The dark matter problem: the past and the future

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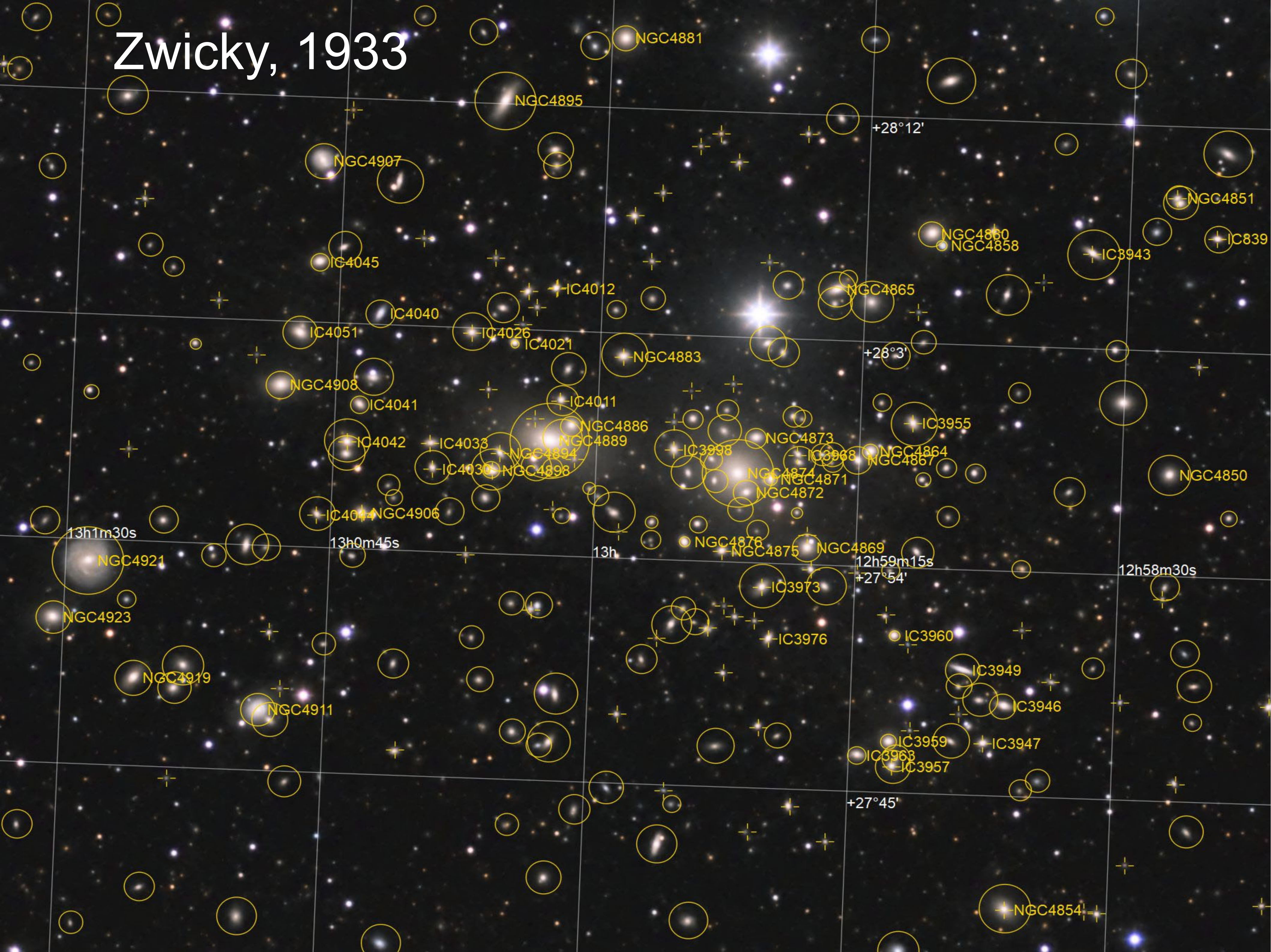
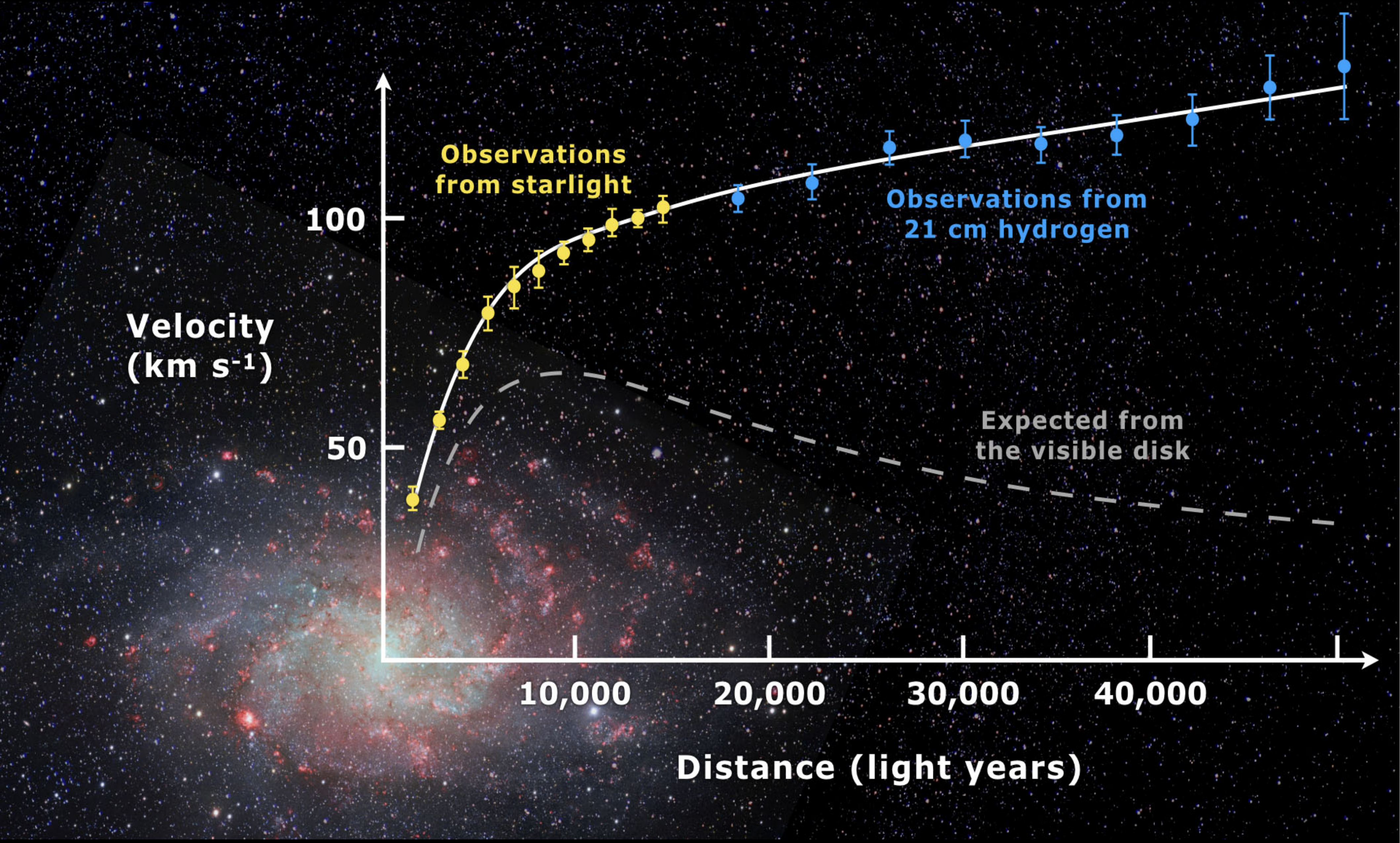
1) Why dark matter?


Zwicky, 1933
NGC4881
NGC4895
+28°12'
NGC4907
NGC4851
NGC4860
NGC4858
IC839
IC3943
IC4045
IC4012
NGC4865
IC4040
IC4051
IC4026
IC4021
NGC4883
+28°3'
NGC4908
IC4041
IC4011
IC3955
NGC4886
NGC4889
IC4042
IC4033
NGC4873
IC3998
NGC4894
IC3968
NGC4864
NGC4867
IC4030
NGC4898
NGC4874
NGC4871
NGC4850
NGC4872
IC4044
NGC4906
13h1m30s
13h0m45s
13h
NGC4876
NGC4875
NGC4869
NGC4921
12h59m15s
+27°54'
12h58m30s
IC3973
NGC4923
IC3976
IC3960
IC3949
NGC4919
NGC4911
IC3946
IC3959
IC3947
IC3963
IC3957
+27°45'
NGC4854

Rotation curves of galaxies, 1977
Dark matter or modified gravity?



If a galaxy has a spherically symmetric density distribution $\rho(R)$, its mass depends on radius as $M(R) = \int_0^R \rho(r) \cdot 4\pi r^2 dr$. Speed V of the Keplerian rotation of a body on the circular orbit of radius R is given by Newton's law:

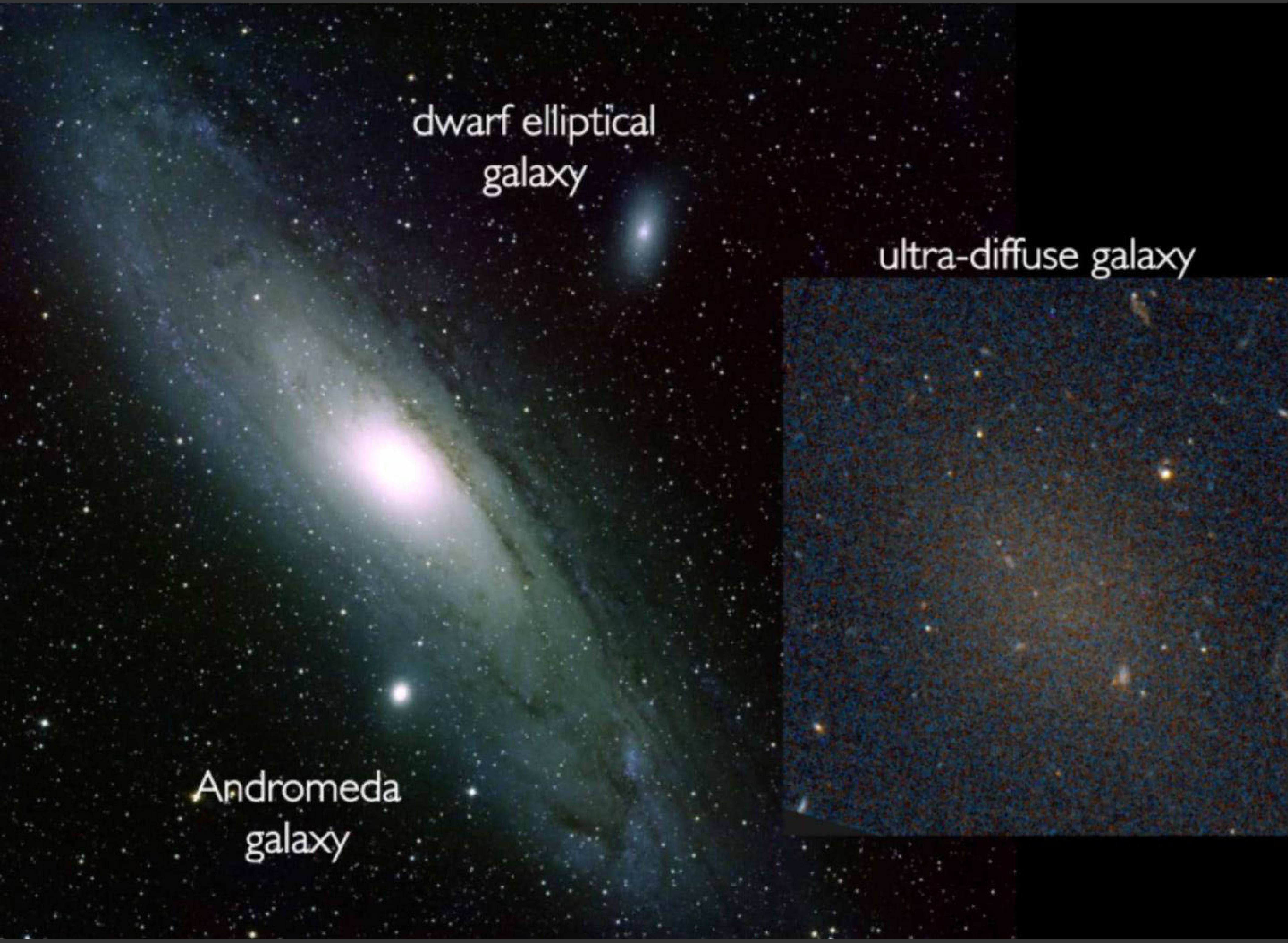
$$\frac{V^2}{R} = G\frac{M(R)}{R^2} \Longrightarrow V = \sqrt{\frac{GM(R)}{R}}$$

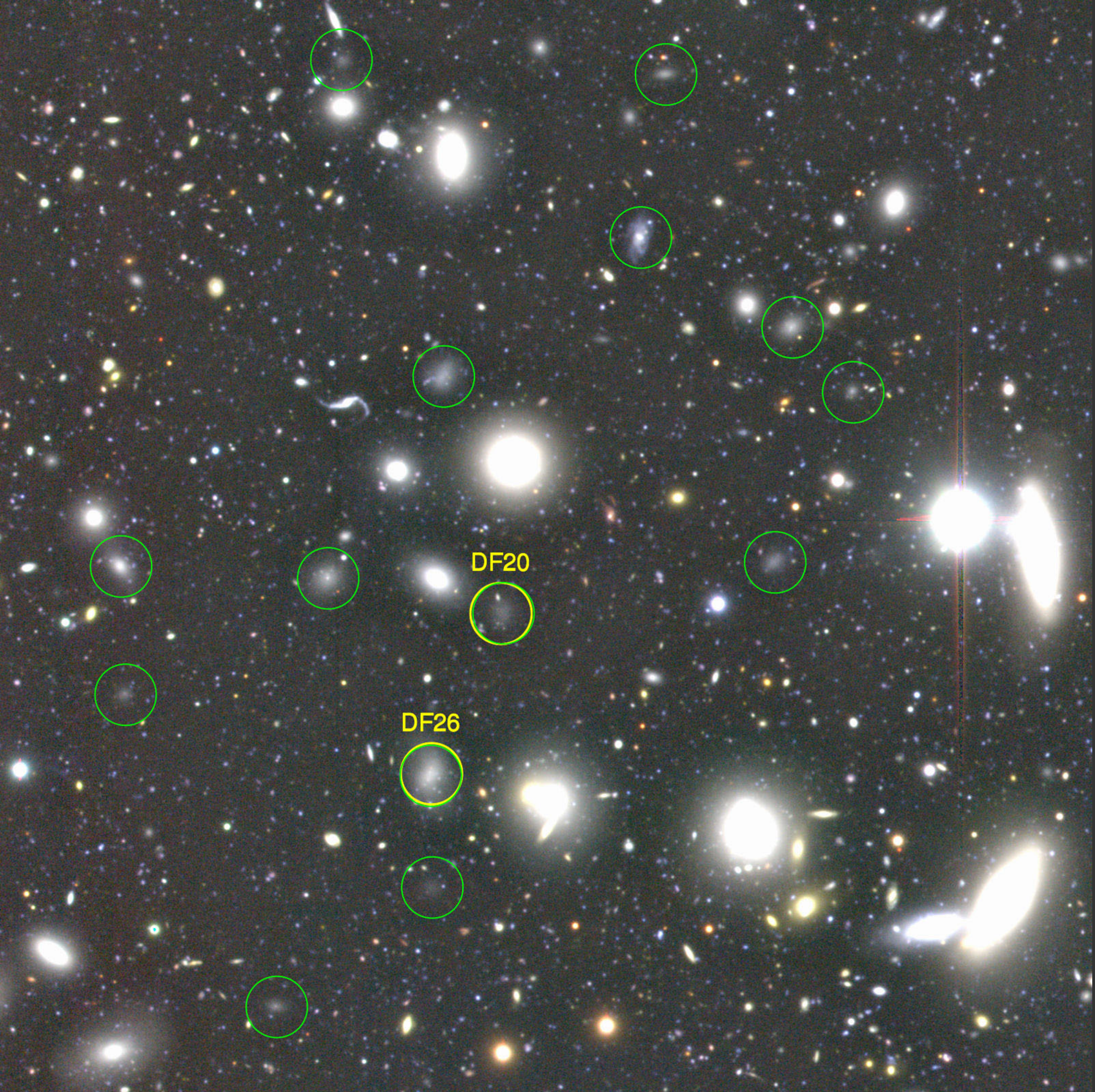
Outside the galaxy, M stops growing with radius, and we get:

$$M = const \Longrightarrow V = \sqrt{\frac{GM}{R}} \propto R^{-1/2}.$$

The flat tail $V = const$ corresponds to $M(R) \propto R$ and $\rho \propto R^{-2}$.

Interacting galaxies


dwarf elliptical galaxy
ultra-diffuse galaxy
Andromeda galaxy



Ultra diffuse galaxies in the Coma cluster

Segue 1, a satellite of the Milky Way

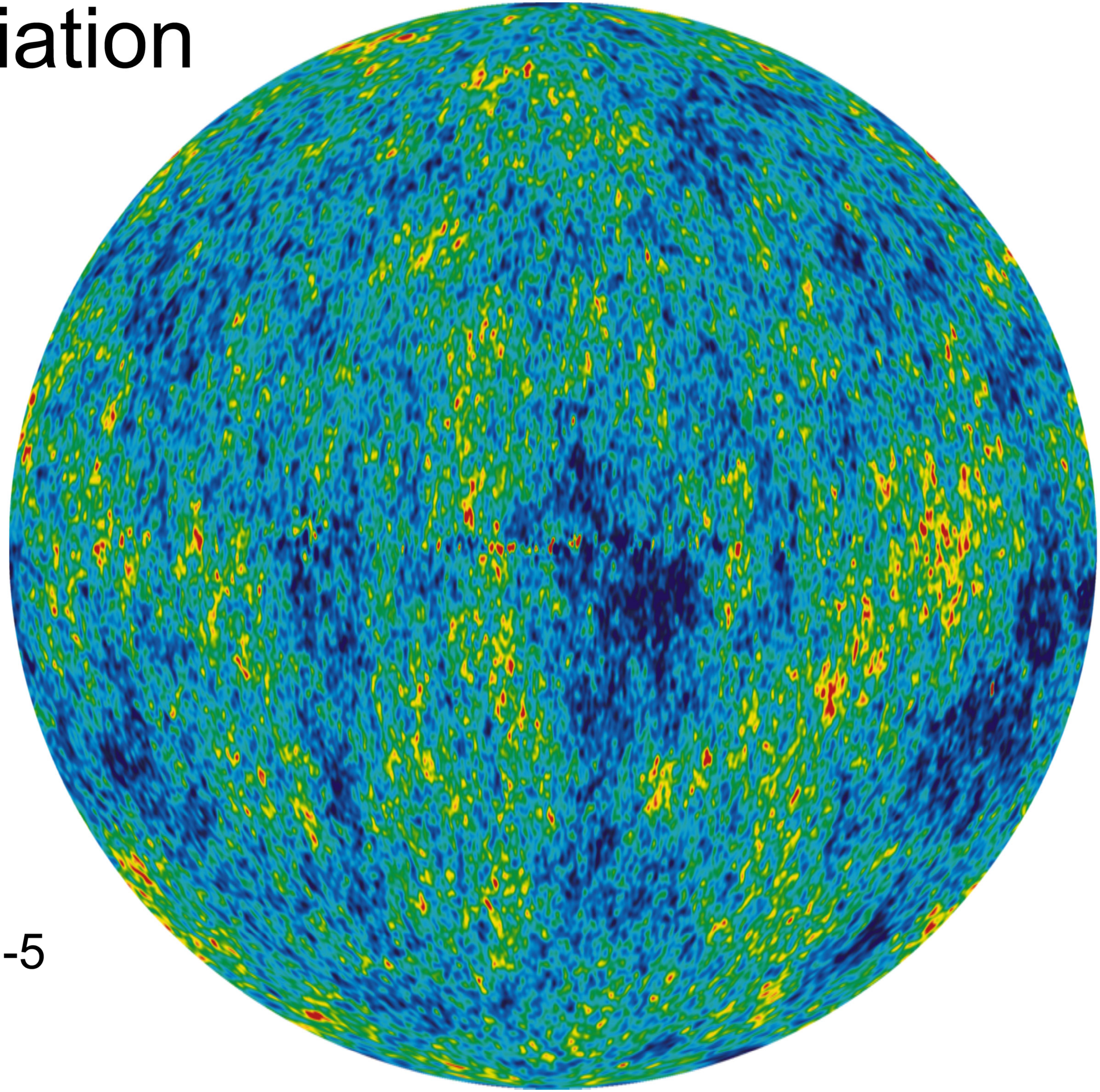
$M \sim 10^6\ M_{sun}$

Relic radiation

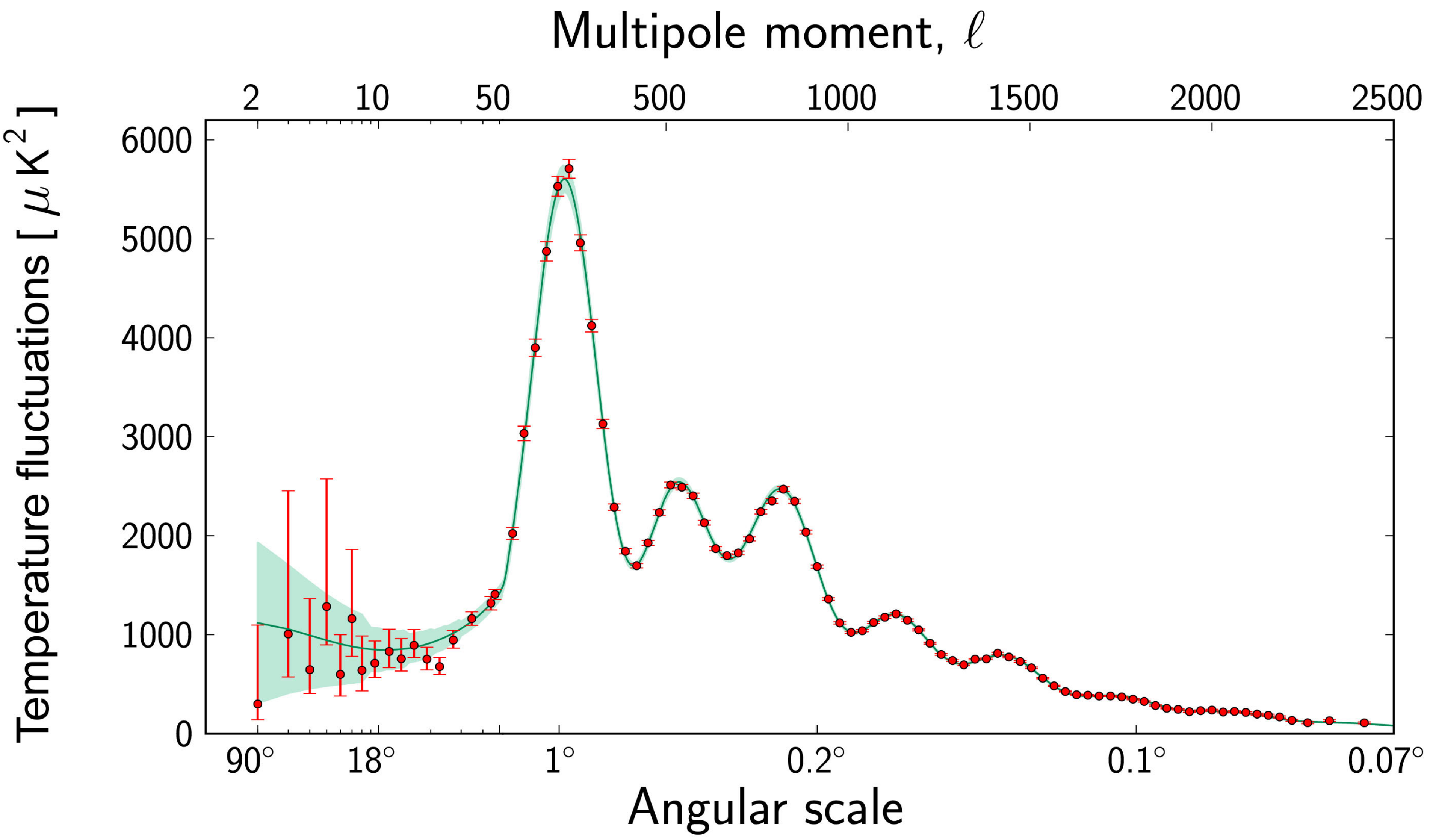
$\Omega_m \approx 0.31$

$\Omega_b \approx 0.05$

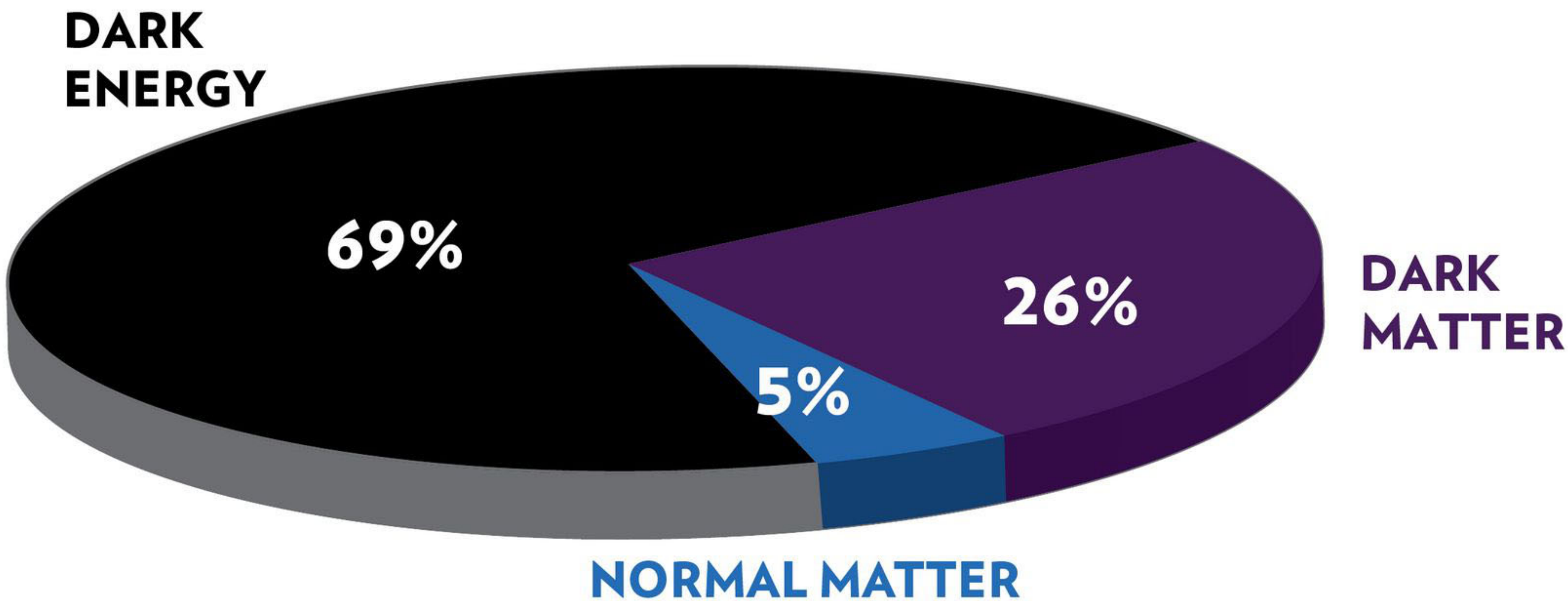
$\Delta T/T \sim 10^{-5}$



Spatial spectrum of relic radiation



ENERGY DISTRIBUTION OF THE UNIVERSE



Relic radiation

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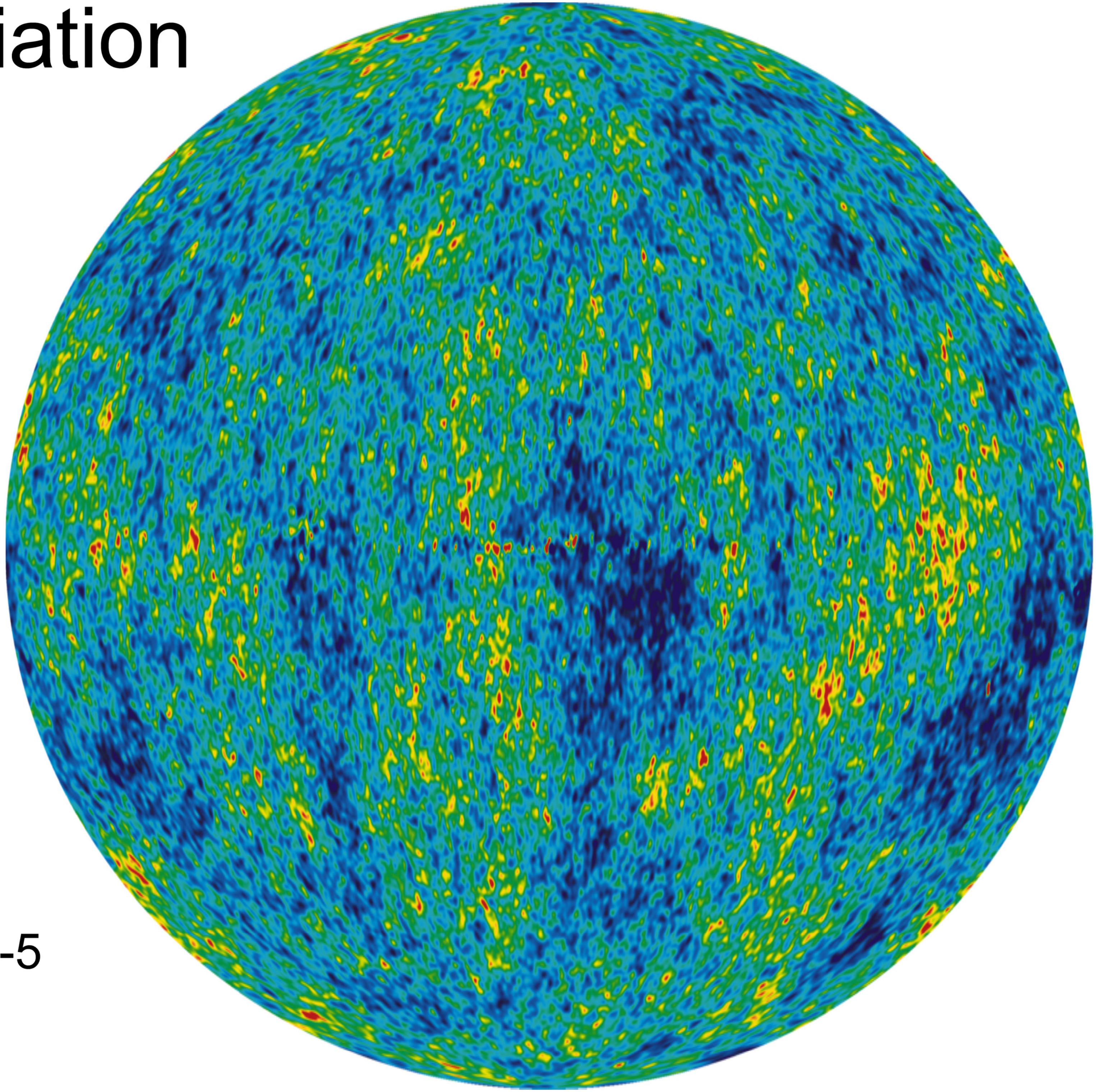
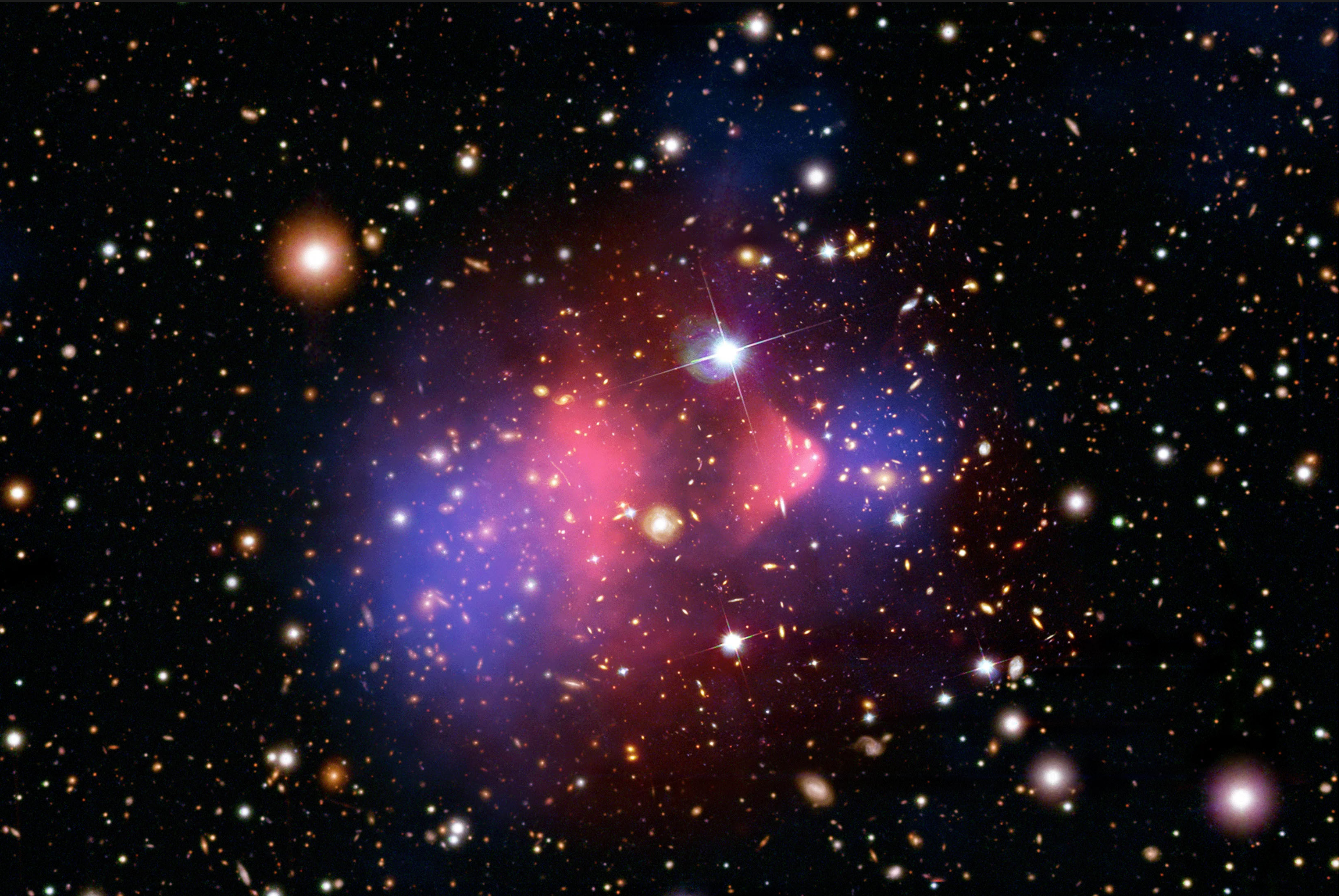


The metric of the Friedmann universe has the form $ds^2 = c^2dt^2 - a^2(t)dl^2$, where $a(t)$ is scale factor. Instead of $a(t)$ or t, the redshift $z + 1 = a_0/a(t)$ is usually used. The radiation temperature in the Universe is $T \propto a^{-1}(t) \propto (z + 1)$.

For CMB ($z_r \sim 1200$) $\dfrac{\delta T}{T} \sim 10^{-5}$. Relative disturbance of density of the "ordinary" matter at this moment is $\dfrac{\delta T}{T} \sim \dfrac{\delta \rho_b}{\rho_b} < 10^{-4}$.

The density perturbations grow after the CMB formation as $\dfrac{\delta \rho}{\rho} \propto a(t)$ (the matter-dominated Universe). If there were no dark matter, the matter density perturbations would now have an amplitude $\dfrac{\delta \rho_b}{\rho_b} \sim z_r \cdot 10^{-4} \simeq 0.1$, and there would be no cosmic structures.

The bullet cluster, 1E 0657-56



2) Candidates

WIMP

Weakly Interacting Massive Particle

$$\Omega_{dm}\left(\frac{H}{100\ \mathrm{km/(s\ Mpc)}}\right)^2 \simeq \left(3\cdot 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}/\langle\sigma v\rangle\right)$$

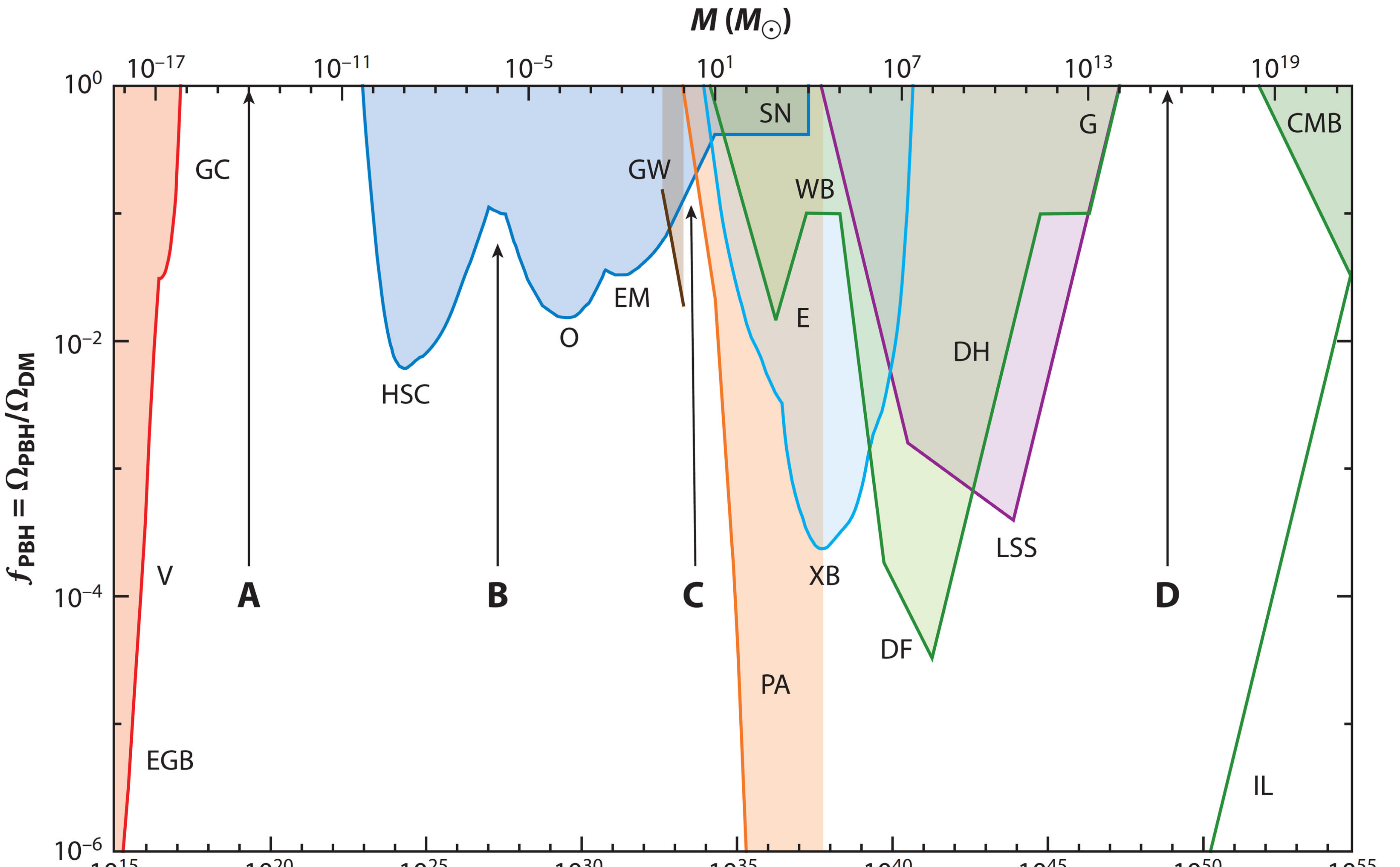
1) Neutralino
2) The lightest Kaluza–Klein particle
3) ....

Many other candidates

1) axions
2) primordial black holes
3) light boson condensate
4) dark photons
5) sterile neutrinos
6) technicolor dark matter
7) many other candidates
8) something else..

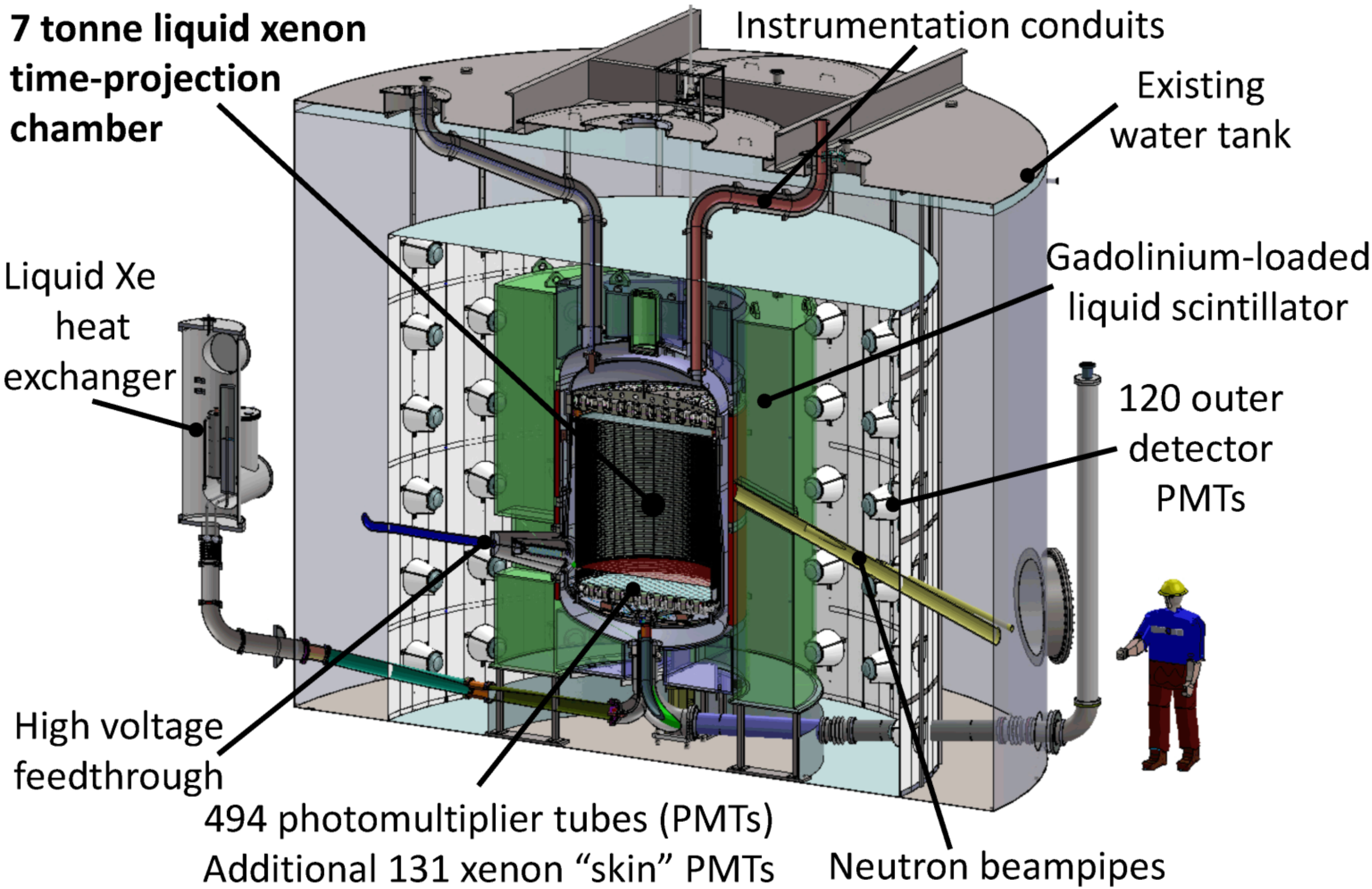
The dark matter can be cold or warm, but cannot be hot!

Primordial black holes *(Carr & Kühnel, 2020)*

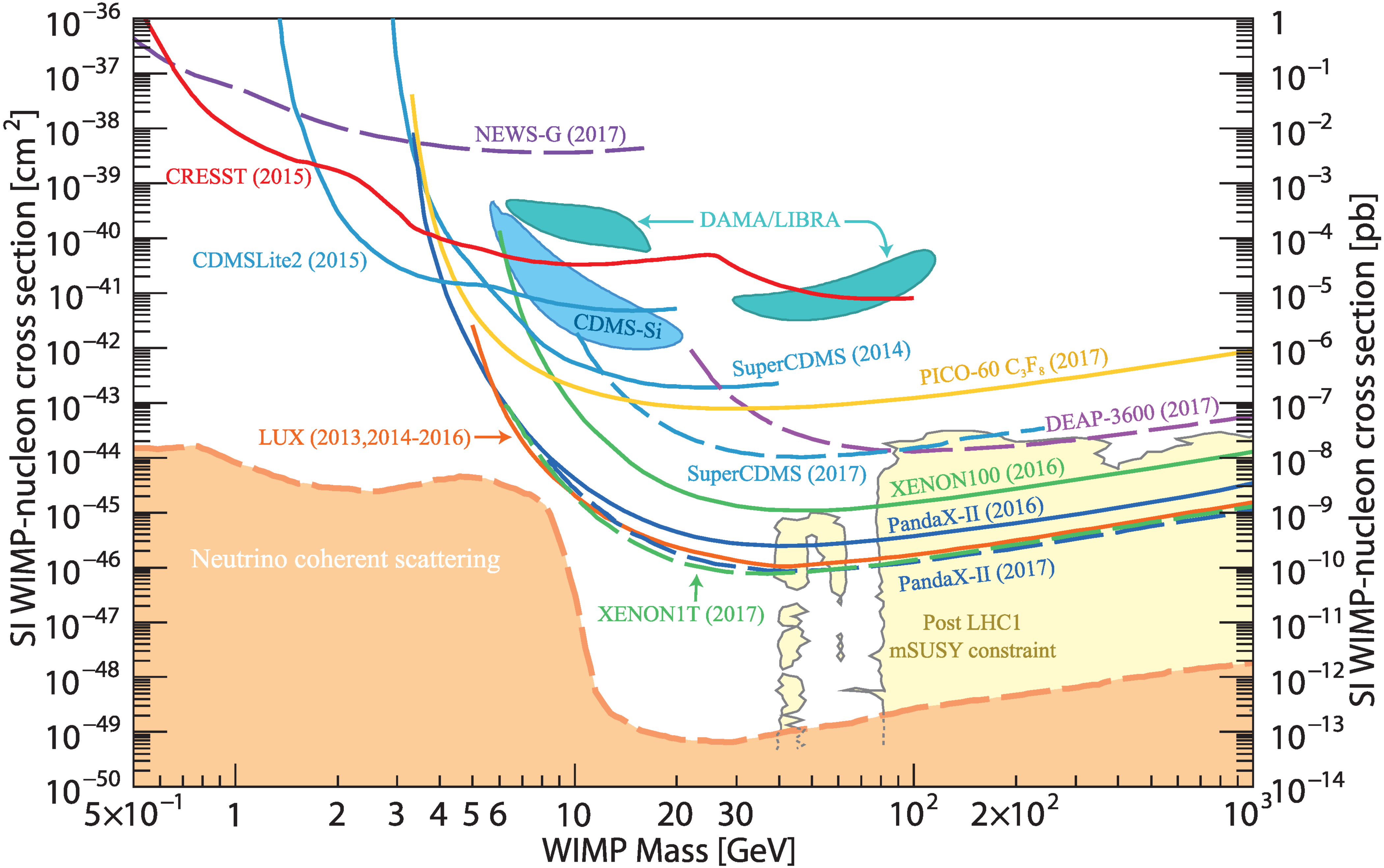


3) How to search it?

The LZ Detector

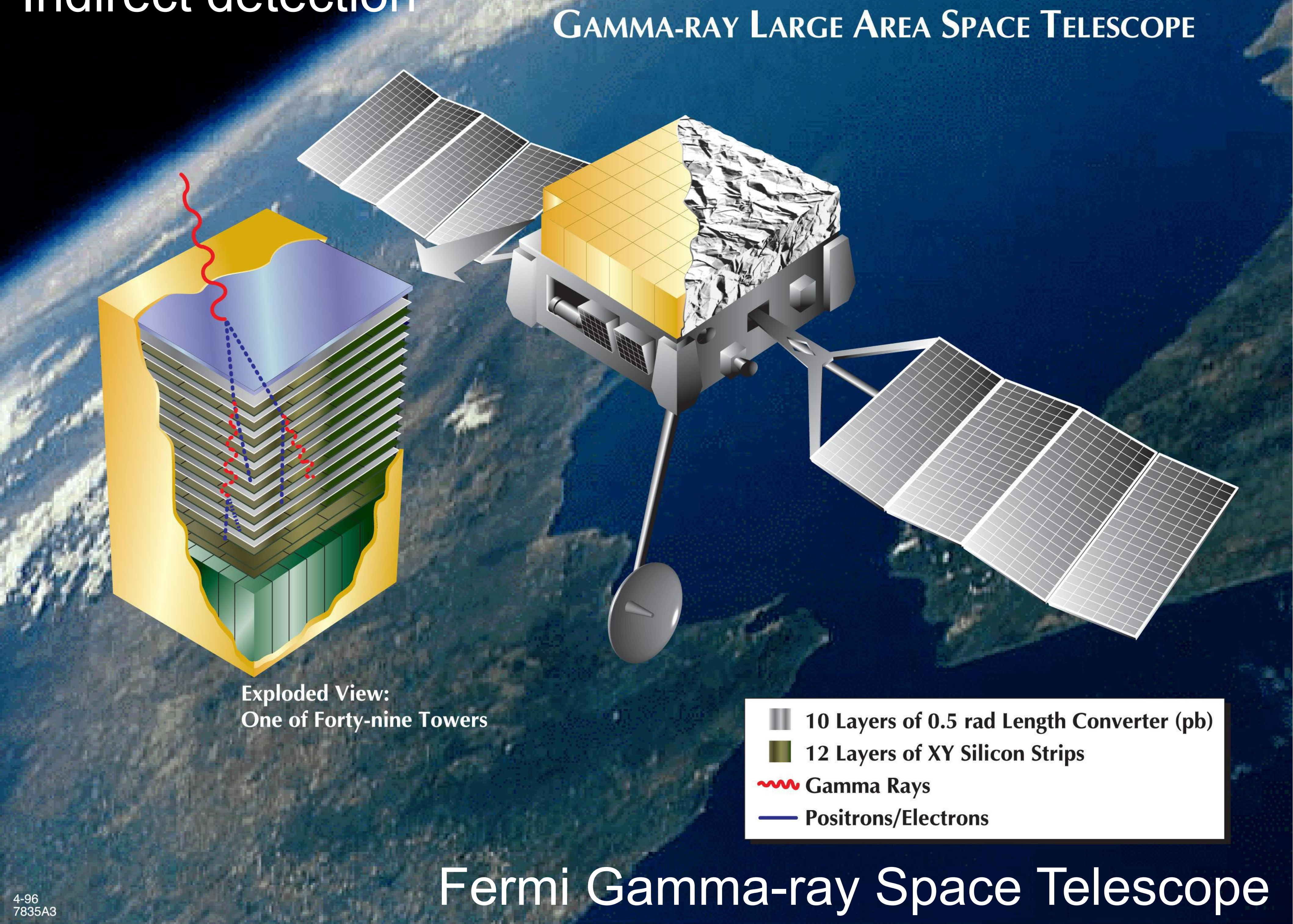


Results

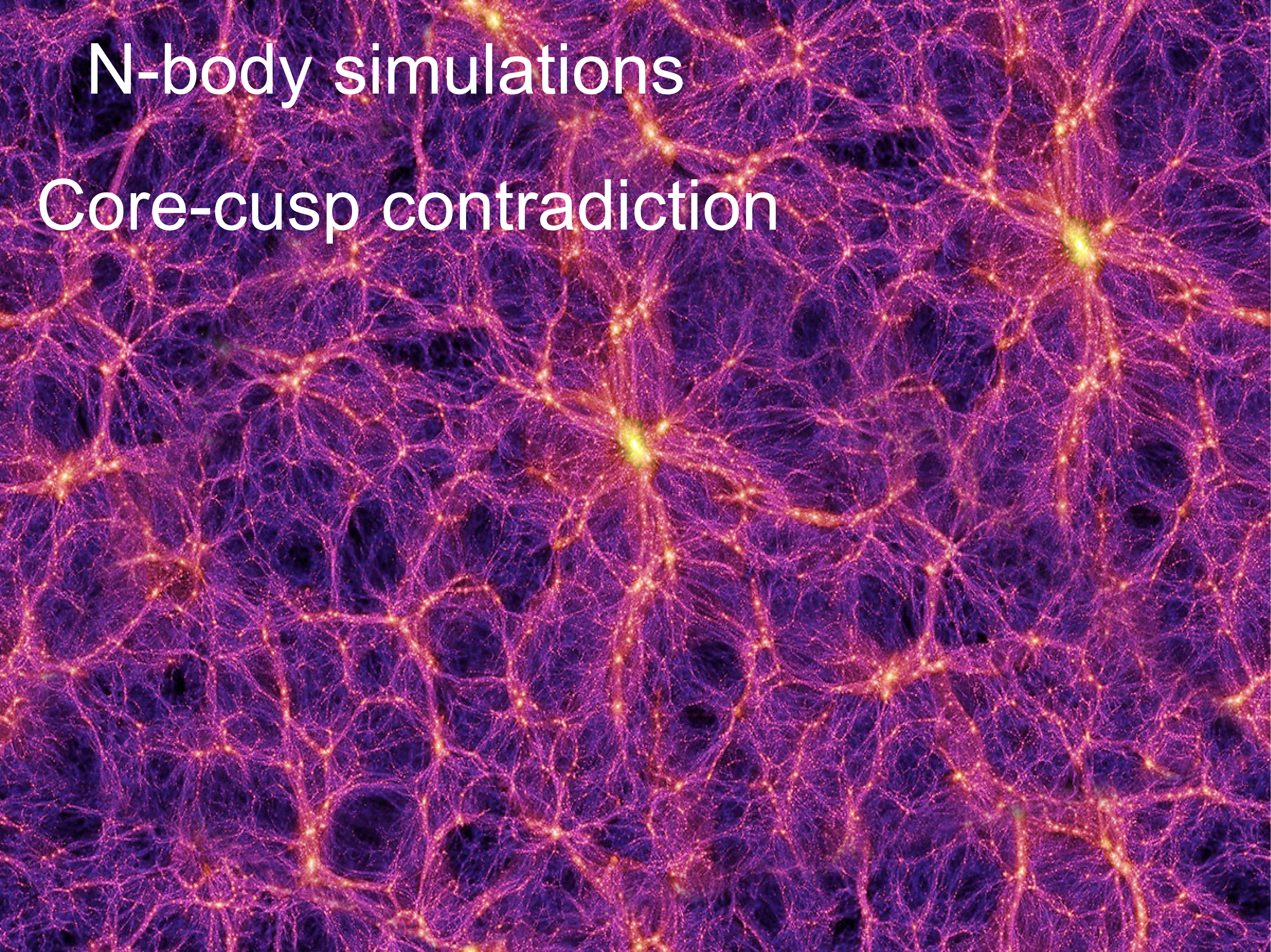


NEWS-G (2017)
CRESST (2015)
DAMA/LIBRA
CDMSLite2 (2015)
CDMS-Si
SuperCDMS (2014)
PICO-60 C3F8 (2017)
DEAP-3600 (2017)
LUX (2013,2014-2016)
SuperCDMS (2017)
XENON100 (2016)
PandaX-II (2016)
PandaX-II (2017)
Neutrino coherent scattering
XENON1T (2017)
Post LHC1
mSUSY constraint
SI WIMP-nucleon cross section [cm2]
SI WIMP-nucleon cross section [pb]
WIMP Mass [GeV]

Indirect detection



Fermi Gamma-ray Space Telescope


N-body simulations
Core-cusp contradiction

Isothermal profile

$$\rho \sim r^{-2}$$

Navarro-Frenk-White profile

$$\rho_{NFW} = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

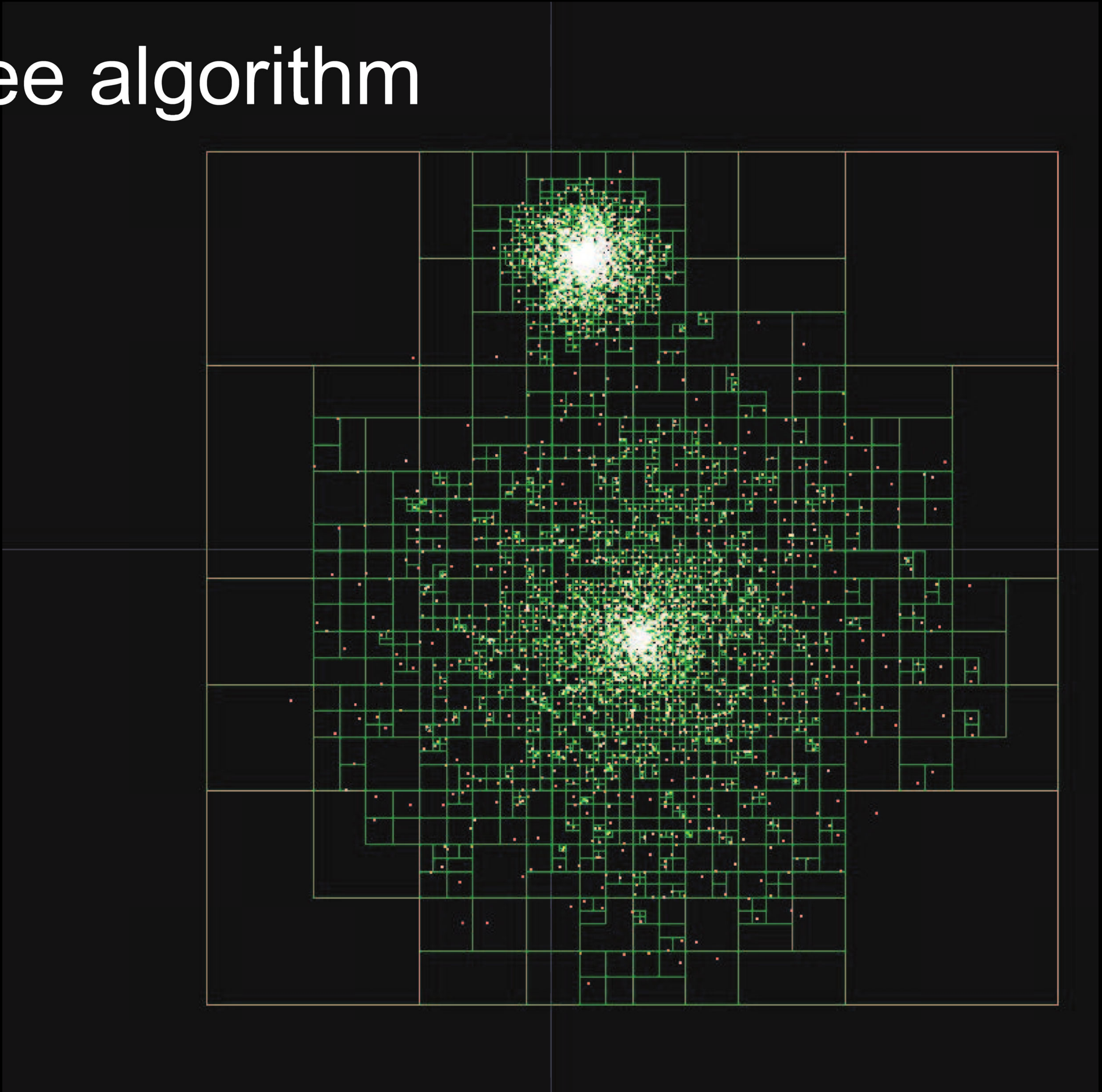
Einasto profile

$$\rho_{Ei} = \rho_s \exp\left\{-2n\left[\left(\frac{r}{r_s}\right)^{\frac{1}{n}} - 1\right]\right\}$$

Pseudo-isothermal profile

$$\rho = \frac{\rho_0 r_0^2}{r^2 + r_0^2}$$

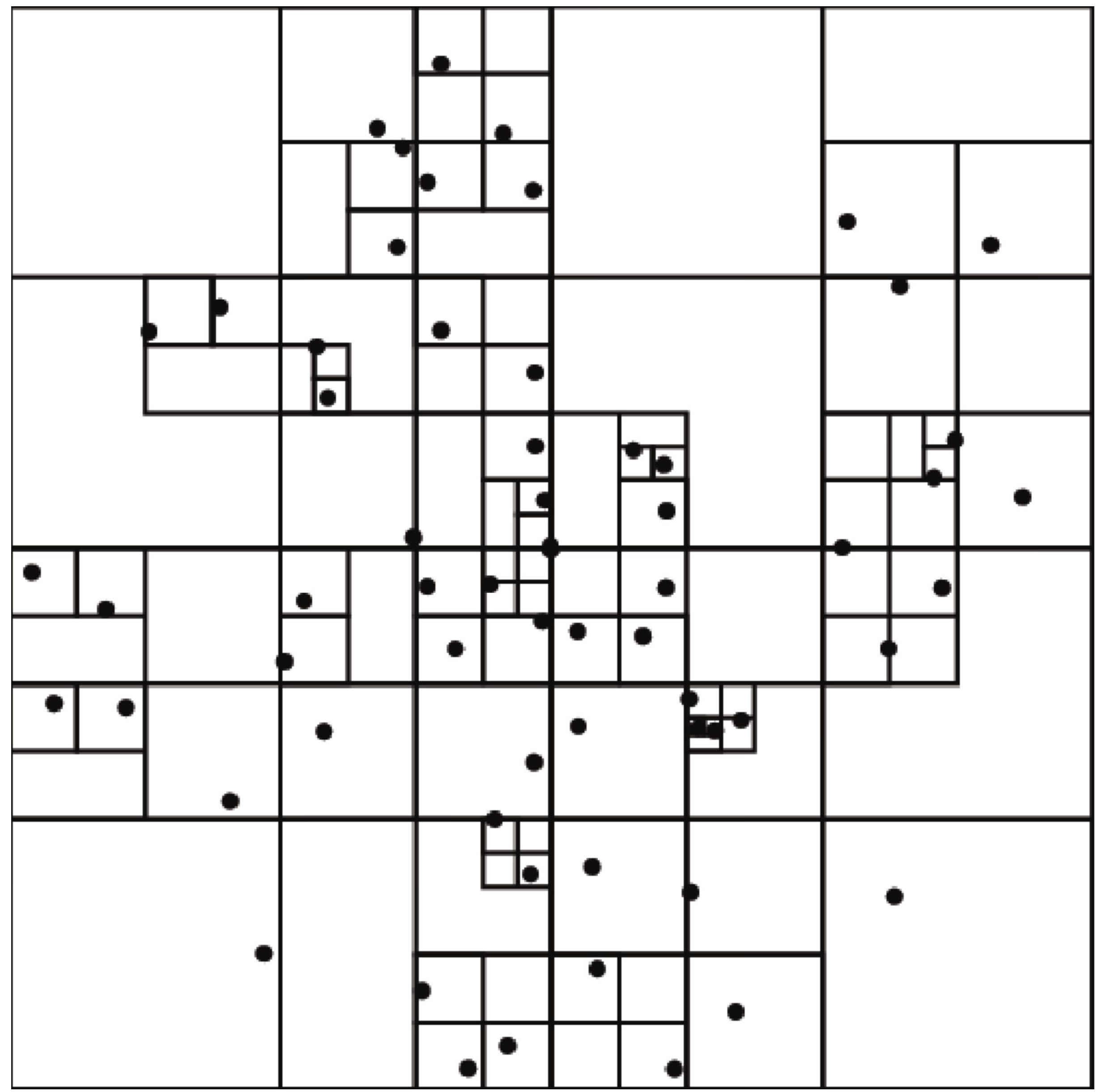
Tree algorithm



Tree algorithm

Cell opening

$$\frac{GM_{cell}}{r^2}\left(\frac{l}{r}\right)^2 \leq f_{acc}|\vec{a}|$$



Trajectory calculation algorithms