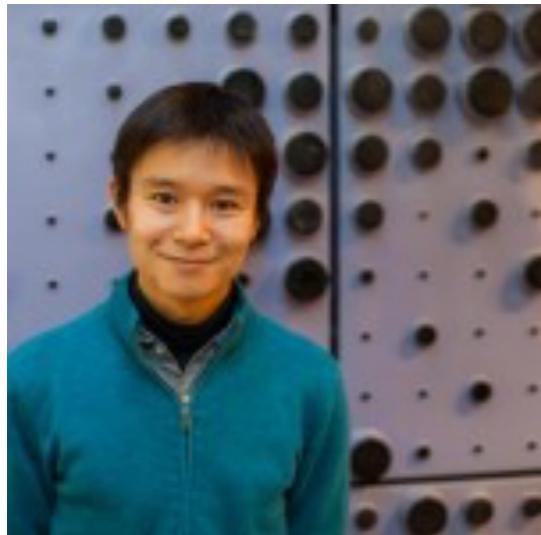


GRAPPA Student Seminar

Shin'ichiro Ando, Gianfranco Bertone,
Daniele Gaggero, Bradley Kavanagh



Lecturers



Shin'ichiro Ando
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Week 1



Gianfranco Bertone
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Week 2



Daniele Gaggero
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Week 3



Bradley Kavanagh
(b.j.kavanagh@uva.nl)
Week 3

Dark Matter

500 Mpc/h

31.25 Mpc/h

Key questions on dark matter

- How do we know that they really exists (vs modified Newtonian dynamics)?
- Why do we know that they are not made of particles that we know?
- What are candidates that are well motivated?
- How can we identify non-gravitational nature of dark matter?

4 main subjects for Student Seminar

- Dark matter in cosmology
- Dark matter candidates
- Indirect detection
- Direct detection

4 main subjects for Student Seminar

- **Dark matter in cosmology**
- Dark matter candidates
- Indirect detection
- Direct detection

1. Λ CDM, Ω_b , Ω_{DM} , CMB
2. Numerical simulations
3. Cracks in Λ CDM

4 main subjects for Student Seminar

- Dark matter in cosmology
- **Dark matter candidates**
- Indirect detection
- Direct detection

1. WIMPs (fundamental motivations, SUSY, UED, simplified models)
2. Non WIMPs (fuzzy DM, axions, sterile neutrinos, WIMPzillas)
3. Primordial black holes

4 main subjects for Student Seminar

- Dark matter in cosmology
- Dark matter candidates
- **Indirect detection**
 - 1. Gamma rays
 - 2. Anti-matter
 - 3. High-z (CMB, 21cm, etc.)
- Direct detection

4 main subjects for Student Seminar

- Dark matter in cosmology
- Dark matter candidates
- Indirect detection
- **Direct detection**
 - 1. DM-nucleus scattering
 - 2. DM-electron scattering
 - 3. Neutrino floor and getting beyond it

Course schedule

	Tuesday	Wednesday	Friday
Week 1	Lecture 1 (Ando)	Scripts	Q&A (Ando)
Week 2	Lecture 2 (Bertone)	Scripts	Q&A (Bertone)
Week 3	Lecture 3 (Gaggero/Kavanagh)	Scripts	Q&A (Gaggero/Kavanagh)
Week 4	Presentations	Scripts	Feedback

But note that full-time commitment is assumed and required!

Tasks for Student Seminar

- Write **review articles** on dark matter that is to be published online (and linked from GRAPPA webpage)
- Develop **numerical codes** (using jupyter notebook) to compute various relevant processes and quantities
- Summarize own findings in **presentations** that is to be given the fourth week; each of you should present

Review articles: Contribution to Dark Matter Wiki

Dark Matter Wiki

The most up-to-date resource for Dark Matter studies

DM in Cosmology

Candidates

Colliders Searches

Direct Detection

Indirect Detection

Tools and Resources



Welcome!

Search ...

About us

GRAPPA

Contact us

Email Us

Proudly powered by WordPress

<http://www.darkmatterwiki.net>

Review articles

- **Four groups** (consisting of a few students each) work on four different topics
 - DM in cosmology
 - Candidates
 - Indirect detection
 - Direct detection
- Lectures in weeks 1-3 are designed to give you an **overview** of each subject, but you need to study yourself much more in depth than is covered by the lectures

Review articles

- Provide your input via LaTeX file
- Use BibTeX to handle references and copy & paste from INSPIREHEP.net
- Aim at ~30 A4 pages for each group (~10 pages each week)
- Upload files on GitHub folder (discussed in detail tomorrow):
[https://github.com/bradkav/GRAPPA Student Seminar 2018](https://github.com/bradkav/GRAPPA_Student_Seminar_2018)
- We will make sure to convert them to an appropriate format for the wiki page

Tips for finding literature

- It might be a good idea to **start with other review articles** (Annual Reviews, Physics Reports, Progress on Progress in Physics, etc.)
 - But make sure NOT to copy and paste what are discussed there
- Often these reviews are outdated, so the **contents need to be updated** accordingly
- Find them on search engines such as INSPIRE, NASA ADS, arXiv, Google, etc.
- There are of course very many papers out there, so it is impossible to read them all; so focus ones which got many **citations**

Recommended articles

- “Supersymmetric dark matter”: Jungman, Kamionkowski, Griest, hep-ph/9506380
- “Particle dark matter: Evidence, candidates and constraints”: Bertone, Hooper, Silk, hep-ph/0404175
- “WIMP dark matter candidates and searches - current issues and future prospects”: Roszkowski, Maria Sessolo, Trojanowski, arXiv:1707.06277 [hep-ph]

Writing simple scripts

- Wednesdays are devoted for developing simple scripts
- Each group works on writing numerical codes to calculate:
 - **Cosmology:** CMB anisotropies
 - **Candidates:** Thermal freezeout
 - **Indirect detection:** Line-of-sight integral of density squared
 - **Direct detection:** Rates of dark matter scattering
- Use **jupyter notebook** with **python** language; files to be uploaded on GitHub and linked from the Dark Matter Wiki
- More details tomorrow

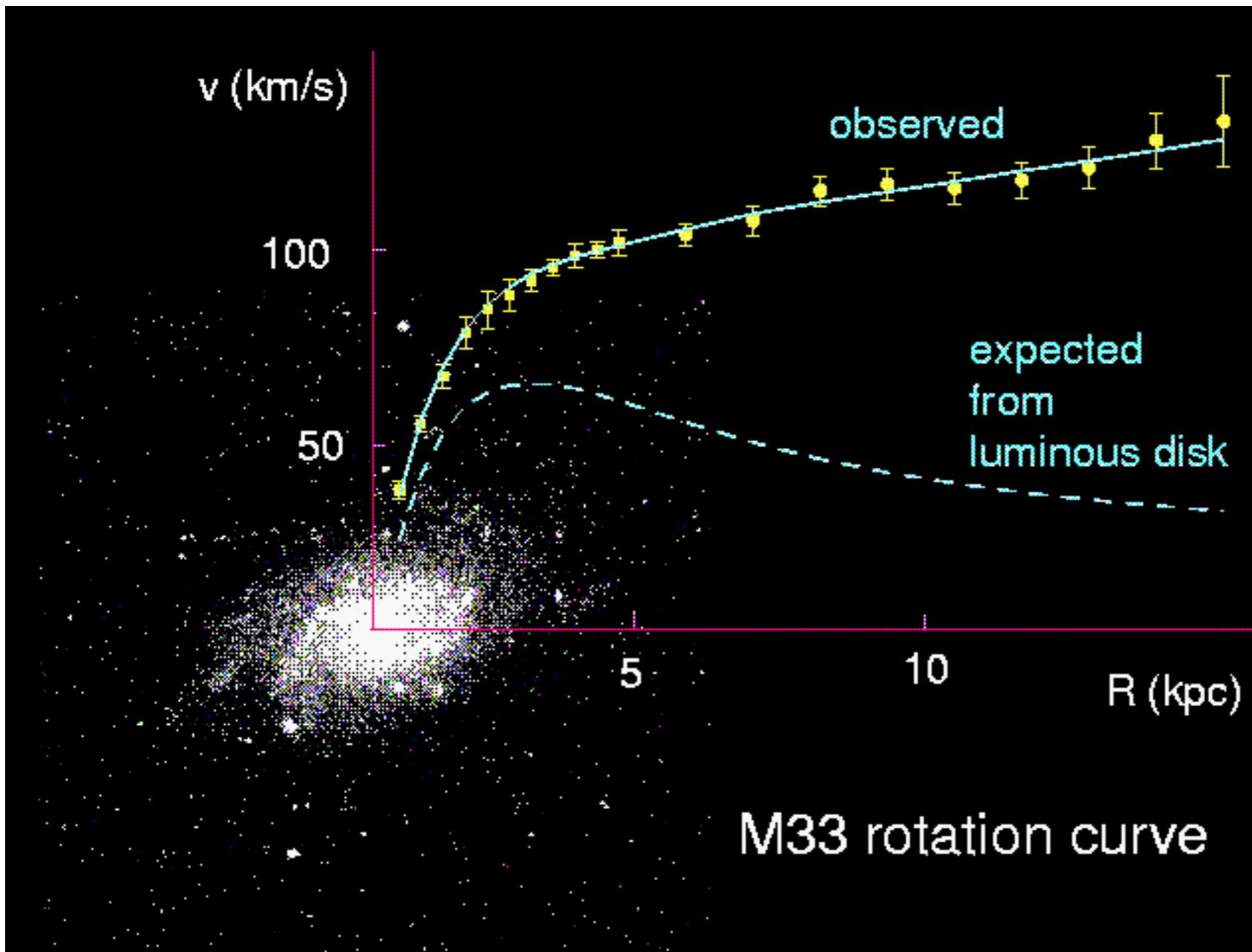
What to do today after the lecture

- Send your preference regarding which subject you want to work on: **1. cosmology**, **2: candidates**, **3: indirect detection**, **4: direct detection**
 - Send three topics in order of preference
- Install essential tools for coding with python: python (version 3.6), ipython, matplotlib, numpy, scipy, jupyter notebook, etc.

Lecture 1

Dark Matter in Cosmology

Evidence for dark matter: Rotation curves



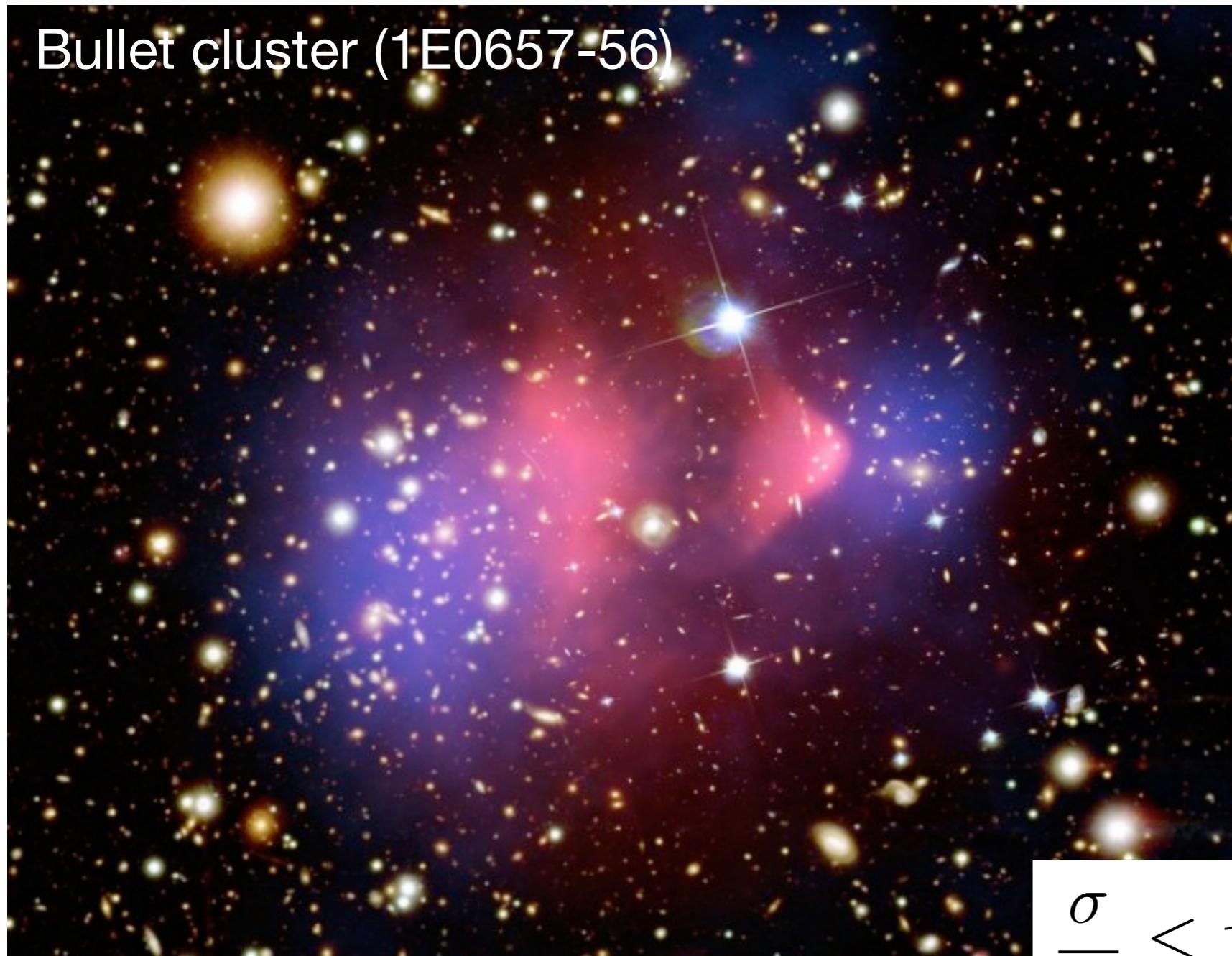
Bergström, *Rep. Prog. Phys.* **63**, 793 (2000)

$$v^2 = \frac{GM(< r)}{r}$$

- Inferring enclosed mass for luminous matter (stars assuming reasonable mass-to-light ratio) significantly **under-predicts** rotation-curve data
- **Implication:** “Dark” matter exists (but it doesn’t exclude not-so-bright stars or black holes)

Evidence for dark matter: Bullet clusters

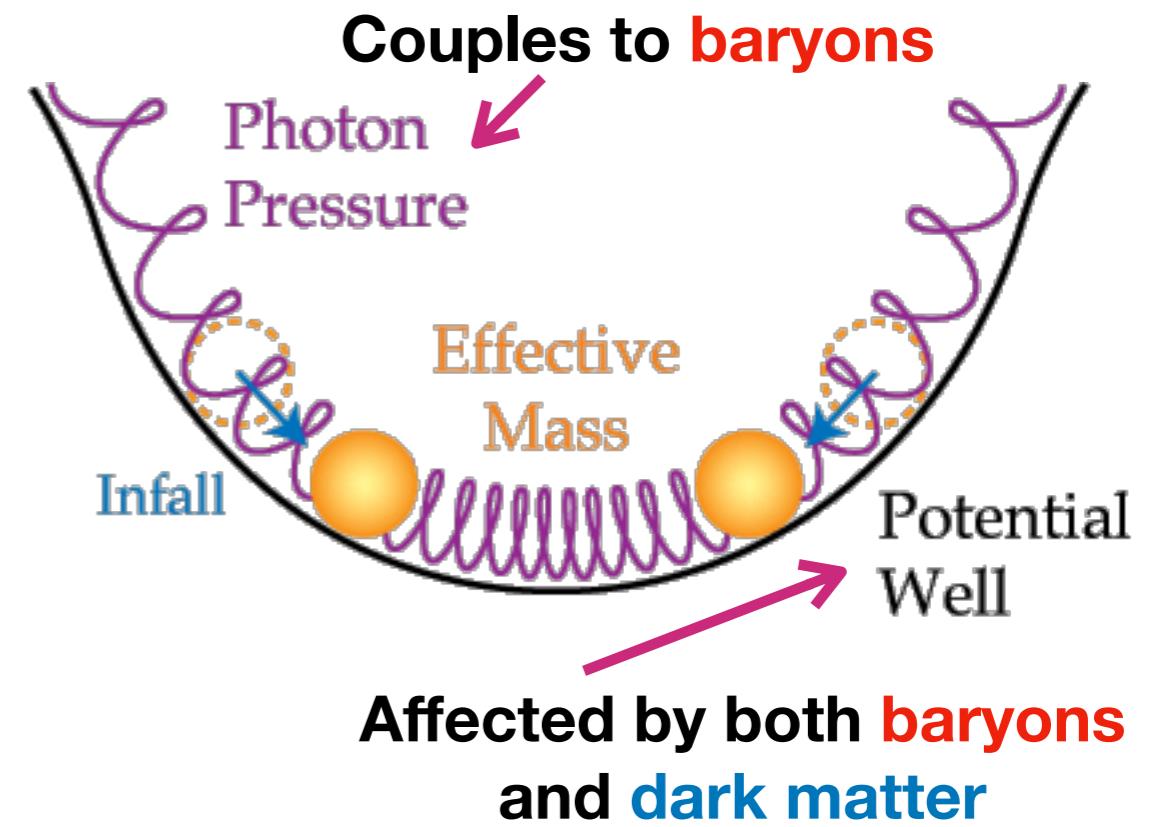
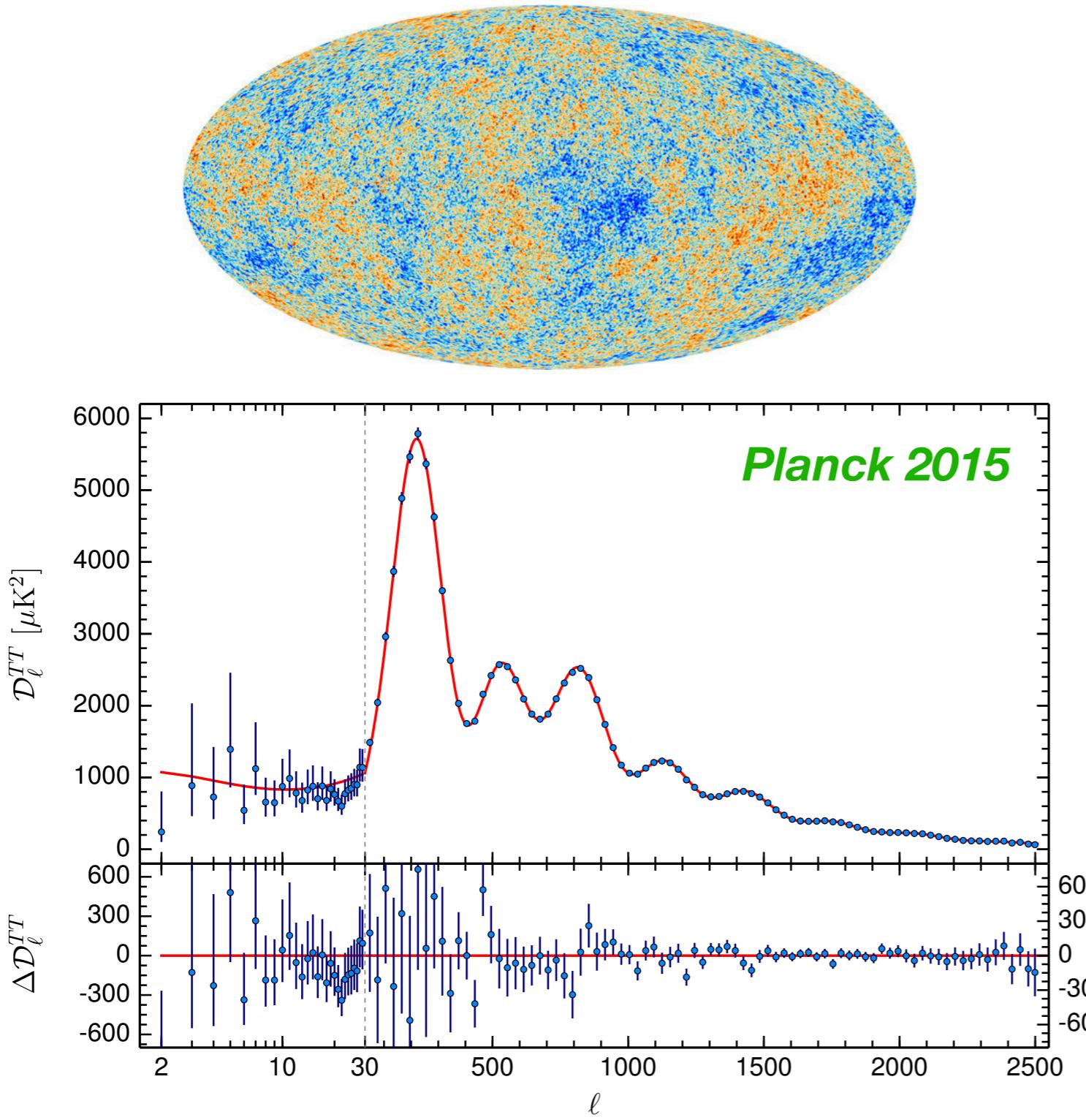
Bullet cluster (1E0657-56)



- **Red:** X-ray image (baryonic gas)
- **Blue:** Weak gravitational lensing (dark matter)
- Gas is collisional (Coulomb force) so feels drag from each other; dark matter goes through
- **Implication:** Dark matter is collisionless

$$\frac{\sigma}{m} \lesssim 1 \text{ cm}^2/\text{g} = 2 \text{ barn/GeV}$$

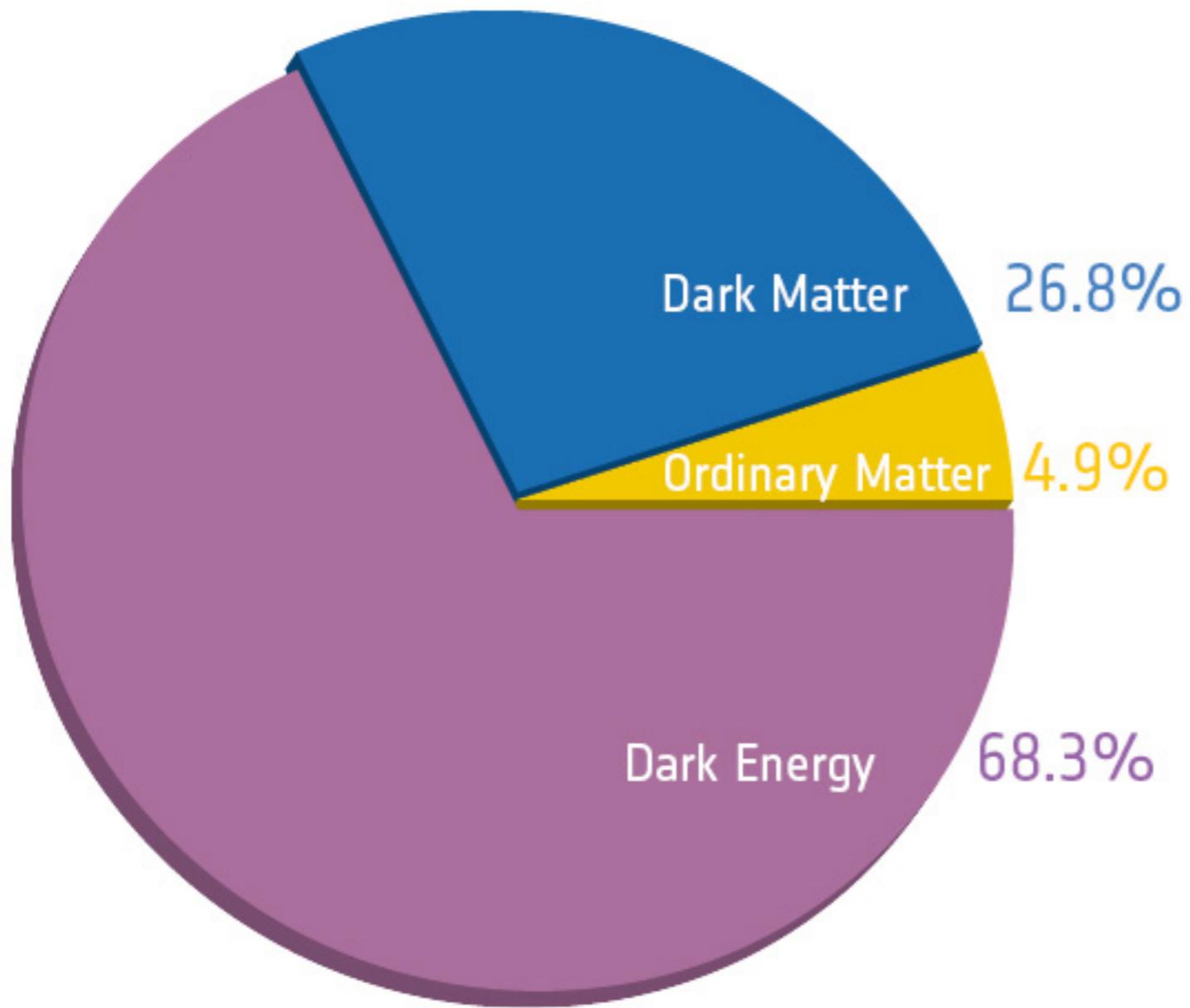
Evidence for dark matter: Baryon acoustic oscillation (BAO)



- Measured both in CMB and galaxy power spectrum
- *Implication:* Dark matter can **not** be made of baryons

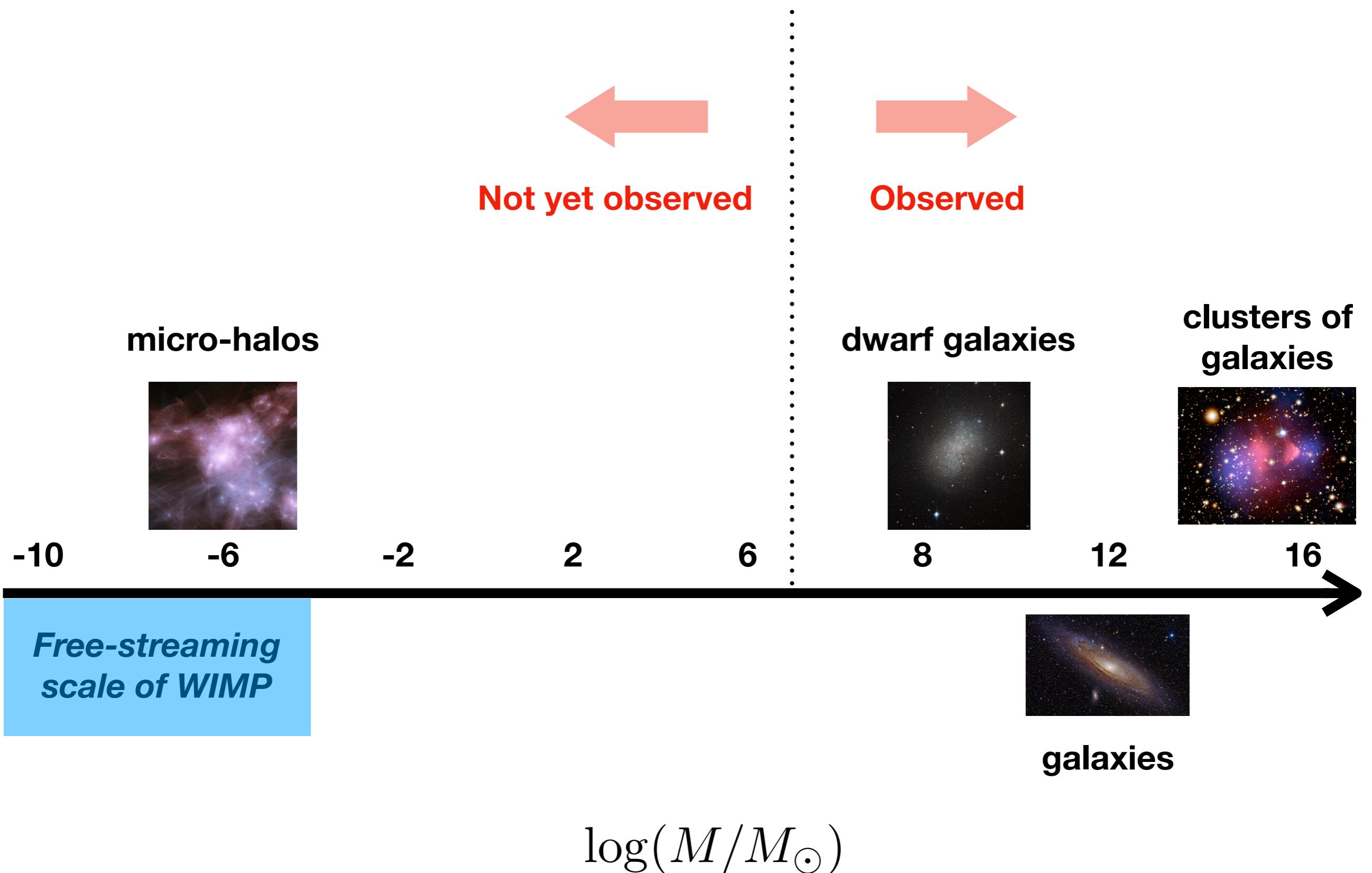
Result from all the cosmology data

Planck 2015



- CMB, galaxy power spectrum, weak lensing, supernova Ia, etc.
- 27% of the total energy / 85% of the total matter is made of dark matter
- Properties of dark matter
 - Collisionless
 - Non-baryonic
 - Doesn't interact with photons
 - Cold (or warm; hot dark matter erases too many structures)

Dark matter: Origin of all the structures



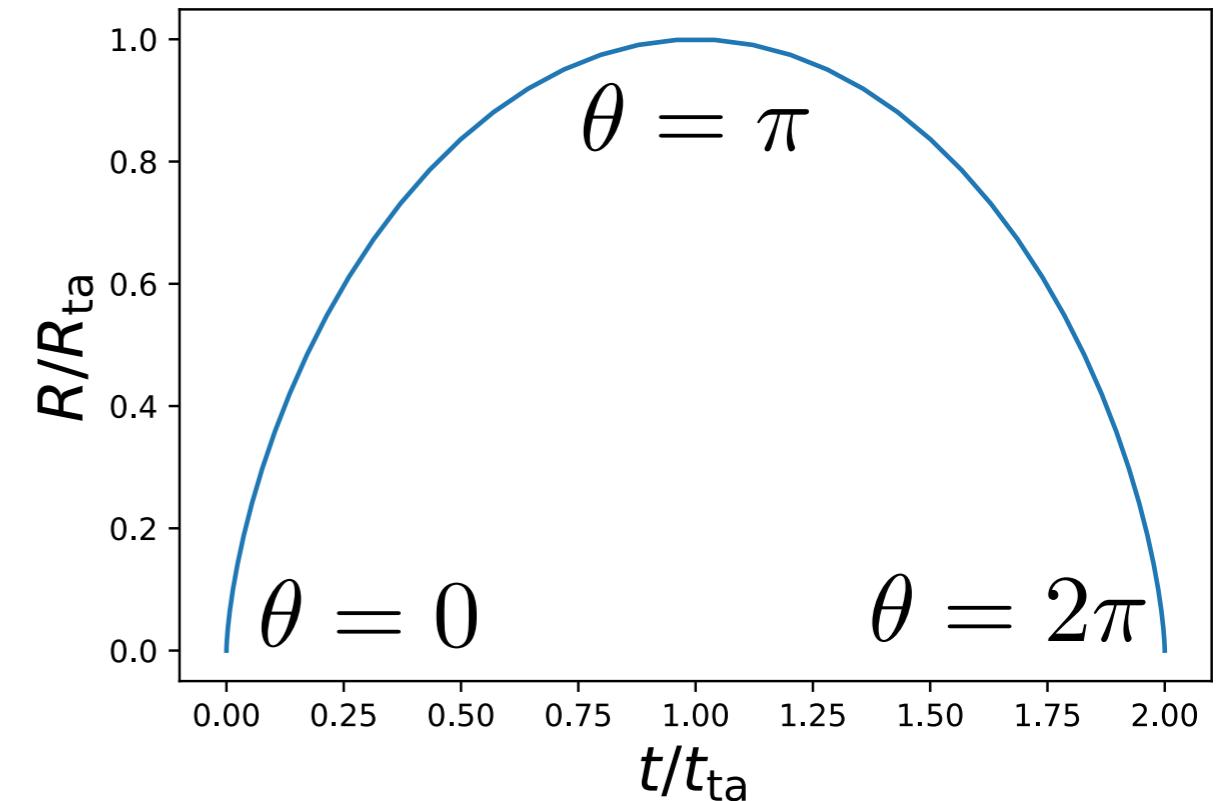
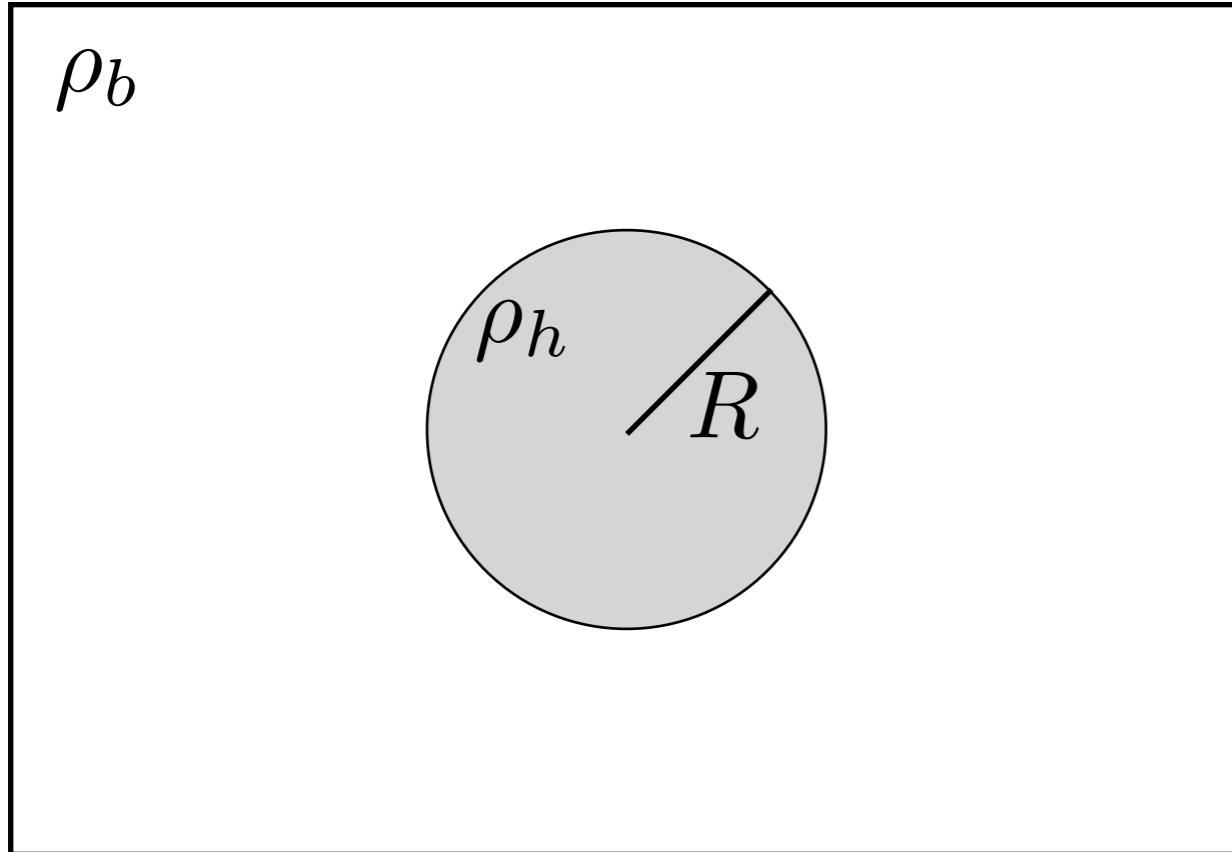
Spherical collapse model

- How dense are collapsed dark matter halos (that host galaxies, clusters of galaxies, etc.)?
- Over-density of virialized halos compared with background

$$\Delta_{\text{vir}} = 18\pi^2$$

*Useful for simulations
to find halos*

Spherical collapse model



Parameterized solution
(cf., expanding *closed* Universe)

$$t = \frac{A^3}{\sqrt{GM}} (\theta - \sin \theta)$$

$$R = A^2(1 - \cos \theta)$$

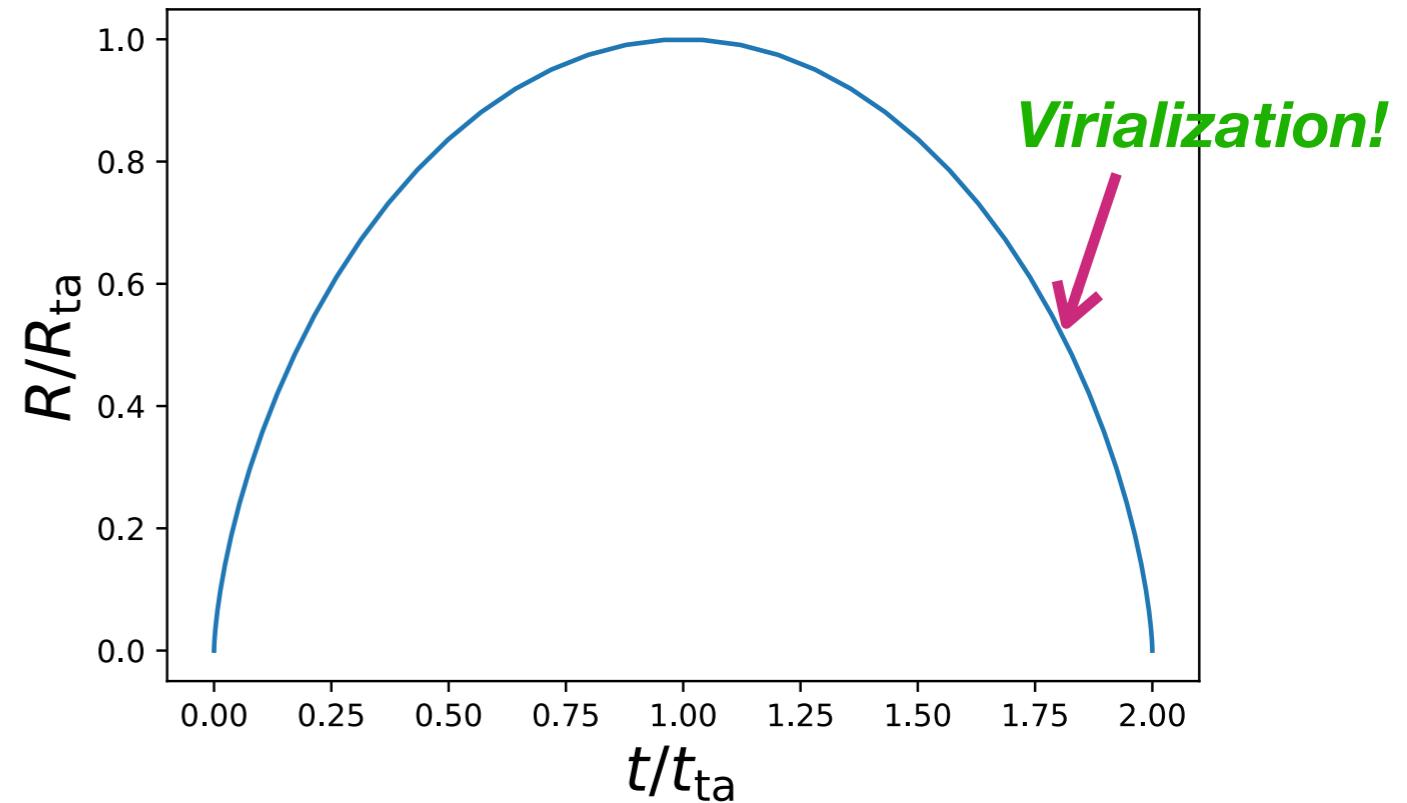
Spherical collapse model

When do halos virialize?

Virial theorem:

$$2K_{\text{vir}} + U_{\text{vir}} = 0$$

(for $1/R$ potential)



Total energy conservation:

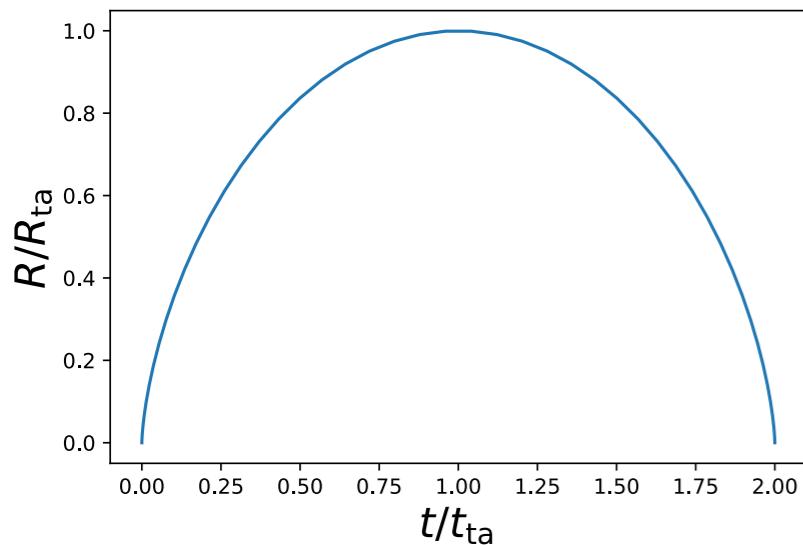
$$K_{\text{vir}} + U_{\text{vir}} = U_{\text{ta}}$$

$$U_{\text{vir}} = 2U_{\text{ta}}$$



$$R_{\text{vir}} = \frac{R_{\text{ta}}}{2}$$

Spherical collapse model



$$t = \frac{A^3}{\sqrt{GM}} (\theta - \sin \theta)$$

$$R = A^2(1 - \cos \theta)$$

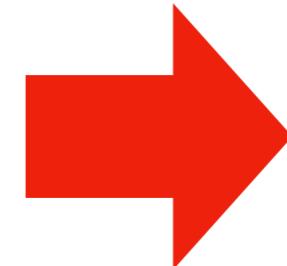
$$R_{\text{vir}} = \frac{R_{\text{ta}}}{2}$$

How dense is a virialized halo compared with background?

$$\rho_{\text{vir}} = \frac{3M}{4\pi R_{\text{vir}}^3} = \frac{6M}{\pi R_{\text{ta}}^3} = \frac{3\pi}{G t_{\text{col}}^2} \quad (t_{\text{col}} = 2t_{\text{ta}})$$

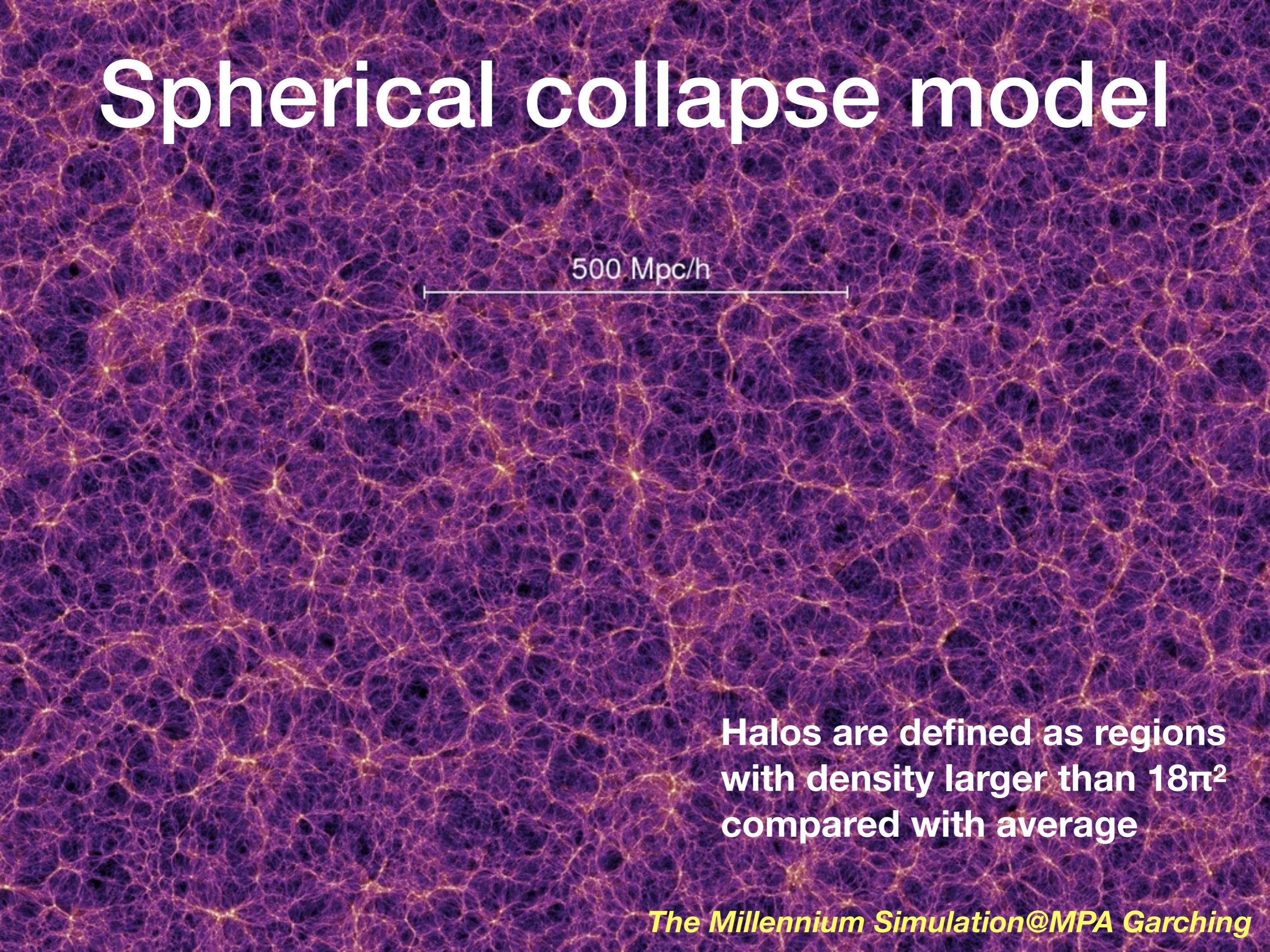


$$\rho_b(t_{\text{col}}) = \frac{1}{6\pi G t_{\text{col}}^2}$$



$$\frac{\rho_{\text{vir}}}{\rho_b(t_{\text{col}})} = 18\pi^2$$

Spherical collapse model



500 Mpc/h

Halos are defined as regions
with density larger than $18\pi^2$
compared with average

Spherical collapse model

- How dense are collapsed dark matter halos (that host galaxies, clusters of galaxies, etc.)?
- Over-density of virialized halos compared with background

$$\Delta_{\text{vir}} = 18\pi^2$$

*Useful for simulations
to find halos*

Spherical collapse model

- How dense are collapsed dark matter halos (that host galaxies, clusters of galaxies, etc.)?
- Over-density of virialized halos compared with background

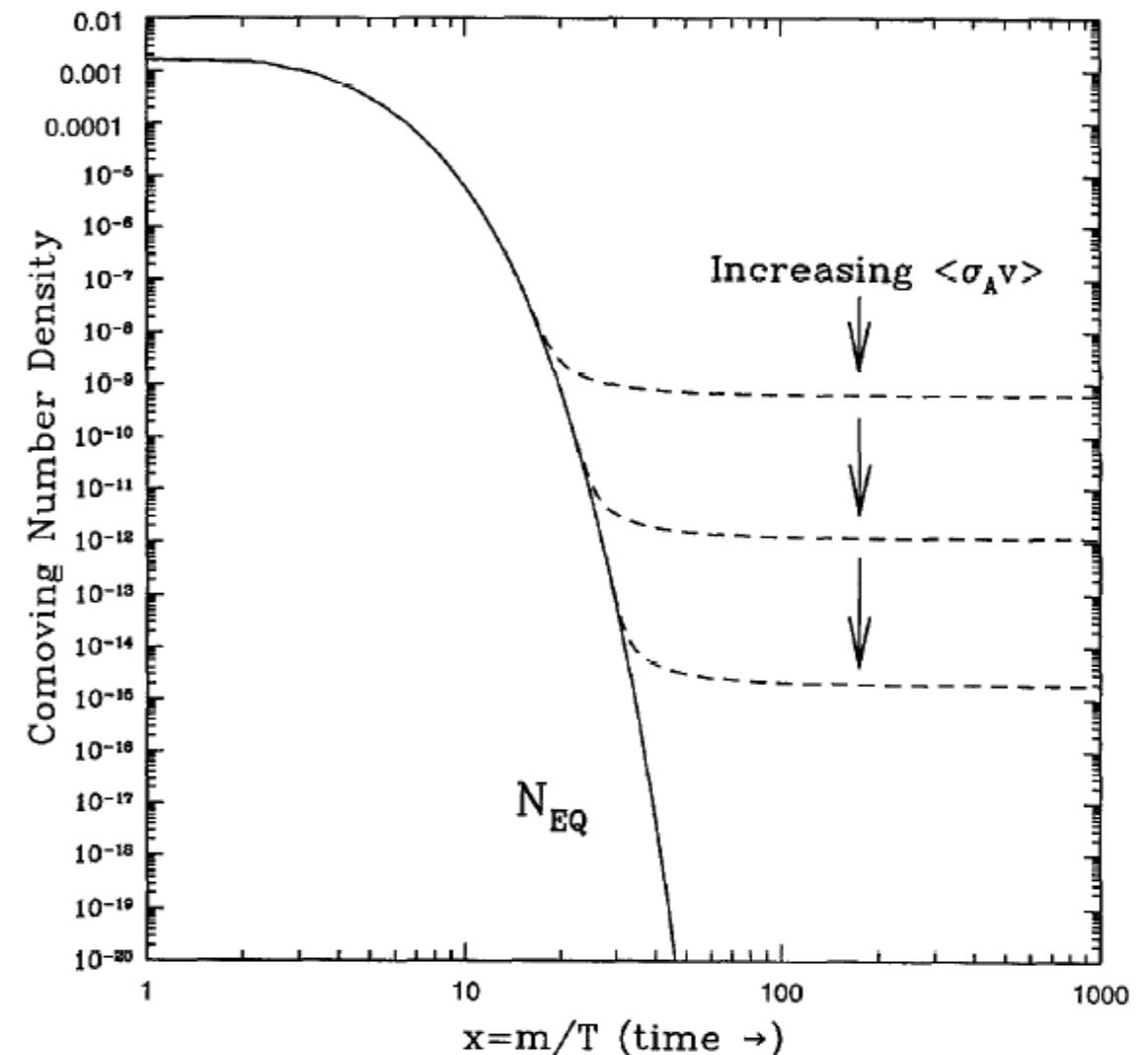
$$\Delta_{\text{vir}} = 18\pi^2 + 82[\Omega_m(z) - 1] - 39[\Omega_m(z) - 1]^2$$

Λ CDM: Bryan & Norman (1998)

Dark Matter Candidates

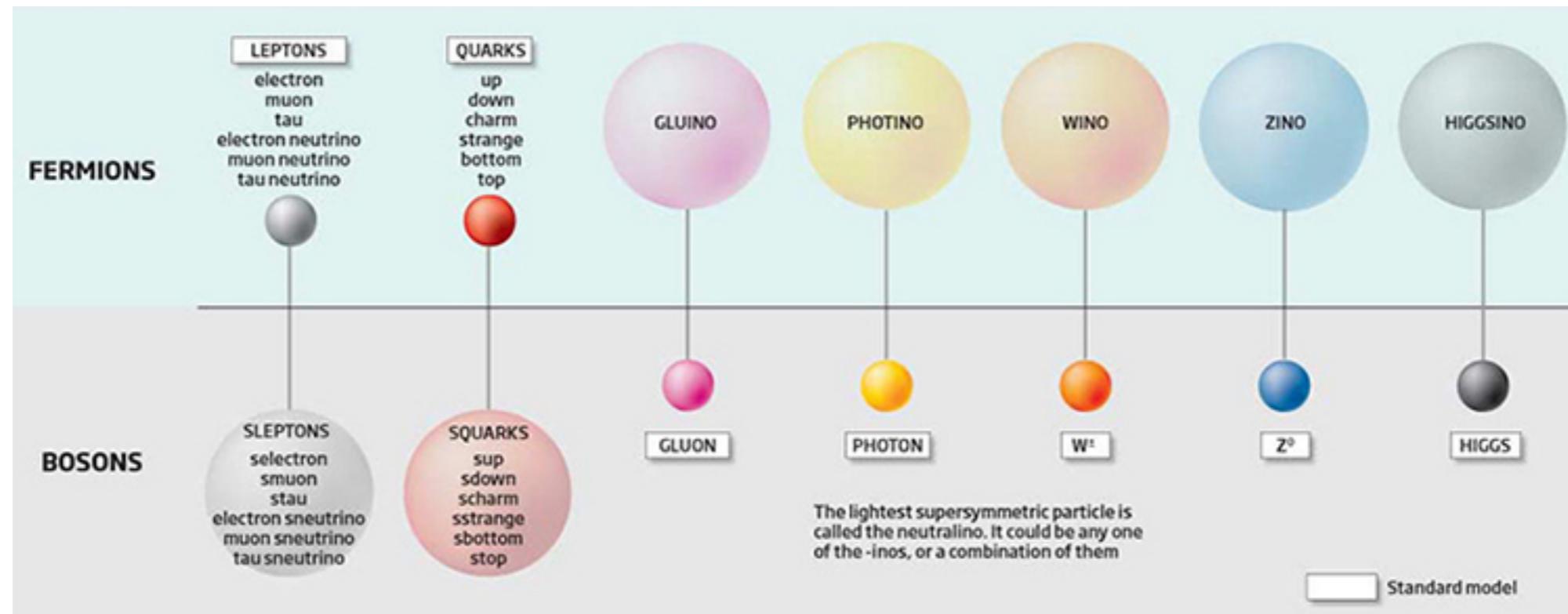
Dark matter candidate: WIMP

- Weakly Interacting Massive Particle (**WIMP**)
- Current dark matter density: determined by competition between Hubble expansion and annihilation (e.g., Steigman et al. 2012)
 - Later, expansion becomes too fast for WIMPs to annihilate (thermal **freeze-out**)
- WIMP models can naturally explain the relic abundance
- E.g., neutralino predicted by supersymmetry



$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle}$$
$$\langle \sigma_{\text{ann}} v \rangle \sim \alpha^2 (100 \text{ GeV})^{-2}$$
$$\sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

Supersymmetry (SUSY)



- SUSY extension of the Standard Model is well motivated
 - Stability of Higgs mass
 - Unification of gauge couplings
- It supplies SUSY partners to every Standard Model particle

Higgs mass

$$m_H^2 \phi^2 = \text{bare mass } M_{H,0}^2 + \text{Fermion 1-loop} + \text{Scalar 1-loop}$$

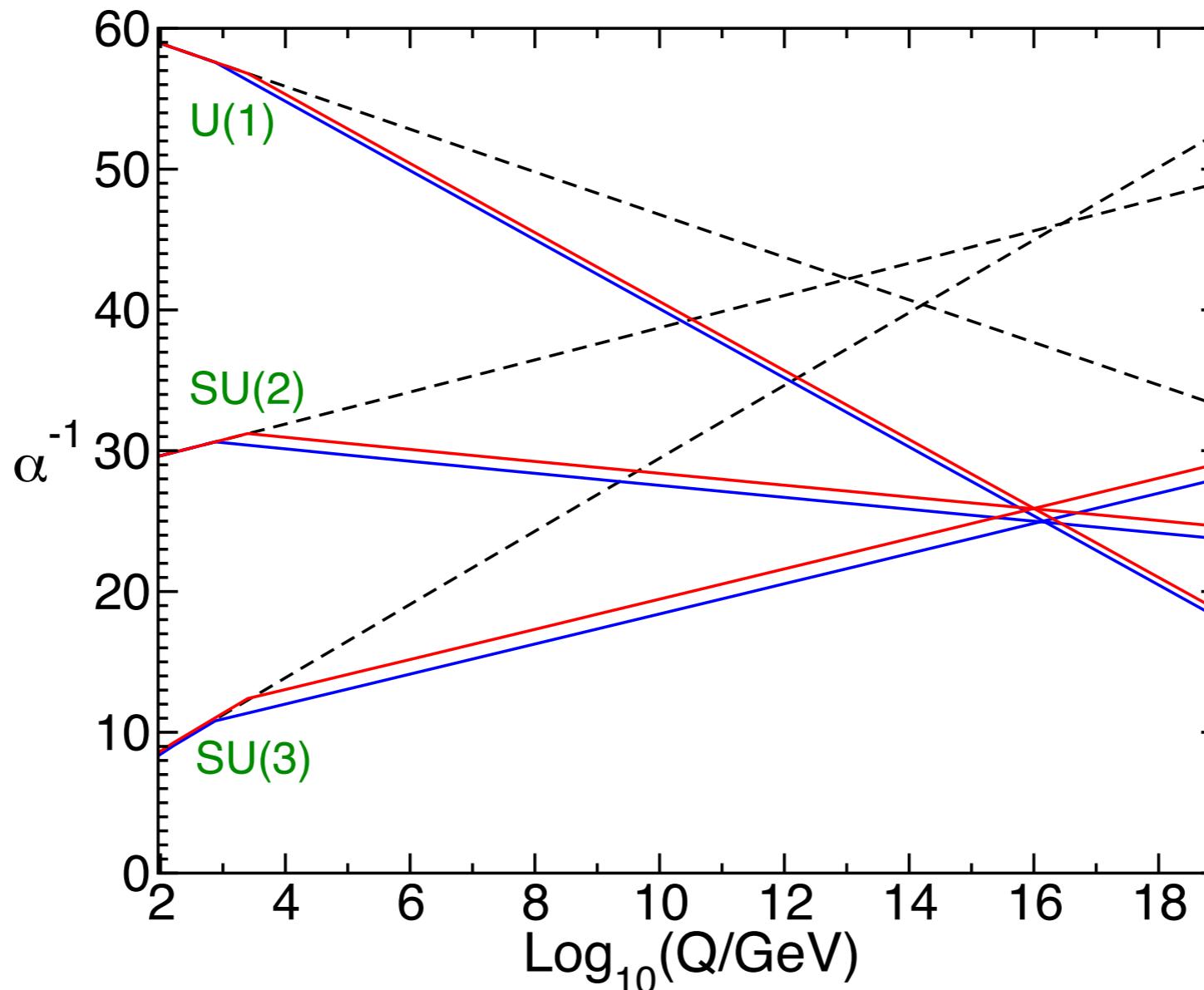
$\sim \Lambda^2$

$\sim -\Lambda^2$

The diagram illustrates the cancellation of the bare Higgs mass. It starts with a bare mass term represented by a dashed line. This is followed by a plus sign and two loop corrections. The first correction is a fermion loop with a top quark (t) and an anti-top quark (tilde t), labeled 'Fermion 1-loop ~ Lambda^2'. The second correction is a scalar loop with a top quark (tilde t) and an anti-top quark (t), labeled 'Scalar 1-loop ~ -Lambda^2'. The minus sign in front of the scalar loop indicates it cancels the bare mass term.

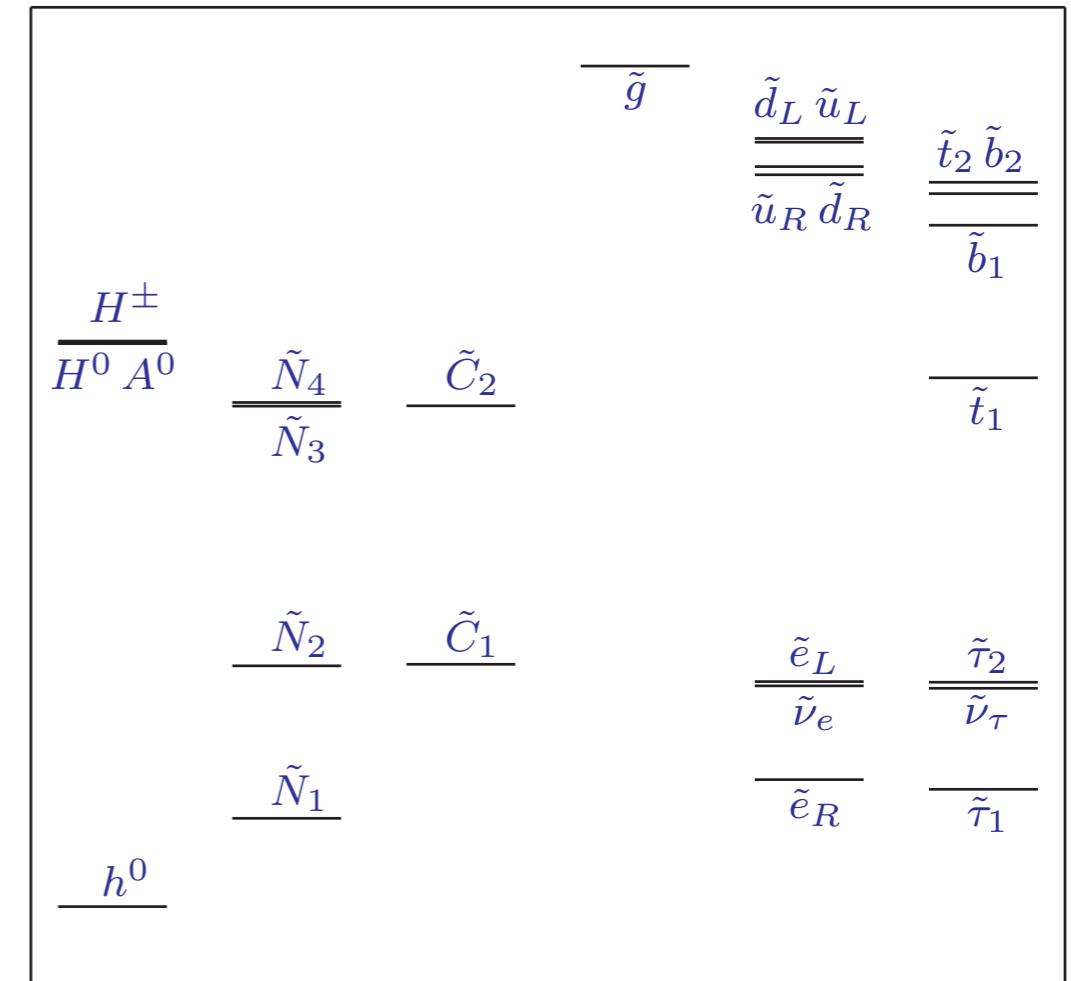
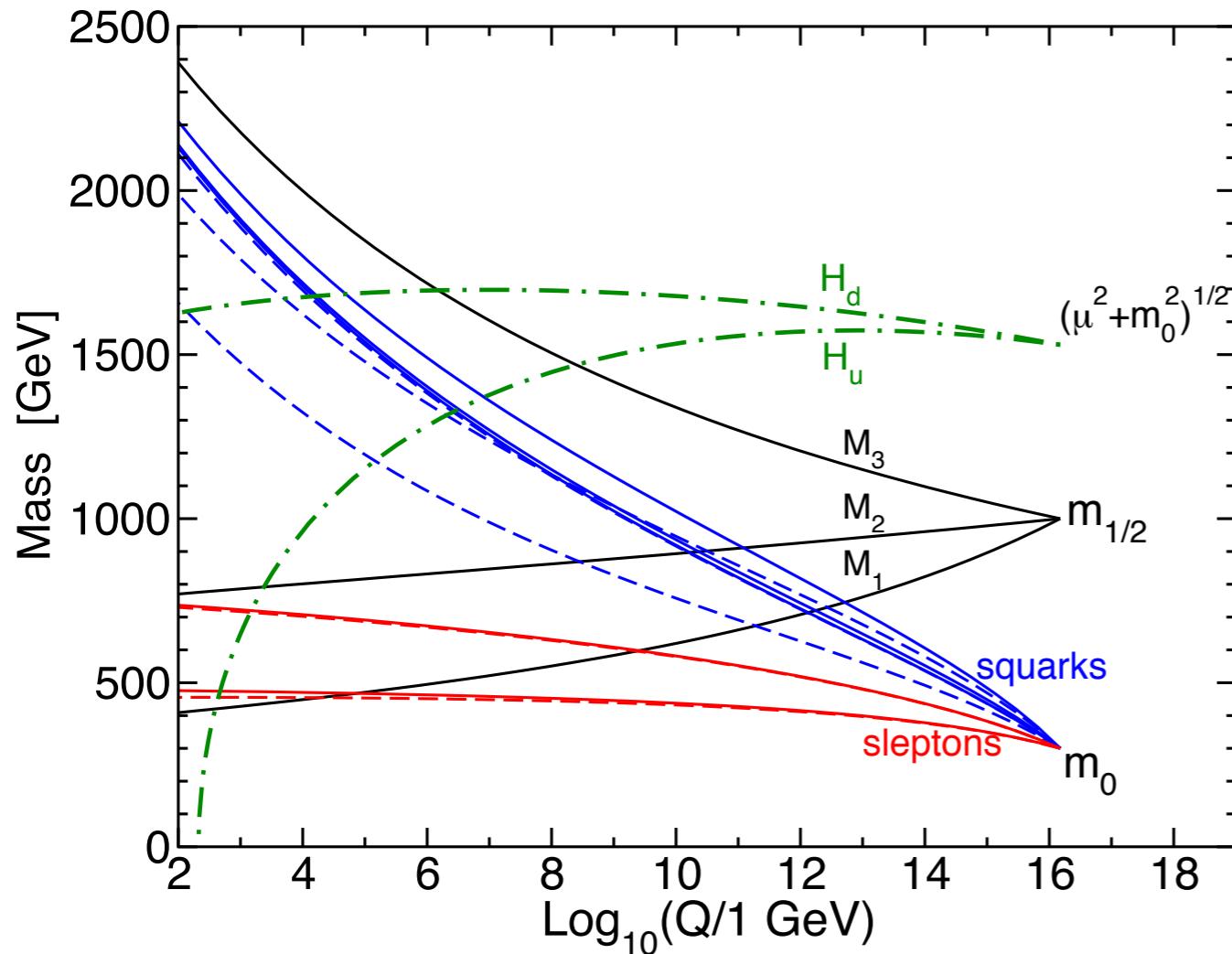
Cancellation happens to make Higgs mass at electroweak scale

Unification of gauge coupling



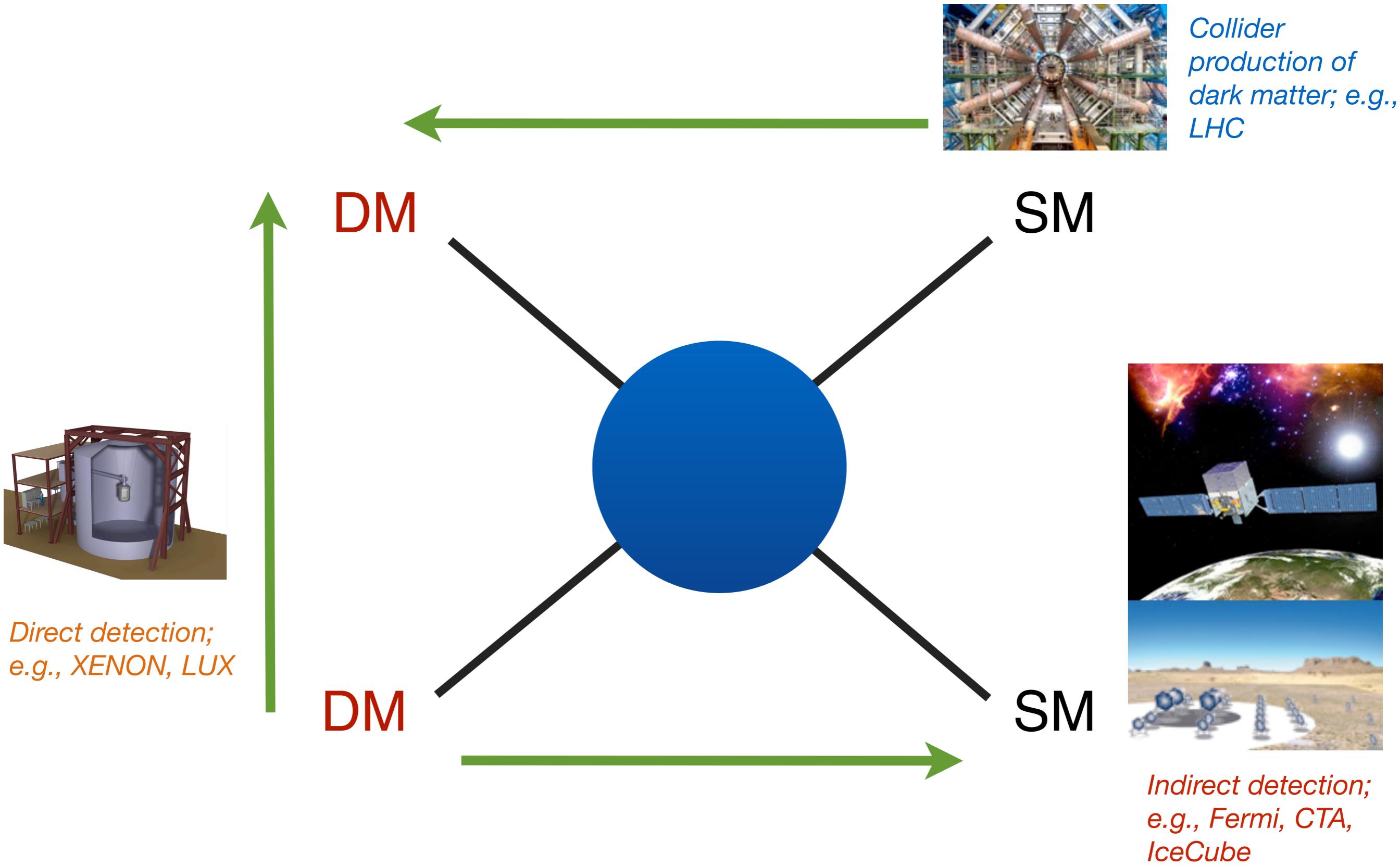
MSSM predicts unification at 10^{16} GeV energy scale

SUSY neutralino

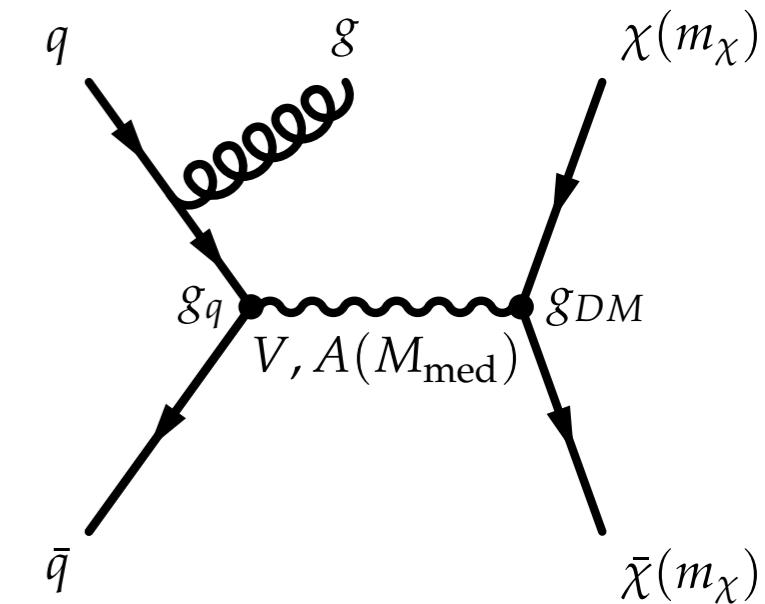
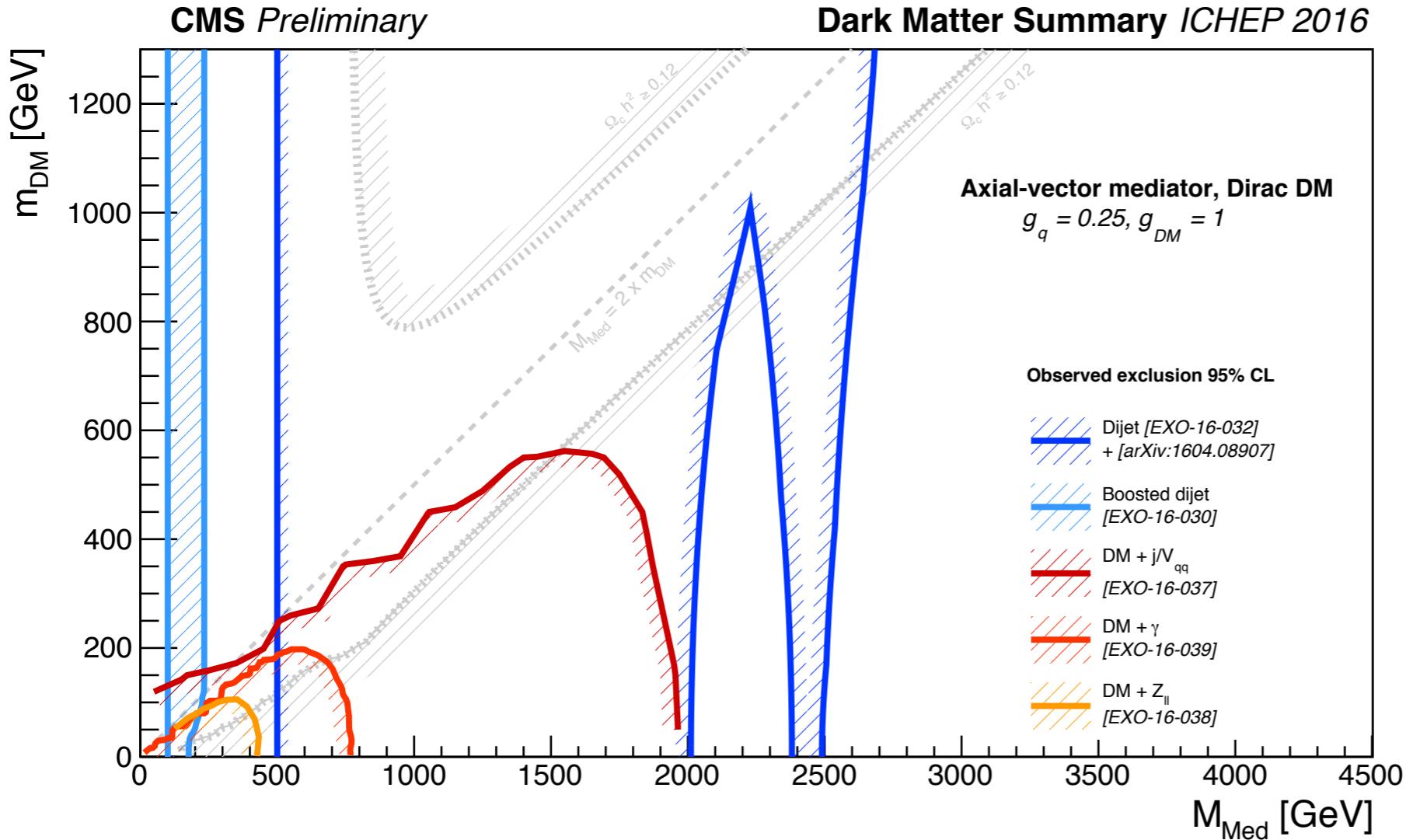


- Mass eigenstate for neutral SUSY partners of photons, Z and Higgs bosons
- In many models, they are the lightest SUSY particles: hence dark matter candidate

Three routes to DM



Collider searches

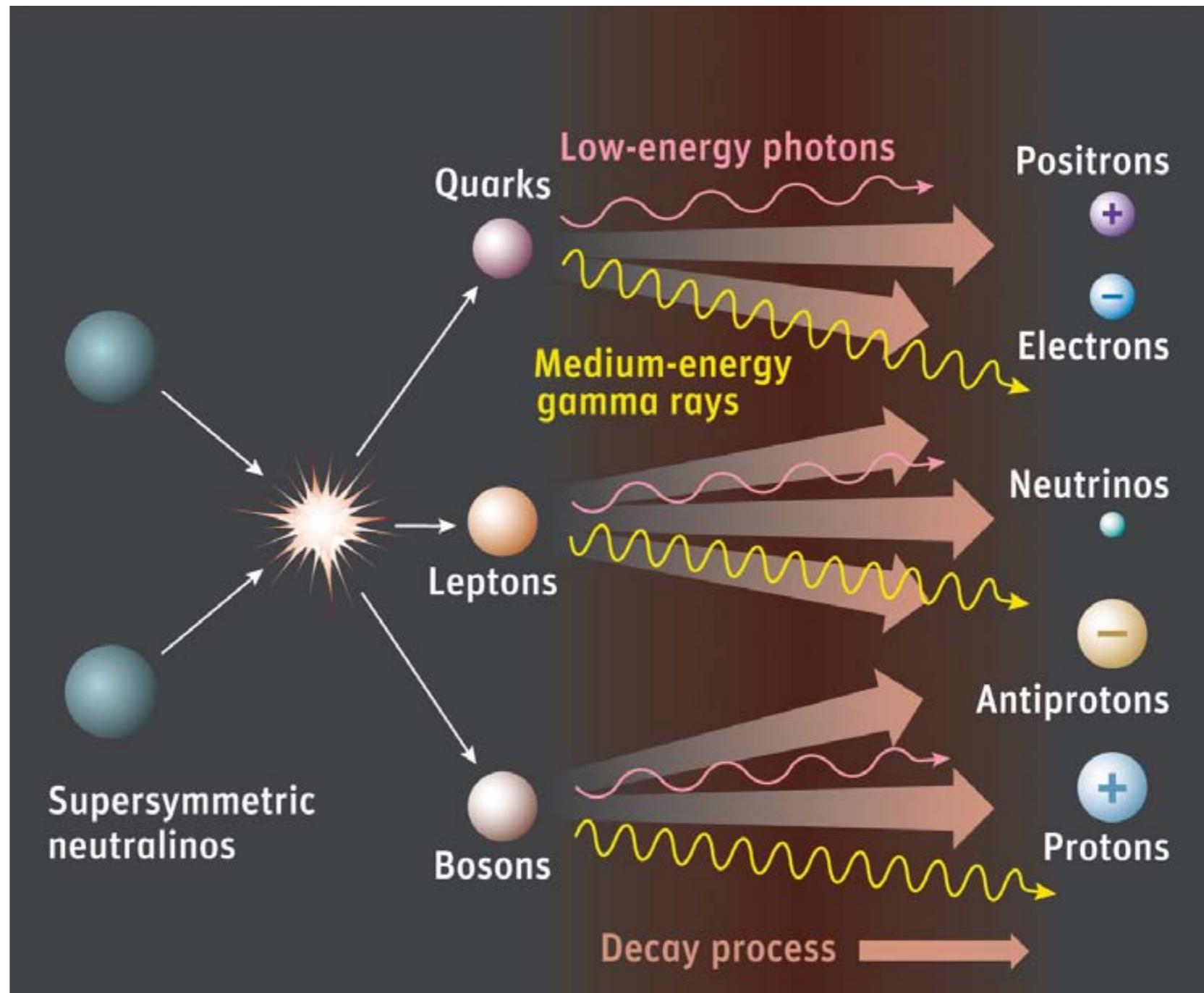


- Large parameter regions tested with ATLAS/CMS data, for the simplest models (vector, axial-vector, scalar, or pseudo-scalar Dirac fermion DM)

Dark Matter Indirect Detection

Dark matter annihilation

- WIMPs annihilate into standard model particles (photons, positrons, neutrinos, etc.)
- Each of these particles carry a fraction of WIMP mass energy ($E \sim \text{GeV}-\text{TeV}$)
- Annihilation rate is proportional to density squared and to annihilation cross section and relative velocity:
 $\sigma_{\text{ann}} v$



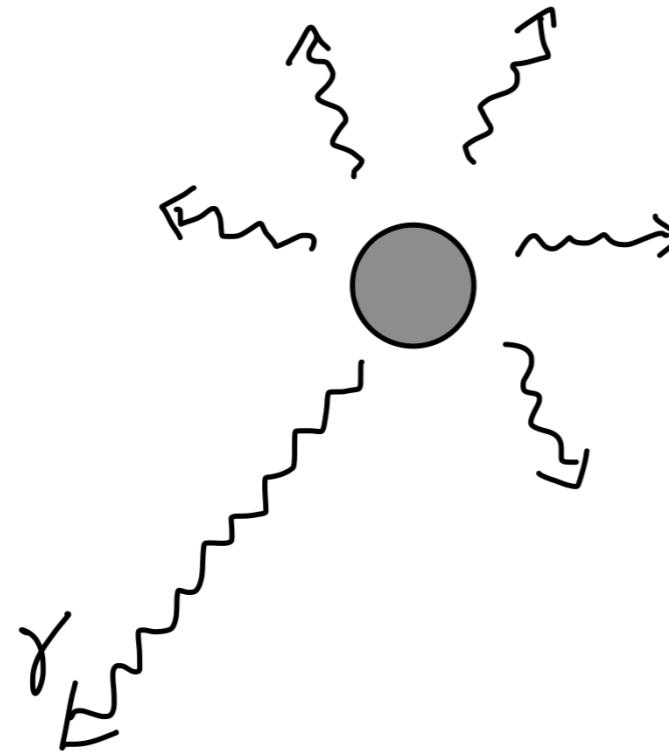
Rate of annihilation: Simple consideration

- Suppose you are a WIMP particle in a region of mass density ρ_χ
- Other WIMP particles are around you with velocity v , and if one of them hit you, you are both eliminated
- Incoming flux of the other WIMPs is $n_\chi v = \frac{\rho_\chi v}{m_\chi}$
- You encounter the others with the rate of $n_\chi \sigma v$
- If we look at this region of unit volume, such encounters happen at the rate of

$$\frac{n_\chi^2 \sigma v}{2} = \frac{\rho_\chi^2 \sigma v}{2m_\chi}$$

: rate of annihilation per volume

Gamma-ray flux from dark matter annihilation



Annihilation rate per volume

$$\frac{\langle \sigma v \rangle \rho_\chi^2}{2m_\chi^2}$$

Differential gamma-ray luminosity

$$\mathcal{L}(E) = \frac{\langle \sigma v \rangle}{2m_\chi^2} \frac{dN_{\gamma, \text{ann}}}{dE} \int dV \rho_\chi^2$$

Differential flux

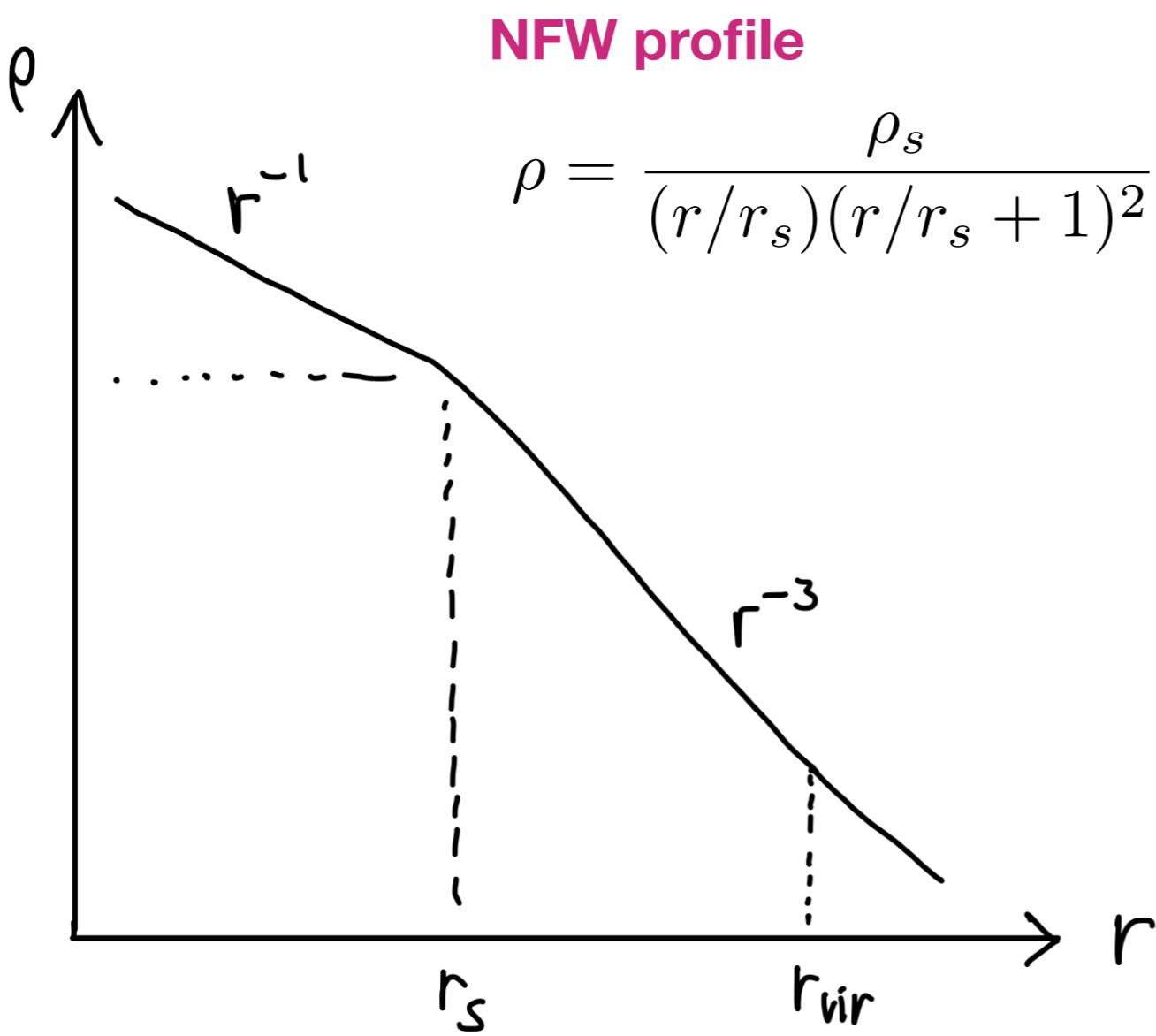


$$\mathcal{F}(E, z) = \frac{\mathcal{L}((1+z)E)}{4\pi r^2}$$

r : comoving distance to the halo

Gamma-ray flux from dark matter annihilation

Halo mass M at redshift z



Virial radius

$$r_{\text{vir}} = \left(\frac{3M}{4\pi\Delta_{\text{vir}}(z)\rho_c(z)} \right)^{1/3}$$

Scale radius

$$r_s = \frac{r_{\text{vir}}}{c_{\text{vir}}}$$

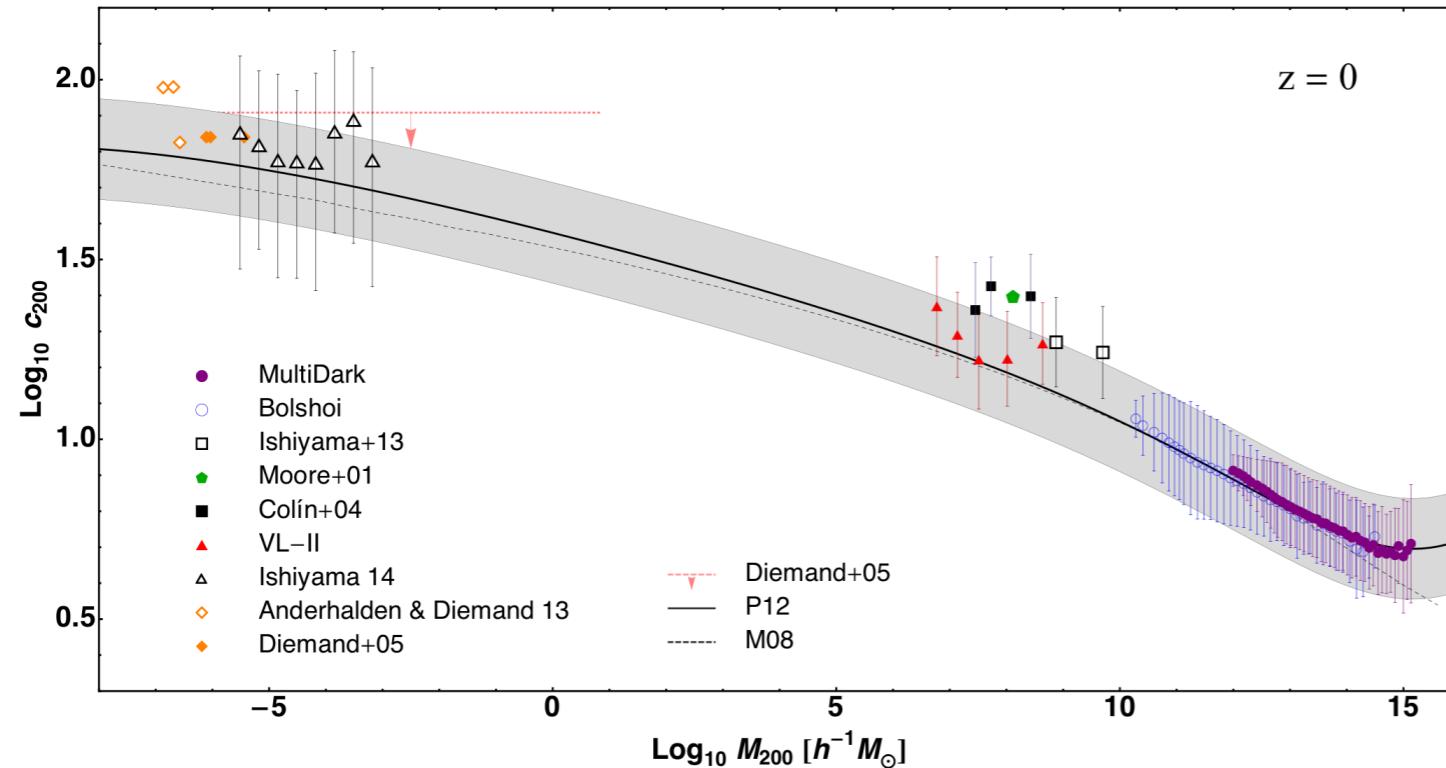
Characteristic density

$$\rho_s = \frac{M}{4\pi r_s^3 [\ln(1 + c_{\text{vir}}) - c_{\text{vir}}/(1 + c_{\text{vir}})]}$$

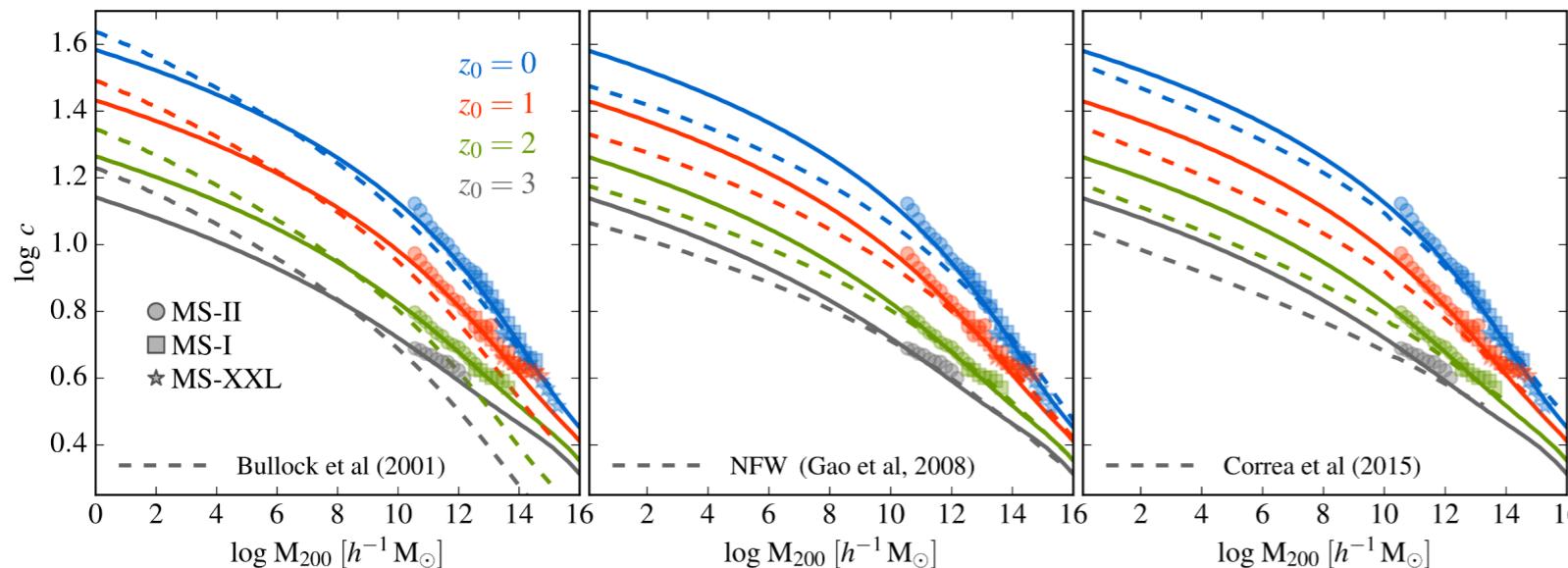
All relevant parameters derived as a function of M and z

Gamma-ray flux from dark matter annihilation

Sanchez-Conde, Prada, *Mon. Not. R. Astron. Soc.* **442**, 2271 (2014)



Ludlow et al., *Mon. Not. R. Astron. Soc.* **460**, 1214 (2016)



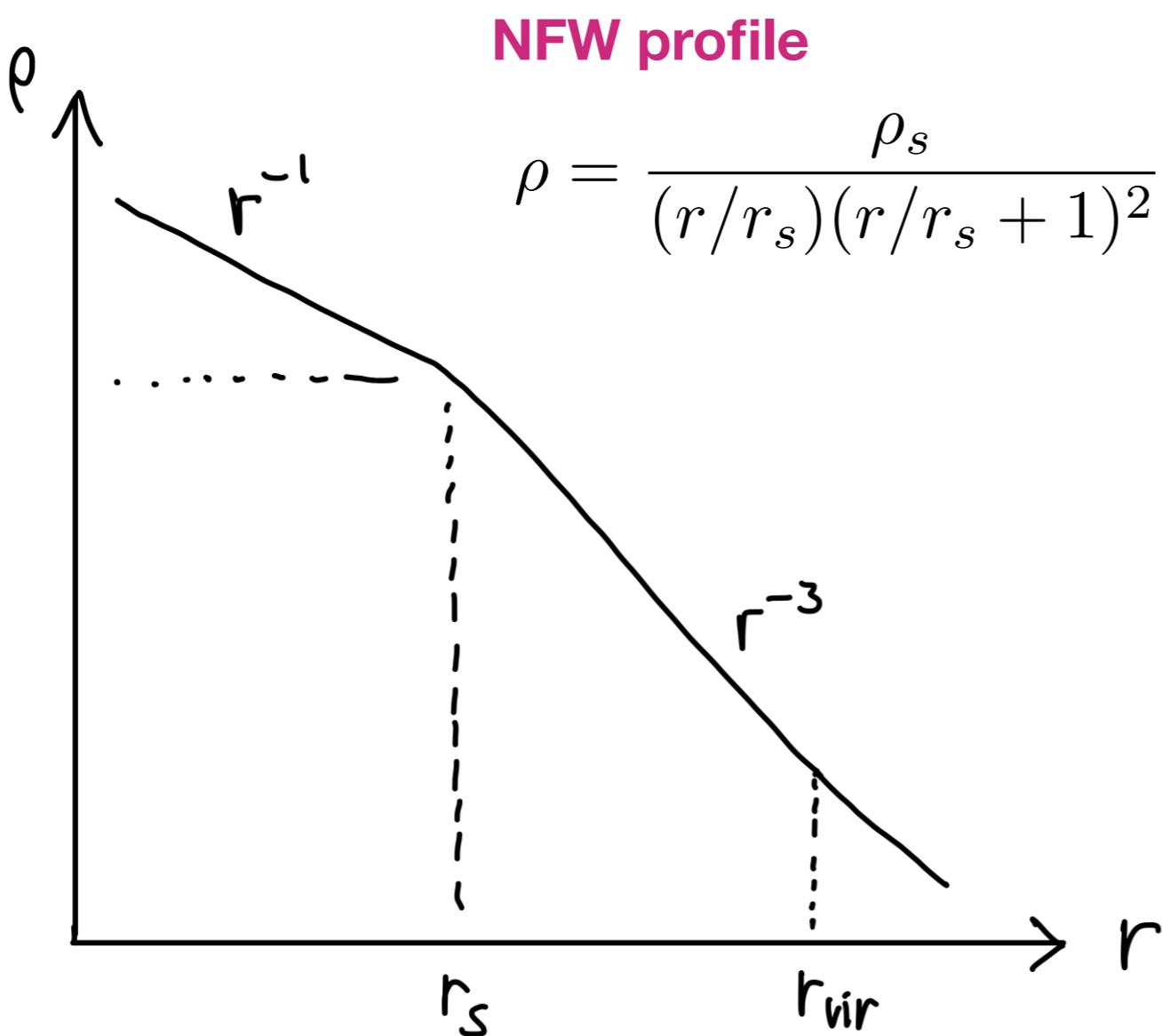
Halo concentration

$$c_{\text{vir}} = \frac{r_{\text{vir}}}{r_s}$$

- Halo concentration-mass relation is well calibrated through simulations
- From largest to smallest halos
- From low to high redshifts ($0 < z < 5$)
- About 20-30% scatter from one halo to another

Gamma-ray flux from dark matter annihilation

Halo mass M at redshift z



Virial radius

$$r_{\text{vir}} = \left(\frac{3M}{4\pi\Delta_{\text{vir}}(z)\rho_c(z)} \right)^{1/3}$$

Scale radius

$$r_s = \frac{r_{\text{vir}}}{c_{\text{vir}}}$$

Characteristic density

$$\rho_s = \frac{M}{4\pi r_s^3 [\ln(1 + c_{\text{vir}}) - c_{\text{vir}}/(1 + c_{\text{vir}})]}$$

$$\int dV \rho^2 = \frac{4\pi\rho_s^2 r_s^3}{3} \left[1 - \frac{1}{(1 + c_{\text{vir}})^3} \right]$$

Gamma-ray flux from dark matter annihilation

- A quick exercise: **How many dark matter annihilations are happening per second in the entire Milky Way?**

Milky Way halo: $M = 10^{12} M_\odot$

$$r_{\text{vir}} = \left(\frac{3M}{4\pi\Delta_{\text{vir}}\rho_c} \right)^{1/3} \sim 200 \text{ kpc}$$

$$r_s = \frac{r_{\text{vir}}}{c_{\text{vir}}} \sim 20 \text{ kpc} \quad (c_{\text{vir}} = 10)$$

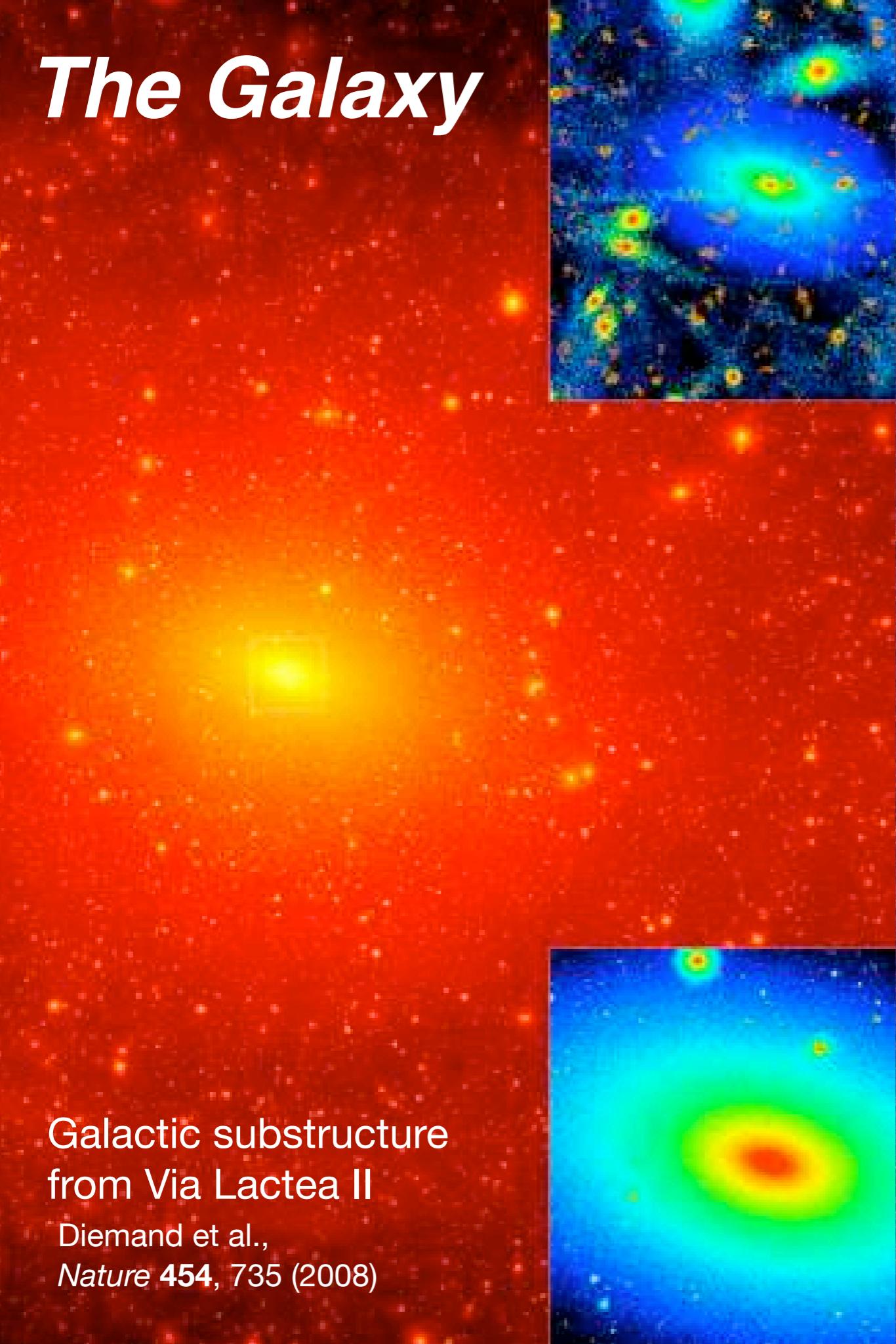
$$\rho_s = \frac{M}{4\pi r_s^3 [\ln(1 + c_{\text{vir}}) - c_{\text{vir}}/(1 + c_{\text{vir}})]} \sim 0.3 \text{ GeV cm}^{-3}$$

Annihilation rate:

$$\boxed{\frac{\langle\sigma v\rangle}{2m_\chi^2} \int dV \rho_\chi^2 = 6 \times 10^{37} \text{ s}^{-1} \left(\frac{\langle\sigma v\rangle}{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}} \right) \left(\frac{m_\chi}{100 \text{ GeV}} \right)^{-2}}$$

The Galaxy

Galactic substructure
from Via Lactea II
Diemand et al.,
Nature 454, 735 (2008)

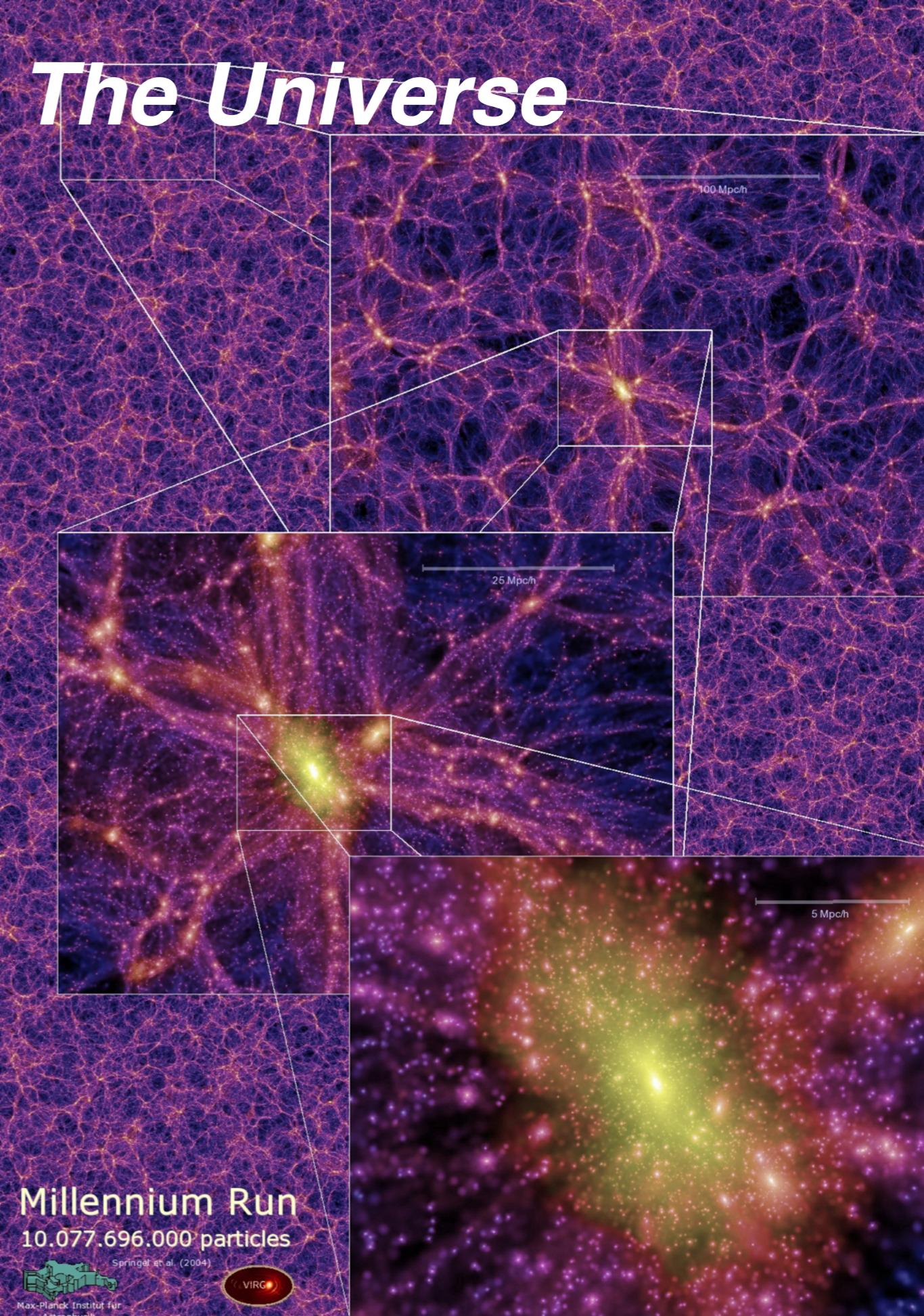


The Universe

Millennium Run
10.077.696.000 particles



Springel et al. (2004)



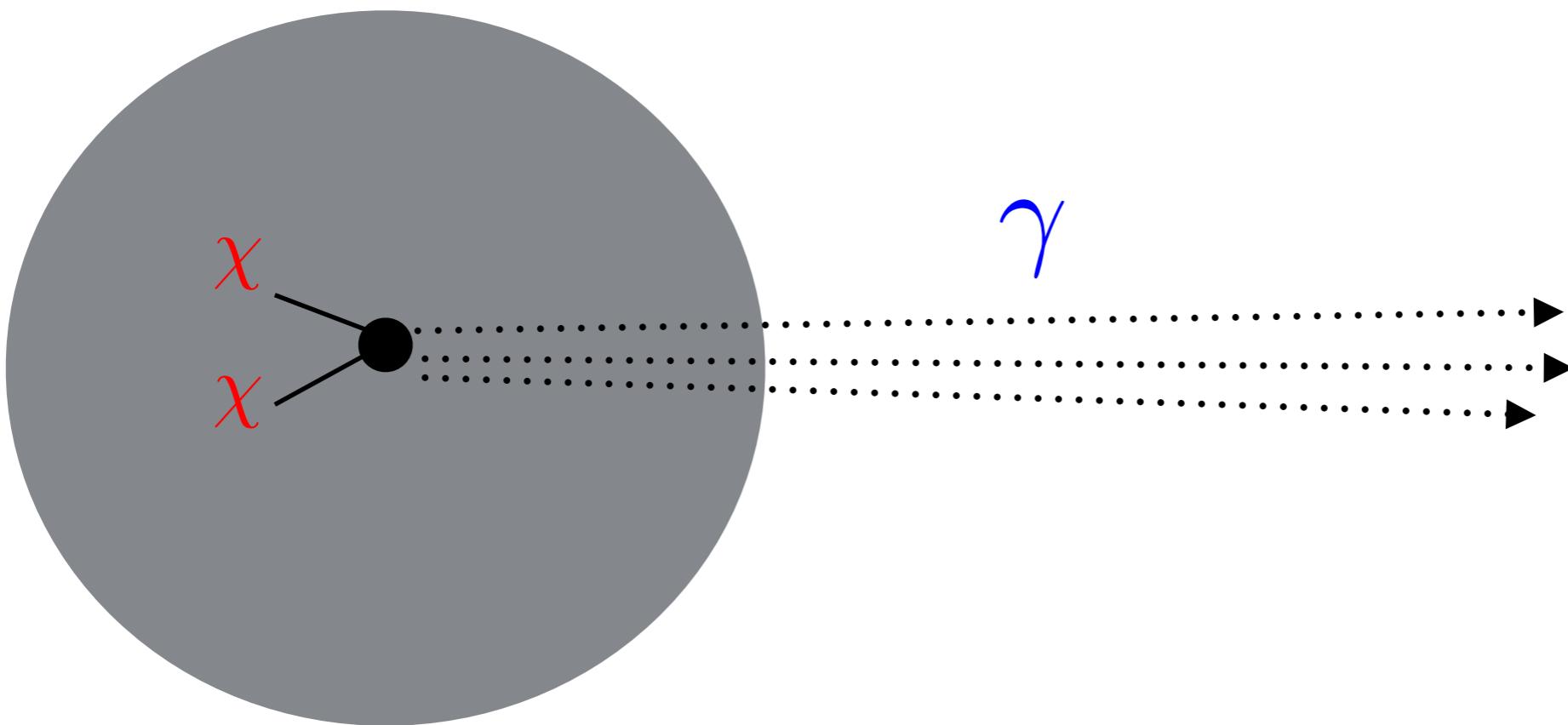
Gamma-ray flux from dark matter annihilation

Particle physics

$$I_\gamma(E_\gamma, \psi) = \frac{1}{2} \frac{\langle \sigma v \rangle}{m_\chi^2} \frac{dN_{\gamma, \text{ann}}}{dE_\gamma}$$

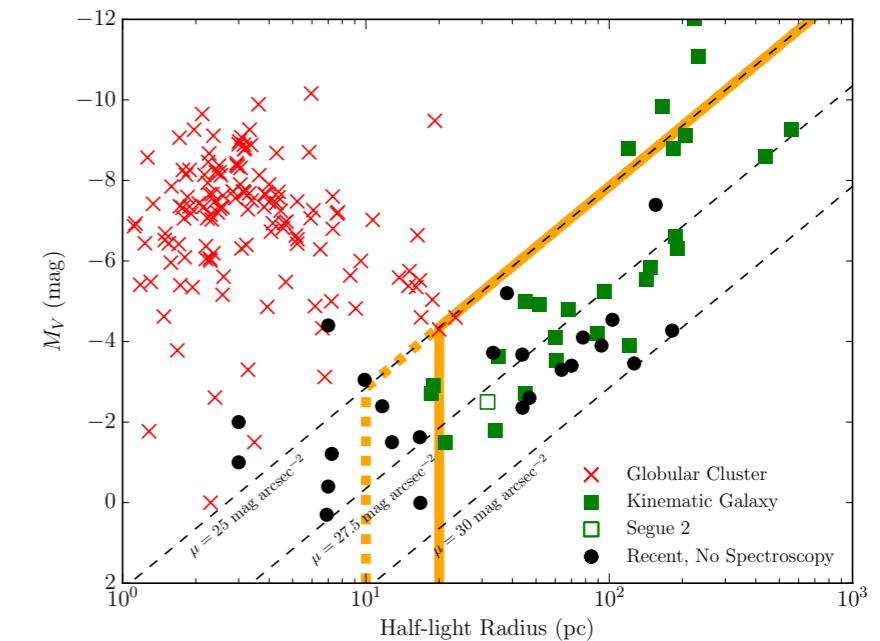
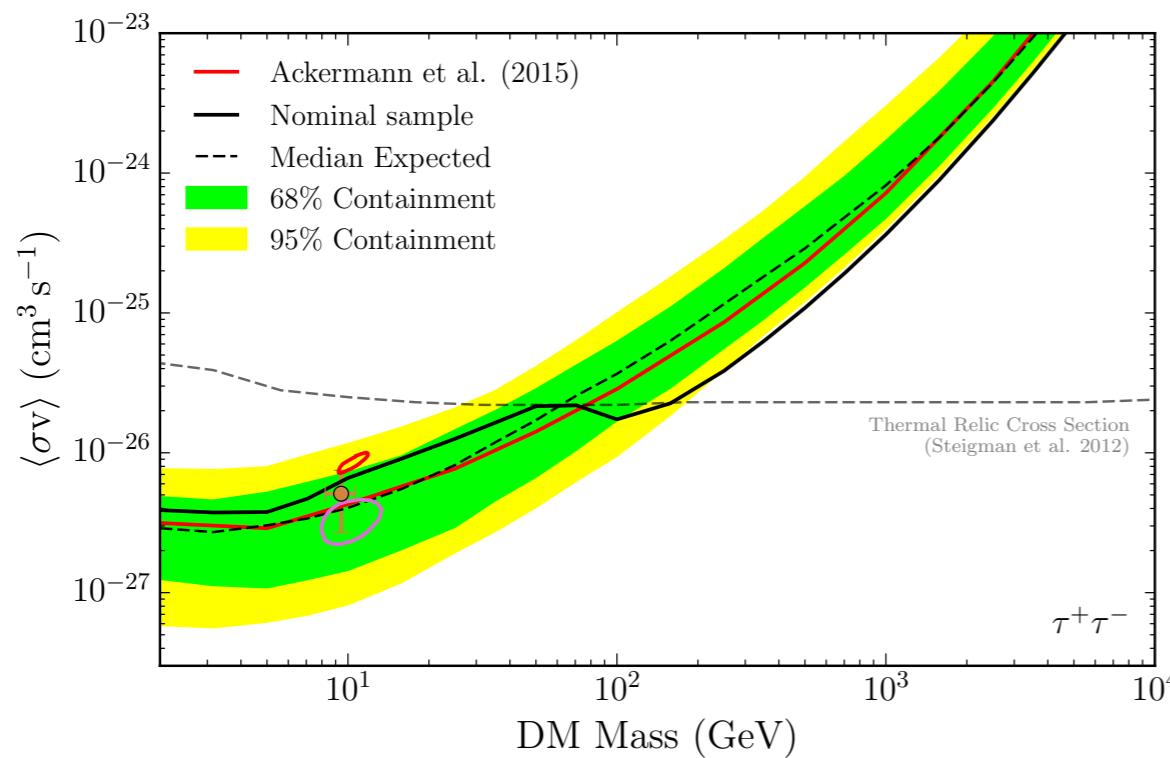
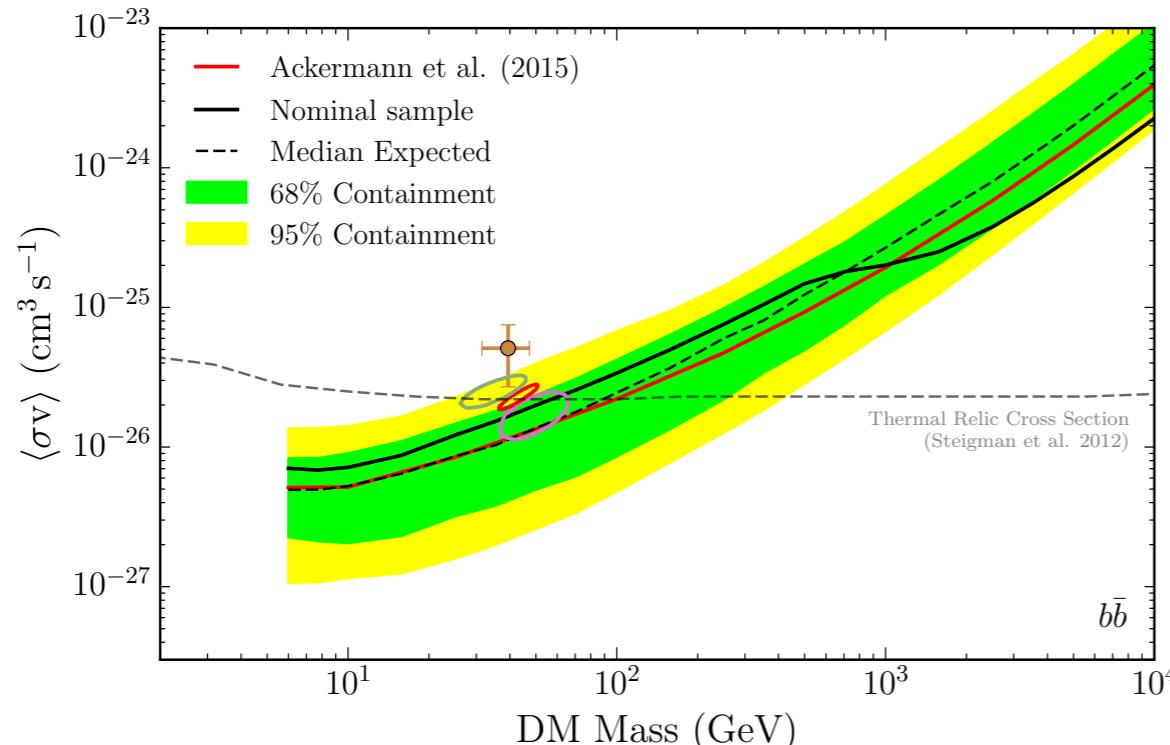
Astrophysics

$$\frac{1}{4\pi} \int d\ell \rho_\chi^2(r[\ell, \psi])$$



Constraints from dwarf spheroidal galaxies

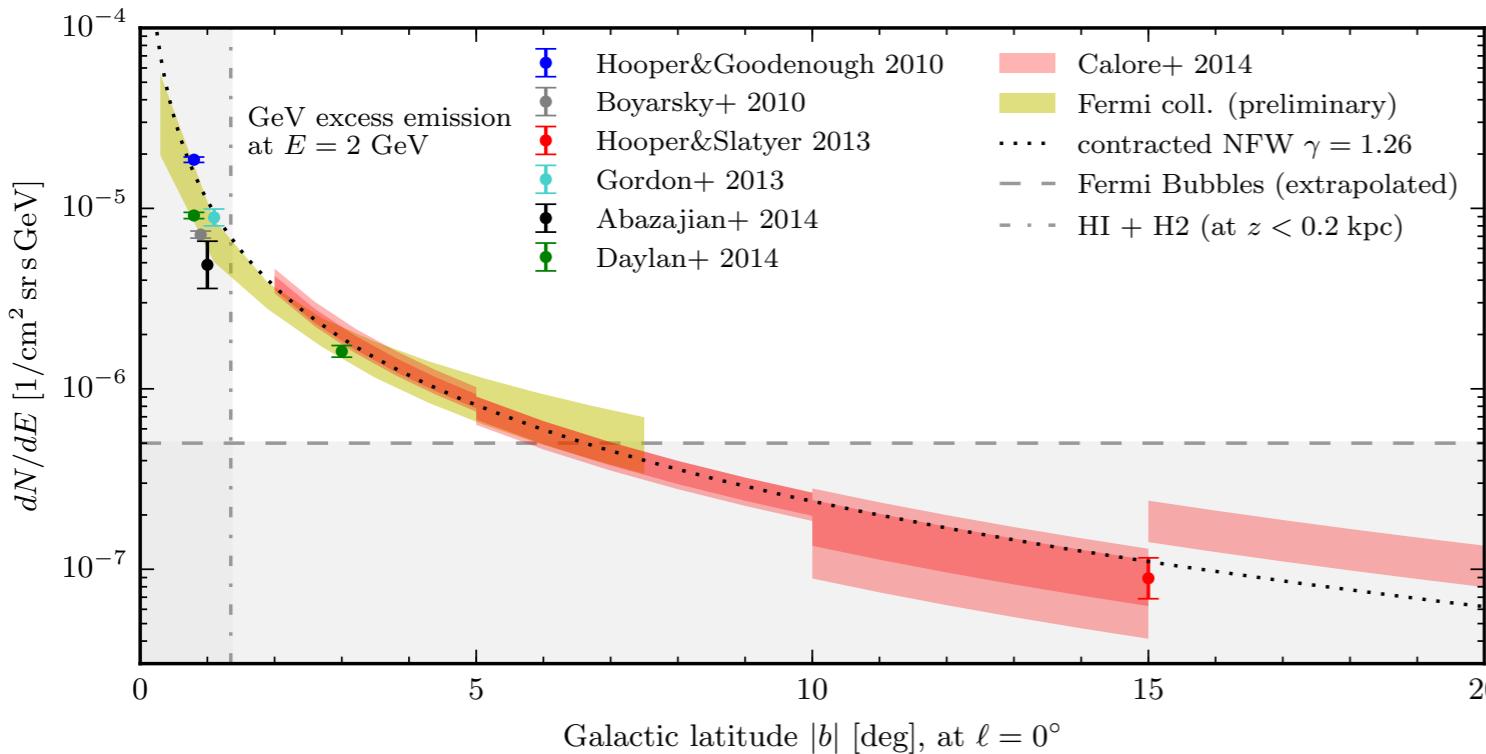
Fermi-LAT, Astrophys. J. 834, 110 (2017)



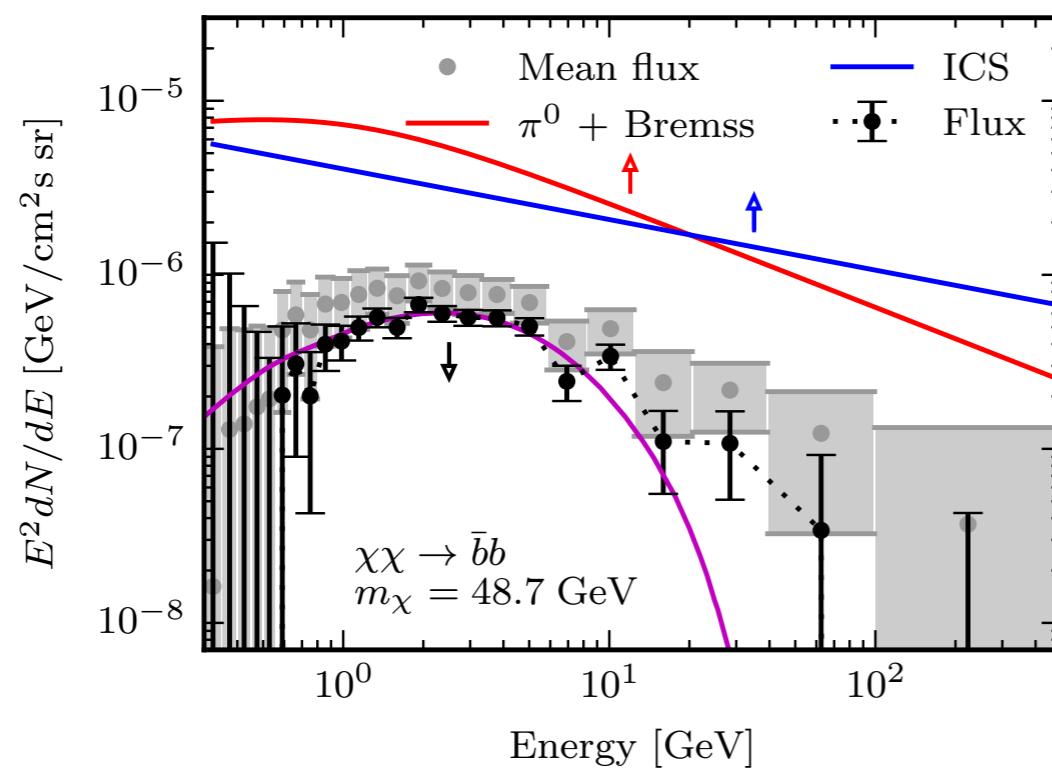
- Highly DM dominated system → suitable environment to test DM annihilation
 - Most robust constraints
- The latest results with PASS 8 data are pretty stringent
- They exclude the canonical cross section for WIMPs lighter than several tens of GeV
 - Nominal sample: 41 dwarfs
 - Ackermann et al. (2015): 15 dwarfs

GeV excess: Signals of dark matter annihilation?

Calore et al., *Phys. Rev. D* **91**, 063003 (2015)

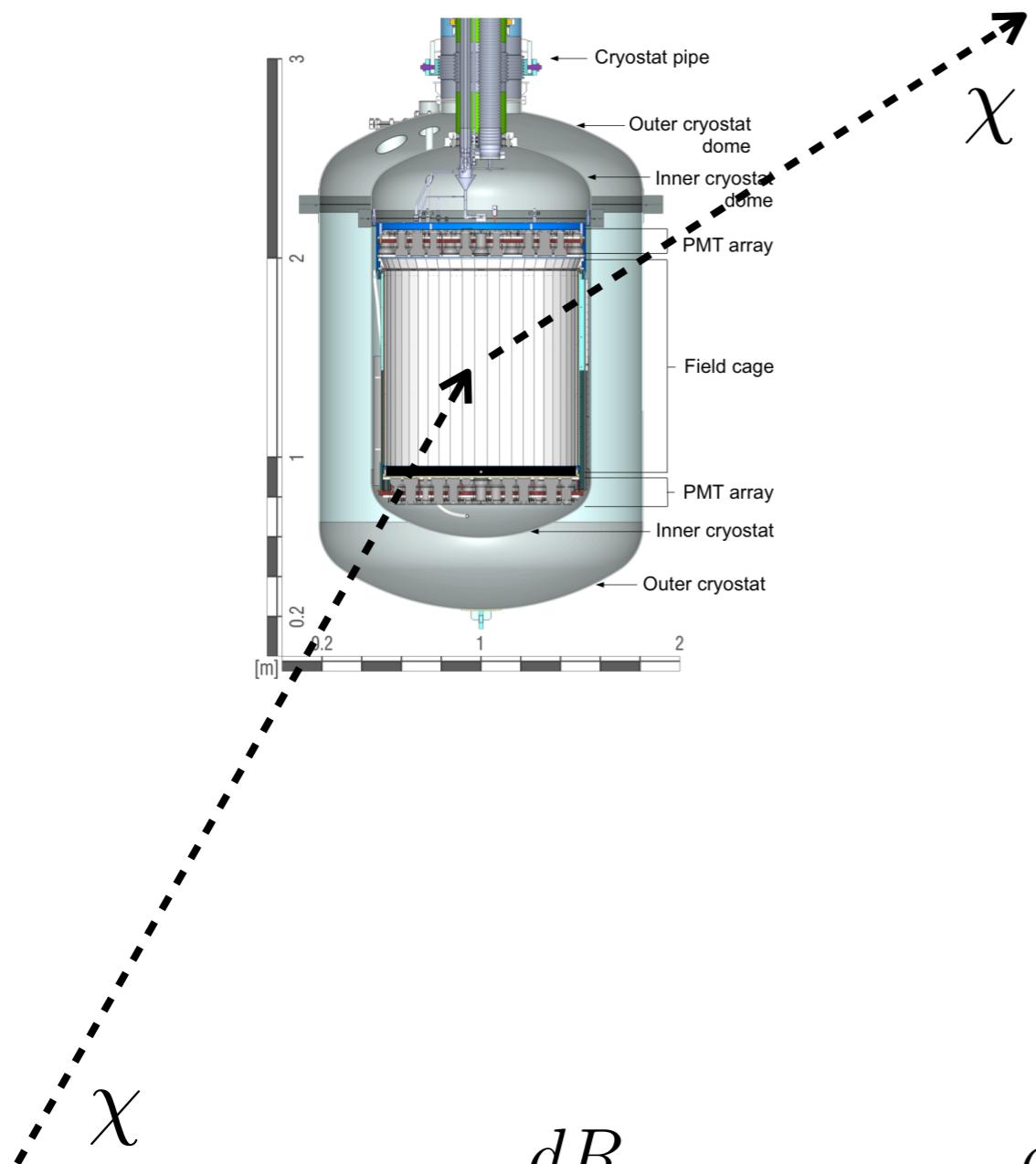


- Gamma-ray excess in GeV regime from the Galactic centre (many sigma) of unknown origin
- Brightness profile is consistent with NFW^2 (with inner slope of -1.26)
- Spectral shape is also consistent with expectation from annihilation
 - mass: ~ 50 GeV
 - cross section: $\sim 2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$



Dark Matter Direct Detection

Scattering of dark matter



- Dark matter deposits tiny energy to underground detectors
- The rate of scattering = (flux) x (cross section) x (target number)
- $\text{flux} = n v$
- Deposited energy: tens of keV

$$\frac{dR}{dE}(E, t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v}, t) \cdot \frac{d\sigma}{dE}(E, v) d^3v$$

Simple example calculation

- Local dark matter density: $\sim 0.4 \text{ GeV/cm}^3$
- Velocity distribution function $f(v)$: typical velocity $\sim 10^{-3} c$
- WIMP mass: 100 GeV
- Scattering cross section with nuclei: $\sim 10^{-38} \text{ cm}^2$
- Scattering rate per unit detector mass ($M = 100 \text{ GeV}$):

$$R \sim \frac{N}{MN} \phi_\chi \sigma \sim 0.1 \text{ kg}^{-1} \text{ yr}^{-1}$$

Differential event rate

- Event rate per detector mass per recoil energy, dR/dE
- Differential cross section, $d\sigma/dE$
- Multiply by the number of nuclei, N , and divide by the detector mass, MN
- Multiply by the WIMP flux with velocities v in unit volume of the velocity space, d^3v
- $f(v)$: WIMP velocity distribution in the detector frame

Differential event rate

$$\frac{dR}{dE} = \frac{\rho}{mM} \int_{v_{\min}} d^3v \frac{d\sigma}{dE} v f(v)$$

- Necessary ingredients
 - Dark matter mass
 - Dark matter - nucleus scattering cross section
 - Local dark matter density
 - Local dark matter velocity distribution

Spin-independent and spin-dependent scatterings

- SI: interact with mass $\propto A^2$
- SD: interact with spins $\propto J(J + 1)$

Spin-independent cross section

$$\frac{d\sigma}{dE} = \frac{MA^2}{2\mu_p v^2} \sigma_{\text{SI}} F^2(E)$$

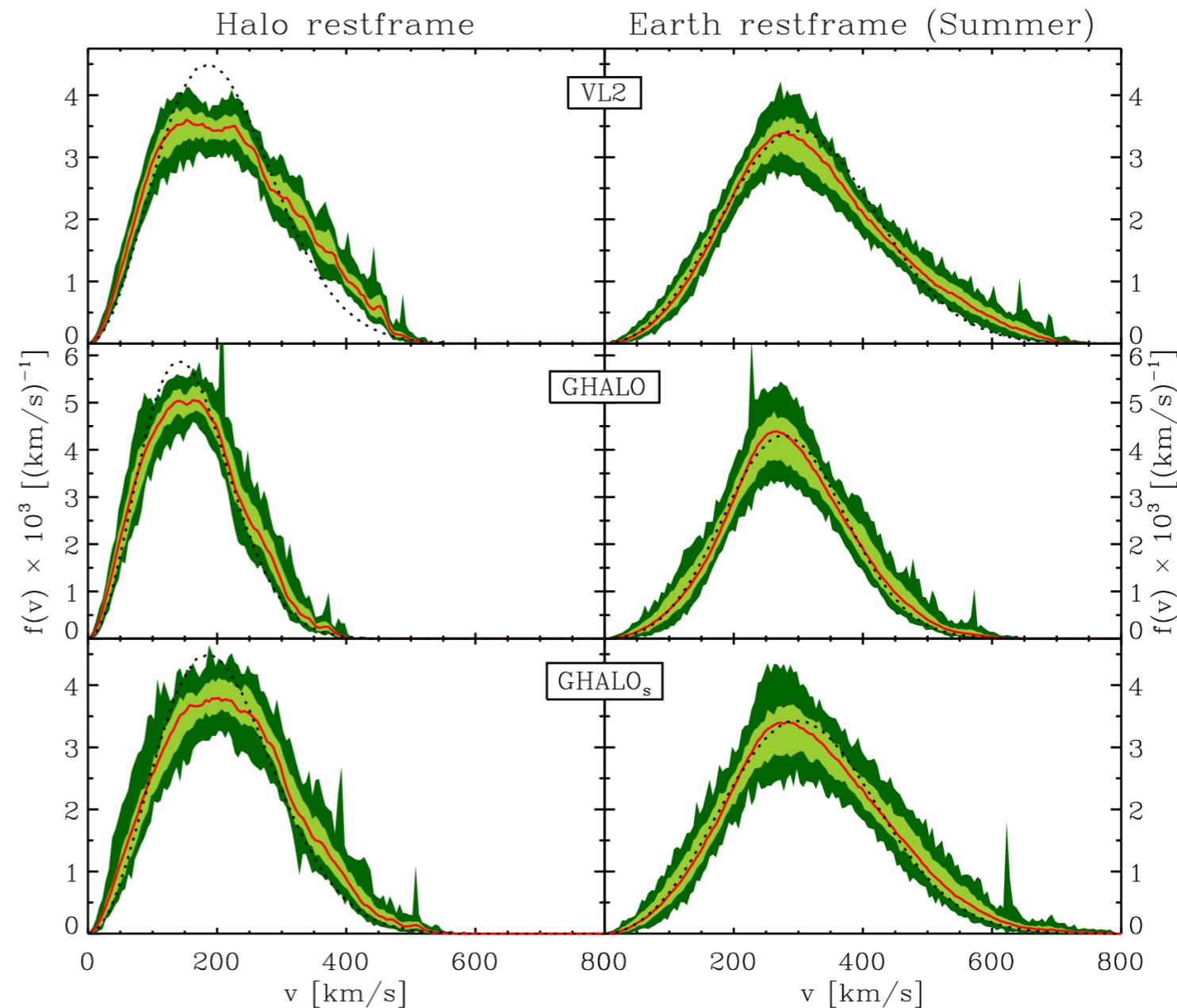
σ_{SI} : WIMP-proton cross section
 μ_p : WIMP-proton reduced mass
 $F(E)$: nuclear form factor

Local dark matter distribution

- Isotropic Maxwellian velocity distribution in the Galactic rest frame

$$f(v) = \frac{1}{(\pi v_0^2)^{3/2}} \exp\left(-\frac{v^2}{v_0^2}\right)$$

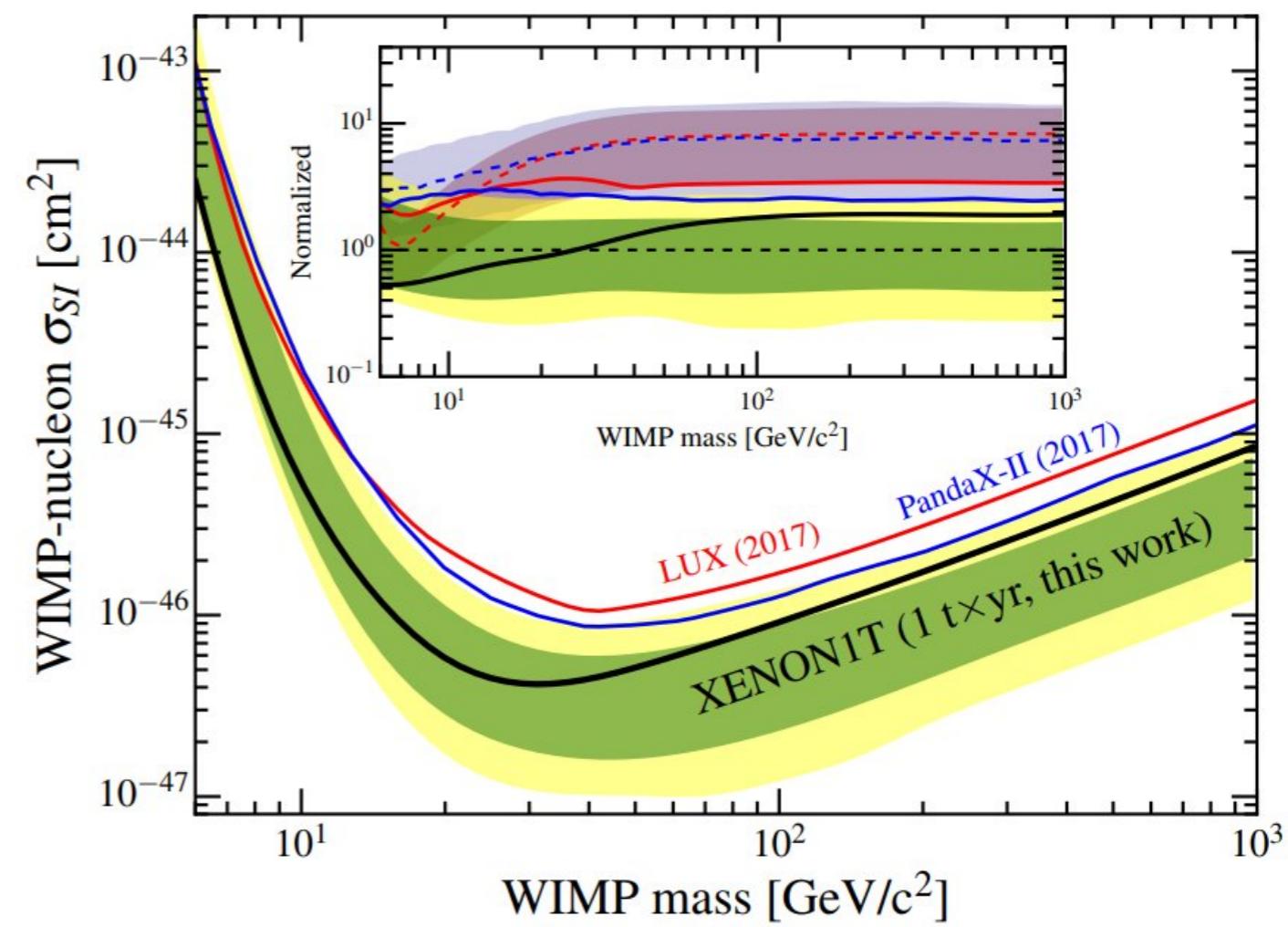
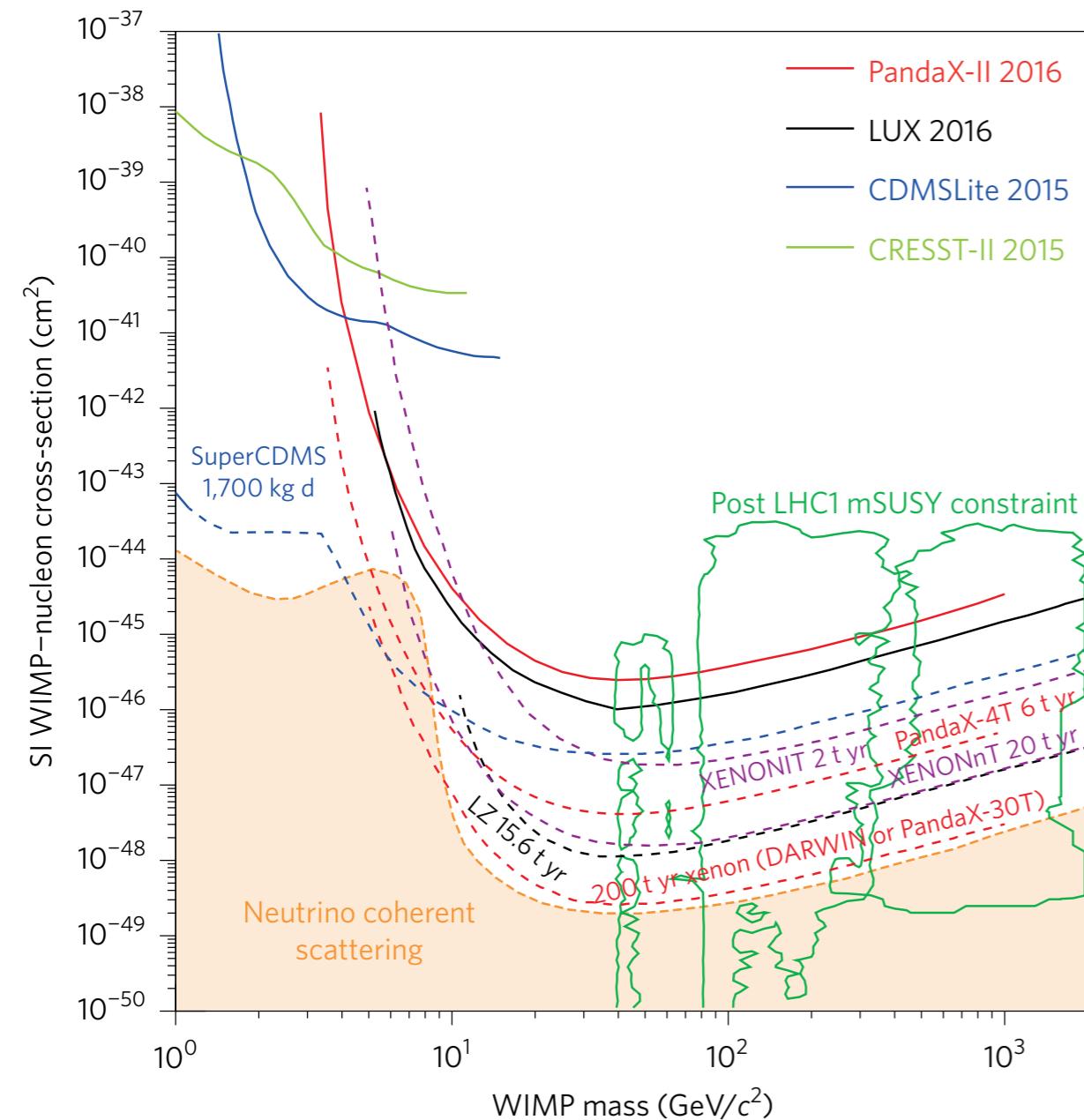
- Circular speed at Sun's location: $v_0 = 220$ km/s
- Local dark density: $\rho \sim 0.2 - 0.6$ GeV/cm³



Direct detection experiments

Liu, Chen, Ji, *Nature Phys.* **13**, 212 (2017)

Aprile et al., arXiv:1805.12562 [astro-ph.CO]



Summary

To be discussed in review:

Dark matter in cosmology

- Various astronomical and cosmological methods that established existence of dark matter
- How can one exclude hypothesis of baryonic dark matter?
- How can one exclude hot dark matter? Why can neutrinos not be dark matter?
- Can modified Newtonian dynamics (MOND) be alternative scenario?

To be discussed in review:

Dark matter candidates

- Why are WIMPs popular model of dark matter?
- Thermal freezeout mechanism
- What are models of WIMPs that are motivated by physics Beyond the Standard Model (SUSY, universal extra-dimensions)?
- Brief discussion on particle physics constraints (besides direct and indirect detection experiments)

To be discussed in review:

Indirect detection

- General discussion how the gamma-ray flux depends on annihilation cross section, WIMP mass, dark matter density, etc.
- What is the dark matter distribution in dark matter halos such as Milky Way, and where can one expect strong signal from WIMP annihilation?
- What are existing/upcoming gamma-ray telescopes and what are the current constraints on the annihilation cross section?

To be discussed in review:

Direct detection

- General discussion how the direct detection rate depends on scattering cross section, WIMP mass, local dark matter distribution, etc.
- What is the local dark matter density and velocity distribution, and their uncertainties?
- What are existing/upcoming direct-detection experiments and what are the current constraints on the scattering cross section (both SI and SD)?

What to do today after the lecture

- Send your preference regarding which subject you want to work on: **1. cosmology**, **2: candidates**, **3: indirect detection**, **4: direct detection**
 - Send three topics in order of preference
- Install essential tools for coding with python: python (version 3.6), ipython, matplotlib, numpy, scipy, jupyter notebook, etc.

Groups

- **Cosmology**
 - Bovenschen, Heikamp, Litsa
- **Candidates**
 - Grey, Koole, Oogjes, van Beek
- **Indirect detection**
 - de Ruiter, Hofland, Jung
- **Direct detection**
 - Bosch, Briel, van Urk