Dark matter – Evidence and Candidates

ISAPP School 2019 – The dark side of the universe
29 May 2019, Heidelberg, Germany

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University of Amsterdam (UvA)

Dark Matter dominates the Universe

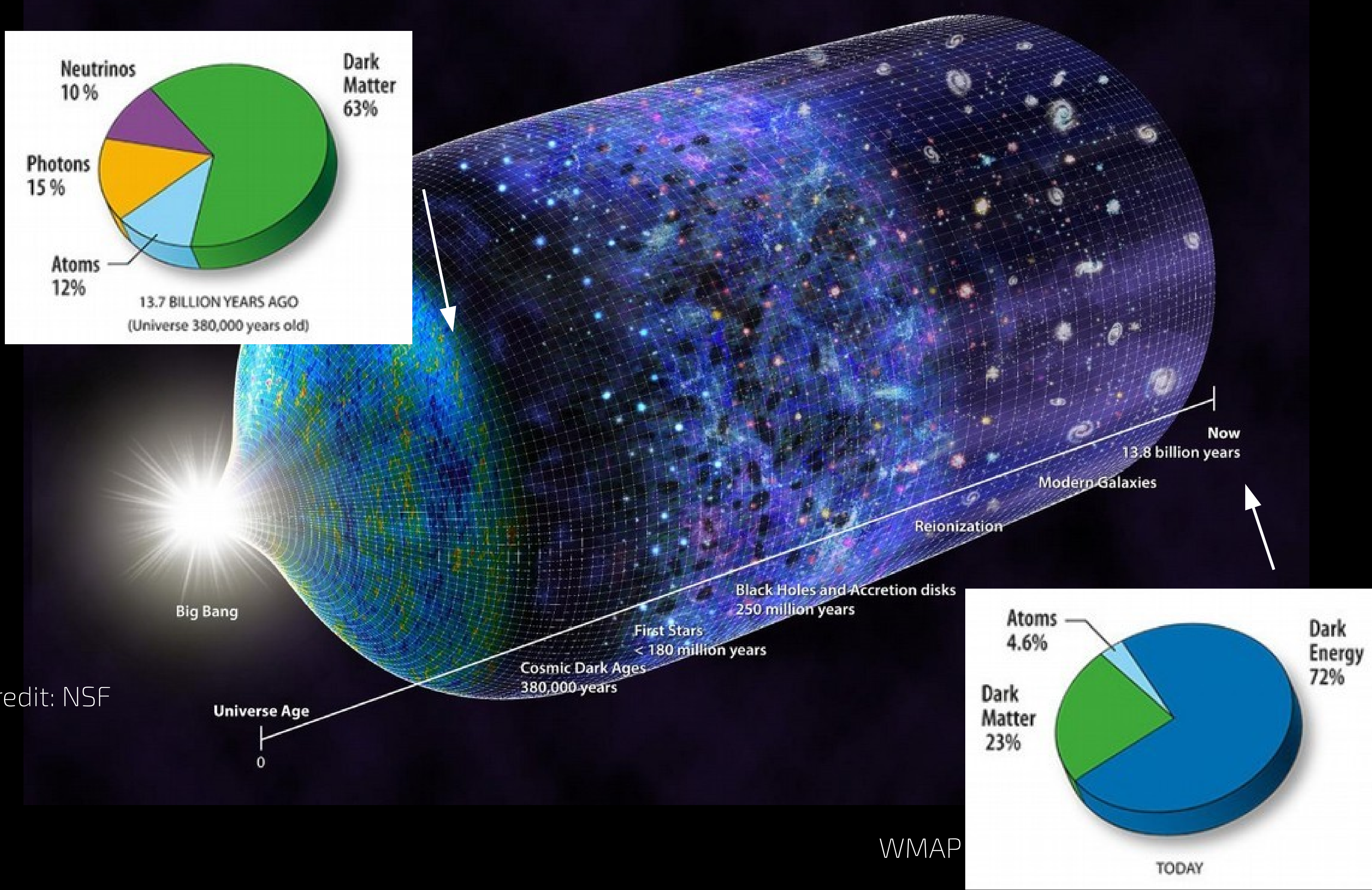


Image credit: NSF

WMAP

DM was dominant force in Universe from ~40kyrs to ~5Gyrs. Without DM, Universe would look very different. **But what is it?**

Outline

Lectures 1 & 2

- Historical introduction – *How dark matter came to matter*
- Dark matter evidence – *Modern perspective*
- Dark matter candidates – WIMPs, Sterile neutrinos, Axions

Lectures 3 & 4

- Indirect DM searches

How dark matter came to matter

A brief history

It took ~150 years to build the Church of the Holy Spirit in Heidelberg. DM research happens on similar time scales, at least over the course of generations. We have learned *a lot* during the last few decades, but a lot remains to be learned.

1900s - 1930s: Kinematics of local stars

Jan Oort

First dynamical tests of the local mass density (mentioning "dark matter")

- Kelvin 1906: Modeling dynamics of nearby stars as gas
- Kapteyn 1922: One of the first full models for mass and kinematics of the Milky Way
- Oort 1932: One of the first measurements of the local mass density derived from local vertical motion of stars

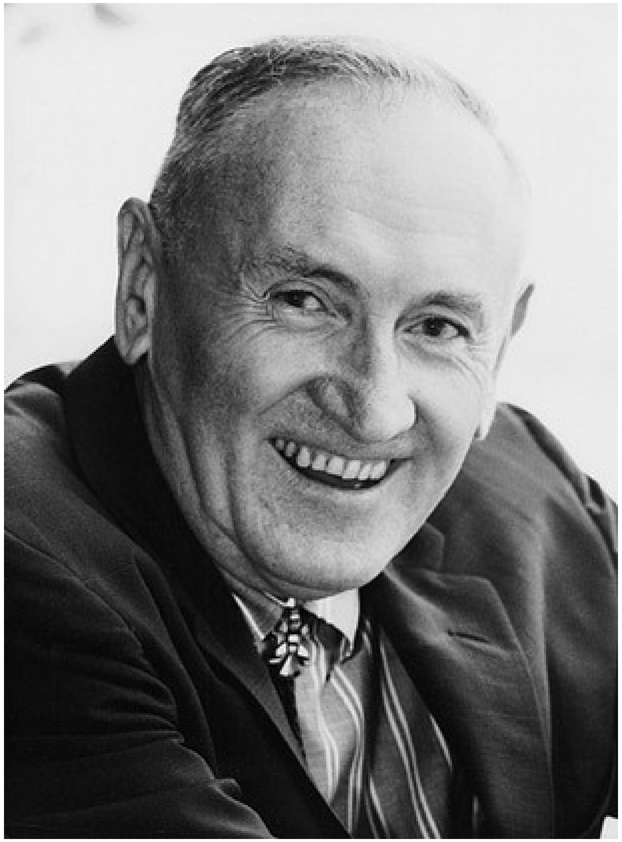
See Bertone & Hooper 2017 for a "History of Dark matter"

"We may conclude that the total mass of nebulous or meteoric matter near the sun is less than 0.05 Msol/pc^3; it is probably less than the total mass of visible stars, possibly much less."

Jan Oort 1922

Lord Kelvin 1906, Ernst Öpik 1915, Kapteyn 1922, James Jeans 1922, Bertil Lindbald 1926, Jan Oort 1932

1930s: Galaxy clusters



Fritz Zwicky

Pioneering use of virial theorem to interpret large velocities of eight galaxies within the Coma cluster. Zwicky studied the Hubble expansion and found a surprisingly large velocity dispersion of galaxies that are part of the the Coma cluster.

→ mass-to-light ratio of many hundreds

Coma cluster

“If this would be confirmed, we would get the surprising results that dark matter is present in much greater amount than luminous matter.”

Fritz Zwicky 1933

Similar results for Virgo cluster (Sinclair Smith 1937)

Kinematics of galaxies in galaxy clusters

The amount of gas and galaxies containt in the Coma cluster (modern estimate from 1993) is

$$M \simeq 1.6 \times 10^{14} M_\odot$$

The virial theorem states that – for Newton gravity – the average kinetic and potential energies in a relaxed (virialized) system are related via

$$2\langle T \rangle + \langle U_{\rm tot} \rangle = 0 \qquad\qquad U(r) \propto r^{-1}$$

where

$$|U| = \frac{GM^2}{R} \qquad\qquad T = \frac{1}{2} M \langle v^2 \rangle = \frac{3}{2} M \langle v_{||}^2 \rangle$$

For the velocities of galaixes in the Coma cluster, one finds that

$$M \simeq 1.9 \times 10^{15} M_\odot$$

Zwicky 1933

→ Factor 10 times more dark than visible matter

The mass-to-light ratio in the 1950s

Objects	Distance (in kpc)	Luminosity (in sol. lum.)	Mass (in sol. mass)	Mass/Lum. f
Solar Neighborhood	—	—	—	4
Triangulum Nebula, M33	480	1.4×10^9	5×10^9	4
Large Magellanic Cloud	44	1.2×10^9	2×10^9	2
Andromeda Nebula	460	9×10^9	1.4×10^{11}	16
Globular Cluster, M92	11	1.7×10^5	$<8 \times 10^5$	<5
Elliptical Galaxy, NGC 3115	2100	9×10^8	9×10^{10}	100
Elliptical Galaxy, M32	460	1.1×10^8	2.5×10^{10}	200
Average S in Double Gal.	—	1.3×10^9	7×10^{10}	50
Average E in Double Gal.	—	8×10^8	2.6×10^{11}	300
Average in Coma Cluster	25000	5×10^8	4×10^{11}	800

FIG. 1. A snapshot of the dark matter problem in the 1950s: the distance, mass, luminosity, and

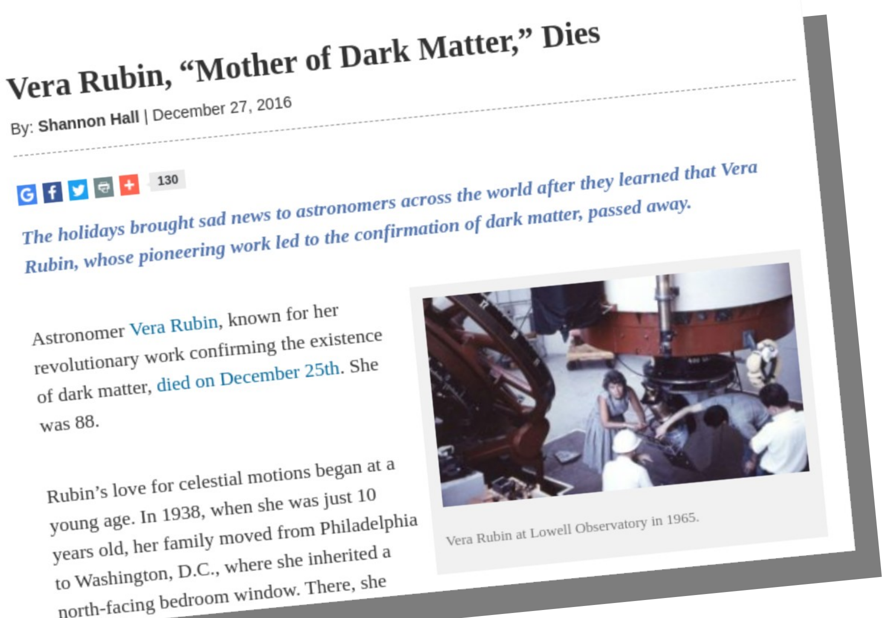
Snapshot of the dark matter problem in the 1950s. A large mass-to-light ratio was observed in many objects, ranging from LMC over M31 to the Coma cluster (with M/L ~ 800 that that point). Still, this was not seen as evidence for new particles, but rather dim stars, comets, etc.

Schwarzschild 1954

The 1970s revolution

Started with publication of M31 optical rotation curves by Vera Rubin and Kent Fort in 1970.

Vera Rubin



Vera Rubin, “Mother of Dark Matter,” Dies

By: **Shannon Hall** | December 27, 2016

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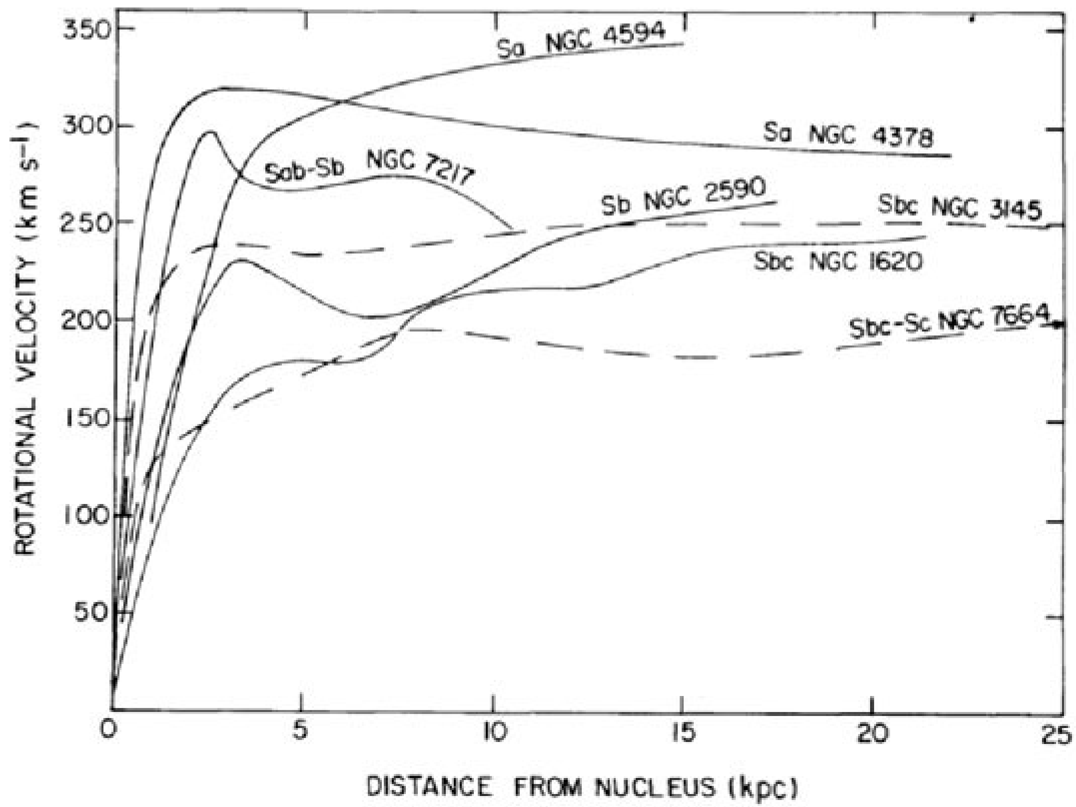
The holidays brought sad news to astronomers across the world after they learned that Vera Rubin, whose pioneering work led to the confirmation of dark matter, passed away.

Astronomer Vera Rubin, known for her revolutionary work confirming the existence of dark matter, died on December 25th. She was 88.

Vera Rubin at Lowell Observatory in 1965.

Rubin’s love for celestial motions began at a young age. In 1938, when she was just 10 years old, her family moved from Philadelphia to Washington, D.C., where she inherited a north-facing bedroom window. There, she



Rubin+ 1978

Flat rotation curves

Circular velocity of starts determined by enclosed mass

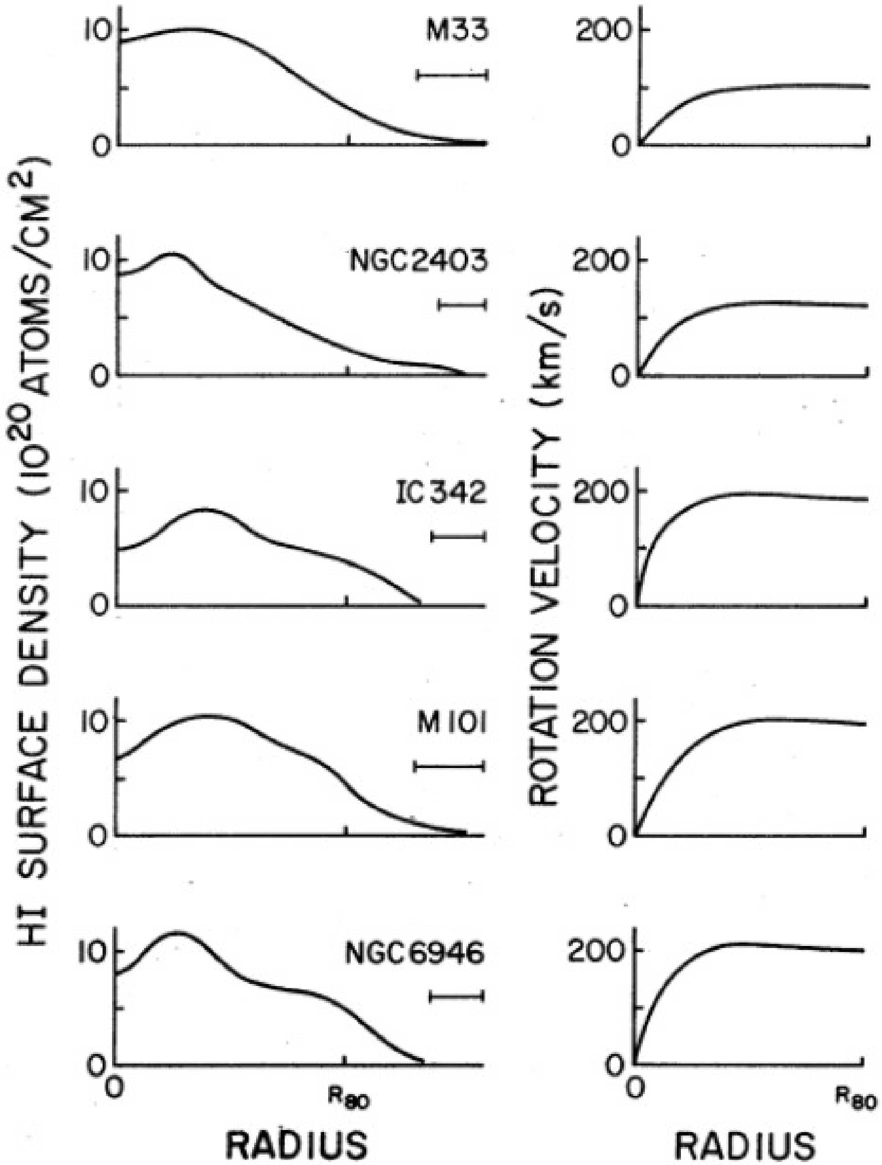
$$v_c^2(<R) = R\frac{d\phi_{\rm tot}}{dR} = \frac{GM(<R)}{R}$$

$$M(<R) \equiv 4\pi\int_0^R r^2\rho(r)dr$$

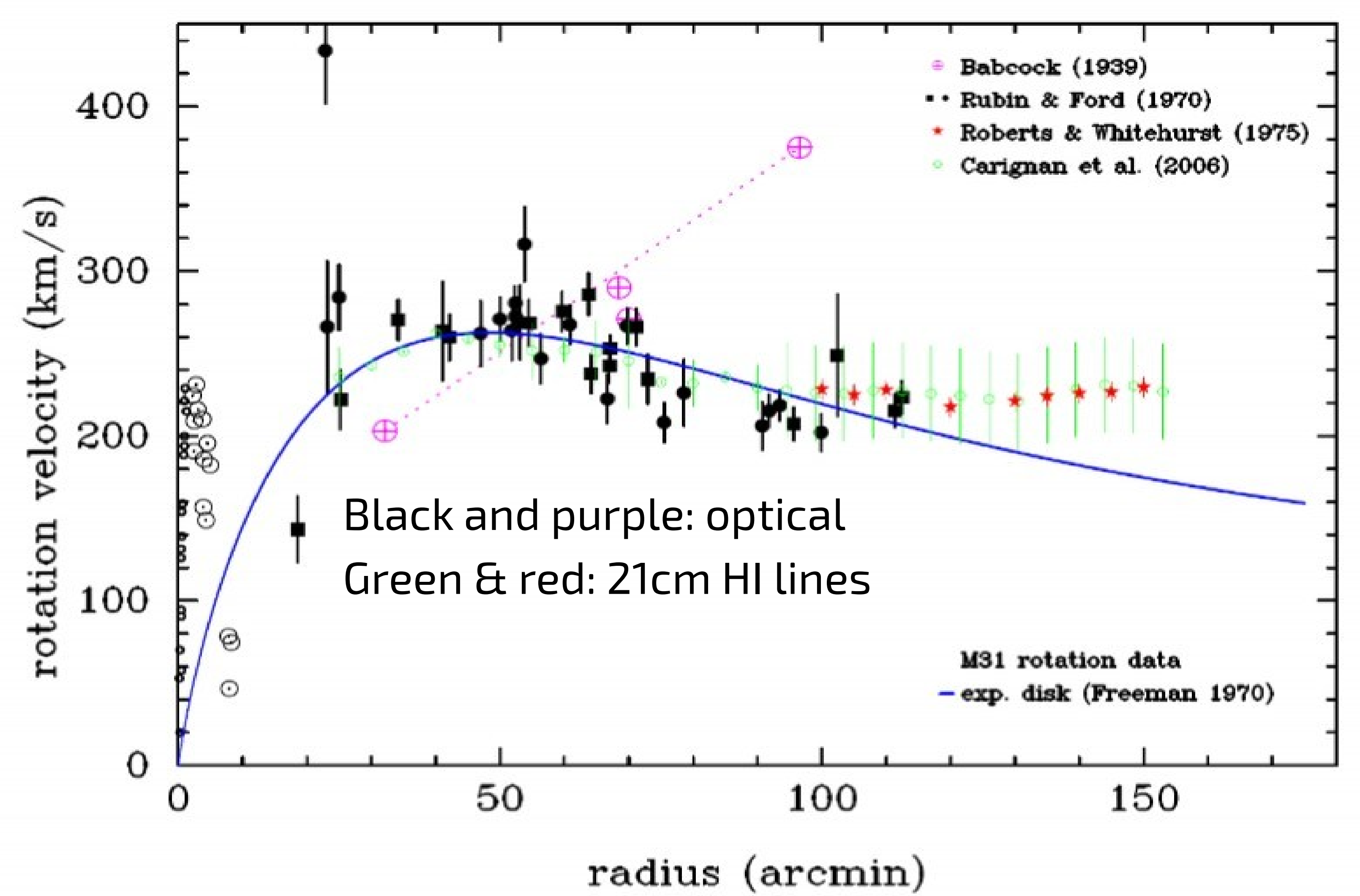
Centrally concentrated mass implies $v_c^2 \propto \frac{1}{R}$

Actually observed $v_c^2 \sim constant$

Suggests $\rho(r) \propto \frac{1}{r^2}$



The 1970s revolution



Radio observations of the 21cm hyperfine transition of neutral hydrogen (HI), done by Roberts and oters, played a big role in establishing the existence of flat rotation curves robustly.

The 1970s revolution

- The 1970s "revolution" was actually a slow process that involved many astronomers, and optical and radio observation, which consistently pointed towards flat rotation curves towards large radii.

- Missing mass in galaxy clusters was know to be a problem.

- After the discovery of the cosmic microwave background in 1965, in 1973 (Reeves et al) it becomes clear that Big Bang Nucleosynthesis only allows for 10% of the critical density being due to baryons.

$$\Omega_b = \frac{\rho_b}{\rho_\mathrm{crit}} \sim 0.1$$

  Leaves the desire to "close the Universe" with some additional component.

→ Possibilitiy of additional mass started to be taken more serious by astronomers and by theoretical physicists and cosmologists. BBN suggested that this additional mass could be plausibly of non-baryonic nature.

The advent of DM candidates

1976: Light Neutrinos

Zeldovich& Gershtein 1966 → Upper limit on neutrino masses 400 eV

Szalay & Marx 1976 → ~10 eV neutrinos might account for “missing mass”

White, Frenk & Davis 1983 → neutrinos (hot DM) excluded

1977: Heavy neutrinos

Hut; Lee & Weinberg; Sato & Kobayashi; Zeldovich 1977 → multi-GeV neutrinos are allowed
"Of course, if a stable heavy neutral lepton were discovered with a mass of order 1-15 GeV, the gravitational field of these heavy neutrinos would provide ***a plausible mechanism for closing the universe.****"* (Lee & Weinberg 1977)

1977: Gravitinos

Hut 1977 → “cosmological gravitino problem”

Pagels & Primack 1982 → “*Gravitinos could also provide the* ***dark matter required in galactic halos and small clusters of galaxies***”

1977: Axions

Wilczek; Weinberg 1977 → Peccei-Quinn mechanism implies Nambu-Goldstone boson

Abbott & Sikivie 1983 → Misalignment mechanism and cold DM

1983: Neutralinos

Weinberg & Goldberg 1983 → photino DM

Ellis, Hagelin, Nanopoulos, Olive & Srednicki → **neutralino DM**

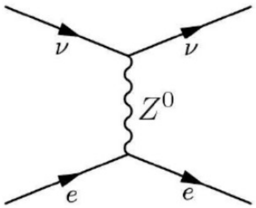
1993: Sterile neutrinos

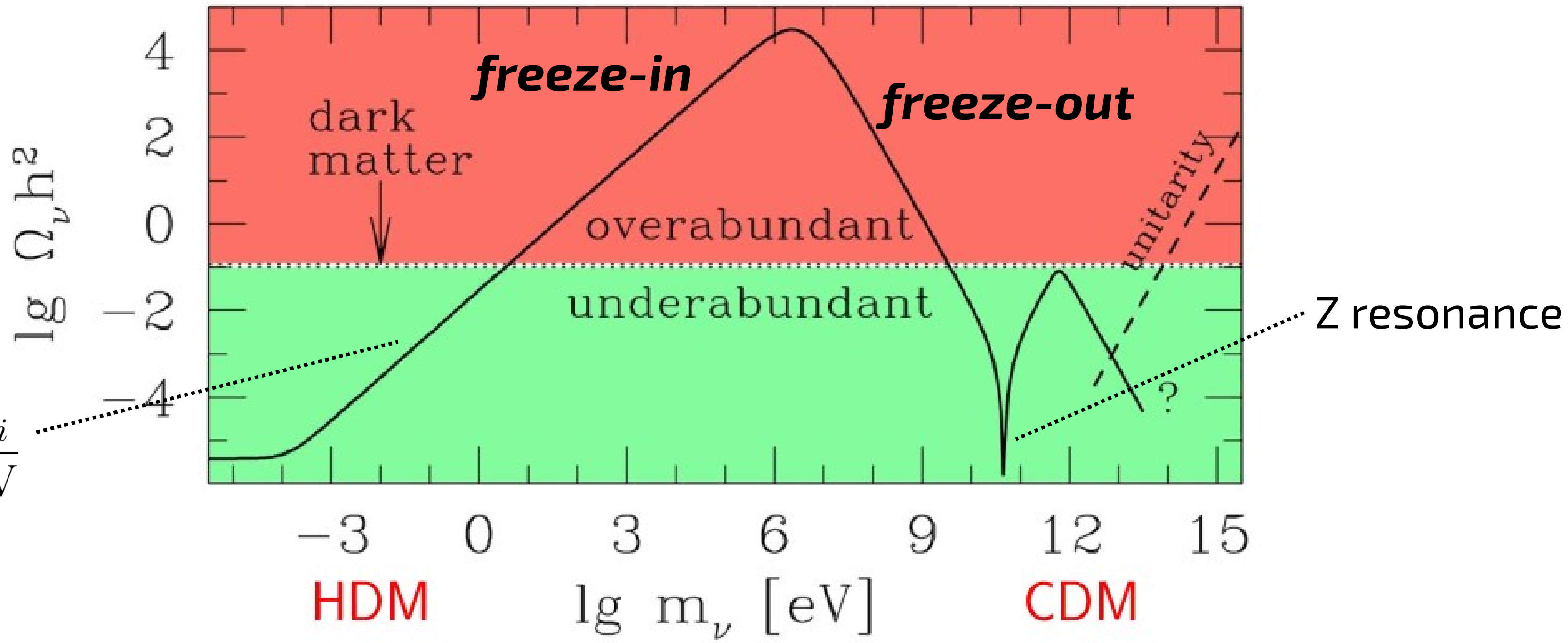
Dodelson & Lawrence 1993 → sterile neutrinos with masses above ~ keV as DM candidate

The original WIMPs

Graciela Gelmini-UCLA

The original WIMP Lee and Weinberg 1977 considered active neutrinos- now 4th gen- took Dirac neutrinos, $\chi \neq \bar{\chi}$ but without an asymmetry(Fig from P. Gondolo)





$$\Omega_\nu h^2 \simeq \sum_i \frac{g_i m_i}{90\,\mathrm{eV}}$$

Two solutions for CDM, one on each side of the Z-resonance:

$\sigma \simeq G_F^2 m_\chi^2$ thus $\Omega_\chi h^2 \simeq (GeV/m_\chi)^2$ and $\sigma \simeq g_w^4/m_\chi^2$ thus $\Omega_\chi h^2 \simeq (m_\chi/TeV)^2$

For 4th. gen. active neutrinos, $m < m_Z/2$ forbidden by LEP-but similar for other models

Hot, warm and cold dark matter

Dark Matter is classified as "HOT" or "WARM" of "COLD" if it is

RELATIVISTIC (moves with c), SEMI-RELATIVISTIC or NON-RELATIVISTIC

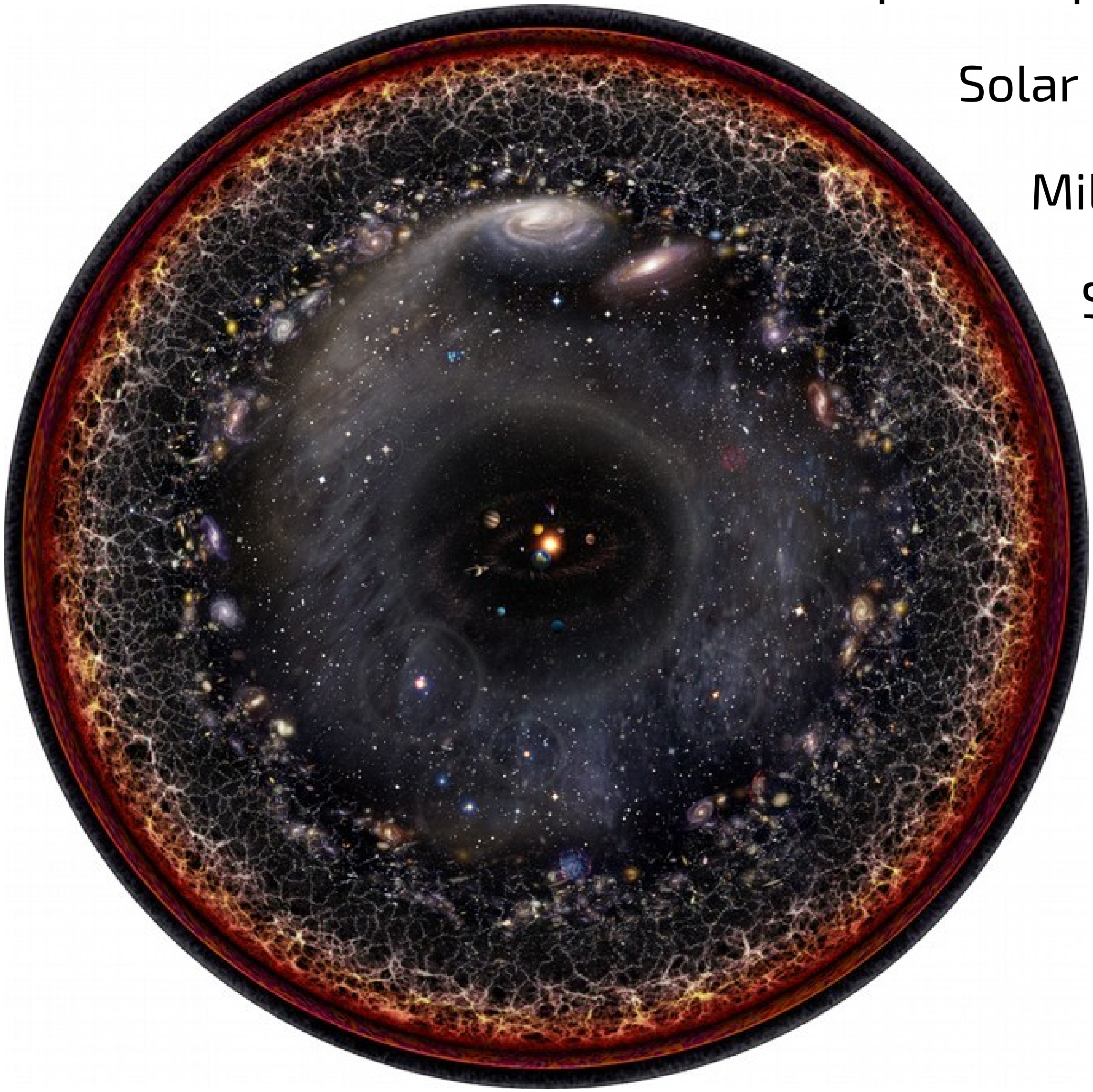
at the moment dwarf galaxy core size structures start to form (when $T \sim$ keV). We know since the 1980's (Fig. S. White 1986) that these structures (or smaller ones) form first and structure cannot form with relativistic matter.

ISSAP, Texel, Amsterdam, Netherlands, June 30, 2017 41

40 years

Evidence for particle dark matter

Modern perspective



Solar neigbourhood

Milky Way rotation

Satellite galaxies

Nearby galaxies

Galaxy groups/clusters

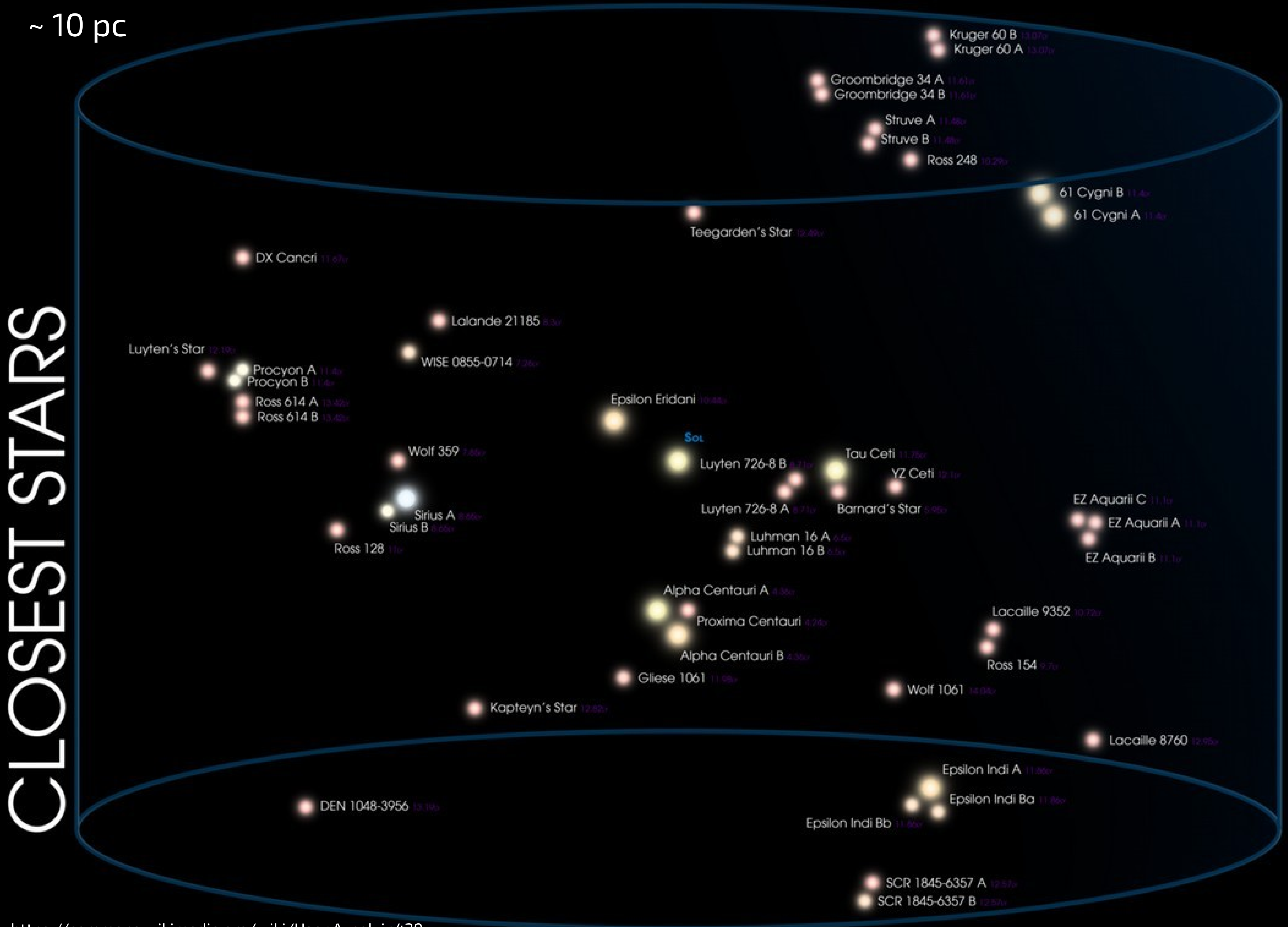
Large scale structure

Cosmic microwave background

Primoridal nucleosynthesis

Image credit: Wikipedia

~ 10 pc



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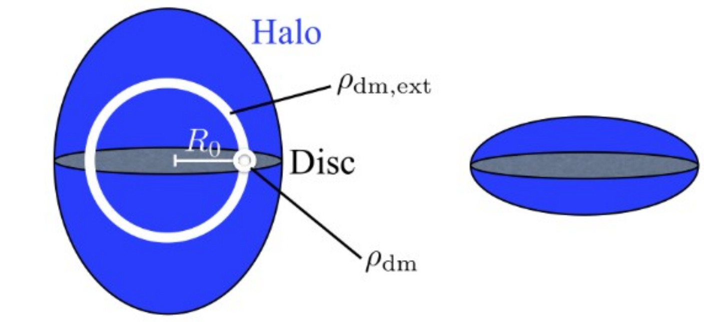
Local DM density

Tracer stars expected to follow collisionless Boltzmann equation

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \nabla_x f \cdot \mathbf{v} - \nabla_v f \cdot \nabla_x \Phi = 0$$

with gravitational potential

$$\nabla_x \cdot \nabla_x \Phi = \nabla_x^2 \Phi = 4\pi G \rho$$



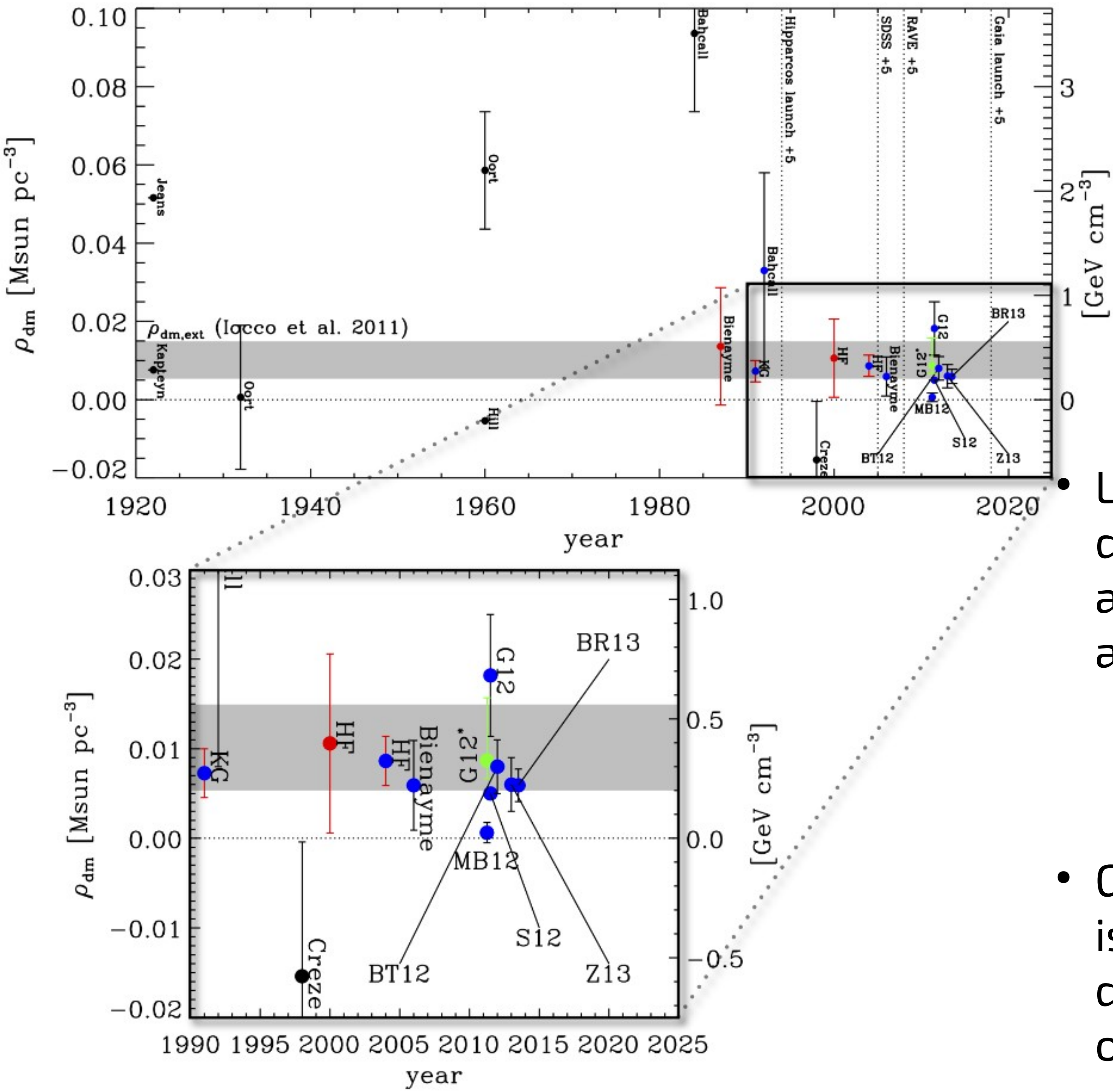
Moment method: Integrating over moments gives
Jeans equation (here 1-dim in vertical direction):

$$\underbrace{\frac{1}{R}\frac{\partial\left(R\nu\sigma_{Rz}\right)}{\partial R}}_{\text{tilt term } \mathcal{T}} + \frac{\partial}{\partial z}\left(\nu\sigma_z^2\right) + \nu\frac{\partial\Phi}{\partial z} = 0$$

Measuring vertical velocity dispersion of tracer stars
→ Constraints on local DM density

Justin Read 2014

Local DM density measurements



Justin Read 2014

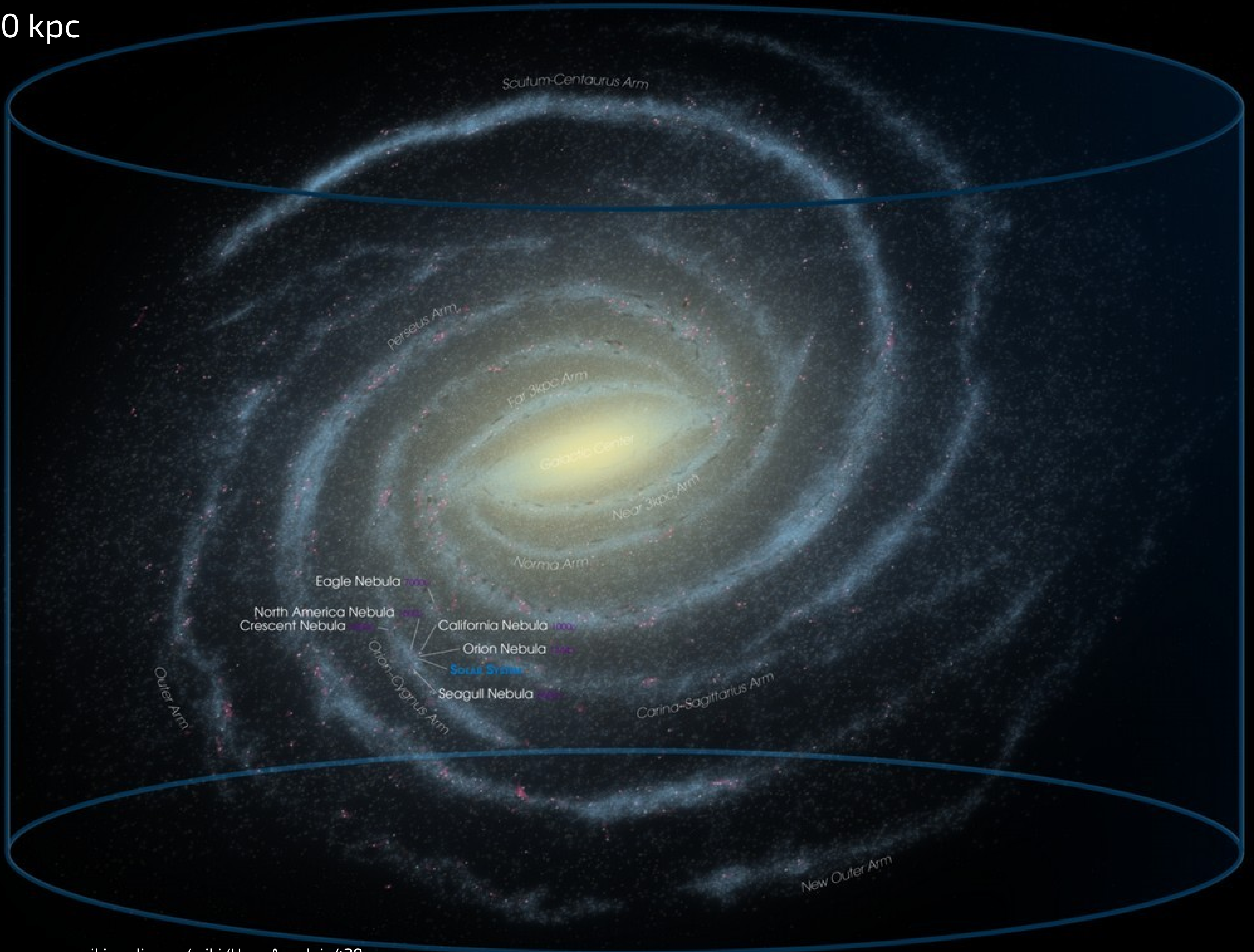
- Local measurements of the DM density have come a long way and now converge to numbers around

$$\rho \sim 0.2 - 0.55 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

- GAIA observations show that MW is not in equilibrium, which drastically complicates problem of further bringing error bars down

~ 50 kpc

MILKY WAY GALAXY



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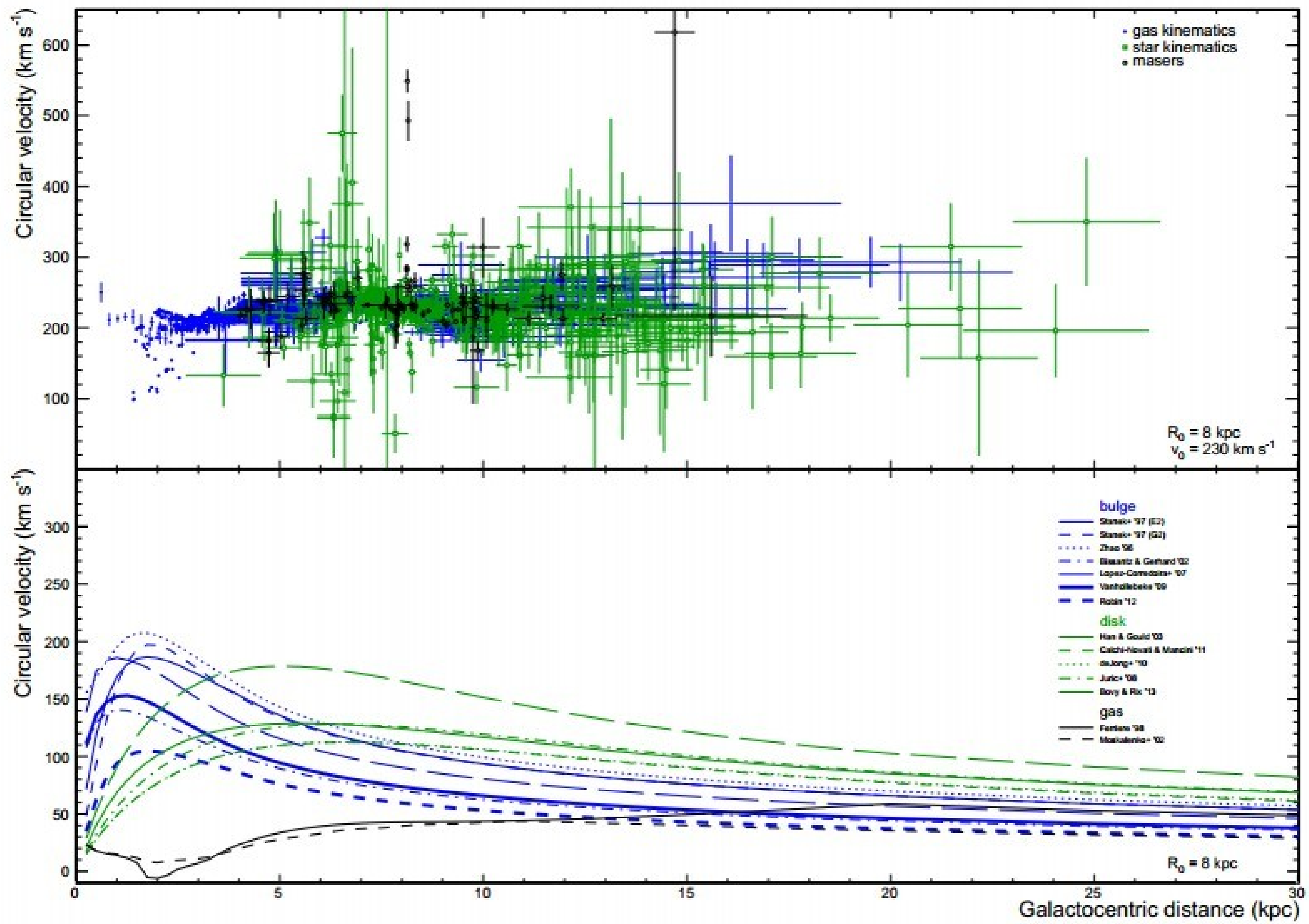
Milky Way rotation curves, ca. 2015

Rotation curves, measured from gas and stellar dynamics, all data combined. The rotation curve is flat from the inner few parsec out to ~25 kpc (we are at ~8.5 kpc).

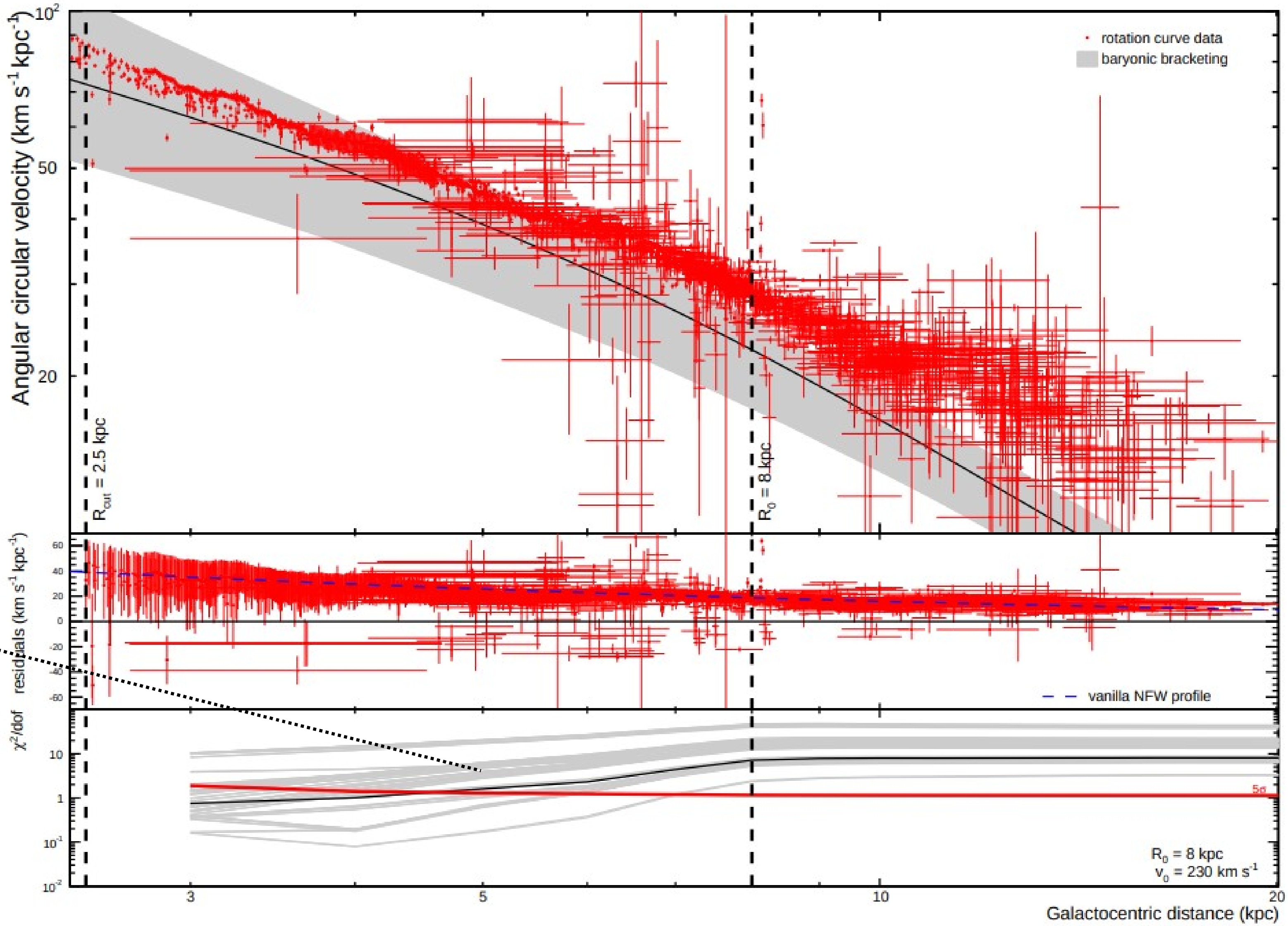
Range of models for stellar and gas mass (callibrated on observations), for comparison.



Iocco+ 2015

Milky Way rotation curves, ca. 2015

Gray bar is envelope of all gas + star mass models, red “crosses” show DM density. There is a clear excess above predictions from baryonic matter alone at > 8 kpc and below.

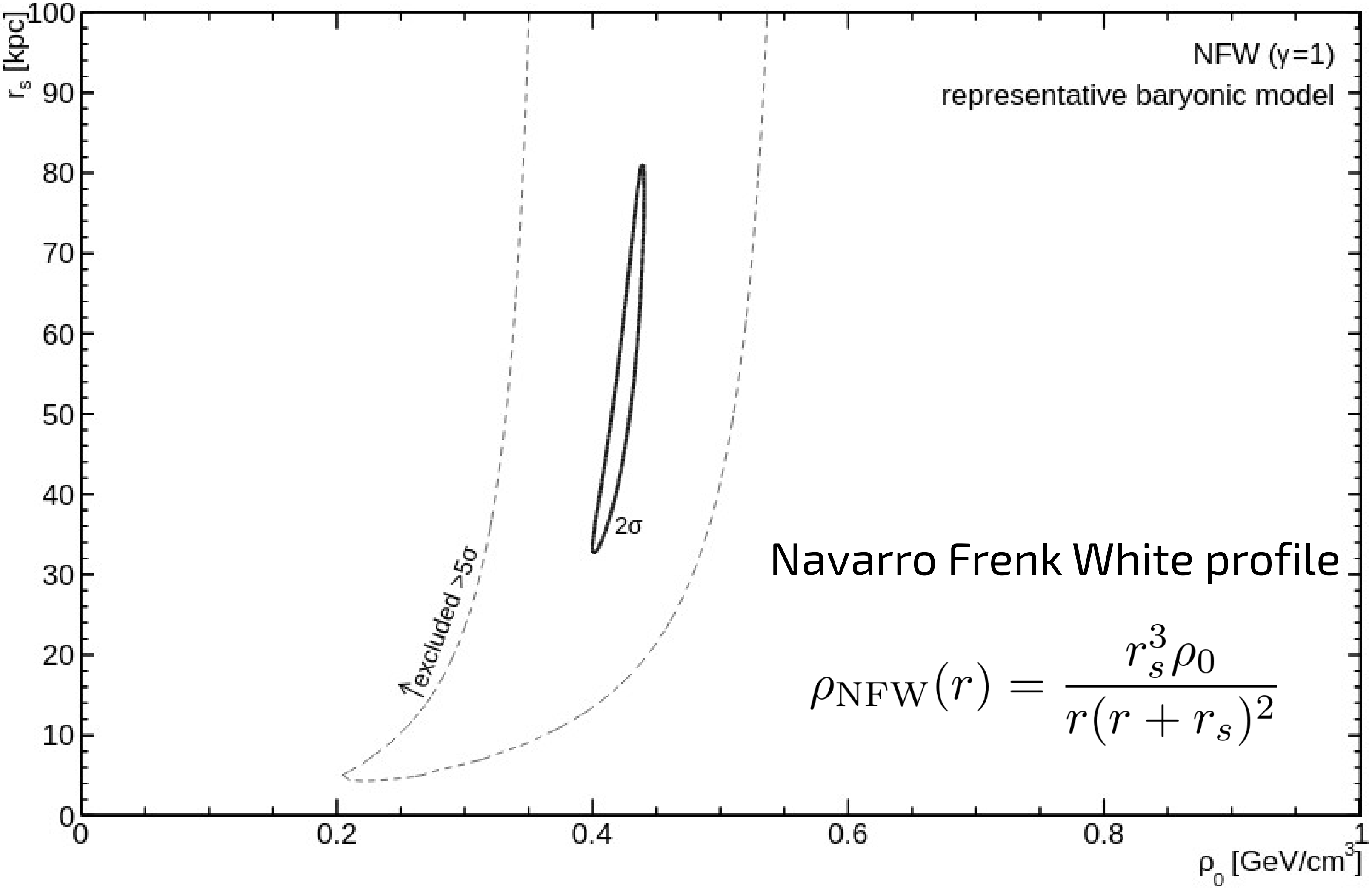


DM component is detectable down to about r~5 kpc, before Baryons take completely over.

→ No strong observational constraints on DM distribution in inner galaxy.

Iocco+ 2015

Constraints on DM profile



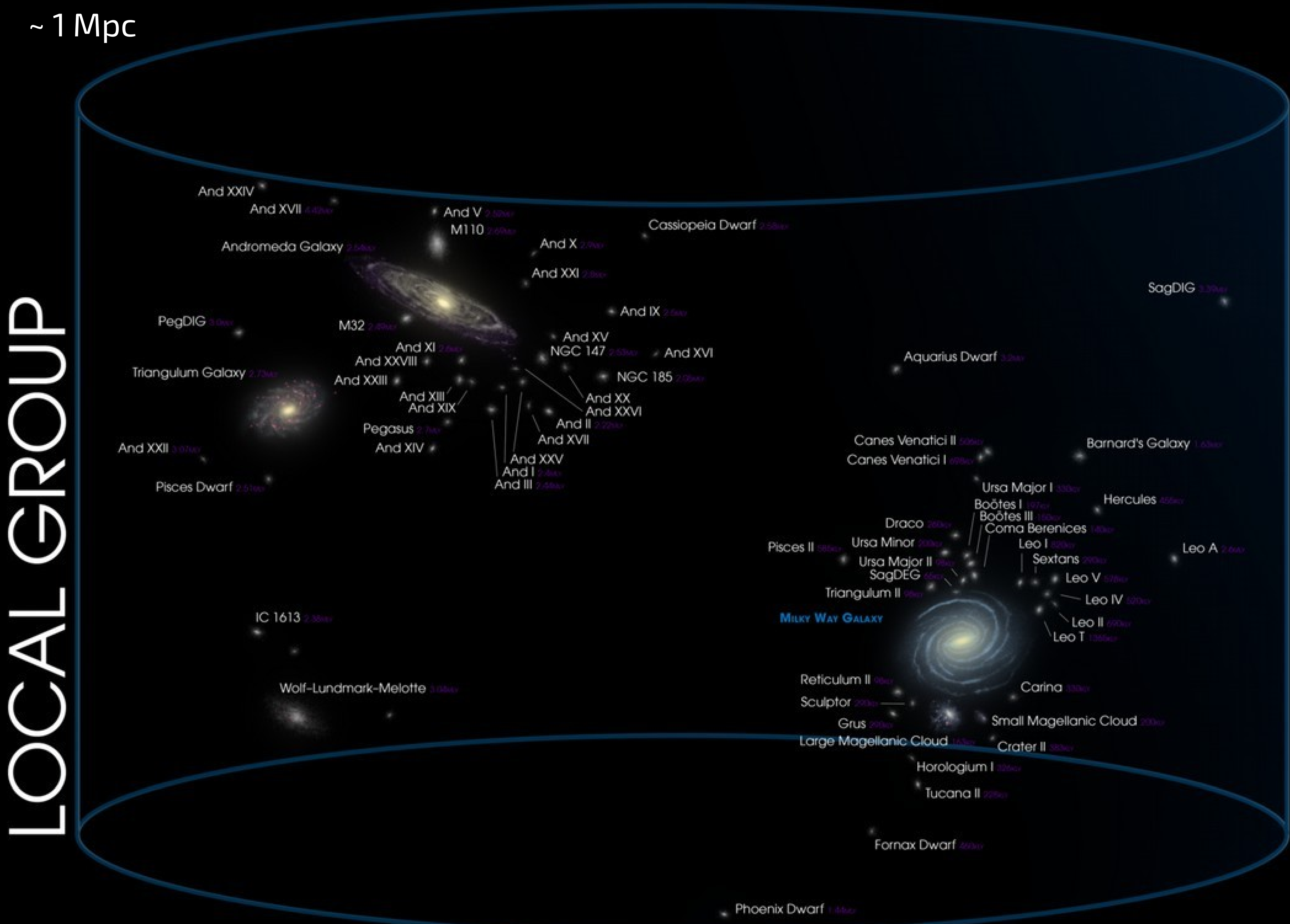
Navarro Frenk White profile

$$\rho_{\mathrm{NFW}}(r) = \frac{r_s^3 \rho_0}{r(r + r_s)^2}$$

Assuming a specific functional form for the DM profile of the Milky way allows to derive formally very strong constraints on the local dark matter density. However, systematical uncertainties due to baryonic models, DM profile shape are large and up to O(1).

Iocco+ 15

~ 1 Mpc



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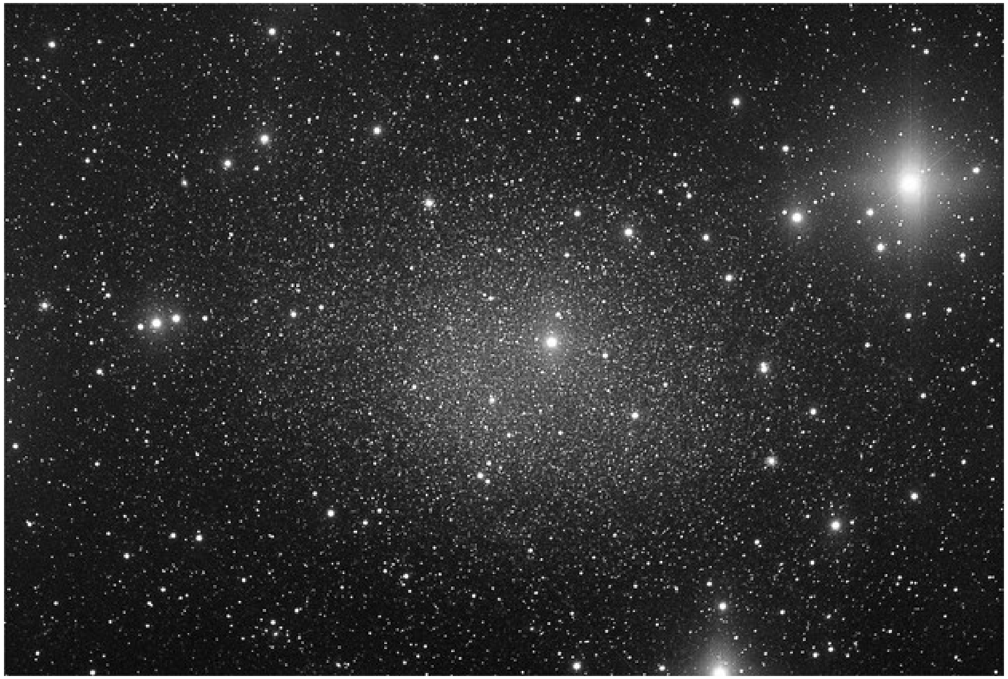
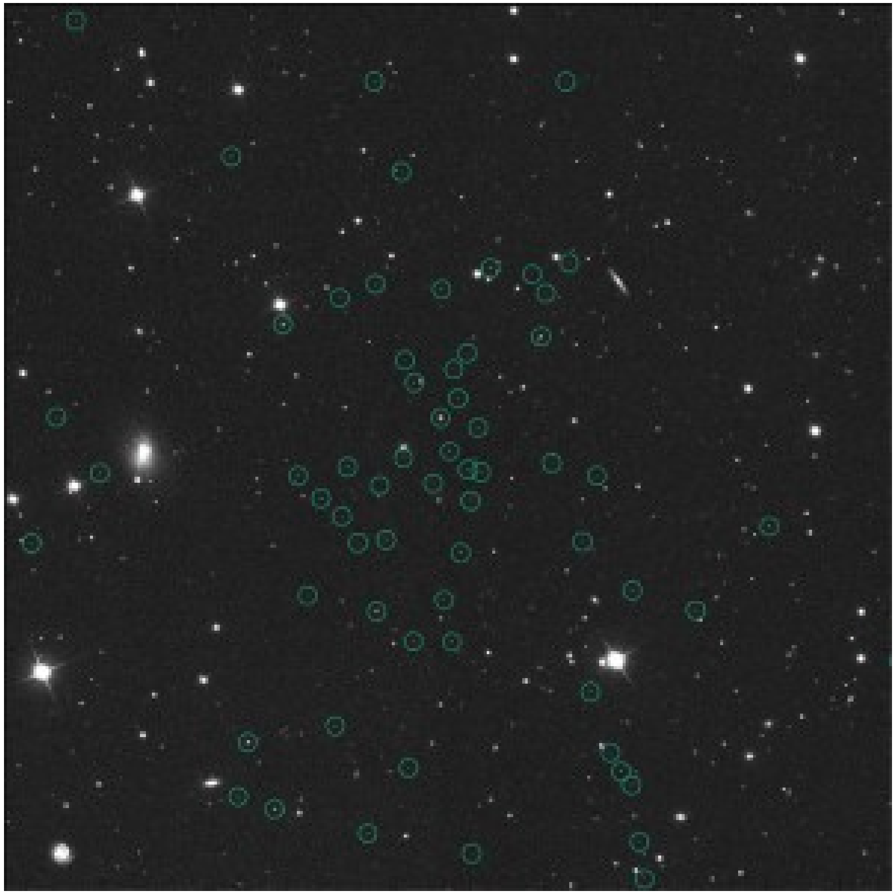
Dwarf spheroidal galaxies

Classical dwarf spheroidal
(Fornax)



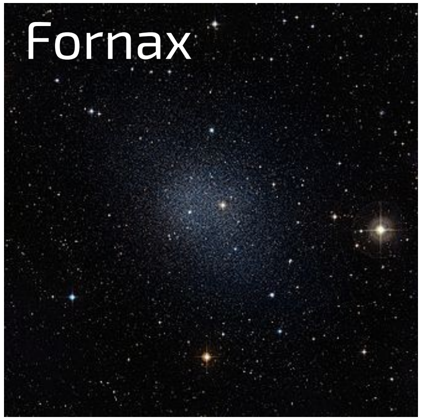
Classica dSphs consist of thousand of gravitationally bound stars. Their motion allows to map out the grav. potential reasonably well.

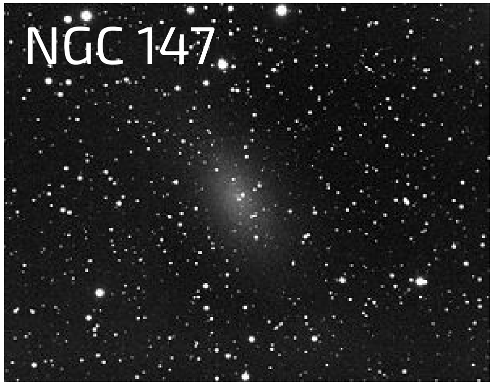
Ultra-faint dwarf spheroidal
(Segue 1)

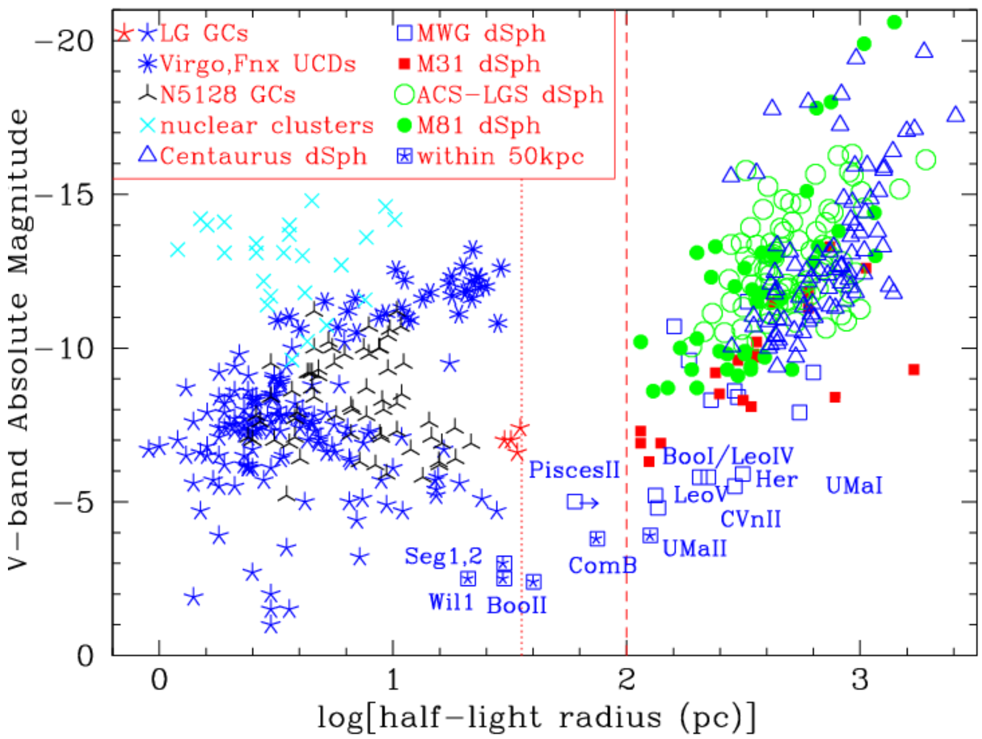


“Ultrafaint dwarfs” consists just of dozens of stars. CDM predicts hundreds of them, but only dozens have been found so far.

Dwarf spheroidal galaxies





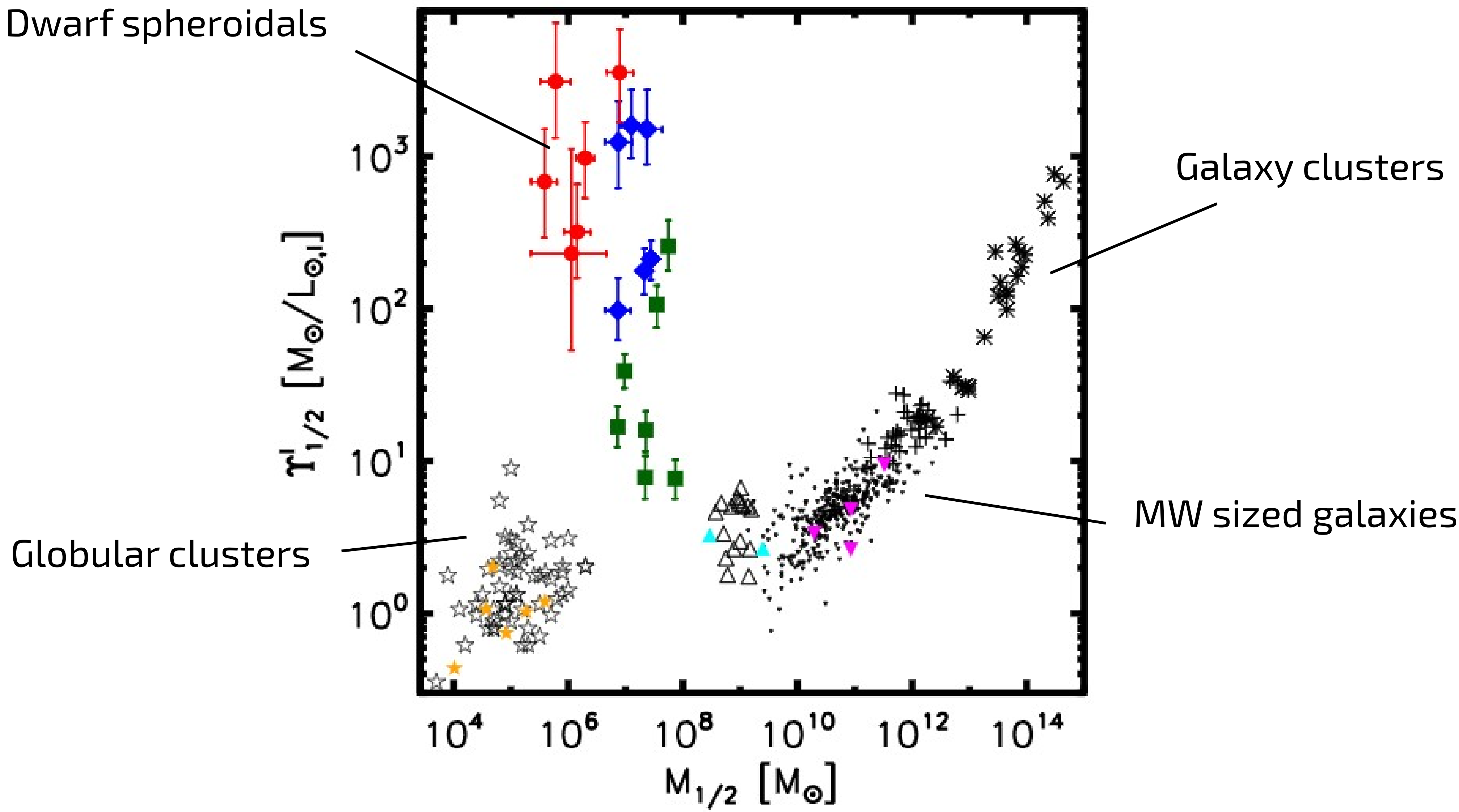


Credit: Wyse+ 2010

Dwarf spheroidal galaxies

- 9 classical dwarfs
- >25 ultra-faint dwarfs around found in recent surveys (SDSS, DES)
- dSphs have very large M/L ratios → Completely DM dominated
- Astrophysically inactive → no gamma-ray emission expected

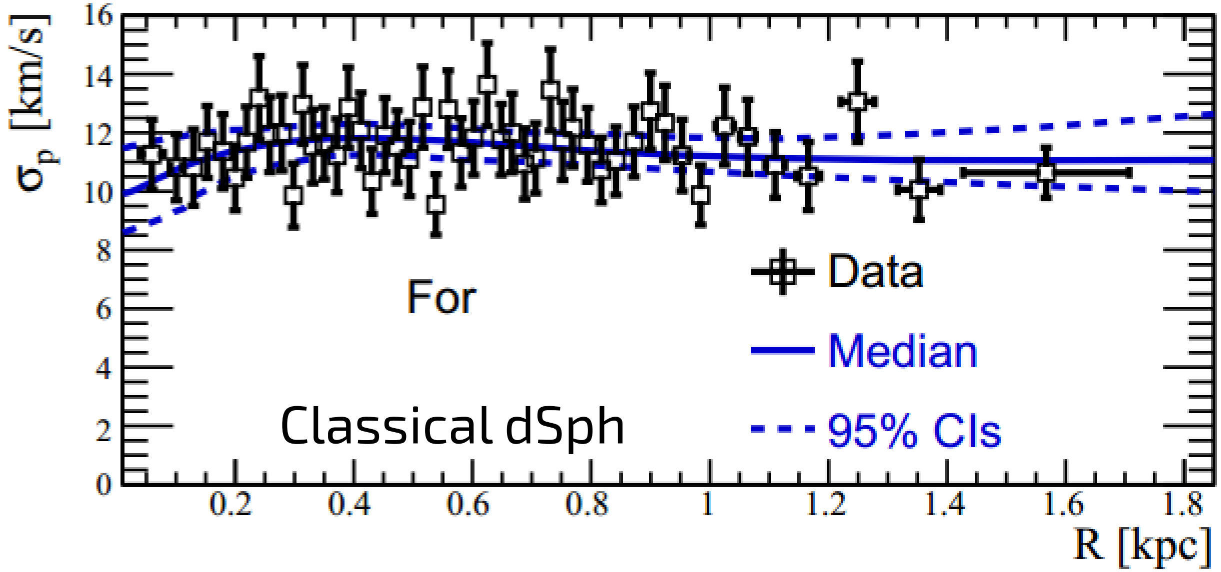
M/L for smallest to largest objects



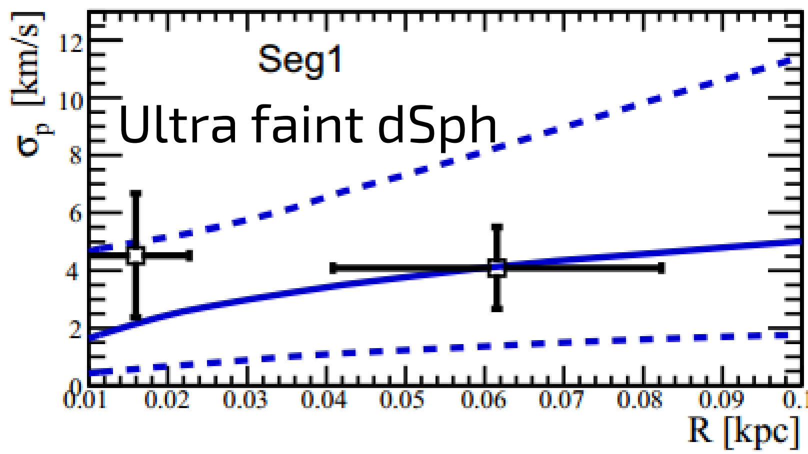
Relative inefficiency of star formation in very small or very large DM halos leads to large mass-to-light ratios for these objects.

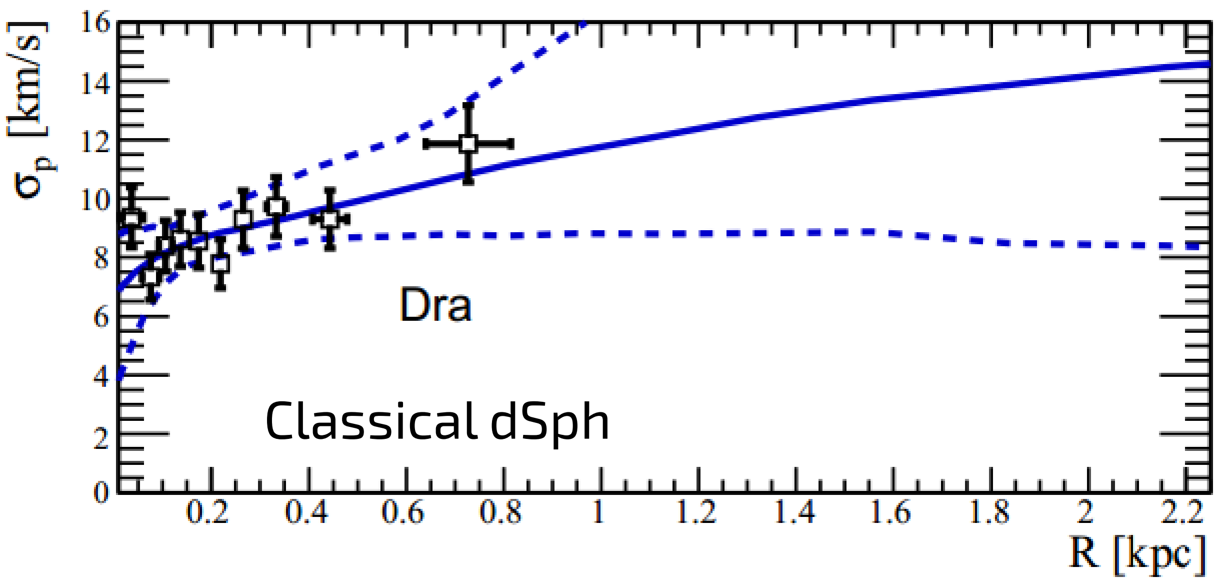
Wolf+ 2009

Example velocity dispersion measurements



Line-of-sight projected velocity dispersion



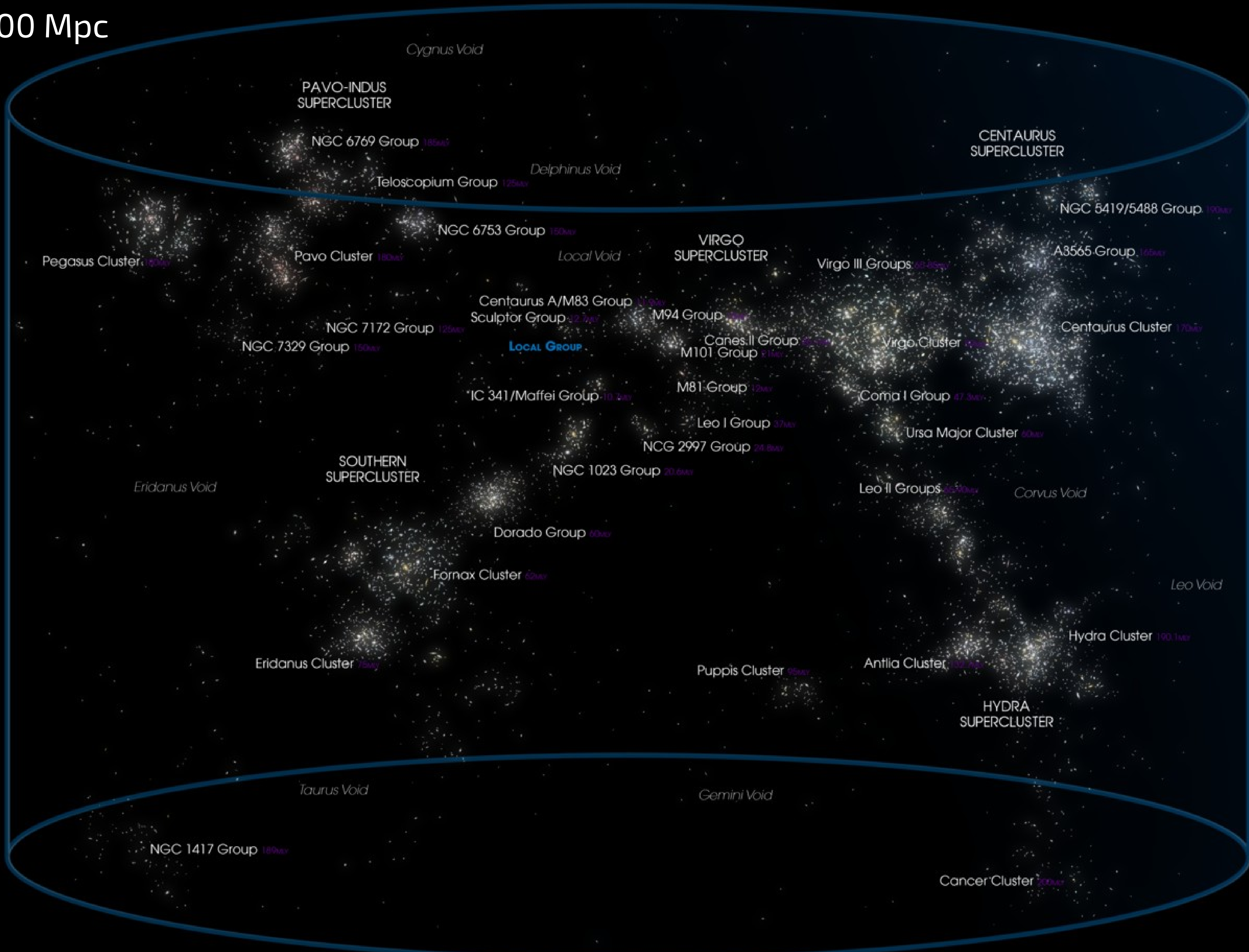


Projected (along radial direction) velocity dispersion of stars can be well reproduced with common DM profiles. For typical ultra faint dSphs the measurements remain very uncertain, dependent on methods and assumptions.

Bonnivard+ 2015

~ 100 Mpc

LANIAKEA



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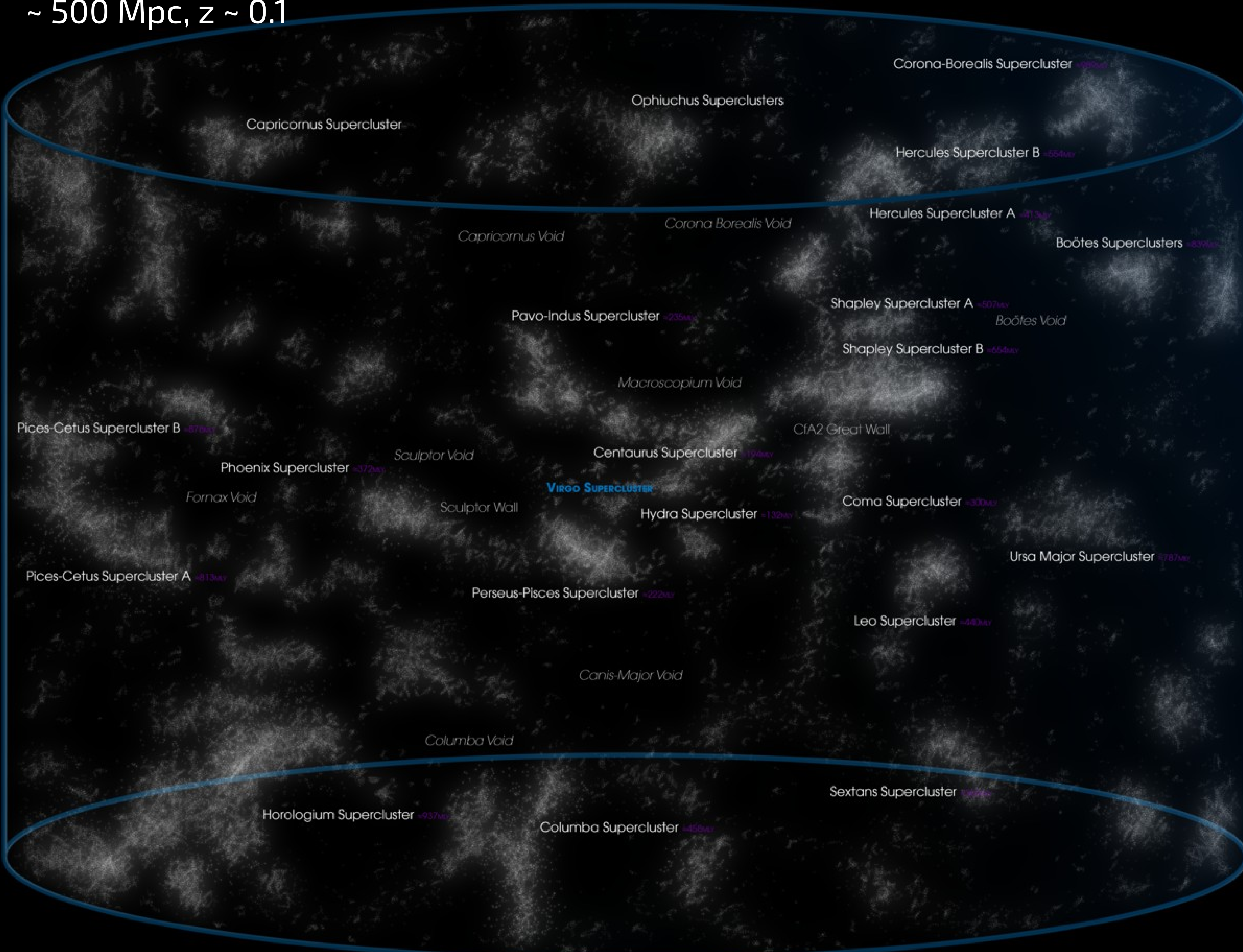
LOCAL SUPERCLUSTERS

~ 500 Mpc, z ~ 0.1



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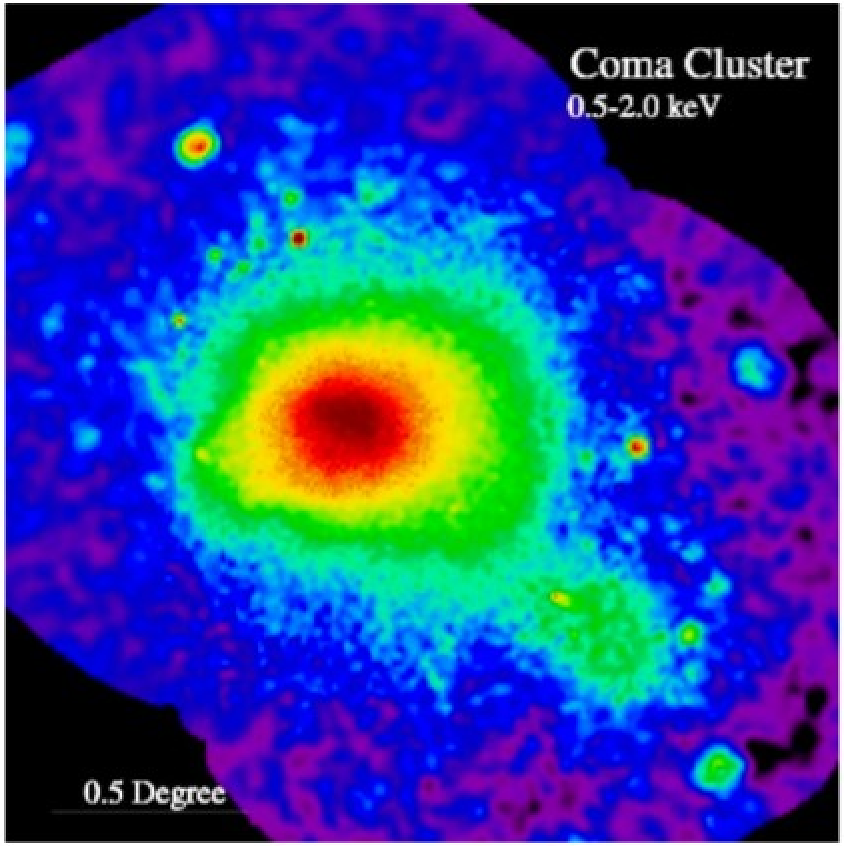
X-ray emission from intracluster gas



Most of the baryonic gas in galaxy clusters is in the form of hot, integralactic gas, which can be traced via X-ray emission.

Assuming hydrostatic equilibrium and spherical mass distribution:

$$\frac{dP_{\rm gas}}{dr} = -\frac{GM_{\rm cl}(\leq r)\rho_{\rm gas}}{r^2}$$

Using ideal gas law

$$M_{\rm cl}(\leq r) = -\frac{kT}{\mu m_p G}\left(\frac{d\ln\rho_{\rm gas}(r)}{d\ln r} + \frac{d\ln T}{d\ln r}\right) r$$

The X-ray mass of galaxy clusters typically exceeds gaseous and stellar mass by factors of a few, reasonably consistent with values inferred from the CMB.

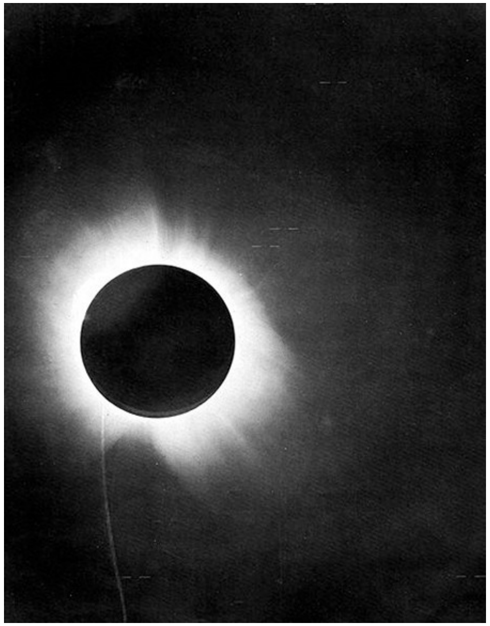
$$\frac{M_{\rm cl}}{M_{\rm gas+stars}} \sim 5$$

Gravitational lensing

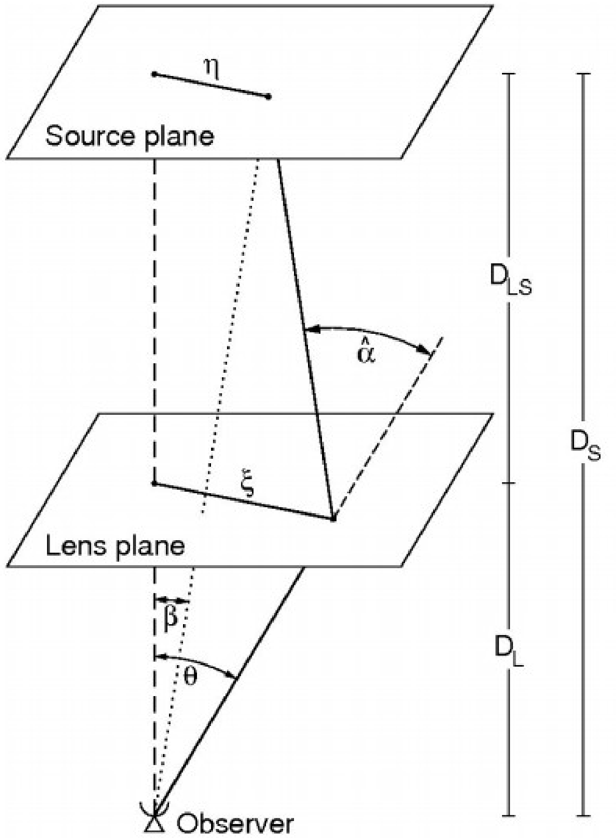
Historic example

May 1919, Eddington

Confirmation of GR



Basic idea



Column density of mass, integrated along line-of-sight

$$\Sigma(\vec{\xi}) = \int \rho(\vec{\xi}, z)\, \mathrm{d}z$$

Calculation of angular displacement

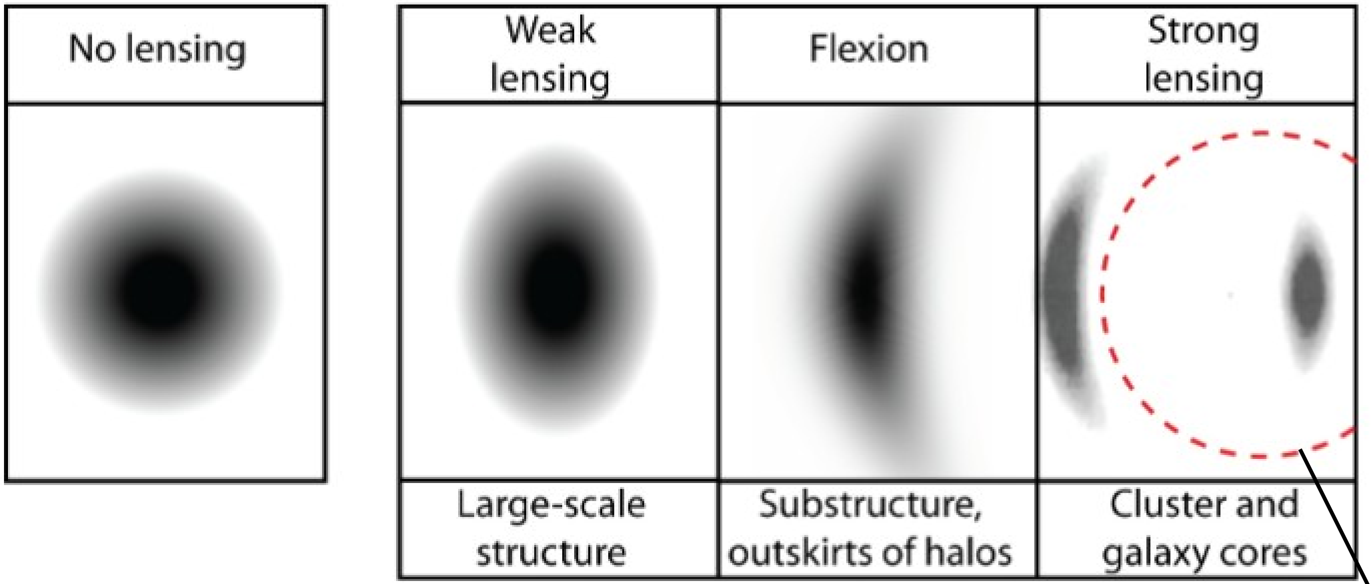
$$\vec{\hat{\alpha}}(\vec{\xi}) = \frac{4G}{c^2} \int \frac{(\vec{\xi} - \vec{\xi}')\Sigma(\vec{\xi}')}{|\vec{\xi} - \vec{\xi}'|^2}\, \mathrm{d}^2\xi'$$

$$\boxed{\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})} \qquad \vec{\alpha}(\vec{\theta}) \equiv \frac{D_{\mathrm{LS}}}{D_{\mathrm{S}}} \vec{\hat{\alpha}}(\vec{\theta})$$

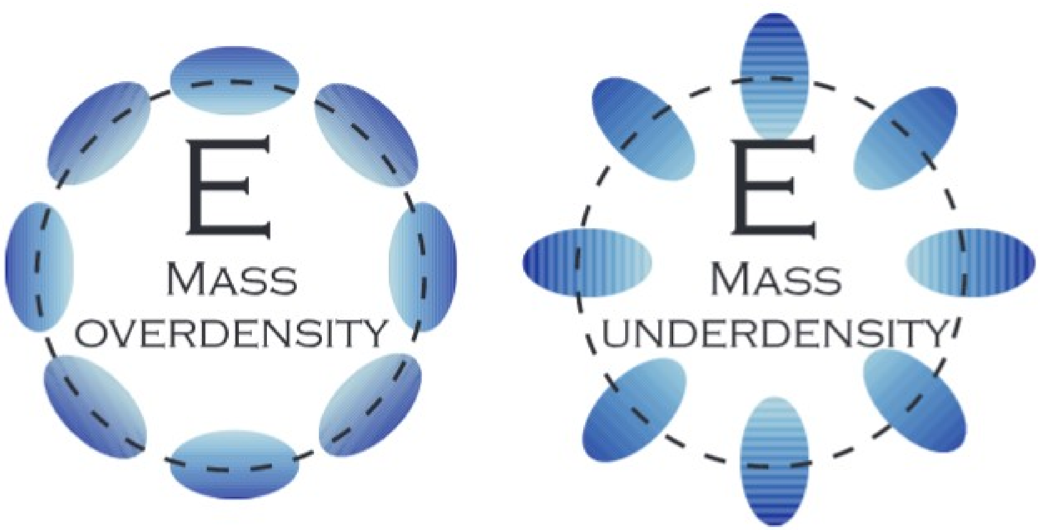
Bartelmann & Schneider 2001 Massey+ 2010 M. Meneghetti, lecture notes

Gravitational lensing

Weak lensing is only concerned with affine transformations of the lensed structures, the underlying grav. potential can be inferred statistically. **Strong lensing** is caused by high overdensities and completely distortes the source image.



The effect of mass over- and under-densities.

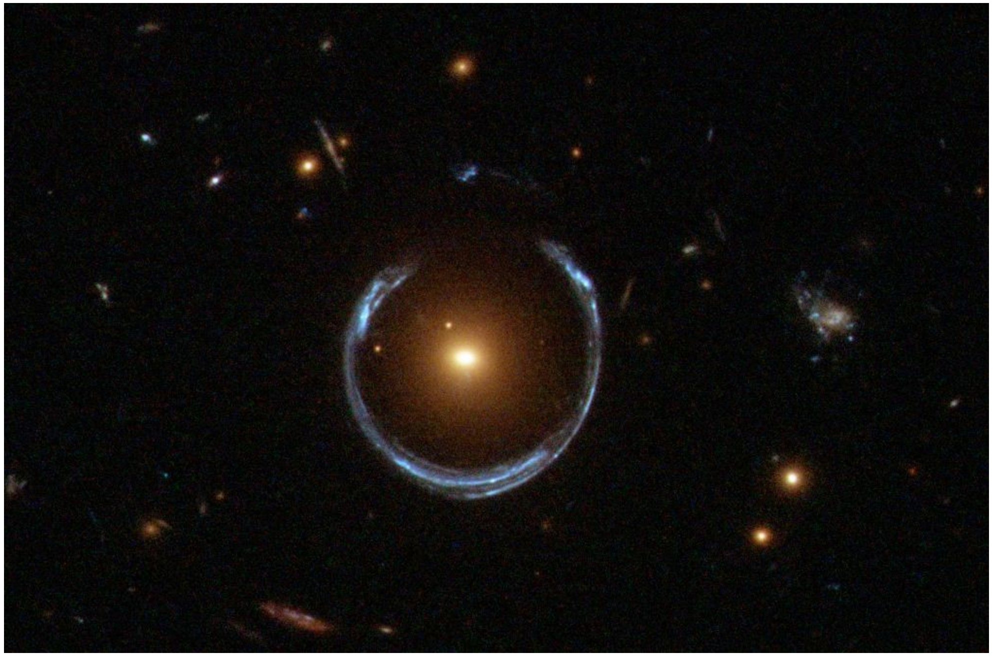


Einstein ring, caused by exact alignment between source, ring and observer

$$\theta_1 = \sqrt{\frac{4GM}{c^2}\,\frac{d_{LS}}{d_L d_S}};$$

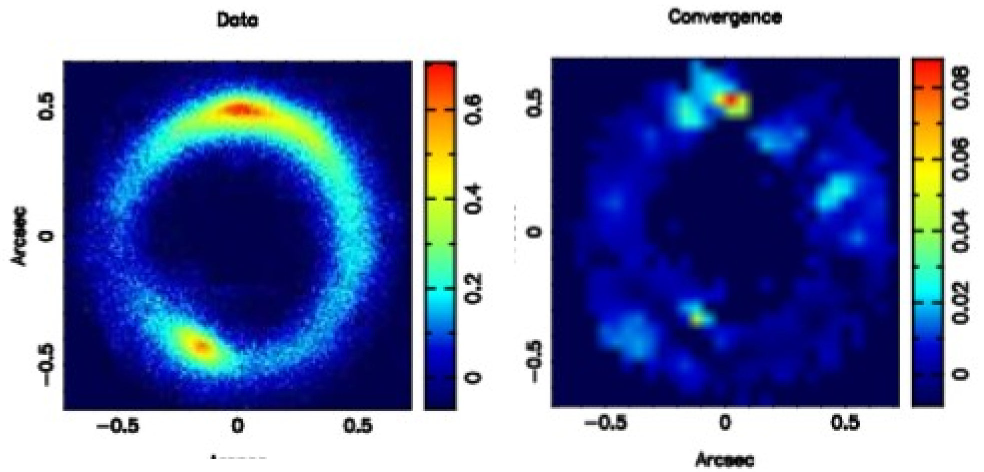
Bartelmann & Schneider 2001

Strong gravitational lensing



LRG 3-757 (HST)

Strong lensing systems are rare. The Einstein ring constraints the mass of the main lens, **while small perturbations in the ring are caused by smaller galaxies in the main lens or along the line-of-sight**. The below example corresponds to a relatively small halo (dSph size).



Detection of ~2e8 Msol dark satellite in Einstein ring of JVAS B1938+666 (Keck II)

Vegetti+ 2012

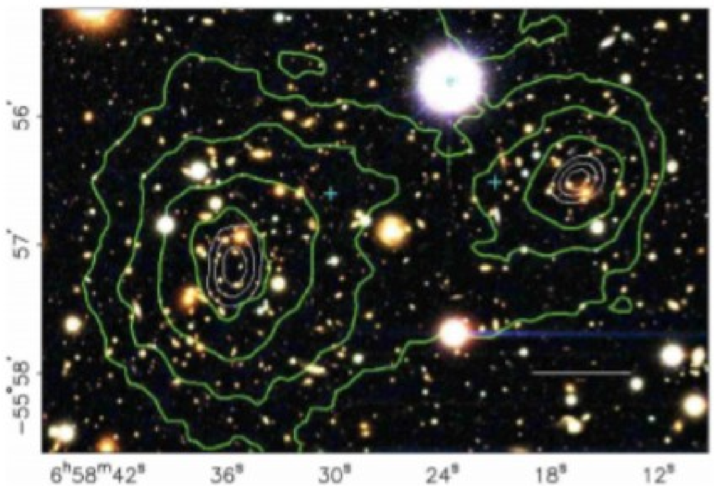
DM/baryon mass segregation

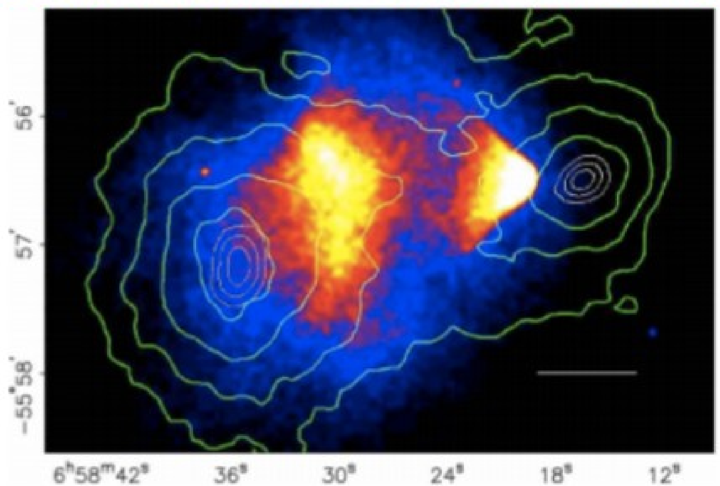
Optical, X-ray and weak leansing measurements can be used to disentangle stellar, gaseous and dark mass. In colliding galaxy clusters, the different behaviour of gas (colliding) and galaxies / dark matter (collisionless) can be directly observed.

Bullet Cluster (1E 0657-56)

Clowe+, ApJ 604 (2004) 596-603; Clowe+ ApJ, 648 (2006) L109

~1.1 Gpc

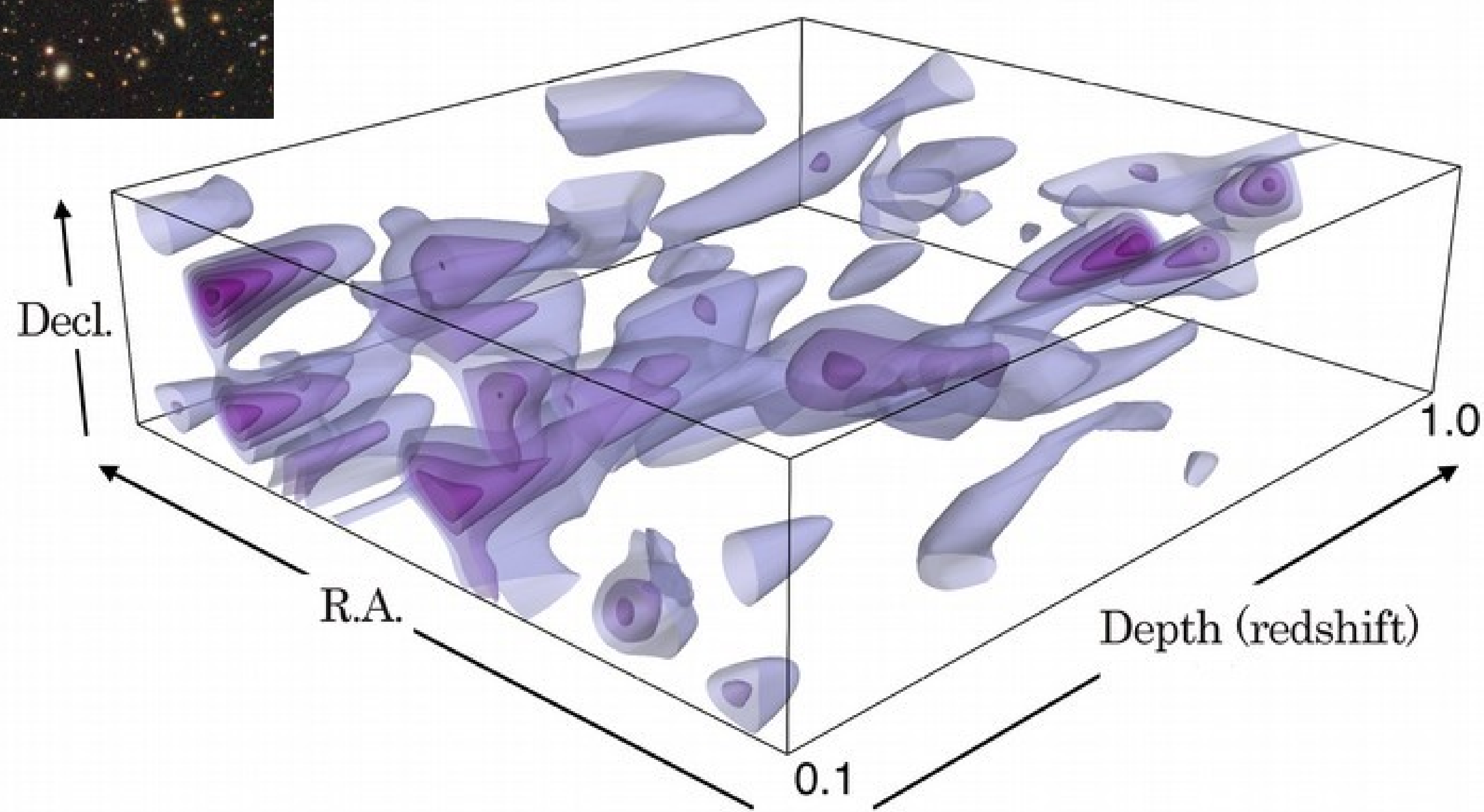




James Jee+, ApJ 783 (2014) 78

Weak lensing beyond the local superclusters

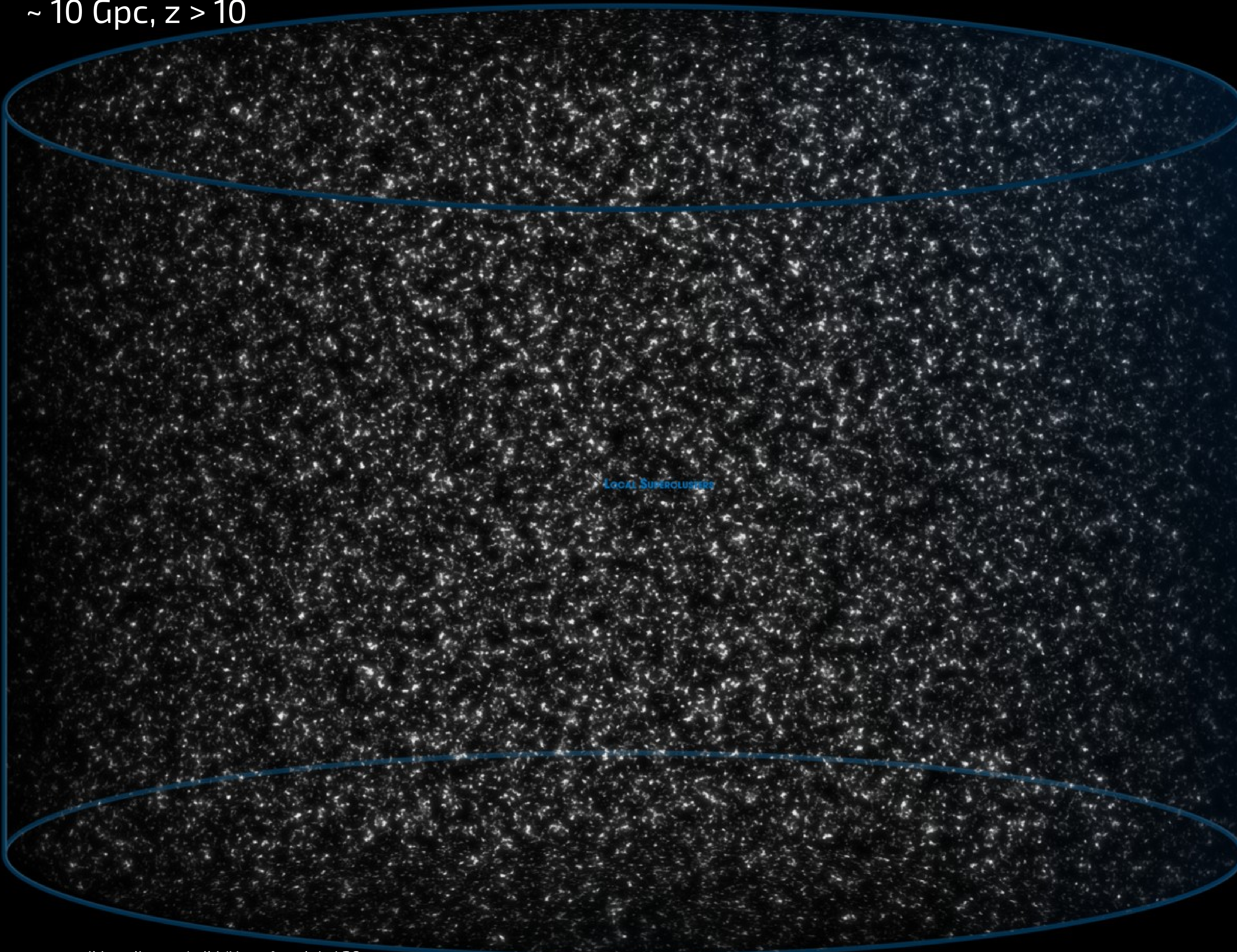
Weak lensing reconstruction of DM distribution up to redshift z = 1.0, based on observations with the Hyper Suprime-Cam on the Sabura Telescope



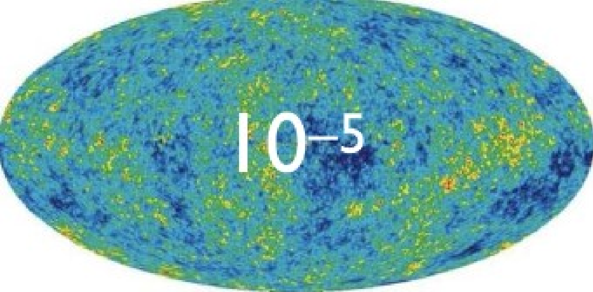
https://www.nao.ac.jp/en/news/science/2018/20180302-hsc.html

OBSERVABLE UNIVERSE

~ 10 Gpc, z > 10

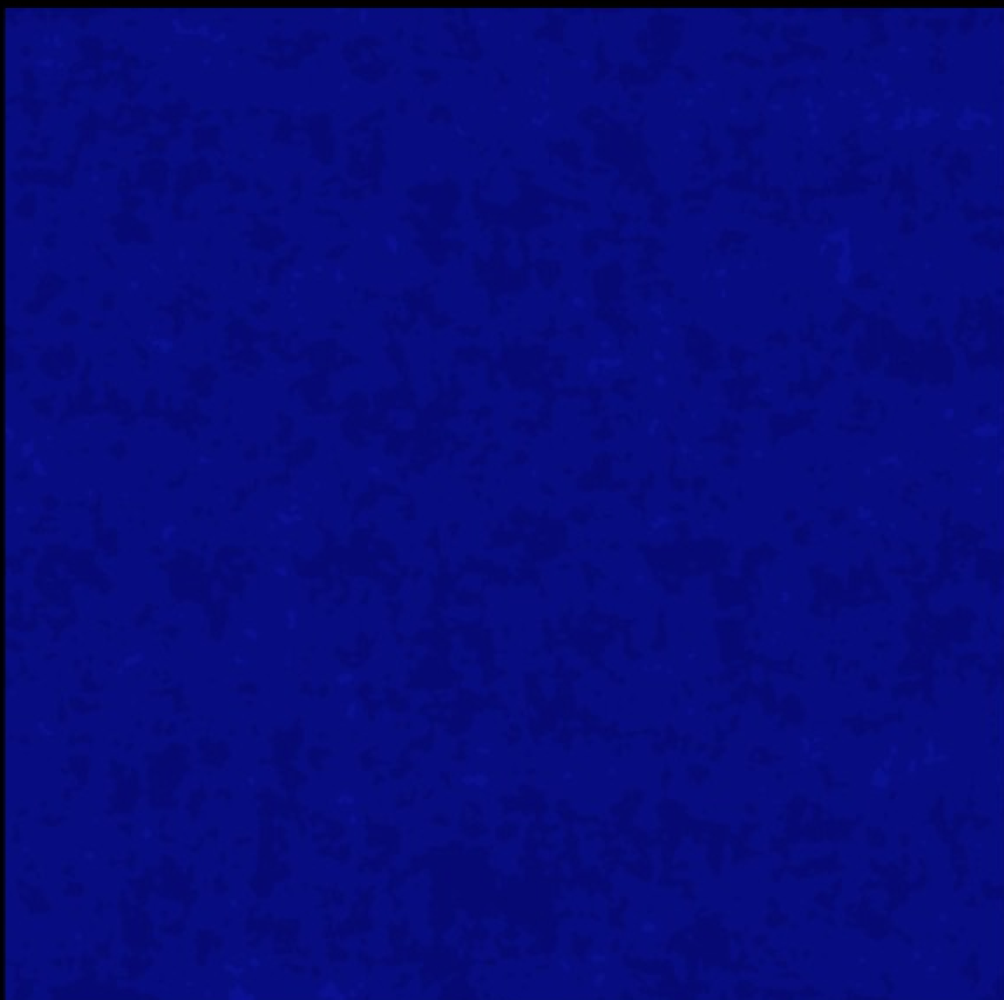


https://commons.wikimedia.org/wiki/User:Azcolvin429

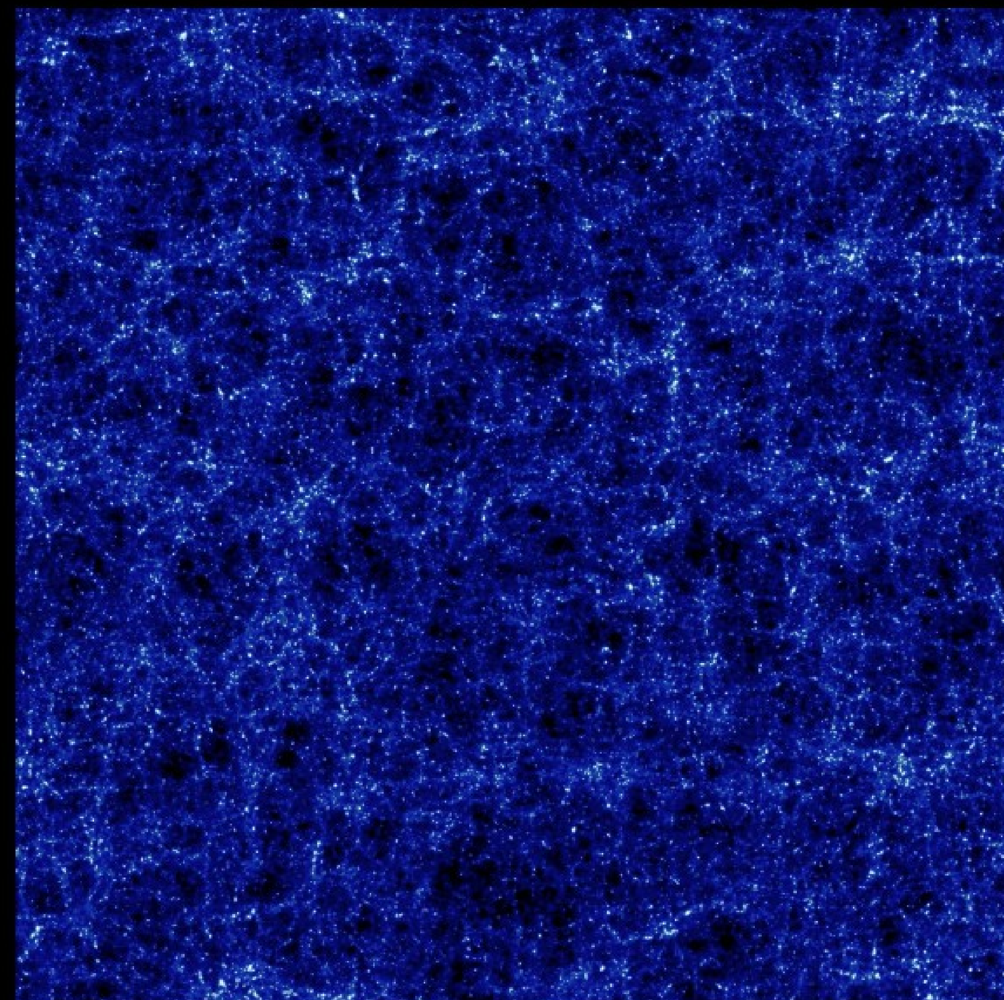


Dark Matter is our Mom

[Slide stolen from H. Murayama]



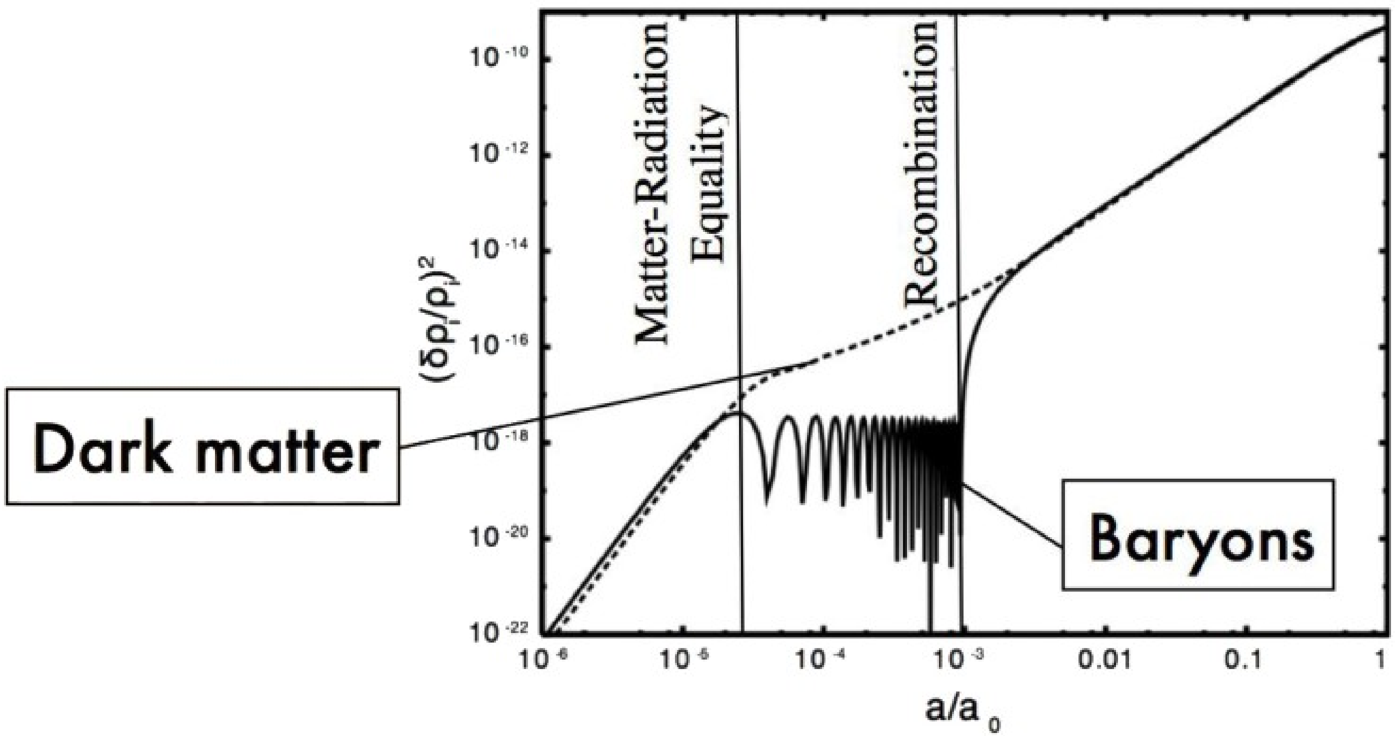
without dark matter



with dark matter

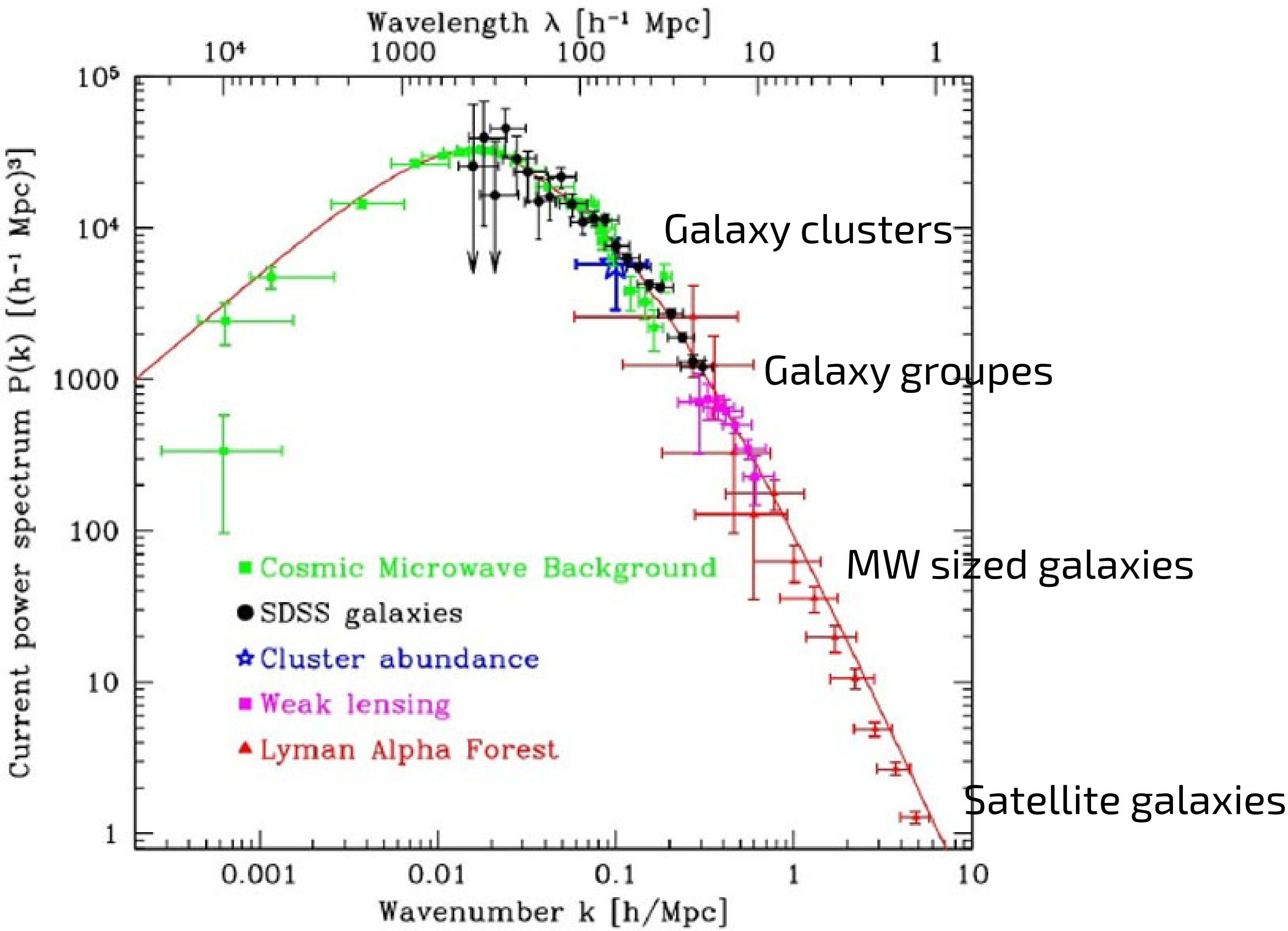
DM is needed for Structure Formation

Structure in baryons cannot grow until "recombination" -(before: photon pressure in plasma). Baryons must fall into potential wells of DM, or not enough time for structures to form: in Matt-Dom Universe $(\delta\rho/\rho)_m \sim a$ could go from 10^{-5} to 10^{-2} but need > 1

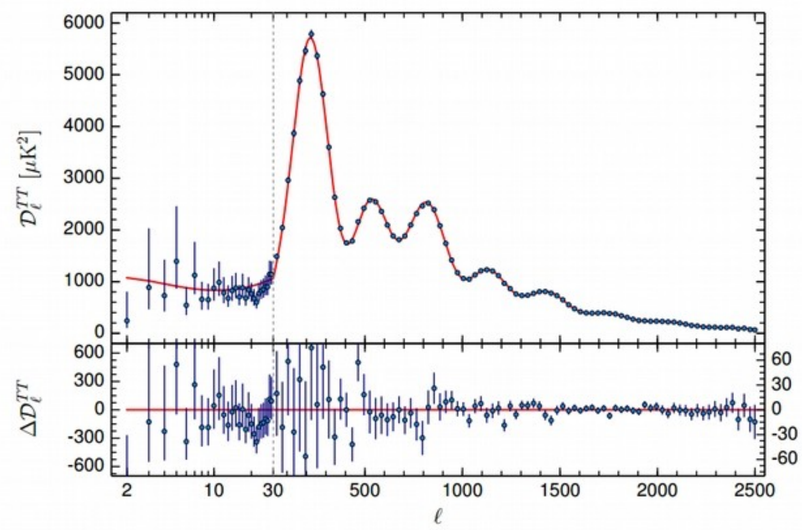


Slide credit: F. Donato

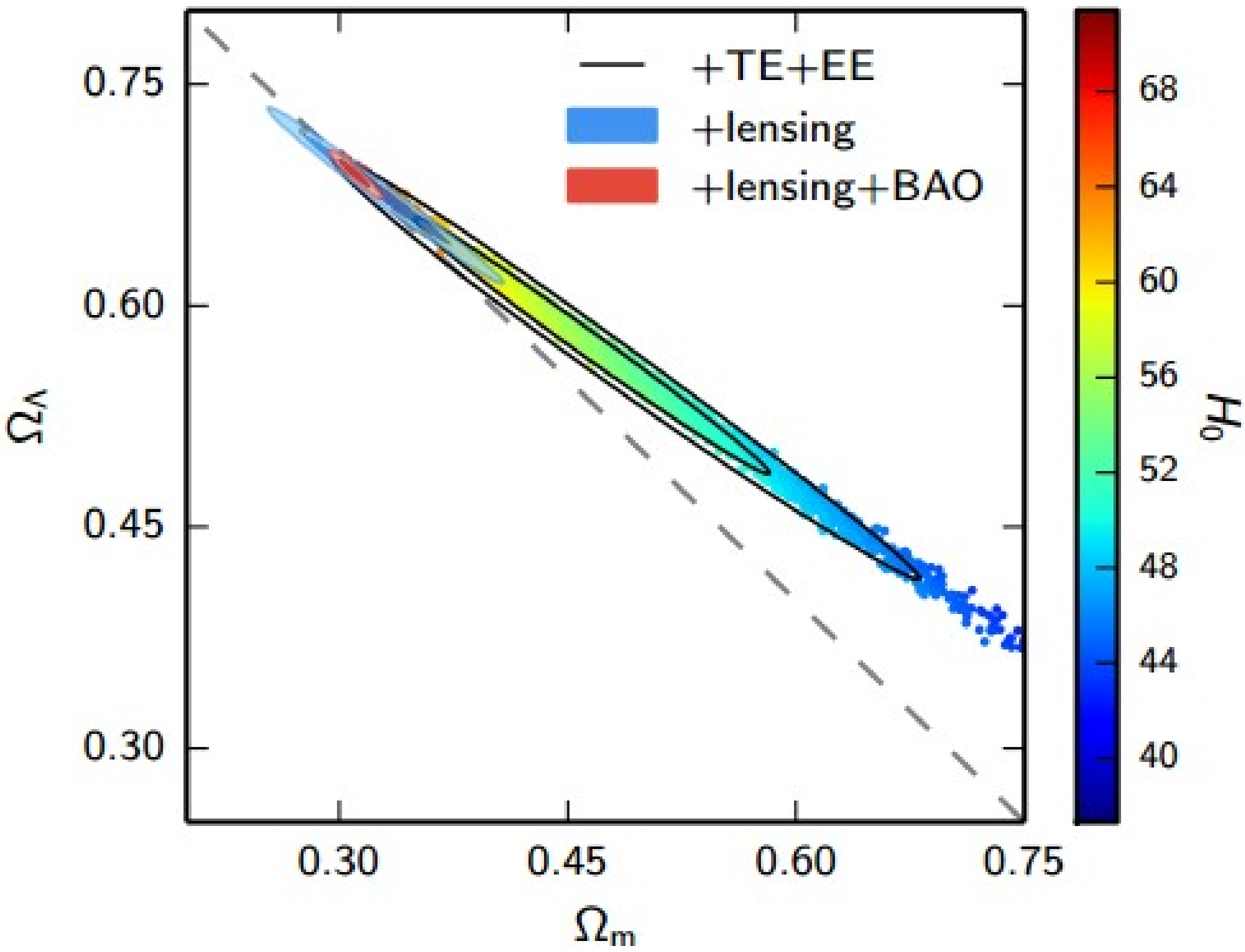
Towards the largest scales / early times



~380 000 yrs: Planck CMB observations



Planck 2017



Observations of the temperature and polarization fluctuations of the cosmic microwave background provide strong constraints on all cosmological parameters, including the DM density.

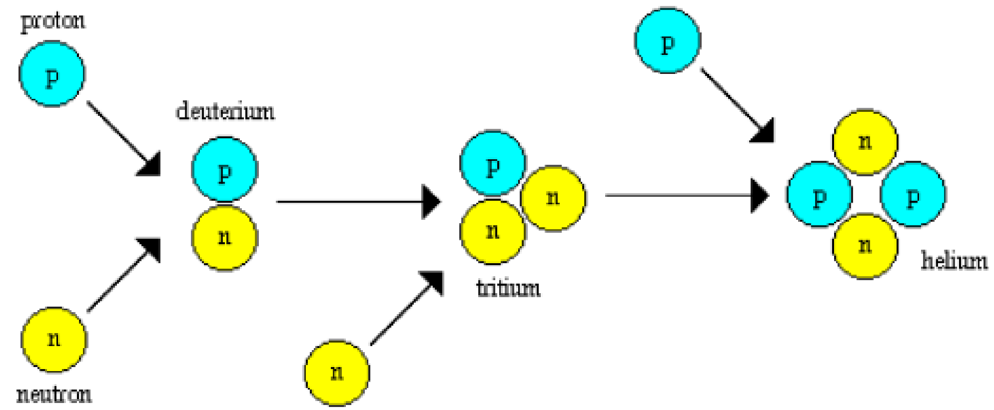
Planck coll 2015

First few min: Big Bang Nucleosynthesis

Production of 4He

- Production of Helium requires the existence of deuterium

$$\mathrm{D} + p^+ \leftrightarrow {}^3\mathrm{He} + \gamma \ ,$$
$$\mathrm{D} + {}^3\mathrm{He} \leftrightarrow {}^4\mathrm{He} + p^+ \ .$$



- Binding energy of deuterium is low

$$B_\mathrm{D} \equiv m_n + m_p - m_\mathrm{D} = 2.22 \ \mathrm{MeV}$$

while binding energy of Helium is 28.3 MeV

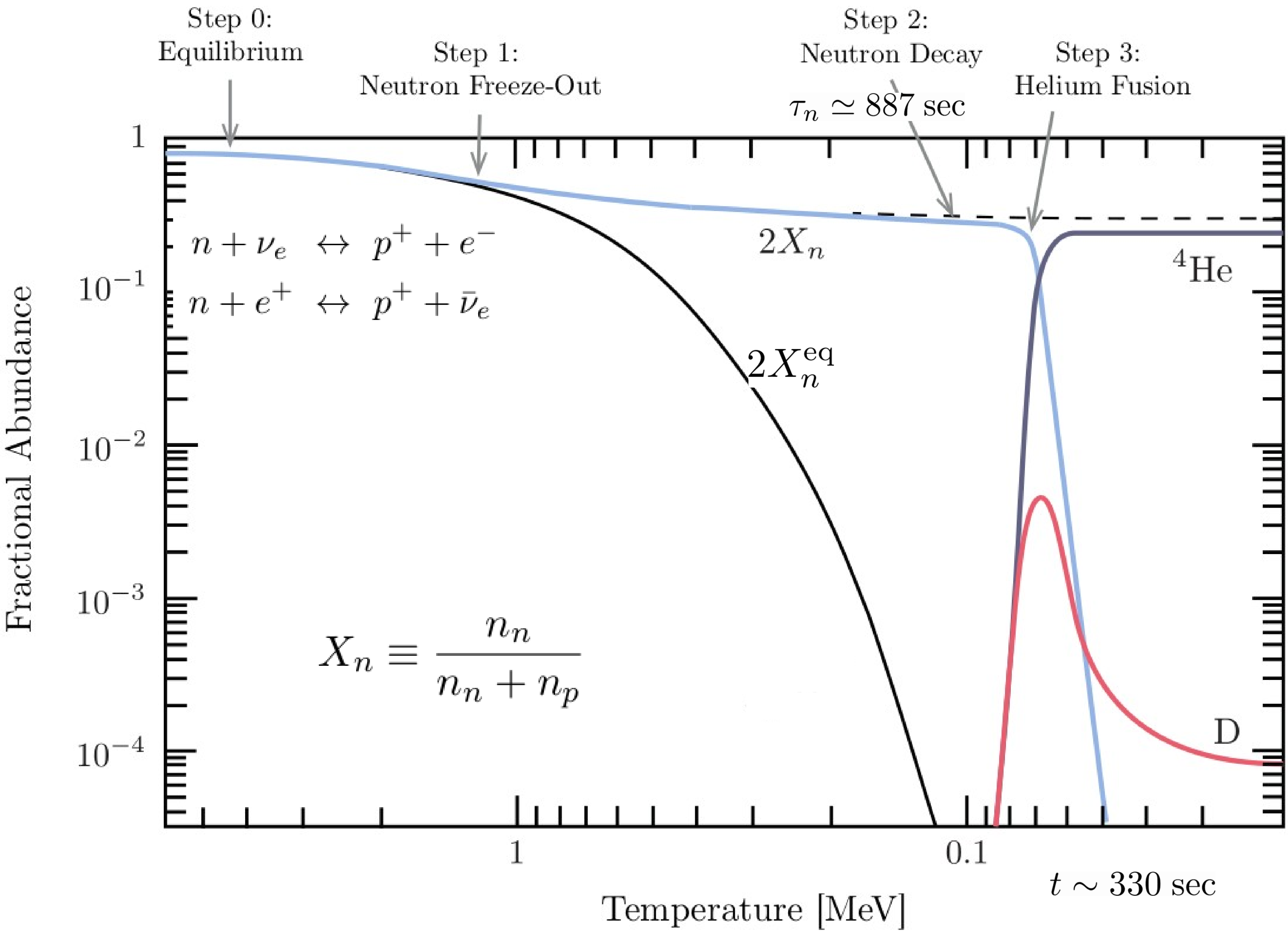
- Photon dissociation competes with deuterium formation → "**Deuterium bottleneck**"

$$n + p^+ \leftrightarrow \mathrm{D} + \gamma$$

$$\left(\frac{n_\mathrm{D}}{n_p}\right)_\mathrm{eq} \approx \eta_b \left(\frac{T}{m_p}\right)^{3/2} e^{B_\mathrm{D}/T}$$

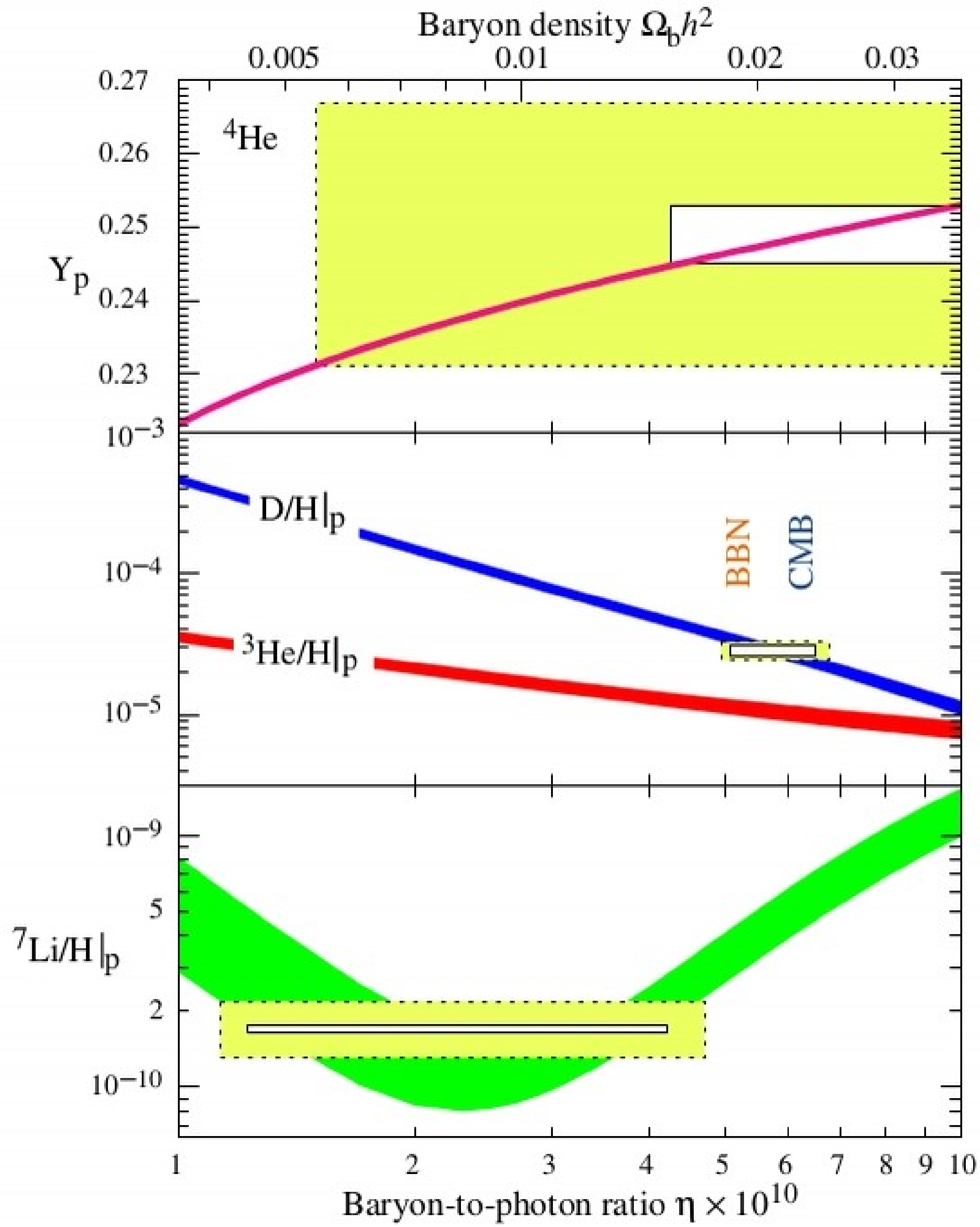
Lower baryon number → deuterium formation becomes efficient at lower temperature → less neutrons → less 4He

Big Bang Nucleosynthesis

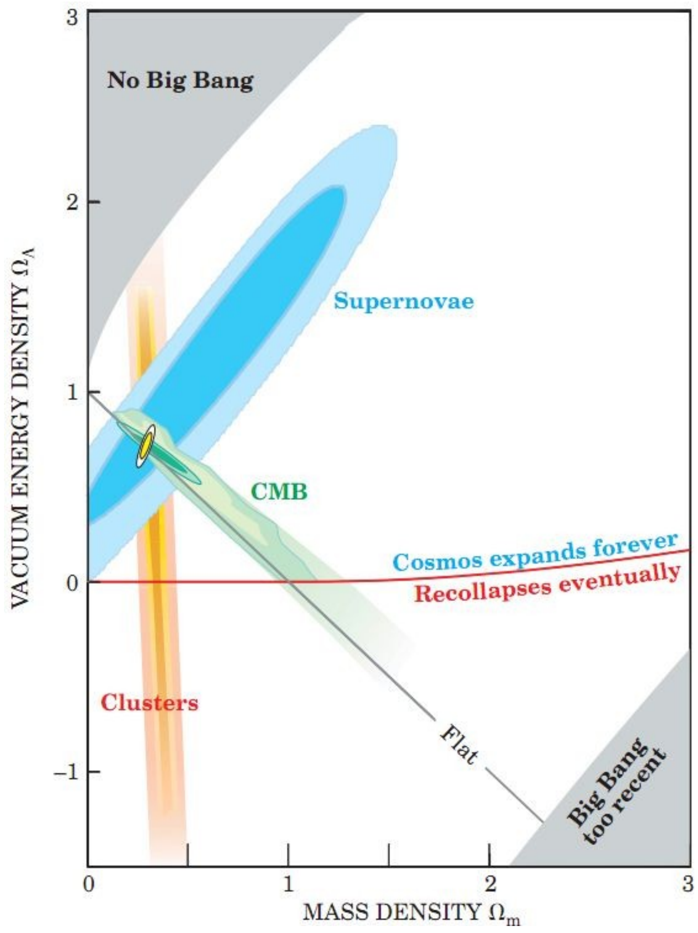


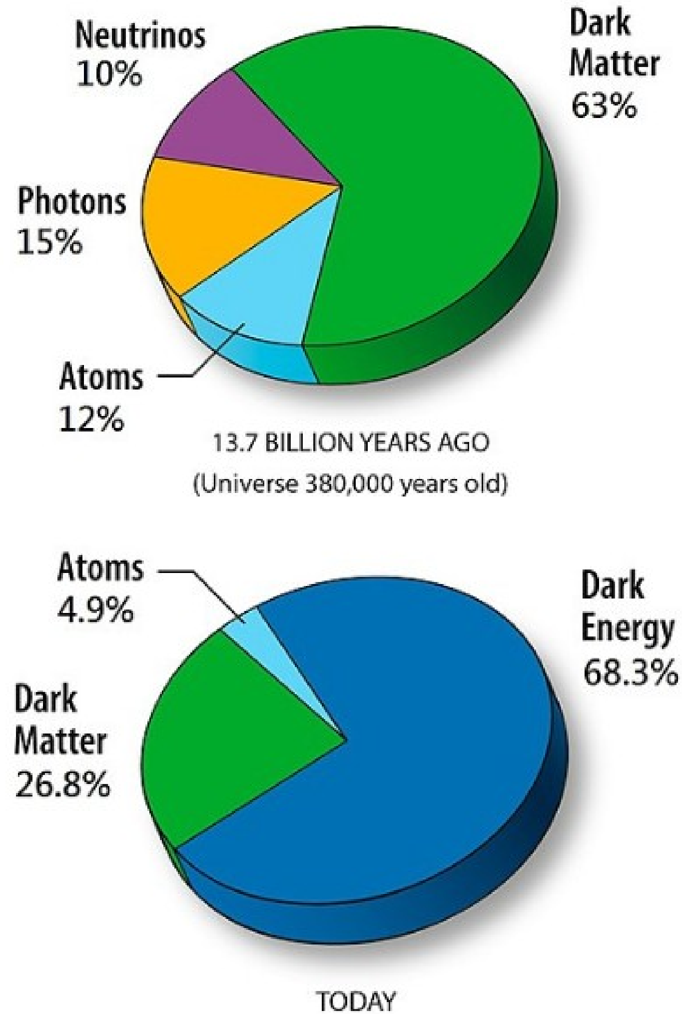
Big Bang Nucleosynthesis

Abundance of primordial elements provides robust constraint on Baryon density ~5 min after the big bang



Summary





The effects of DM can be observed at dwarf spheroidal to cosmological scales. Dark matter provides a unified framework for interpreting these observations (BBN, CMB, LSS, cluster masses, galaxy and dSph mases).

Candidates for dark matter

Modified Newtonian Dynamics (MOND)?

See: Famaey & McGaugh 2012

M. Milgrom (1983)

Idea

- At very small *accelerations*, Newton's Law is modified (increase "inertia")

$$F_N = ma \underset{a < a_0}{\rightarrow} F = m\frac{a^2}{a_0} \qquad\qquad a_0 \simeq 10^{-8}\,\mathrm{cm/s^2} \sim \mathrm{cH_0}$$

- Gravity part unchanged $$F_{\mathrm{gravity}} = \frac{GMm}{r^2}$$

- This can also account for flat rotation curves

$$F_{\mathrm{gravity}} \underset{a < a_0}{=} F_N \quad \& \quad a = \frac{v^2}{r} \qquad \Rightarrow \qquad \frac{GMm}{r^2} = m\frac{a^2}{a_0} = \frac{mv^4}{a_0 r^2}$$

$$\Rightarrow \qquad v = (GMa_0)^{1/4}$$

- MOND is only non-relativistic, so it cannot be tested on cosmological scales (e.g. gravitational lensing). It is an effective prescription, not a full theory.
- TeVeS (tensor vector scalar; J. Bekenstein, 2004) MOND generalization exists, which contains additional dynamical field.

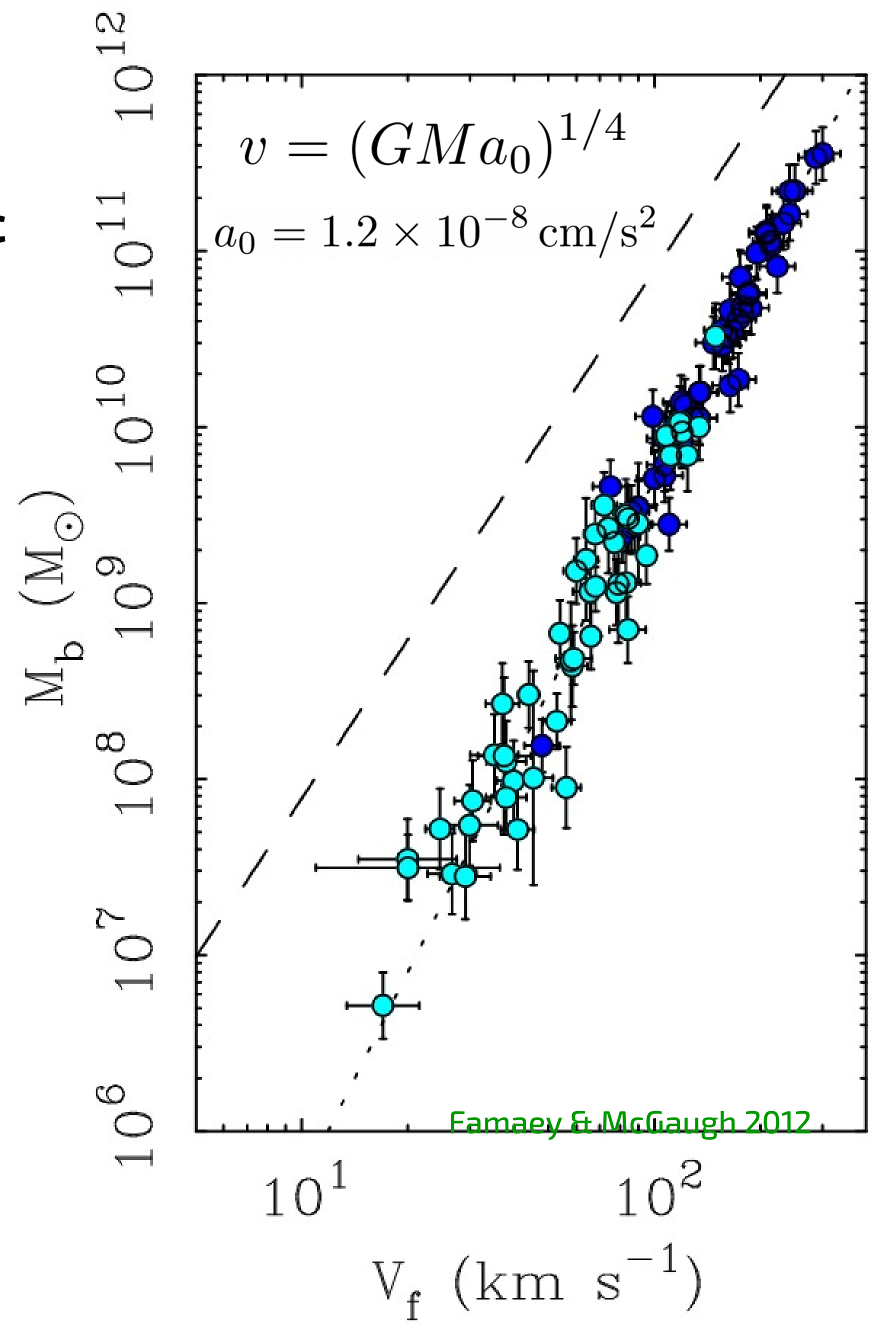
Tully-Fisher relation

Tully-Fisher relation describes surprisingly tight correlation between the angular velocity of spiral galaxies and their **baryonic mass**.

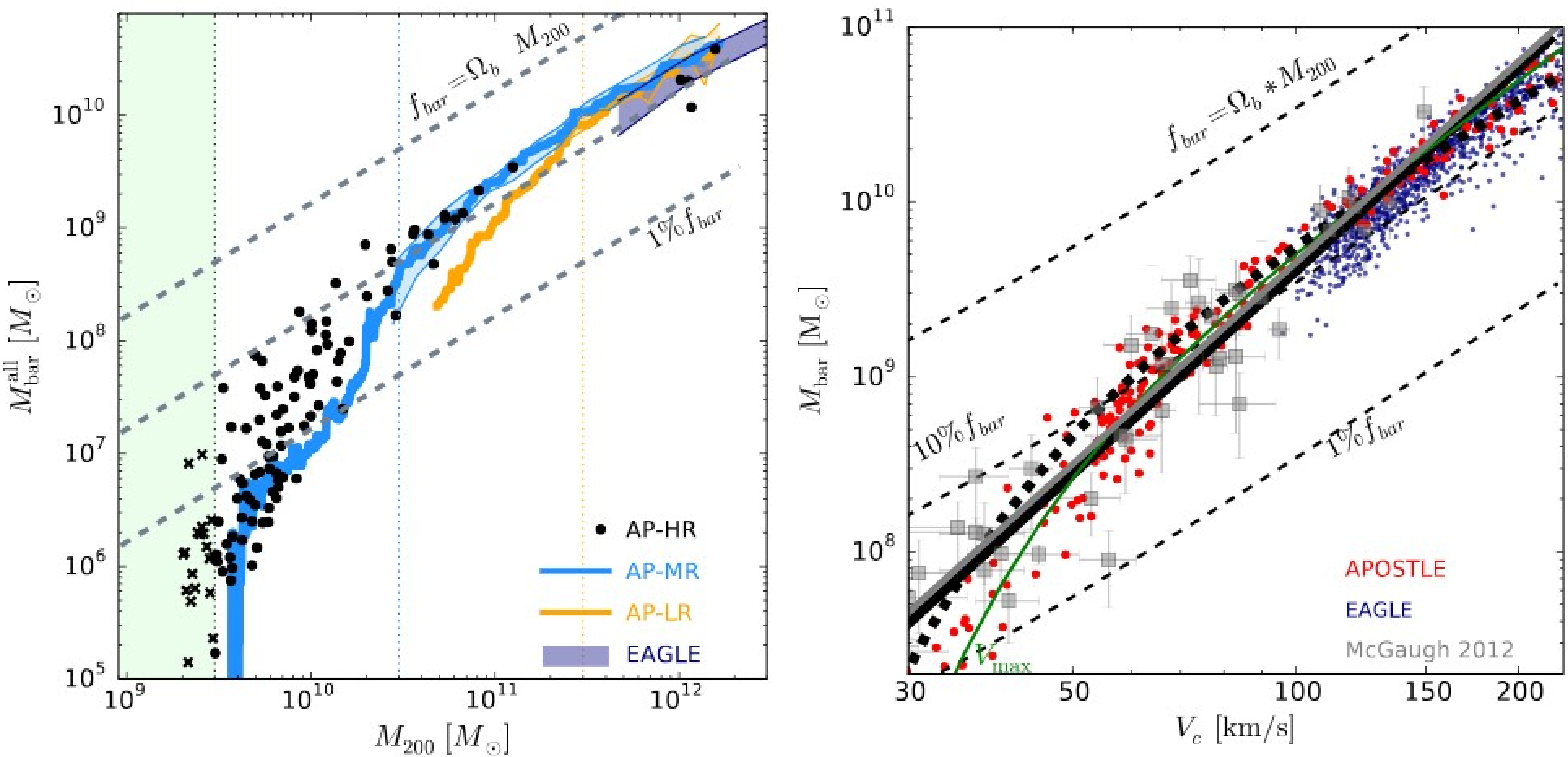
MOND correctly accounts for normalization and slope of the correlation over four orders of magnitude in Galaxy mass.

Lambda-CDM predicts dashed line, ***assuming that all baryons trace DM.***

- Where are the baryons? Could be removed by stellar feedback.
- If caused by feedback, why is scatter around dotted line so small (would naively expect broader distribution)



APOSTLE/EAGLE simulations of CDM



- Stellar feedback removes substantial amounts of baryonic matter
- Resulting Tully-Fisher plot resembles MOND results
- However, simulations tuned to observations, still no *a priori* predictions of CDM

Sales+ 2016

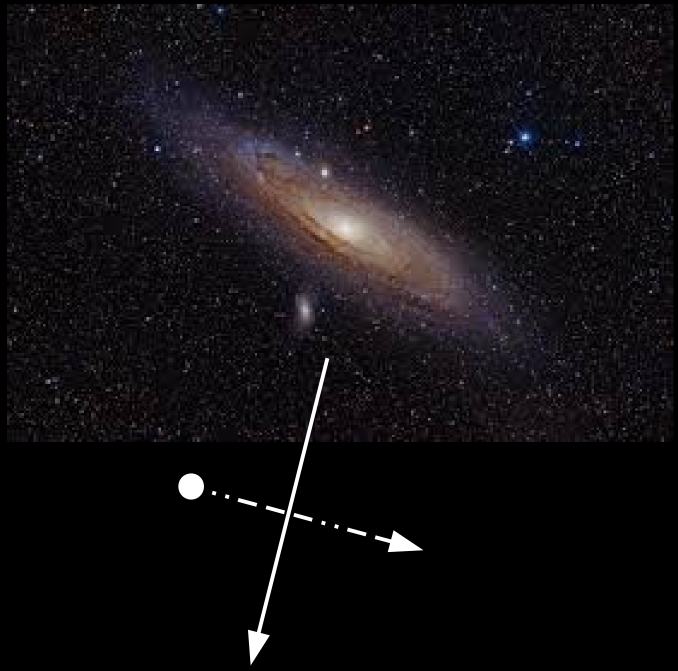
CDM vs MOND

	Cold Dark Matter	Modified Newtonian Dynamics
CMB: Magnitude of fluctuations	**yes**	**no**
CMB: Angular power spectrum	**yes**	**no**
Baryon acoustic oscillations in galaxy distribution	**yes**	**no**
Bullet cluster (DM / gas segregation)	**yes**	maybe*
Spiral galaxy rotation curves	**yes**	**yes**
Tully-Fisher	probably yes**	**yes**
Faber-Jackson	probably yes**	**yes**
Simultaneous explanation of DM in dwarf galaxies and clusters	**yes**	maybe

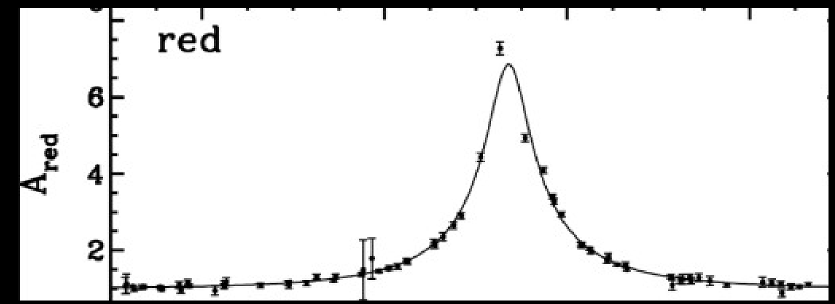
*could work in more complete theories of MOND (e.g. Israel & Moffat 2016)

** impact of baryons in galaxy formation is difficult to simulate a priori

Dim stars, black holes, ...

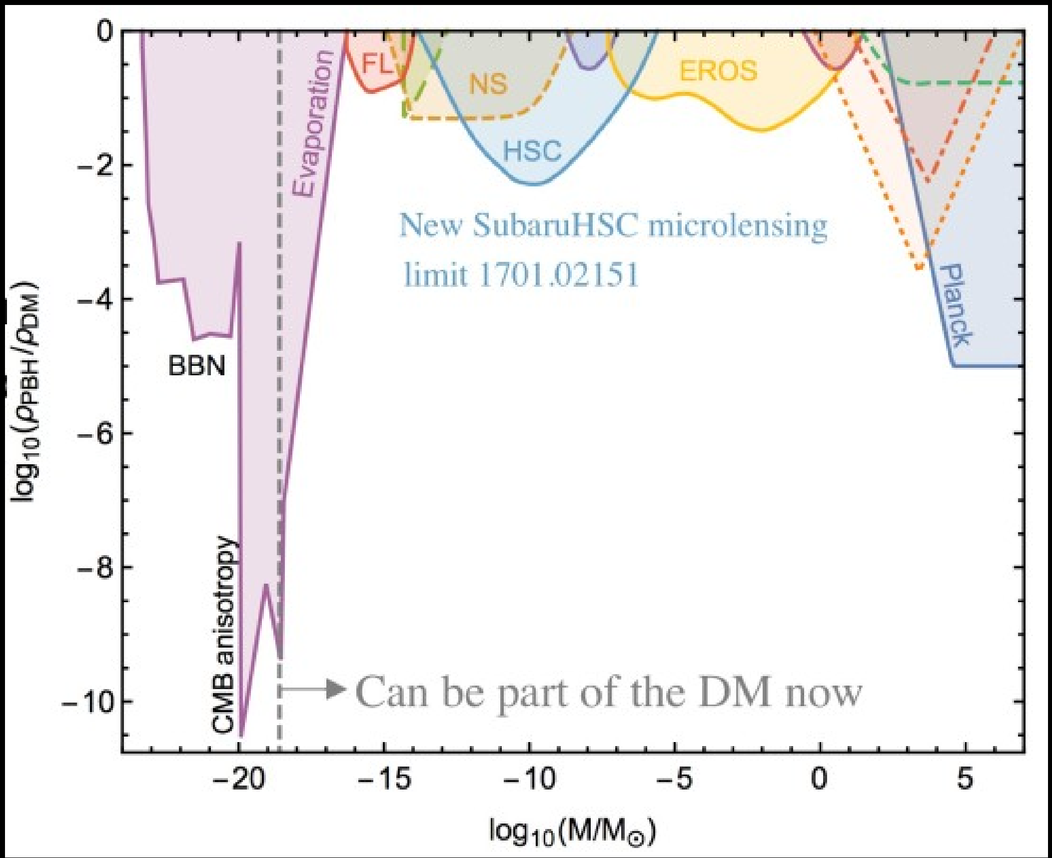


Searches for Massive Compact Halo Objects (MACHOs)



Search for microlensing events in M31 with HST.

Carr+ 17



Niikura, H. et al. Microlensing constraints on primordial black holes with the Subaru/HSC Andromeda observation. arXiv [astro-ph.CO] (2017).

Uncertainty principle

- Dark matter needs to clump to form structures
- Newton potential

$$V = G_N \frac{Mm}{r}$$

- Generates "Bohr" radius

$$r_B = \frac{\hbar^2}{G_N M m^2}$$

- If mass *m* too small, particles would not fit into Galaxy!

$m \gtrsim 10^{-22}\,\mathrm{eV}$ Uncertainty principle bound

See Hu+ 2000, astro-ph/0003365

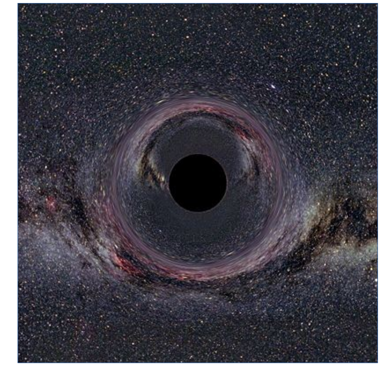
What we actually know about DM

Uncertainty principle
(if DM is bosonic)

Hu+ 2000

MACHO searches
(massive compact
halo objects)

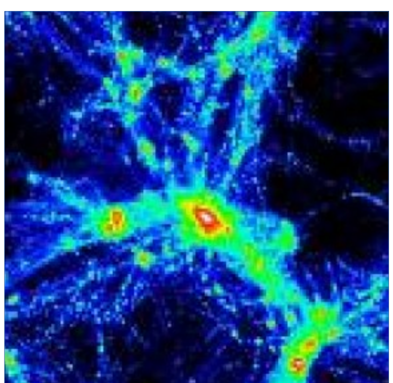
$$10^{-22}\mathrm{eV} \lesssim m_{\mathrm{DM}} \lesssim 10^{48}\mathrm{GeV}$$



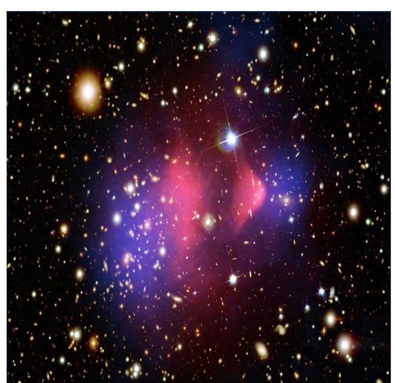
Tisserand+ 2007

Up to now, there are only various upper and lower limits:

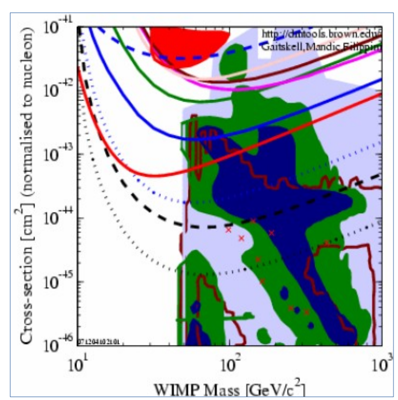
cold:
negligible velocity dispersion

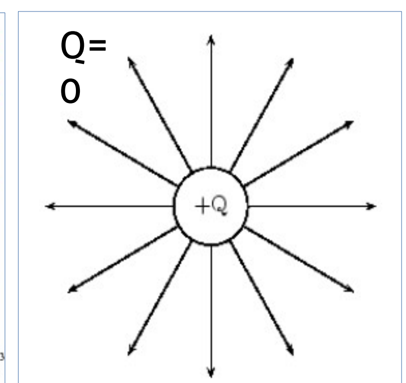


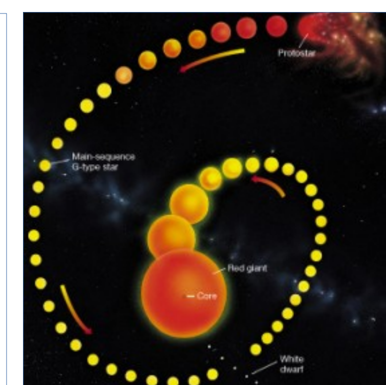
collisionless:
negligible self-interaction



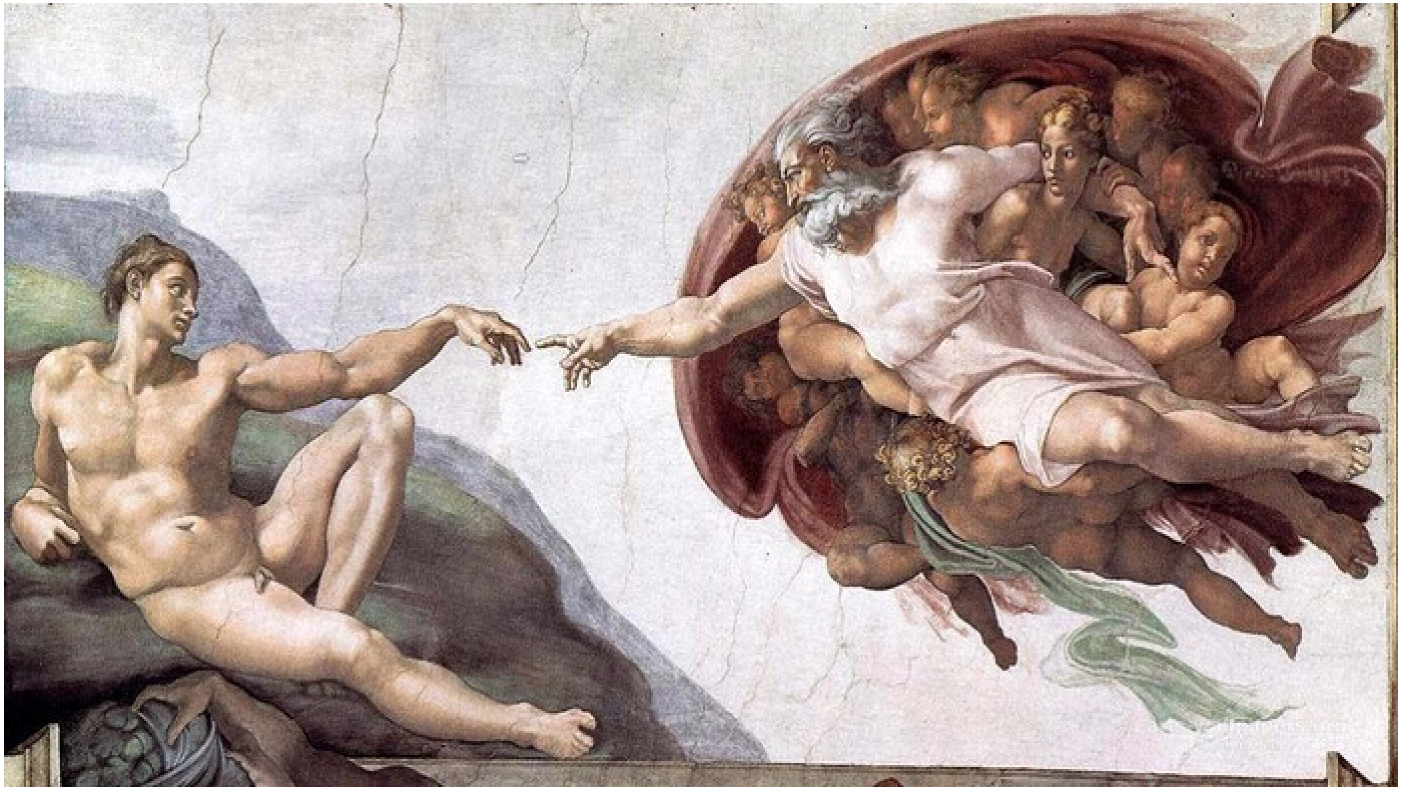
weakly coupled:
negligible interaction with the rest of the world







Sociology ~1980 - ~2015



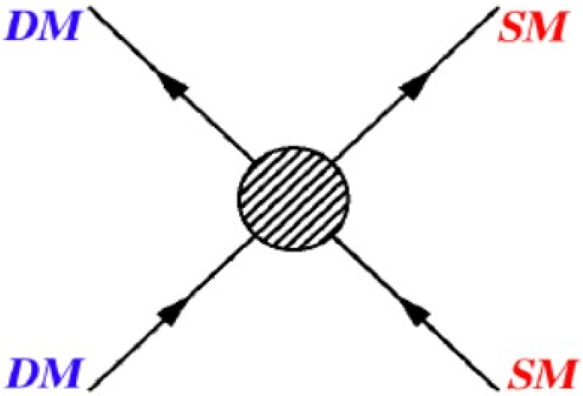
- Standard models has problems (gauge hierachy, strong CP, neutrino masses, baryon asymmetry)
- Dark matter candidates shall not be arbitrarily constructed out of nothing
- Rather, dark matter should arise miraculously as by-product of solution to hierachy problem etc

The WIMP Miracle

The “WIMP miracle”

Weakly interacting massive particles (WIMPs)

“weak” coupling + “weak” mass scale ➡ correct relic density



Happens for

$$\langle \sigma_{DM\,DM \to SM\,SM} v_{\rm rel} \rangle \simeq \frac{\alpha^2}{m^2}$$

$$\alpha \simeq 10^{-2}$$

$$m \simeq 300\,\mathrm{GeV}$$

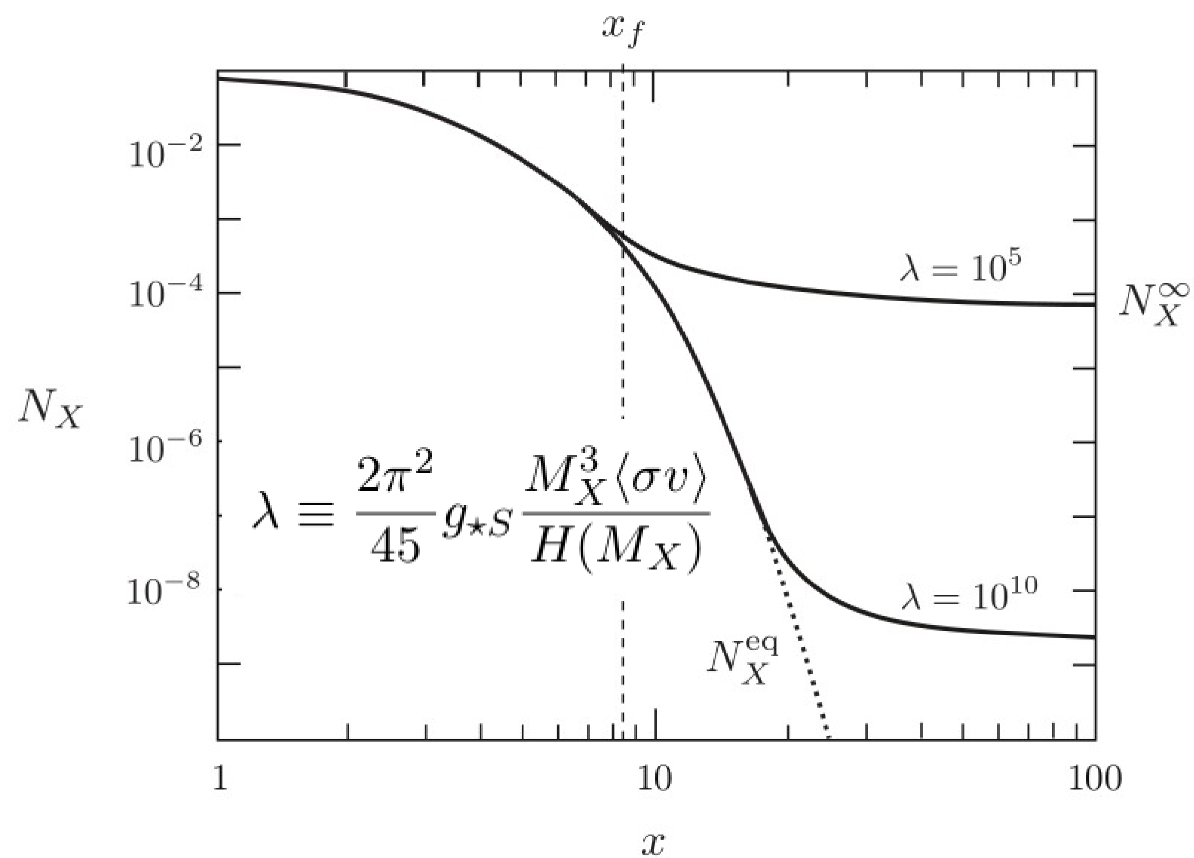
Freeze out mechanism

Boltzmann equation for particles in comoving volume

$$\frac{dN_X}{dt} = -s\langle\sigma v\rangle\left[N_X^2 - (N_X^{\mathrm{eq}})^2\right]$$

$$N_X \equiv n_X/s \qquad x \equiv \frac{M_X}{T}$$

$$X + \bar{X} \leftrightarrow \ell + \bar{\ell}$$



Relic density today

$$\Omega_X = \frac{\rho_{X,0}}{\rho_{\mathrm{crit},0}} = \frac{M_X N_X^\infty s_0}{\rho_{\mathrm{crit},0}}$$

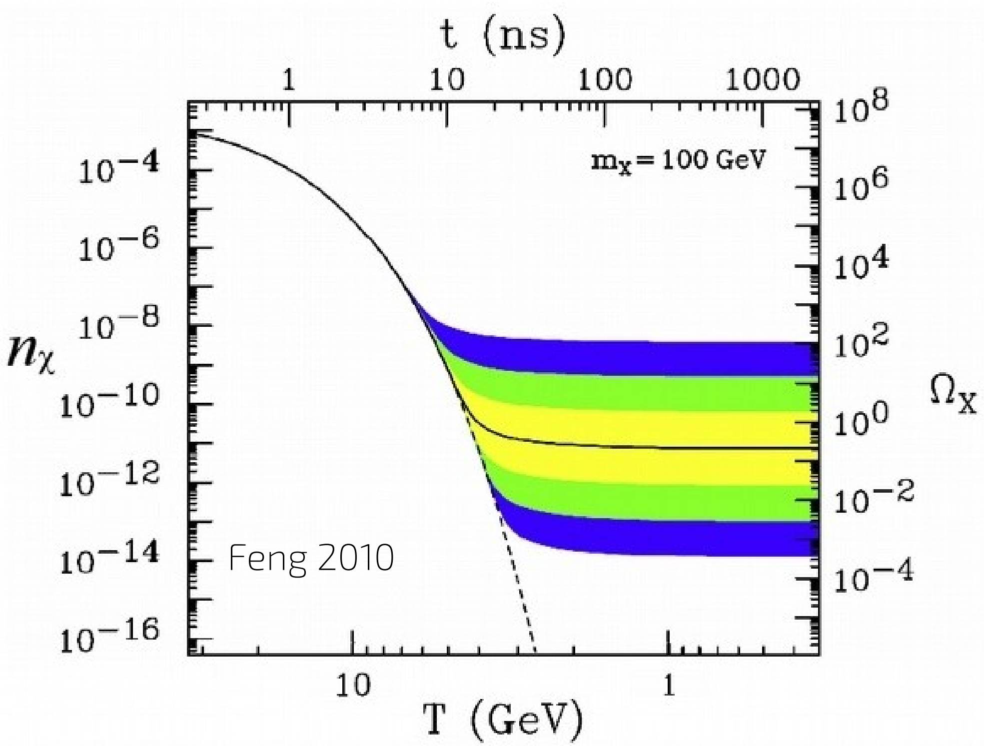
“WIMP miracle”

$$\Omega_X h^2 \sim 0.1 \frac{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle} \sim \frac{10^{-3}G_F}{\langle\sigma v\rangle}$$

WIMPs

s-wave annihilation $(\sigma v \approx \text{const})$

→ Direct link between relic density and velocity weighted cross section today



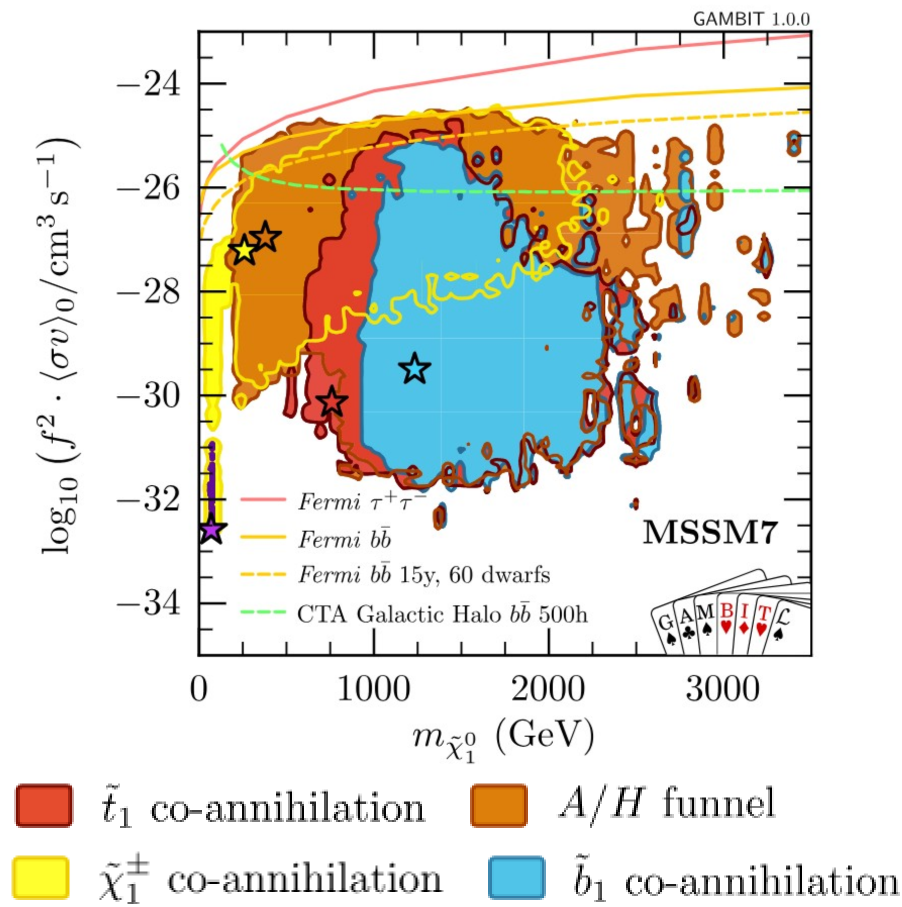
$$\frac{\Omega_\chi h^2}{0.1} \approx \frac{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma v\rangle}$$

s-wave: $\langle \sigma v\rangle_{T\sim\mathrm{GeV}} = (\sigma v)_{v=0}$

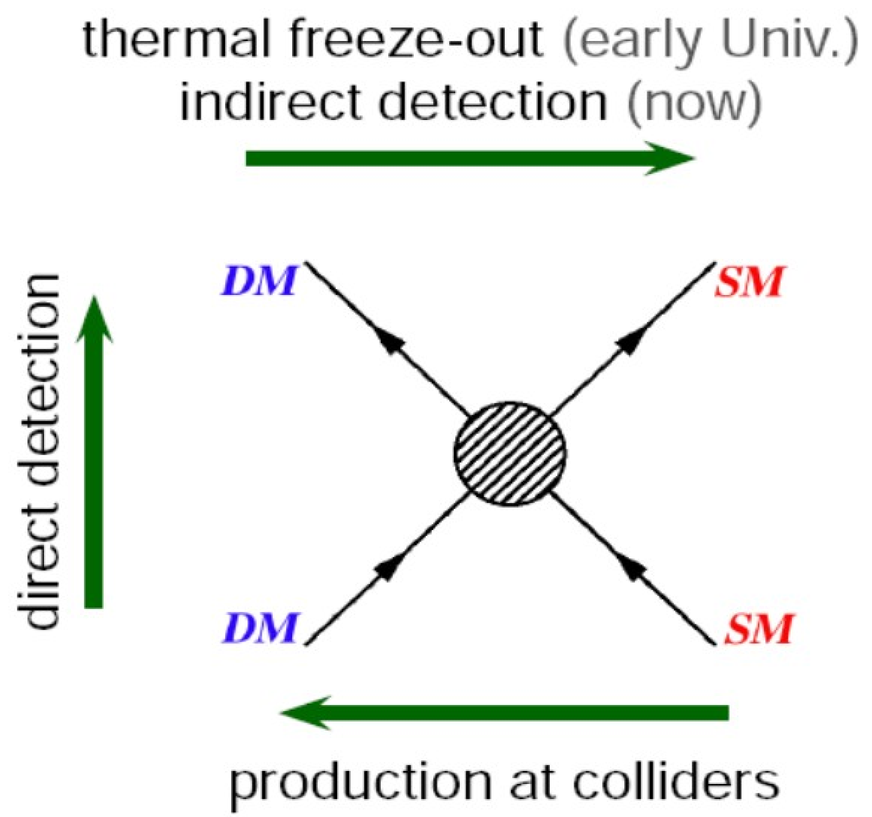
in general

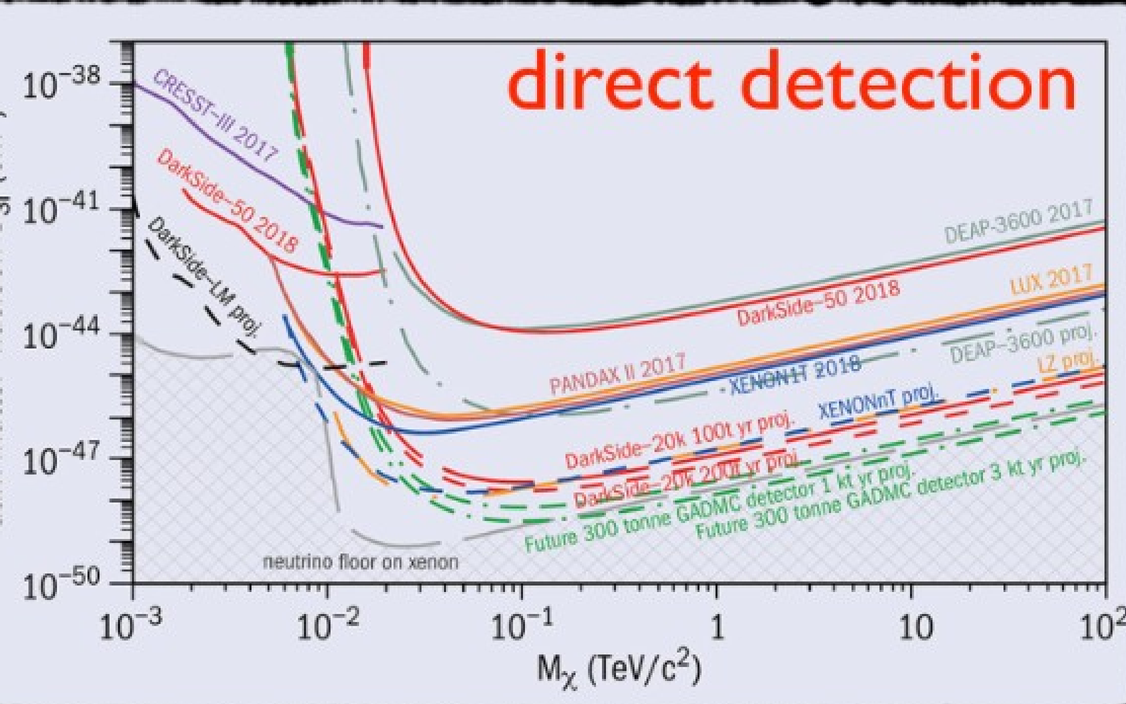
$$\langle \sigma v\rangle_{T\sim\mathrm{GeV}} \neq (\sigma v)_{v=0}$$

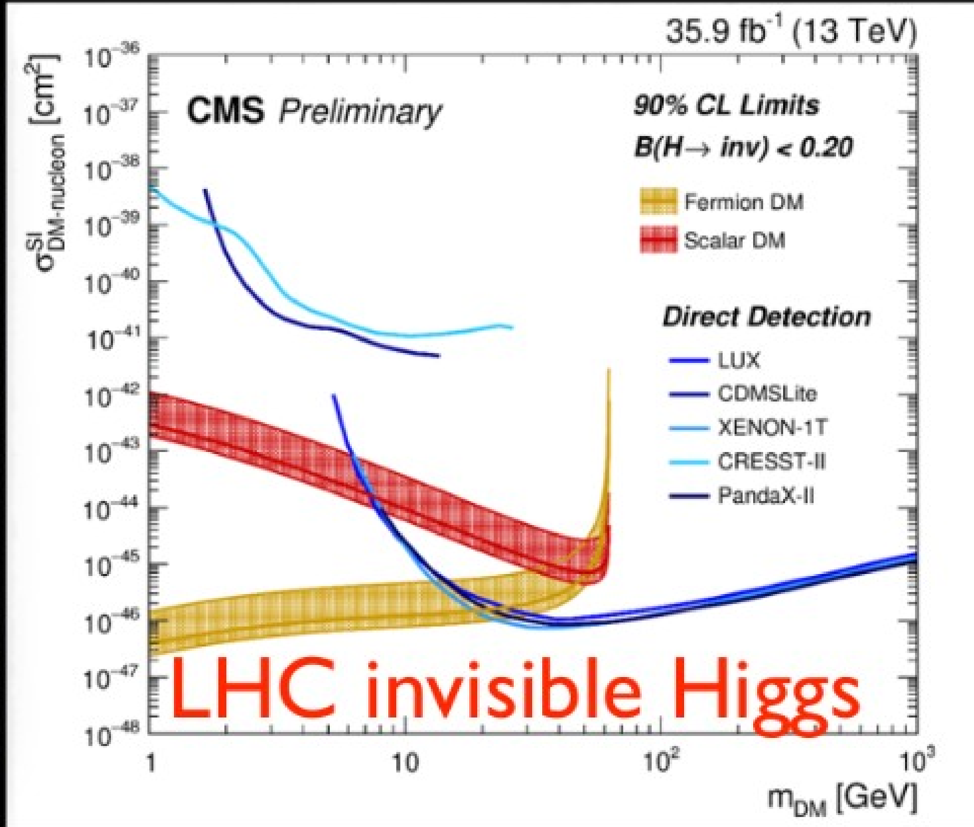
Example MSSM7
(rescaled by DM fraction)

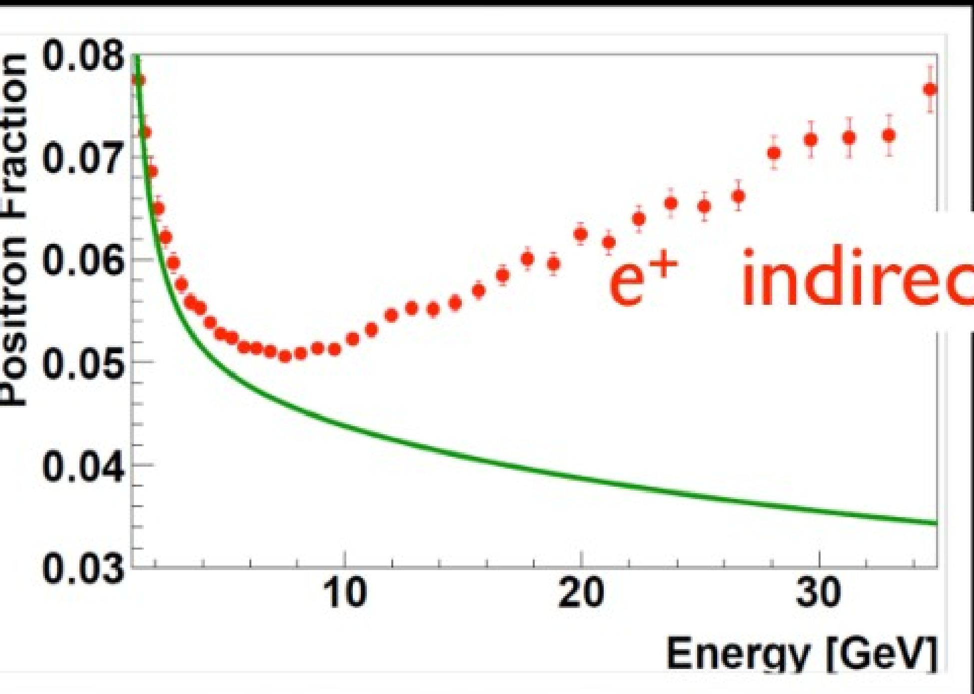


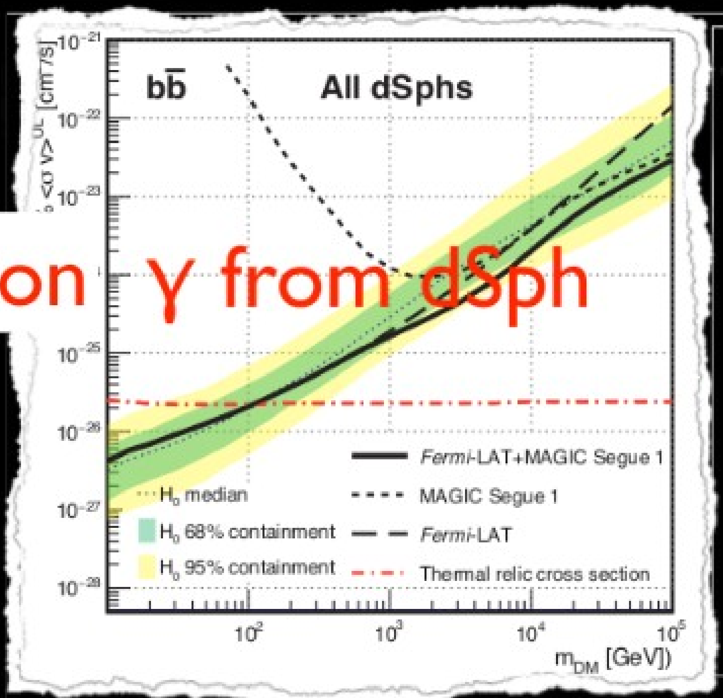
WIMP can be probed in many ways




direct detection
CRESST-III 2017
DarkSide-50 2018
DarkSide-LM proj.
DEAP-3600 2017
LUX 2017
PANDAX II 2017
XENON1T 2018
DEAP-3600 proj.
LZ proj.
XENONnT proj.
DarkSide-20k 100t yr proj.
DarkSide-20k 200t yr proj.
Future 300 tonne GADMC detector 1 kt yr proj.
Future 300 tonne GADMC detector 3 kt yr proj.
neutrino floor on xenon
M_χ (TeV/c^2)


35.9 fb^{-1} (13 TeV)
CMS Preliminary
90% CL Limits
$B(H\to inv) < 0.20$
Fermion DM
Scalar DM
Direct Detection
LUX
CDMSLite
XENON-1T
CRESST-II
PandaX-II
$\sigma^{SI}_{DM\text{-}nucleon}$ [cm^2]
LHC invisible Higgs
m_{DM} [GeV]


Positron Fraction
Energy [GeV]
e^+ indirect detection

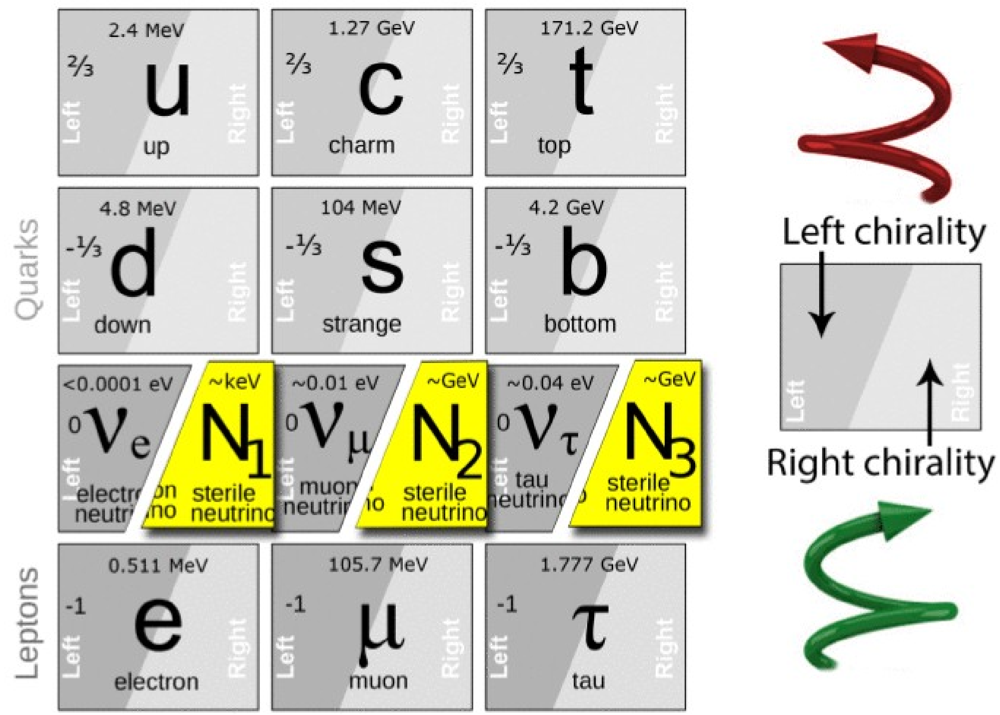

$b\bar{b}$
All dSphs
γ from dSph
Fermi-LAT+MAGIC Segue 1
MAGIC Segue 1
Fermi-LAT
Thermal relic cross section
H_0 median
H_0 68% containment
H_0 95% containment
m_{DM} [GeV]

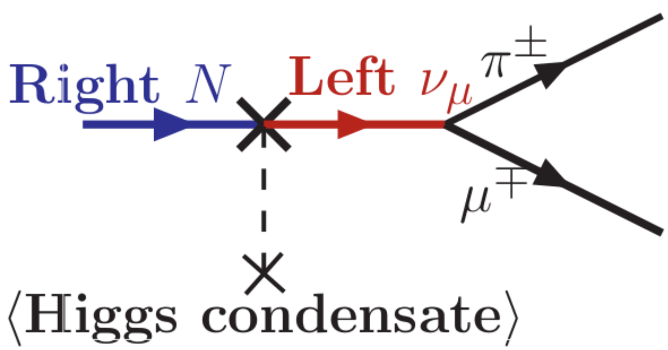
The various approaches

	09:00-10:30	10:30-11:00	11:00-12:30	12:30-14:30	14:30-16:00	16:00-16:30	16:30-18:00
Tuesday May 28	Particle physics (W. Rodejohann) Cosmology (B.M.Schäfer)	coffee break	Particle physics (W. Rodejohann) Cosmology (B.M.Schäfer)	lunch break	Particle physics (W. Rodejohann) Cosmic accelerators (F. Rieger)	coffee break	Particle physics (W. Rodejohann) Cosmic accelerators (F. Rieger)
Wednesday May 29	Neutrino - theory I (E. Akhmedov)	coffee break	Neutrino - theory II (E. Akhmedov)	lunch break	Dark Matter - evidences and candidates (WIMPs , axions, sterile ν) (C. Weniger)	coffee break	Dark Matter - indirect detection (C. Weniger)
Thursday May 30	Neutrino experiments (Ch. Weinheimer)	coffee break	Astronophysical neutrinos (G. Raffelt)	lunch break	Dark Matter - direct detection (WIMPs and Axions) (R. Budnik)	coffee break	Dark Matter - direct detection (WIMPs and Axions) (R. Budnik)
Friday May 31	Neutrino experiments (Ch. Weinheimer)	coffee break	Neutrinos and BSM (S. Davidson)	lunch break	The hot thermal Universe (BBN, BAU, ...) (S. Davidson)	coffee break	Dark Matter at the LHC (H.-C. Schultz-Coulon)
Saturday June 1	Excursion day						
Sunday June 2	Dark Matter - phenomenology (J. Kopp)	coffee break	Dark Matter and BSM (J. Kopp)	lunch break	Cosmology (CMB, GR lensing, structure) (B.M. Schäfer)	coffee break	POSTER SESSION
Monday June 3	DISCUSSION SESSION	coffee break	Gravitational Wave experiments (H. Lück)	lunch break	Dark Energy experiments (M. Kowalski)	coffee break	-- free --
Tuesday June 4	Gravitational waves theory (M. Mapelli)	coffee break	Dark Energy theory (C. de Rham)	lunch break	The high energy Universe (experiments) (U. Katz)	coffee break	The high energy Universe (theory) (F. Aharonian)

Sterile neutrinos

- Right-handed neutrino is **neutral** – no electromagnetic interactions
- Right-handed neutrino is a **lepton** – no strong interactions
- Weak interactions are different for left- and right-particles – right-handed neutrino is **sterile**





Slide credit: Oleg Ruchaisky

Thermal production of sterile neutrinos

Dodelson & Widrow 1994

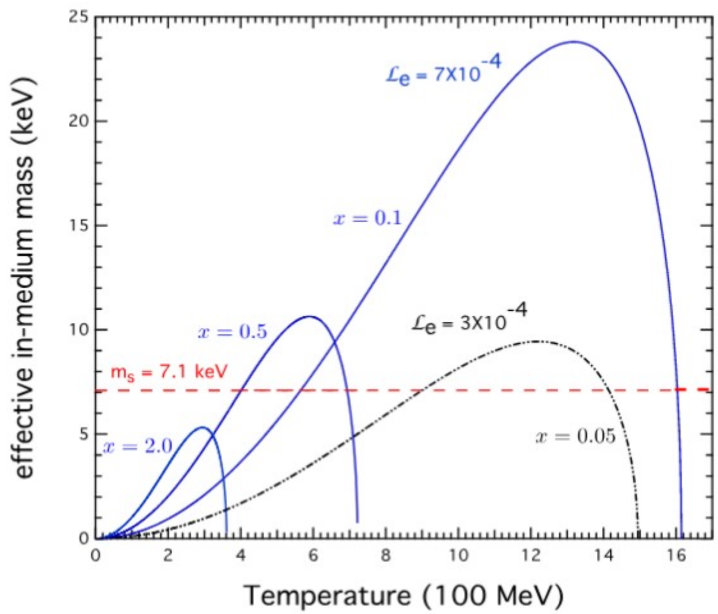
- Production by active-neutrino scattering induced decoherence

$$\Gamma_{\nu_\alpha} \sim G_F^2 T^5$$

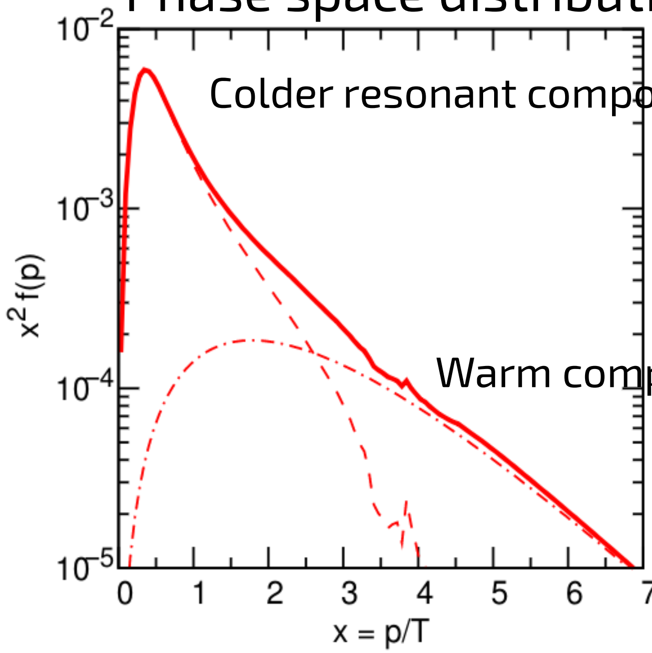
- Lepton-asymmetry in primordial plasma can cause resonant enhancement of production → "cold" additional component

$$|\nu_\alpha\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle,$$
$$|\nu_s\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle,$$

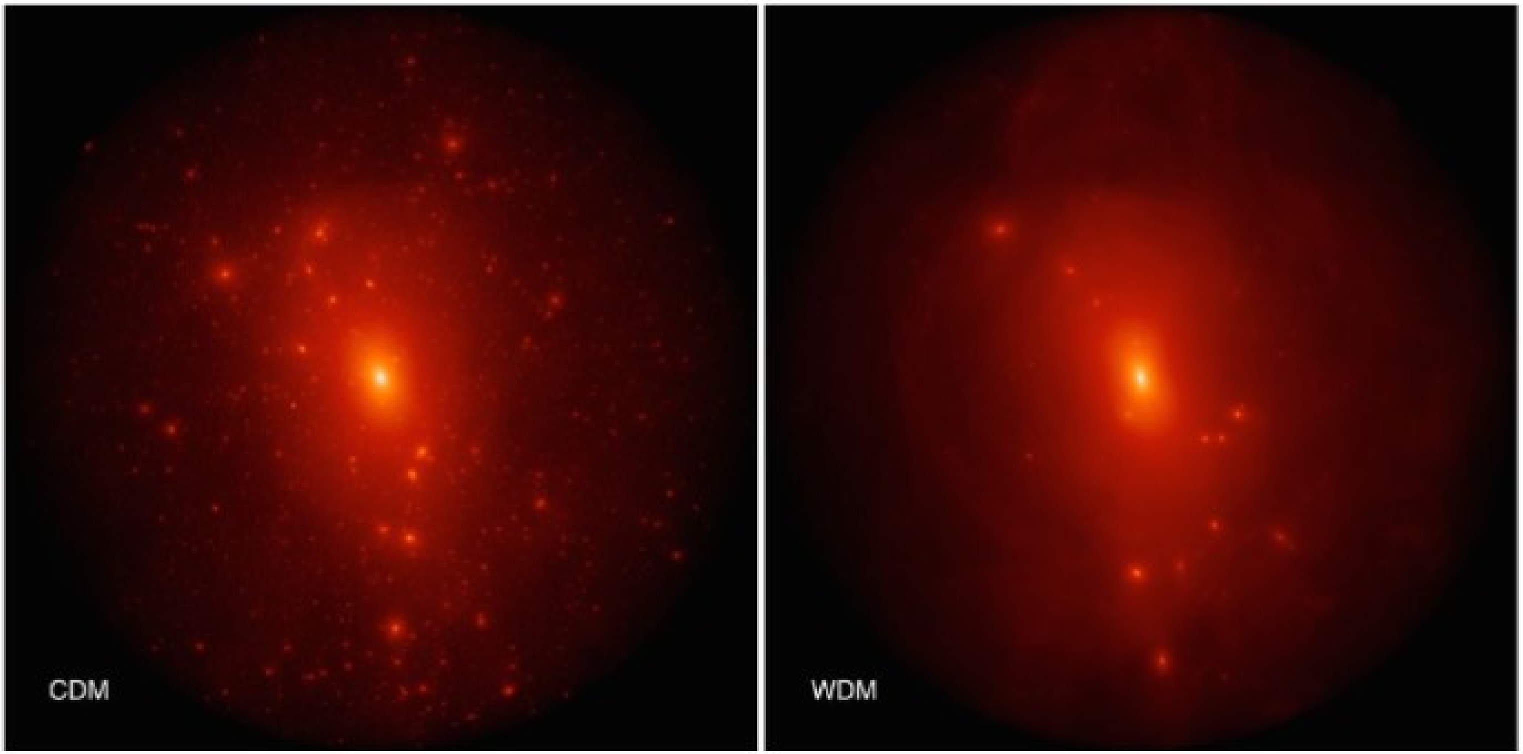
Drewes+17



Phase space distribution



Impact on small scale structure



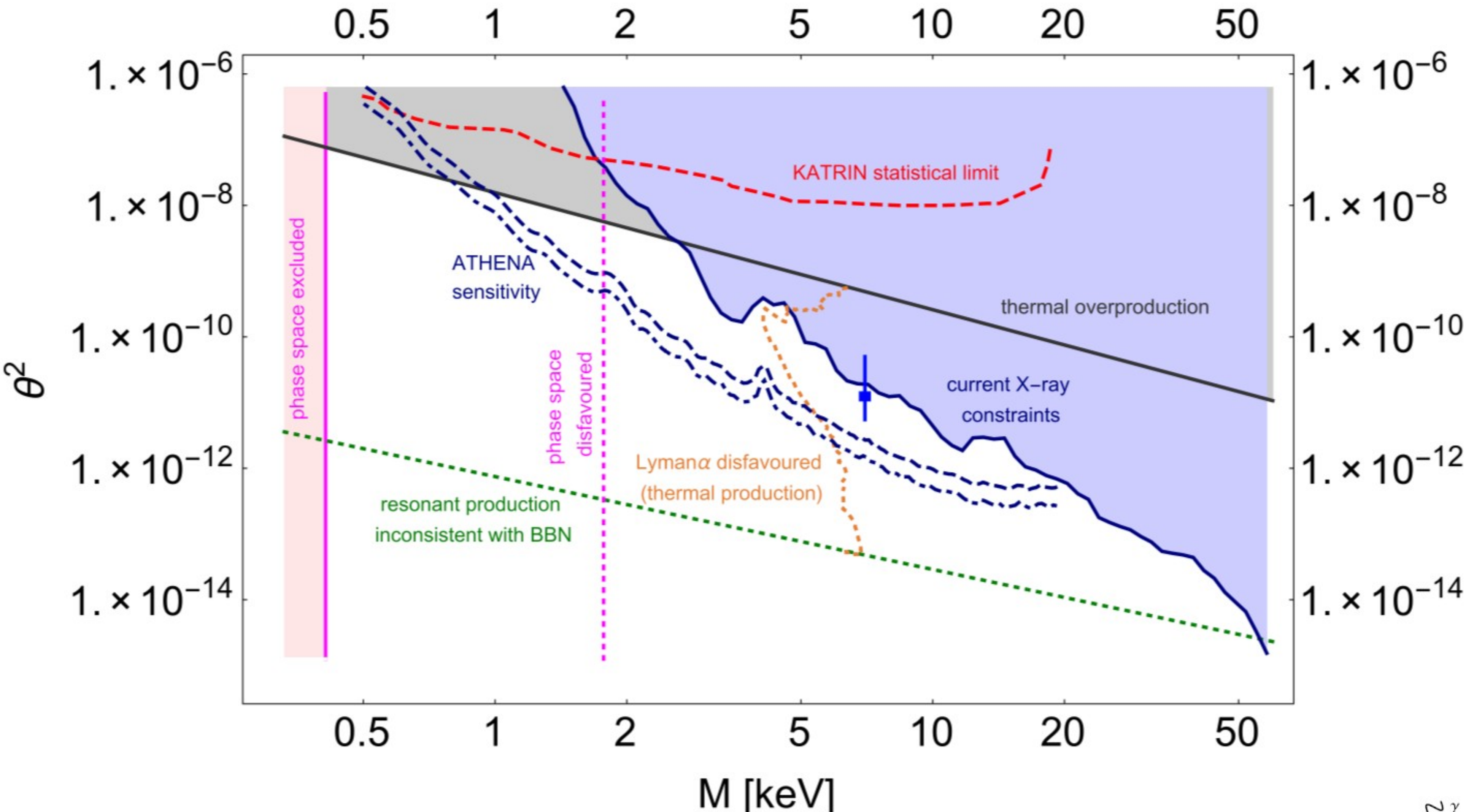
Suppression of small scale structure

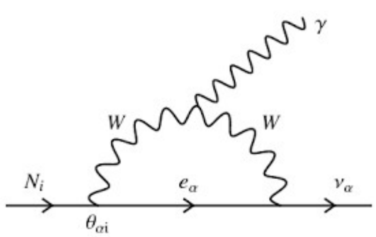
The **free-streaming scale** is the distance that particles traveled before onset of structure formation. Current constraints from Lyman-alpha and other observations below ~0.5 Mpc.

$$\lambda_{\rm FS} \sim 1{\rm Mpc}\frac{\rm keV}{m_{\rm DM}}\frac{\langle p_{\rm DM}\rangle}{\langle p_\nu\rangle}$$

Lovell+11; Drewes+17

Summary constraints on sterile neutrino DM





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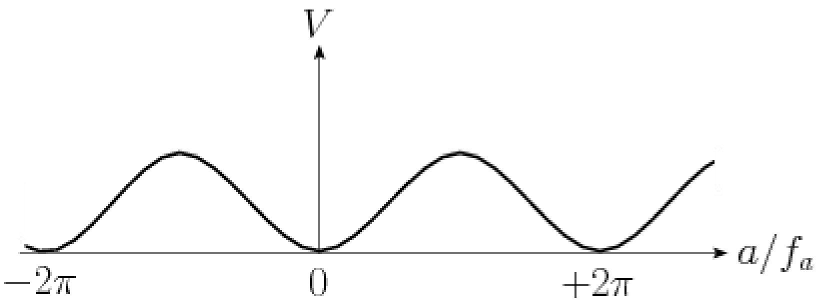
QCD axions

- Solve strong CP problem of the SM by dynamical relaxation of CP violating term (Peccei & Quinn 1977)

$$\mathcal{L}_{\rm QCD} \supset -\frac{\alpha_{\rm S}}{8\pi}\theta_{\rm QCD} G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a}$$



- Axion is pseudo-Goldstone boson of axial U(1) symmetry of quarks (and optionally leptons), at some scale f_a
- Natural coupling to QCD sector, induced model-dependent coupling to photons and leptons
- Relatively few parameters
- Misalignment mechanism can give rise to cold dark matter

$$m_{a,0} \simeq \frac{\sqrt{z_d}}{1+z_d}\frac{f_{\pi^0}}{f_a} m_{\pi^0} \simeq 5.70(7)\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

Axion production via misalignment

- We here assume Peccei-Quinn symmetry breaking well *before* inflation, only realignment mechanism contributes to relic density
- Periodic potential after QCD phase transition

$$V(\theta) = f_a^2 m_a^2 \left[1 - \cos(\theta)\right]$$

- Equations of motion after QCD phase transition, periodic potential takes the general form

$$\ddot{\theta} + 3H(t)\,\dot{\theta} + m_a^2(t)\,\sin(\theta) = 0$$

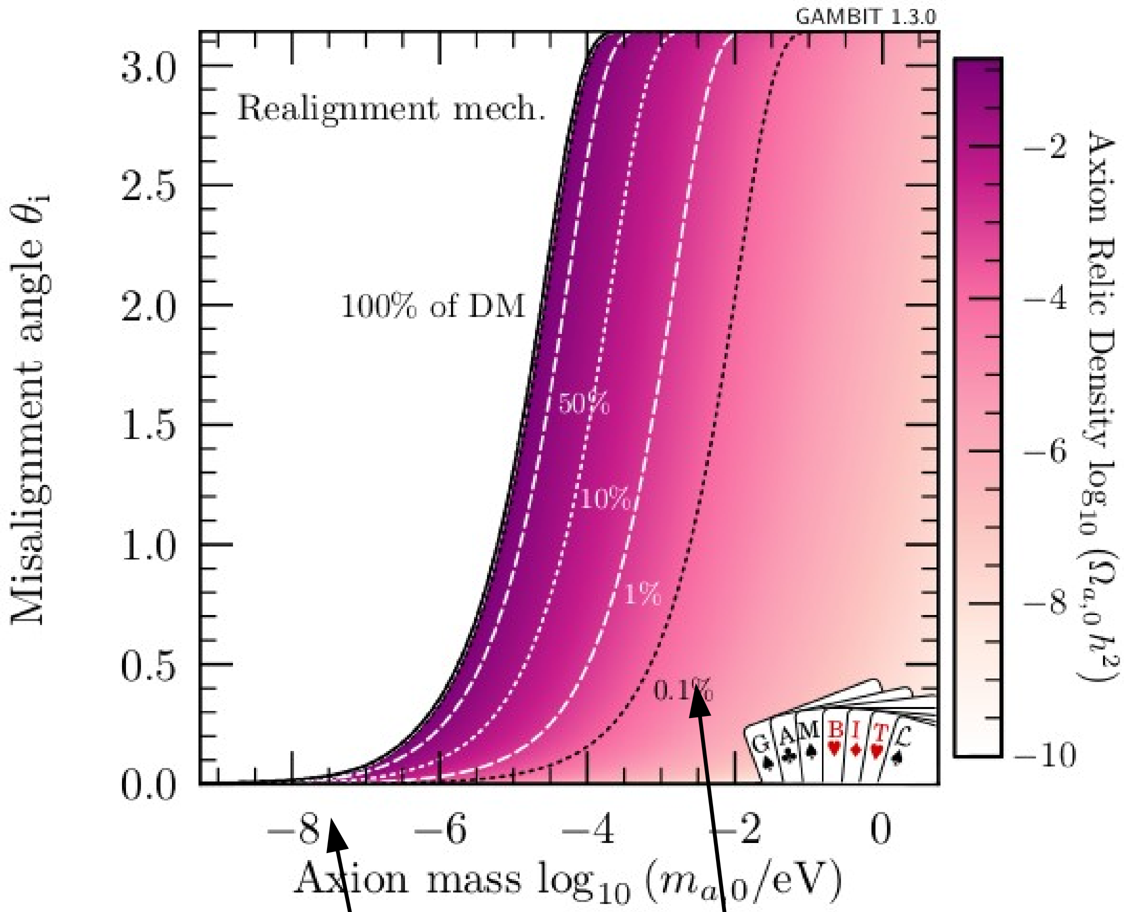
- WKB approximation for solution looks like

$$\theta(t) \propto \left[m_a(t)\, a^3(t)\right]^{-\frac{1}{2}} \cos\left(\int_{t_\star}^{t} m_a(\tau)\,\mathrm{d}\tau + \delta_\star\right)$$

Implies that energy density scales like matter at late times

$$\langle \varepsilon \rangle \propto m_a\, a^{-3}$$

Relic density

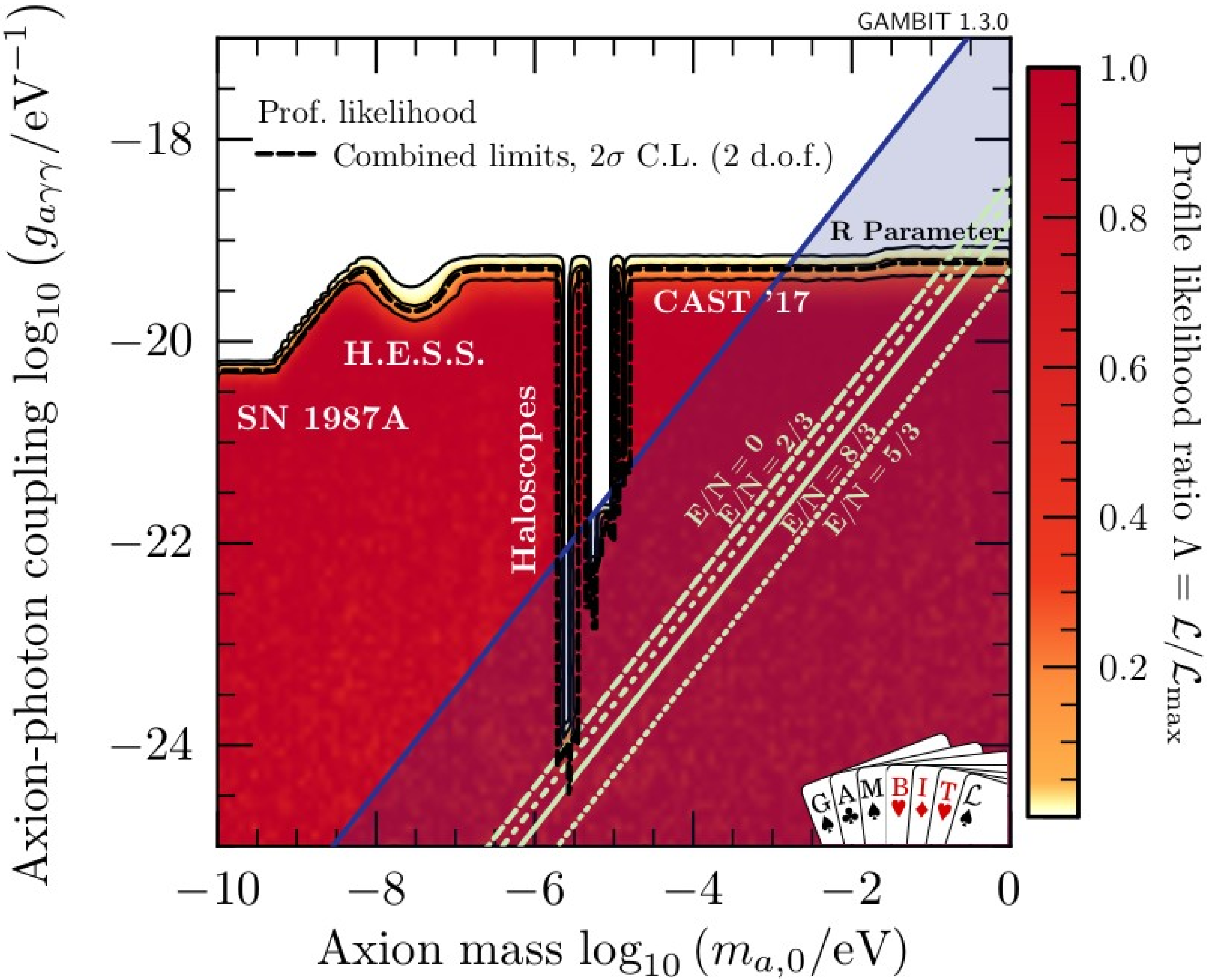


Fine-tuning
to avoid overproduction

Fractional dark matter

Hoof+ 18

Constrained parameter space



$$\mathcal{L}_a^{\rm int} = -\frac{g_{a\gamma\gamma}}{4} A F_{\mu\nu}\widetilde{F}^{\mu\nu} - \frac{g_{aee}}{2m_e}\bar{e}\gamma^\mu\gamma_5 e\partial_\mu a$$

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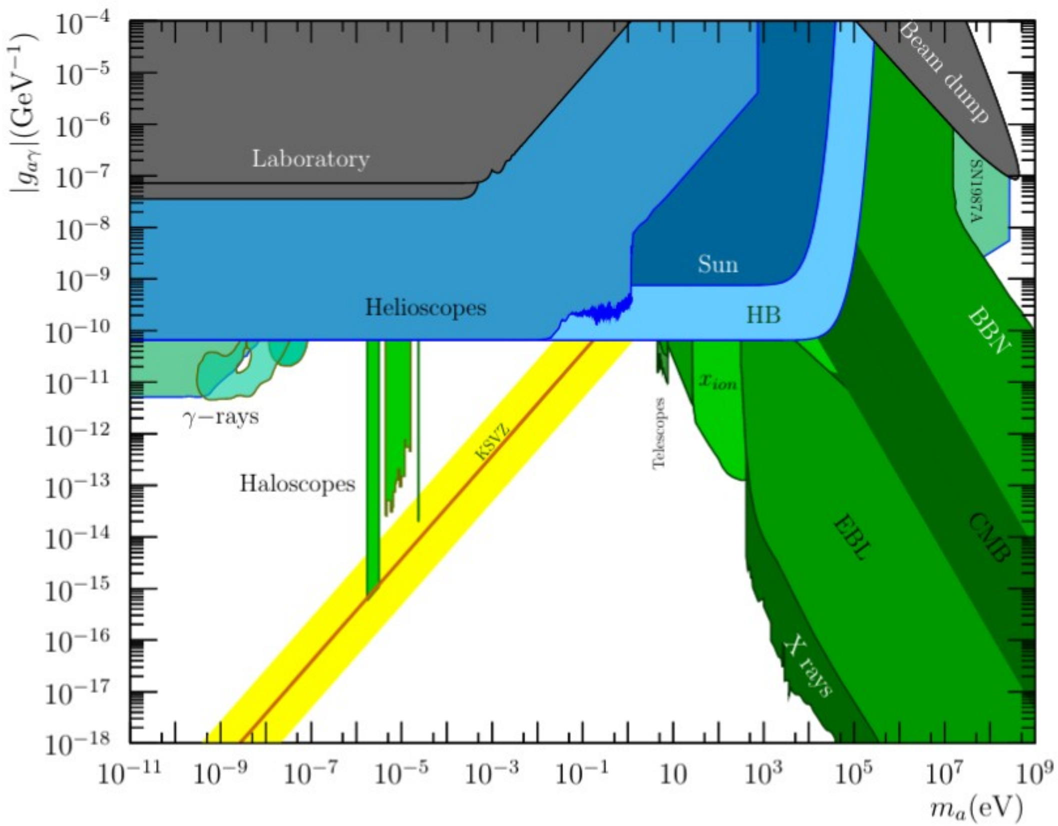
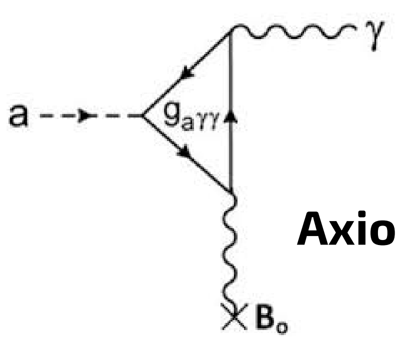
Constraints on ALPs



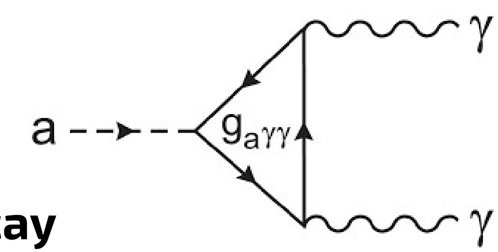
Irastorza & Redondo 2018

$$\mathcal{L}_a^{\mathrm{int}} = -\frac{g_{a\gamma\gamma}}{4} A F_{\mu\nu} \widetilde{F}^{\mu\nu}$$



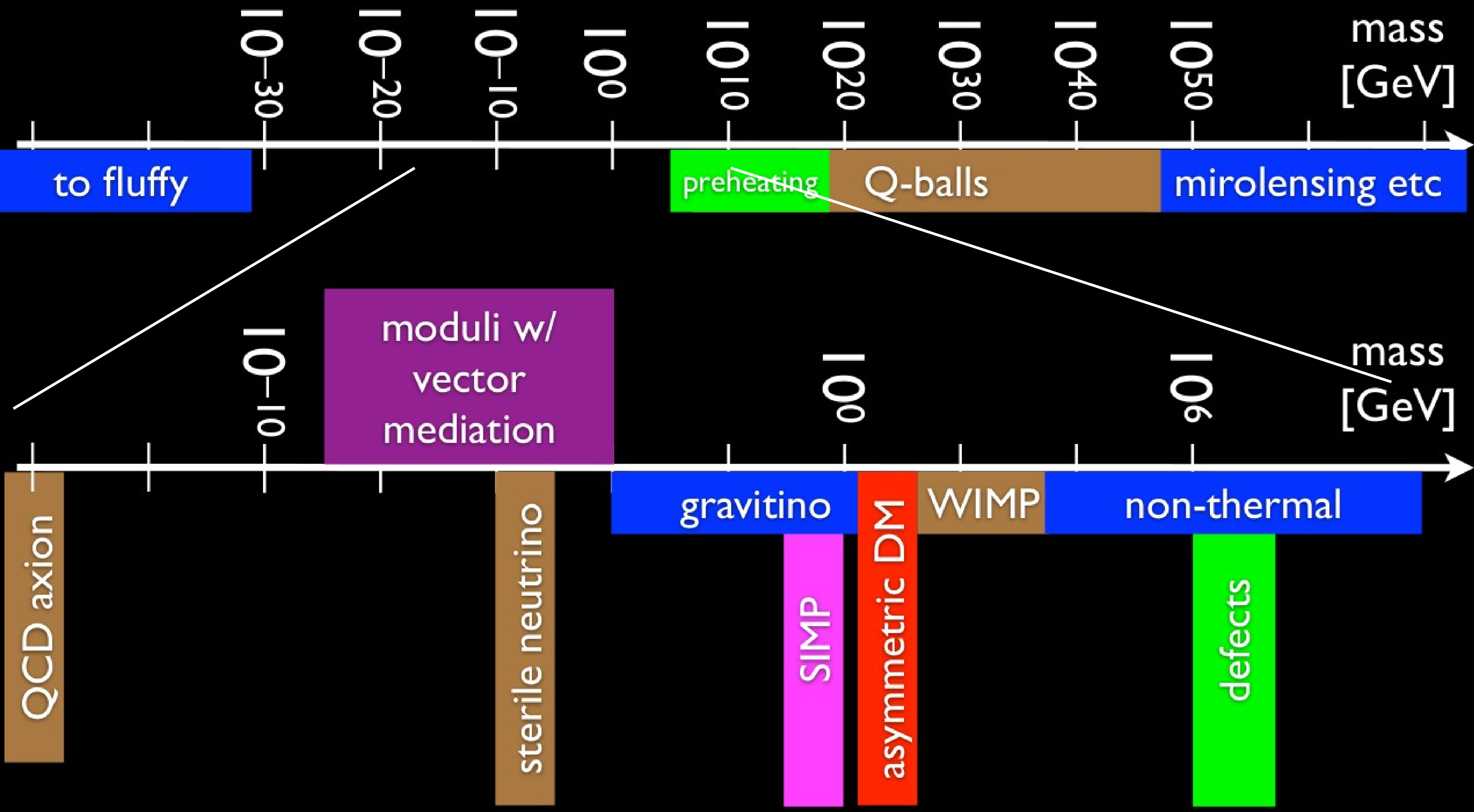
Axion-photon conversion

Axion decay
& stimulated emission



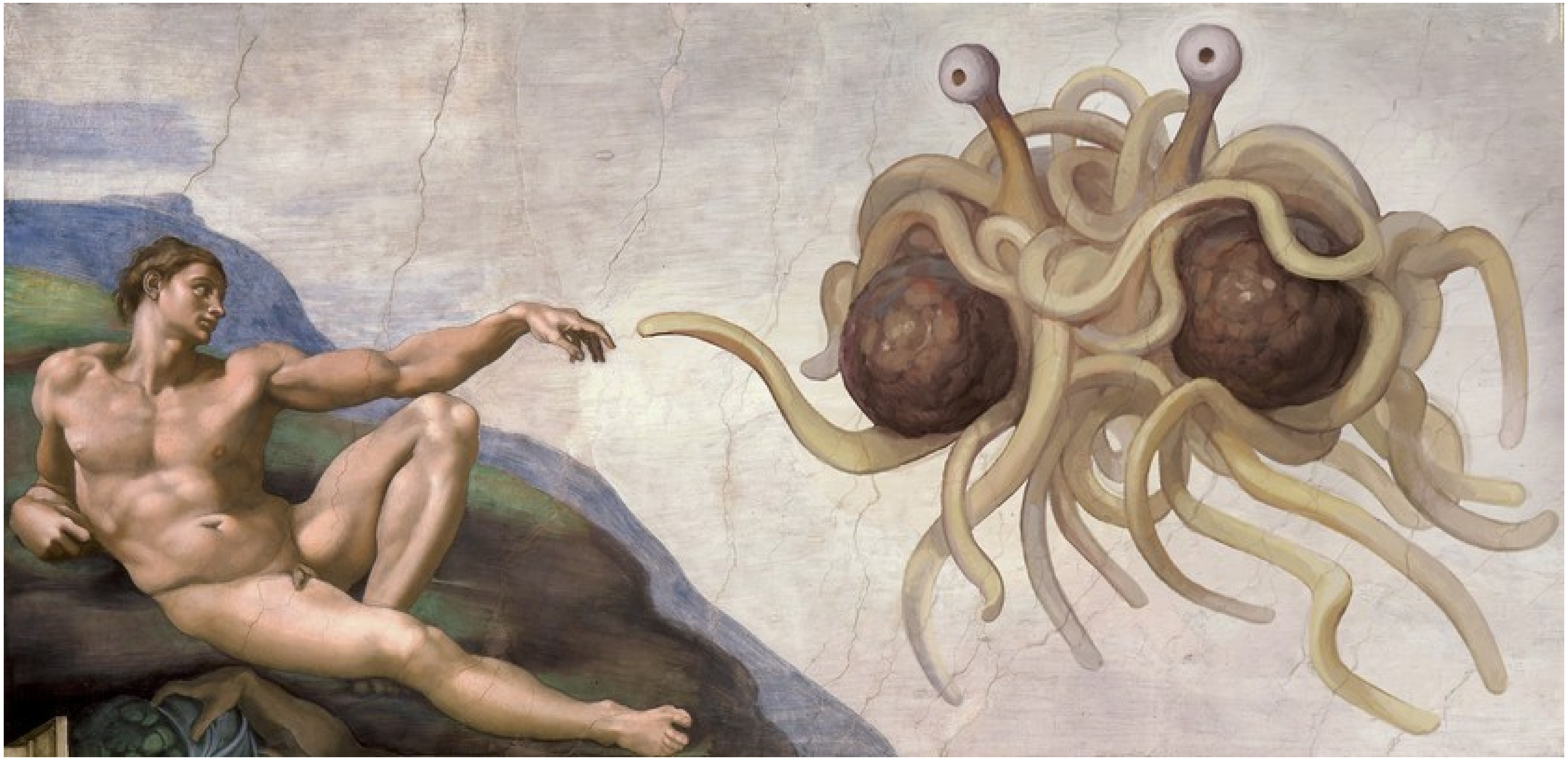
Maybe red herring?

Much more diverse



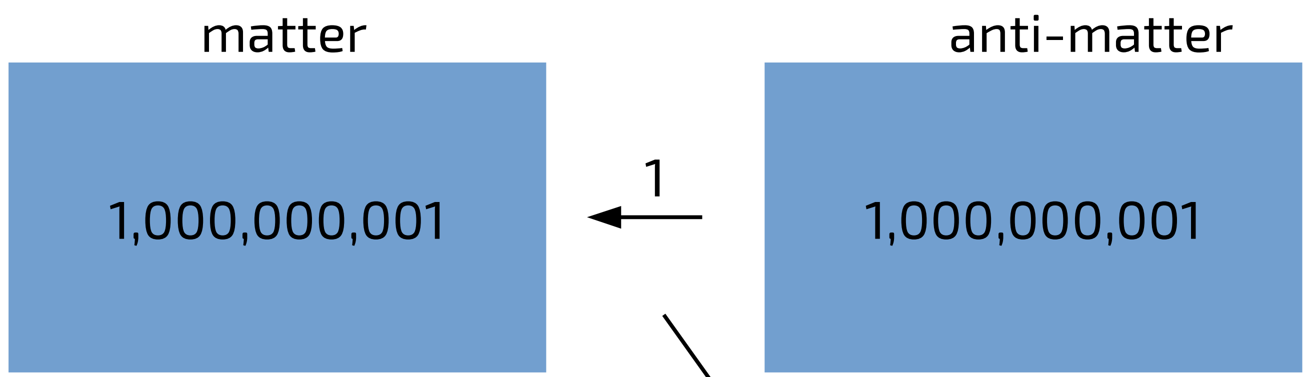
Slide credit: H. Murayama

Sociology post ~2010



- Dark matter exists, needs to be explained on its own
- Perhaps nothing to do with "big problems" of SM
- We can make up our own models, explore the phenomenology landscape
- Maybe dark matter is much lighter & weaker coupled, or much heavier, than we thought?

For example: Asymmetric DM



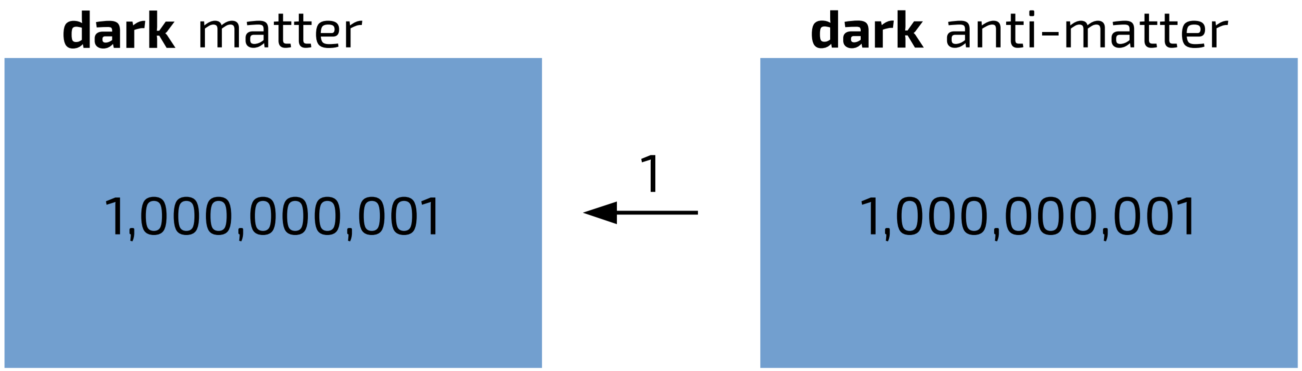
2 (us)

- Tiny baryon asymmetry was generated somehow after inflation

$$\eta_b \equiv \frac{n_b}{n_\gamma} \sim 10^{-9}$$

- Everything annihilated away up to tiny residual (lucky us!)

For example: Asymmetric DM



$$m_{\rm dm} = \frac{\eta_b}{\eta_{\rm dm}} \frac{\Omega_{\rm dm}}{\Omega_b} m_p \approx 6\,{\rm GeV} \times \frac{\eta_b}{\eta_{\rm dm}}$$

- Motivation for 1-10 GeV dark matter
- Signal depends on portal between dark and visible sectors

Gelmini, Hall, Lin 1987

Kaplan, Luty, Zurek 2009

End

Thank you!