The Evidence for Dark Matter

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Preliminaries

- rcrocker@fastmail.fm
- please email me!
- DM = dark matter
- I work on the Galactic Centre, perhaps the best place in the sky to look for *indirect signatures* of dark matter

Useful References and Resources

- Roos 2012, *Astrophysical and cosmological probes of dark matter,* arXiv:1208.3662v3
- Garrett and Duda 2011, *Dark Matter: A Primer*
- Weiner: *What We Know and Don't Know about Dark Matter* (YouTube)
- Gary Bernstein: *The evidence for Dark Matter* (YouTube)
- Wikipedia: 'Dark Matter', etc

Overview

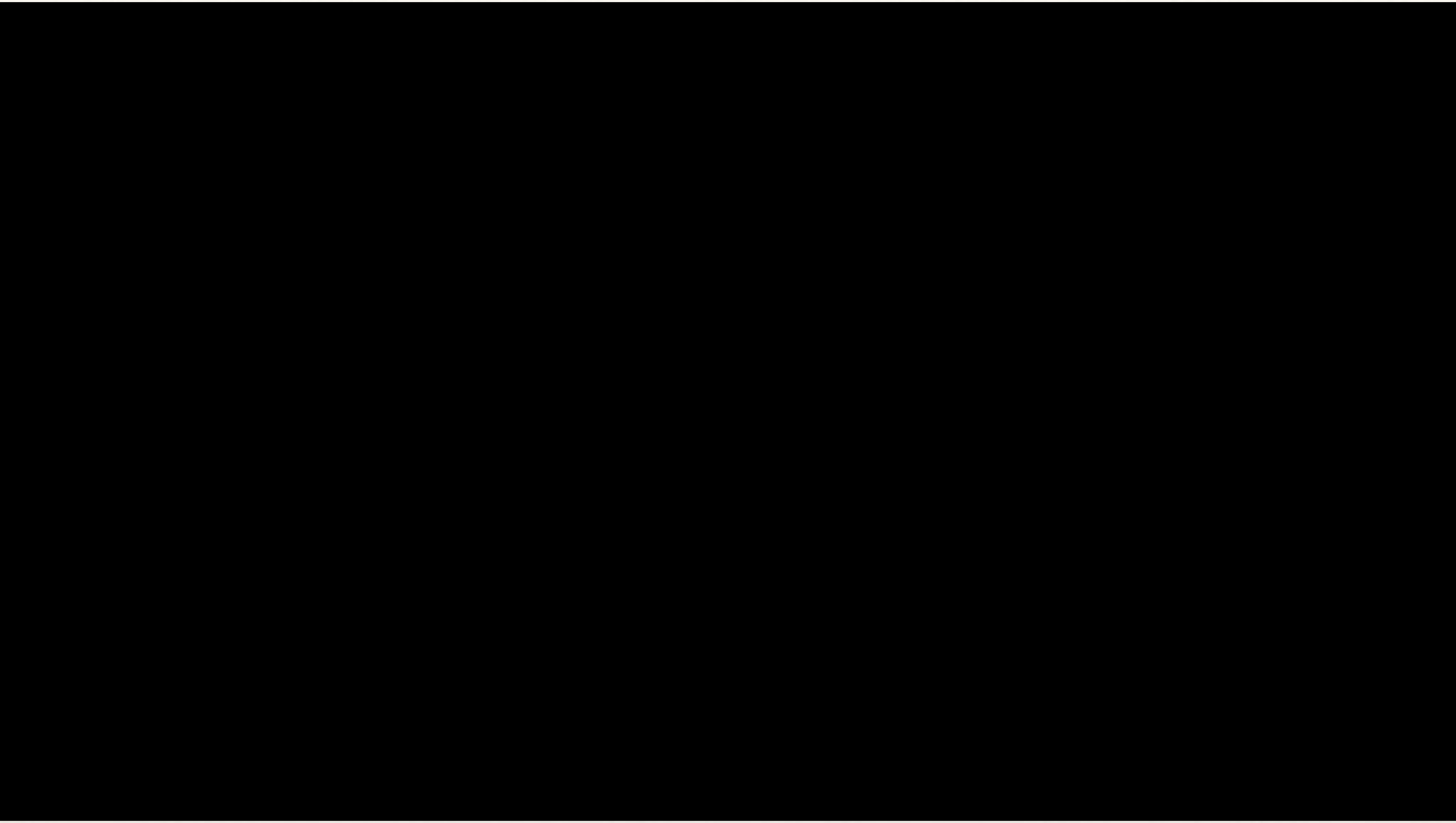
- "Dark matter" unfortunate terminology; neither "dark" (because does not absorb EM radiation at any wavelength) nor "matter" in the sense that we tend to use it

- "Invisible stuff" or "invisible substance" would be better;

- DM is the scaffolding of the Universe; it "explains" how structure formed and how quickly it formed; it dominates the matter content of the Universe

Overview of Current Understanding of DM

- We are immersed in DM which is blowing at/through us right now at ~220 +/- 30 km/s from direction of constellation Cygnus
- DM is INERT, STABLE & SLOW (note the SM neutrino has properties 1 & 2 but not 3 — so it's not the DM)
- This makes it sound like it would result in very boring phenomenology — but that's not true: purely gravitational interactions lead to very rich phenomenology



Time evolution of a 10 Mpc (comoving) region within **Illustris** from the start of the simulation to z=0. The movie transitions between the dark matter density field, gas temperature (blue: cold, green: warm: white: hot), and gas metallicity (purple).

Note the filaments of DM with quasi-spherical, gravitationally-bound halos of DM at their intersections — dark matter forms the scaffolding for the visible universe

Overview

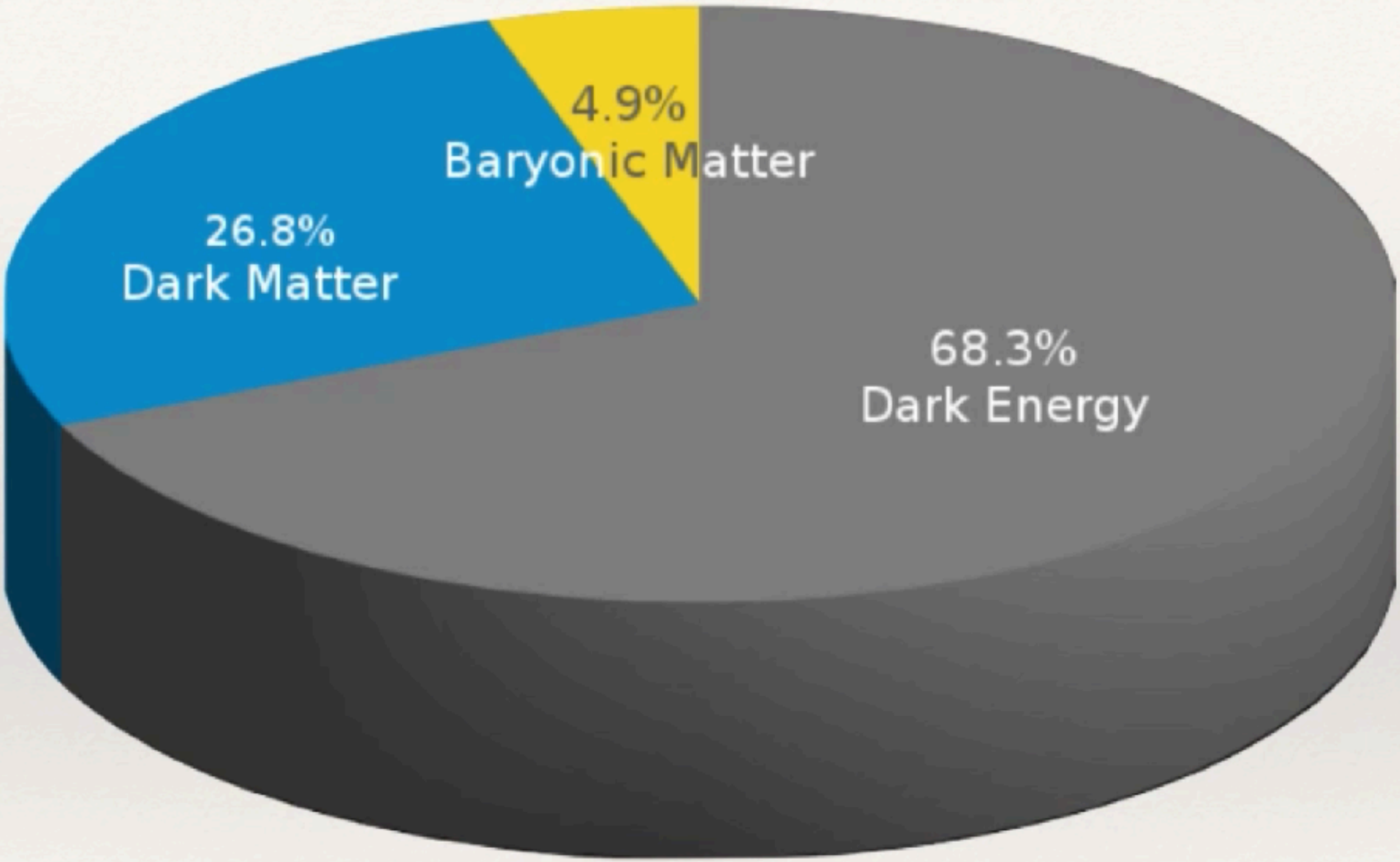
- The primary evidence for dark matter is that
  - calculations show that many galaxies would fly ap… would not have formed or move as they do, if they … ount of unseen matter.[2]

Other lines of evidence include

- observations in gra…
- from the … ound,
- … ations of the observable universe's current structure,
- … ion and evidence of galaxies,
- … ass location during galactic collisions
- from the motion of galaxies within galaxy clusters.

⇒ there is FIVE TIMES as much DM in the Universe as "ordinary matter"

[Wikipedia]



https://inspirehep.net/record/1261376/plots

Overview

- *But wait!* On the other hand…
    - Nobody has ever ‘directly’ detected or produced dark matter
    - We really only know what it apparently is *not* rather than what it is
    - It can apparently pass through the Earth without hindrance
- *Begs the question*: is DM just the current-day Luminiferous Aether? A theoretician’s *kludge*?

Some thoughts

‘Dark Matter’ in the Solar System

Dim matter

1781: Sir Herschel discovers Uranus

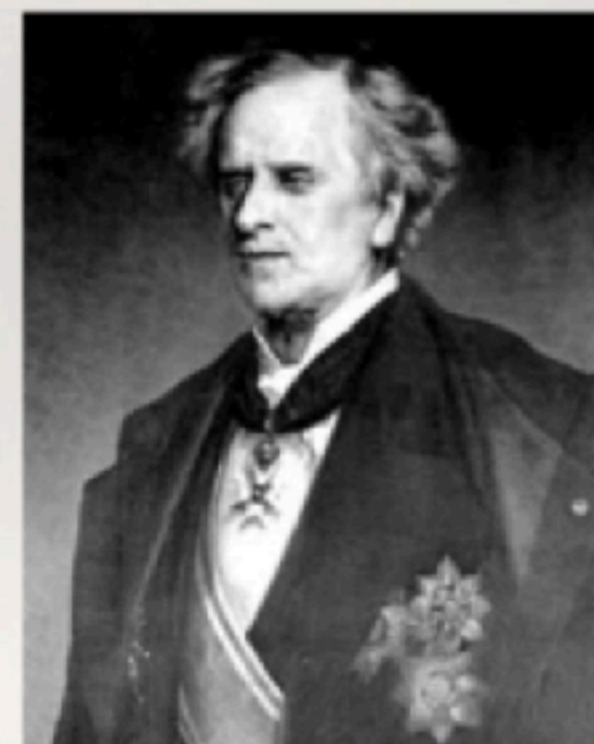
1830: Uranus is 0.004° away from elliptical path. It gets worse by 1840's.

Sep 1845: Charles Couch Adams predicts position of a new planet to explain deviation of Uranus. Local astronom little.

June 1846: Urbai ndependently predicts a new position.

Neptune = the first dark matter

Charles Couch Adams

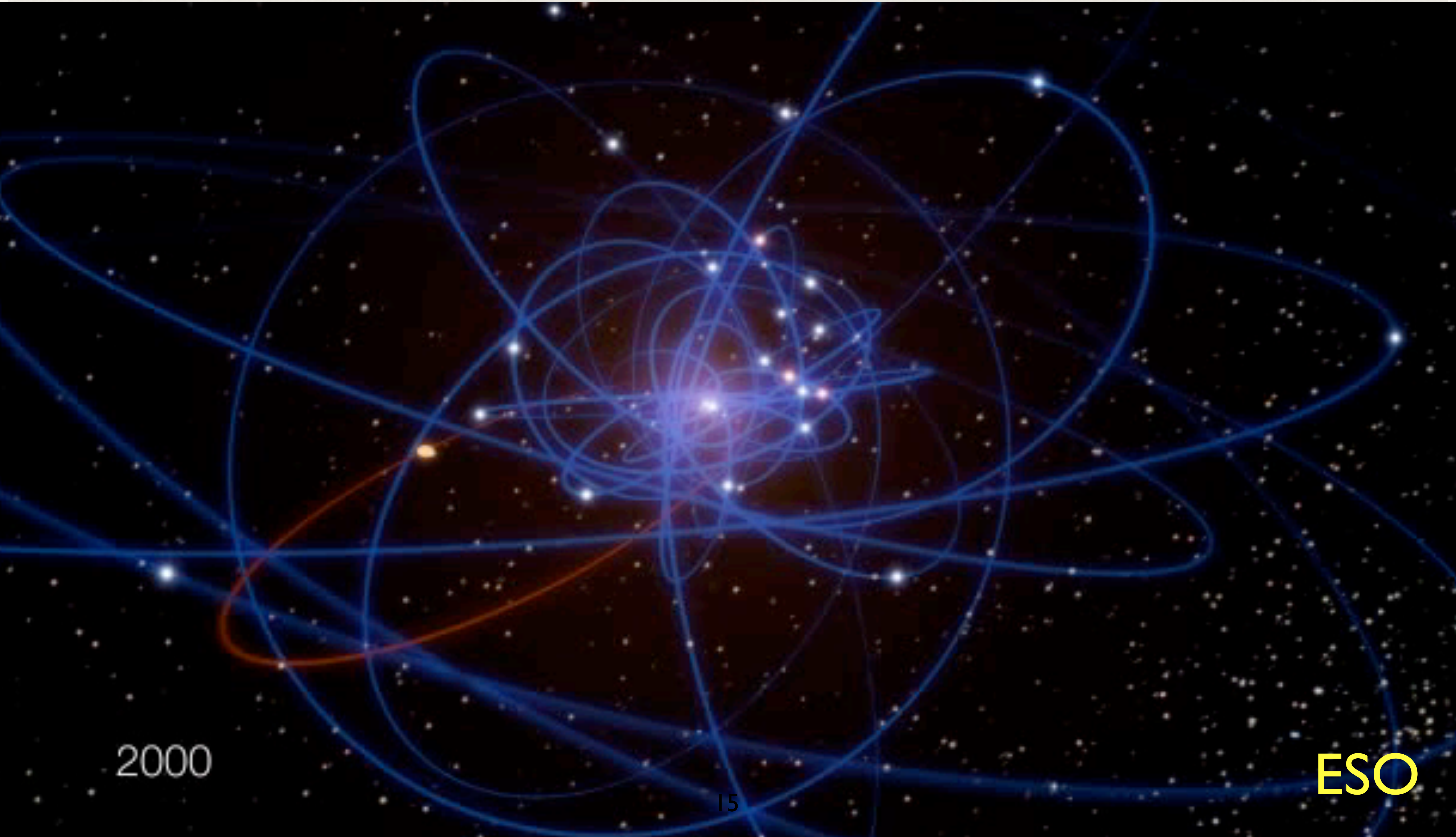


Urbain Le Verrier

Gary Berstein

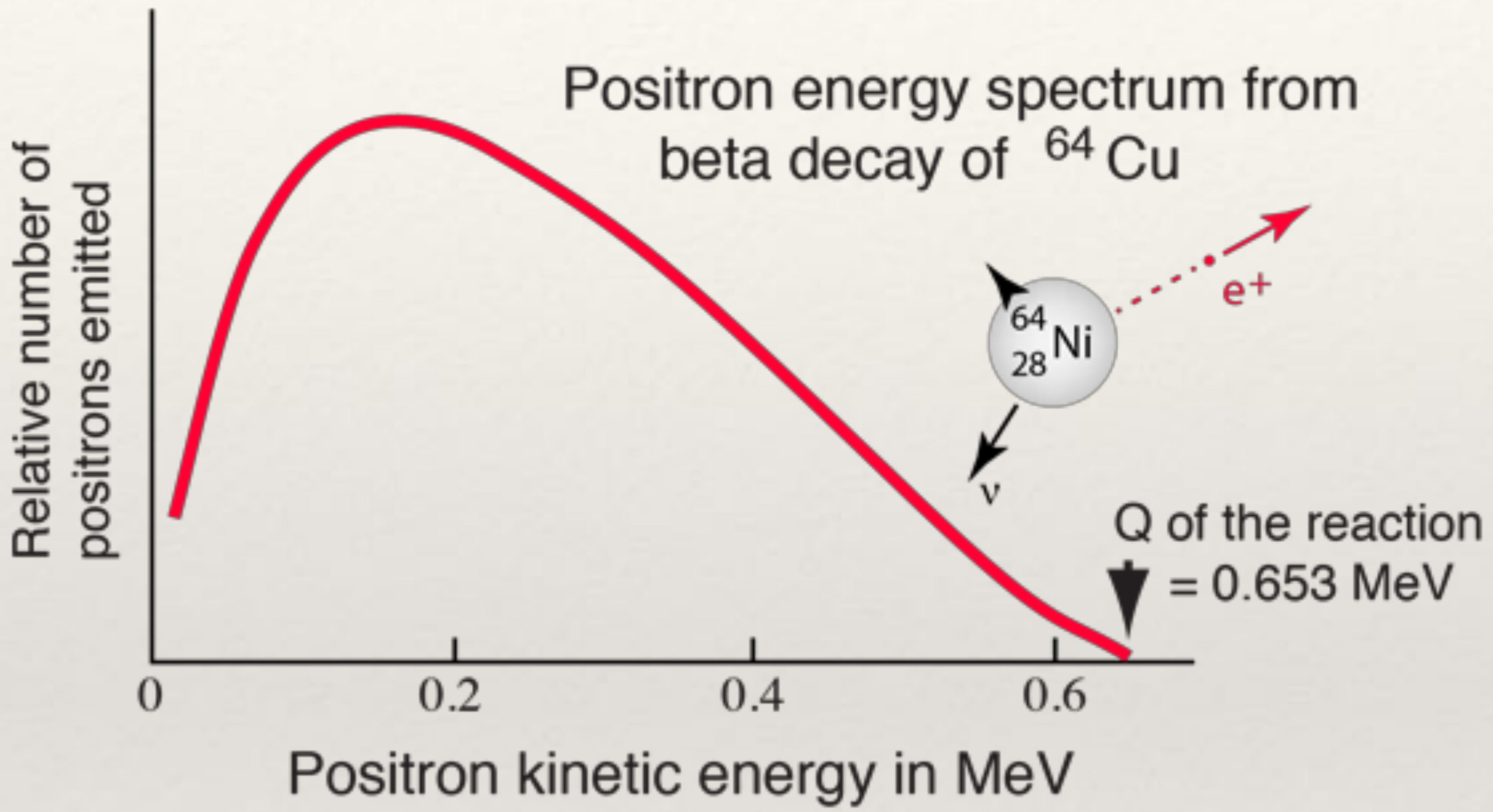
‘Dark Matter’ in the Galaxy

There is no doubt the Galaxy contains dark matter: there is a 4 Million Solar Mass chunk at its dynamical centre



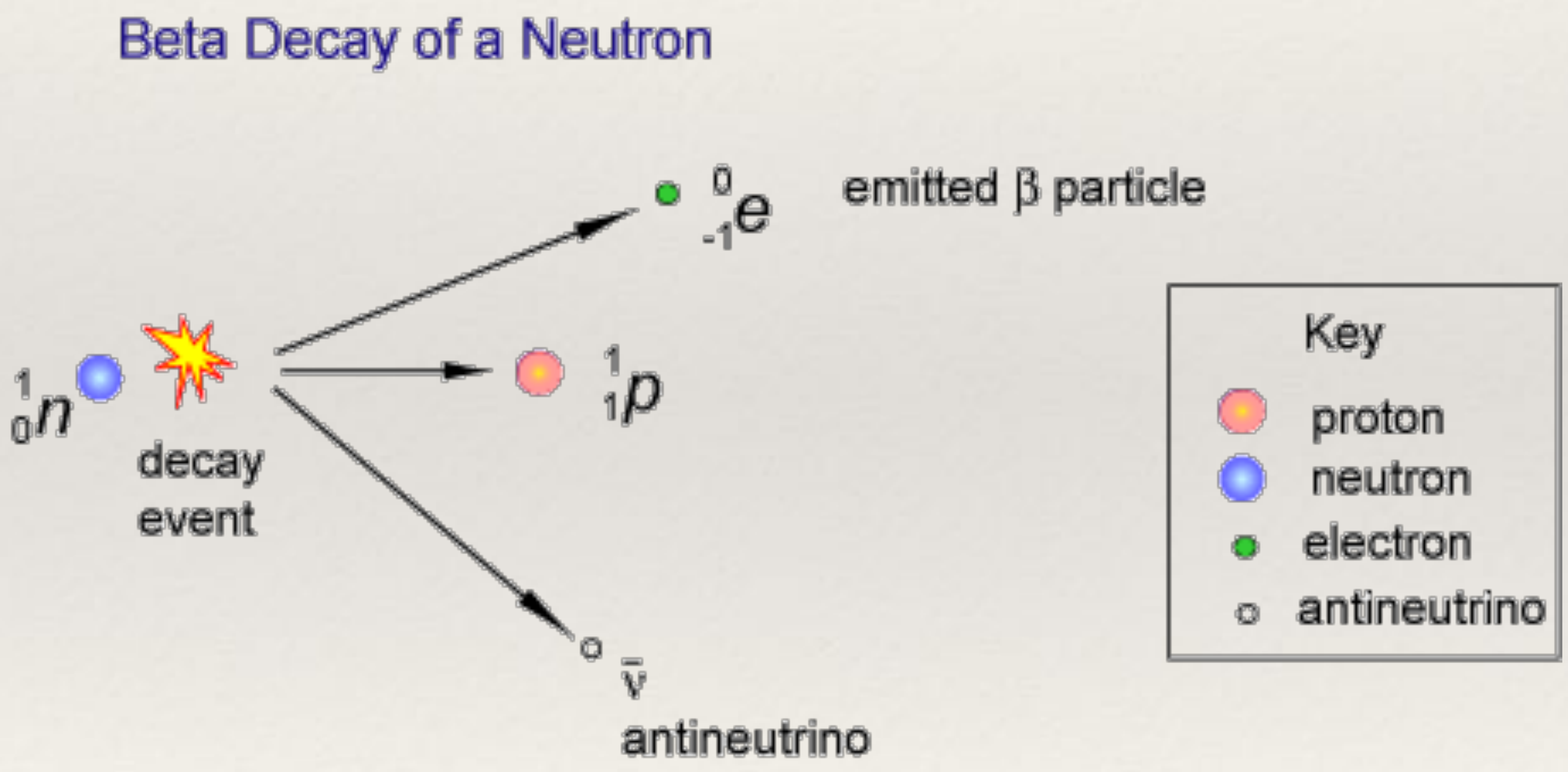
Nuclear ‘Dark Matter’

Beta decay



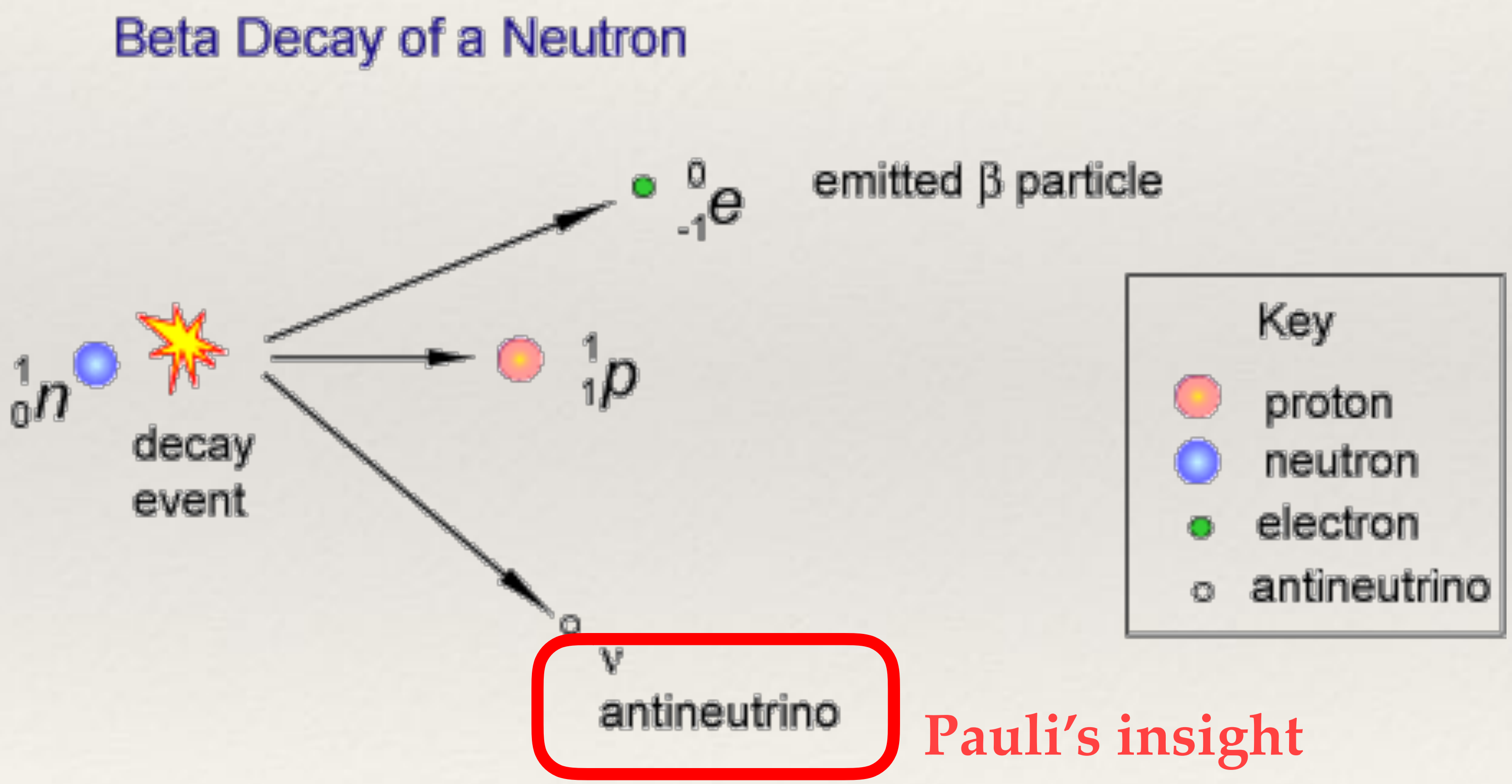
http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/beta.html

Beta decay



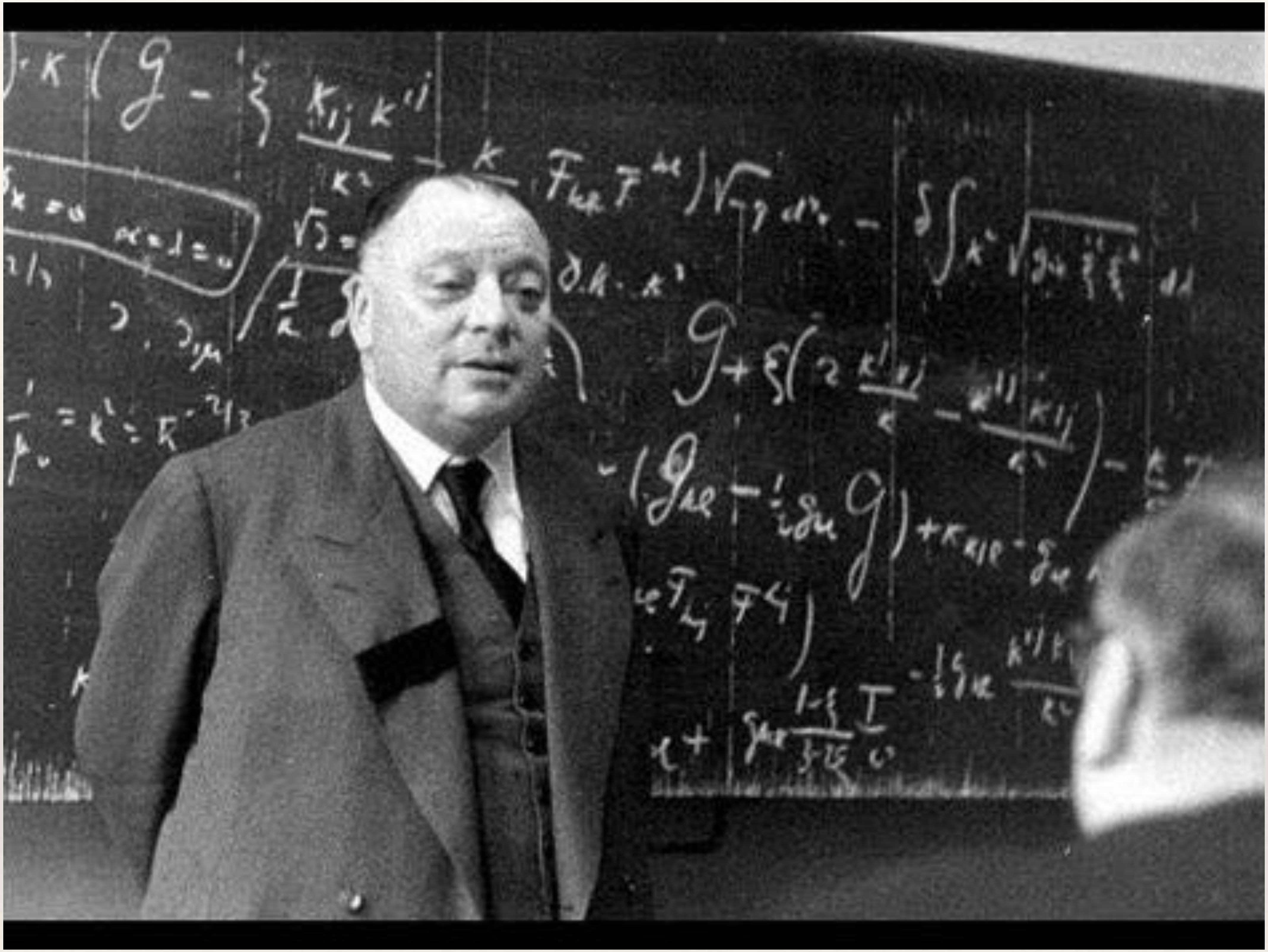
http://www.atnf.csiro.au/outreach/education/senior/cosmicengine/sun_nuclear.html

Beta decay

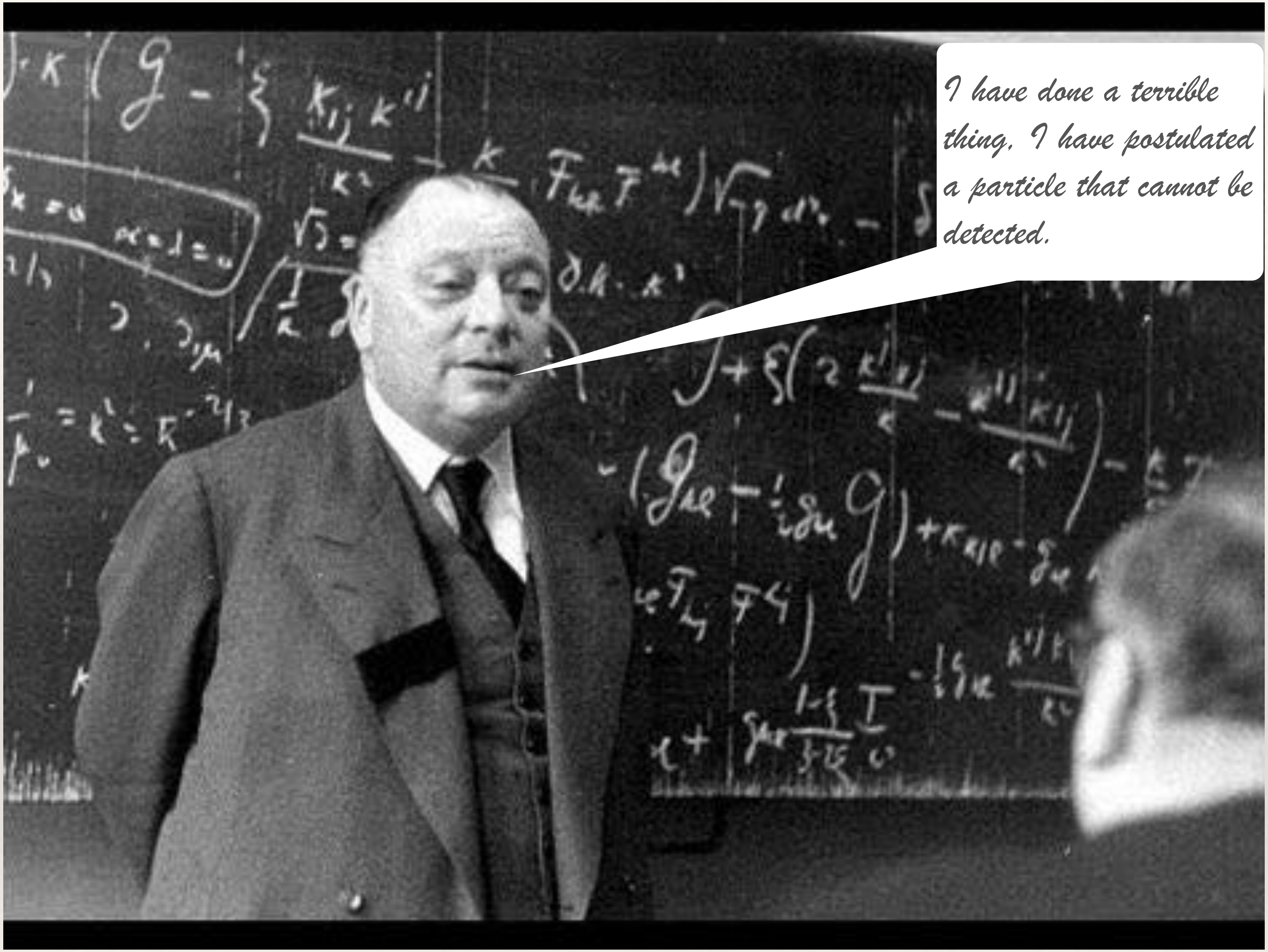


Pauli's insight

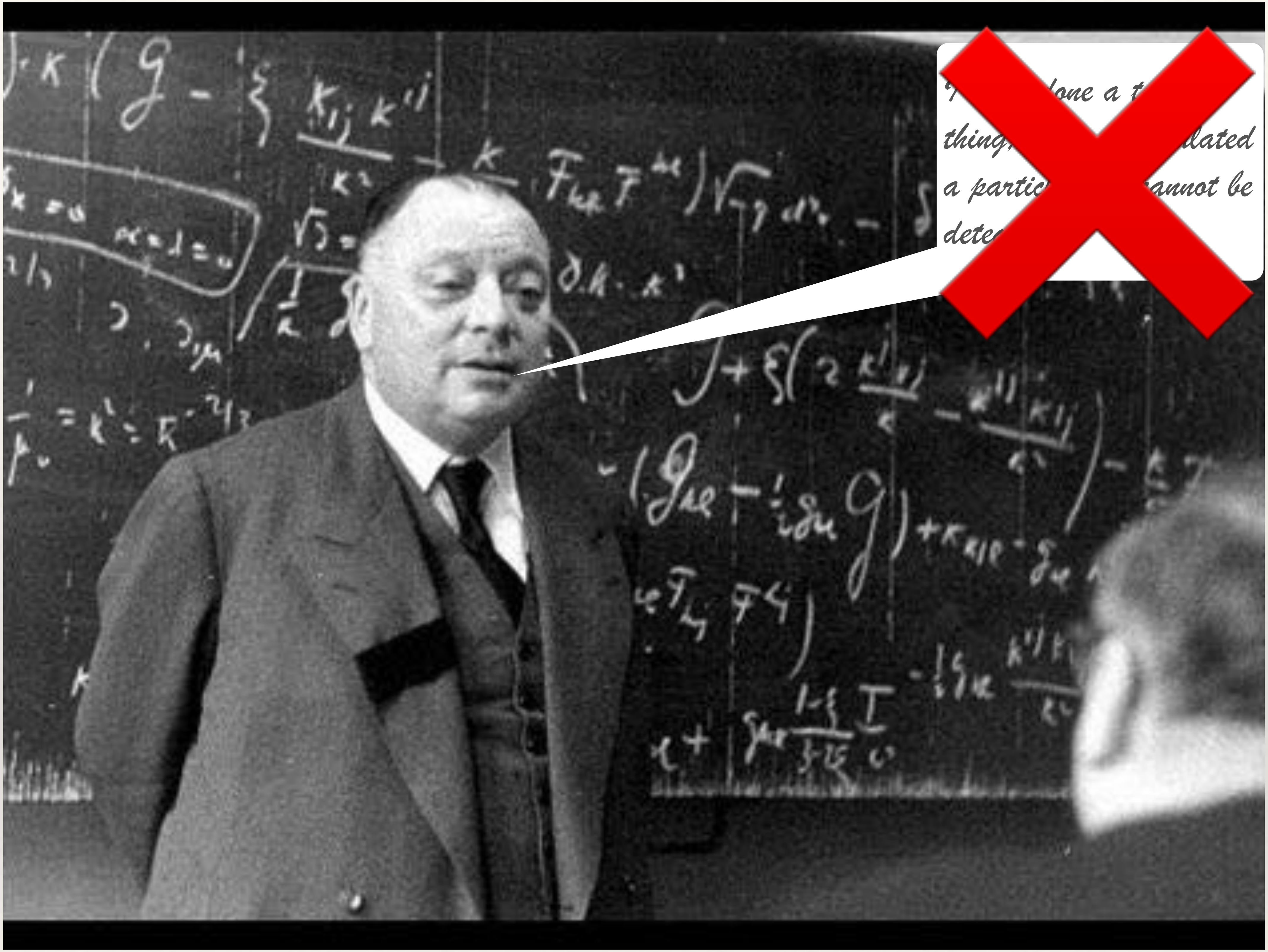
http://www.atnf.csiro.au/outreach/education/senior/cosmicengine/sun_nuclear.html



Wolfgang Pauli (1900-1958)


I have done a terrible thing, I have postulated a particle that cannot be detected.

(c. 1930)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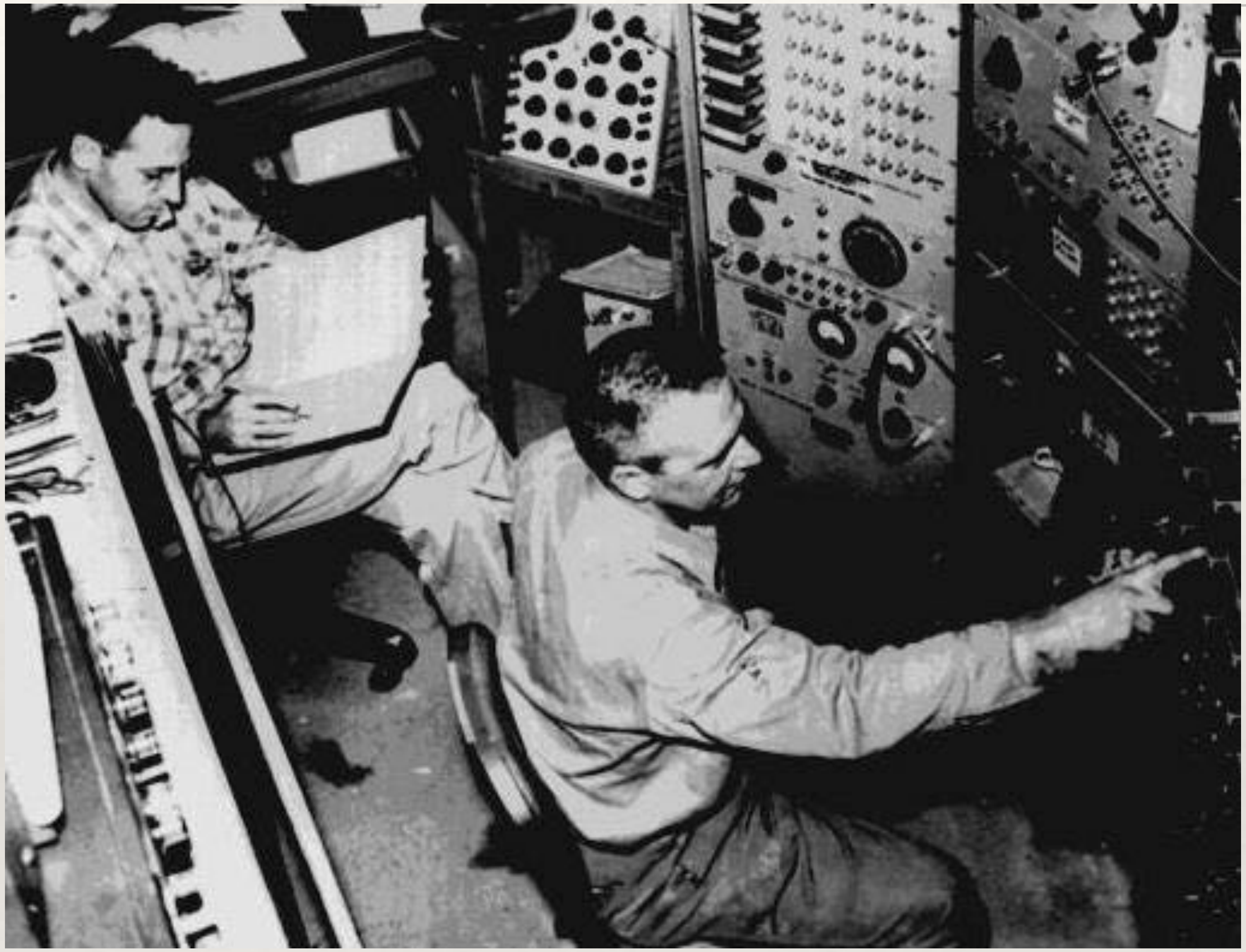
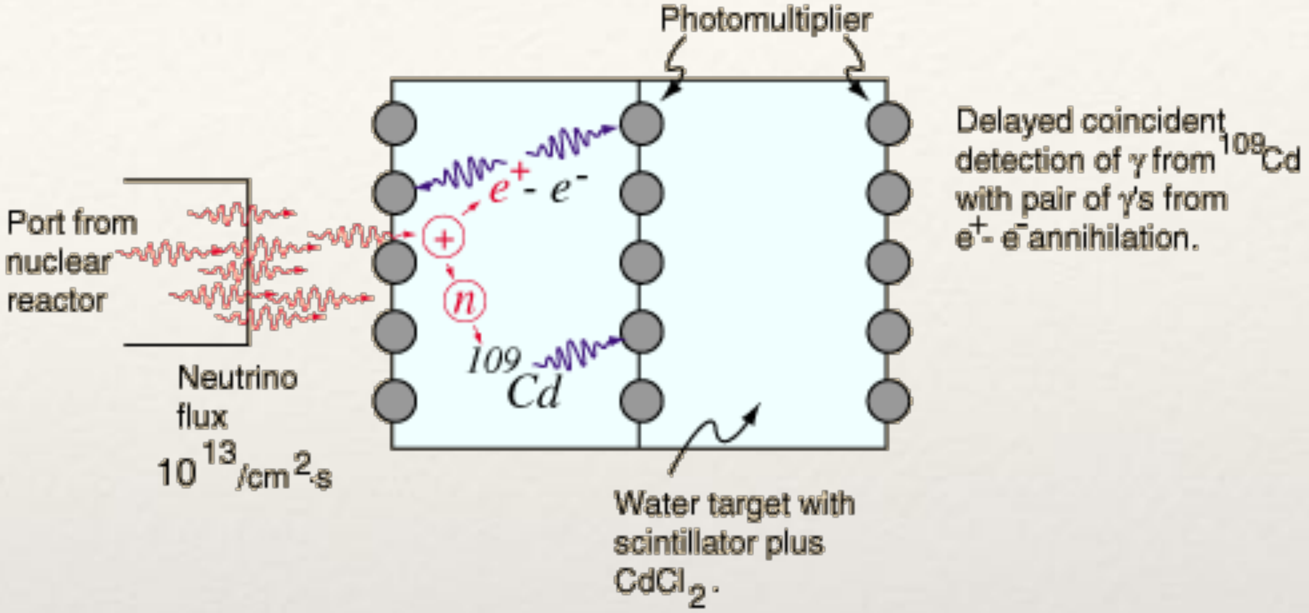
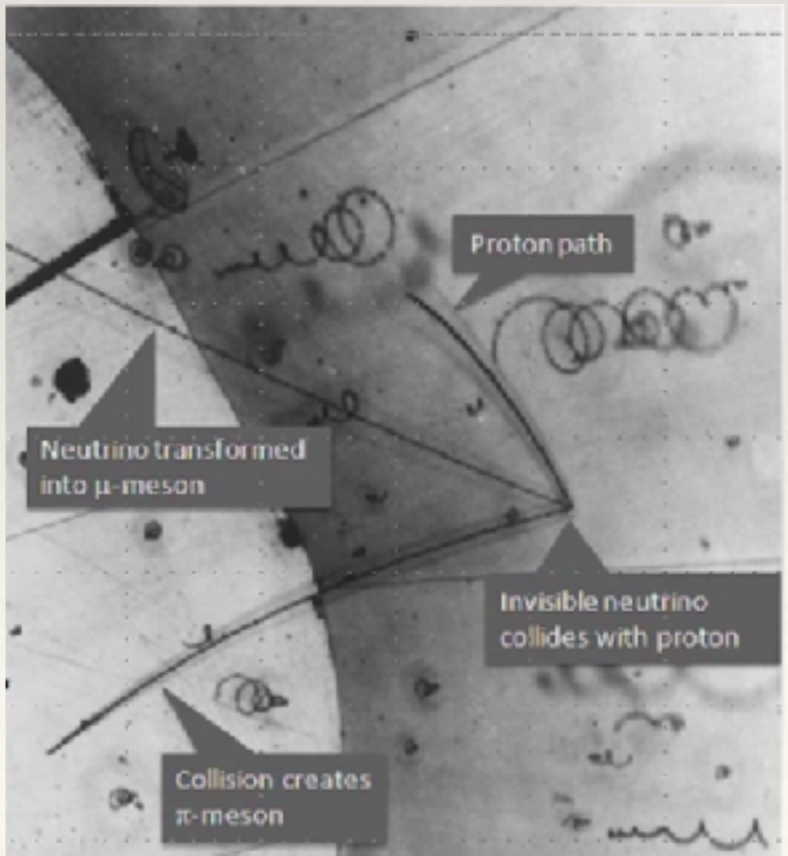
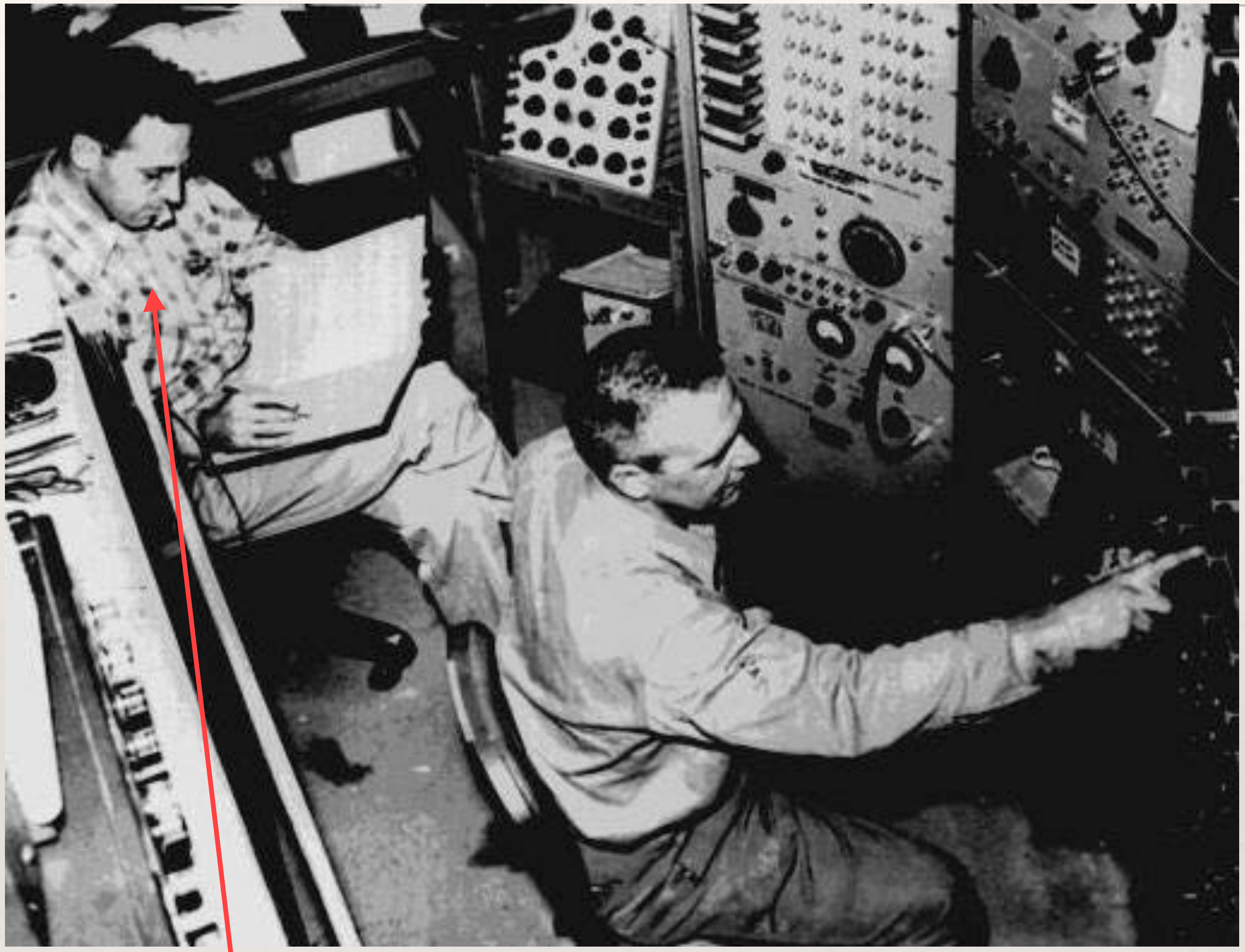
Reines & Cohen **1956**: experimental detection of the neutrino

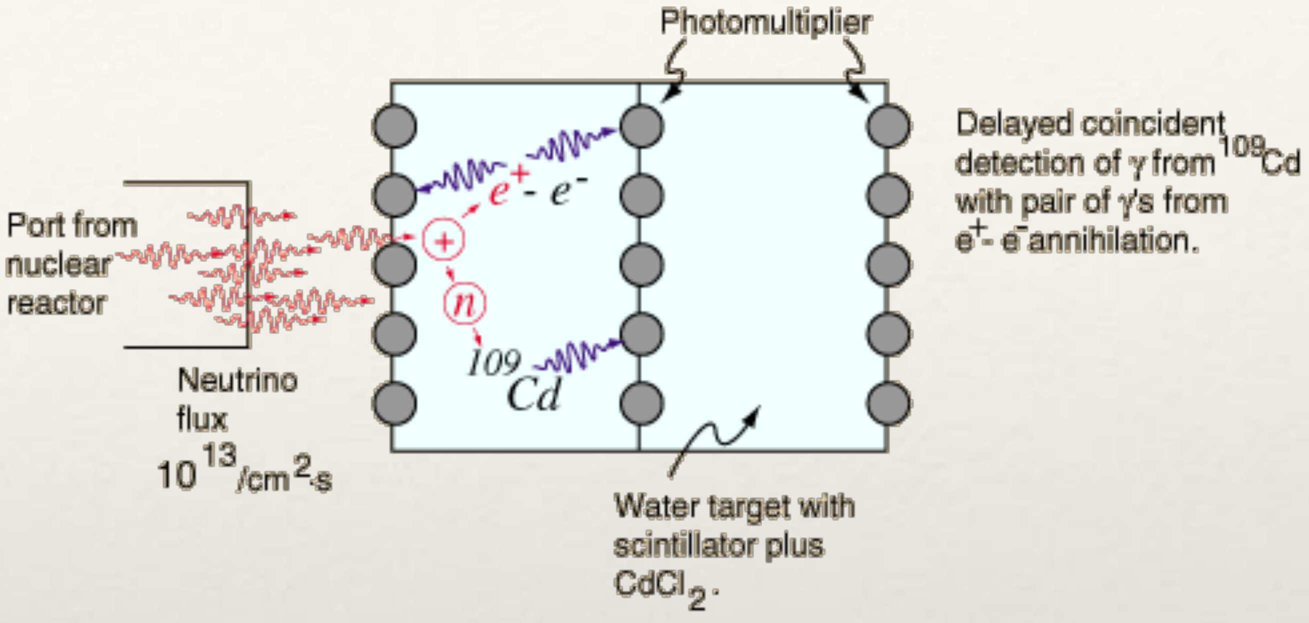


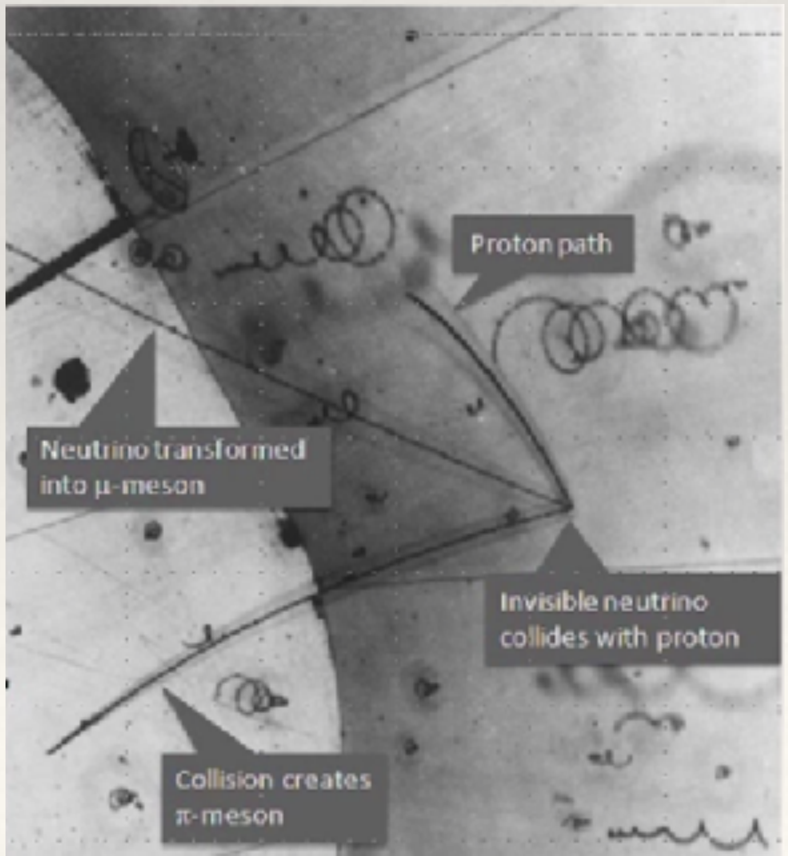




Reines & Cohen 1956: experimental detection of the neutrino







Reines: Nobel Prize 1995

Philosophy

- So neutrinos exist, and we could correctly infer their existence before they could be detected
- Another example: Higgs boson took ~50 years to detect after its theoretical prediction
- General lesson: there's no guarantee that all the important components of the Universe will be "easily" detectable to us

Cautionary Tail

Dim matter

1781: Sir Herschel discovers Uranus

1830: Uranus is 0.004° away from elliptical path. It gets worse by 1840's.

Sep 1845: Charles Couch Adams predicts position of a new planet to explain deviation of Uranus. Local astronomers do little.

June 1846: Urbain Le Verrier independently predicts a new planet's position.

Charles Couch Adams

Urbain Le Verrier

Gary Berstein

Even dimmer matter…

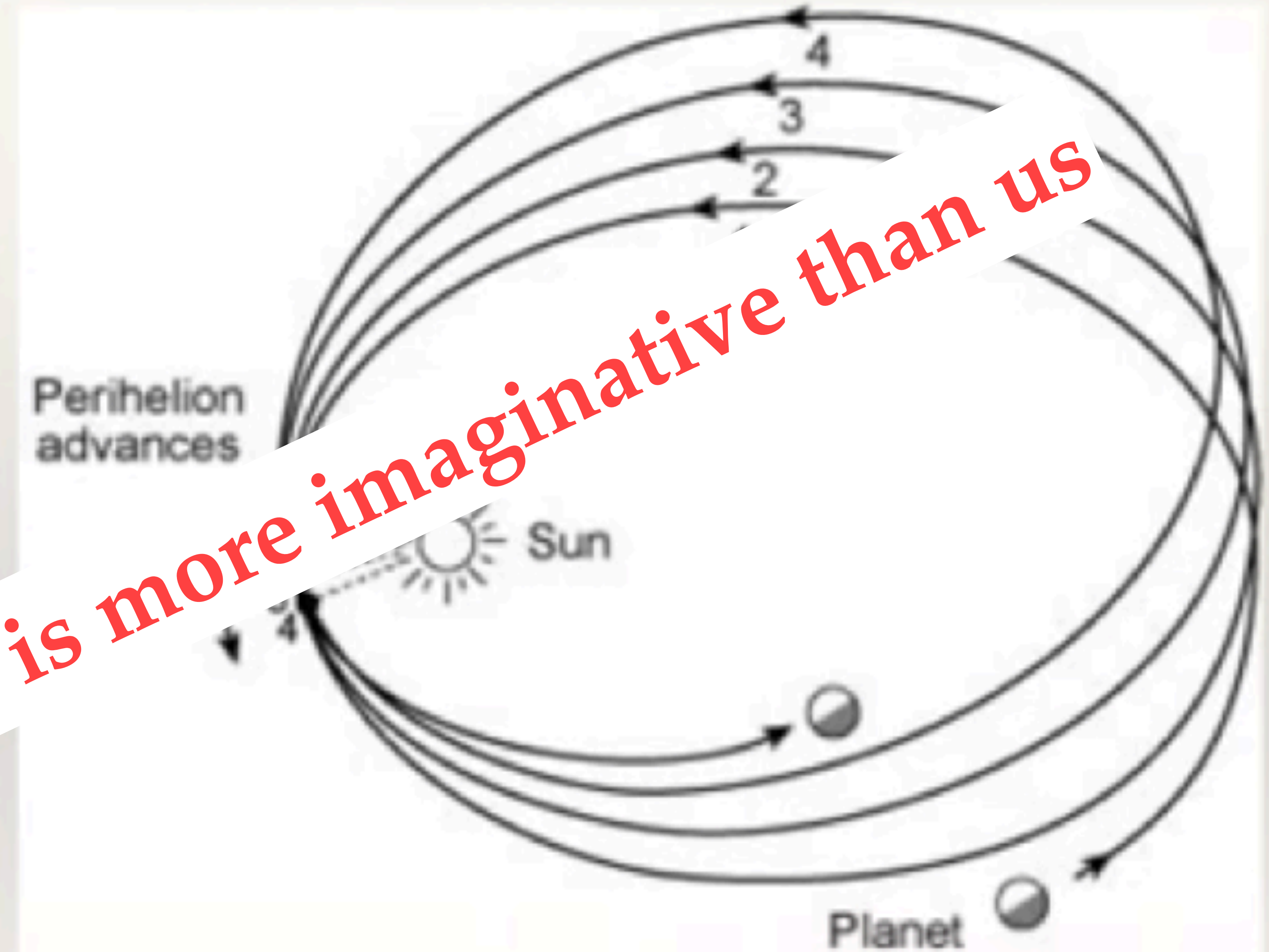
1859: Mercury's orbit is know to "precess" by about 0.01° per century different from Newton's predictions. Le Verrier proposes an additional **Planet Vulcan**

Many claims of discov

Planet Vulcan

ides!

Caution: Nature is more imaginative than us



Copyright 2010, Kenneth R. Lang

Philosophy: *is DM just the current-day Luminiferous Aether?*

So, is DM just the current-day Luminiferous Aether?

…please form your own opinion over the course of these lectures!

Evidence for Dark Matter

Coma Cluster

Fritz Zwicky (1898-1974); Coma Cluster work in 1933
(another iconoclastic Swiss!)

“dunkle Materie”

Stephen Maurer:
When researchers talk about neutron stars, dark matter, and gravitational lenses, they all start the same way: "Zwicky noticed this problem in the 1930s. Back then, nobody listened..."

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

F. ZWICKY

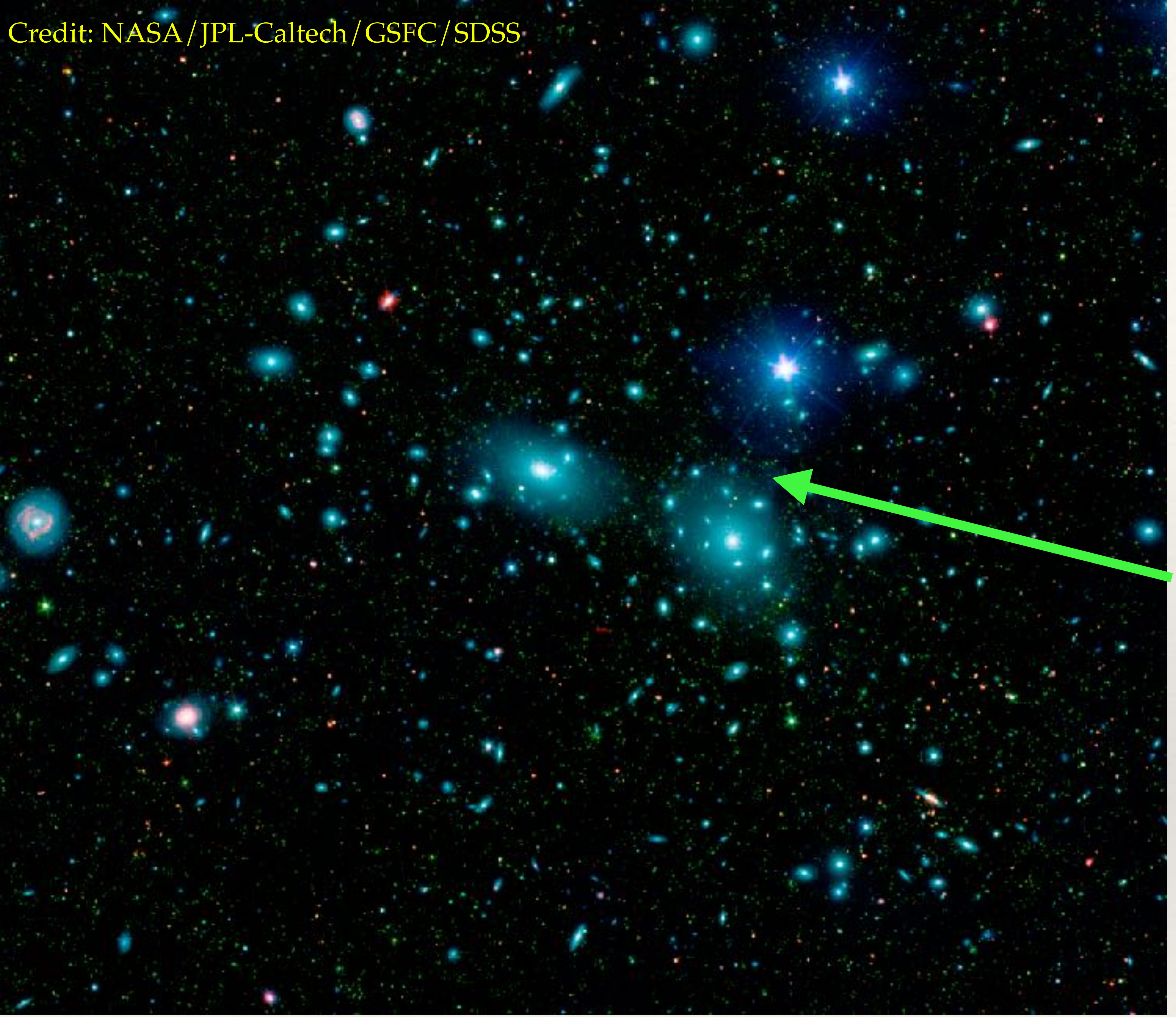
ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_{\odot}$ for the average mass of its member nebulae.

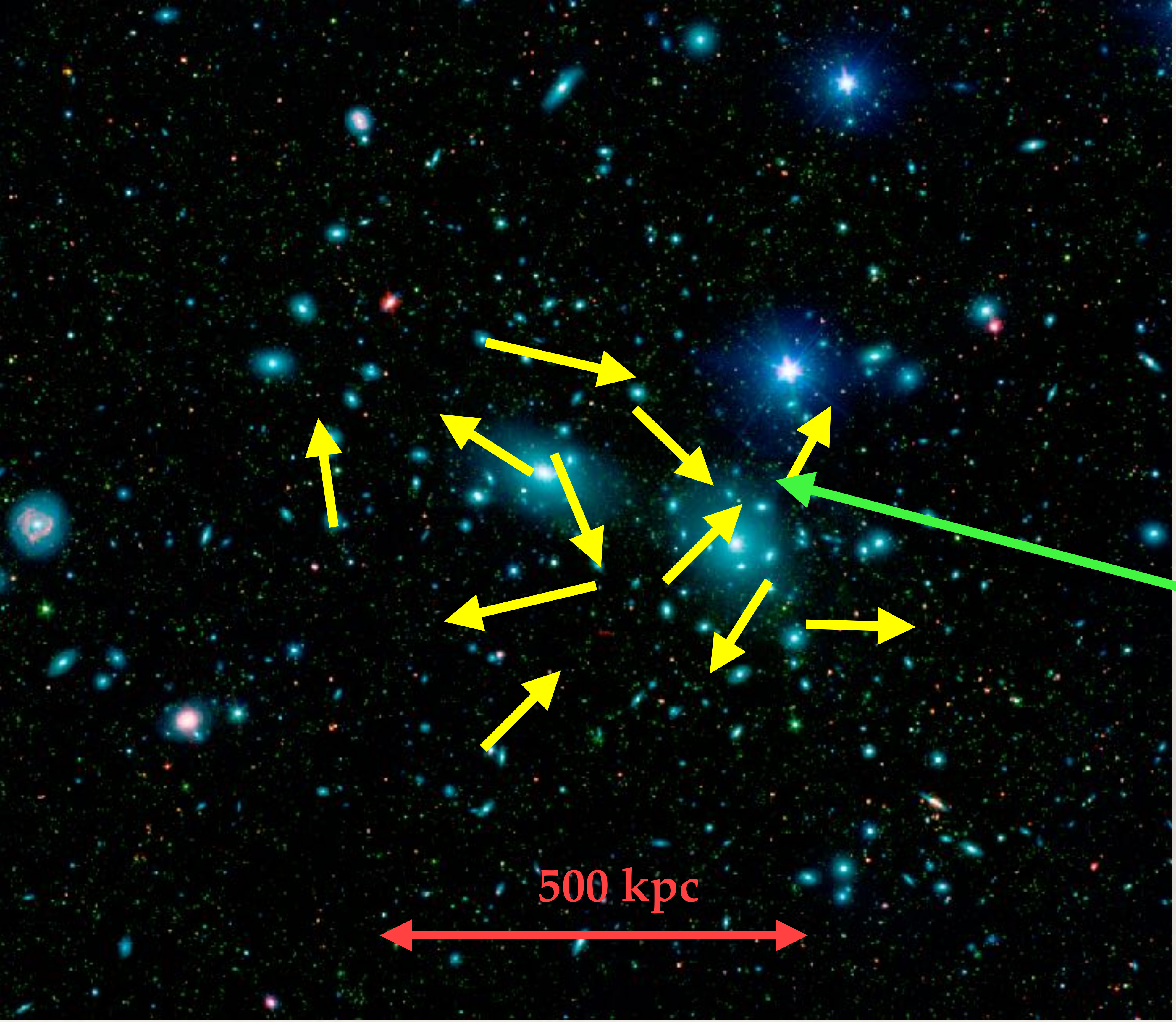
Method iv calls for the observation among nebulae of certain *gravitational lens* effects.



100s of galaxies!

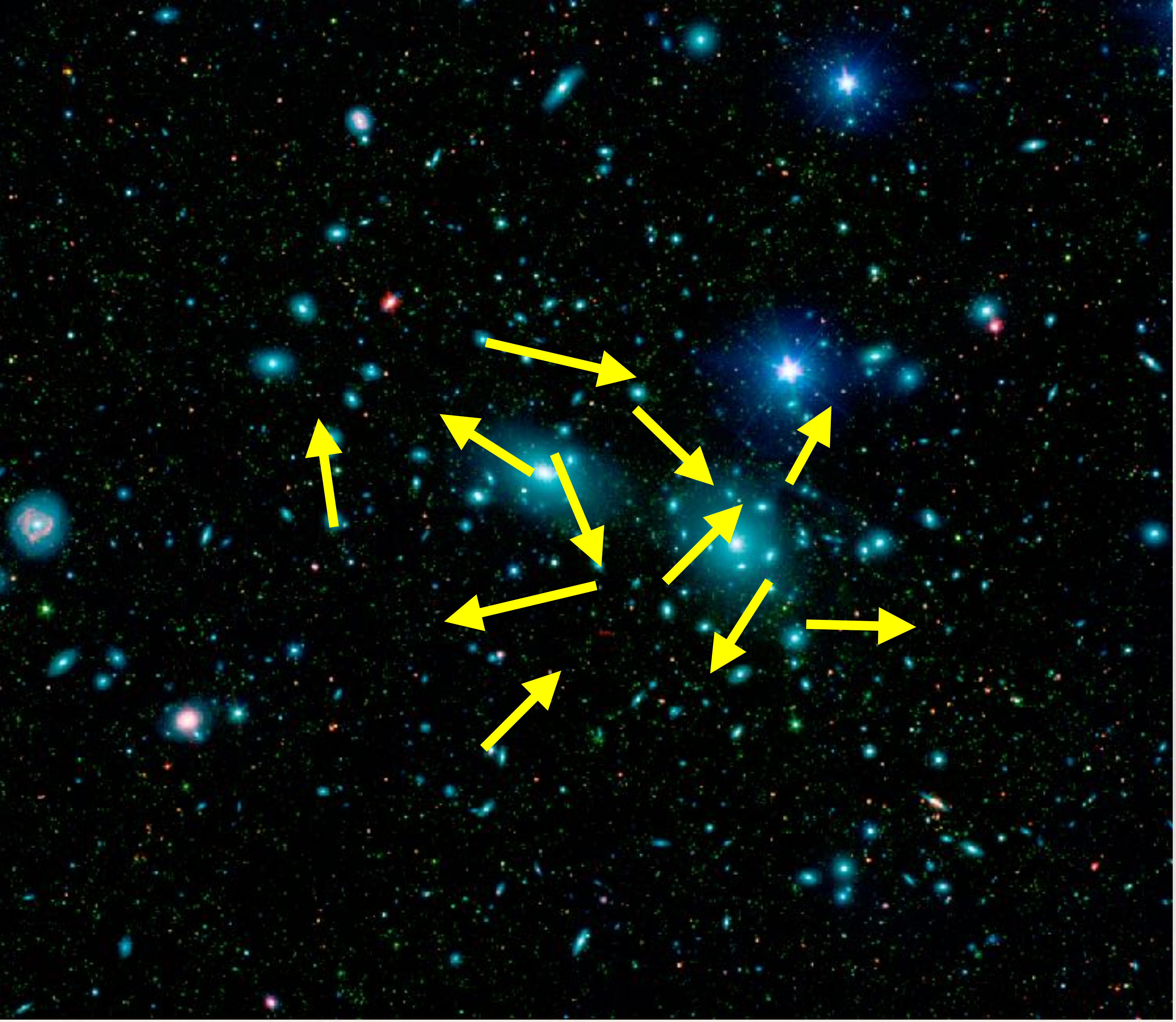
Coma is ~100 Mpc away

A Sloan Digital Sky Survey/Spitzer Space Telescope mosaic of the Coma Cluster in long-wavelength infrared (red), short-wavelength infrared (green), and visible light. The many faint green smudges are dwarf galaxies in the cluster.



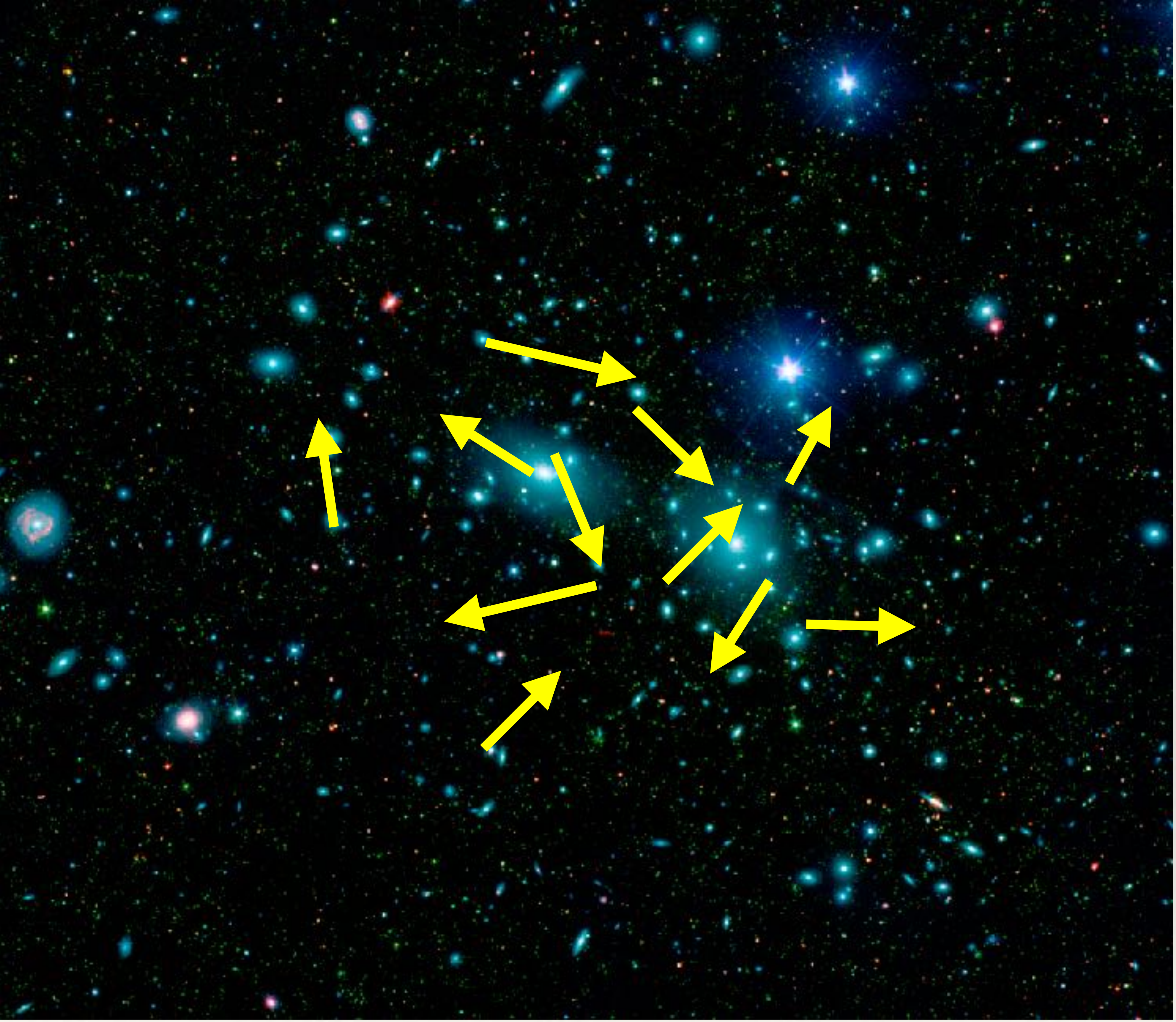
v ~ 1000 km/s

t_{orbit} ~ Gyr



$M_{tot}(R) \sim v^2 R / G_N$

$\Rightarrow M_{tot} \sim 500 \times M_{stars}$



$M_{tot}(R) \sim v^2 R / G_N$

$\Rightarrow M_{tot} \sim 500 \times M_{stars}$

What is the missing mass? Gas? Planets?

Coma Cluster

- Zwicky did not have observational capability to measure hot ("ICM") gas
- modern understanding is that big clusters are 85% DM, 14% ICM and 1% stars
- care taken with virial theorem because not all galaxies "in" a cluster way be virialised — some could be falling in, or being ejected; virial radius roughly separates galaxies bound into cluster from rest of universe
- virial radius often defined as region within which the mean density is 200 x the background density

What to do about Zwicky?

1. His measurements are wrong
2. The galaxy cluster is coming apart
3. There is a lot of "normal" matter that is not in the form of glowing stars
4. There is a whole new kind of matter that does not emit light
5. Newton's theory of gravity is wrong for large objects
6. It's too weird to be true, we'll just ignore it.

Gary Berstein

Virial Theorem

- Consider a statistically steady, spherical, self-gravitating system of N objects with average mass m and average velocity dispersion σ.
- The total kinetic energy of such a system is: $E = (1/2)Nm\sigma^2$
- If average separation is r the potential energy of system is:

$$U = -(1/2)N(N-1)Gm^2/r \ .$$

- The virial theorem gives us that in such a system: $E = -U/2$.
- So the total dynamical mass can be estimated as: $M_{dyn} = Nm = 2r\sigma^2/G$

(formulae from Roos 2010)

Virial Theorem

- So the total dynamical mass can be estimated as: $M_{dyn} = Nm = 2r\sigma^2/G$
- Turning this around: $\sigma^2 \propto (M_{dyn}/L)IR$

…where:

I: surface luminosity,

R: scale,

Mdyn/*L*: mass-to-light ratio

Virial Theorem

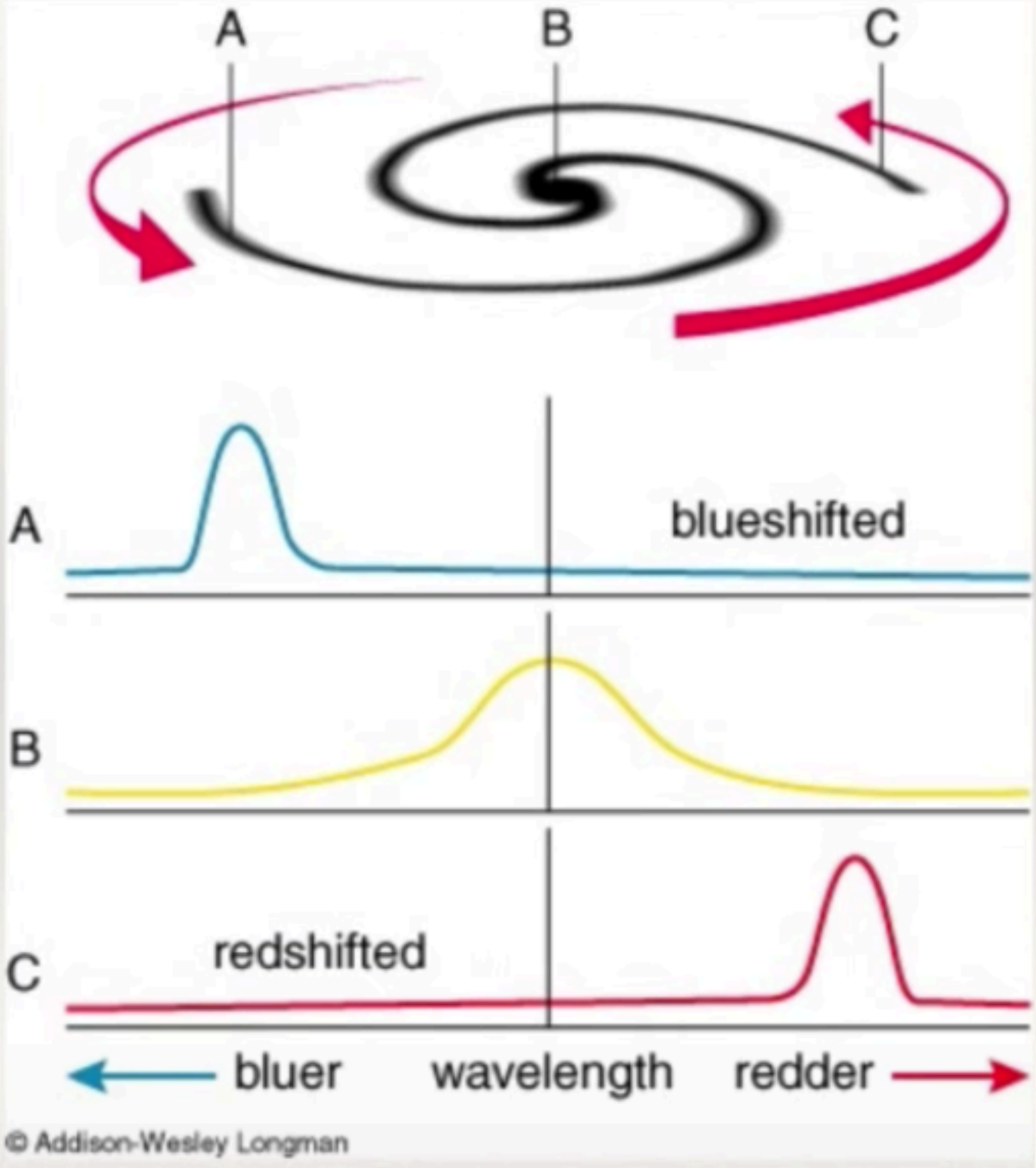
If we choose for the scale *R* the half-light radius R_e, this implies a relationship between the observed central velocity dispersion σ_0, I_e and R_e called the *Fundamental Plane*

$$R_e \propto (\sigma_0)^a (I_e)^b \ .$$

The virial theorem predicts the values a = 2, b = 1 for the coefficients. This relationship is found in ellipticals.

Rotation Curves
(of spiral galaxies)

Rotation Curves



Rotation Curves

Spiral galaxies are stable, gravitationally-gravitationall…
whose visible matter — stars and gas — describ…
relatively thin disk.

Stronger case than Coma cluster because the dominant gravitating mass has to be distributed differently from the luminous mass

Setting the centrifugal acceleration at r … r we have:

$v/r = G\,M(r)/r^2$

Given the central … galaxies, we would then expect stellar and …

$$v^2 = GM(r)/r.$$

…… obeyed in spiral galaxies (assuming $M(r)$ to be the visi… …rge radii. In fact, instead of $v \propto r^{-1/2}$ we find $v \approx const$

Assu…g Newtonian Gravity (or GR more generally) this implies in spiral galaxies $M(r) \approx r$ …which is *not* obeyed by the visible matter

Rotation Curves

- Freeman 1970

- Rubin & Ford 1970,1980

ON THE DISKS OF SPIRAL AND S0 GALAXIES

K. C. FREEMAN
Mount Stromlo and Siding Spring Observatories, Research School of Physical Sciences, Australian National University

Received 1969 August 19; revised 1969 December 8

ABSTRACT

Surface photometry shows that most spiral and S0 galaxies have two main components: a spheroidal component, and an exponential disk component with radial surface-brightness distribution $I(R) = I_0 e^{-\alpha R}$. The exponential disk is the subject of this paper. First, for the exponential disk in centrifugal equilibrium with surface density $\mu(R) = \mu_0 e^{-\alpha R}$, we derive the circular-velocity field and the mass-angular momentum distribution $\mathfrak{M}(h)$; $\mathfrak{M}(h)$ is the total mass with angular momentum per unit mass less than h. $\mathfrak{M}(h)$ for the exponential disk is almost identical with $\mathfrak{M}(h)$ for a family of rigidly rotating spheres of uniform density. We then collect photometric data for the disks of thirty-six spiral and S0 galaxies, and find the following: (i) Twenty-eight of the thirty-six galaxies have approximately the same intensity scale I_0 (21.65 B-mag per square second of arc), with a standard deviation of only 0.30 mag per square second of arc, despite a range of nearly 5 mag in absolute magnitude. This constancy of I_0 produces the correlation between apparent magnitude and angular diameter found by Hubble. (ii) S0–Sbc systems have any value of the disk length scale α^{-1} between 1 and 5 kpc, while later-type systems have predominantly low values of α^{-1} ($\lesssim 2$ kpc). (iii) The relative brightness and size of the spheroidal and disk components are only weakly correlated with morphological type.

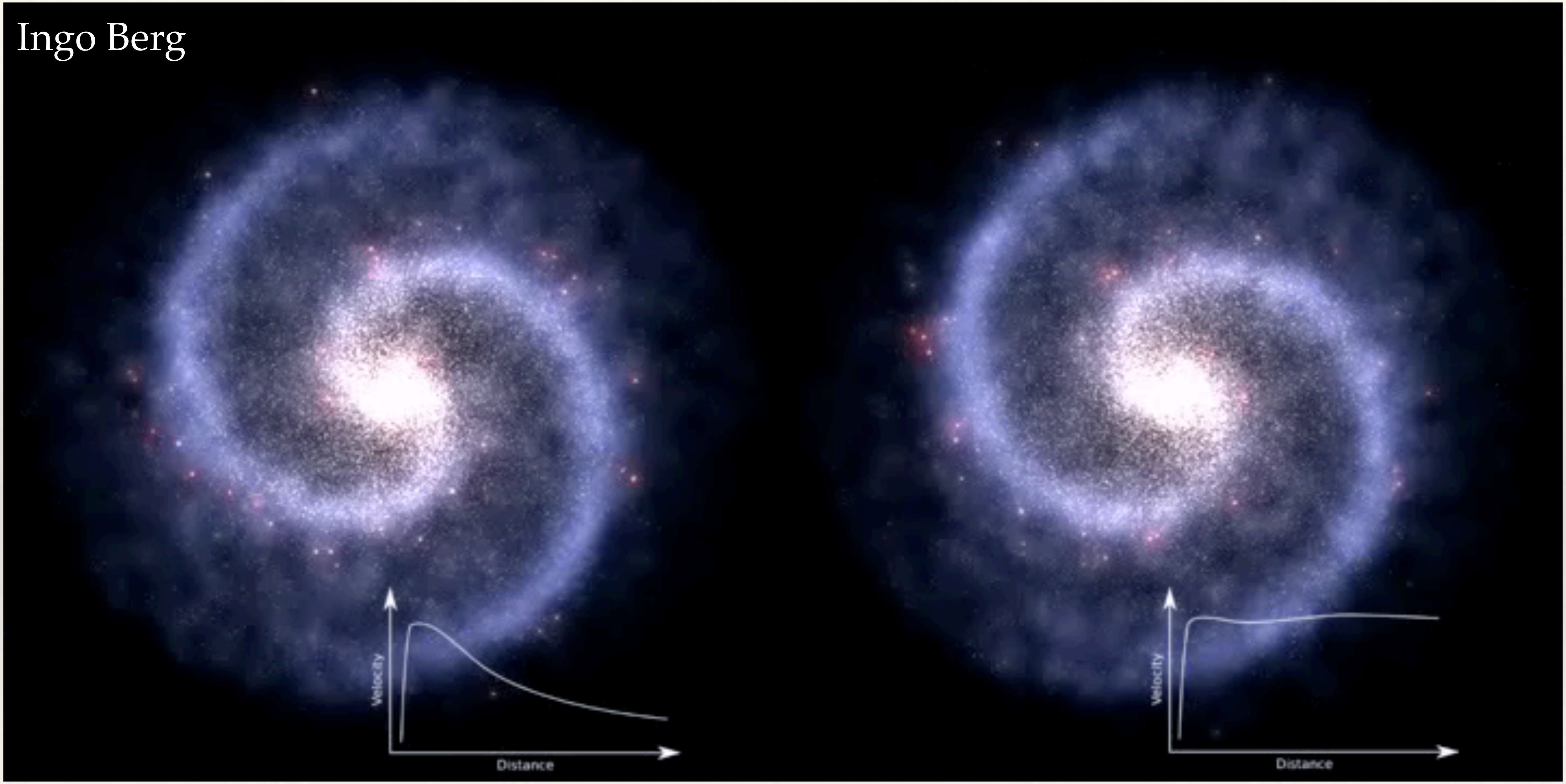
If conclusion (i) implies that μ_0 is approximately constant, then the disk's total mass $\mathfrak{M}$ and angular momentum $\mathfrak{H}$ satisfy $\mathfrak{H} \propto \mathfrak{M}^{7/4}$. If $\mathfrak{M}(h)$ is invariant as a protogalaxy collapses to form a galaxy, then all protogalaxies destined to be S0 or spiral galaxies have a similar $\mathfrak{M}(h)$ (in dimensionless variables), at least for the range of h corresponding to the disk. If $\mathfrak{M}(h)$ is not invariant, then there exists a very efficient mechanism which establishes the characteristic $\mathfrak{M}(h)$ for these systems as they form.

The exponential nature of the disk is not defined by $\mathfrak{M}(h)$ alone; its cause remains uncertain.

c) NGC 300

Shobbrook and Robinson (1967) find the H I linear dimensions of this system to be about twice the optical photometric dimensions. The theoretical R_T for $\alpha = 0.35$ per minute of arc (de Vaucouleurs and Page 1962) is 6′. The H I rotation curve has V_{max} at $R \approx 15'$, which also happens to be the photometric outer edge of the system. If the H I rotation curve is correct, then there must be undetected matter beyond the optical extent of NGC 300; its mass must be at least of the same order as the mass of the detected galaxy. There is no optical rotation data for NGC 300.

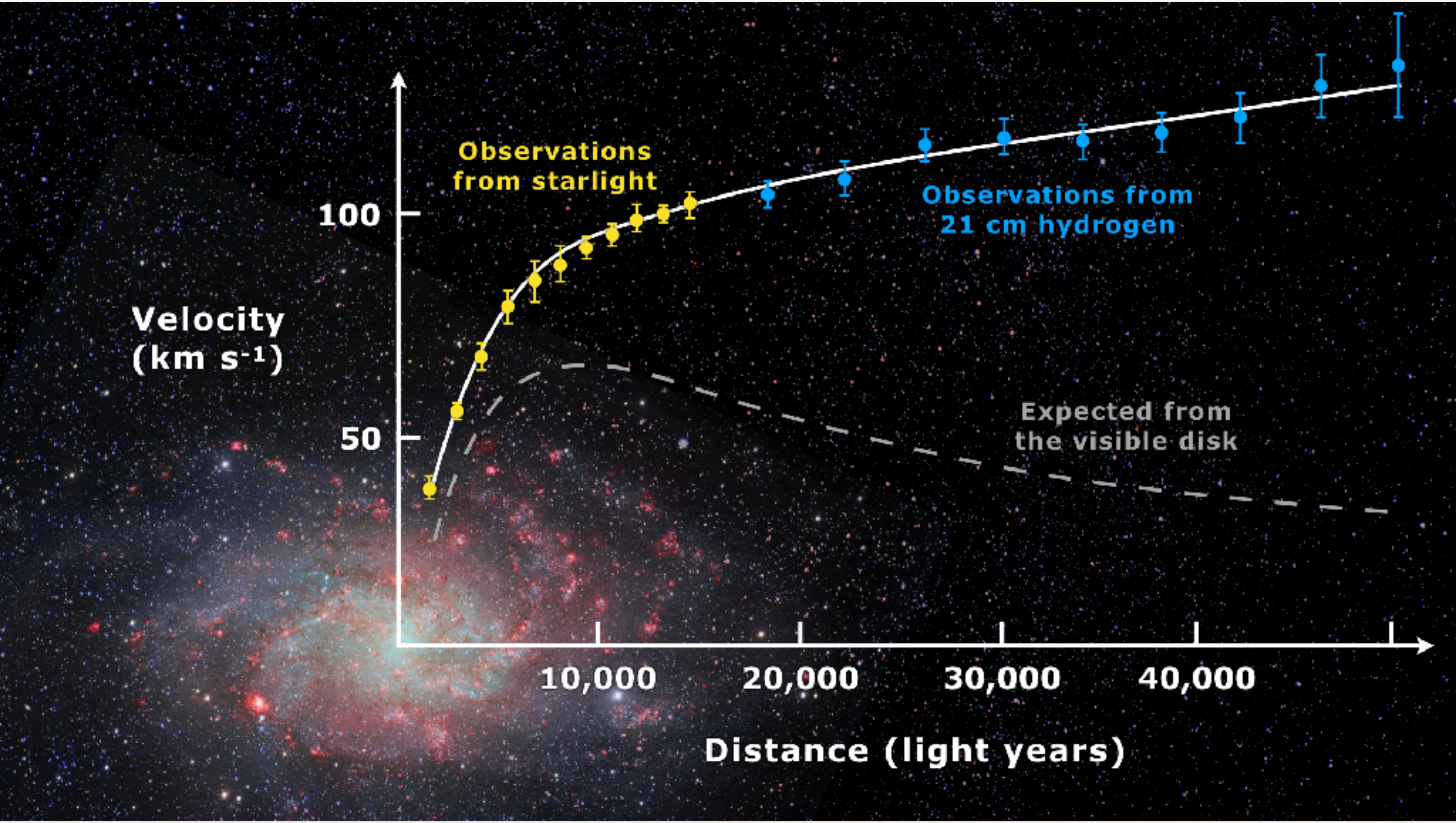
d) M33



Left: A galaxy with a rotation curve as predicted before the effects of dark matter were known. Right: A galaxy with a flat rotation curve that can be explained by the effects of dark matter.

Rotation Curves

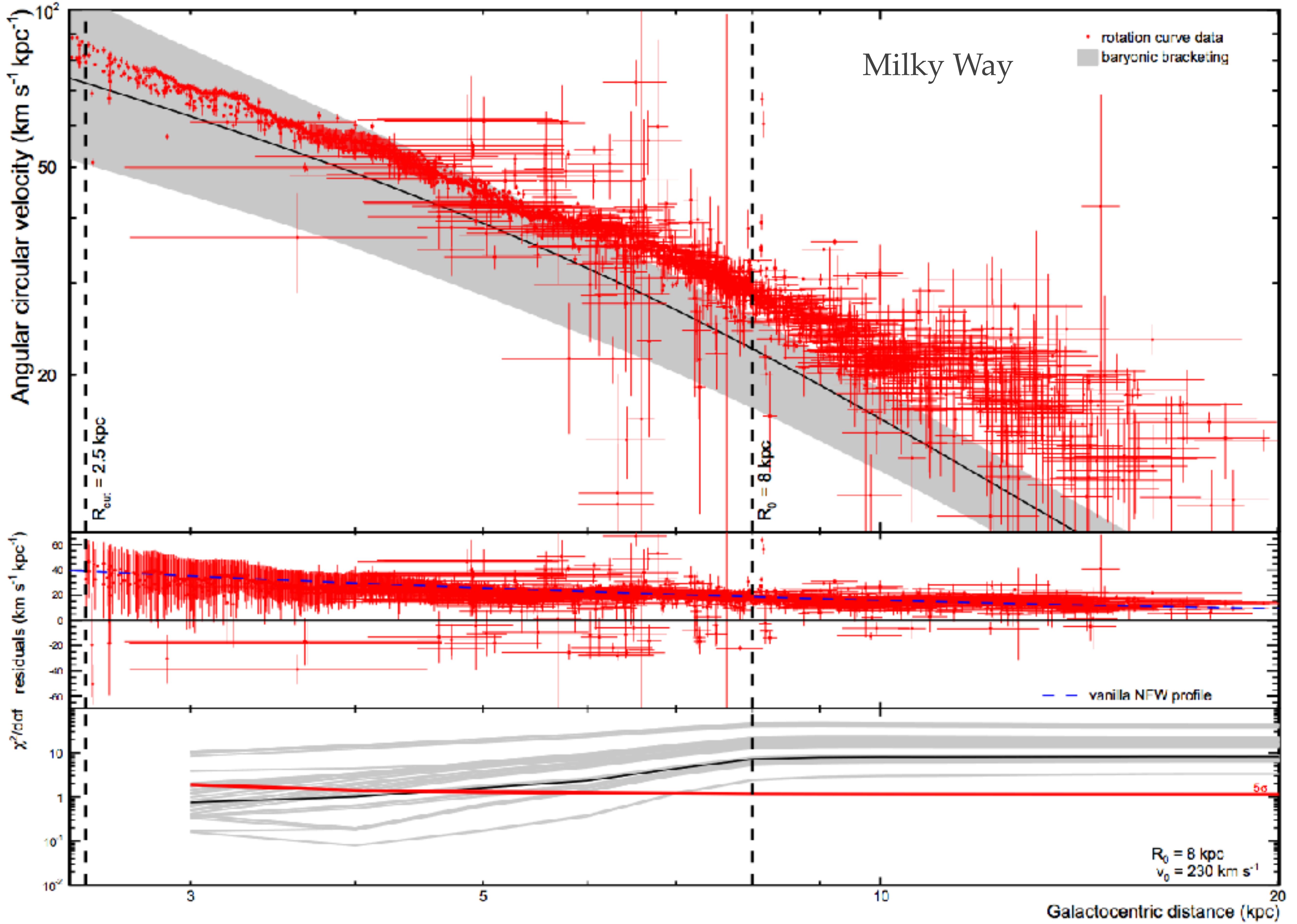
- Rotation curves of most spiral galaxies can be fit with a superposition of components: stellar and gaseous disks; stellar bulge; AND a dark halo that can usually be modelled as a quasi-isothermal sphere.
- Baryonic matter (=stars + gas) dominate the potential in the central region of galaxies…importance of DM increases with radius
- In summary: *light does not trace mass*
- On the other hand: *light predicts mass* (Tully Fisher relation)



Rotation curve of spiral galaxy Messier 33 (yellow and blue points with error bars), and a predicted one from distribution of the visible matter (grey line).

Mario De Leo, Wikipedia

Milky Way Rotation Curve

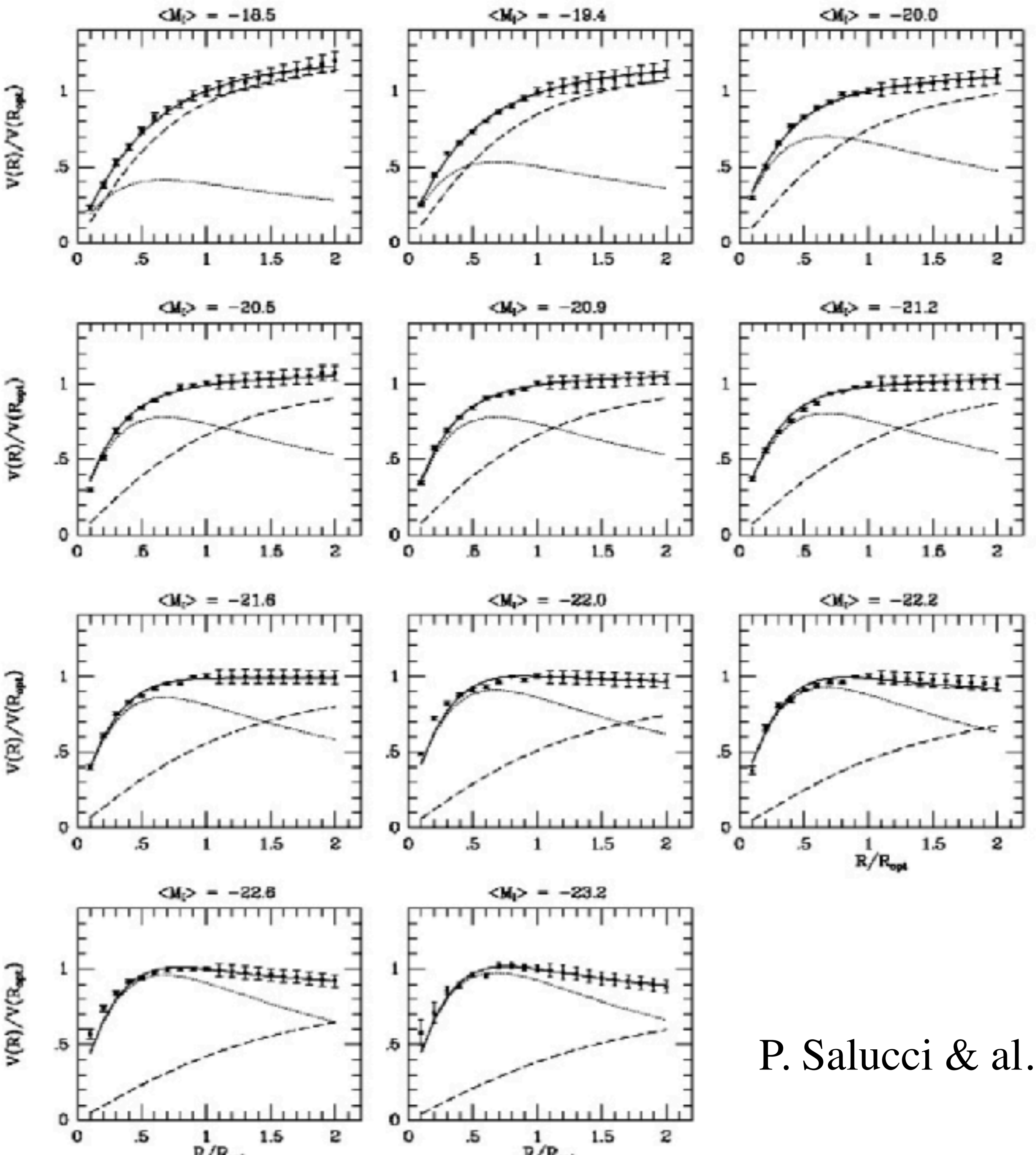


Pato et al. 2015

www.eso.org

Rotation Curves

- In general, the shape of the rotation curve depends on the halo virial mass
- The old idea that the rotation curve stays constant after maximum velocity is attained is a simplification not borne out by reality



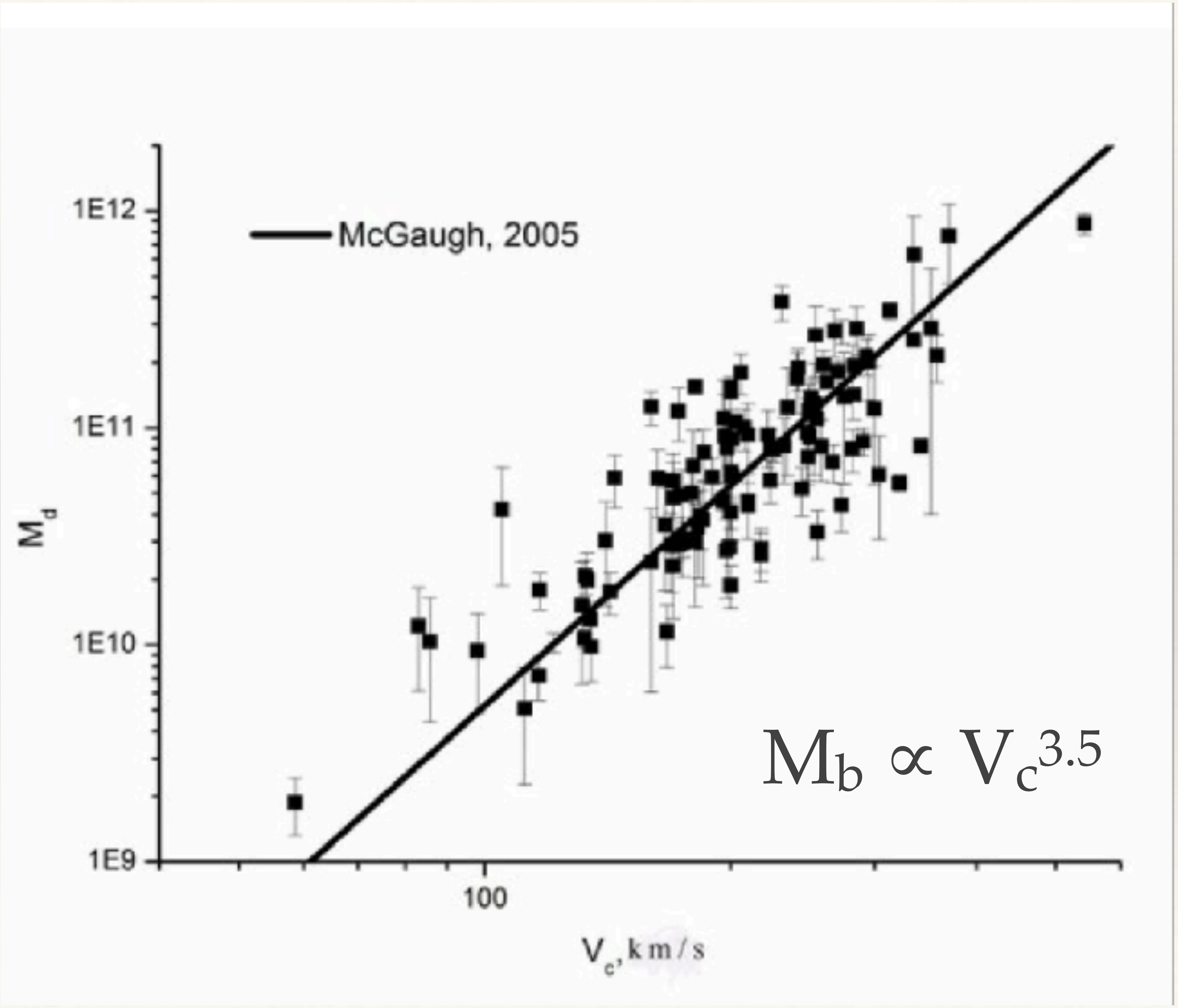
halo mass increasing →

P. Salucci & al.

Tully-Fisher Relation

- Tully–Fisher relation (TFR) is an empirical relationship between the mass or intrinsic luminosity of a spiral galaxy and its asymptotic rotation velocity or emission line width.
- The Baryonic Tully–Fisher relation (BTFR) states that baryonic mass is proportional to velocity to the power of roughly 3.5–4.
- A galaxy's rotation velocity (and hence line width) is primarily determined by the mass of the dark matter halo in which it lives, making the TFR a manifestation of the connection between visible and dark matter mass.

Tully-Fisher Relation



Khoperskov

PRL 117, 201101 (2016)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
11 NOVEMBER 2016

Radial Acceleration Relation in Rotationally Supported Galaxies

Stacy S. McGaugh and Federico Lelli
Department of Astronomy, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, Ohio 44106, USA

James M. Schombert
Department of Physics, University of Oregon, Eugene, Oregon 97403, USA
(Received 18 May 2016; revised manuscript received 7 July 2016; published 9 November 2016)

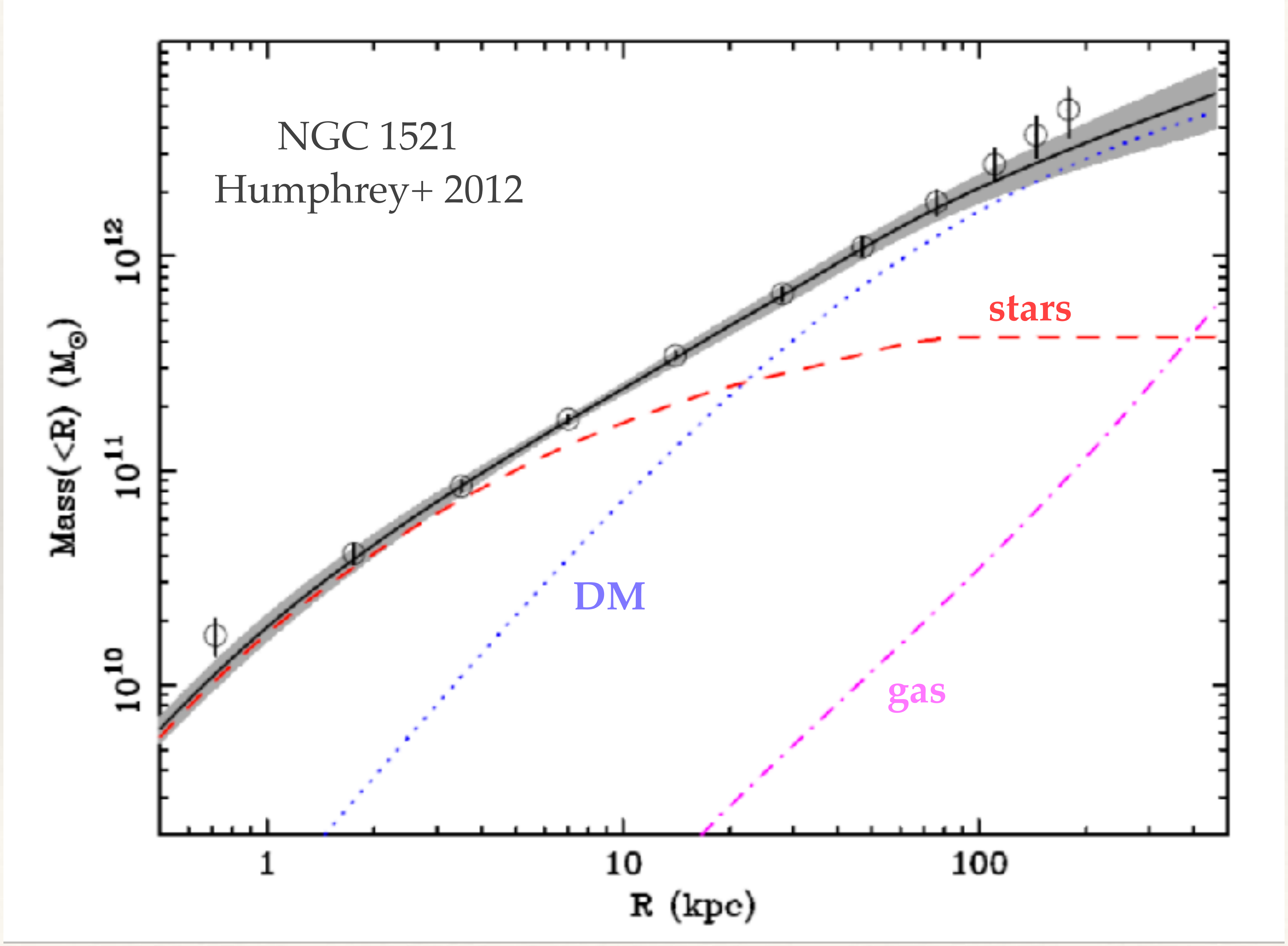
We report a correlation between the radial acceleration traced by rotation curves and that predicted by the observed distribution of baryons. The same relation is followed by 2693 points in 153 galaxies with very different morphologies, masses, sizes, and gas fractions. The correlation persists even when dark matter dominates. Consequently, the dark matter contribution is fully specified by that of the baryons. The observed scatter is small and largely dominated by observational uncertainties. This radial acceleration relation is tantamount to a natural law for rotating galaxies.

DOI: 10.1103/PhysRevLett.117.201101

Elliptical Galaxies

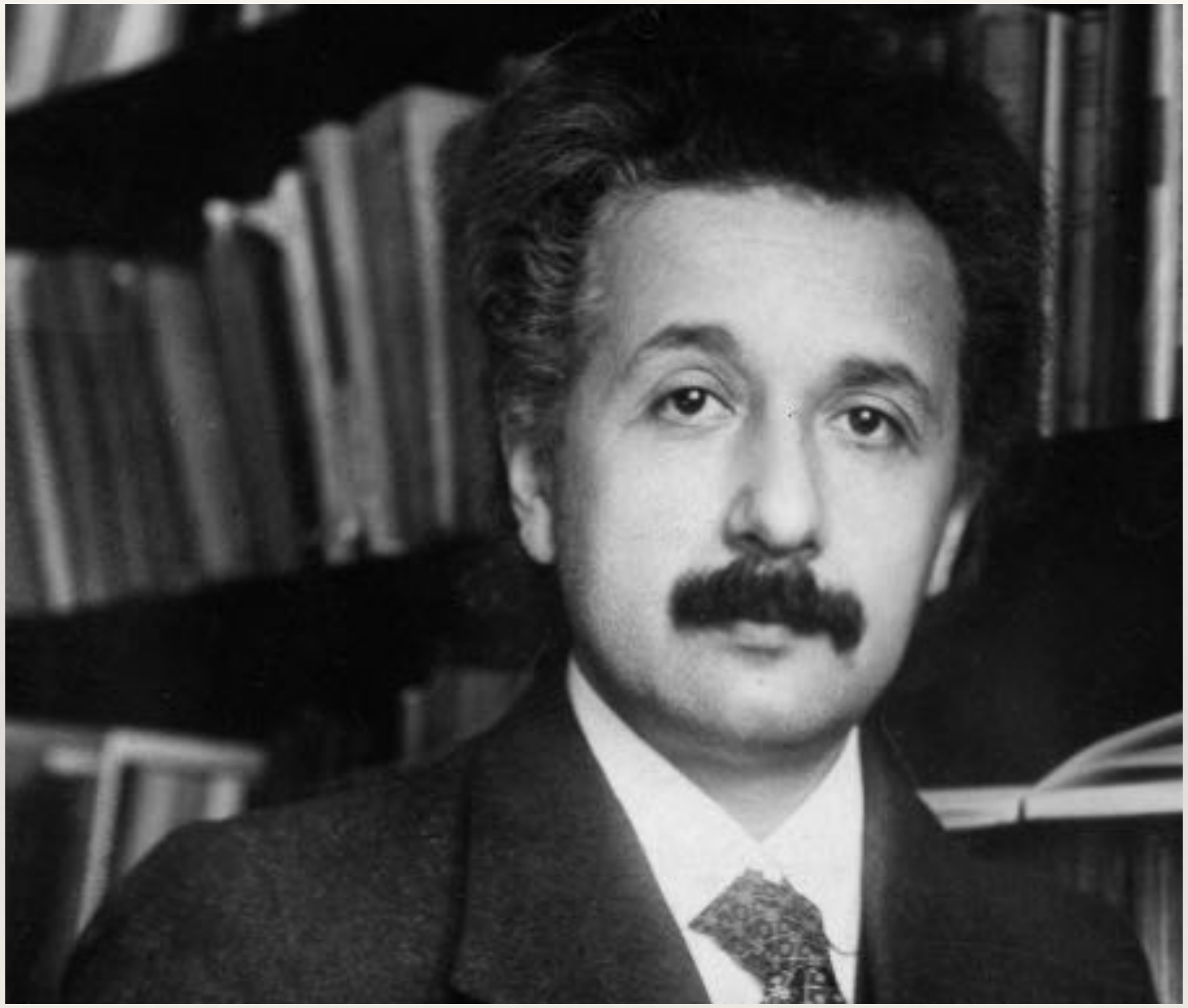
- The analogue of the Tully-Fisher Relation for non-rotationally-supported galaxies, such as ellipticals, is known as the Faber–Jackson Relation.
- Inside the half light radius R_e the contribution of the dark matter halo to the central velocity dispersion is often very small, < 100 km s^{-1}; stars dominate the central potential
- …But at large radii, DM increasingly dominates

Elliptical Galaxies



Gravitational Lensing Evidence for DM

Gravitational lensing: a consequence of General Relativity



LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

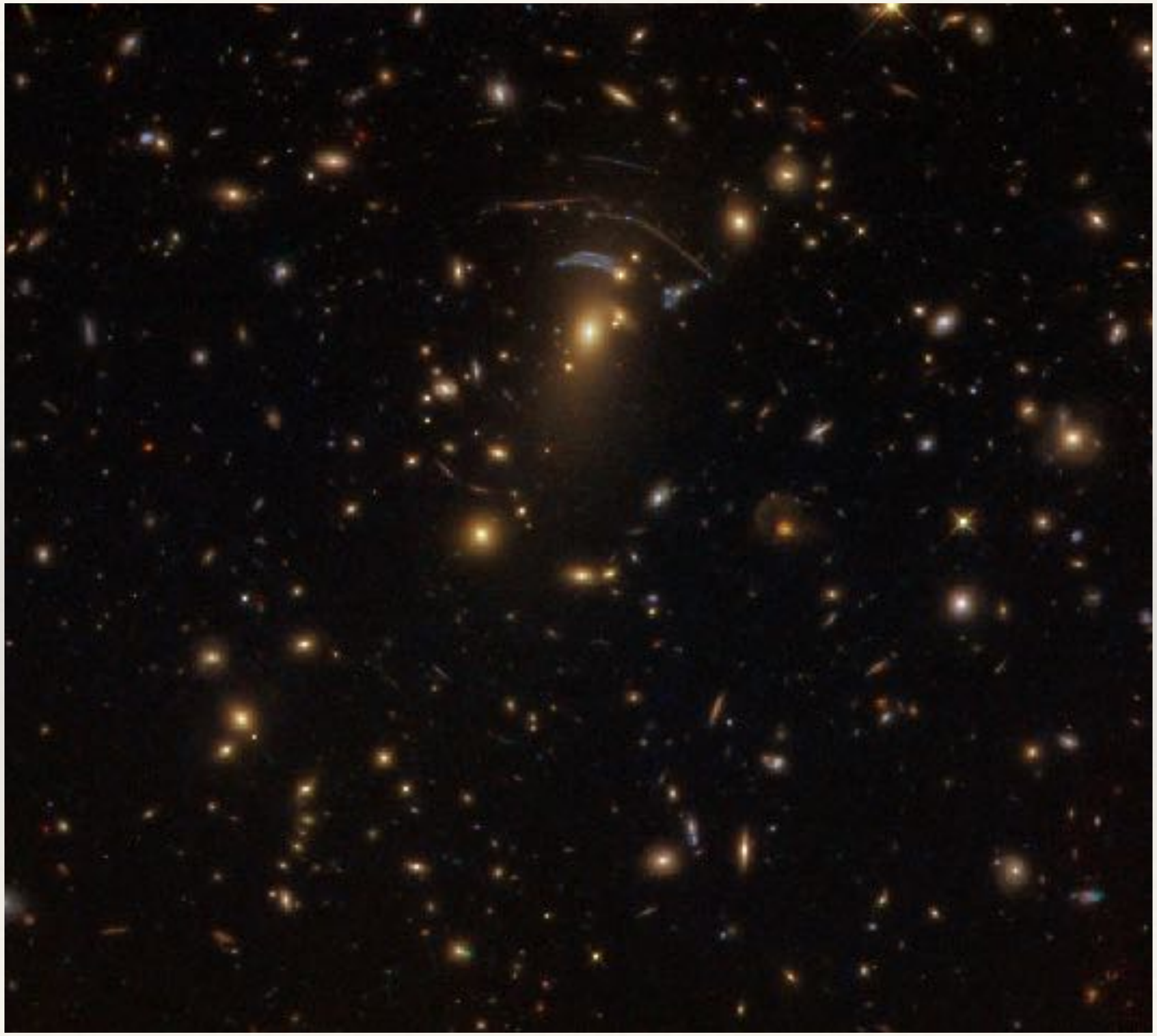
Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

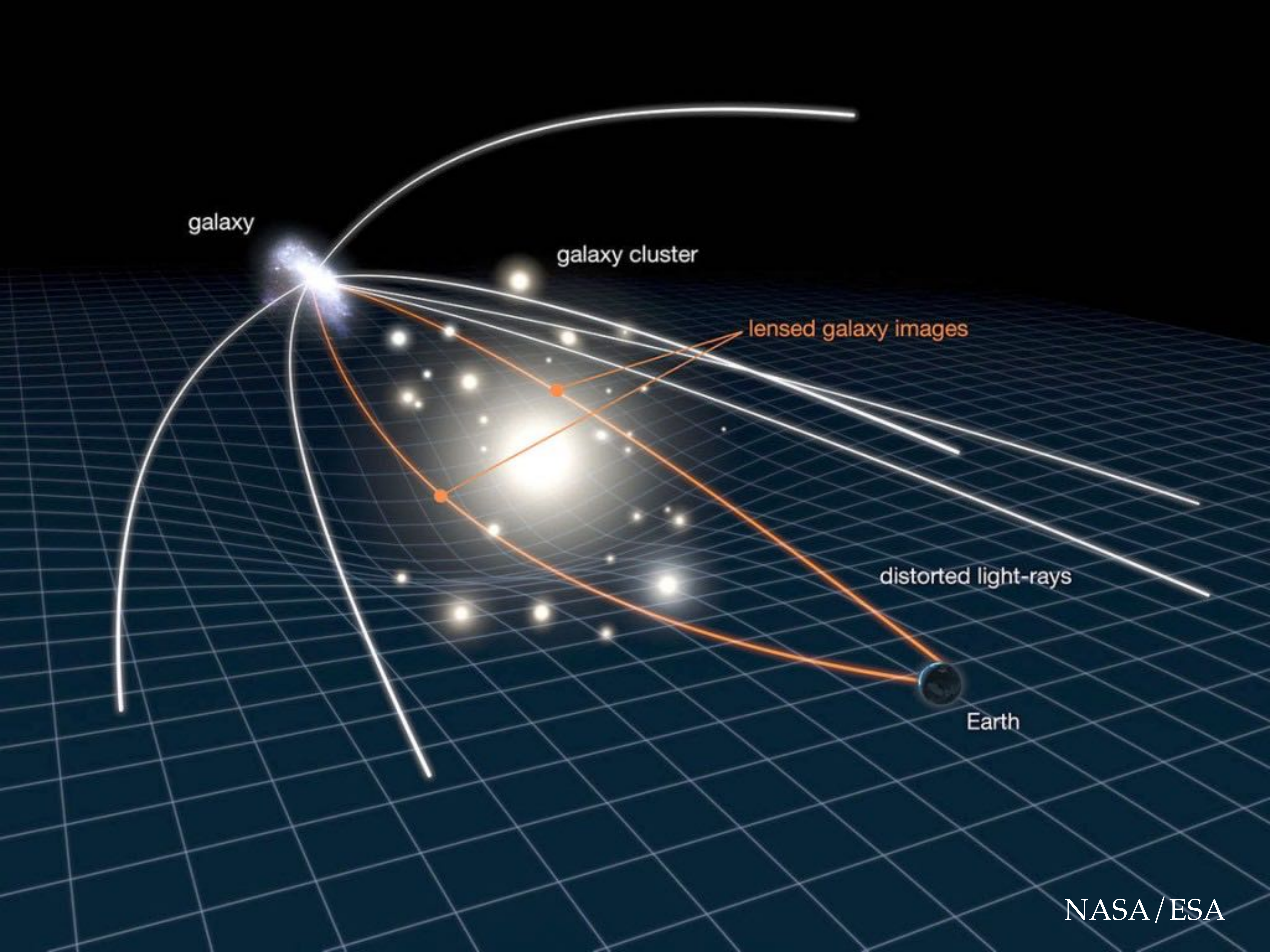
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Gravitational Lensing Evidence for DM

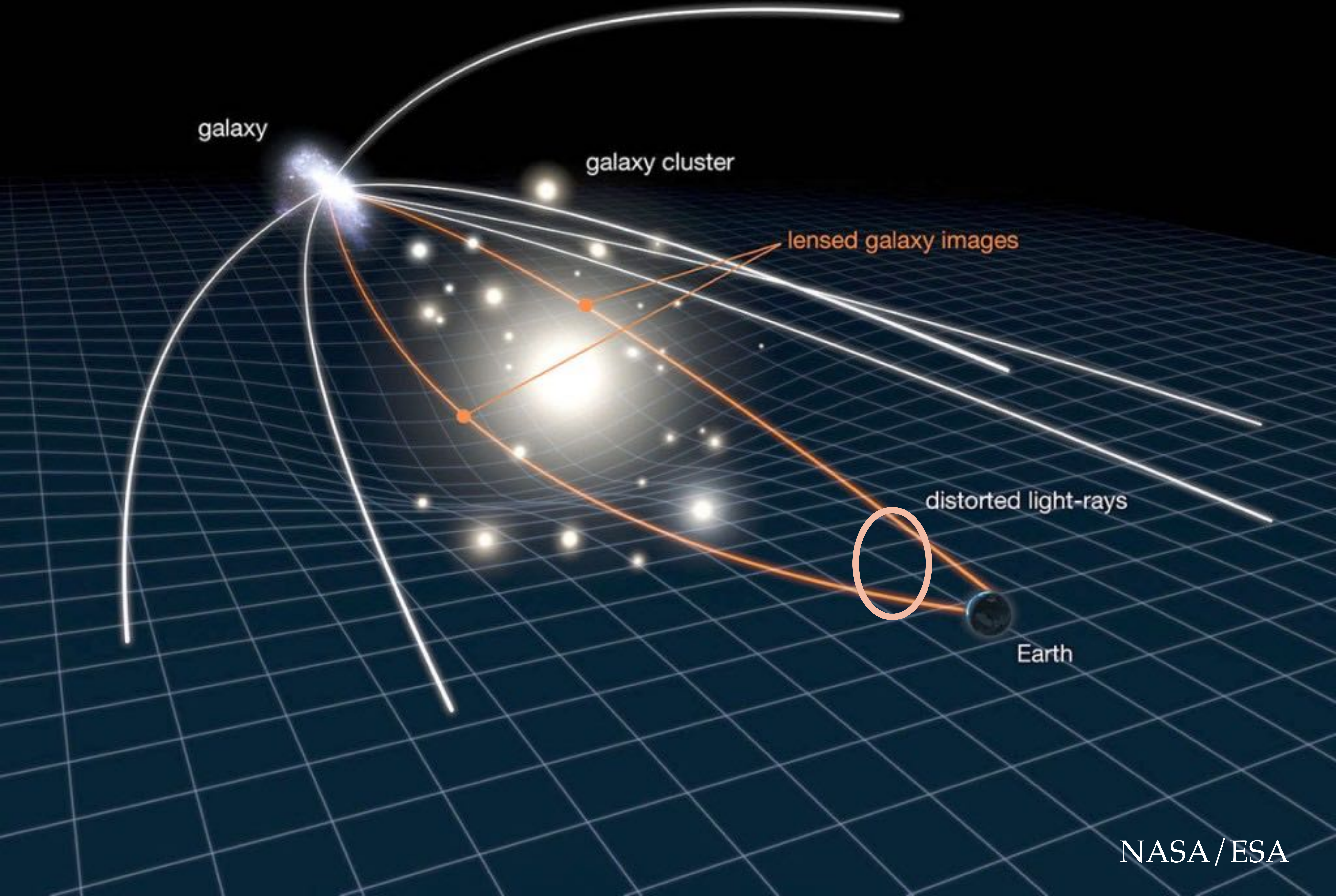
- **Strong lensing**: gravitational lensing that is strong enough to produce multiple images, arcs, or even Einstein rings.
- Basically, the lensing is strong enough to be seen by eye.
- Strong lensing only happens when a massive cluster of galaxies lies between us and some other galaxies.
- It's rare because there are not that many clusters in the sky large enough to induce the effect.



SDSS J1138+2754 taken by Hubble's WFC3 camera [www.spacetelescope.org]


galaxy
galaxy cluster
lensed galaxy images
distorted light-rays
Earth

NASA/ESA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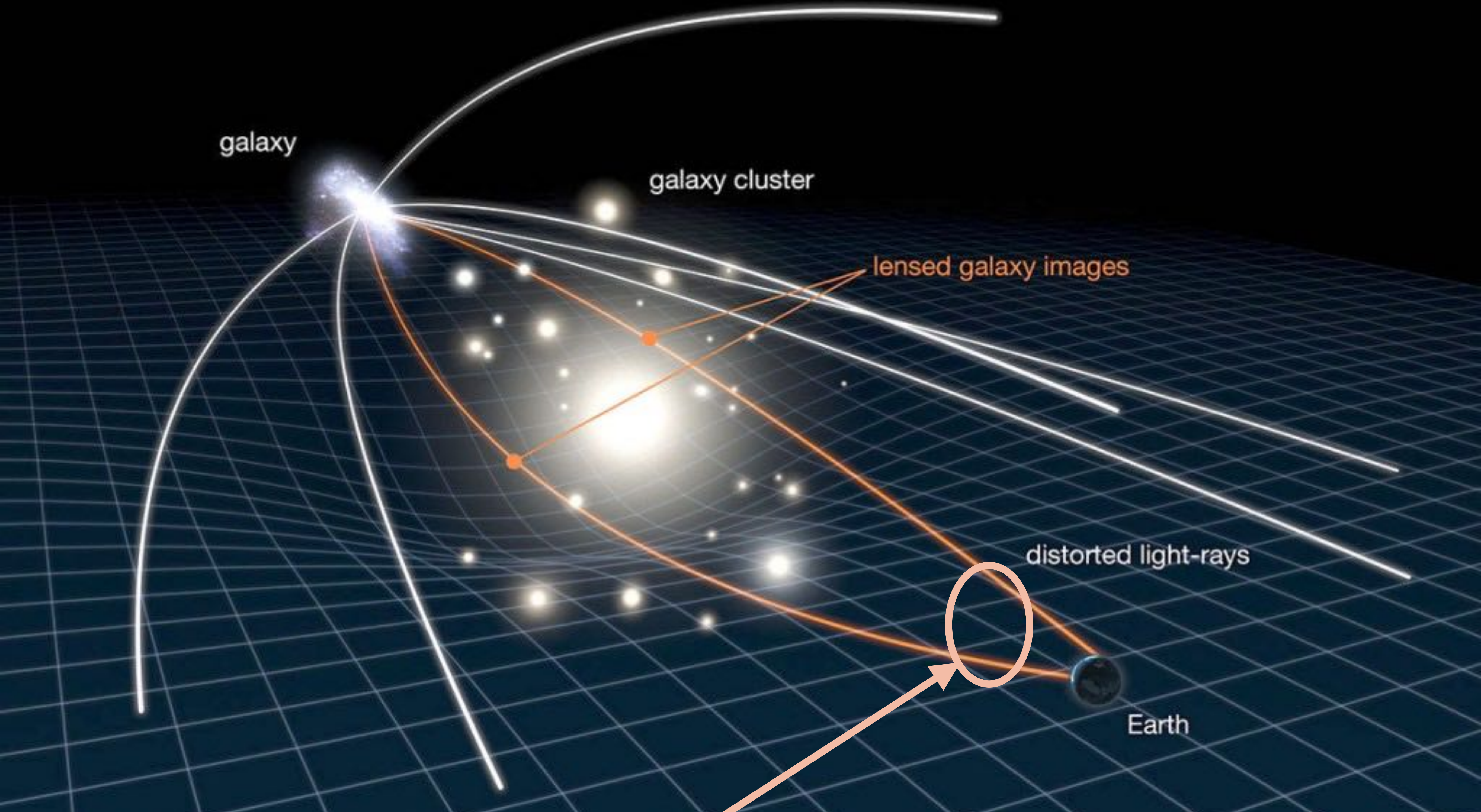
NASA/ESA

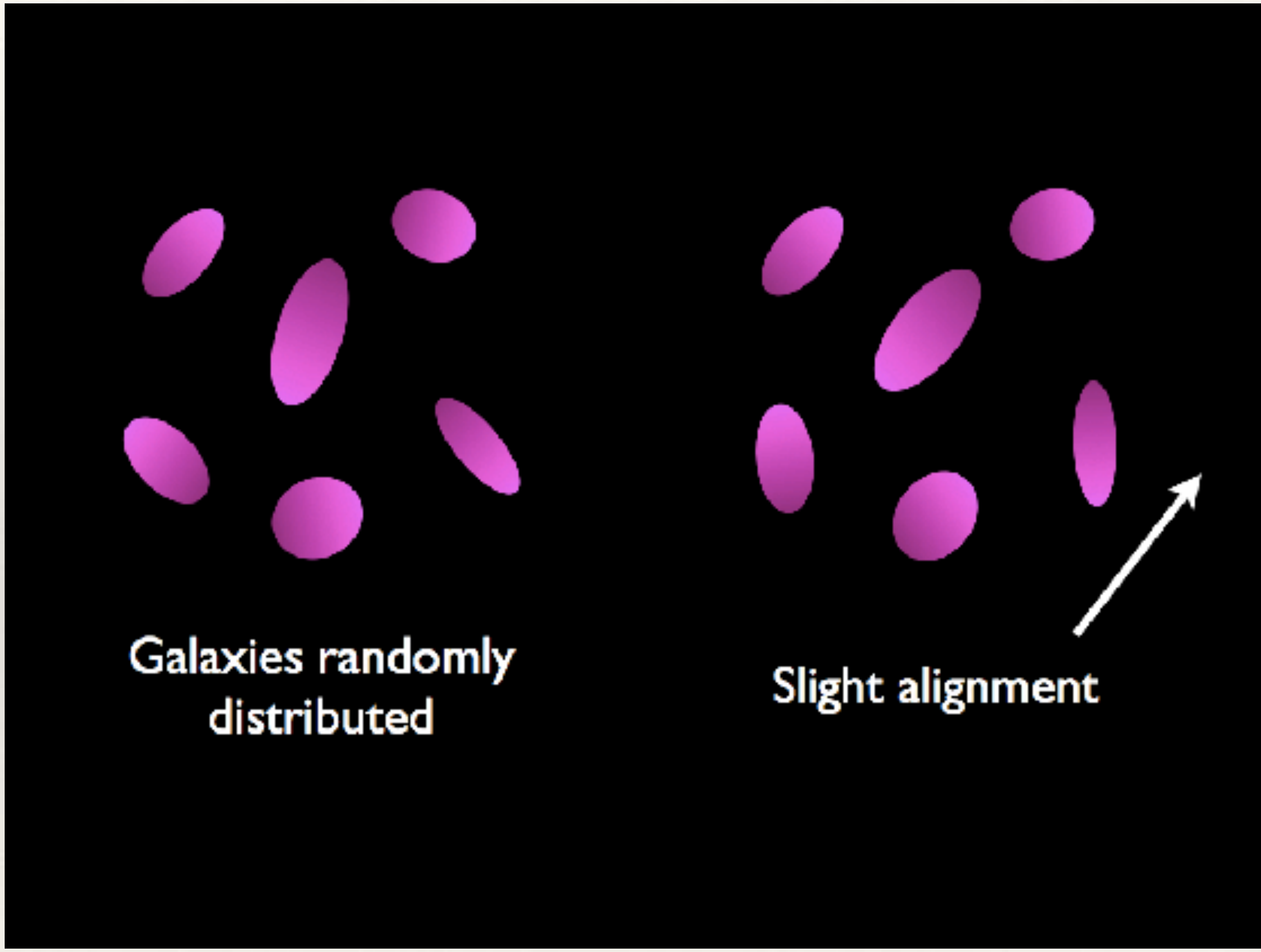


$$\theta_E = \sqrt{\frac{4\,G_N\,M}{c^2}\;\frac{d_{LS}}{d_L\,d_S}}$$

NASA/ESA

Gravitational Lensing Evidence for DM

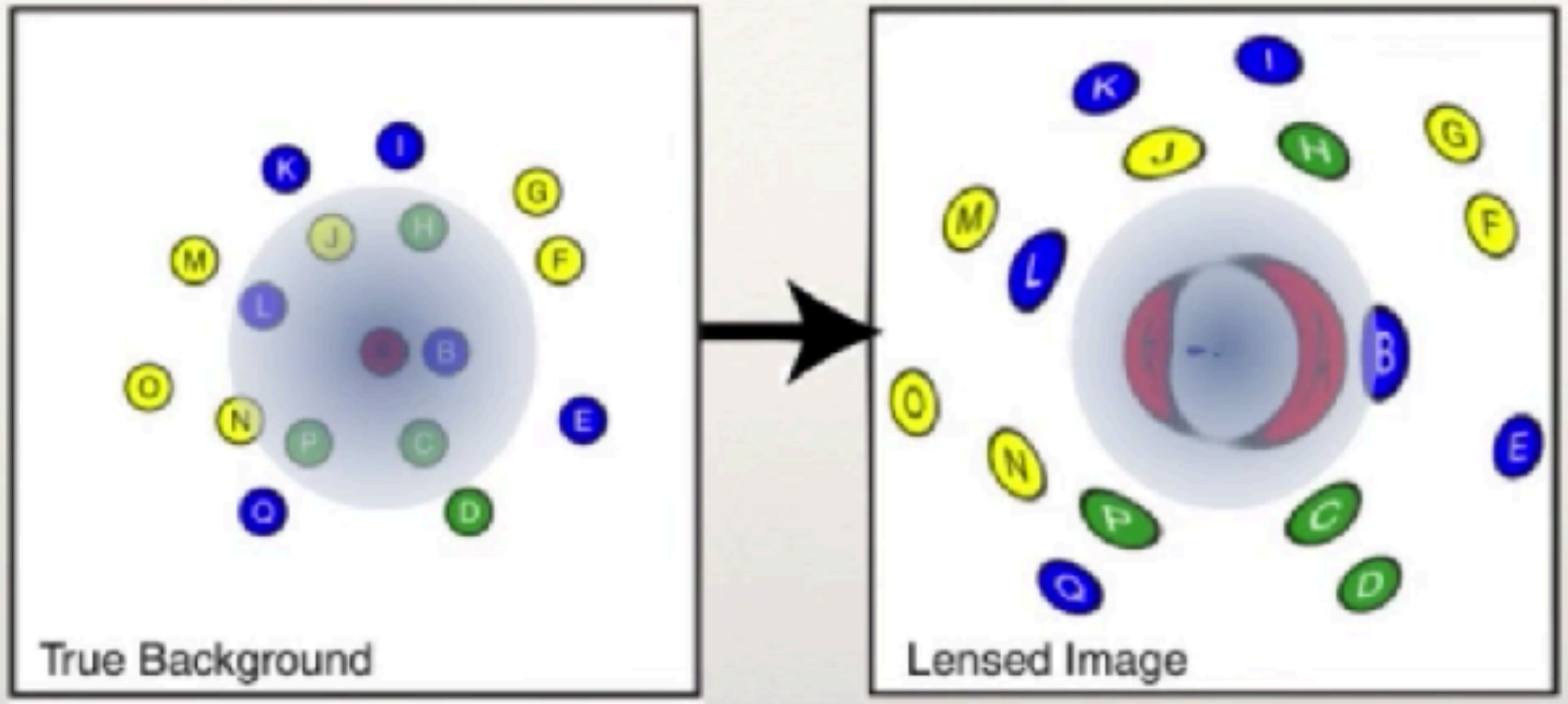
- **Weak lensing**: gravitational lensing that can be treated in the limit that light rays move in straight lines, with a discrete deflection in the lens plane (thin lens approx).
- Can only be inferred statistically (first detection in 2000)
- The fact that there is some dark matter in between us and every distant galaxy we see means that ALL galaxies are lensed - even if it is only slightly. In fact, most galaxies are lensed such that their shapes are altered by only 1%



E Grocutt, IfA, Edinburgh

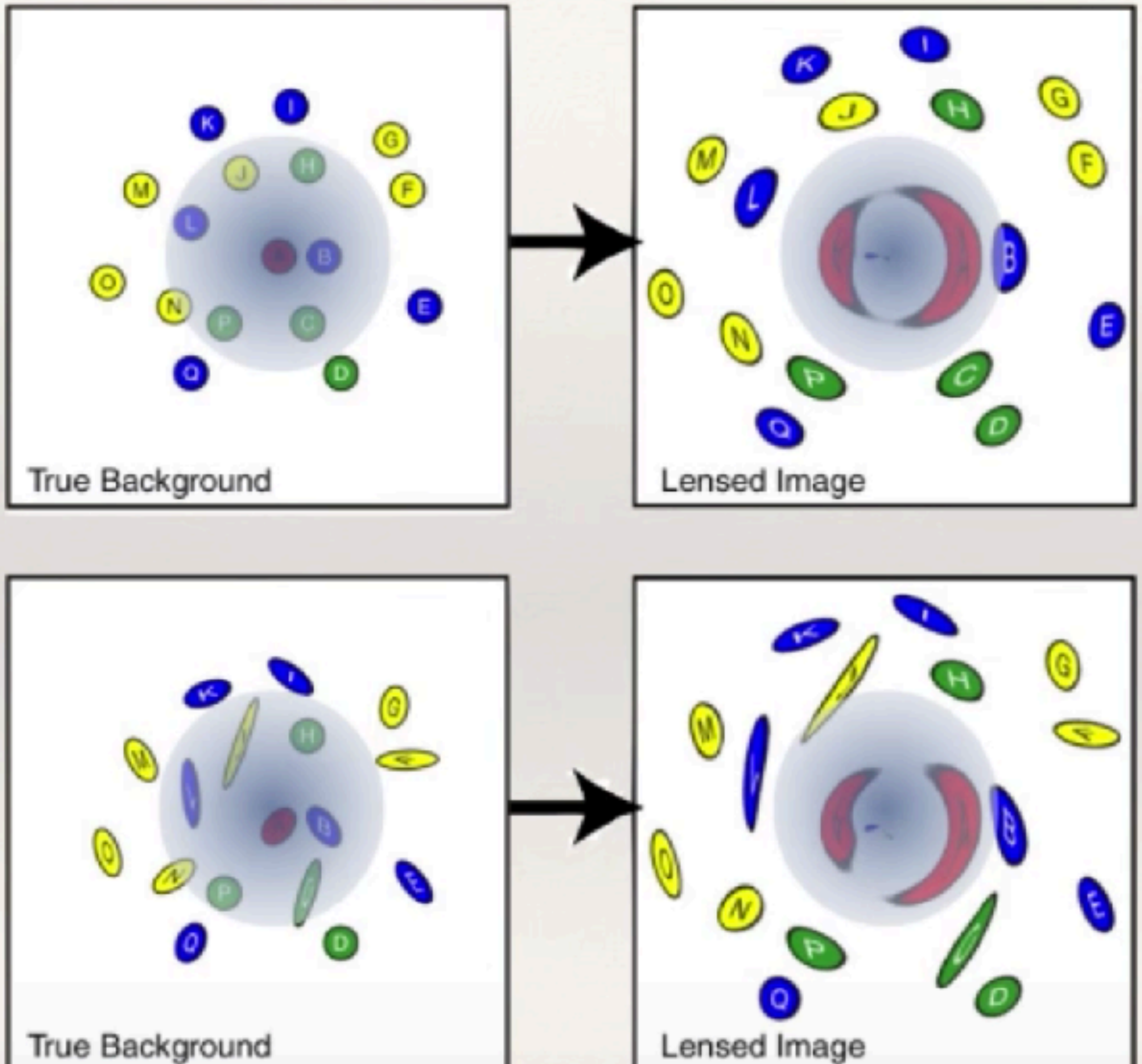
http://www.cfhtlens.org/public/what-gravitational-lensing

Weak vs strong lensing



Gary Berstein

Weak vs strong lensing



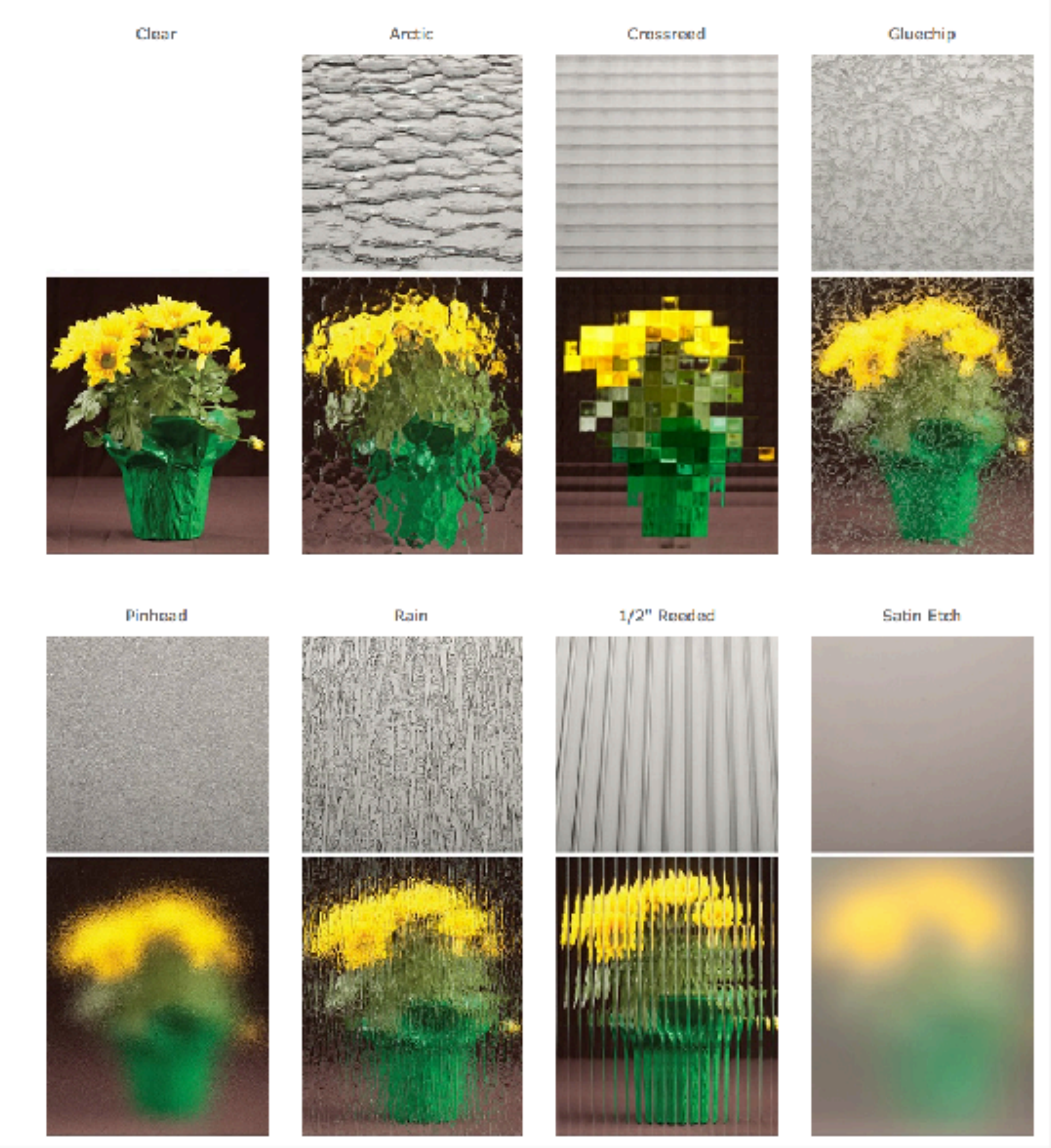
Gary Berstein

Mapping dark matter with weak lensing:

- Measure the shapes of galaxy "wallpaper" behind your dark matter.
- A ***LOT*** of galaxies - many thousands or millions!
- The alignment of the galaxy shapes tells reveals location of mass in the lens - *even if this mass is invisible!*

Gary Berstein

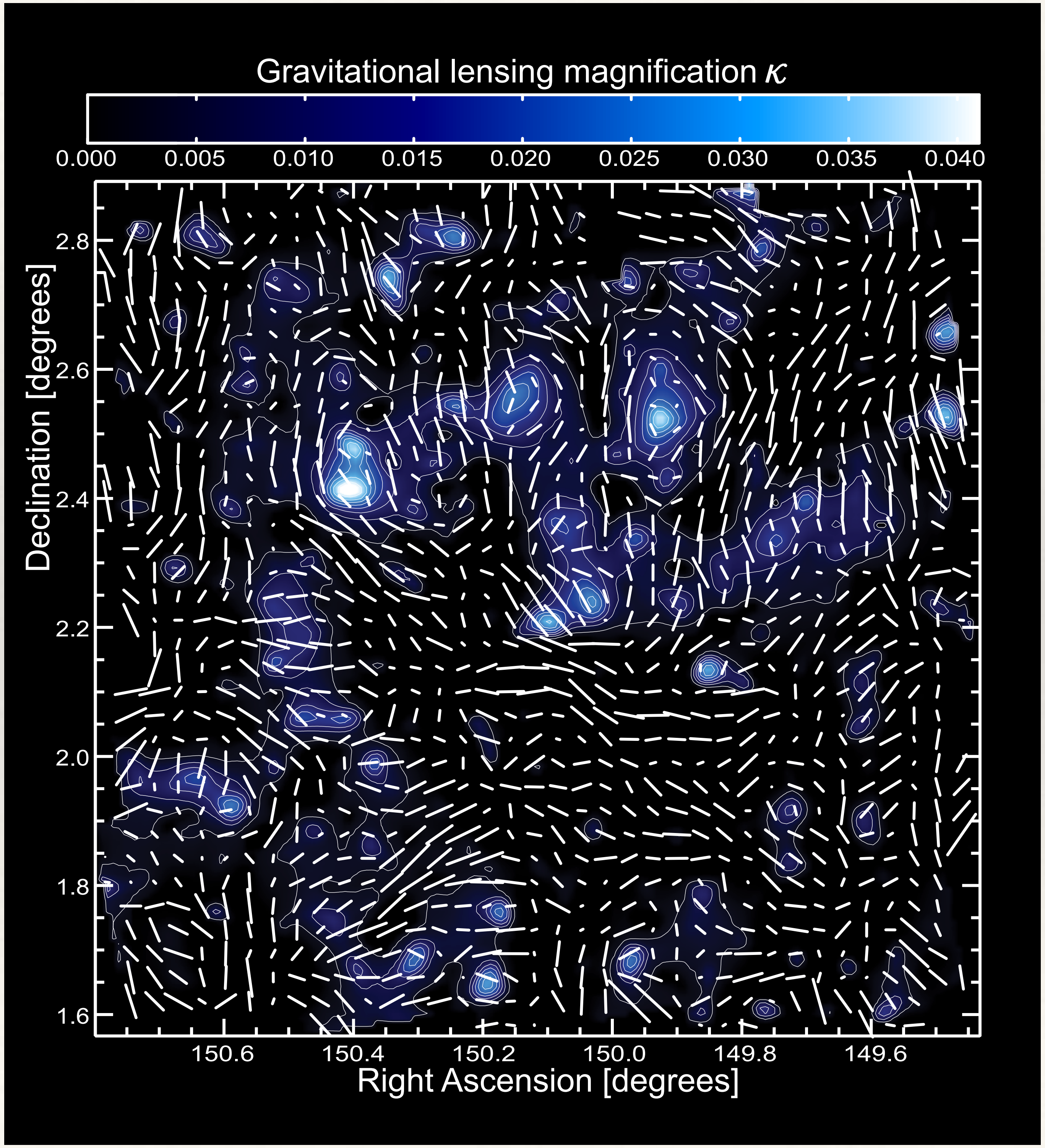
Sounds complicated, but you can do something similar "with your eye":



https://www.plygem.ca/wps/portal/ca/ideas-and-learning/learning/glass-technology

Gravitational Lensing Evidence for DM

- HST COSMOS field weak lensing project: generated a three-dimensional map that provides the first direct look at the large-scale distribution of dark matter in the universe.
- The map reveals a loose network of **filaments** that grew over time and intersect in massive structures at the locations of clusters of galaxies
- The map stretches halfway back to the beginning of the universe and shows how dark matter has grown increasingly "clumpy" as it collapses under gravity
- The dark matter map was constructed by measuring the shapes of half a million faraway galaxies



Richard Massey / Nature

nature 445, 229–338 18 January 2007
www.nature.com/nature
no.7125 npg

18 January 2007 | www.nature.com/nature | $10

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

nature

NEUROBIOLOGY
Robots that think they're insects

PANDEMIC FLU
Why the 1918 outbreak was so deadly

MOLECULAR MAGNETS
An attractive proposition

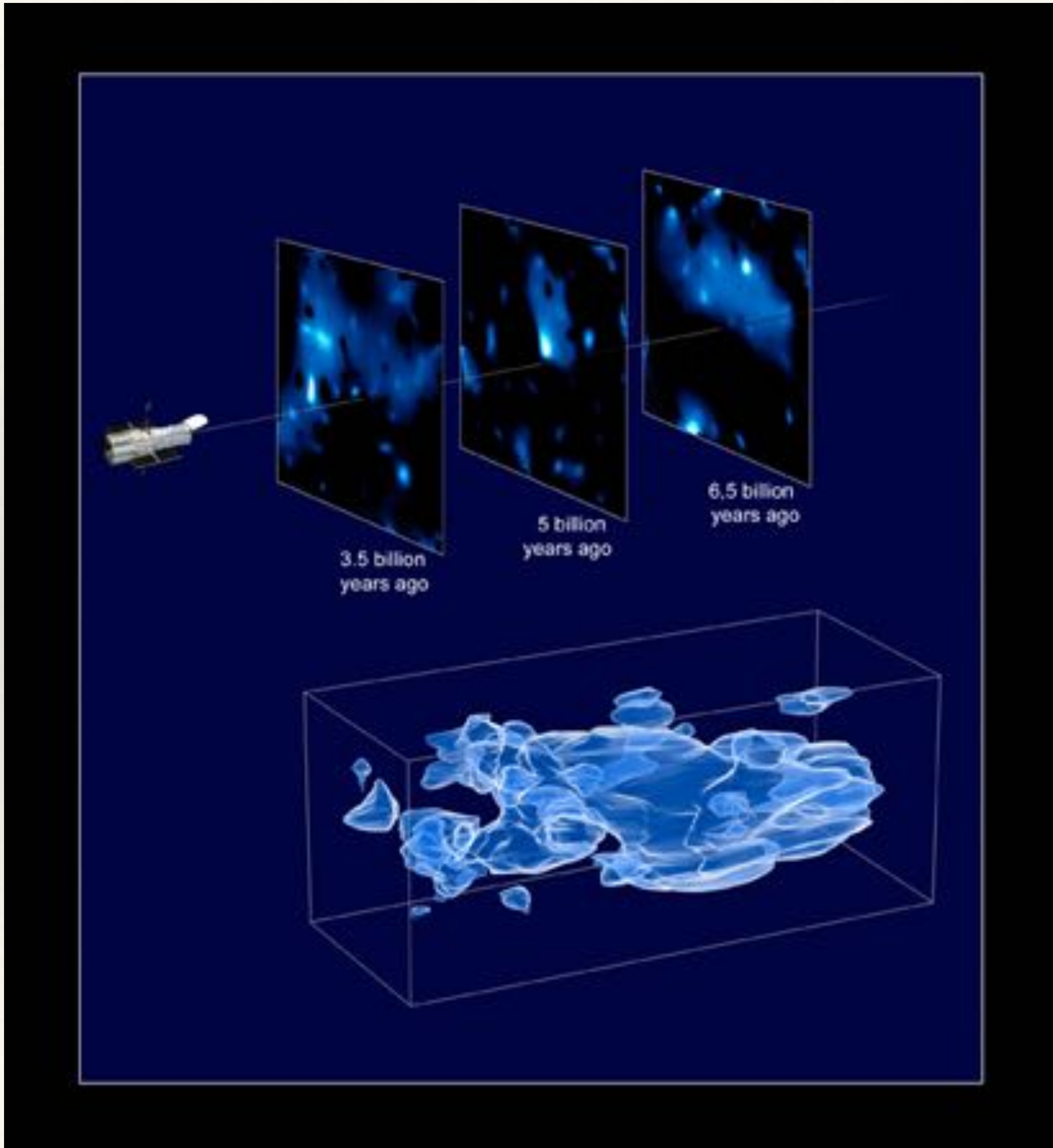
THE UNSEEN UNIVERSE

Dark matter maps reveal cosmic scaffolding

NATUREJOBS
Beating retirement

$10.00US $12.99CAN
03>

Gravitational Lensing Evidence for DM



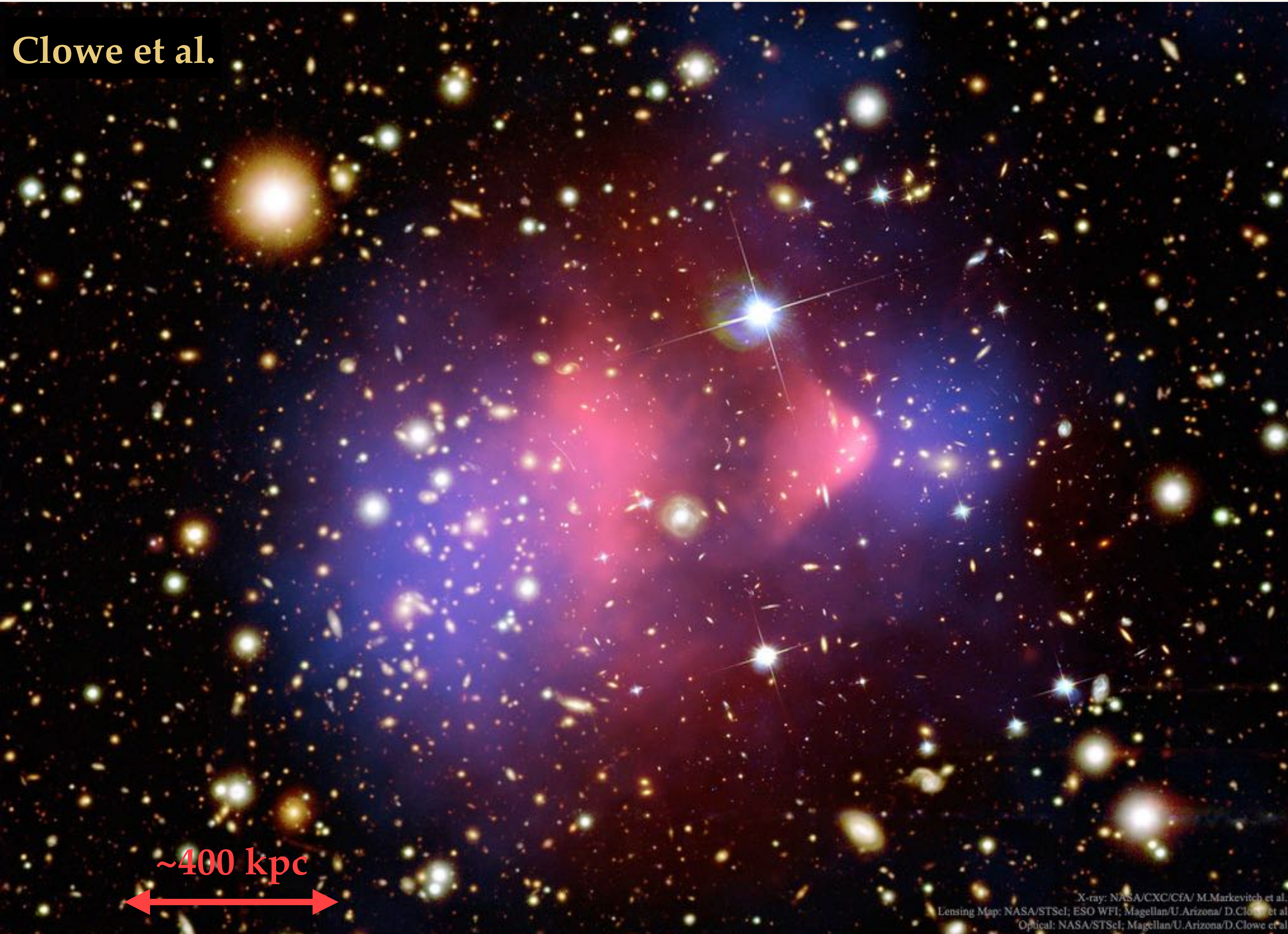
Richard Massey / American Scientist

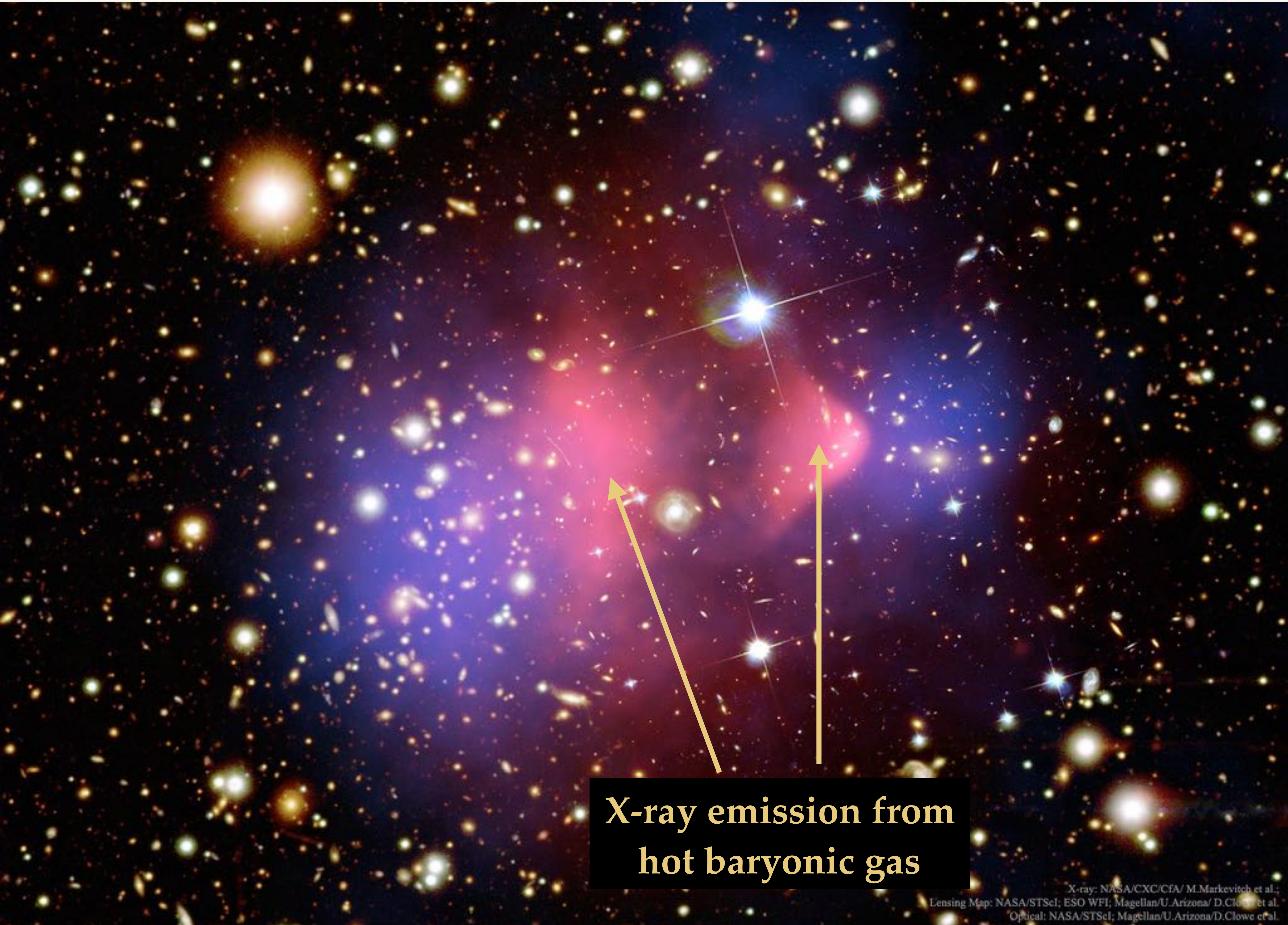
The Bullet Cluster

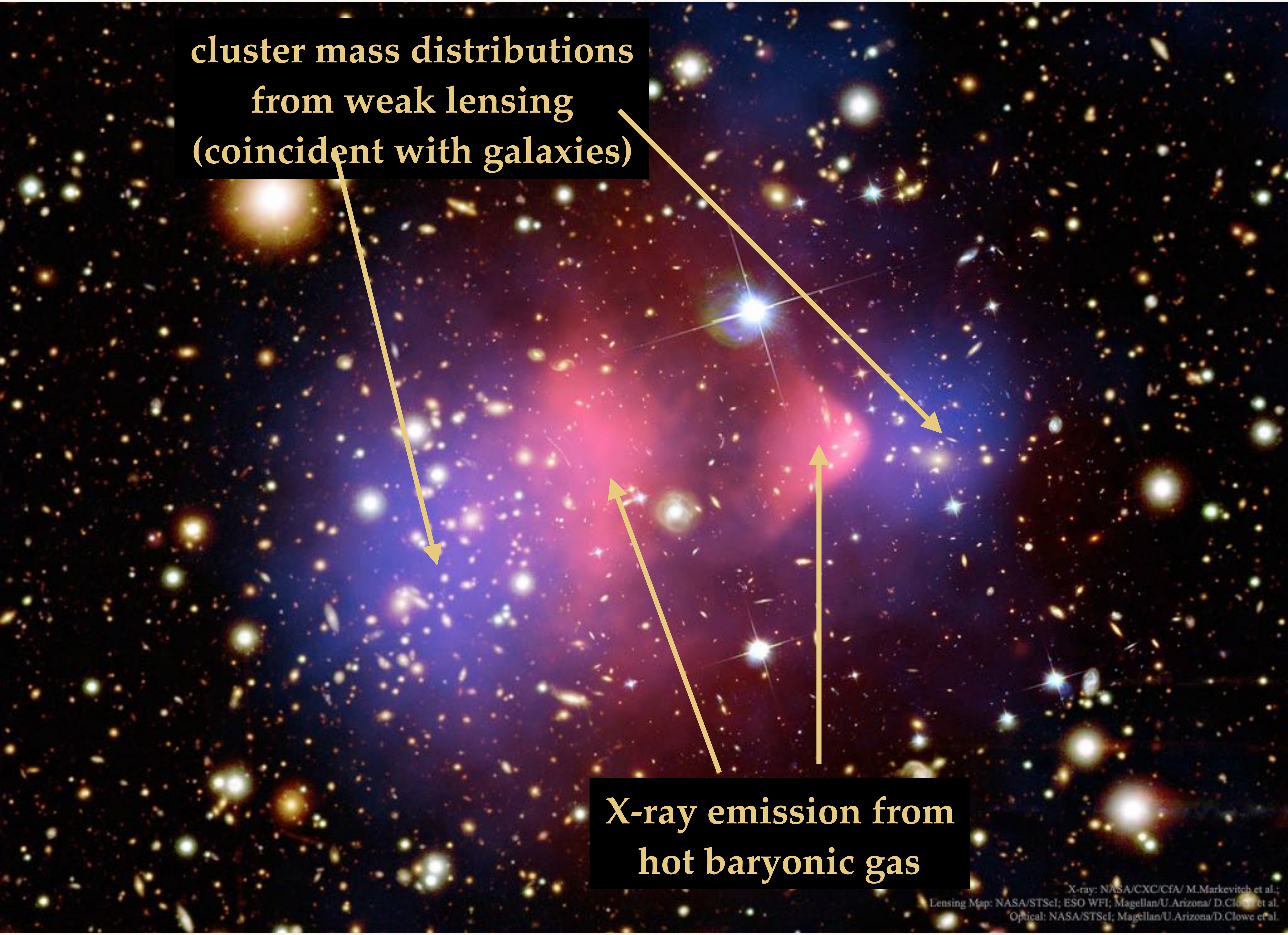
A Smoking Gun for DM?

The Bullet Cluster

- The Bullet Cluster is a pair of galaxy clusters that collided ~100 Myr ago
- First example system where *centre of mass* and *centre of baryons* are distinctly separate from each other as demonstrated by combination of *X-ray* and *weak lensing* data


Clowe et al.
~400 kpc
X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Cl et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

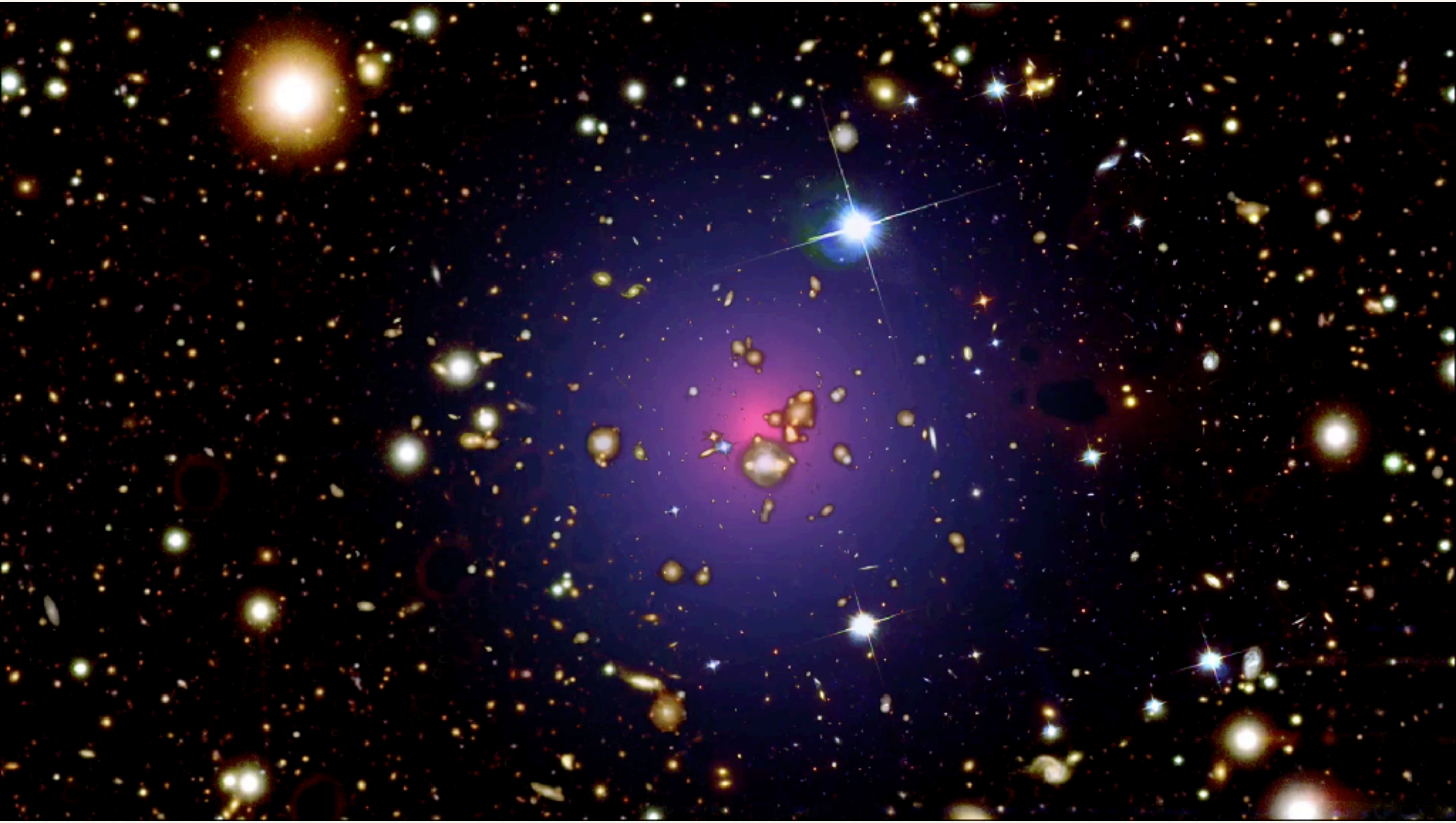

X-ray emission from
hot baryonic gas
X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

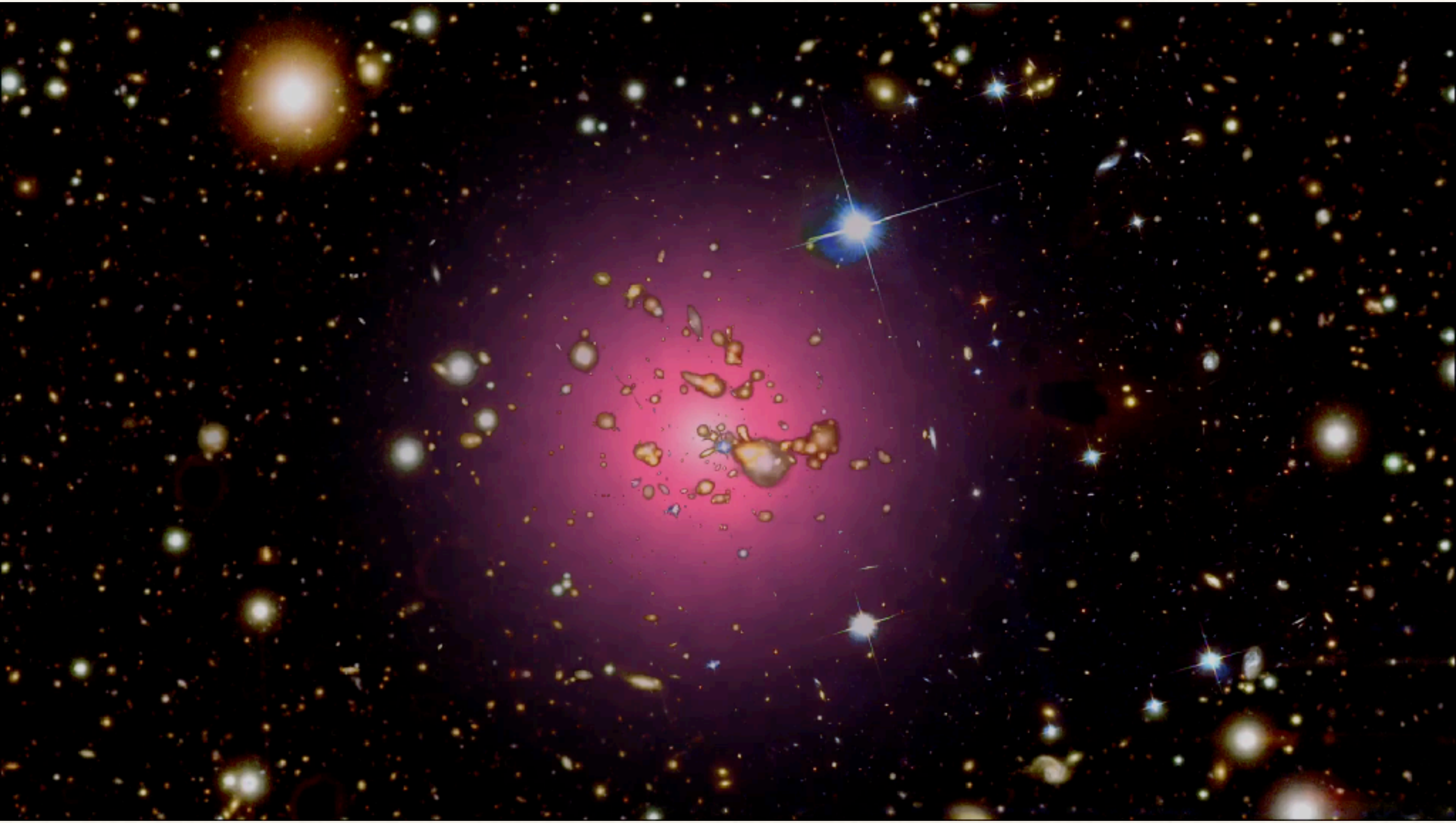

cluster mass distributions
from weak lensing
(coincident with galaxies)
X-ray emission from
hot baryonic gas
X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

The Bullet Cluster

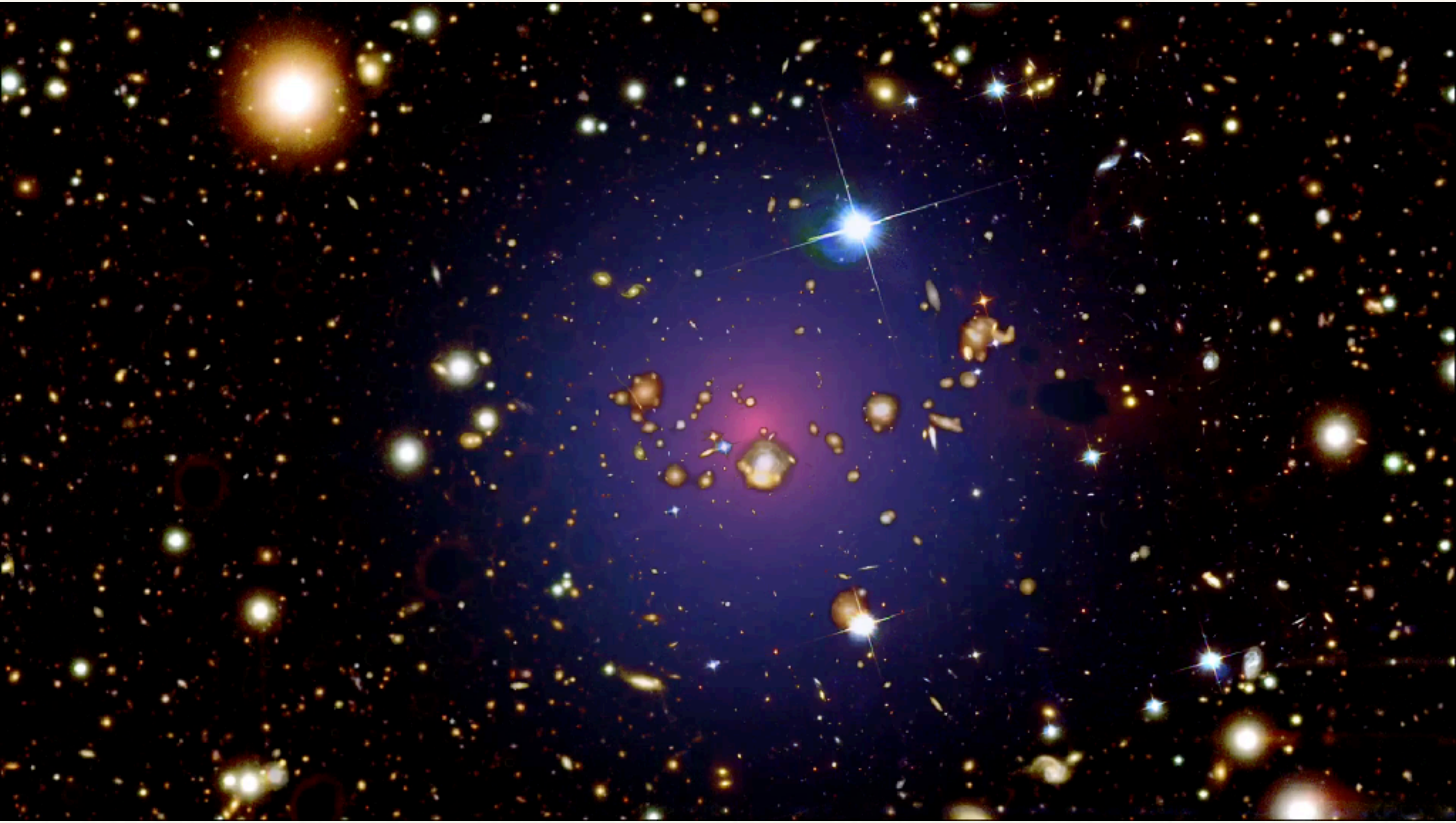
Simulations by Andrew Robertson, Durham

Andrew Robertson, Durham





Simulation where the total masses of the two clusters were the same as in the CDM simulations, but made entirely out of gas (except for the small component of stellar mass).

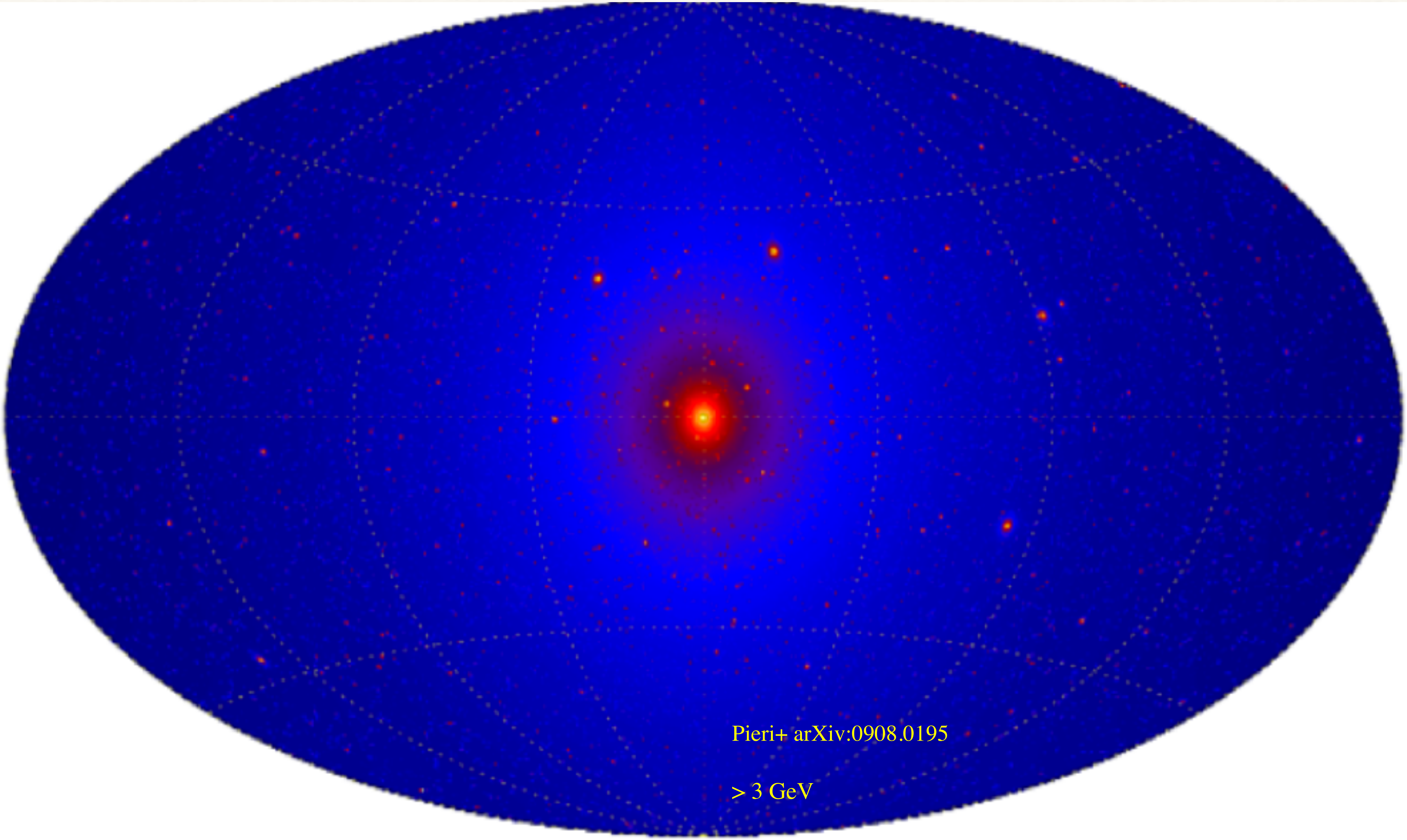


Extra Slides

My research

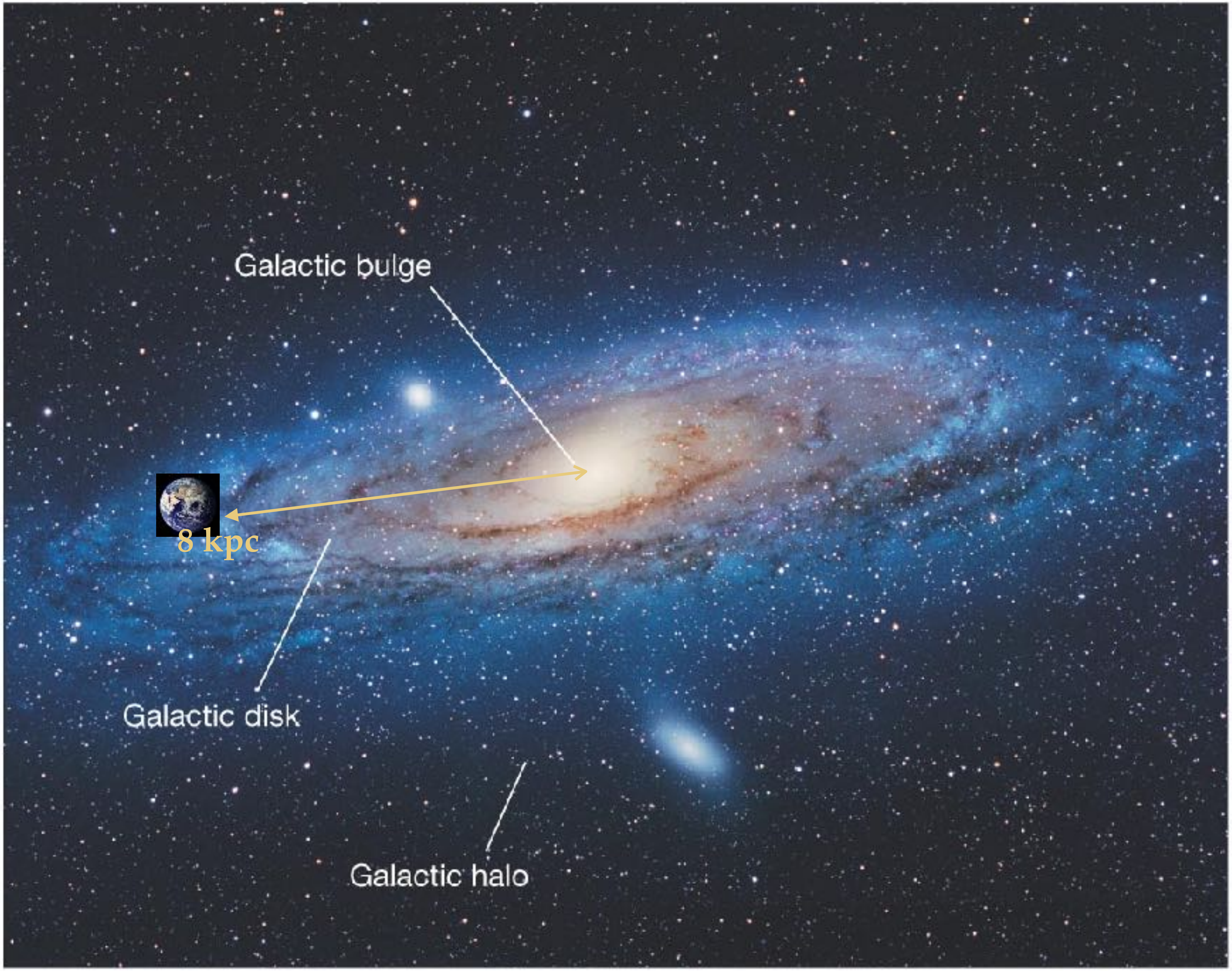
Why is the Galactic Centre interesting for (e.g.) a particle physicist?

- High dark matter density should mean that the Galactic Centre is one of the best places in the sky to seek indirect evidence of its annihilation (Bergström+97)

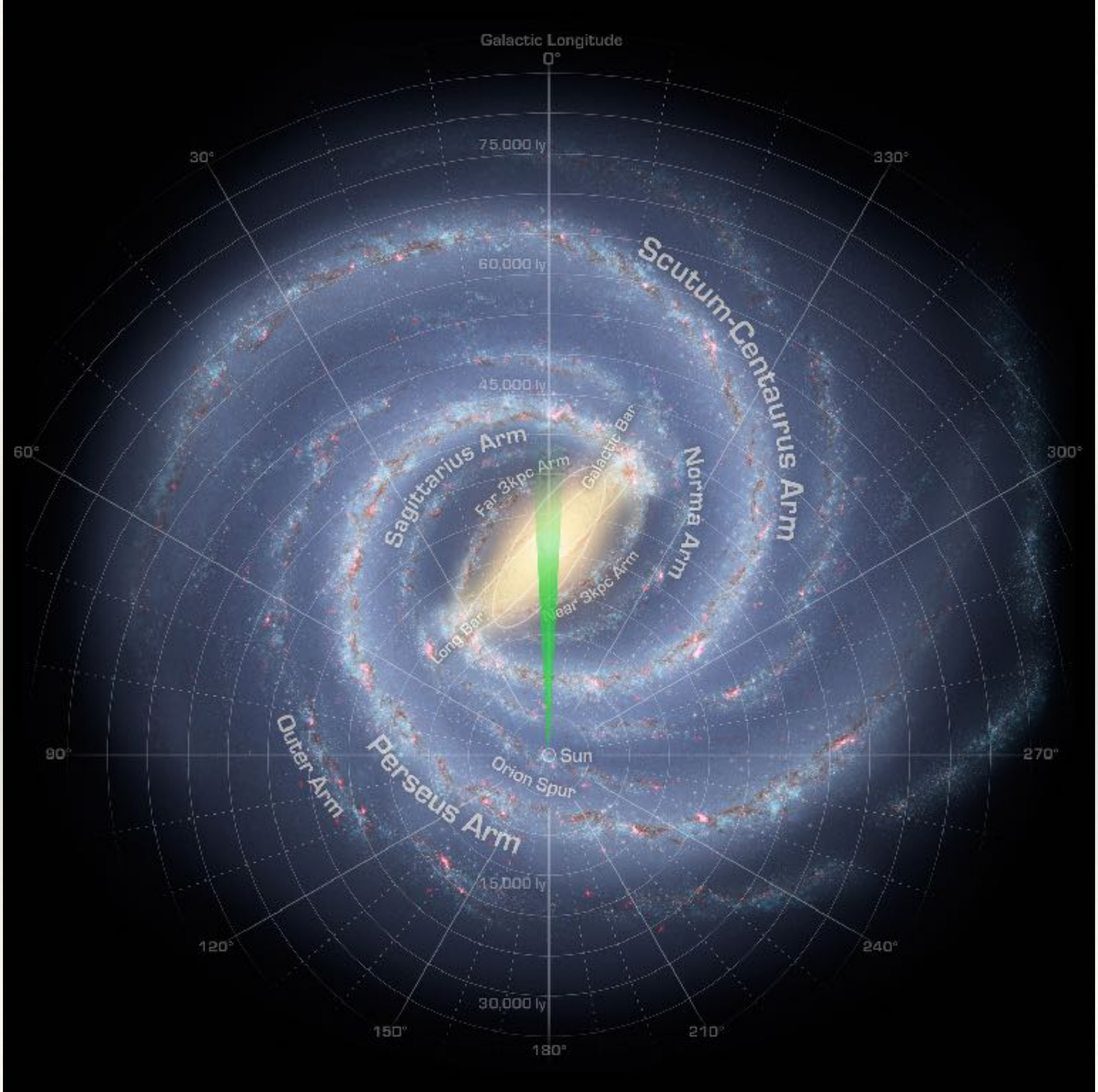

Pieri+ arXiv:0908.0195
> 3 GeV

Preface: why is the Galactic Centre interesting?

- High dark matter density should mean that the Galactic Centre is one of the best places in the sky to seek indirect evidence of its annihilation (Bergström+97)
- On the other hand:



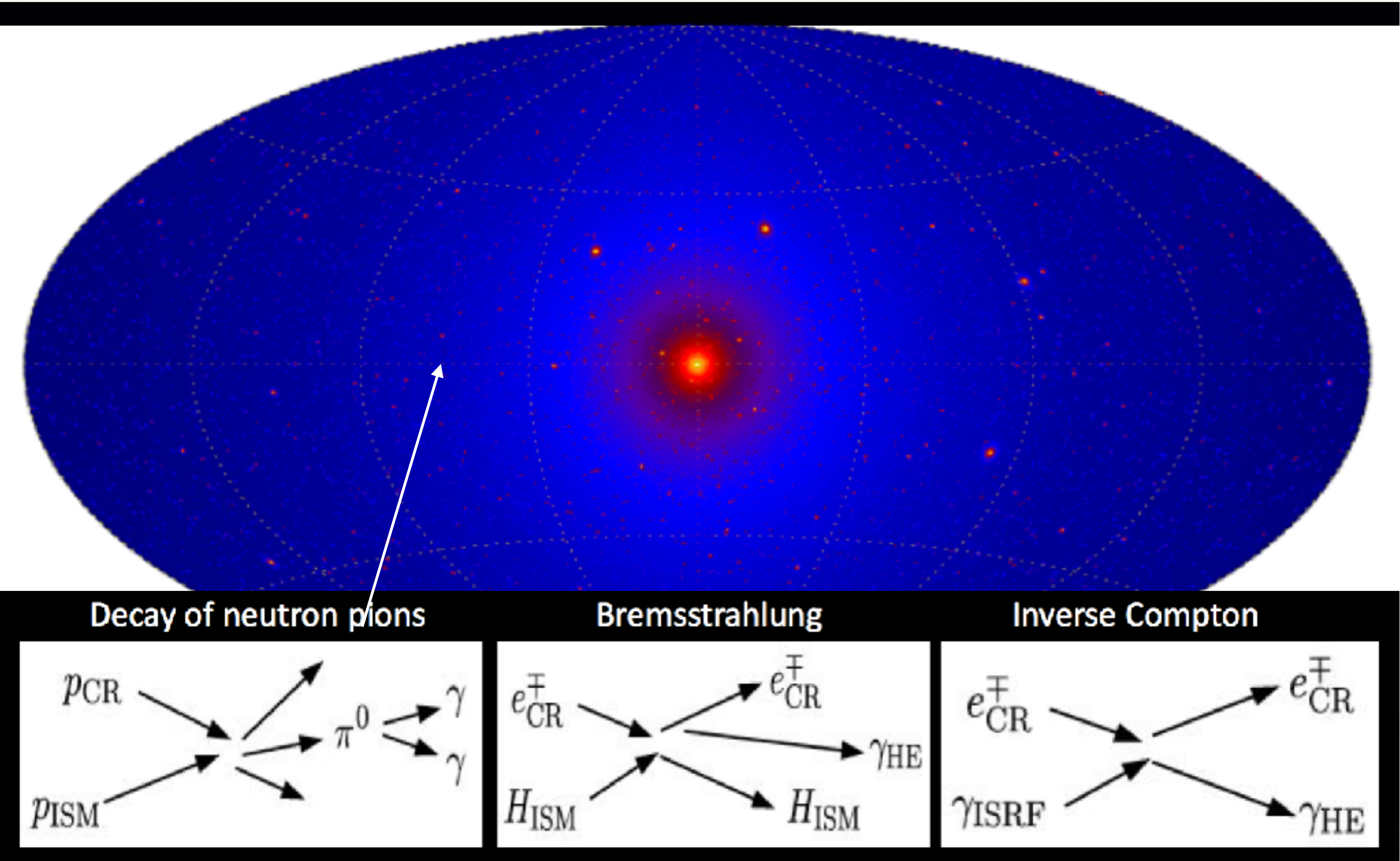
(a)


Galactic Longitude
0°
75,000 ly
60,000 ly
45,000 ly
30°
330°
60°
300°
90°
270°
120°
240°
150°
210°
180°
15,000 ly
30,000 ly
Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Near 3kpc Arm
Long Bar
Sun
Orion Spur
Perseus Arm
Outer Arm

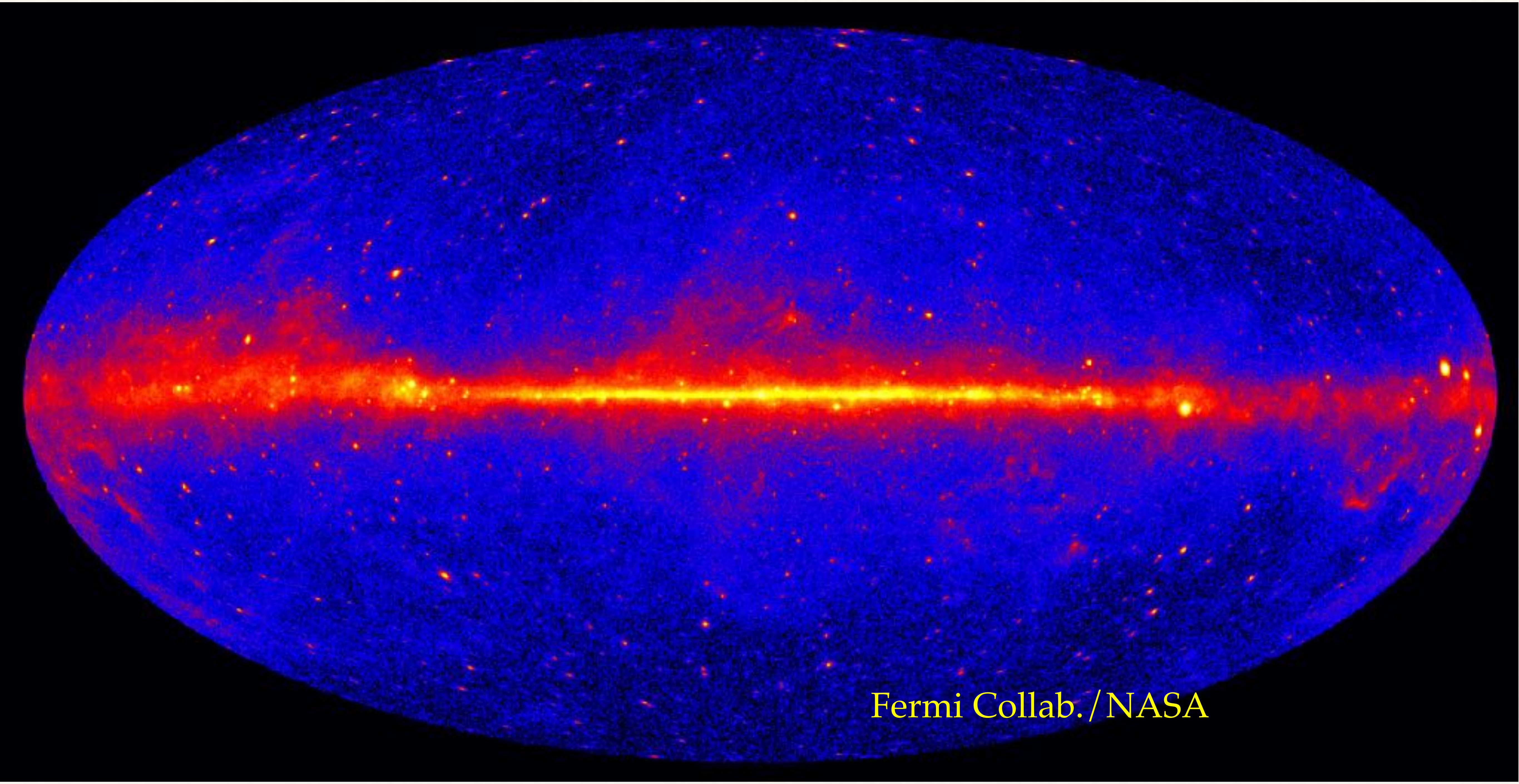

ESO

Preface: why is the Galactic Centre interesting?

- High dark matter density should mean that the Galactic Centre is one of the best places in the sky to seek indirect evidence of its annihilation (Bergström+97)
- On the other hand:
  - There's a lot of Galaxy between us and the GC



Decay of neutron pions
Bremsstrahlung
Inverse Compton
p_{CR}
p_{ISM}
π^0
γ
γ
$e^{\mp}_{CR}$
$e^{\mp}_{CR}$
H_{ISM}
γ_{HE}
H_{ISM}
$e^{\mp}_{CR}$
$e^{\mp}_{CR}$
γ_{ISRF}
γ_{HE}


Fermi Collab./NASA

Preface: why is the Galactic Centre interesting?

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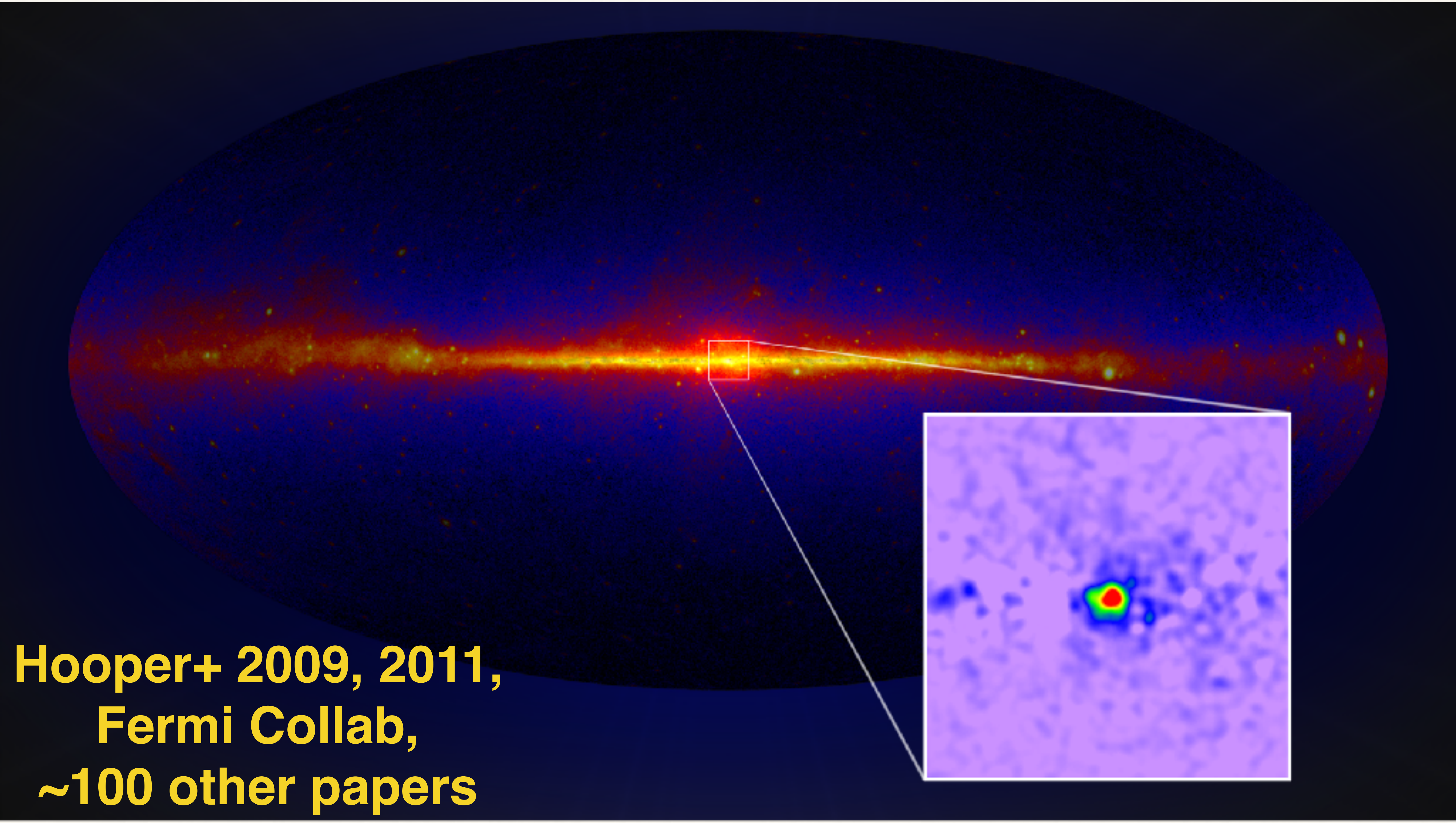
- On the other hand:
  - There's a lot of Galaxy between us and the GC

Galactic Centre: Dark Matter (?)

Galactic Centre Dark Matter(?)

- Dark matter motivated searches for anomalous signals from the GC have done remarkably well in turning up such signals

Galactic Centre Excess



Hooper+ 2009, 2011,
Fermi Collab,
~100 other papers

Galactic Center Excess (GCE)

From the Galactic Center out to mid-latitudes

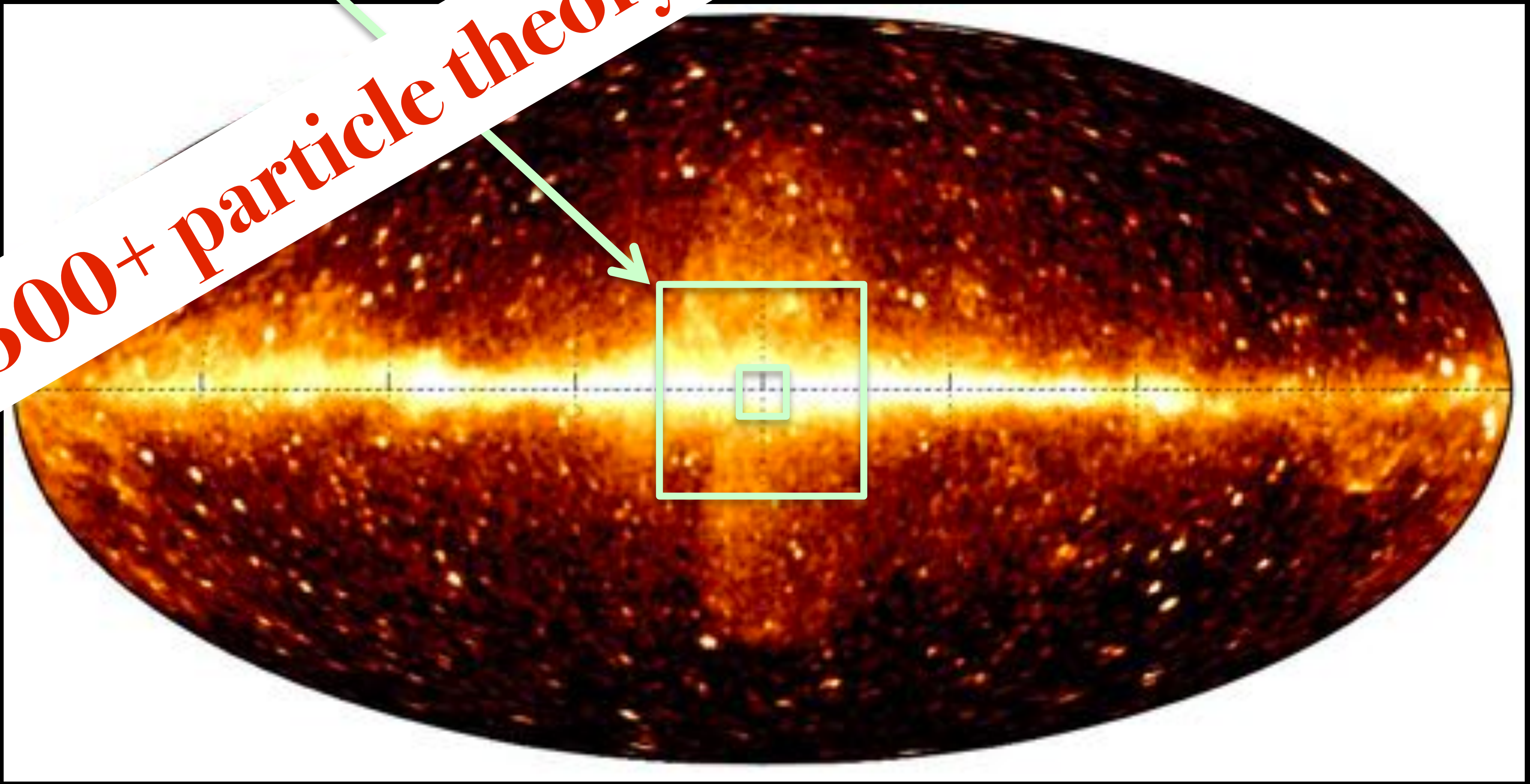
Goodenough & Hooper (2009)
Vitale & Morselli (2009)
Hooper & Goodenough (2011)
Hooper & Linden (2011)
Boyarsky et al (2011)
Abazajian & Kaplinghat (2012)
Gordon & Macias (2013)
Hooper & Slatyer (2013)
Huang et al (2013)
Macias & Gordon (2014)
Abazajian et al (2014, 2015)
Calore et al (2014)
Zhou et al (2014)
Daylan et al (2014)
Selig et al (2015)
Huang et al (2015)
Gaggero et al (2015)
Carlson et al (2015, 2016)
Yand & Aharonian (2016)
Horiuchi et al (2016)
Lee et al (2016)
Bartels et al (2016)
Linden et al (2016)
Ackermann et al (2017)
Ajello et al (2017)
Macias et al (2017)
Bartels et al (2017)
...

(not a complete list)

Method

Found by morpholog… plate fitting

500+ particle theory papers



Fermi (2017)

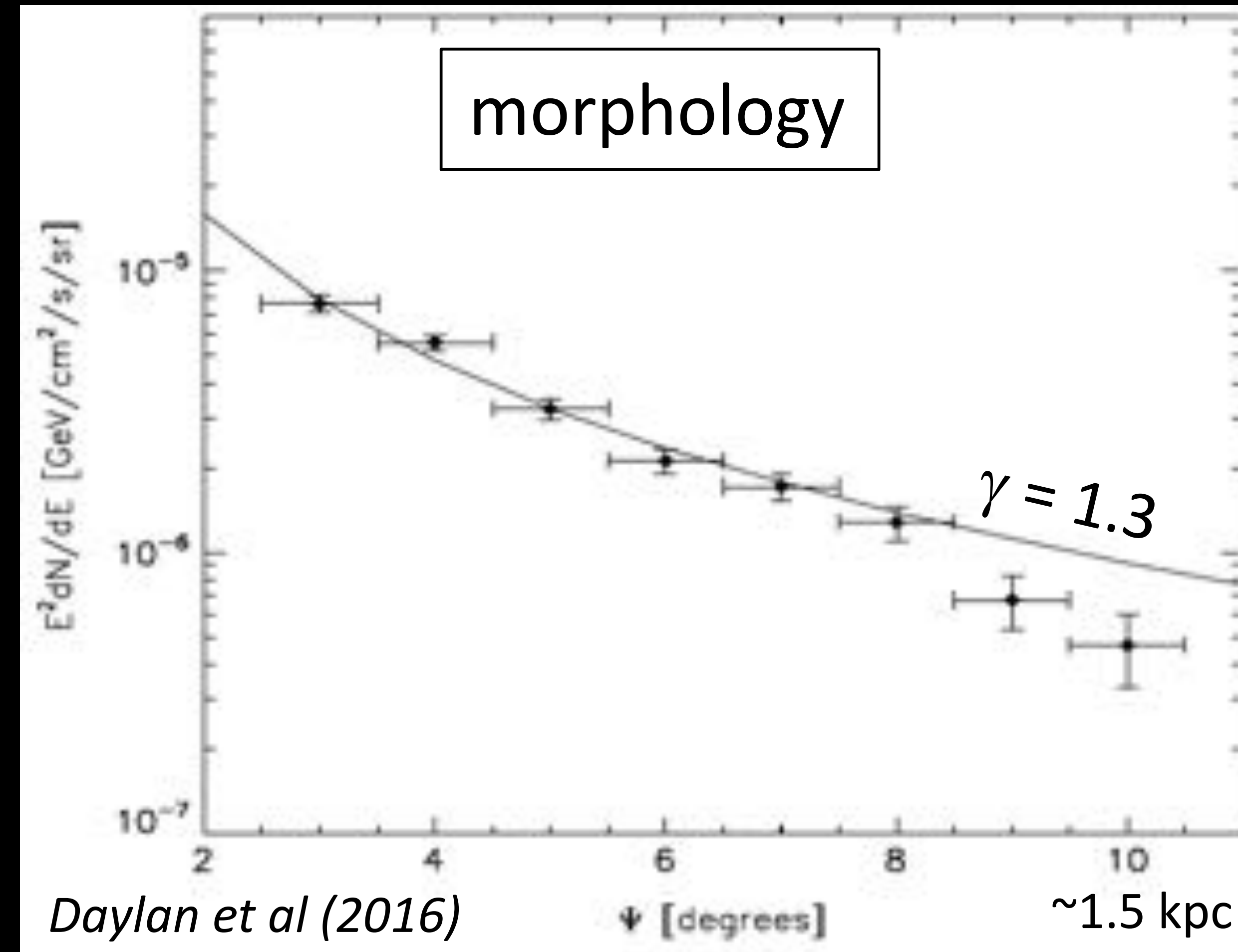
slide credit:

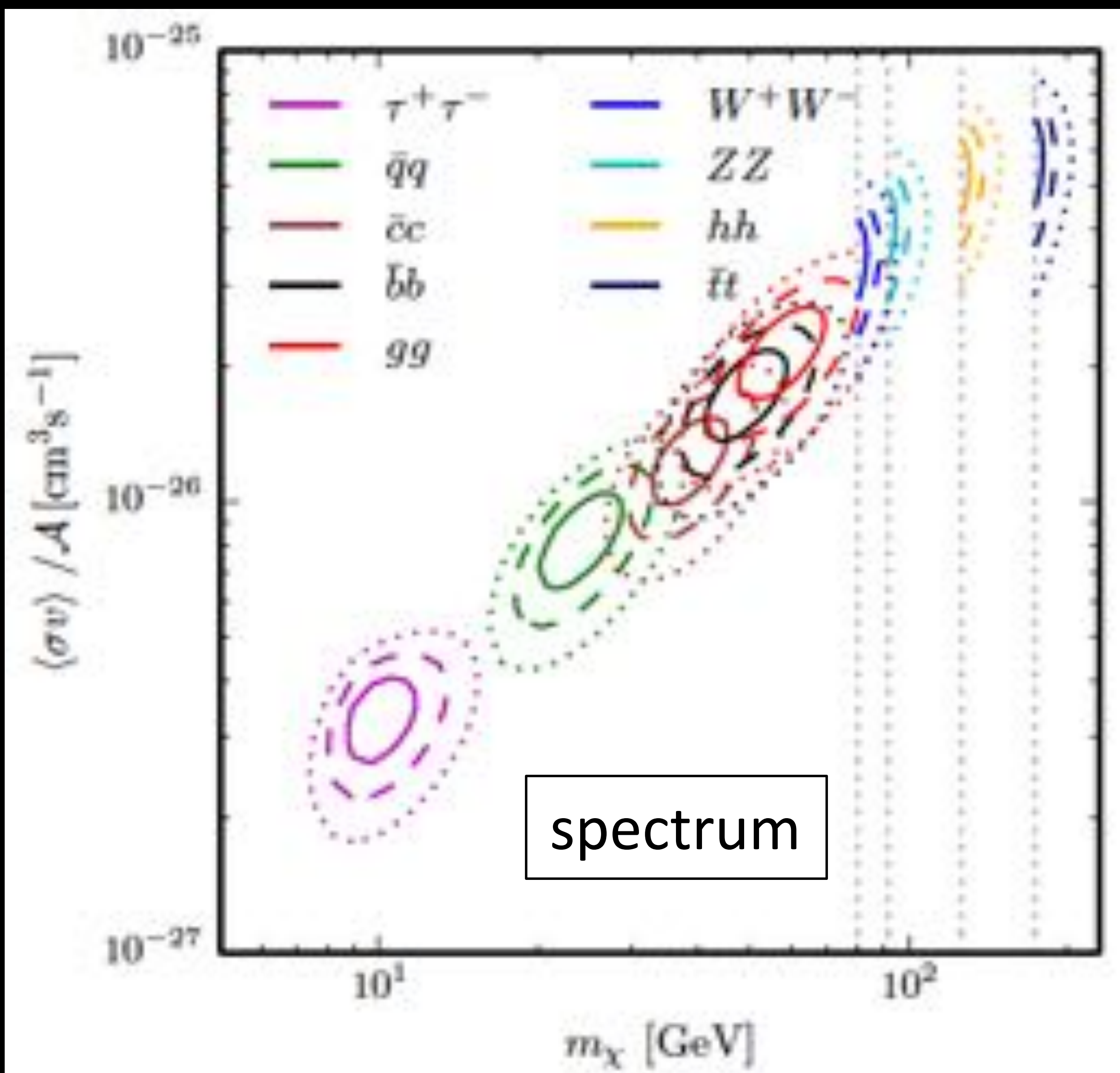
Shunsaku Horiuchi (Virginia Tech)

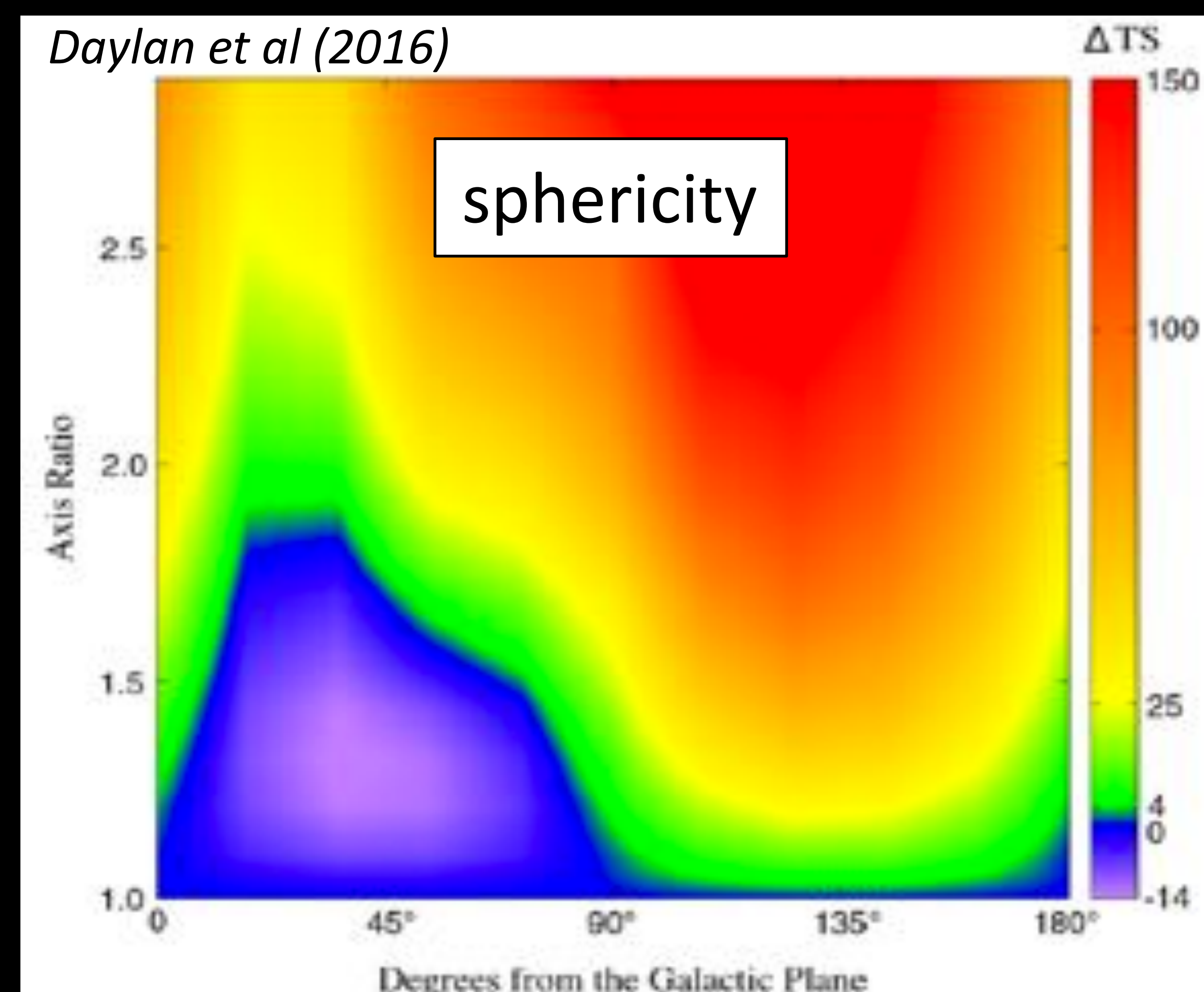
Dark Matter

Dark matter can explain the observations

Annihilation of thermally produced WIMPs explains the spectrum and morphology well







slide credit:
Shunsaku Horiuchi (Virginia Tech)

Calore et al (2014)

Three points about the GCE

- The signal is spectrally similar to that detected from pulsars and millisecond pulsa[illegible]Ps)
- Photon count statistics [illegible] sub-threshold point sources are contrib[illegible]100% of the signal
- (Macias+2018) [illegible] is spatially correlated with old stellar population of the Inner Galaxy

...to be continued

Figure 2: Evidence for dark matter. In the top panel we show the angular velocity measurements from the compilation shown in Fig. 1 (red dots) together with the bracketing of the contribution of all baryonic models (grey band) as a function of galactocentric distance. Error bars correspond to 1σ uncertainties, while the grey band shows the envelope of all baryonic models including 1σ uncertainties. The contribution of a fiducial baryonic model is marked with the black line. The residuals between observed and predicted angular velocities for this baryonic model are shown in the middle panel. The dashed blue line shows the contribution of a Navarro-Frenk-White profile with scale radius of 20 kpc normalised to a local dark matter density of 0.4 GeV/cm^3. The bottom panel displays the cumulative reduced χ^2 for each baryonic model as a function of galactocentric distance. The black line shows the case of the fiducial model plotted in black in the top panel, while the thick red line represents the reduced χ^2 corresponding to 5σ significance. In this figure we assume a distance to the galactic centre $R_0 = 8$ kpc and a local circular velocity $v_0 = 230$ km/s, and we ignore all measurements below $R_{cut} = 2.5$ kpc.