Dark Matter
Lecture 1: Evidence and candidates

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Dark matter lectures

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Content: first lecture

- **Overview: cosmological parameters in the standard model of cosmology**
- **Dark matter in galaxies and in the Milky Way**

  structure of the Milky Way

  galactic rotation curve and what can we learn from it

  dark matter distribution

  simulations of the Milky Way's dark halo

  - spatial distribution of dark matter
  - velocity distribution of dark matter
  - the dark matter disk

- **Candidates for dark matter, overview**

  neutrinos

  WIMPs and freeze-out

  candidates from supersymmetry

  - allowed parameter space in a constrained SUSY model

Content: second lecture

- **Direct detection of WIMPs: principles**

  expected rates in a terrestrial detector

  kinematics of elastic WIMP-nucleus scattering

  differential rates

  corrections I: movement of the Earth

  corrections II: form factors

  cross sections for scattering on nucleons

  - spin independent

  - spin dependent

- **Expected WIMP signal and backgrounds**

  time and directional signal dependance

  quenching factors and background discrimination

  background sources in direct detection experiments

  detector strategies: overview

Content: third lecture

- **Overview of experimental techniques**

    example: theoretical predictions and experimental limits

    vanilla exclusion plot

    WIMP mass and cross section determination

    complementarity between different targets and astrophysical uncertainties

- **Cryogenic experiments at mK temperatures**

    Principles of phonon mediated detectors

    Detection of fast and thermalized phonons

    Temperature measurements: thermistors, SC transition sensors (SPT, TES)

- **Phonon and light detectors**

    Example: CRESST

- **Phonon and charge detectors**

    Examples: CDMS, EDELWEISS

- **Future detectors**

    Challenges; examples: SuperCDMS, EURECA, GEODM

Content: fourth lecture

- **Liquid Noble Element Experiments**

  Principles and properties of noble liquids

  Charge and light in noble liquids

  Calibration issues (electronic and nuclear recoils)

- **Single Phase Experiments**

  Principles

  Examples: XMASS, DEAP/CLEAN

- **Double Phase Experiments**

  Principles

  Examples: XENON, ZEPLIN, ArDM, WARP, LUX

- **Future detectors**

  Challenges

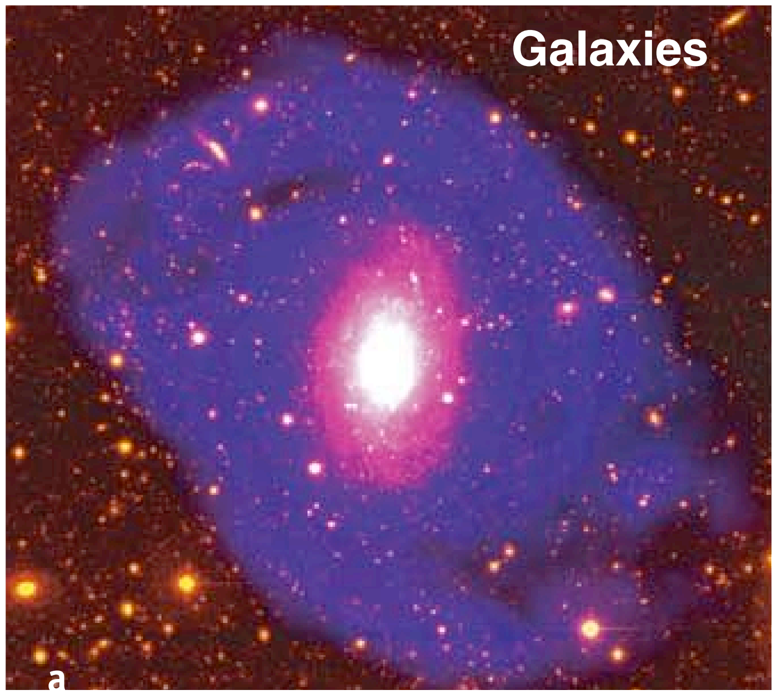
  Examples: DARWIN, MAX, LZS

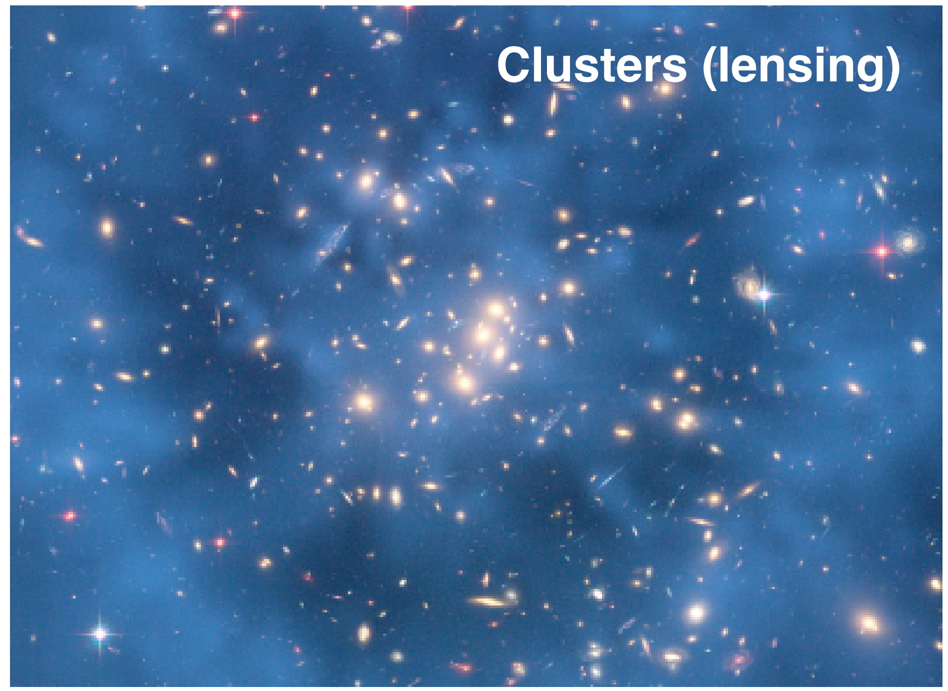
- **Overall summary and conclusions**

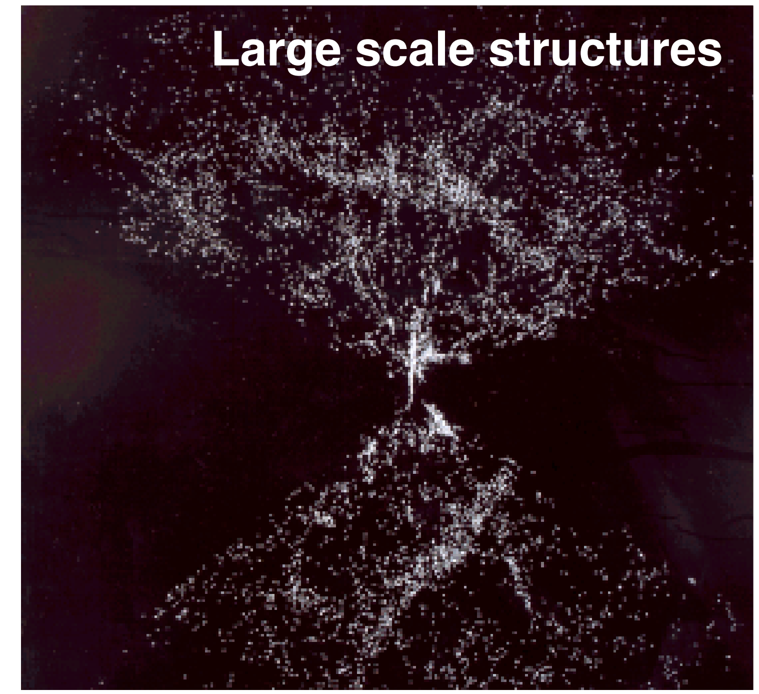
Literature

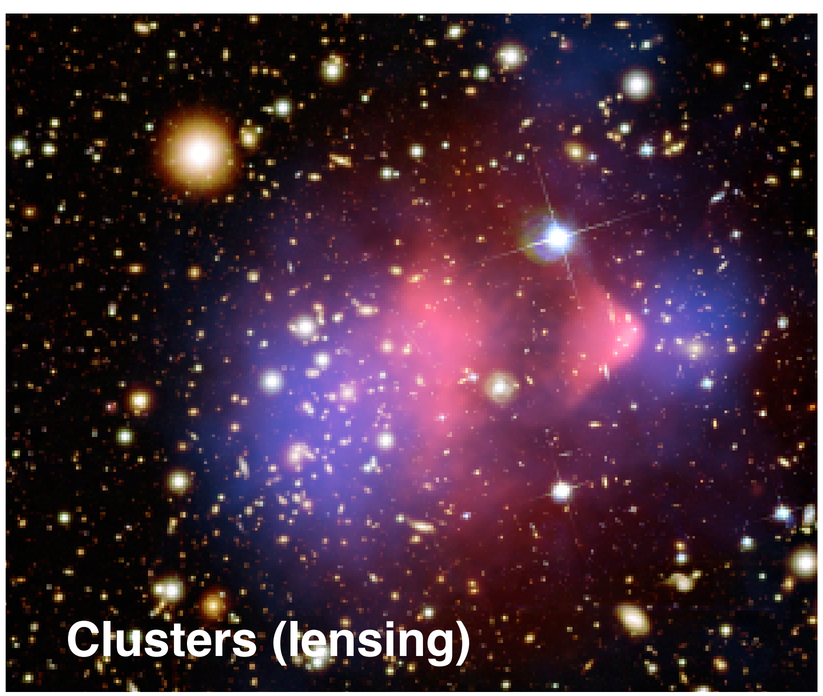
1. "Particle Dark Matter", editor Gianfranco Bertone; Cambridge University Press, December 2009
2. Cold thermal relics: *"The Early Universe"*, by Edward W. Kolb, Michael S. Turner, Addison Wesley, 1990
3. Introduction to supersymmetry: *"Weak Scale Supersymmetry"*, by Howard Baer, Xerxes Tata, Cambridge University Press, 2006
4. Direct and indirect detection: *"Supersymmetric Dark Matter"*, by G. Jungmann, M. Kamionkowski and K. Griest, Physics Reports 267 (1996)
5. Principles of direct dark matter detection: *"Review of mathematics, numerical factor and corrections for dark matter experiments based on elastic nuclear recoils"*, by J.D. Lewin and P.F. Smith, Astroparticle Physics 6 (1996)
6. Reviews of direct detection experiments: *"Direct Detection of Dark Matter"* by R.J. Gaitskell, Ann. Rev. Nucl. Part. Sci. 54 (2004), L. Baudis, *"Direct Detection of Cold Dark Matter"* SUSY07 Proceedings
7. Low background techniques: *"Low-radioactivity background techniques"* by G. Heusser, Ann. Rev. Part. Sci. 45 (1995)
8. Particle Astrophysics: *"Particle and Astroparticle Physics"* by U. Sarkar. Taylor & Francis 2008; *"Particle Astrophysics"* by D. Perkins, Oxford University Press 2003
9. mK Cryogenic Detectors: *"Low-Temperature Particle Detectors"*, by N.E. Booth, B. Cabrera, E. Fiorini, Annu. Rev. Nucl. Part. Sci. 46, 1996
10. Liquid xenon detectors: *"Liquid xenon detectors for particle physics and astrophysics",* by E. Aprile and T. Doke, Reviews of Modern Physics, Volume 82, 2010
11. PDG: Particle Detectors for Non-Accelerator Physics (http://pdg.lbl.gov/2010/reviews/rpp2010-rev-particle-detectors-non-accel.pdf)

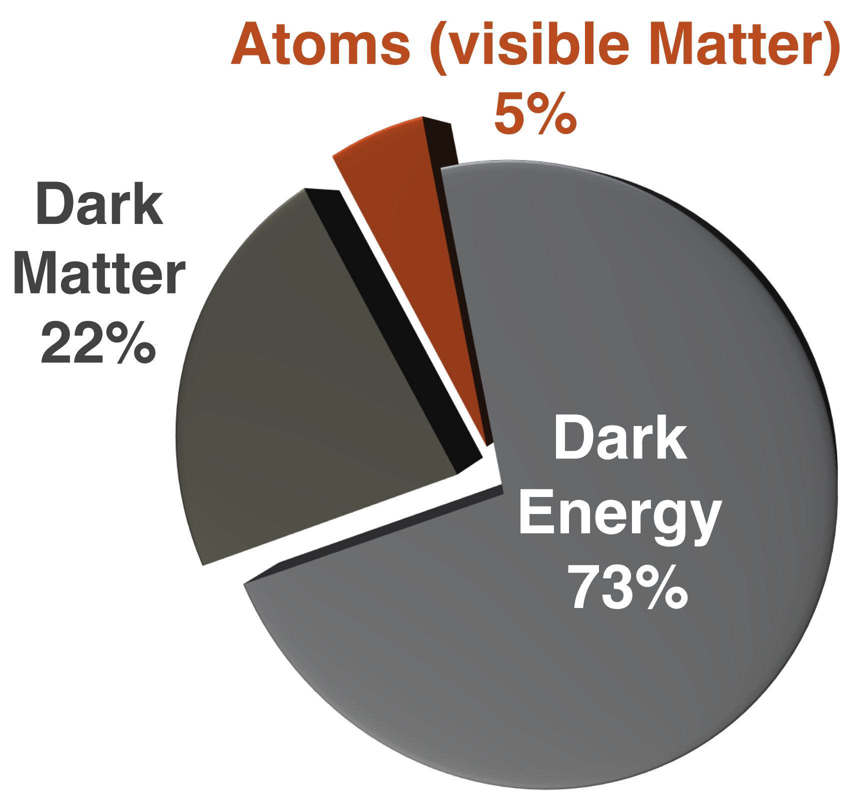
The Standard Model of Cosmology

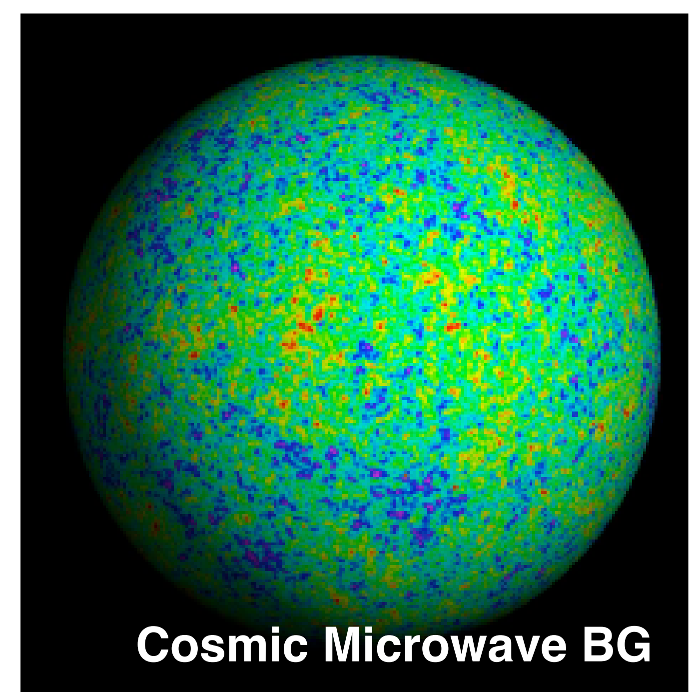




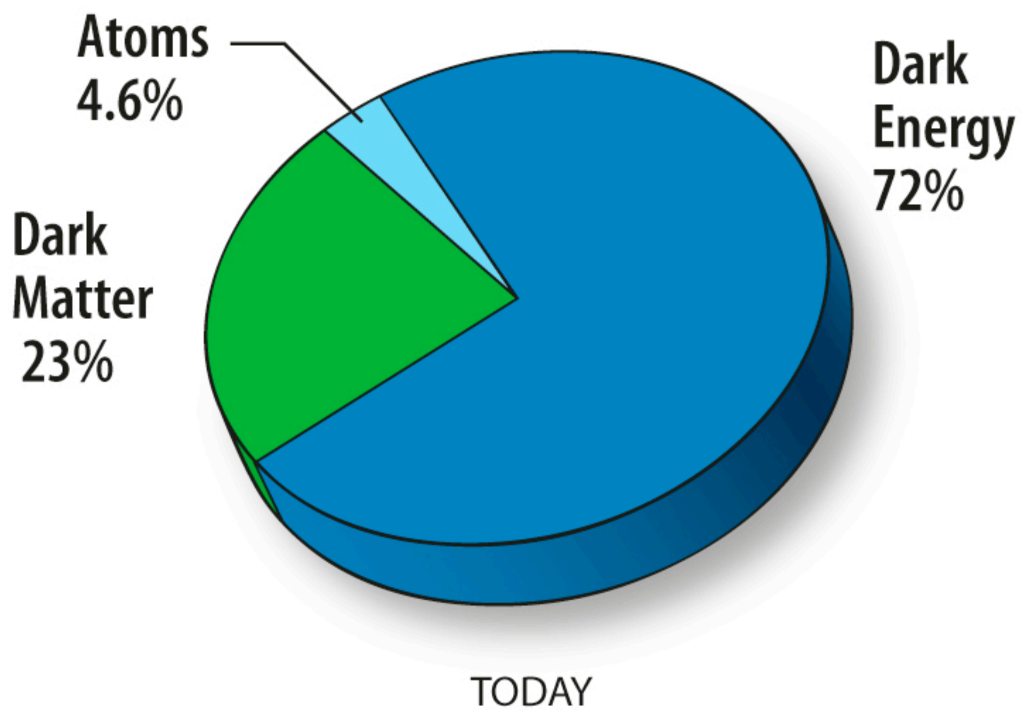








Overview: WMAP results



Credit: NASA / WMAP Science Team

- WMAP data reveals that its contents include 4.6% atoms, the building blocks of stars and planets.
- Dark matter comprises 23% of the universe. This matter, different from atoms, does not emit or absorb light. It has only been detected indirectly by its gravity.
- 72% of the universe, is composed of "dark energy", that acts as a sort of an anti-gravity. This energy, distinct from dark matter, is responsible for the present-day acceleration of the universal expansion.

The Standard Model of Cosmology

- **Cosmological Parameters (WMAP7)**
  - ➡ Total matter and energy density: $\Omega_{tot} = 1.02 \pm 0.02$
  - ➡ Total matter density: $\Omega_m = 0.266 \pm 0.029$
  - ➡ Density of baryons: $\Omega_b = 0.0449 \pm 0.0028$
  - ➡ Energy density of the vacuum: $\Omega_\Lambda = 0.743 \pm 0.029$
  - ➡ Hubble constant: $H_0 = (71.0 \pm 2.5)$ km/s/Mpc
  - ➡ Age of the Universe: $\tau_U = (13.75 \pm 0.13)$ Gy

http://lambda.gsfc.nasa.gov/product/map/current/parameters.cfm

$$\Omega_x \equiv \frac{\rho_x}{\rho_c}$$

density parameter

$$\rho_c \equiv \frac{3H_0^2}{8\pi G} = 9.47 \times 10^{-27} \, kg \; m^{-3}$$

$$\rho_c \simeq 6 \, \mathrm{H-atoms} \, \mathrm{m}^{-3}$$

critical density

expansion rate

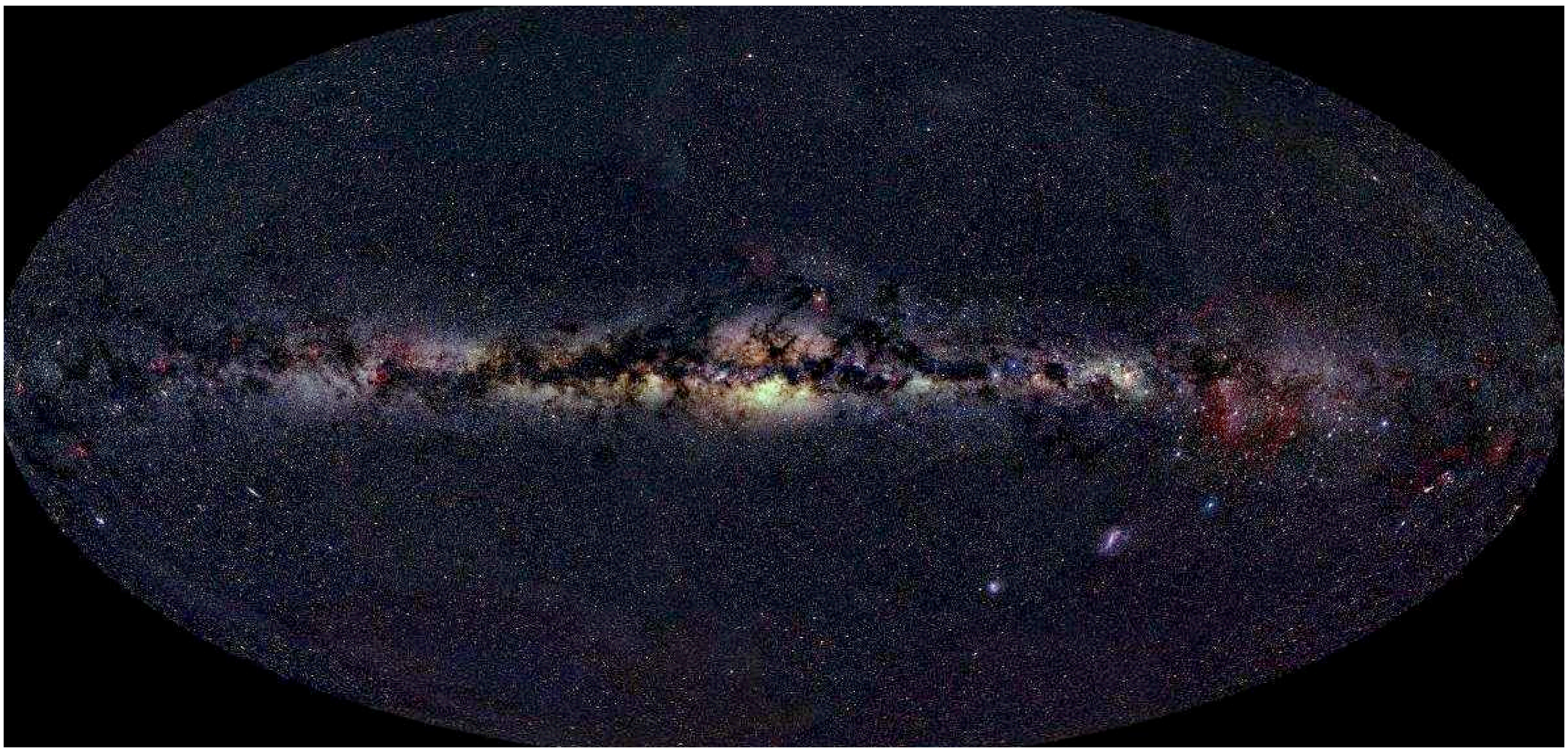
$$H(t) \equiv \frac{\dot{a}}{a}$$

a(t) = scale factor, describes the expansion of the Universe

Dark Matter in the Milky Way and in galaxies

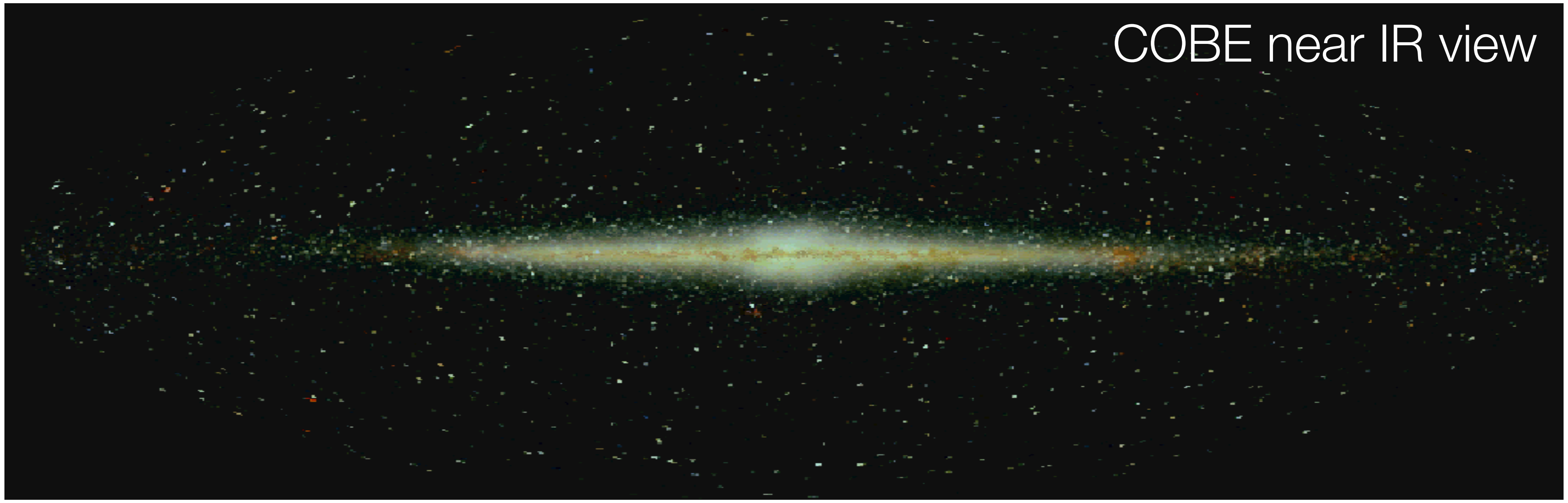
The Milky Way as a galaxy

- Complex system made of stars, dust, gas and dark matter



The Milky Way as a galaxy, initial remarks

- Its study has proven to be quite challenging, as we live at the edge of a disk of stars, dust and gas that severely impacts our ability to “see” beyond our stellar neighborhood when we look along the plane of the disk, and the problem is most severe when we look towards the Galactic Center (GC)
- Much of what is known today about the formation and evolution of our galaxy is encoded in the motion of its constituents
- Measuring this motion is complicated, because it occurs from an “observing platform” that is itself undergoing a complex motion that involves the motion of the Earth around the Sun and the Sun’s path around the Galaxy
- As we shall see, the detailed study of these motions lead to the conclusion that the *luminous, baryonic matter in the Galaxy is only a small fraction of what the Milky Way is composed of*



Structure of the Milky Way

- **The Milky Way consists of:**

  galactic thin disk (scale height* $z_{thin} \approx$ 350 pc), composed of relatively young stars an region of current star formation

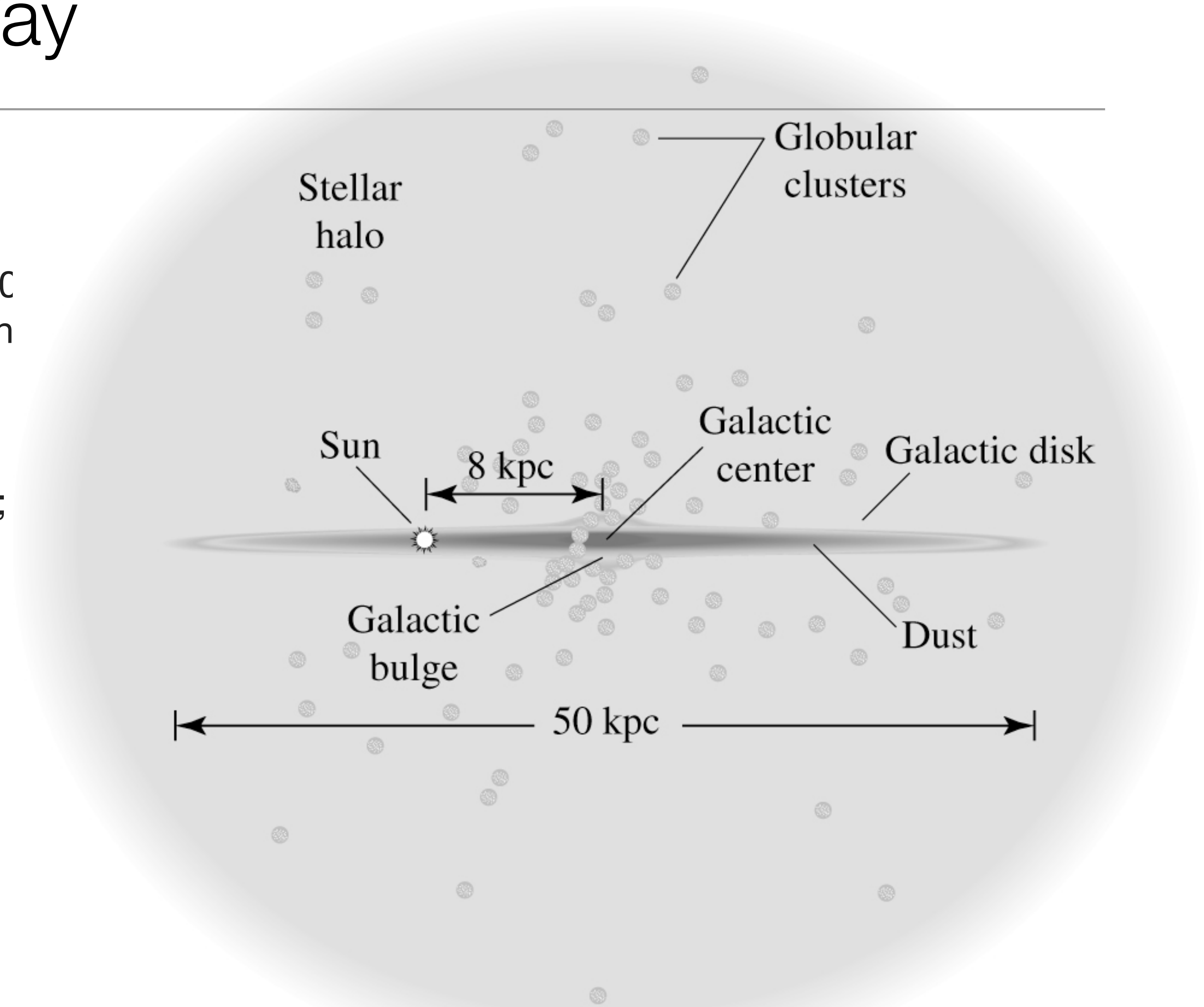
  galactic thick disk ($z_{thick} \approx$ 1000 pc), composed of an older population of stars; the stars per unit volume is only about 8.5% of the one in the think disk

  galactic bulge

  visible (stellar) halo

  dark halo

  dark disk (new!)



- **The distance Sun - Galactic Center (GC)**

  R_0 = 8.5 kpc (official value, IAU 1985)

  new value **R_0 = 8.0±0.5 kpc**

- **The diameter of the disk** (including dust, stars and gas) is: **D ≈ 50 kpc**

* one scale height (z) = the distance over which the number density decreases by e^{-1}

Mass-to-light ratio

- Based on data from star counts and orbital motions, the estimated stellar mass of the thin disk is roughly:

$$\sim 6 \times 10^{10} M_\odot$$

- To this, we must add the contribution from dust and gas:

$$\sim 0.5 \times 10^{10} M_\odot$$

- The luminosity of stars in the think disk in the blue-wavelength band is:

$$L_B \simeq 1.8 \times 10^{10} L_\odot$$

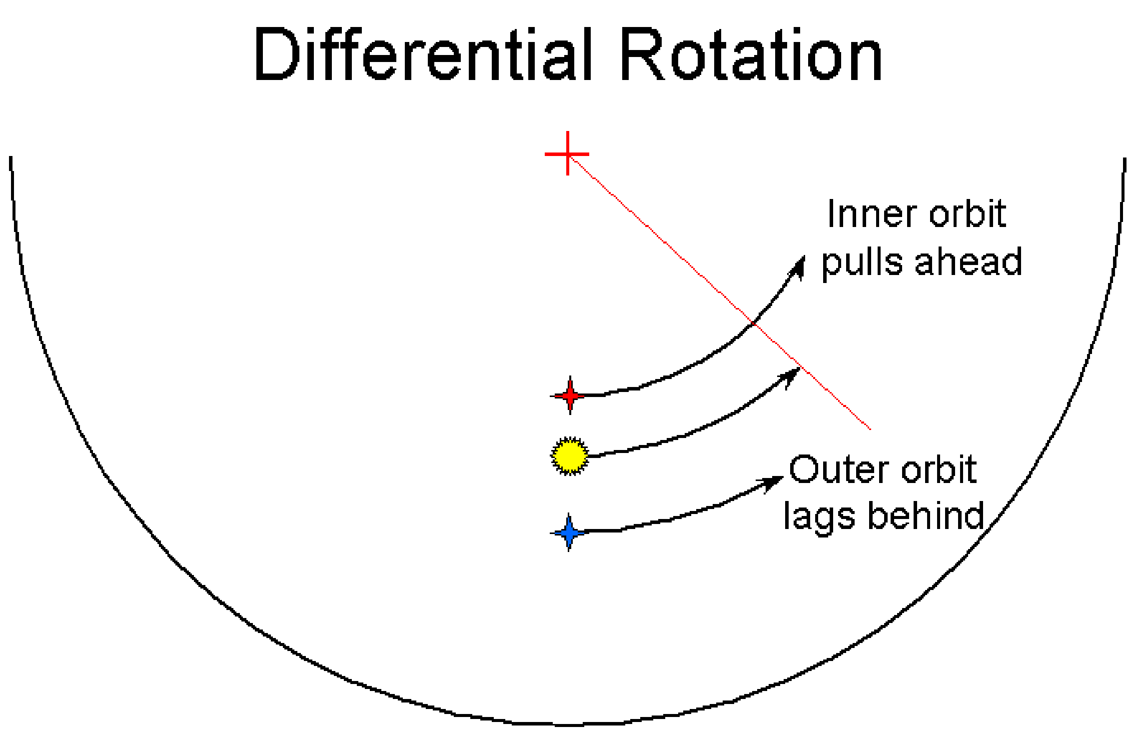
- From this, we obtain a *mass-to-light ratio* of:

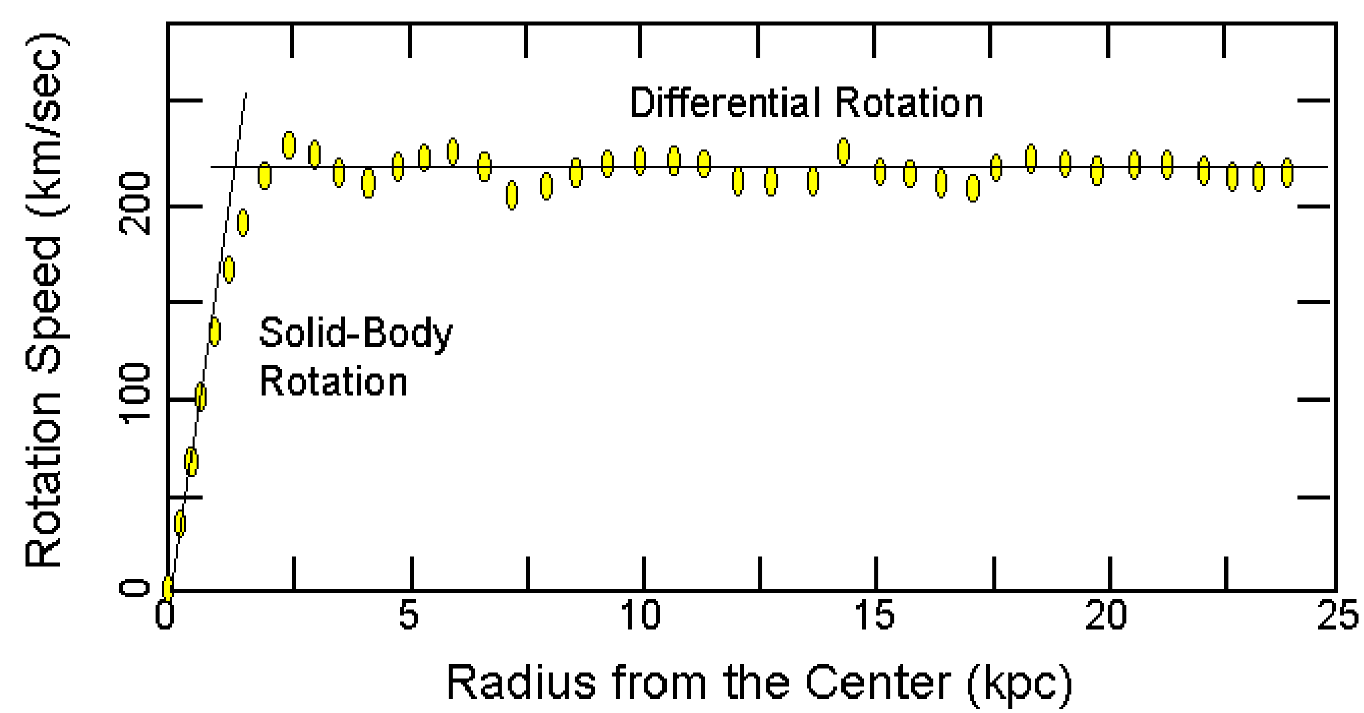
$$\frac{M}{L_B} \simeq 3 \frac{M_\odot}{L_\odot}$$

- For the thick disk, the blue-band luminosity is ~ 1% of the one of the thin disk, with the mass around 3% of the thin-disk mass (it has been much more difficult to detect; diagnostic importance for the dynamics of the disk); the bulge is very similar to the thin disk.

Differential rotation of the Milky Way

- The galactic disk undergoes a differential rotation
- That is, the angular velocity is not constant, but decreases as one moves outwards (with exception of the central region)
- The local rotation of the Milky Way was first studied by Jan Oort, 1927; he also derived a series of relations that became the framework with which astronomers have attempted to determine the differential rotation of the Milky Way
- We will not go into details in this lecture, we are concerned with the outcome and its interpretation

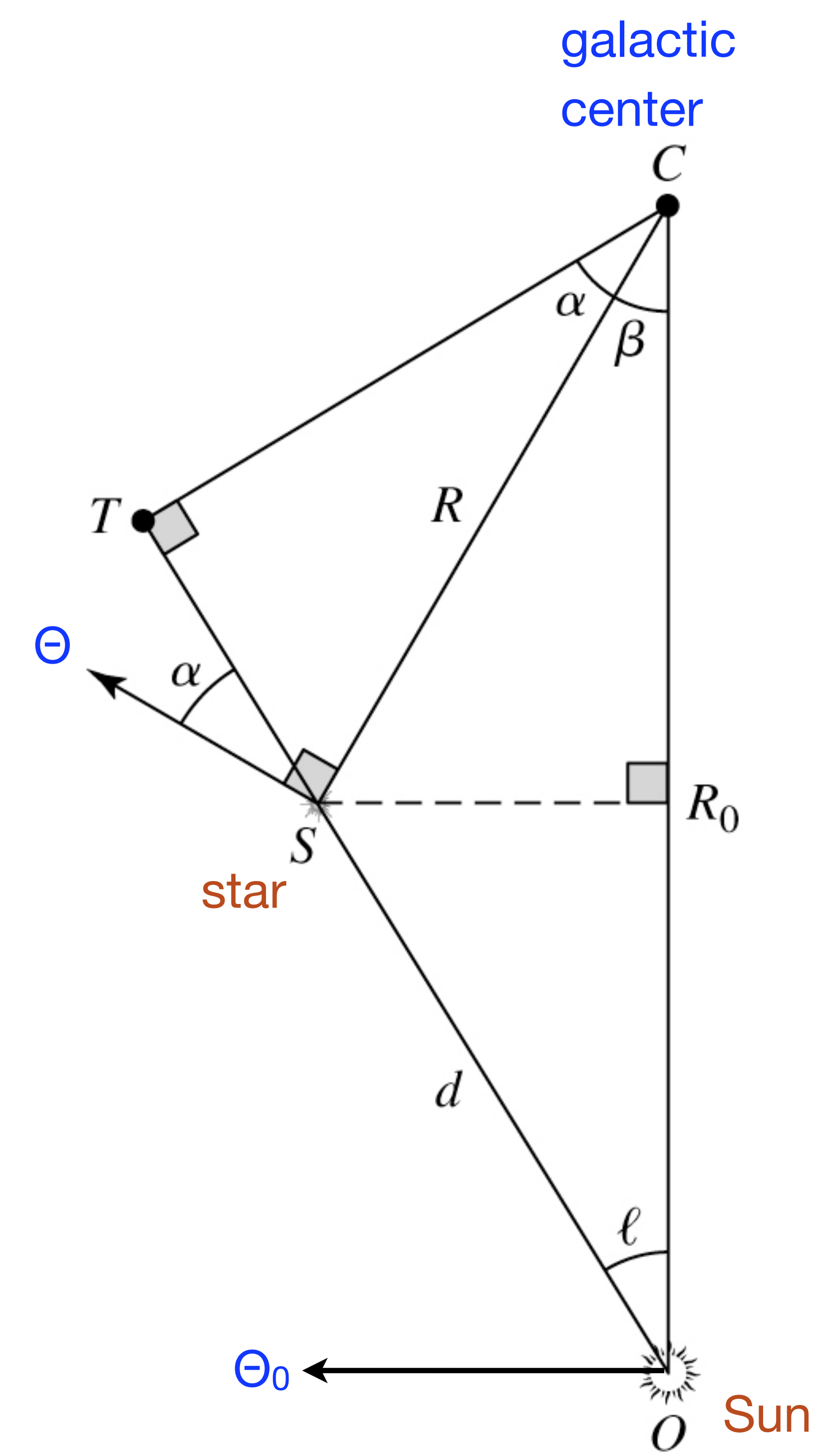




Rotation curve of the Milky Way

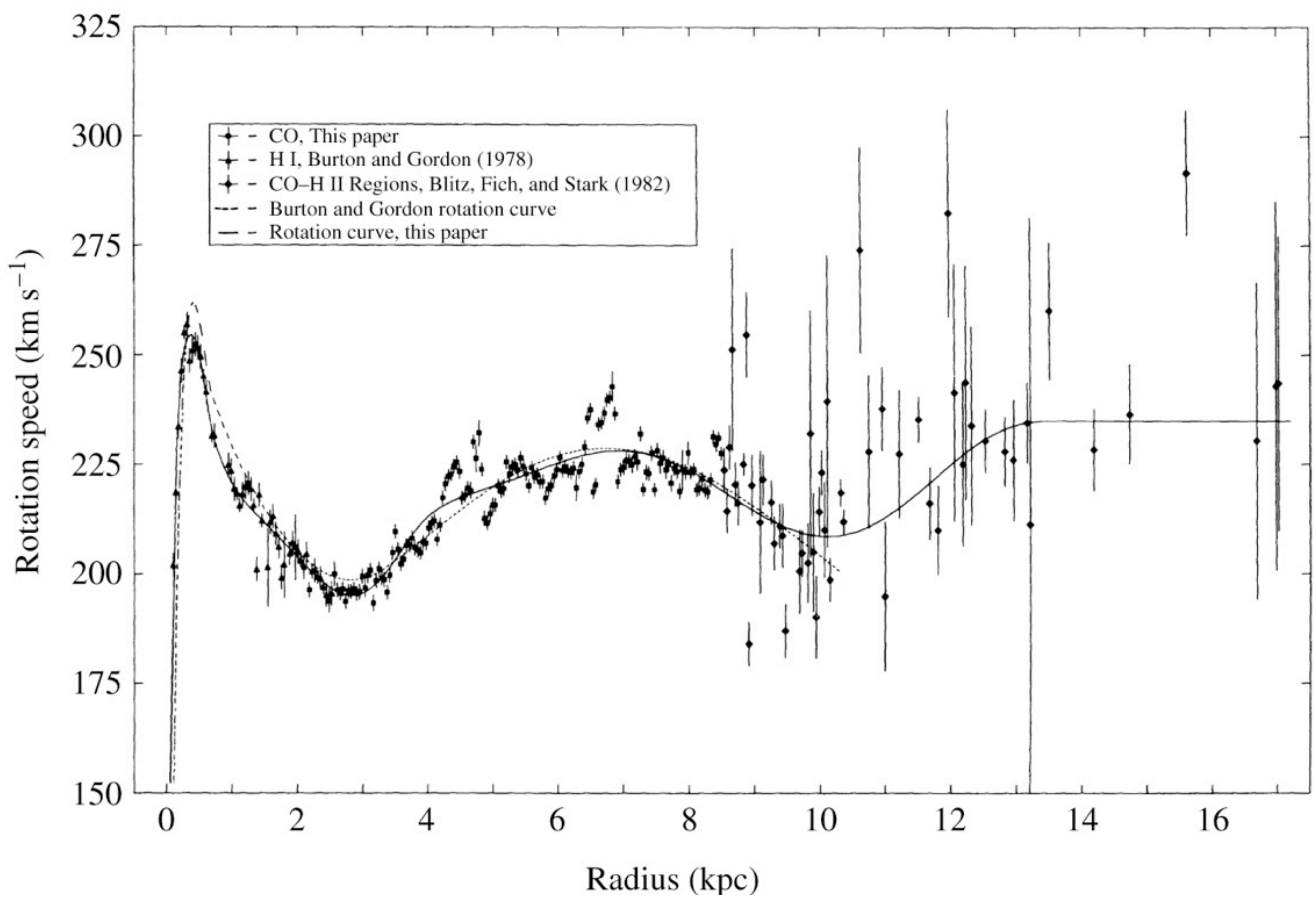
- One measures the relative velocities between stars and the Sun, that is - the relative radial v_r and transversal v_t velocities of stars (in fact, the proper motion, $\mu = v_t/d$, that is converted into a transverse velocity if the distance to the star is known)
- Requires some trigonometry, Oort's coordinates etc...
- Measurements of $\Theta(R)$ at $R > R_0$ requires measurement of objects for which distances can be determined directly, for instance variable (Cepheids or RR-Lyrae) stars
- Each object with known d and v_r gives one datapoint for the galactic rotation curve

$$\Theta_0 = \Theta(R_0) = 220\,\mathrm{km\,s^{-1}}$$



Rotation curve of the Milky Way

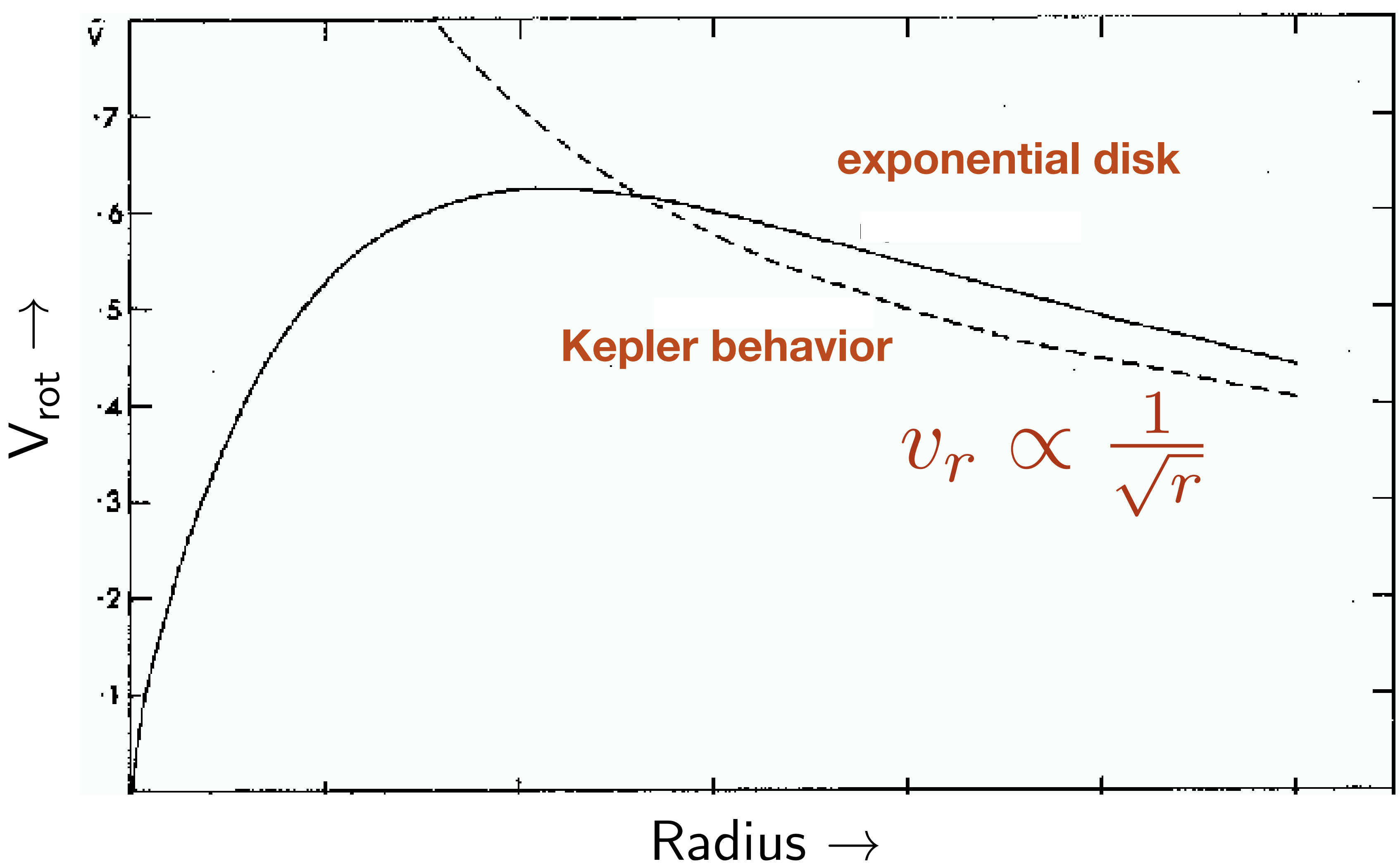
- Inner part: rigid-body rotation $\Theta \propto R, \;\; \omega = \frac{\Theta}{R} = \mathrm{konst.}$
- *The rotation curve for $R > R_0$ does not decrease significantly*
- $\Theta(R)$ at $R > R_0$ is practically constant, we shall see the implications later



Rotation curve of the Milky Way

- As we discussed, the movement of stars and gas, as a function of *distance r to the GC* is observed

  => **rotation curve, $v_r(r)$**
- If the mass of the MW would be distributed similar to its luminosity, which decreases exponentially as one moves to larger radii => **$v_r(r)$** in the outer parts of the disk should go with $1/\sqrt{r}$ (Kepler behavior)



Galactic Rotation Curve

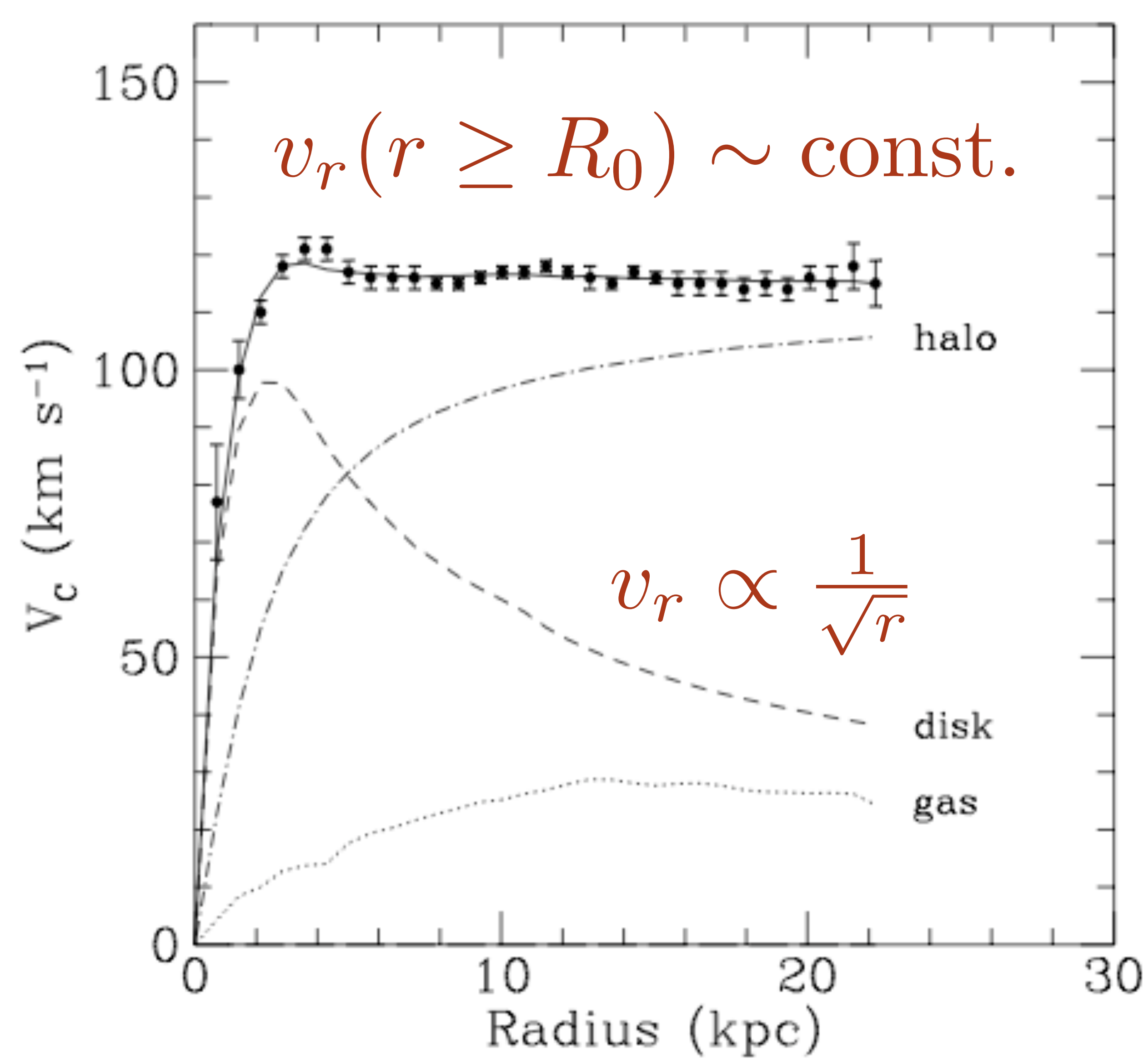
- From balancing the centripetal force with gravity we expect: (M$_r$ = total mass interior to r)

$$\frac{m v_r^2}{r} = G\frac{M_r m}{r^2}$$

$$v_r^2 = G\frac{M_r}{r}$$

$$v_r = \sqrt{\frac{GM_r}{r}}$$

$$\Rightarrow v_r \propto \frac{1}{\sqrt{r}}$$



- **Observations:**

$$v_r(r \geq R_0) \approx const.$$

$$\Longrightarrow M_r \propto r$$

=> a non-visible mass component, which increases linearly with radius, must exist

Galactic Rotation Curve

- The rotation curve depends on the distribution of mass => we can thus use the measured rotation curve to learn about the dark matter distribution

  "Rigid body" rotation: the mass must be ~ spherically distributed and the density ρ ~ constant

  Flat rotation curve: most of the matter in the outer parts of the galaxy is spherically distributed, and the density is

$$\rho(r) \propto r^{-2}$$

- To see this, we assume a constant rotation velocity V. The force, acting on a star of mass m by the mass M_r of the galaxy inside the star's position r is:

$$\frac{mV^2}{r} = \frac{GM_r m}{r^2}$$

- if we assume spherical symmetry. We solve for M_r:

$$M_r = \frac{V^2 r}{G}$$

- and then differentiate with respect to the radius r of the distribution:

$$\frac{dM_r}{dr} = \frac{V^2}{G}$$

Galactic Rotation Curve

- We then use the equation for the *conservation of mass* in a spherically symmetric system:

$$\frac{dM_r}{dr} = 4\pi r^2 \rho(r)$$

- and obtain for the *mass density in the outer parts of the Milky Way*:

$$\rho(r) = \frac{V^2}{4\pi r^2 G}$$

- the r^{-2} -dependency is in strong contrast to the number density of stars in the visible, stellar halo, which varies with $r^{-3.5}$, *thus decays much more rapidly as one would expect from the galactic rotation curve*

=> the main component of the Milky Way's mass is in a form non-luminous, or dark matter [so far, the dark matter has been observed only indirectly, through its gravitational influence on visible matter]

Galactic Rotation Curve

- We need to modify the previous equation:

$$\rho(r) = \frac{V^2}{4\pi G r^2}$$

- in order to force the density function to approach a constant value near the center (rather than to diverge!), to be consistent with the **observational evidence of a rigid-body rotation**
- Thus, a better form for the density distribution is given by:

$$\rho(r) = \frac{C_0}{a^2 + r^2}$$

- where C_0 and a are obtained from fits to the overall measured rotation curve:

$$C_0 = 4.6 \times 10^8 M\ \mathrm{kpc}^{-1}$$

$$a = 2.8\ \mathrm{kpc}$$

We note that:

for $r \gg a \Rightarrow \rho(r) \propto r^{-2}$
for $r \ll a \Rightarrow \rho(r) \propto$ const.

Remark re: galactic rotation curve

- The previous equation can not be correct to arbitrarily large values of r
- Reason: the total amount of mass in our Galaxy would increase without bound, since

$$M_r \propto r$$

- That means that the density function for the dark matter halo must eventually terminate or at least decrease sufficiently rapidly so that the mass integral remains finite:

$$\int_0^\infty \rho(r) 4\pi r^2 \, dr$$

Rotation curves of other galaxies

- The rotation curves of other galaxies are easier to measure, as we can observe them from outside
- Measurements are done via the Doppler effect, test ‘particles’ are stars and HI-gas (21-cm line)
- The extent of the HI-gas in the disk >> dimensions of the stellar disk

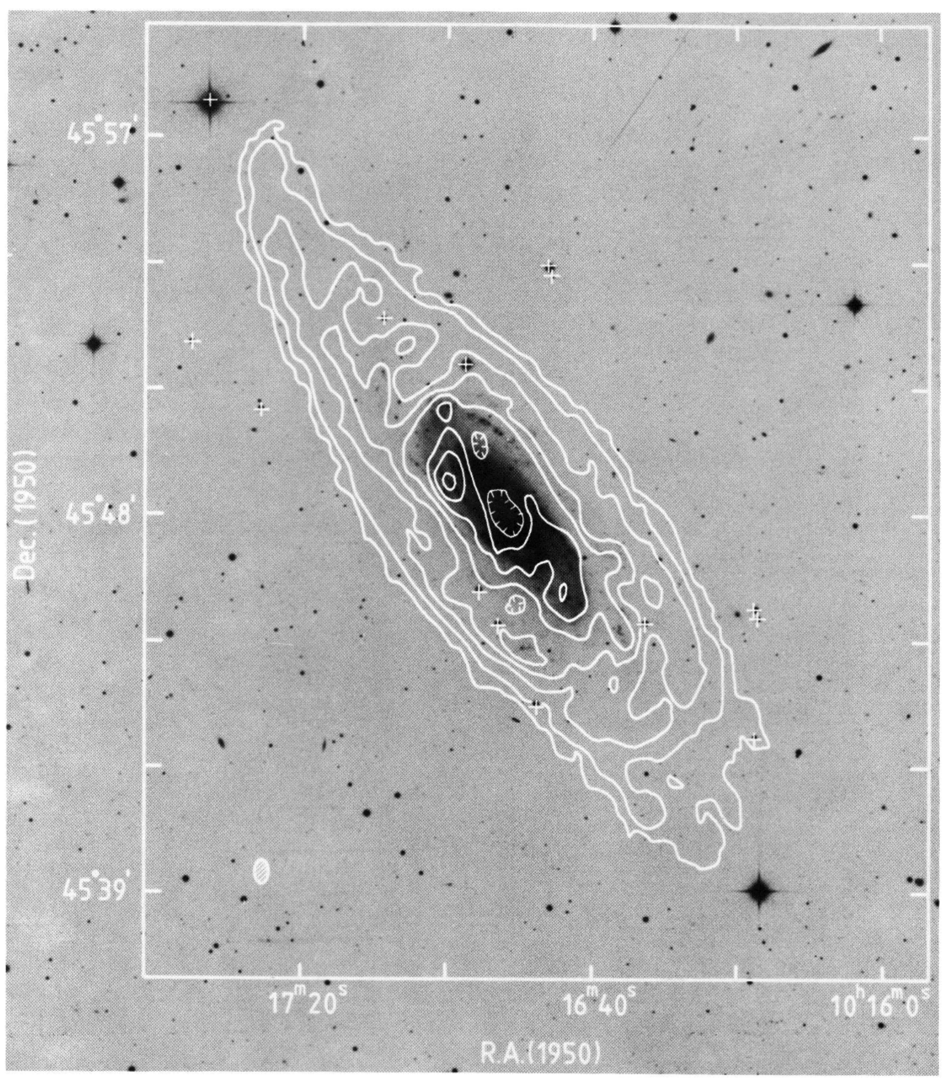
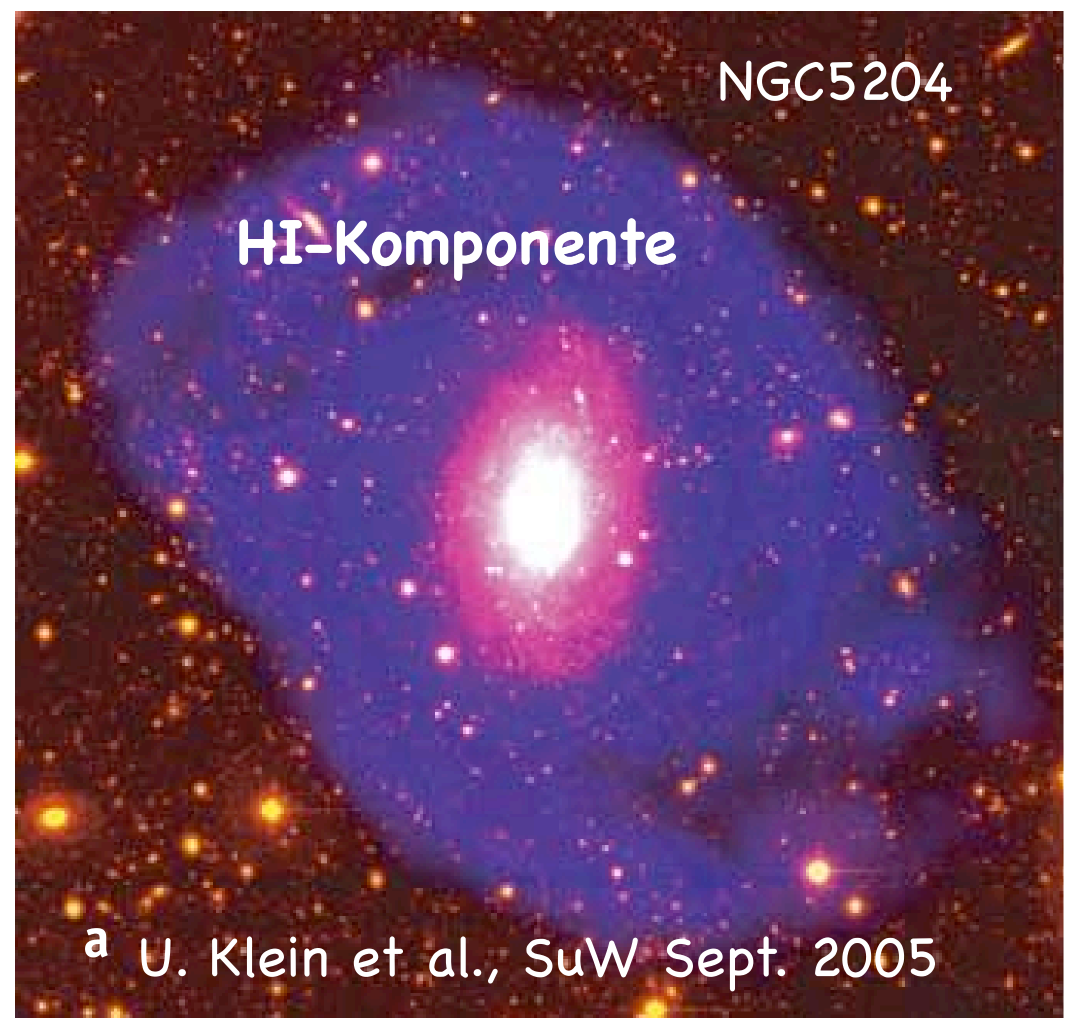
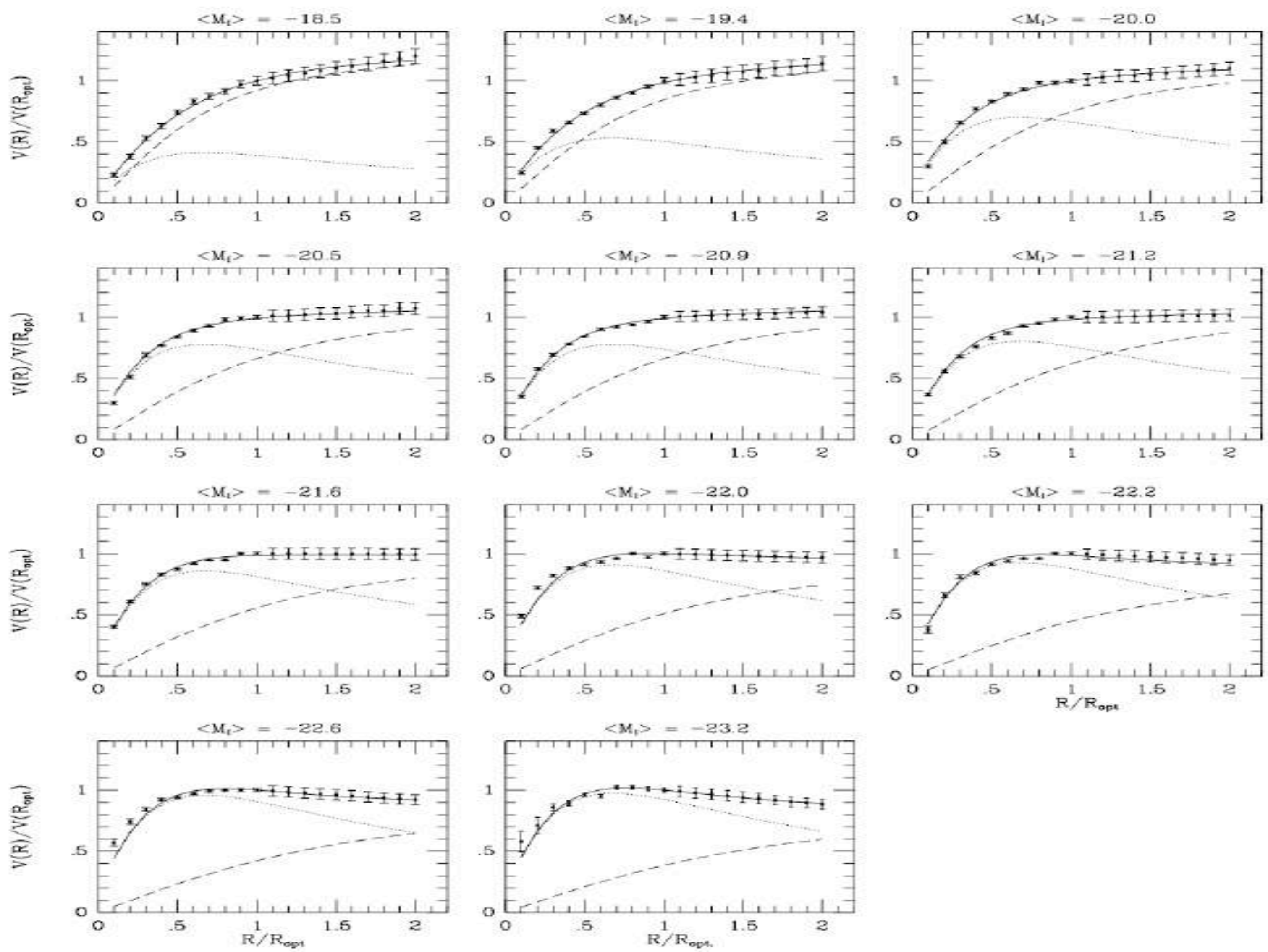


Fig. 2.—Full resolution (25″ × 35″) map of the H I column density distribution of NGC 3198 superposed on an optical image of the galaxy (IIIa-J) (with Wr 2c), kindly made available by J. W. Sulentic. Contour levels are 1, 4, 8, 12, …, 28 times 10^{20} atoms cm^{-2}.



Galactic rotation curves

- Rotation curves were measured for many thousands of galaxies
- Some of the first measurements were done by Vera Rubin and her team, in the 70s
- We observe that rotation curves stay flat as far out as one can measure, and they can be described by so-called *universal density profiles*



Galactic rotation curves

- Galaxies are thus surrounded by a halo of dark matter; from the rotation curves, one can derive - as we have seen - the density profiles. The rotation curve can be described by

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

M(R): mass inside radius R

- The rotation curve that we would expect from luminous matter alone is:

$$v_{lum}^2(r) = \frac{GM_{lum}(r)}{r}$$

(in the simple case of spherical geometry)

- If we take a constant and plausible value for *M/L of the visible matter* (M/L is determined from the spectral light distribution of stars, plus knowledge about the star populations, or from fits of the inner parts of the rotation curves, where the dark matter contribution can be neglected), we can determine:

$$M_{lum}(r)$$

Galactic rotation curves

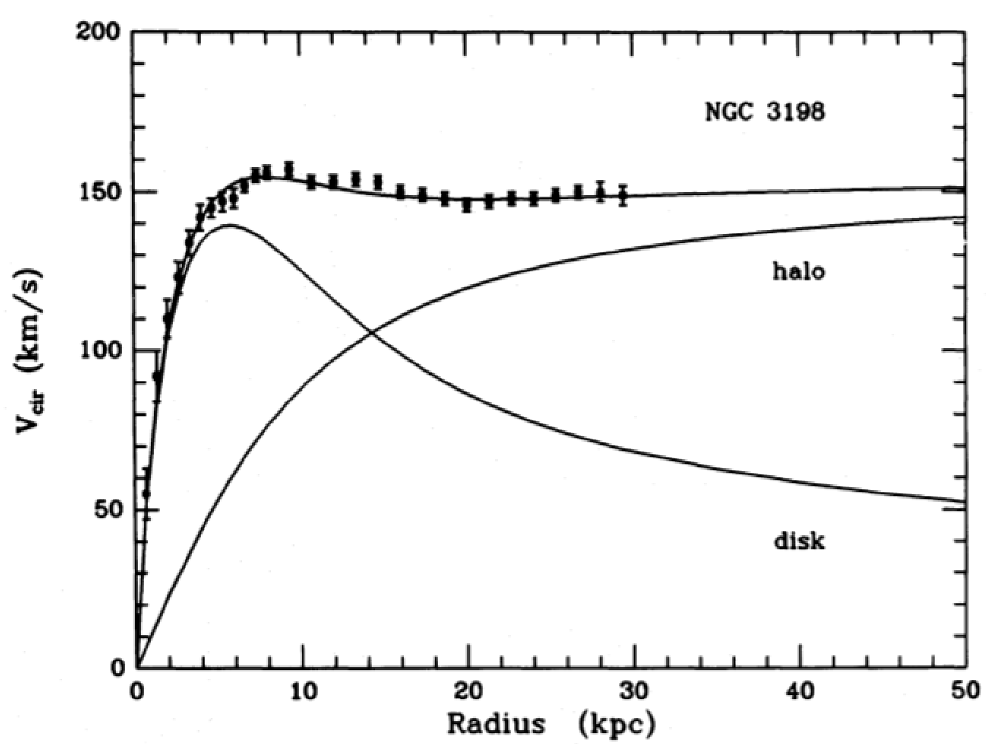
- Then, from the discrepancy between v^2_{lum} and v^2, we can determine the contribution of the dark matter:

$$v^2_{dark}(r) = v^2(r) - v^2_{lum}(r) = \frac{GM_{dark}}{r}$$

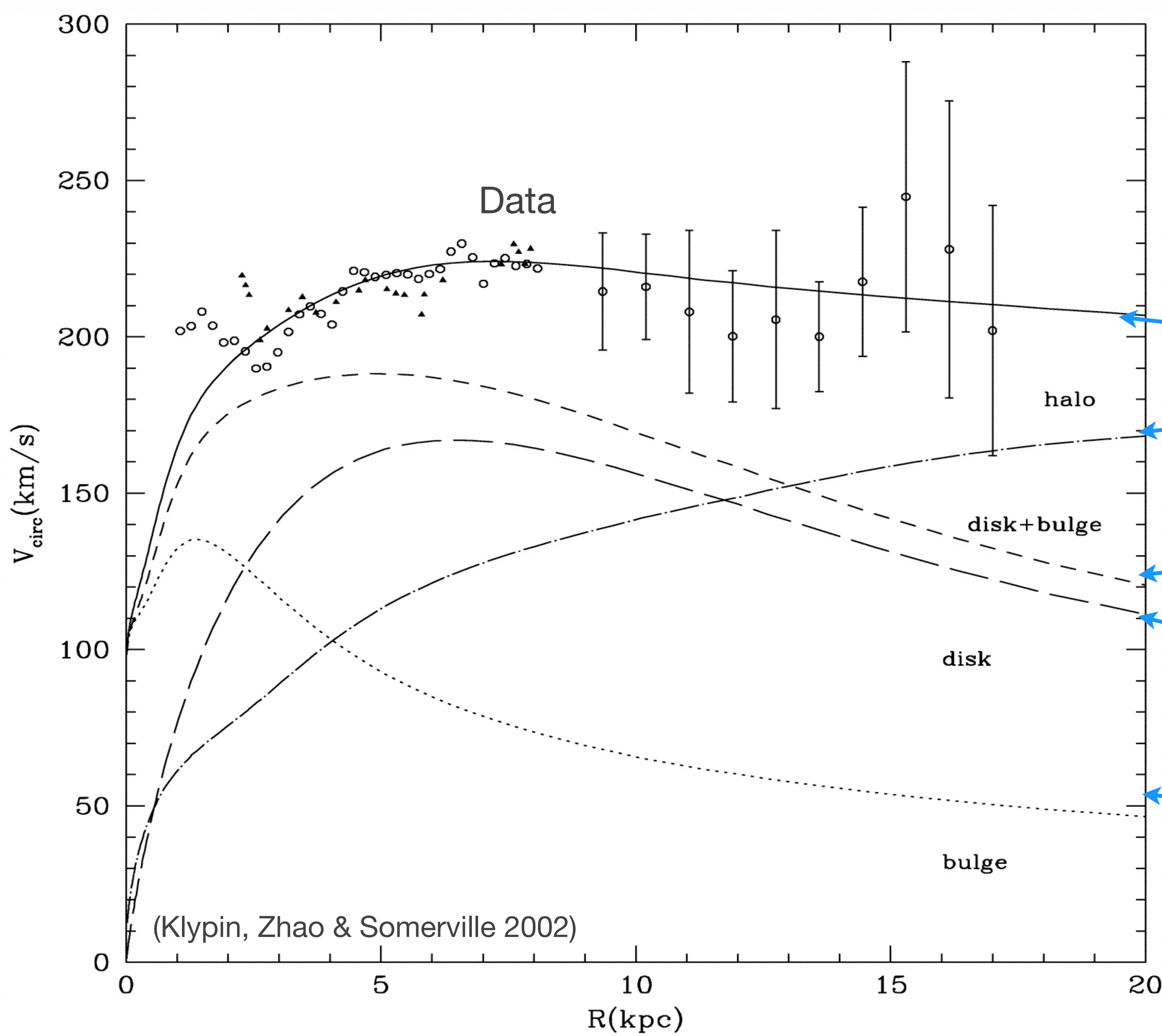
- and finally obtain:

$$M_{dark}(r) = \frac{r}{G}\left[v^2(r) - v^2_{lum}(r)\right]$$

- One example for a decomposition is shown here:



Milky Way: fits to the observed rotation curve



Sum of halo + disk + bulge

Dark matter halo

Disk + Bulge

Disk

Bulge

$$M_{tot,lum} \approx 9 \times 10^{10} M$$

$$M_{25\,kpc} \approx 2.8 \times 10^{11} M$$

$$M_{230\,kpc} \approx 1.3 \times 10^{12} M$$

In reality one models each contribution (disk, bulge) separately

What can we learn from the rotation curve?

- As we saw, a mass that grows linearly would derive from a density distribution falling like $\rho(r) \sim 1/r^2$
- We would now like to learn something about the distribution of dark matter
- We assume the dark matter is made of a *collisionless gas (particles which are for instance weakly interacting) with isotropic initial velocity distribution*
- Its equation of state is given by:

$$p(r) = \rho(r) \cdot \sigma^2 = \rho(r)\langle(v_x - \bar{v}_x)^2\rangle$$

σ = velocity dispersion

- If we impose the condition of *hydrostatic equilibrium* on the system, with pressure balancing gravity, we obtain:

$$\frac{dp(r)}{dr} = -G\frac{M(r)}{r^2}\rho(r)$$

M(r) = total mass interior to r

What can we learn from the rotation curve?

- Using the expression for p(r) and multiplying by $\frac{r^2}{\rho}\frac{1}{\sigma^2}$ yields the equation:

$$\frac{r^2}{\rho}\frac{d\rho(r)}{dr} = -\frac{1}{\sigma^2}GM(r)$$

- We now differentiate with respect to r and obtain:

$$\frac{d}{dr}\left(r^2\frac{d\ln\rho}{dr}\right) = -\frac{G}{\sigma^2}\frac{dM(r)}{dr} = -\frac{4\pi G}{\sigma^2}r^2\rho(r)$$

- where we have used again the equation for the conservation of mass:

$$\frac{dM}{dr} = 4\pi r^2\rho(r)$$

What can we learn from the rotation curve?

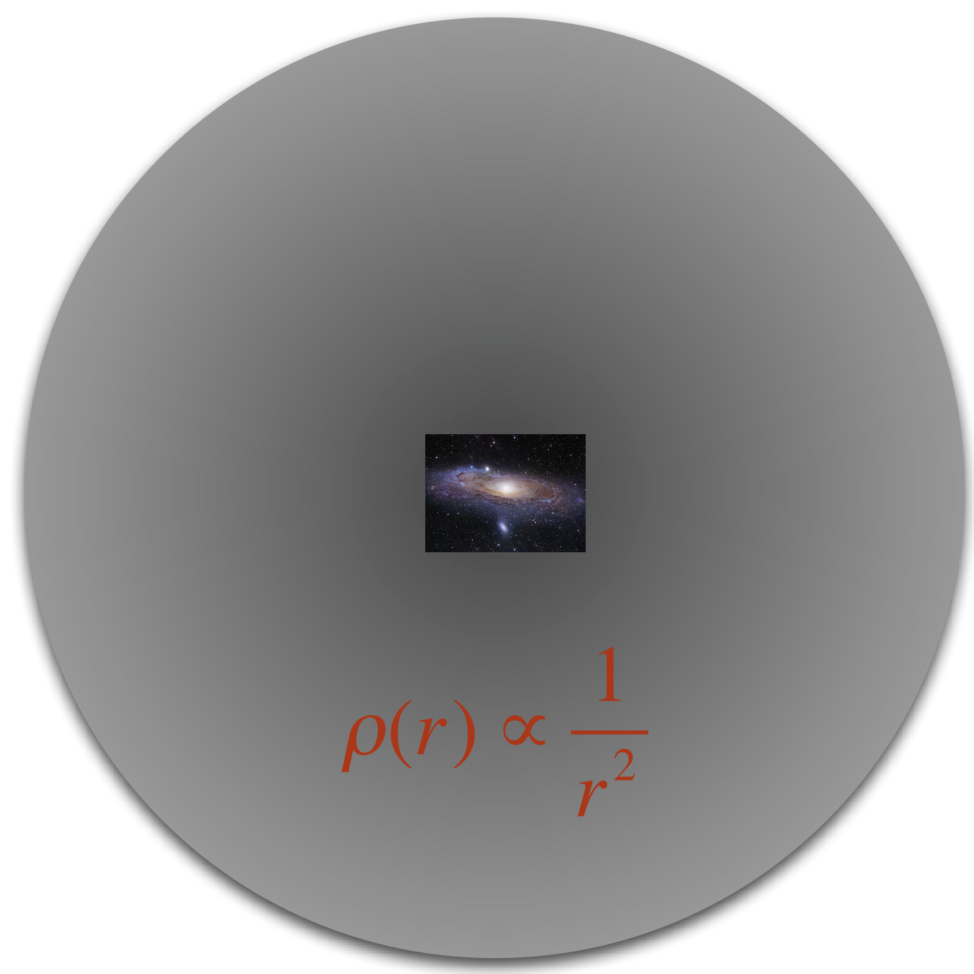
- Solving this equation yields:

$$\rho(r) = \frac{\sigma^2}{2\pi G \cdot r^2}$$

- This configuration corresponds to a spherical,

  isothermal distribution of the dark matter : “isothermal sphere”

- It describes the gravitational collapse of collisionless particles*



- *explained in detail in Binney and Tremaine, Galactic Dynamics, Princeton Univ. Press 2008

The Standard Halo Model

- A system of many particles is described by its *distribution function f(**x**,**v**,t) which is the number density of particles in phase space (**x**,**v**).* The steady-state phase space distribution function for a collection of collisionless particle is given by the solution to the collisionless Boltzmann equation:

$$\frac{\delta f}{\delta t} + \mathbf{v} \cdot \frac{\delta f}{\delta \mathbf{x}} - \frac{\delta \phi}{\delta \mathbf{x}} \frac{\delta f}{\delta \mathbf{v}} = 0 \qquad \phi(\mathbf{x}) \text{ gravitational potential}$$

- The standard halo model (SHM) is an isotropic, isothermal sphere with density profile r^{-2}. In this case, the solution of the collisionless Boltzmann equation is a so-called Maxwellian velocity distribution, given by:

$$f(\mathbf{v}) = N \exp\left(-\frac{3|\mathbf{v}|^2}{2\sigma^2}\right)$$

- where N is a normalization constant. The velocity dispersion is related to the asymptotic value *of the circular speed,* which is the speed at which objects on circular orbits orbit the Galactic centre

$$v_{\mathrm{c},\infty} = \sqrt{2/3}\,\sigma$$

The Standard Halo Model

- Usually it is assumed that the rotation curve has already reached its asymptotic value at the solar radius $r = R_0$, such that

$$\sigma = \sqrt{3/2}\, v_{\rm c}$$

- where

$$v_{\rm c} \equiv v_{\rm c}(R_0)$$

- As we saw, the density distribution in the SHM is formally infinite and hence the velocity distribution also extends to infinity. In reality however, the Milky Way halo is finite, and particles with speeds greater than the escape speed:

$$v_{\rm esc}(r) = \sqrt{2|\phi(r)|} \qquad \phi(r) \text{ is the potential}$$

- will not be gravitationally bound to the Milky Way.

The Standard Halo Model

- This is addressed by truncating the velocity distribution at the measured local escape speed

$$v_{\rm esc} \equiv v_{\rm esc}(R_0)$$

- such that

$$f(\mathbf{v}) = 0 \text{ for } |\mathbf{v}| \geq v_{\rm esc}$$

- This is clearly unphysical, an alternative is to make the truncation smooth:

$$f(\mathbf{v}) = \begin{cases} N\left[\exp\left(-\frac{3|\mathbf{v}|^2}{2\sigma^2}\right)\exp\left(-\frac{3v_{\rm esc}^2}{2\sigma^2}\right)\right], & |\mathbf{v}| < v_{\rm esc}\,, \\ 0\,, & |\mathbf{v}| \geq v_{\rm esc}\,. \end{cases}$$

The Standard Halo Model

- The standard parameter values used for the SHM are the following:

- local density

$$\rho_0 \equiv \rho(R_0) = 0.3\,\mathrm{GeV\,cm^{-3}}$$

$$\rho_0 = 0.008 M_\odot \mathrm{pc}^{-3} = 5 \times 10^{-25} \mathrm{g\,cm^{-3}}$$

- local circular speed

$$v_\mathrm{c} = 220\,\mathrm{km\,s^{-1}}$$

- local escape speed

$$v_\mathrm{esc} = 544\,\mathrm{km\,s^{-1}}$$

- The escape speed is the speed required to escape the local gravitational field of the MW, and the local escape speed is estimated from the speeds of high velocity stars
- The RAVE survey has measured:

$$498\,\mathrm{km\,s^{-1}} < v_{esc} < 608\,\mathrm{km\,s^{-1}}$$

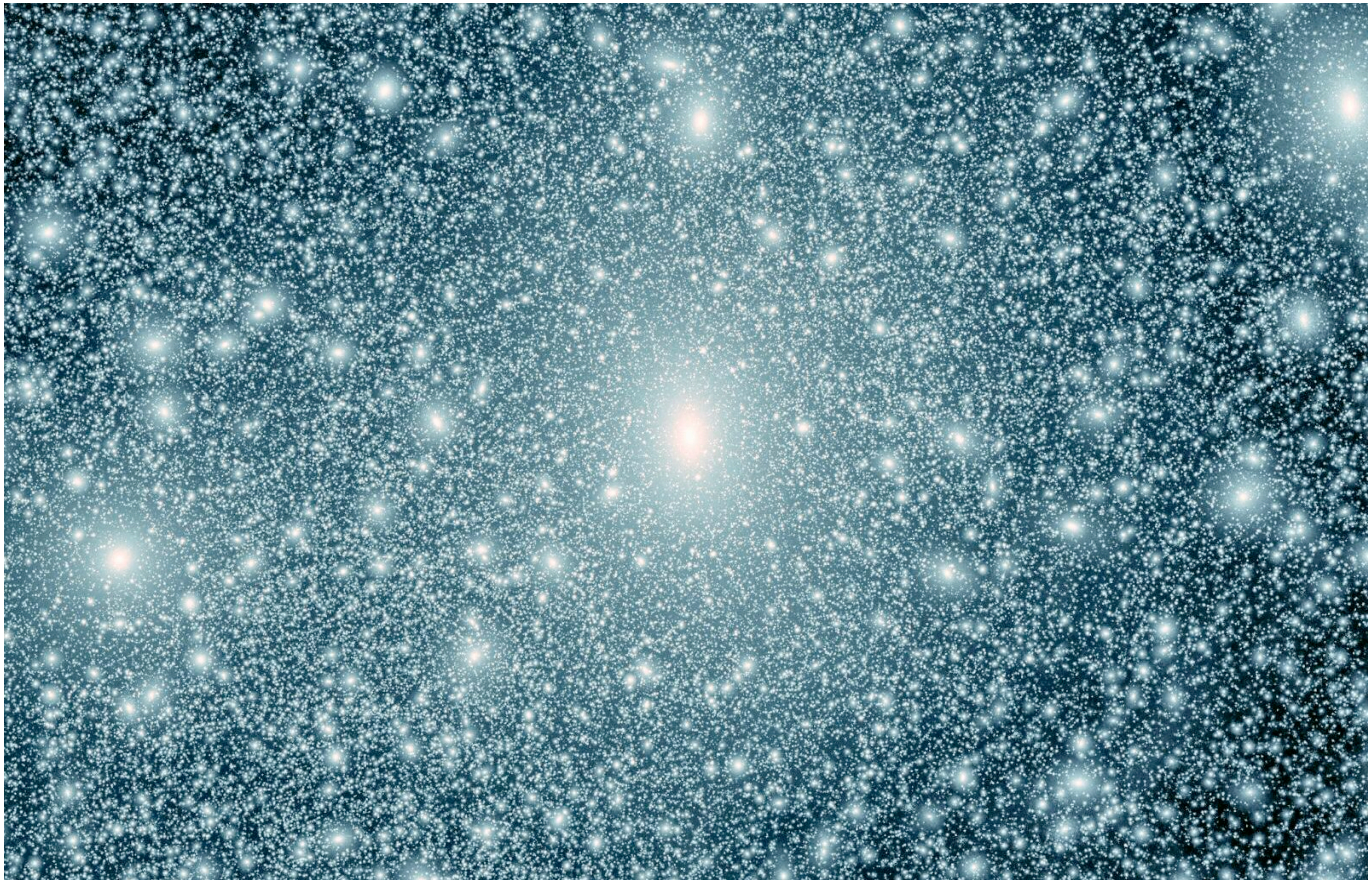
Simulations of cold dark matter halos

- To go beyond the smooth spherical isotropic model for the Galactic halo, numerical studies of the formation of dark matter halos are used

- Such studies (N-body simulations of the gravitational collapse of a collisionless system of particles) have yielded global properties of halos (e.g., their mass profiles and substructure properties) that are tested against observational data ranging from the scale of dwarf galaxies to galaxy clusters

- There is quite some uncertainly regarding the inner (< few 100 pc) density profiles, however:
    - these central regions in galaxies, groups and clusters are dominated by baryons
    - hence, predictions of the dark matter and total mass distribution require a realistic treatment of the baryons and their dynamical interactions with dark matter

Example: GHALO simulation

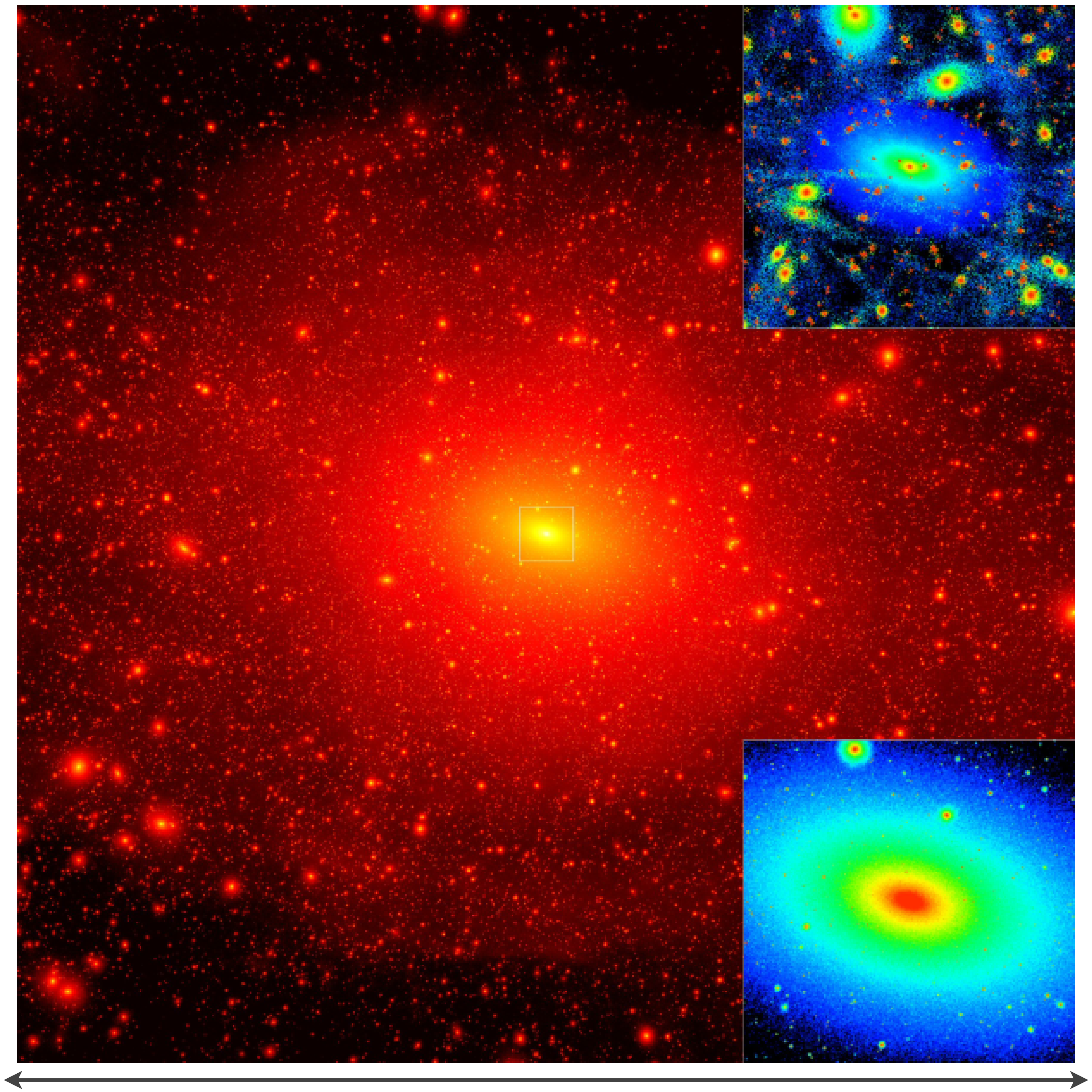


Ben Moore, UZH:

GHALO: A billion particle simulation of the dark matter distribution surrounding a galaxy. 3 million cpu hours with the parallel gravity code pkdgrav (Stadel et al 2008)

50 parsec, $1000 M_{\odot}$ resolution, 100,000 substructures

Example: Simulations of the Milky Way Dark Halo



inner 20 kpc: phase space density

high resolution (10^9 particles, each particles has 1000 $M_{\odot}$) cosmological CDM simulation of a Milky Way type halo

inner 20 kpc: density

(J. Diemand et all, Nature 454, 2008, 735-738) ~ 600 kpc

Distribution of the Dark Matter - Numerical Simulations

- **NFW - Profile (Navaro, Frenk, White, 1996)**, through numerical simulations of the formation of dark matter halos:

$$\rho_{NFW}(r) = \frac{\rho_0}{(r/a)(1 + r/a)^2}$$

- The NWF density profile behaves as ~ $\mathbf{r^{-2}}$ for a large part of the halo, and is flatter ~ $\mathbf{r^{-1}}$ in the vicinity of the GC and falls steeper at the 'edge' of the halo ~ $\mathbf{r^{-3}}$.

- **More general:**

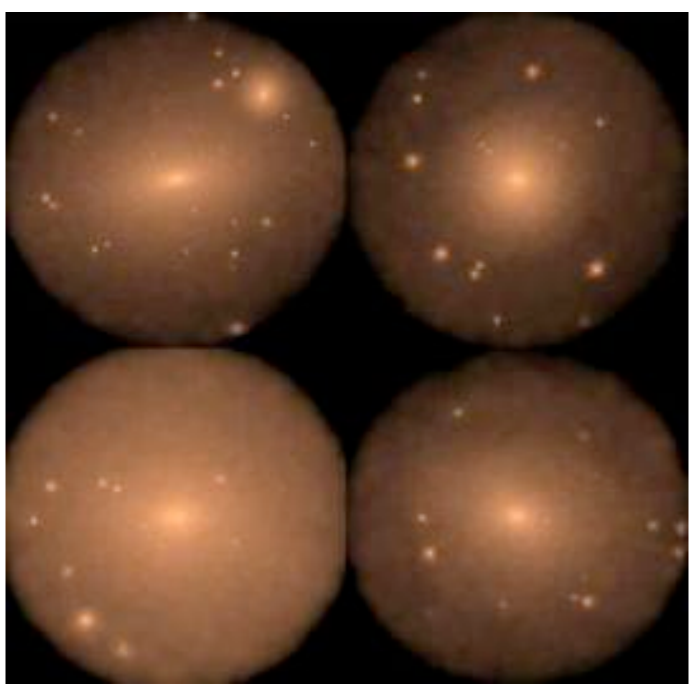
$$\rho(r) = \rho_0 \left(\frac{r}{a}\right)^{\gamma - 1} \left[1 + \frac{r}{a}\alpha\right]^{(\gamma-\beta)/\alpha}$$

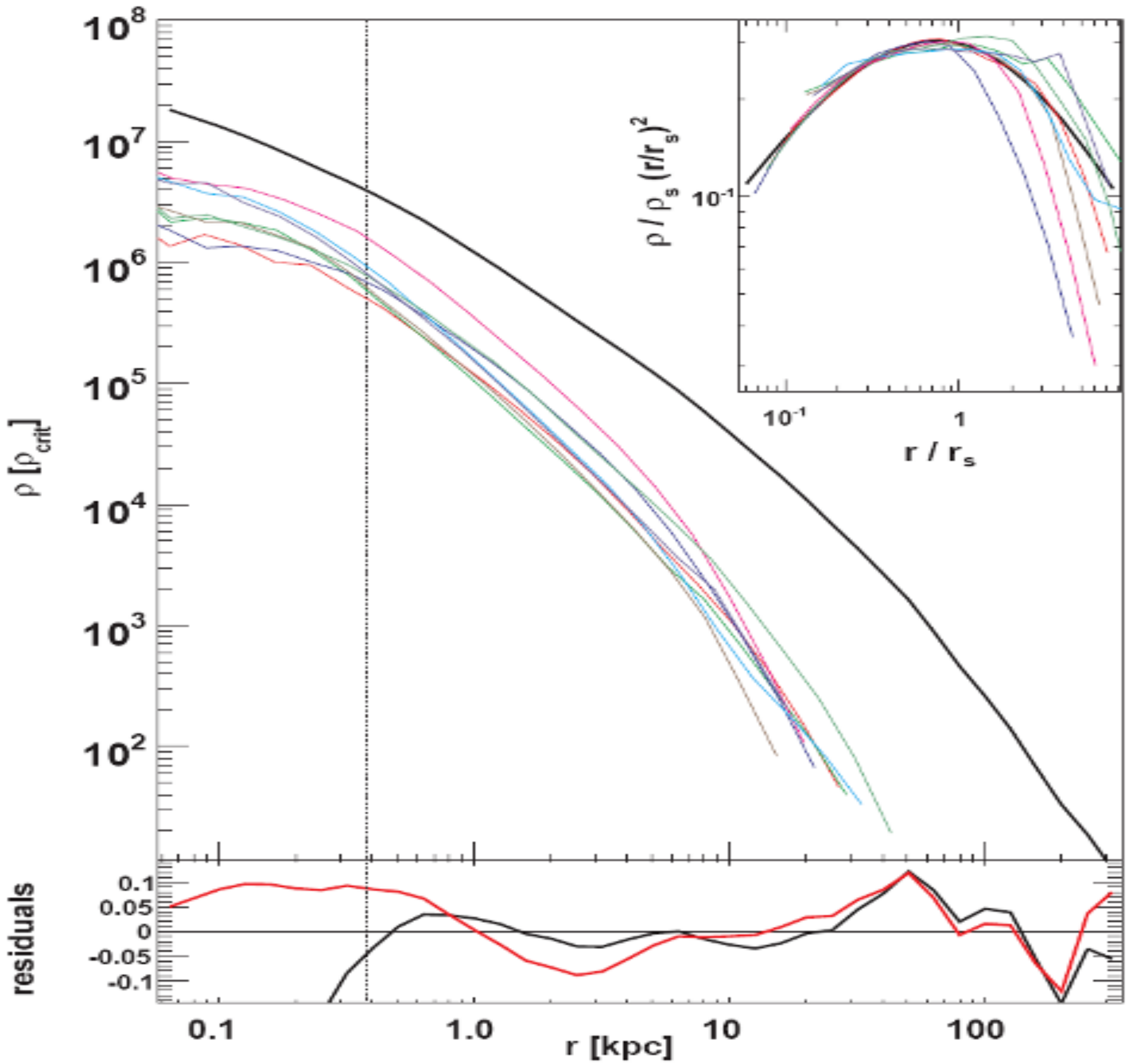
	α	β	γ	a(kpc)
Kravtsov	**2.0**	**3.0**	**0.4**	**10.0**
NFW	**1.0**	**3.0**	**1.0**	**20.0**
Moore	**1.5**	**3.0**	**1.5**	**28.0**
Isother.	**2.0**	**2.0**	**0**	**3.5**

different groups obtain different profiles for the inner parts of the galaxy (from the numerical simulations)

Examples for density profile curves

- Density profile curve from the Via Lactea II simulation
- for the main dark matter halo and eight large subhalos

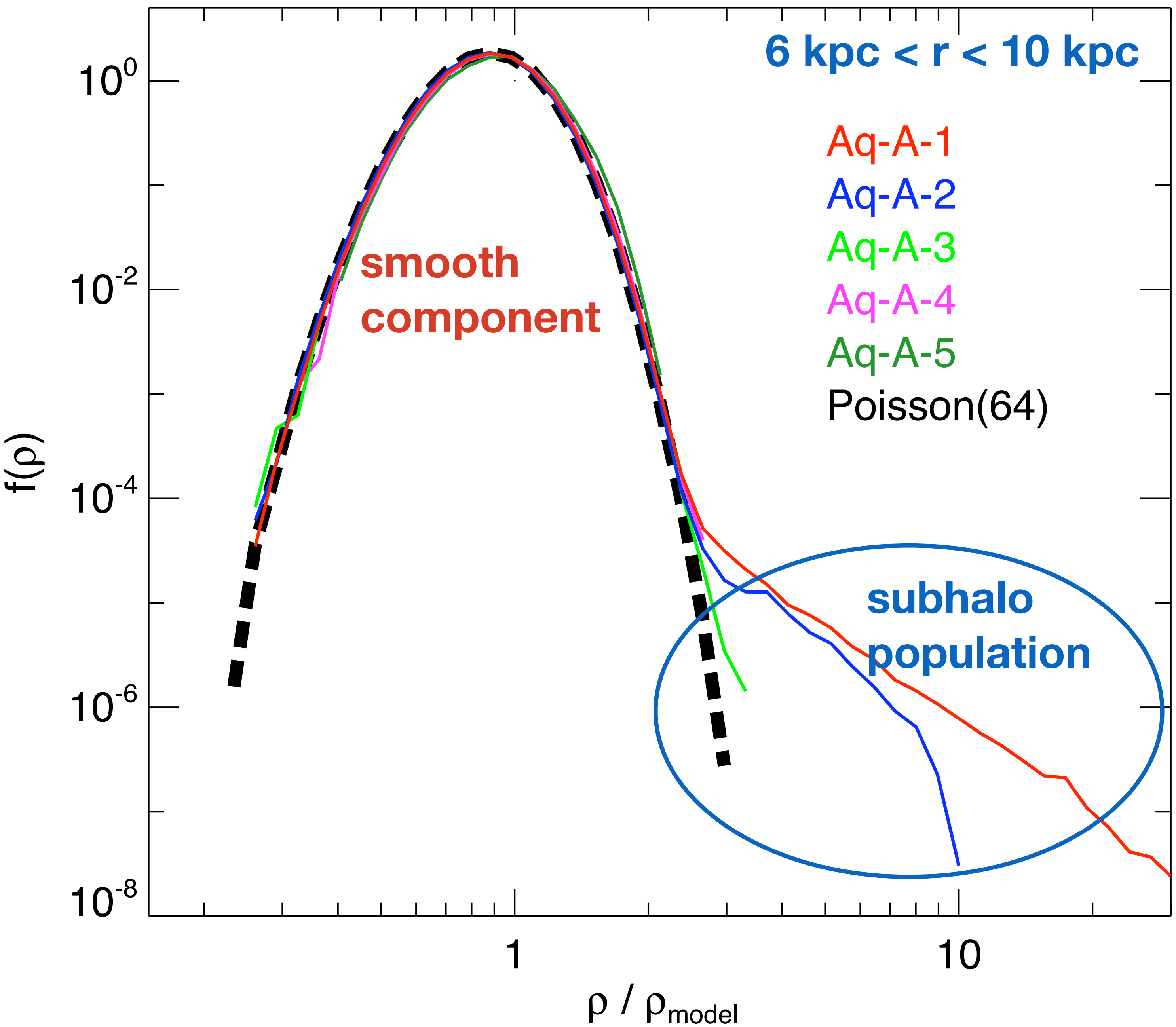




Spatial Distribution of the Dark Matter

- **1. Question**: how smooth is the dark matter *mass distribution* at the solar position?

Density probability distribution around the solar circle



High resolution simulations of six galaxy halos taken from the Aquarius Project

Parameters for the Aquarius simulations:

$\Omega_m = 0.25$
$\Omega_\Lambda = 0.75$
$H_0 = 100\ h\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$
$h = 0.73$

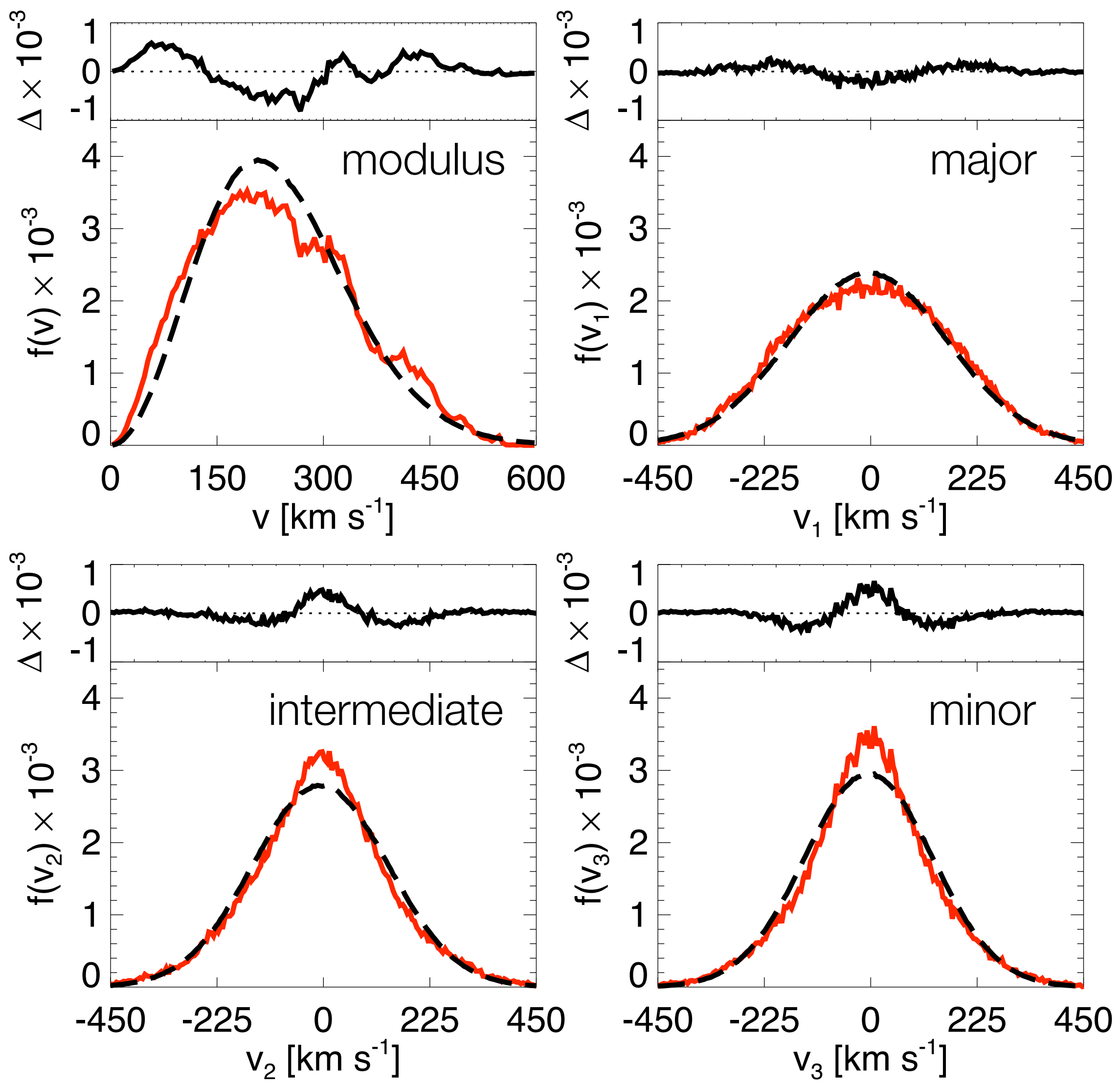
Answer:
- very smooth
- substructure is far from Sun

The Aquarius project, 6 halos
MNRAS 395, 2009

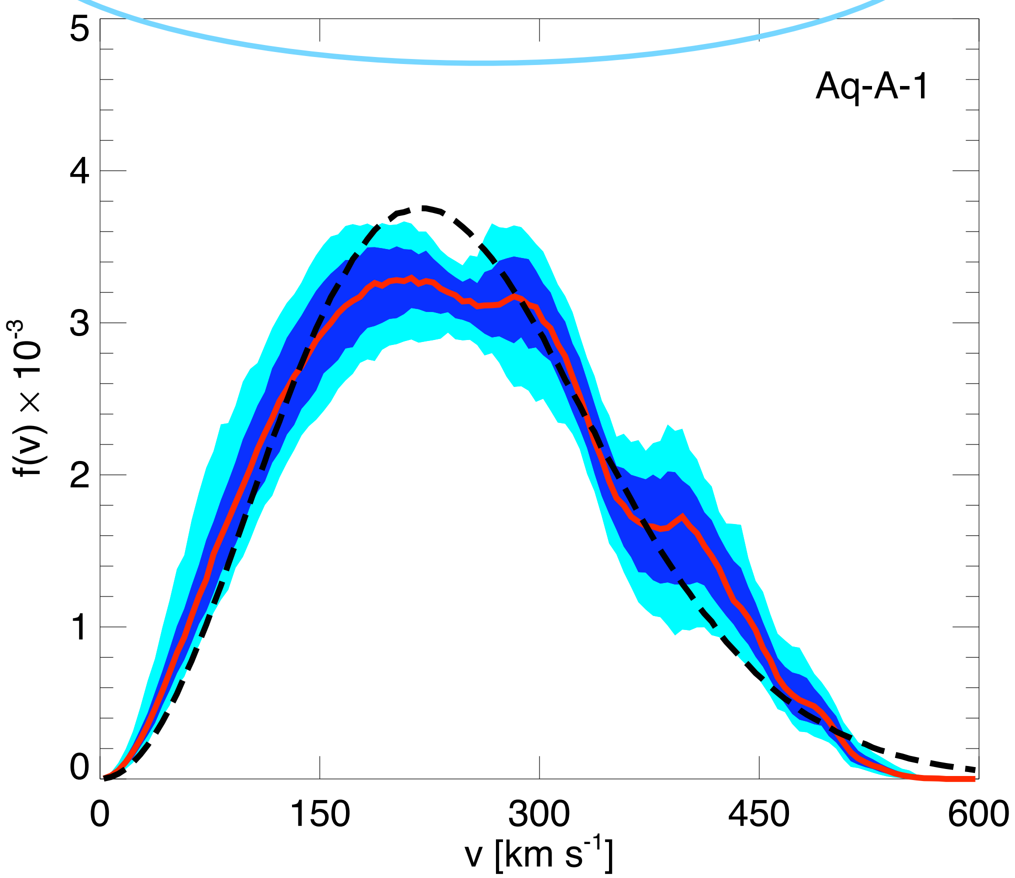
Velocity Distribution of the Dark Matter

- **2. Question:** how smooth is the dark matter *velocity distribution* at the solar position?

Velocity distribution in a 2 kpc box the solar circle



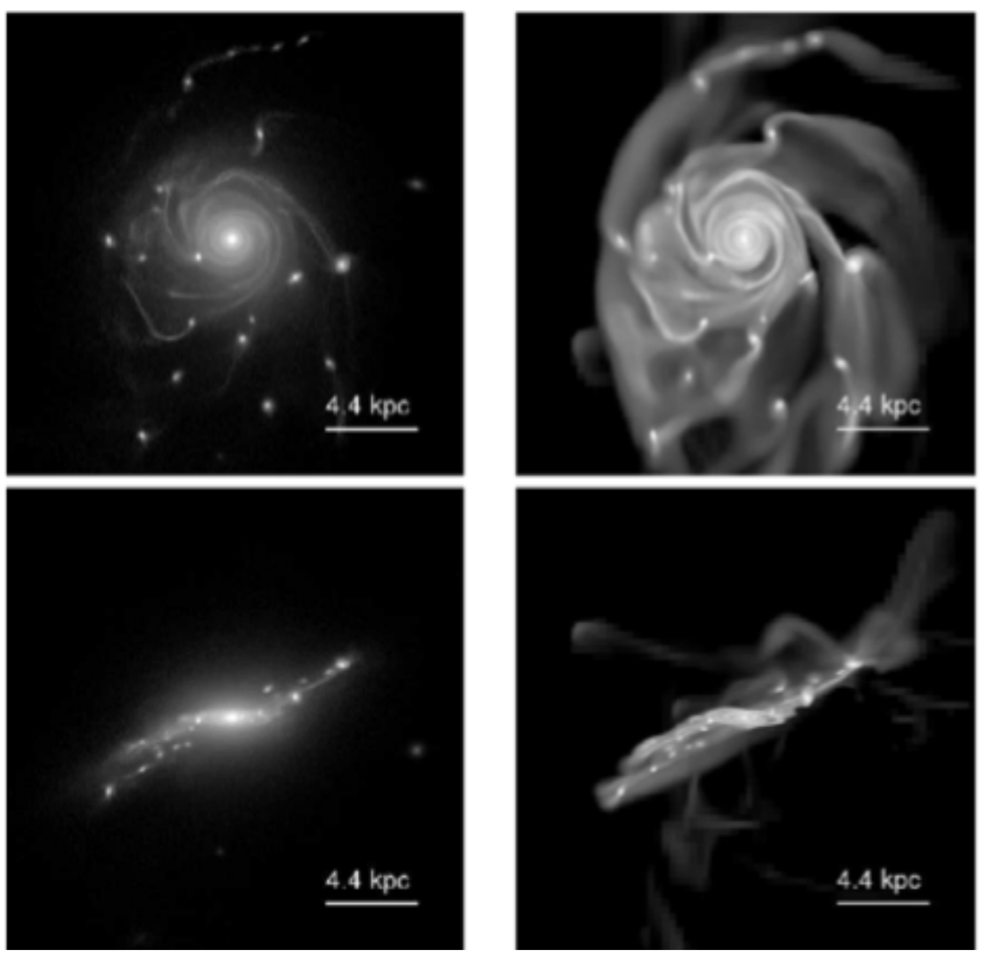
Answer: smooth, no streams almost Maxwellian



The Aquarius project, 6 halos
MNRAS 395, 2009

Including Baryons

- **But: can we ignore the baryons?**
- The dark matter only simulations have certainly established a baseline for future work
- This is an area of intense current activity



Disk formation and the origin of clumpy galaxies at high redshift

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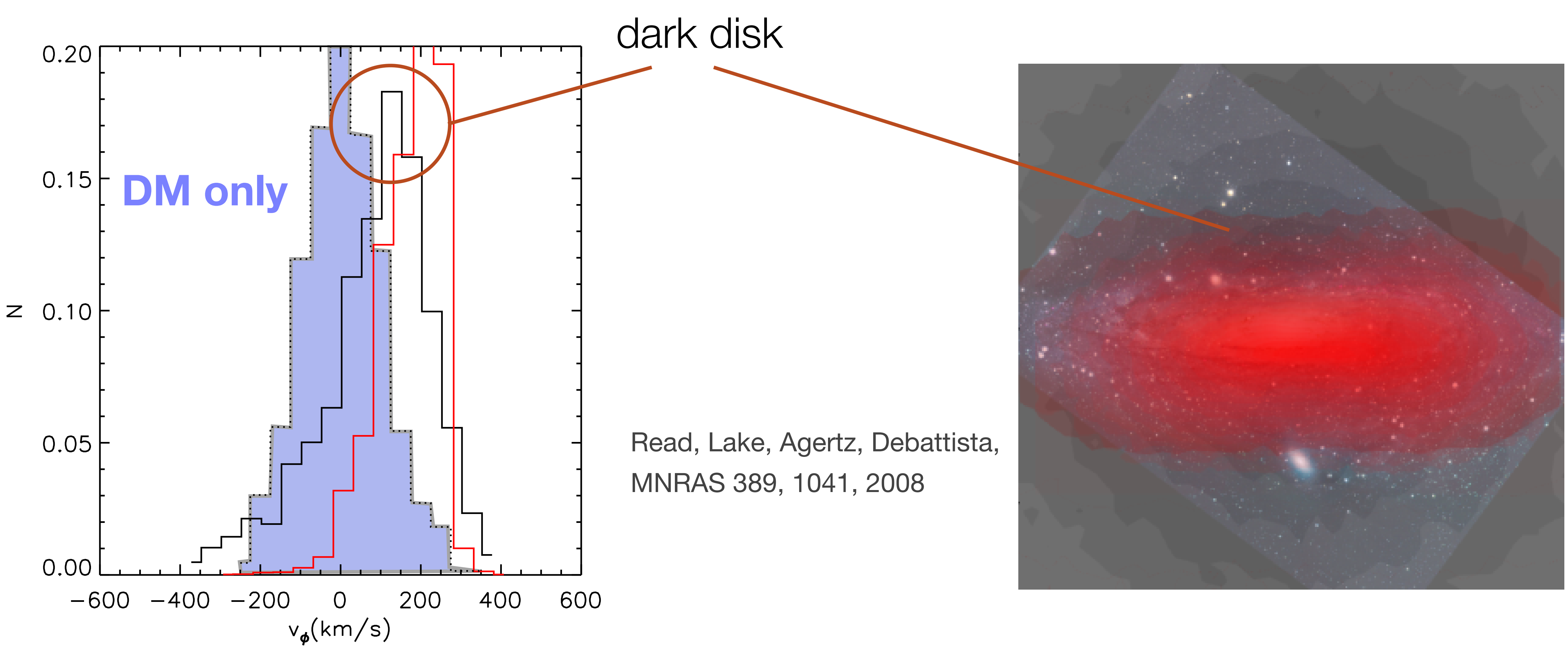
31 July 2009

Ben Moore, UZH:

By 2015 we will reach the 1 parsec resolution required to resolve the molecular disks and spatially resolved star formation.

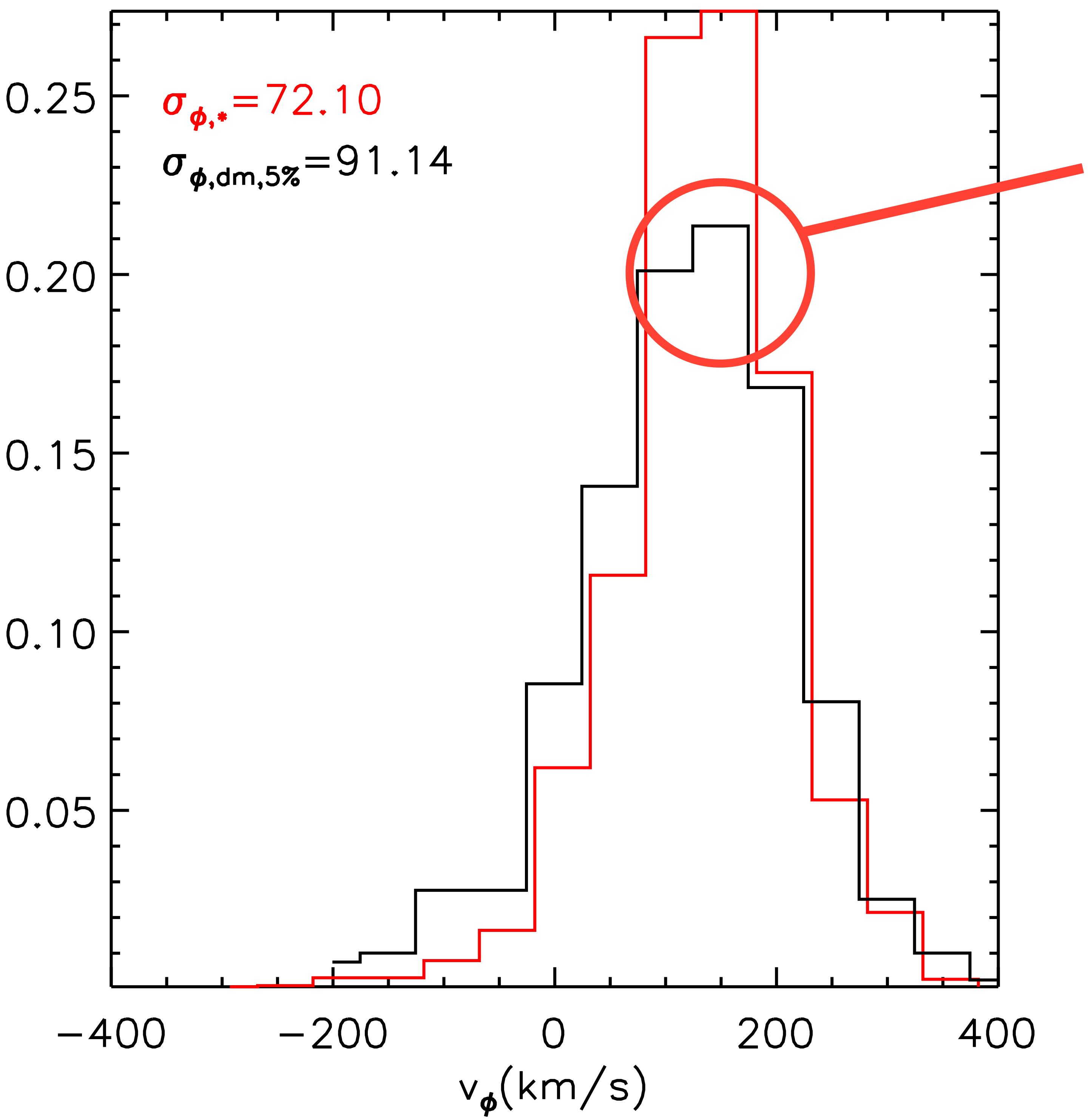
A Dark Matter Disk in the Milky Way?

- In ΛCDM numerical simulations which include the influence of baryons on the dark matter, it has been found that:
  - ➡ stars and gas settle onto the disk early on, affecting how smaller dark matter halos are accreted
  - ➡ the largest satellites are preferentially dragged towards the disk by dynamical friction, then torn apart, forming a disk of dark matter
  - ➡ in the standard cosmology, the disk dark matter density is constrained to about 0.5 - 2 x halo density
  - ➡ as we shall see, its lower rotation velocity with respect to the Earth has implications for direct detection experiments



Read, Lake, Agertz, Debattista, MNRAS 389, 1041, 2008

Detecting the dark disk: hunting for accreted stars



- Dark disk velocity matches the accreted stars
- RAVE/GAIA will obtain 6D phase space information + chemistry for a million/billion of stars in the Galaxy => hunt for the accreted stars that trace the kinematics of the dark disk

Dark Matter Candidates

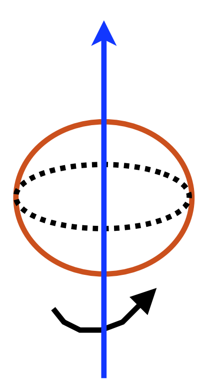
Reminder: the Standard Model Particle Content

Matter: 3 Families (Fermions)

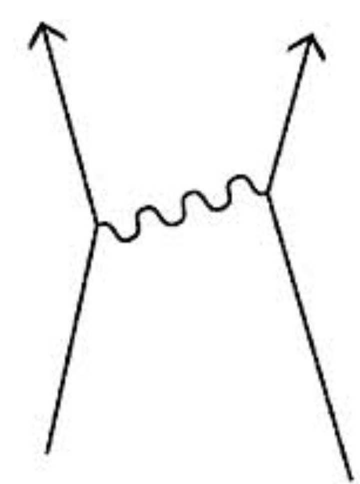
QUARKS	up	charm	top
	down	strange	bottom
LEPTONS	electron	muon	tau
	ν_e	ν_μ	ν_τ

Forces (Bosons)

Photons	Electromagnetism
Gluons	Strong force
W and Z Bosons	Weak force
Graviton	Gravitation



Leptons, Quarks
Spin 1/2



Forces are mediated by the exchange of particles

There is no candidate in the SM, which could provide the dark matter!

Dark Matter Candidates

- **New elementary particles, which could have been produced in the early Universe**
- **These are either long lived ($\tau >> t_U$) or stable**
- **Neutrinos:** they exist, but their mass is too small and there are problems with structure formation. Neutrinos are examples for **Hot Dark Matter (HDM)**: relativistic at the time of decoupling, can thus not reproduce the observed large-scale structure in the Universe
- **Axions:** $m \approx 10^{-5}$ eV; light pseudo-scalar (0^-) particle postulated in connection with the absence of CP violation in QCD
- **WIMPs** (Weakly Interacting Massive Particles): $M \approx 10$ GeV - few TeV

  these particles are examples for **Cold Dark Matter (CDM)** -> particles which were non-relativistic at the time of decoupling

  WIMP-candidates: from supersymmetry (neutralinos); from theories with universal extra dimensions (UED) (lightest Kaluza-Klein particle), and from most other theories beyond the SM
- **Superheavy dark matter** ($m \approx 10^{12}$ - 10^{16} GeV): particles which could have been produced at the end of inflation, by different mechanisms (non-thermally), with unknown interaction strength; SIMPzillas -- WIMPzillas

Neutrinos as Dark Matter Candidates

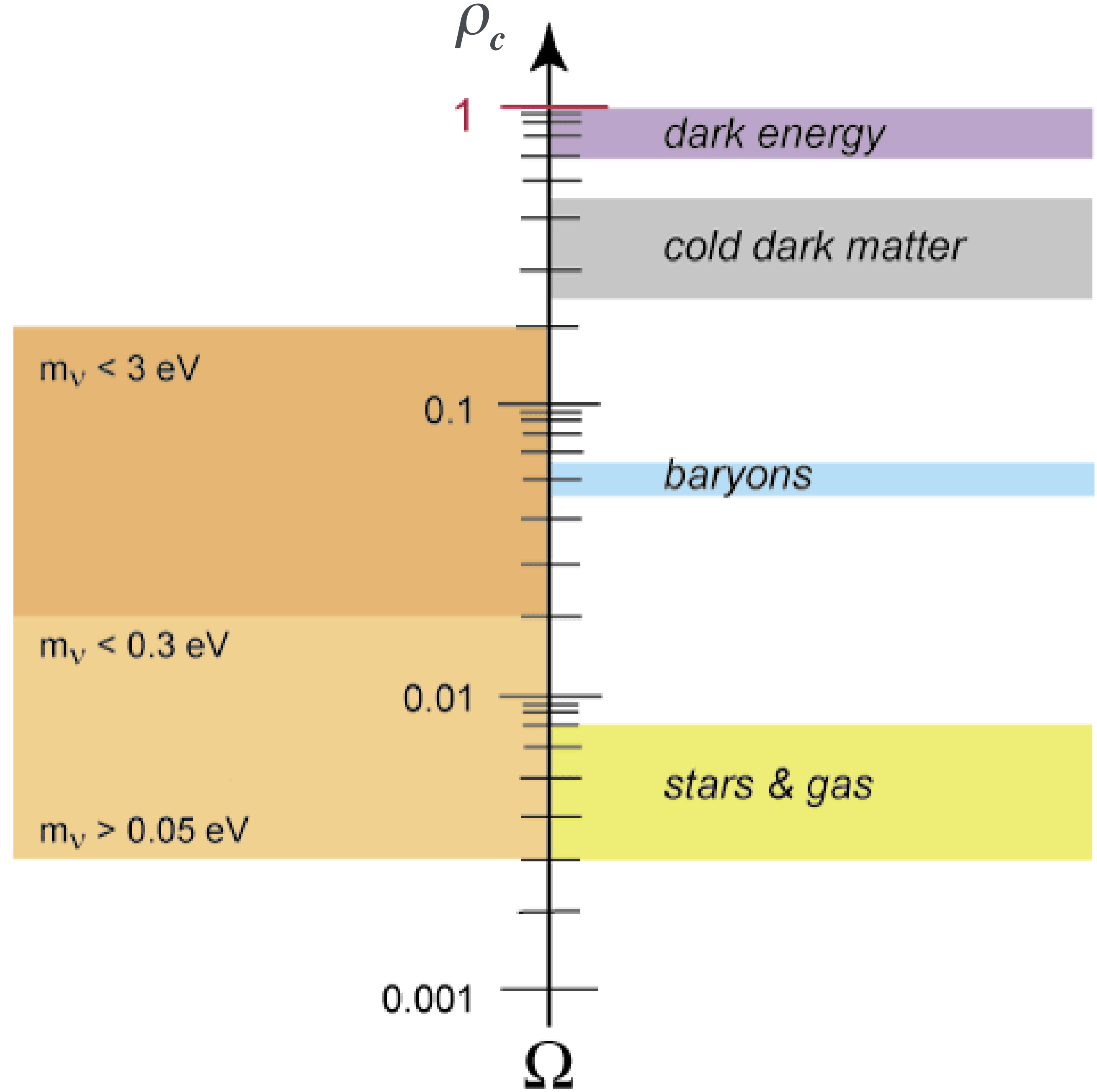
- **Neutrinos: thermal relics of the early Universe**
- **Number density: similar to photons**
  - ➡ **~ 10^9 neutrinos/proton!**
  - ➡ **~ 113 neutrinos/cm³ ! (411/cm³ for photons)**
- **Depending on their mass, neutrinos could have a (small) contribution to the dark matter**
  - ➡ direct limits on the ν_e mass (^{3}H β-decay):

$$m_{\nu_e} < 2.5\ eV$$

  - ➡ from cosmological observations:

$$\sum_i m_{\nu_i} < (0.17 - 2.0)\ eV$$

$$\Omega = \frac{\rho}{\rho_c}$$



Total density Ω in units of the critical density

Dark Matter Candidates: WIMPs

- General class of dark matter candidates: weakly interacting massive particles
- Interest in WIMPs comes from the fact that WIMPs in thermal equilibrium with the other particles in the early Universe naturally have the right abundance to be the cold dark matter
- Also, the same interactions that give the right WIMP density make the detection of WIMPs possible *(hypothesis is testable!)*
- The determination of the WIMP relic density depends on the history of the Universe before BBN (which occurred ~ 200 s after the BB, $T \approx 0.8$ MeV, and is the earliest epoch from which we have a trace, namely the abundance of light elements)
- WIMPs have their number fixed at $T_0 \approx M/20$, so WIMPs with $M_W > 100$ MeV would freeze out before BBN and would thus be the earliest remnants
- Hence, if discovered, they would give information about the pre-BBN phase of the Universe

Dark Matter Candidates: WIMPs

- To compute the WIMP relic density, one must make assumptions about the pre-BBN epoch
  - ➡ the entropy of matter and radiation were conserved
  - ➡ WIMPs were produced thermally (i.e., via interactions with particles in the plasma)
  - ➡ they decoupled while the expansion of the Universe was dominated by radiation
  - ➡ they were in thermal and chemical equilibrium before they decoupled*
- Important reactions were the production and annihilation of WIMP pairs in particle-antiparticle collisions, such as:

$$\chi\bar{\chi} \leftrightarrow e^{+}e^{-}, \mu^{+}\mu^{-}, q\bar{q}, W^{+}W^{-}, ZZ, HH, \ldots$$

**one can thus use thermodynamics to calculate the history of the early universe* (thermal equilibrium means all particle species have the same temperature; chemical equilibrium means that the chemical potentials of different particle species are related according to their reaction formulas)

Dark Matter Candidates: WIMPs

- Let us then assume that a **stable, neutral**, **massive, weakly interacting particle χ** (WIMP) with a mass **m_χ** existed in the early Universe. At early times, for $T \gg m_\chi$ the number density: $n_\chi \propto T^3$
- At lower temperatures, $T \ll m_\chi$, the equilibrium abundance is exponentially suppressed
- If the particle would have remained in thermal equilibrium until today, its abundance would be negligible:

$$\frac{n_\chi}{s} \propto \left(\frac{m_\chi}{T}\right) e^{-\frac{m_\chi}{T}}$$

n_χ = number density
s = entropy density

$s \cdot a^3$ = ct; a = cosmic scale factor

r(t) = a(t) · y, y = comoving coordinate
T = temperature

- Since the particle is stable, its **number density n_χ per comoving volume a^3** can be changed only by annihilation and inverse annihilation processes into other particles:

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

X = all the species into which the χ can annihilate (quark-antiquark pairs, lepton-antileptons, Higgs-boson pairs, gauge-boson pairs etc - depending on the WIMP mass)

Dark Matter Candidates: WIMPs

- The particles were in equilibrium as long as their **reaction rate Γ** was larger than the **expansion rate H**

$$\Gamma \gg H$$

expansion rate: $H(t) \equiv \frac{\dot{a}}{a}$, reaction rate: $\Gamma = n_\chi \langle \sigma_A v \rangle$

σ_A = total annihilation cross section
v = relative velocity of the annihilating WIMPs

$\langle \sigma_A v \rangle$: thermally averaged total cross section for annihilation into lighter particles times their relative velocity

- Once the temperature **T drops below $\mathbf{m_\chi}$**, the number density of WIMPs will drop exponentially, and the rate of annihilation Γ drops below the expansion rate H:

$$\Gamma \leq H$$

- At this point the WIMPs will cease to annihilate efficiently
- They fall out of equilibrium, and we are left with a *relic cosmological abundance ("freeze-out")*

Dark Matter Candidates: WIMPs

- One can calculate the **relic number density of the species χ** by solving the Boltzmann equation (where we have already summed over all annihilation channels), which describes the time evolution of the number density of WIMPs:

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma_A v \rangle \left(n_\chi^2 - n_{\chi(eq)}^2 \right)$$

decrease due to the Hubble expansion of the Universe

change due to annihilation and creation:
- the depletion rate due to the annihilation is ~ $n_\chi \times n_\chi$
- particles are also created by the inverse process with a rate proportional to $[n_{\chi(eq)}]^2$

n_χ = actual number density
$n_{\chi(eq)}$ = equilibrium number density

- In the absence of number-changing interactions, the term in brackets would be zero, we would find, as expected:

$$n_\chi \propto a^{-3}$$

Freeze-out of WIMPs

- In the radiation dominated era (first few 10^5 years) the **expansion rate H** is given by

$$H = 1.66\sqrt{g_{eff}}\frac{T^2}{m_{Pl}}$$

g_{eff} = effective number of relativistic degrees of freedom
$m_{Pl} \cong 10^{19}$ GeV

- and the **time-T relation** is:

$$t = 0.30\frac{m_{Pl}}{\sqrt{g_{eff}}T^2}\left(\frac{1\,MeV}{T}\right)\ \mathrm{s}$$

At t ~1 s, T ~ 10^{10}K and typical particle energies are 1 MeV

- **Goal:** obtain an **evolution equation of n_χ as a function of T**. If ones introduces the dimensionless variable **$x = m_\chi/T$** and normalizes **n_χ** to the entropy density, **$Y_\chi = n_\chi/s$** one obtains (after some steps...) for the **number density:**

$$\frac{x}{Y_{\chi(eq)}}\frac{dY_\chi}{dx} = -\frac{\Gamma_A}{H}\left[\left(\frac{Y_\chi}{Y_{\chi(eq)}}\right)^2 - 1\right]$$

where $\Gamma_A = n_{\chi(eq)}\langle\sigma_A v\rangle$

Freeze-out of WIMPs

$$\frac{x}{Y_{\chi(eq)}}\frac{dY_\chi}{dx} = -\frac{\Gamma_A}{H}\left[\left(\frac{Y_\chi}{Y_{\chi(eq)}}\right)^2 - 1\right]$$

- this equation can be solved numerically with the boundary condition that for **small x** (early times):

$$Y_\chi \sim Y_{\chi(eq)}$$

at high T the particle χ was in thermal equilibrium (all particle species have the same T) with the other particles

- As expected, the evolution is governed by $\mathbf{\Gamma_A/H}$, the interaction rate divided by the Hubble expansion rate
- **Find T_f and x_f at freeze-out, as well as the asymptotic value $Y_\chi(\infty)$ of the relic abundance**
- The freeze-out temperature turns out to be (corresponding to a typical WIMP speed at freeze-out of $v_f = (3T_f/2m_\chi)^{1/2} \approx 0.27c$):

$$T_f \simeq \frac{m_\chi}{20}$$

Freeze-out of WIMPs

- After freeze-out, the abundance per comoving volume remains constant
- The entropy per comoving volume in the Universe also remains constant, so that **n_χ/s is constant**, with $s \approx 0.4\, g_{eff}\, T^3$
- Using the relation we had for H, and the freeze-out condition $\Gamma_A = H$, one finds:

$$\left(\frac{n_\chi}{s}\right)_0 = \left(\frac{n_\chi}{s}\right)_f \simeq \frac{100}{m_\chi m_{Pl} g_{eff}^{1/2} \langle \sigma_A v \rangle} \simeq \frac{10^{-8}}{(m_\chi/GeV)(\langle \sigma_A v \rangle / 10^{-27} cm^3 s^{-1})}$$

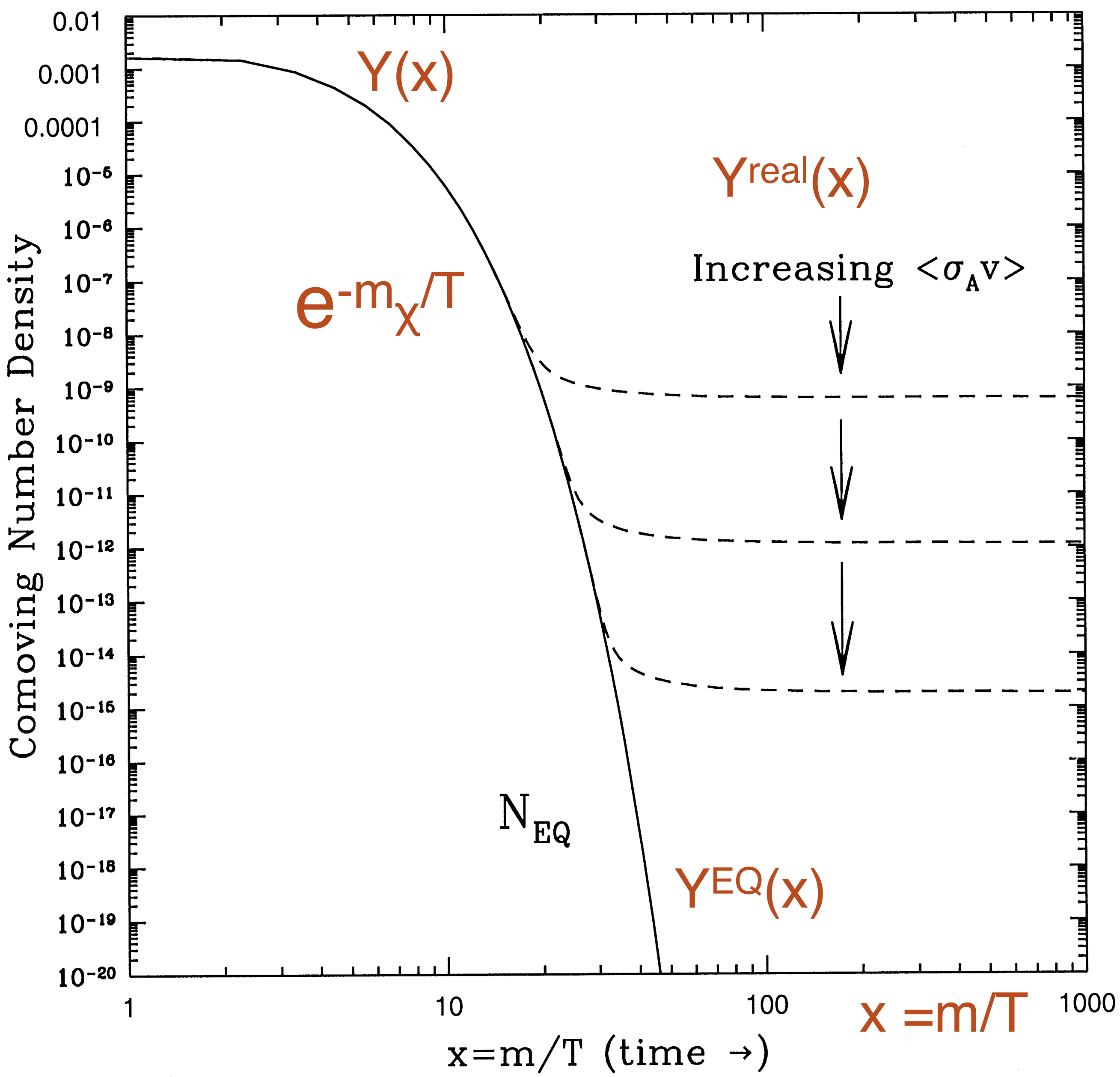
f -- value at freeze-out
0 -- value today

- The current entropy density: $s_0 \approx 4000\ cm^{-3}$ and $\rho_c \approx 10^{-5}\ h^2\ GeV\ cm^{-3}$ [h = H/(100 km s^{-1} Mpc^{-1})]
- One finds then for the present mass density in units of the critical density ρ_c:

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \simeq 3 \times 10^{-27} cm^3 s^{-1} \frac{1}{\langle \sigma_A v \rangle}$$

- This is independent of the WIMP mass, and inversely proportional to the annihilation cross section

Mass of a Thermal Relic Particle



If a relic particle exists, its abundance will be:

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \frac{3\times 10^{-27}\, cm^3 s^{-1}}{\langle \sigma_A \mathrm{v} \rangle}$$

For a new particle with a weak-scale interaction, we have:

$$\langle \sigma_A \mathrm{v} \rangle \propto \frac{\alpha^2}{m_\chi^2} \approx \frac{\alpha^2}{(100 GeV)^2} \approx 10^{-25}\, cm^3 s^{-1}$$

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

Close to the value required for the dark matter in the Universe!

⇒ the observed relic density points to the **weak scale!**

Dark Matter Candidates from Supersymmetry

Supersymmetry

New fundamental space-time symmetry that relates the properties of fermions ⇔ bosons

⇒ SM particles get superpartners (differ in spin by 1/2, otherwise same quantum numbers)

Ordinary Particles	**Supersymmetric Partners**
Higgs Boson (spin 0)	Higgsino (spin 1/2)
Fermions (spin 1/2) Quarks · Leptons	Bosons (spin 0) Squarks · Sleptons
Gauge Bosons (spin 1) $W^{\pm}$ · Z, B gluons, photons *charged* · *neutral*	Gauginos (spin 1/2) Winos · Zinos, Binos gluinos, photinos *charginos* · *neutralinos*
Graviton (spin 2)	Gravitino (spin 3/2)

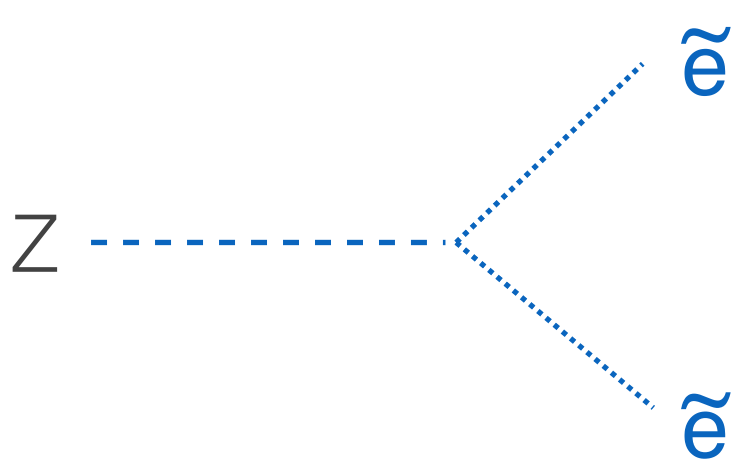
Once we include interactions, the SUSY particles will acquire interactions similar to those of the quarks and leptons.
Example: the spin-0 squarks and sleptons couple to the photon and the Z-boson in the same way as quarks and leptons

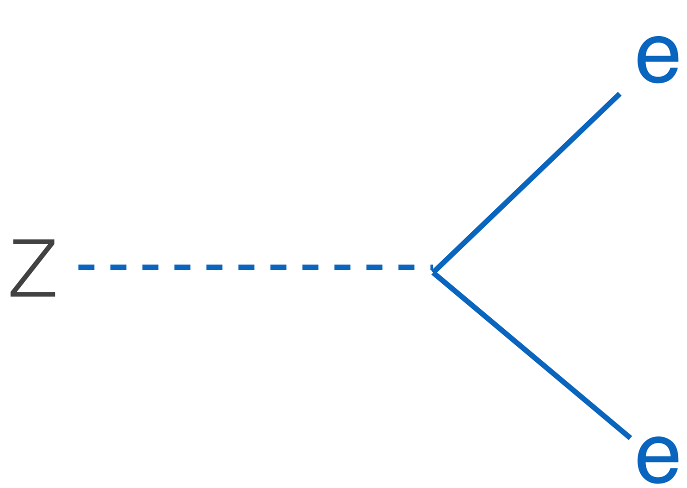
Supersymmetry

- **Stabilizes the hierarchy problem:**
  weak scale (200 GeV) …. GUT scale (10^{16} GeV)…. Planck scale (10^{19} GeV): radiative corrections to the masses of scalar particles (for instance the Higgs) are quadratically divergent, but in SUSY the corrections due to fermions and bosons cancel, thereby stabilizing existing mass hierarchies
  [SUSY does not explain why the ratio between weak and the GUT and/or Plack scale is so small]

- **Promises unification of gauge couplings at GUT scale** [if the superpartner masses are in the range 100 GeV - 10 TeV]

- If SUSY was exact, the squarks and sleptons would have the same mass as the quarks and leptons => would contribute to the Z-decay width
- **no SUSY particles have been observed so far => the symmetry must be broken**
- **is it still relevant?**





Supersymmetry

- The SUSY breaking scale must be around the TeV scale to ensure that the EWSB scale is not destabilized by quadratic divergencies coming from a higher scale (there are several possible mechanisms for this, introducing uncertainties in the low-energy predictions of SUSY)
- The dynamics of SUSY breaking are yet to be discovered; it is assumed that the breaking occurs in a 'hidden sector' [a sector of the theory which is decoupled from our world of q, l, Higgs bosons and their superpartners]

- Can we still solve the hierarchy problem?

- The cancellation of quadratic divergencies persists even if SUSY is not exact, but is 'softly' broken (only a certain subset of SUSY-breaking terms are present in the theory; these must be gauge invariant). The couplings of these operators = 'soft parameters', and the part of the Lagrangian containing these terms = **the soft SUSY breaking Lagrangian**

$$L = L_{SUSY} + L_{soft}$$

L_{soft} contains 105 new parameters

it includes mass terms for all superpartners (if all the mass eigenstates would be measured, 32 of the 105 parameters would be determined).

The MSSM: Simplest SUSY Extension to the SM

- **The Minimal Supersymmetric Standard Model:** phenomenological model; contains the smallest number of new particles and new interactions consistent with phenomenology + all possible supersymmetry breaking soft terms (the origin of which is not specified -> the uncertainty in these terms comes from the lack of knowledge of the SUSY breaking mechanism)
- **The gauge symmetry group is the one of the Standard Model:**

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

- We need now **two Higgs duplets** to give mass to up- and down-type quarks

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

- Their vacuum expectation values are:

$$\langle H_d \rangle = \begin{pmatrix} \mathrm{v}_d \\ 0 \end{pmatrix}, \quad \langle H_u \rangle = \begin{pmatrix} 0 \\ \mathrm{v}_u \end{pmatrix}$$

- with:

$$\mathrm{v}_d^2 + \mathrm{v}_u^2 = \mathrm{v}^2, \quad \mathrm{v} = 174 \text{ GeV and } \tan\beta = \frac{\mathrm{v}_u}{\mathrm{v}_d} \qquad 0 \le \beta \le \frac{\pi}{2}$$

The MSSM

- **In the Standard Model:** we have a single Higgs duplet => one scalar field, as 3 components were 'eaten' by the then massive EW gauge bosons (the photon remains massless)
- **In the MSSM:** 3 components are 'eaten' => 5 physical Higgs bosons
  - ➡ 2 real scalars: h, H
  - ➡ 1 pseudo-scalar: A
  - ➡ 2 charged Higgs: $H^{\pm}$
- It is predicted that the lightest Higgs mass (h) is $m_h \leq 135$ GeV -> testable at LHC!

Standard Model particles and fields		Supersymmetric partners			
		Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^{\pm}$	W-boson	$\tilde{W}^{\pm}$	wino		
H^-	Higgs boson	$\tilde{H}_1^-$	higgsino	$\tilde{\chi}_{1,2}^{\pm}$	chargino
H^+	Higgs boson	$\tilde{H}_2^+$	higgsino		
B	B-field	$\tilde{B}$	bino		
W^3	W^3-field	$\tilde{W}^3$	wino		
H_1^0	Higgs boson			$\tilde{\chi}_{1,2,3,4}^0$	neutralino
H_2^0	Higgs boson	$\tilde{H}_1^0$	higgsino		
H_3^0	Higgs boson	$\tilde{H}_2^0$	higgsino		

R-Parity

- Even the minimal superpotential (including the minimal particle and field content) has terms that violate lepton and baryon number by one unit, for instance through decays such as:

$$p \to e^+ + \pi^0$$

$$p \to \mu^+ + \pi^0$$

- **To prevent rapid proton decay, a discrete symmetry, R-parity, is imposed:**

$$R = (-1)^{3B+L+2s}$$

B = baryon number
L = lepton number
s = spin

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B = baryon number
L = lepton number
s = spin

electron: B=0, L=1, s=1/2 => R = $(-1)^2$ = 1

photon: B=0, L=0, s=1 => R = $(-1)^2$ = 1

R-Parity

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s = spin

electron: B=0, L=1, s=1/2 => R = $(-1)^2$ = 1

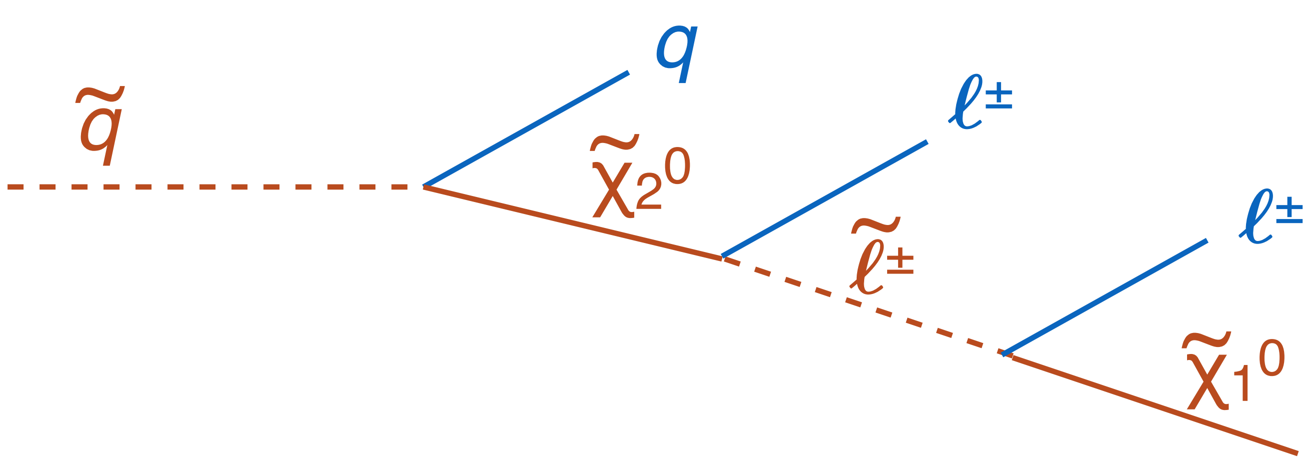
photon: B=0, L=0, s=1 => R = $(-1)^2$ = 1

selectron: B=0, L= 1, s=0 => R = $(-1)^1$ = -1

photino: B=0, L=0, s=1/2 => R = $(-1)^1$ = -1

R-Parity

- If R-parity is exactly conserved, then all lepton- and baryon-violating terms in the superpotential must be absent
  - ➡ R = + 1 for SM particles (even)
  - ➡ R = - 1 for SUSY particles (odd) - they have the same B, L quantum numbers, but differ by 1/2 units of spin)
- **Implications of R-parity conservation:**
  - ➡ at any vertex, superparticles will enter in pairs => when a superparticle decays, the decay products will contain at least one superparticle:



  - ➡ **the lightest sparticle (LSP), R = -1, is absolutely stable**
- The LSP thus naturally becomes a viable dark matter candidate: it is neutral, a color singlet and must interact only very weakly with other particles
- **Examples:** the sneutrino, the gravitino, the neutralino

The Lightest SUSY Particle

- **Sneutrinos**: cosmologically interesting if mass region 550 GeV - 2300 GeV
  - ➡ but scattering cross section is much larger than the limits found by direct detection experiments!

- **Gravitinos**: superpartner of the graviton; only gravitational interactions, very difficult to observe. Also, can pose problems for cosmology (overproduction in the early Universe, destroy abundance of primordial elements in some scenarios)

- **Neutralinos**: by far the most interesting dark matter candidates!.The superpartners of the B, W^3 gauge bosons and the neutral Higgs bosons mix into 4 Majorana fermionic eigenstates called neutralinos. The neutralino mass matrix:

$$M_{\tilde{\chi}_i^0} = \begin{pmatrix} m_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & m_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

$c_\beta = \cos(\beta)$, $s_\beta = \sin(\beta)$
$c_W = \cos(\theta_W)$, $s_W = \sin(\theta_W)$

$\tan(\beta) = v_u/v_d$

μ = higgsino mass parameter in the superpotential

m_1, m_2 = bino, wino mass parameters

The Lightest SUSY Particle

- **The lightest neutralino:** a linear combination

$$\chi_1^0 = \alpha_1 \tilde{B} + \alpha_2 \tilde{W} + \alpha_3 \tilde{H}_u^0 + \alpha_4 \tilde{H}_d^0$$

- **Its most relevant interactions for dark matter searches are:**
  ➡ self-annihilation and co-annihilation
  ➡ elastic scattering off nucleons

- Neutralinos are expected to be extremely non-relativistic in the present epoch, so one can keep only the *a-term* in the expansion of the annihilation cross section:

$$\sigma \mathrm{v} = a + b\mathrm{v}^2 + O(\mathrm{v}^4)$$

- **At low velocities, the leading channels for neutralino annihilations are to:**
  ➡ fermion-antifermion pairs
  ➡ gauge boson pairs
  ➡ final states containing the Higgs boson

Supersymmetric Models

- MSSM: although relatively simple, it contains more than 100 free parameters
- For practical studies, the number of free parameters needs to be reduced by (theoretically motivated) assumptions

- **In general, there are 2 philosophies:**

- **top-down approach:** set boundary conditions at the GUT scale, run the renormalization group equations (RGEs) down to the weak scale in order to derive the low-energy MSSM parameters relevant for colliders and dark matter searches. The initial conditions for the RGEs depend on the mechanism by which SUSY breaking is mediated to the effective low energy theory (for example, models with gravity-mediated and gauge-mediated SUSY breaking)

- **bottom-up approach:** in the absence of a fundamental theory of supersymmetry breaking, 'fix' the parameters at the weak scale (for instance, assume that the mass parameters are generation-independent)

Supersymmetric Models

- **The minimal supergravity (mSUGRA) model:** phenomenological model based on a series of theoretical assumptions, namely MSSM parameters obey a set of boundary conditions at the GUT scale:
- **Gauge coupling unification:**

$$\alpha_1(M_U) = \alpha_2(M_U) = \alpha_3(M_U) = \alpha_U$$

- **Unification of gaugino masses:**

$$m_1(U) = m_2(U) = m_3(U) = m_{1/2}$$

- **Universal scalar masses:**

  sfermion and higgs boson masses m_0

- **Universal trilinear coupling:**

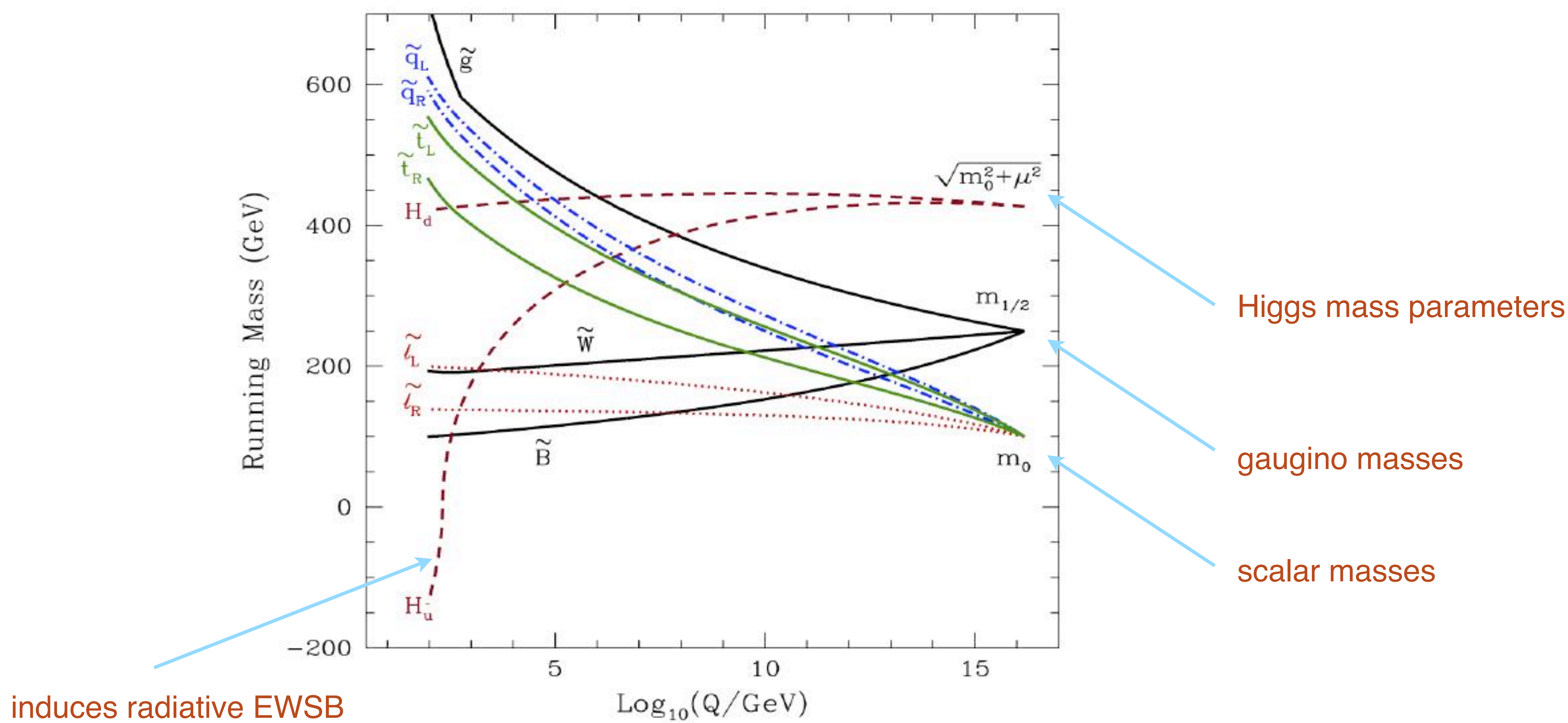
$$A_u(U) = A_d(U) = A_l(U) = A_0$$

- **Five free parameters:**

$$\tan\beta,\ \ m_{1/2},\ \ m_0,\ \ A_0,\ \ \mathrm{sign}(\mu)$$

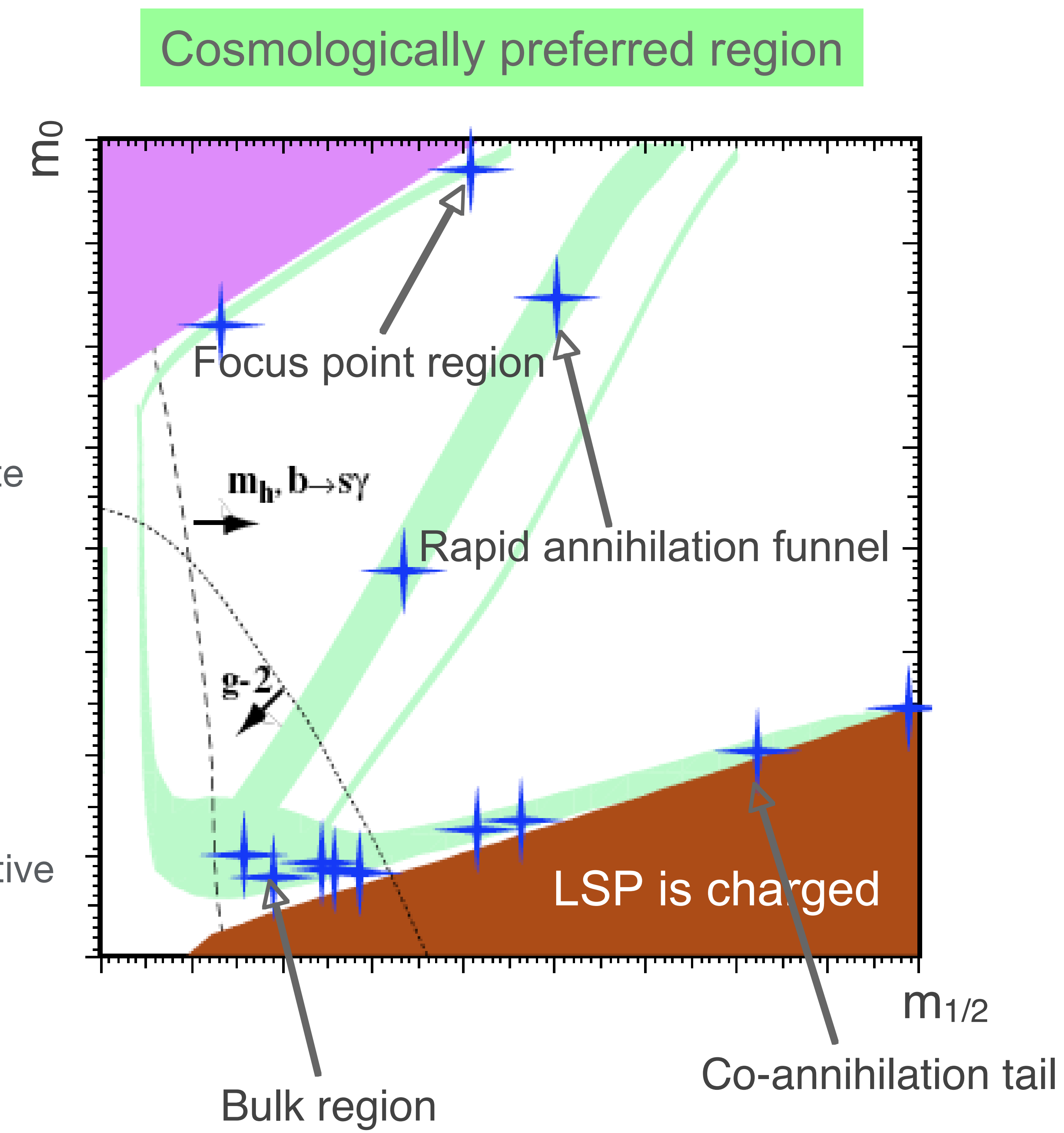
Supersymmetric Models

- Evolution of gaugino masses, scalar masses and Higgs boson mass parameters from the GUT scale ($M_{GUT} \approx 2 \times 10^{16}$ GeV) to the weak scale ($M_{weak} \approx 1$ TeV): **from few input parameters, all the masses of the superparticles are determined**

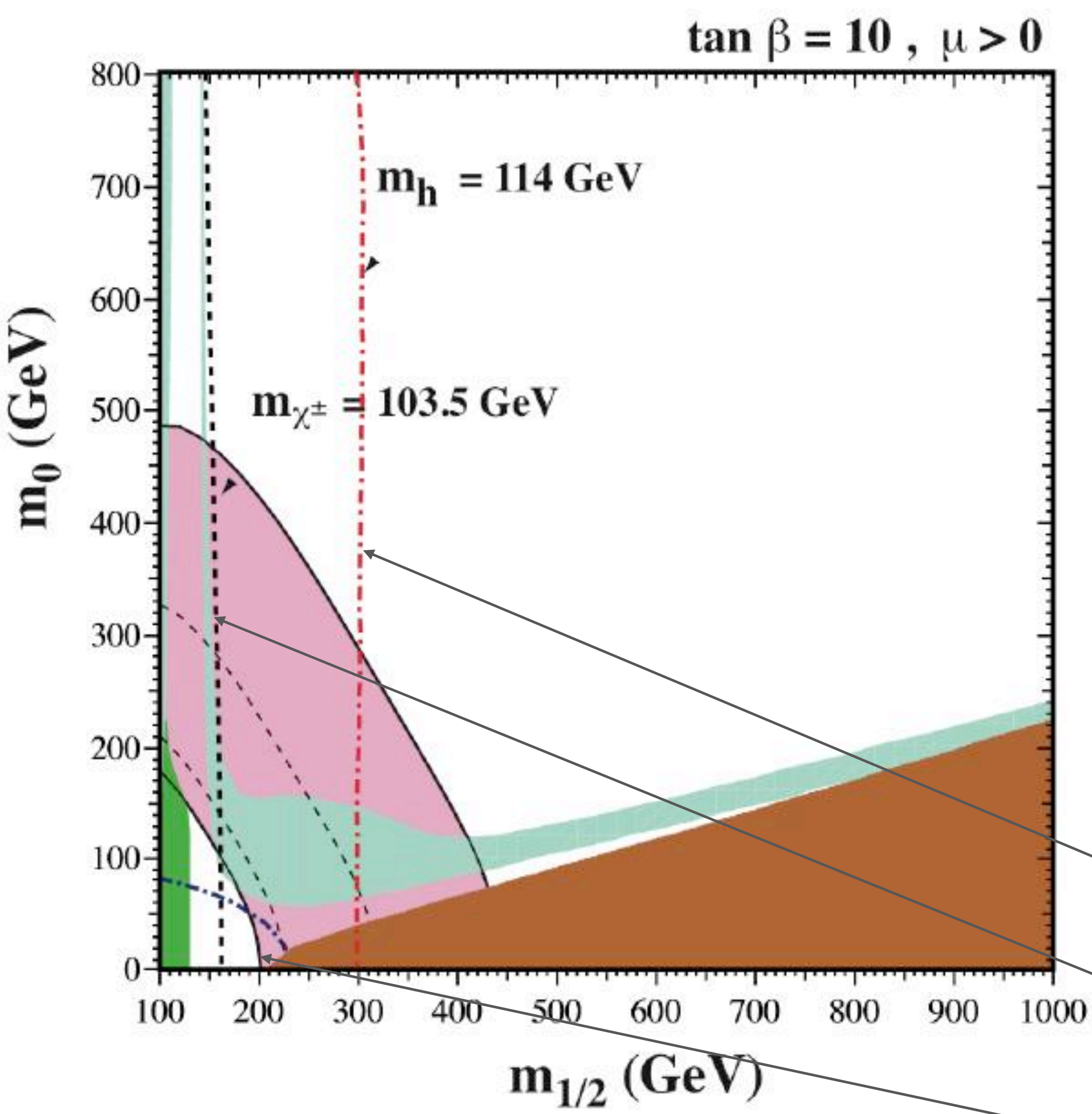


Supersymmetric Models

- **Benchmark scenarios:**
- the parameters of models with an acceptable cosmological relic density falls in one of the regions shown here
- **Co-annihilation tail:** the mass of the neutralino and the stau are nearly degenerate
- **Rapid annihilation funnel:** the mass of the neutralino is close to one-half of the mass of A (pseudo-scalar Higgs)
- **Focus point region**: at high values of m_0 (edge of parameter space allowing for radiative EW symmetry breaking)



Constraints on SUSY



mSUGRA model:

Brown region: LSP is a selectron, thus not a viable DM candidate

Green region: excluded by b -> sγ constraint

Long blue region: provides a relic density of $0.1 \leq \Omega h^2 \leq 0.3$

Pink region: 2σ range for g_μ-2 (dashed curves = 1σ bound)

Limit on Higgs mass from LEP2

Limit on chargino mass from LEP2

99 GeV selectron mass contour from LEP2

Dark Matter Candidates from Universal Extra Dimensions

Universal Extra Dimensions

- UED: all SM particles propagate into flat extra dimensions (R^{-1} ~ TeV)

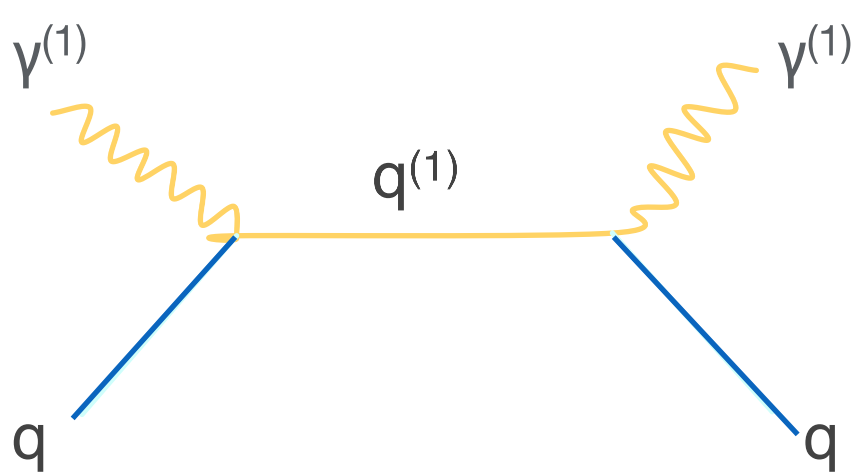
- for each SM particle => infinite tower of partner states with the same quantum numbers (identical spins, identical couplings) and with unknown masses:

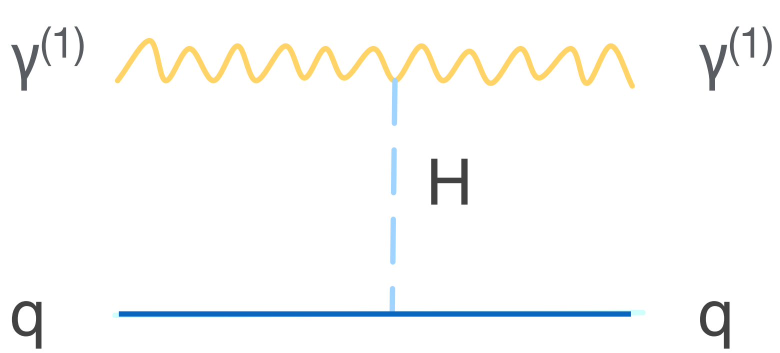
$$m_n^2 \propto \frac{n^2}{R^2} \qquad n = 0 \rightarrow \text{SM particles}$$

- **Translational invariance along the 5th dimension:**
  - ➡ discrete symmetry called Kaluza-Klein parity $P_{kk} = (-1)^n$
  - ➡ the lightest KK-mode is stable
  - ➡ the LKP yields a good dark matter candidate

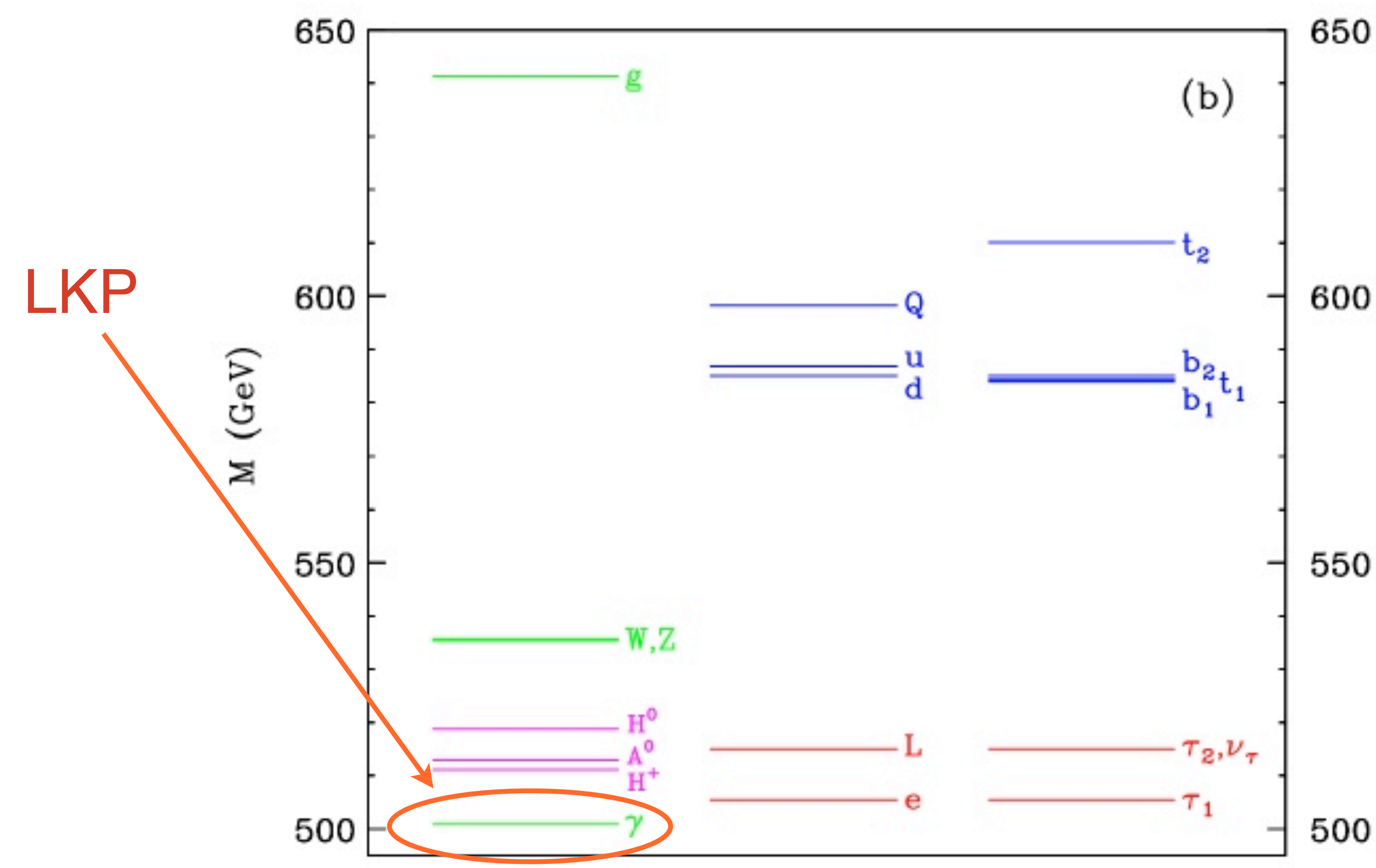
Universal Extra Dimensions: the LKP

- The lightest Kaluza-Klein particle is most likely the $\gamma^{(1)}$
  - ➡ however other candidates are possible ($\nu^{(1)}$, $Z^{(1)}$, $H^{(1)}$,...)





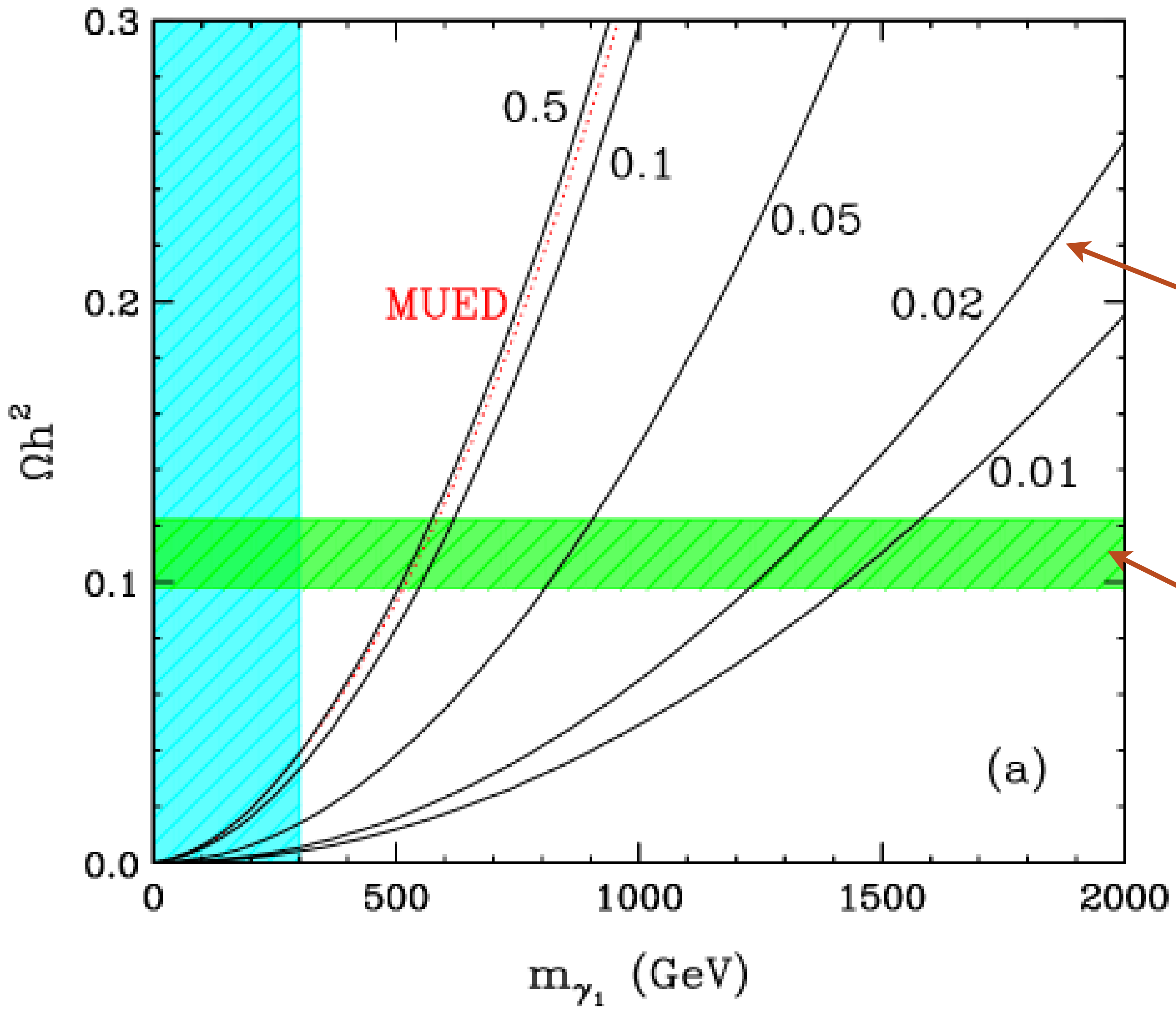
1st KK-mode spectrum from Cheng, Matchev, Schmalz, PRD66 (2002)



LKP Relic Density

- The relic density of the LKP has been calculated including all co-annihilation processes (when the LKP is nearly degenerate with other particles, its relic abundance is determined not only by its self-annihilation cross section, but also by annihilation processes involving other particles)

K. Kong, K. Matchev,JHEP 0601 (2006)



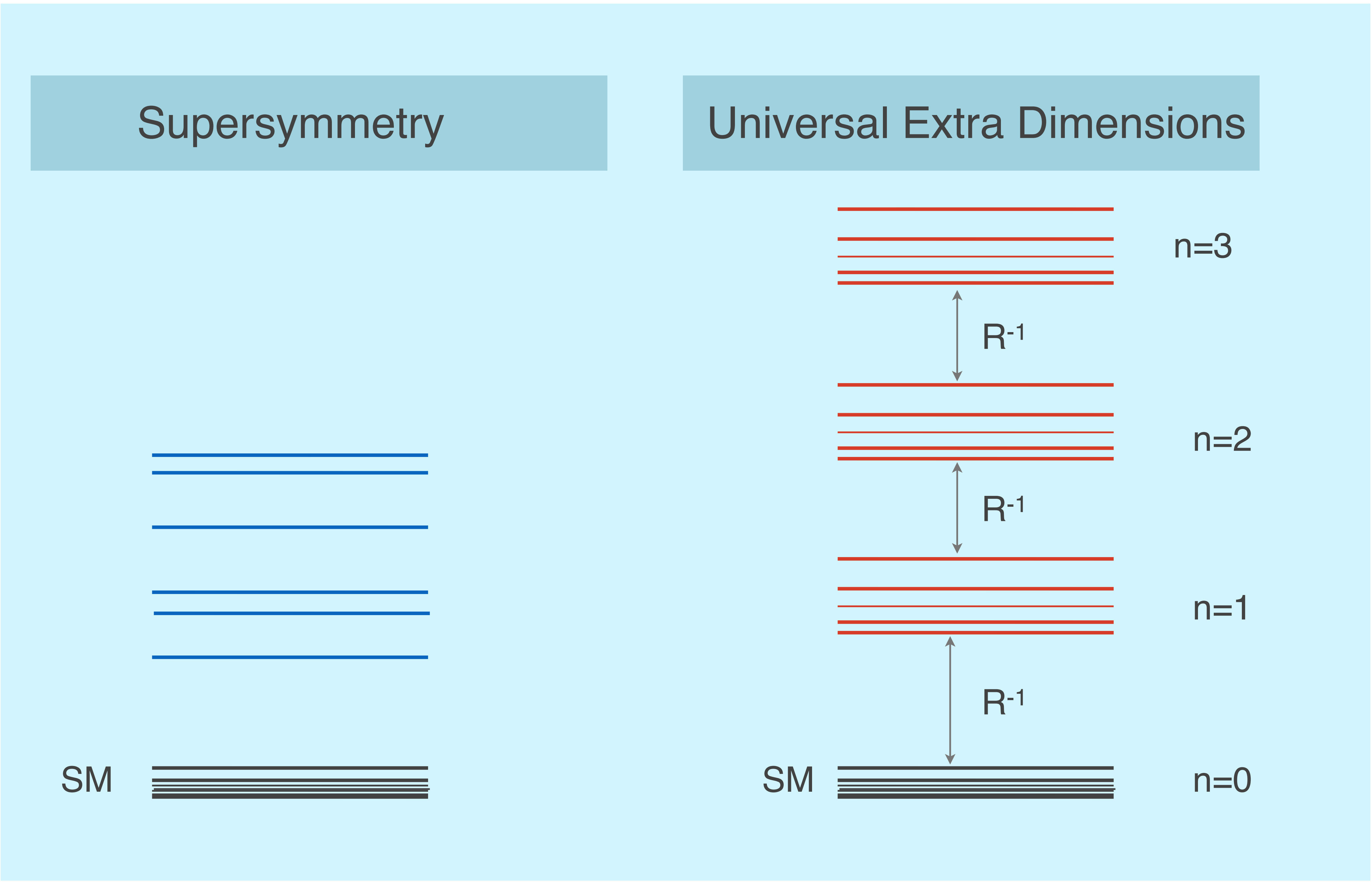
The mass splitting between the LPK and the KK-quarks (given by radiative corrections and boundary interactions at the cutoff scale Λ) **is taken as a free parameter:**

$$\Delta_{q(1)} = \frac{m_{q(1)} - m_{LKP}}{m_{LKP}}$$

Relic density region preferred by WMAP:

$$0.1037 < \Omega_{CDM} h^2 < 0.1161$$

SUSY and UED



LSP, spin-1/2

LKP, spin-1

End