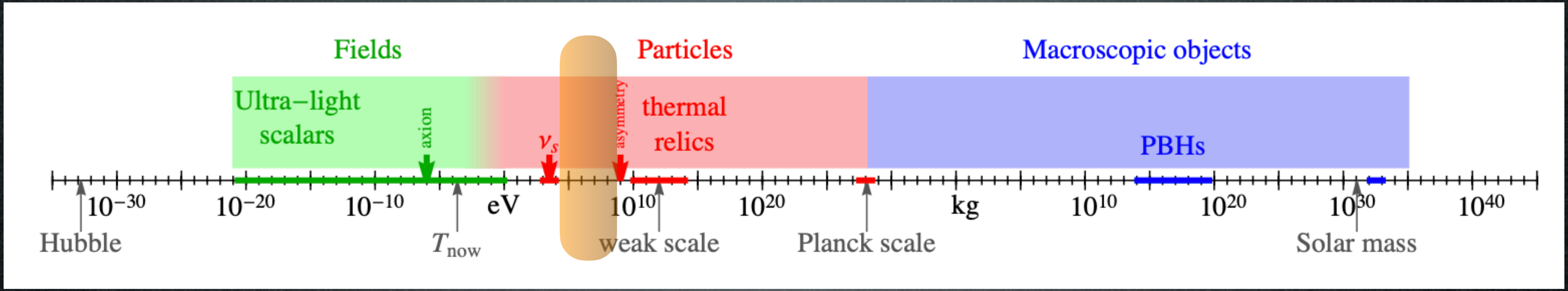

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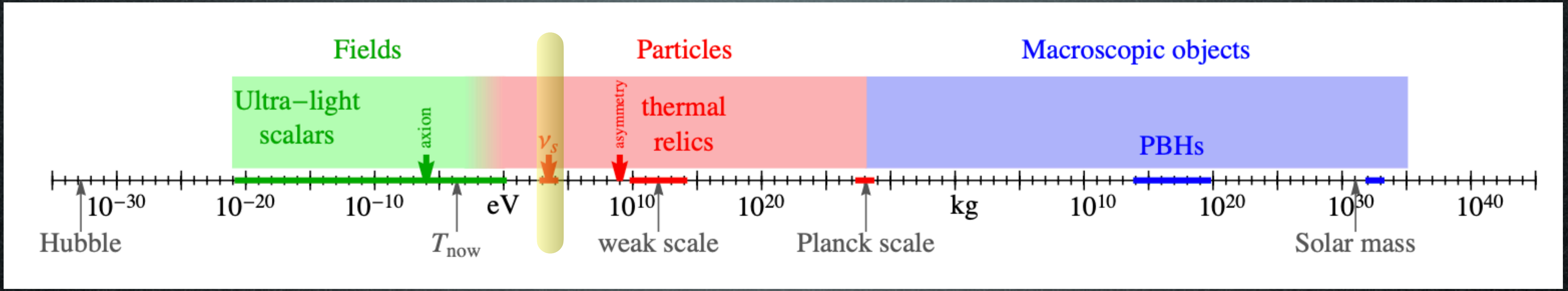


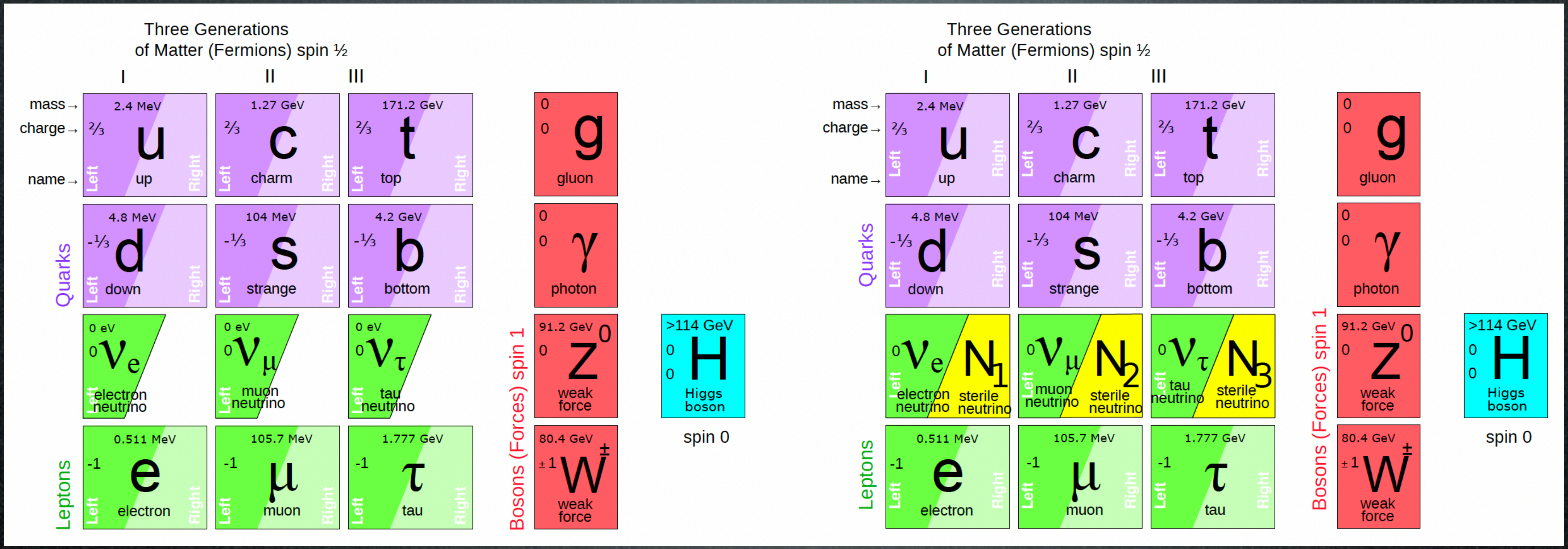
KeV DM

Sterile neutrinos

Sterile neutrinos

Theoretically 'motivated':

one can complete the SM lepton sector



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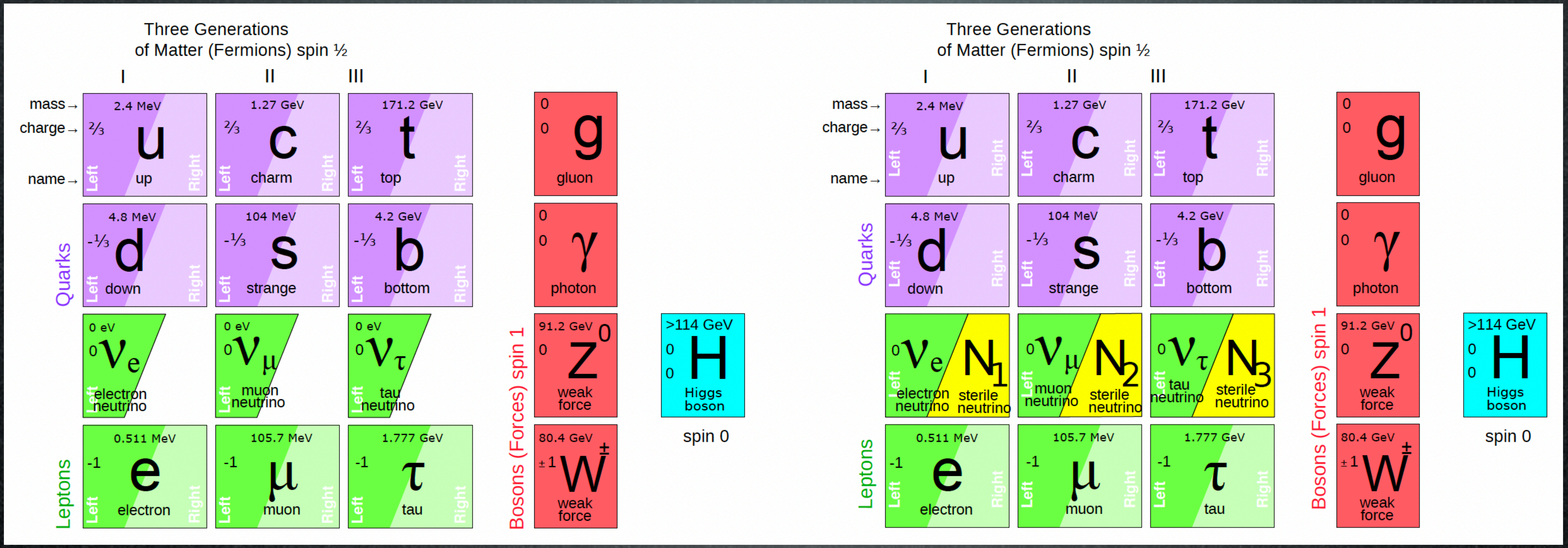

$m_\nu \gtrsim$ few KeV to be cold enough

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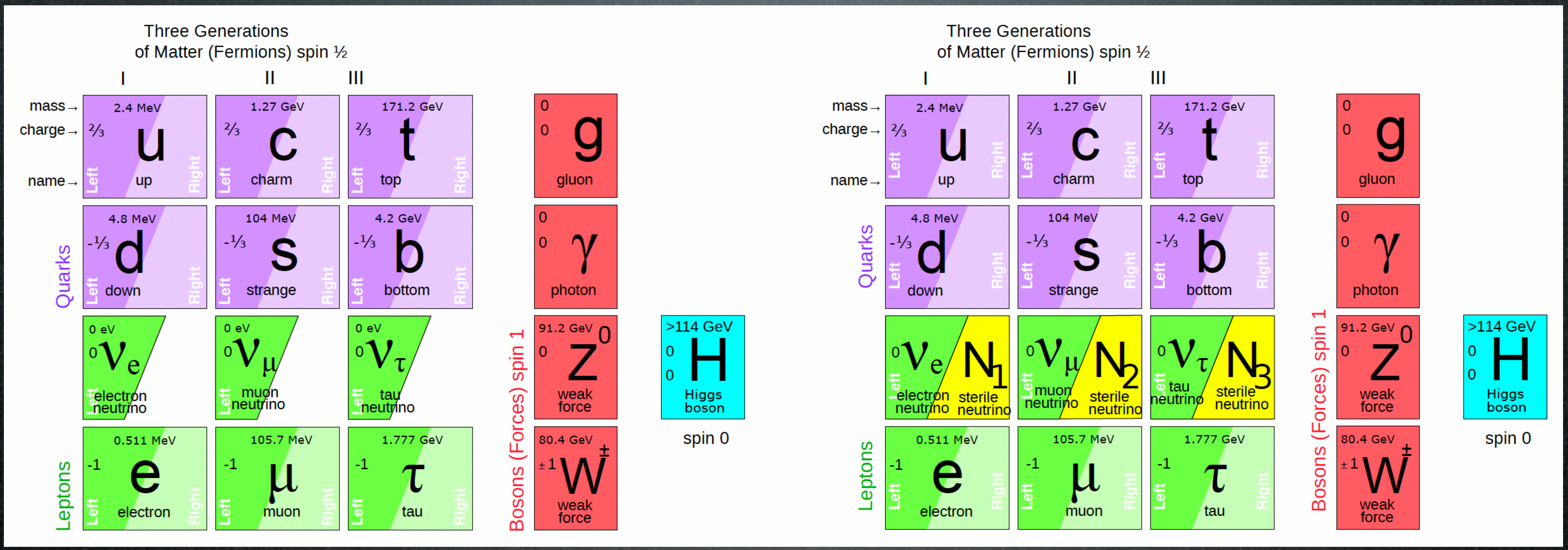

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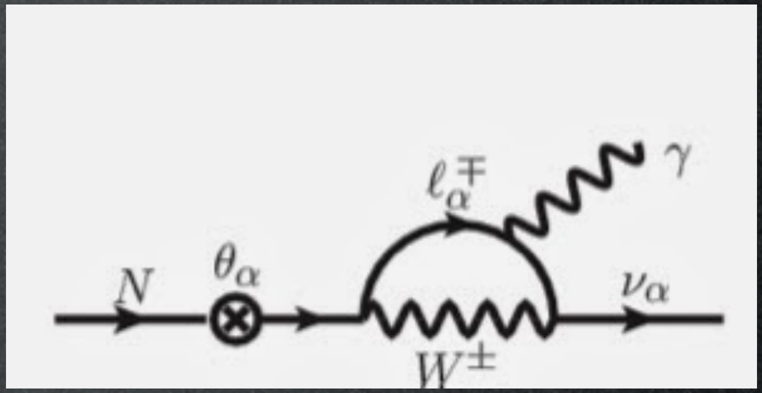
Sterile neutrino decay



X-ray line

Bulbul et al., 1402.2301

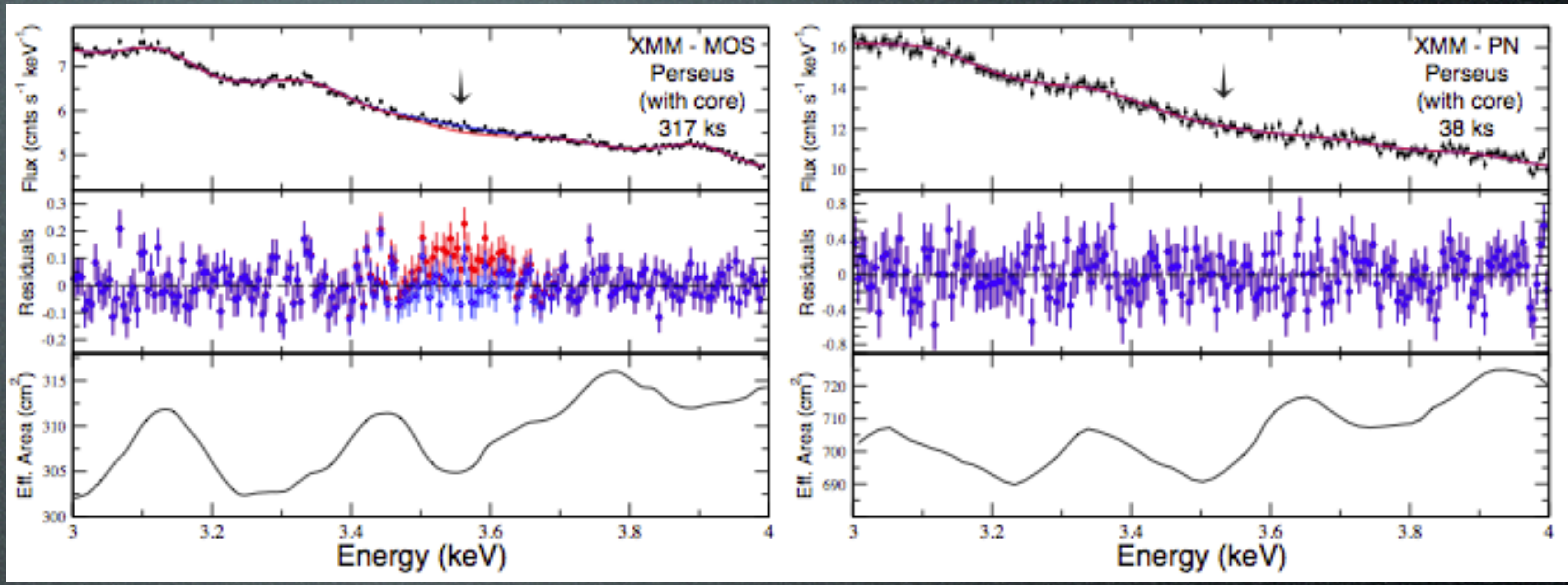
3.55 - 3.57 ± 0.03 KeV

73 clusters

(Chandra & XMM-Newton)

z = 0.01 - 0.35

$\gtrsim 4\sigma$



Boyarsky, Ruchayskiy, 1402.4119

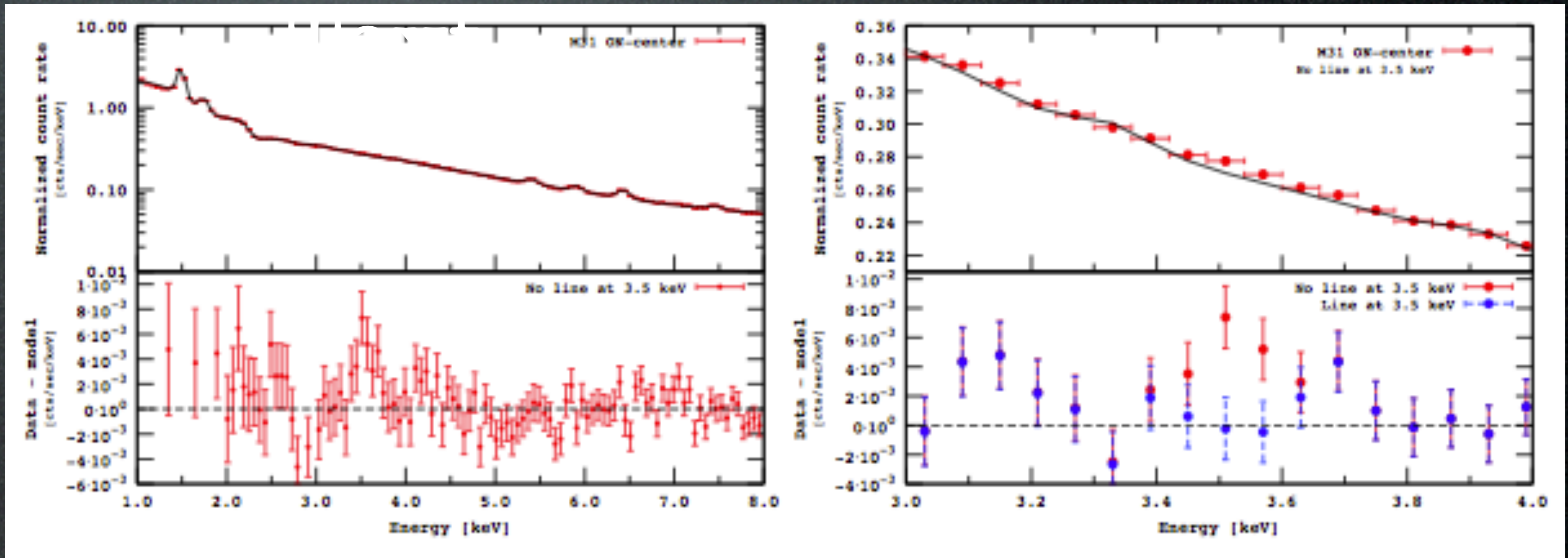
3.5 KeV

Andromeda galaxy + Perseus cluster

(XMM-Newton)

z = 0 and 0.0179

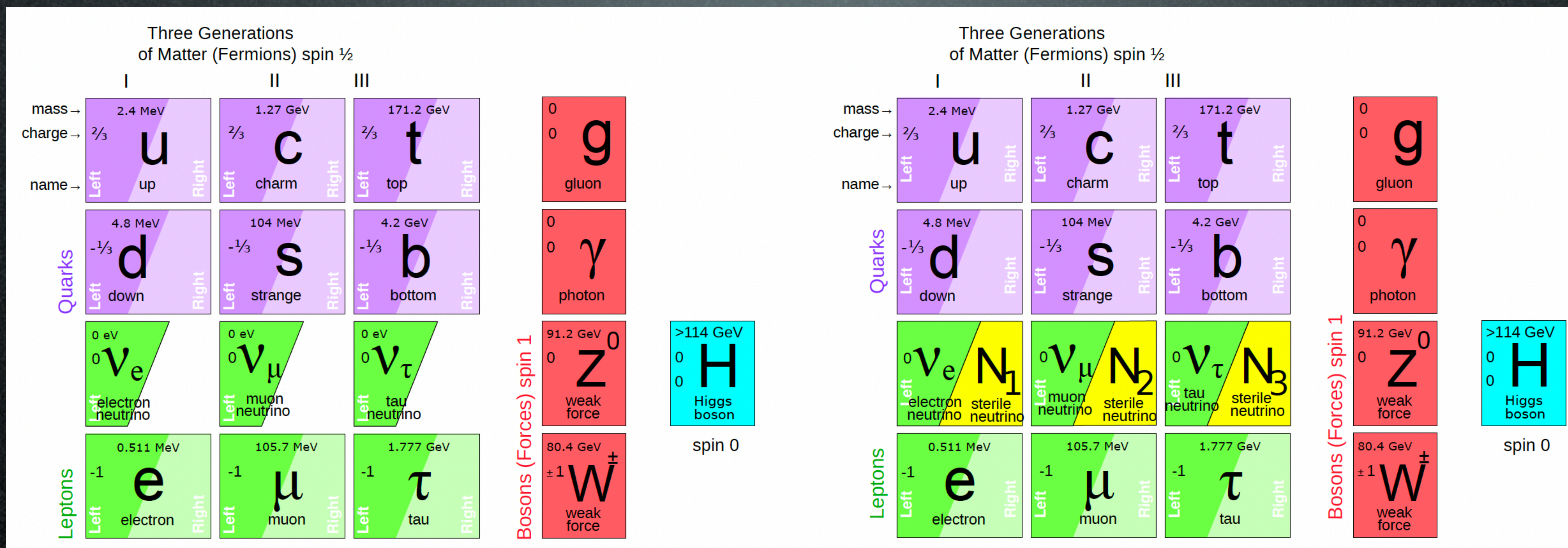
4.4σ



Sterile neutrinos

Theoretically 'motivated':

one can complete the SM lepton sector



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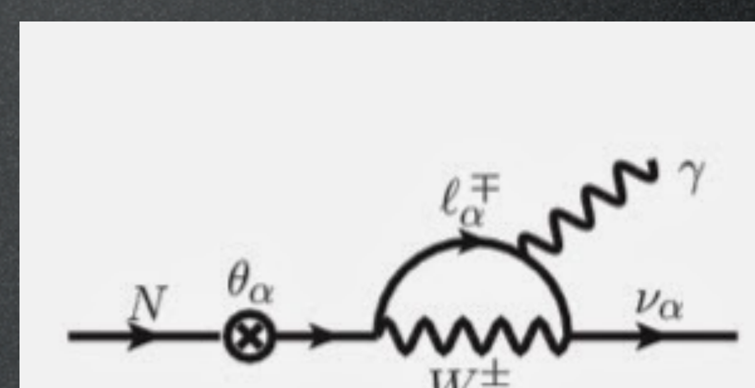
Sterile neutrino decay

$m_\nu = 7.1$ KeV

$\tau \simeq 10^{29}$ sec

$\sin^2 2\theta \sim$ few 10^{-11}



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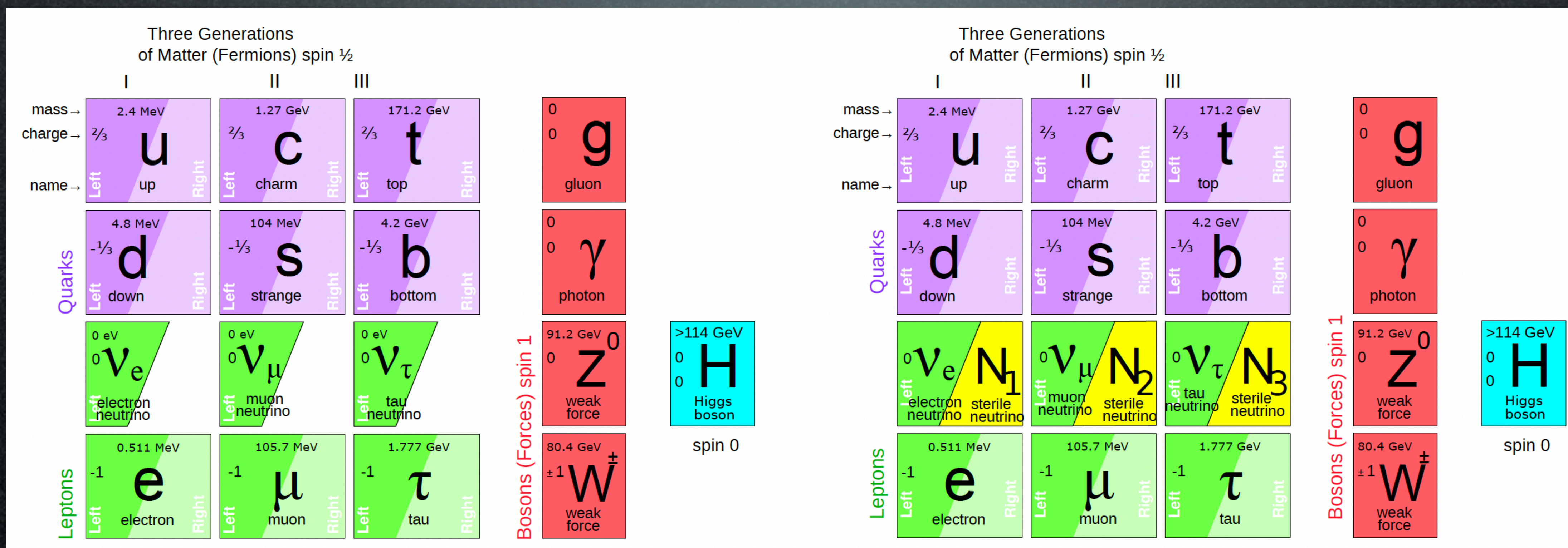

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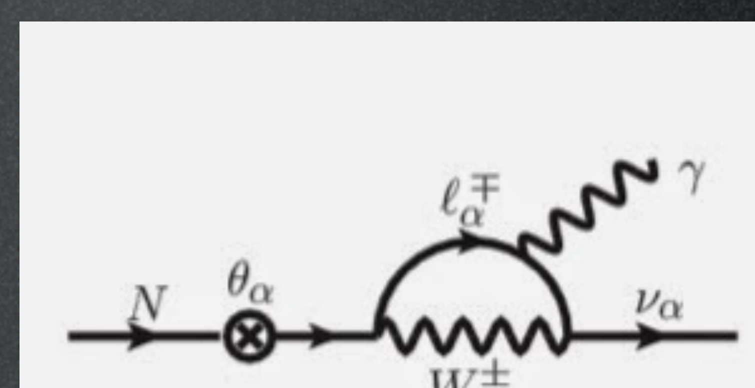
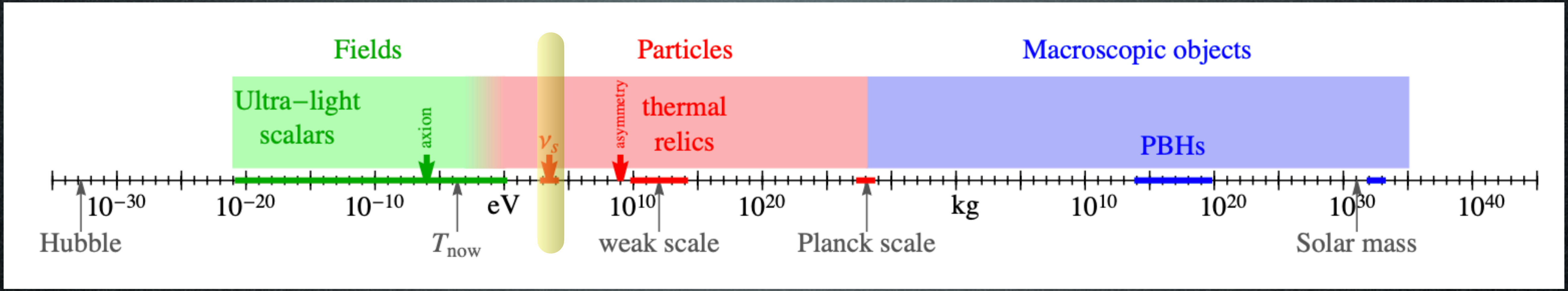


neutral ☑
cold ☑
stable ☑
feebly int. ☑

Candidates

A matter of perspective: plausible mass ranges



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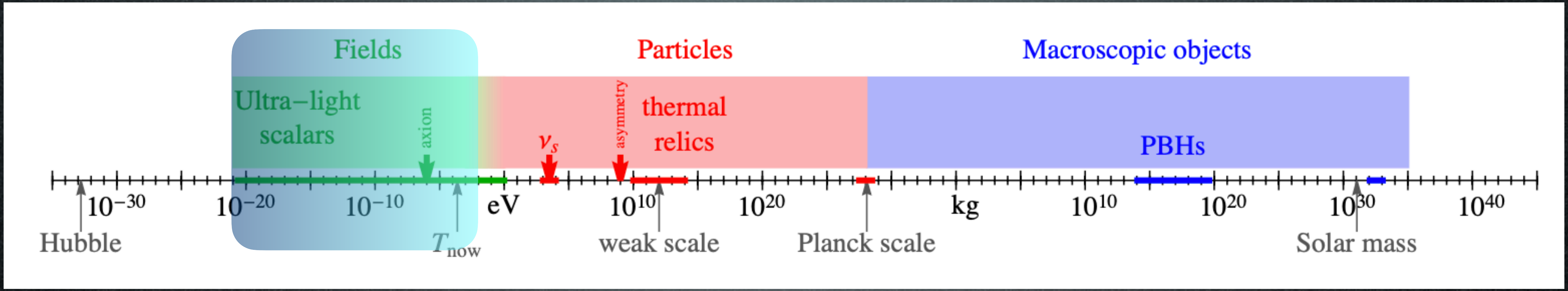

Ultralight DM

Axions

Axions

Theoretically motivated:

one can add to the SM $\mathscr{L} = \mathscr{L}_{\mathrm{SM}} - \theta \frac{g_3^2}{64\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}$

$$\left(\tilde{G}^a_{\mu\nu} \equiv \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} G^a_{\alpha\beta} \right)$$

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Perhaps because θ is dynamical (a field)

and driven to (almost) zero by its potential (symmetrical under $U(1)_{PQ}$).

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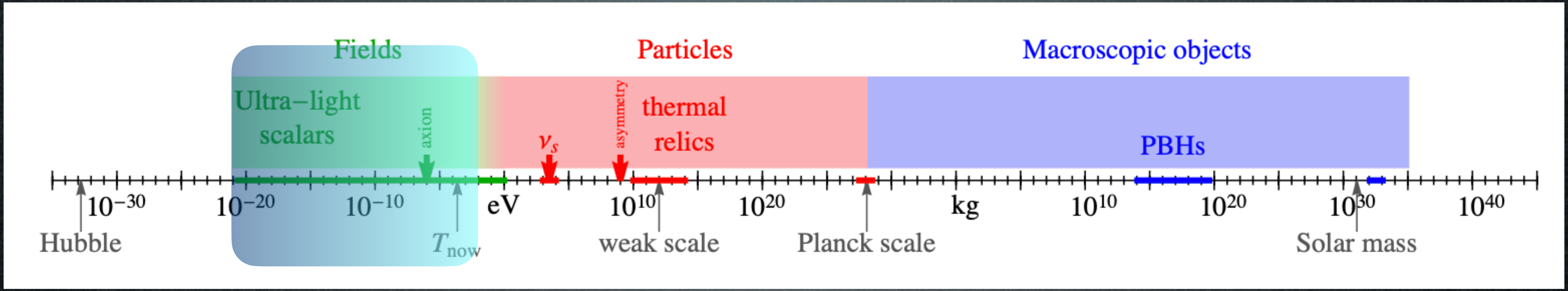

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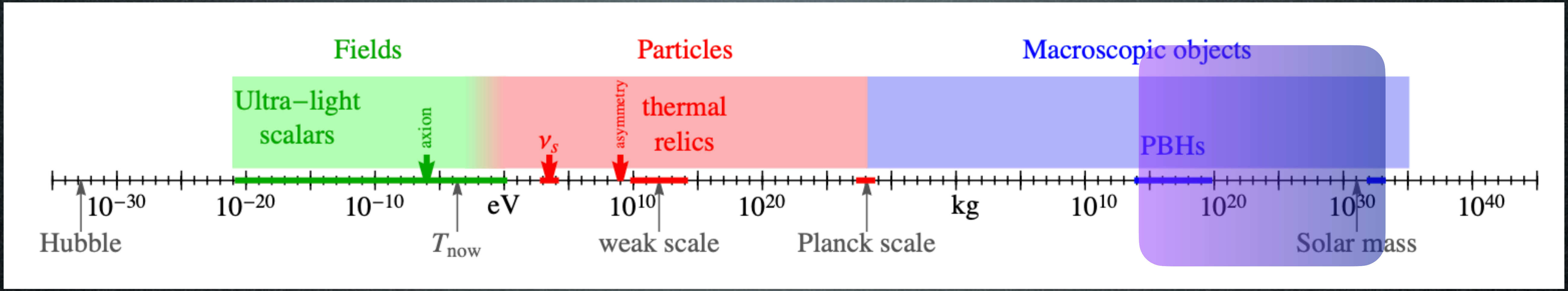

PBH DM

Primordial Black Holes

DM can **NOT** be:

an astro *je ne sais pas quoi*:

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- brown dwarves

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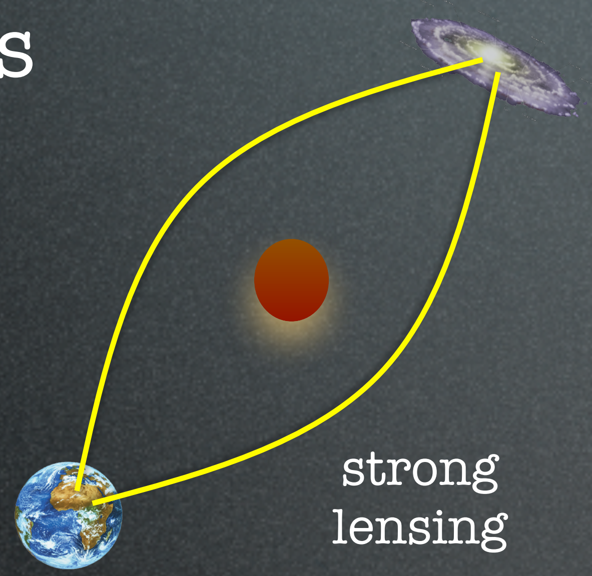
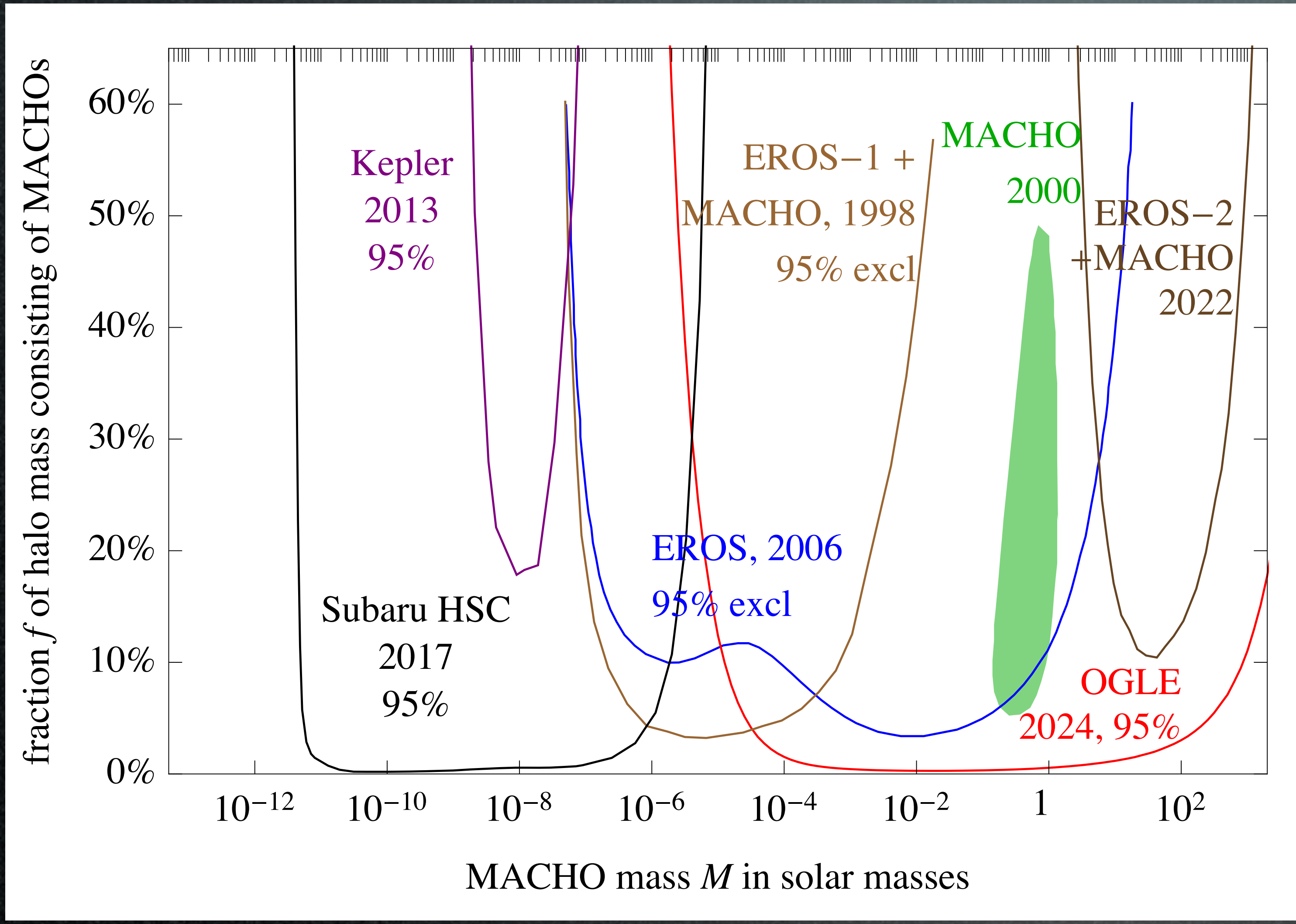


MACHOs or PBHs as DM



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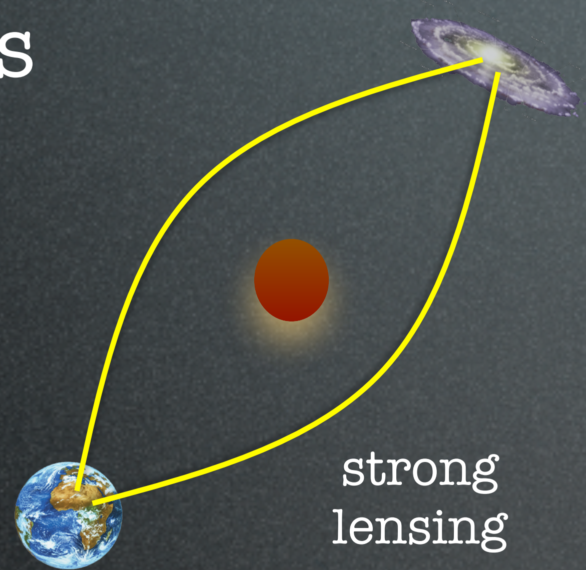

a baryon of the SM:

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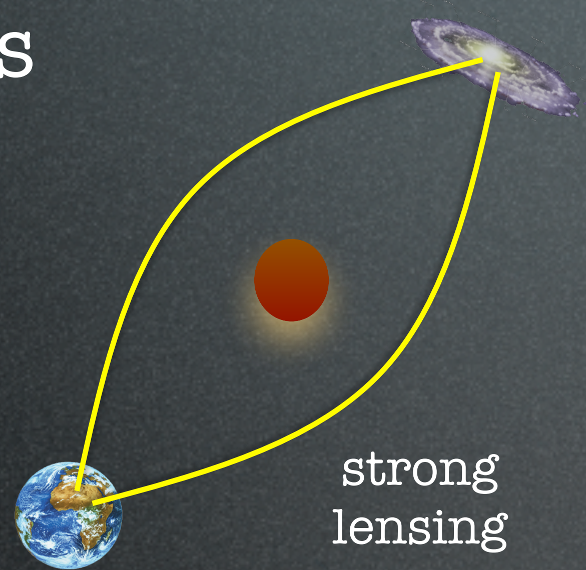

a baryon of the SM:

- BBN computes the abundance of He in terms of primordial baryons: too much baryons => Universe full of Helium
- CMB says baryons are 4% max

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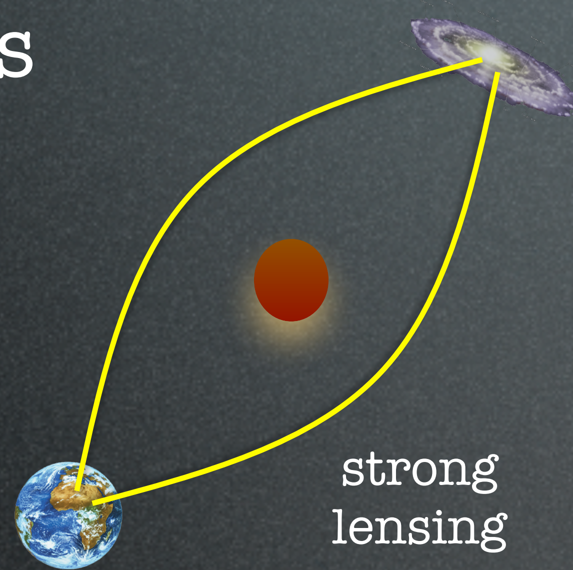

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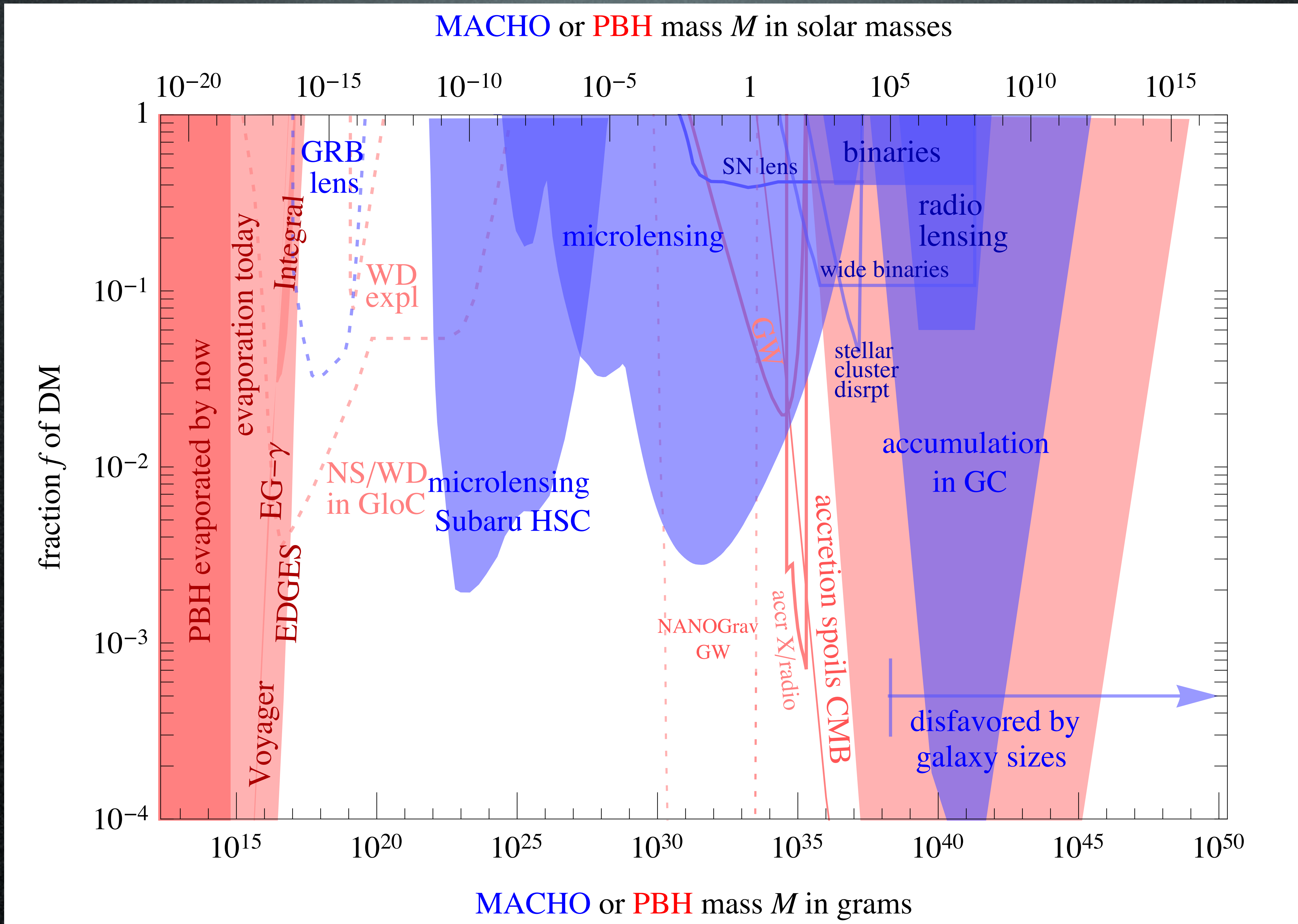
A loophole: Primordial Black Holes!

- produced before BBN
- with masses too small/large to lens
- perhaps GW observatories are seeing them?

PBHs as DM

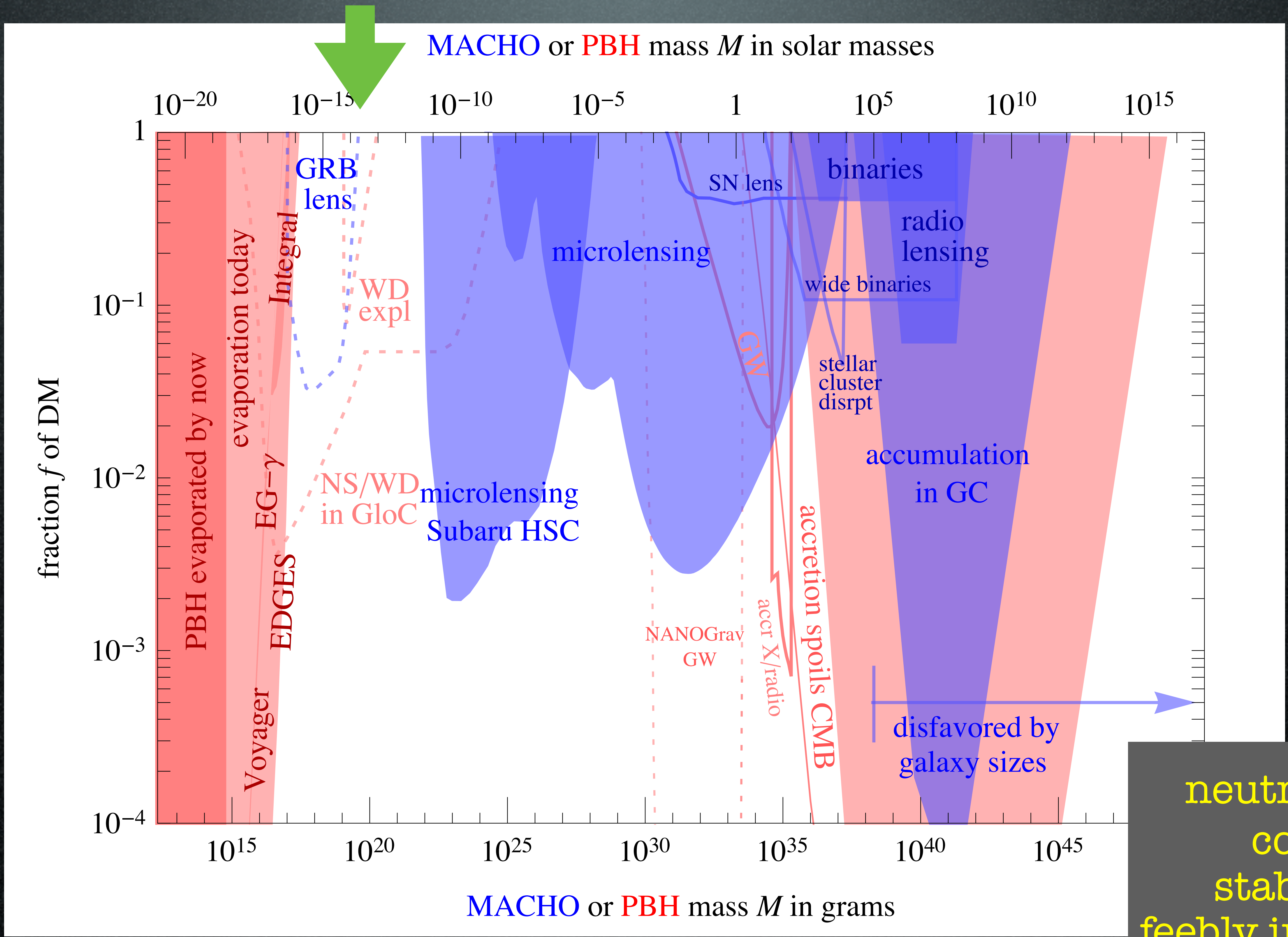
huge range of sizes: $M \simeq 10^{15}(t/10^{-23}\ \text{sec})\ \text{g}$ (with many constraints)



M. Cirelli, A. Strumia, J. Zupan 2406.01705

PBHs as DM

window still open?



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PBHs as DM

Constraints on Primordial Black Holes

DM could consist of PBHs

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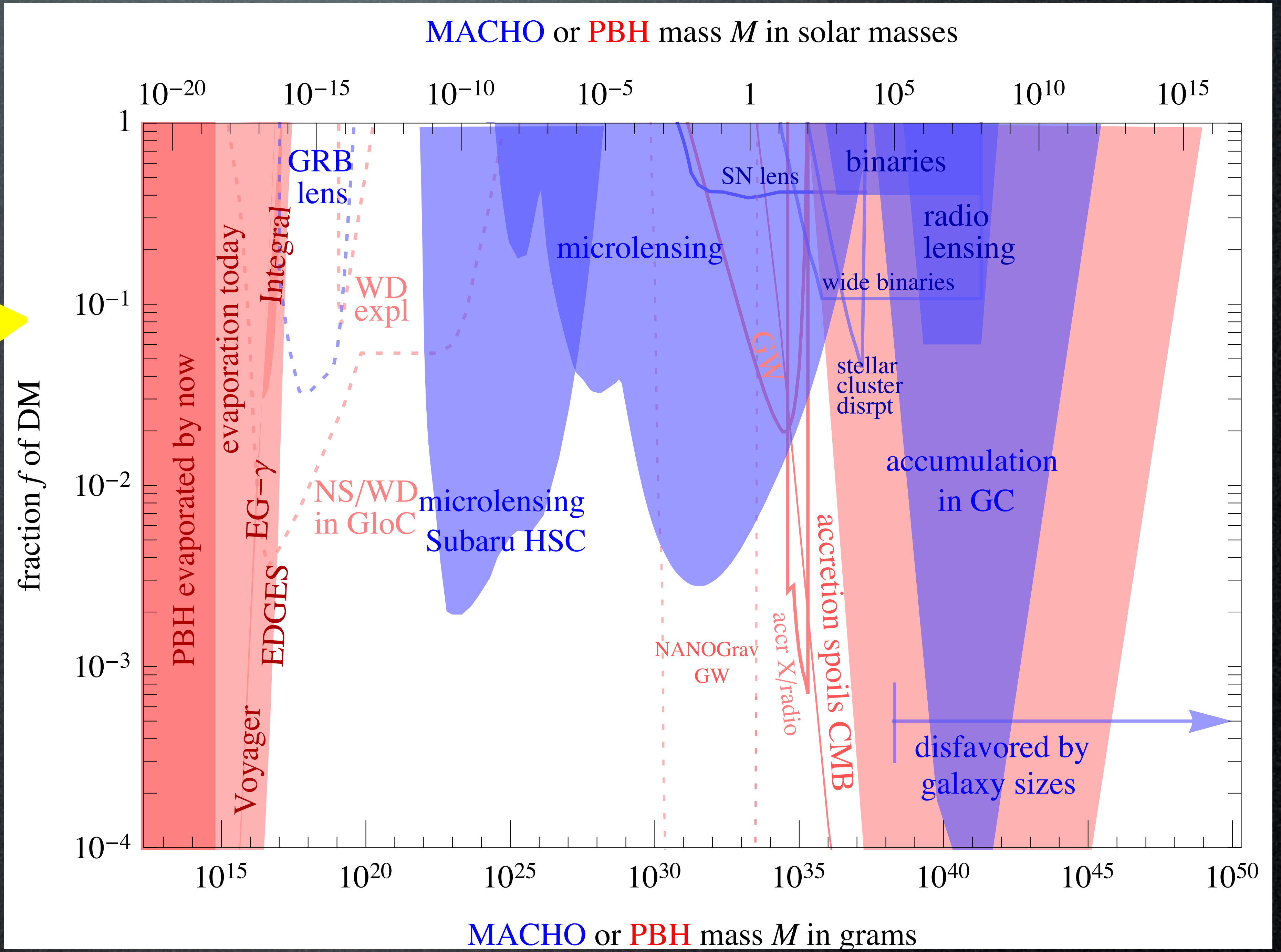

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'small' PBHs emit today by Hawking evaporation

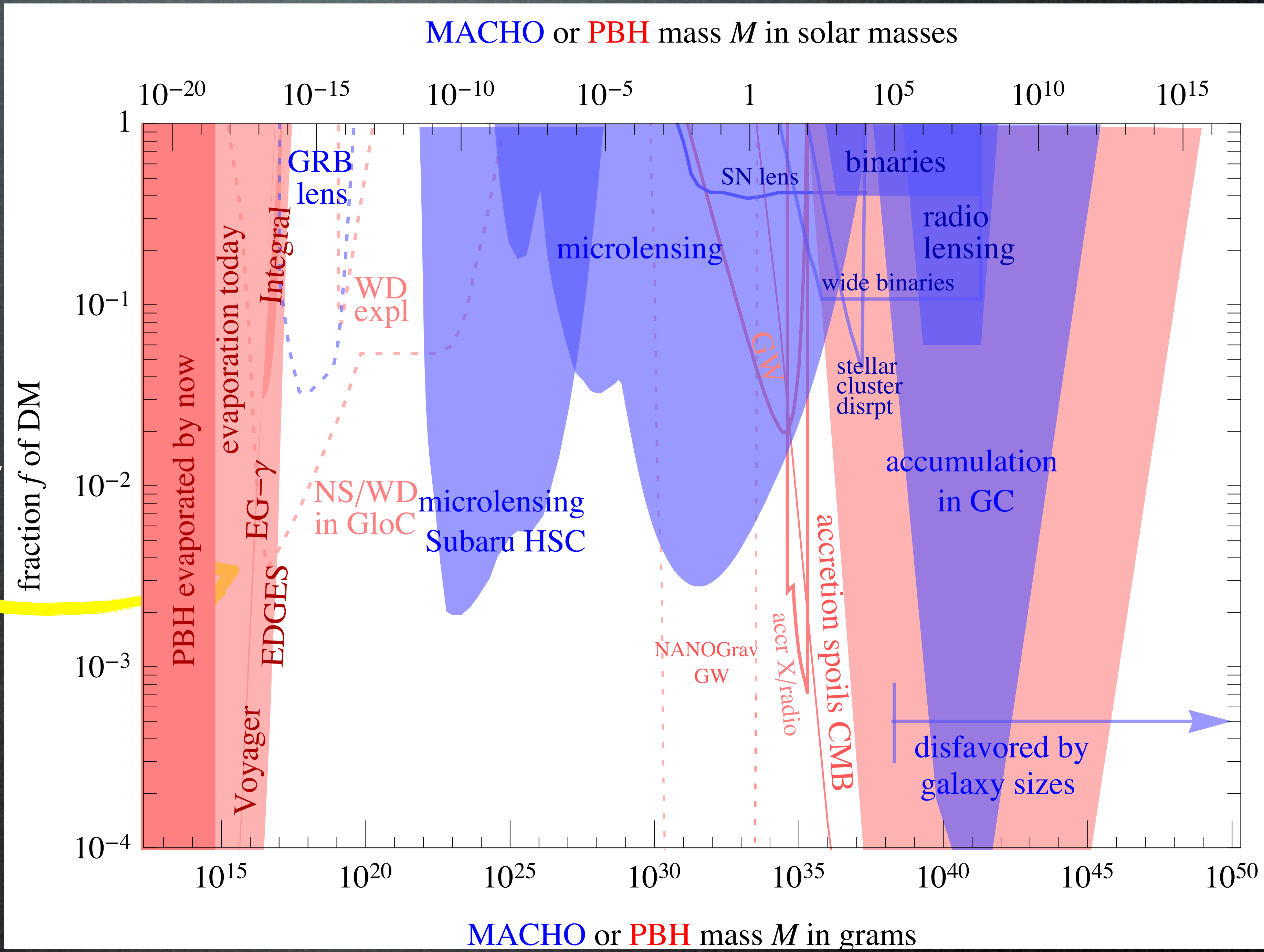
$$T = \frac{1}{8\pi\, G_N M}$$

rate

$$\frac{dM}{dt} \simeq -5\times 10^{25}\, f(M) \left(\frac{\text{g}}{M}\right)^2 \text{g/s}$$

spectrum

$$\frac{dN}{dt\, dE} = \frac{27}{2\pi}\frac{G^2M^2E^2}{e^{E/T}+1}$$



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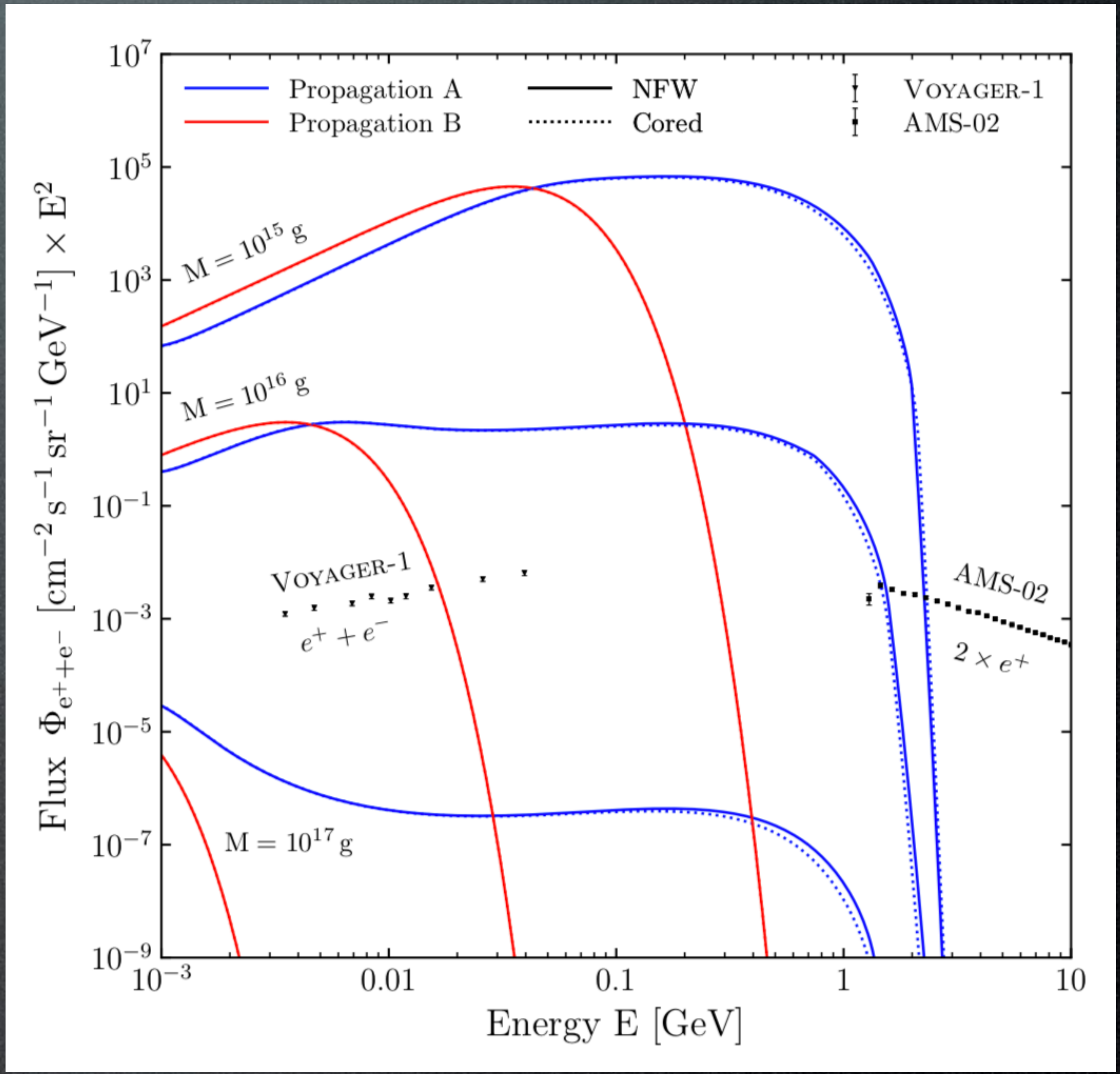

Boudaud, Cirelli 1807.03075, PRL 122 (2019)

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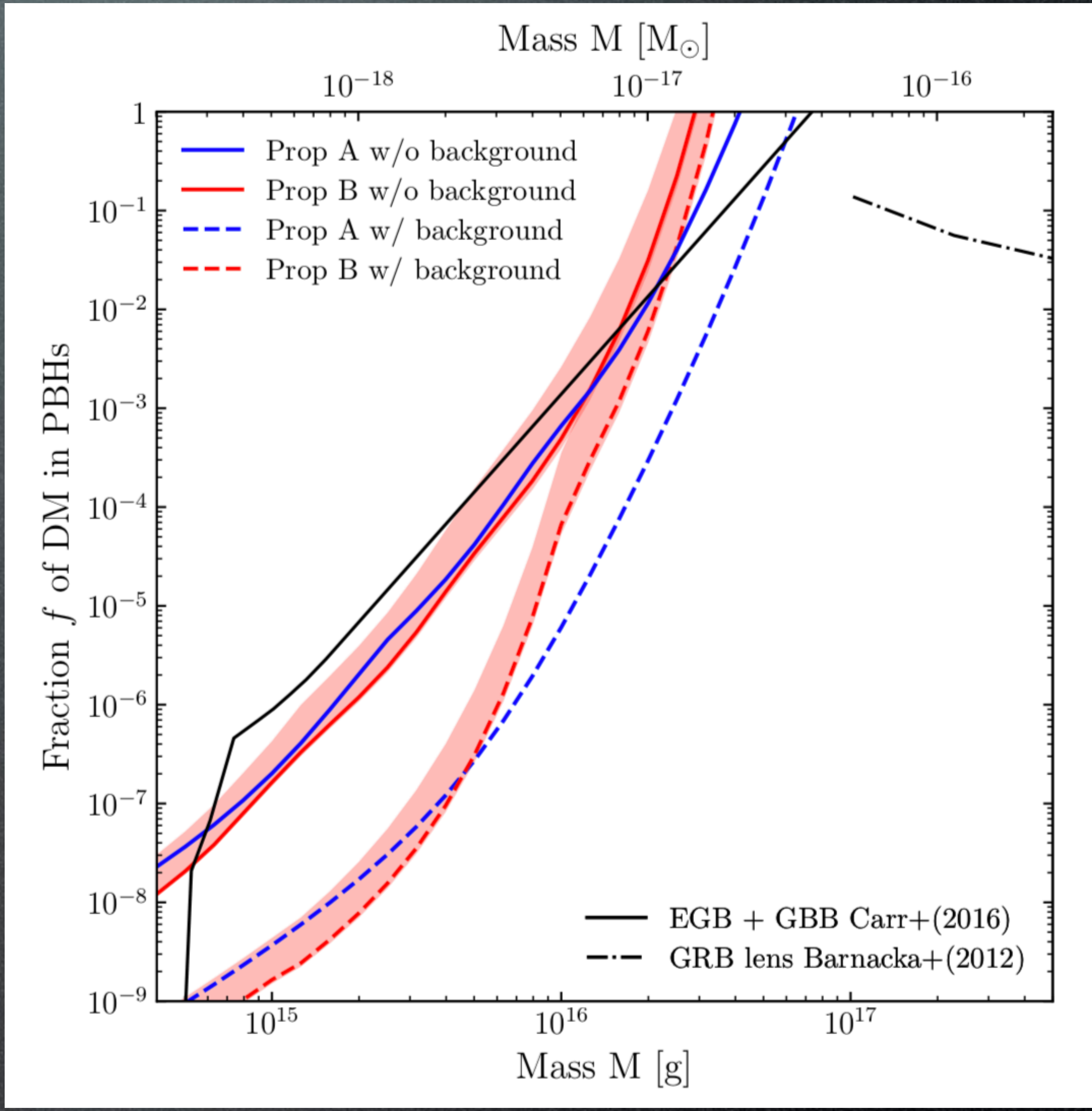

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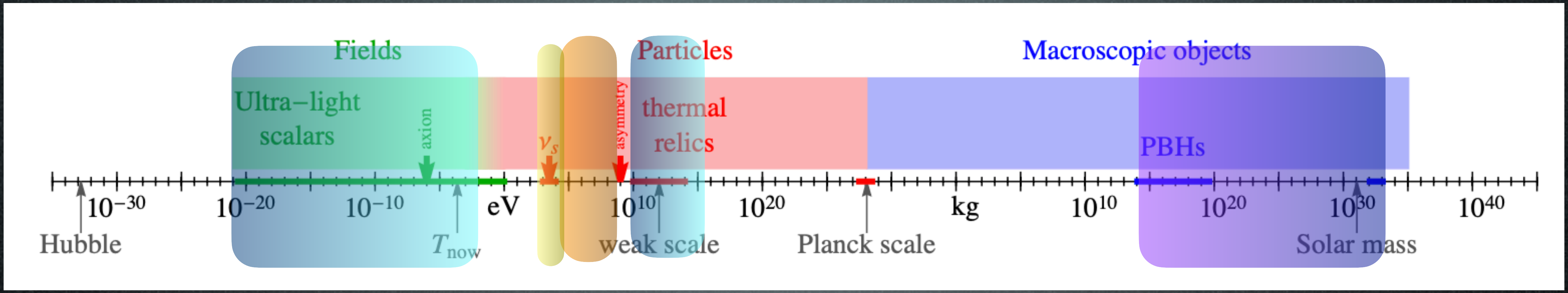
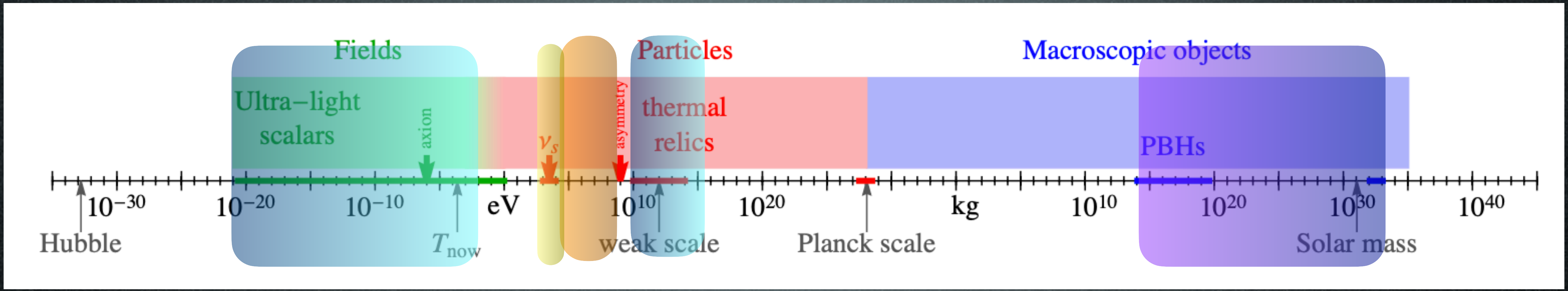
Candidates recap



90 orders of magnitude!

Candidates recap



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neutral ☐
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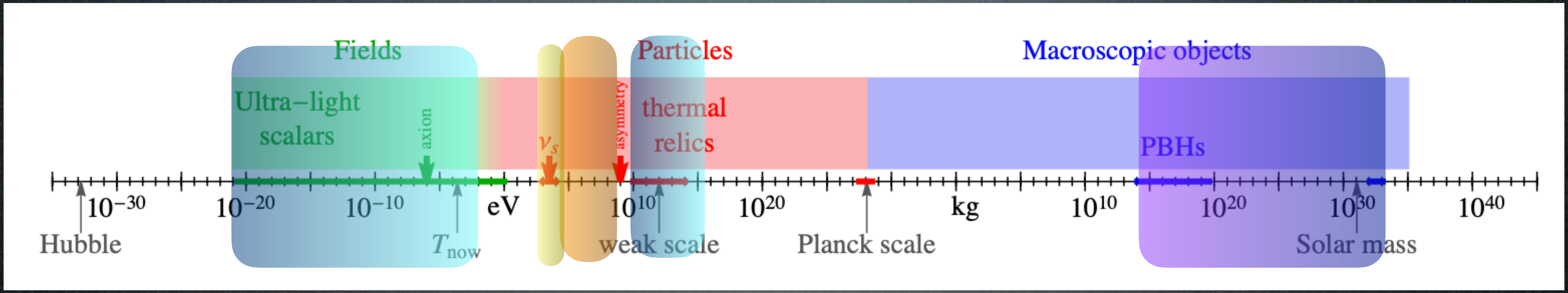
Basic concept: add **something** to the SM

Candidates recap



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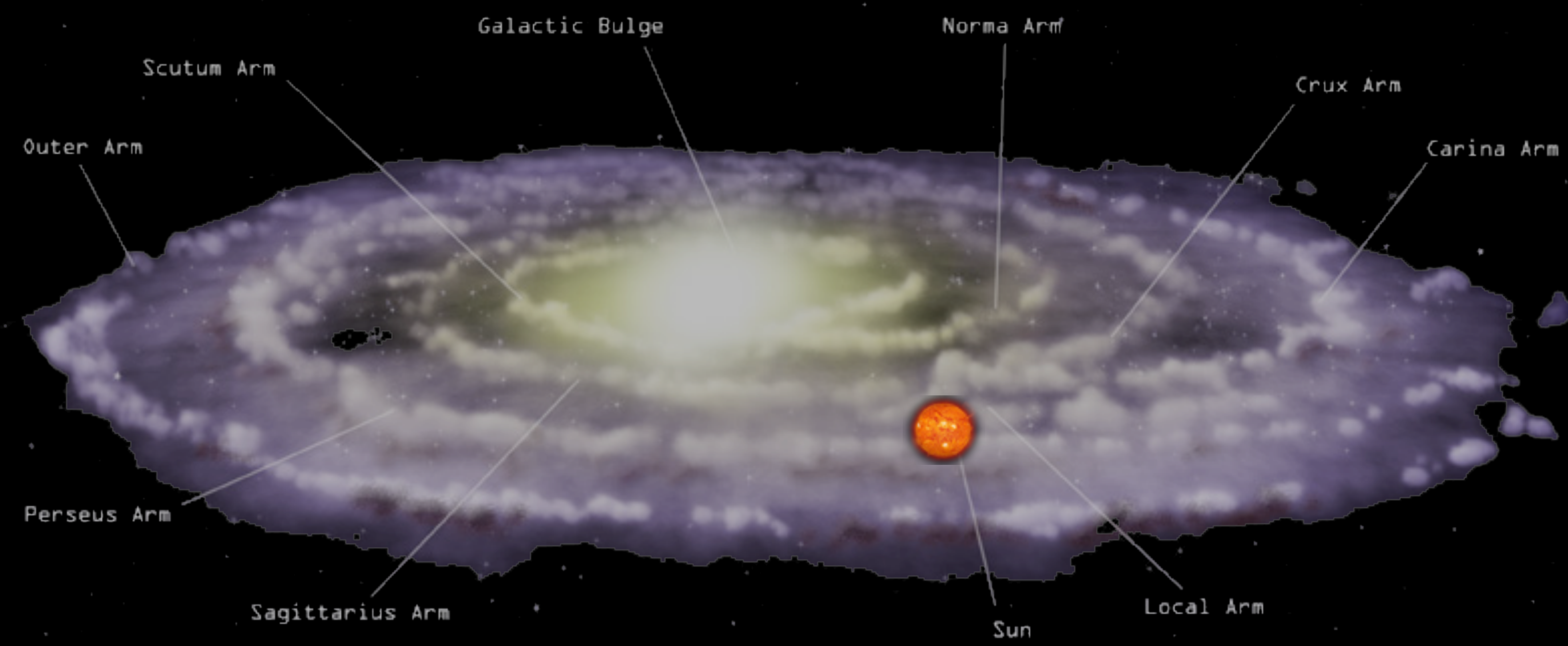
Basic concept: add **something** to the SM

- SuSy DM — byproduct of wider theories
- Scalar singlet DM — 'ad hoc' theories
- Sub-GeV DM — byproduct or pheno motivated
- Sterile neutrinos — theory/pheno motivated
- Axions — byproduct of wider theory
- PBHs — non-particle DM
- …… — ……

Where is Dark Matter?

In the galaxy



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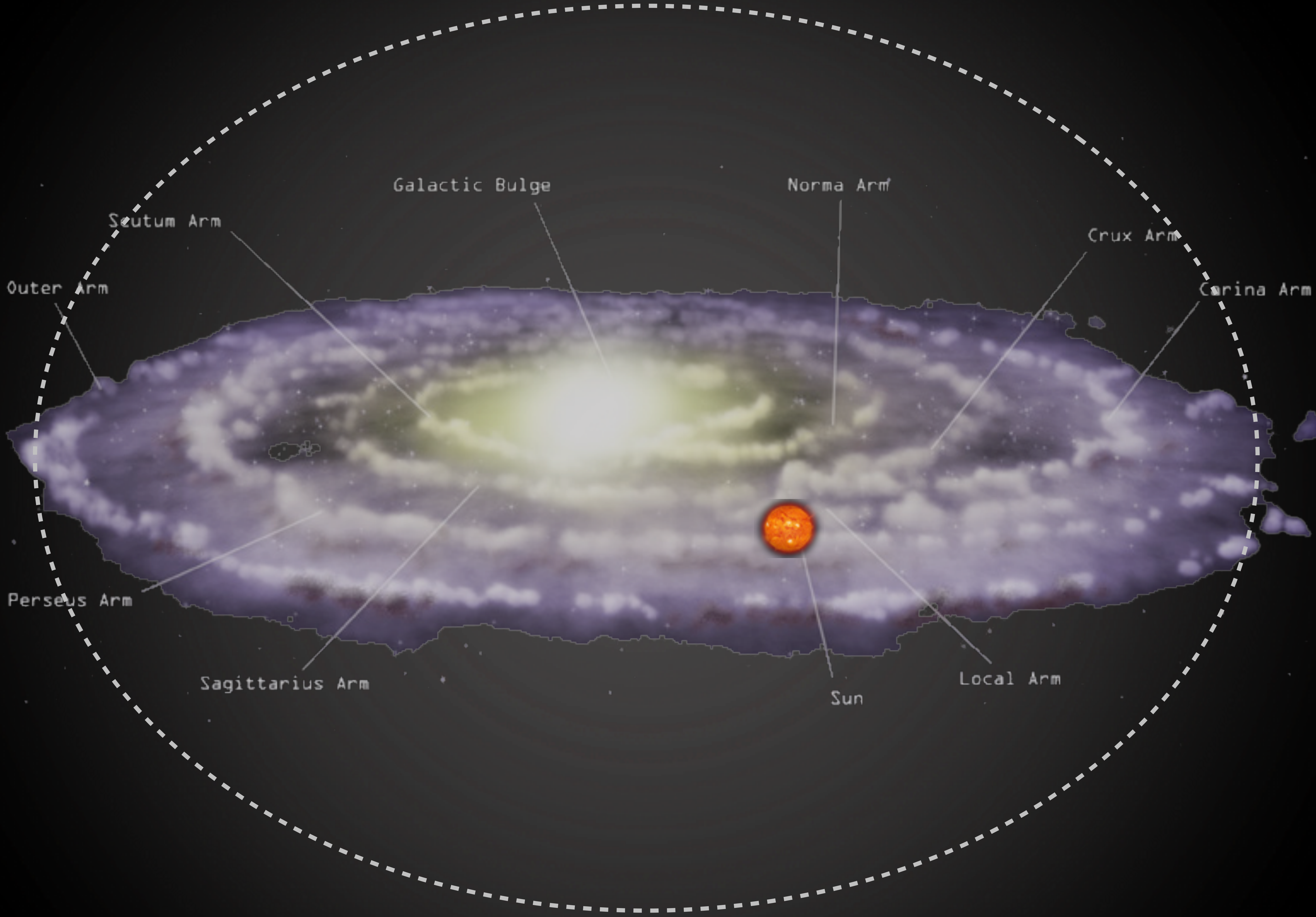

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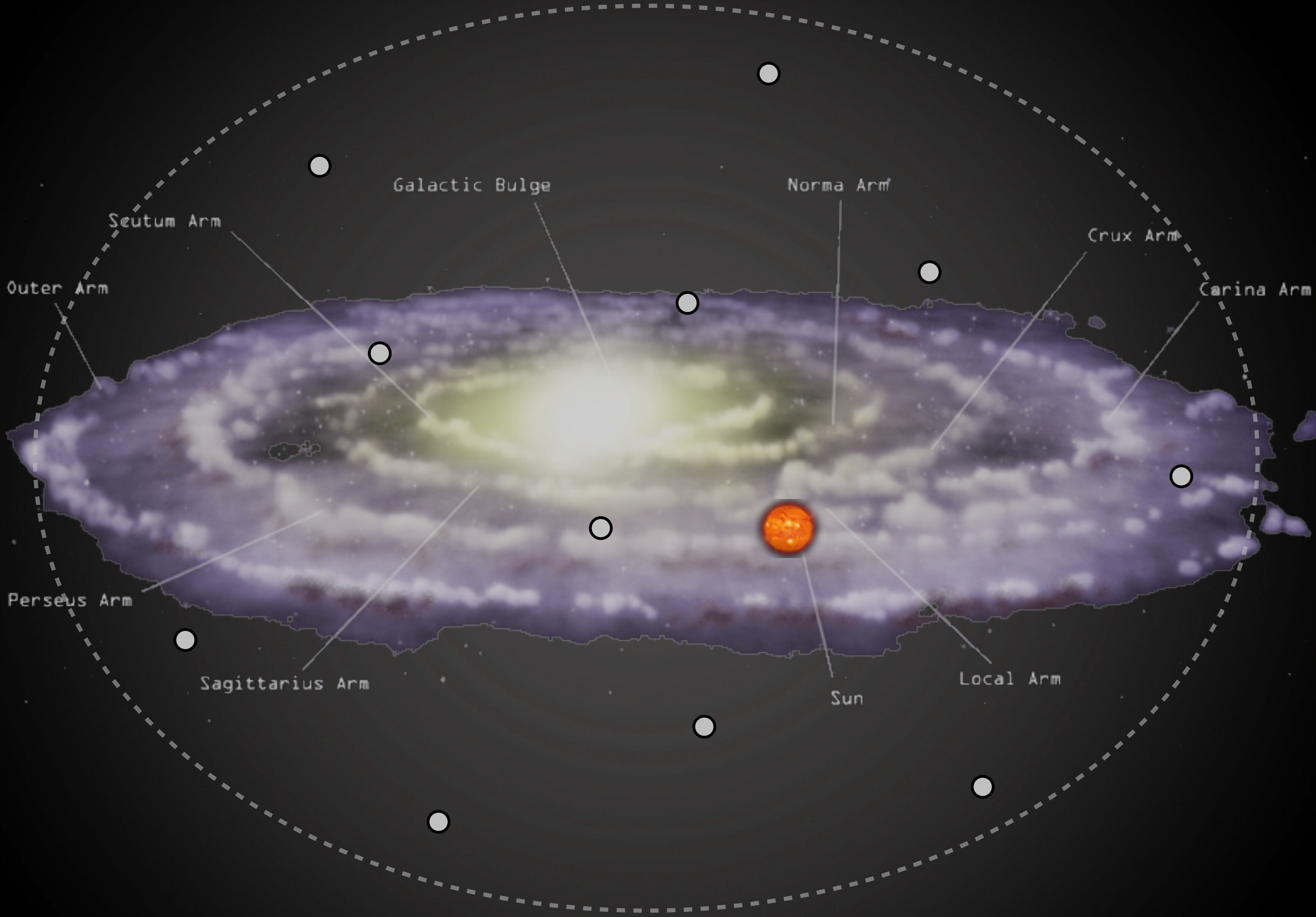

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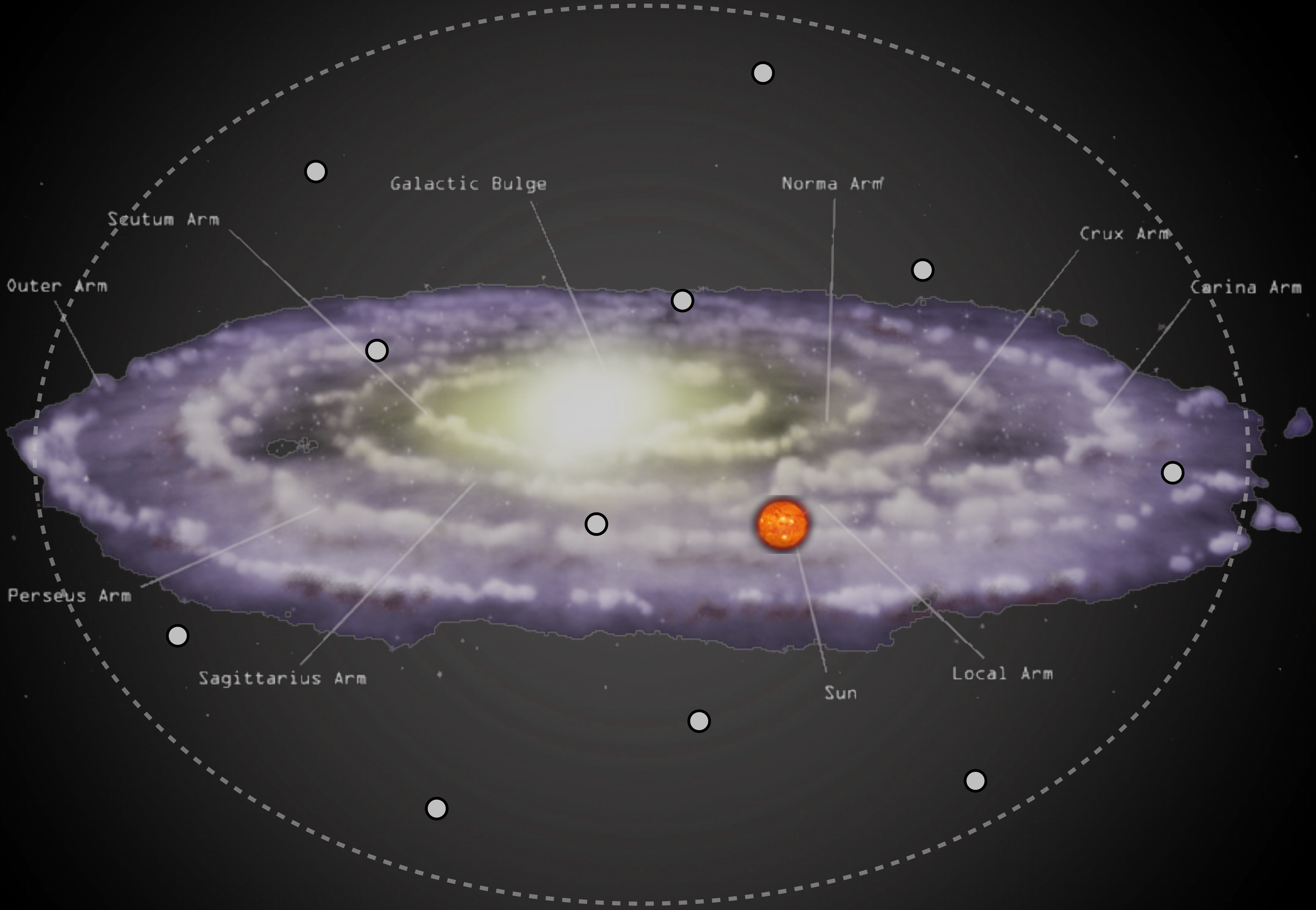


DM halo profiles

From N-body numerical simulations:

$$\text{NFW}: \quad \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\text{Ein}}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

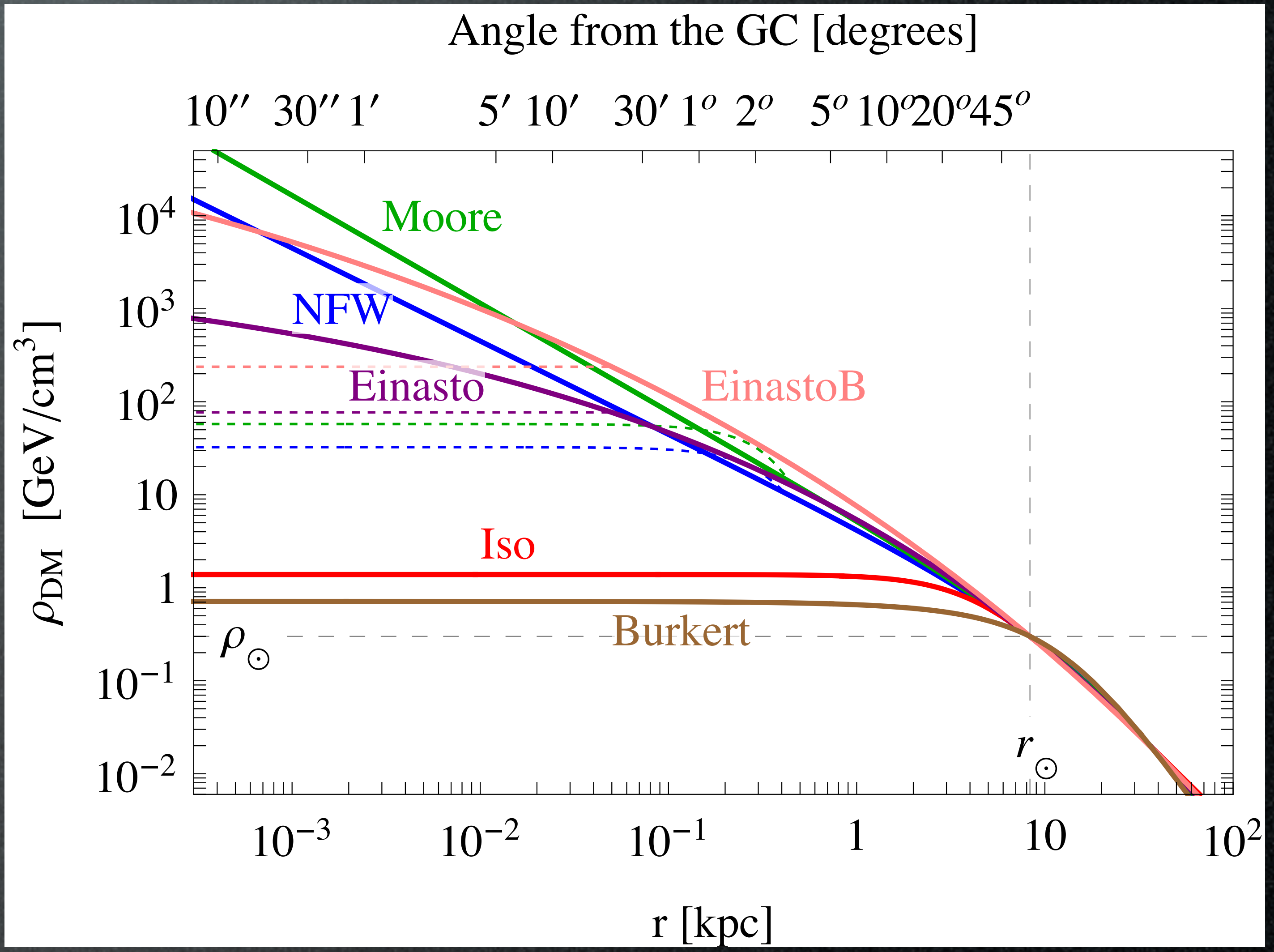
$$\text{Isothermal}: \quad \rho_{\text{Iso}}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\text{Moo}}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$

DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105

At small r: $\rho(r) \propto 1/r^\gamma$



6 profiles:

cuspy: NFW, Moore

mild: Einasto

smooth: isothermal, Burkert

EinastoB = steepened Einasto

(effect of baryons?)

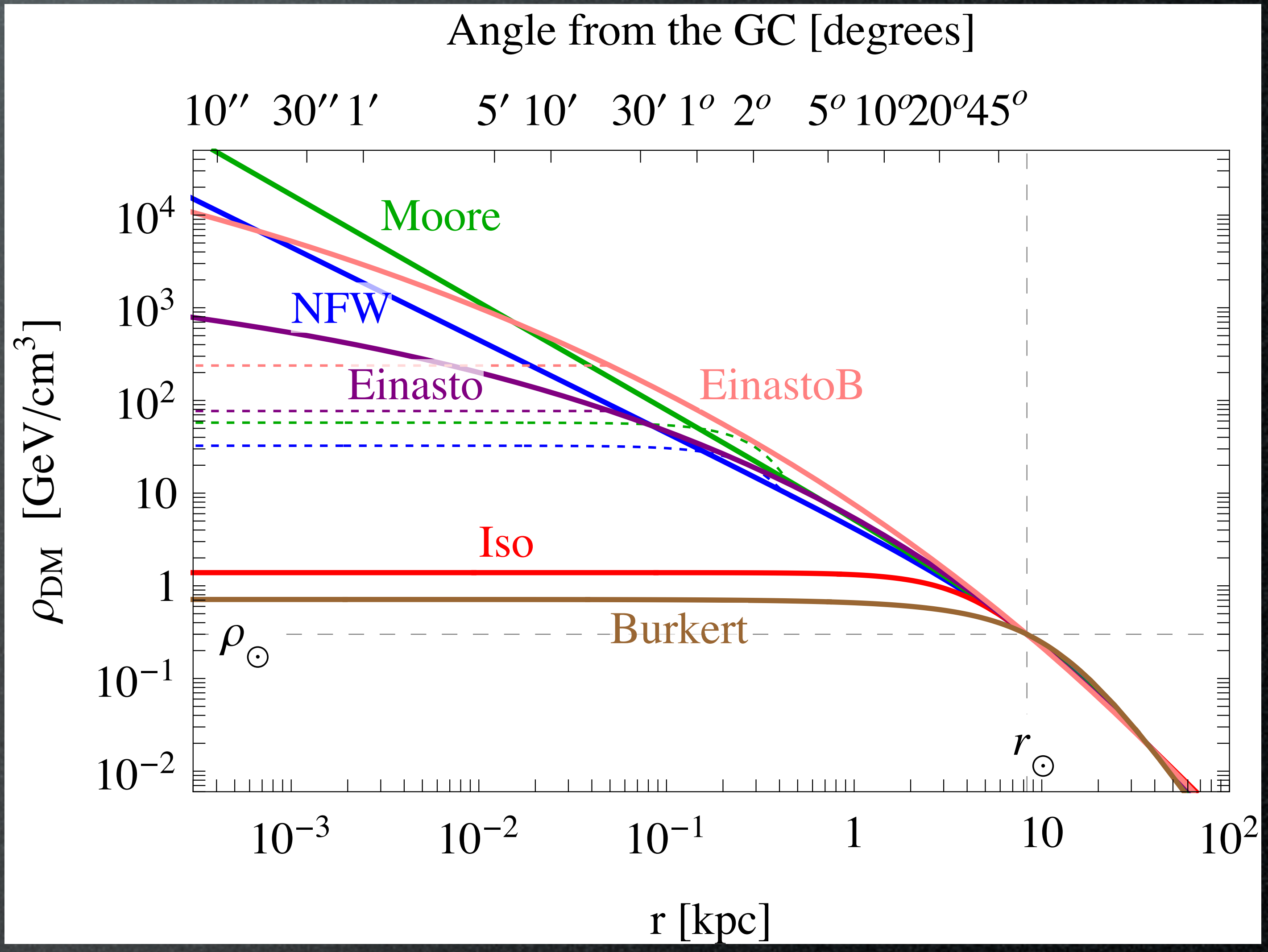
DM halo profiles

From N-body numerical simulations:

Common features:

$\rho_\odot \simeq 0.4 \text{ GeV/cm}^3$

Total mass of the MW: $\simeq 10^{12}\ M_\odot$



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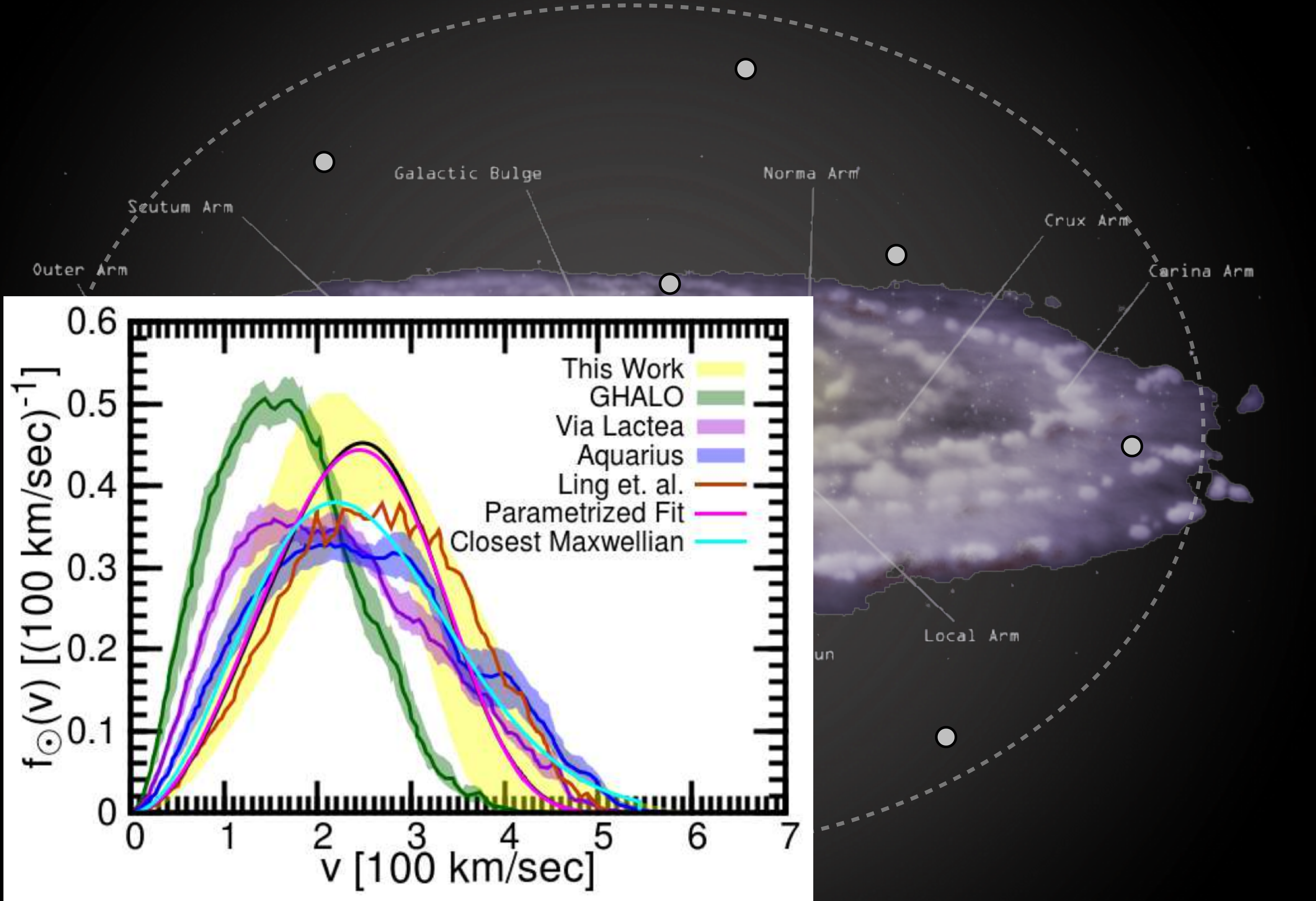

How was Dark Matter produced?

How was Dark Matter produced?

Basic concept: a relic from the Early Universe

- Thermal relic / freeze-out DM
- Asymmetric DM
- Freeze-in DM
- Oscillations