5 June 2018

GRAPPA Student Seminar

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GRAPPA
GRavitation AstroParticle Physics Amsterdam

Lecturers

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Week 1

Gianfranco Bertone
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Week 2

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Week 3

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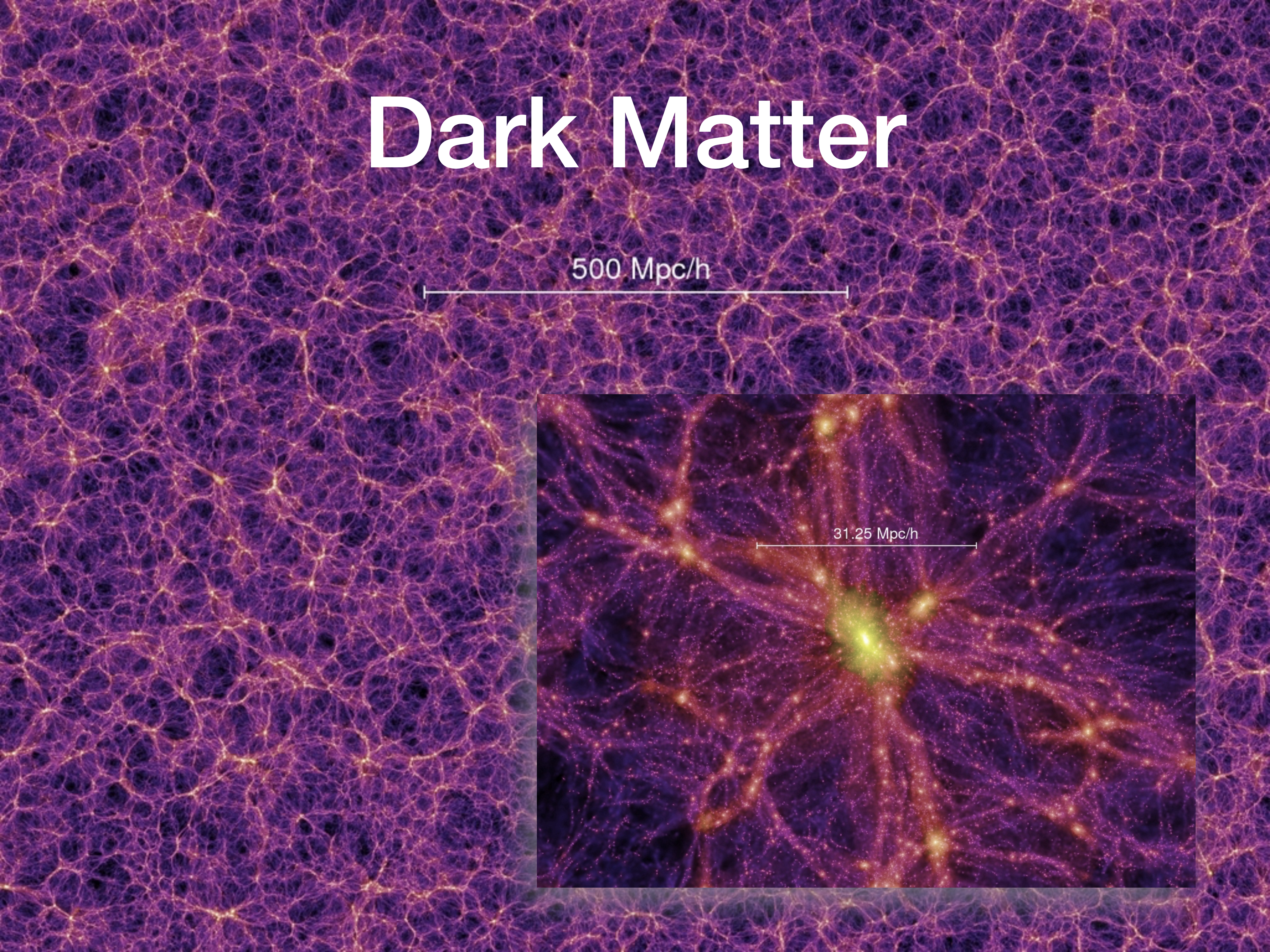
Week 3

Dark Matter



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. ΛCDM, Ω_b, Ω_{DM}, CMB
2. Numerical simulations
3. Cracks in ΛCDM

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**
- Direct detection

1. Gamma rays
2. Anti-matter
3. High-z (CMB, 21cm, etc.)

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

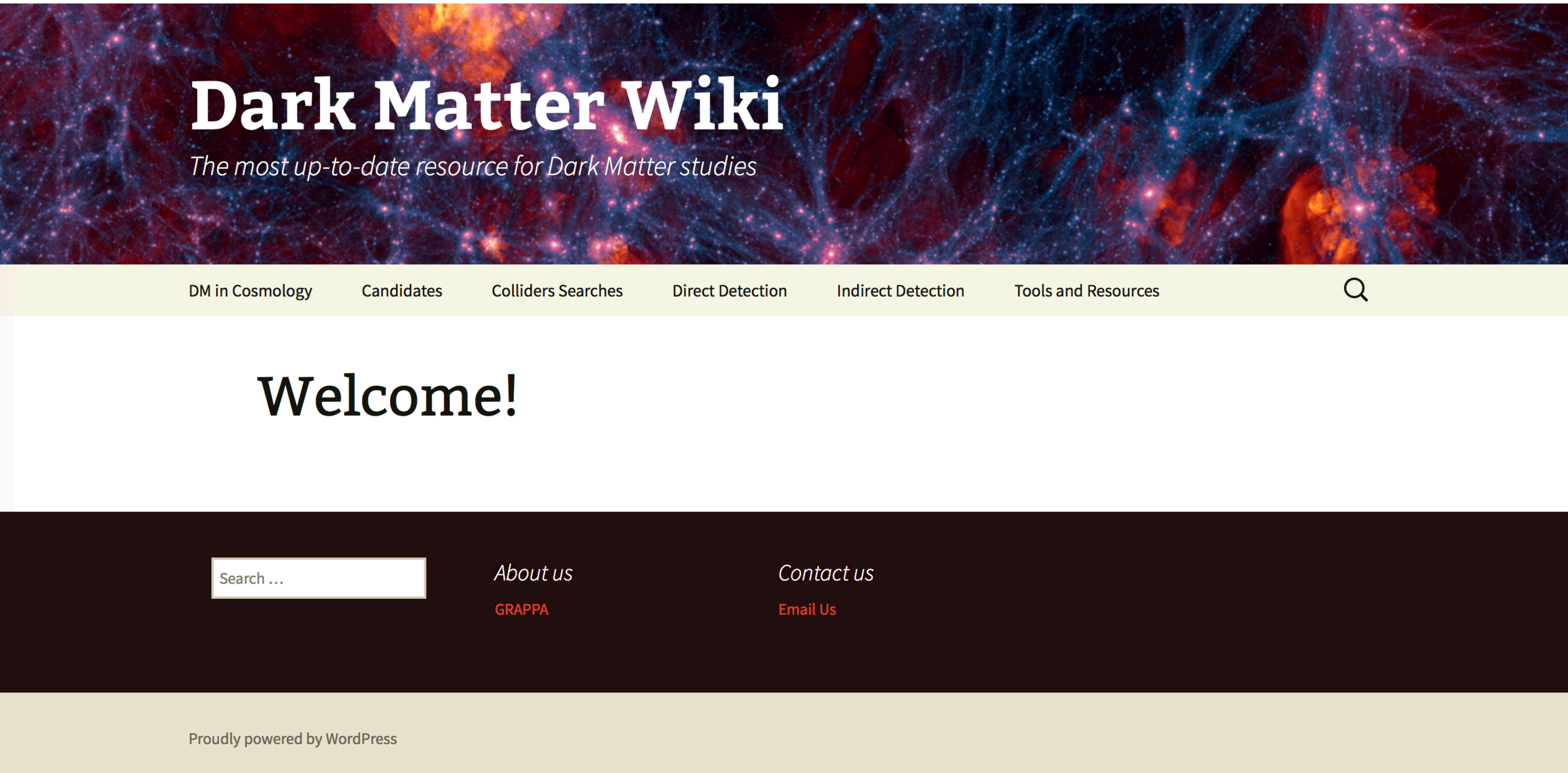
	Tuesday	Wednesday	Friday
Week 1	Lecture 1 (Ando)	Scripts	Q&A (Ando)
Week 2	Lecture 2 (Bertone)	Scripts	Q&A (Bertone)
Week 3	Lecture 3 (Gaggero/Kavanagh)	Scripts	Q&A (Gaggero/Kavanagh)
Week 4	Presentations	Scripts	Feedback

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 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



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)
- Work in a GitHub folder (discussed in detail tomorrow): 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

- “Particle dark matter: Evidence, candidates and constraints”: Bertone, Hooper, Silk, hep-ph/0404175

- “Supersymmetric dark matter”: Jungman, Kamionkowski, Griest, hep-ph/9506380

- “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 DarkMatterWiki
- More details tomorrow

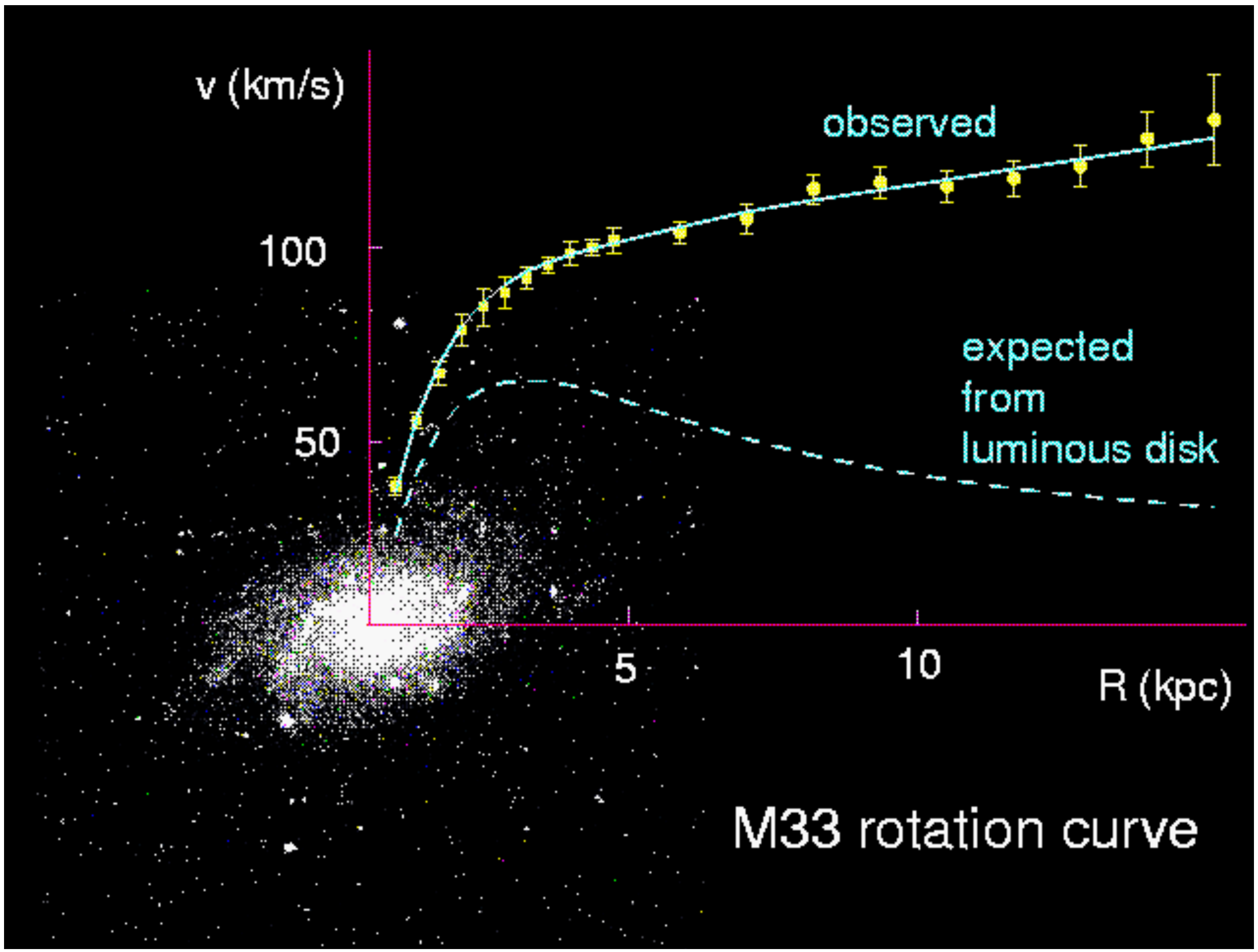
What to do today after the lecture

- 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, ipython, matplotlib, numpy, scipy, jupyter notebook, etc.

Lecture 1

Dark Matter in Cosmology

Evidence for dark matter: Rotation curves



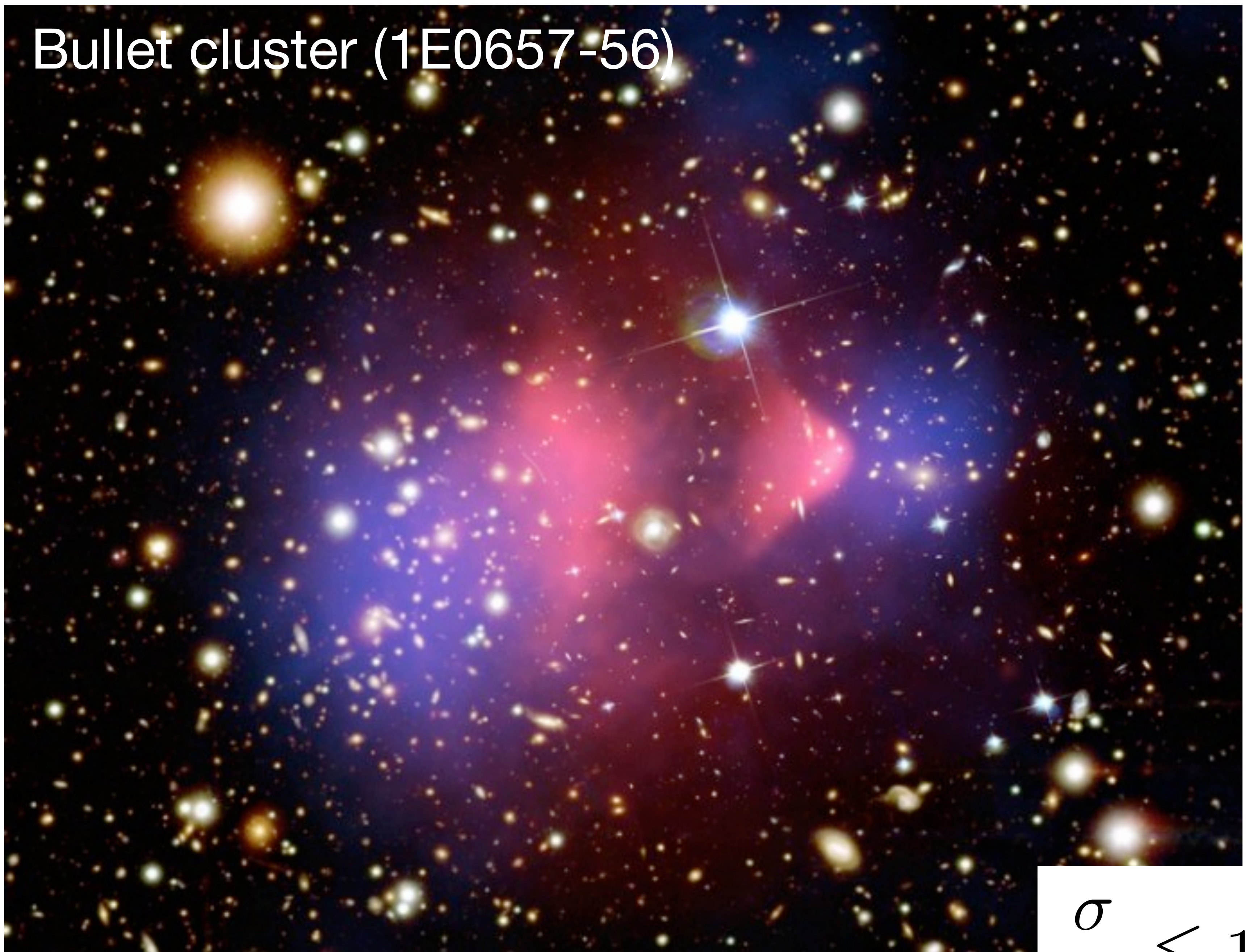
Bergström, *Rep. Prog. Phys.* **63**, 793 (2000)

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

- 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)

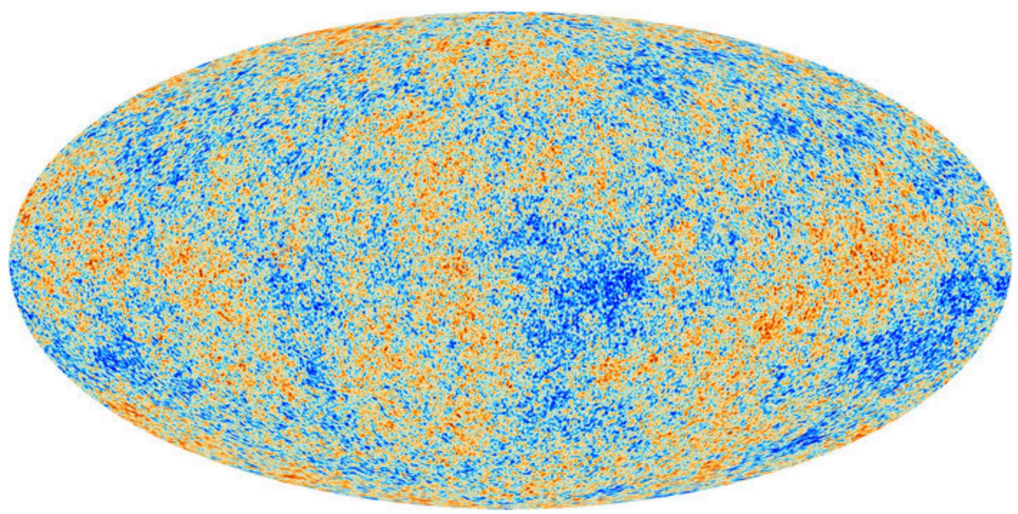
Evidence for dark matter: Bullet clusters

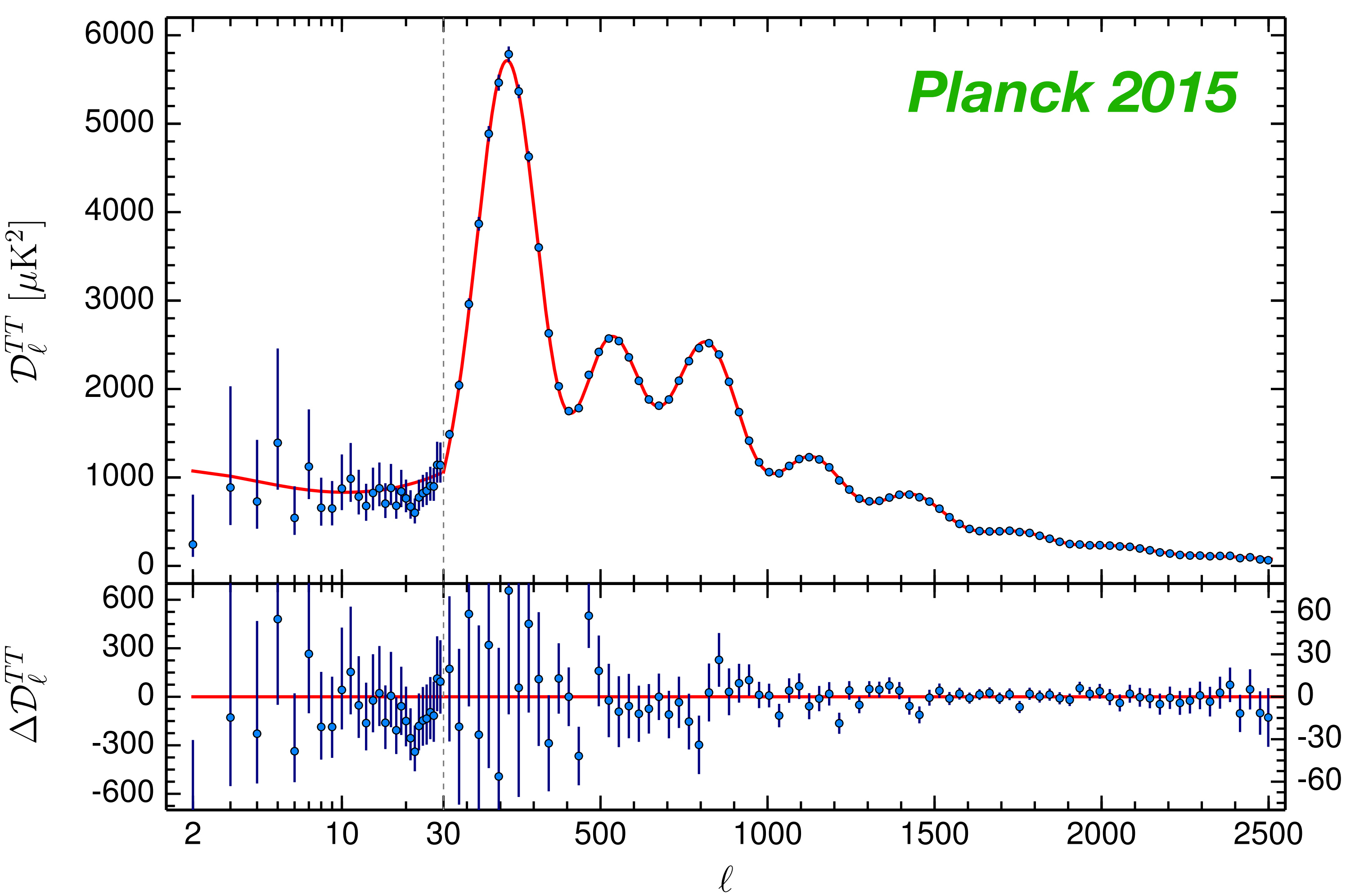


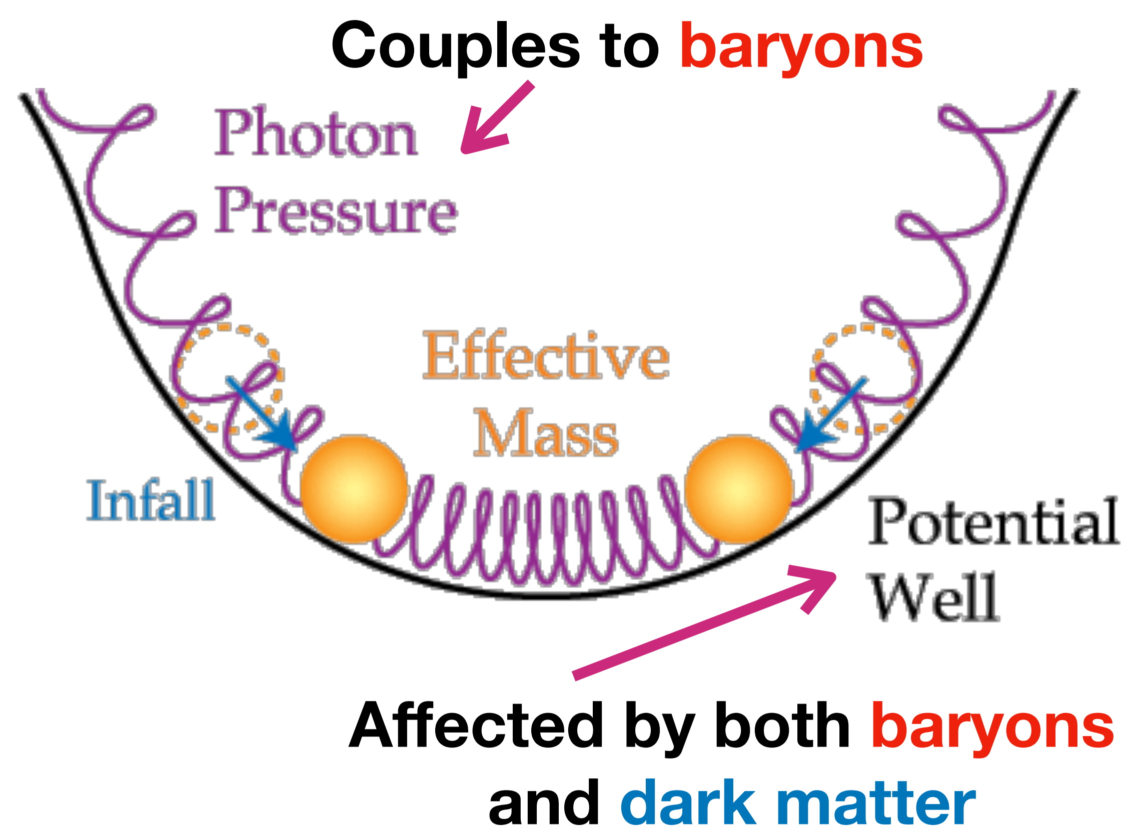
- Red: X-ray image (baryonic gas)
- Blue: Weak gravitational lensing (dark matter)
- Gas is collisional (Coulomb force) so feels drag from each other; dark matter goes through
- *Implication*: Dark matter is collionless

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

Evidence for dark matter: Baryon acoustic oscillation (BAO)



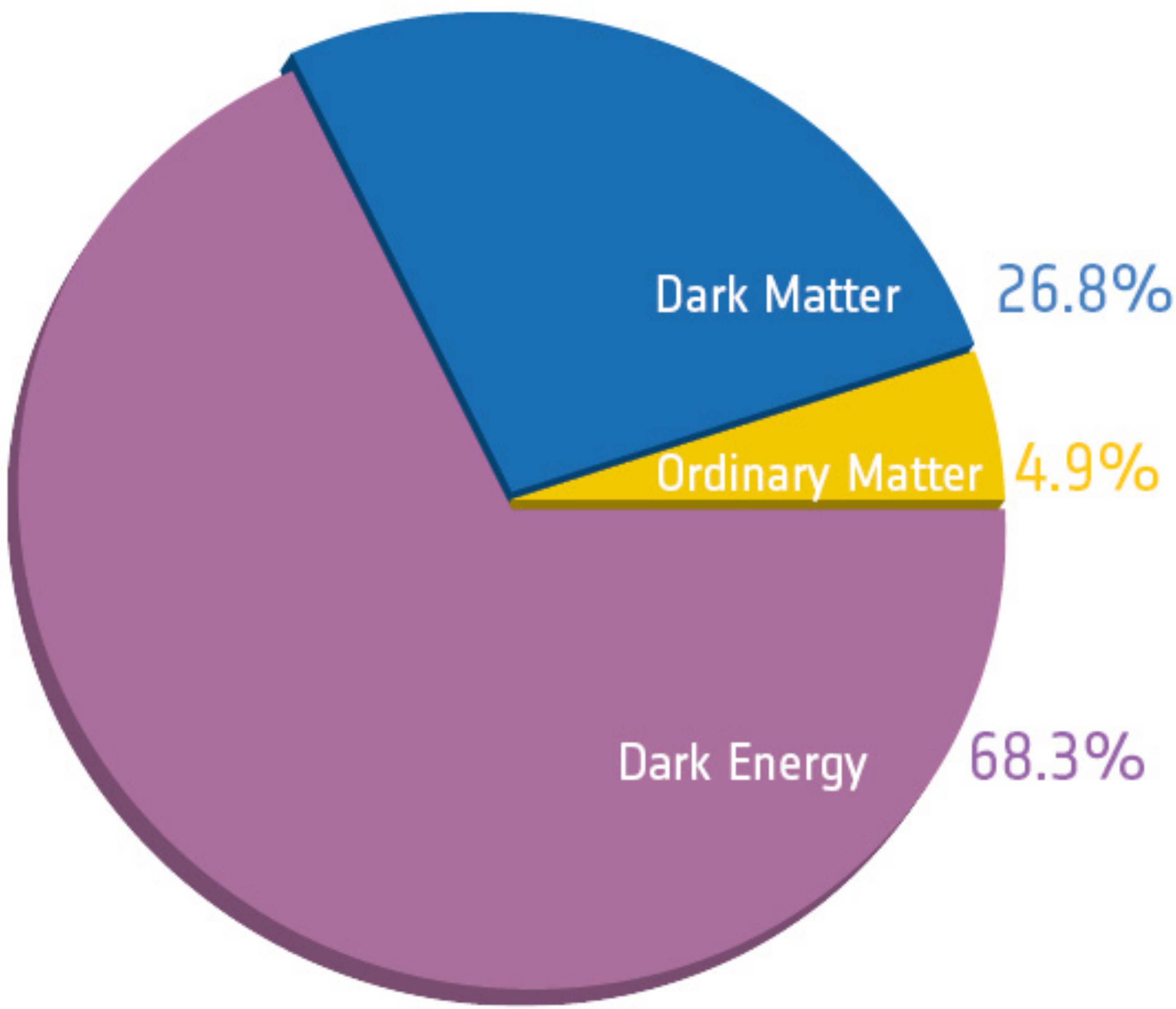




- Measured both in CMB and galaxy power spectrum
- *Implication*: Dark matter can ***not*** be made of baryons

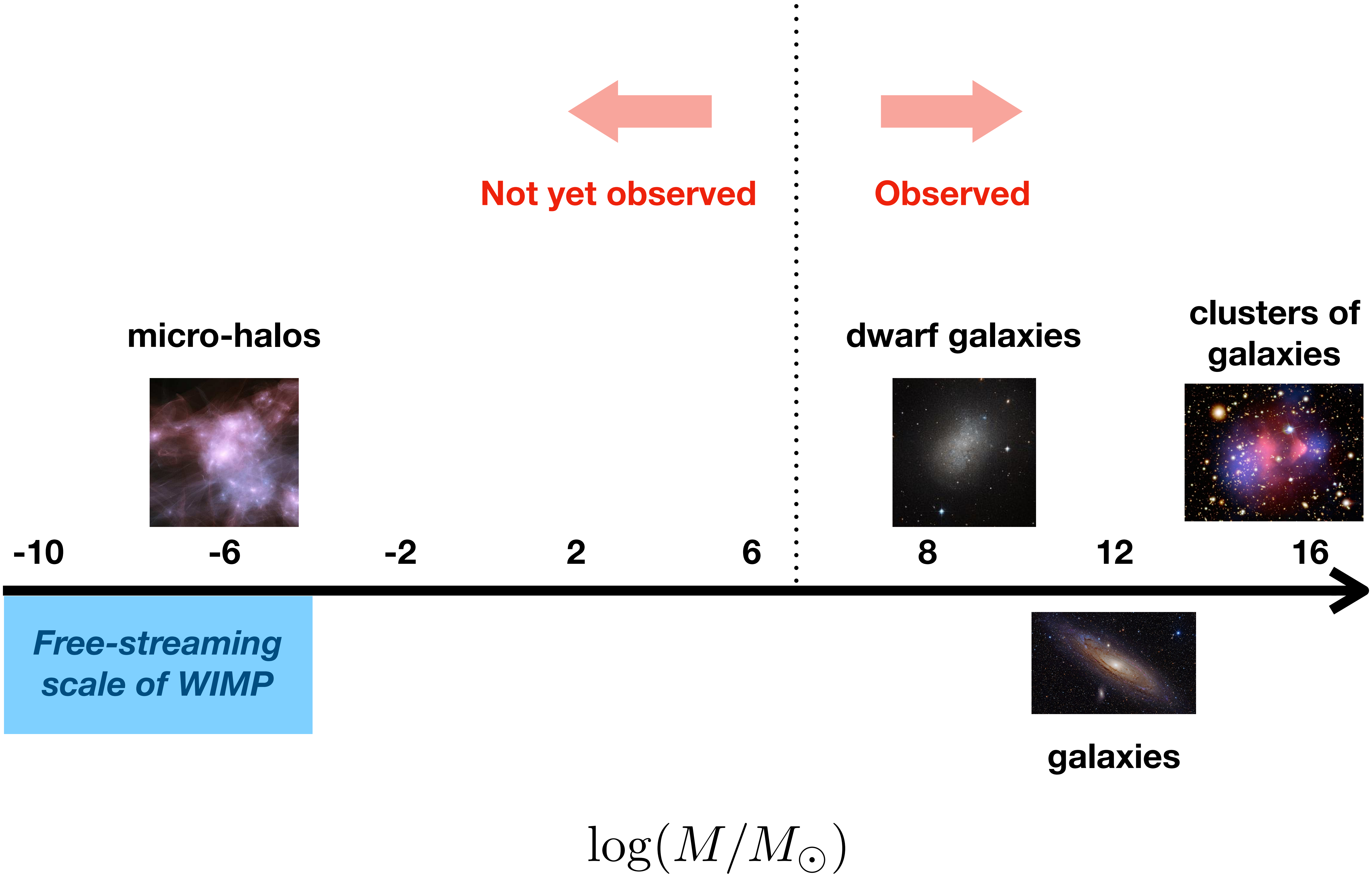
Result from all the cosmology data

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

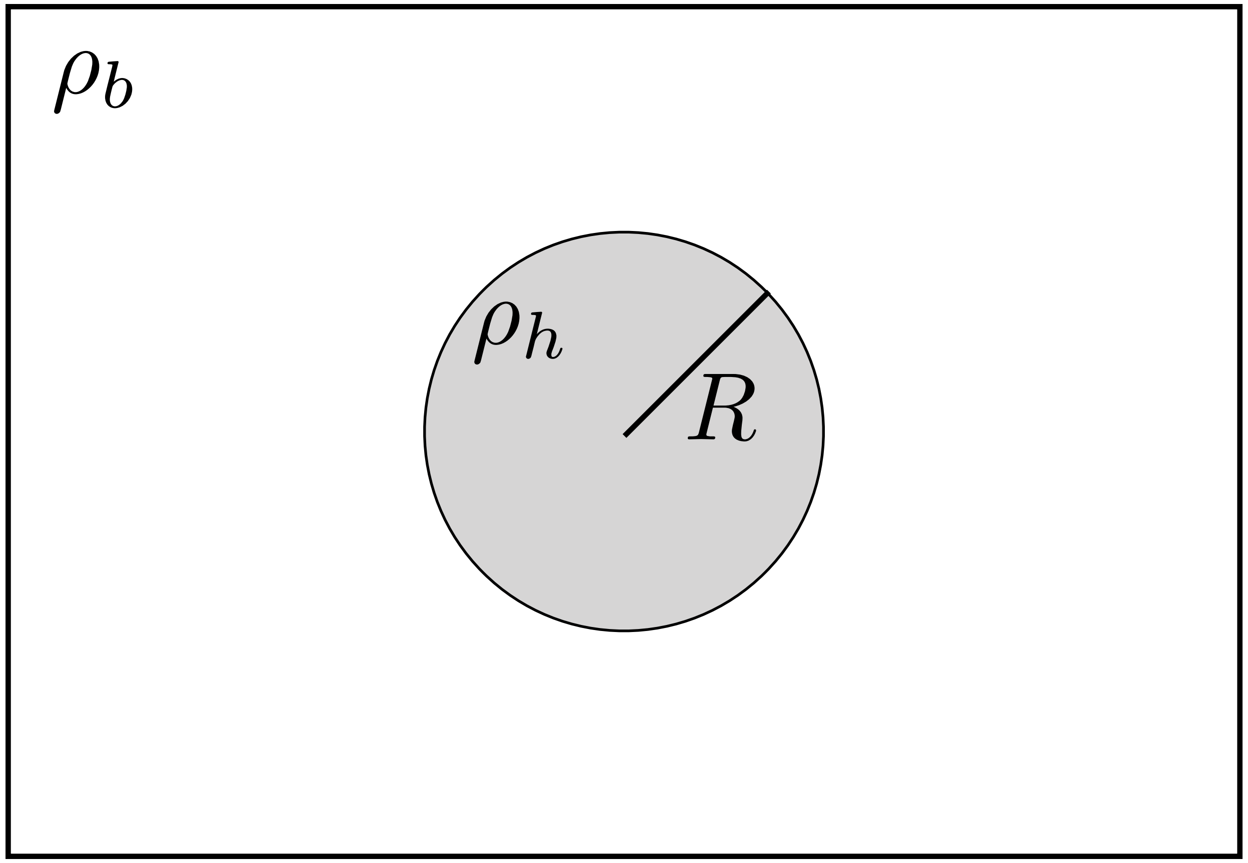
- How dense are collapsed dark matter halos (that host galaxies, clusters of galaxies, etc.)?

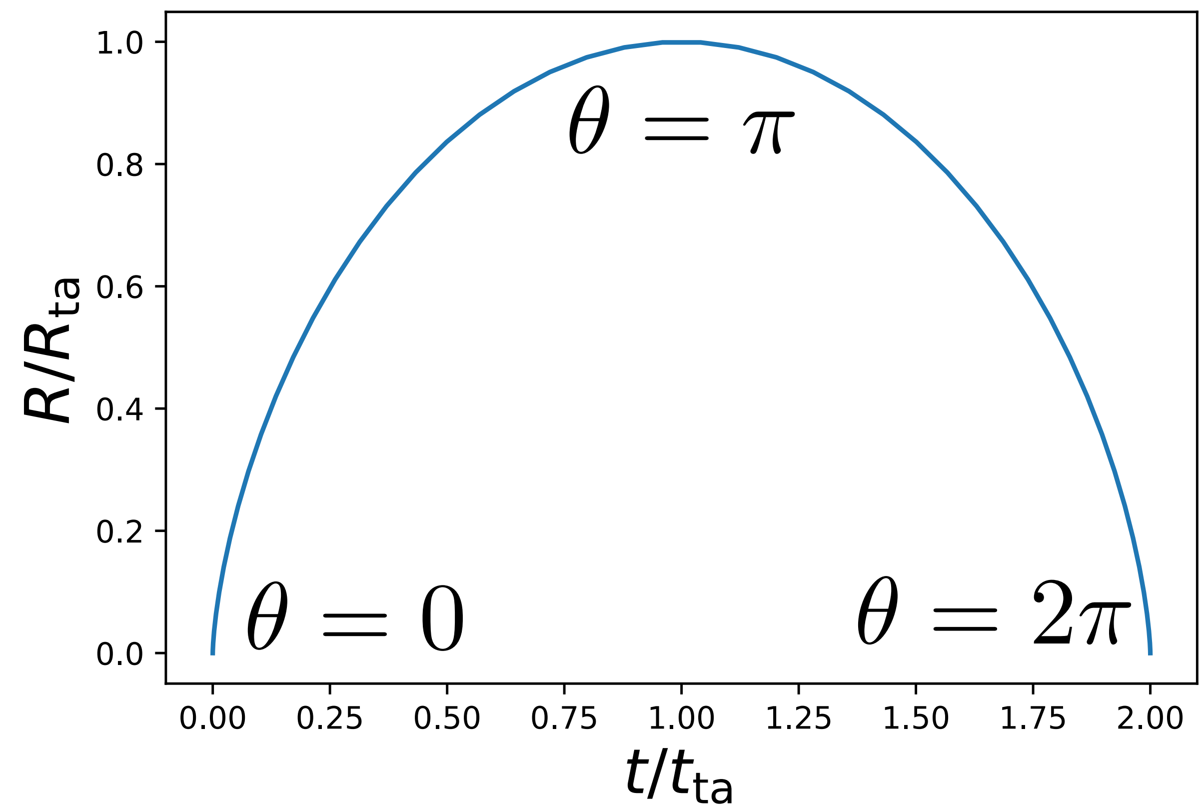
- Over-density of virialized halos compared with background

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

Useful for simulations to find halos

Spherical collapse model





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

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

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

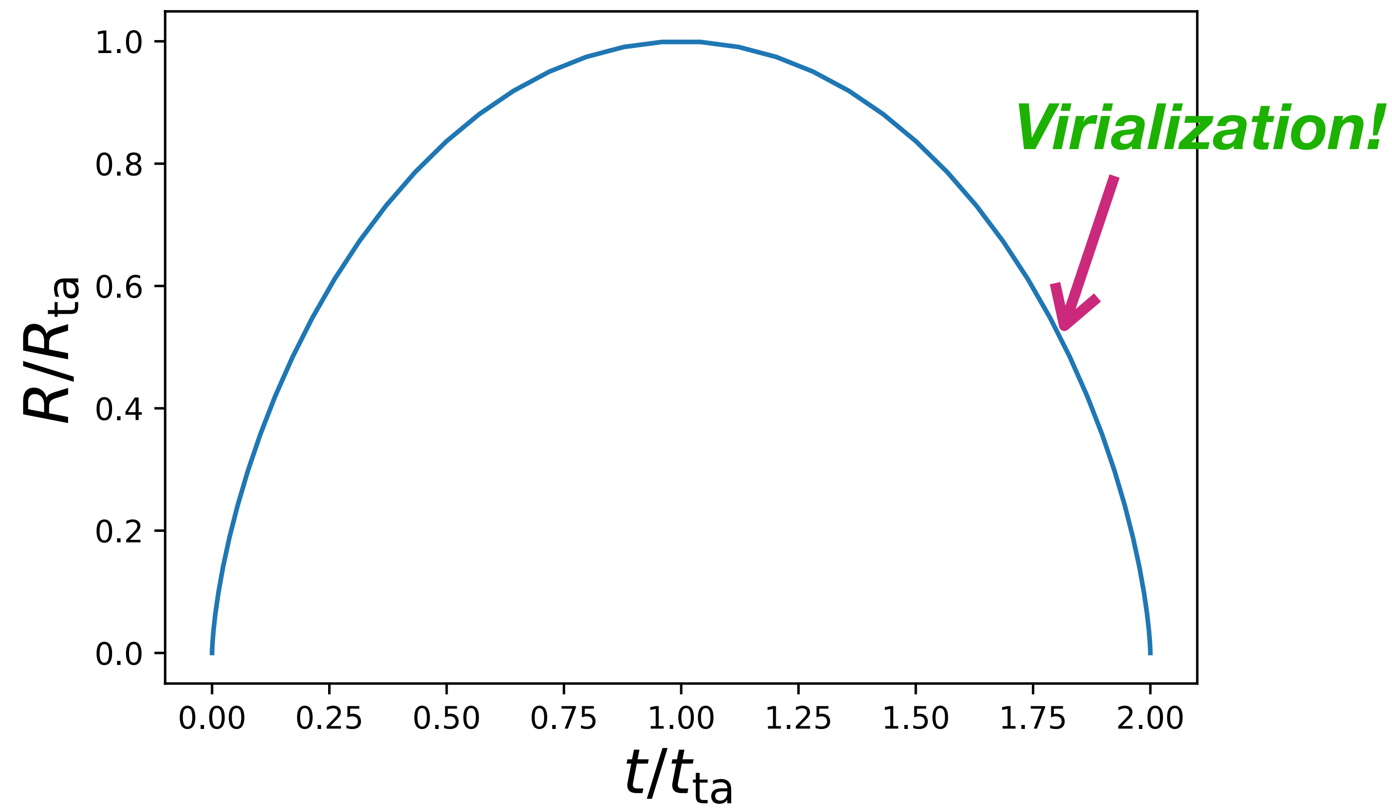
Spherical collapse model

When do halos virialize?

Virial theorem:

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

(for 1/*R* potential)



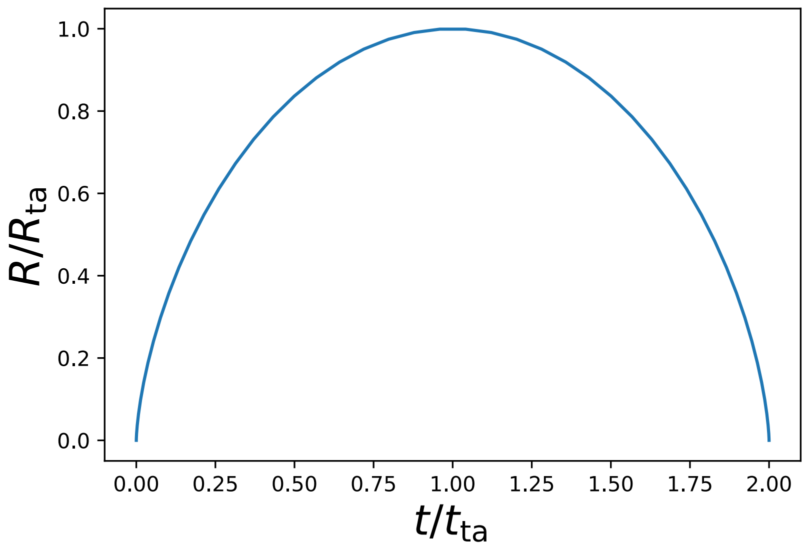
Total energy conservation:

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

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

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

Spherical collapse model



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

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

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

How dense is a virialized halo compared with background?

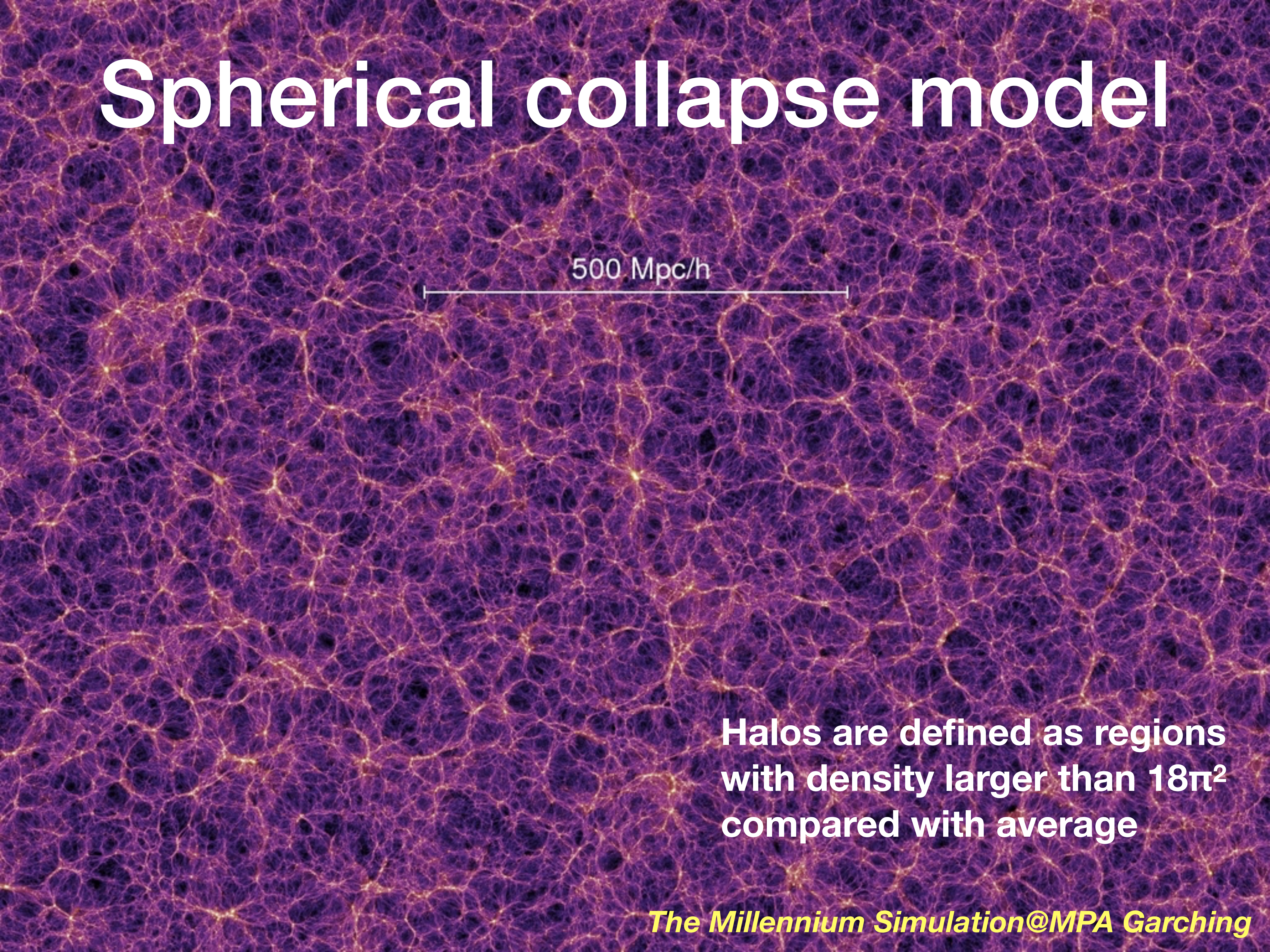
$$\rho_{\rm vir} = \frac{3M}{4\pi R_{\rm vir}^3} = \frac{6M}{\pi R_{\rm ta}^3} = \frac{3\pi}{G t_{\rm col}^2}$$

$$(t_{\rm col} = 2t_{\rm ta})$$

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

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

Spherical collapse model



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

The Millennium Simulation@MPA Garching

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

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

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

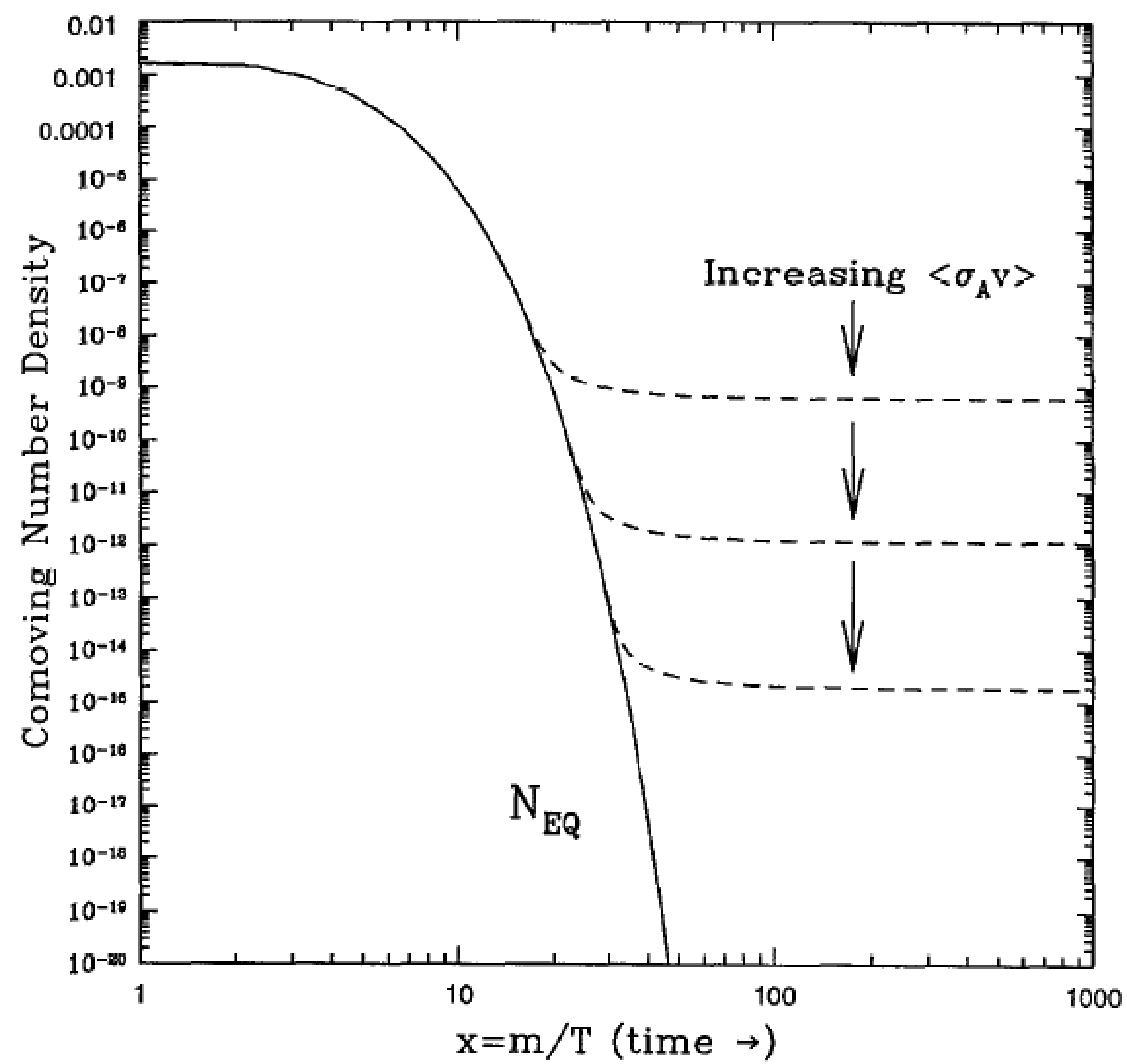
$$\Delta_{\rm vir} = 18\pi^2 + 82[\Omega_m(z) - 1] - 39[\Omega_m(z) - 1]^2$$

ΛCDM: 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

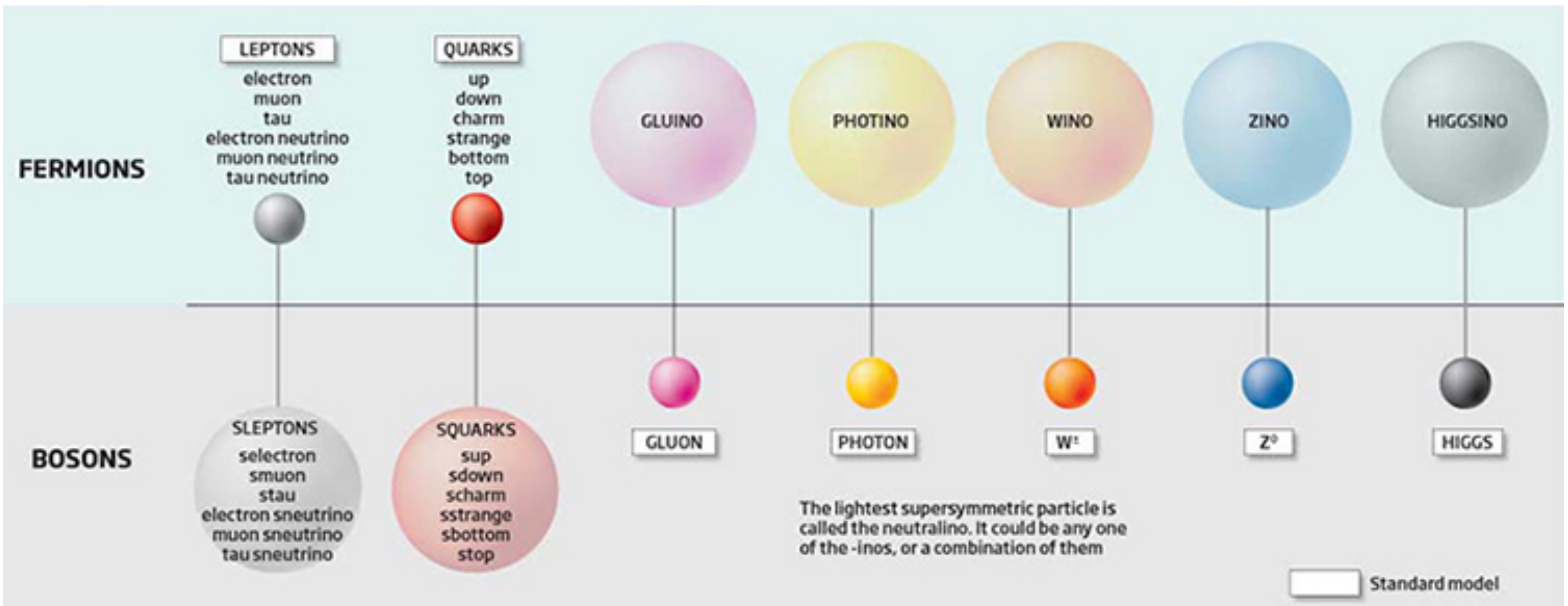


$$\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle\sigma_{\rm ann} v\rangle}$$

$$\langle\sigma_{\rm ann} v\rangle \sim \alpha^2 (100\ \mathrm{GeV})^{-2}$$

$$\sim 3\times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

Supersymmetry (SUSY)

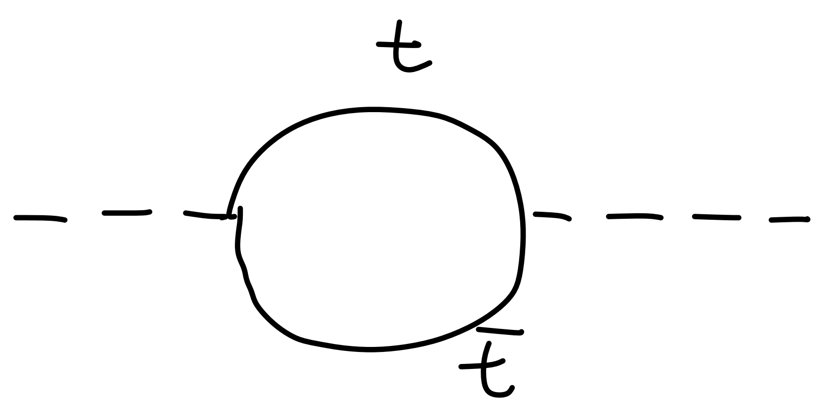


- SUSY extension of the Standard Model is well motivated
  - Stability of Higgs mass
  - Unification of gauge couplings

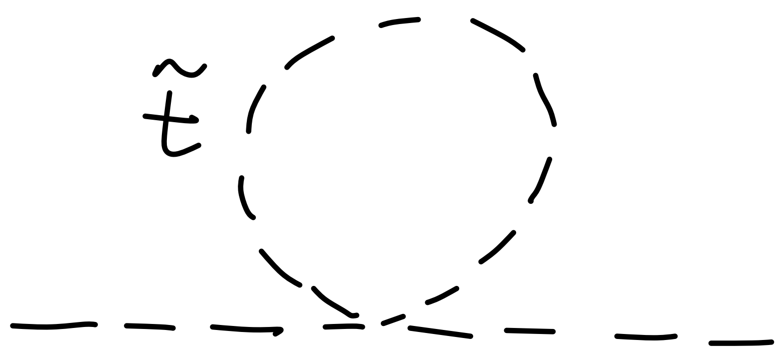
- It supplies SUSY partners to every Standard Model particle

Higgs mass

$m_H^2 \phi^2 =$  bare mass $m_{H,0}^2$

$+$ 

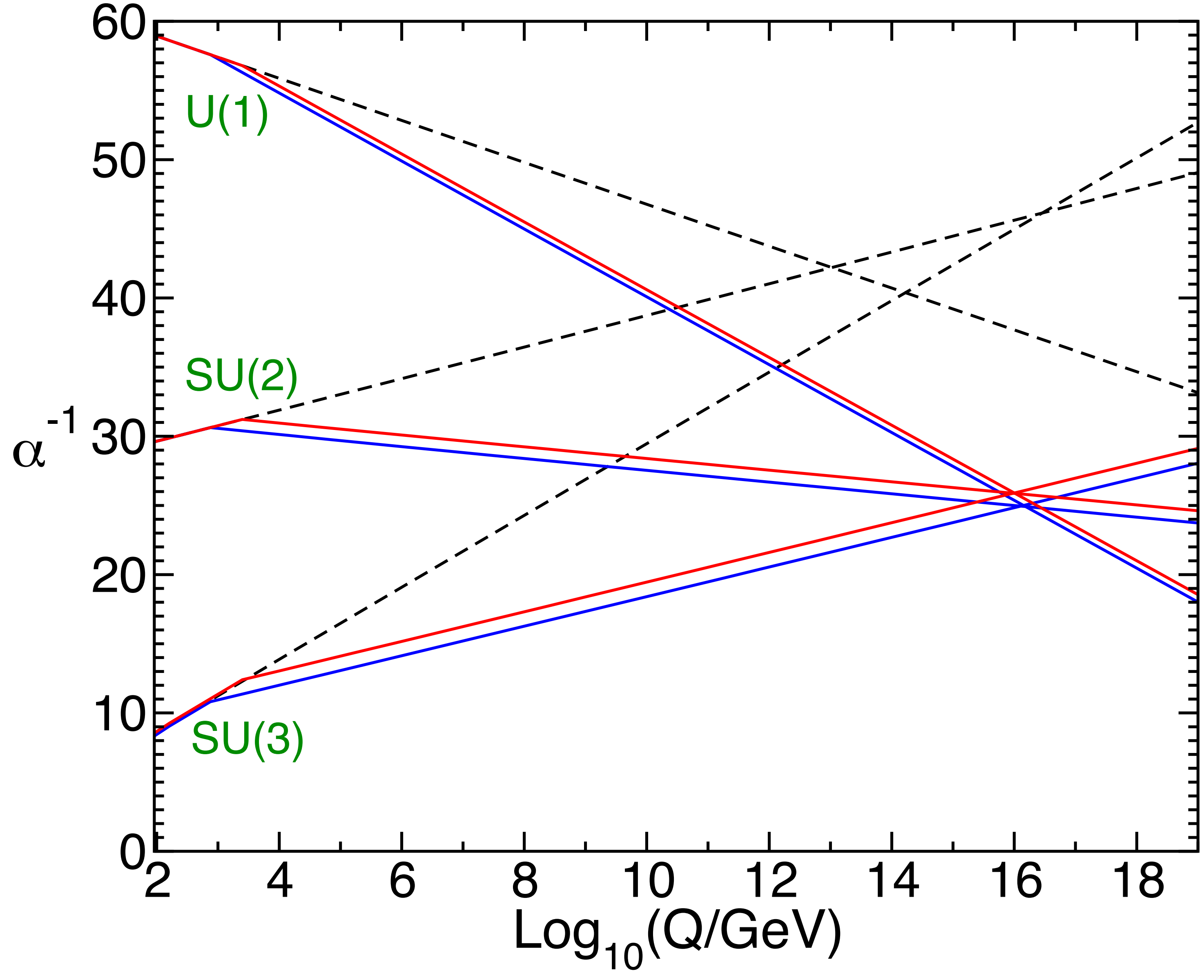
Fermion 1-loop $\sim \Lambda^2$

$+$ 

Scalar 1-loop $\sim -\Lambda^2$

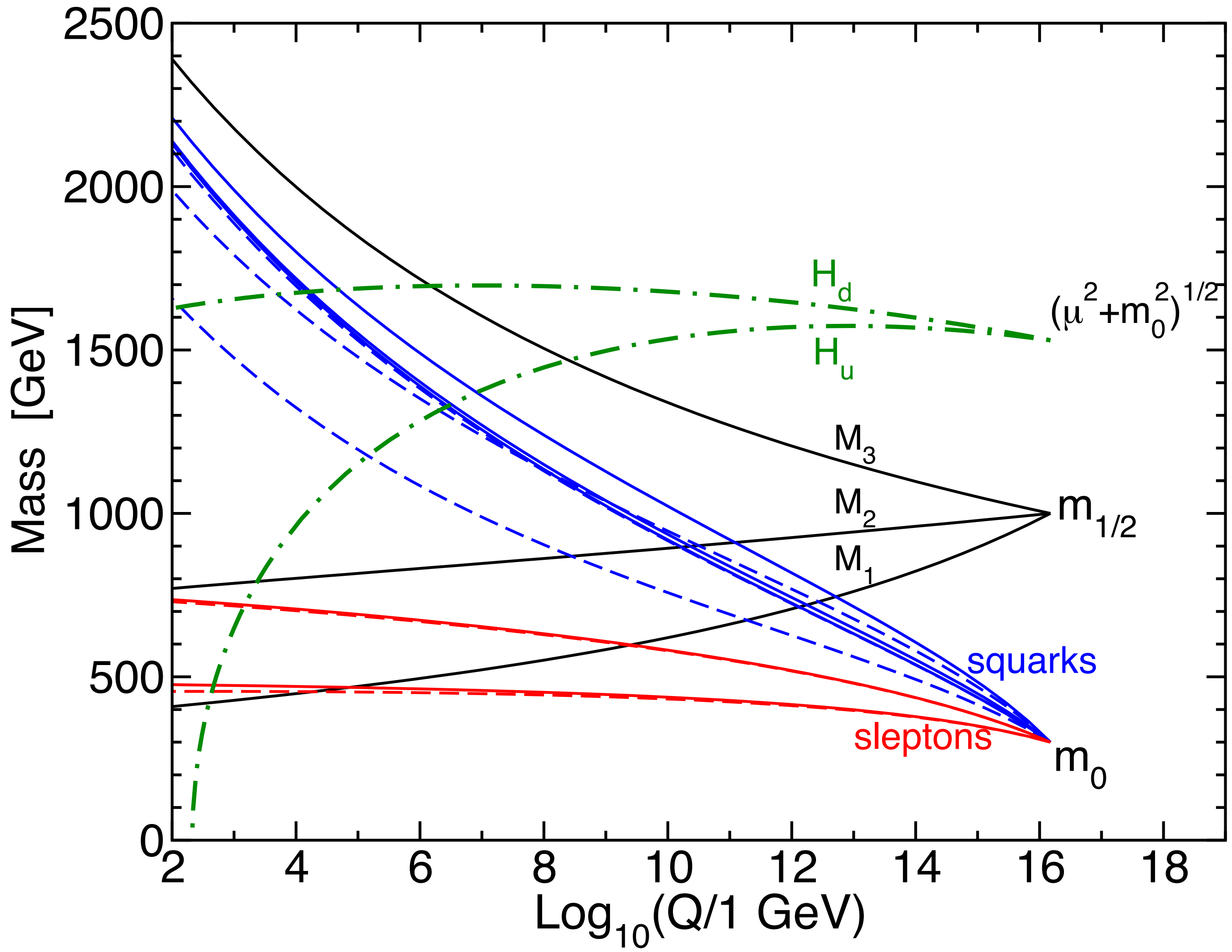
Cancellation happens to make Higgs mass at electroweak scale

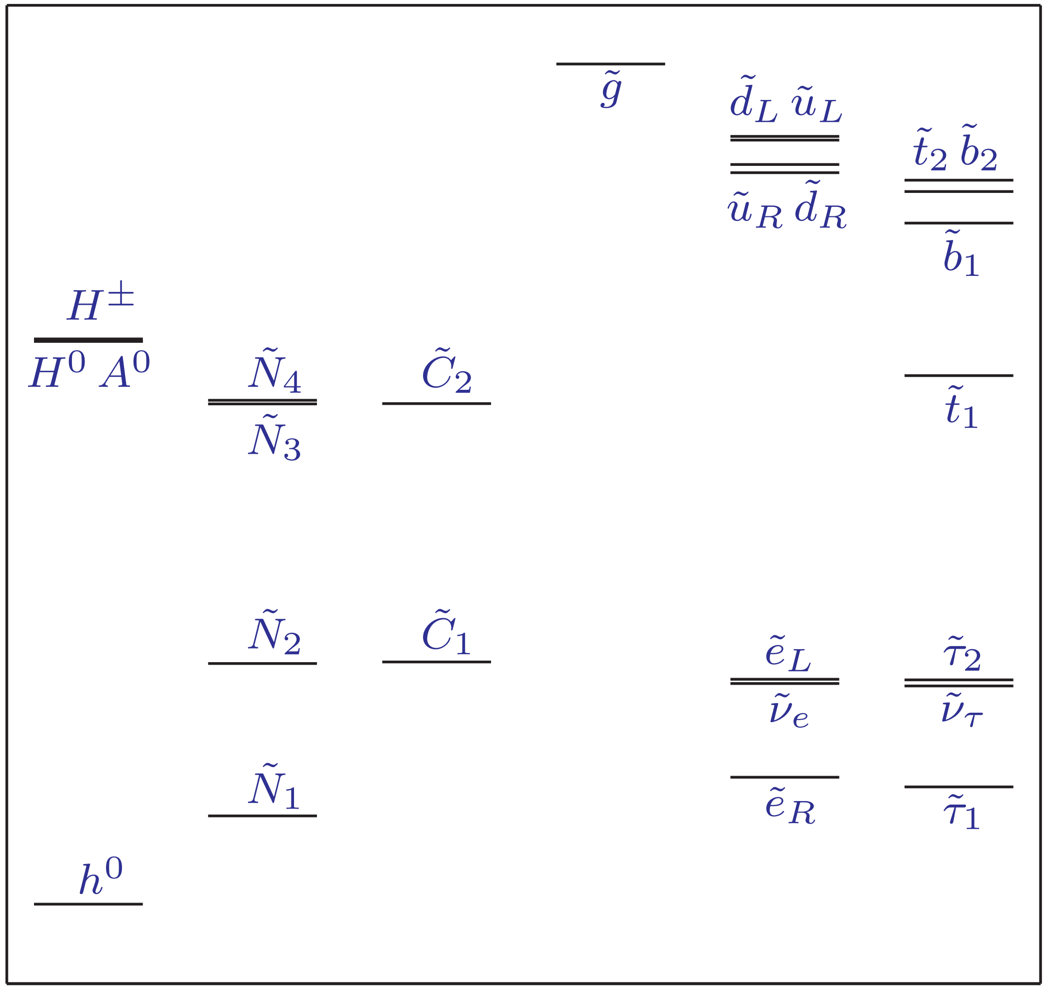
Unification of gauge coupling



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

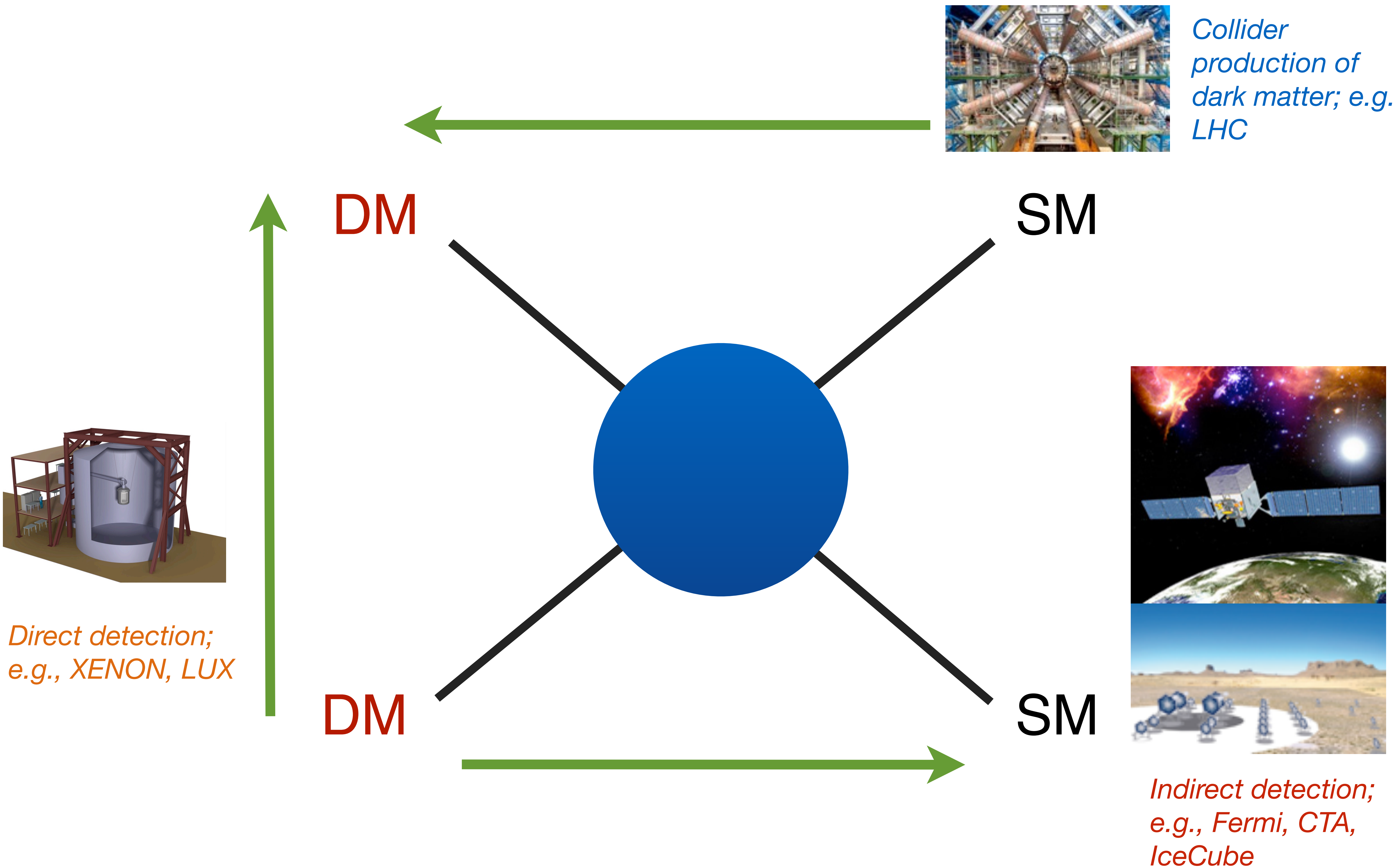
SUSY neutralino



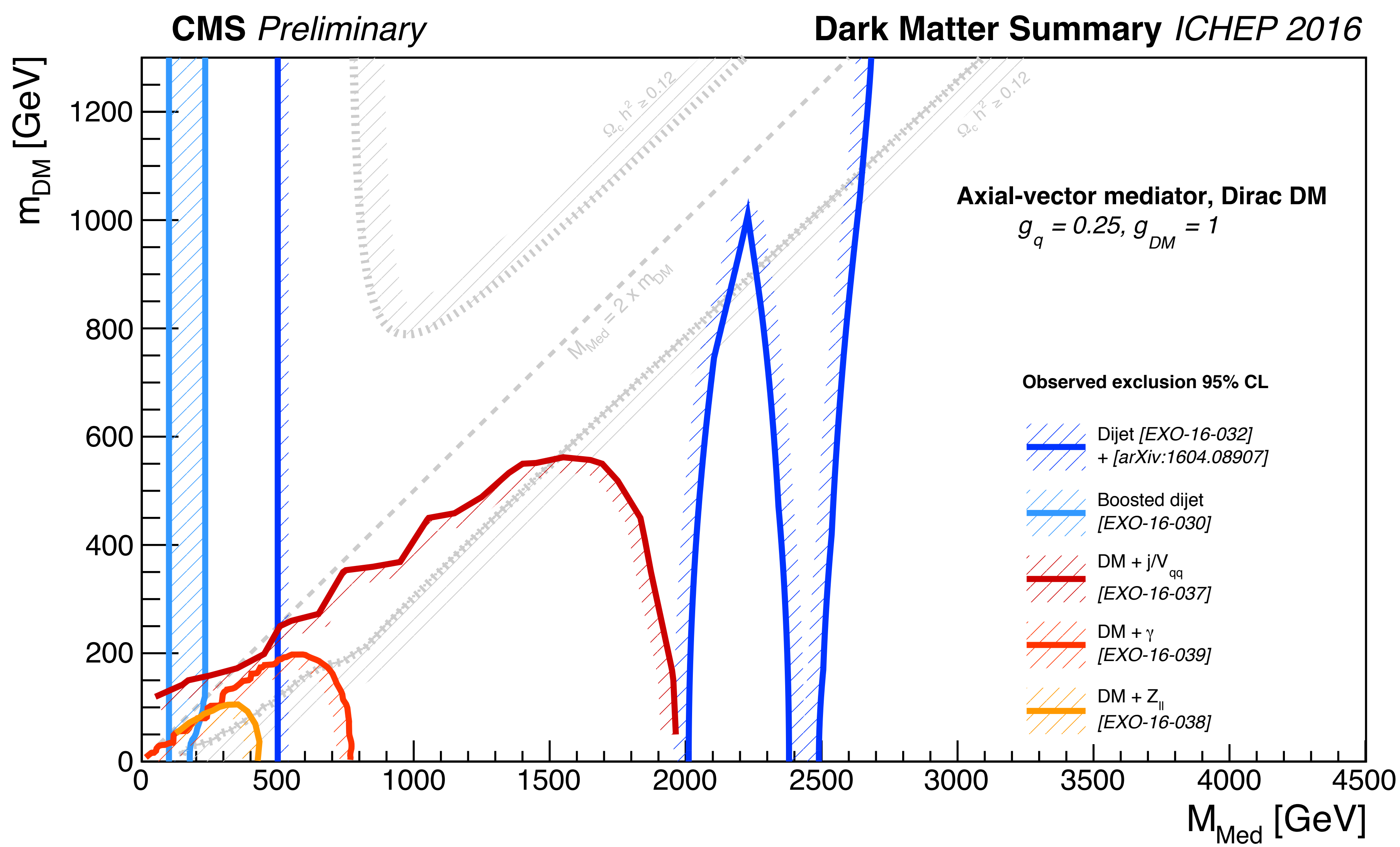


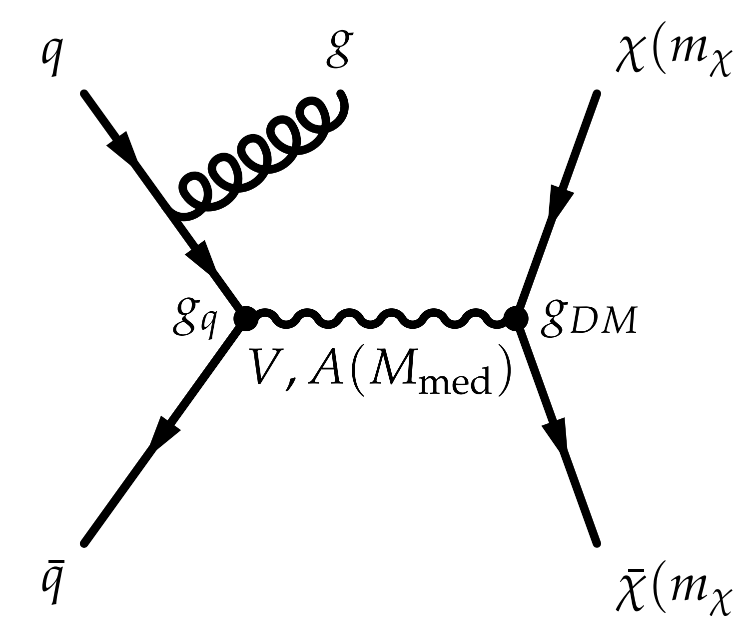
- Mass eigenstate for neutral SUSY partners of photons, Z and Higgs bosons
- In many models, they are the lightest SUSY particles: hence dark matter candidate

Three routes to DM



Collider searches



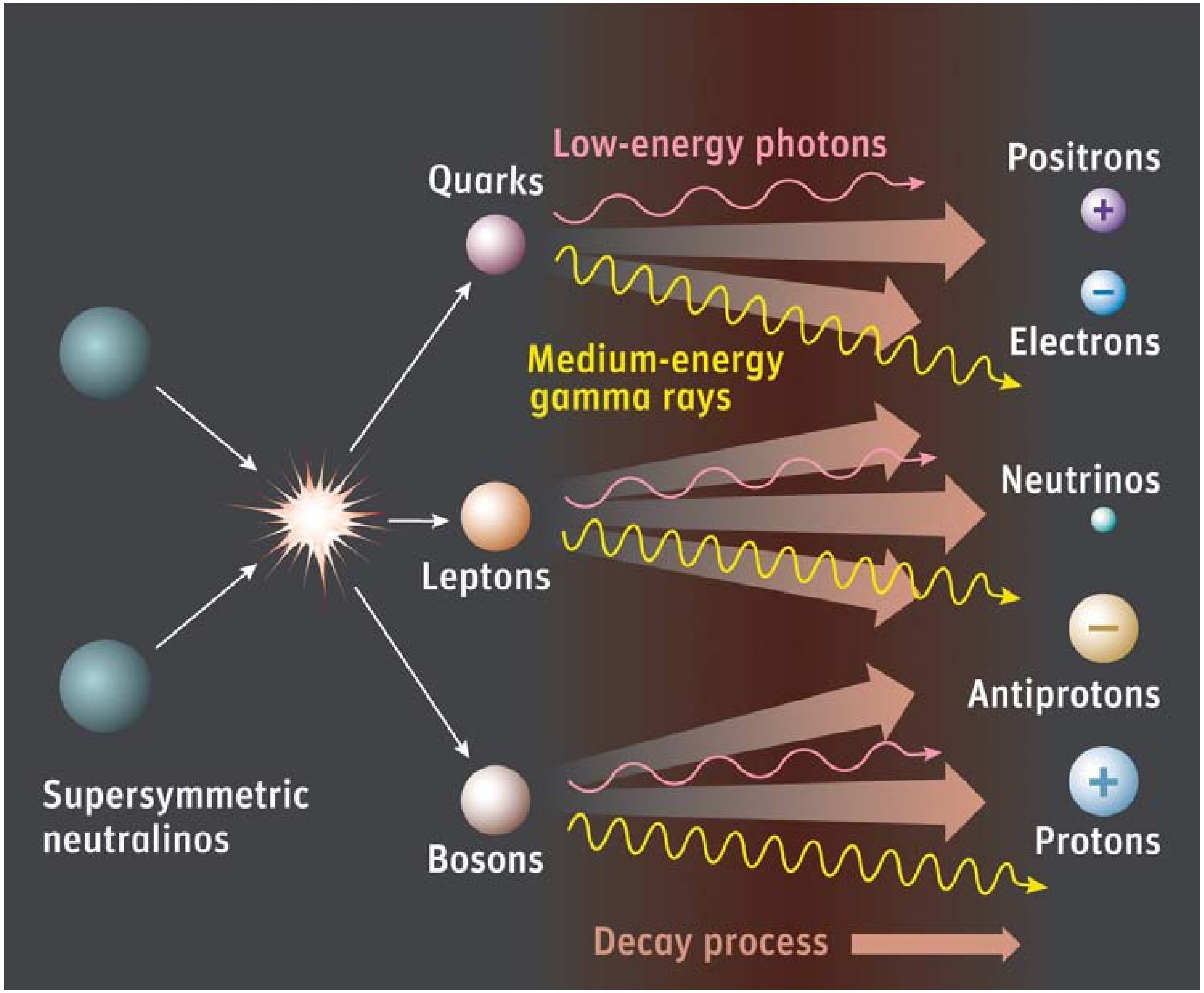


- Large parameter regions tested with ATLAS/CMS data, for the simplest models (vector, axial-vector, scalar, or pseudo-scalar Dirac fermion DM)

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 ~ GeV–TeV)
- Annihilation rate is proportional to density squared and to annihilation cross section and relative velocity: $\sigma_{ann}V$

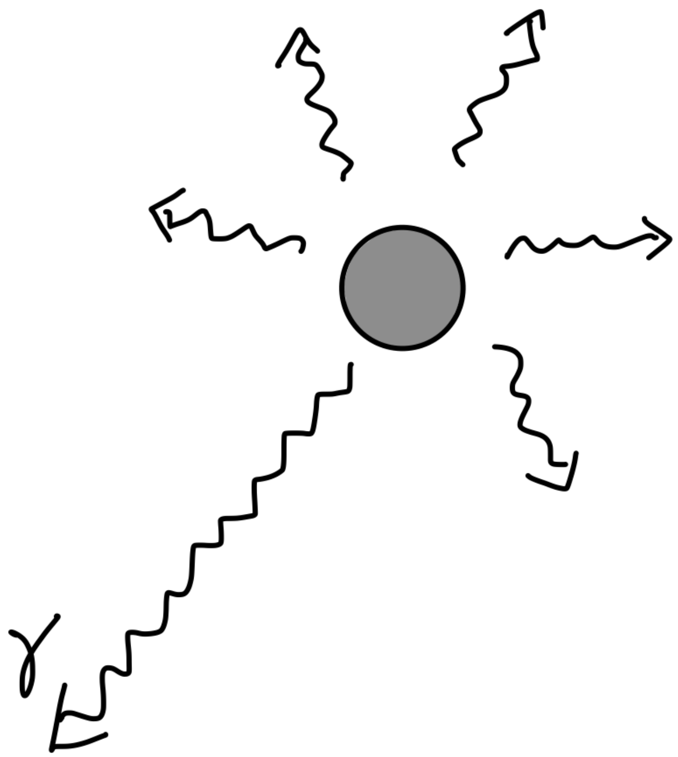


Rate of annihilation: Simple consideration

- 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 $n_\chi v = \dfrac{\rho_\chi v}{m_\chi}$
- 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

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

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

Differential flux

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

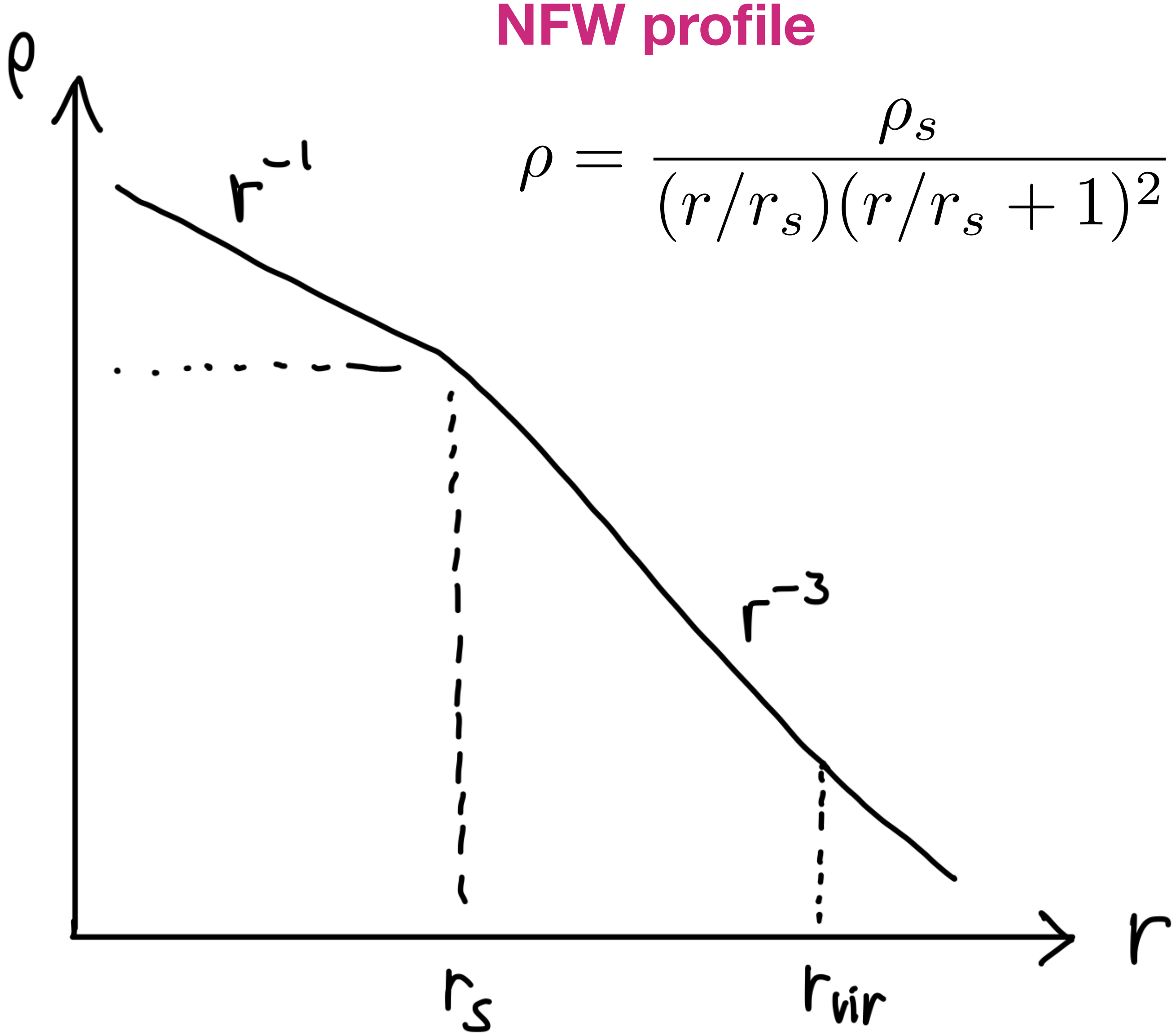
***r*: comoving distance to the halo**

Gamma-ray flux from dark matter annihilation

Halo mass *M* at redshift *z*

NFW profile

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



Virial radius

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

Scale radius

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

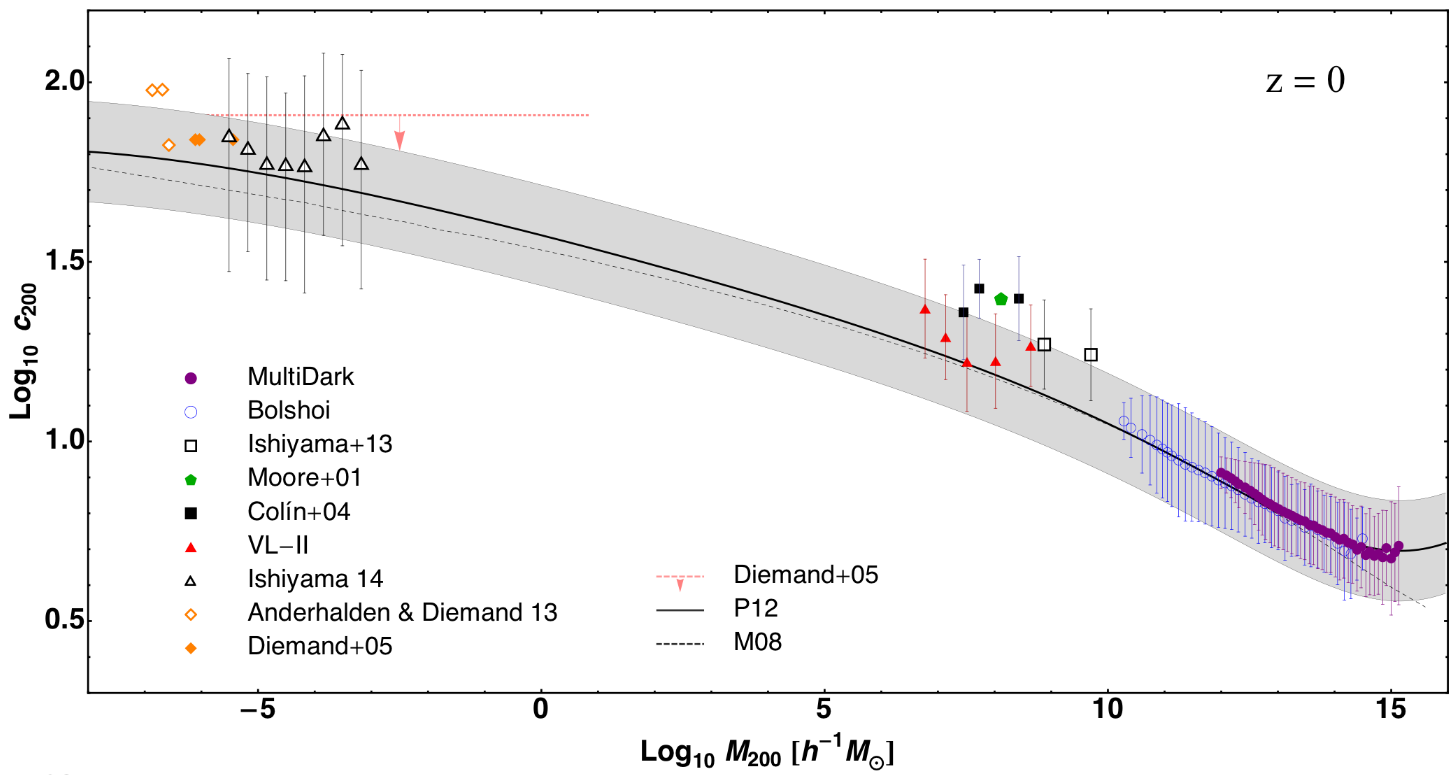
Characteristic density

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

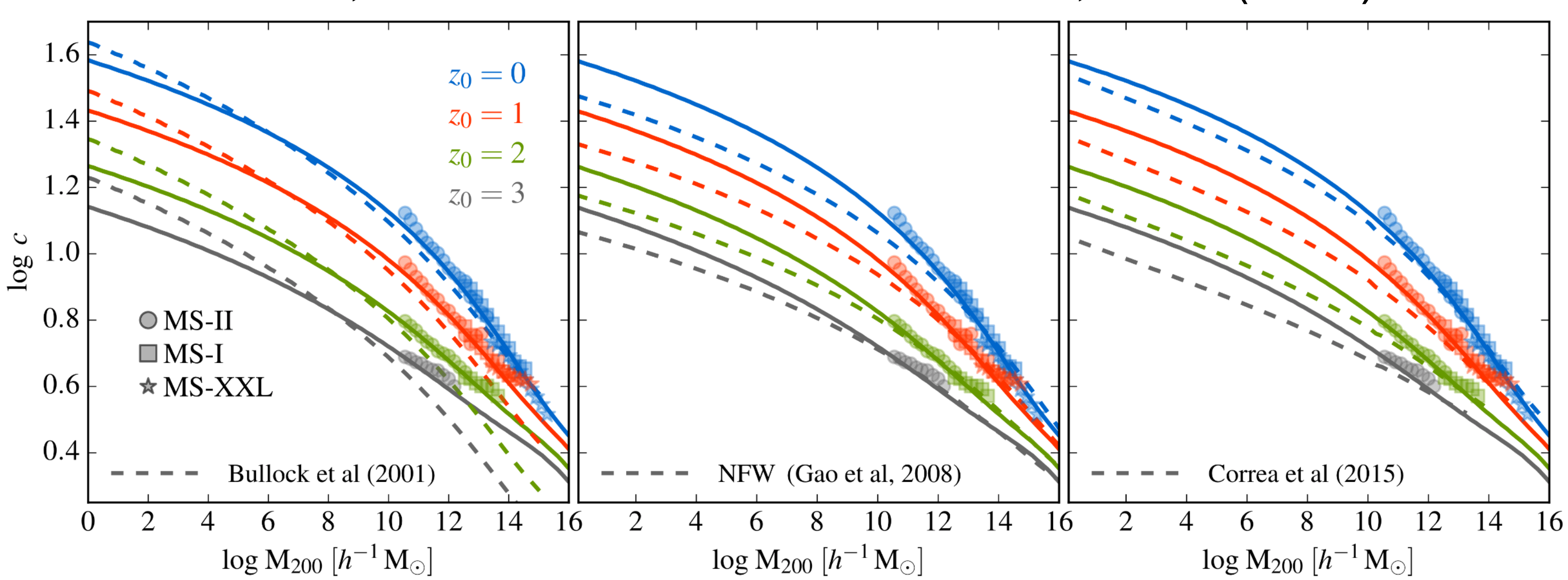
All relevant parameters derived as a function of *M* and *z*

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)



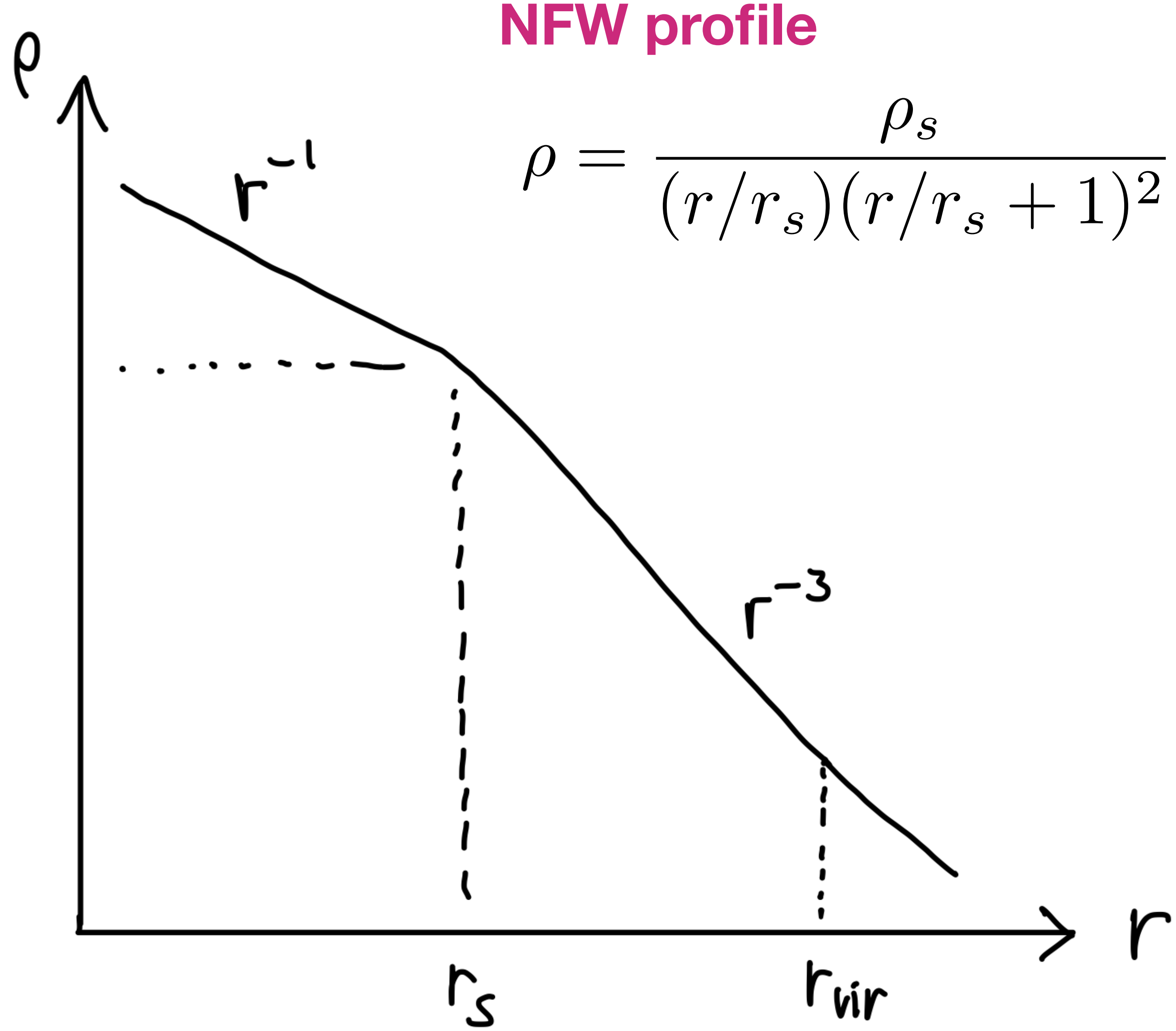
Halo concentration

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

- 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*



NFW profile

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

Virial radius

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

Scale radius

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

Characteristic density

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

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

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

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

$$r_s = \frac{r_{\rm vir}}{c_{\rm vir}} \sim 20\ \mathrm{kpc} \qquad (c_{\rm vir} = 10)$$

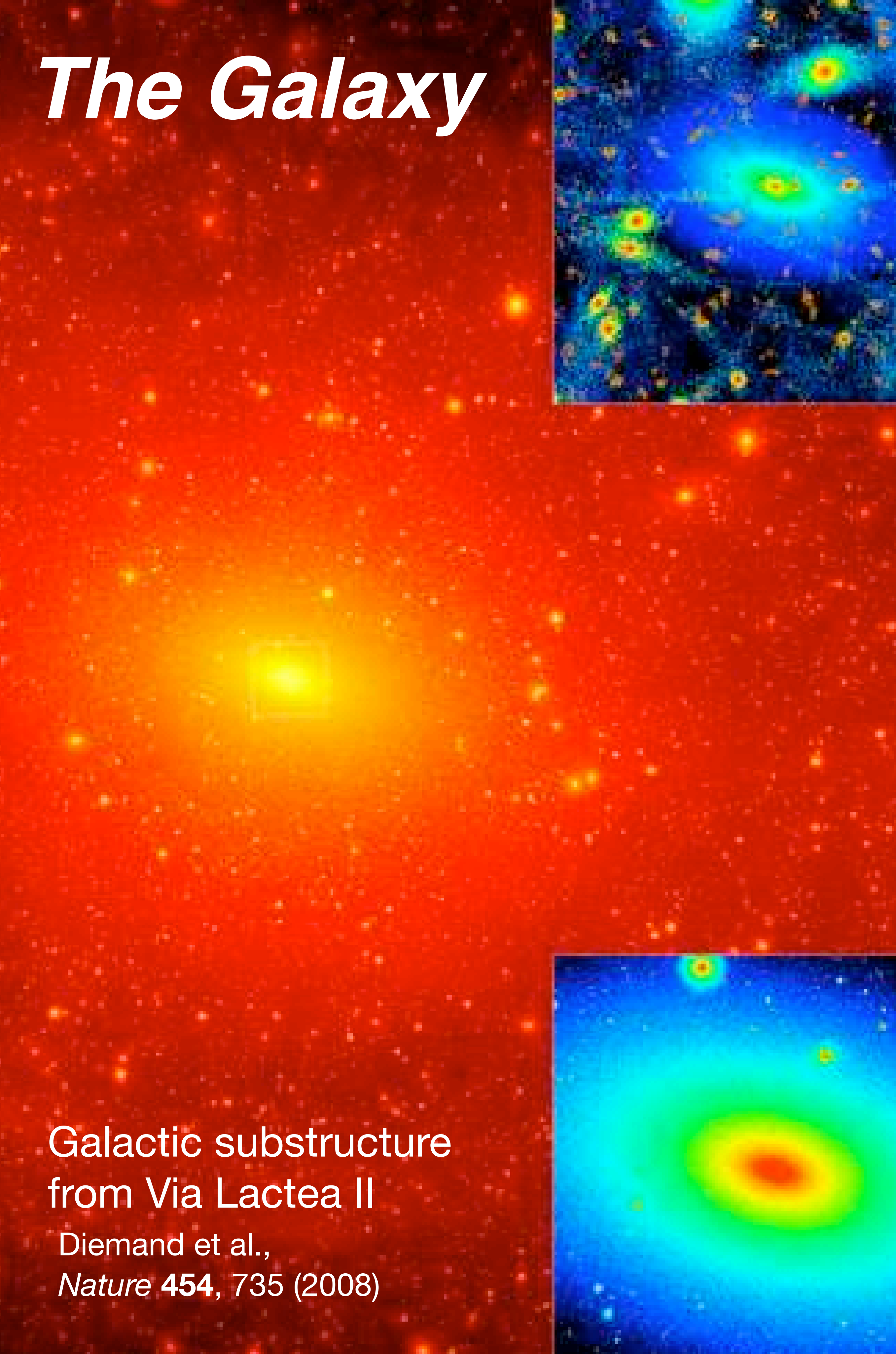
$$\rho_s = \frac{M}{4\pi r_s^3[\ln(1+c_{\rm vir}) - c_{\rm vir}/(1+c_{\rm vir})]}$$

$$\sim 0.3\ \mathrm{GeV\ cm^{-3}}$$

Annihilation rate:

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

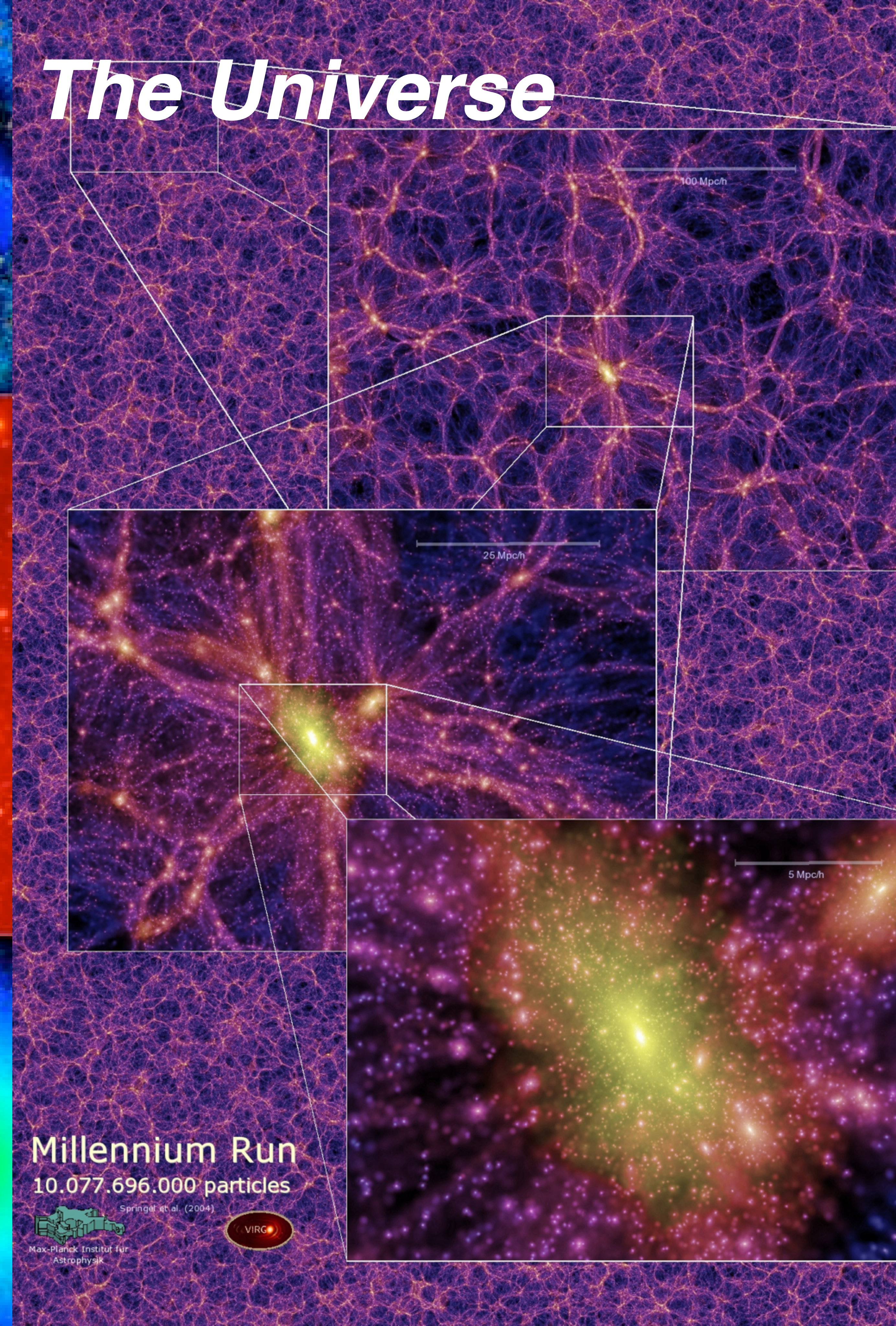
The Galaxy



Galactic substructure from Via Lactea II

Diemand et al., *Nature* **454**, 735 (2008)

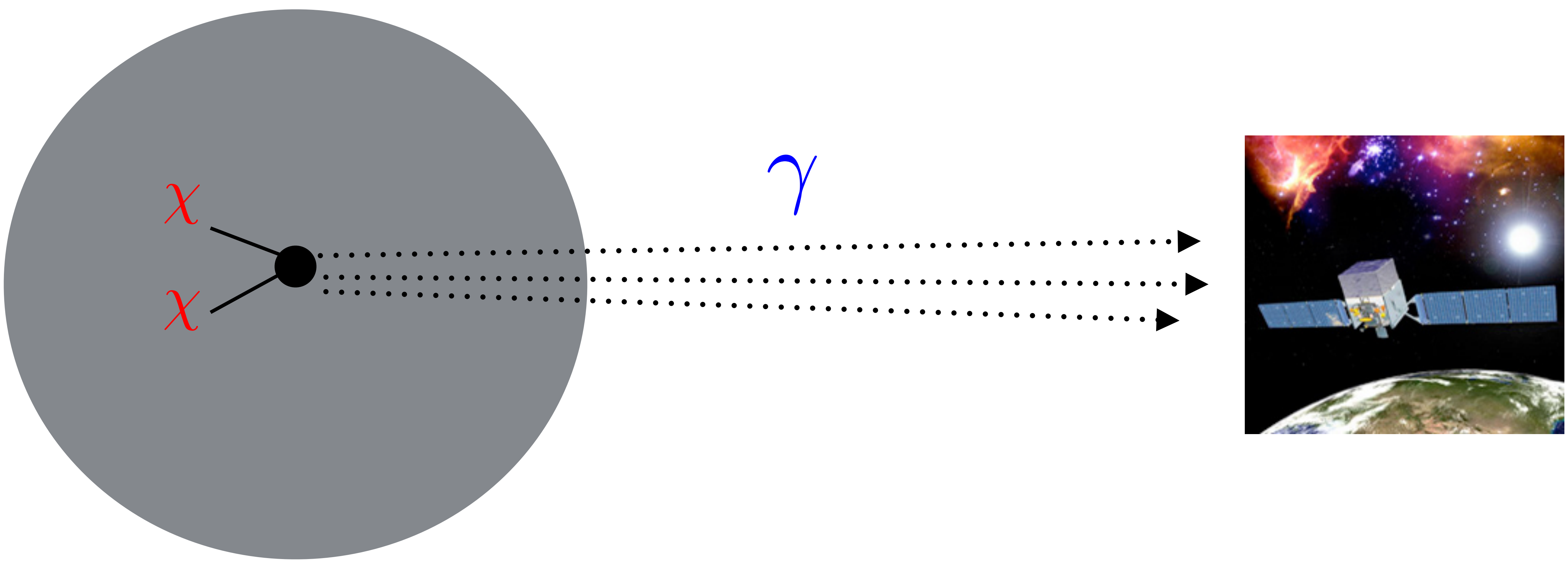
The Universe



Gamma-ray flux from dark matter annihilation

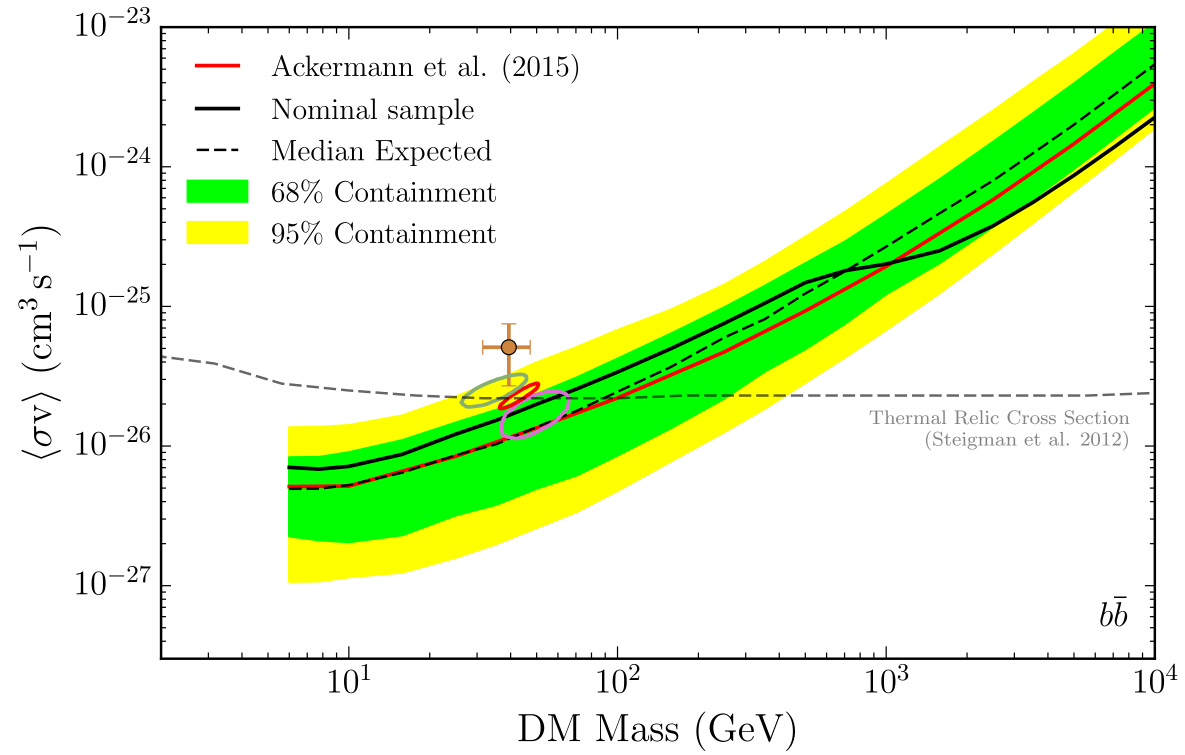
Particle physics **Astrophysics**

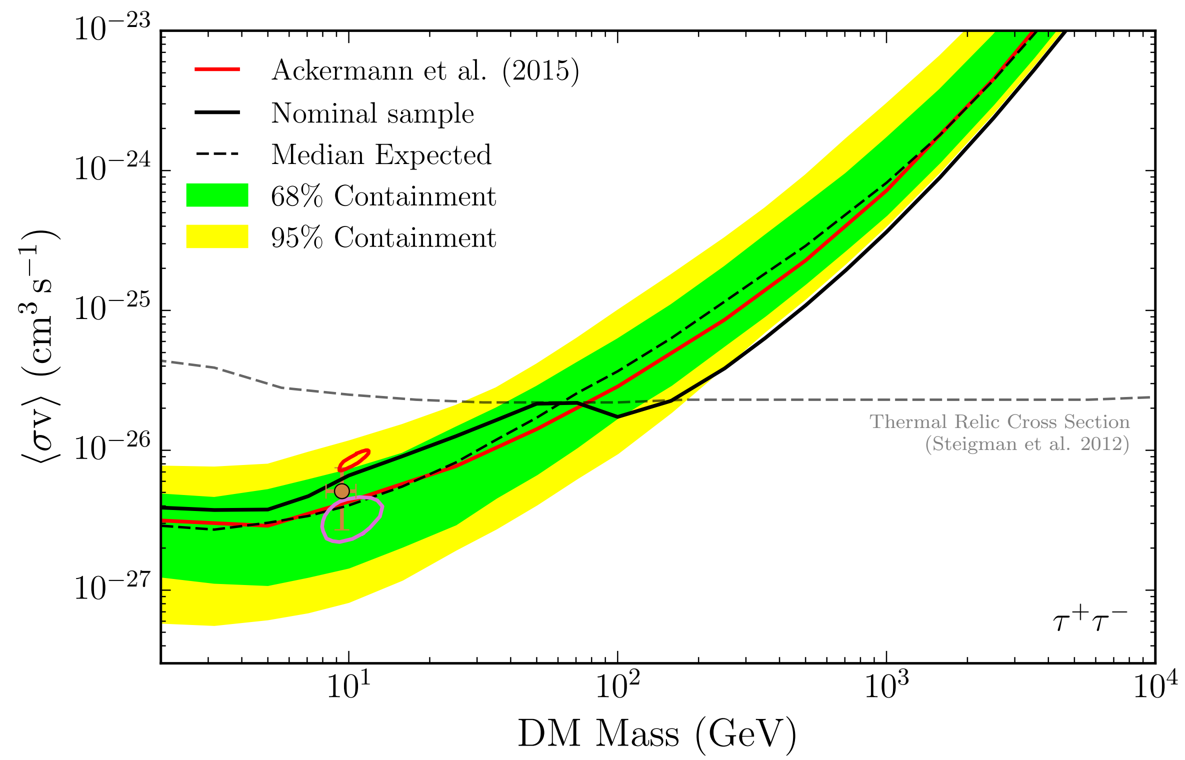
$$I_\gamma(E_\gamma, \psi) = \frac{1}{2}\frac{\langle \sigma v \rangle}{m_\chi^2}\frac{dN_{\gamma,\mathrm{ann}}}{dE_\gamma}\frac{1}{4\pi}\int d\ell\ \rho_\chi^2(r[\ell,\psi])$$

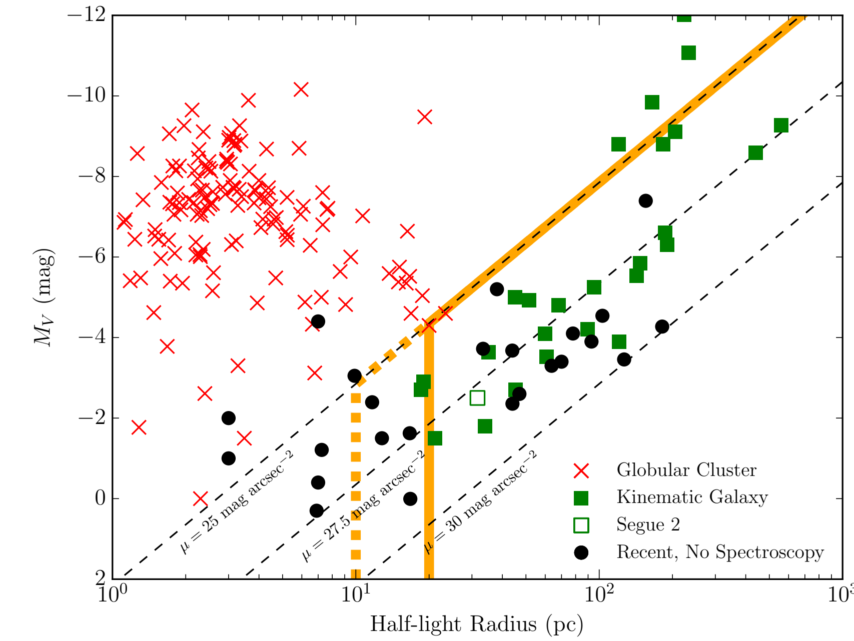


Constraints from dwarf spheroidal galaxies

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



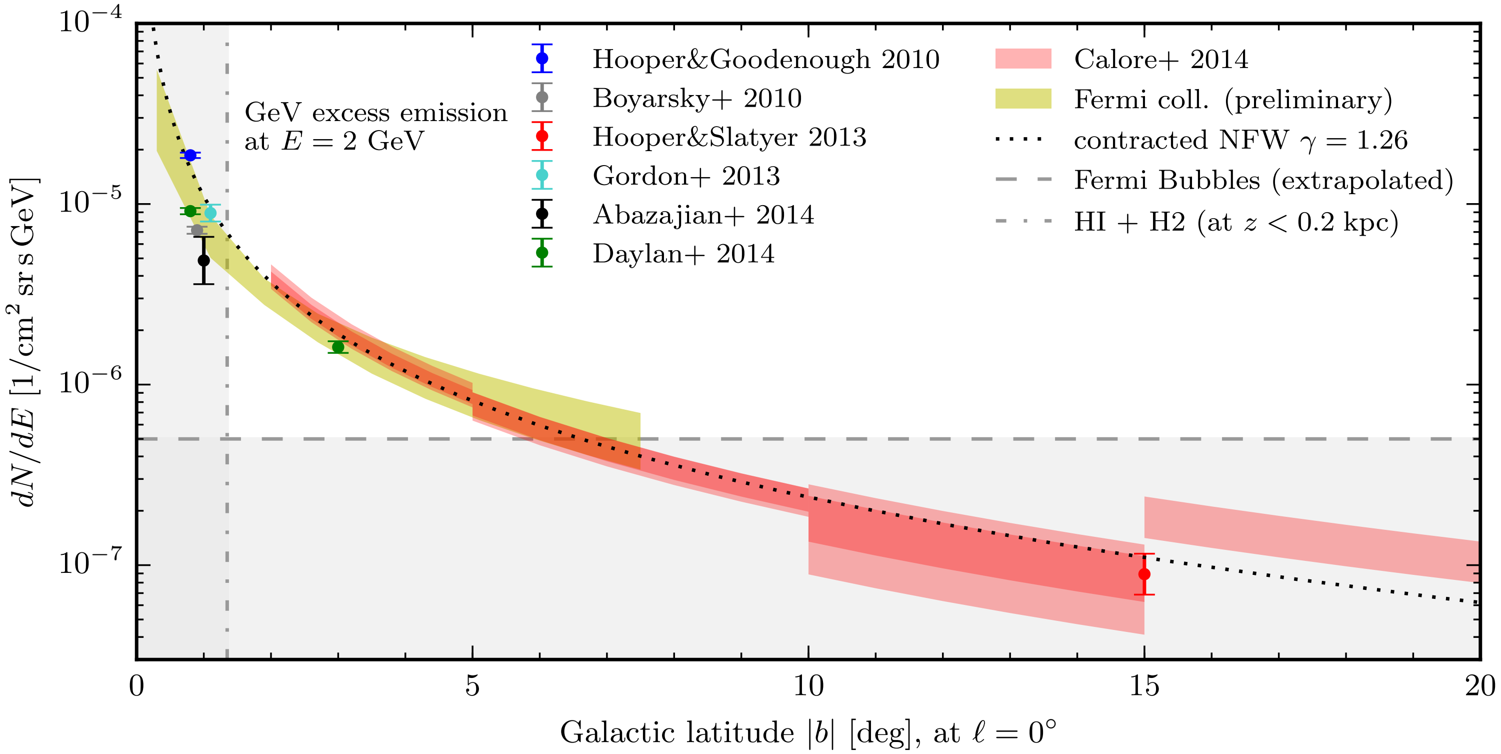


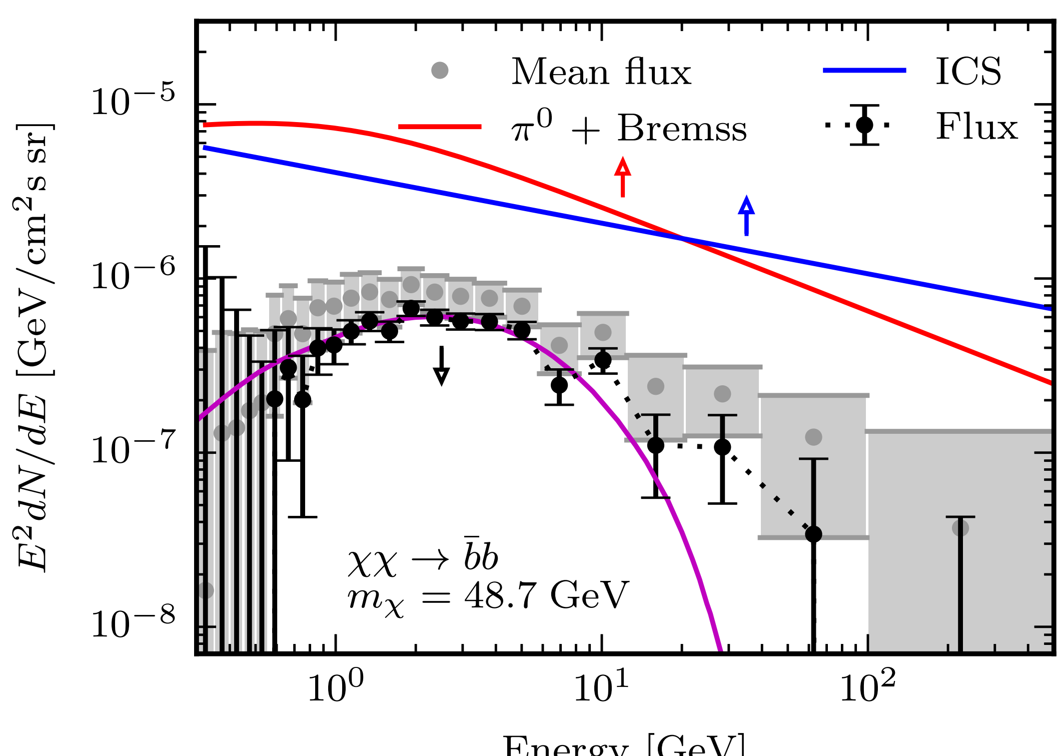


- Highly DM dominated system → suitable environment to test DM annihilation
  - Most robust constraints
- The latest results with PASS 8 data are pretty stringent
- They exclude the canonical cross section for WIMPs lighter than several tens of GeV
  - Nominal sample: 41 dwarfs
  - Ackermann et al. (2015):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

GeV excess: Signals of dark matter annihilation?

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

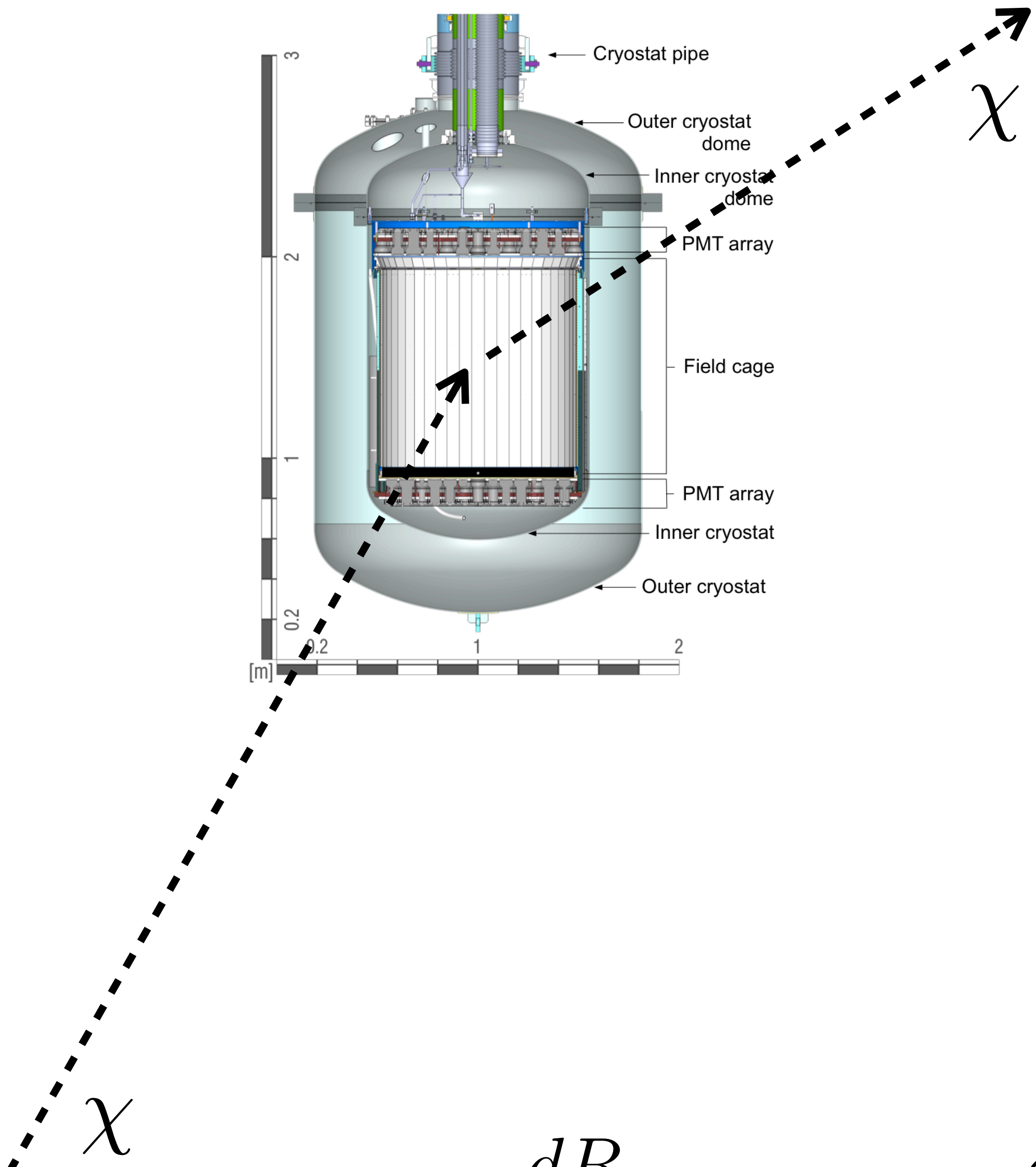




- Gamma-ray excess in GeV regime from the Galactic centre (many sigma) of unknown origin
- Brightness profile is consistent with NFW^2 (with inner slope of –1.26)
- Spectral shape is also consistent with expectation from annihilation
  - mass: ~50 GeV
  - cross section: ~2×10^{-26} cm^3 s^{-1}

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)
- flux = *n v*
- Deposited energy: tens of keV

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

Simple example calculation

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

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

Differential event rate

- Event rate per detector mass per recoil energy, $\mathrm{d}R/\mathrm{d}E$
- Differential cross section, $\mathrm{d}\sigma/\mathrm{d}E$
- 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

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

- 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

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

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

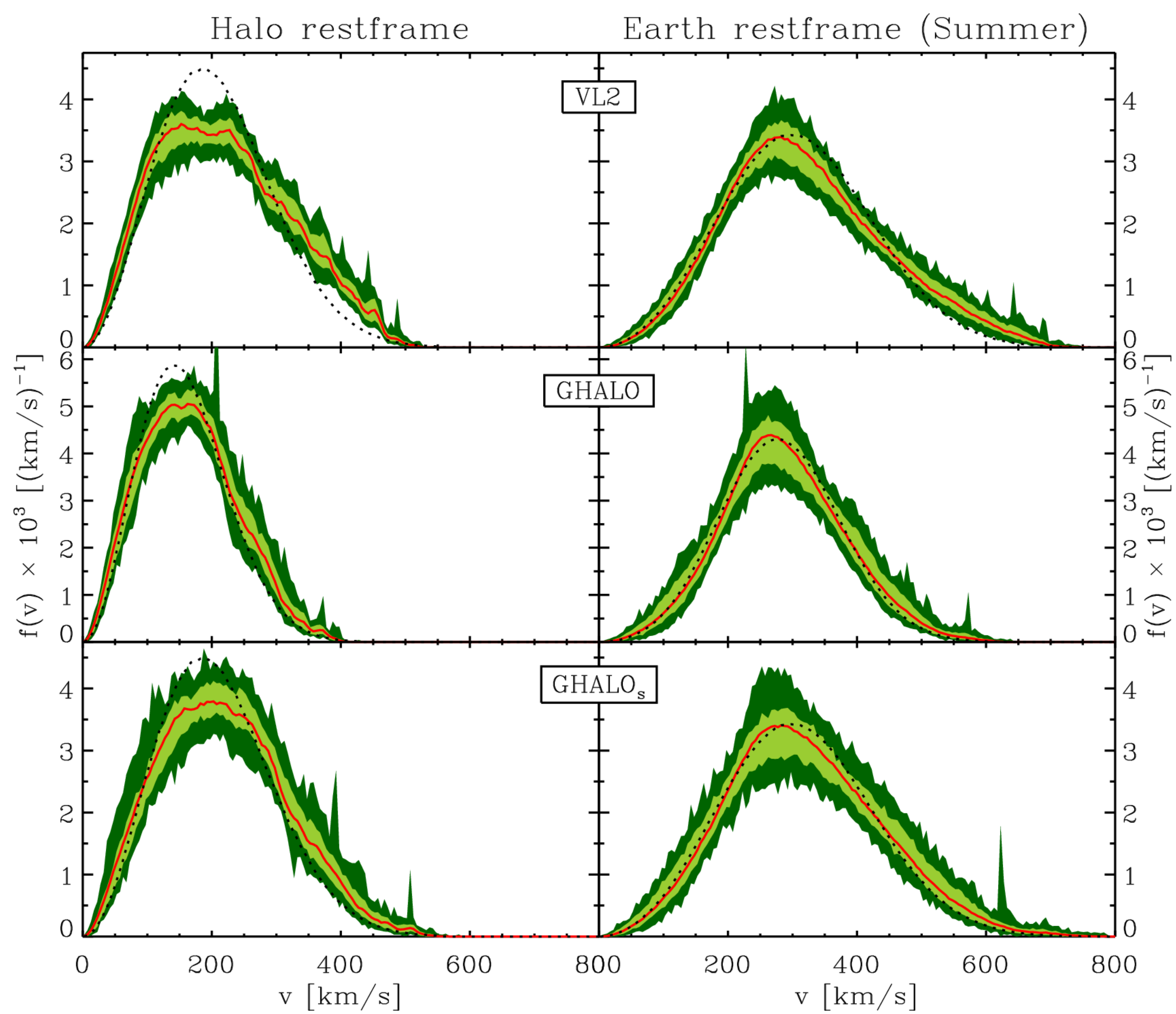
Local dark matter distribution

- Isotropic Maxwellian velocity distribution in the Galactic rest frame

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

- Circular speed at Sun's location: v_0 = 220 km/s

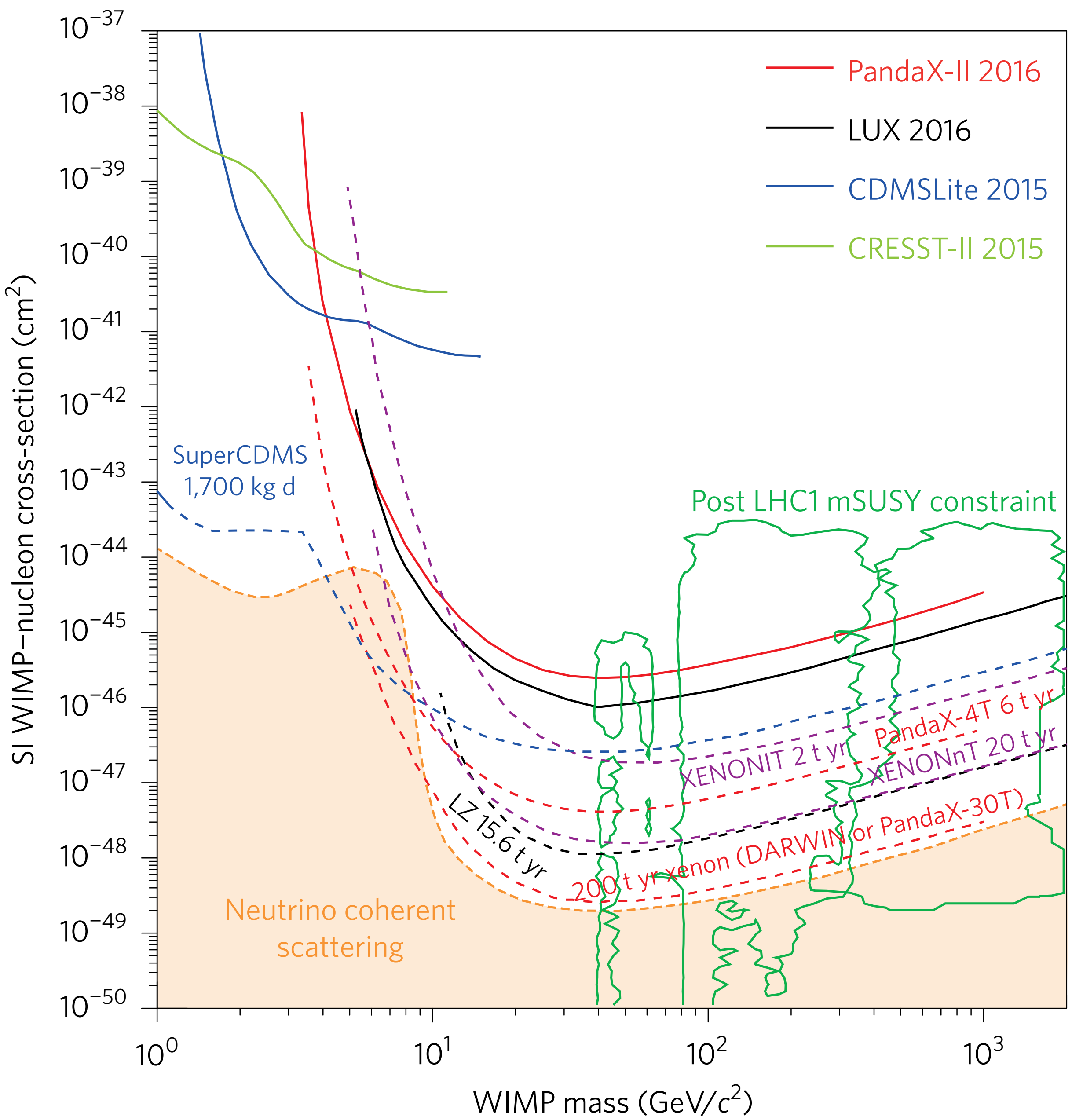
- Local dark density: ρ ~ 0.2 - 0.6 GeV/cm^3



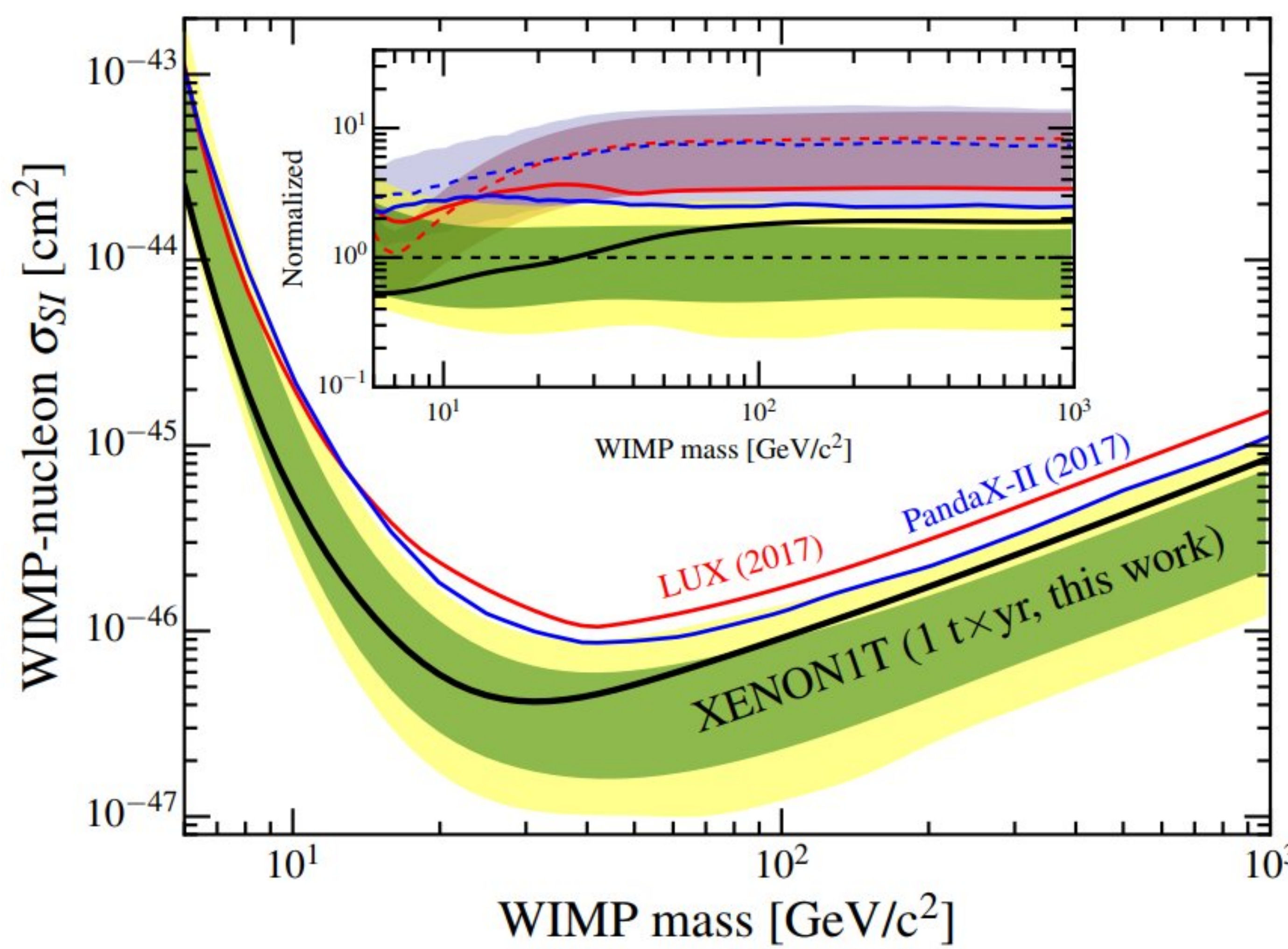
Kuhlen et al., *JCAP* **1002**, 030 (2010)

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: Indiret 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)?