Particle Dark Matter

Gianfranco Bertone

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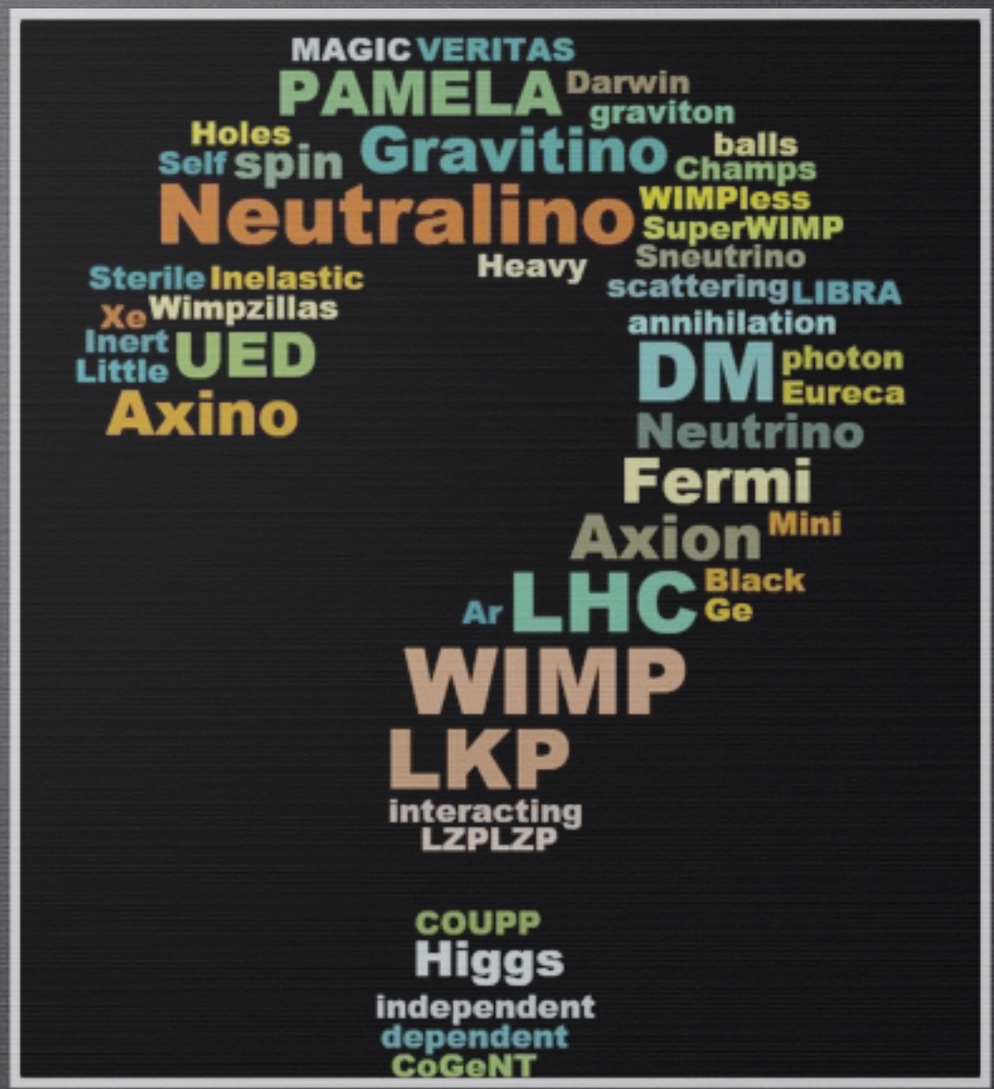
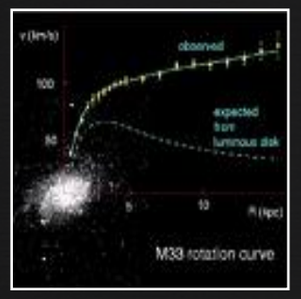


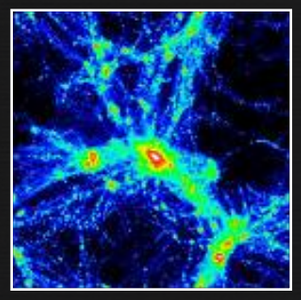
Evidence for Dark Matter

Evidence for the existence of an unseen, *"dark"*, component in the energy density of the Universe comes from several independent observations at different length scales

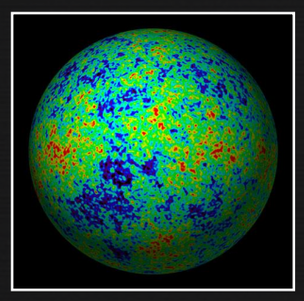
COSMOLOGICAL OBSERVATIONS



• Rotation Curves

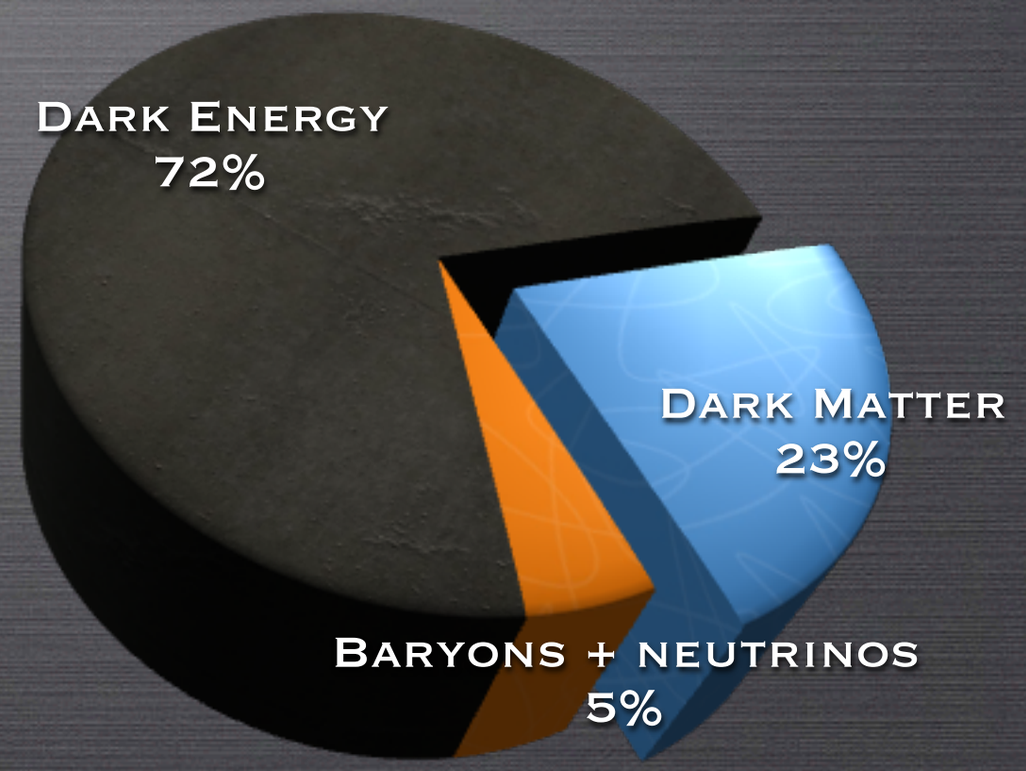


• Clusters of galaxies



•CMB

•Type Ia Supernovae



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An extraordinarily rich zoo of non-baryonic Dark Matter candidates! In order to be considered a viable DM candidate, a new particle has to pass the following 10-point test

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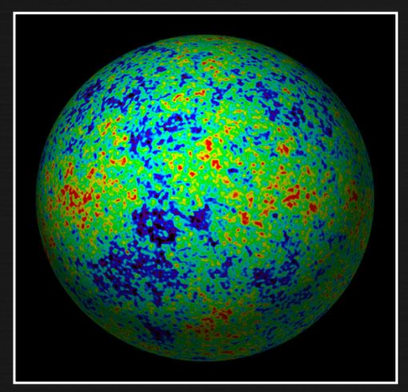

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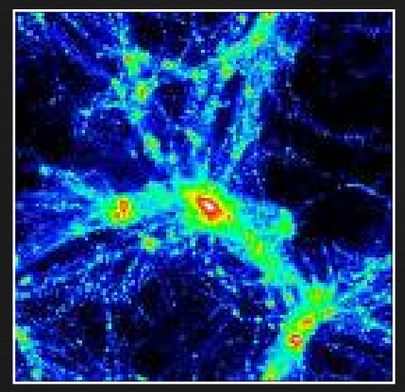

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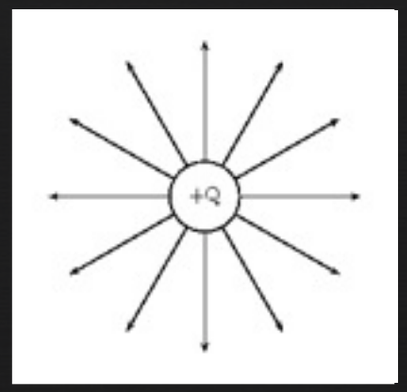

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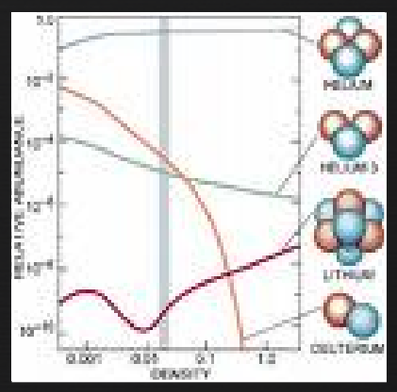

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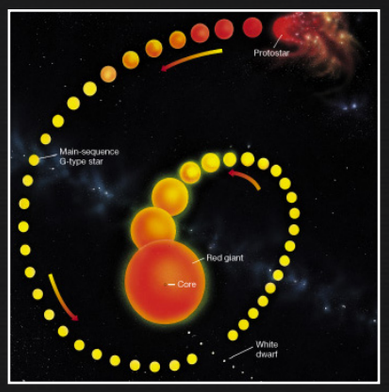

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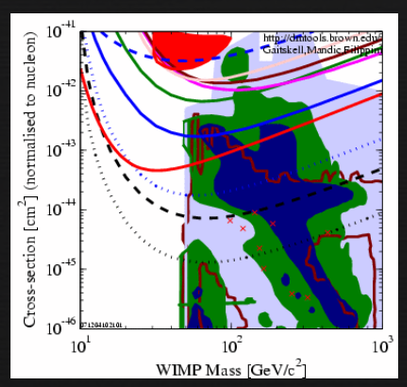

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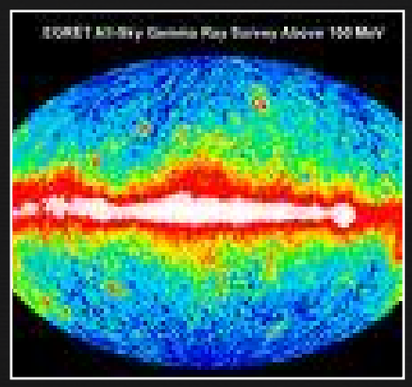

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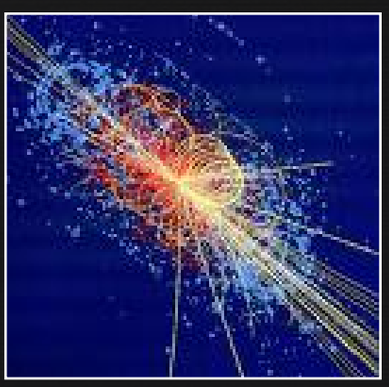


Taoso, GB & Masiero 2007

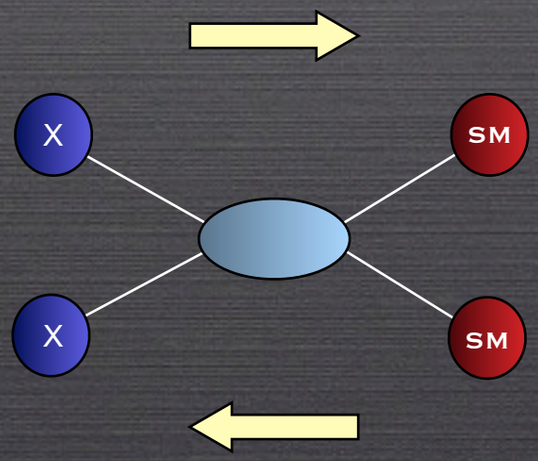
Relic Density of DM

The evolution of any component of the Universe can be described by a Boltzmann equation

$$\mathbf{L}[f] = \mathbf{C}[f]$$

that connects the evolution of phase space (Liouville operator) with the interactions of the system (Collision operator).

We can apply it to reactions relevant for DM particles



Relic Density of DM

In this case the Boltzmann equation reduces to

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - (n^{eq})^2 \right)$$

where we have introduced

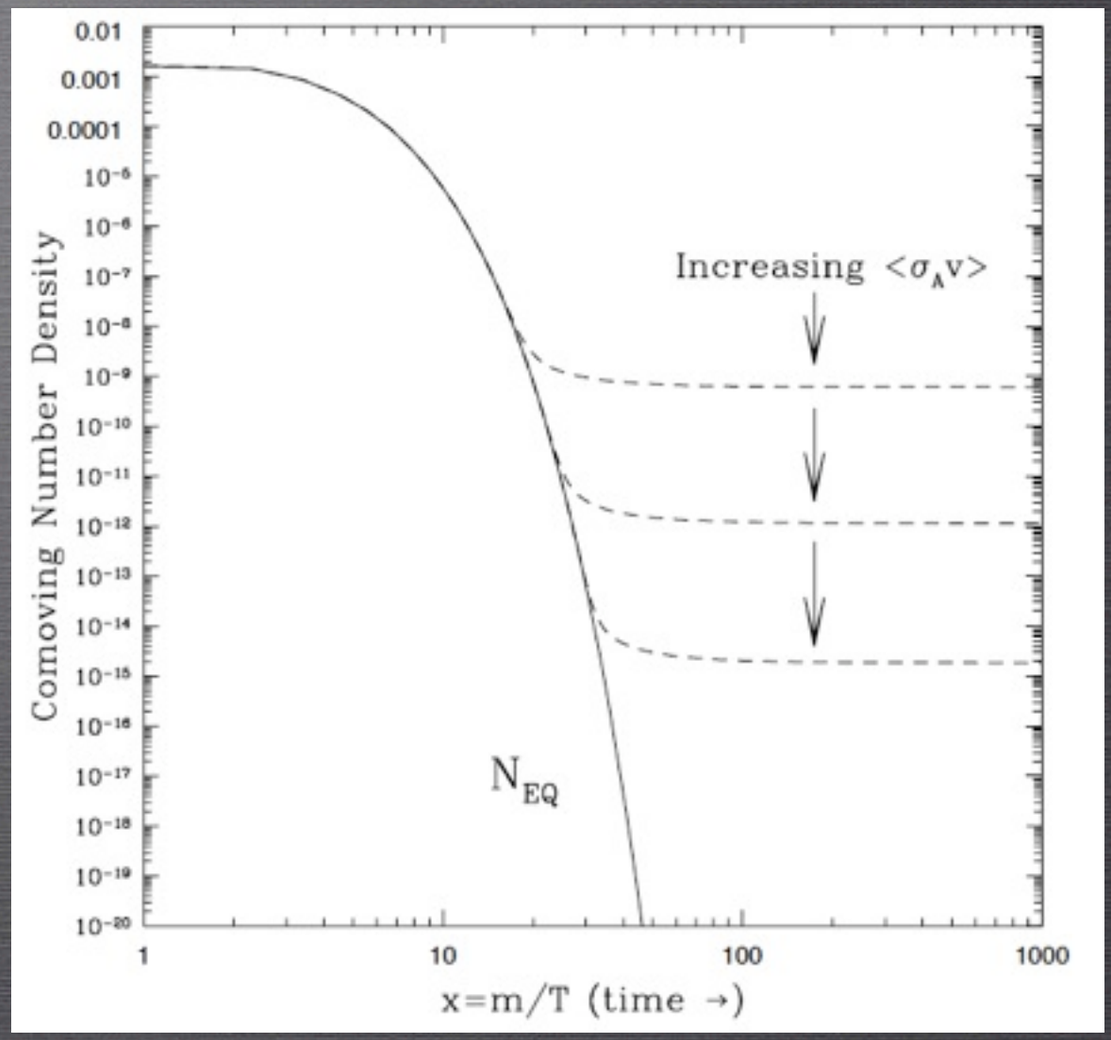
$$n^{eq} = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T}$$

and

$$\langle \sigma_{\rm ann} v \rangle = \frac{\int_0^\infty dp\, p^2\, W_{\chi\chi}(s)\, K_1(\sqrt{s}/T)}{m_\chi^4\, T\, [K_2(m_\chi/T)]^2}$$

(W_{ij} is the invariant annihilation rate)

$$W_{ij}(s) = 4\,\sigma_{ij} \sqrt{(p_i \cdot p_j)^2 - m_i^2 m_j^2}$$



The "relic" density of DM, normalized to the critical density turns out to be

$$\Omega h^2 \approx \frac{3 \times 10^{-27}\ {\rm cm}^3/{\rm s}}{\langle \sigma_{\rm ann} v \rangle}$$

Relic Density of DM

Relic Density constraints on the mass of the WIMP

$$20\mathrm{GeV} \lesssim m_\chi \lesssim 120\mathrm{TeV}$$

Lee-Weinberg Limit

B. W. Lee and S. Weinberg,
Phys. Rev. Lett. 39, 165 (1977)

Unitarity Bound

S. Weinberg, 1995, The Quantum Theory of Fields Vol 1, Cambridge University Press.

K. Griest and M. Kamionkowski,
Phys. Rev. Lett. 64 (1990) 615

This is why we will discuss gamma-rays, O(100) GeV anti-matter and neutrinos etc...

Relic Density of DM

Important correction to Standard freeze-out: co-annihilations!

Effective depletion of the relic density through reactions like

$$\tilde{\chi}_1^0 \tau \to \tilde{\tau} \gamma, \qquad \tilde{\tau} \tilde{\chi}_1^+ \to \tau W^+$$

We can deal with this (relatively) easily, under the assumption that: a) all co-ann. particles decay to the lightest DM particle and b) decay times are << expansion rate of the Universe.

In this case, we can extend our formalism as follows:

$$\langle \sigma_{\rm eff} v \rangle = \frac{\int_0^\infty dp_{\rm eff}\, p_{\rm eff}^2\, W_{\rm eff}(s)\, K_1(\sqrt{s}/T)}{m_\chi^4 T \left[\sum_{i=1}^N \frac{g_i}{g_\chi} \frac{m_i^2}{m_\chi^2} K_2(m_i/T)\right]^2},$$

where $s = 4p_{\rm eff} + 4m_\chi^2$, g_i is the number of internal degree of freedom (statistical weight factor) for the i-th coannihilating particle, and

$$W_{\rm eff}(s) = \sum_{ij} \frac{F_{ij}}{F_{\chi\chi}} \frac{g_i g_j}{g_\chi^2} W_{ij}(s).$$

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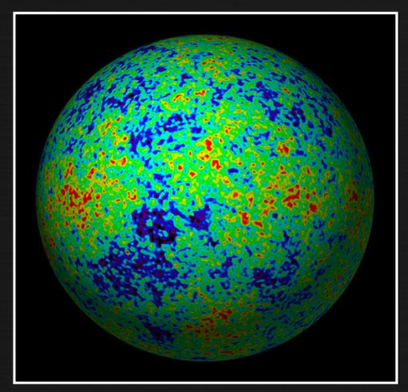

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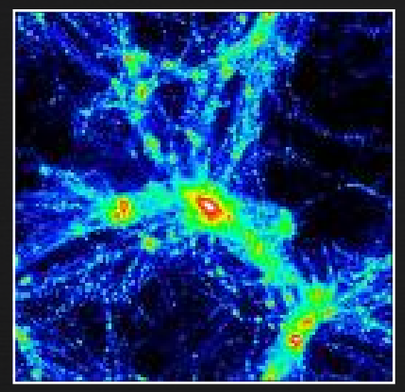

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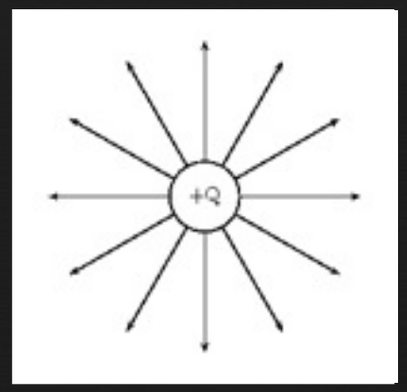

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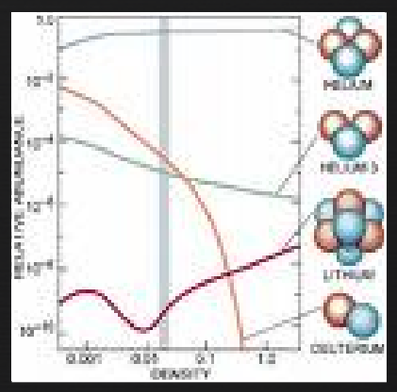

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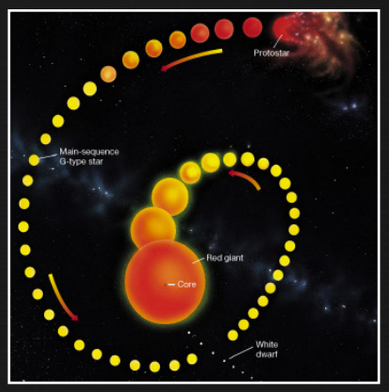

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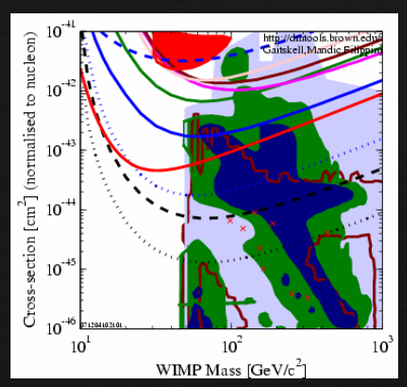

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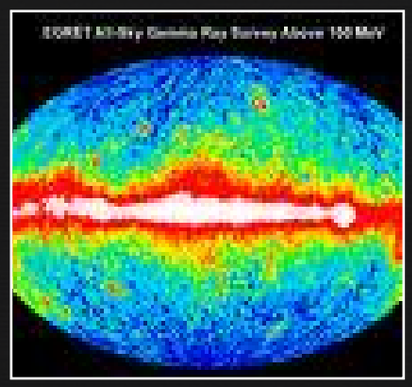

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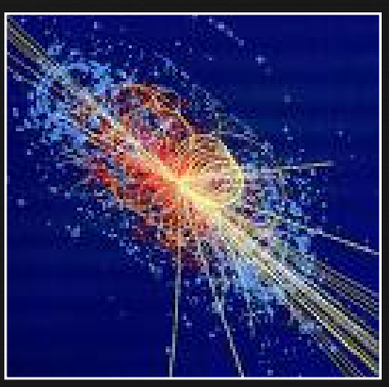

Taoso, GB & Masiero 2007

3) Neutral

ChaMPs, SuperChaMPs, Milli-charged, etc..

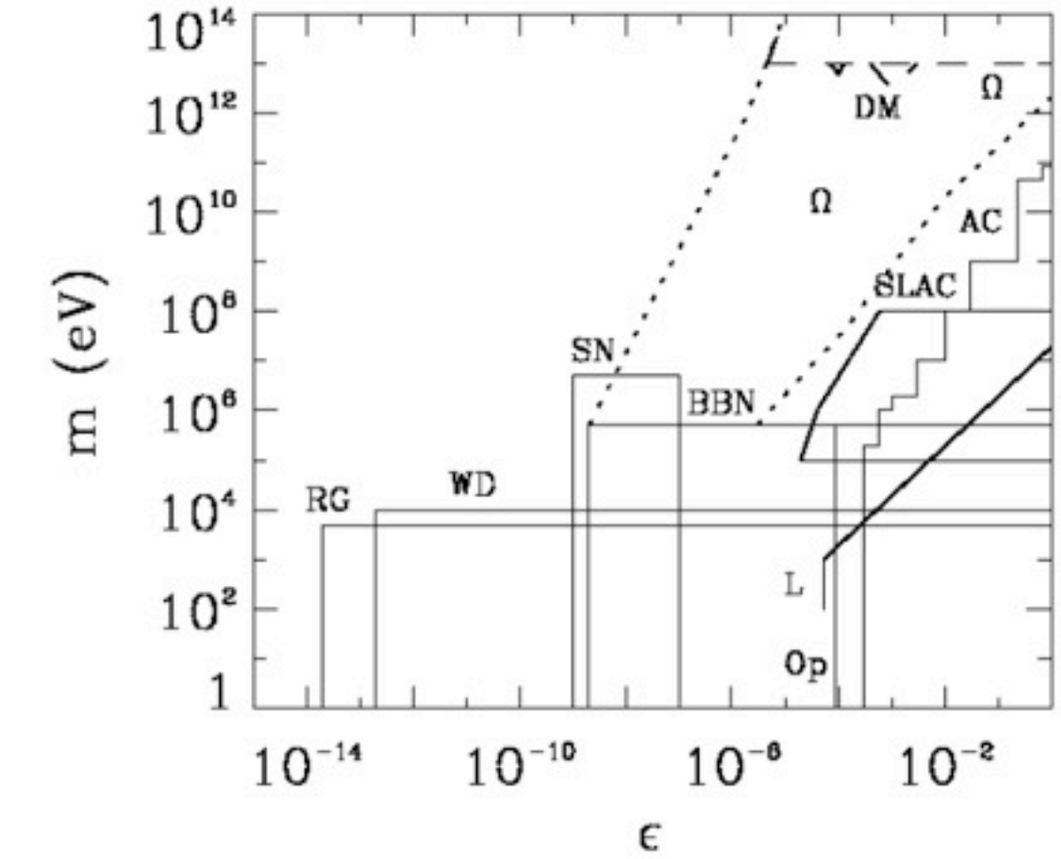

Figure 3: Excluded regions in the mass-charge plane for milli-charged particles. The constraints are relative to: RD plasmon decay in red giants; WD plasmon decay in white dwarfs; BBN big bang Nucleosynthesis; SN Supernova 1987A; AC accelerator experiments; SLAC SLAC millicharged particle search; L Lamb Shift; Op invisible decay of orthopositronium; DM Dark Matter searches. From Ref. [143].

BTM07

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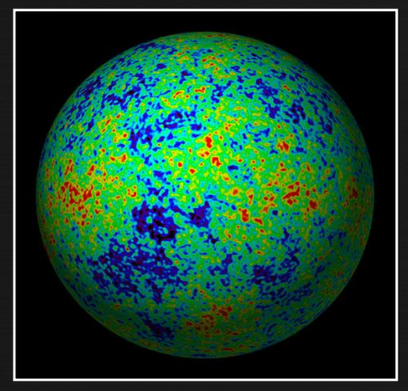

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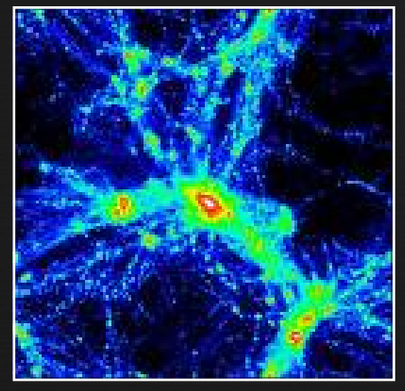

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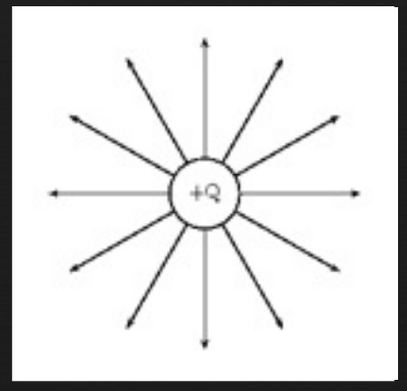

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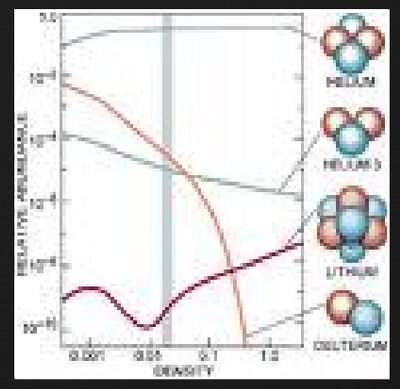

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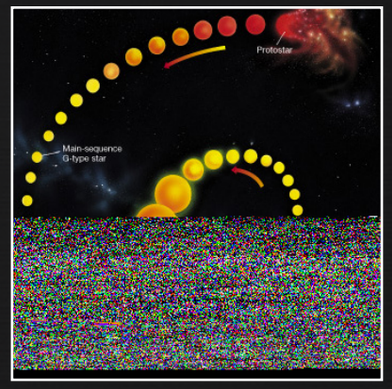

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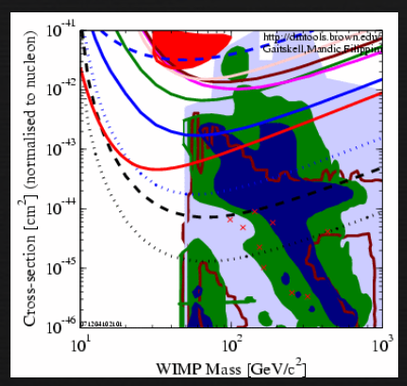

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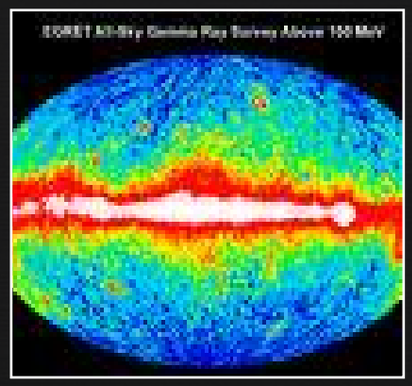

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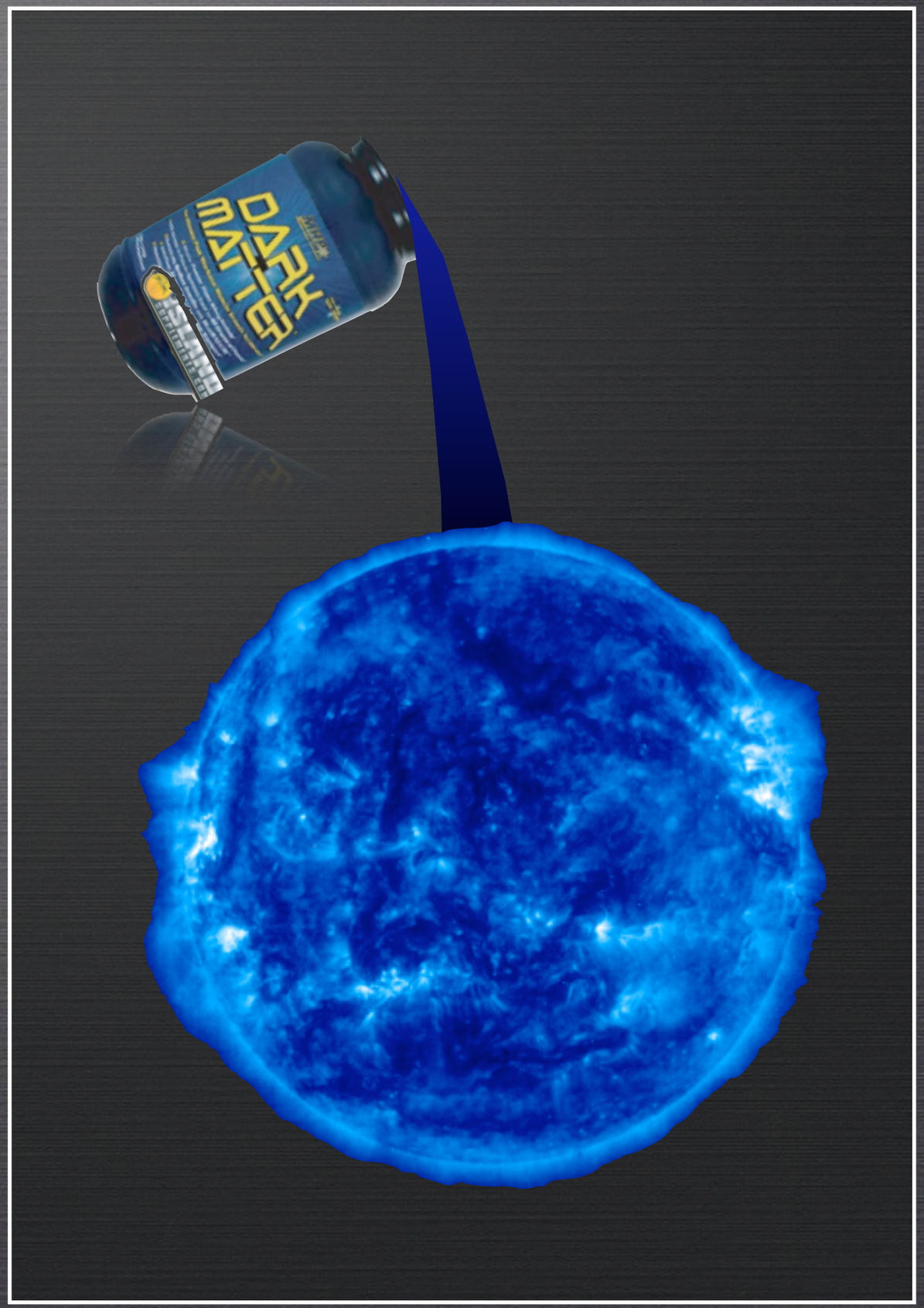
Taoso, GB & Masiero 2007

Dark Matter and Stars

- Black Holes
- White Dwarfs
- Neutron Stars
- Main Sequence
- Pop III Stars



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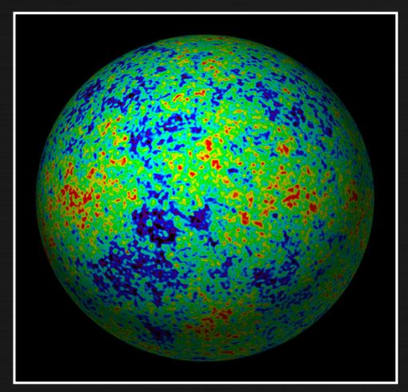

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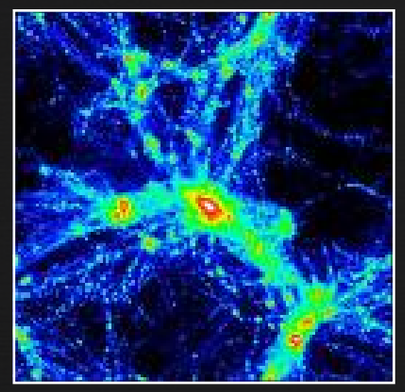

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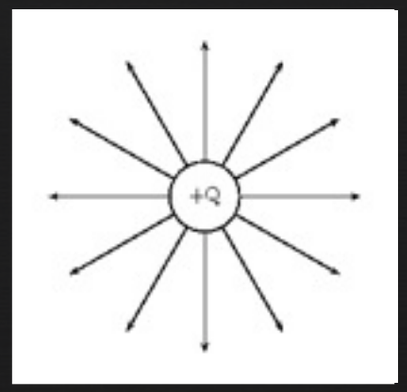

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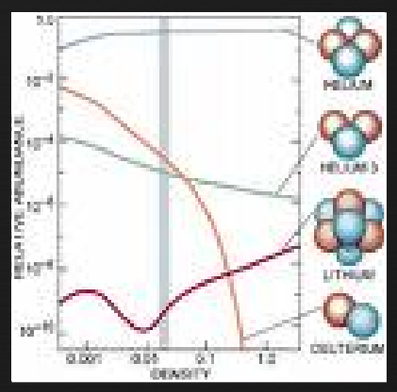

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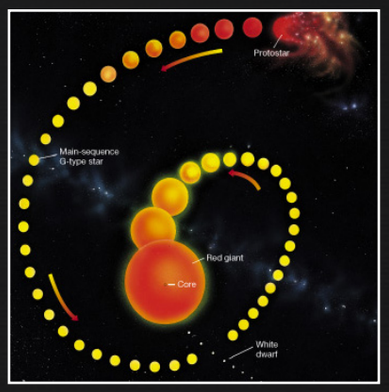

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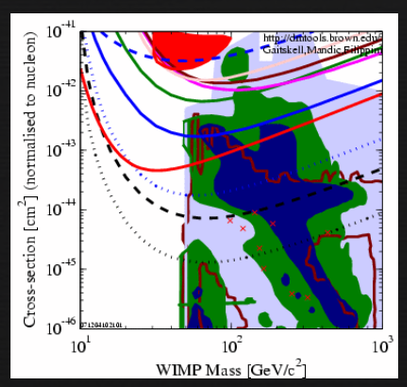

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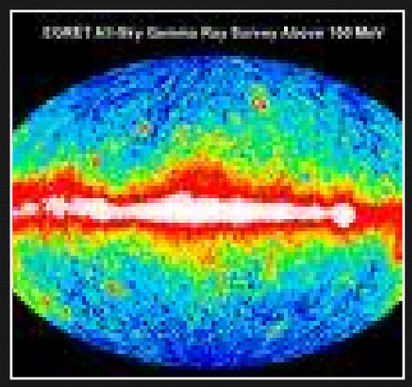

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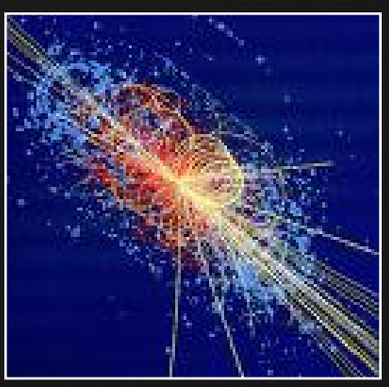
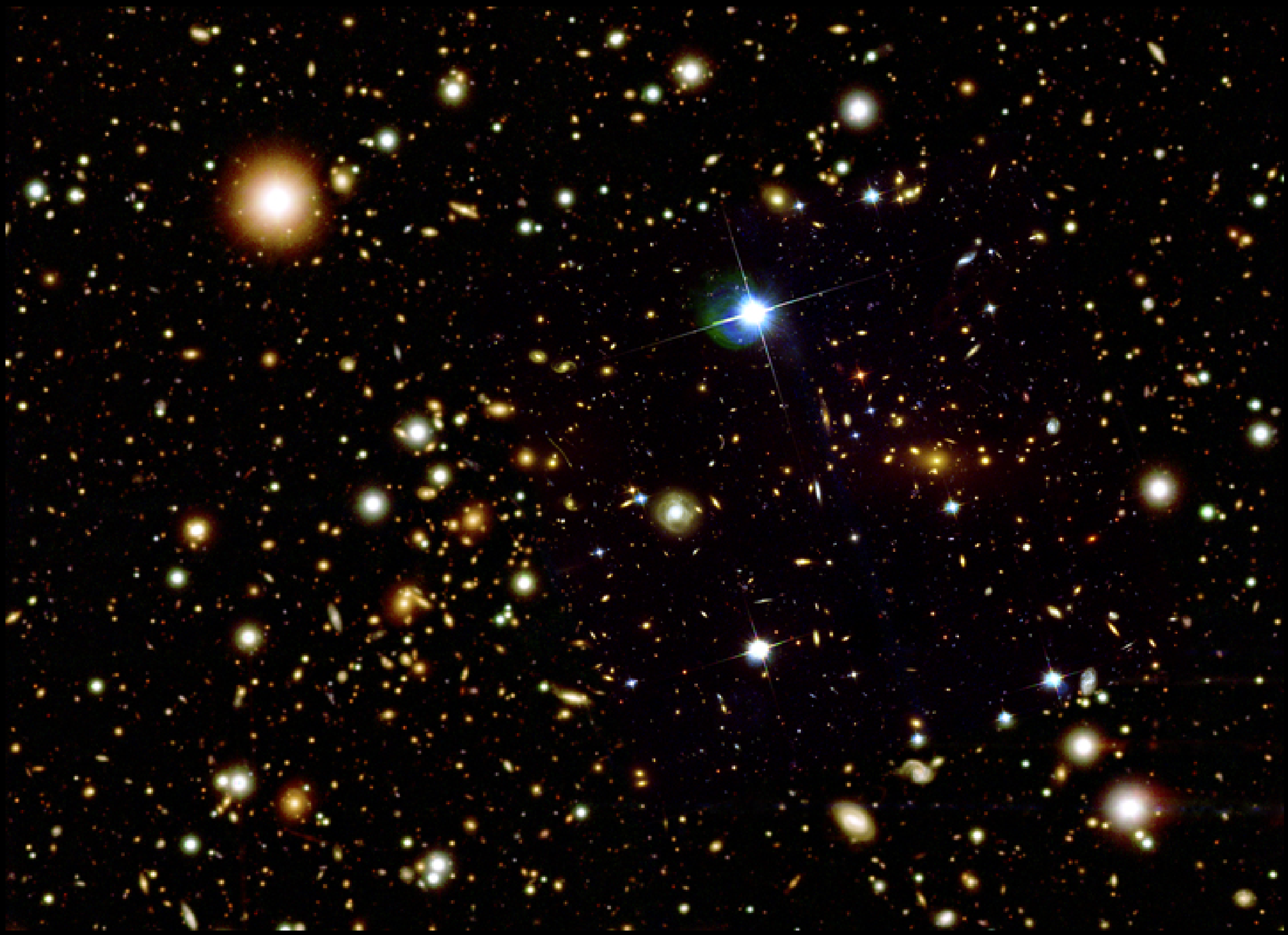
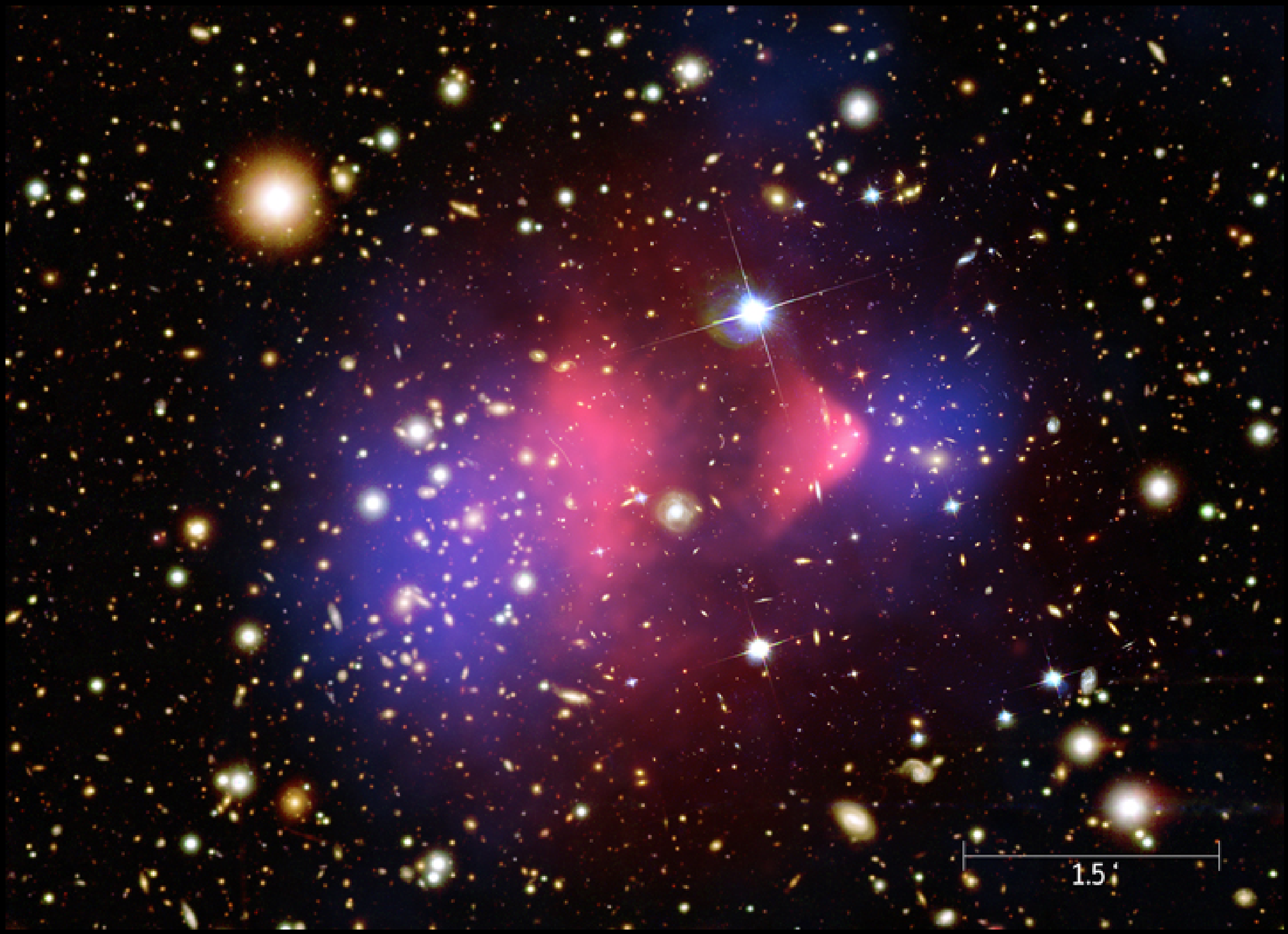


Taoso, GB & Masiero 2007




1.5 '

(Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)

DM ≠ Baryons

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6) Constraints on self-interactions x-section

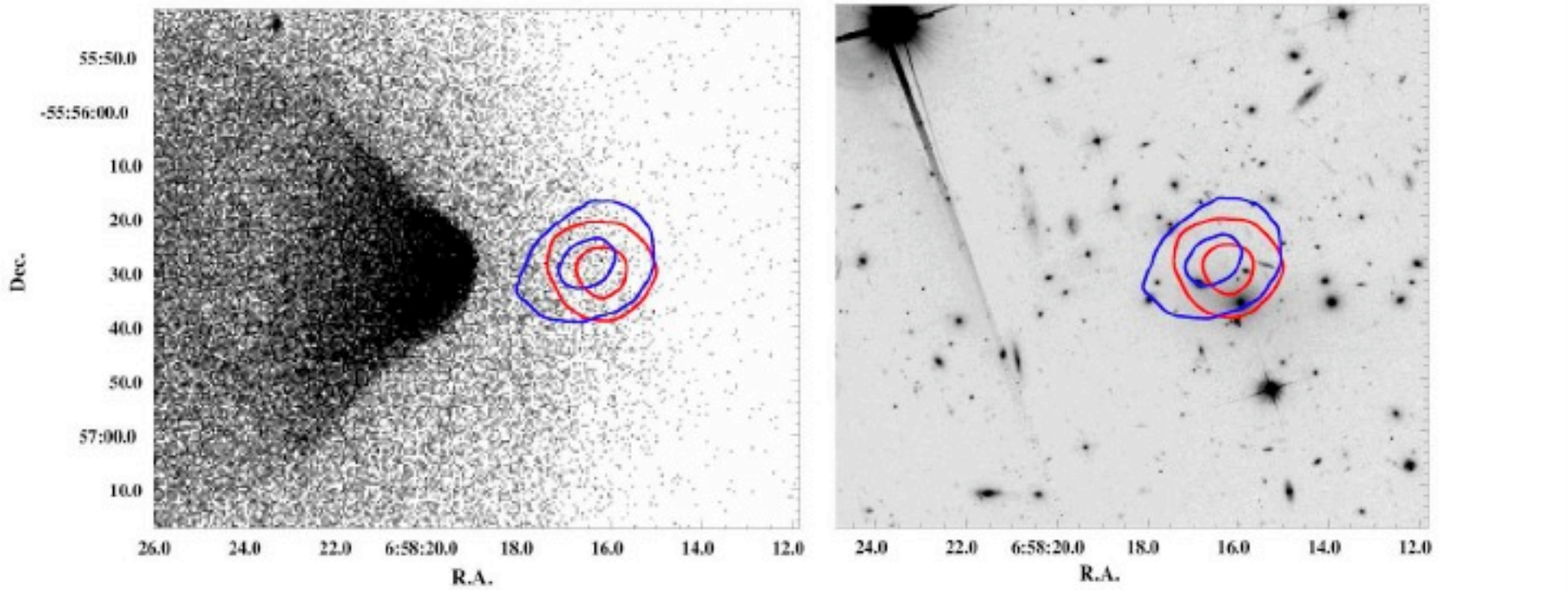

Fig. 2.— Close up of the subcluster bullet region, with the DM (blue) and galaxy (red) centroid error contours overlain. The contours show the 68.3% and 99.7% error regions. The left panel shows the X-ray *Chandra* image, while the right shows the optical *HST* image.

Randall et al. 2007

$$\sigma/m < 1.25 \text{ cm}^2 \text{ g}^{-1}$$

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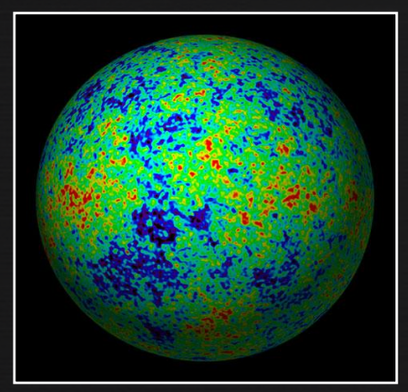
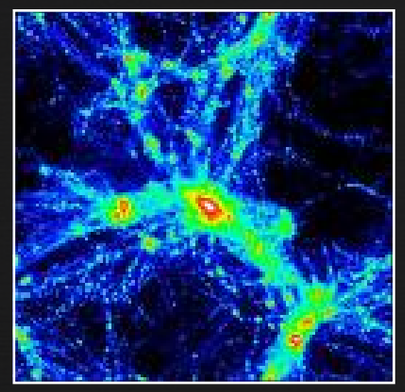
An extraordinarily rich zoo of non-baryonic Dark Matter candidates! In order to be considered a viable DM candidate, a new particle has to pass the following 10-point test

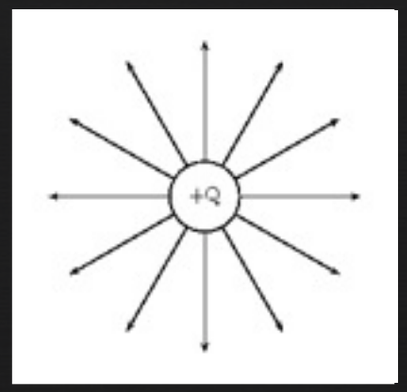
1) Ωh^2 OK?



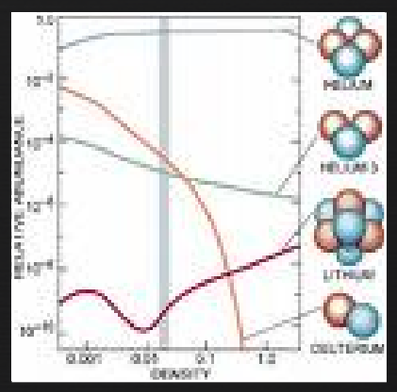
2) Is it cold?



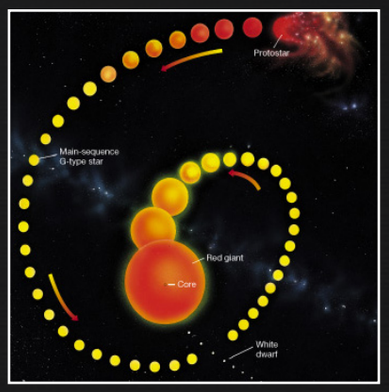
3) Is it neutral?



4) Is BBN ok?

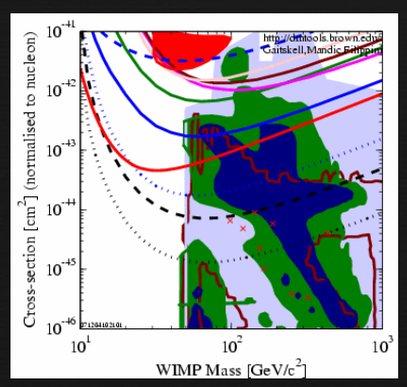


5) Stars OK?

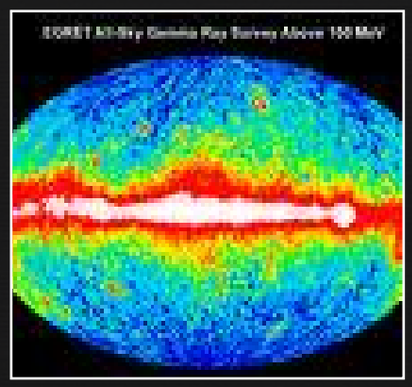


6) Collisionless?

7) Couplings OK?

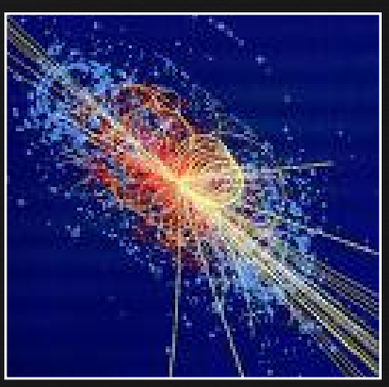


8) γ-rays OK?



9) Astro bounds?

10) Can probe it?



Taoso, GB & Masiero 2007

The DM candidates Zoo

lightest T-parity odd particle

strongly interacting massive particles

KALUZA-KLEIN NEUTRINO

bulk black hole

fuzzy

ULTRA LIGHT PSEUDO-GOLDSTONE BOSONS

Axion

WIMPzillas

Axino

Cryptons

Q-balls

D-matter

NEUTRALINO

Sterile Neutrino

Sneutrino

Branons

Self-Interacting

LIGHTEST Z3 CHARGED KALUZA-KLEIN EXCITATION

Kaluza-Klein DM

INERT HIGGS DOUBLET

gauge singlet scalars

HEAVY DOUBLE CHARGED LEPTONS

The DM candidates Zoo

WIMPs

Natural Candidates

Arising from theories addressing the stability of the electroweak scale etc.

- **SUSY** Neutralino
- Also: LKP, LZP, LTP, etc.

Ad-Hoc Candidates

Postulated to solve the DM Problem

- Minimal DM
- Maverick DM
- etc.

Other

- **Axions**
  Postulated to solve the strong CP problem

- **Sterile Neutrinos**

- **SuperWIMPs**
  Inherit the appropriate relic density from the decay of the NTL particle of the new theory

- **WIMPless**
  Appropriate relic density achieved by a suitable combination of masses and couplings

Physics Beyond the SM

There are good reasons to believe that "new physics" should appear at ~TeV energies

- Divergences in loop corrections to Higgs boson mass

$$\delta m_s^2 \sim \left(\frac{\alpha}{2\pi}\right)(\Lambda^2 + m_B^2) - \left(\frac{\alpha}{2\pi}\right)(\Lambda^2 + m_F^2) = \left(\frac{\alpha}{2\pi}\right)(m_B^2 - m_F^2)$$

- Hierarchy problem (why E_{EW} is not E_{Pl})

- Unification of all interactions at high E

- Extra-dimensions suggested by String Theory

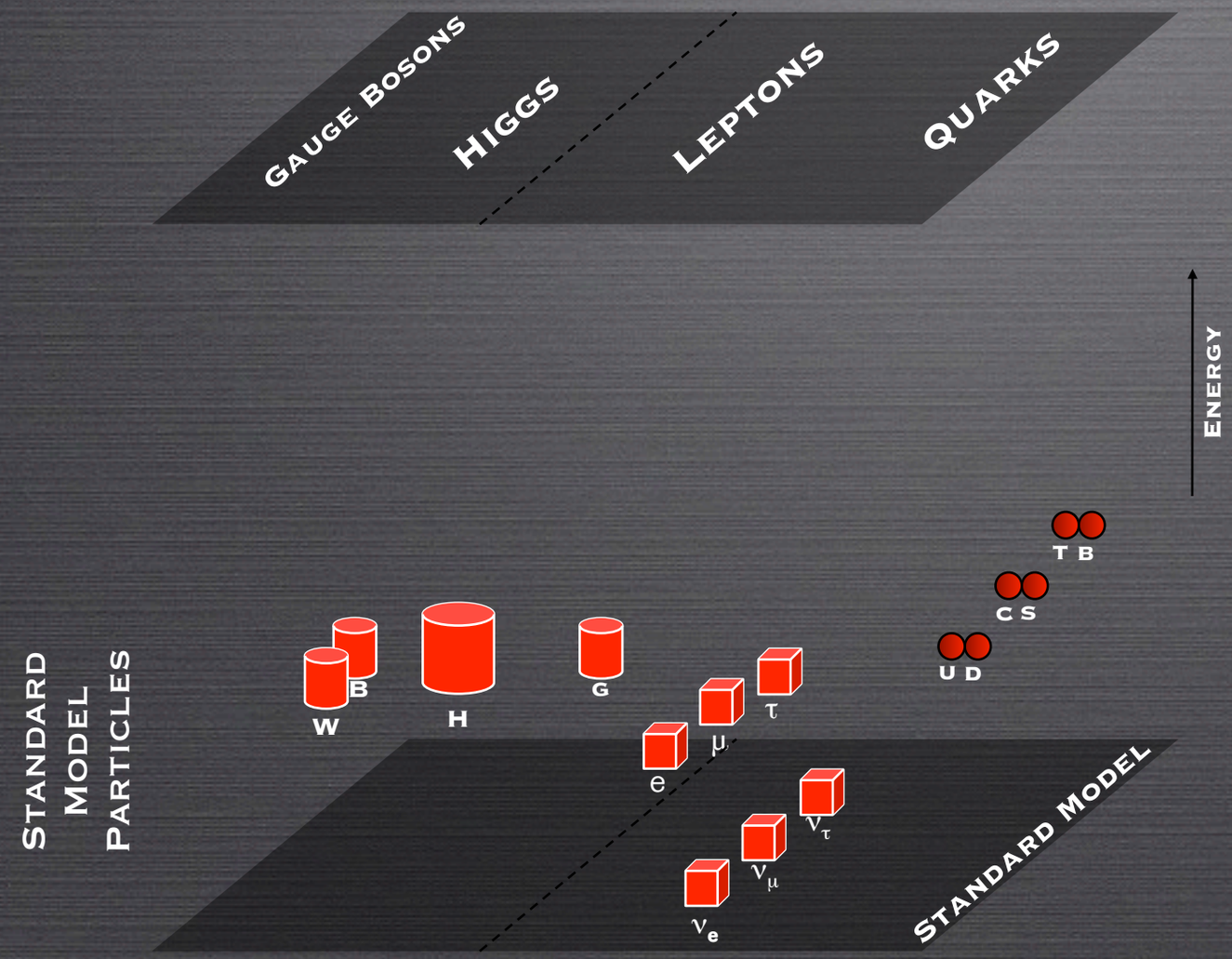
- Dark Matter!

Supersymmetry, in particular, is an exciting possibility addressing almost all points.

Extra-dimensions also very popular.

Beyond the Standard Model

The Standard Model provides an accurate description of all known particles and interactions, however there are good reasons to believe that the Standard model is a low-energy limit of a more fundamental theory



To explain the origin of the weak scale, extensions of the standard model often postulate the existence of new physics at ~100 GeV

On the left, schematic view of the structure of possible extensions of the standard model

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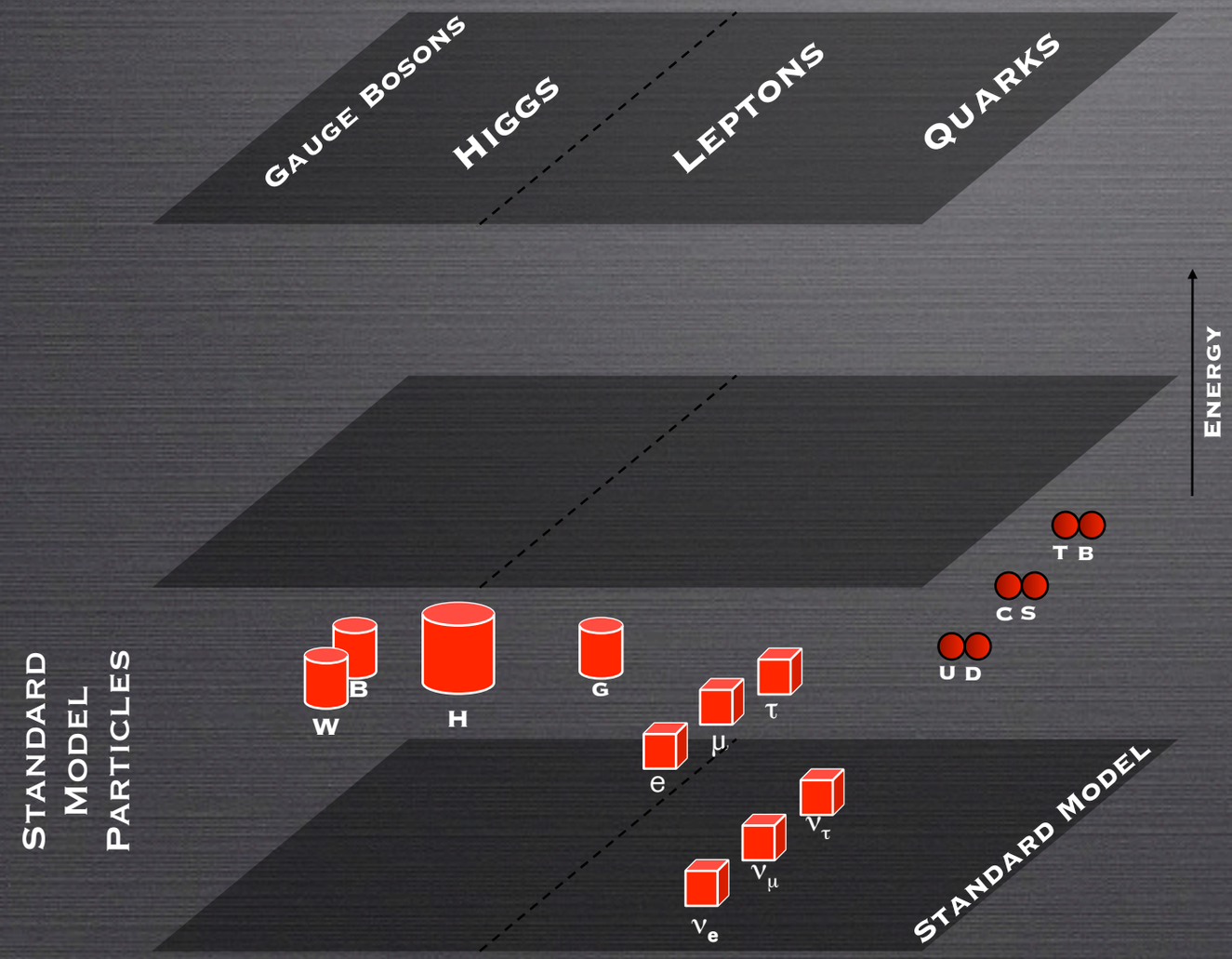

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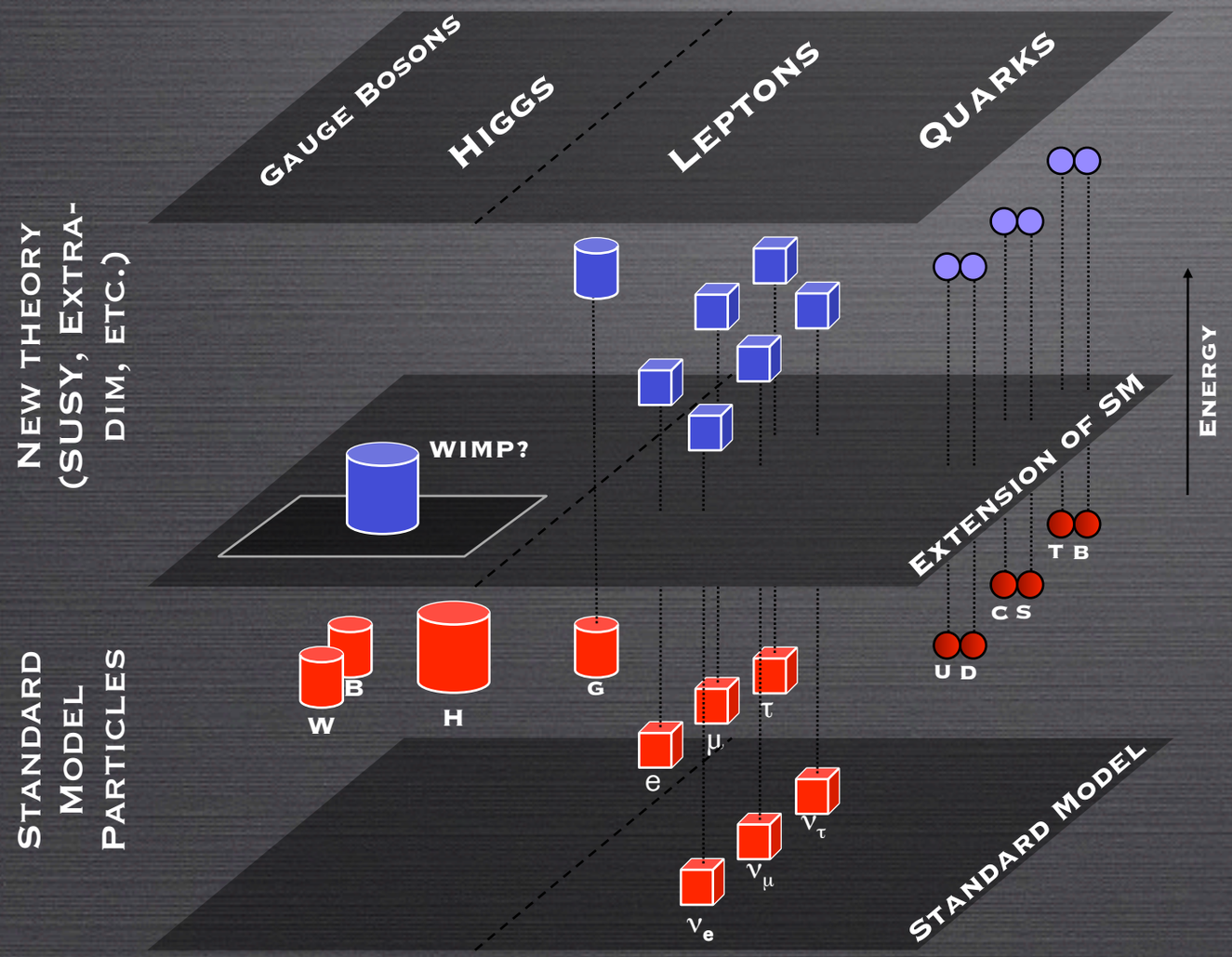

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Beyond the Standard Model

Minimal Supersymmetry

Basics

- A new symmetry that mixes internal (color, isospin, flavour, etc.) and spacetime (rotation, translation, boost) symmetries

- Relates Bosons to fermions (in fact, associates them in 1-to-1 correspondence)

$$Q|\text{fermion}\rangle = |\text{boson}\rangle; \quad Q|\text{boson}\rangle = |\text{fermion}\rangle$$

- Addresses stability of Higgs mass, unifications of interactions

- Provides DM candidates!

Beyond the Standard Model

Minimal Supersymmetry

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	$\tilde{\chi}^\pm_{1,2}$	chargino
H^-	Higgs boson	$\tilde{H}_1^-$	higgsino		
H^+	Higgs boson	$\tilde{H}_2^+$	higgsino		
B	B-field	$\tilde{B}$	bino	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
W^3	W^3-field	$\tilde{W}^3$	wino		
H_1^0	Higgs boson	$\tilde{H}_1^0$	higgsino		
H_2^0	Higgs boson	$\tilde{H}_2^0$	higgsino		
H_3^0	Higgs boson				

- Mass of SUSY partners ≠ Mass of SM particles ⇒ SUSY must be broken at some energy

- SUSY breaking terms contain a large number of free parameters, so that the whole theory has ~120 free parameters ⇒ a nightmare for phenomenology!!

- Fortunately, not all parameters are relevant for DM, and furthermore, the number can be drastically reduced under "simplifying assumptions" (e.g. no FCNC, universality of masses, etc.)

Beyond the Standard Model

Minimal Supersymmetry

- To forbid interactions leading to fast proton decay, impose conservation of R-parity

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

- (where B, L and s are the Baryon number, Lepton number and spin)

- Under this definition, all SM particles have R=1 and all SUSY particles have R=-1

- this new symmetry prevents the decay of the lightest SUSY particles (LSP) into SM particles

- The LSP is therefore STABLE over cosmological timescales!

The Lightest Neutralino

Is the lightest SUSY particle in many "incarnations" of SUSY setups.

$$\mathcal{M}_{\chi^0} = \begin{pmatrix} M_1 & 0 & -m_Z \cos\beta \sin\theta_W & m_Z \sin\beta \sin\theta_W \\ 0 & M_2 & m_Z \cos\beta \cos\theta_W & -m_Z \sin\beta \cos\theta_W \\ -m_Z \cos\beta \sin\theta_W & m_Z \cos\beta \cos\theta_W & 0 & -\mu \\ m_Z \sin\beta \sin\theta_W & -m_Z \sin\beta \cos\theta_W & -\mu & 0 \end{pmatrix}$$

M1: Bino mass
M2: Wino mass
μ: Higgsino mass parameter
tanβ: ratio of VEV of the two Higgs

$$\mathcal{M}^{\text{diag}}_{\chi^0} = N^* M_{\chi^0} N^{-1}$$

$$\chi^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1 + N_{14}\tilde{H}_2$$

Beyond the Standard Model

cMSSM

A Neutralino Mass Eigenstates

In the Minimal Supersymmetric Standard Model (MSSM), the neutral electroweak gauginos ($\tilde{B}, \tilde{W}^3$) and higgsinos ($\tilde{H}_1^0, \tilde{H}_2^0$) have the same quantum numbers and, therefore, mix into four mass eigenstates called neutralinos. The neutralino mass matrix in the $\tilde{B}$-$\tilde{W}^3$-$\tilde{H}_1^0$-$\tilde{H}_2^0$ basis is given by

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & -M_Z\sin\beta\cos\theta_W \\ -M_Z\cos\beta\sin\theta_W & M_Z\cos\beta\cos\theta_W & 0 & -\mu \\ M_Z\sin\beta\sin\theta_W & -M_Z\sin\beta\cos\theta_W & -\mu & 0 \end{pmatrix}, \tag{146}$$

where M_1, M_2 and μ are the bino, wino and higgsino mass parameters, respectively, θ_W is the Weinberg angle and $\tan\beta$ is the ratio of the vacuum expectation values of the Higgs bosons. This matrix can be diagonalized by the matrix, N.

$$M_{\chi^0}^{\rm diag} = N^\dagger M_{\chi^0} N. \tag{147}$$

The masses of the four mass eigenstates are then given by [207, 62]

$$\epsilon_1 M_{\chi_1^0} = -(\tfrac{1}{2}a - \tfrac{1}{6}C_2)^{1/2} + \left[-\tfrac{1}{2}a - \tfrac{1}{3}C_2 + \frac{C_3}{(8a - \frac{8}{3}C_2)^{1/2}}\right]^{1/2} + \tfrac{1}{4}(M_1 + M_2)\,, \tag{148}$$

$$\epsilon_2 M_{\chi_2^0} = +(\tfrac{1}{2}a - \tfrac{1}{6}C_2)^{1/2} - \left[-\tfrac{1}{2}a - \tfrac{1}{3}C_2 - \frac{C_3}{(8a - \frac{8}{3}C_2)^{1/2}}\right]^{1/2} + \tfrac{1}{4}(M_1 + M_2)\,, \tag{149}$$

$$\epsilon_3 M_{\chi_3^0} = -(\tfrac{1}{2}a - \tfrac{1}{6}C_2)^{1/2} - \left[-\tfrac{1}{2}a - \tfrac{1}{3}C_2 + \frac{C_3}{(8a - \frac{8}{3}C_2)^{1/2}}\right]^{1/2} + \tfrac{1}{4}(M_1 + M_2)\,, \tag{150}$$

$$\epsilon_4 M_{\chi_4^0} = +(\tfrac{1}{2}a - \tfrac{1}{6}C_2)^{1/2} + \left[-\tfrac{1}{2}a - \tfrac{1}{3}C_2 - \frac{C_3}{(8a - \frac{8}{3}C_2)^{1/2}}\right]^{1/2} + \tfrac{1}{4}(M_1 + M_2)\,, \tag{151}$$

where ϵ_i is the sign of the ith eigenvalue of the neutralino mass matrix, and

$$C_2 = (M_1 M_2 - M_Z^2 - \mu^2) - \frac{3}{8}(M_1 + M_2)^2\,, \tag{152}$$

$$C_3 = -\frac{1}{8}(M_1 + M_2)^3 + \frac{1}{2}(M_1 + M_2)(M_1 M_2 - M_Z^2 - \mu^2) + (M_1 + M_2)\mu^2 + (M_1\cos^2\theta_W + M_2\sin^2\theta_W)M_Z^2 + \mu M_Z^2\sin 2\beta\,, \tag{153}$$

$$C_4 = -(M_1\cos^2\theta_W + M_2\sin^2\theta_W)M_Z^2\mu\sin 2\beta - M_1 M_2\mu^2 + \frac{1}{4}(M_1 + M_2)[(M_1 + M_2)\mu^2 + (M_1\cos^2\theta_W + M_2\sin^2\theta_W)M_Z^2 + \mu M_Z^2\sin 2\beta] + \frac{1}{16}(M_1 M_2 - M_Z^2 - \mu^2)(M_1 + M_2)^2 - \frac{3}{256}(M_1 + M_2)^4\,, \tag{154}$$

$$a = \frac{1}{2^{1/3}}\mathrm{Re}\left[-S + i(D/27)^{1/2}\right]^{1/3}\,, \tag{155}$$

$$D = -4U^3 - 27S^2\,, \quad U = -\frac{1}{3}C_2^2 - 4C_4, \quad S = -C_3^2 - \frac{2}{27}C_2^3 + \frac{8}{3}C_2C_4\,. \tag{156}$$

The four masses above are not generally in the order $M_{\chi_1^0} < M_{\chi_2^0} < M_{\chi_3^0} < M_{\chi_4^0}$, although it is conventional to relabel the states, from lightest to heaviest.

The mixing matrix, N, is then given by [207, 62]

$$\frac{N_{i2}}{N_{i1}} = -\frac{1}{\tan\theta_W}\frac{M_1 - \epsilon_i M_{\chi_i^0}}{M_2 - \epsilon_i M_{\chi_i^0}}\,, \tag{157}$$

$$\frac{N_{i3}}{N_{i1}} = \frac{-\mu[M_2 - \epsilon_i M_{\chi_i^0}][M_1 - \epsilon_i M_{\chi_i^0}] - M_Z^2\sin\beta\cos\beta[(M_1 - M_2)\cos^2\theta_W + M_2 - \epsilon_i M_{\chi_i^0}]}{M_Z[M_2 - \epsilon_i M_{\chi_i^0}]\sin\theta_W[-\mu\cos\beta + \epsilon_i M_{\chi_i^0}\sin\beta]}\,, \tag{158}$$

$$\frac{N_{i4}}{N_{i1}} = \frac{-\epsilon_i M_{\chi_i^0}[M_2 - \epsilon_i M_{\chi_i^0}][M_1 - \epsilon_i M_{\chi_i^0}] - M_Z^2\cos^2\beta[(M_1 - M_2)\cos^2\theta_W + M_2 - \epsilon_i M_{\chi_i^0}]}{M_Z[M_2 - \epsilon_i M_{\chi_i^0}]\sin\theta_W[-\mu\cos\beta + \epsilon_i M_{\chi_i^0}\sin\beta]}\,, \tag{159}$$

and

$$N_{i1} = \left[1 + \left(\frac{N_{i2}}{N_{i1}}\right)^2 + \left(\frac{N_{i3}}{N_{i1}}\right)^2 + \left(\frac{N_{i4}}{N_{i1}}\right)^2\right]^{-1/2}. \tag{160}$$

The lighest neutralino (χ_1^0) is a mixture of gauginos and higgsinos:

$$\chi_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0. \tag{161}$$

The gaugino fraction of χ_1^0 is defined as

$$f_G = N_{11}^2 + N_{12}^2 \tag{162}$$

and its higgisino fraction as

$$f_H = N_{13}^2 + N_{14}^2. \tag{163}$$

Beyond the Standard Model

cMSSM

- Unification of the gaugino masses

$$M_1(M_U) = M_2(M_U) = M_3(M_U) \equiv m_{1/2}$$

- Universal scalar [sfermion and Higgs boson] masses

$$M_{\tilde{Q}}(M_U) = M_{\tilde{u}_R}(M_U) = M_{\tilde{d}_R}(M_U) = M_{\tilde{L}}(M_U) = M_{\tilde{l}_R}(M_U) = M_{H_u}(M_U) = M_{H_d}(M_U) \equiv m_0$$

- Universal trilinear couplings:

$$A_u(M_U) = A_d(M_U) = A_l(M_U) \equiv A_0$$

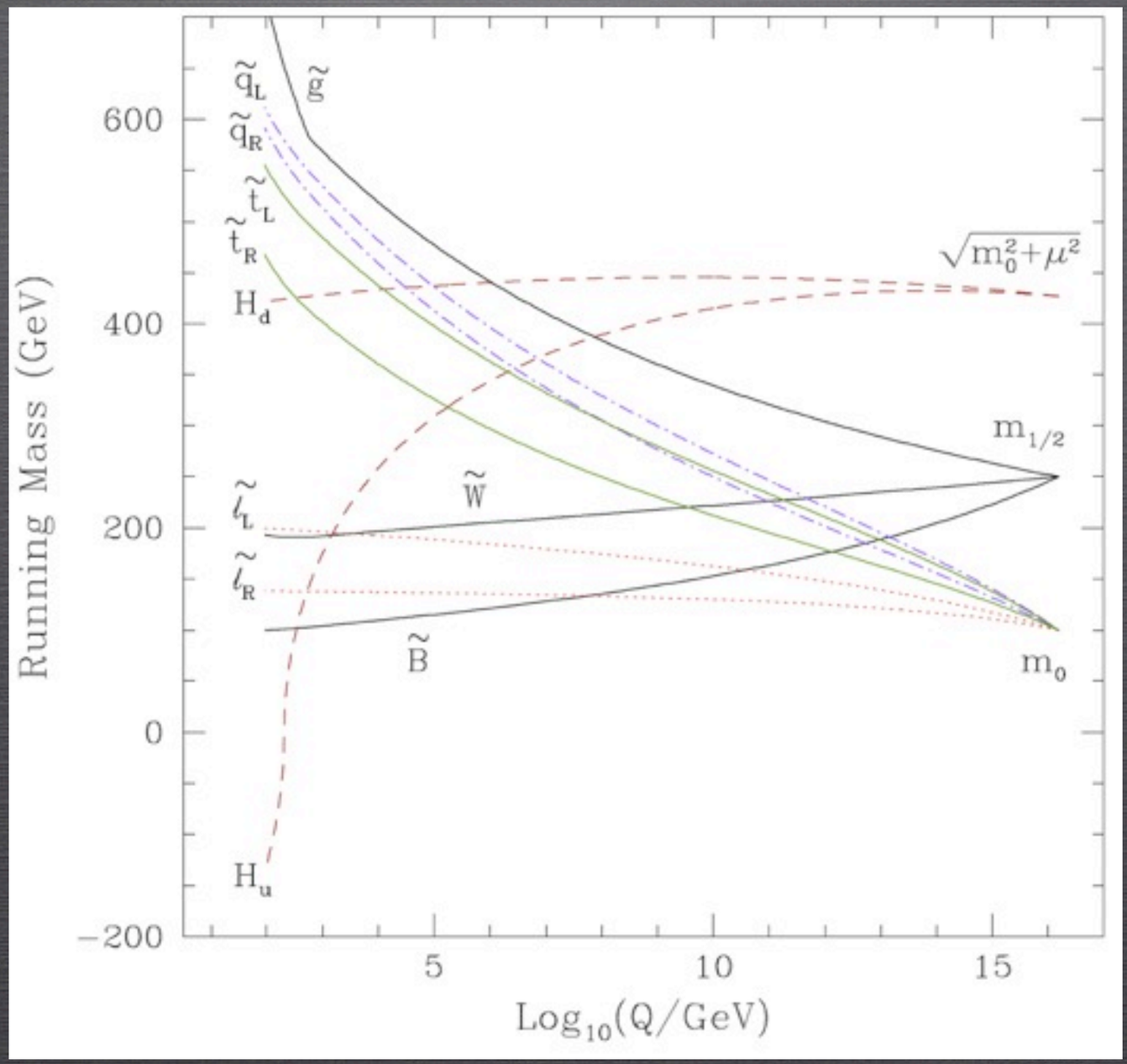
only 4 (continuous) + 1 (discrete) parameters left!

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

where tanβ is the ratio of the vacuum expectation values of the two Higgs fields and μ is the higgsino mass parameter.

Beyond the Standard Model

cMSSM



The renormalization-group evolution of the mass parameters in the CMSSM, assuming m1/2 = 250 GeV, m0 = 100 GeV, tan = 3, A0 = 0, and μ < 0. Fig by

Beyond the Standard Model

cMSSM

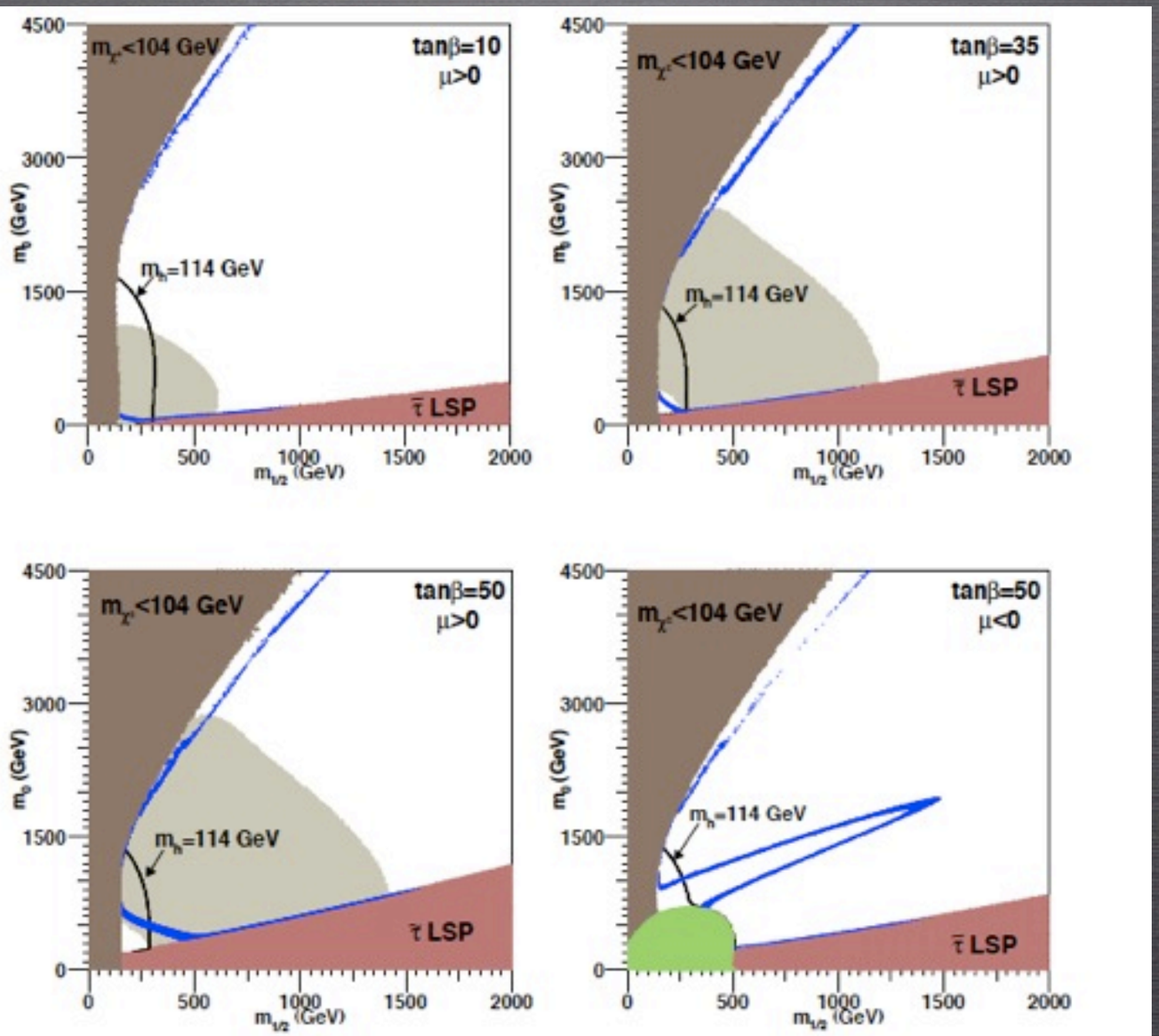


Figure 3. Representative regions of the CMSSM parameter space. The blue regions predict a neutralino density consistent with the measured dark matter abundance. The shaded regions to the upper left and lower right are disfavored by the LEP chargino bound and as a result of containing a stau LSP, respectively. The LEP bound on the light Higgs mass is shown as a solid line ($m_h = 114$ GeV). The region favored by measurements of the muon's magnetic moment are shown as a light shaded region (at the 3σ confidence level) [31]. In each frame, we have used $A_0 = 0$ and $\mu > 0$. (Figures generated by Gabriel Caceres, using the package DarkSUSY [29].)

Beyond the Standard Model

(Universal) Extra dimensions

- Our extra dimension is a circle (S1)

- Wave functions of any states to be periodic

- Mathematically, a “particle-in-a-box” problem

- 5th component of Momentum is quantized in units of 1 / R

- To an observer unaware of the extra-dimension, non-zero momentum states will appear as massive

$$m^2_{X^{(n)}} = \frac{n^2}{R^2} + m^2_{X^{(0)}}$$

- KK-parity plays the role of R-arity here, and makes the LKP stable

Beyond the Standard Model

(Universal) Extra dimensions

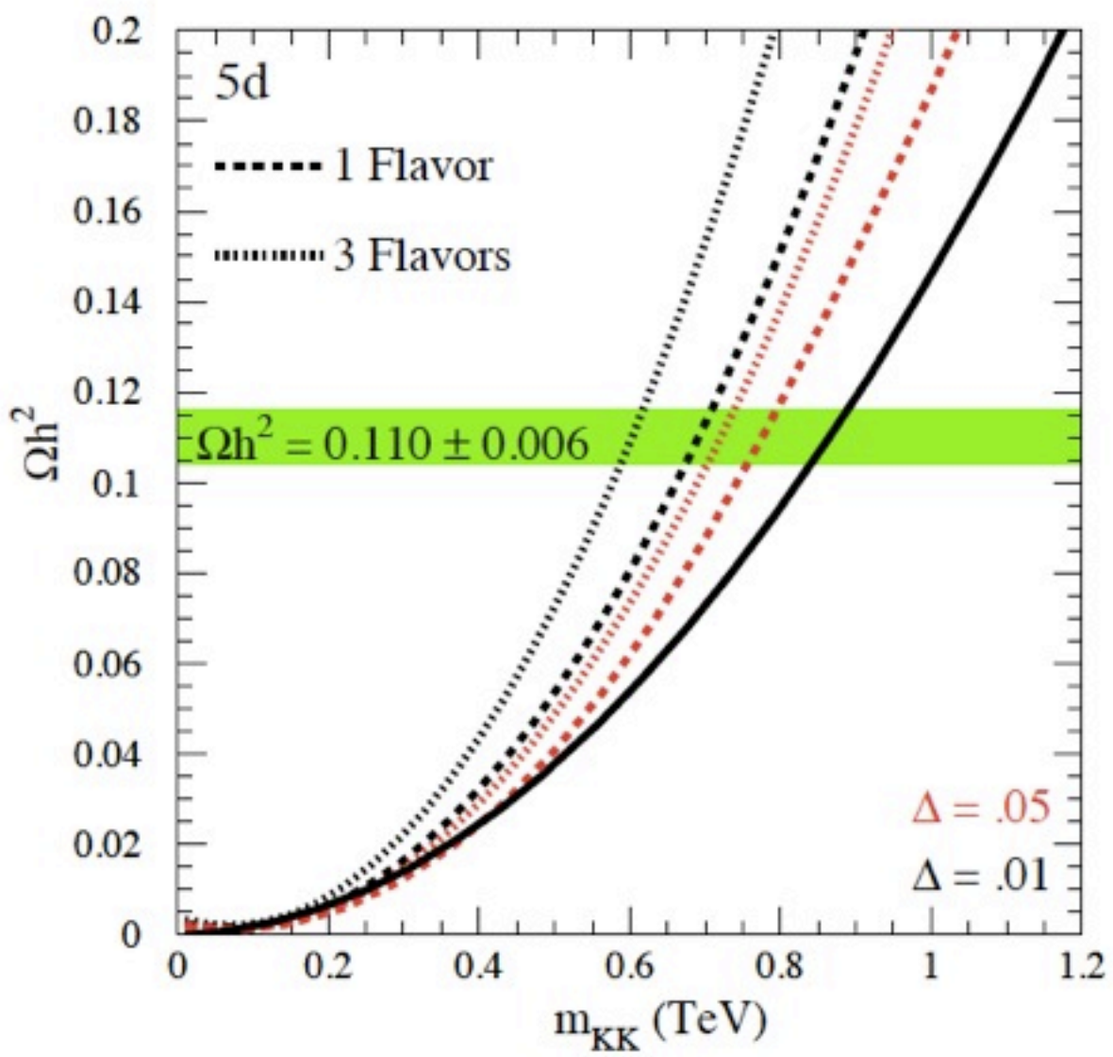


Figure 4. The thermal relic abundance of KK dark matter ($B^{(1)}$) without the effects of any other KK species (solid line) and including the effects of KK leptons 5% and 1% heavier than the LKP (dashed and dotted lines). Shown as a horizontal band is the measured dark matter abundance [6]. Adapted from Ref. [37].

Beyond the Standard Model

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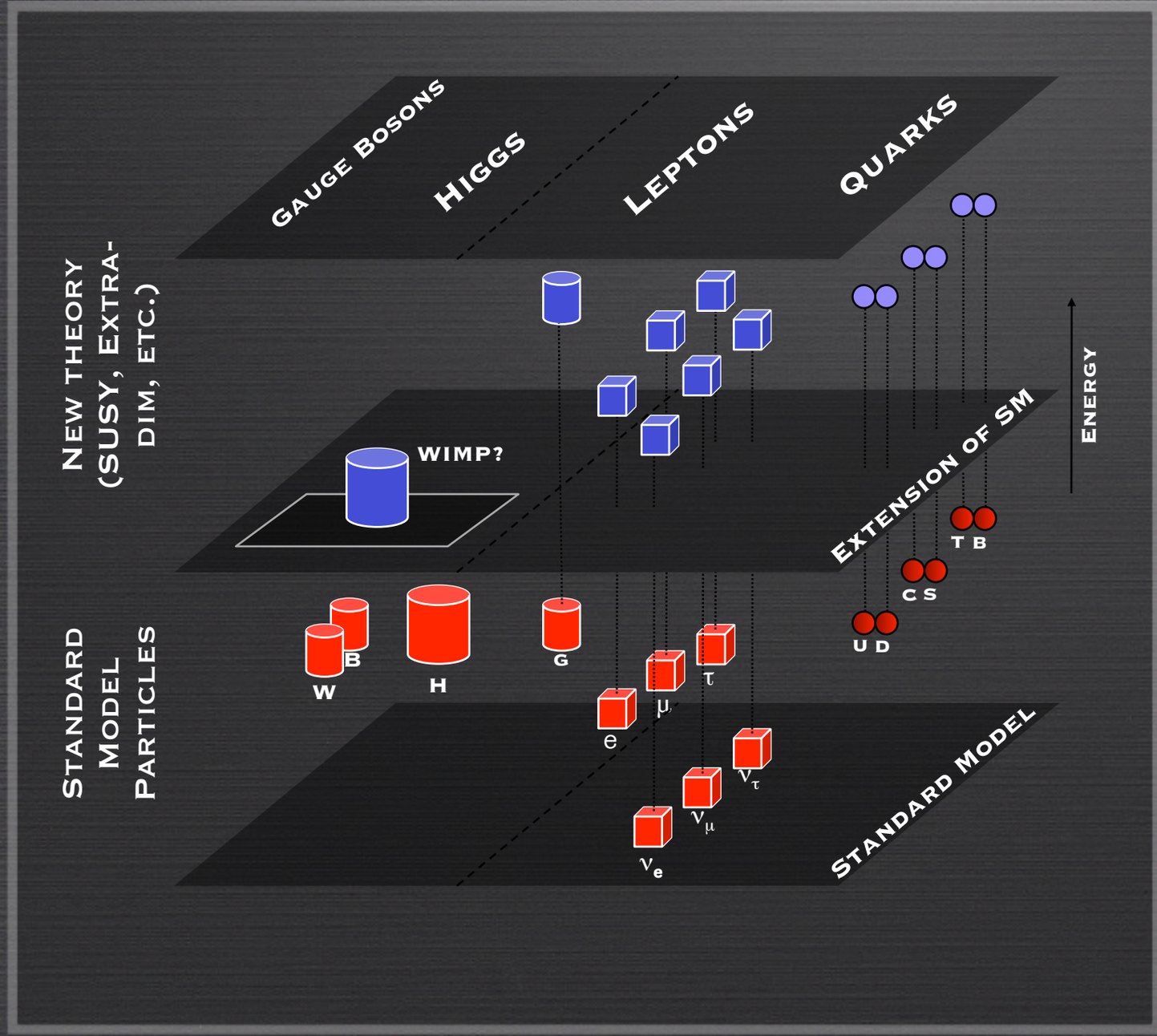
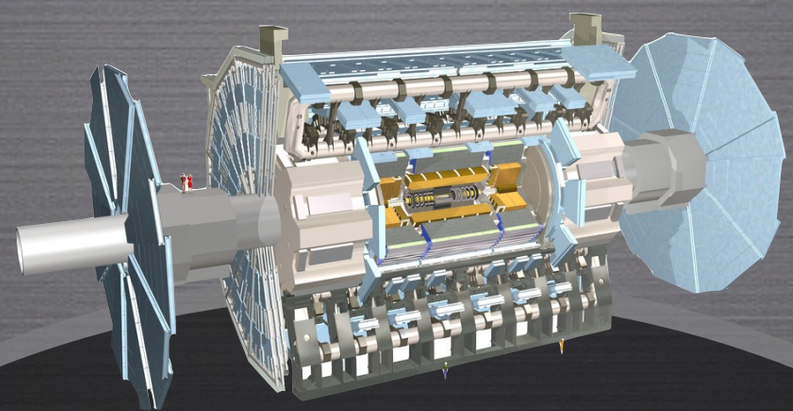


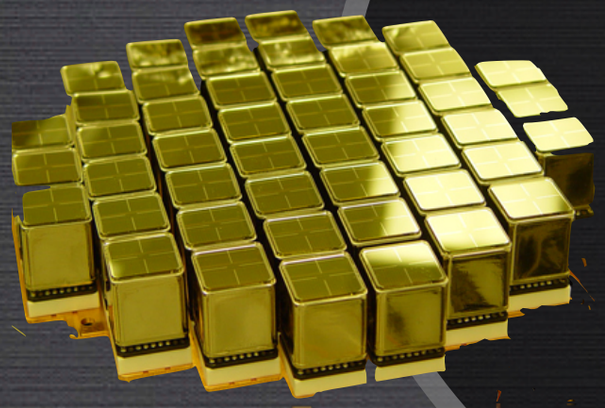
To explain the origin of the weak scale, extensions of the standard model often postulate the existence of new physics at ~100 GeV

On the left, schematic view of the structure of possible extensions of the standard model

Summary



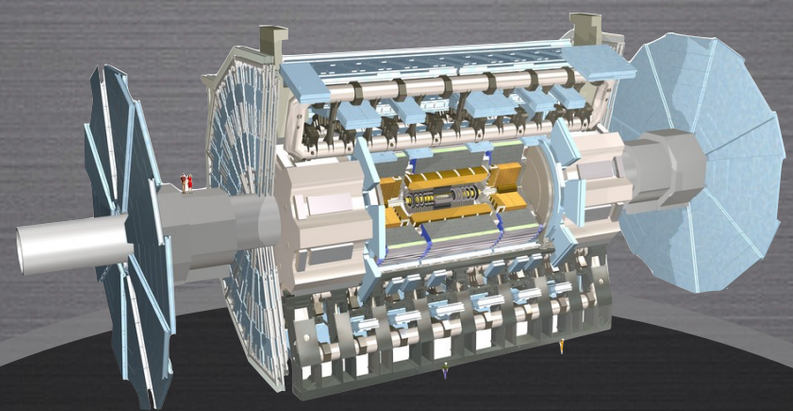
Colliders



Direct Detection

Indirect Detection

Summary



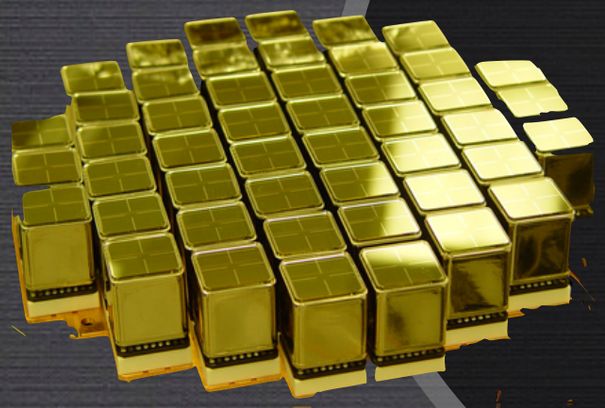
Colliders

1.Status

2.Complementarity

3.Interplay with Astrophysics

4.Identification

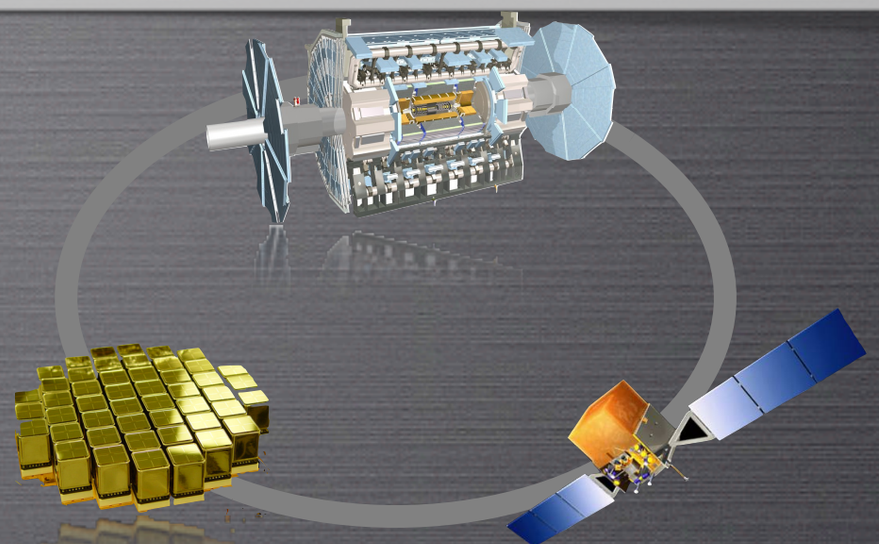


Direct Detection

Indirect Detection

Where do we stand?

We have built (are building) experiments to search for Dark Matter, and we have been making predictions for decades



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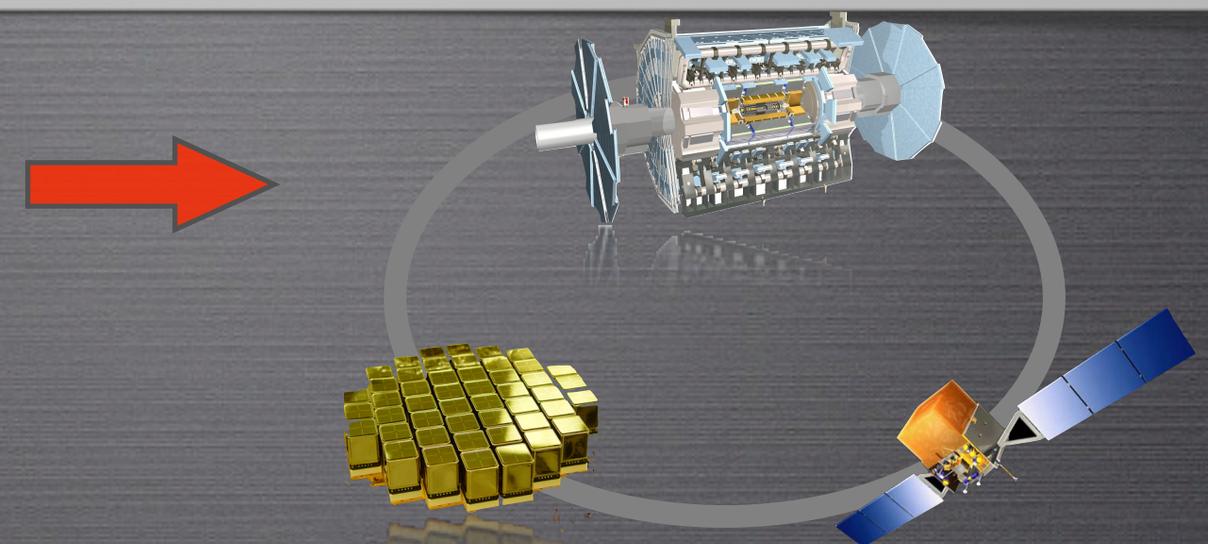
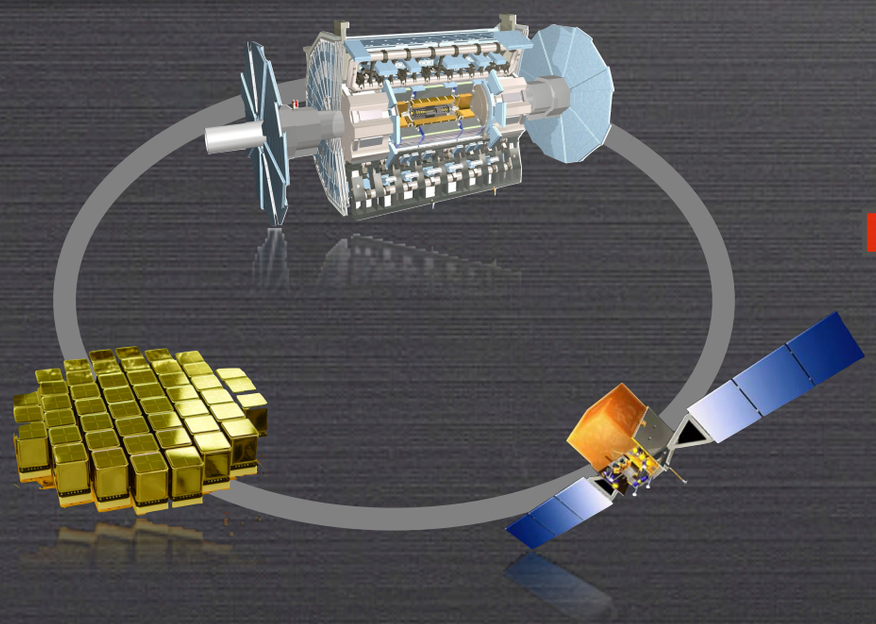
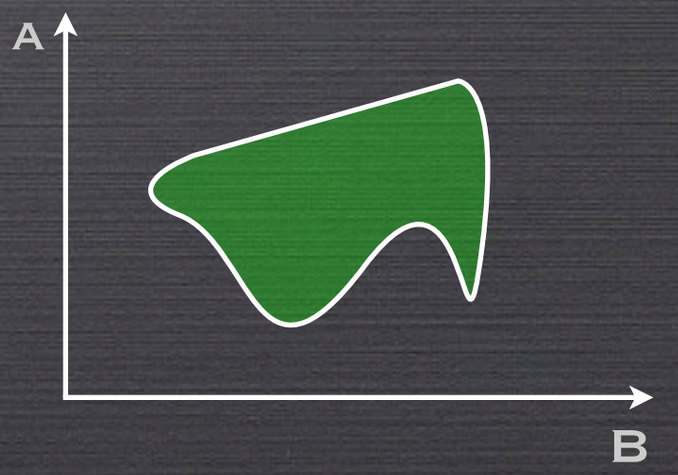
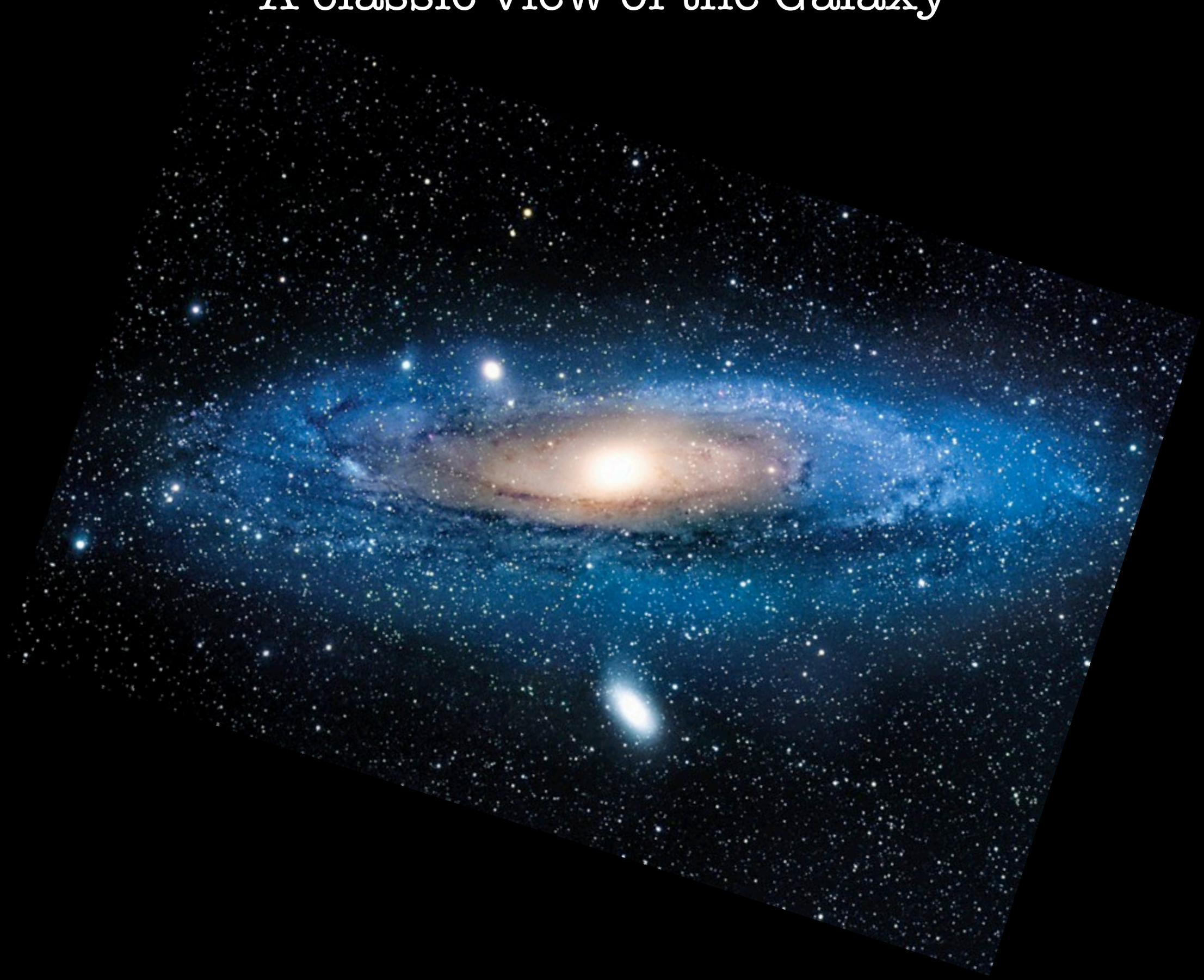


We are getting ready to solve the "inverse Problem" (and hoping that there will be a problem to solve..!)





A classic view of the Galaxy



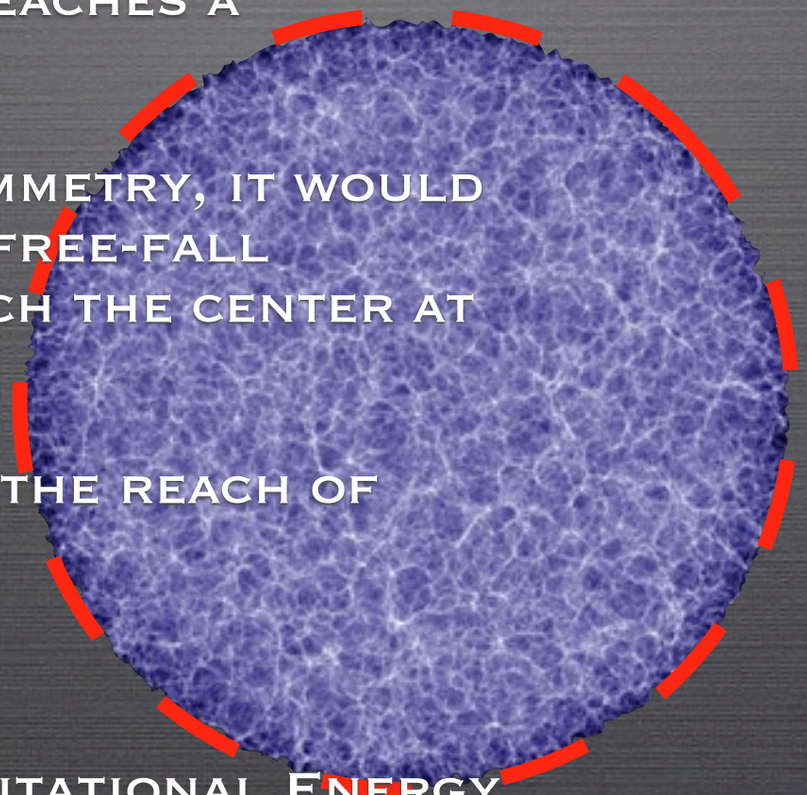
Formation of Structures

Spherical Collapse

Overdense region initially follow expansion of the Universe

Turnaround: expansion reaches a maximum

For perfect spherical symmetry, it would collapse to a point (on a free-fall timescale. All points reach the center at the same time)



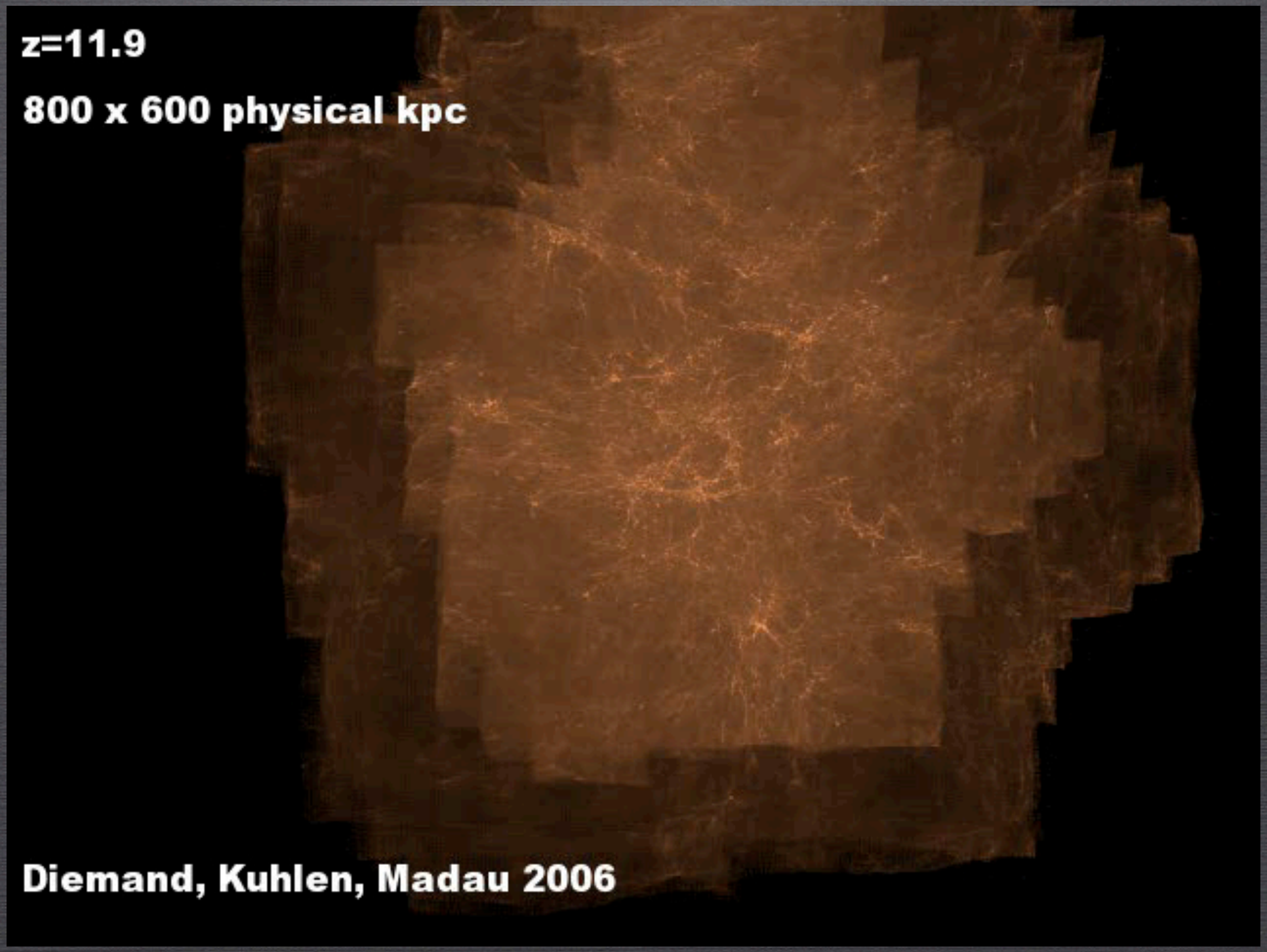
Collapse is prevented by the reach of "Virial Equilibrium"

$2K + W = 0$

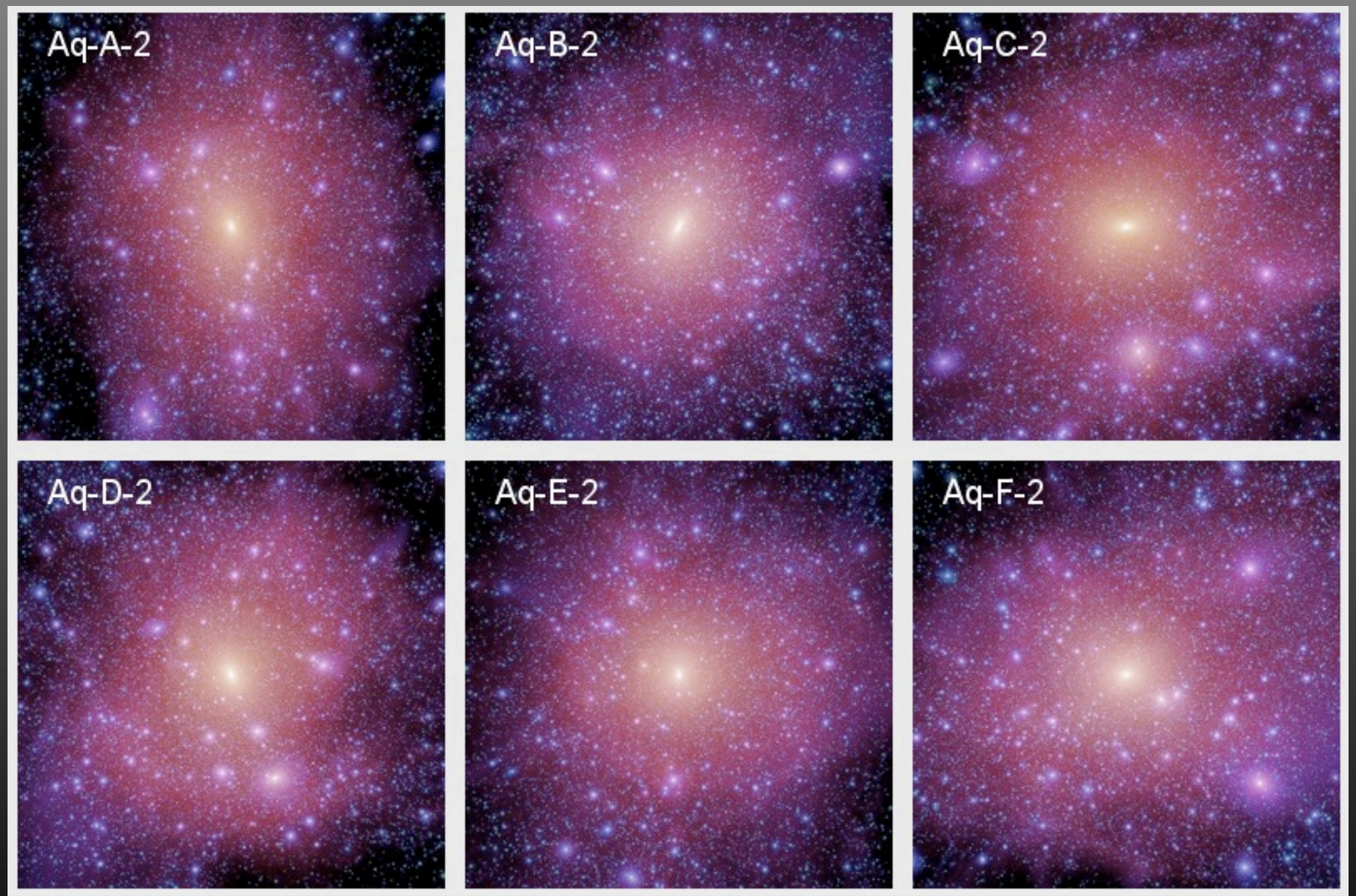
between Kinetic and Gravitational Energy

We should now introduce mass functions, the Press-Schechter formalism (along with the 'extended' version), halo models etc.

Numerical simulation of a Milky-Way like halo



How is DM distributed inside the Galaxy?



http://www.mpa-garching.mpg.de/aquarius/

Six Milky-Way sized halos at z=0, re-simulated from halos in full cosmological context , to achieve resolutions up to 160 / 224 million particles within r_200.

A modern view of the Galaxy

Reconstructed density profiles

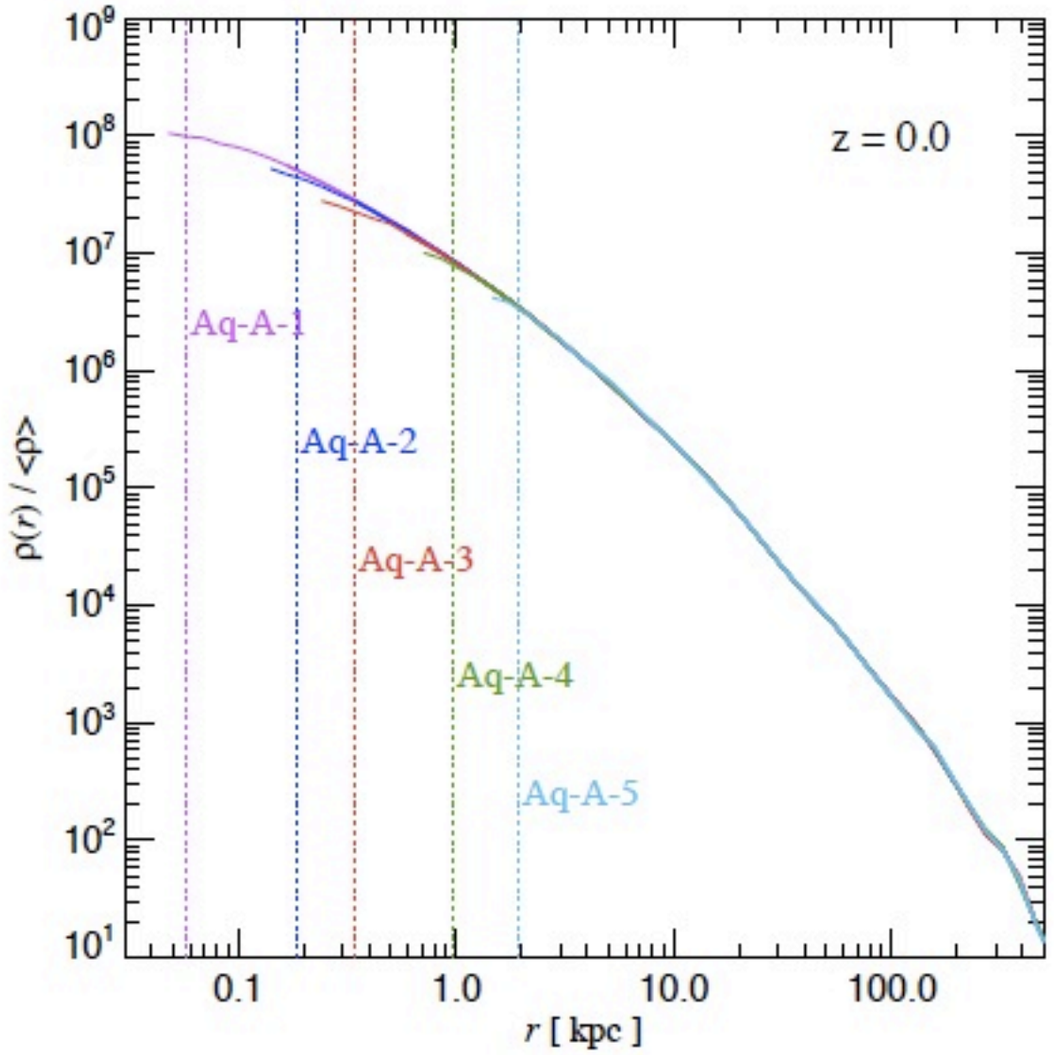


Figure 4. Spherically averaged density profile of the Aq-A halo at $z = 0$, at different numerical resolutions. Each of the profiles is plotted as a thick line for radii that are expected to be converged according to the resolution criteria of Power et al. (2003). These work very well for our simulation set. We continue the measurements as thin solid lines down to 2ϵ, where ϵ is the Plummer-equivalent gravitational softening length in the notation of Springel et al. (2001b). The dotted vertical lines mark the scale 2.8ϵ, beyond which the gravitational force law is Newtonian. The mass resolution changes by a factor of 1835 from the lowest to the highest resolution simulation in this series. Excellent convergence is achieved over the entire radial range where it is expected.

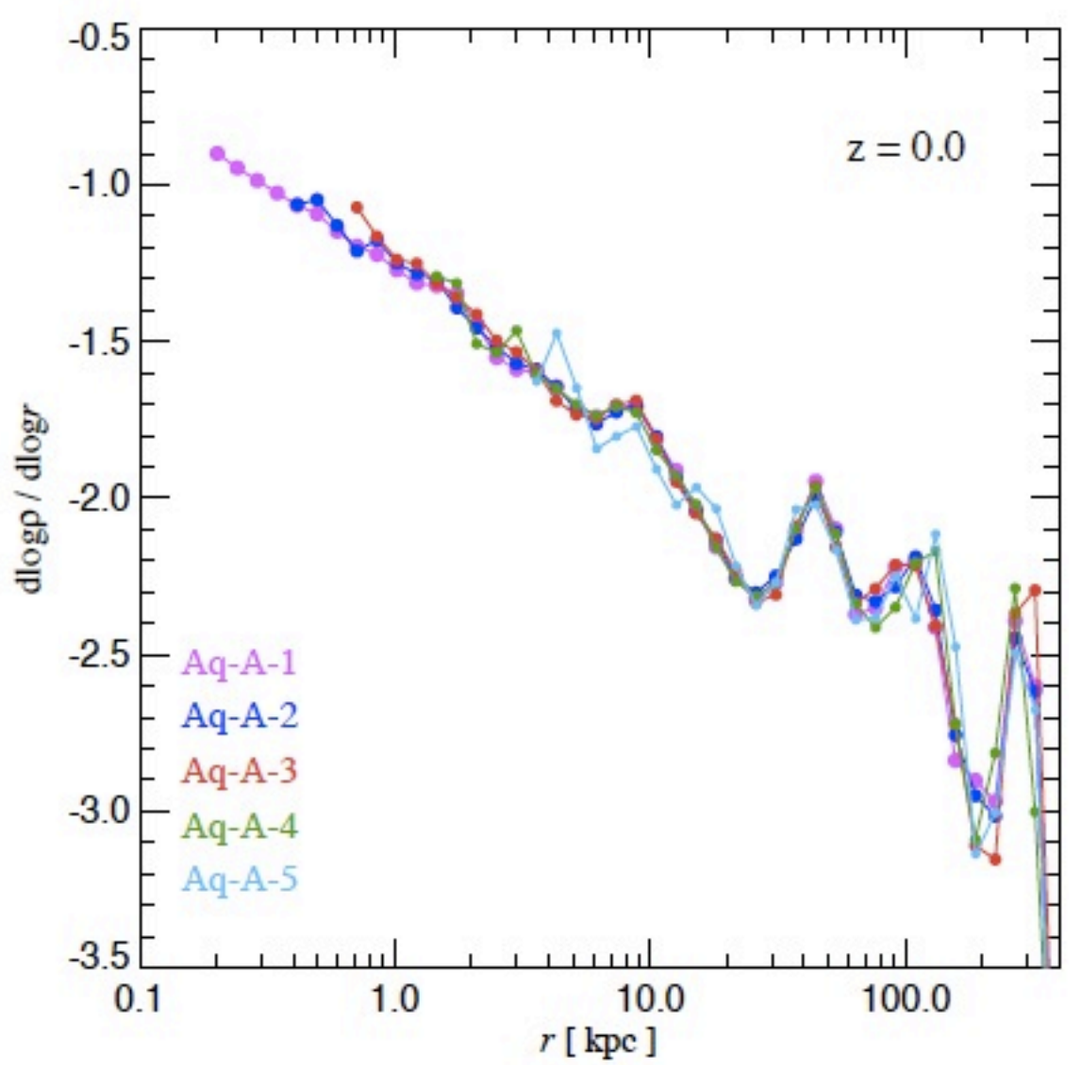
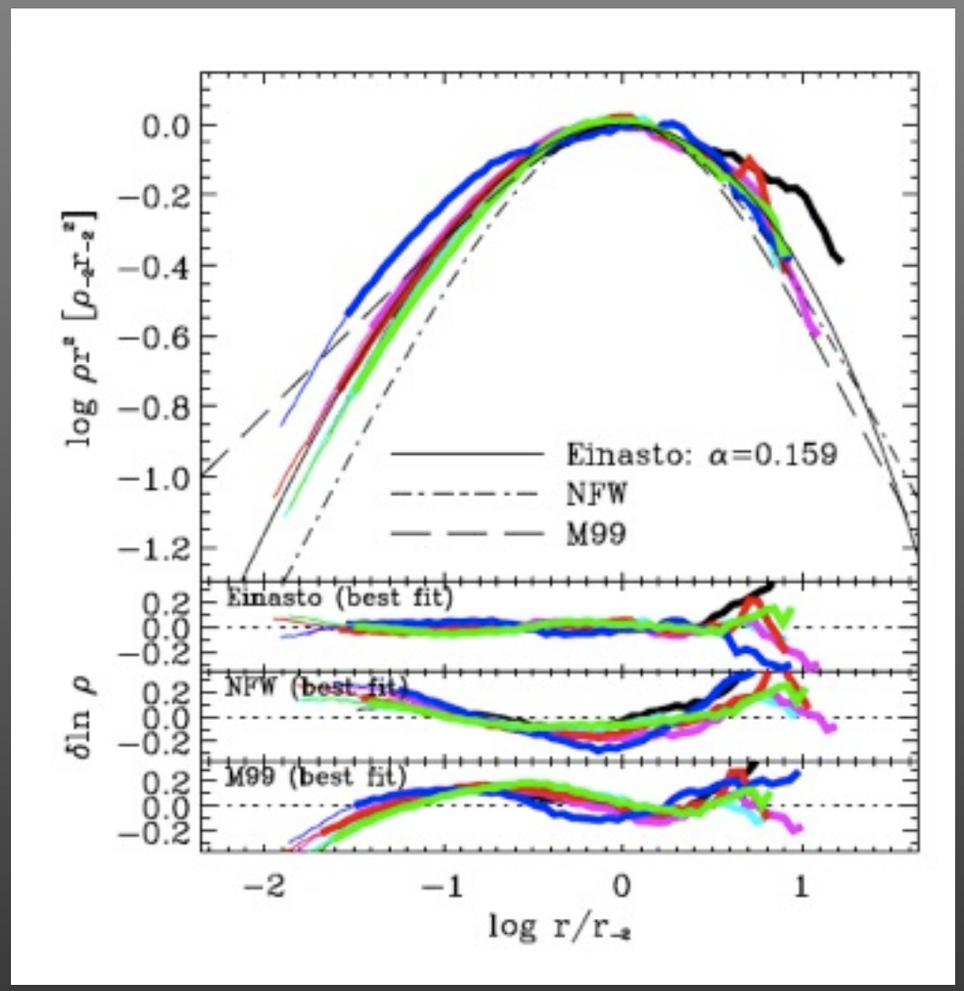


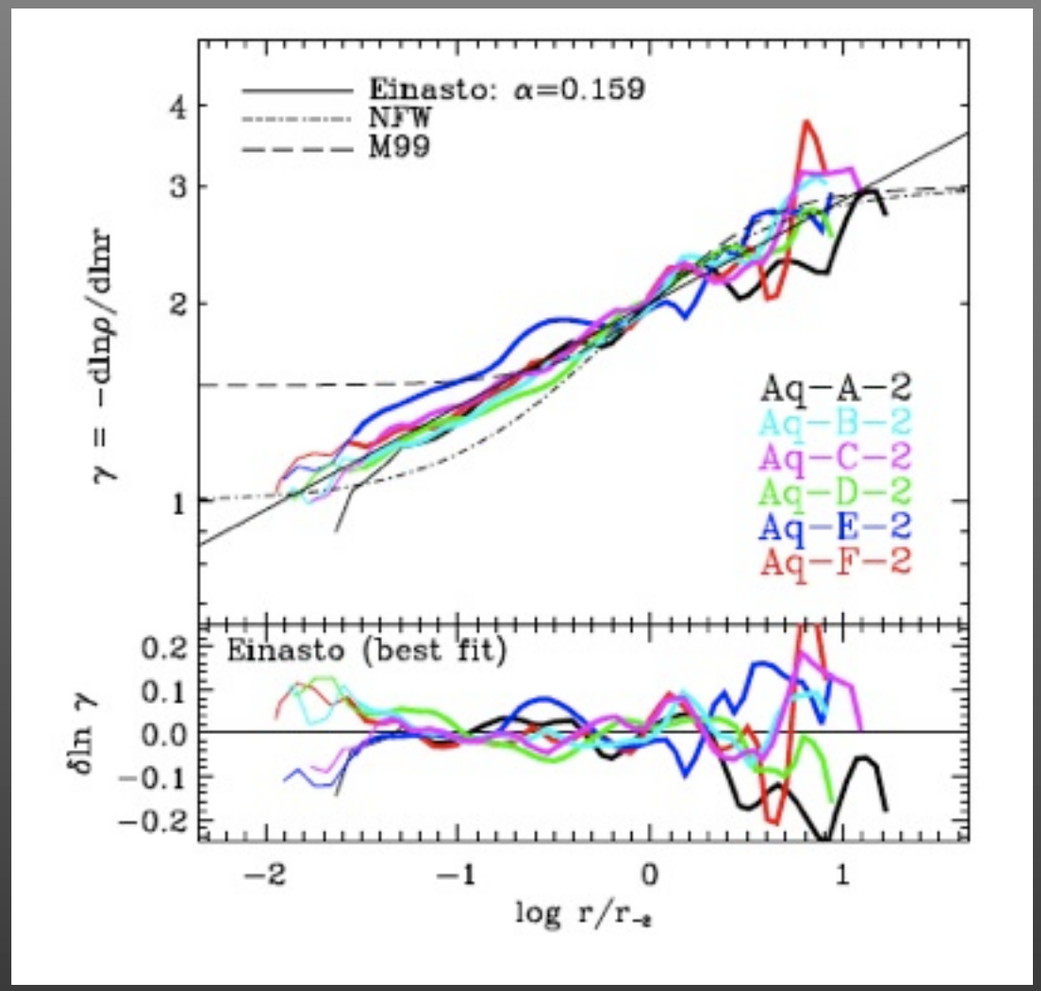
Figure 5. Local logarithmic slope of the density profiles as a function of radius for the Aq-A halo simulated at different numerical resolution. Only the radial region that should be converged according to the criteria of Power et al. (2003) is shown. Note that the large fluctuations in the outer parts are caused by substructures but nevertheless reproduce well between simulations. In this regime, we expect significant halo-to-halo scatter.

Springel et al. 2008

Reconstructed density profiles



Navarro et al. 2008



Navarro et al. 2008

Fitting formulae

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

$$\rho(r) = \frac{\rho_M}{(r/r_M)^{1.5}[1+(r/r_M)^{1.5}]},$$

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

NFW

Moore

Einasto

Substructures

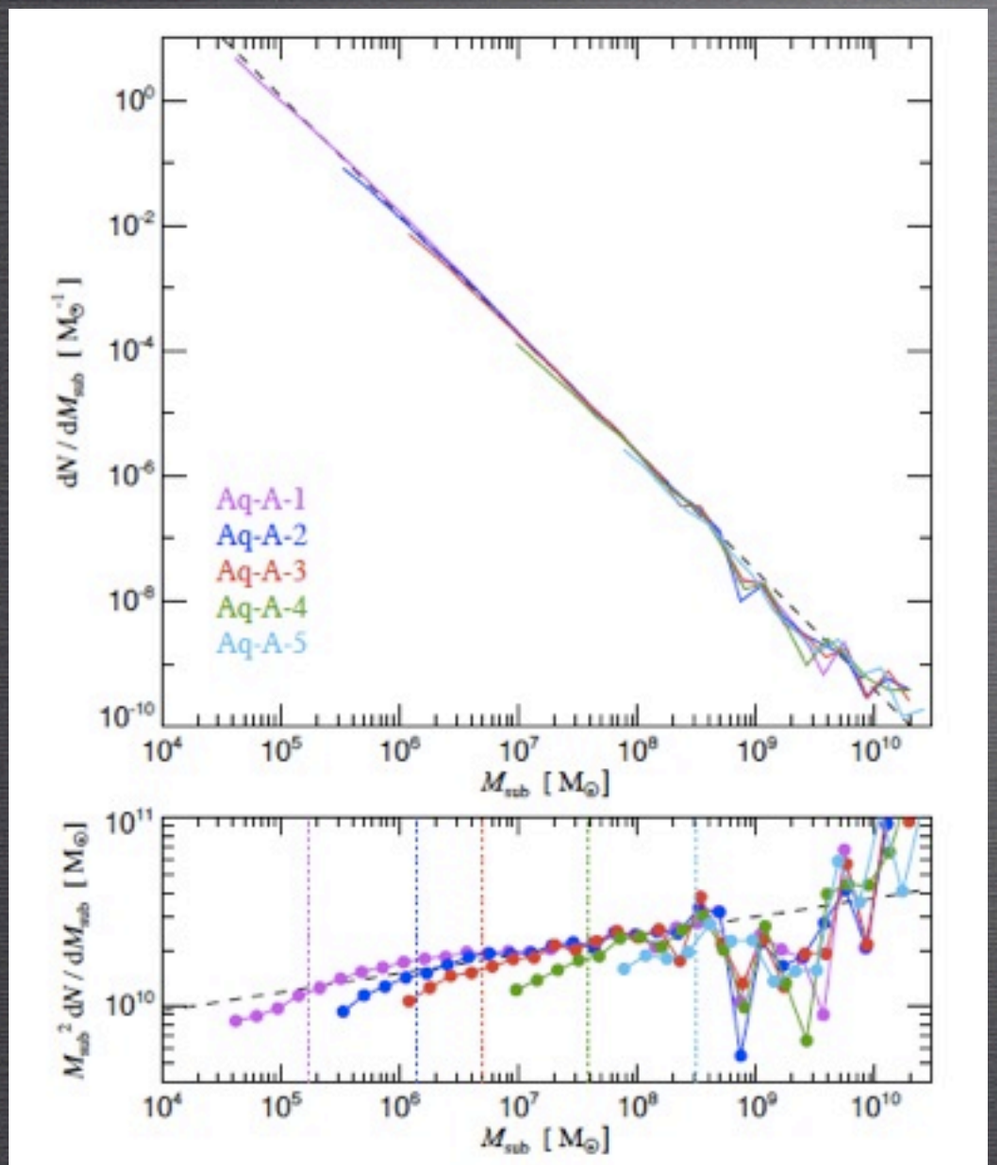


Figure 6. Differential subhalo abundance by mass in the 'A' halo within the radius r_{50}. We show the count of subhalos per logarithmic mass interval for different resolution simulations of the same halo. The bottom panel shows the same data but multiplied by a factor $M_{\rm sub}^2$ to compress the vertical dynamic range. The dashed lines in both panels show a power-law $\mathrm{d}N/\mathrm{d}M \propto M^{-1.9}$. For each of the resolutions, the vertical dotted lines in the lower panel mark the masses of subhalos that contain 100 particles.

Subhalo mass function

$$\frac{\mathrm{d}N}{\mathrm{d}M} = a_0 \left(\frac{M}{m_0}\right)^n$$

with n=1.9-2.0. The total density receives two contributions

$$\rho_{\rm tot}(r) \;=\; \rho_{\rm sm}(r) + \rho_{\rm sub}(r)$$

$$4\,\pi \int_0^{R_{\rm vir}} dr\, r^2\, \rho_{\rm tot}(r) = M_{\rm MW}$$

and the distribution of subhalos is "anti-biased" with respect to the smooth component

$$\rho_{\rm tot}(r) \;= (1 - f_{\rm sub})\, M_{\rm MW}\, g_{\rm sm}(r) + f_{\rm sub}\, M_{\rm MW}\, g_{\rm sub}(r)$$

$$g_{\rm sub}(r) = K\, r\, g_{\rm sm}(r)$$

Substructures

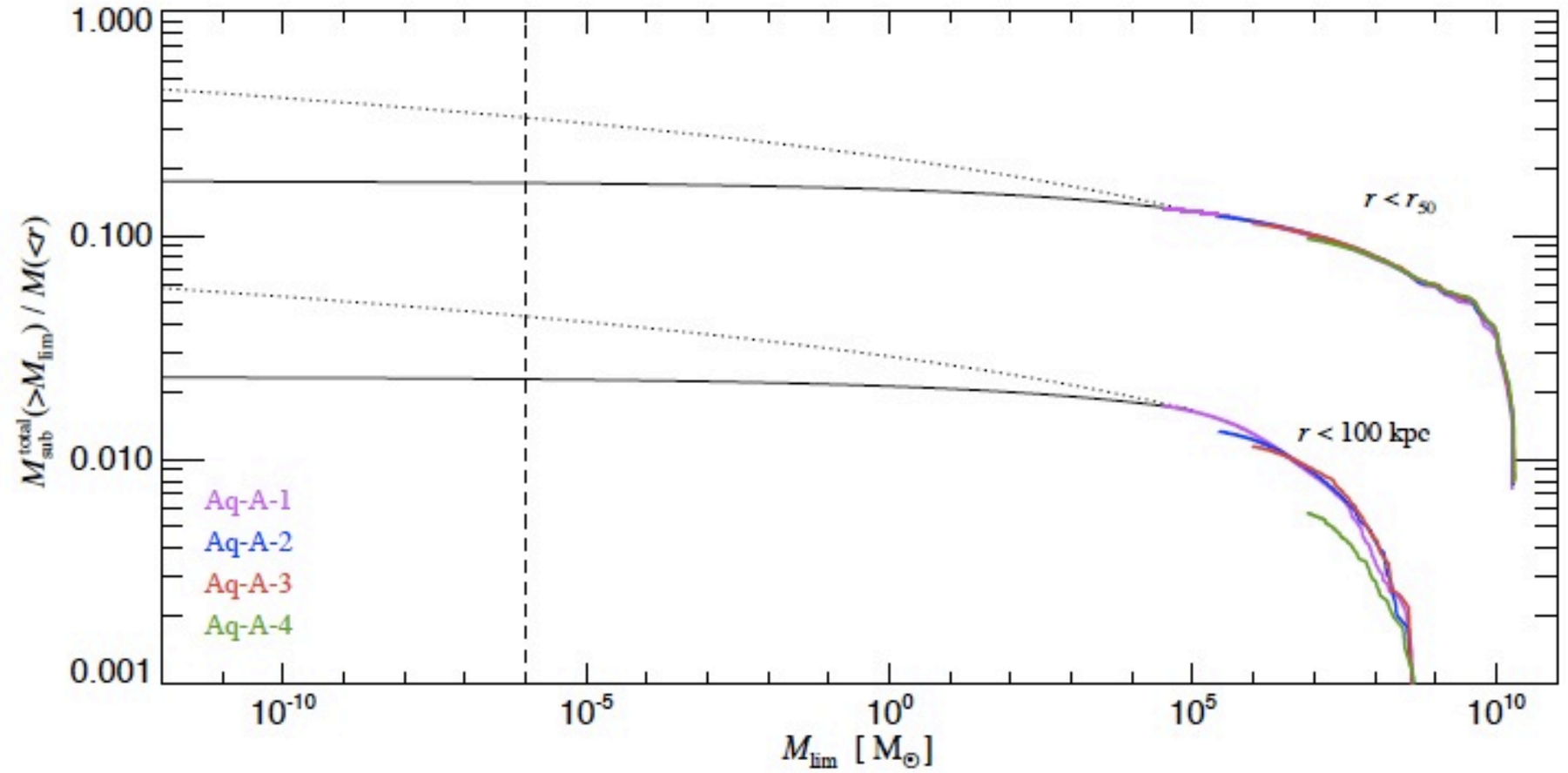
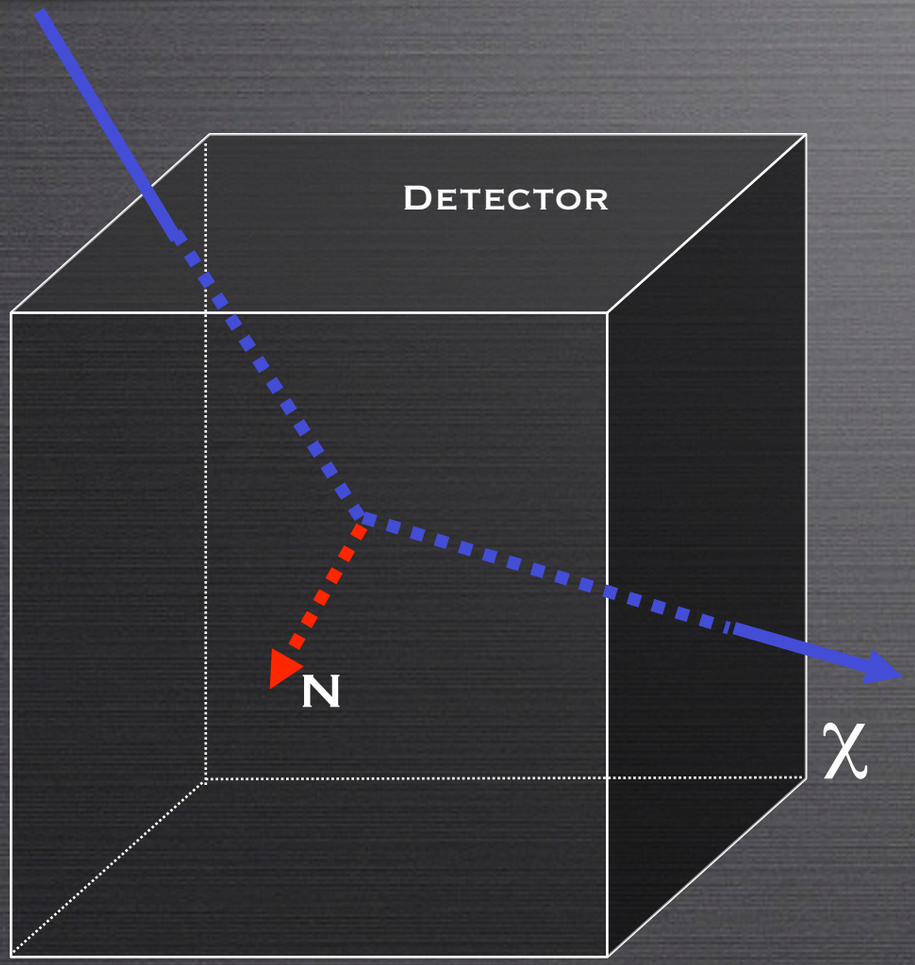


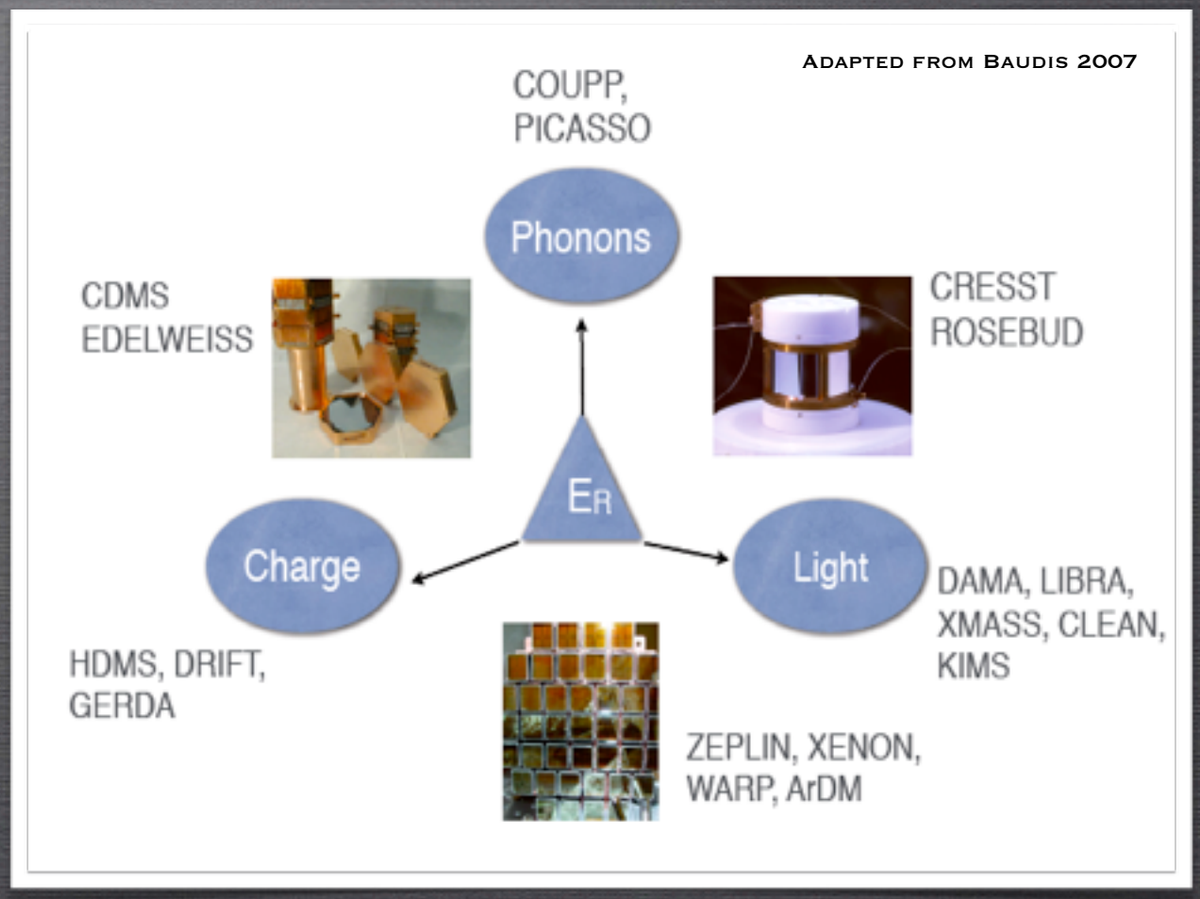
Figure 7. Expected mass fraction in subhalos as a function of the limiting mass $M_{\rm lim}$, inside r_{50} (top curves) and inside 100 kpc (bottom curves). The solid thin lines show an extrapolation of the direct simulation result with an $n = -1.9$ power-law for the differential subhalo mass function. In this case, the total substructure mass converges at the low-mass end. The dotted lines show the prediction for the logarithmically divergent case, $n = -2$. In this case, we would expect the mass in substructures down to an Earth mass (vertical dashed line) to be about twice what we can resolve directly. This mass is a reasonable estimate for the thermal free-streaming limit in many supersymmetric theories where the dark matter particle is a neutralino. However, the parameters of these theories are sufficiently uncertain that the thermal limit could lie as low as $10^{-12}\,{\rm M}_\odot$. Even in this case, the lumpy component of the halo would still be subdominant within r_{50}, and would be a small fraction of the total mass of $9.32 \times 10^{11}\,{\rm M}_\odot$ within 100 kpc.

Springel et al. 2008

Direct Detection

Principle and Detection Techniques





DM Scatters off nuclei in the detector

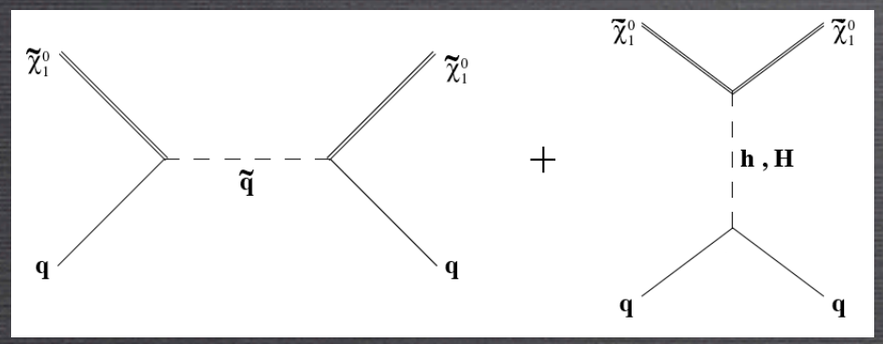
Detection of recoil energy via ionization (charges), scintillation (light) and heat (phonons)

Direct Detection

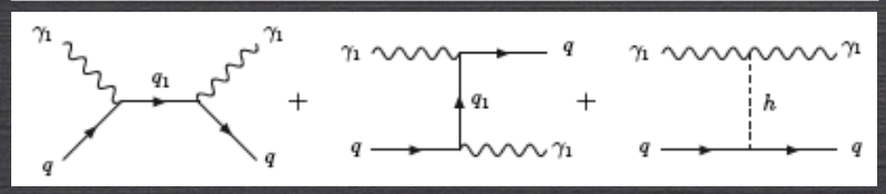
Differential Event Rate

$$\frac{dR}{dE_R}(E_R) = \frac{\rho_0}{m_\chi m_N} \int_{v>v_{min}} v f(\vec{v} + \vec{v_e}) \frac{d\sigma_{\chi N}}{dE_R}(v, E_R) d^3\vec{v}$$

SUSY: squarks and Higgs exchange



UED: 1st level quarks and Higgs exchange



Theoretical Uncertainties

Ellis, Olive & Savage 2008; Bottino et al. 2000; etc.

Uncertainties on f(v)

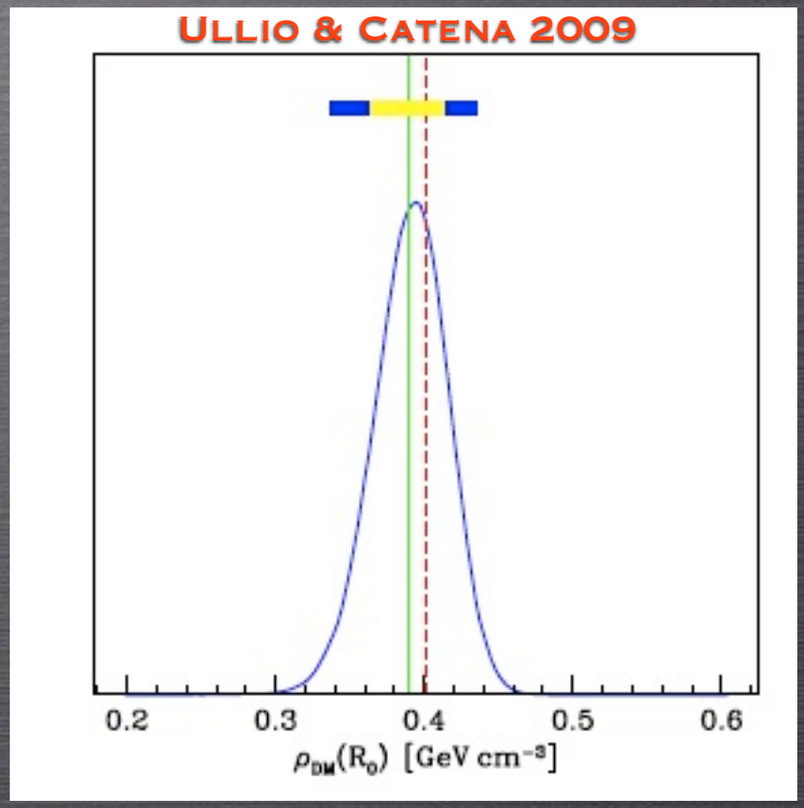
Ling et al. 2009; Widrow et al. 2000; Helmi et al 2002

Direct Detection

Local Density

Dynamical Constraints

- Terminal Velocity of Gas Clouds
- Blue Horizontal-Branch (BHB) halo stars from the SDSS
- Estimates of Oort's constants
- Motion of stars perpendicular to the Galactic plane
- Velocity distribution of MW satellites



$$\rho_{DM}(R_0) = 0.389 \pm 0.025\,\mathrm{GeV\,cm^{-3}}$$

Constraints on M(<R) -> contraints on Q_X

See also Strigari and Trotta 2009; Weber and De Boer 2009; Salucci et al. 2010; Garbari, Lake & Read 2010

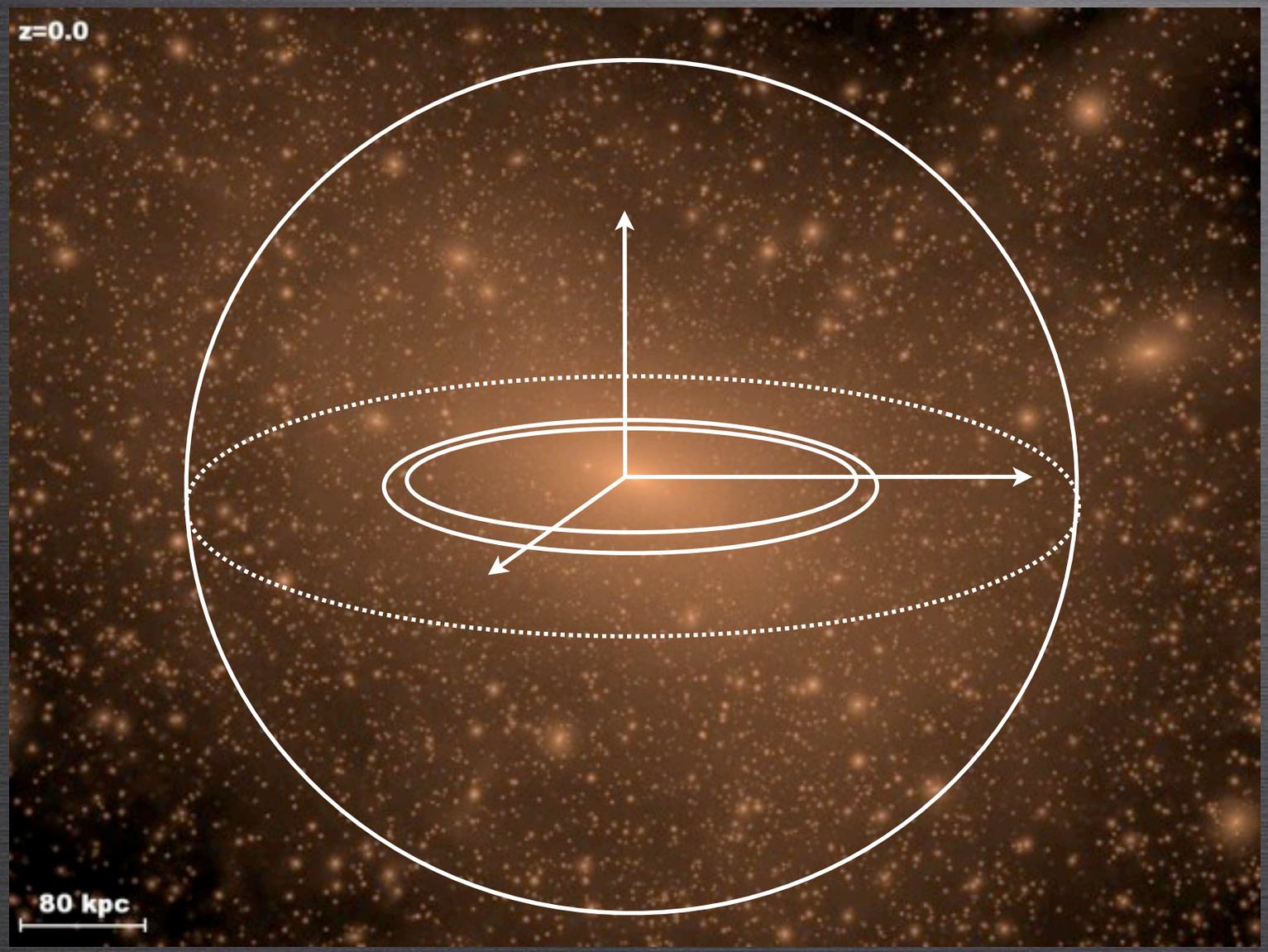
Triaxial Halos

Pato, Agertz, GB, Moore, Teyssier, Moore 2010

http://www.ucolick.org/~diemand/vl/images.html

Triaxial Halos

Pato, Agertz, GB, Moore, Teyssier, Moore 2010



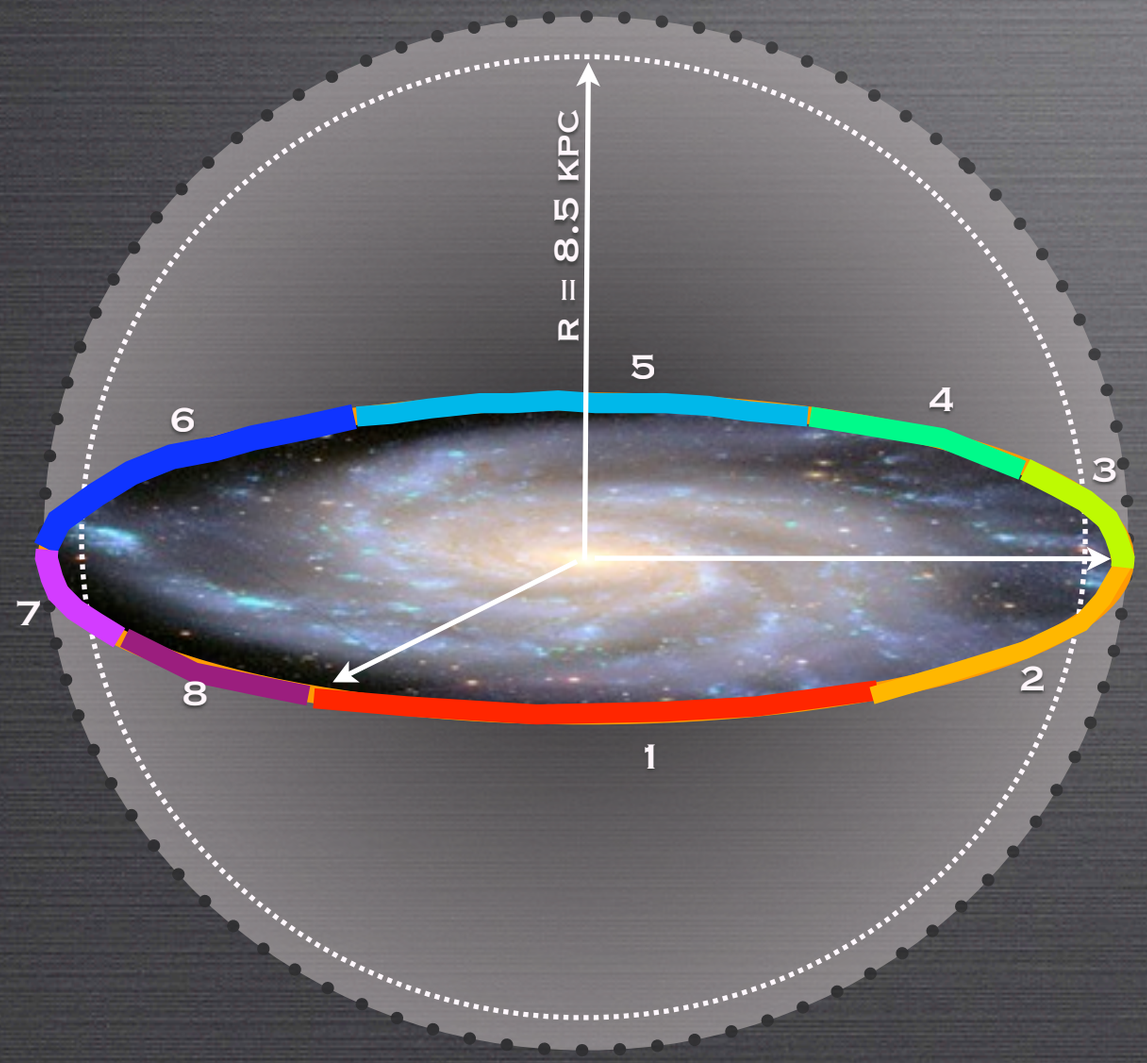
Moment of Inertia Tensor

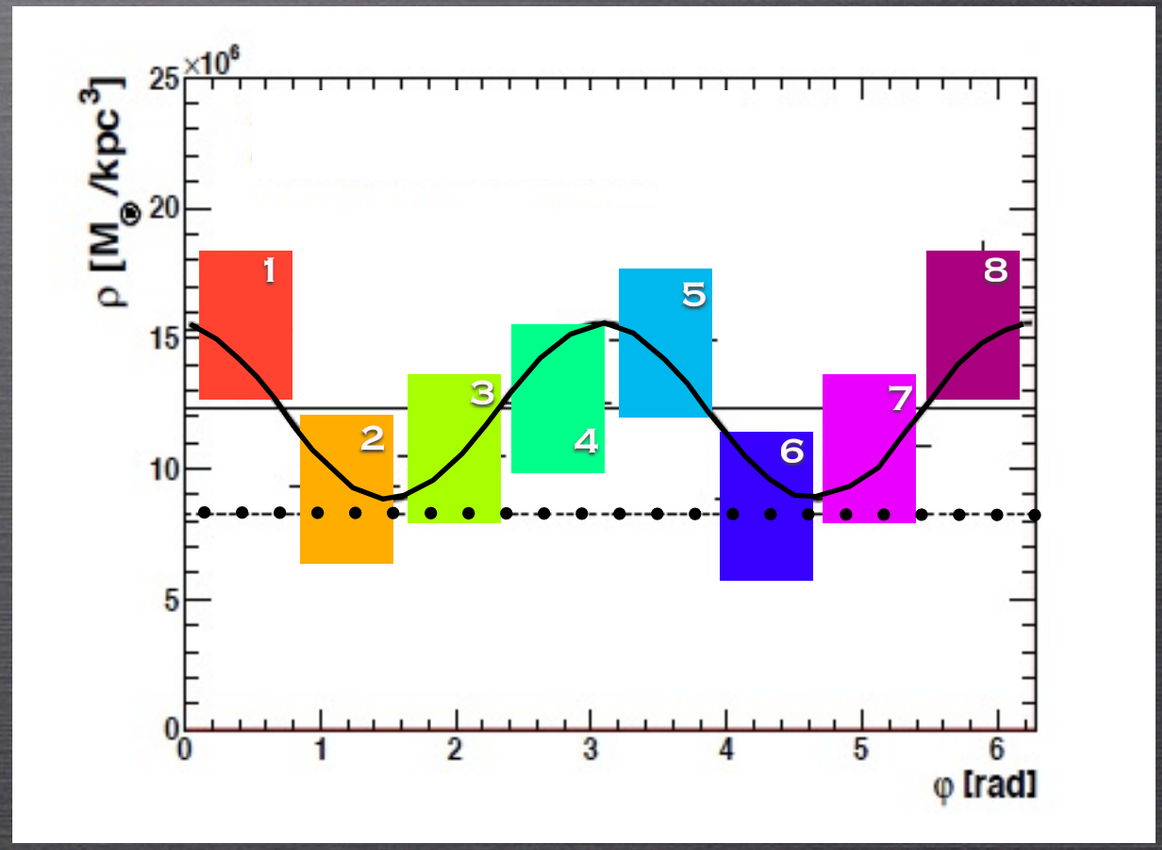
$$I_{ij} = \frac{\sum_{k=1}^{N} m_k r_{i,k} r_{j,k}}{\sum_{k=1}^{N} m_k}.$$

Rotation Axes
(A,B,C)

Modulation of DM density

at fixed GC-distance (Pato, Agertz, GB, Moore, Teyssier, Moore 2010)





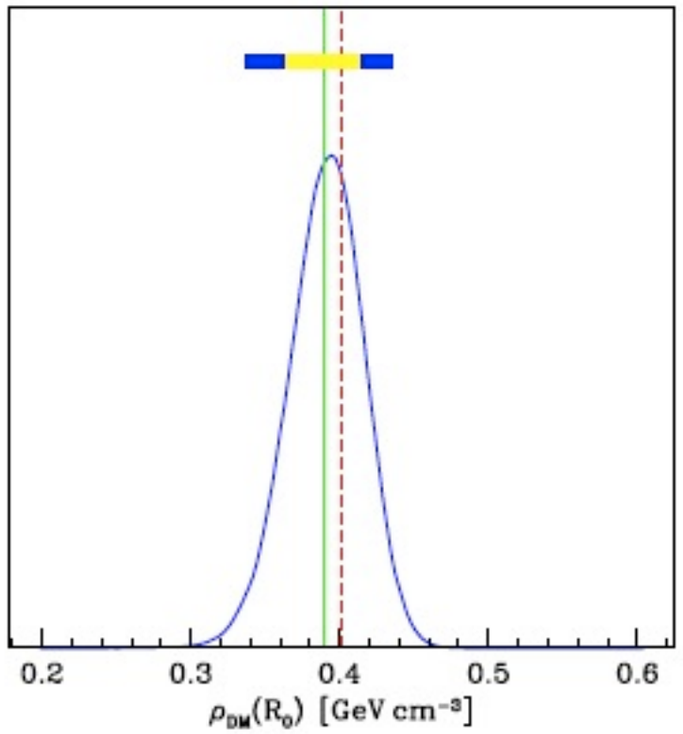
Pato, Agertz, GB, Moore, Teyssier, Moore 2010

Direct Detection

Uncertainties on the Local Density

"Statistical"

Ullio & Catena 2009



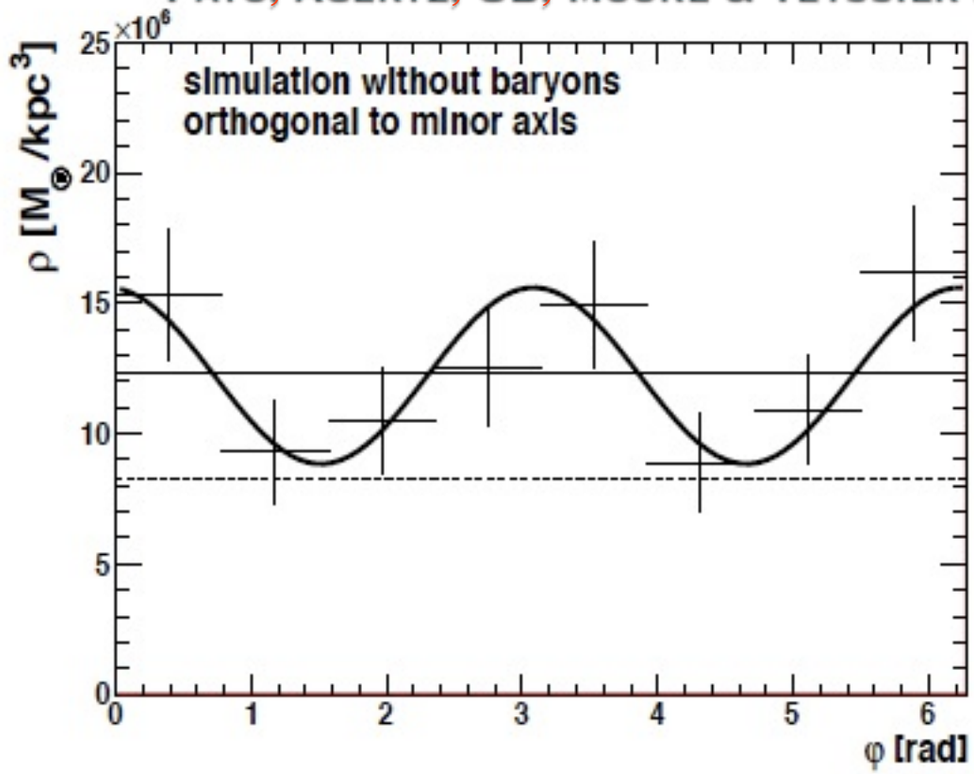
$$\rho_{DM}(R_0) = 0.389 \pm 0.025\,\mathrm{GeV\ cm^{-3}}$$

From dynamical Observables (see also Strigari & Trotta 2009)

+

"Systematic"

Pato, Agertz, GB, Moore & Teyssier 2010



$$\rho_0/\bar{\rho}_0 = 1.01 - 1.41$$ w/ Baryons

$$\rho_0/\bar{\rho}_0 = 0.39 - 1.94$$ DM only

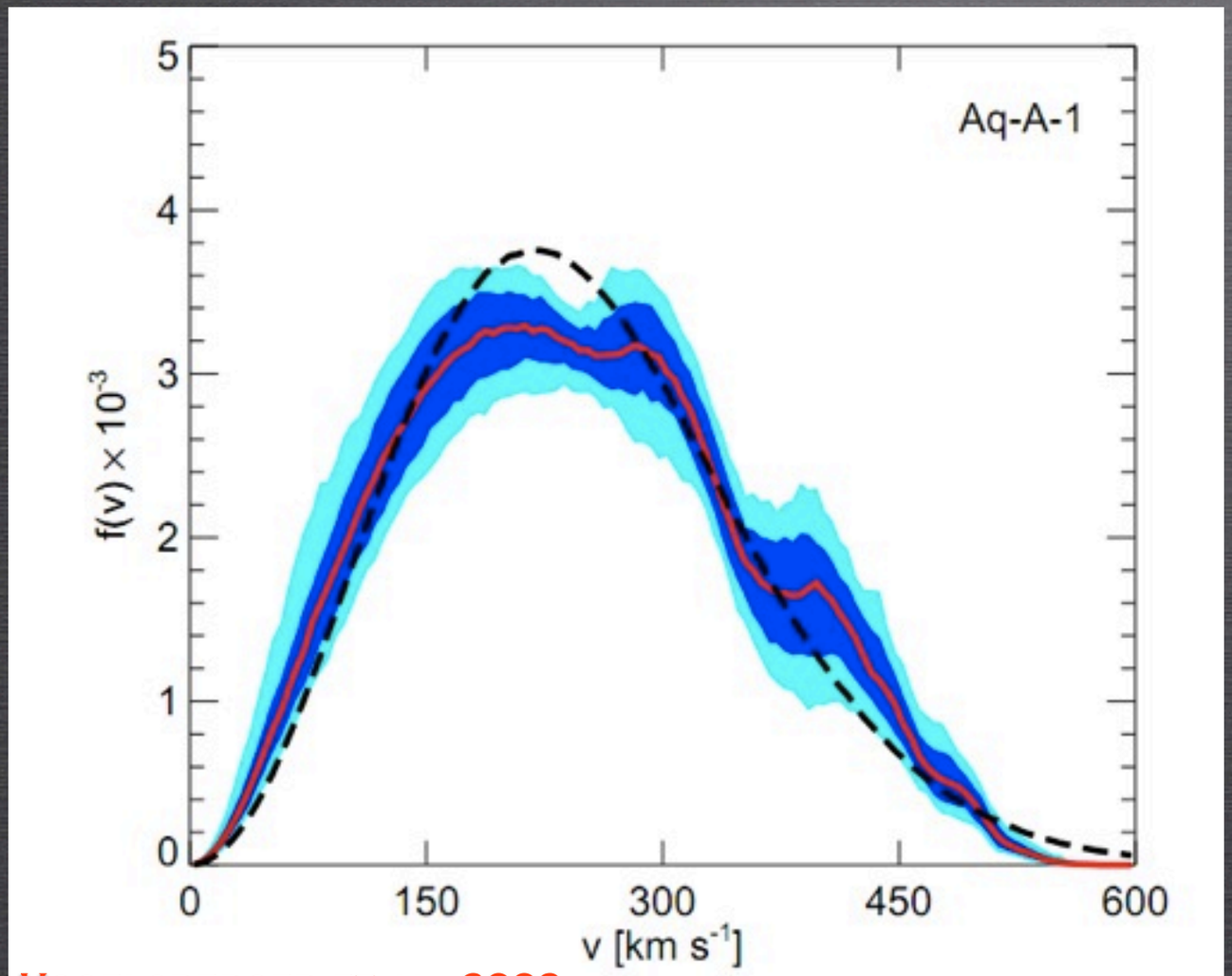
$$\rho_0 = 0.466 \pm 0.033(\mathrm{stat}) \pm 0.077(\mathrm{syst})\ \mathrm{GeV\ cm^{-3}}$$

Direct Detection

Velocity Distribution

$$f(w) = \begin{cases} \frac{1}{N_f}\left[\exp\left(\frac{v_{esc}^2 - w^2}{k v_0^2}\right) - 1\right]^k & \text{if } w \le v_{esc} \\ 0 & \text{if } w > v_{esc} \end{cases}$$

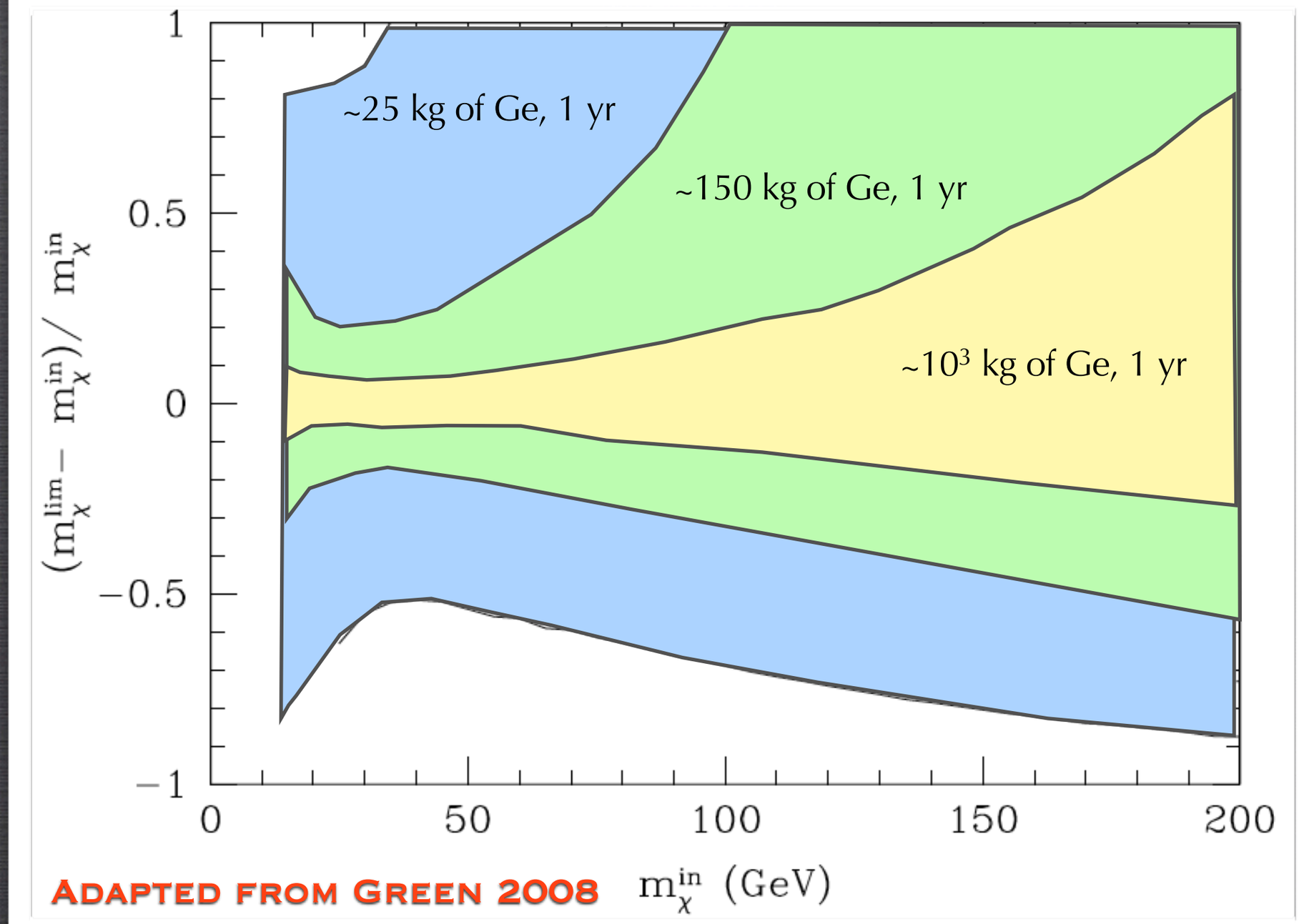
k=[0.5,3.5]
v_0 = [200,260] km s^{-1}
v_{esc} =[489, 577] km s^{-1}



Vogelsberger et al. 2009

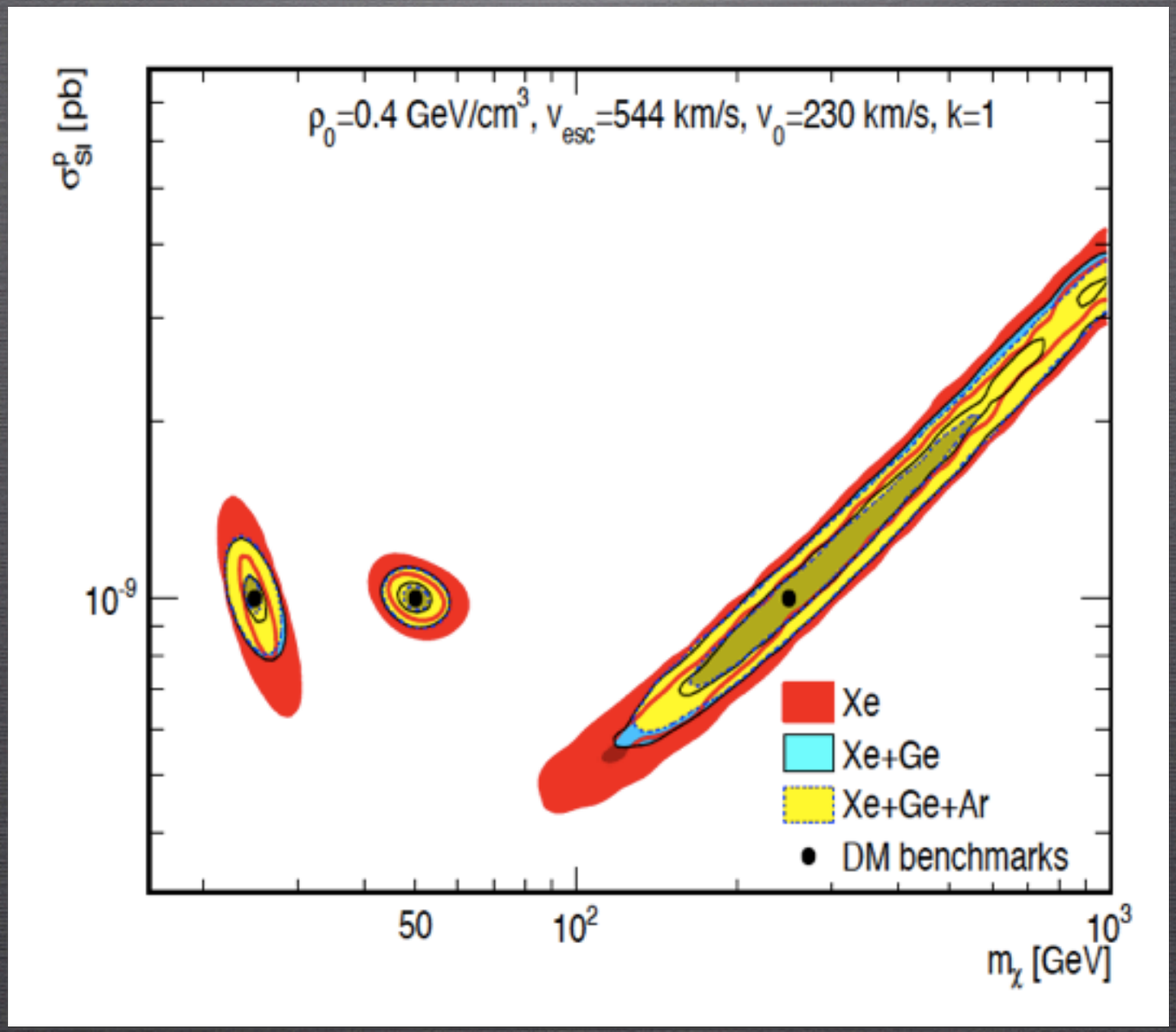
Direct Detection

95% C.L. constraint on the reconstructed DM mass



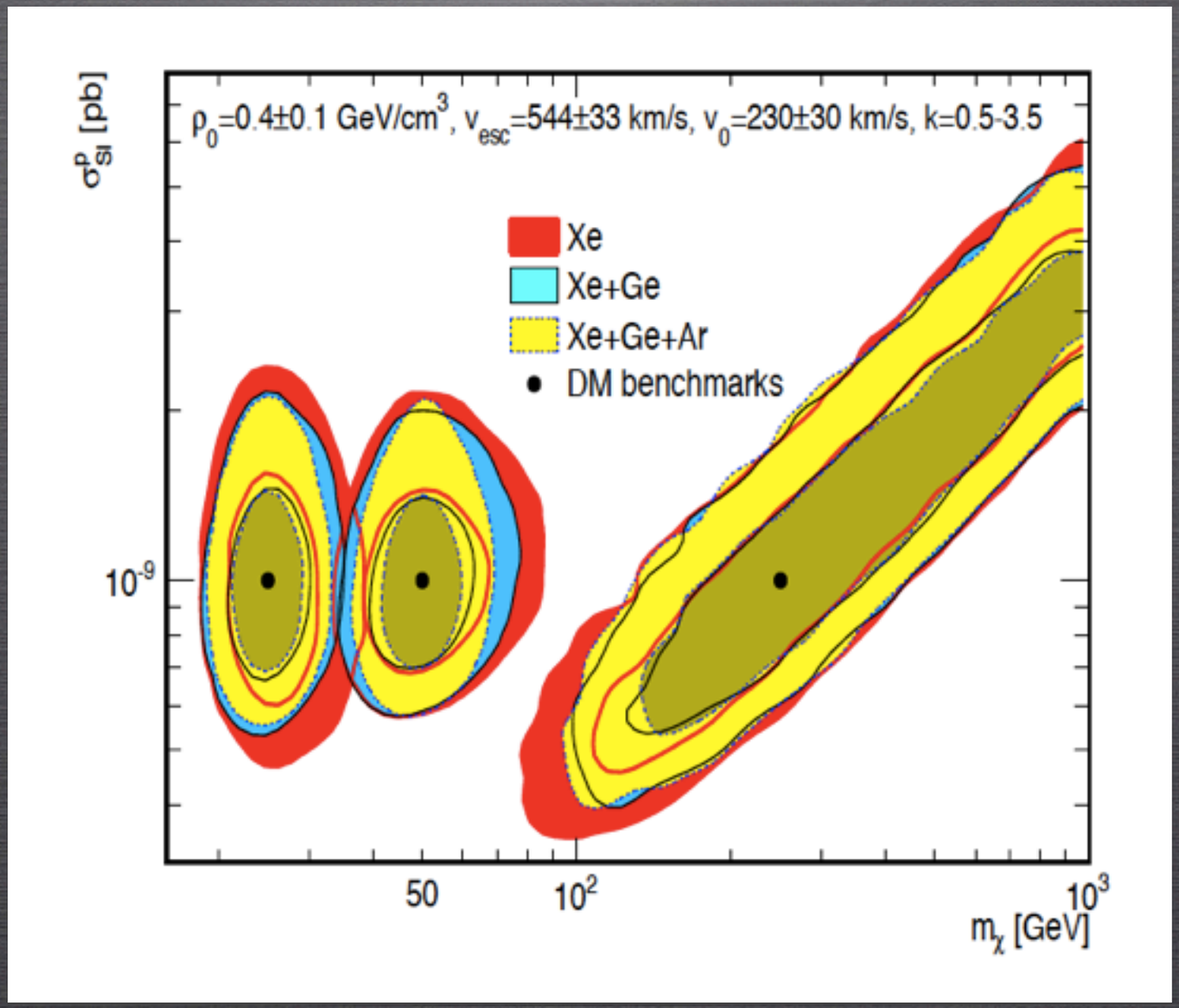
Adapted from Green 2008

Complementarity of DD targets



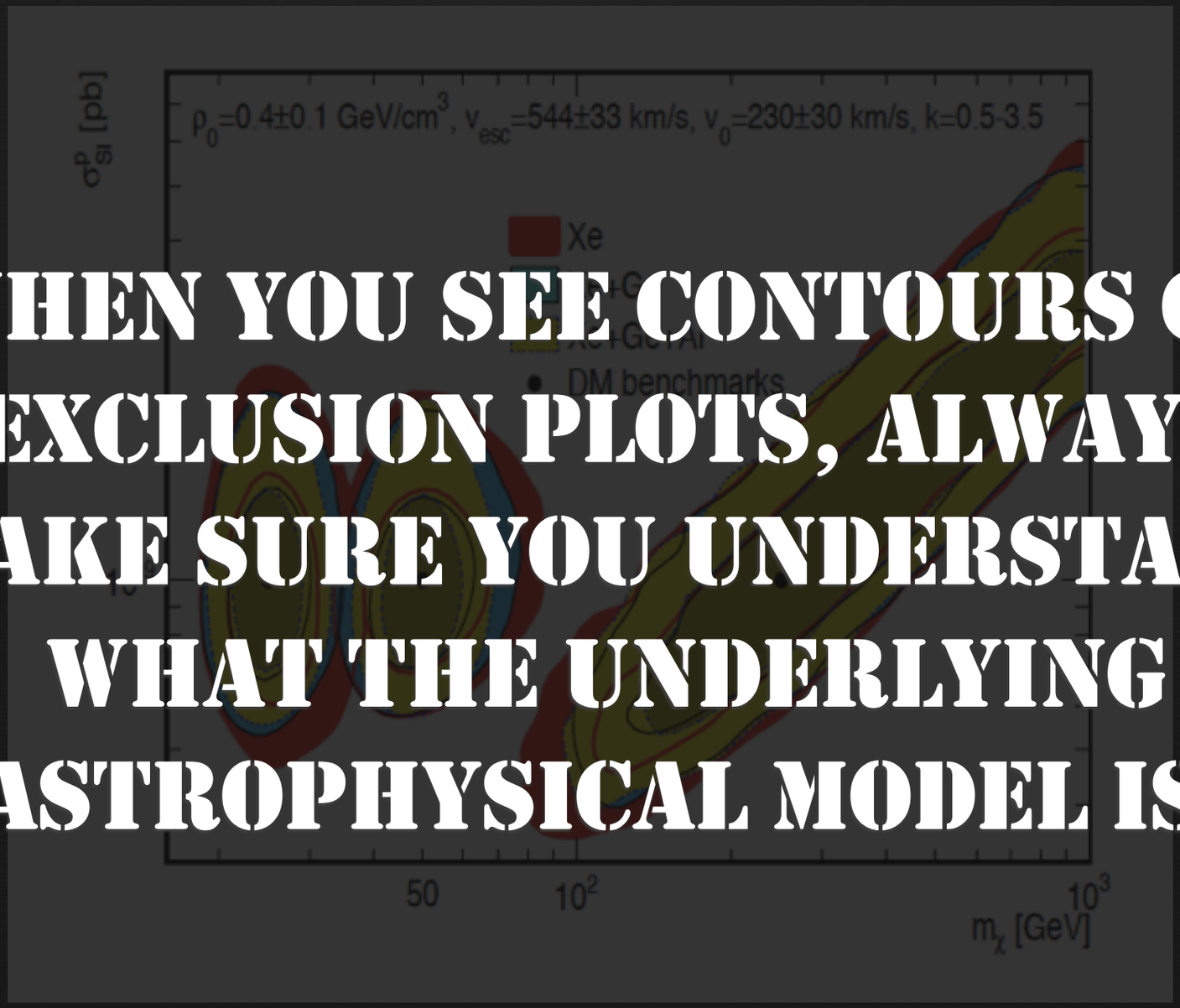
target	ϵ [ton×yr]	η_{cut}	A_{NR}	ϵ_{eff}	[ton×yr]	E_{thr} [keV]	$\sigma(E)$ [keV]	background events/ϵ_{eff}
Xe	5.0	0.8	0.5	2.00		10	Eq. (7)	< 1
Ge	3.0	0.8	0.9	2.16		10	Eq. (6)	< 1
Ar	10.0	0.8	0.8	6.40		30	Eq. (8)	< 1

Complementarity of DD targets



Pato, Baudis, GB, Ruiz, Strigari, Trotta, arXiv:1012.3458

Complementarity of DD targets

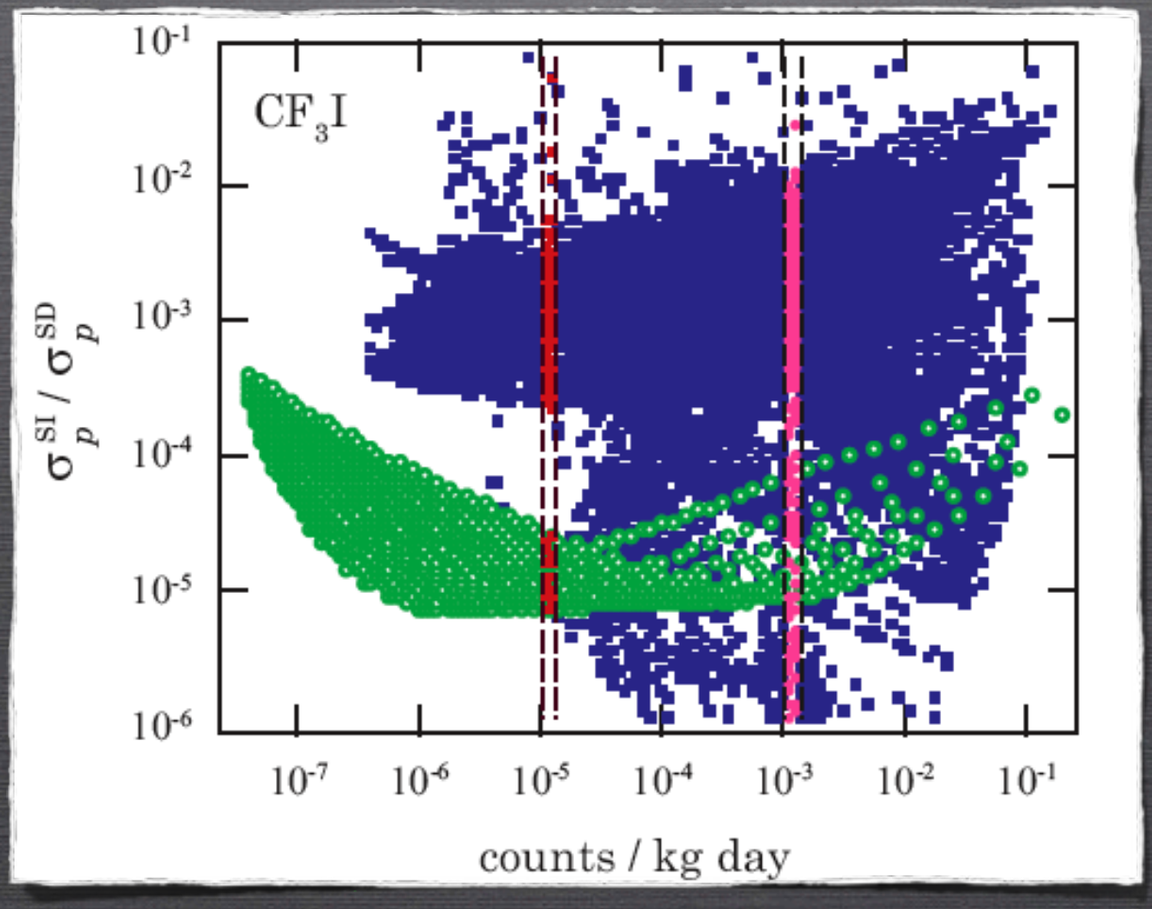


WHEN YOU SEE CONTOURS OR EXCLUSION PLOTS, ALWAYS MAKE SURE YOU UNDERSTAND WHAT THE UNDERLYING ASTROPHYSICAL MODEL IS!

Pato, Baudis, GB, Ruiz, Strigari, Trotta, arXiv:1012.3458

Direct Detection

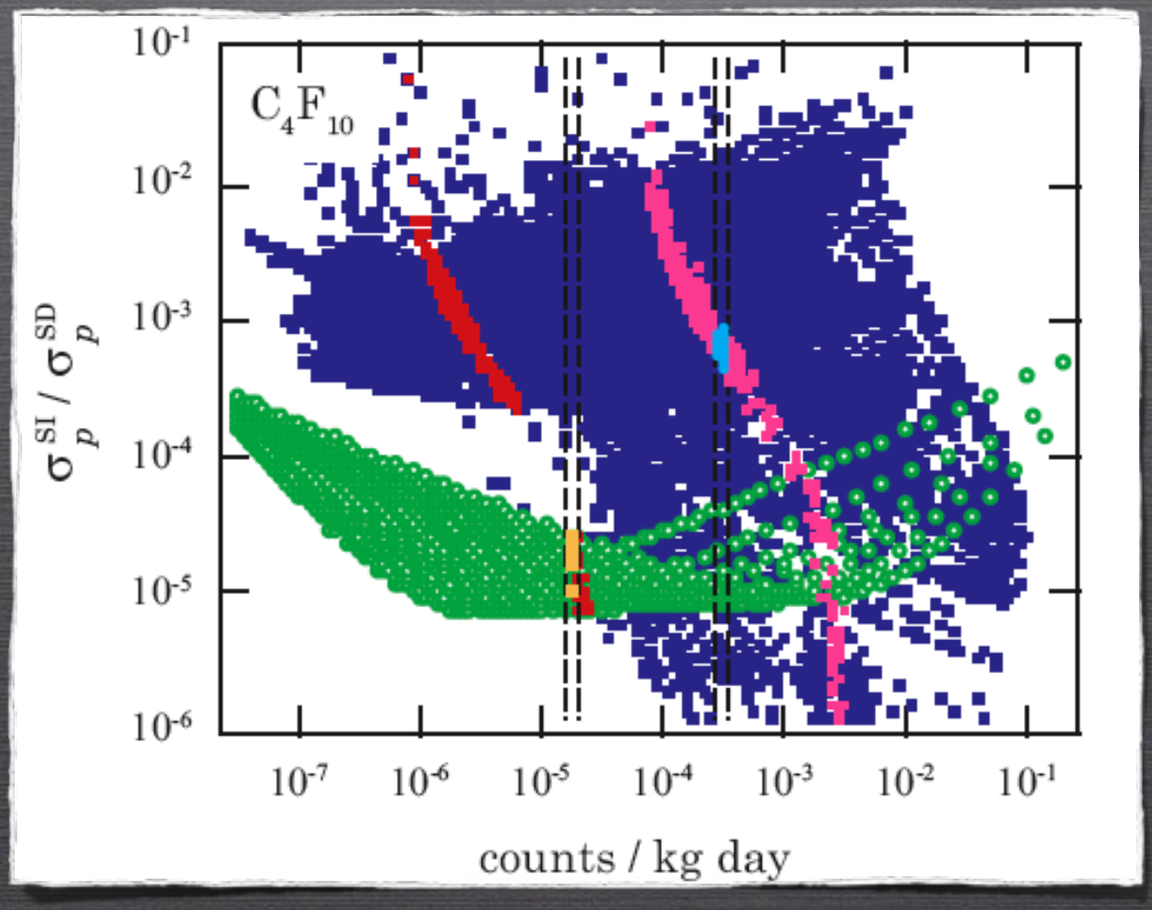
Better constraints combining results from different targets



The case of COUPP. GB, Cerdeno, Collar & Odom 2007

Direct Detection

Better constraints combining results from different targets



The case of COUPP. GB, Cerdeno, Collar & Odom 2007

Or combine with information from Accelerators...