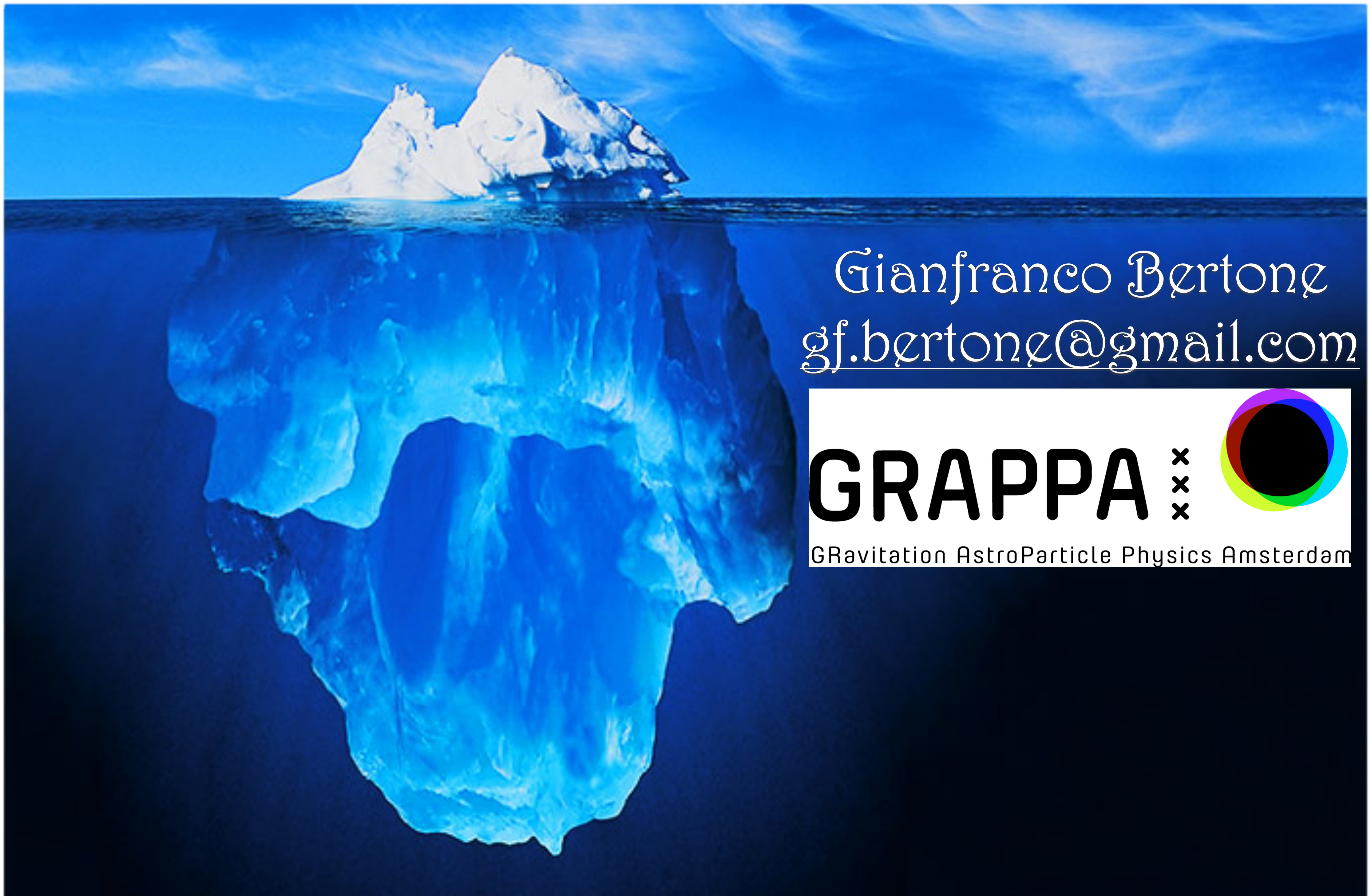
Dark Matter in Astrophysics and Cosmology



Gianfranco Bertone
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GRAPPA
GRavitation AstroParticle Physics Amsterdam

Plan of the lectures

- Lecture 1 (*now*)
  - Brief History of DM
  - Evidence for Dark Matter
  - Dark Matter Candidates

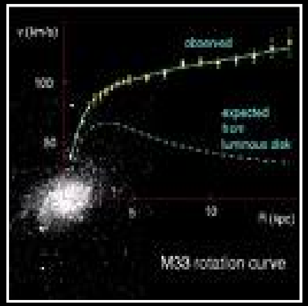
- Lecture 2 (*later*)
  - Dark Matter searches
  - WIMP miracle
  - Dark Matter distribution

- Lecture 3 (*tomorrow*)
  - Indirect detection..
  - ..with gamma-rays
  - ..with neutrinos, anti-matter etc.

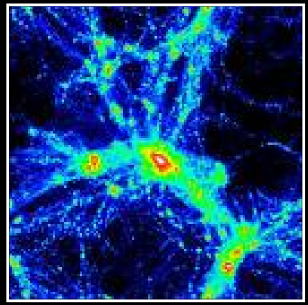
Evidence for Dark Matter

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

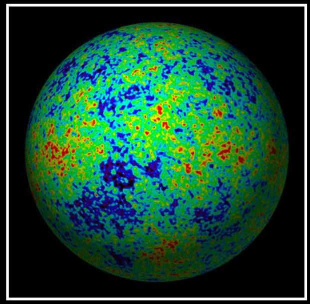
COSMOLOGICAL OBSERVATIONS



• Rotation Curves



• Clusters of galaxies



• CMB

• Type Ia Supernovae

Evidence for Dark Matter

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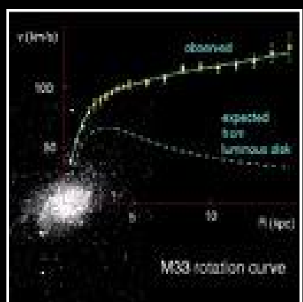
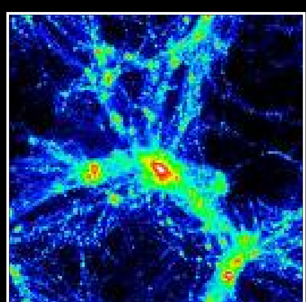
COSMOLOGICAL OBSERVATIONS



- Rotation Curves



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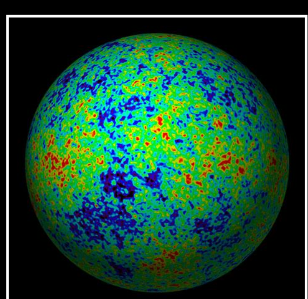
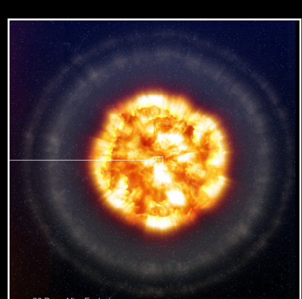
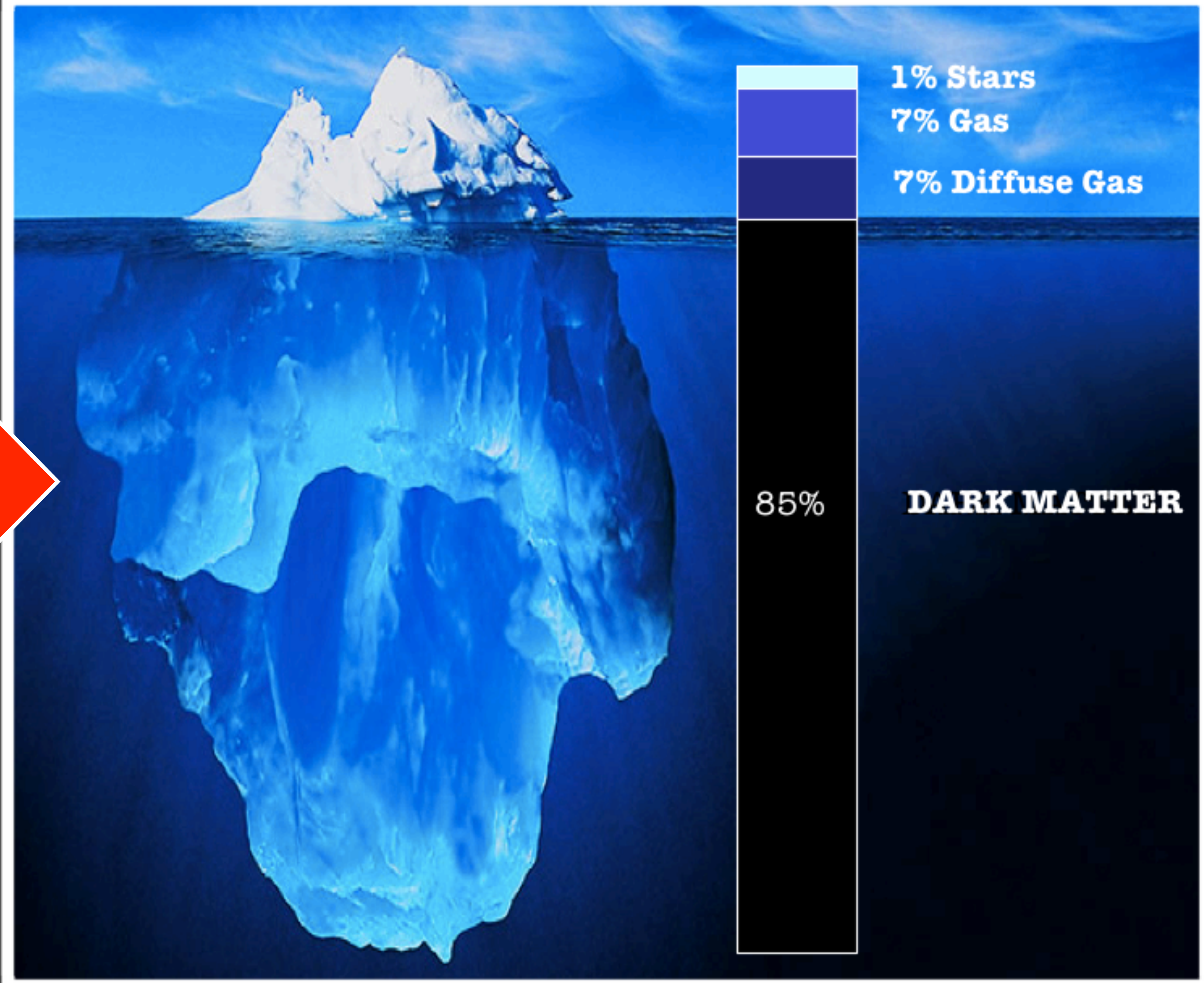


- CMB



- Type Ia Supernovae



A little history of Dark Matter: Jacobus Kapteyn

First Attempt at a Theory of the Arrangement and Motion of the Sidereal System

Astrophysical Journal, vol. 55, p.302 (1922)

FIRST ATTEMPT AT A THEORY OF THE ARRANGEMENT AND MOTION OF THE SIDEREAL SYSTEM[1]

By J. C. KAPTEYN[2]

ABSTRACT

First attempt at a general theory of the distribution of masses, forces, and velocities in the stellar system.—(1) *Distribution of stars.* Observations are fairly well represented, at least up to galactic lat. 70°, if we *assume that the equidensity surfaces are similar ellipsoids of revolution*, with axial ratio 5.1, and this enables us to compute quite readily (2) *the gravitational acceleration at various points due to such a system*, by summing up the effects of each of ten ellipsoidal shells, in terms of the acceleration due to the average star at a distance of a parsec. The *total number of stars* is taken as 47.4×10^9. (3) *Random and rotational velocities.* The nature of the equidensity surfaces is such that the stellar system cannot be in a steady state unless there is a general rotational motion around the galactic polar axis, in addition to a random motion analogous to the thermal agitation of a gas. In the neighborhood of the axis, however, there is no rotation, and the behavior is assumed to be like that of a gas at uniform temperature, but with a gravitational acceleration ($G\eta$) decreasing with the distance ρ. Therefore the density Δ is assumed to obey the barometric law: $G\eta=-\bar{u}^2(\delta\Delta/\delta\rho)/\Delta$; and taking the mean random velocity $\bar{u}$ as 10.3 km/sec., the author finds that (4) *the mean mass of the stars* decreases from 2.2 (sun = 1) for shell II to 1.4 for shell X (the outer shell), the average being close to 1.6, which is the value independently found for the average mass of both components of visual binaries. In the galactic plane the resultant acceleration—gravitational minus centrifugal—is again put equal to $-\bar{u}^2(\delta\Delta/\delta\rho)/\Delta$, $\bar{u}$ is taken to be constant and the average mass is assumed to decrease from shell to shell as in the direction of the pole. The angular velocities then come out such as to make the linear rotational velocities about constant and equal to 19.5 km/sec. beyond the third shell. If now we suppose that part of the stars are rotating one way and part the other, the relative velocity being 39 km/sec., we have a quantitative explanation of the phenomenon of star-streaming, where the relative velocity is also in the plane of the Milky Way and about 40 km/sec. It is incidentally suggested that when the theory is perfected it may be possible to determine *the amount of dark matter* from its gravitational effect. (5) The *chief defects of the theory* are: That the equidensity surfaces assumed do not agree with the actual surfaces, which tend to become spherical for the shorter distances; that the *position of the center of the system* is not the sun, as assumed, but is probably located at a point some 650 parsecs away in the direction galactic long. 77°, lat. −3°; that the average mass of the stars was assumed to be the same in all shells in deriving the formula for the variation of $G\eta$ with ρ on the basis of which the variation of average mass from shell to shell and the constancy of the rotational velocity were derived—hence either the assumption or the conclusions are wrong; and that no distinction has been made between stars of different types.

Jacobus Kapteyn

First appearance of the term 'Dark Matter'
(in ~ modern sense) in scientific literature

Remark. Dark matter. It is important to note that what has here been determined is the total mass within a definite volume, divided by the number of luminous stars. I will call this mass the average effective mass of the stars. It has been possible to include the luminous stars completely owing to the assumption that at present we know the luminosity-curve over so large a part of its course that further extrapolation seems allowable.

Now suppose that in a volume of space containing l luminous stars there be dark matter with an aggregate mass equal to Kl average luminous stars; then, evidently the effective mass equals $(l+K)\times$average mass of a luminous star.

We therefore have the means of estimating the mass of dark matter in the universe. As matters stand at present it appears at once that this mass cannot be excessive. If it were otherwise, the average mass as derived from binary stars would have been very much lower than what has been found for the effective mass.

Fritz Zwicky

applies the virial theorem to the Coma Cluster and finds…

THE ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

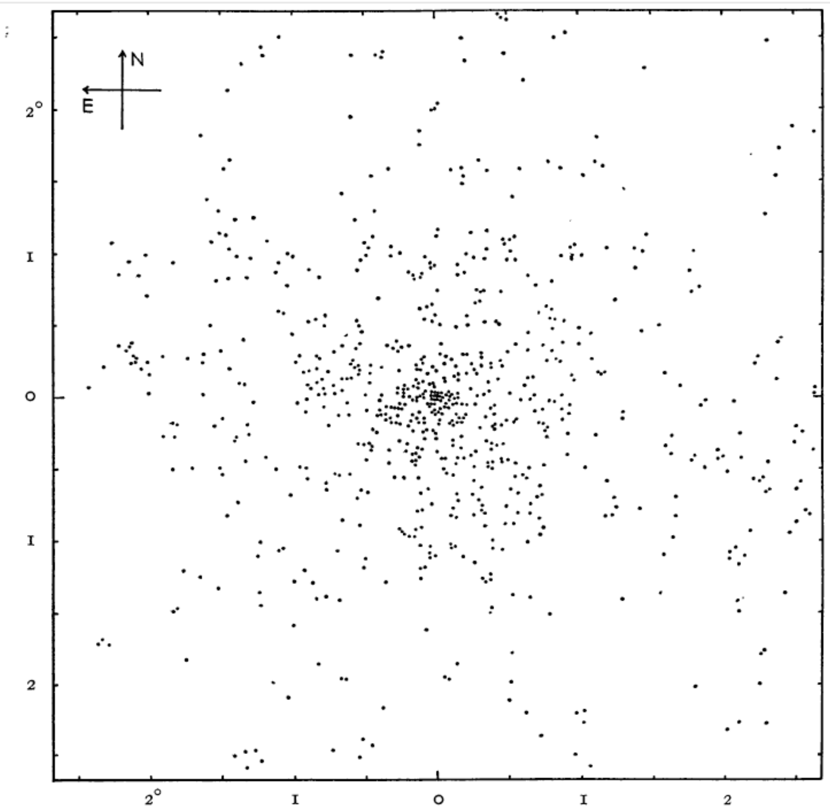
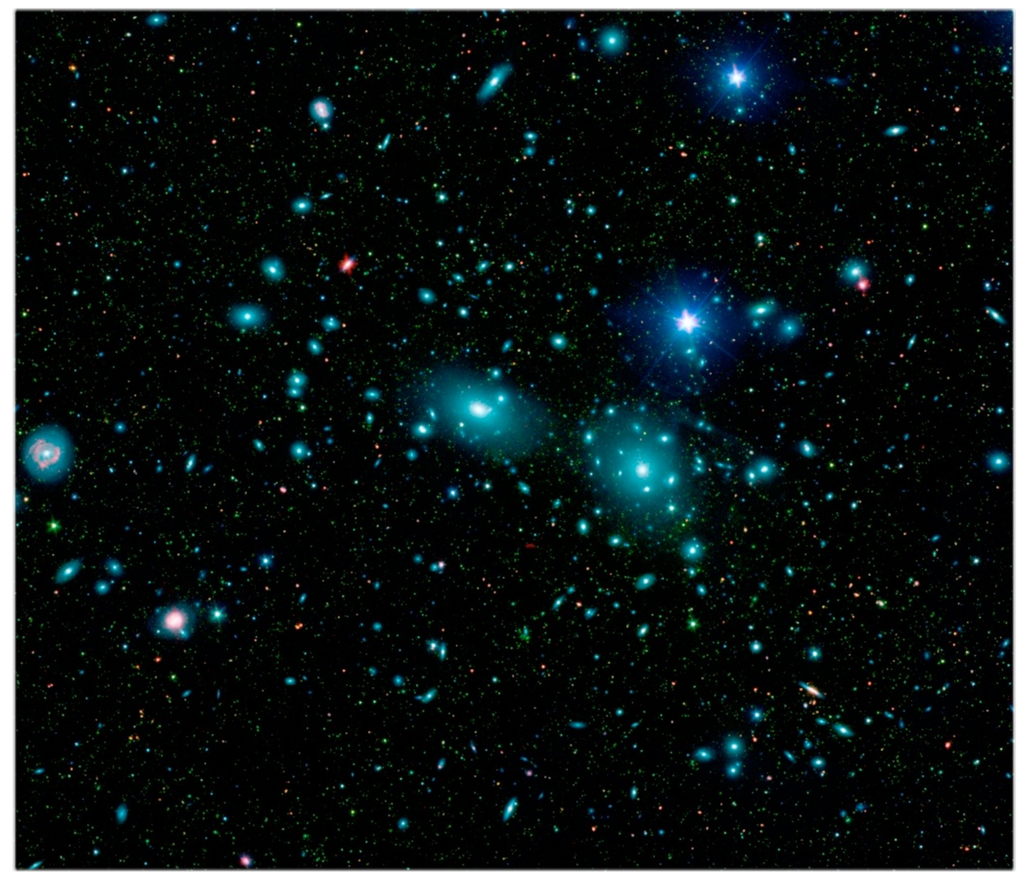


Fig. 3.—The Coma cluster of nebulae

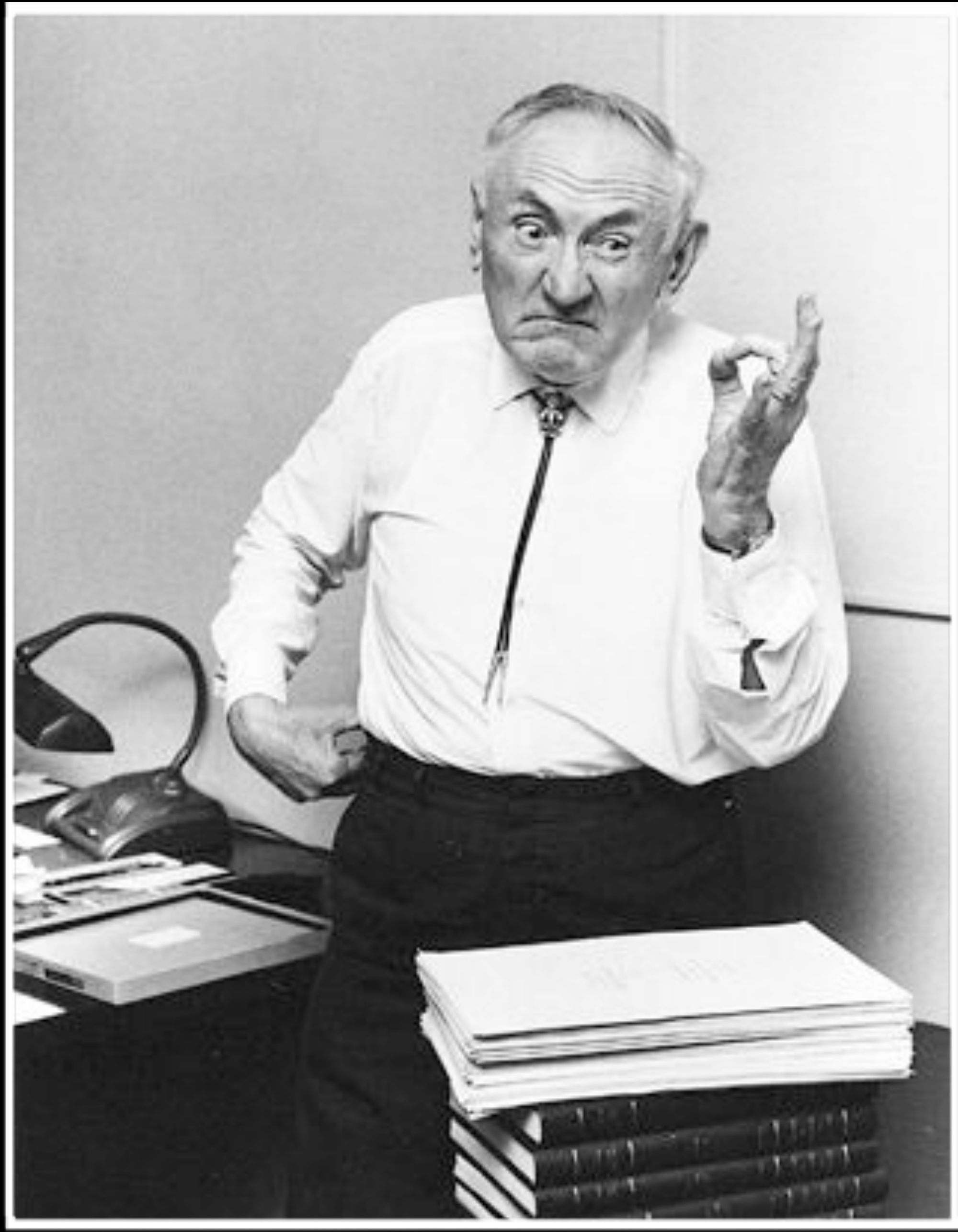


Fritz Zwicky

applies the virial theorem to the Coma Cluster and finds...

In his 1933 paper (in german) he writes

"If this would be confirmed we would get the surprising result that ***dark matter*** *is present in much greater amount than luminous matter."*



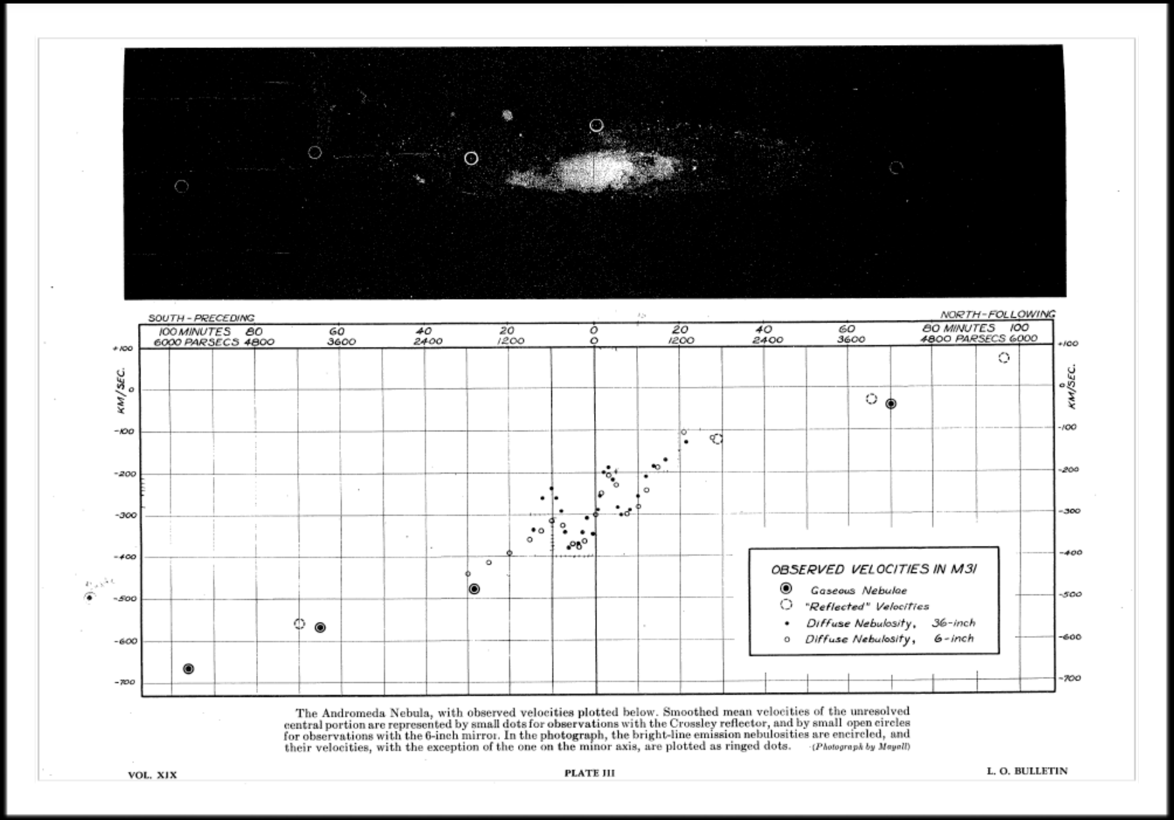
Evidence Slowly Mounts..

Smith 1936.

Mass of Virgo Cluster *“It is possible that [mass estimates] are correct, and that the difference represents a great mass of intranebular material in the cluster”* ApJ, vol. 83, p.23

Babcock 1939.

Rotation Curve of M31 *“The obvious interpretation of the nearly constant velocity for 30′ outward is that a that a very great portion of the mass of the nebula must lie in the outer regions”*



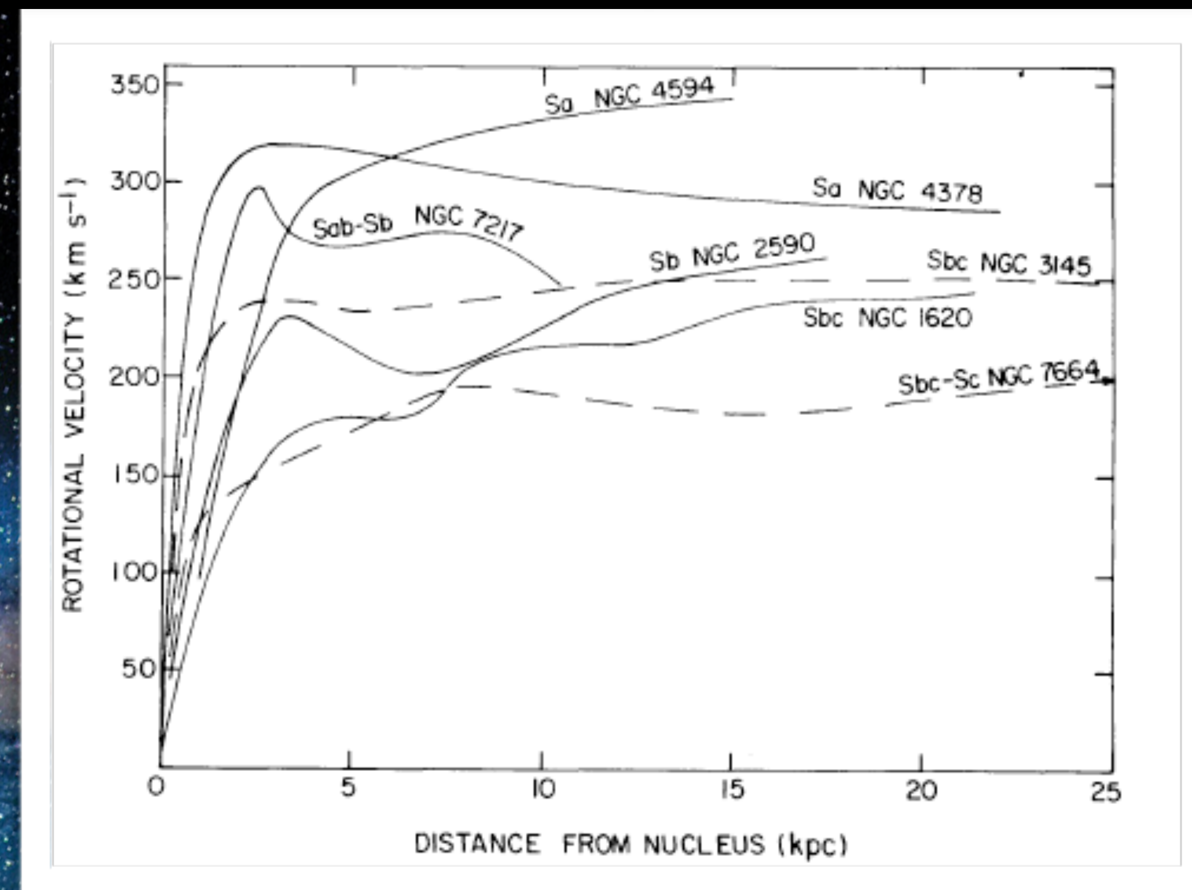
The Andromeda Nebula, with observed velocities plotted below. Smoothed mean velocities of the unresolved central portion are represented by small dots for observations with the Crossley reflector, and by small open circles for observations with the 6-inch mirror. In the photograph, the bright-line emission nebulosities are encircled, and their velocities, with the exception of the one on the minor axis, are plotted as ringed dots. (Photograph by Mayall)

Kahn & Woltjer 1959.

Local Group, Mass of the M31-MW system *“The Discrepancy seems to be well outside the observational errors”*

1970s: Rotation Curves

Roberts, Bosma, Rubin, et al.



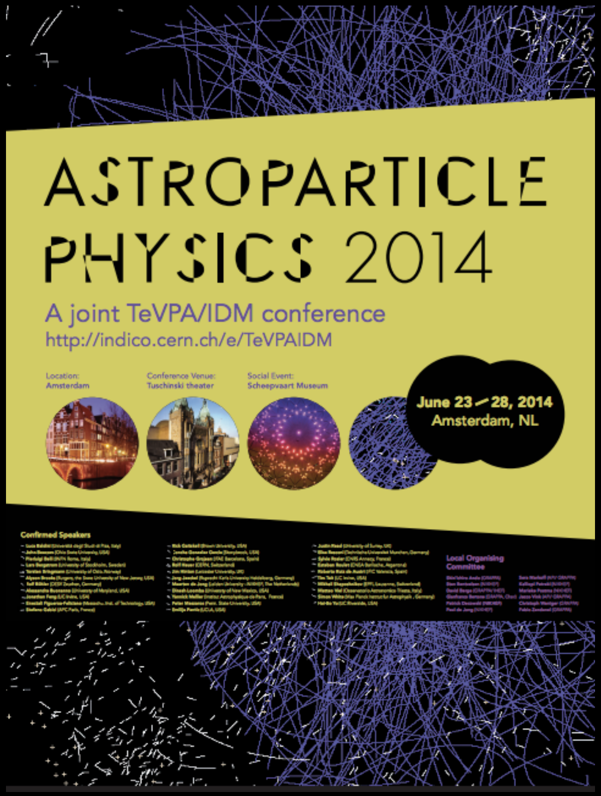
$$v_c(r) = \sqrt{\frac{GM(<r)}{r}}$$

History of Dark Matter in brief

1. **Dark Matter exists**
   Kapteyn 1922, Oort 1927, Zwicky 1933, 1937; Schmidt 1936,; Hulst et al 1957; Freeman 1970; Shostak and Rogstad 1972; Roberts and Rots 1973, Rubin et al. 1978, Bosma 1978

2. **Dark Matter is ubiquitous**
   [Finzi 1959!], Ostriker, Peebles, Yahil 1974, Einasto et al. 1974, Faber & Gallagher 1979

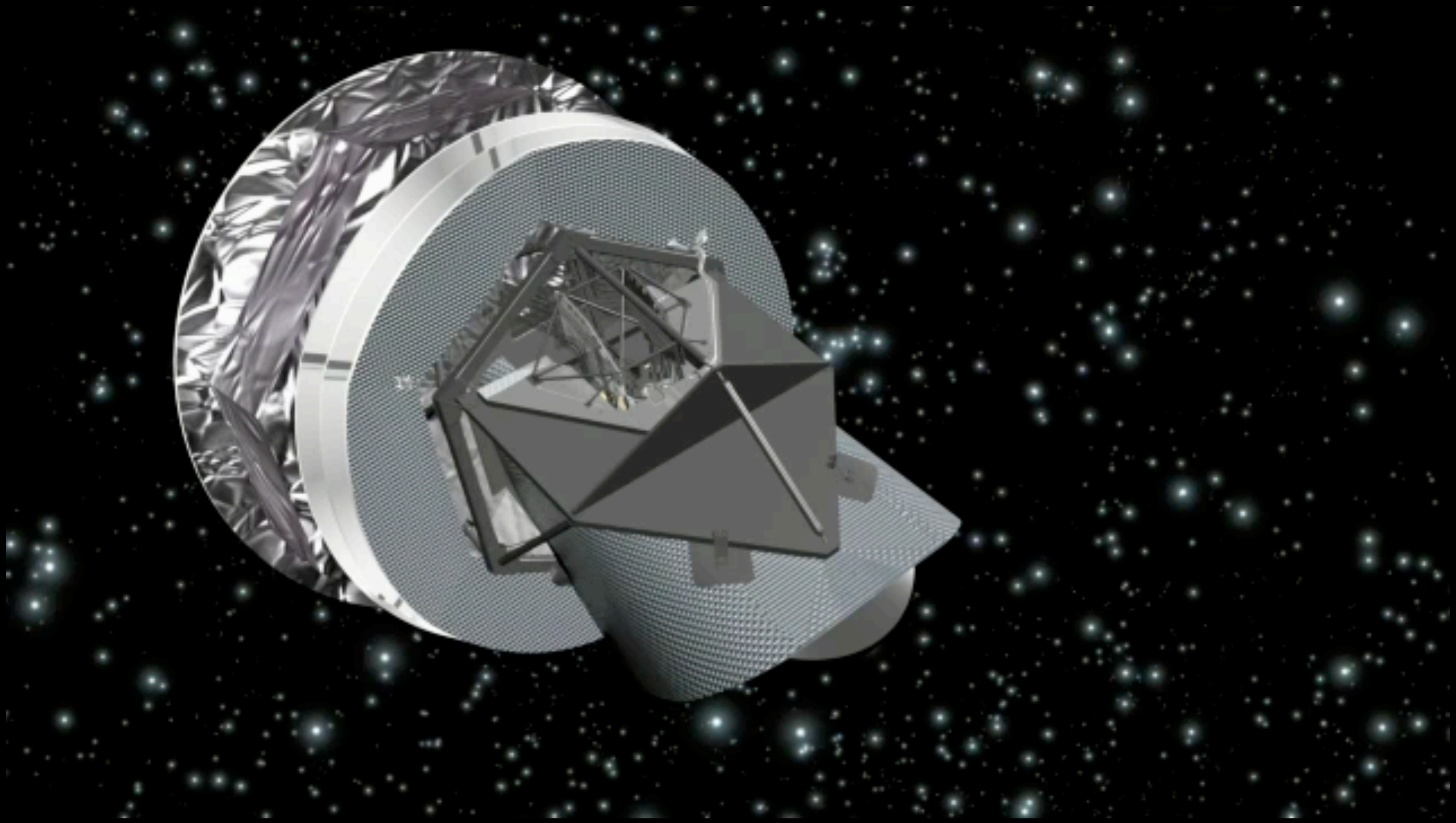
3. **Dark Matter is a *new* particle**
   Peebles 1982 + Pagels, Primack, Bond, Szalay, White, ..



Videos of all lectures will be online soon….

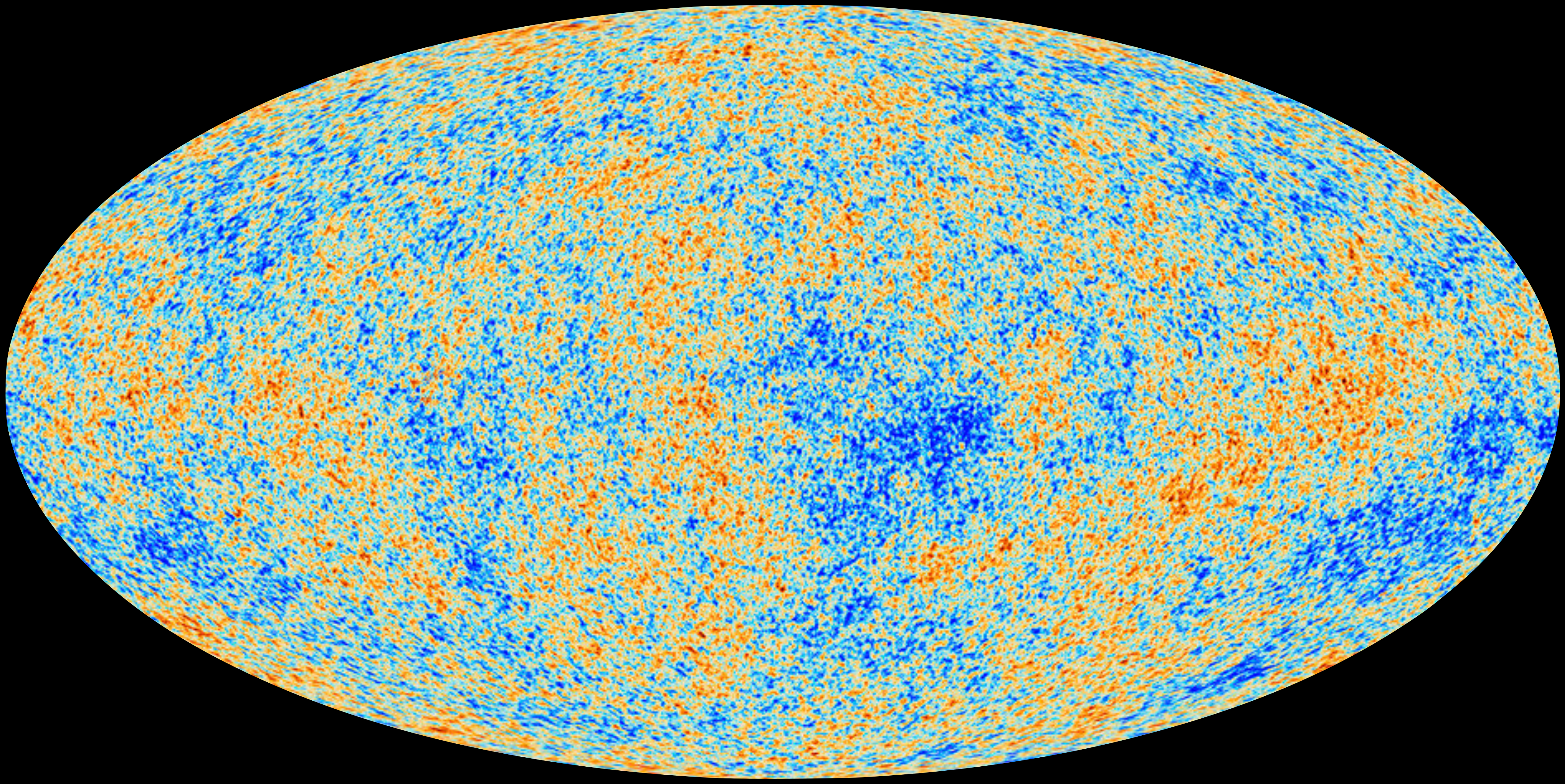
Modern evidence for *non-baryonic* dark matter: CMB experiments

ESA's *Planck* satellite

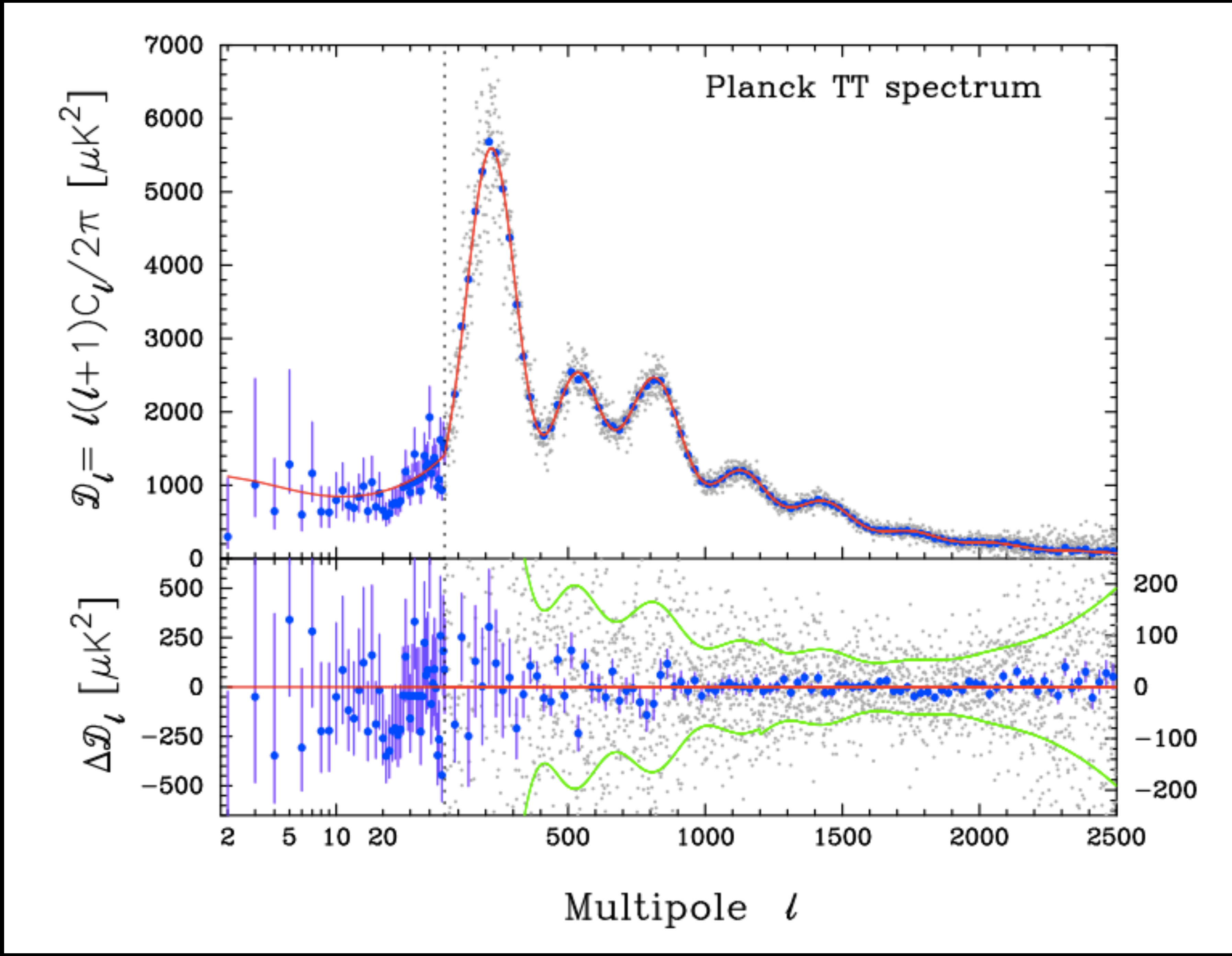


Mission concluded ~ end 2013 (polarization analysis still being analysed, see BICEP2 etc.)

CMB anisotropies



Planck results



http://arxiv.org/abs/1303.5076

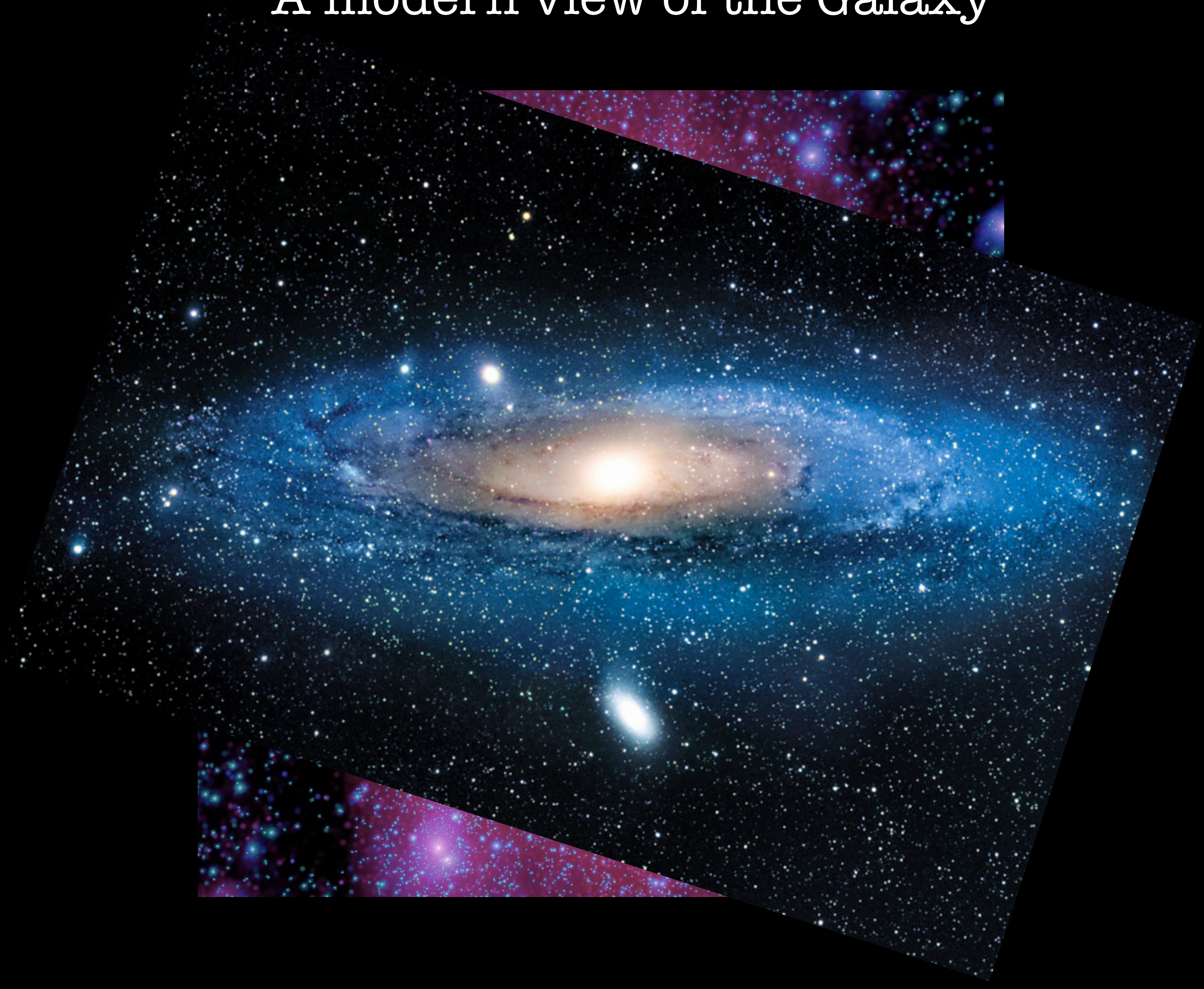
Planck results

Parameter	*Planck* Best fit	*Planck* 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072

(consistent with BBN)

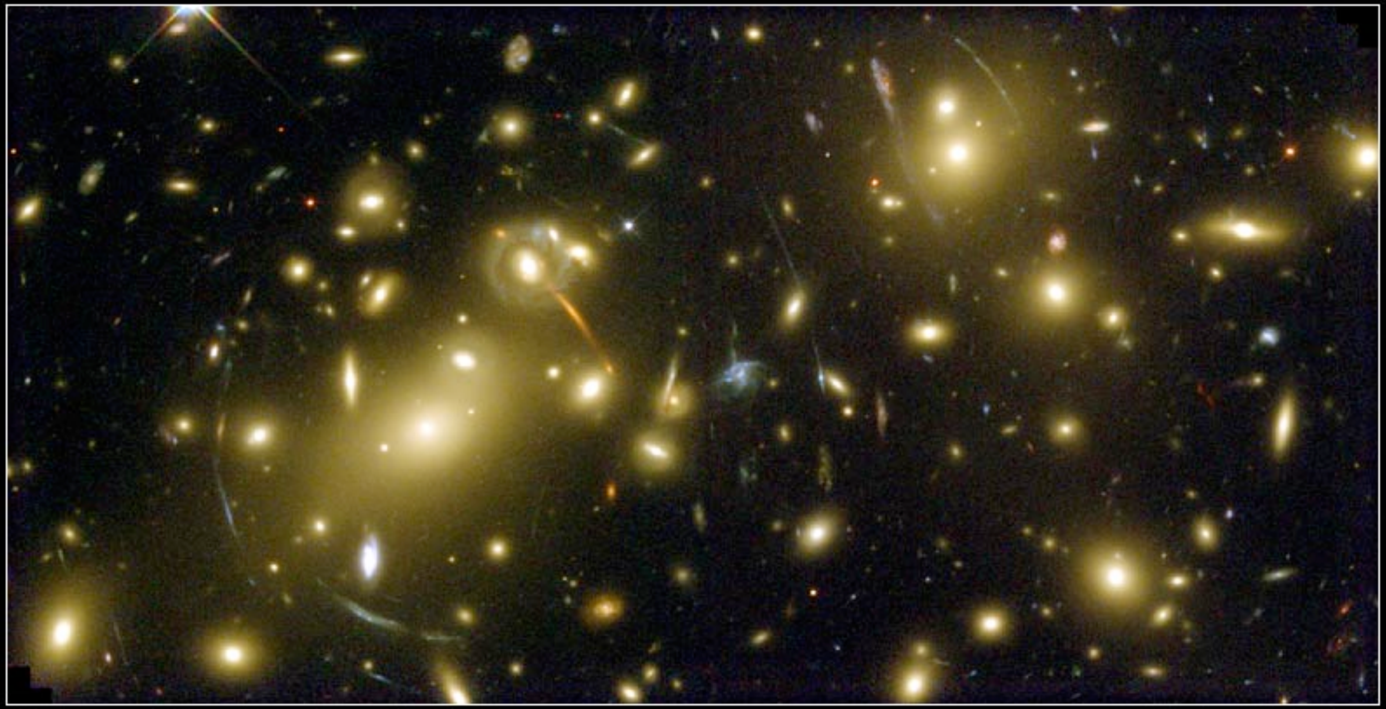
http://arxiv.org/abs/1303.5076

A modern view of the Galaxy



Mass of Galaxy Clusters

The mass of a cluster can be determined via several methods, including application of the virial theorem to the observed distribution of radial velocities, by weak gravitational lensing, and by studying the profile of X-ray emission that traces the distribution of hot emitting gas in rich clusters.



Galaxy Cluster Abell 2218 **HST** • WFPC2

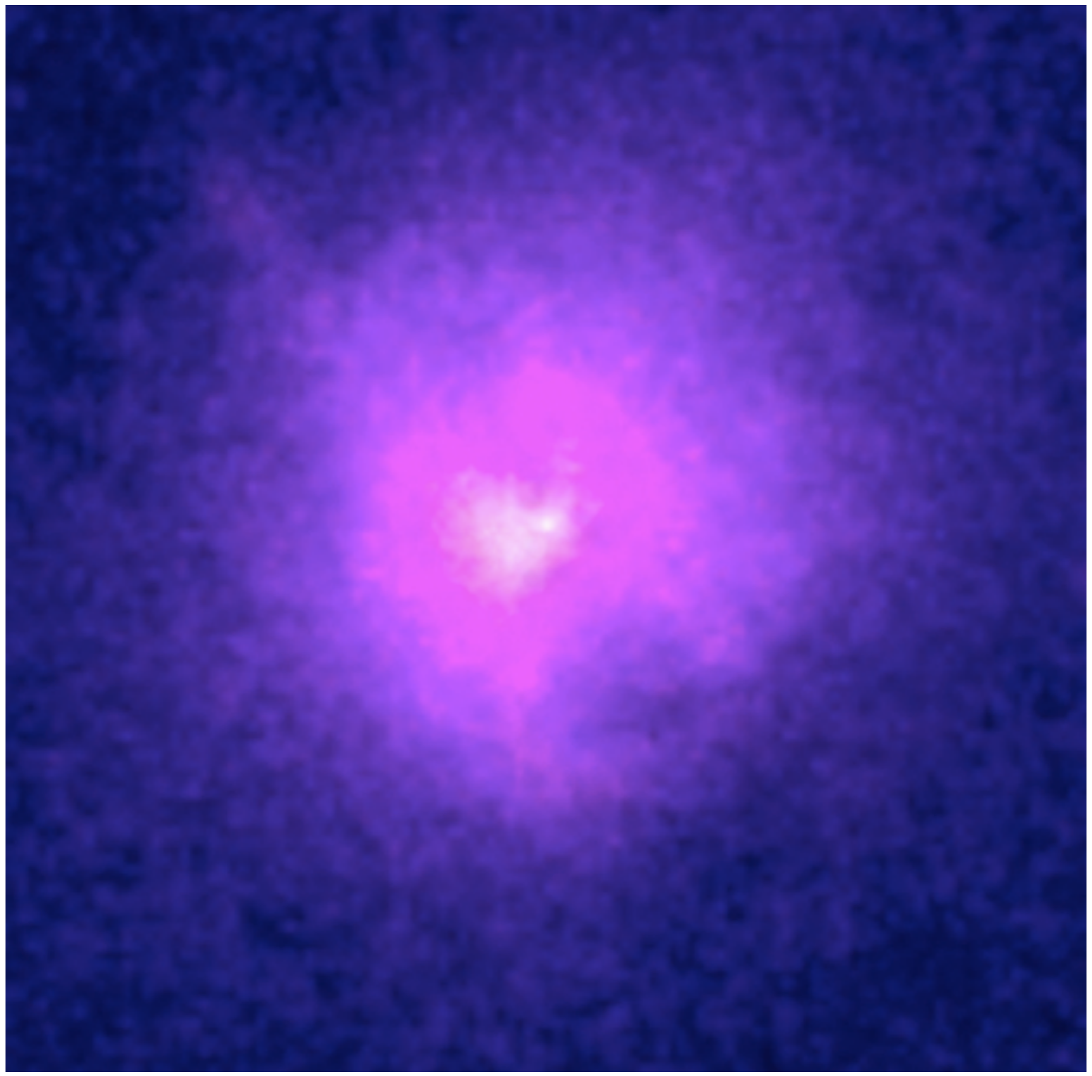
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

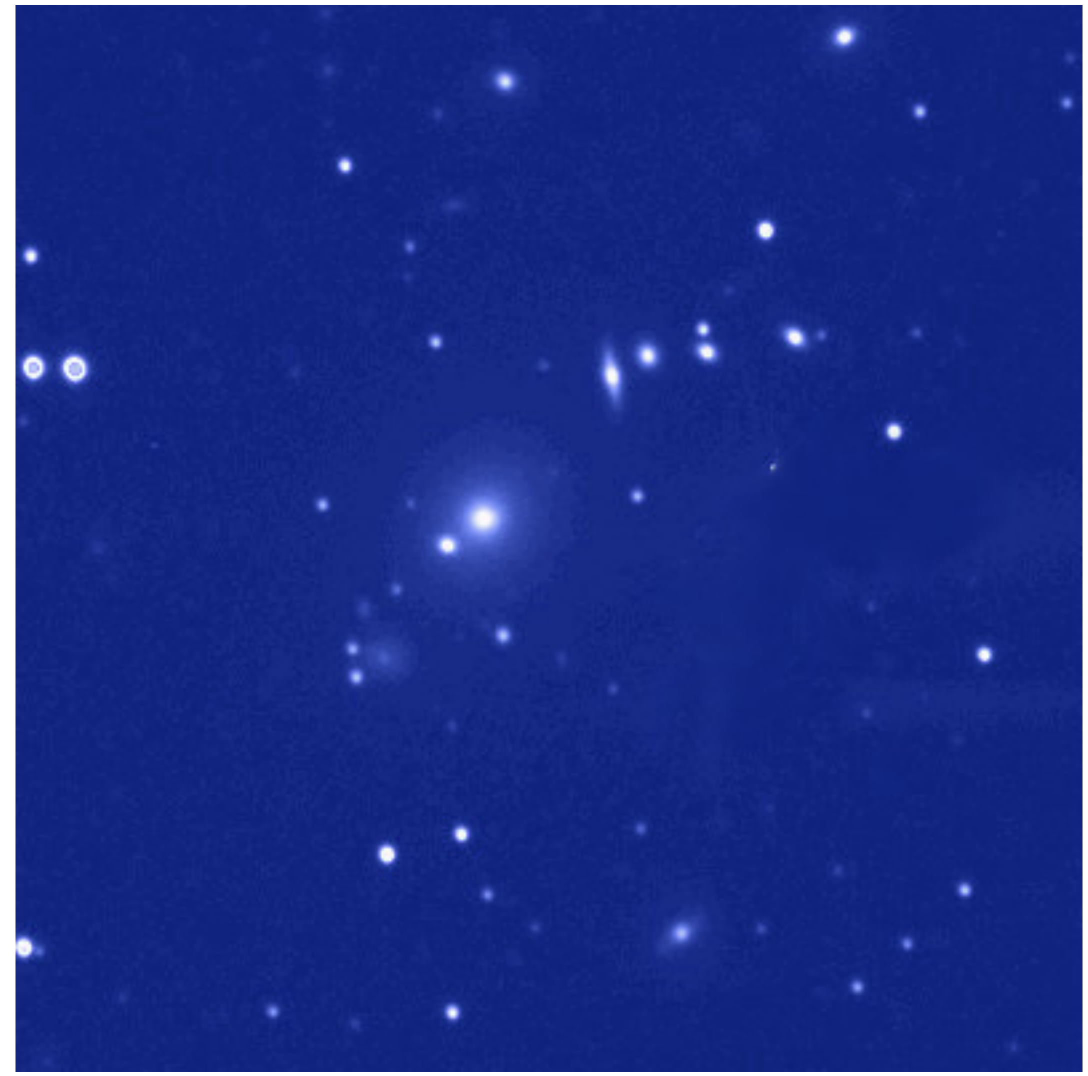
Total mass 10^{14} to 10^{15} $M_\odot$

Gas fraction ~16% (~ 13% ICM, ~ 3% galaxies).

Remaining 84% of the mass is in dark matter

Galaxy Clusters





Hydra A galaxy cluster. Optical observations show a few hundred galaxies in the cluster. Chandra X-ray observations reveal a large cloud of hot gas that extends throughout the cluster. The gas cloud is several million light years across and has a temperature of about 40 million degrees in the outer parts decreasing to about 35 million degrees in the inner region.

Galaxy Clusters

Mass estimates from X-Ray emission

Start from *Hydrostatic equlibrium*

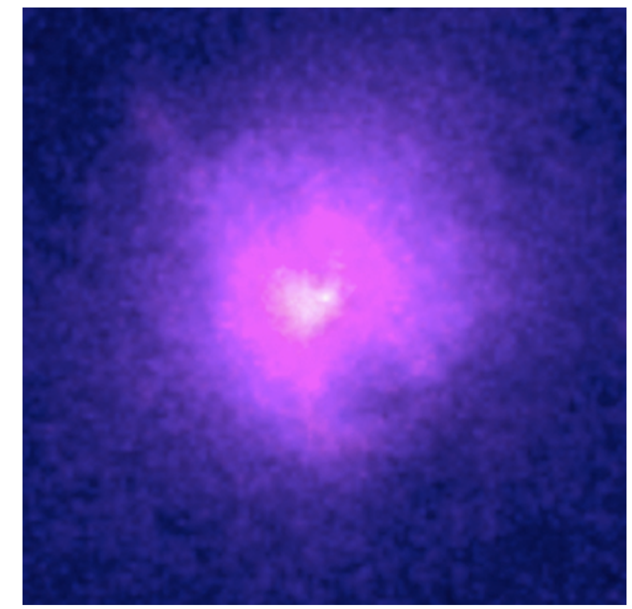
$$\frac{dP}{dr} = -\frac{GM(< r)}{r^2}\rho$$

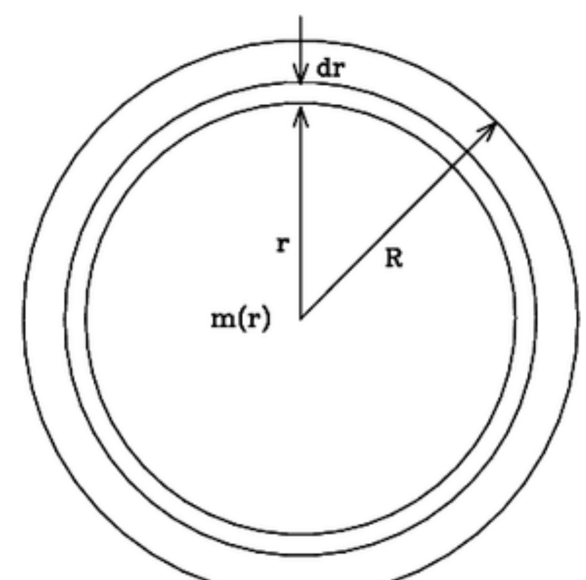
The *equation of state* of the intra-cluster gas allows to express the pressure in terms of the gas temperature and density

$$P = \frac{k}{\mu m_p}\rho T$$

We can now express the total mass in terms of quantities we can infer from observations, i.e. the gas density and temperature

$$M_{\rm tot} = -\frac{kT_g(r)}{\mu m_p} r \left[\frac{d\log\rho_g(r)}{d\log r} + \frac{d\log T_g(r)}{d\log r}\right]$$





Galaxy Clusters

The temperature and density of the gas can be inferred from the gas *emissivity*. This typically goes like

$$\epsilon(E,T) \sim n_e^2\, \zeta(T,m)\, T^{-1/2}\, exp\left(-\frac{E}{kT}\right)$$

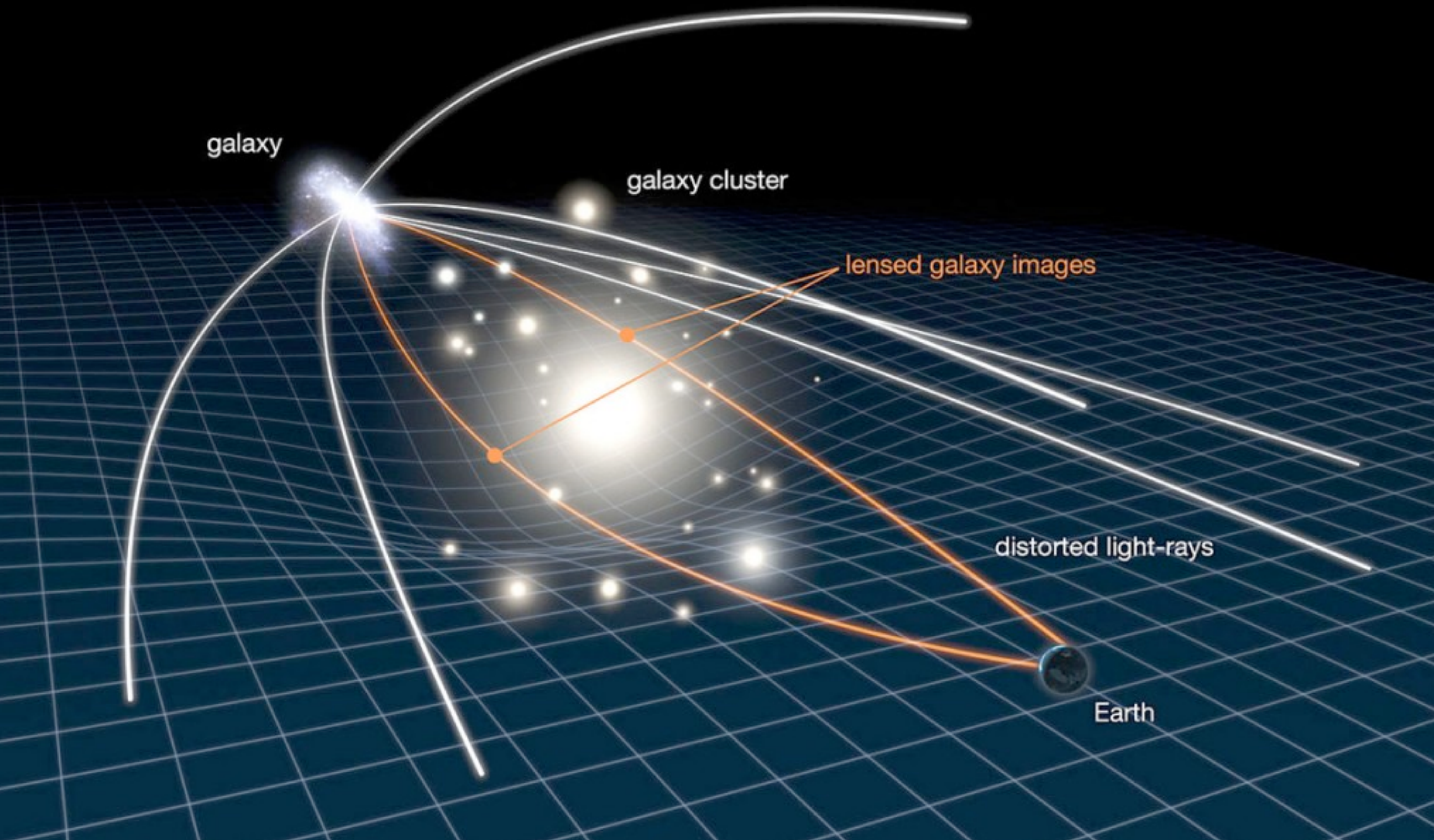
For typical values measured in cluster of galaxies, the total mass

$$M_{\rm tot} = -\frac{kT_g(r)}{\mu m_p} r \left[\frac{d\log\rho_g(r)}{d\log r} + \frac{d\log T_g(r)}{d\log r}\right]$$

turns out to be significantly larger than the mass in the gas, which dominates the baryonic mass in the cluster

$$M_{gas} = 4\pi \int \rho_{gas} r^2 dr \approx 0.2 M_{tot}$$

Gravitational Lensing

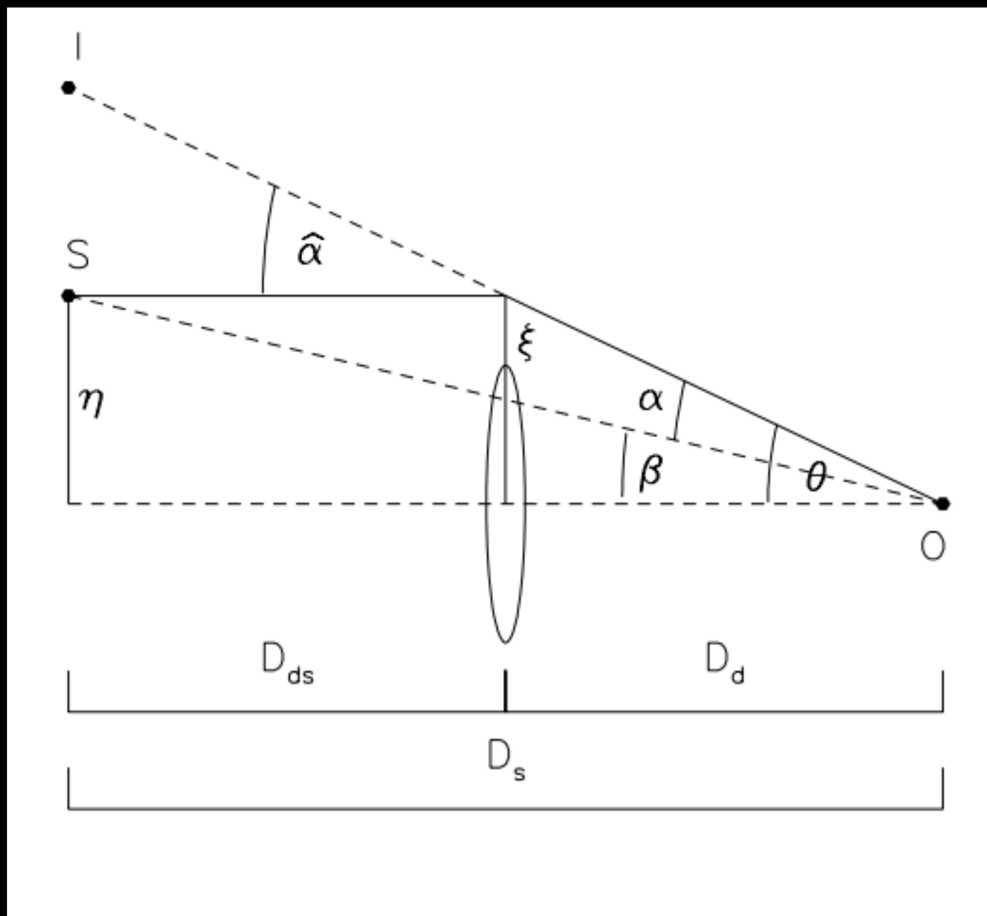


Gravitational Lensing

Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

Lens equation



S: *source*
O: *observer*
Dd: *distance between observer and lens*
Dds: *distance between lens and source*
Ds: *distance between observer and source*
: *deflection angle*
: *angle between the (arbitrarily chosen) optical axis and the true source position*
θ: *angle between the optic axis and the image*

Upon inspection of the figure on the left, one immediately sees that

$$\beta(\theta) = \theta - \alpha(\theta)$$

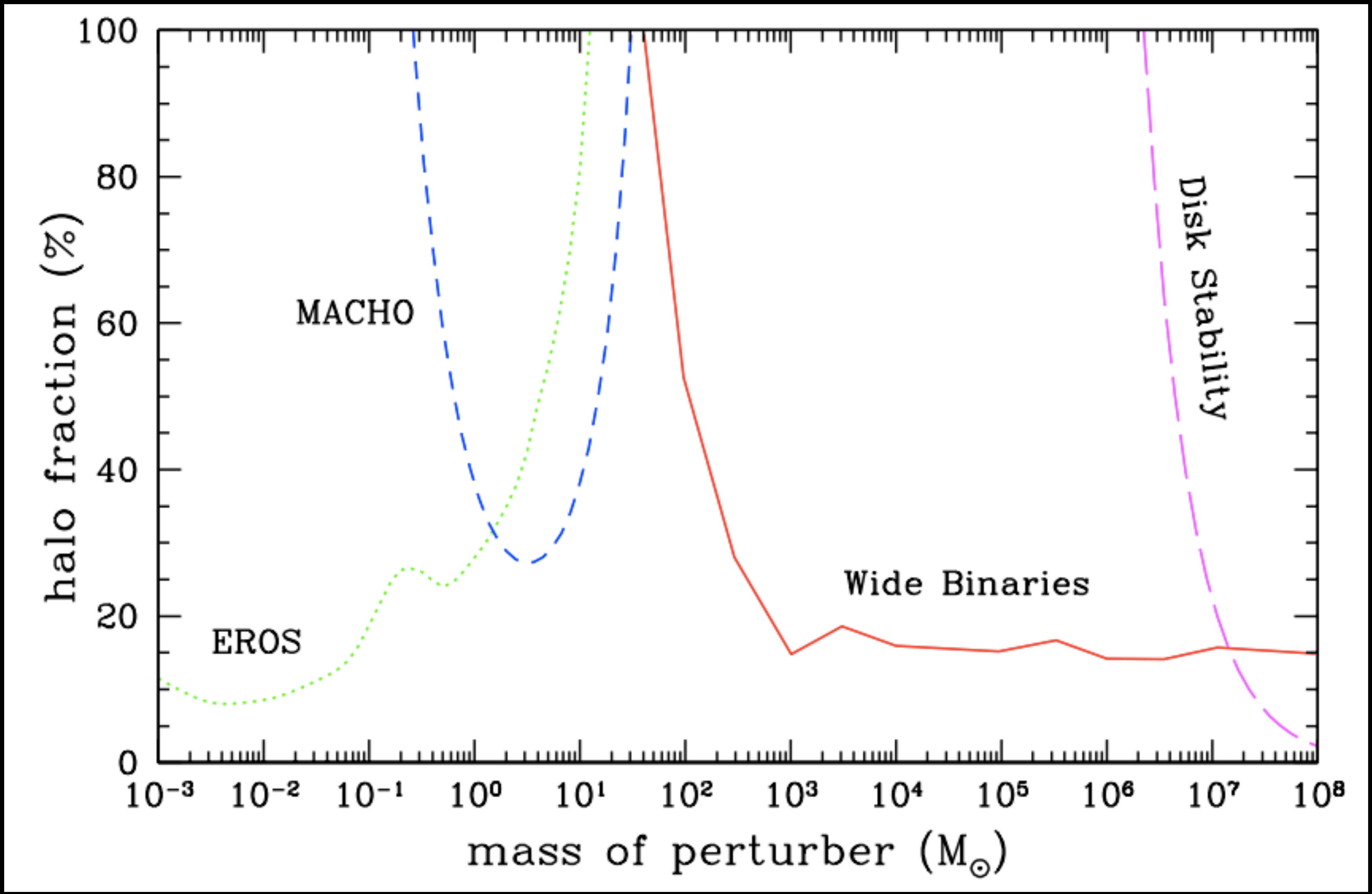
This is the LENSING EQUATION (or ray-tracing equation).

For a circularly symmetric lens, the problem reduces to 1 dimension, and one can prove easily that:

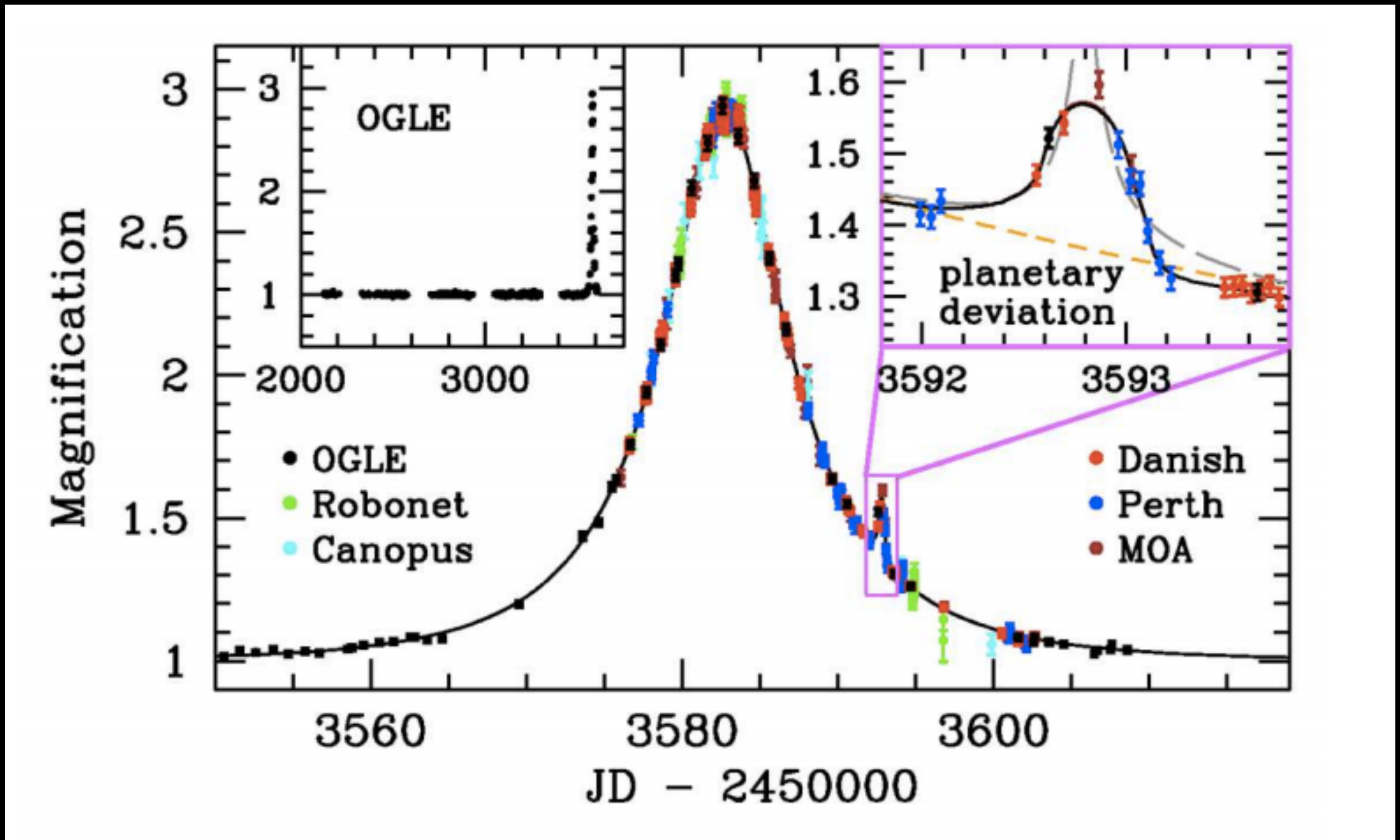
$$\beta(\theta) = \theta - \left(\frac{D_{ds}}{D_d D_s} \frac{4GM}{c^2 \theta} \right)$$

Current constraints

Massive Halo Compact Objects (MaCHOs) canNOT explain Dark Matter
(e.g. http://arxiv.org/abs/astro-ph/0307437)



Recent application: search for exoplanets!



Exoplanets can cause sharp deviations in the otherwise smooth lightcurve of a background star during a microlensing event.

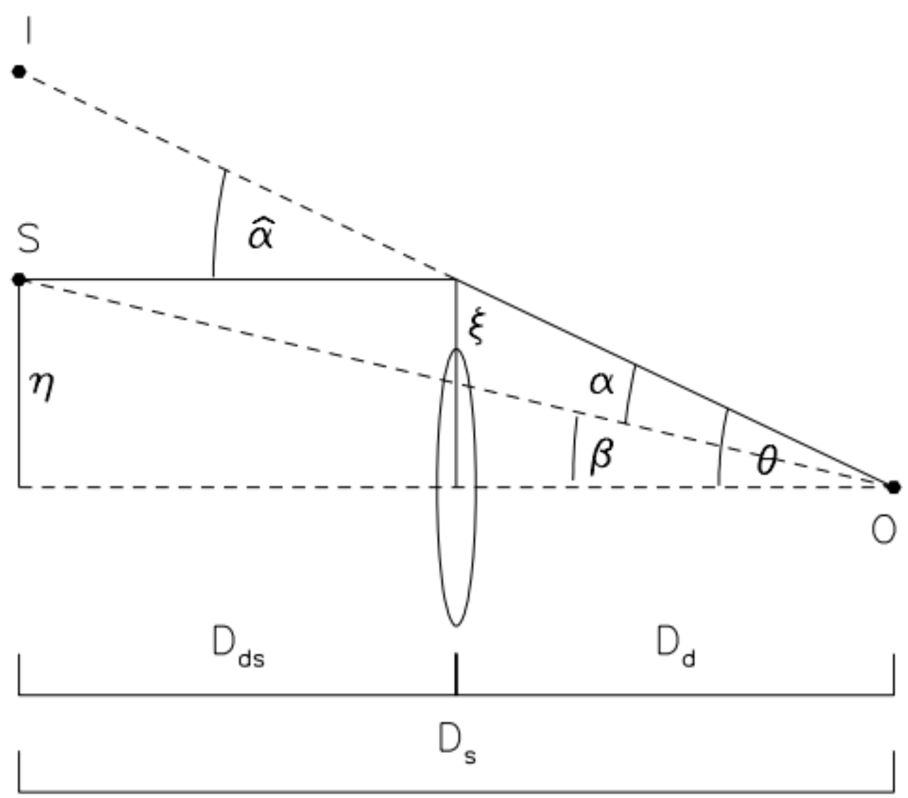
Several tens of extra solar planets have been already detected with this method!

See http://arxiv.org/abs/1207.3720 for more astrophysical applications of gravitational lensing.

See exoplanet.eu for further information on extra solar planets.

Galaxies as lenses

Lensing by point masses is straightforward, but when we consider galaxies as lenses we need to take into account the distribution of mass, which increases somehow the complexity of the modelling.



It is convenient to introduce the Effective Lensing Potential, defined as the - appropriately scaled - projected Newtonian potential of the lens

$$\psi(\vec{\theta}) = \frac{D_{\rm ds}}{D_{\rm d} D_{\rm s}} \frac{2}{c^2} \int \Phi(D_{\rm d}\vec{\theta}, z)\, dz$$

As we shall see, the derivatives of this potential are related to some important quantities.

Lensing Potential

Let’s start from the gradient:

$$\vec{\nabla}_{\theta}\psi = D_{\mathrm{d}}\vec{\nabla}_{\xi}\psi$$

So the gradient of the potential is simply the deflection angle. Let’s try the Laplacian

$$\nabla^2_{\theta}\psi \quad = \quad \frac{2}{c^2}\frac{D_{\mathrm{d}}D_{\mathrm{ds}}}{D_{\mathrm{s}}}\int \nabla^2_{\xi}\Phi\, dz$$

, recall that $\nabla^2_{\theta} = \frac{\partial^2}{\partial\theta_1^2} + \frac{\partial^2}{\partial\theta_2^2}$

We can use Poisson equation to relate the laplacian of the gravitational potential to the mass density rho

$$\nabla^2_{\xi}\phi = 4\pi G\rho$$

and define the surface mass density as the projected density

$$\Sigma(\xi) = \int \rho(\xi, z)dz$$

Convergence

We therefore obtain the following expression for the Laplacian of the potential

$$\nabla_\theta^2 \psi = \frac{2}{c^2} \frac{D_\mathrm{d} D_\mathrm{ds}}{D_\mathrm{s}} \int \nabla_\xi^2 \Phi \, dz = \frac{2}{c^2} \frac{D_\mathrm{d} D_\mathrm{ds}}{D_\mathrm{s}} \cdot 4\pi G \Sigma$$

Let's express this in terms of the 'critical mass density' $\Sigma_\mathrm{cr} = \frac{c^2}{4\pi G} \frac{D_\mathrm{s}}{D_\mathrm{d} D_\mathrm{ds}}$

$$\nabla_\theta^2 \psi = 2 \frac{\Sigma(\vec{\theta})}{\Sigma_\mathrm{cr}} \equiv 2\kappa(\vec{\theta})$$

The surface mass density scaled with its critical value is called the **convergence** κ.

Lensing Potential

We have studied the gradient and the laplacian of the potential. Let's see what the mixed partial derivatives tell us, by studying the Jacobian (matrix of first derivatives) of the lensing mapping

$$A \equiv \frac{\partial\vec{\beta}}{\partial\vec{\theta}} = \left(\delta_{ij} - \frac{\partial\alpha_i(\vec{\theta})}{\partial\theta_j}\right)$$

where we used the lens equation. Now recall that the deflection angle is the gradient of the potential, therefore

$$A \equiv \frac{\partial\vec{\beta}}{\partial\vec{\theta}} = \left(\delta_{ij} - \frac{\partial\alpha_i(\vec{\theta})}{\partial\theta_j}\right) = \left(\delta_{ij} - \frac{\partial^2\psi(\vec{\theta})}{\partial\theta_i\partial\theta_j}\right) = M^{-1}$$

(M is the magnification tensor, so A is sometimes referred to as the inverse magnification tensor) This encodes the distortion of a background source from a foreground lens.

Shear

If we define $\dfrac{\partial^2\psi}{\partial\theta_i\partial\theta_j} \equiv \psi_{ij}$

and recall that the Laplacian of the potential is twice the convergence, then

$$\kappa = \frac{1}{2}(\psi_{11} + \psi_{22}) = \frac{1}{2}\ \mathrm{tr}\ \psi_{ij}$$

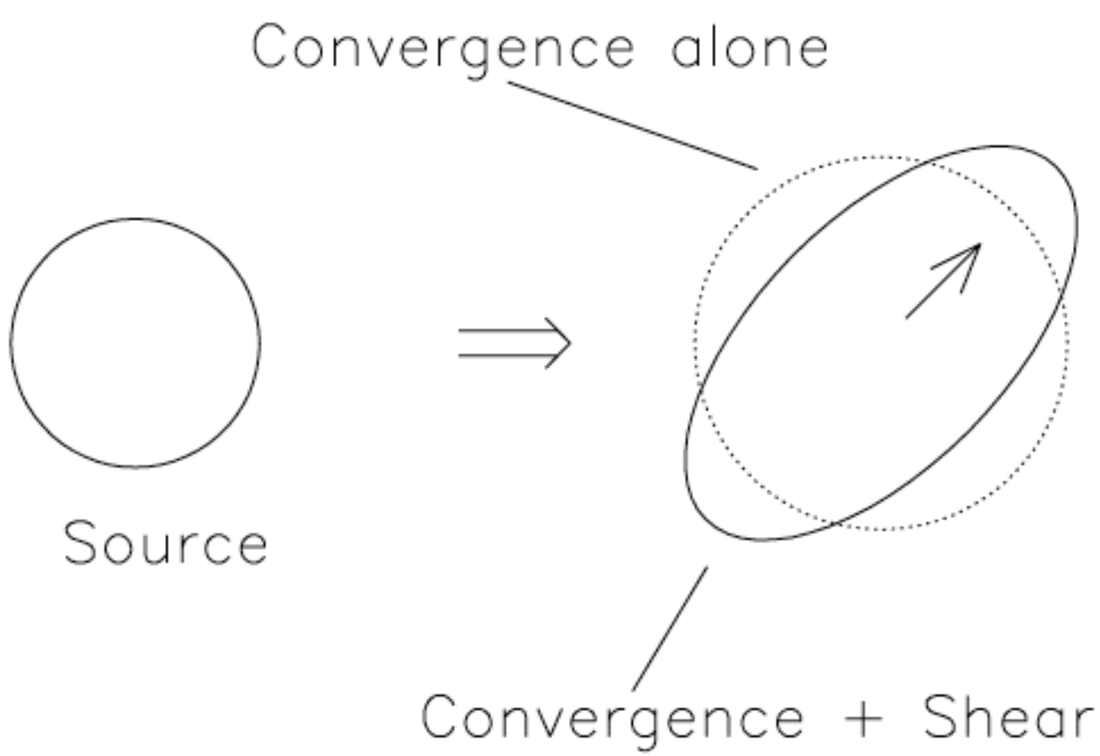
We can construct other linear combinations that contain off-diagonal terms and define the so-called **shear**

$$\begin{aligned}
\gamma_1(\vec{\theta}) &= \frac{1}{2}(\psi_{11} - \psi_{22}) \\
\gamma_2(\vec{\theta}) &= \psi_{12} = \psi_{21}
\end{aligned}$$

Lensing Potential

With these definitions, the Jacobian matrix can be written

$$A = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$



Physical meaning:

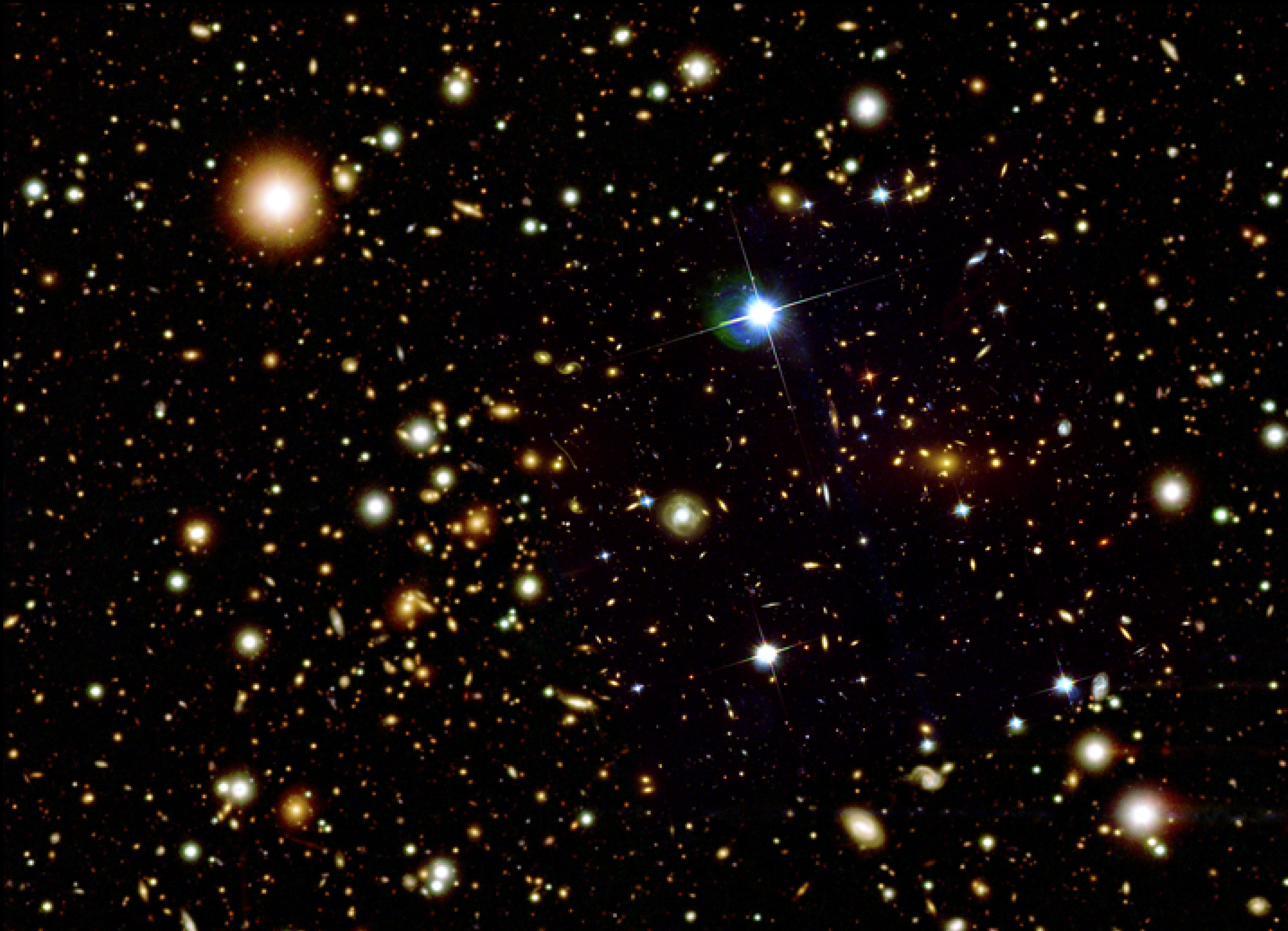
Convergence causes an isotropic focusing of light rays, leading to an isotropic magnification of a source

Shear introduces anisotropy (or astigmatism) into the lens mapping. A circular source of unit radius becomes an elliptical image with major and minor axes

$$(1-\kappa-\gamma)^{-1}, \quad (1-\kappa+\gamma)^{-1}$$

while the total magnification is

$$\mu = \det M = \frac{1}{\det A} = \frac{1}{[(1-\kappa)^2-\gamma^2]}$$

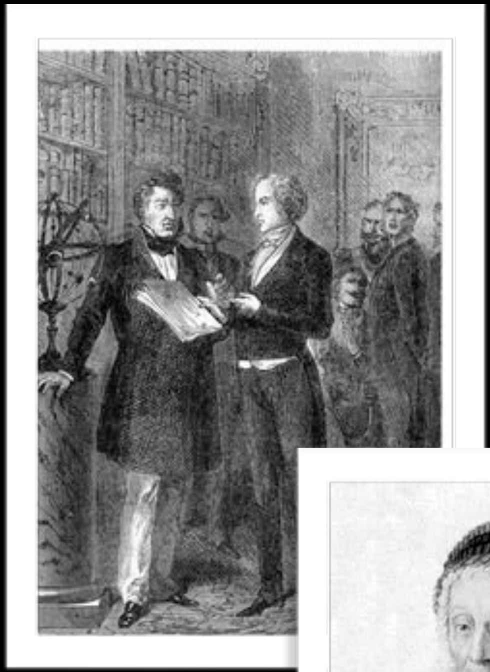
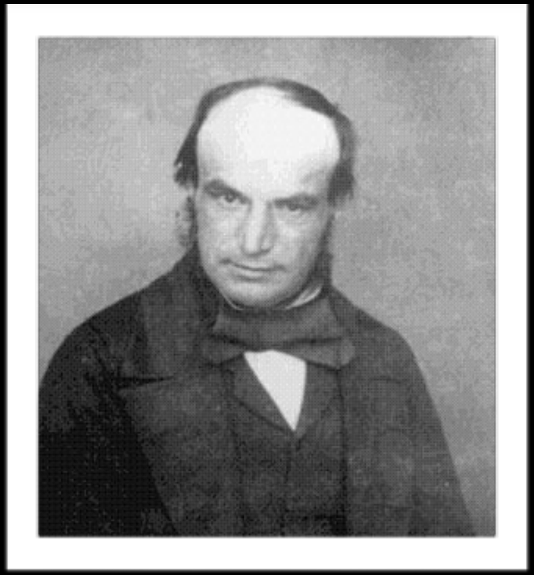


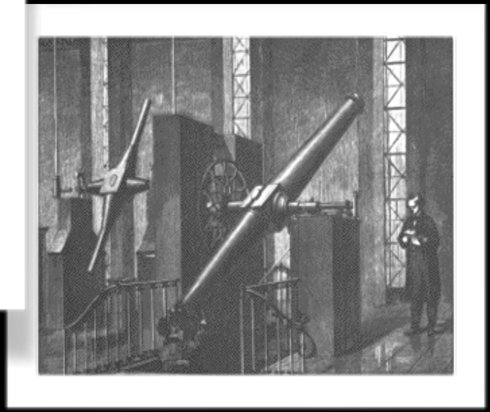
New Matter or New Physics?

In the past, deviations from Newton's law found different explanations

Uranus, Neptune, etc.

"There are more things in heaven and earth, Horatio, ..." – W. Shakespeare

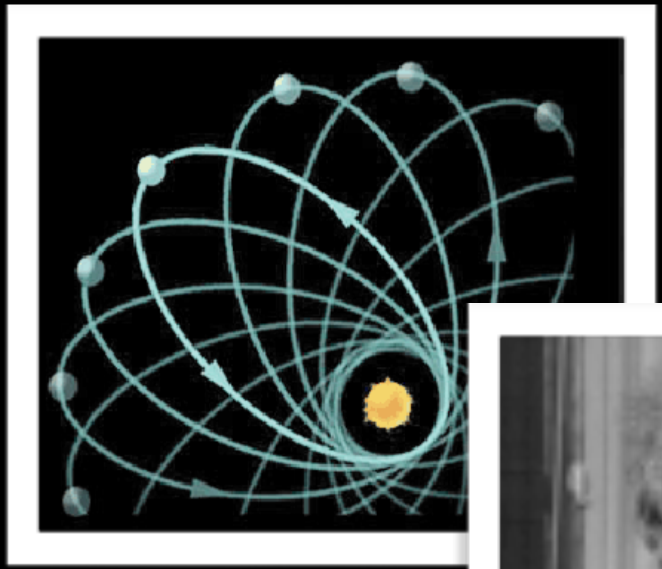
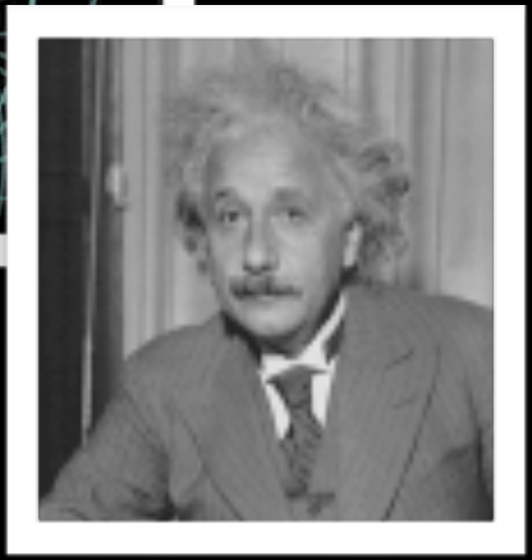





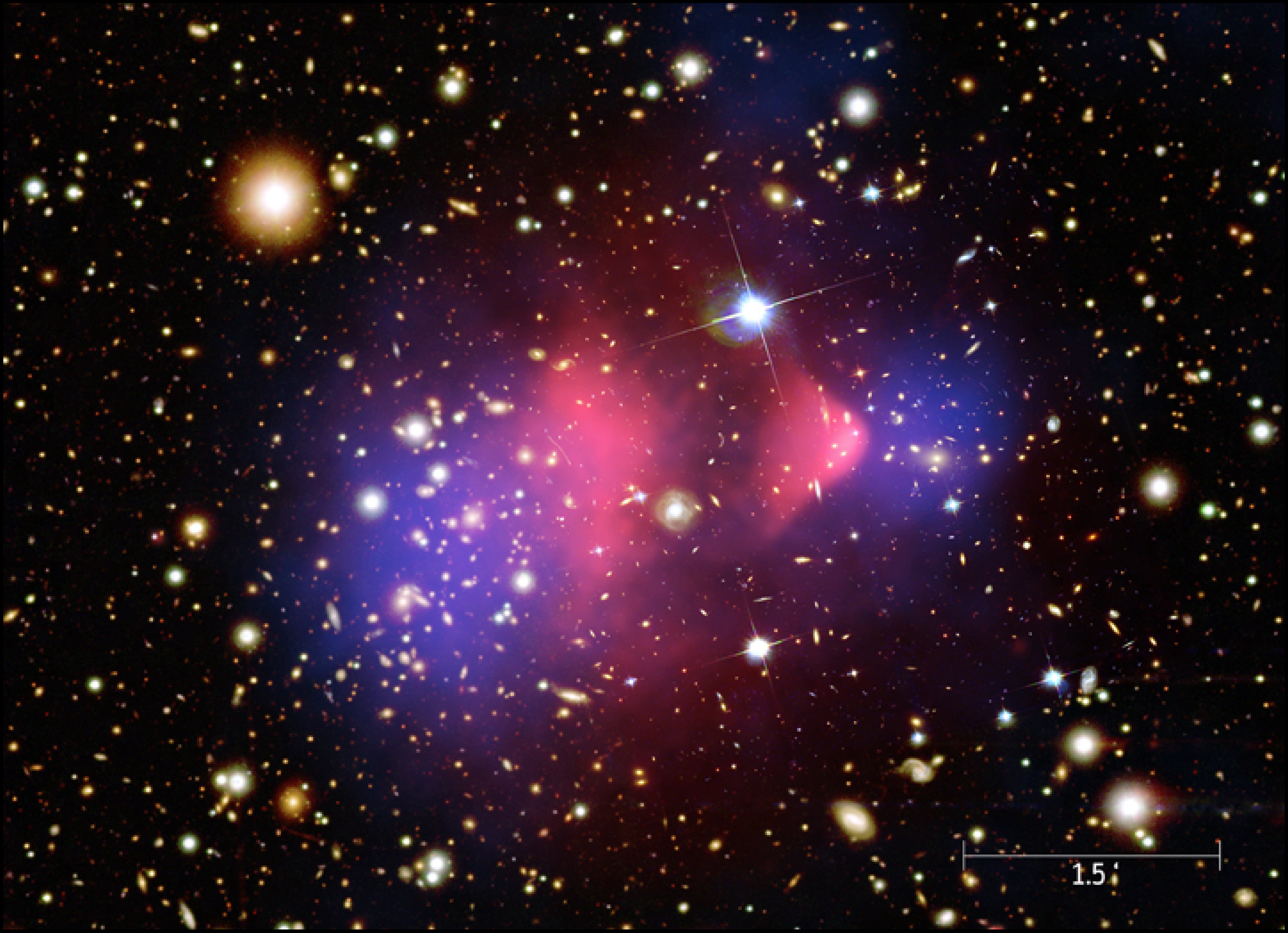
"DARK" PLANETS

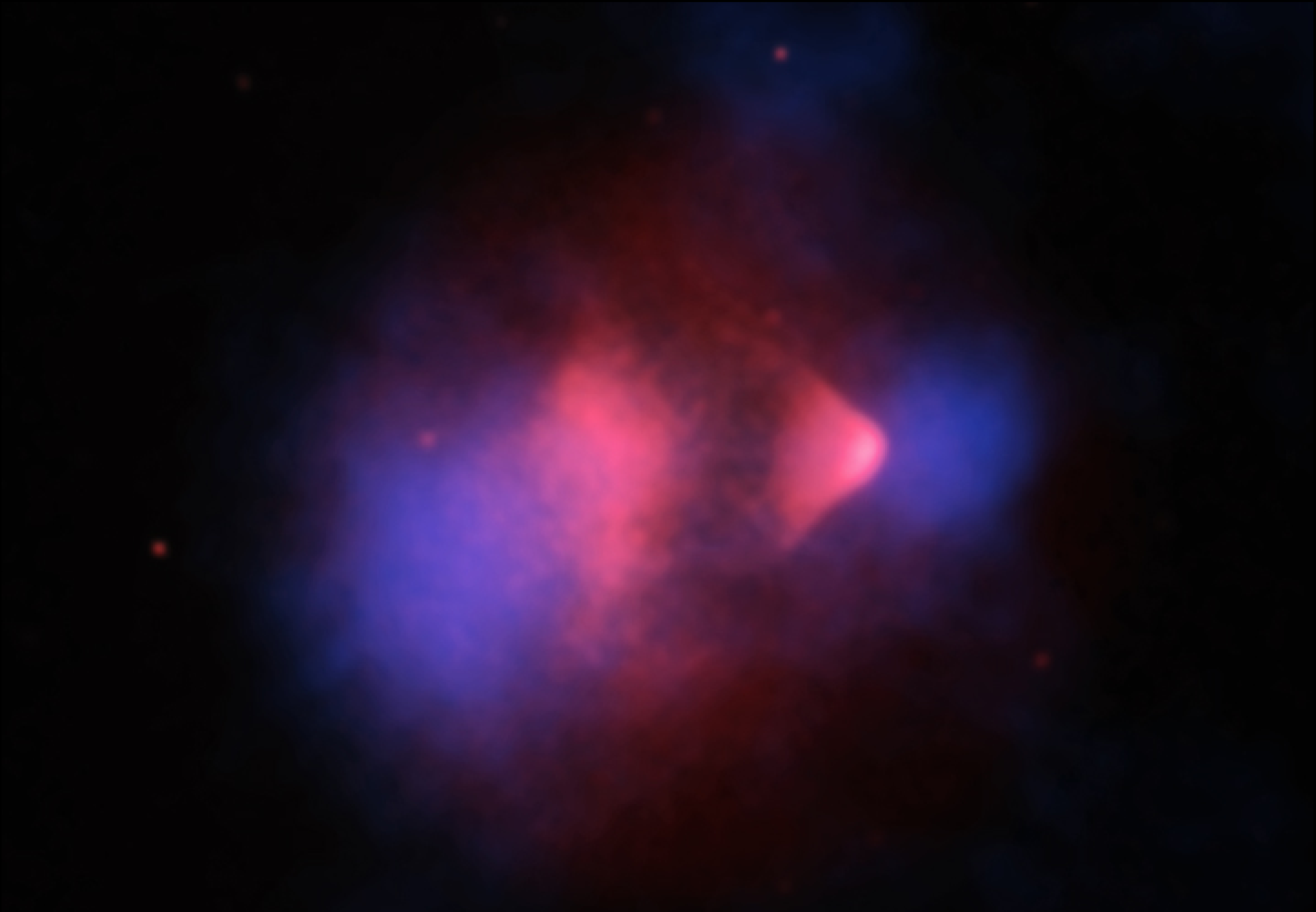
Mercury

"The invisible & the non-existent look very much alike." -Delos B. McKown

REFINED LAWS OF GRAVITATION


1.5 '



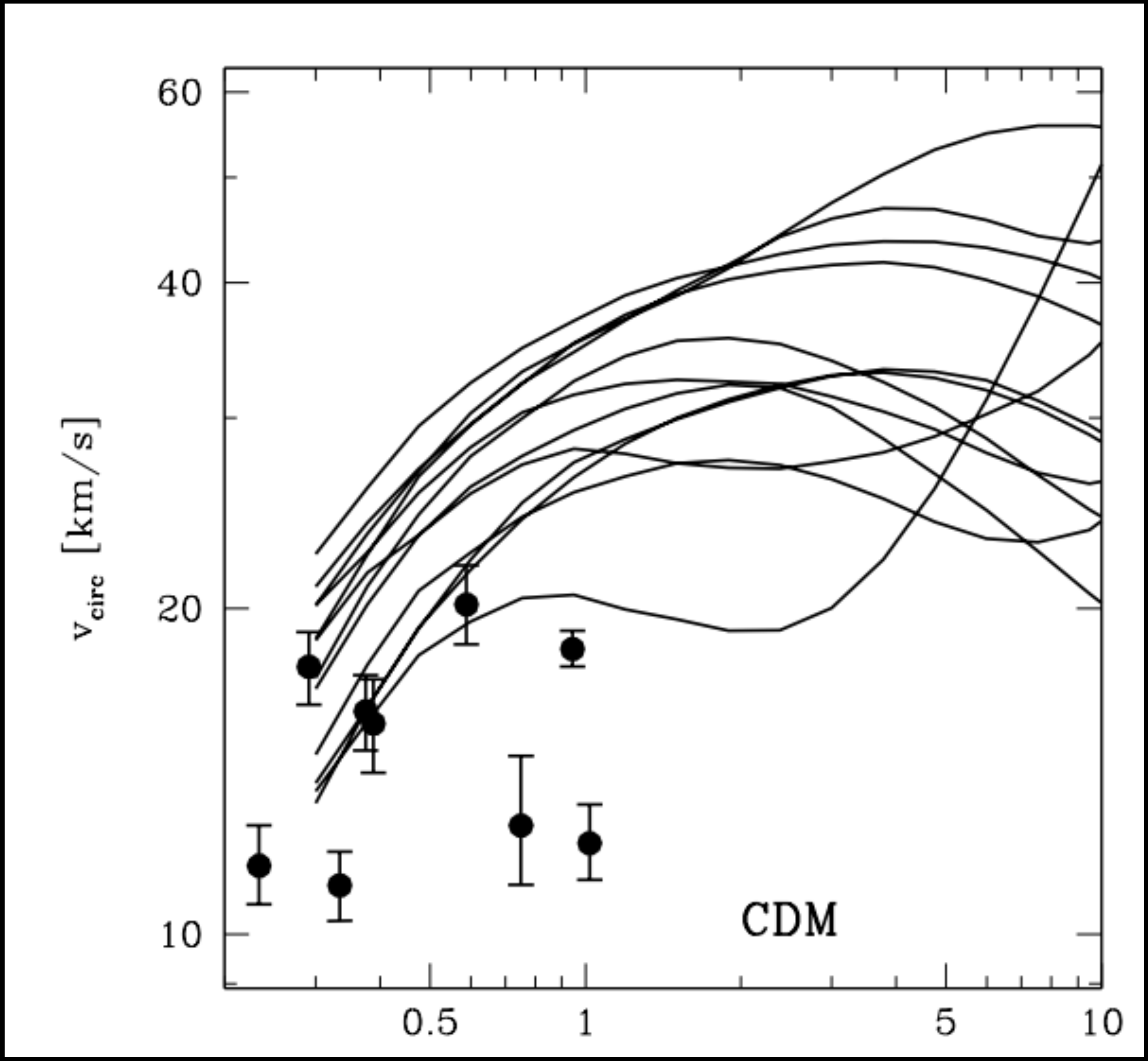
(Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)

DM ≠ Baryons

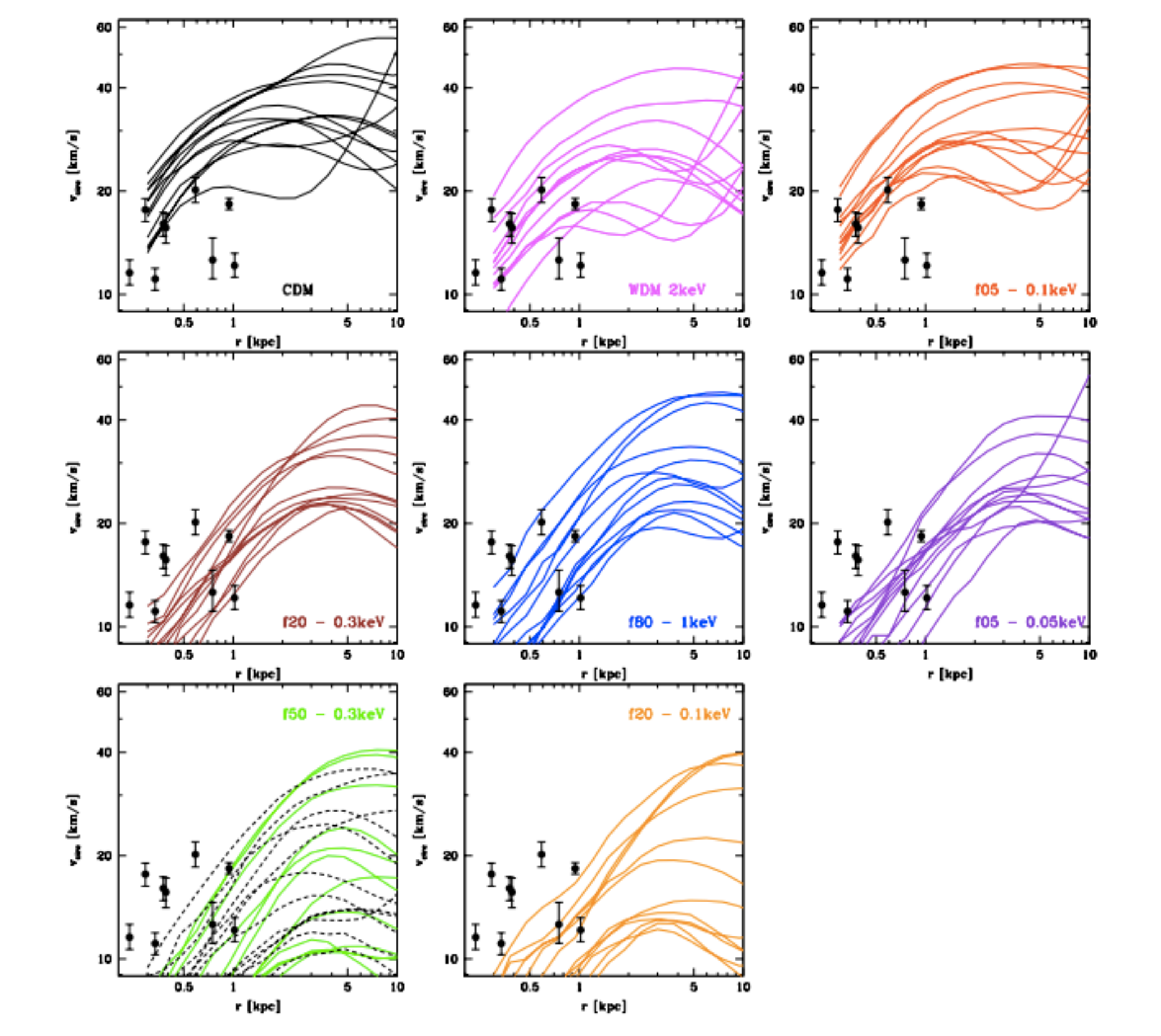
(Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)

Simulating Galaxy Formation

Challenges for the CDM paradigm, the ‘too big to fail’ problem, Boylan-Kolchin et al. 2011



Indication of Warm Dark Matter?
(e.g. Anderhalden, GB et al. 2013)

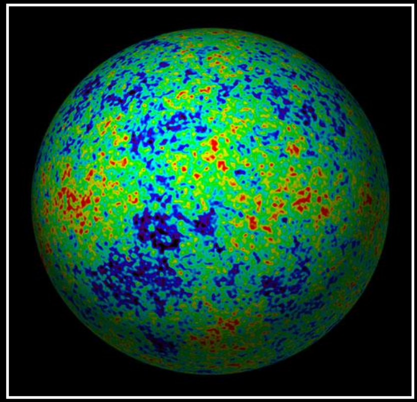


or perhaps baryons play a role? Or maybe the MW mass is smaller than commonly assumed?

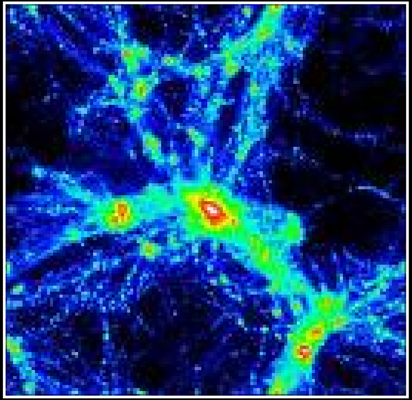
What do we know?

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

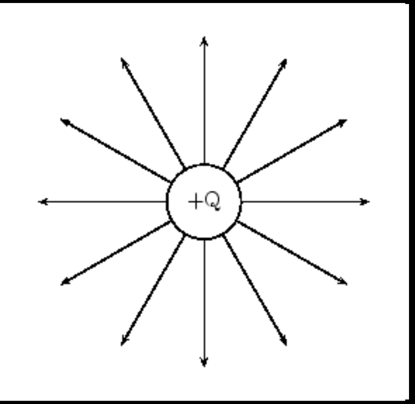
1) Ωh^2 OK?



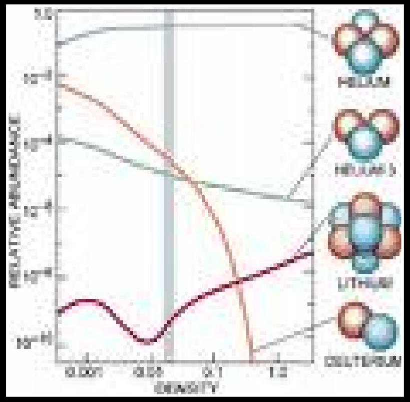
2) Is it cold?



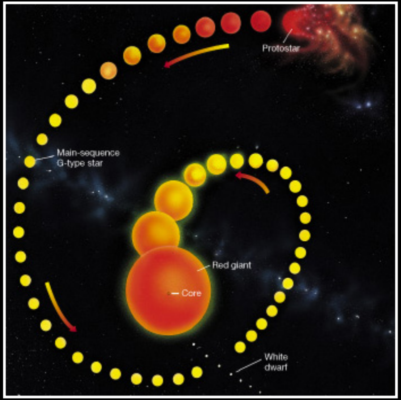
3) Is it neutral?



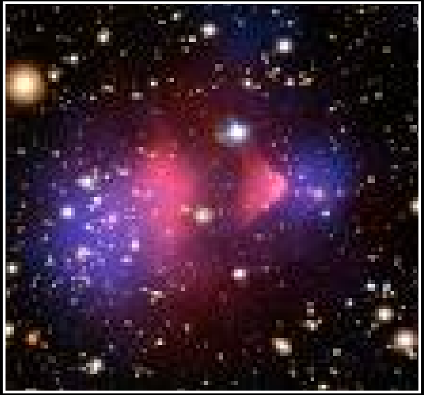
4) Is BBN ok?



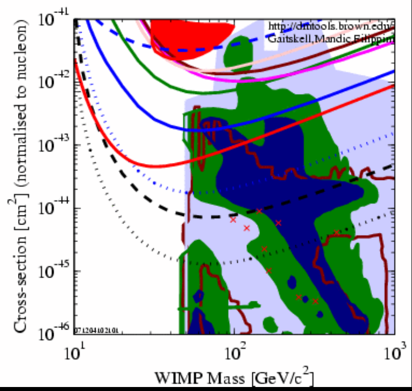
5) Stars OK?



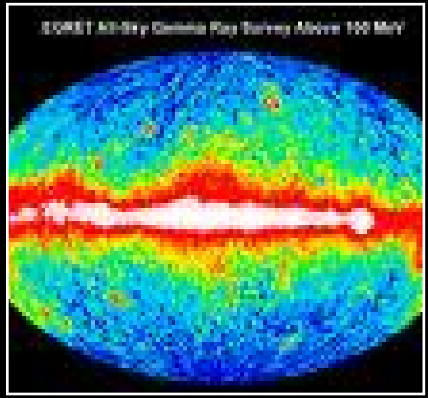
6) Collisionless?



7) Couplings OK?

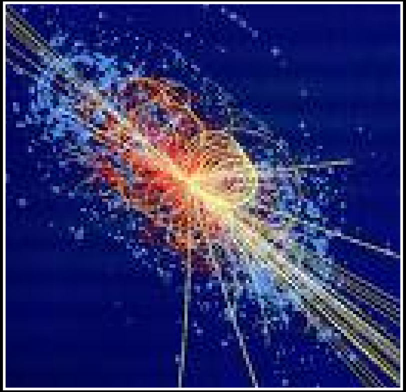


8) γ-rays OK?



9) Astro bounds?

10) Can probe it?



Taoso, GB & Masiero 2007

Dark Matter candidates

- Neutralino?

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

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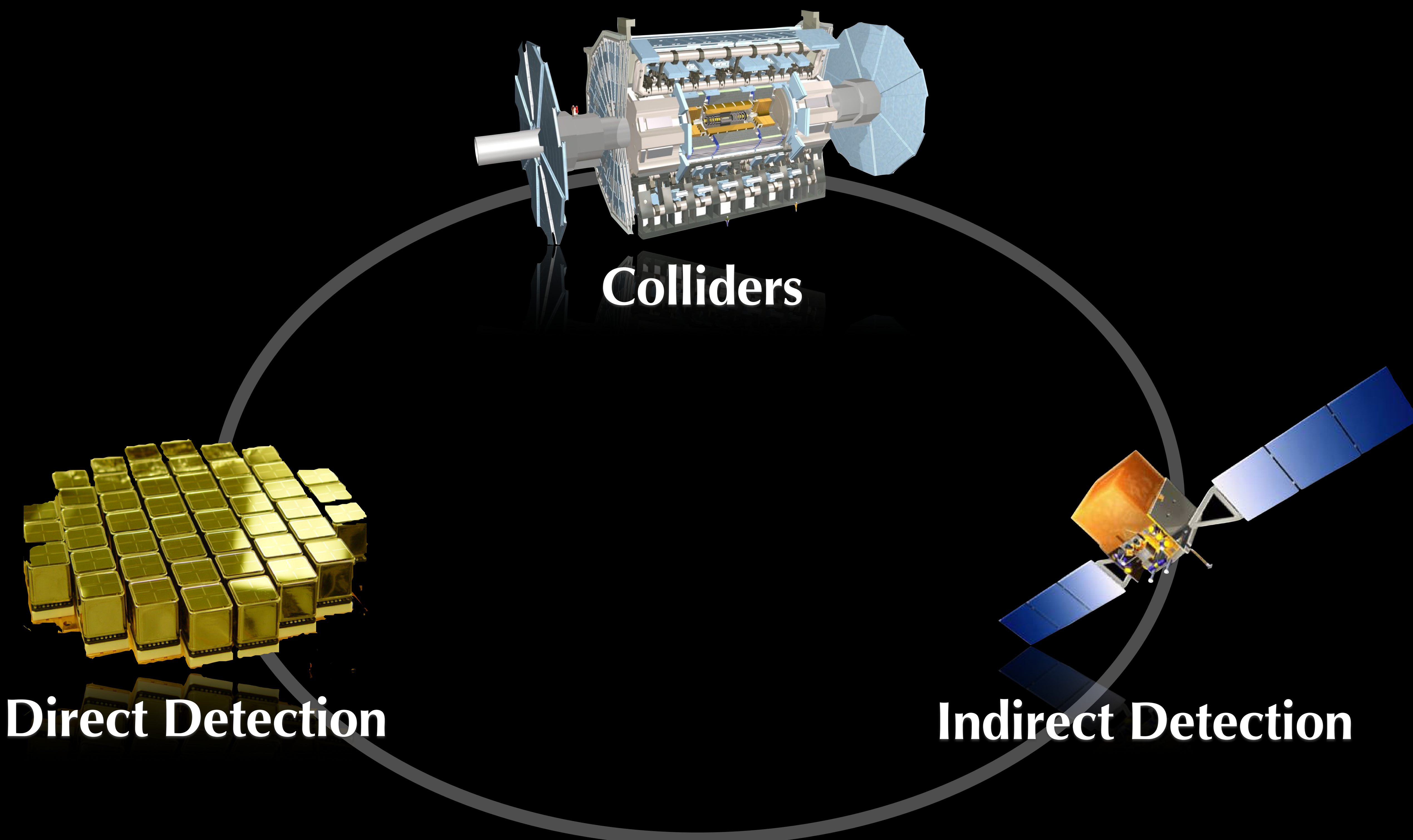
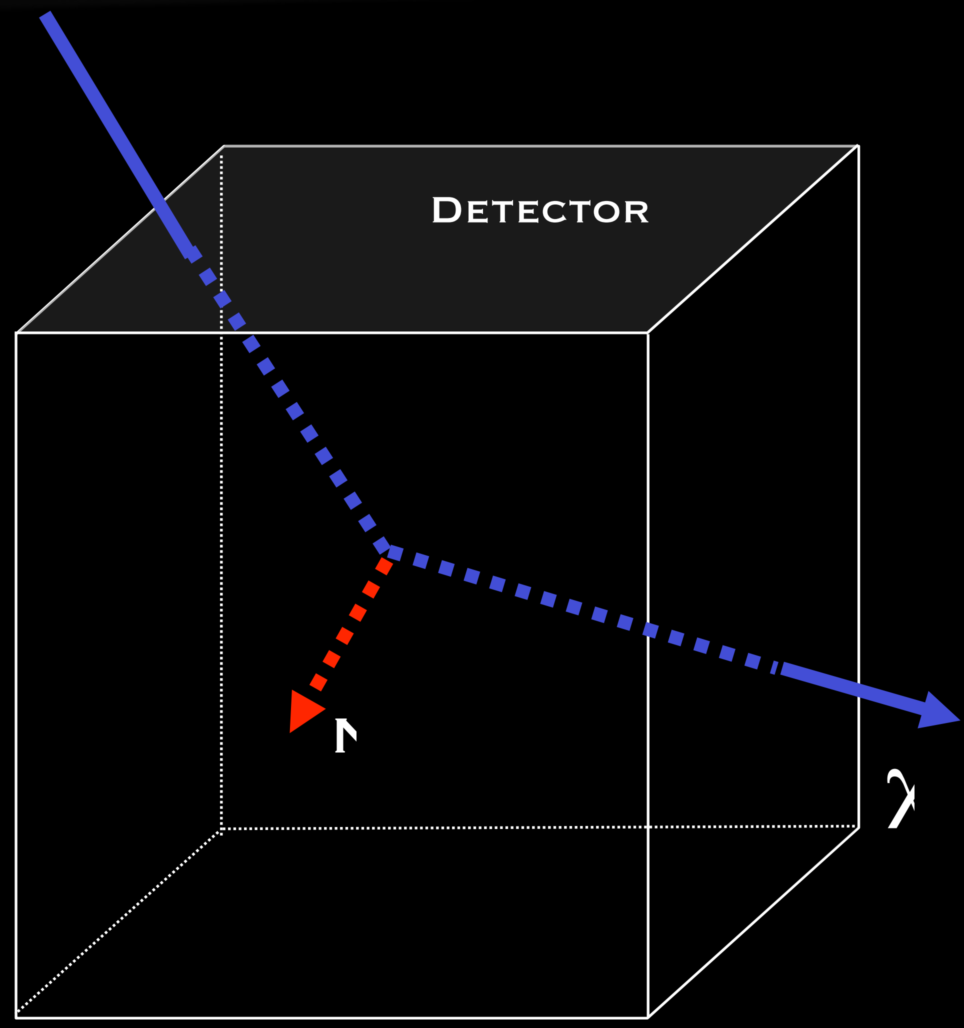
Dark Matter searches

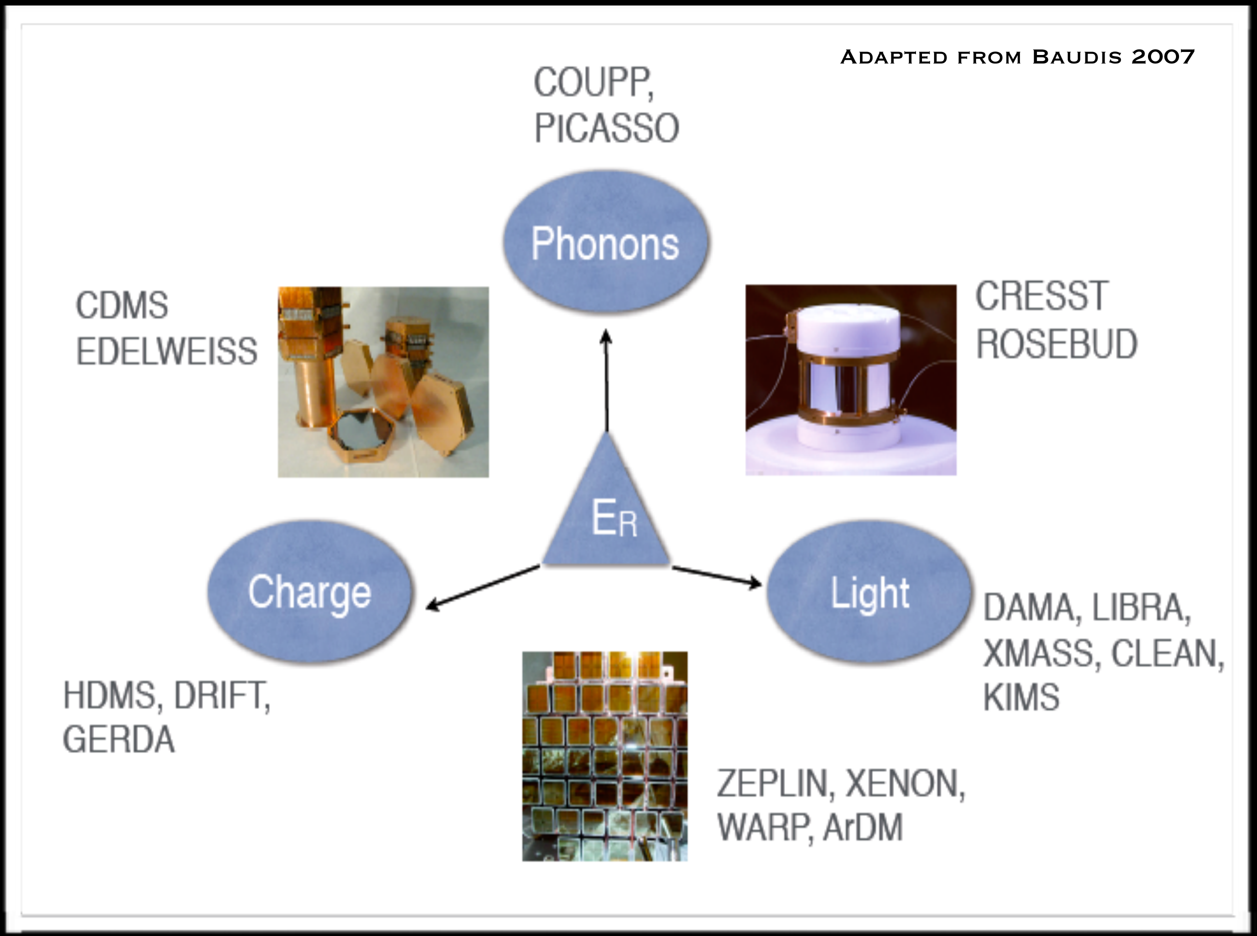


Simulating Galaxy Formation

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)

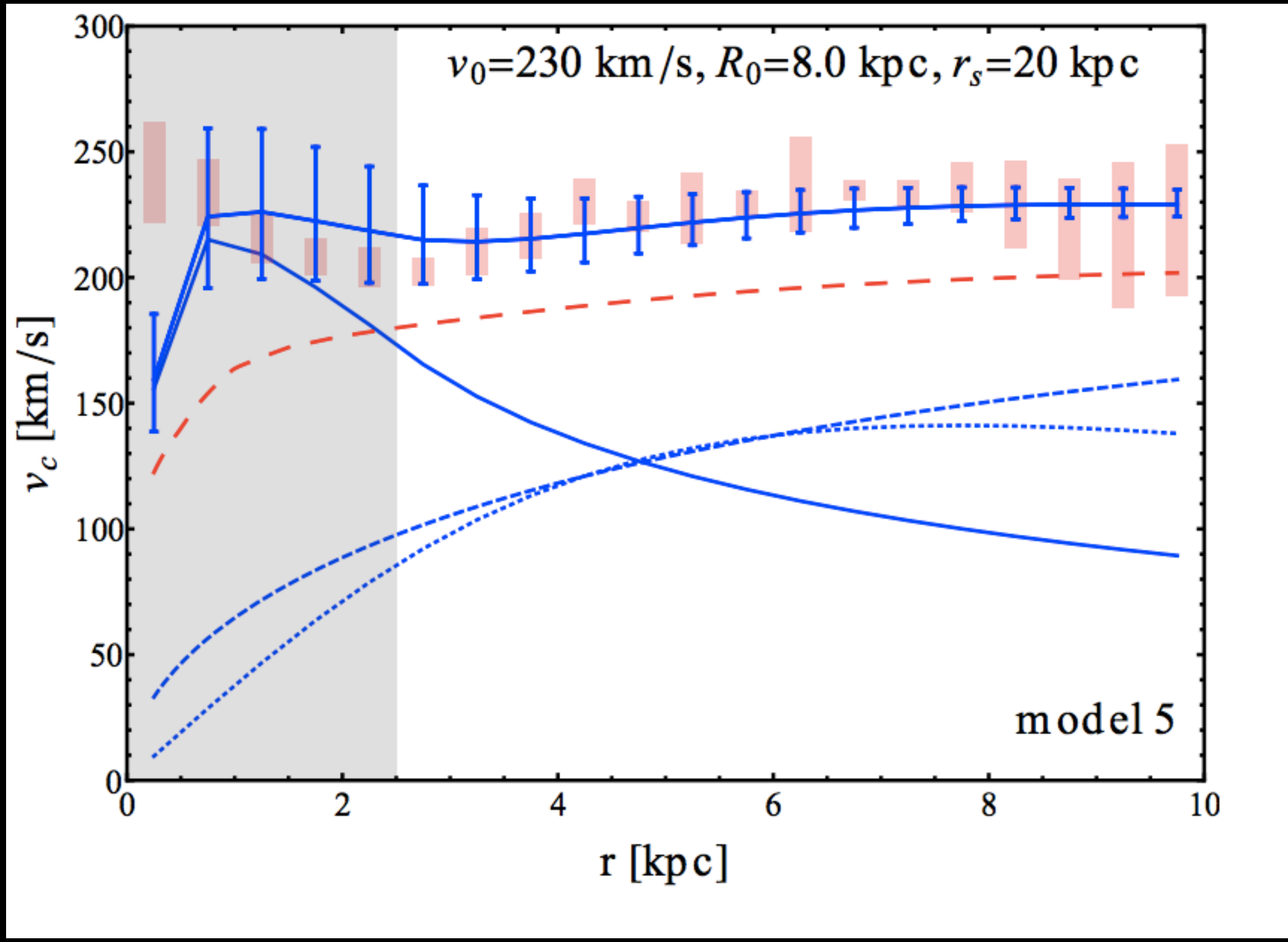
Direct Detection

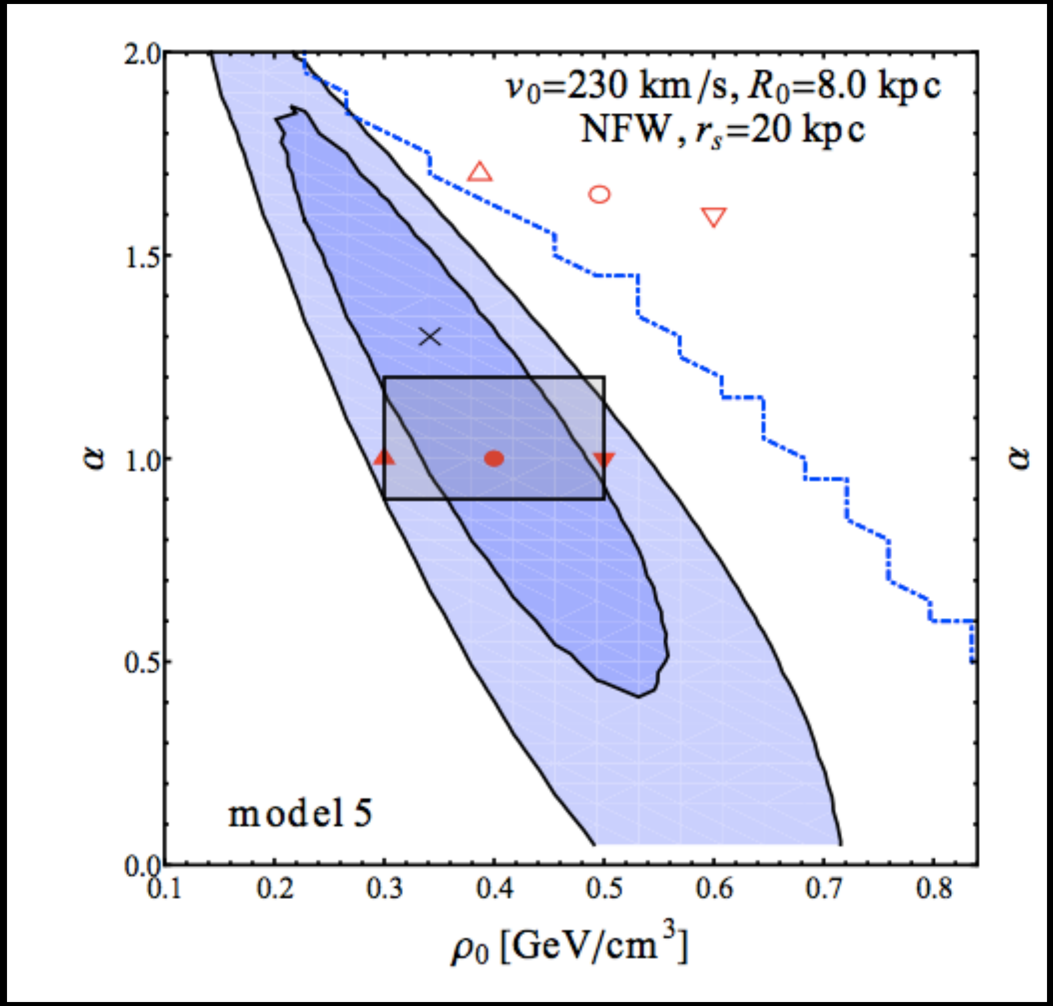
Differential Event Rate

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

Local Dark Matter density

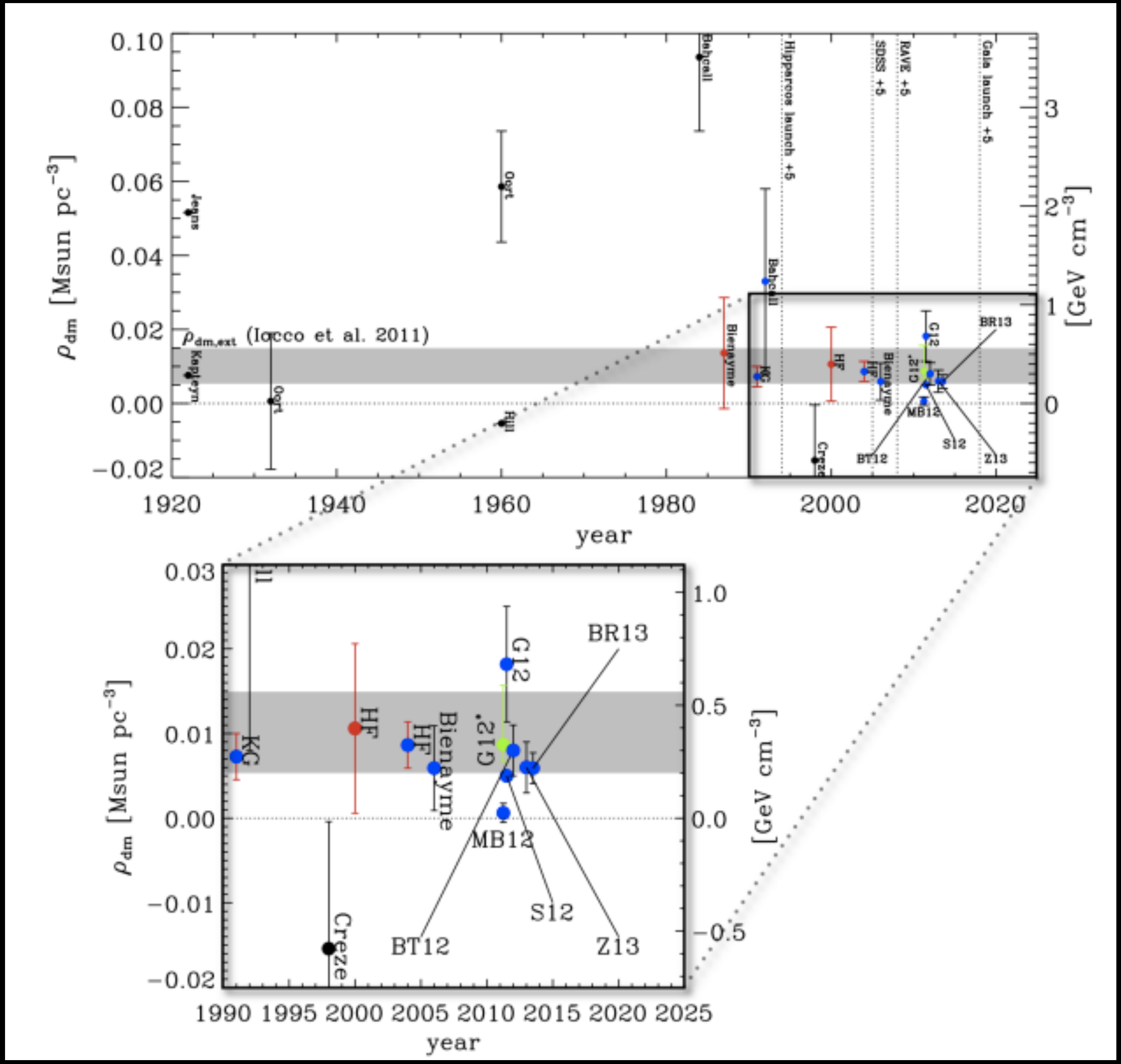
Microlensing and dynamical observations of the Galaxy set interesting constraints on the Dark Matter local density and profile slope towards the galactic centre.





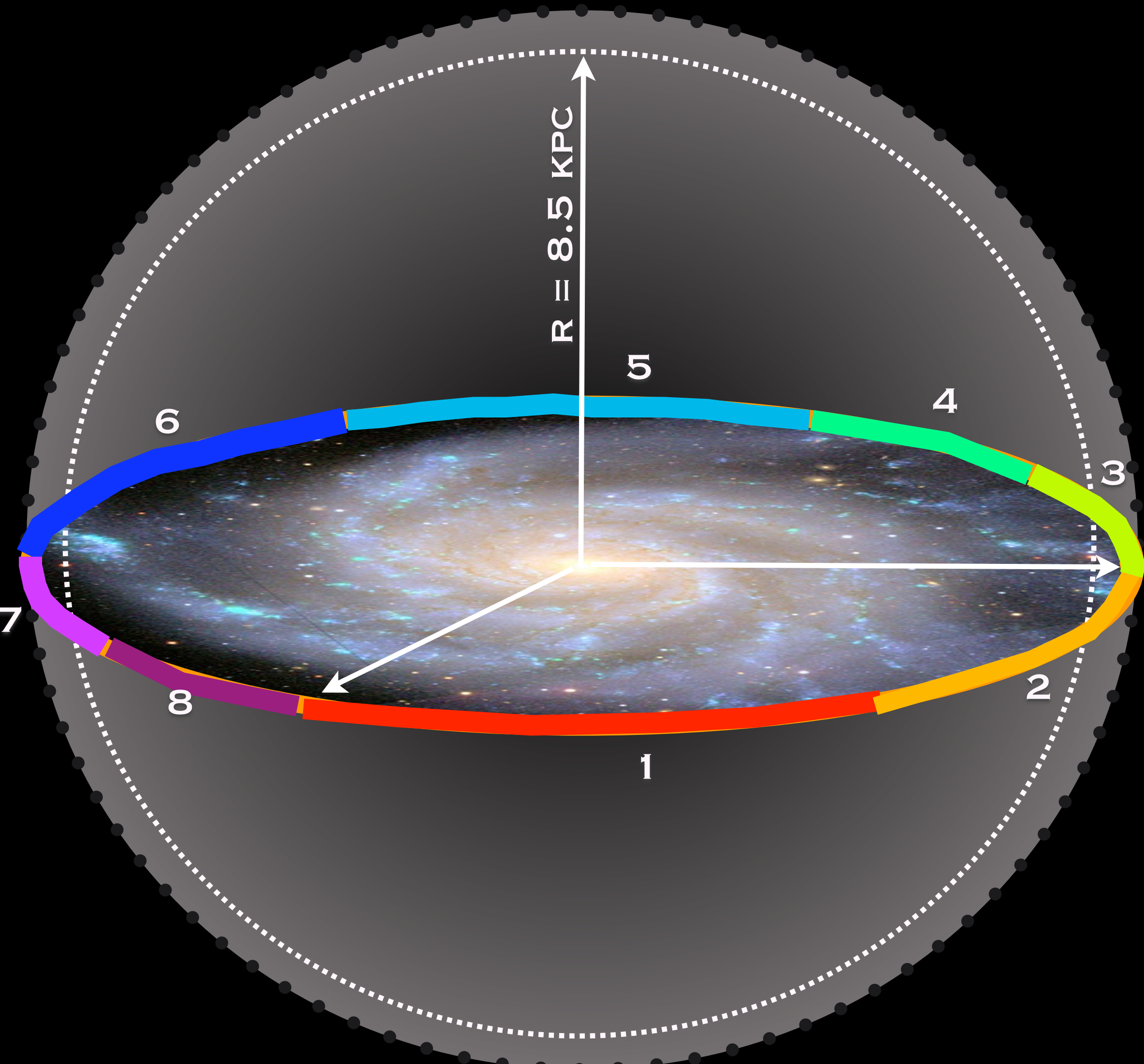
Iocco, Pato & GB 2011

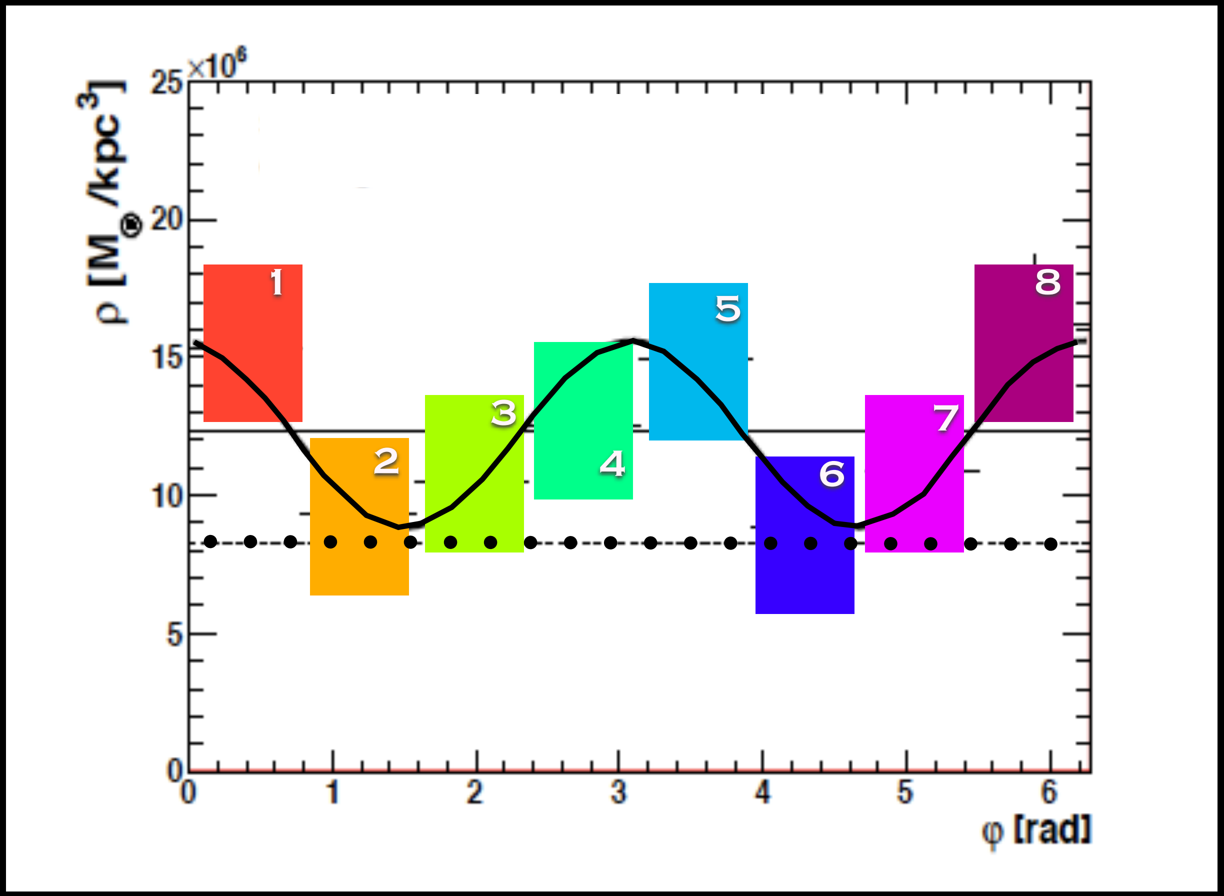
Local Dark Matter density



See excellent review by J. Read, arXiv:1404.1938

Example of Systematic error: Effect of Halo triaxiality



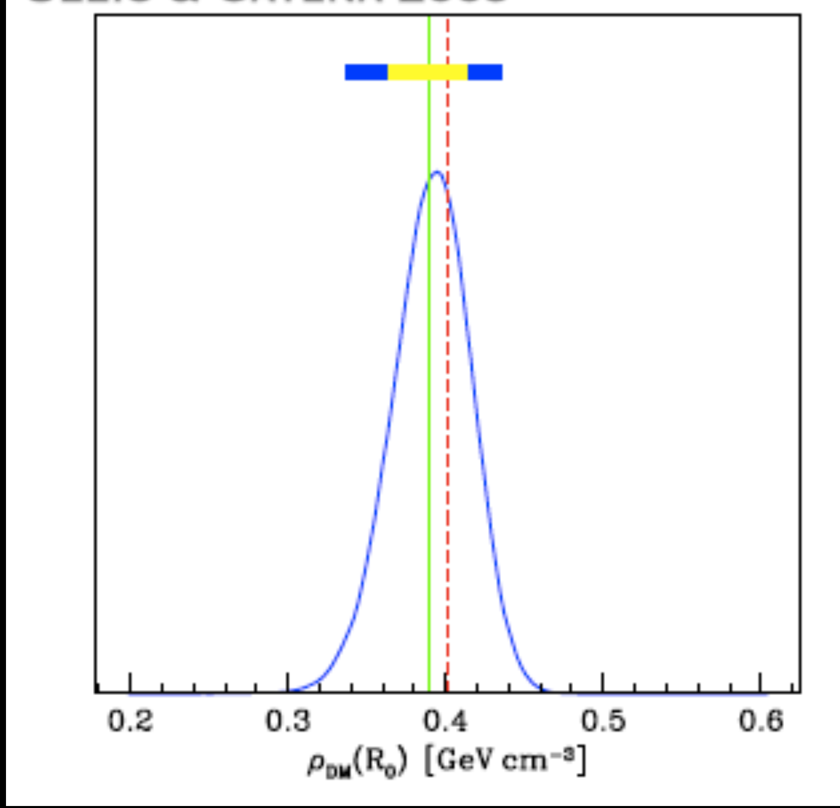


Pato, Agertz, GB, Moore, Teyssier, Moore 2010

Direct Detection

Uncertainties on the Local Density

"Statistical"

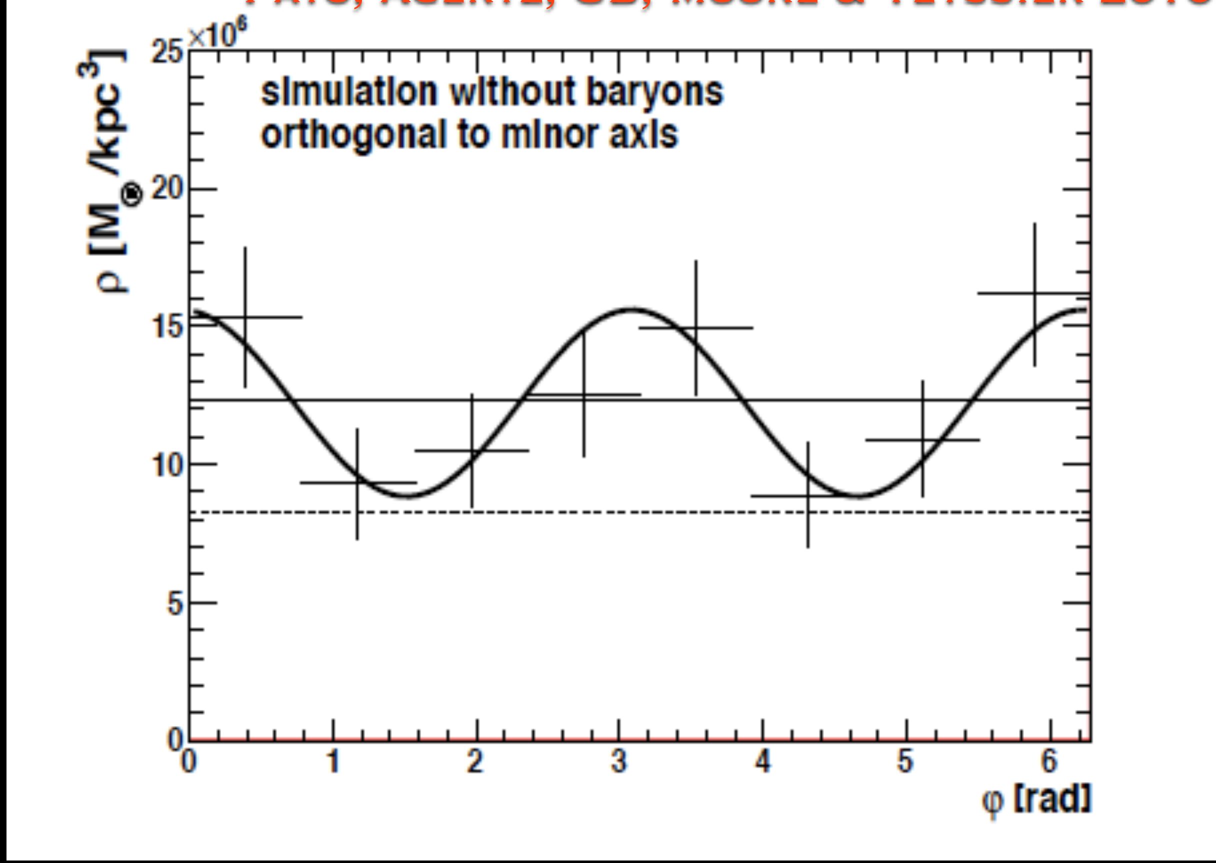


$$\rho_{DM}(R_0) = 0.389 \pm 0.025\,\mathrm{GeV\ cm^{-3}}$$

From dynamical Observables (see also Strigari & Trotta 2009)

+

"Systematic"



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

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

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

Velocity distribution

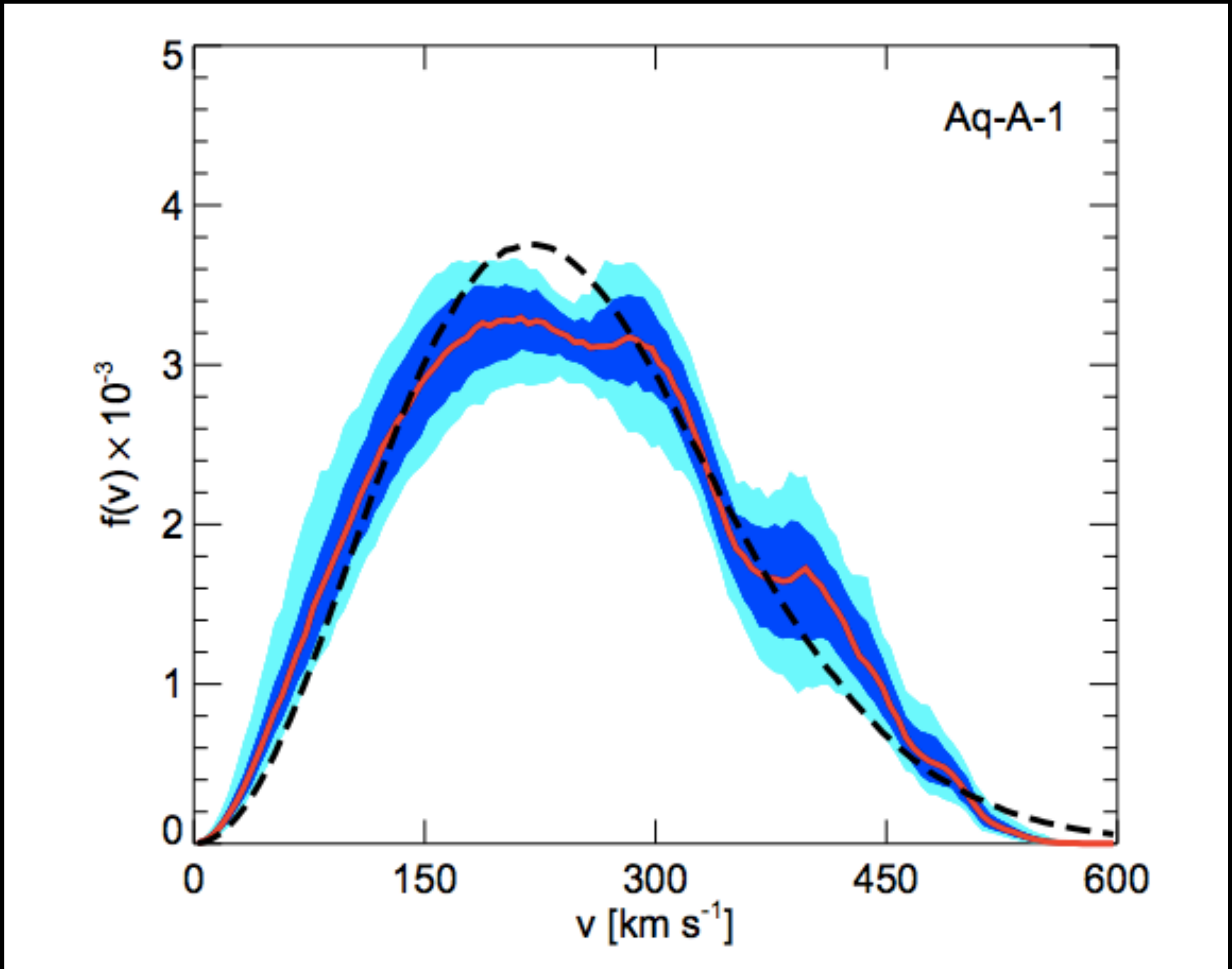
The standard halo model, conventionally used in calculations of exclusion limits and signals, has an isotropic, Gaussian velocity distribution (often referred to as Maxwellian)

$$f(\mathbf{v}) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{|\mathbf{v}|^2}{2\sigma^2}\right)$$

The speed dispersion is related to the local circular speed by σ =sqrt(3/2) v_c and $v_c = (220 \pm 20)$ km s^{-1} so that $\sigma \approx 270$ km s−1. This velocity distribution corresponds to an isotropic singular isothermal sphere with density profile $\rho(r) \propto r^{-2}$.

Velocity distribution

Numerical simulations show that this is probably a good approximation, at least at first order (need refined analysis/simulations to do precision physics, should a signal be observed)



Vogelsberger et al. http://arxiv.org/abs/arXiv:0812.0362