Cosmology & Dark Matter

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Outline

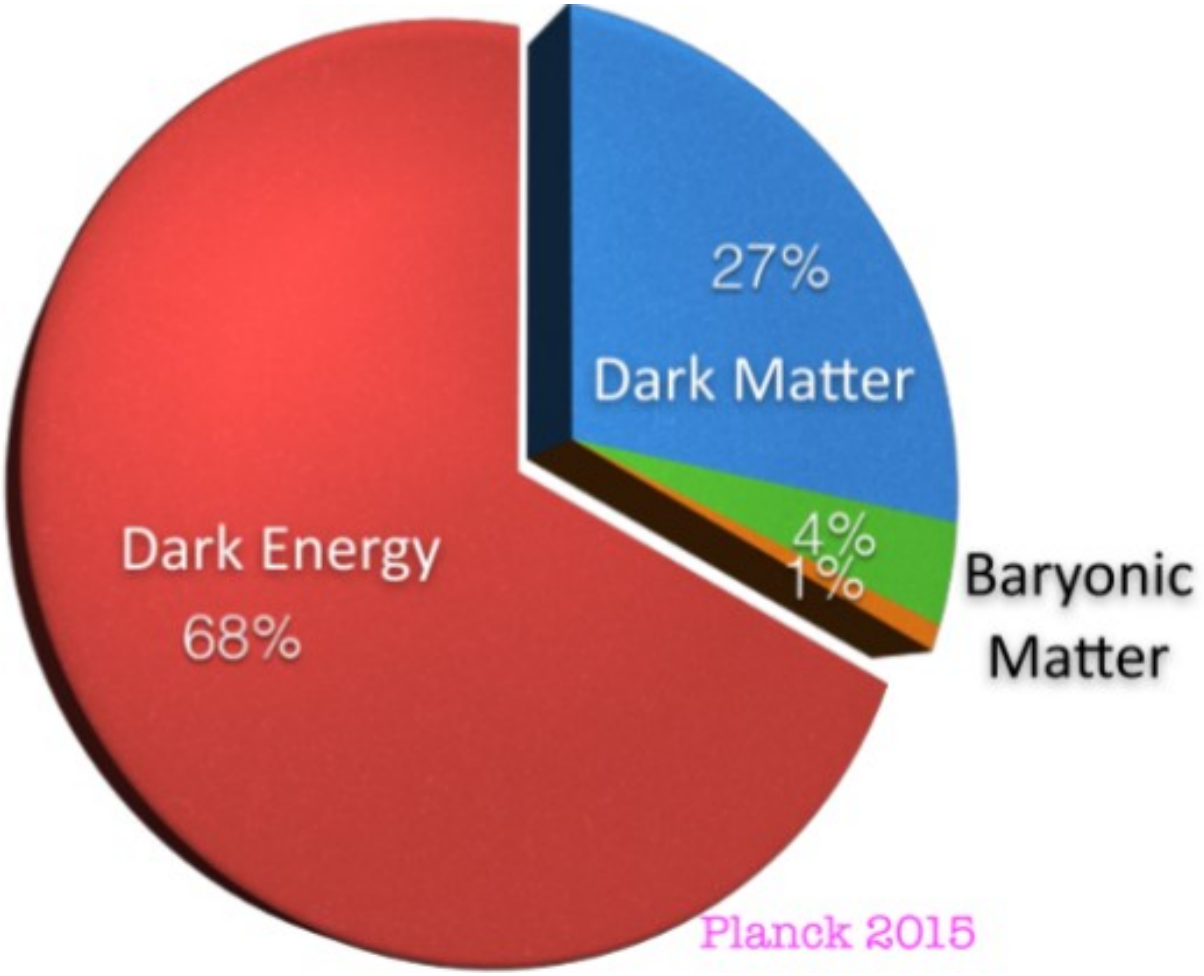
Lecture 3 – The non-linear Universe, dark matter and MOND

- Evidence for dark matter
- N-body simulations of CDM
- CDM problems and solutions
- Status of Modified Newtonian Dynamics (MOND)

Lecture 4 – Searches for particle dark matter

- Properties of dark matter & dark matter production
- Dark matter candidates & Searches
- Indirect searches for dark matter
  - Signal characteristics
  - Searches with cosmic rays
  - Searches with photons
  - Signal hints and challenges

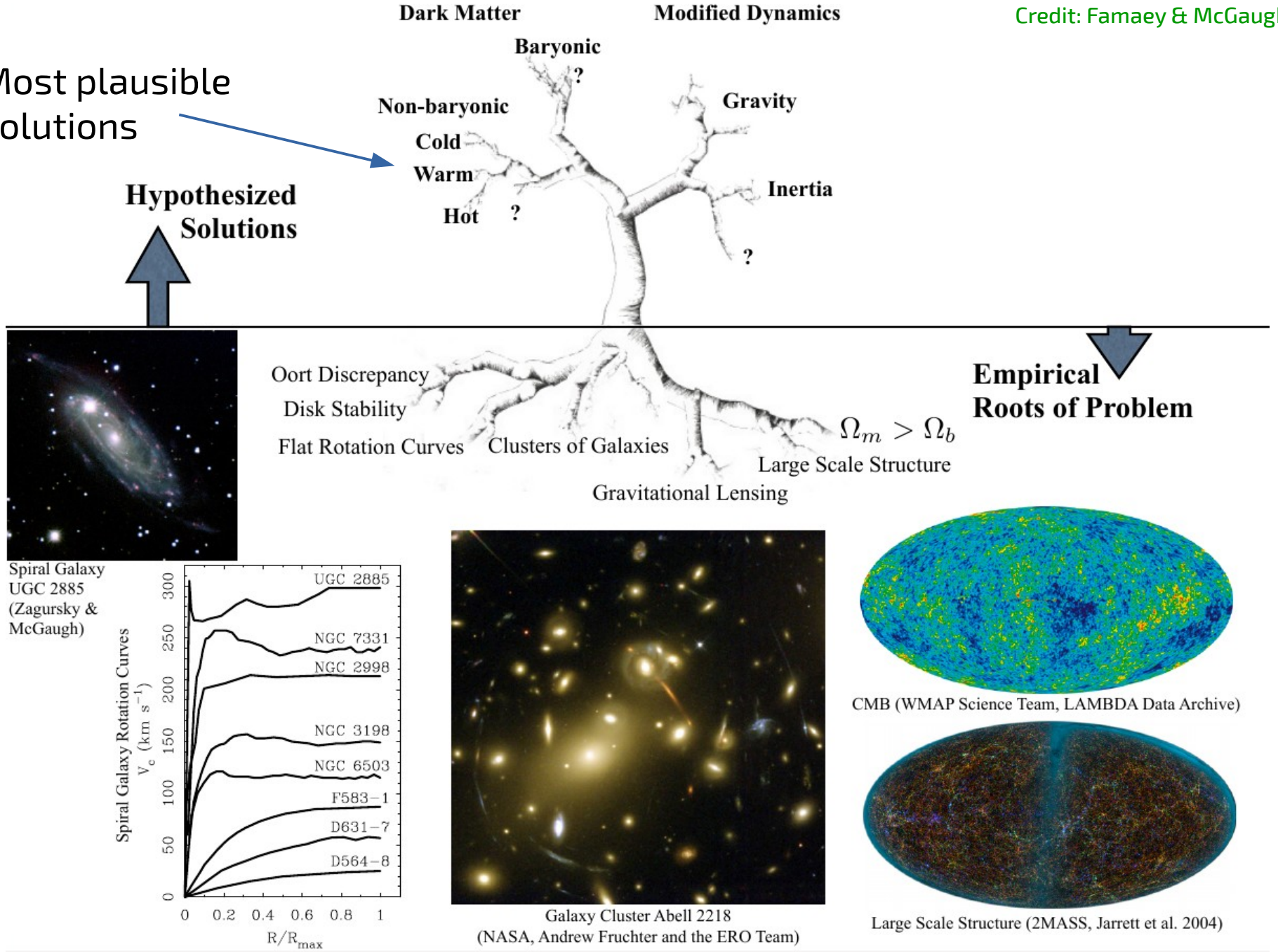
Our Universe



Evidence for dark matter in the Universe

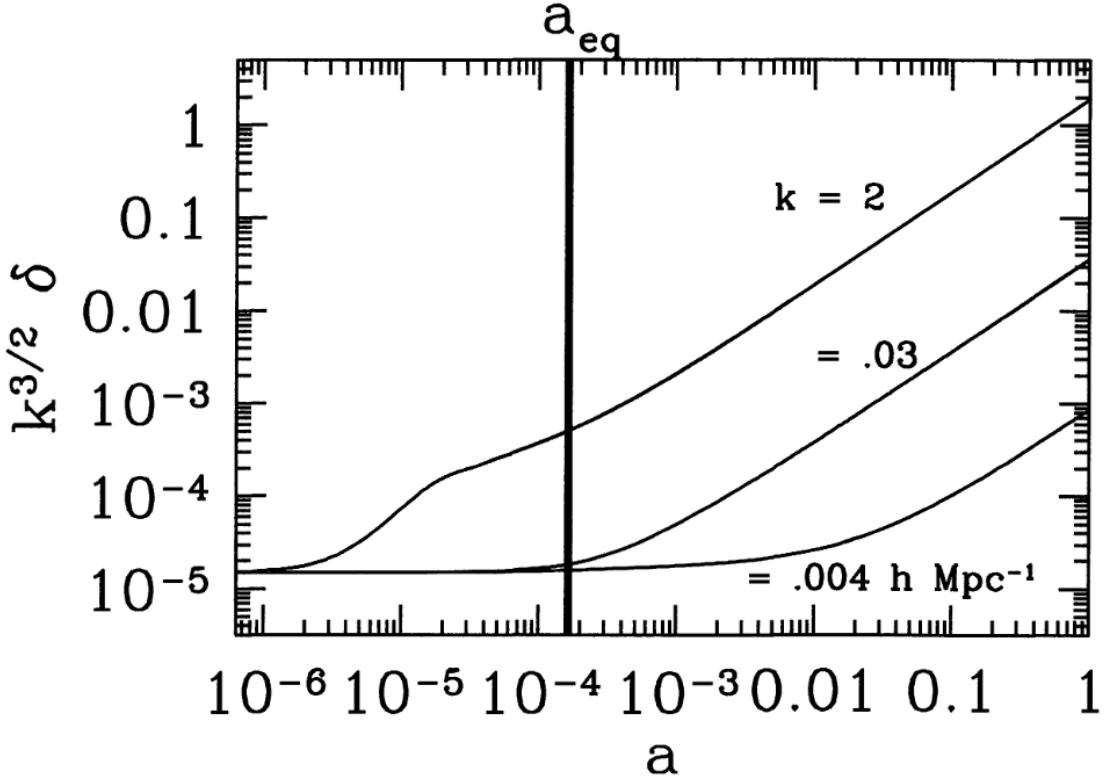
Credit: Famaey & McGaugh 2012

Most plausible solutions



Break down of linear structure formation

$$\rho = \frac{\delta\rho_m}{\bar{\rho}_m}$$



- Fluctuations at scales $R < 10\,h^{-1}\,\mathrm{Mpc}$ have gone non-linear

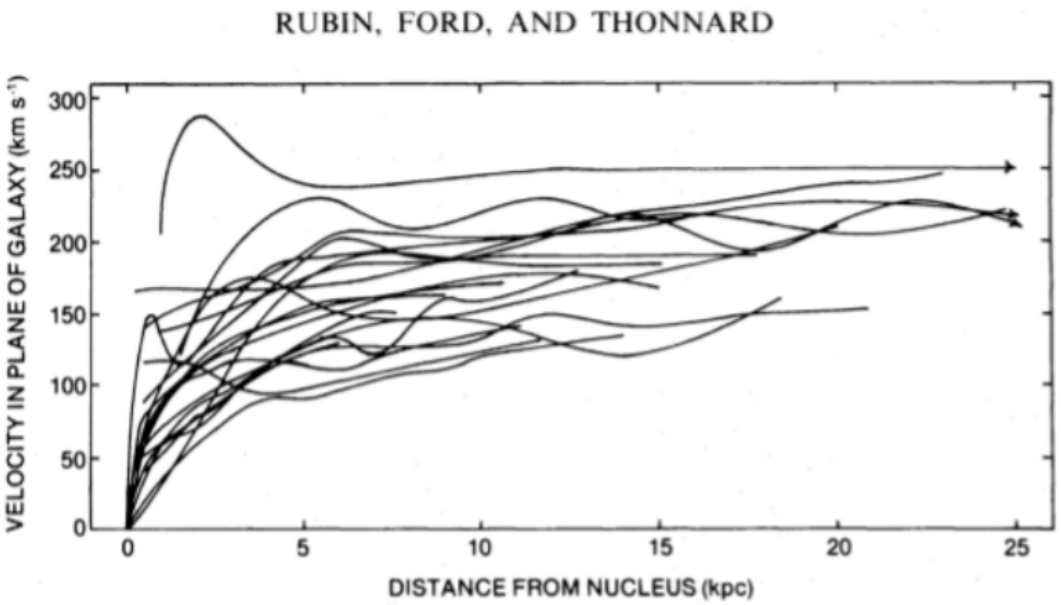
$$M = \rho_m \times V = \rho_m \times \frac{4\pi}{3} R^3$$

$$M \sim 10^{15} M_\odot \left(\frac{R}{10\,h^{-1}\,\mathrm{Mpc}} \right)^3$$

Mass of galaxy clusters

- Formed satellite galaxies, galaxy groups, galaxy clusters

Flat rotation curves



70/80': Observation of spiral galaxy rotation curves (rotationally supported systems)

V. C. Rubin and W. K. Ford, Jr., ApJ 159, 379 (1970);
V. C. Rubin, N.Thonnard and W. K. Ford, Jr., ApJ 238, 471 (1980)

Circular velocity of starts determined by enclosed mass

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

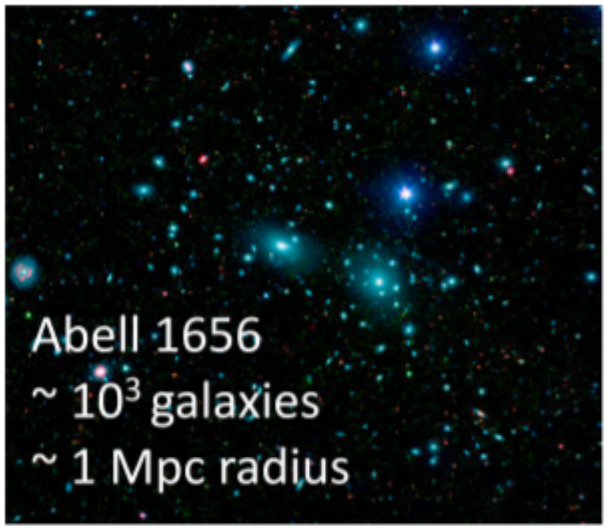
$$M(< R) \equiv 4\pi \int_0^R r^2 \rho(r) dr$$

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

Actually observed $v_c^2 \sim constant$

→ Extended mass profile $\rho(r) \propto \frac{1}{r^2}$

Kinematic of galaxies in galaxy clusters



Pioneering application of the **virial theorem** in astronomy

F. Zwicky, Helvetica Physica Acta (1933) 6, 110-127;
ApJ (1937) 86, 217

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

$$T = N\frac{m}{2}\langle v^2\rangle$$

$$\langle U_{\rm tot}\rangle \sim -\frac{3}{5}\frac{G_N M^2}{R}$$

gravitational potential of a self-gravitating homogeneous sphere of radius R

$$\longrightarrow \quad M \sim \mathcal{O}(1)\frac{R\langle v^2\rangle}{G_N} \sim 3 \times M_{\rm visible}$$

Credit: F. Calore

X-ray emission and gravitational lensing

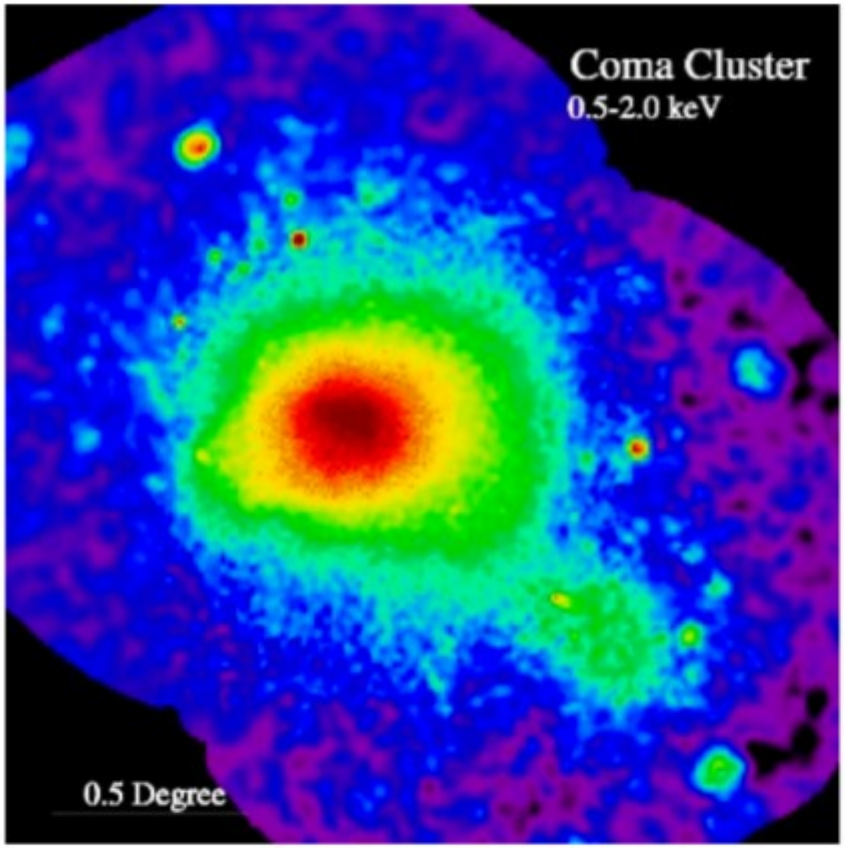


Figure 2. An x-ray image of the Coma cluster obtained with the ROSAT satellite, showing both the main cluster and the NGC4839 group to the south-west. (Credit: S L Snowden, High Energy Astrophysics Science Archive Research Center, NASA.)

Mass in clusters is in the form of hot, intergalactic gas, which can be traced via X rays: X-luminosity and spectrum constrain the mass profile

Lewis, Buote & Stocke, ApJ (2003), 586, 135

Strong gravitational lensing around galaxy cluster CL0024+17, demonstrating at least three layers projected onto a single 2D image.

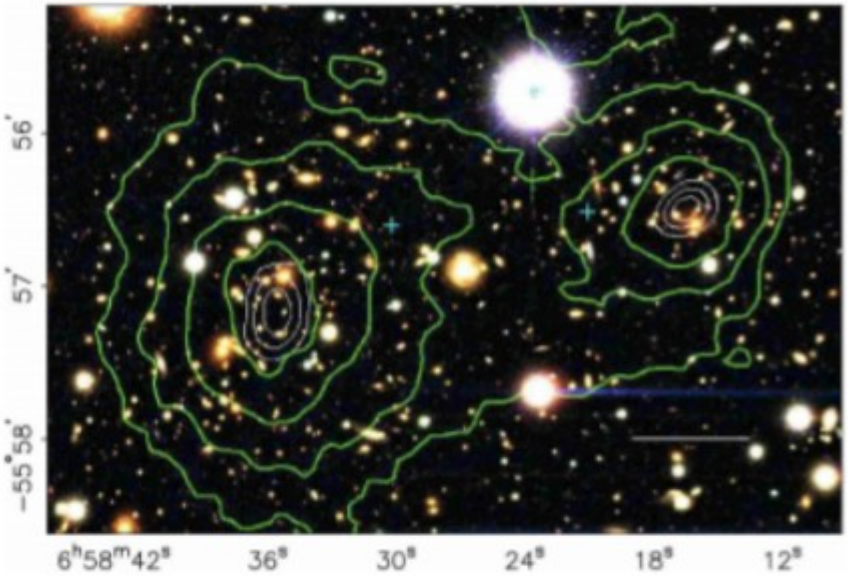
Massey, Kitching & Richard, Rept.Prog.Phys. 73 (2010)

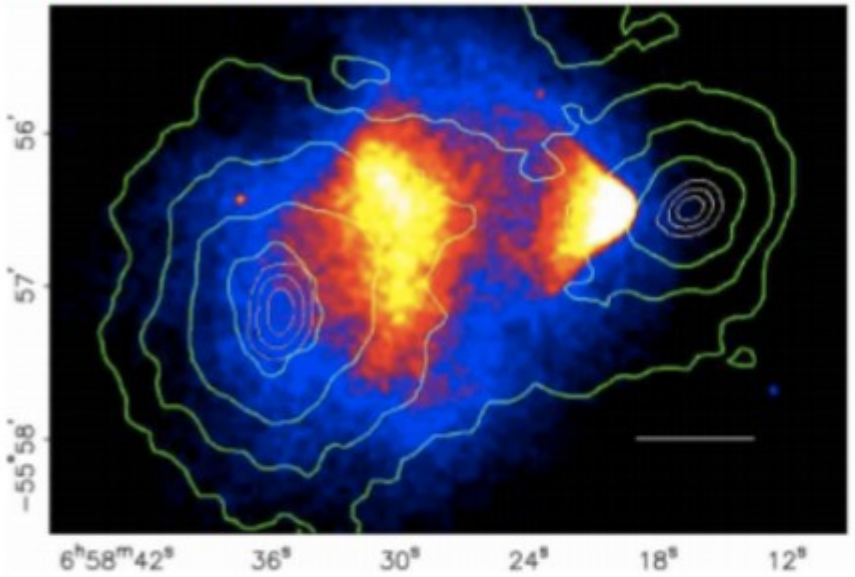
Credit: F. Calore

Mass segregation

Bullet Cluster (1E 0657-56)

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





James Jee+, ApJ 783 (2014) 78

Credit: F. Calore

Towards N-body simulations

Situation

- The Milky Way halo has of the order of 1e67 particles (assuming a DM mass of 1 GeV)
- They do not directly interact, but only via their combined gravitational potential
- We are interested in the **time-evolution of the distribution function** of of DM particles in the non-linear regime

$$f(\boldsymbol{x}, \boldsymbol{v}, t)$$

- The dynamics is described by the **Poisson-Vlasov** equation:

$$\nabla^2 \Phi(\boldsymbol{x}, t) = 4\pi G \int d^3v \, f(\boldsymbol{x}, \boldsymbol{y}, t)$$

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}}\mathbf{v} + \frac{\partial f}{\partial \mathbf{v}}\left(-\frac{\partial \Phi}{\partial \mathbf{x}}\right) = 0$$

Monte Carlo Approach

Why Monte Carlo

- Discretization of distribution function in 6-dim phase space is computationally way too extensive (need to resolve a very large range of scales)
- Solution: Instead, sample “test particles” from distribution function, and track their motion

Equation of motion for individual particle

$$\ddot{\boldsymbol{x}}_{\boldsymbol{i}} = -\nabla_i \Phi(\boldsymbol{x}_i)$$

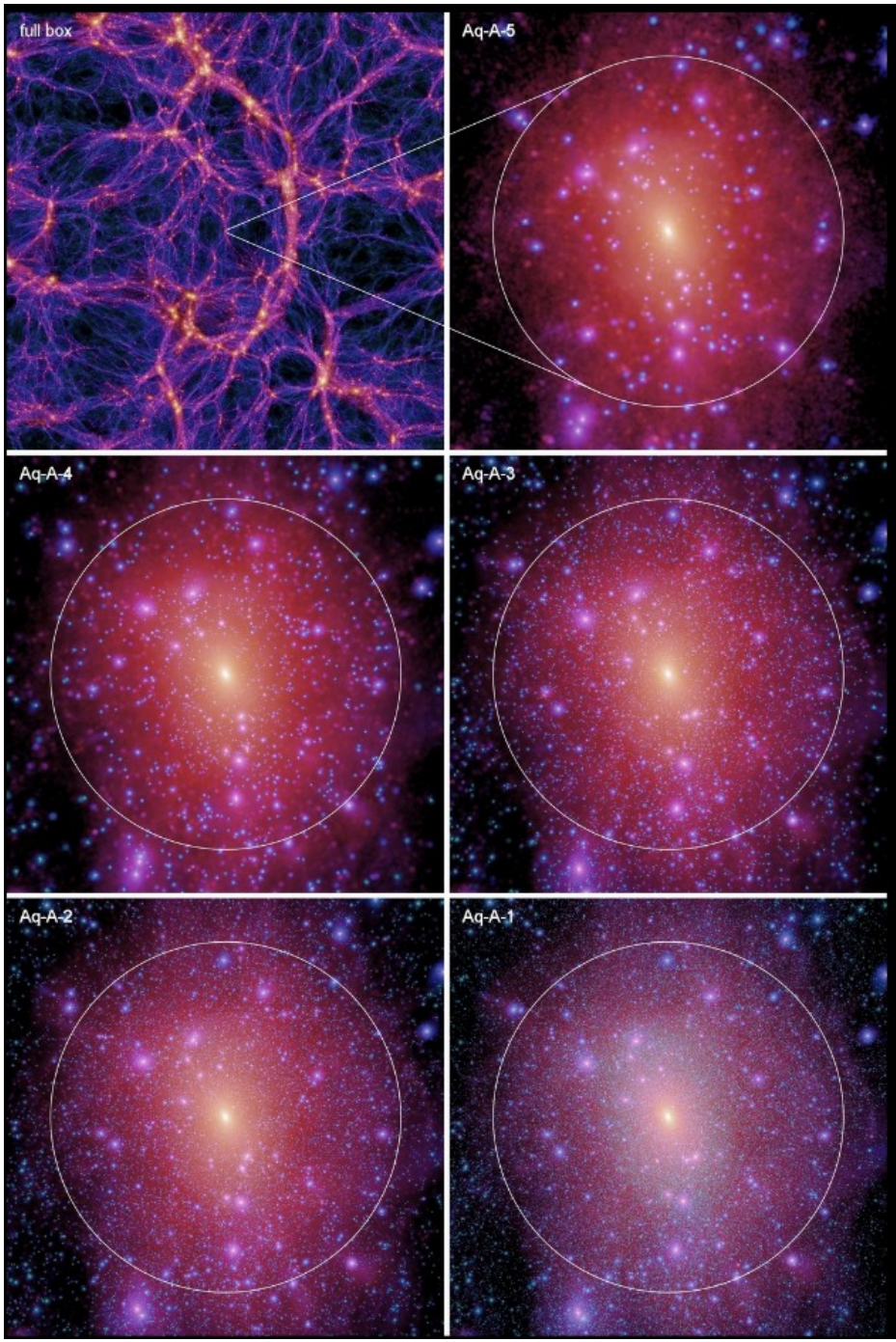
Gravitational potential generated by test particles

$$\Phi(\boldsymbol{x}) = -G \sum_{i=1}^{N} \frac{m_j}{[(\boldsymbol{x} - \boldsymbol{x}_i)^2 + \epsilon^2]^{1/2}}$$

Notes

- Mass of “test particles” usually exceeds solar mass
- Softening required to remove individual particle collisions
- Up to recently, most simulations where “dark matter only”, i.e. the effects of baryons is not included

Aquarius MW halo simulations

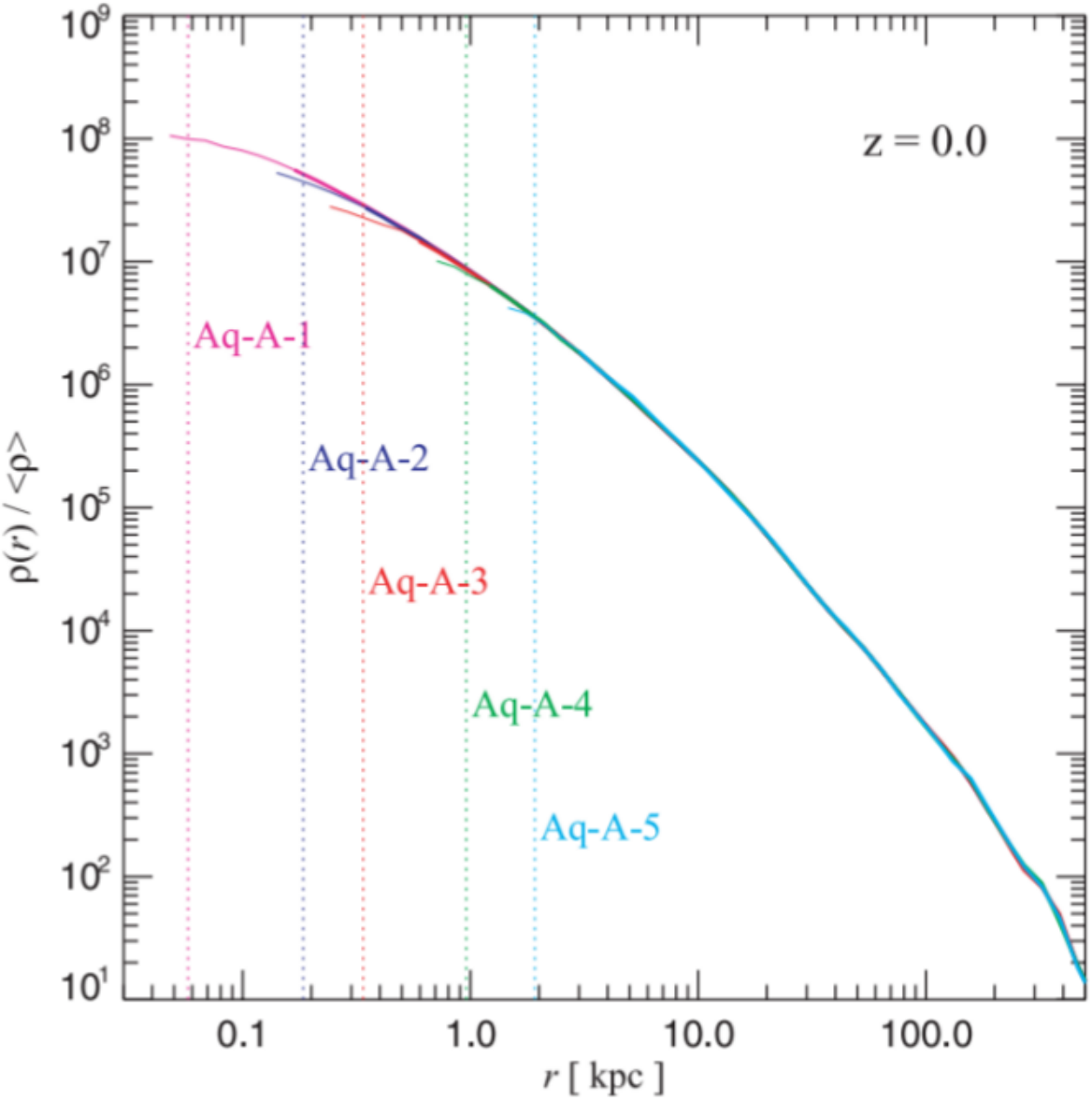


zoom-in simulations of an individual Milky Way-like DM halo: different resolution levels

Springel+ 2008

Credit: M. Vogelsberger

Radial profile of relaxed DM halos

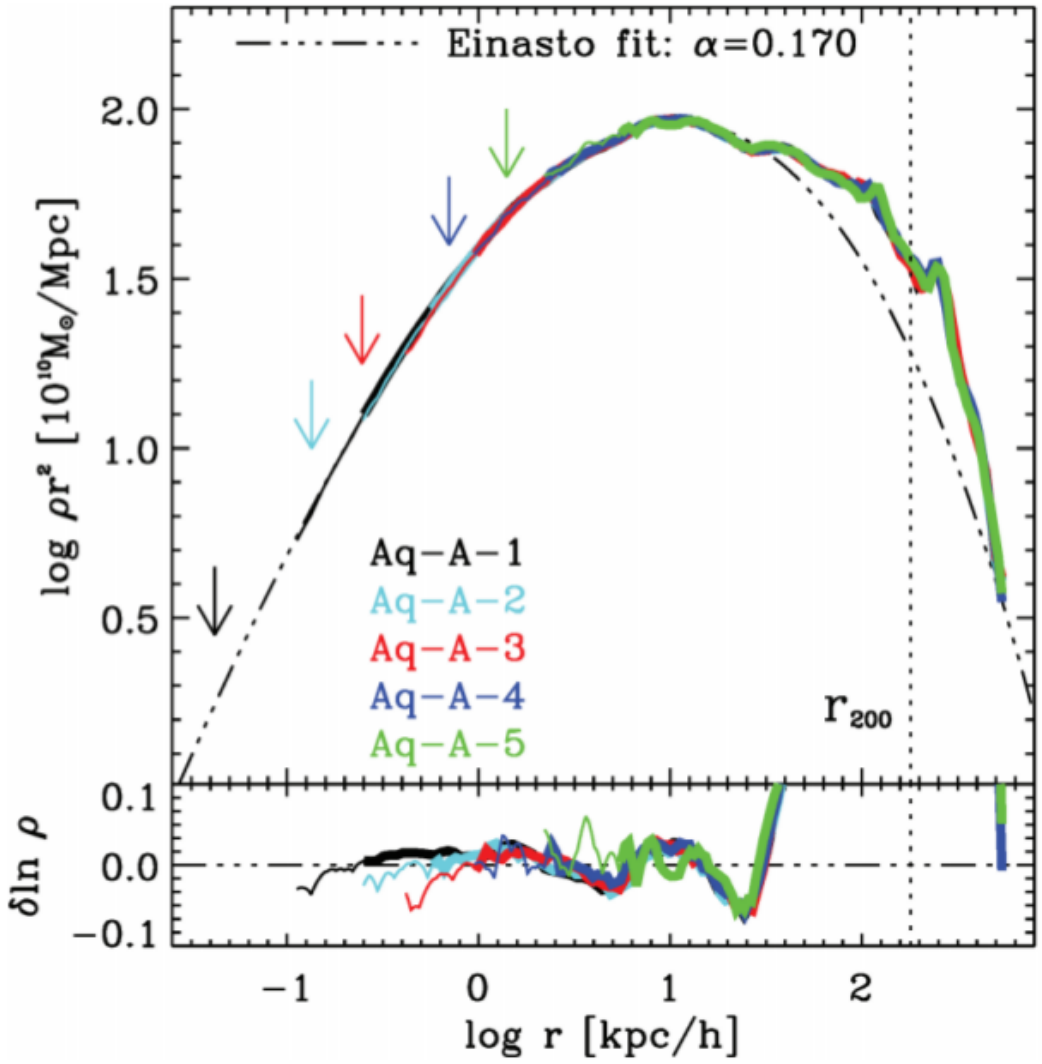


DM halos have a nearly universal spherically averaged density profile: -1 to -3 logarithmic slope

very well converged

Credit: M. Vogelsberger

Fitting functions to DM profile



NFW:

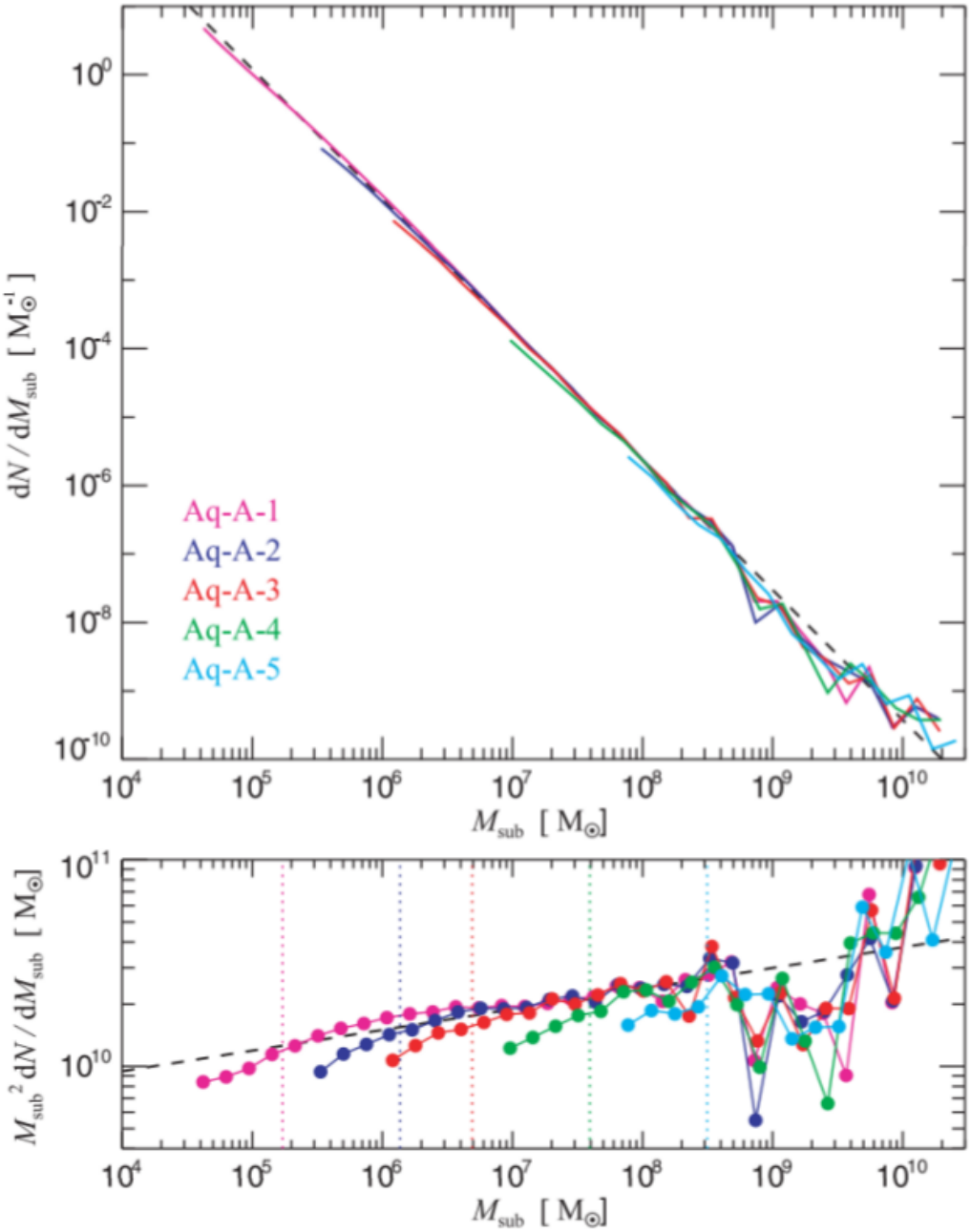
$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

Einasto:

$$\ln[\rho(r)/\rho_{-2}] = (-2/\alpha)[(r/r_{-2})^{\alpha} - 1]$$

Credit: M. Vogelsberger

Subhalo distribution function



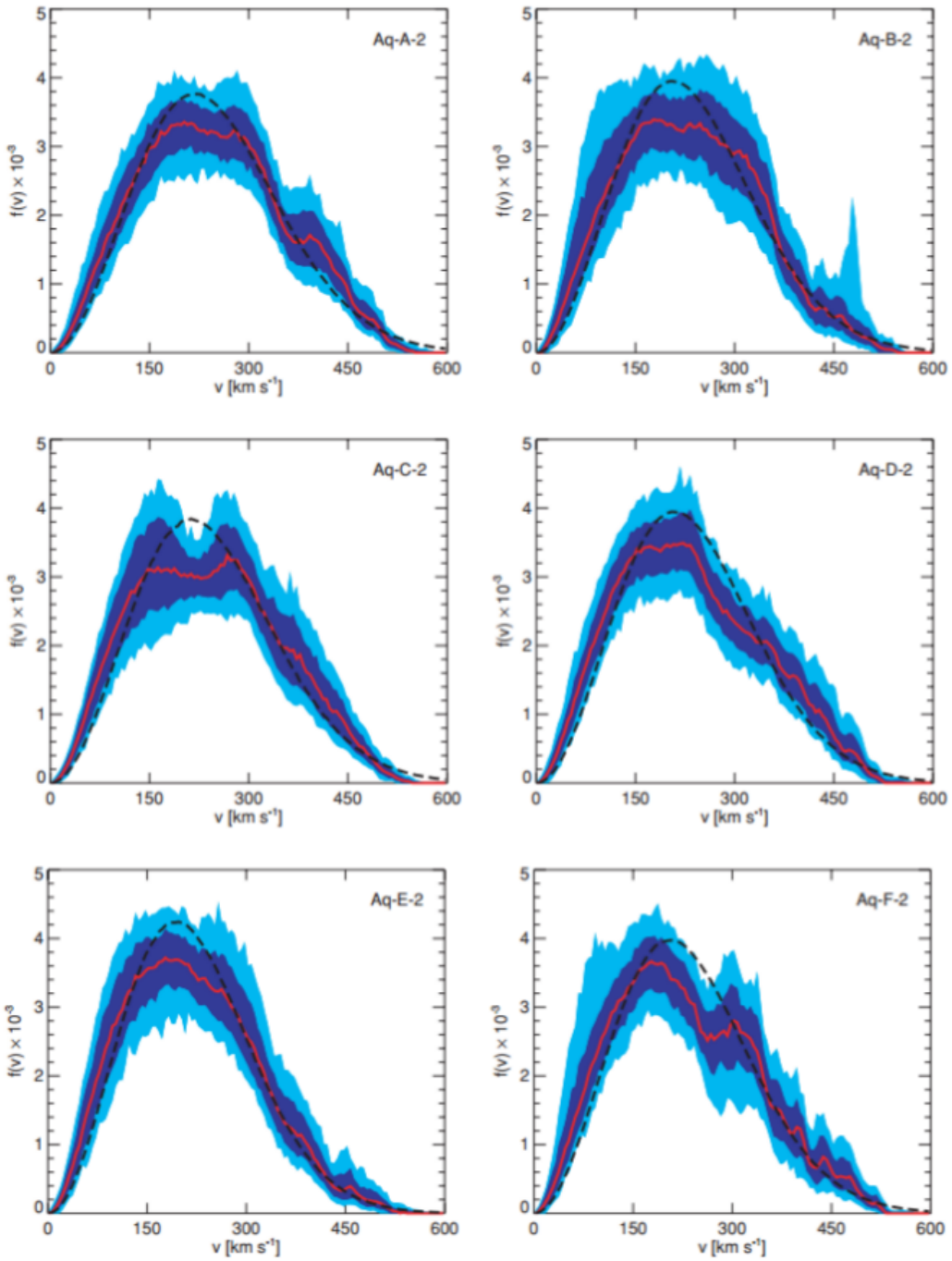
subhalo mass function has a slope close to -2; slightly shallower; extrapolate → annihilation boost

$$\frac{dN}{dM_{\rm sub}} \propto M_{\rm sub}^{-2+\epsilon}$$

Springel+ 2008

Credit: M. Vogelsberger

Velocity distribution of DM



sample of six different halos: all have individually different local DM velocity distributions

DM 'Astronomy'?

This is often approximated by a truncated Maxwellian

$$f(v) \propto v^2 e^{-\frac{3}{2}\frac{v^2}{v_{\rm rms}^2}} \Theta(v - v_{\rm esc})$$

("Standard halo model")

For the Milky Way

$$v_{\rm rms} \sim 270 \frac{\rm km}{\rm s} \qquad v_{\rm esc} \sim 540 \frac{\rm km}{\rm s}$$

Vogelsberger+ 2009

Modified Newtonian Dynamics (MOND)?

See: Famaey & McGaugh 2012

M. Milgrom (1983)

Idea

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

$$F_N = ma \to F = m\frac{a^2}{a_0} \qquad a_0 \simeq 10^{-8}\,\mathrm{cm/s^2} \sim \mathrm{H}_0$$
$$a < a_0$$

- Gravity part unchanged

$$F_{\mathrm{gravity}} = \frac{GMm}{r^2}$$

- This can also account for flat rotation curves

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

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

- 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.
- However, TeVeS (tensor vector scalar; J. Bekenstein, 2004) MOND generalization exists, which contains additional dynamical field. **It remains hard to reproduce all observations as cold DM does.**

Main argument *for* MOND

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

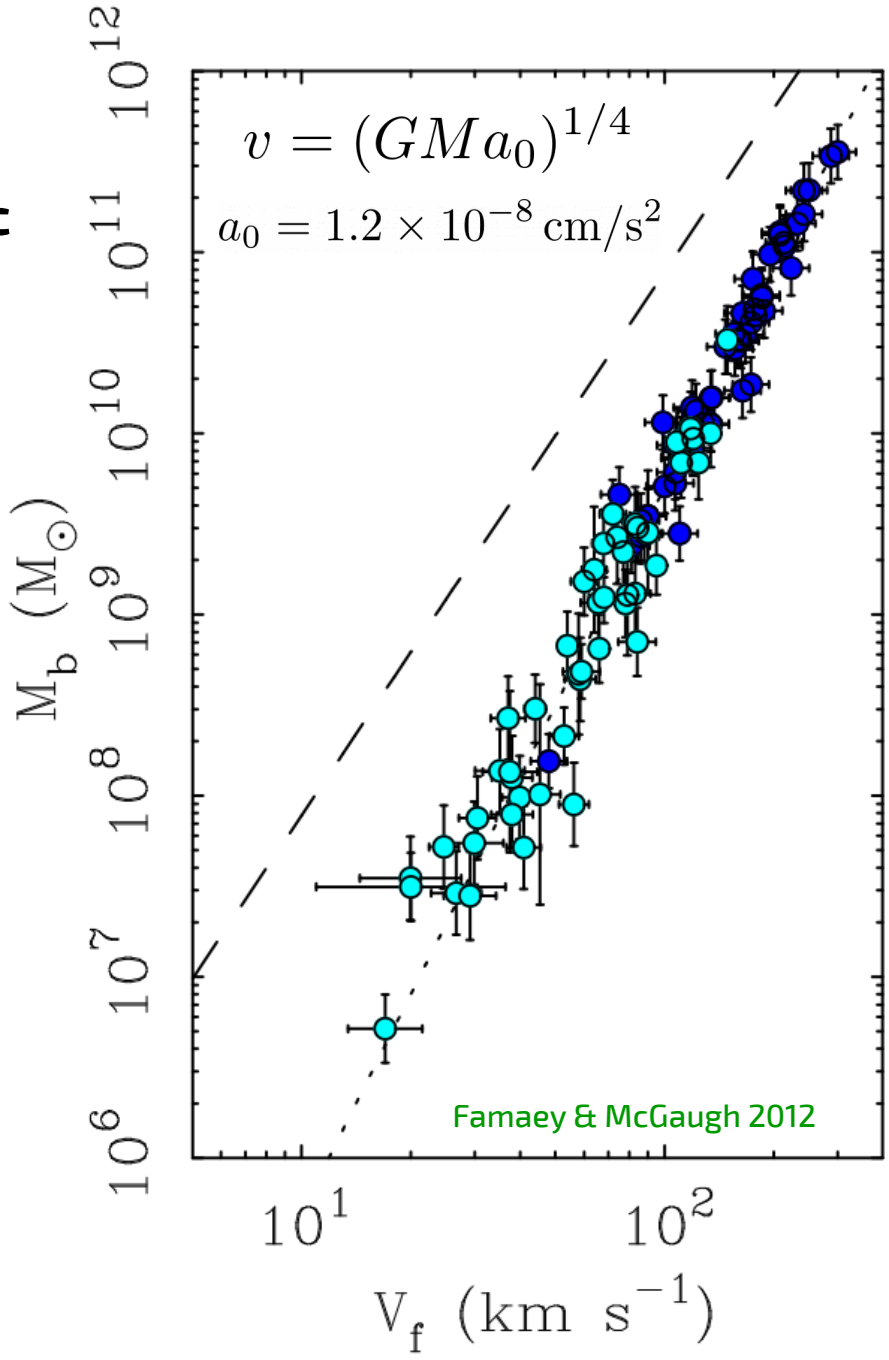
MOND correctly accounts for

- normalization and
- slope

of the correlation over four orders of magnitude in Galaxy mass.

CDM predicts the dashed line, *assuming that all baryons associated with a DM halo are observed.*

Many question: Can **baryonic feedback** during galaxy formation generate such a correlation?



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	no*
Spiral galaxy rotation curves	yes	yes
Tully-Fisher	maybe**	yes
Faber-Jackson	maybe**	yes
Simultaneous explanation of DM in dwarf galaxies and clusters	yes	maybe

*could work in more complete theories of MOND that introduce new fields that “act like DM” for cosmological purposes, or by adding *some* DM

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

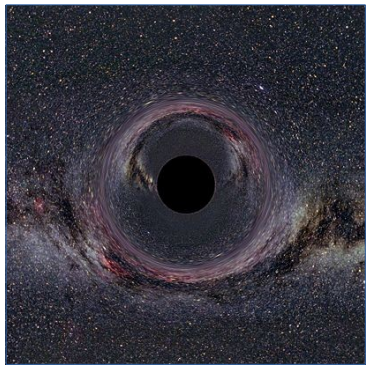
What we know about dark matter

About 80 years after the first discovery of dark matter by Fritz Zwicky and others, we can now bracket its particle mass to within 80 orders of magnitude.

Uncertainty principle
(if DM is bosonic)

Hu+ 2000

MACHO searches
(massive compact
halo objects)

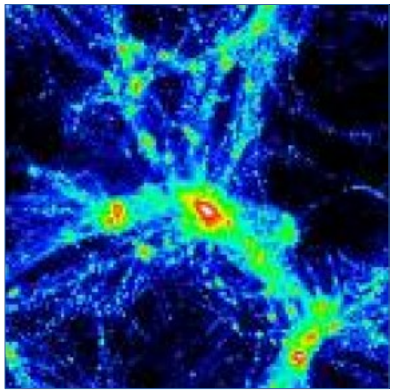


Tisserand+ 2007

$$10^{-22}\mathrm{eV} \lesssim m_{\mathrm{DM}} \lesssim 10^{50}\mathrm{GeV}$$

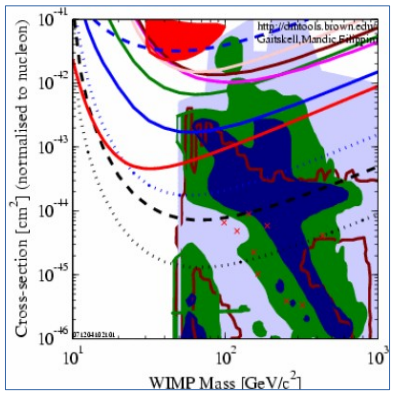
Up to now, there are only various upper and lower limits:

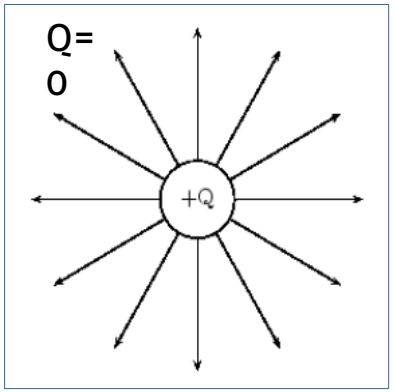
cold:
negligible velocity dispersion

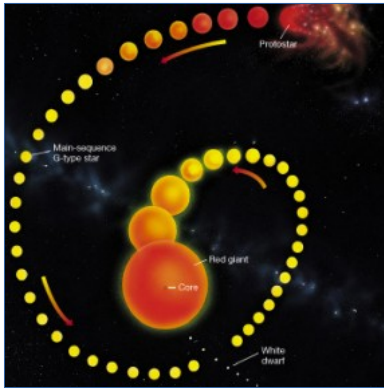


collisionless:
negligible self-interaction

weakly coupled:
negligible interaction with the rest of the world





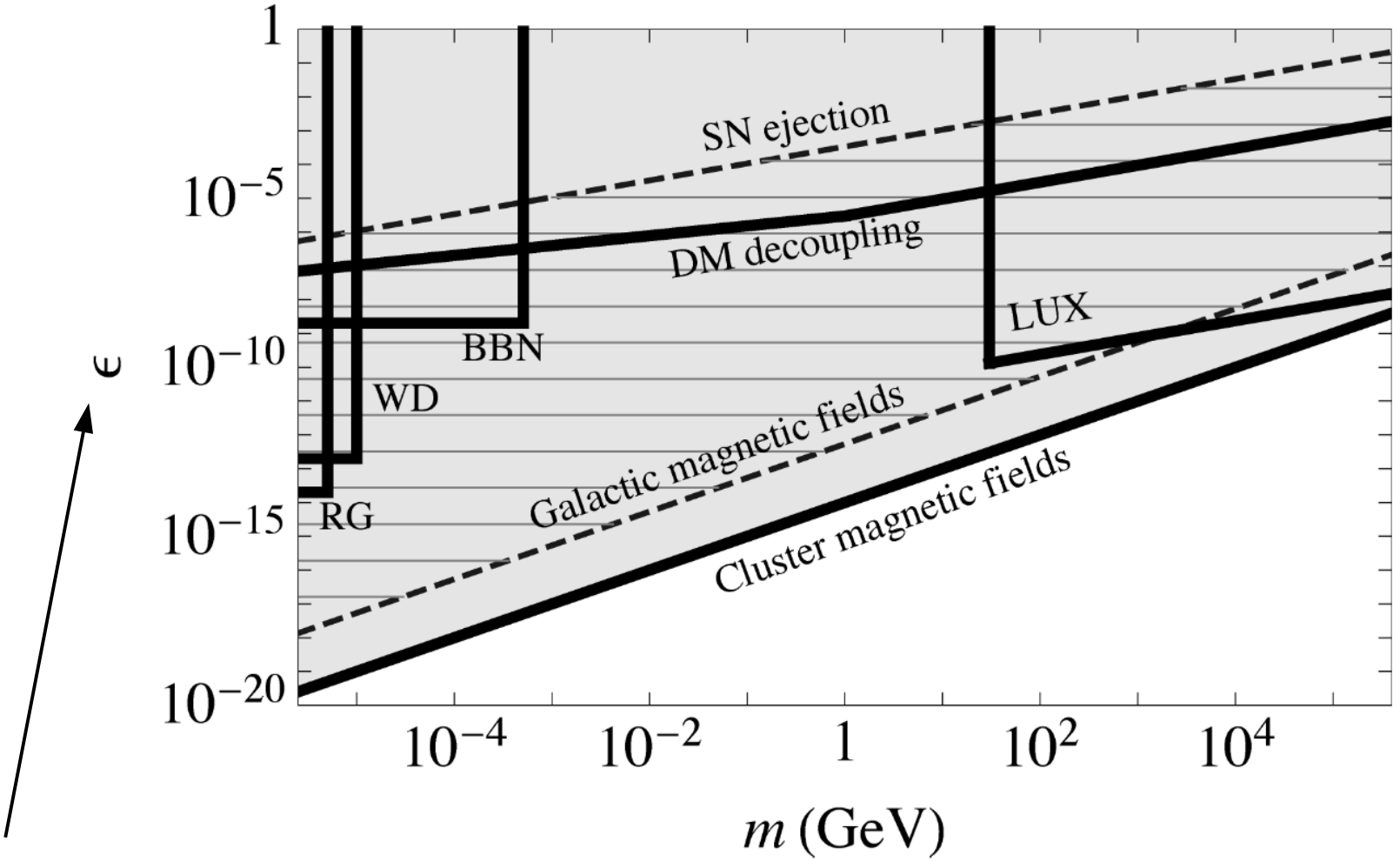


What we know about dark matter

1. Has gravitational interactions and is (meta-)stable.
2. DM seems to be dark, i.e. is not observed to interact with light.
3. DM must be nearly dissipationless
4. DM cannot have large self-interaction (though existing limits are very weak).
5. The DM mass is only constrained to within some ~80 orders of magnitude.
6. DM must be cold or (luke-)warm
7. Particle DM candidates require physics beyond the Standard Model.

Dark matter is really “dark”

Strong constraints on a “milli-charge” of dark matter particles.



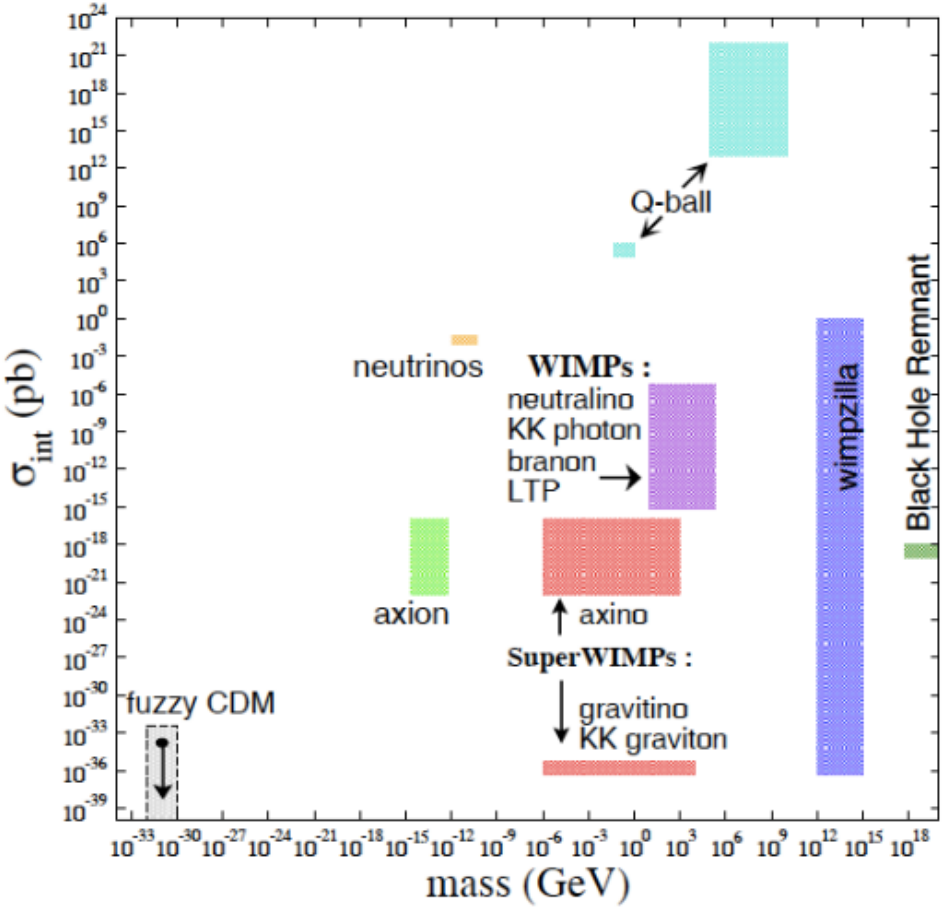
Electric charge of DM compared to electron charge

Kadota+ 2016

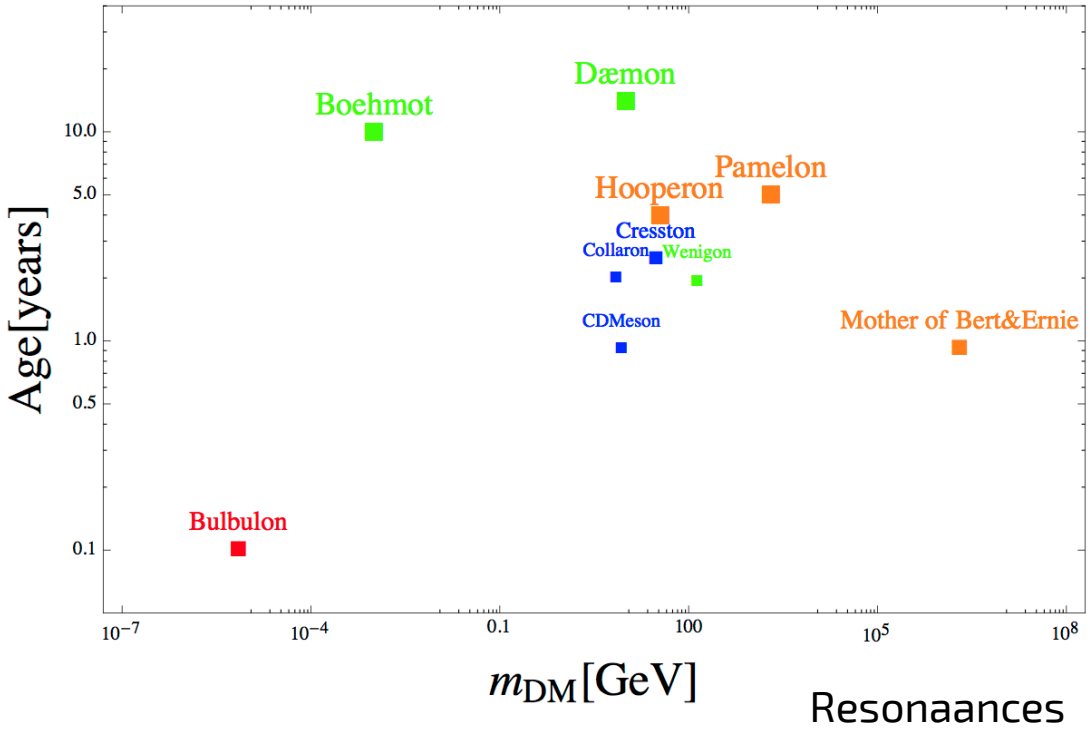
Candidates for particle dark matter

Mass-scales and interactions are suggested by

- Theoretical arguments → Various incarnations of **WIMPs, Sterile neutrinos, Axions, ...**
- Hints in the data → **positron excess, 511 keV line, Fermi GeV excess, PeV neutrinos, ...**



E-K Park 2007



Resonaances

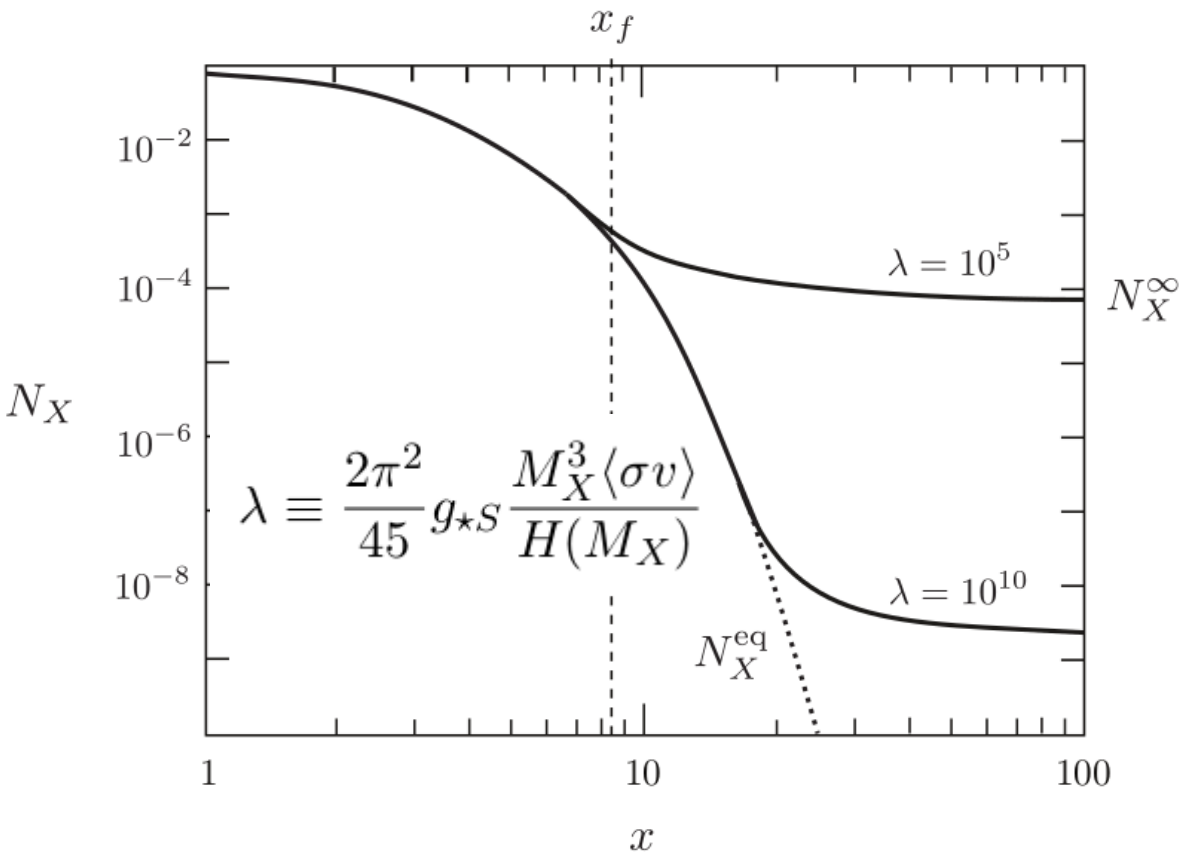
Dark matter relics

Boltzmann equation for particles in comoving volume

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

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

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



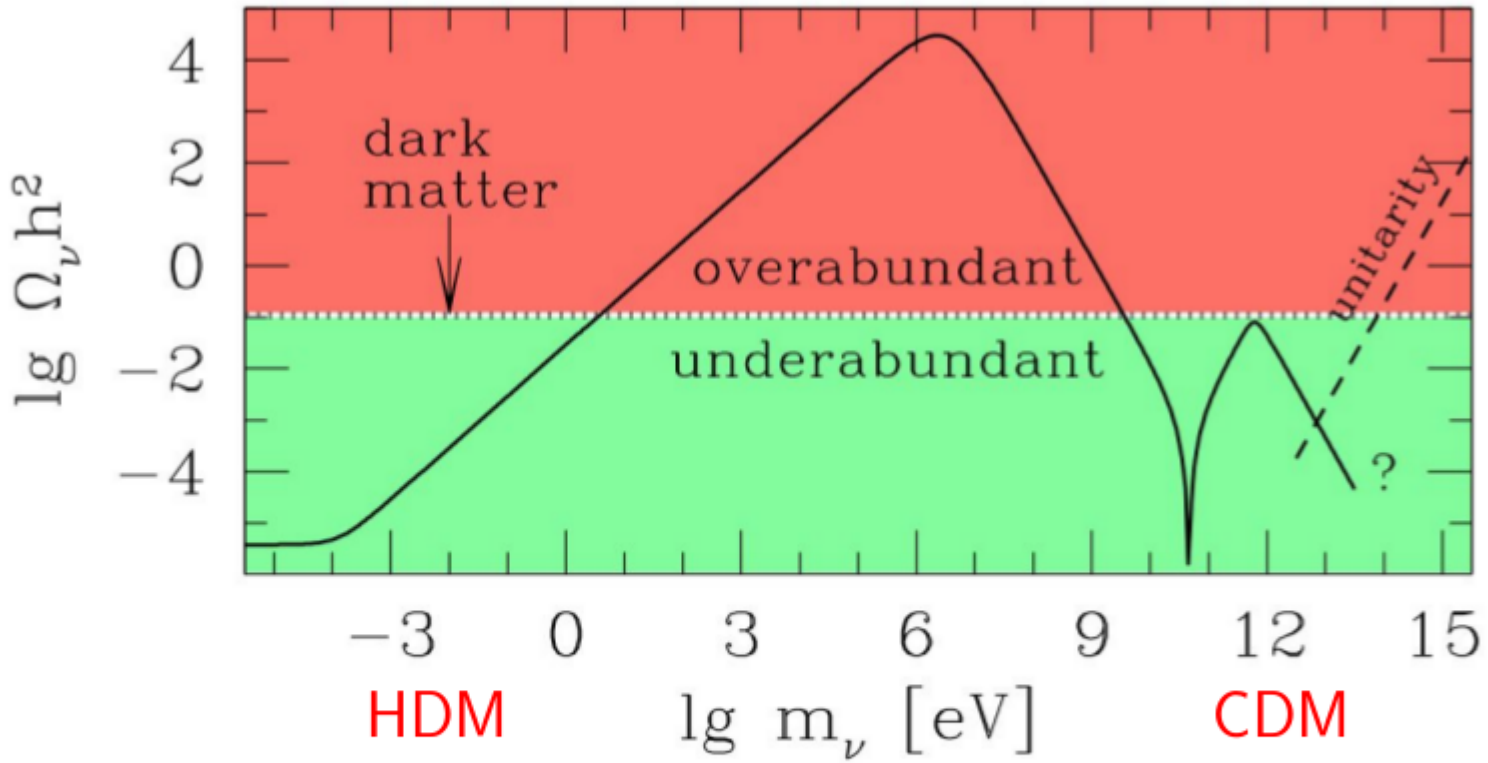
Relic density today

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

"WIMP miracle"

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

Lee & Weinberg (1977) bound



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 $\Omega_\chi h^2 \simeq (m_\chi/TeV)^2$

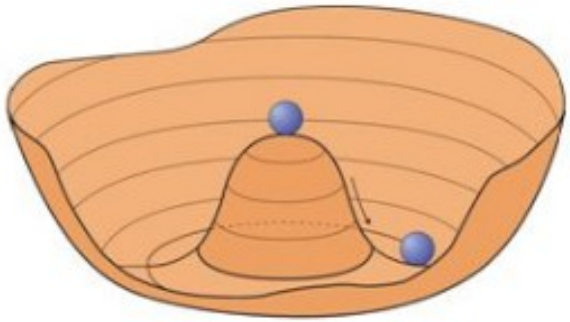
For 4th. gen. active neutrinos, $m < m_Z/2$ forbidden by LEP-but similar for other models

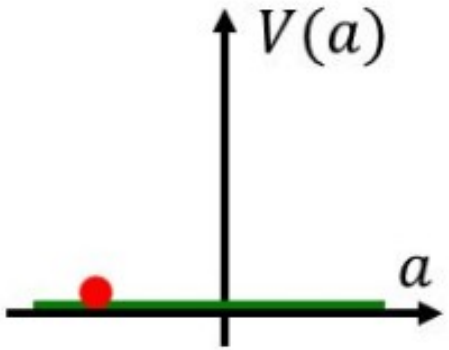
Credit: G. Gelmini

Completely different: Misalignment mechanism

$T \sim f_a$ (very early universe)

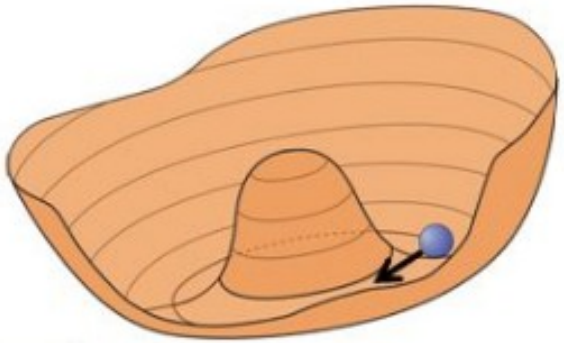
- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"
- Axion field sits fixed at $a_i = \Theta_i f_a$

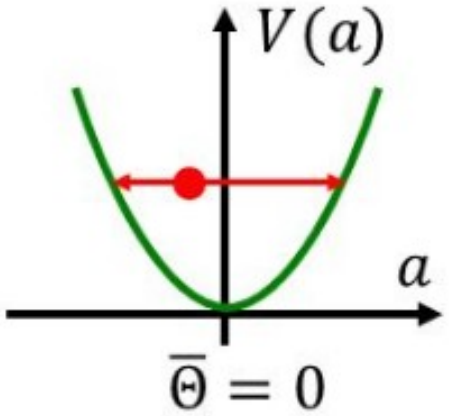




$T \sim 1$ GeV $(H \sim 10^{-9}$ eV)

- Axion mass turns on quickly by thermal instanton gas
- Field starts oscillating when $m_a \gtrsim 3H$
- Classical field oscillations (axions at rest)



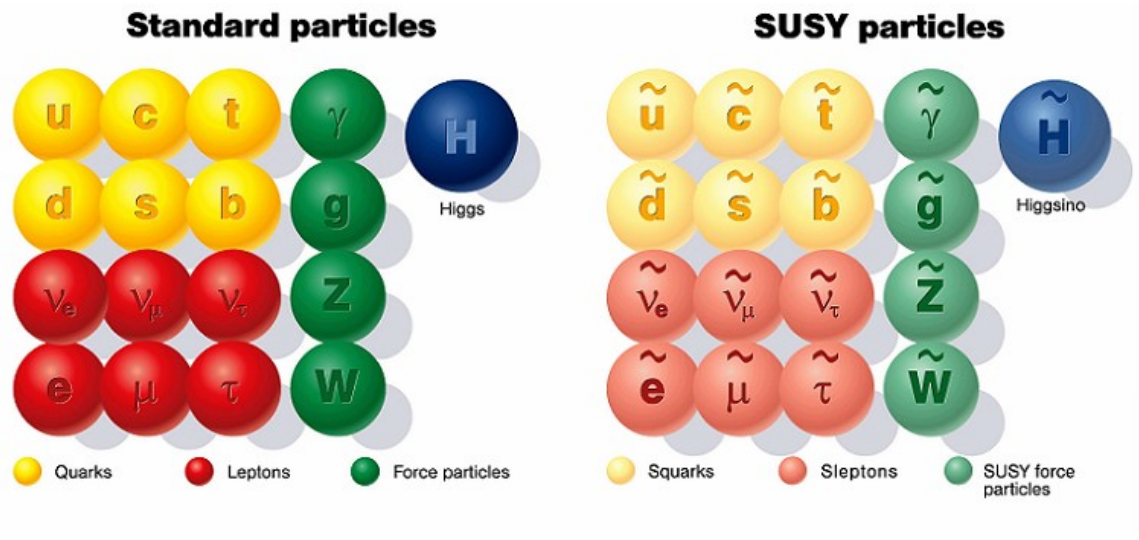


Axions are born as nonrelativistic, classical field oscillations
Very small mass, yet cold dark matter

Credit: G. Raffelt

~1972

Development of super-symmetry algebra



P. Ramond, Phys. Rev. D **3**, 2415 (1971); A. Neveu and J.H. Schwarz, Nucl. Phys. B **31**, 86 (1971); J.L. Gervais and B. Sakita, Nucl. Phys. B **34**, 632 (1971).

Yu. A. Gol'fand and E. P. Likhtman, JETP Lett. **13**, 323 (1971).

J. Wess and B. Zumino, Nucl. Phys. B **70** (1974) 39.

D.V. Volkov and V.P. Akulov, Phys. Lett. B **46**, 109 (1973).

Election of Richard Nixon

Neutralino abundance

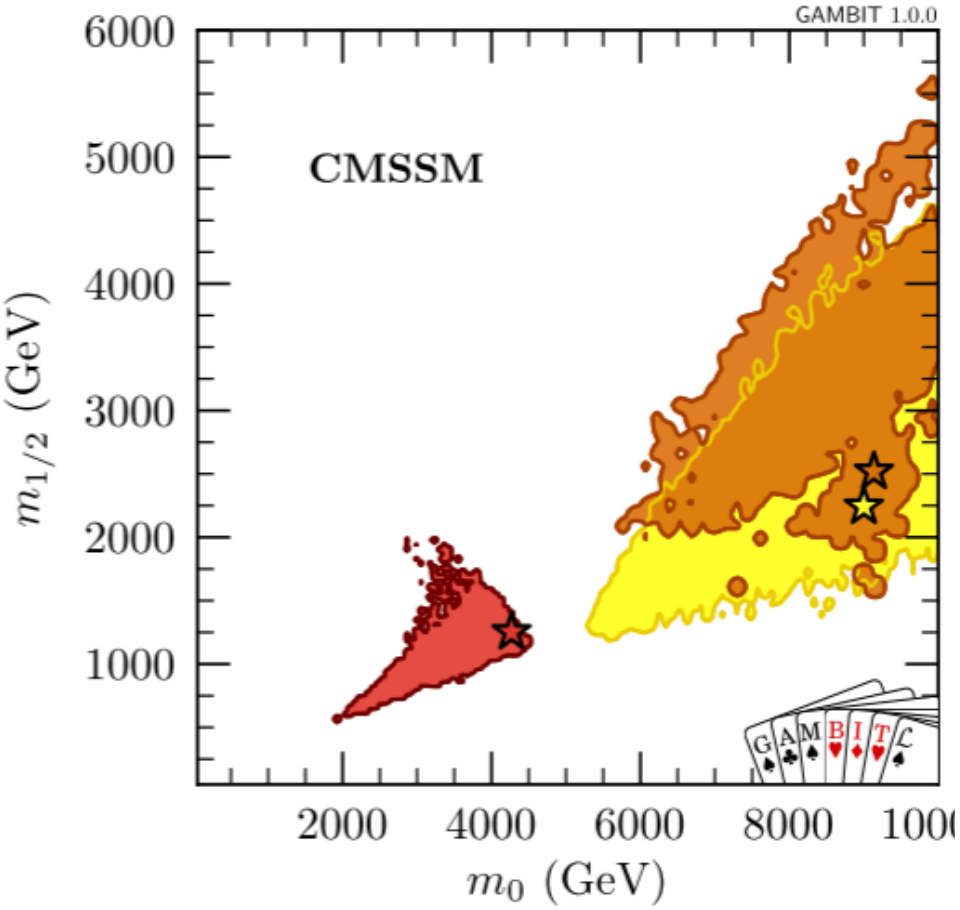
Neutralino LSP relic abundance

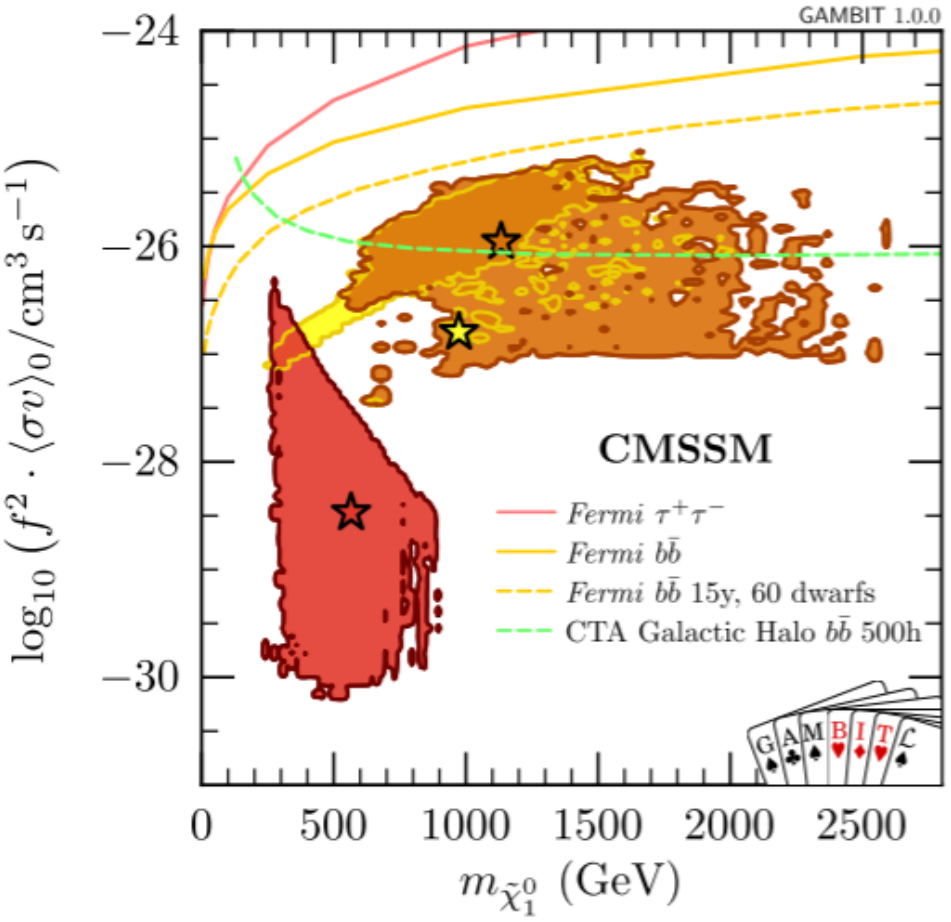
- LSP= $\widetilde{B}$ (typical in CMSSM) is OVERDENSE
  (σ_{annih} into $f\bar{f}$ through $\widetilde{f}$ exchange is helicity suppressed $\sim m_f$)

- LSP= $\widetilde{H}$ and $\widetilde{W}$ (not GU, AMSB) is UNDERDENSE
  unless $m \simeq TeV$ (large σ_{annih} into W^+W^-, ZZ, or $f\bar{f}$)

- RIGHT ABUNDANCE requires a special condition
  – Mixed composition (in CMSSM:"focus point"),
  – pole enhancement of σ_a ($m_\chi \simeq m_A/2$: "A-funnel region"- CP-odd Higgs A)
  –"coannihilation" between the LSP and the NLSP (Next to LSP- stop or other squarks)

Self-annihilation cross-section in CMSSM



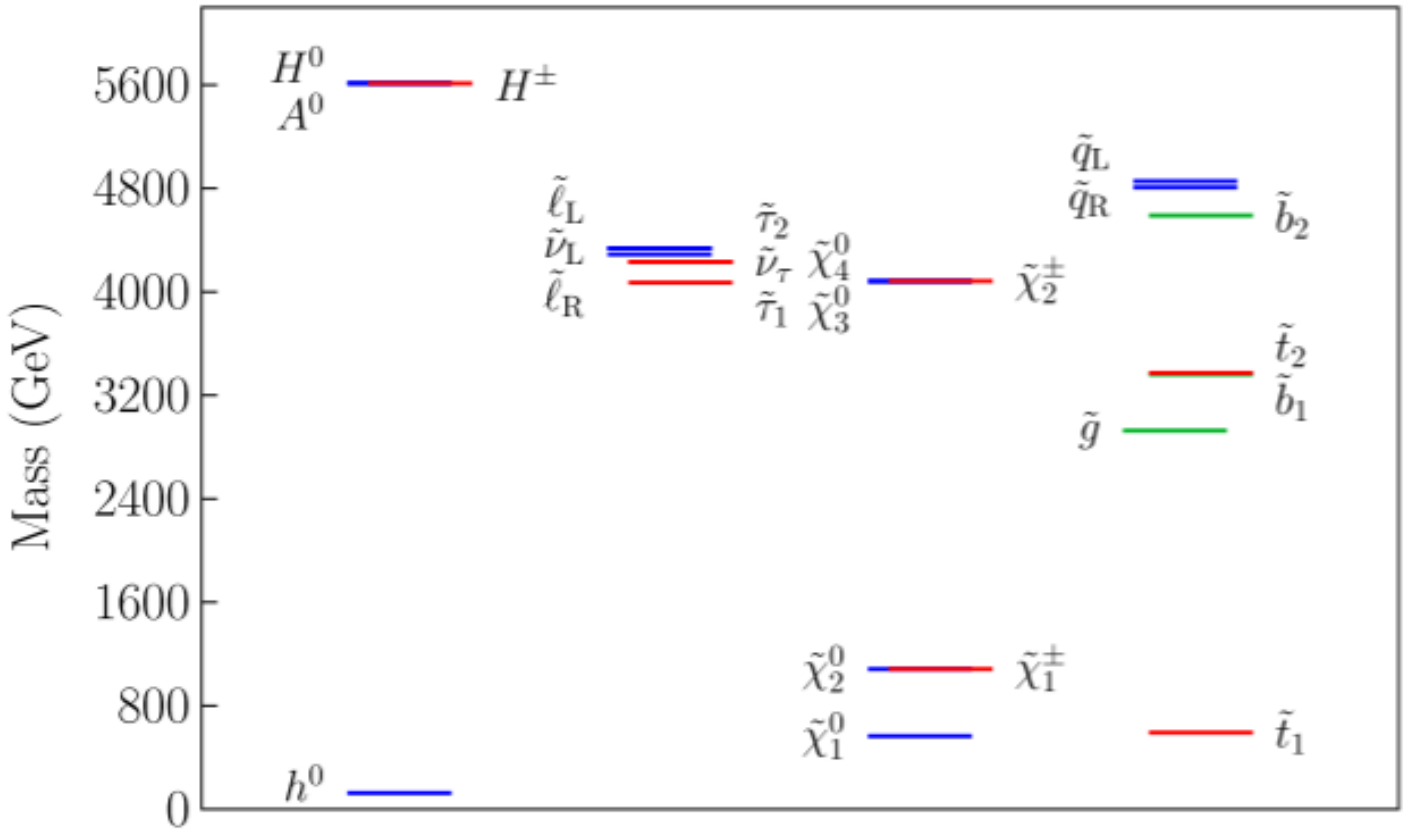


$\tilde{t}_1$ co-annihilation

A/H funnel

$\tilde{\chi}_1^{\pm}$ co-annihilation

Particle spectrum of best-fit point



Best-fit point of stop coannihilation region of the CMSSM