Dark Matter
Lecture 1: Evidence and candidates

September 14, 2009
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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
- **Candidates for dark matter**

  Neutrinos

  WIMPs and freeze-out

  candidates from supersymmetry

  allowed parameter space in a constrained SUSY model
- **Overview: detection methods**

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**

    quenching factors and background discrimination

    main background sources in direct detection experiments

    detector strategies

Content: third lecture

- **Overview of experimental techniques**

  status of experiments, comparison with theoretical predictions

- **Cryogenic experiments at mK temperatures**

  Principles

  Examples of running experiments: CDMS, CRESST, EDELWEISS

  Near future projects

- **Liquid Noble Elements Experiments**

  Principles

  Examples of running experiments: XENON, ZEPLIN, LUX

  Near future projects

- **Directional detectors**

  principles and examples

- **Room Temperature scintillators**

  Principles

  Examples: DAMA/LIBRA, KIMS

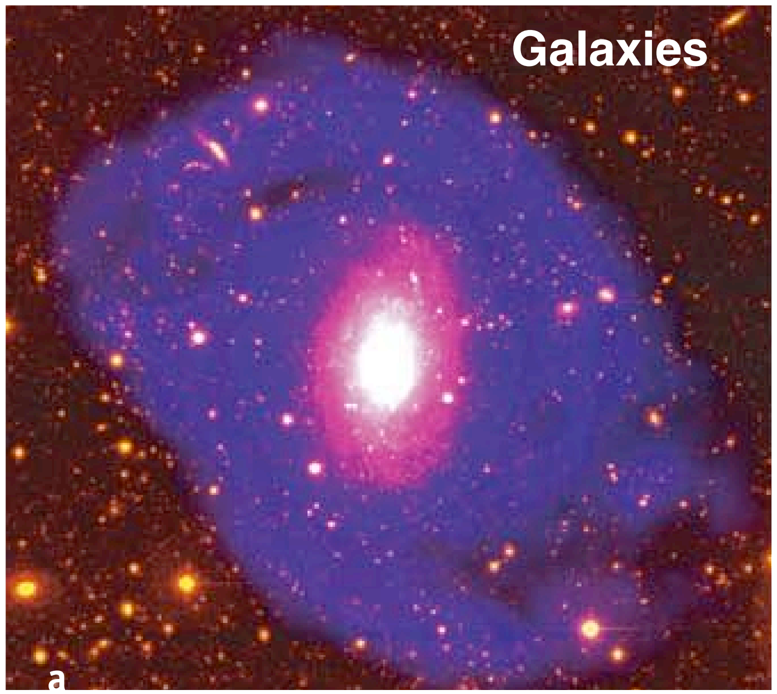
- **Bubble chambers**

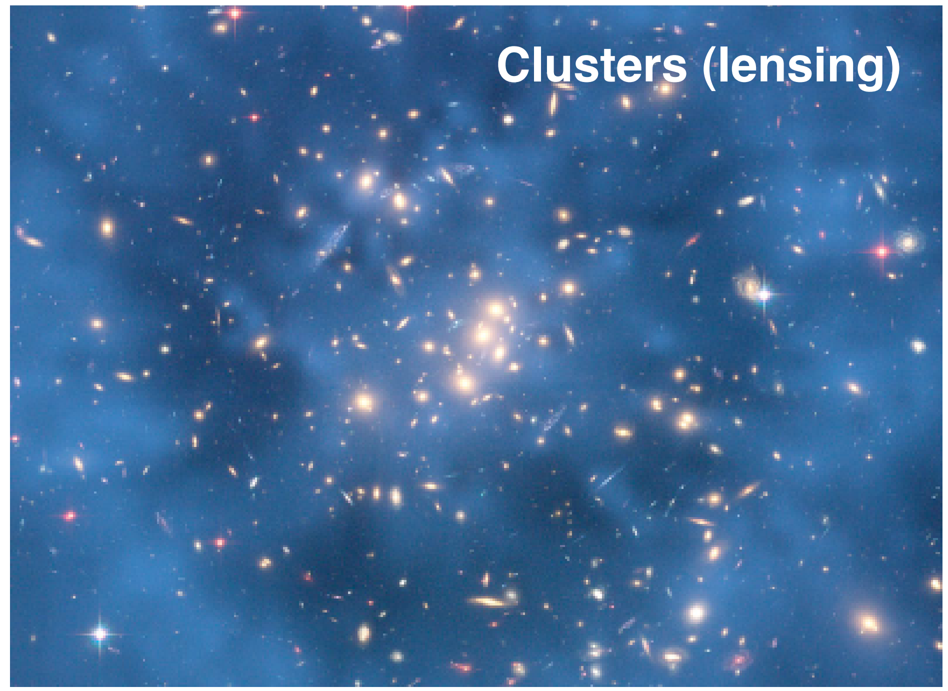
  Principles, example: COUPP

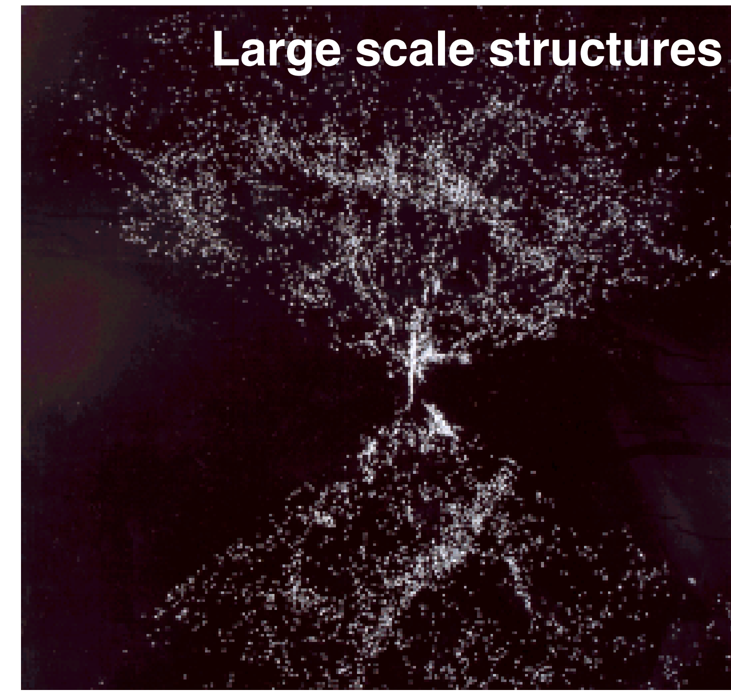
Literature

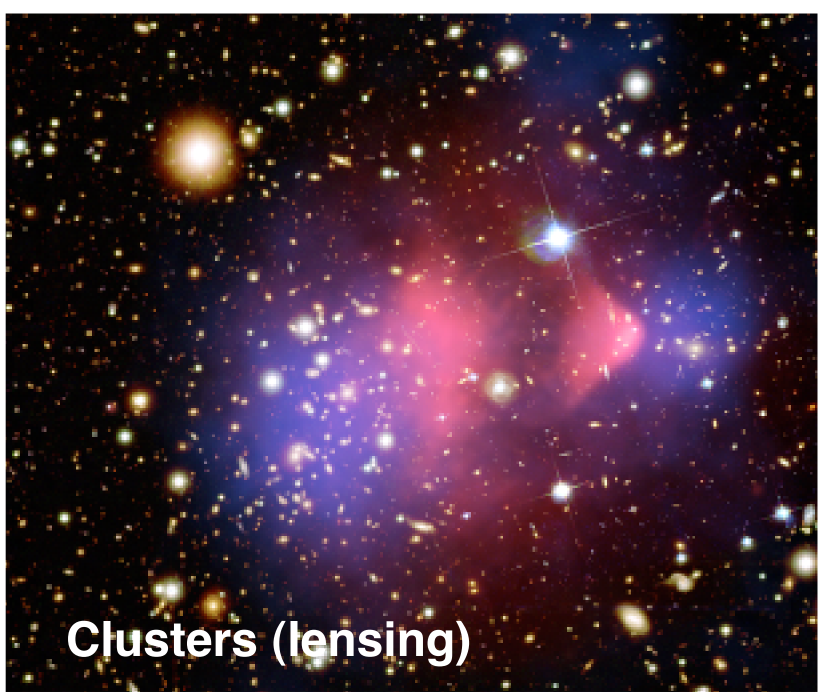
1. “Particle Dark Matter”, editor Gianfranco Bertone; to appear in Cambridge University Press, December 2009
2. Cold thermal relics: *“The Early Universe”*, by Edward W. Kolb, Michael S. Turner, Addison Wesley, 1990
3. Introduction to supersymmetry: *“Weak Scale Supersymmetry”*, by Howard Baer, Xerxes 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

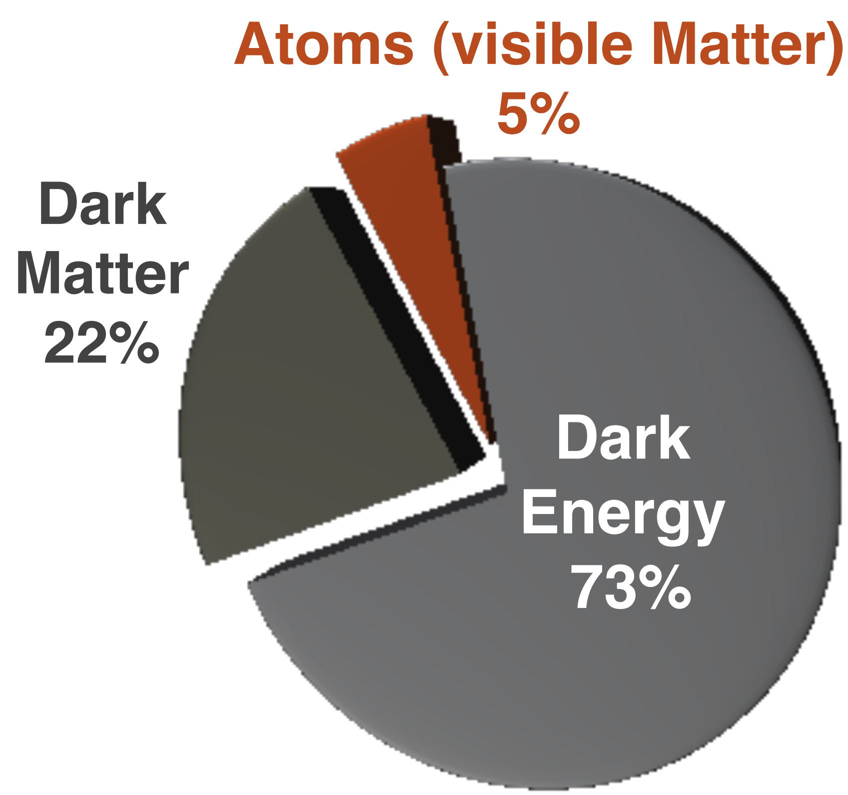
The Standard Model of Cosmology

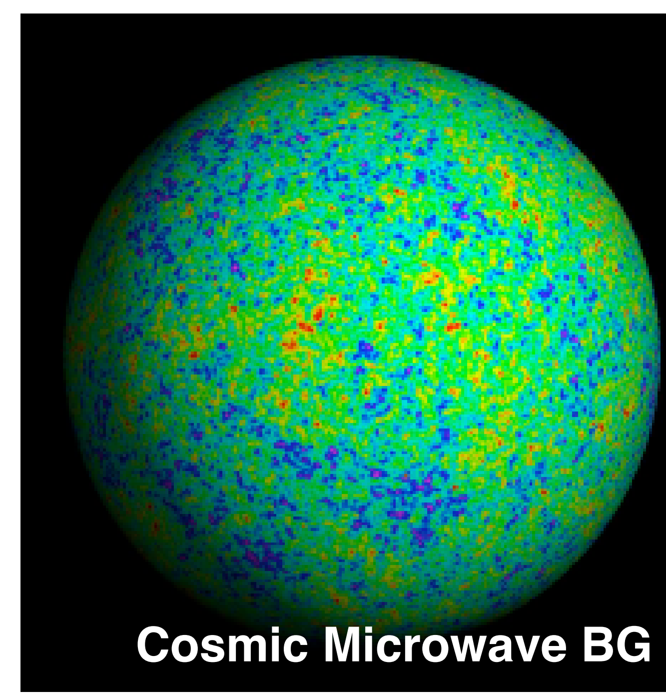












The Standard Model of Cosmology

- **Cosmological Parameters (WMAP5)**
  - ➡ Total matter and energy density: $\Omega_{tot} = 1.02 \pm 0.02$
  - ➡ Total matter density: $\Omega_m = 0.258 \pm 0.030$
  - ➡ Density of baryons: $\Omega_b = 0.0441 \pm 0.0030$
  - ➡ Energy density of the vacuum: $\Omega_\Lambda = 0.742 \pm 0.030$
  - ➡ Hubble constant: H = 100 h km/s/Mpc ; h = 0.719 + 0.026 -0.027
  - ➡ Age of the Universe: $\tau_U = 13.69 \pm 0.13$ Gy

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

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

density parameter

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

critical density $\rho_c \sim 6\ H - Atoms / m^3$

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

expansion rate

Dark Matter in the Milky Way

Structure of the Milky Way

- **The Milky Way consists of:**

  galactic disk

  galactic bulge

  visible (stellar) halo

  dark halo

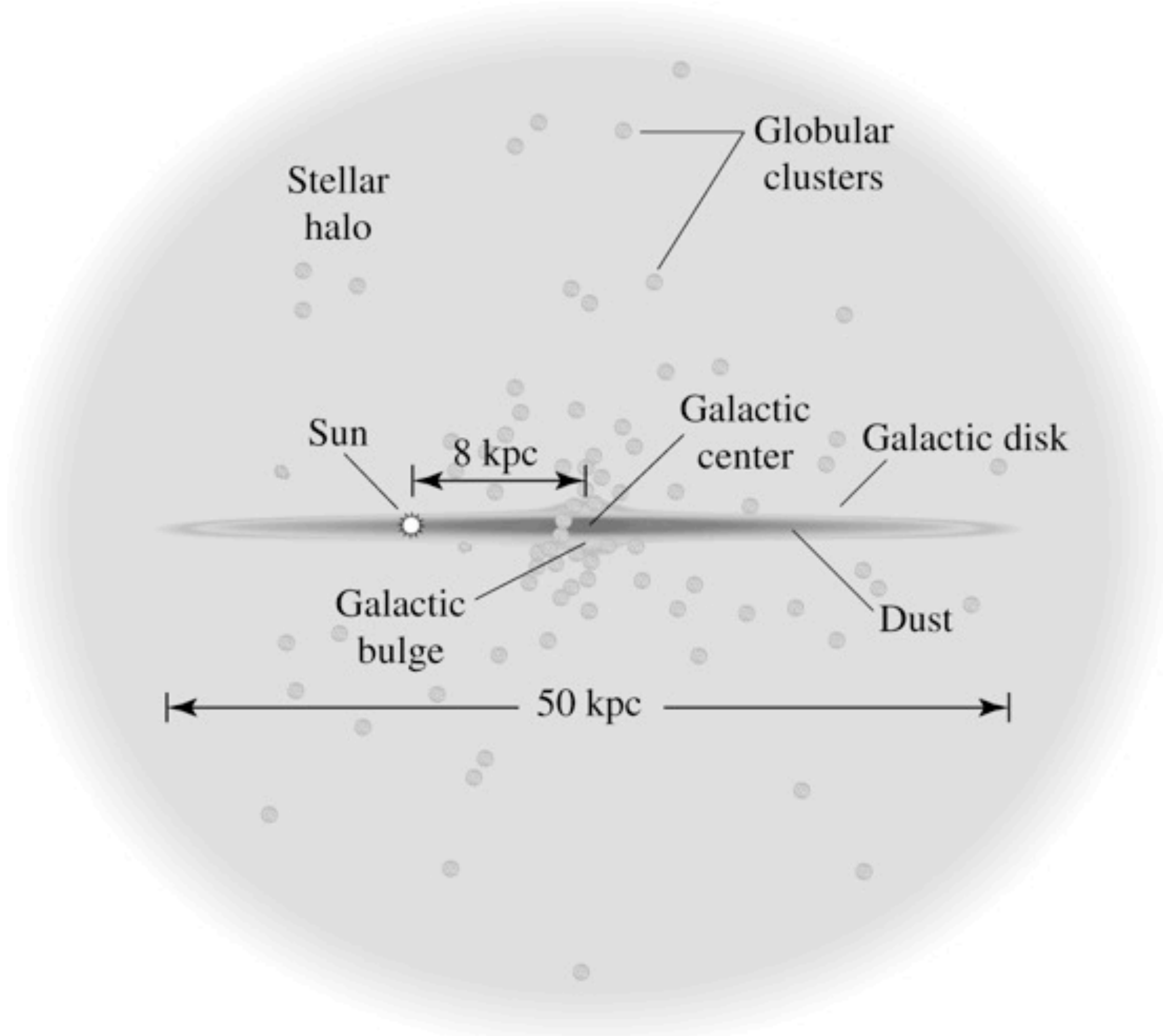
  dark disk (new!)

- **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 is: D ≈ 50 kpc**



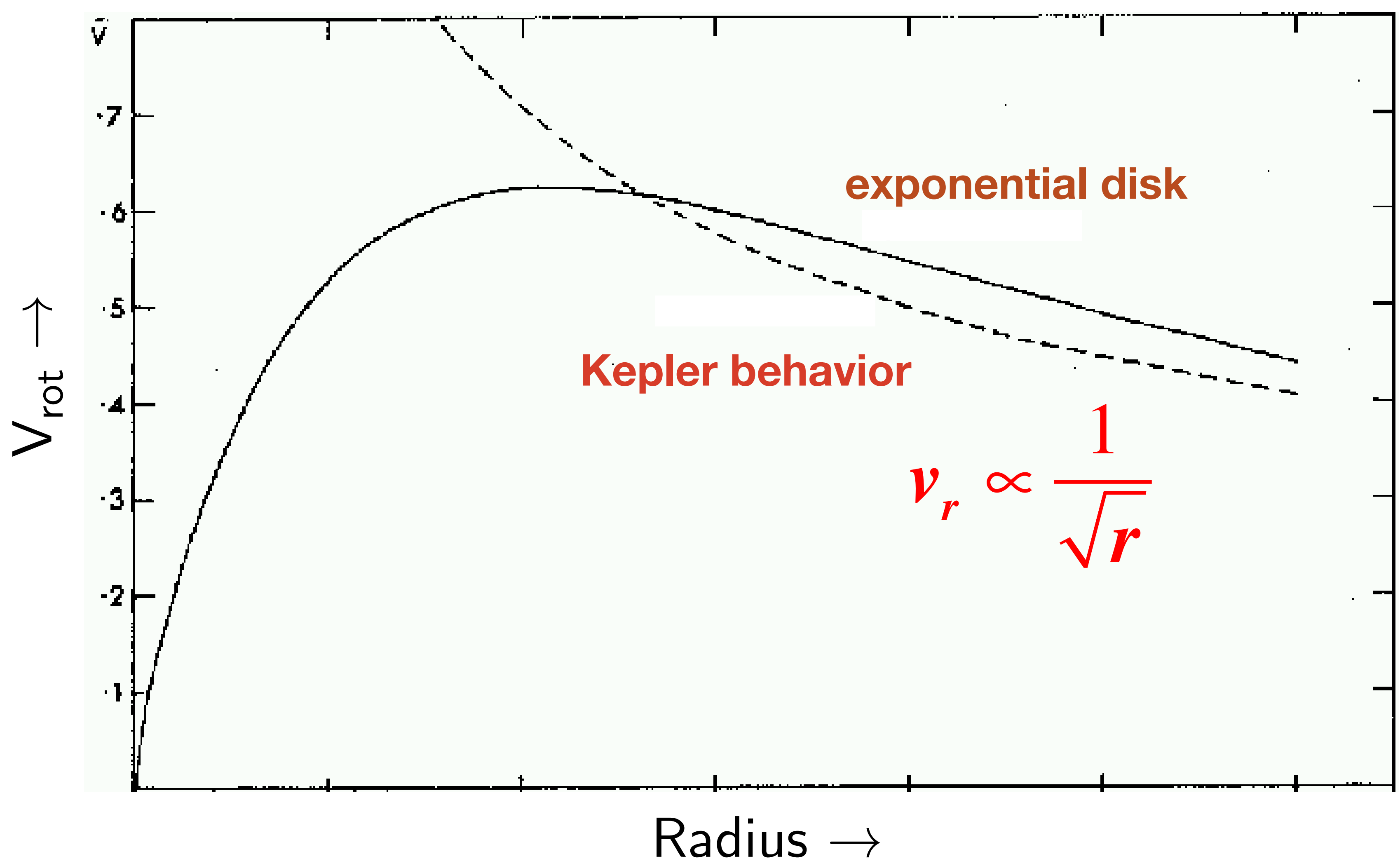
Caroll & Ostlie

Galactic Rotation Curve

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

  => **rotation curve, $v_{rot}(r)$**

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



Galactic Rotation Curve

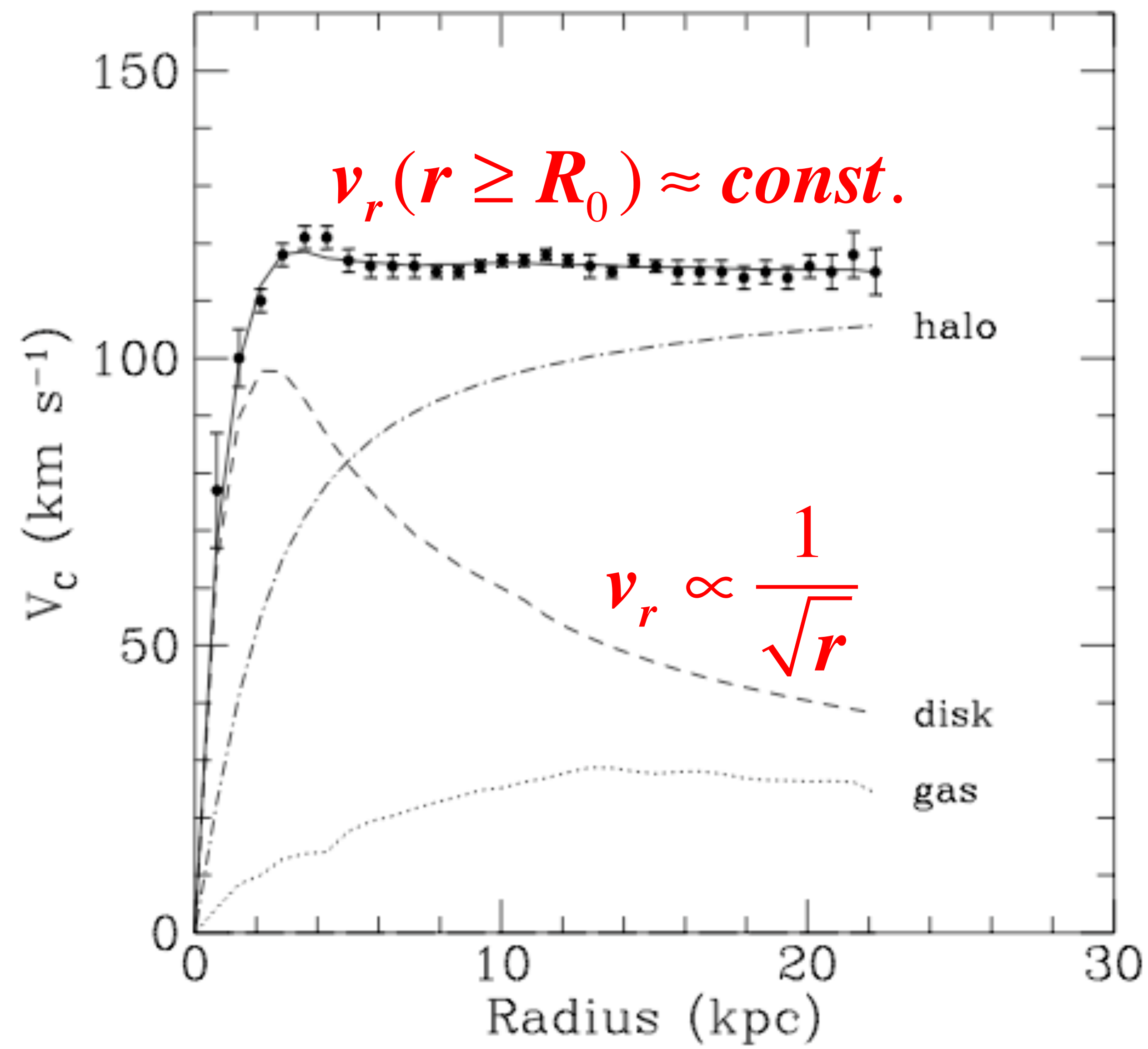
- **Expectations:** from centrifugal force = gravitational attraction

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

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

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

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



- **Observations:**

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

$$\Rightarrow \boldsymbol{M_r \propto r}$$

=> 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 **$1/r^2$-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, though its gravitational influence on the visible matter]

→ **with r = 8 kpc = 2.5×10^{20} m; G = 6.67×10^{-11} $m^3kg^{-1}s^{-1}$ we obtain roughly: ρ = 0.42 GeV/cm^3**

Galactic Rotation Curve

- We need to modify the previous equation

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

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

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

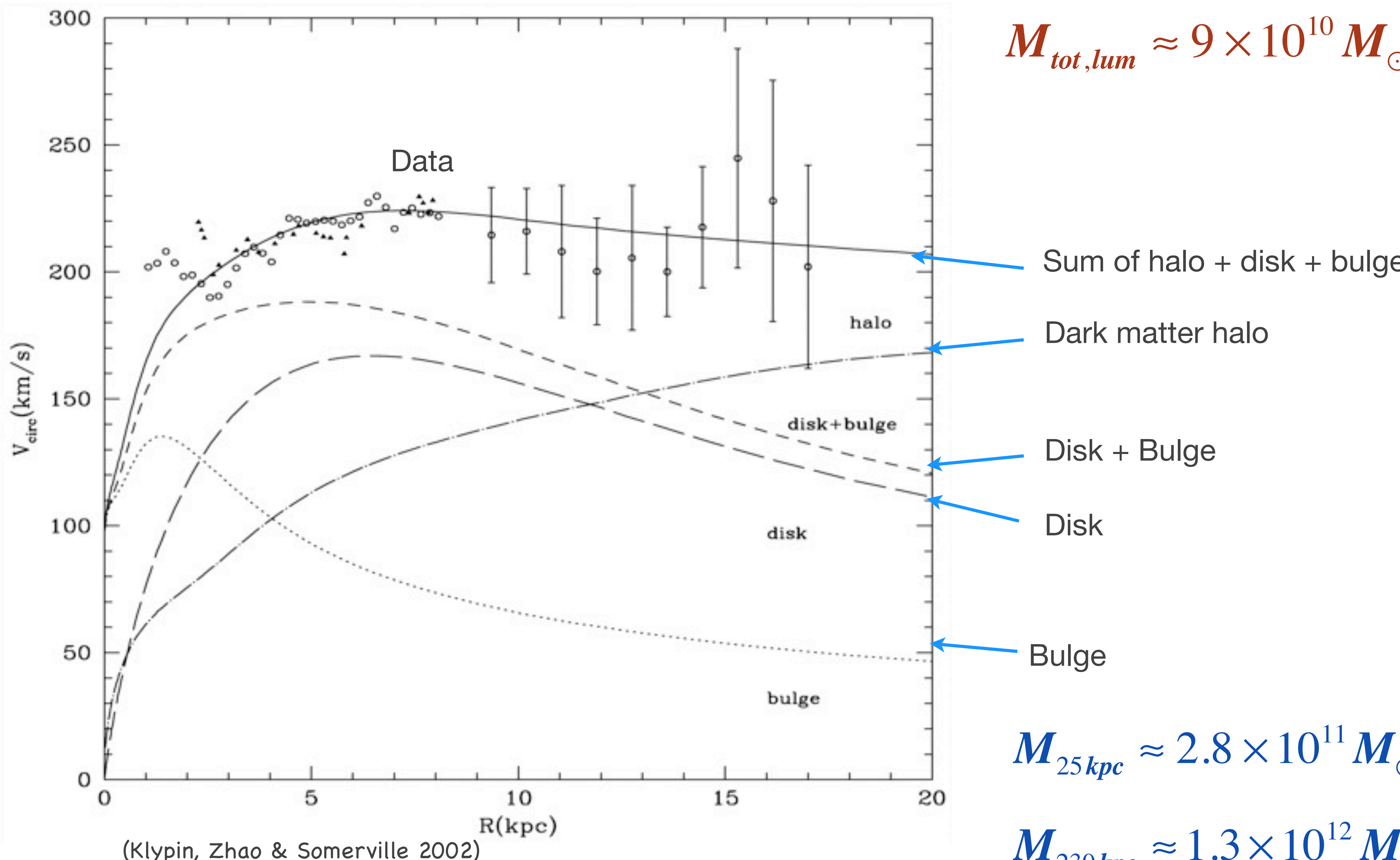
- where $\mathbf{C_0}$ and **a** are obtained from fits to the overall rotation curve:

$$C_0 = 4.6 \times 10^8 M_\odot \mathrm{kpc}^{-1}$$
$$a = 2.8\ \mathrm{kpc}$$

We note that:

for r >> a => $\rho(r) \propto r^{-2}$
for r << a => $\rho(r) \propto$ const.

Fits to the observed rotation curve



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

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

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

What can we learn from the rotation curve?

- As we saw, a mass that grows linearly would derive from a density distribution falling like $\rho(r) \sim 1/r^2$
- Now we assume the dark matter is made of a *collisionless gas with isotropic initial velocity distribution*
- Its equation of state is given by:

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

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

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

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

What can we learn from the rotation curve?

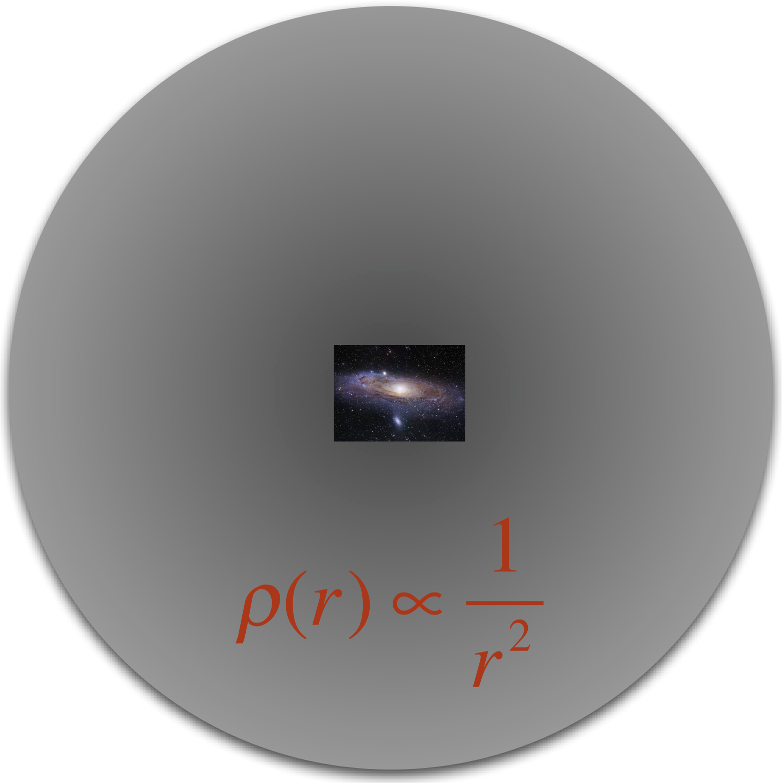
- We now differentiate with respect to r and obtain:

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

where we have used
$dM/dr = 4\pi r^2\rho(r)$

- 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

Distribution of the Dark Matter - Numerical Simulations

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

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

- 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 ~ $\mathbf{r^{-3}}$.

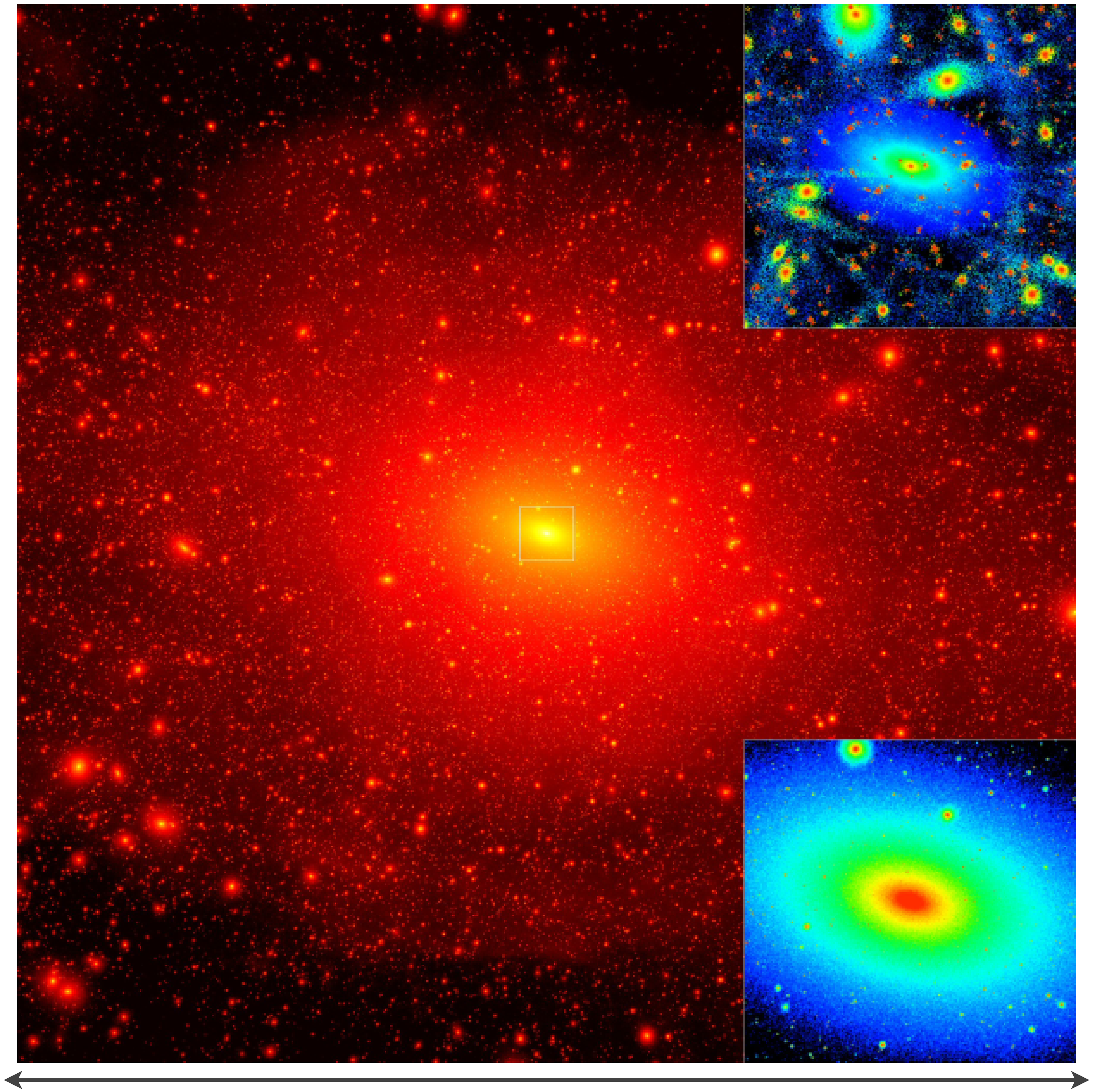
- **More general:**

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

	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)

Simulations of the Milky Way Dark Halo



inner 20 kpc: phase space density

high resolution (10^9 particles) cosmological CDM simulation of a Milky Way type halo

inner 20 kpc: density

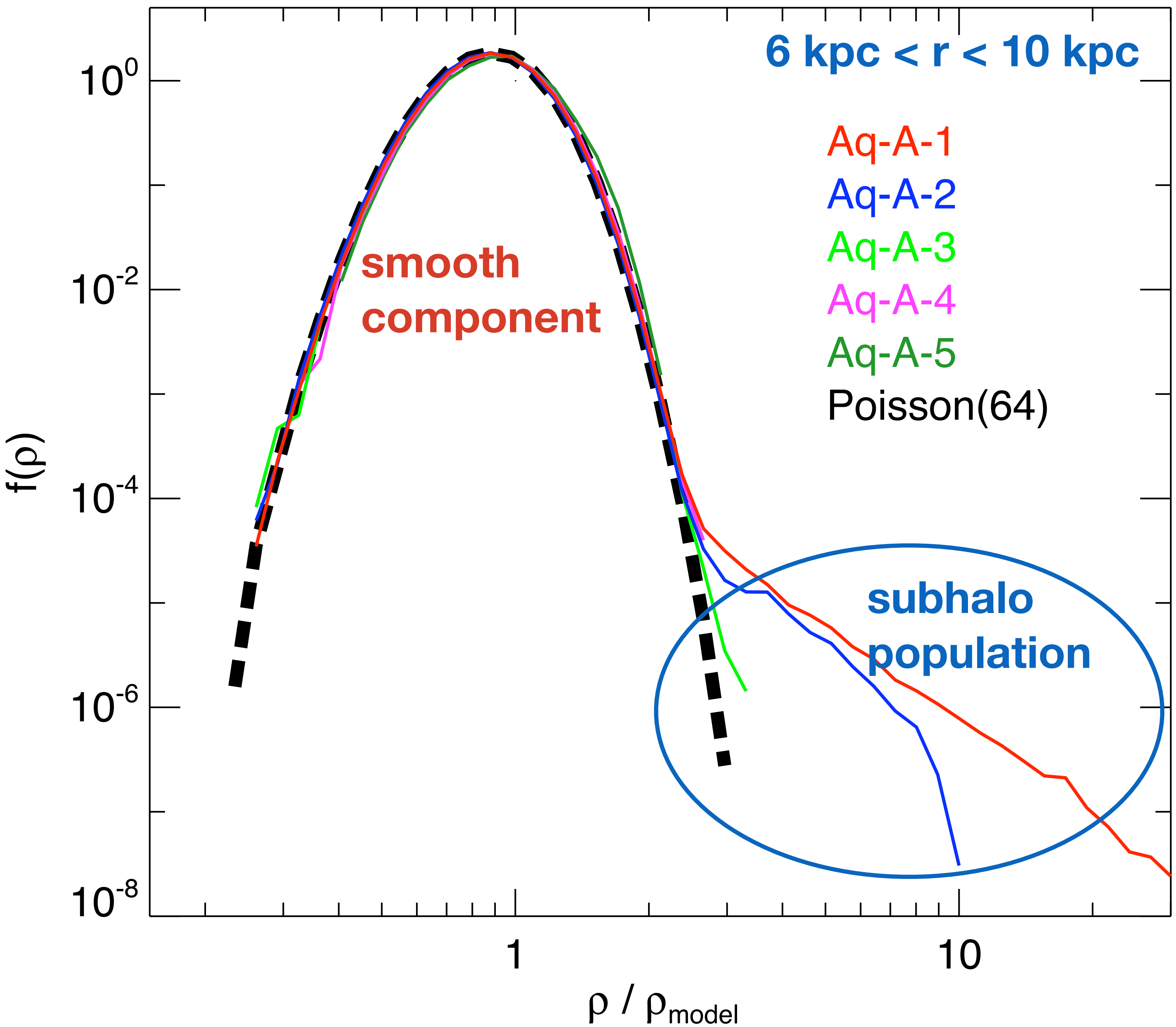
~ 600 kpc

Ben Moore et al, UZH, 2008
http://xxx.lanl.gov/pdf/0805.1244v1

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



The Aquarius project, 6 halos; arXiv: 0812.0362

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

Parameters for the Aquarius simulations:

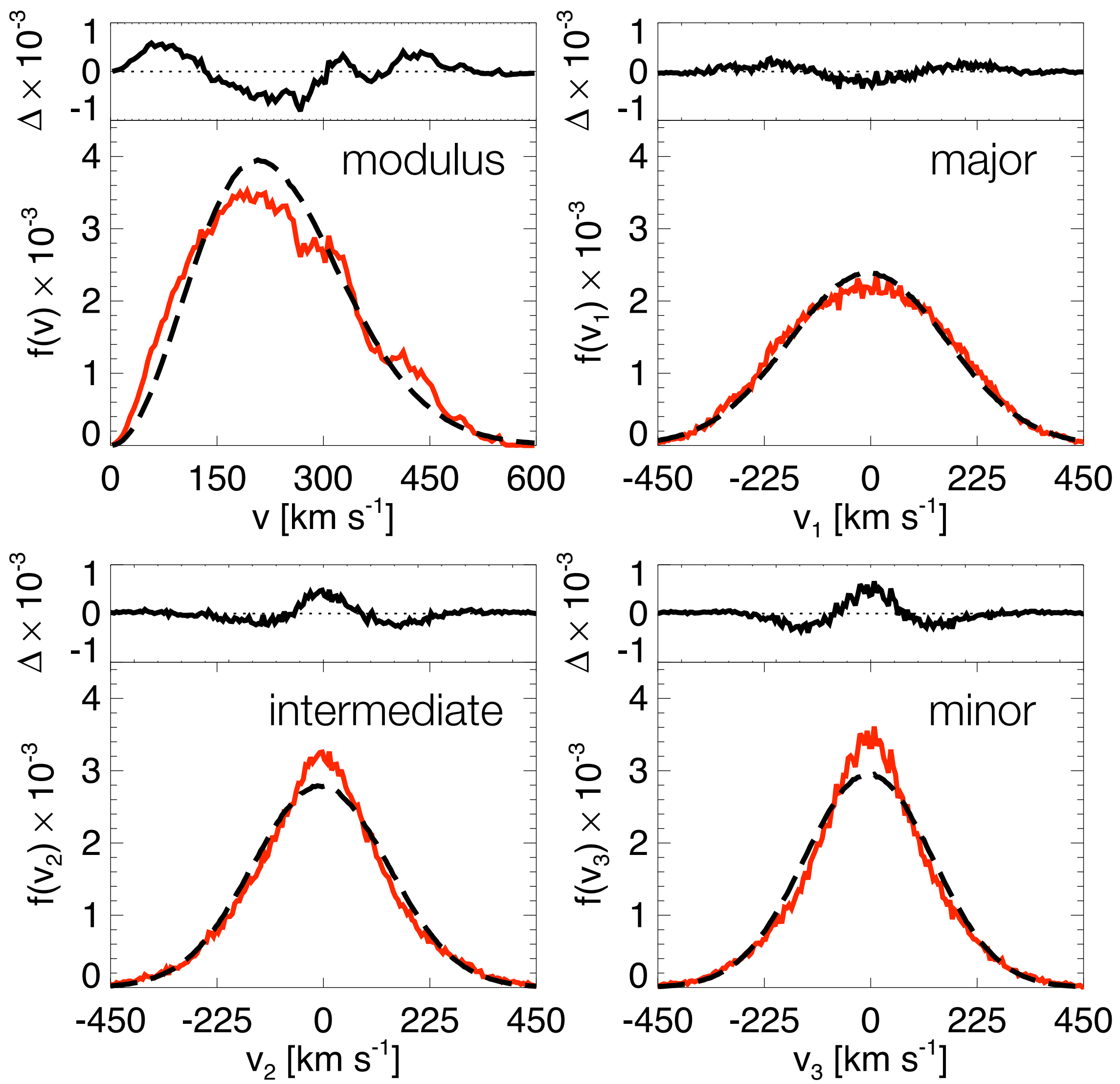
Ω_m = 0.25
Ω_Λ = 0.75
H_0= 100 h km s^{-1} Mpc^{-1}
h = 0.73

Answer: very smooth
Substructure is far from Sun

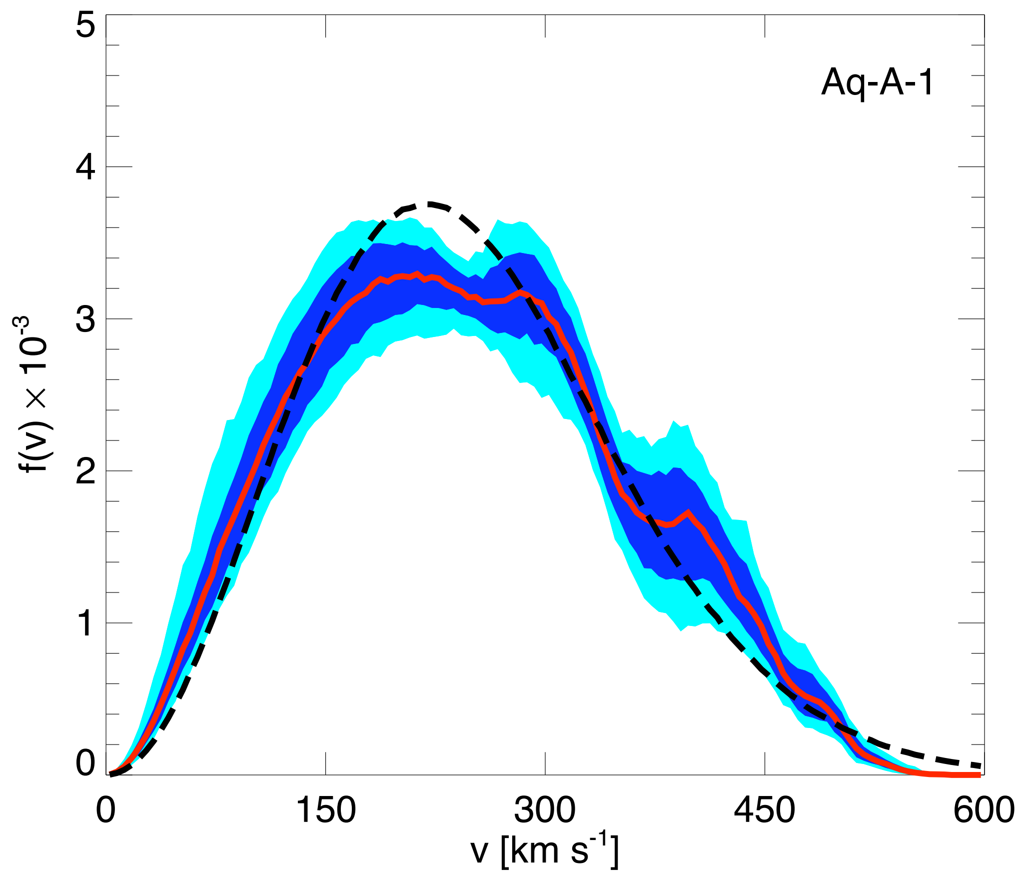
Velocity Distribution of the Dark Matter

- **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

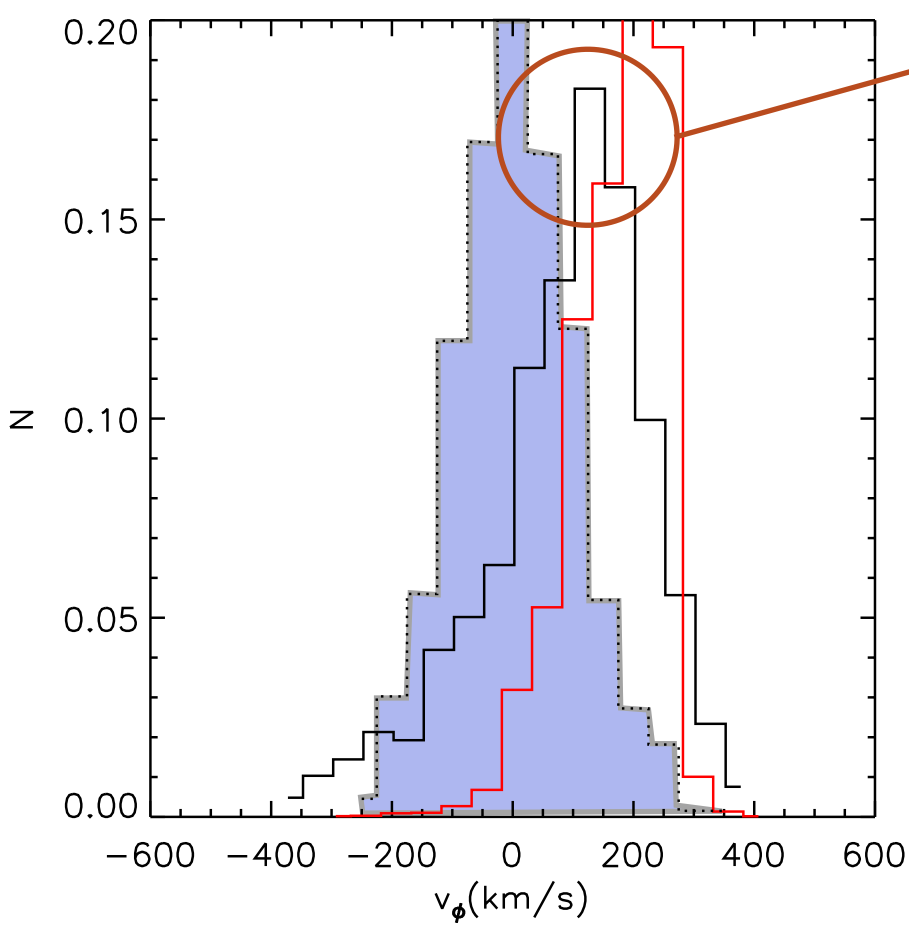


The Aquarius project, 6 halos; arXiv: 0812.0362

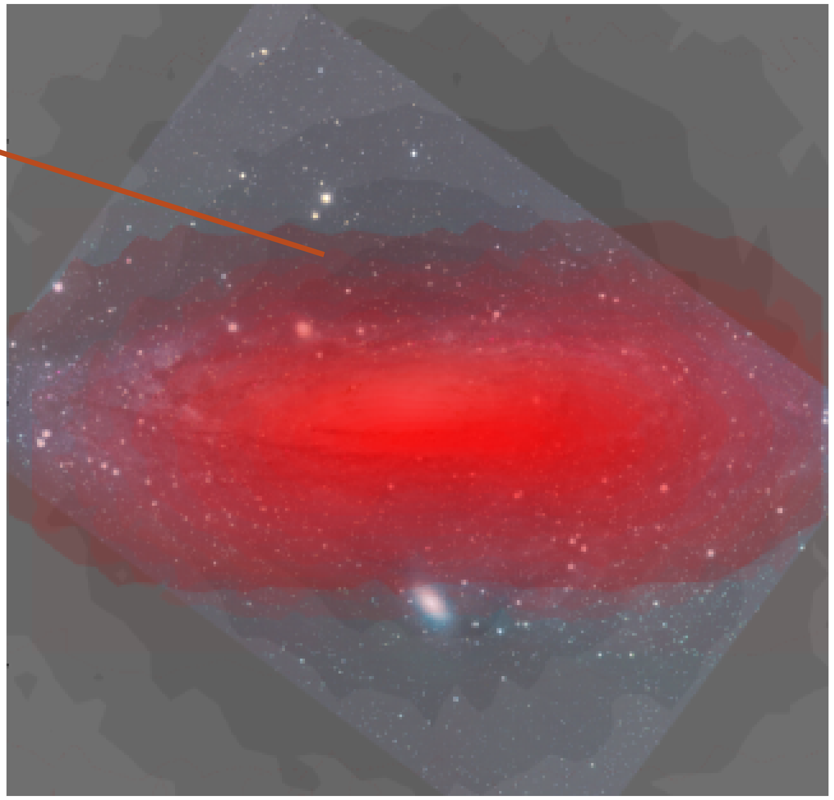
- **But: can we ignore the baryons?**
- The dark matter only simulations have established a baseline for future work.

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



dark disk



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

Dark Matter Candidates

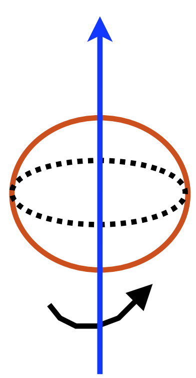
Reminder: the Standard Model Particle Content

Matter: 3 Families (Fermions)

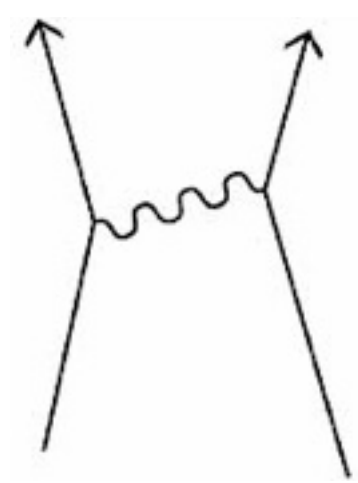
QUARKS	up	charm	top
	down	strange	bottom
LEPTONS	electron	muon	tau
	ν_e	ν_μ	ν_τ

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 ≈ 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 ≈ 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 ≈ 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

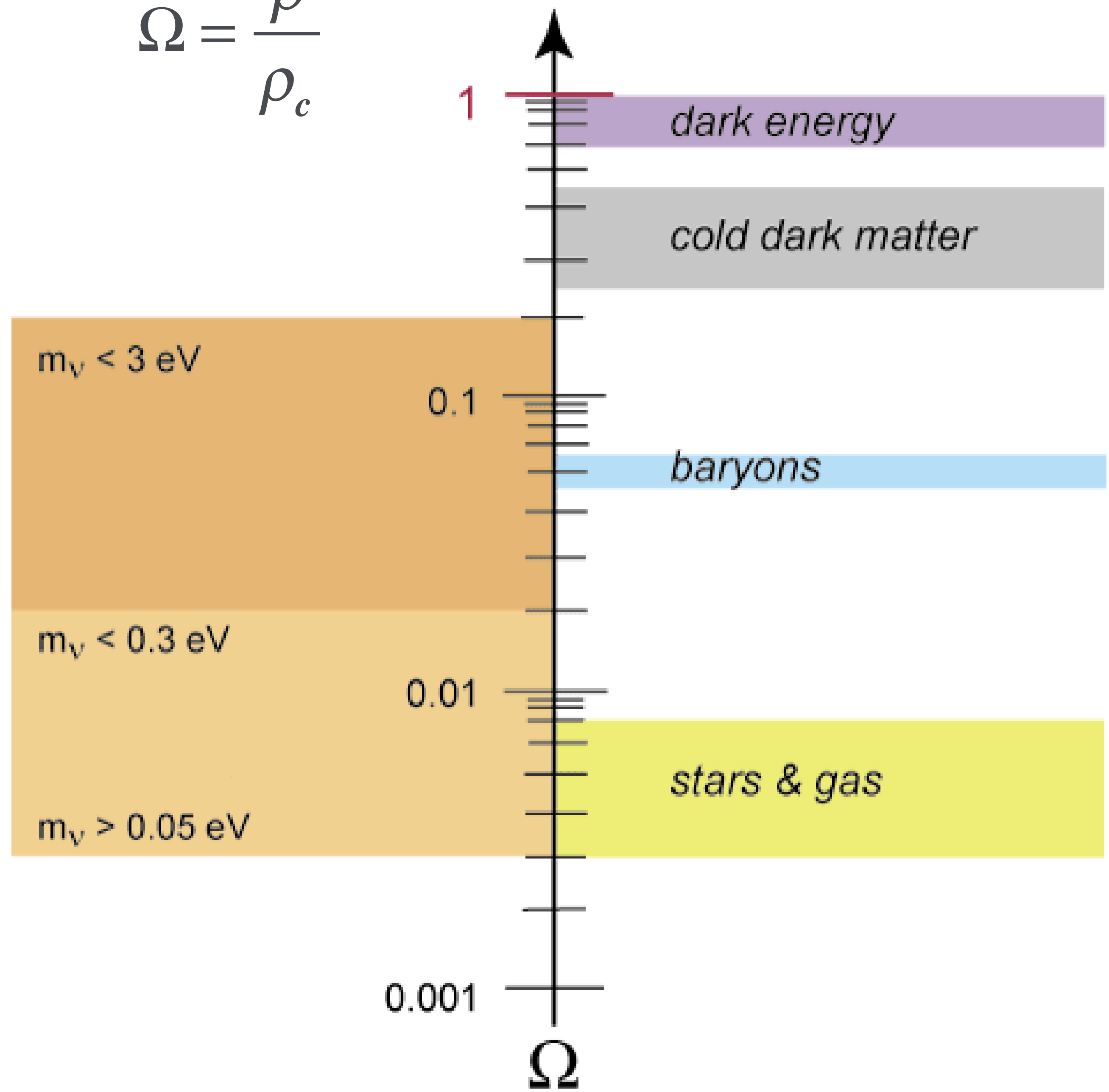
- **Neutrinos: thermal relics of the early Universe**
- **Number density: similar to photons**
  - ➡ **~ 10^9 neutrinos/proton!**
  - ➡ **~ 113 neutrinos/cm^3 ! (411/cm^3 for photons)**
- **Depending on their mass, neutrinos could have a (small) contribution to the dark matter**
  - ➡ direct limits on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

- Assume a **stable, neutral**, **massive, weakly interacting particle** χ (WIMP) with a mass $\mathbf{m_\chi}$ existed in the early Universe. At early times, for $T \gg m_\chi$, $n_\chi \propto T^3$.
- For 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:

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

n_χ = number density
s = entropy density
$s \cdot a^3$ = ct; a = cosmic scale factor

$r(t) = a(t) \cdot y$, y = comoving coord.
T = temperature

- Since the particle is stable, its **number density** $\mathbf{n_\chi}$ **per comoving volume** $\mathbf{a^3}$ 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

Dark Matter Candidates: WIMPs

- The particle will be in equilibrium as long as the **reaction rate Γ** was larger than the **expansion rate H**

$$\Gamma \gg H$$

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

- Once the temperature **T drops below 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**:

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

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

decrease due to 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 $[n_{\chi(eq)}]^2$

$\langle \sigma_A v \rangle$ thermally averaged total annihilation cross section times relative velocity

Freeze-out of WIMPs

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

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

g_{eff} = effective number of relativistic degrees of freedom

$m_{Pl} \cong 10^{19}$ GeV

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

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

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 we introduce the dimensionless variable **$x = m_\chi/T$** and normalize **n_χ** to the entropy density, **$Y_\chi=n_\chi/s$** we obtain (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 $\Gamma_A = n_{\chi(eq)}\langle\sigma_A \mathrm{v}\rangle$

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 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:

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

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 Γ = H**, we find:

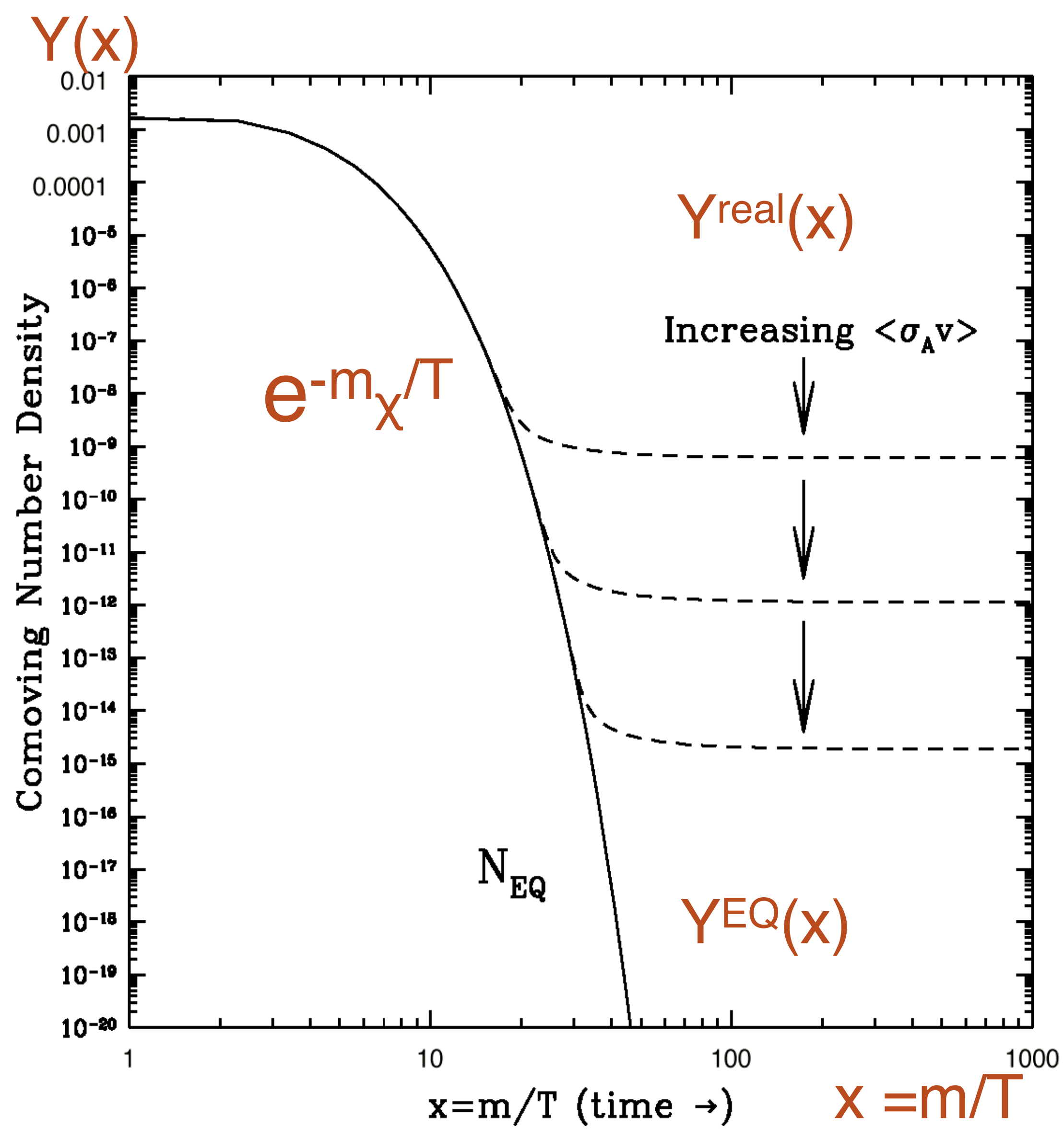
$$\left(\frac{n_\chi}{s}\right)_0 = \left(\frac{n_\chi}{s}\right)_f \simeq \frac{100}{m_\chi m_{Pl} g_{eff}^{1/2} \langle \sigma_A \mathrm{v} \rangle} \simeq \frac{10^{-8}}{\left(m_\chi / GeV\right)\left(\langle \sigma_A \mathrm{v} \rangle / 10^{-27}\, cm^3 s^{-1}\right)}$$

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$^{-1})$]
- **We find for the present mass density in units of the critical density ρ_c:**

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

Mass of a Thermal Relic Particle



Thus, if a relic particle exists, its abundance will be:

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

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

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

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

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)		Bosons (spin 0)	
Quarks	Leptons	Squarks	Sleptons
Gauge Bosons (spin 1)		Gauginos (spin 1/2)	
$W^\pm$	Z, B gluons, photons	Winos	Zinos, Binos gluinos, photinos
charged	*neutral*	*charginos*	*neutralinos*
Graviton (spin 2)		Gravitino (spin 3/2)	

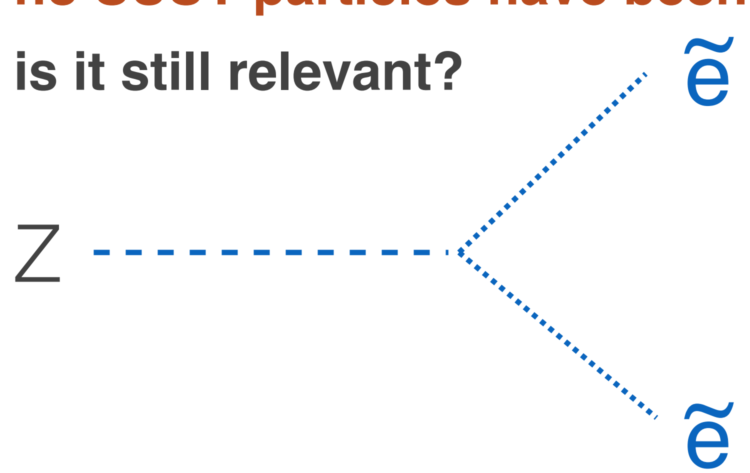
Once we include interactions, the SUSY particles will acquire interactions similar to those of the quarks and leptons.
Example: the spin-0 squarks and sleptons couple to the photon and the Z-boson in the same way as quarks and leptons

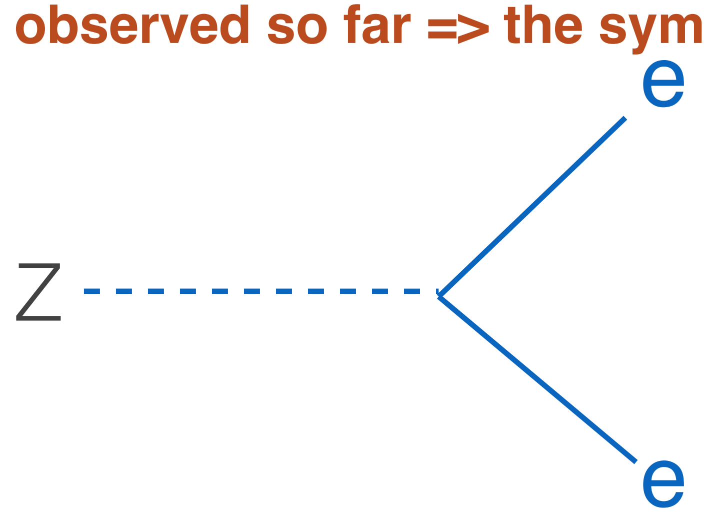
Supersymmetry

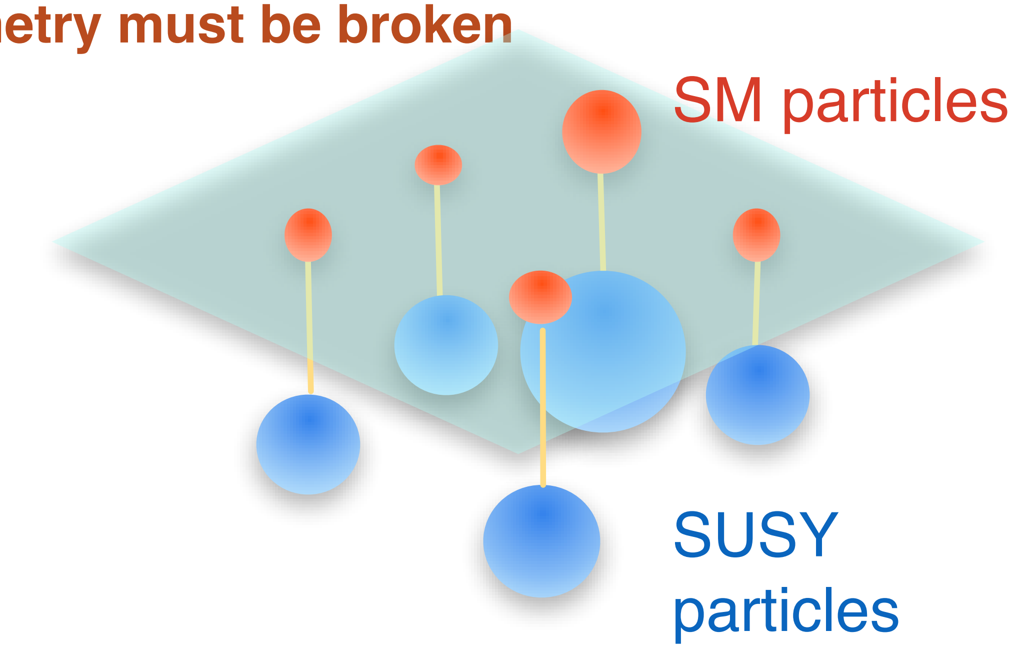
- **Stabilizes the hierarchy problem:**
  weak scale (200 GeV) …. GUT scale (10^{16} GeV)…. Planck scale (10^{19} GeV): radiative corrections to the masses of scalar particles (for instance the Higgs) are quadratically divergent, but in SUSY the corrections due to fermions and bosons cancel, thereby 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:

$$p \rightarrow e^{+} + \pi^{0}$$

$$p \rightarrow \mu^{+} + \pi^{0}$$

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

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

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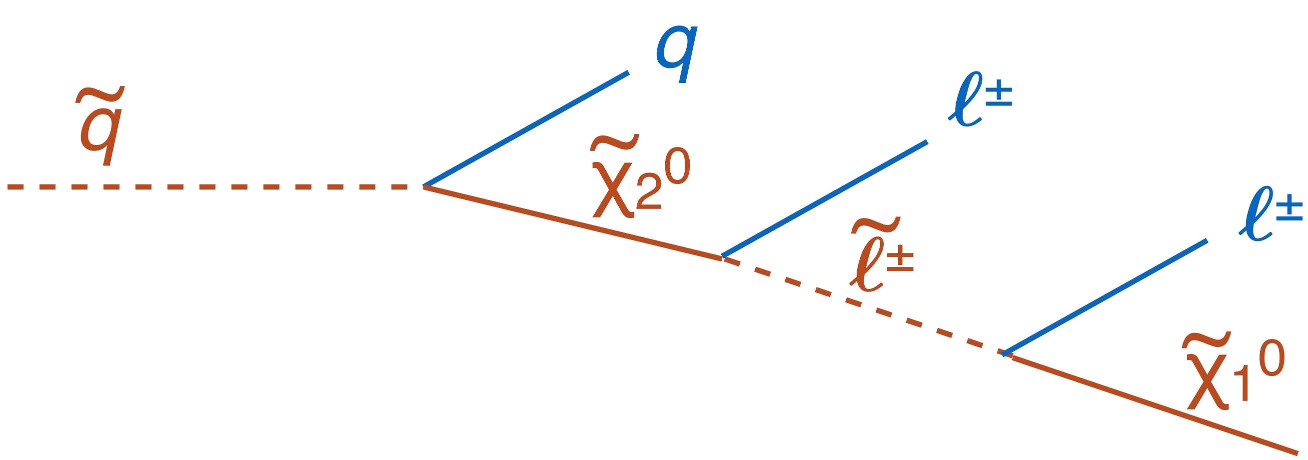
selectron: B=0, L= 1, s=0 => R = $(-1)^1$ = -1

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)

- **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 experiment!

- **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 of 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:**

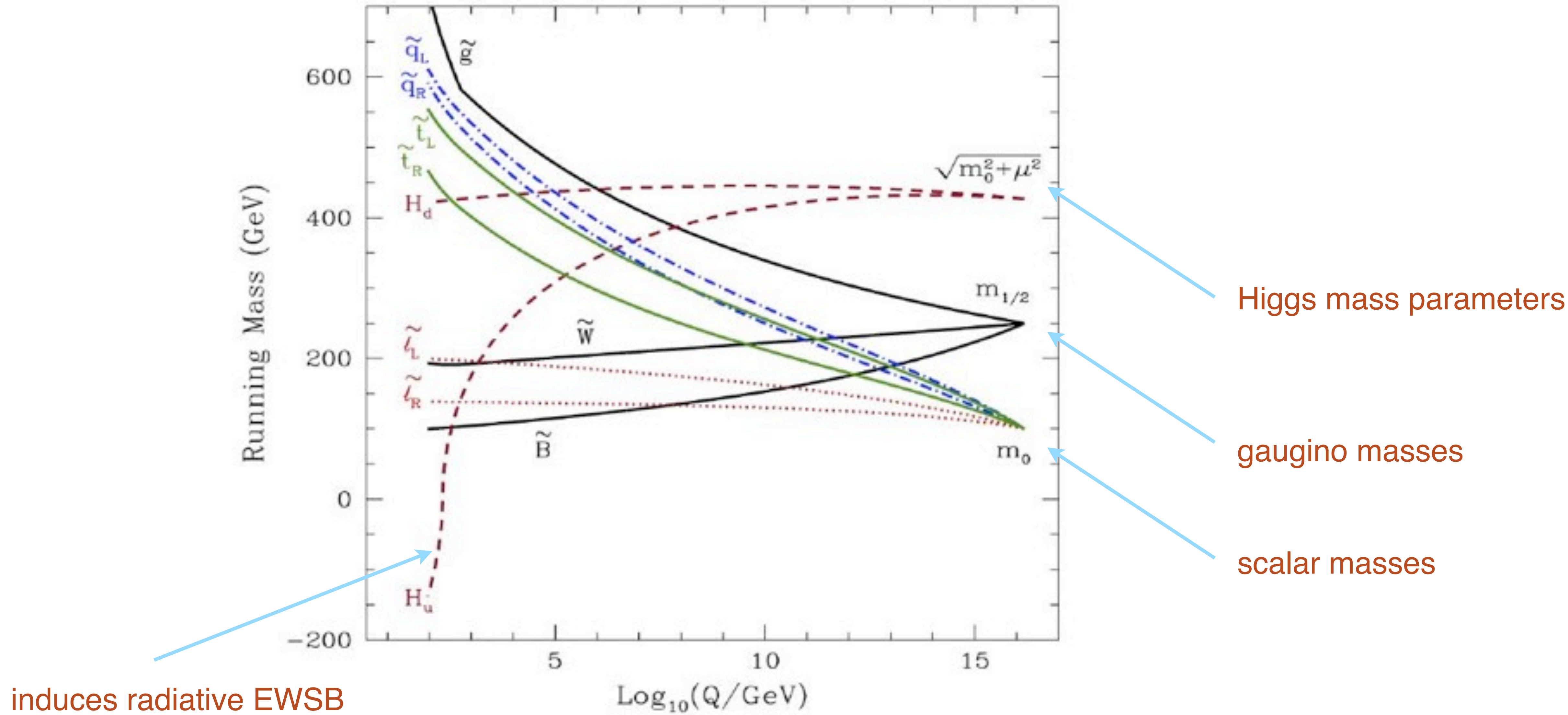
$$A_u(U) = A_d(U) = A_l(U) = A_0$$

- **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 ($M_{GUT} \approx 2\times10^{16}$ GeV) to the weak scale ($M_{weak} \approx 1$ TeV): **from few input parameters, all the masses of the superparticles are determined**



Supersymmetric Models

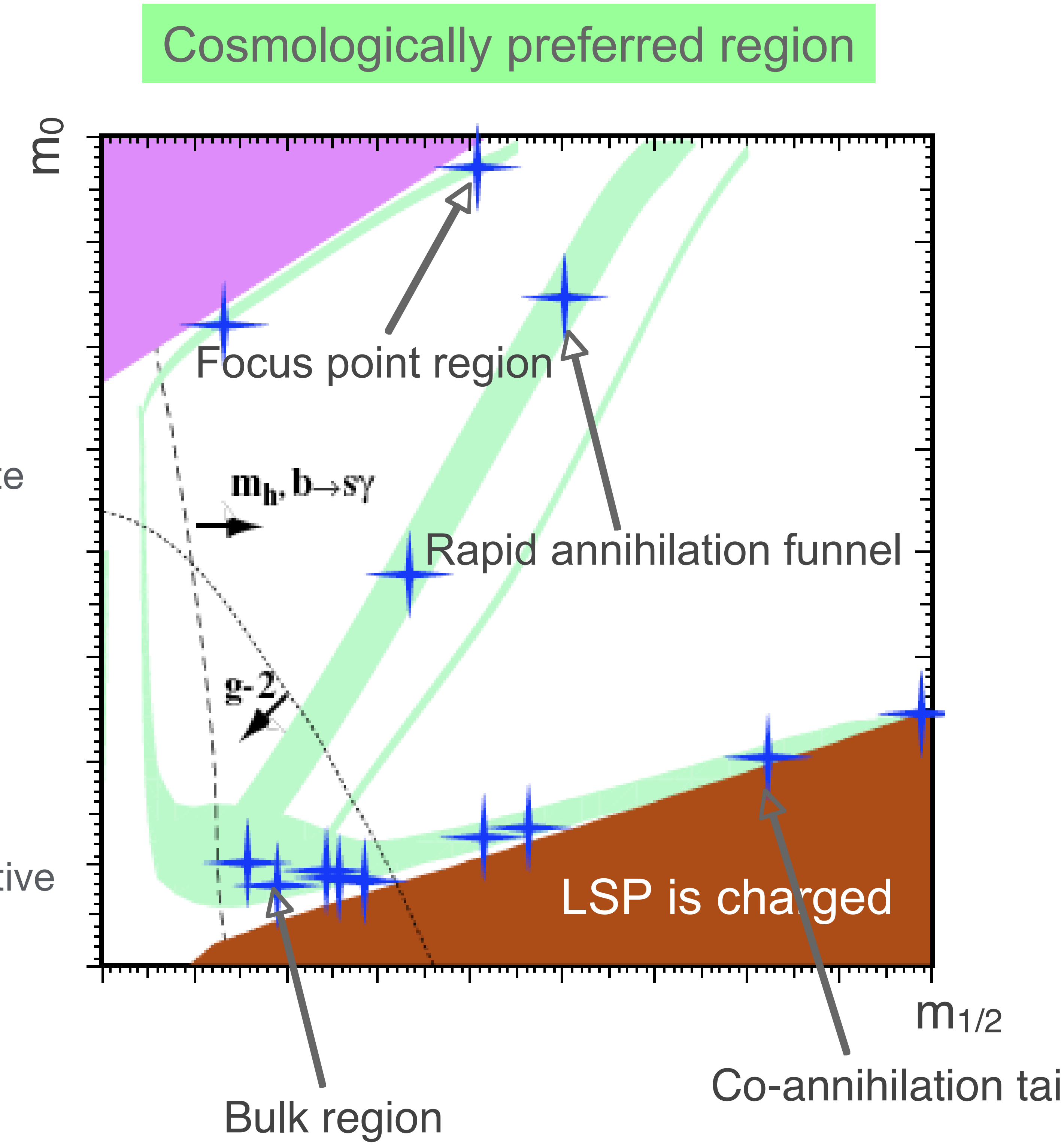
- **Benchmark scenarios:**

- the parameters of models with an acceptable cosmological relic density falls in one of the regions shown here

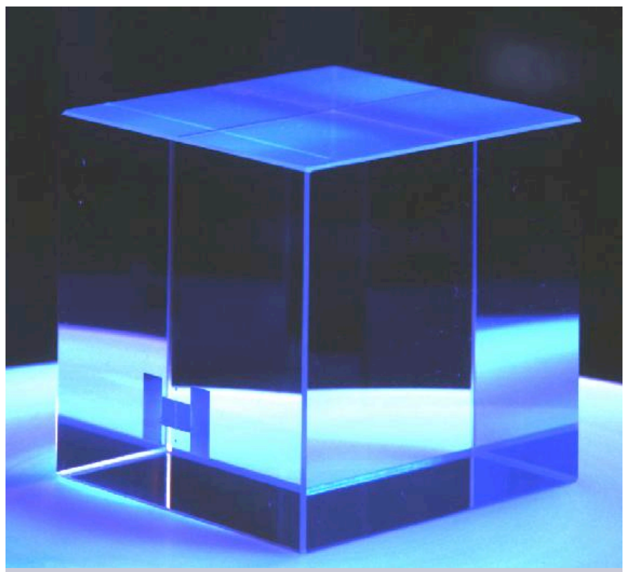
- **Co-annihilation tail:** the mass of the neutralino and the stau are nearly degenerate

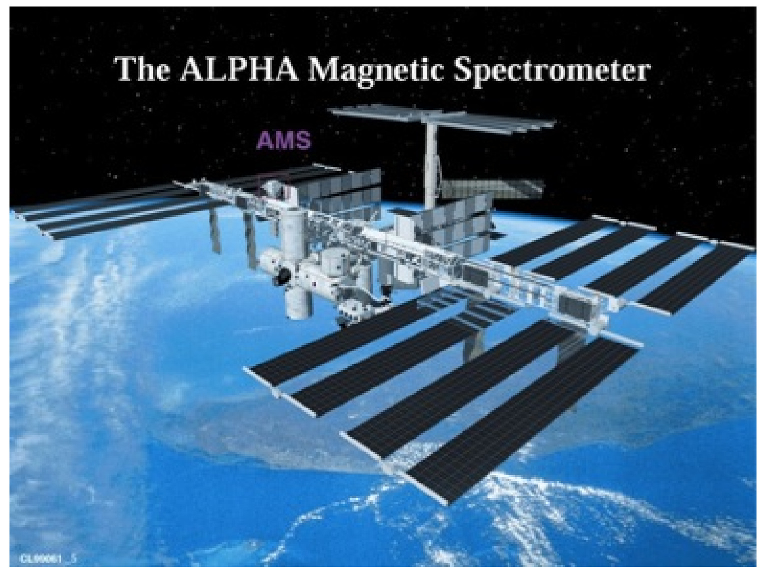
- **Rapid annihilation funnel:** the mass of the neutralino is close to one-half of the mass of A (pseudo-scalar Higgs)

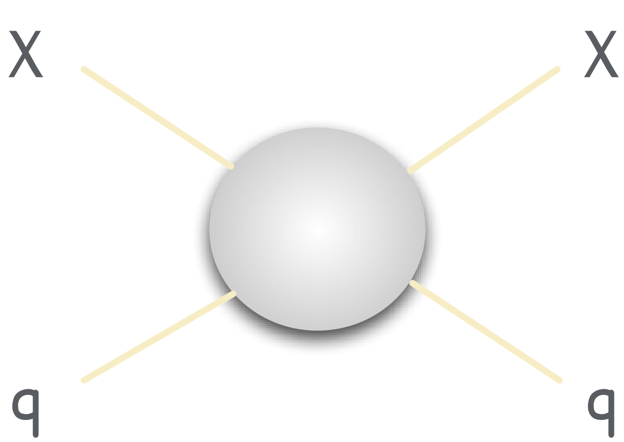
- **Focus point region**: at high values of m_0 (edge of parameter space allowing for radiative EW symmetry breaking)



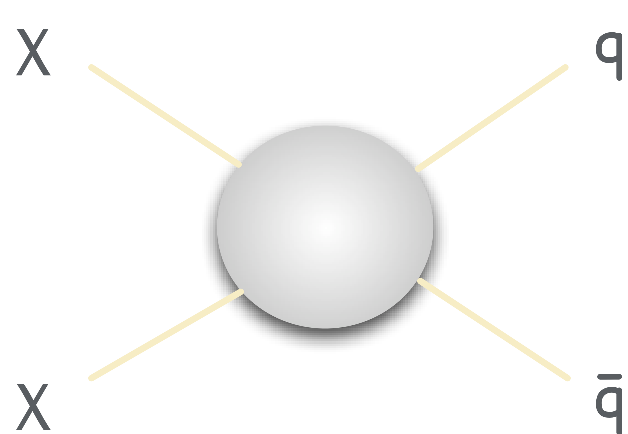
WIMP Searches



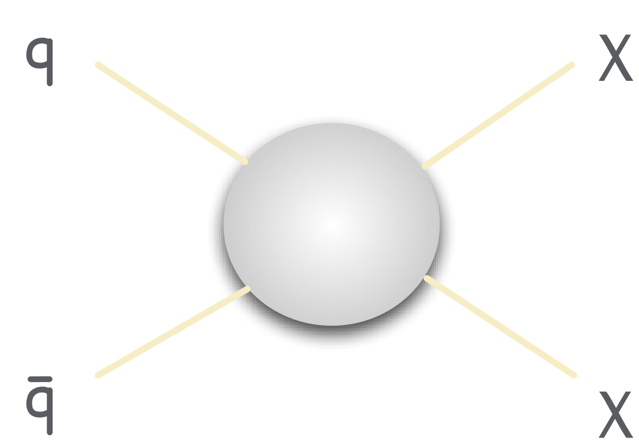




Direct



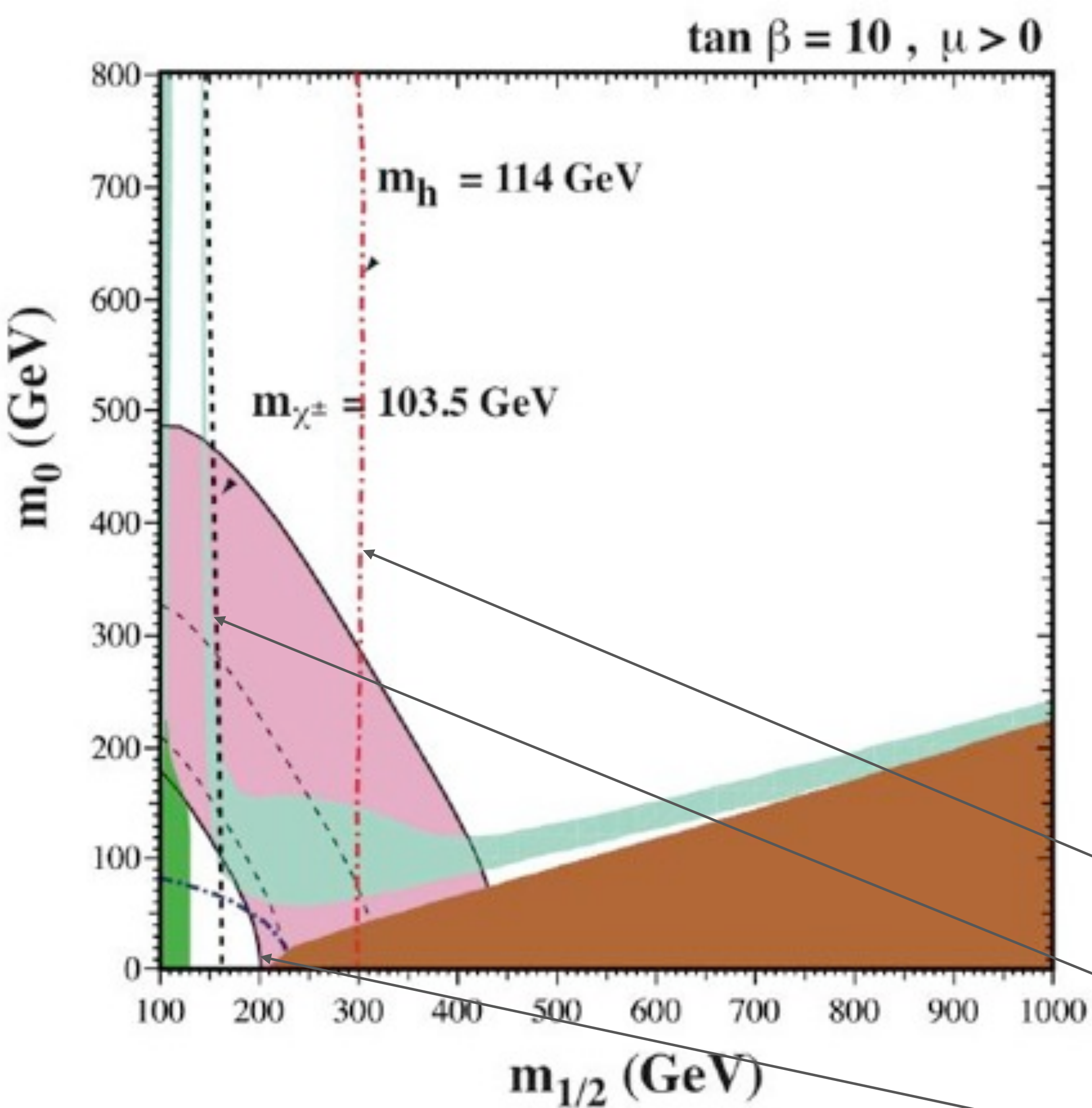
Indirect



Colliders

End

Constraints on SUSY



mSUGRA model:

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

Green region: excluded by $b \to s\gamma$ 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