Introduction to Dark Matter

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IFIC, CSIC-U. Valencia

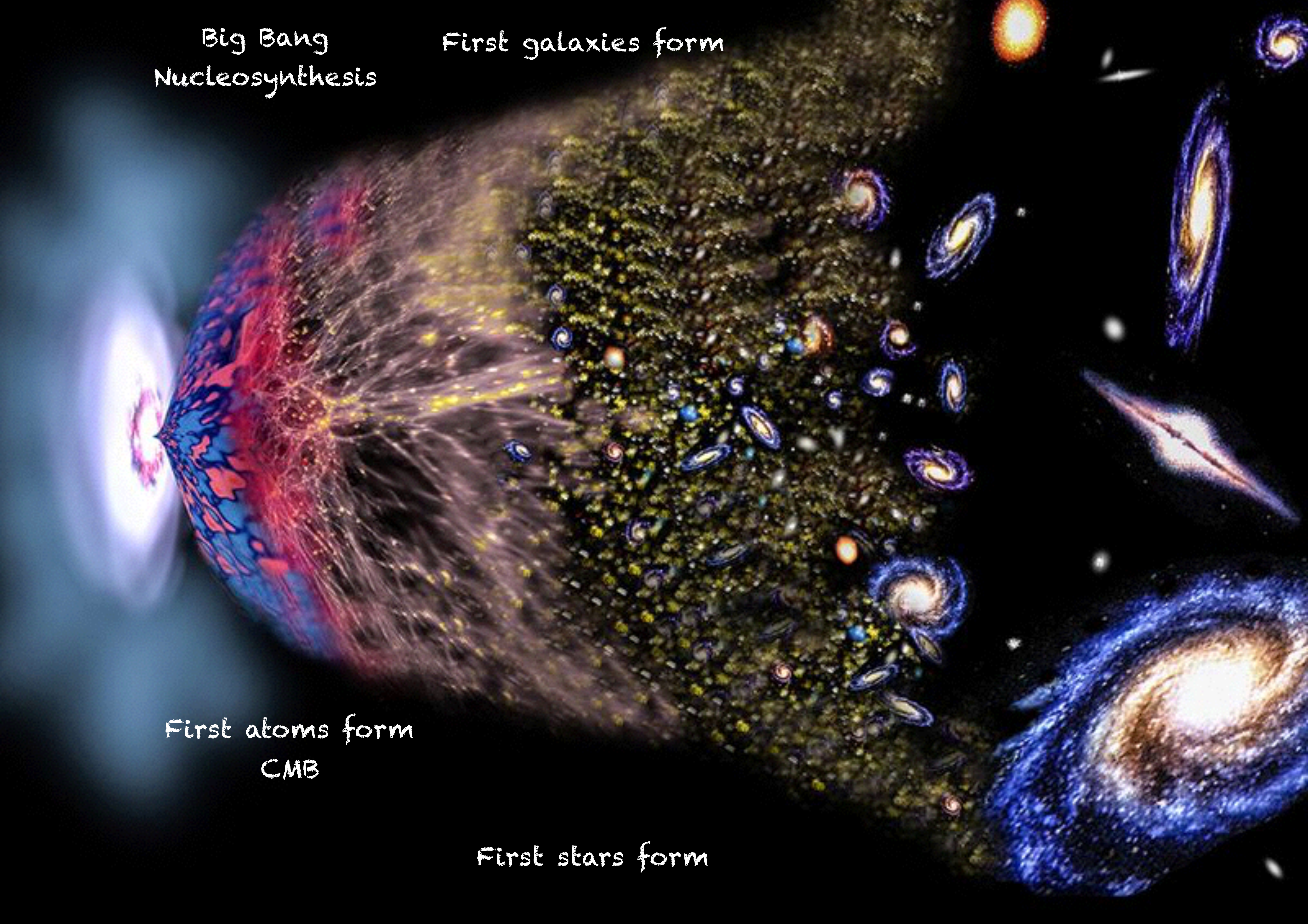
8th IDPASC School,
Valencia, May 21-31, 2018

Plan of lectures

I Evidences and generalities

II Non-gravitational searches

LOOKING BACK IN TIME



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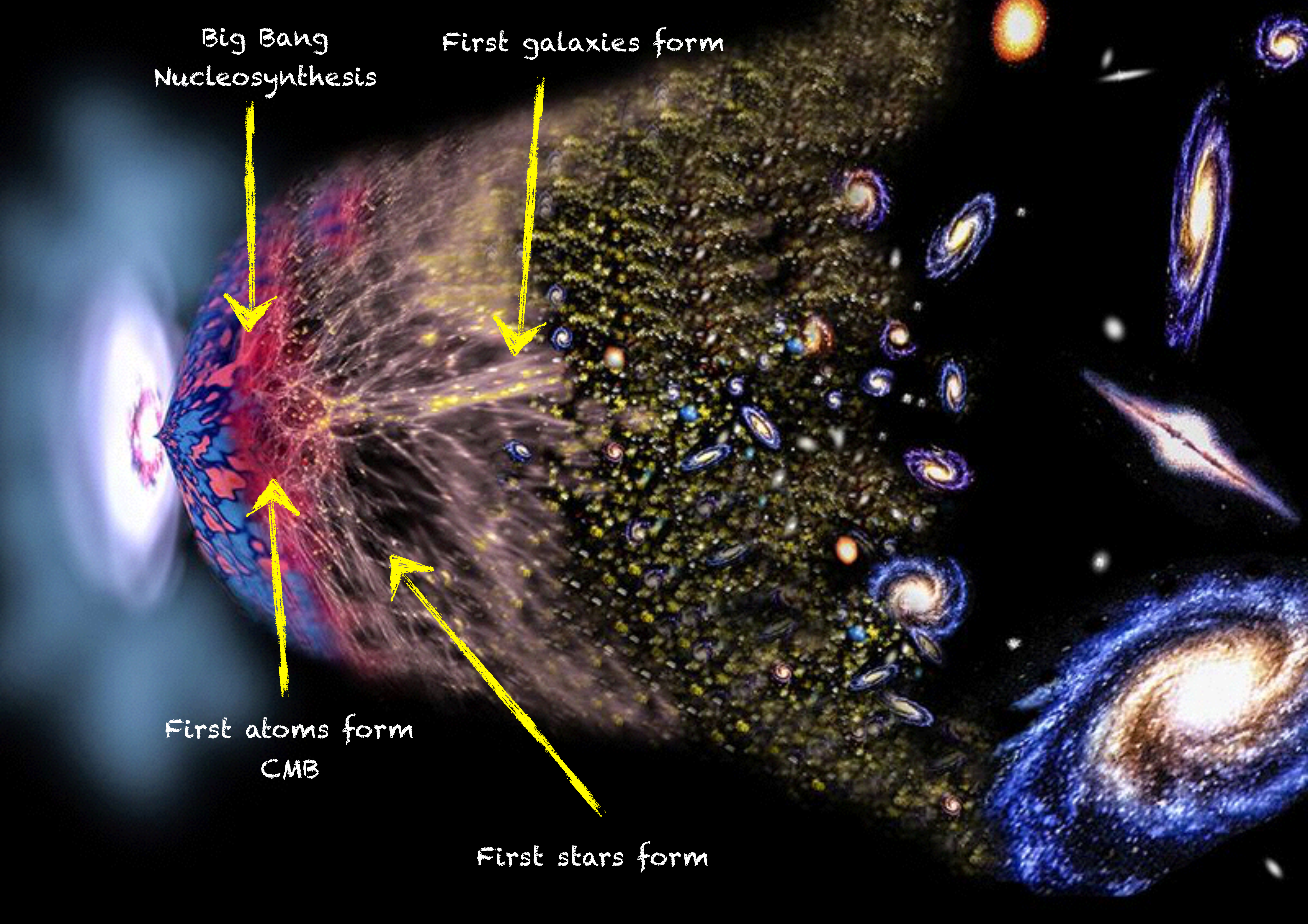

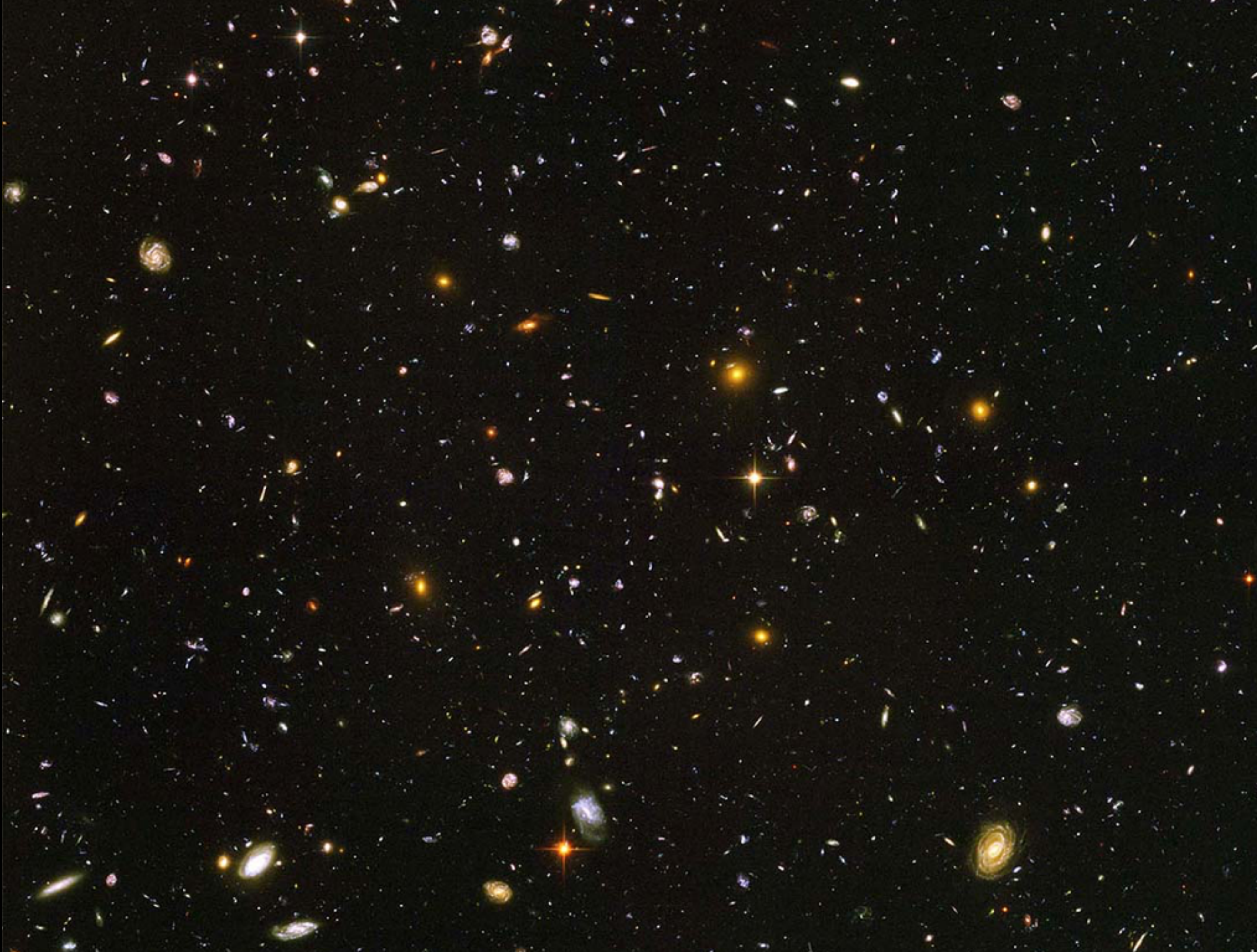


ORDINARY MATTER
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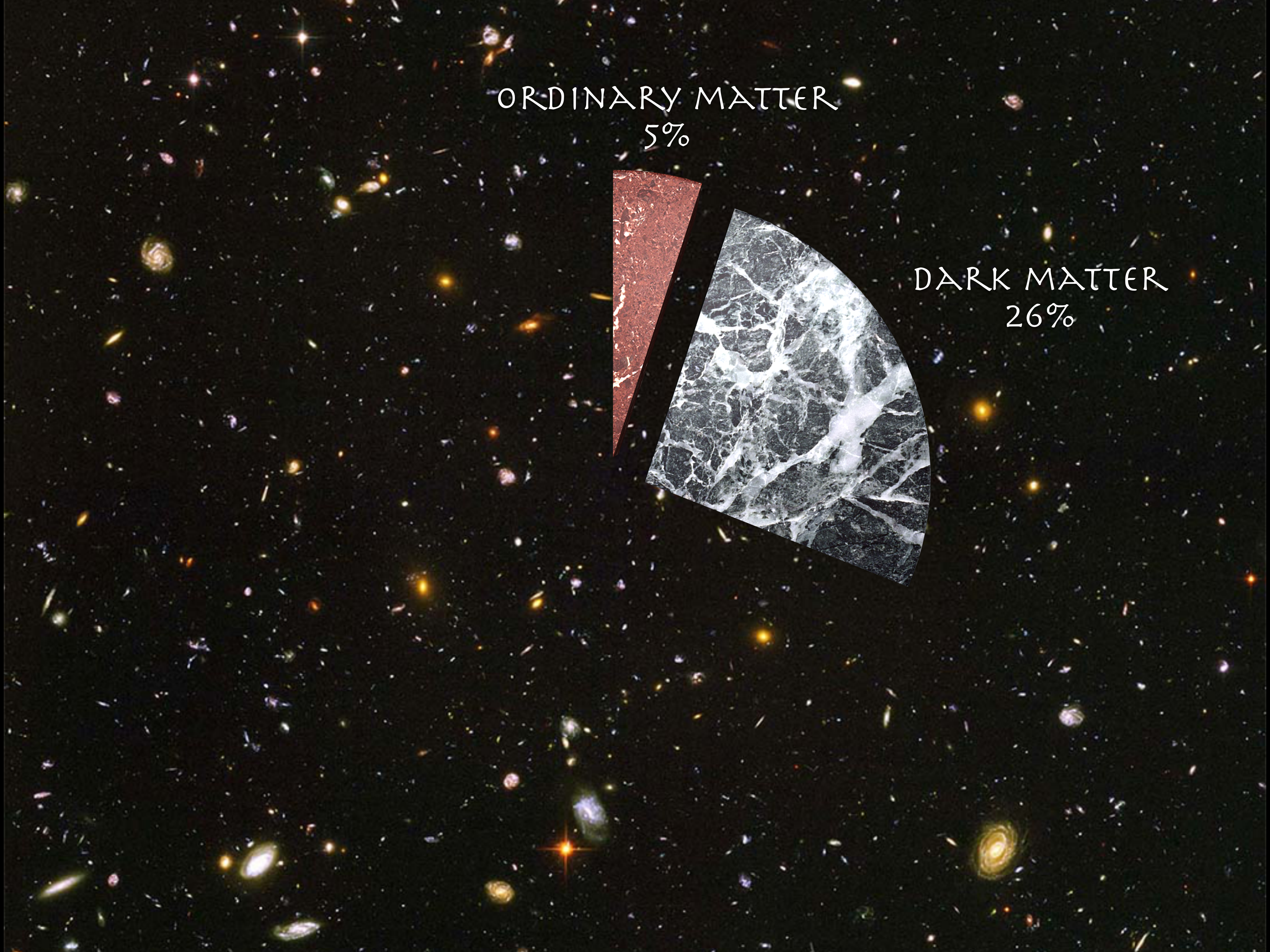
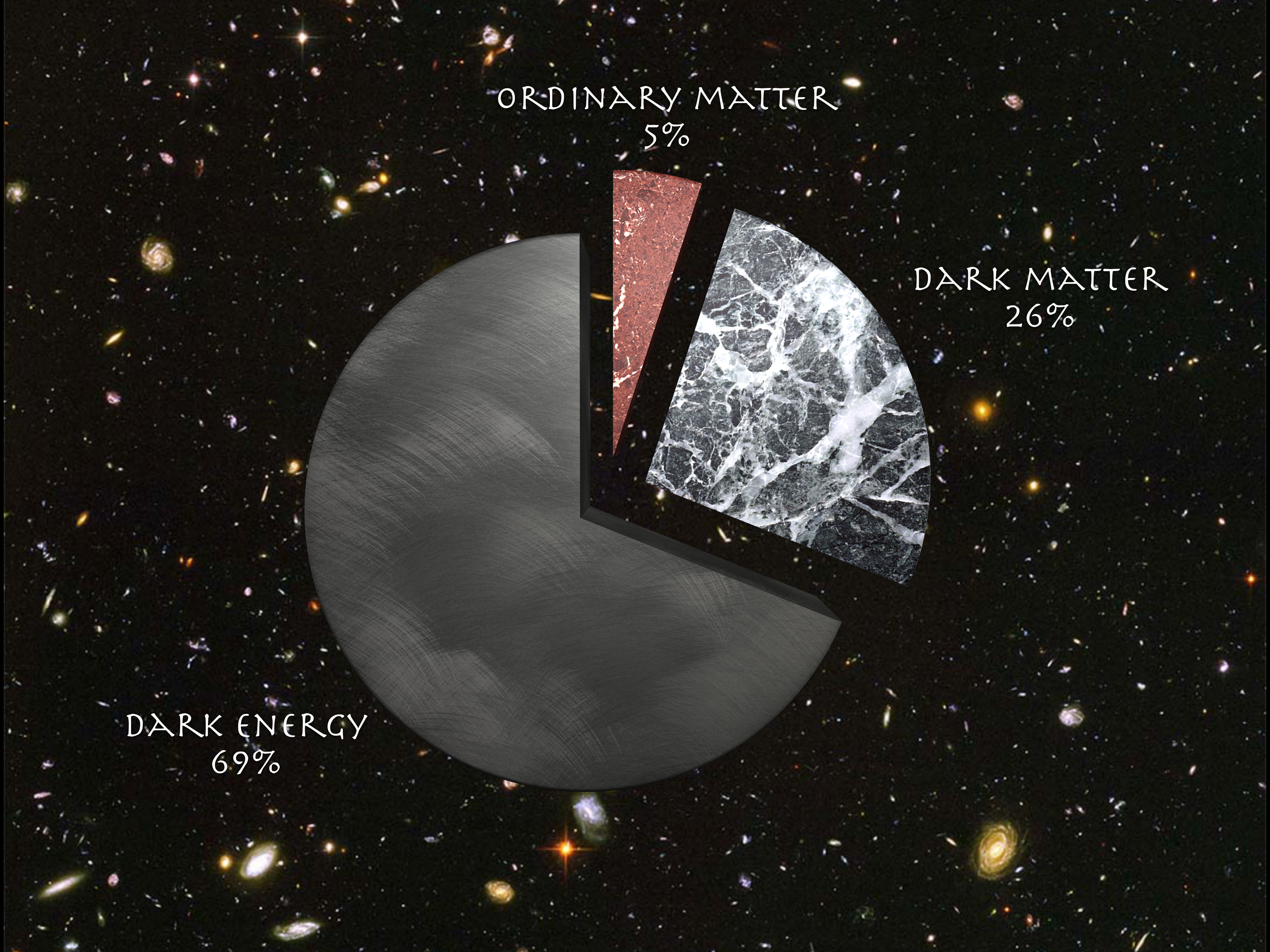

ORDINARY MATTER
5%
DARK MATTER
26%


ORDINARY MATTER
5%
DARK MATTER
26%
DARK ENERGY
69%

HOW DO WE INFER THE EXISTENCE OF DARK MATTER?

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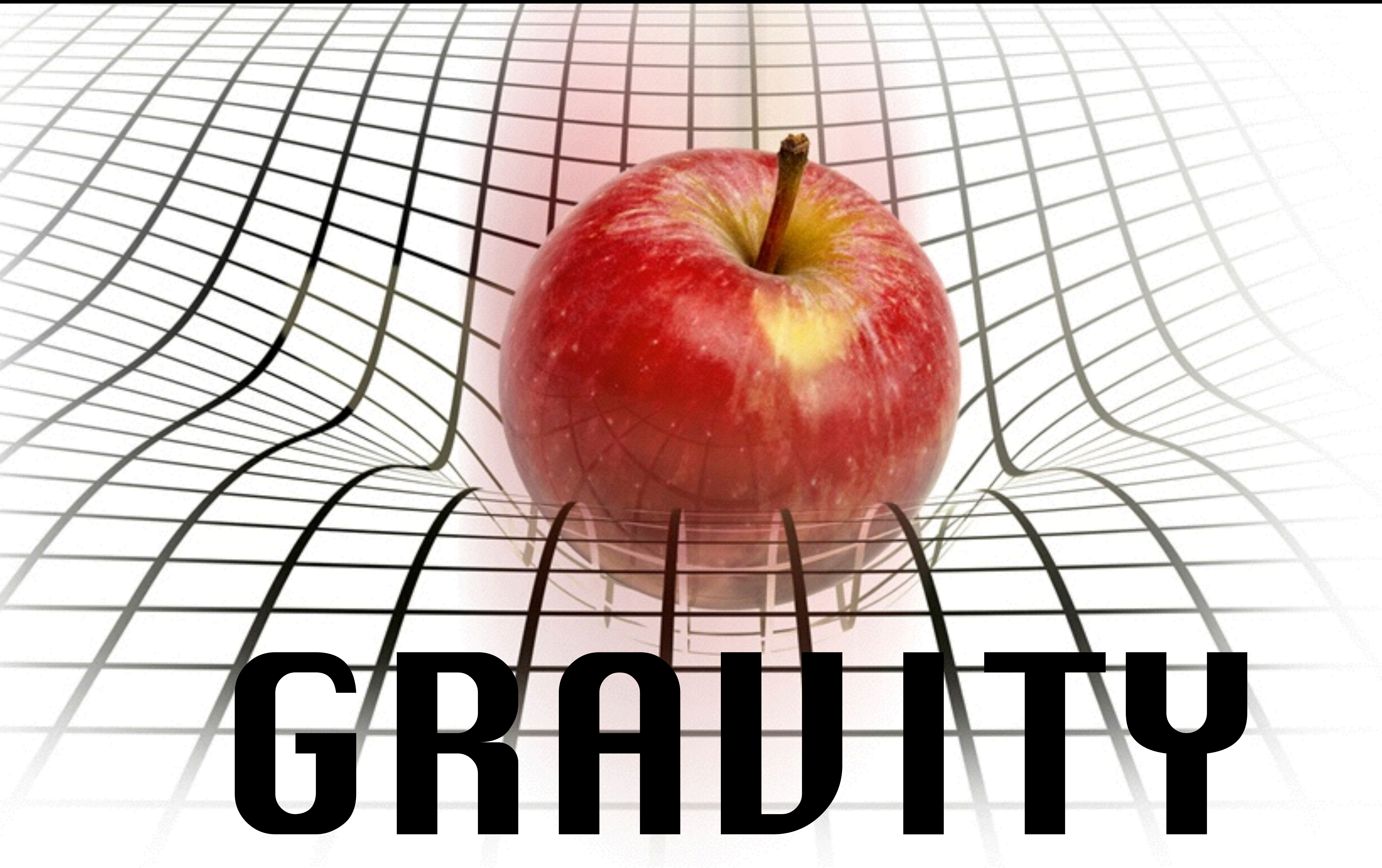


HOW DID WE FIRST INFER THE EXISTENCE OF DARK MATTER?

Anomalies in gravitationally-inferred properties of astrophysical objects:

in the limit of weak gravitational fields (most astronomical objects), GR → Newtonian gravity

How does a system react to gravity?

$$F = m\,a$$

If the force is not resisted the system would collapse: rotation or pressure

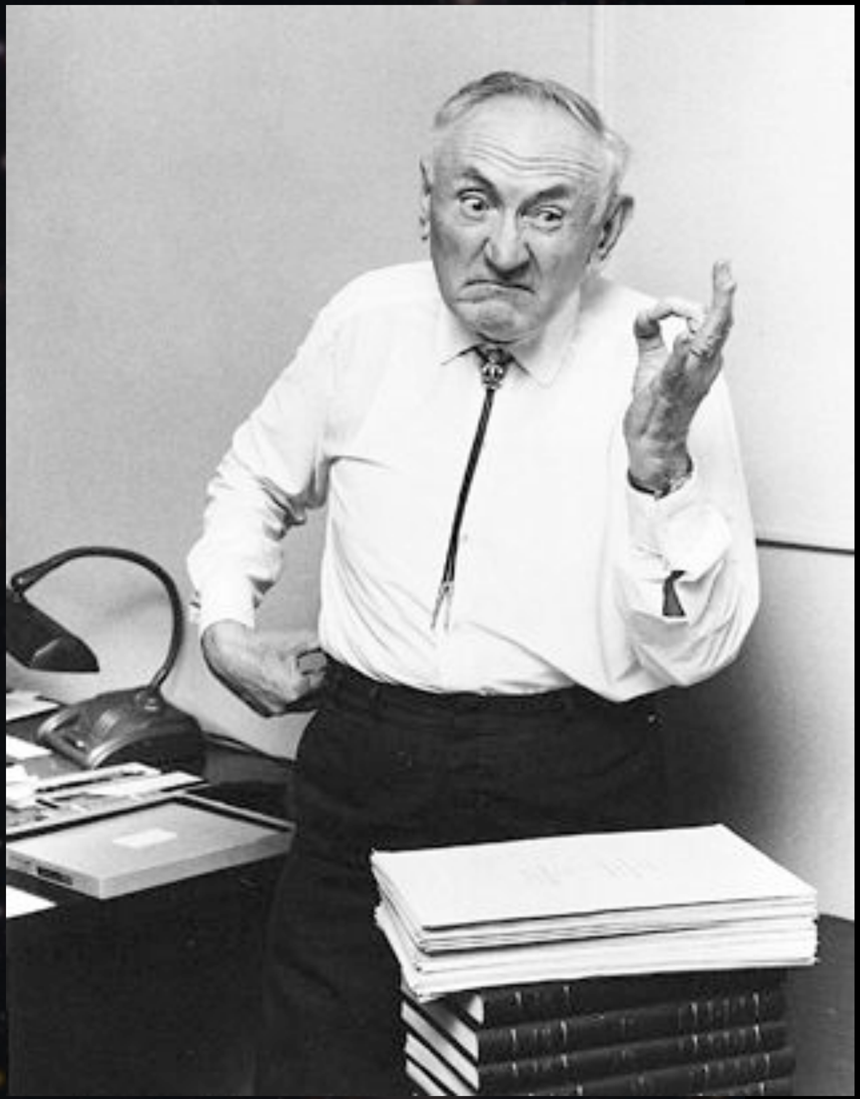
If the system is rotationally supported (spiral galaxies): rotation curves

If the system is pressure-supported (clusters of galaxies): virial theorem

CLUSTERS

FRITZ ZWICKY (1898-1974)

1933 : first time the words Dark Matter were used in the modern sense along with data supporting its existence



He estimated the mass from the virial theorem using the velocities of the galaxies in the Coma cluster

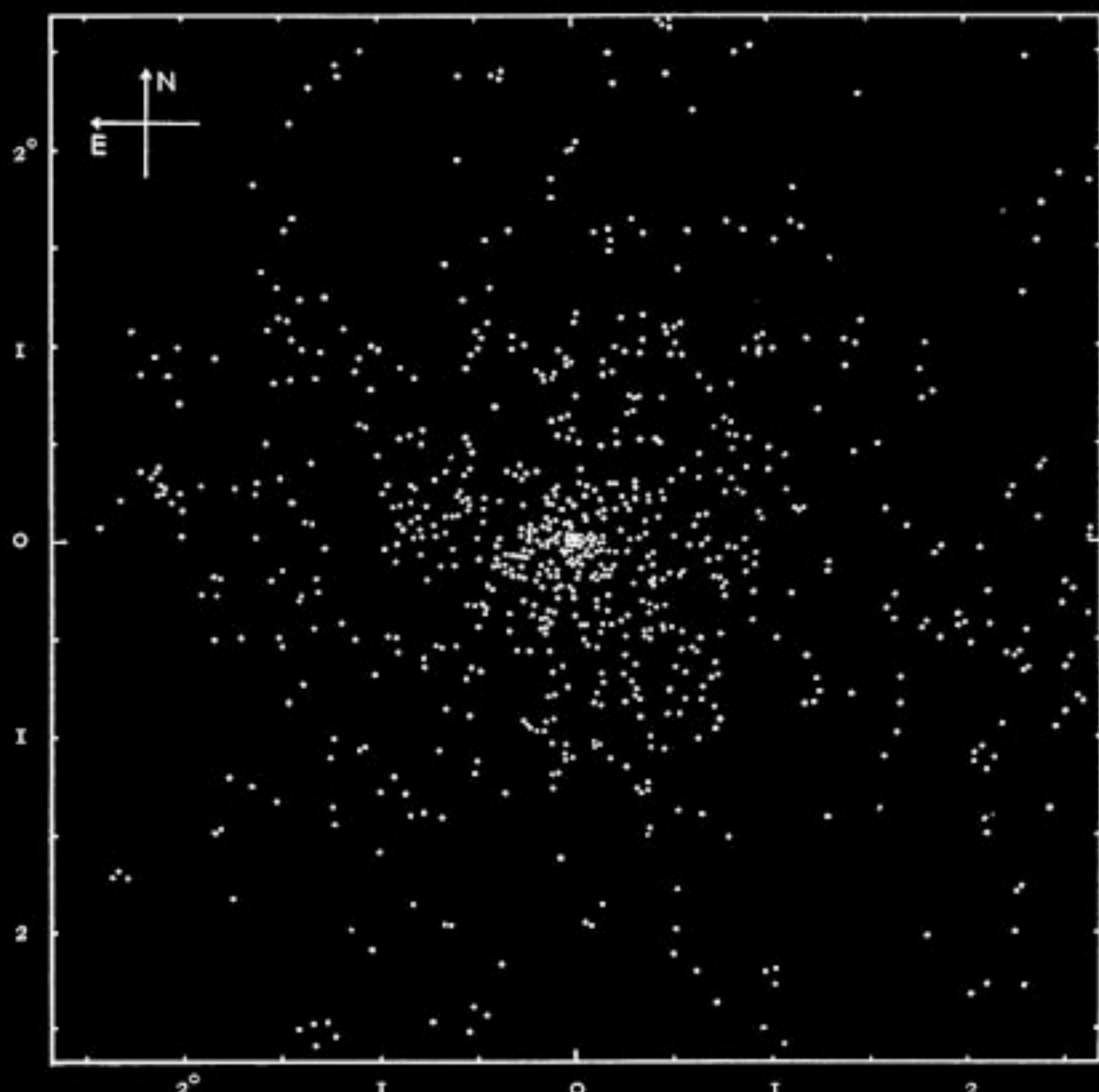
The visible mass was ~100 times less than needed to hold tight the system

"dass dunkle Materie in sehr viel grosserer Dichte vorhanden ist als leuchtende Materie"

"that dark matter is present in much higher density than visible matter"

F. Zwicky, Helv. Phys. Acta 6:110, 1933

COMA CLUSTER



F. Zwicky, Astrophys. J. 86:217, 1937

THE VIRIAL THEOREM

If the cluster is stationary

$$-\langle E_p \rangle = 2\langle K \rangle$$

$$-\langle E_p \rangle \propto \frac{M^2_{cluster}}{\langle R \rangle}$$

$$2\langle K \rangle = M_{cluster} \langle v^2 \rangle$$

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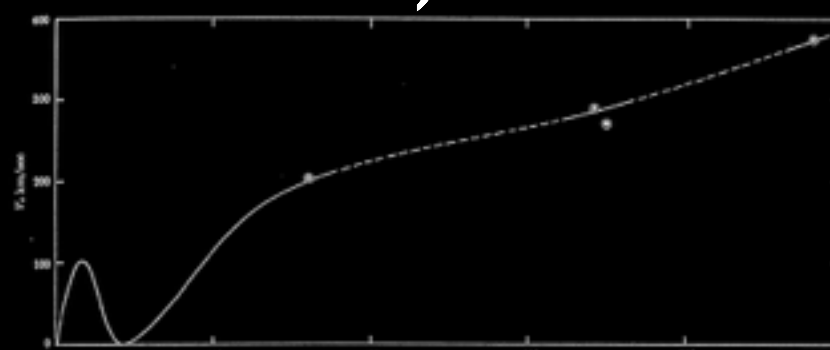
FIRST ROTATION CURVES

VESTO SLIPHER (1875–1969)
FRANCIS PEASE (1881–1938)
MILTON HUMASON (1891–1972)

1914-1918, 1921, 1936-1939: First data on rotation curves

HORACE BABCOCK (1912–2003)

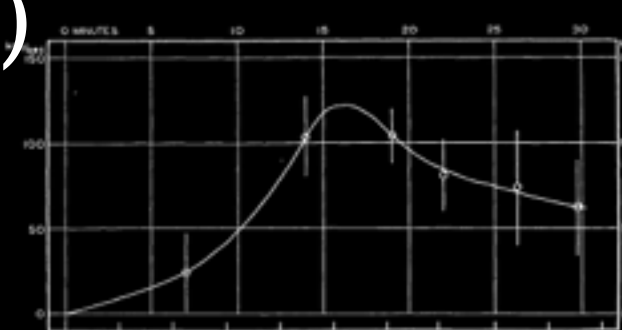
1939: First extended rotation curve
M31



H. Babcock, Lick Obs. Bull. 19:41, 1939

NICHOLAS MAYALL (1906–1993)
LAWRENCE ALLER (1913–2003)

1942: Second extended rotation curve
M33



N. U. Mayall and L. H. Aller
Astrophys. J. 95:5, 1942

TABLE 5

MASS-LUMINOSITY RELATIONS IN M31

x (distance from nucleus)	0′	0′.5	15′	50′	80′
Mass of column (☉)		11000	7900	4100	2200
Volume (cu. psc.)		5400	5300	4500	2400
Mass density (☉/cu. psc.)		2.1	1.5	0.9	0.9
Log I (Redman and Shirley)	(2.00)	1.29	0.10	9.44	9.00
I	(100)	19.5	1.26	0.276	0.100
Luminosity density (☉/cu. psc.)		1.25	0.0827	0.021	0.0144
M/L	0.001 (Hubble)	1.6	18	43	62

H. Babcock, Lick Obs. Bull. 19:41, 1939

Nebula (1)	Type (2)	Period in Years: Nuclear Region (3)	Period in Years: Main Body (4)	Period in Years: Outer Parts (5)	Mass in Suns (6)
Galaxy	(Sc)	....	....	2.2×10^{8}	1 to 2×10^{11}
M 33	Sc	....	5.9×10^{7}	0.6 to 2.0×10^{8}	1.7×10^{9}
M 31	Sb	1.1×10^{7}	9.2×10^{7}	....	9.5×10^{10}
4594	Sa	....	2.0×10^{7}	....	2.8×10^{10}
4111	Sa	1.4×10^{6}	....	....	....
3115	E7	....	4.5×10^{6}	....	1.5×10^{10}

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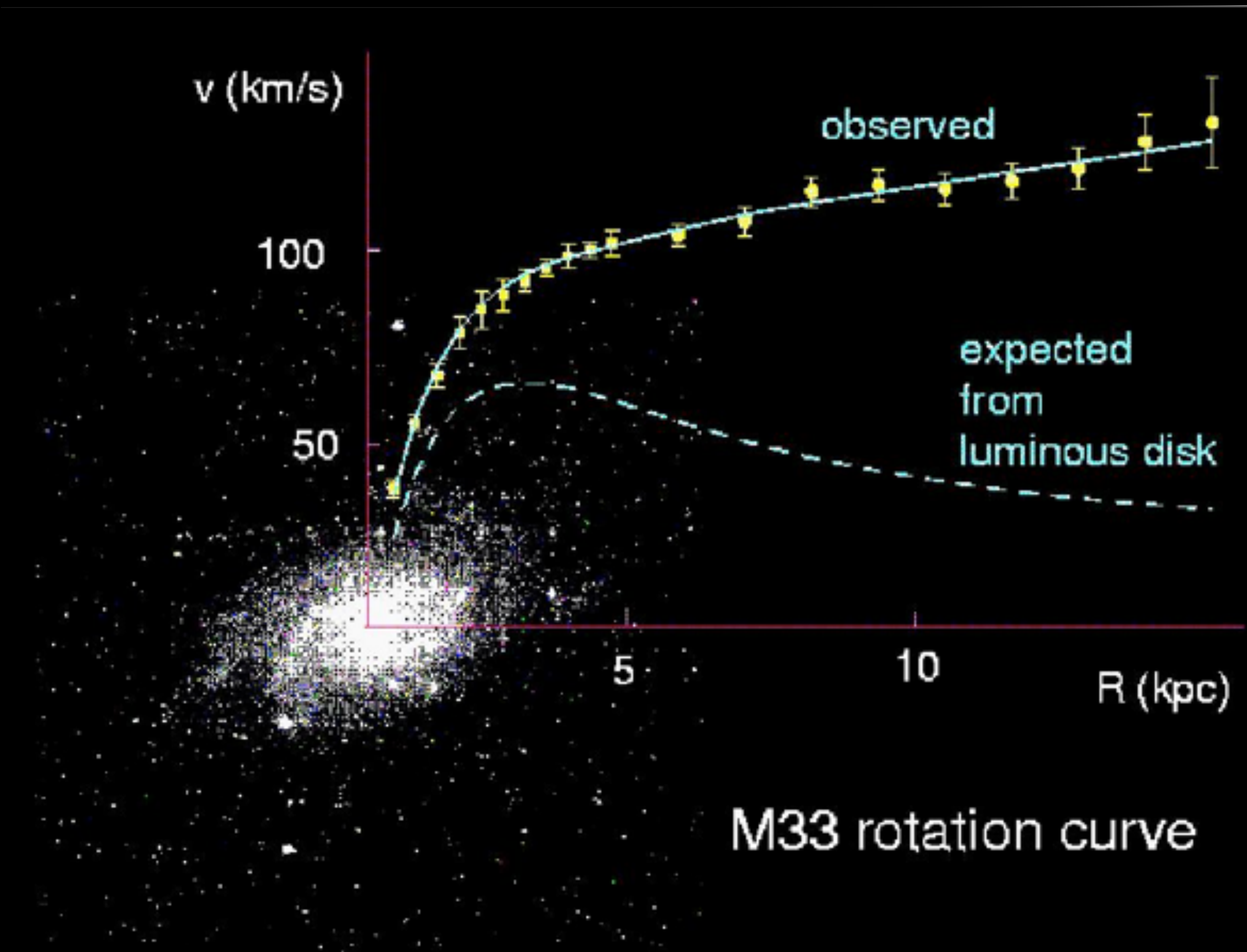
Typical galactic mass then

$\sim 10^9 M_\odot$

centripetal acceleration = gravitational acceleration



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

$M = \text{constant} \Rightarrow v^2 \propto \frac{1}{r}$

$v^2 = \text{constant} \Rightarrow M \propto r$

mass inferred from luminous matter

vs.

mass inferred from rotational curve

50-60'S DATA

Individual galaxies

New data with radio astronomy: Van de Hulst (1957), Volders (1959)...

Milky Way beyond the solar circle: Rubin (1962, 1965)

Many galaxies were studied: Burbidge, Burbidge and Prendergast (1962)

Rubin (1962): "the stellar (rotation) curve is flat, and does not decrease as is expected for Keplerian orbits"

Binary galaxies

Using the fact that the Milky Way and Andromeda are approaching each other the mass of the system was estimated

F. D. Kahn and L. Woltjer, Astrophys. J. 130:705, 1959

More data on binary galaxies: Page, Bergh, Holmberg...

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$$M \geq 1.8 \times 10^{12} M_{\odot}$$

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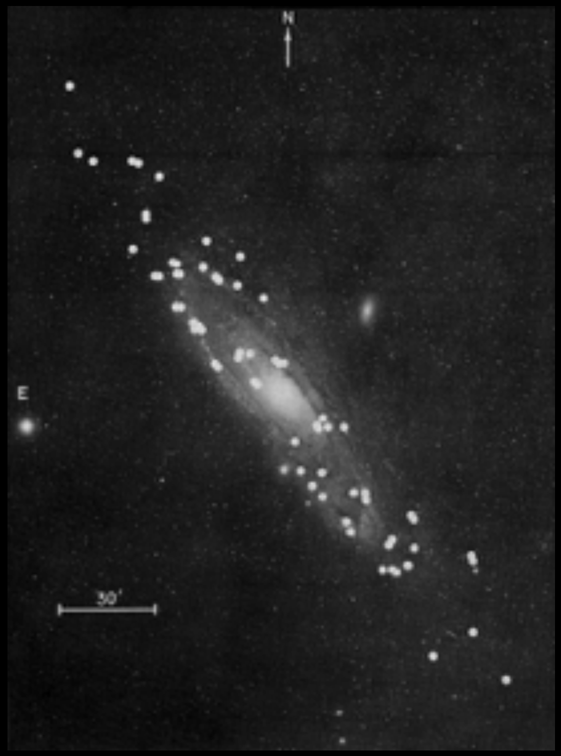
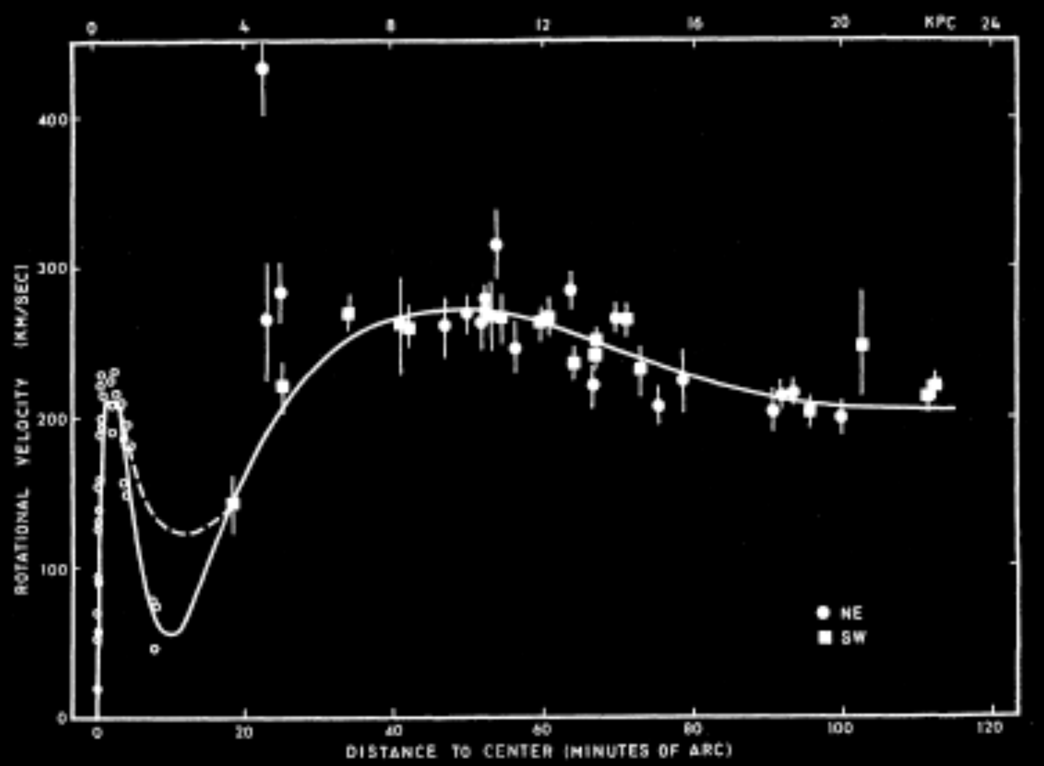
EXTENDED ROTATION CURVES

M31

Improved optical observations

EXTENDED ROTATION CURVES





V. C. Rubin and W. K. Ford, Astrophys. J. 159:379, 1970

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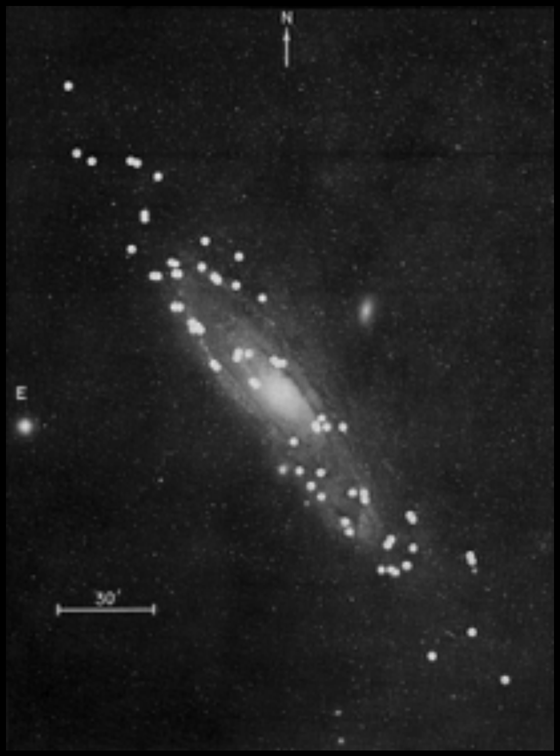

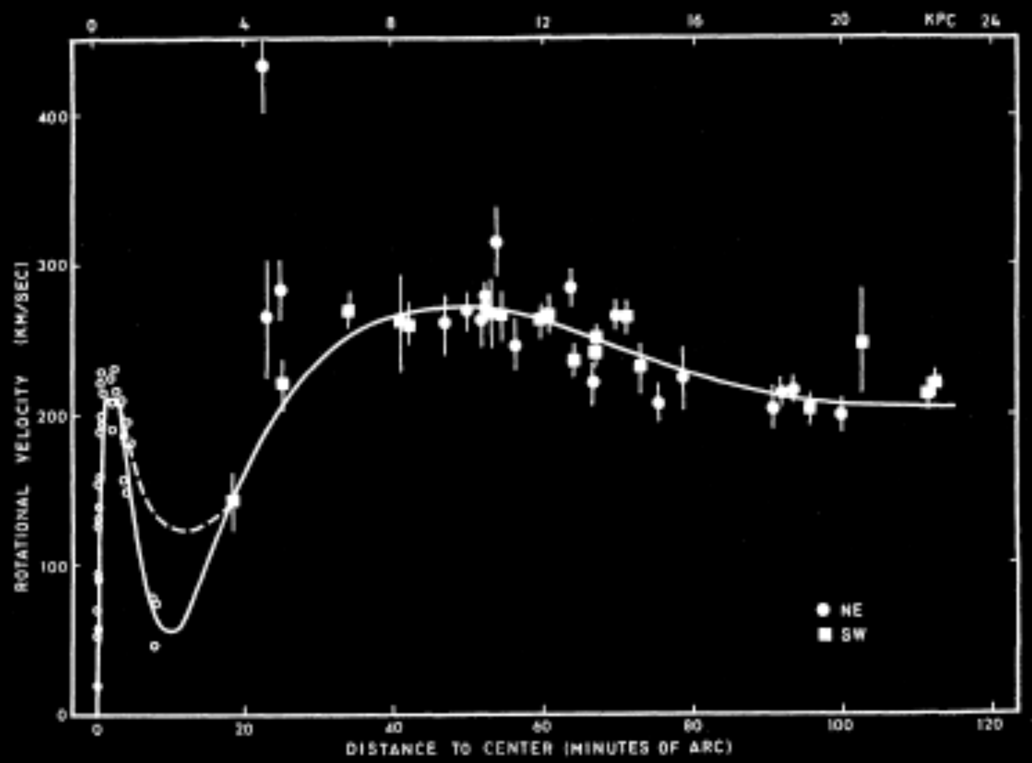

21-cm radio observations

V. C. Rubin and W. K. Ford, Astrophys. J. 159:379, 1970

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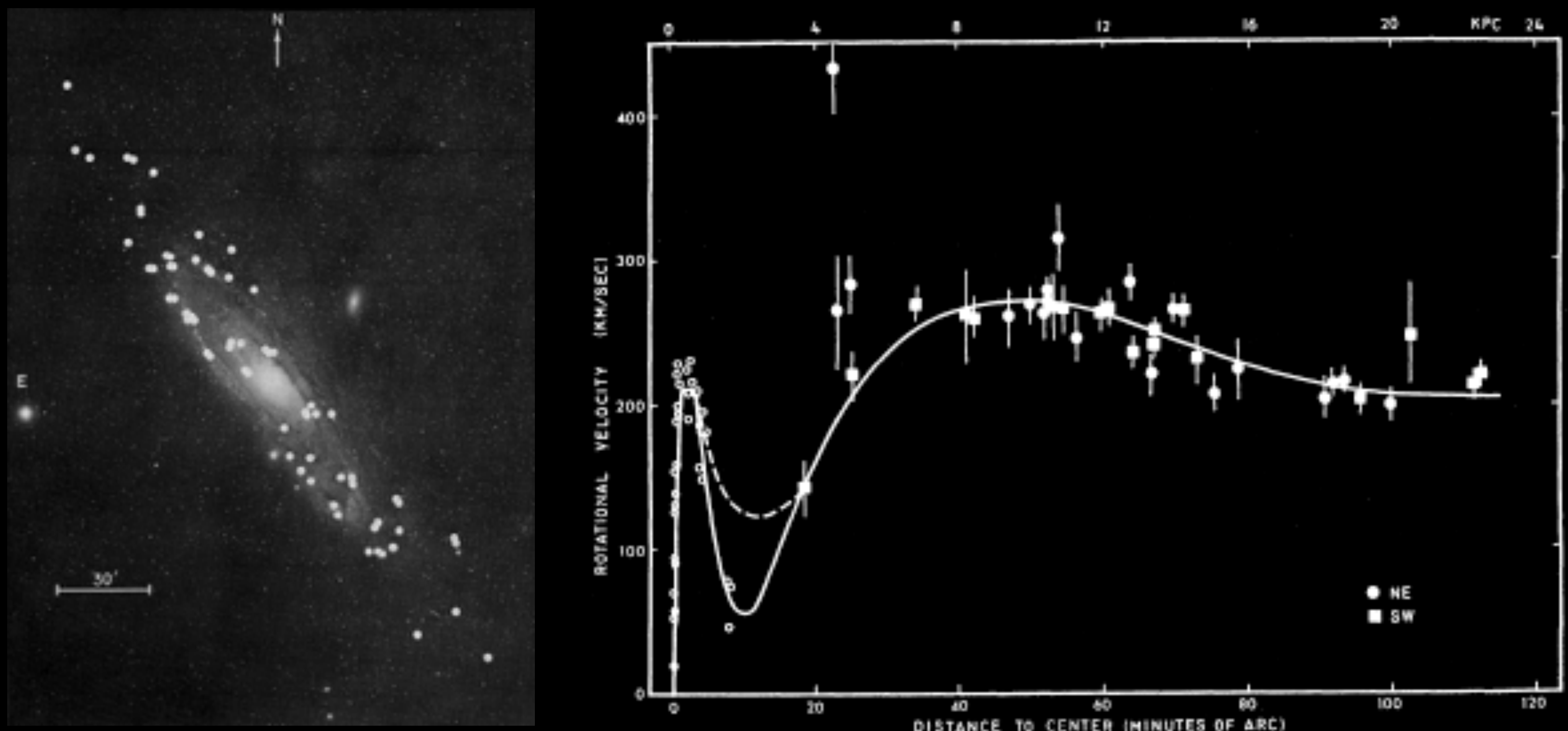

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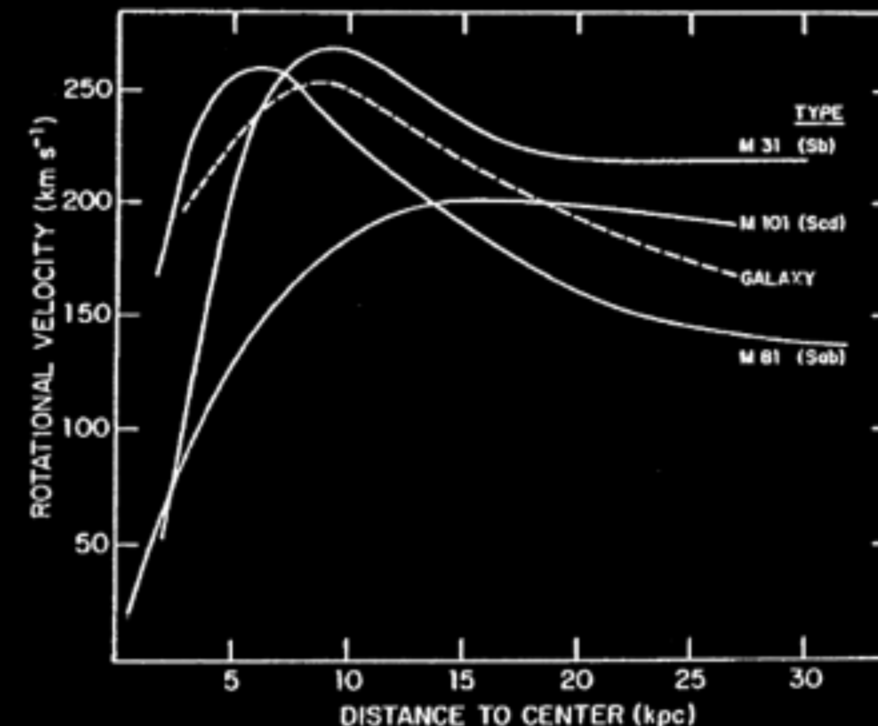

M. S. Roberts and A. H. Rots,
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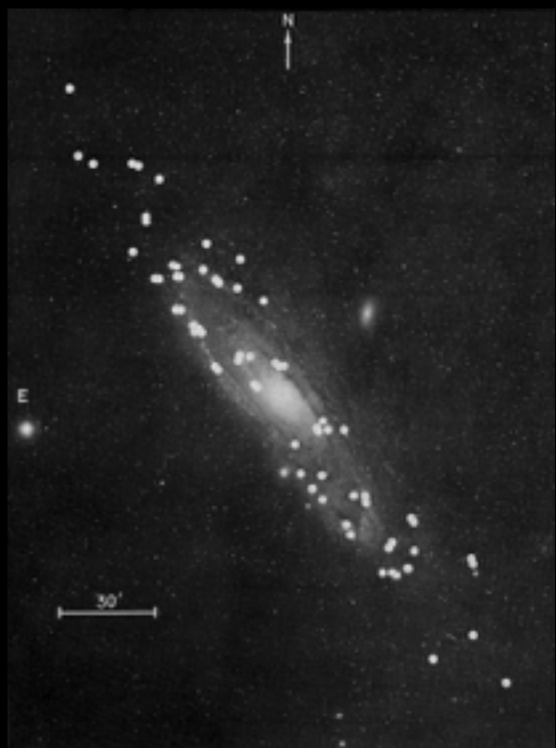

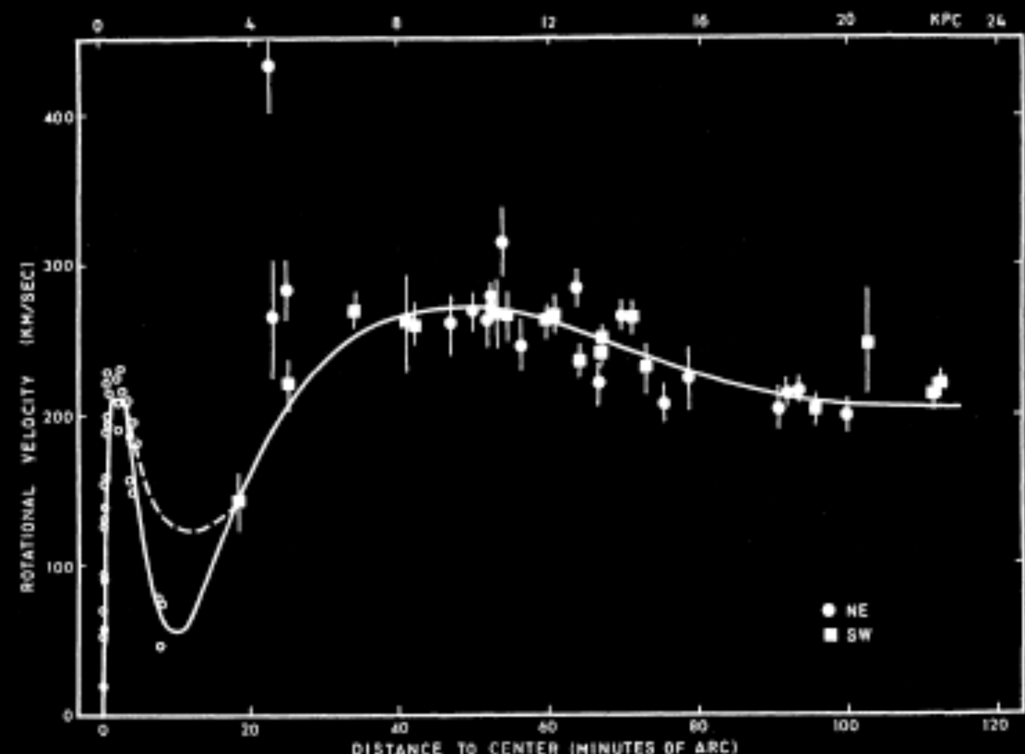

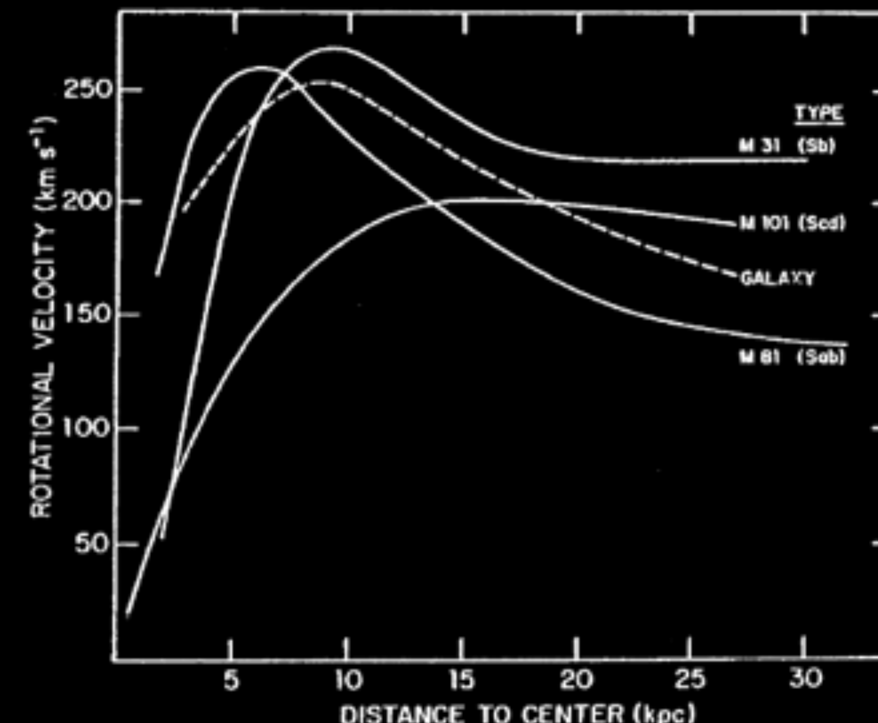

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M31
extended 21-cm observations

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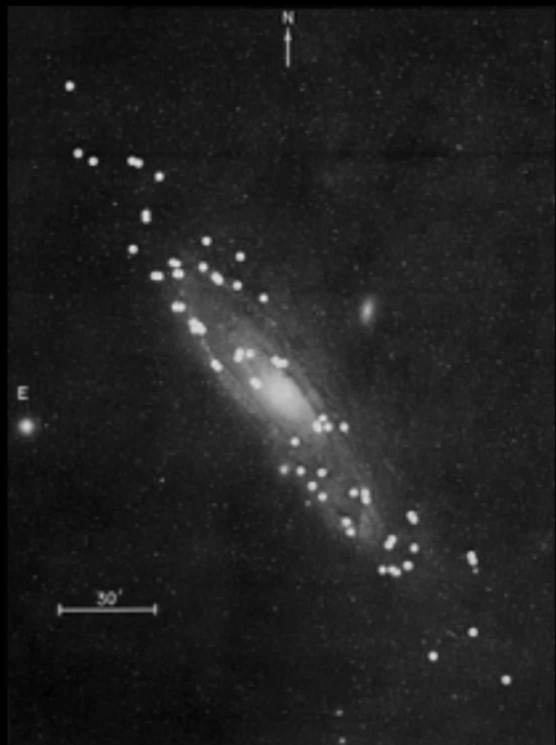

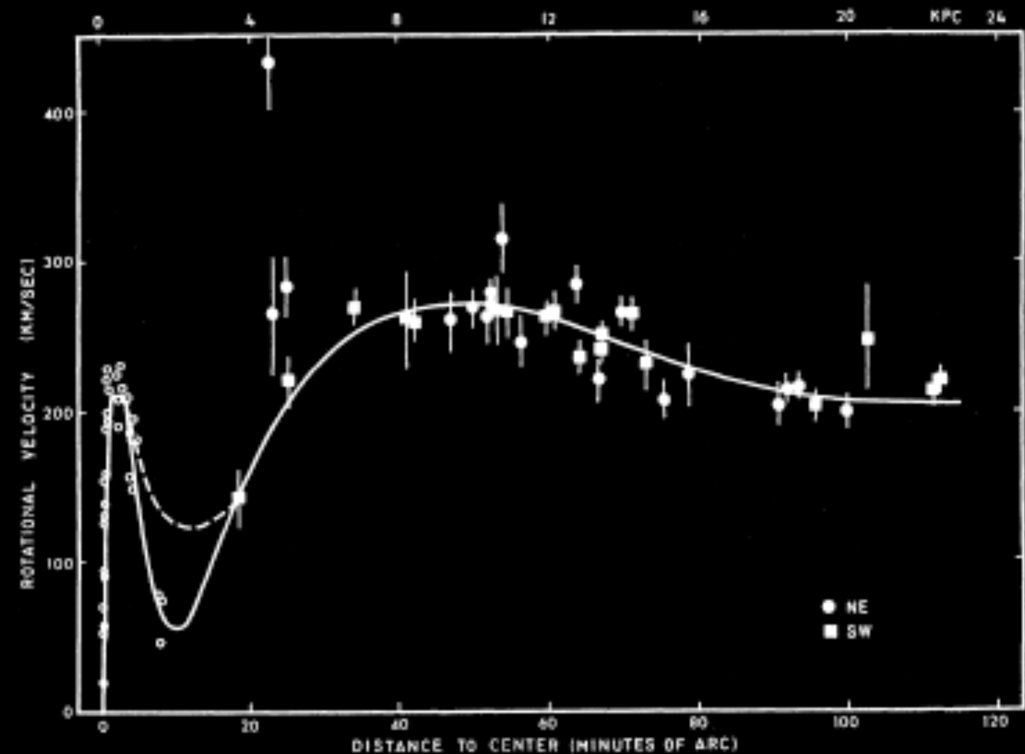

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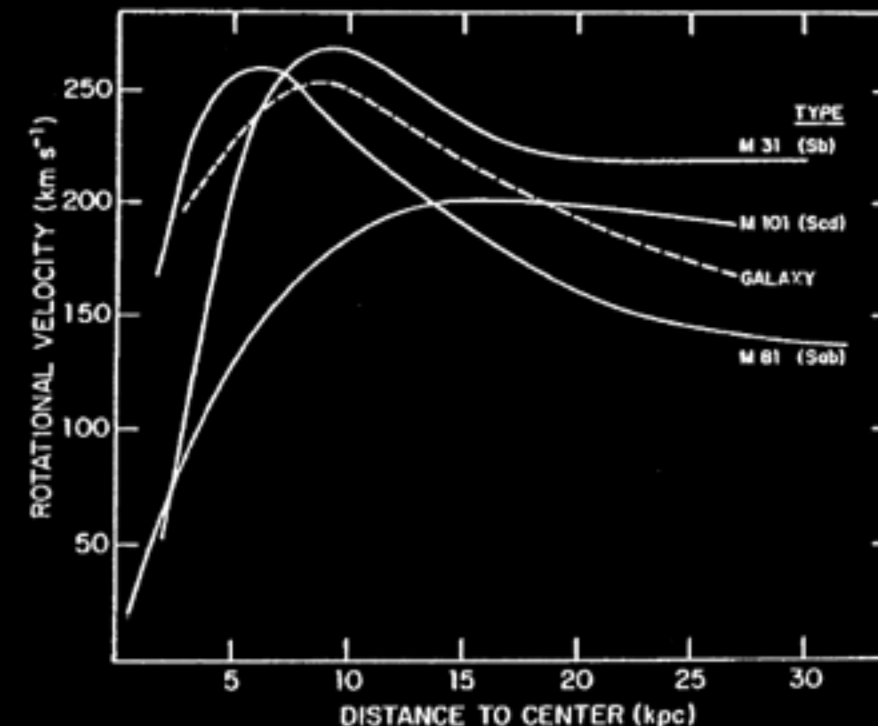

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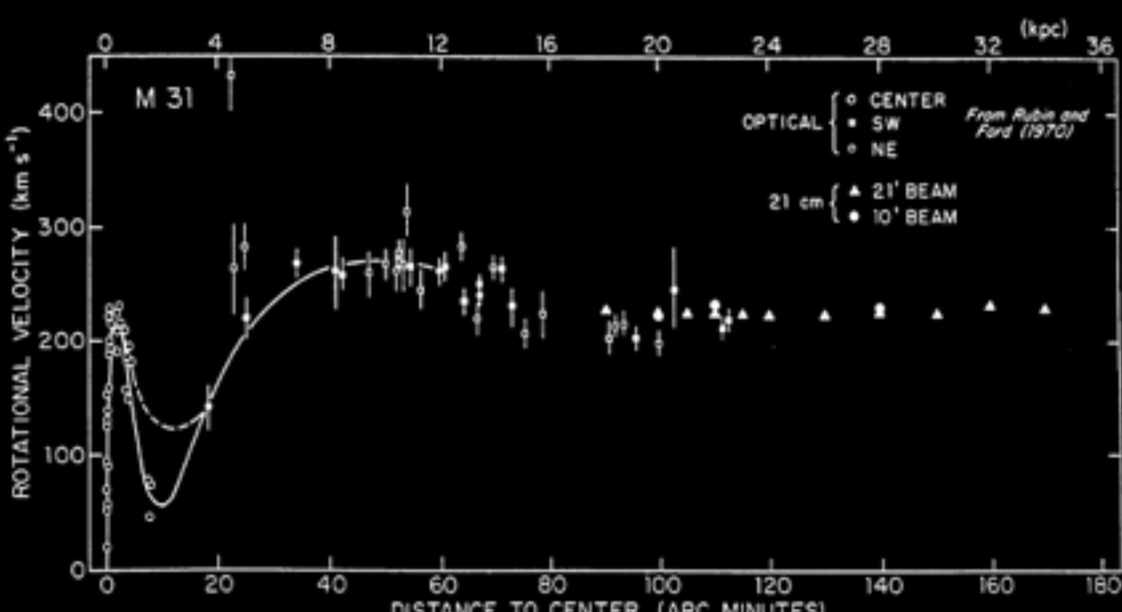

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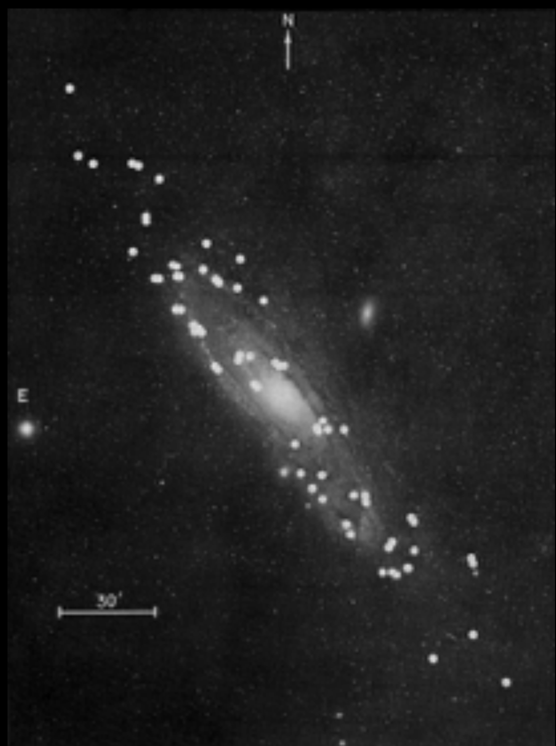

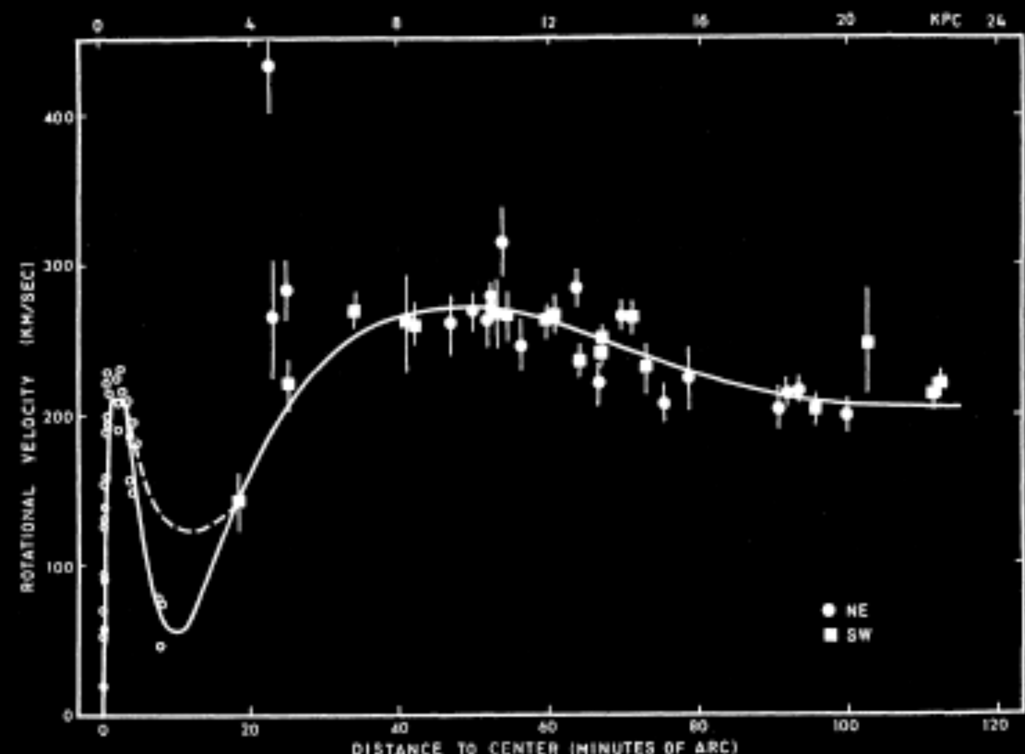

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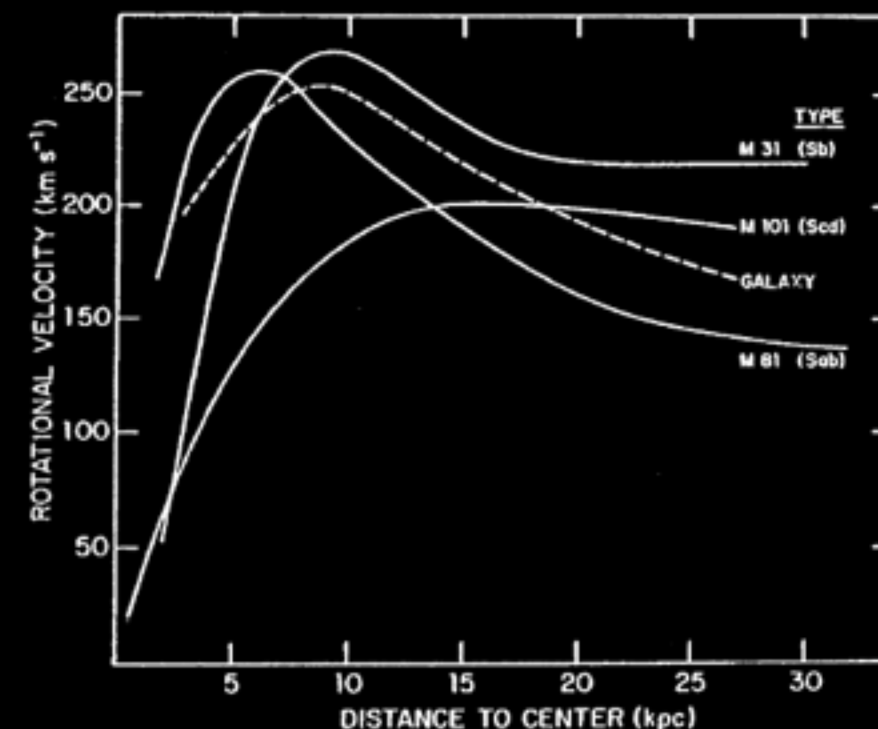

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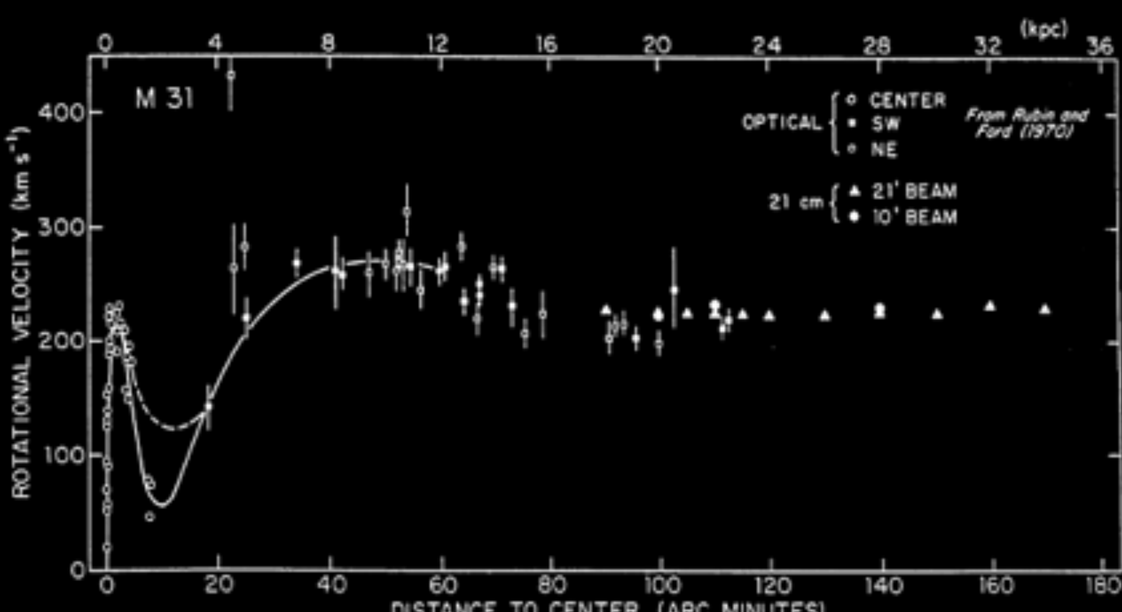

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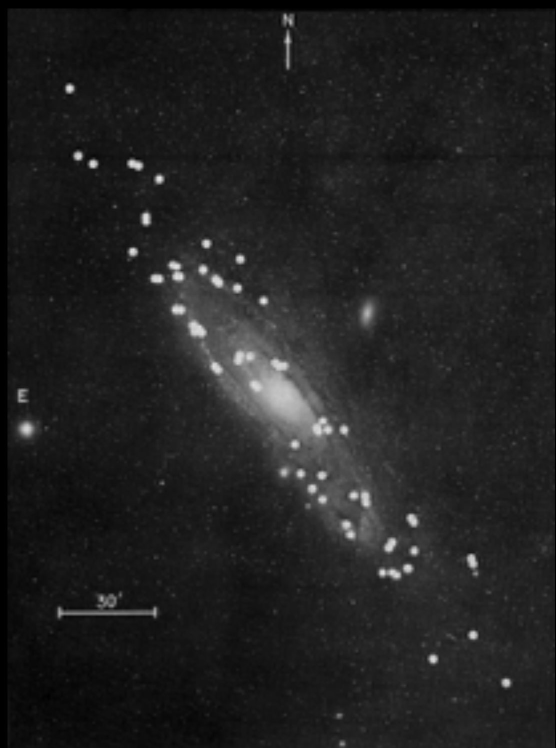

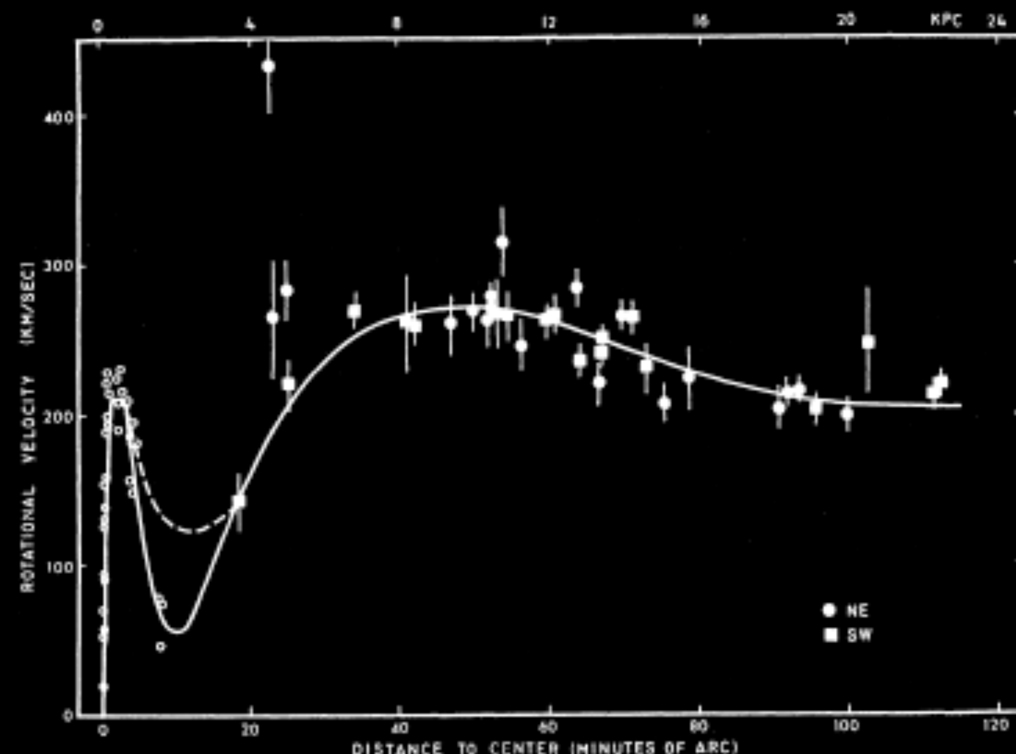

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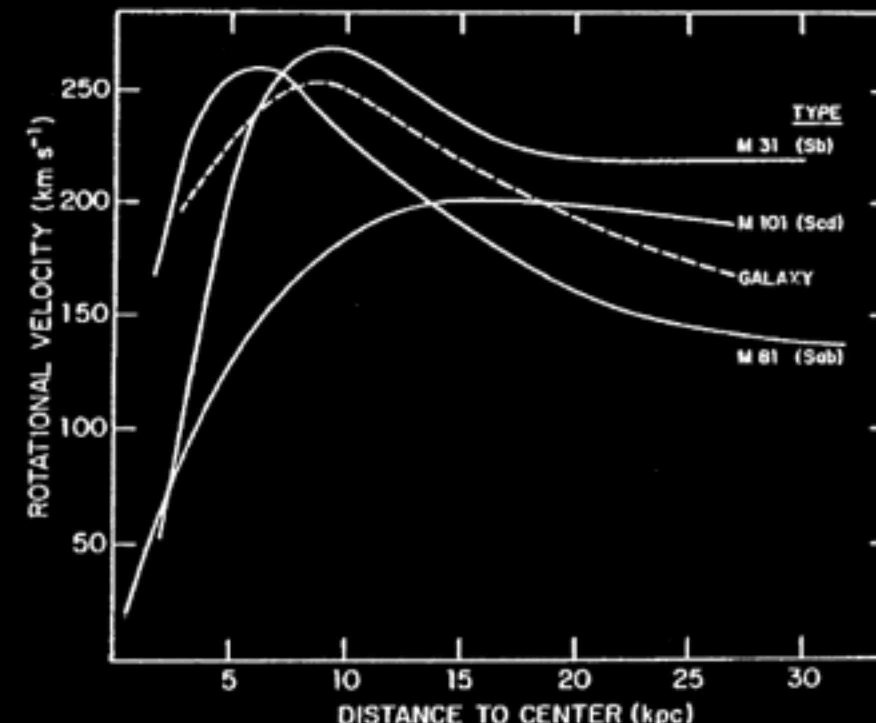

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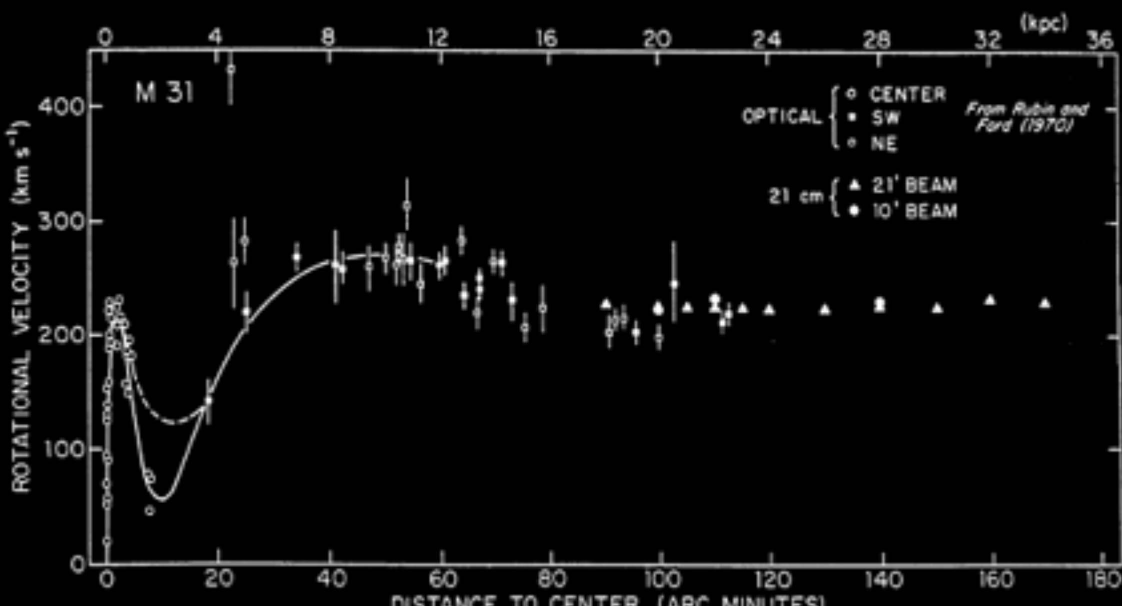

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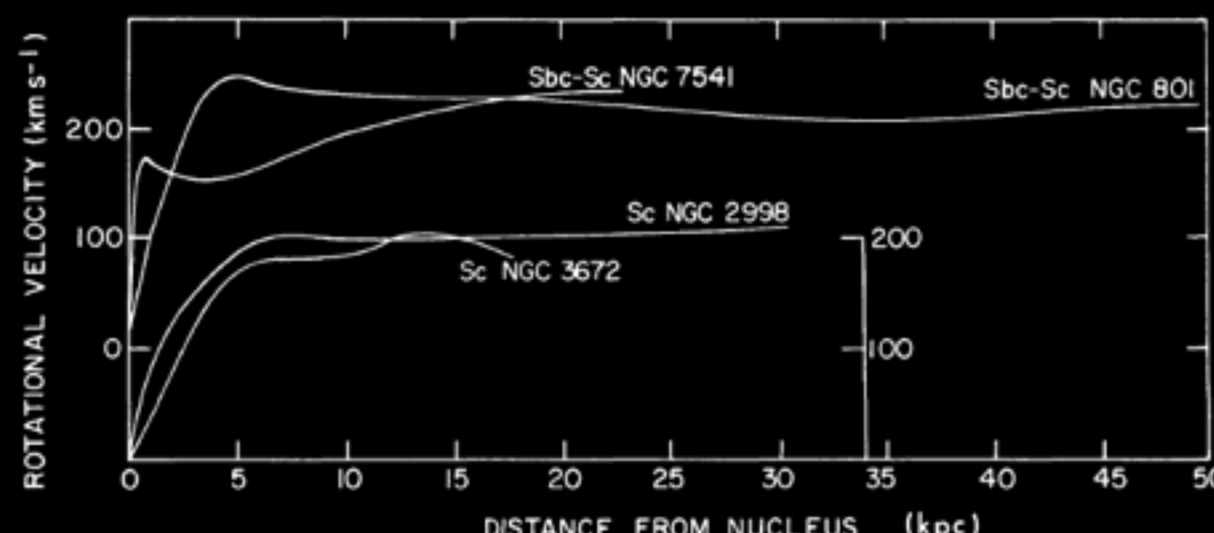

V. C. Rubin, W. K. Ford and N. Thonnard, Astrophys. J. 225:107, 1978
and A. Bosma thesis compiling 21-cm observations

THEORETICAL INPUT

Stability of 2D N-body systems

R. H. Miller and K. Prendergast, Astrophys. J. 151: 699, 1968; 161:903, 1970
F. Hohl, Astrophys. J. 168:343, 1971

Disk of particles supported (almost entirely) by rotation:
they expected that equilibrium implies the gravitational force is balanced by rotation (centripetal force)
→ the shape of the system should not change

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→ the shape of the system should not change

However, this is not what they obtained!
After a few rotation periods, an elongated shape developed, which later dissolved, keeping particles in elongated ellipses at random angles

The system changes from being supported by rotation to being supported by pressure

DARK HALOS

N-body simulations: 300 particles

spiral galaxies are unstable and would form a bar

Virial theorem:

$$2\langle K\rangle + \langle E_p\rangle = 0$$

$$\langle K\rangle = \langle K\rangle_{rot} + \langle K\rangle_{ran}$$

$$\frac{\langle K\rangle_{rot}}{-\langle E_p\rangle} + \frac{\langle K\rangle_{ran}}{-\langle E_p\rangle} = \frac{1}{2} \equiv t + w$$

If t>0.14, the system is unstable:
the moment of inertia increases and the rotational energy decreases, conserving the angular momentum

Milky Way: t ~0.49

J. P. Ostriker and P. J. E. Peebles, Astrophys. J. 186:4670, 1973

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If $t>0.14$, the system is unstable:
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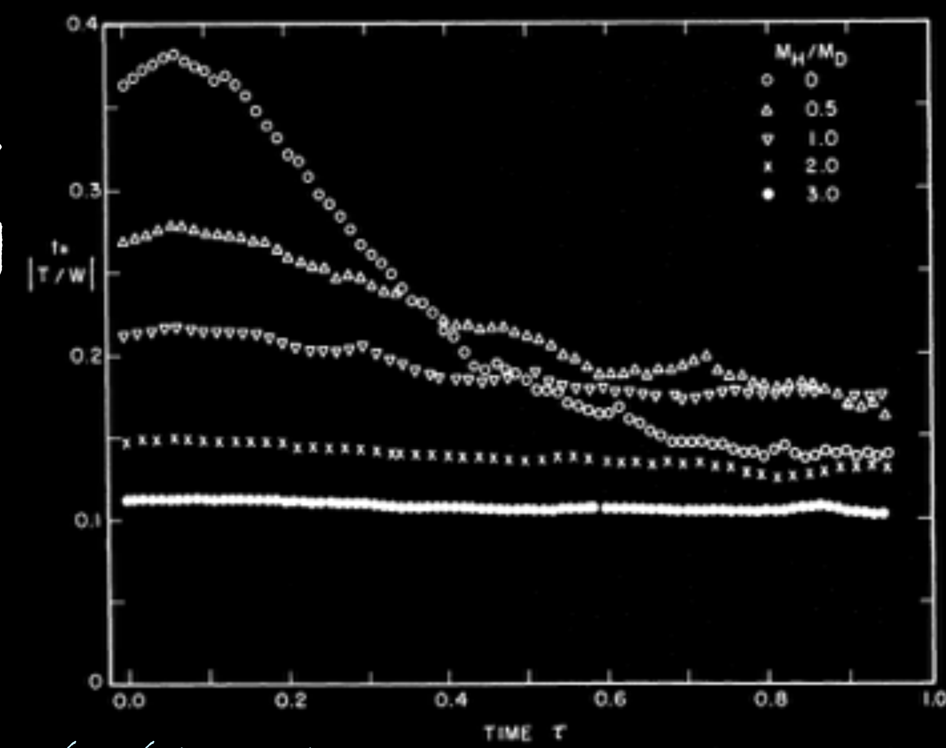
Milky Way: $t \sim 0.49$

Solution: add a dark halo that contributes to the potential energy, but not to the rotational energy



"the halo (spherical) mass interior to the disk must be comparable to the disk mass"

"the halo solution seems the most likely solution for our own Galaxy"

J. P. Ostriker and P. J. E. Peebles, Astrophys. J. 186:4670, 1973

DARK HALOS

Following the arguments of Kahn and Woltjer:
dynamical mass of several systems at different scales

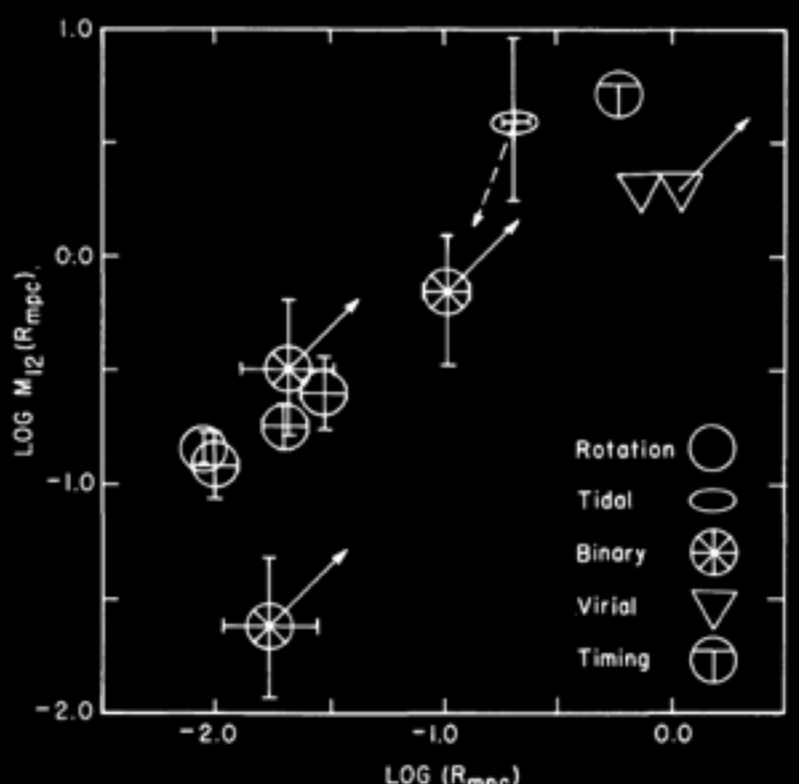
"it is necessary to adopt an alternative hypothesis: that the clusters of galaxies are stabilised by hidden matter"

J. Einasto, A. Kaasik and E. Saar, Nature 250:309, 1974

with available observational data: M/L(r) and $\Omega \sim 0.2$

"Currently available observations strongly indicate that the mass of spiral galaxies increases almost linearly with radius to nearly 1 Mpc. This means [...] ~200 $(M_\odot/L_\odot)$"

J. P. Ostriker, P. J. E. Peebles and A. Yahil, Astrophys. J. 193:1, 1974



EVIDENCE FROM BBN

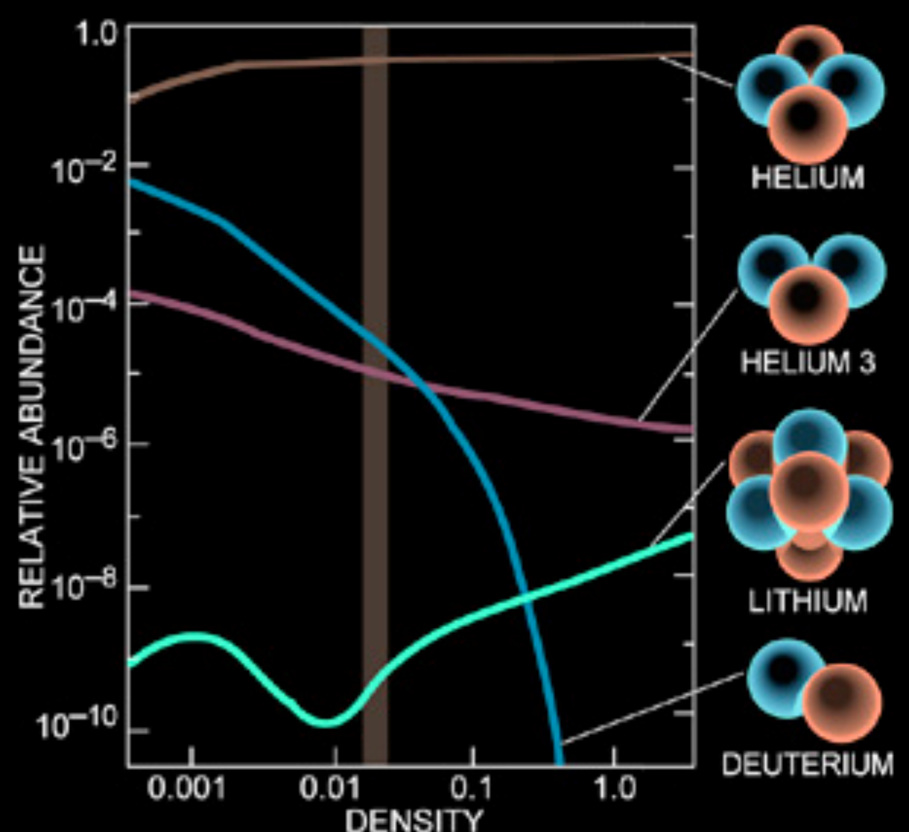
The Universe originated in a hot Big Bang and the primordial elements were synthesized after a few minutes

R. A. Alpher, H. Bethe and G. Gamow, Phys. Rev. 73:803, 1948

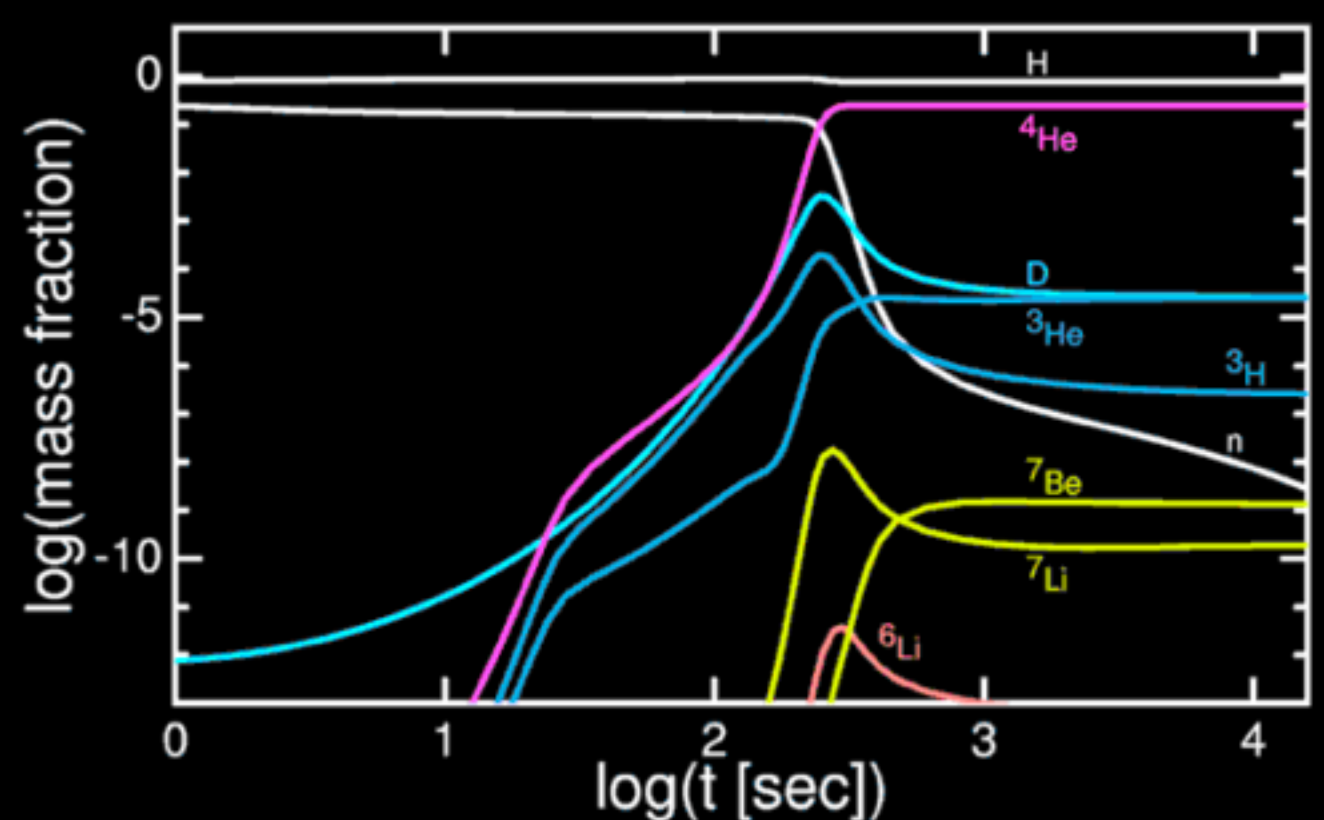
More refined calculations followed the CMB discovery

P. J. E. Peebles, Phys. Rev. Lett 16:410, 1966

R. V. Wagoner, W. A. Fowler and F. Hoyle, Astrophys. J. 148:3, 1967



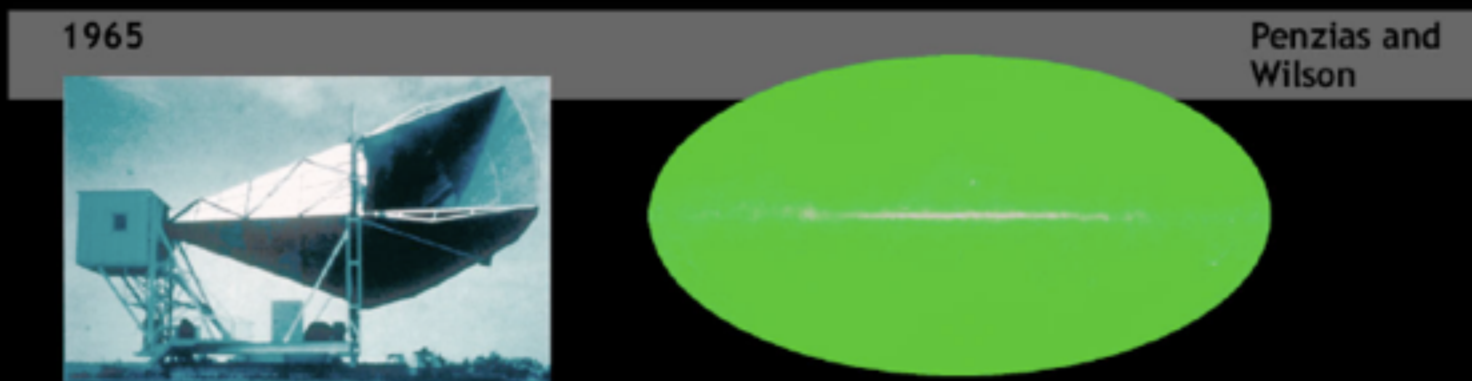
very sensitive to the baryon density



$$\Omega_b \simeq 0.05 \neq \Omega_m \simeq 0.2 \text{ (c. 1974)}$$

EVIDENCE FROM THE CMB

A. Penzias and R. Wilson discovered the CMB in 1964



Very smooth background

If DM is only baryons:
perturbations at ~0.01% level

However, COBE showed
they are at ~0.001% level

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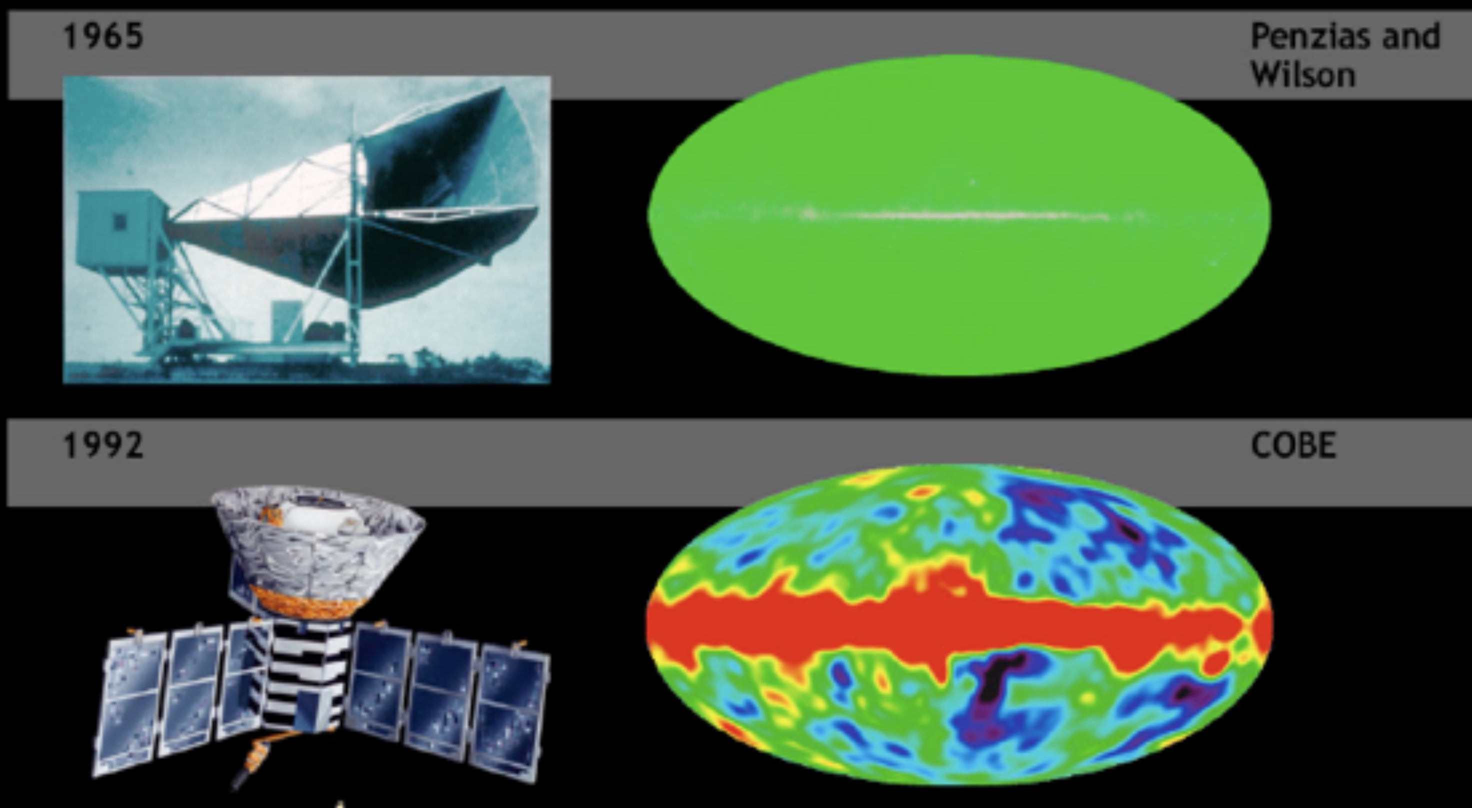

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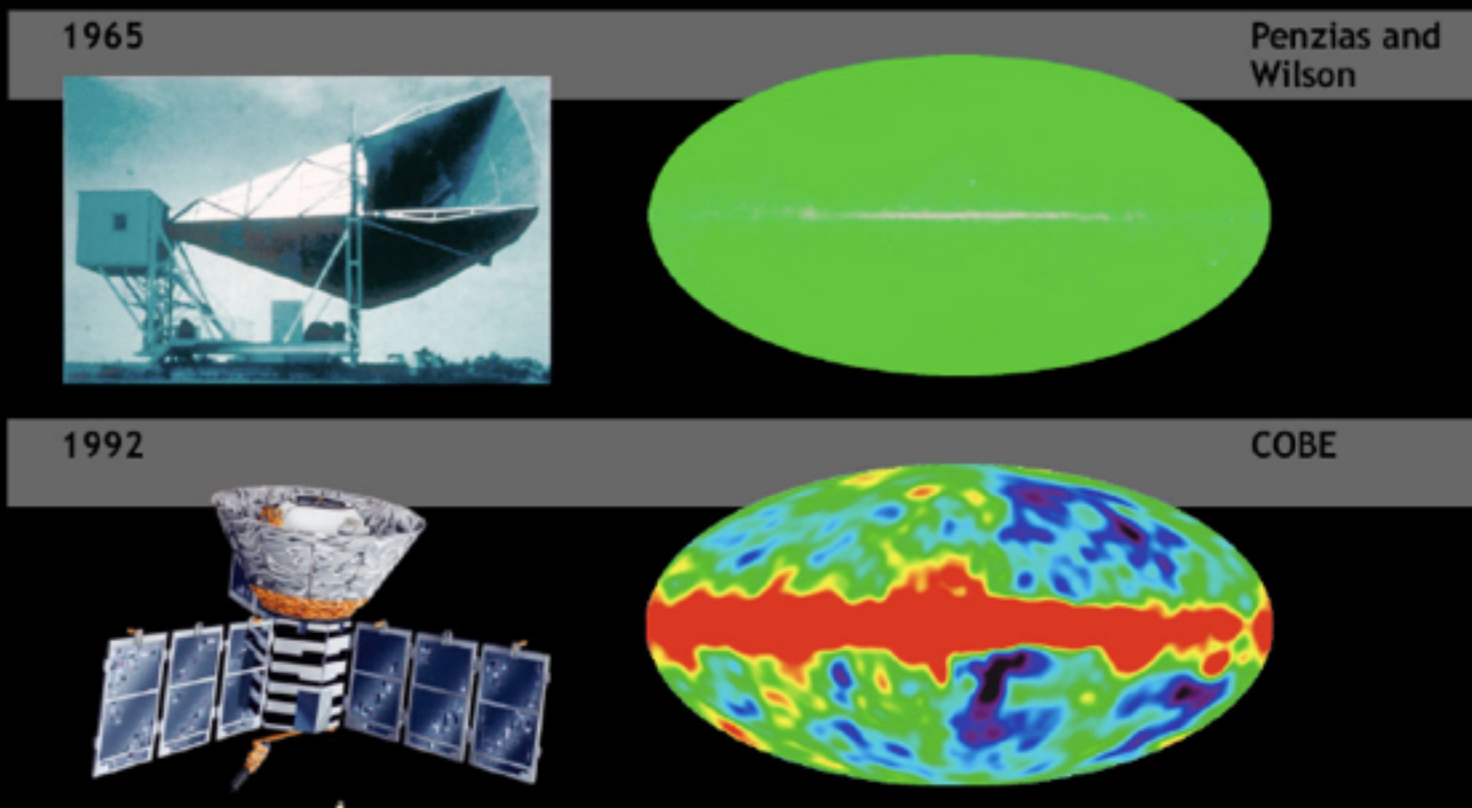

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A. D. Chernin, Astron. Zh. 58:25, 1981

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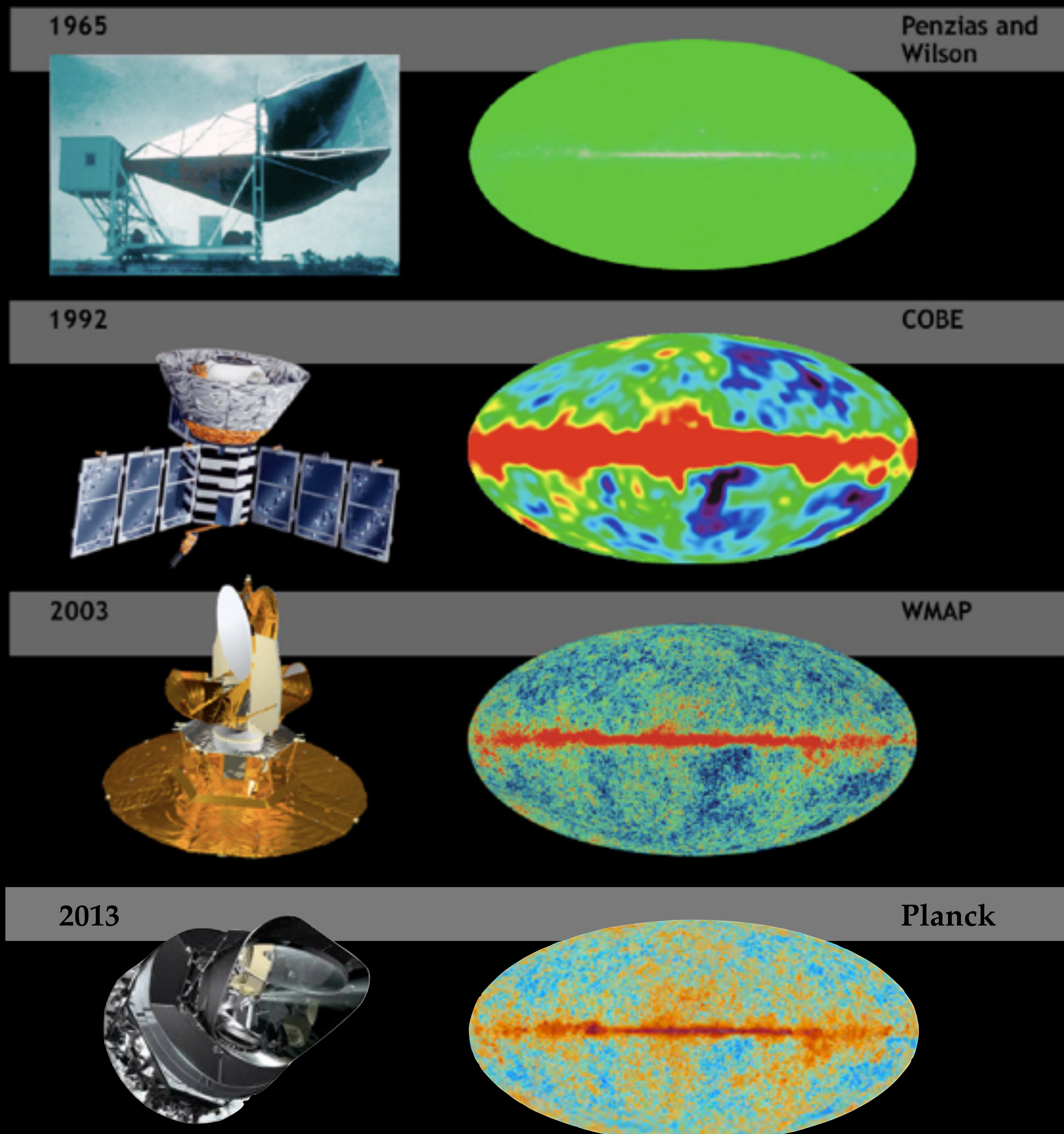

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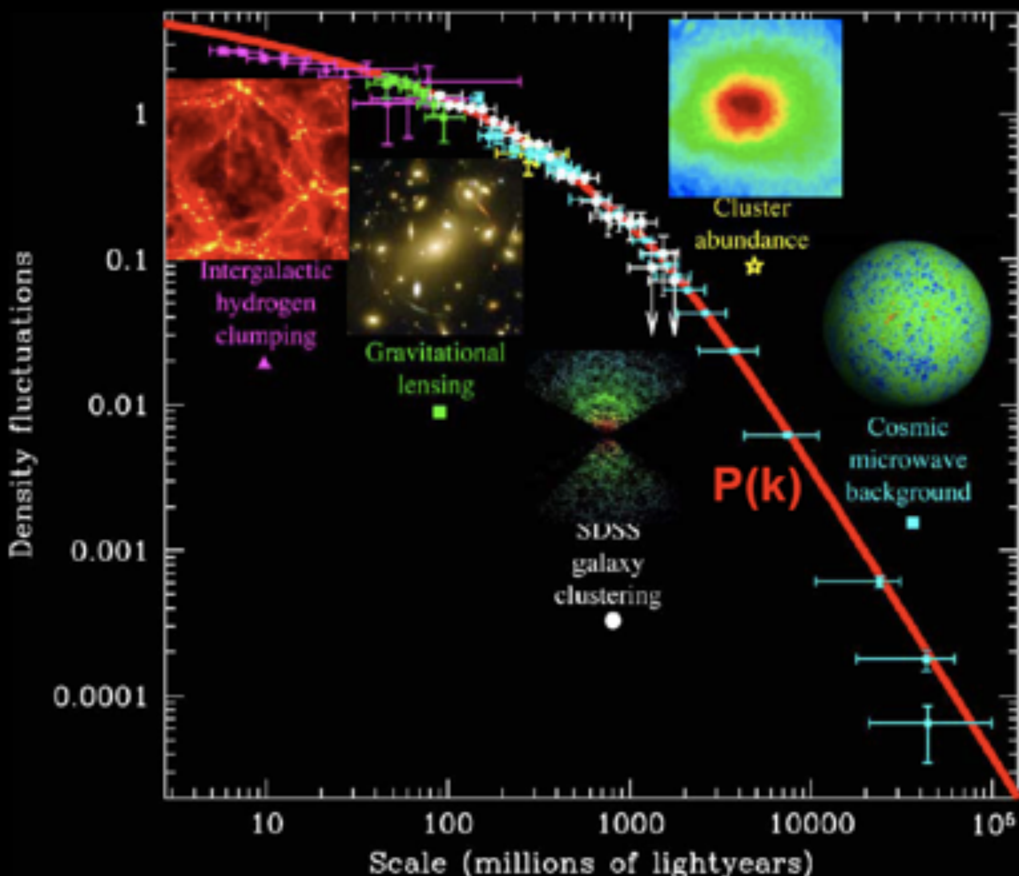
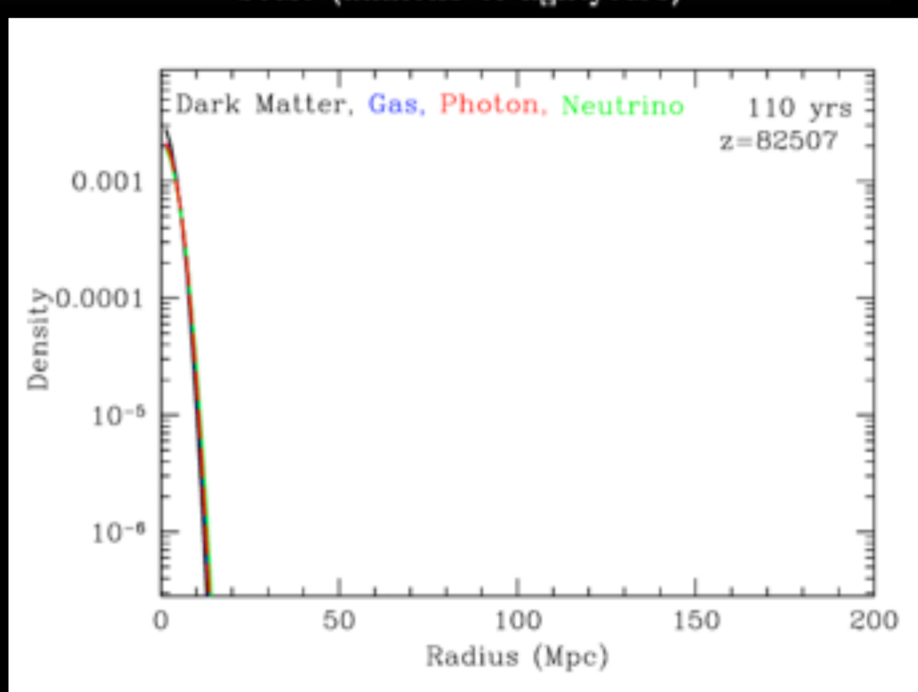
POWER SPECTRA

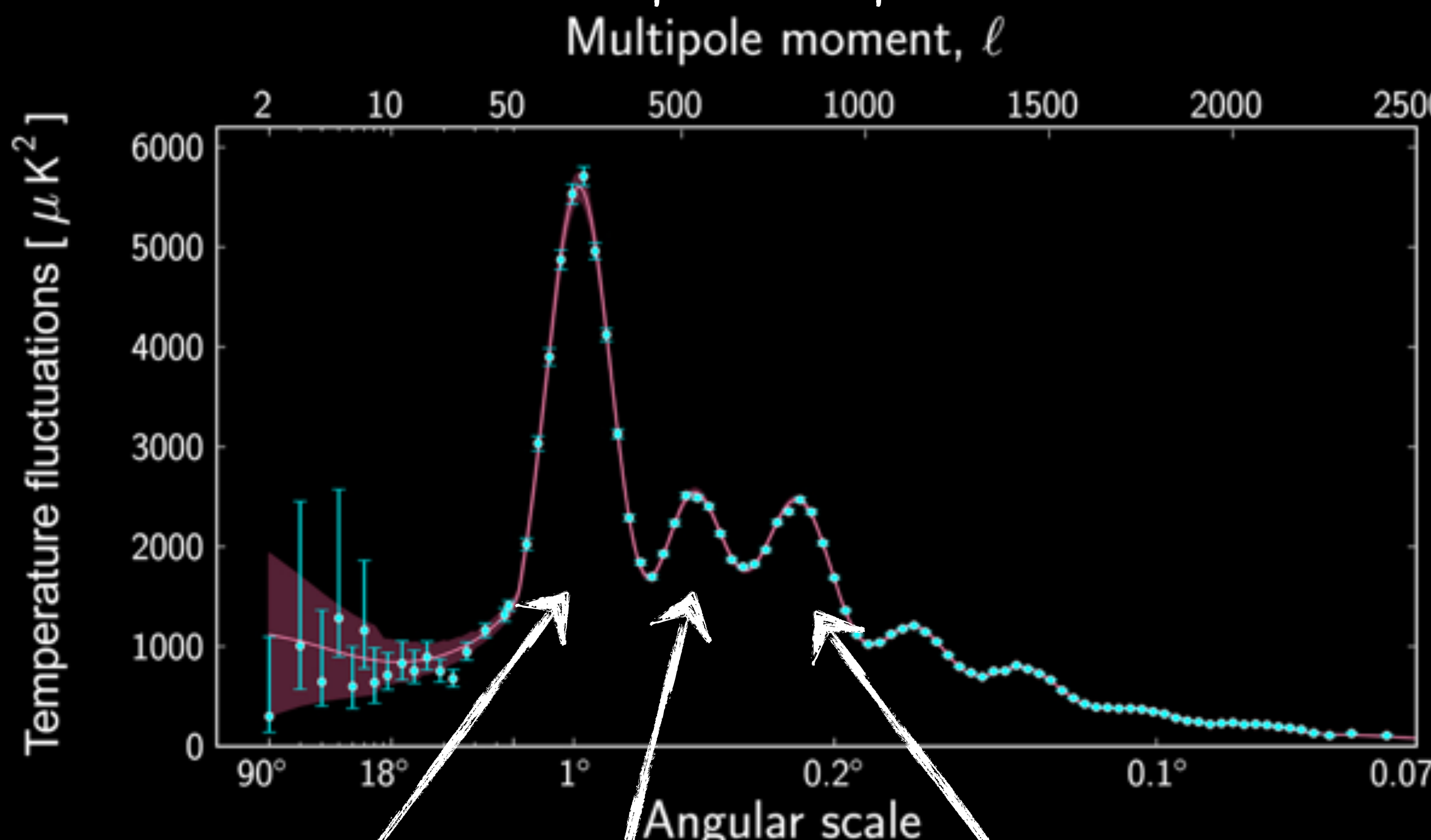
Matter power spectrum



BAO



CMB power spectrum



Total density
position: curvature

Baryonic + DM density

Baryonic density

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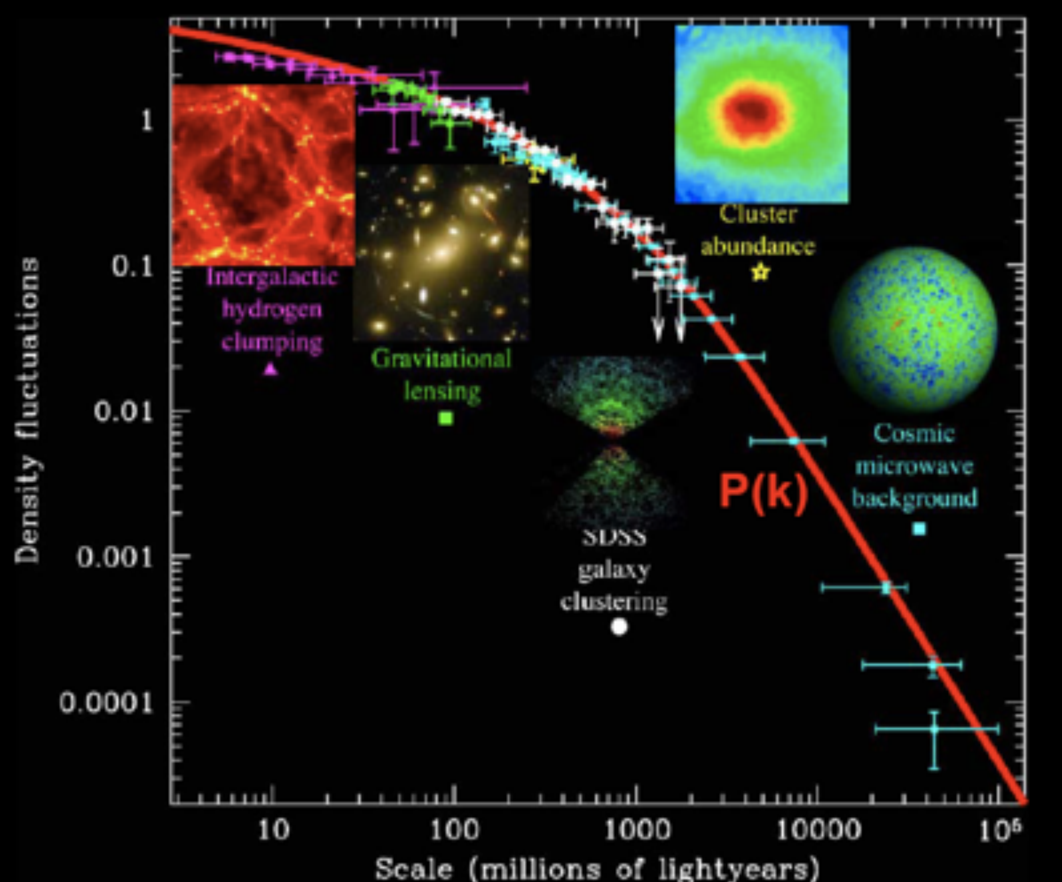

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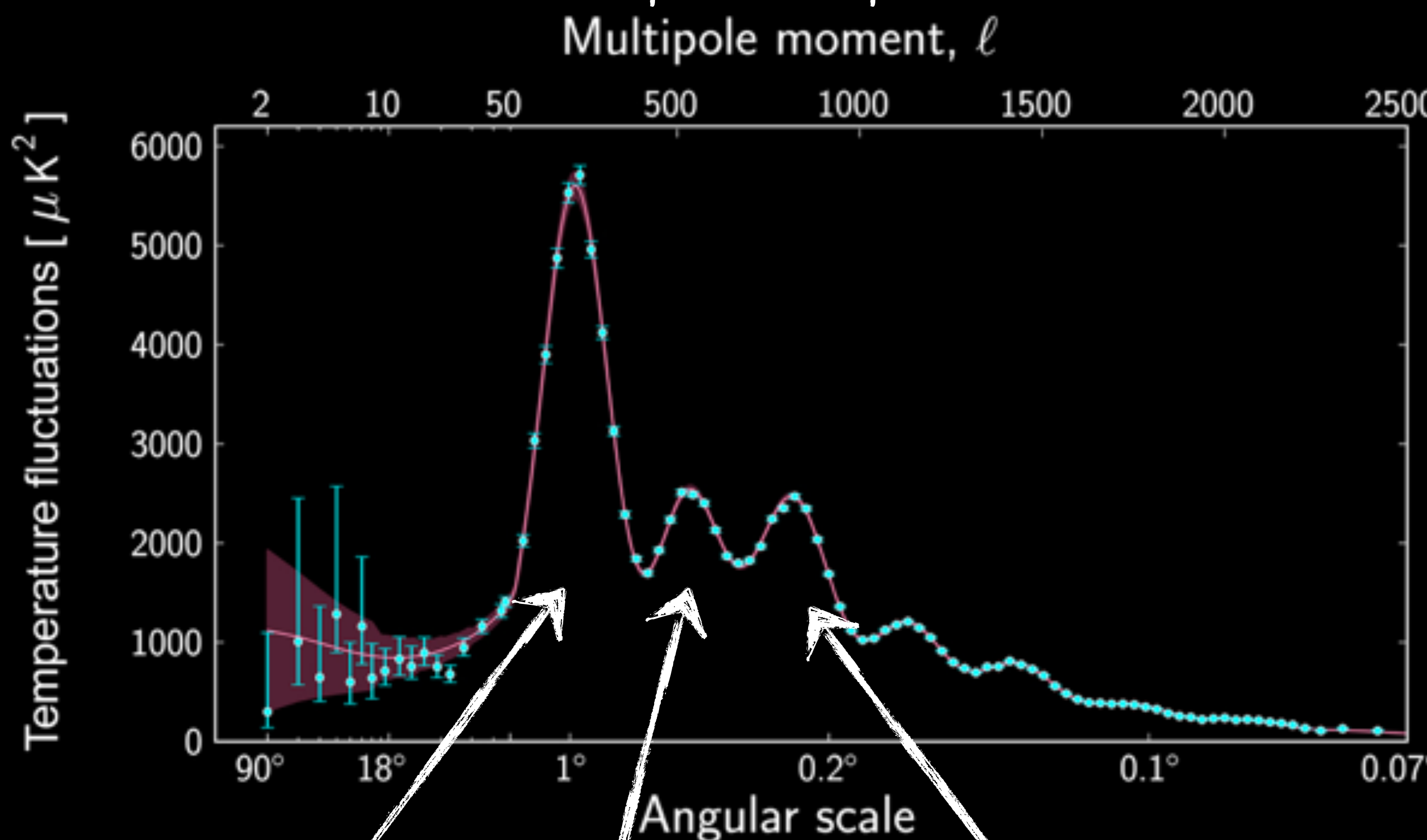

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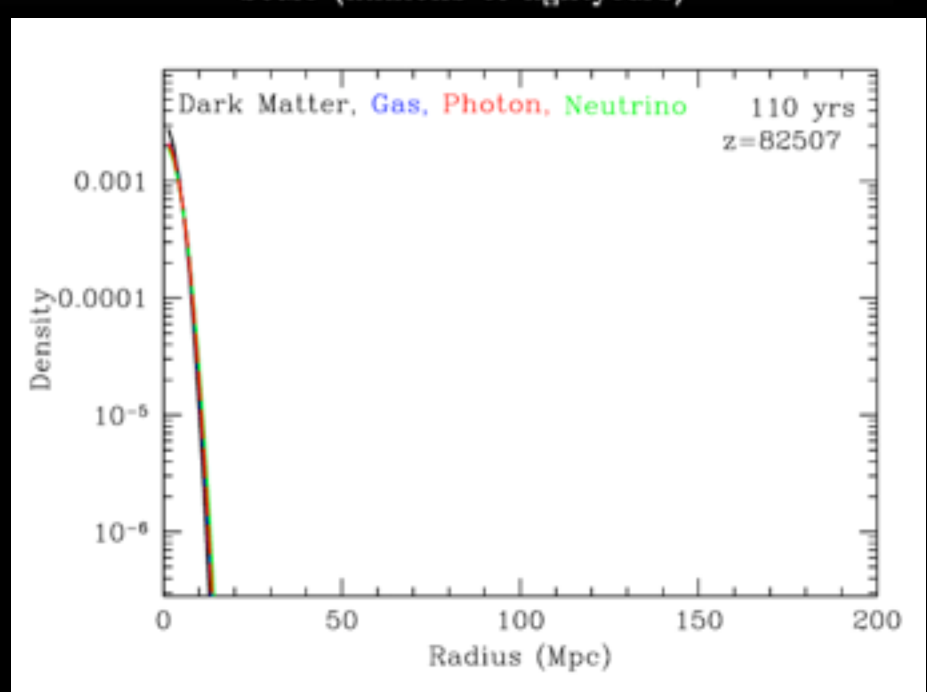

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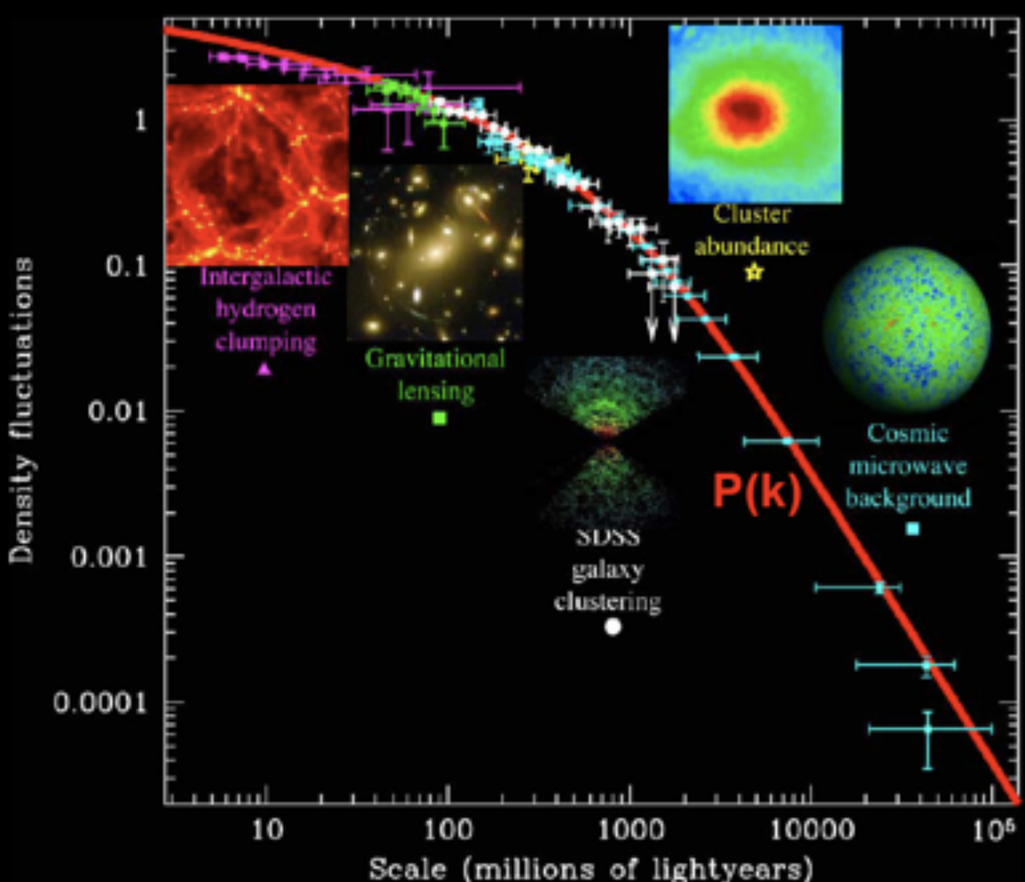

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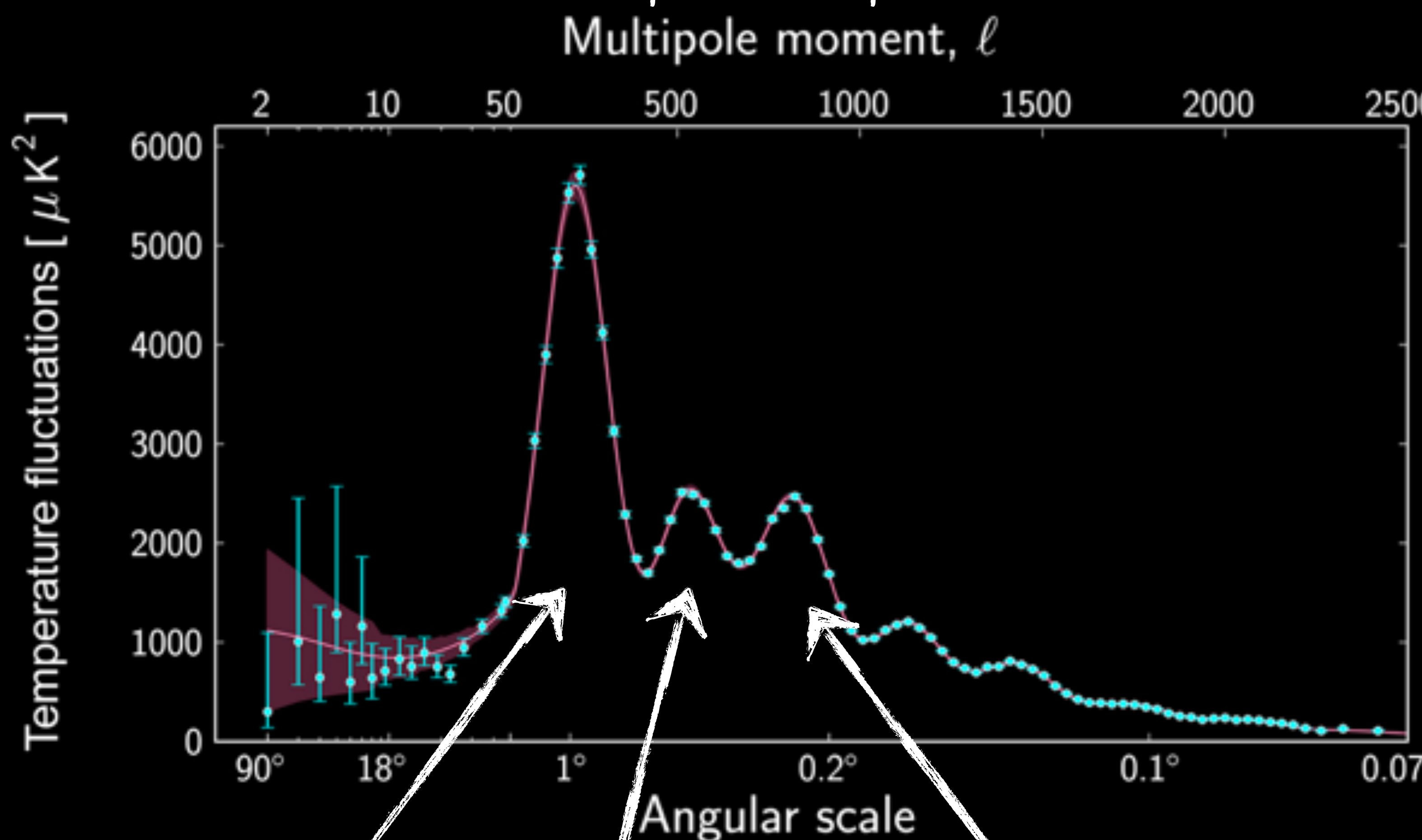

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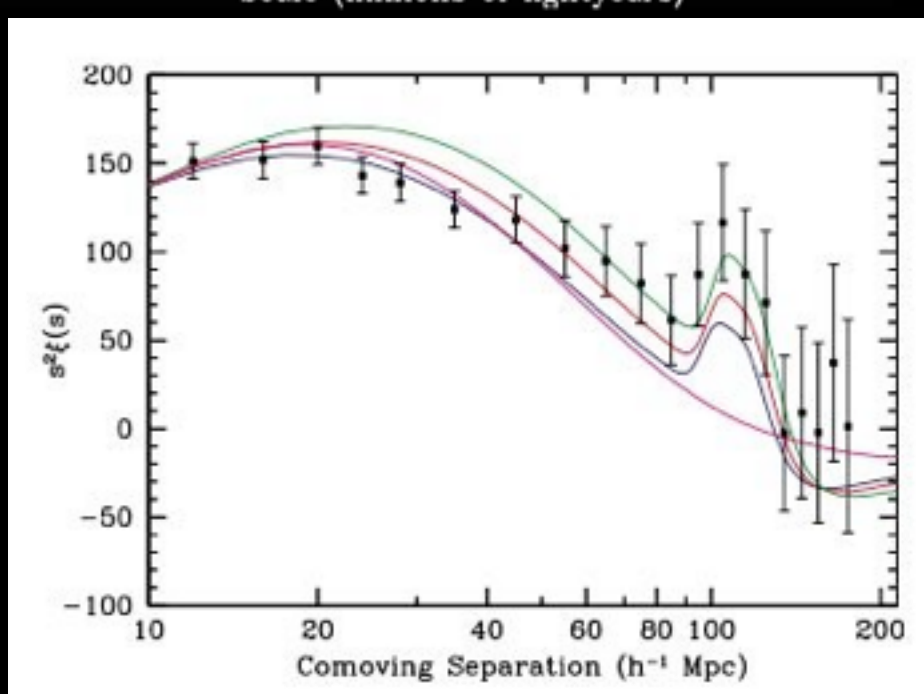
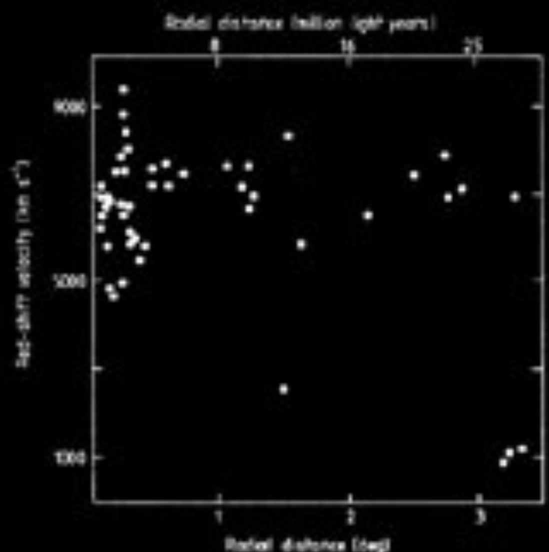


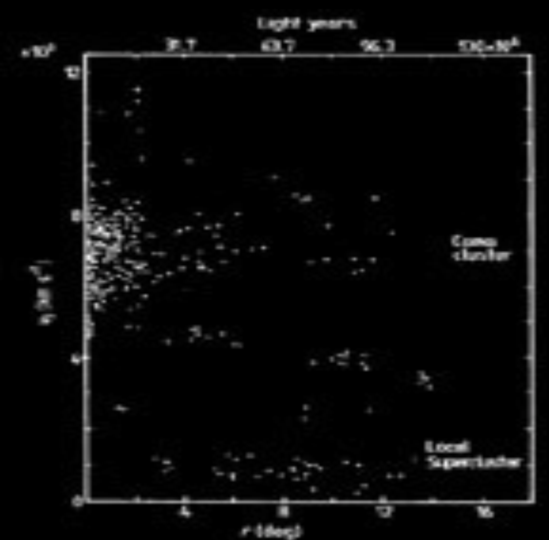
LARGE SCALE STRUCTURE

50 galaxies

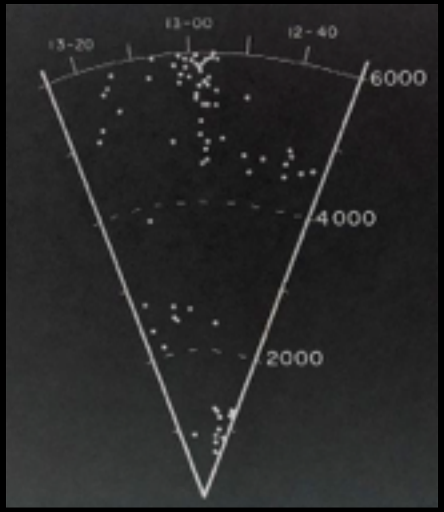


N. U. Mayall, Ann. Astrophys. 23:344, 1960

LARGE SCALE STRUCTURE



G. Chincarini and H. J. Rood,
Nature 257:294, 1975



W. G. Tifft and S. A. Gregory,
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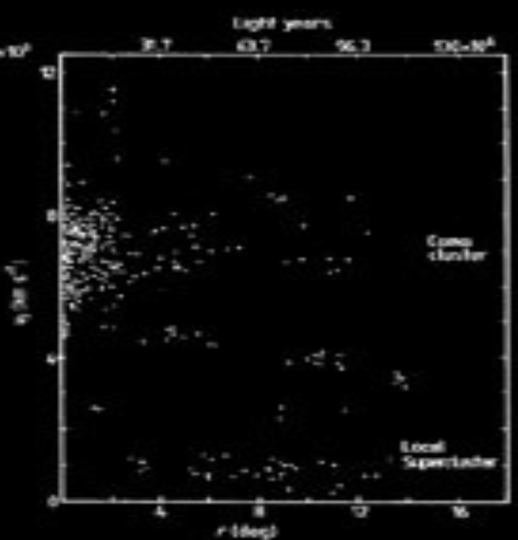

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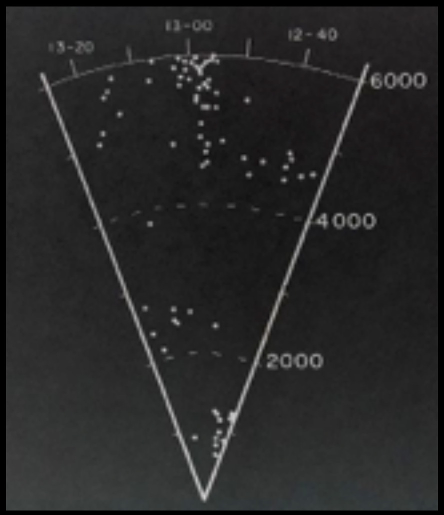

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Lick Survey

1 million galaxies

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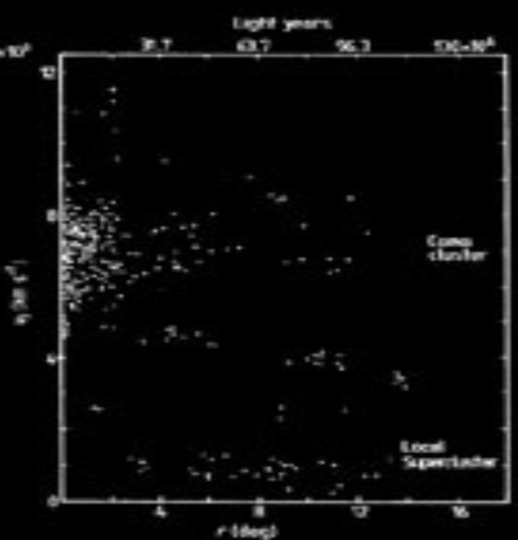

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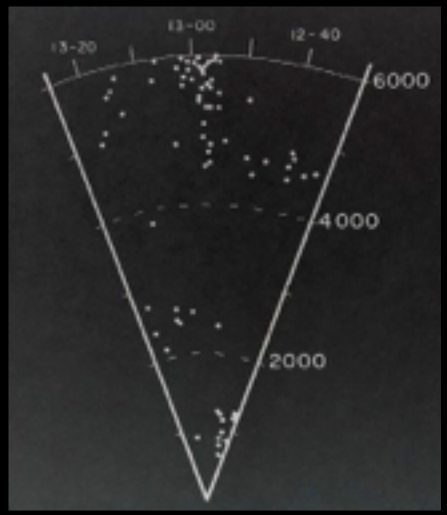

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5800 galaxies

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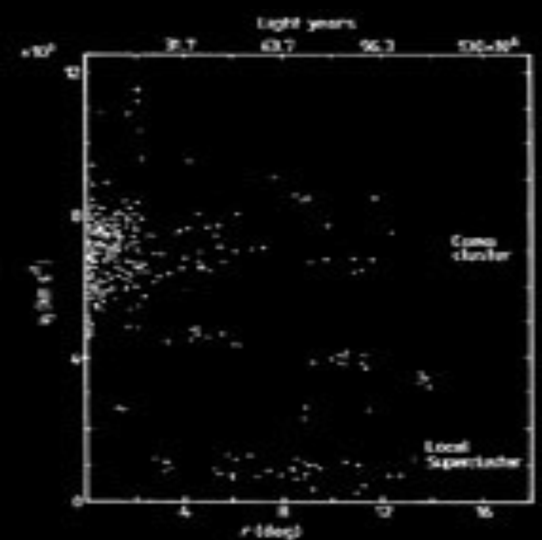

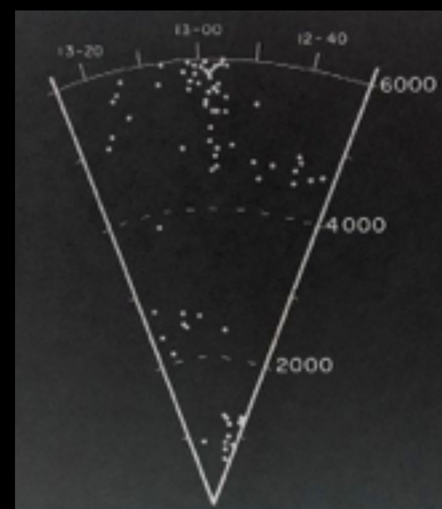

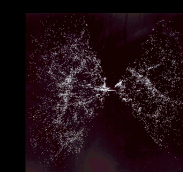

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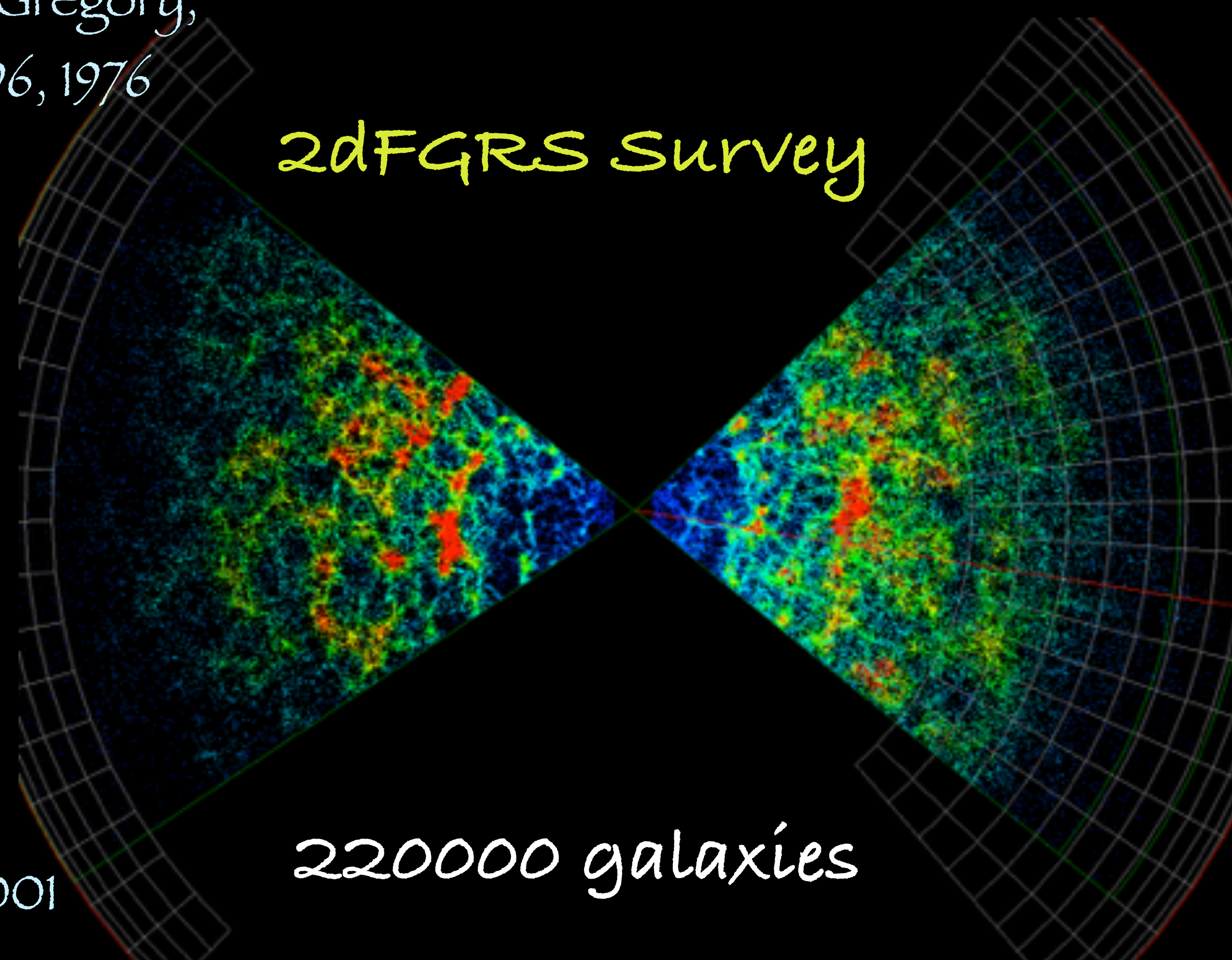
Astrophys. J. 82:249, 1977

2dFGRS Survey



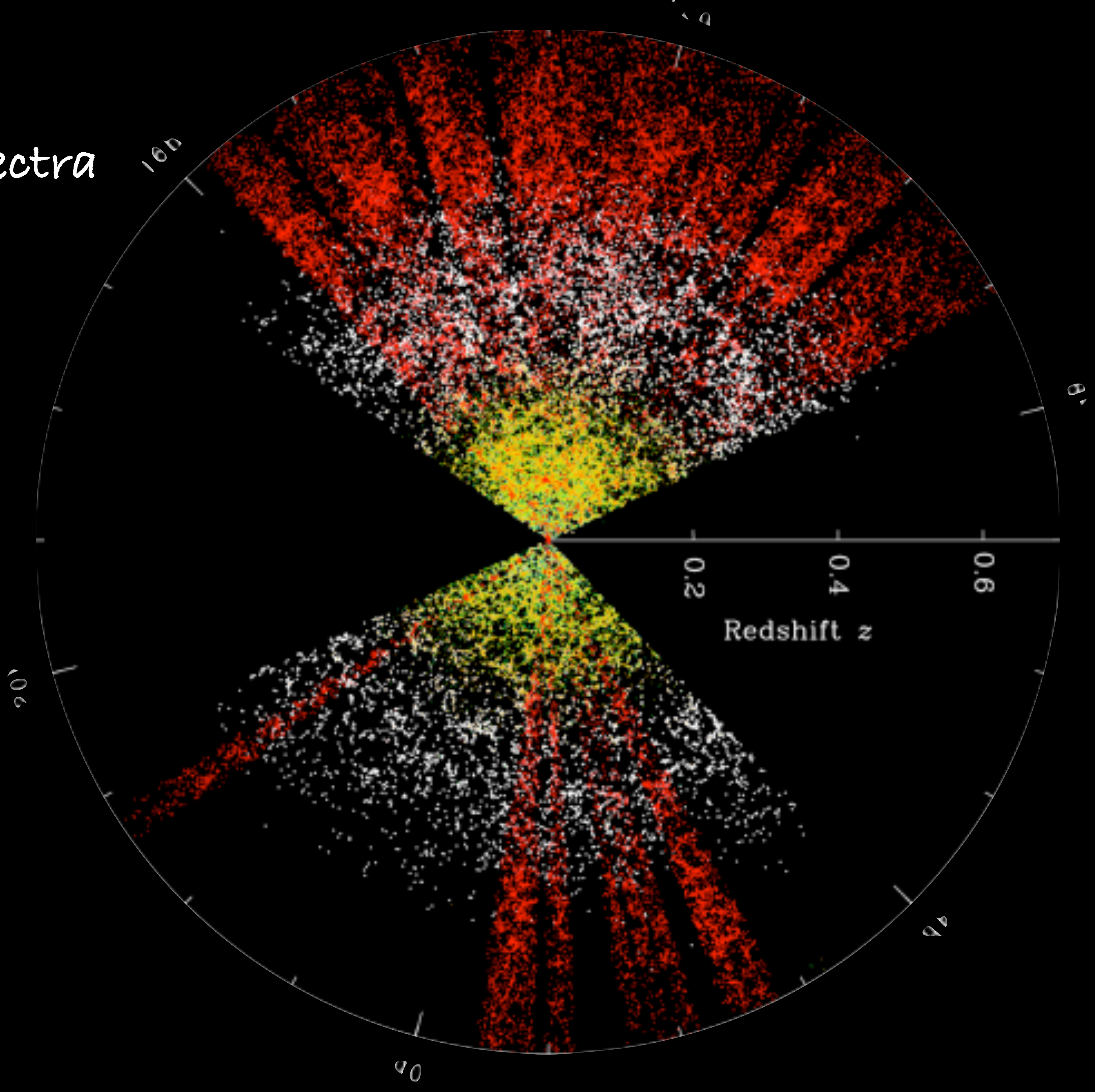
220000 galaxies

M. M. Colless et al.,
Mon. Not. R. Astr. Soc. 328:1039, 2001

LARGE SCALE STRUCTURE

2006:
350000 spectra

SDSS +
SDSS LRGs +
BOSS

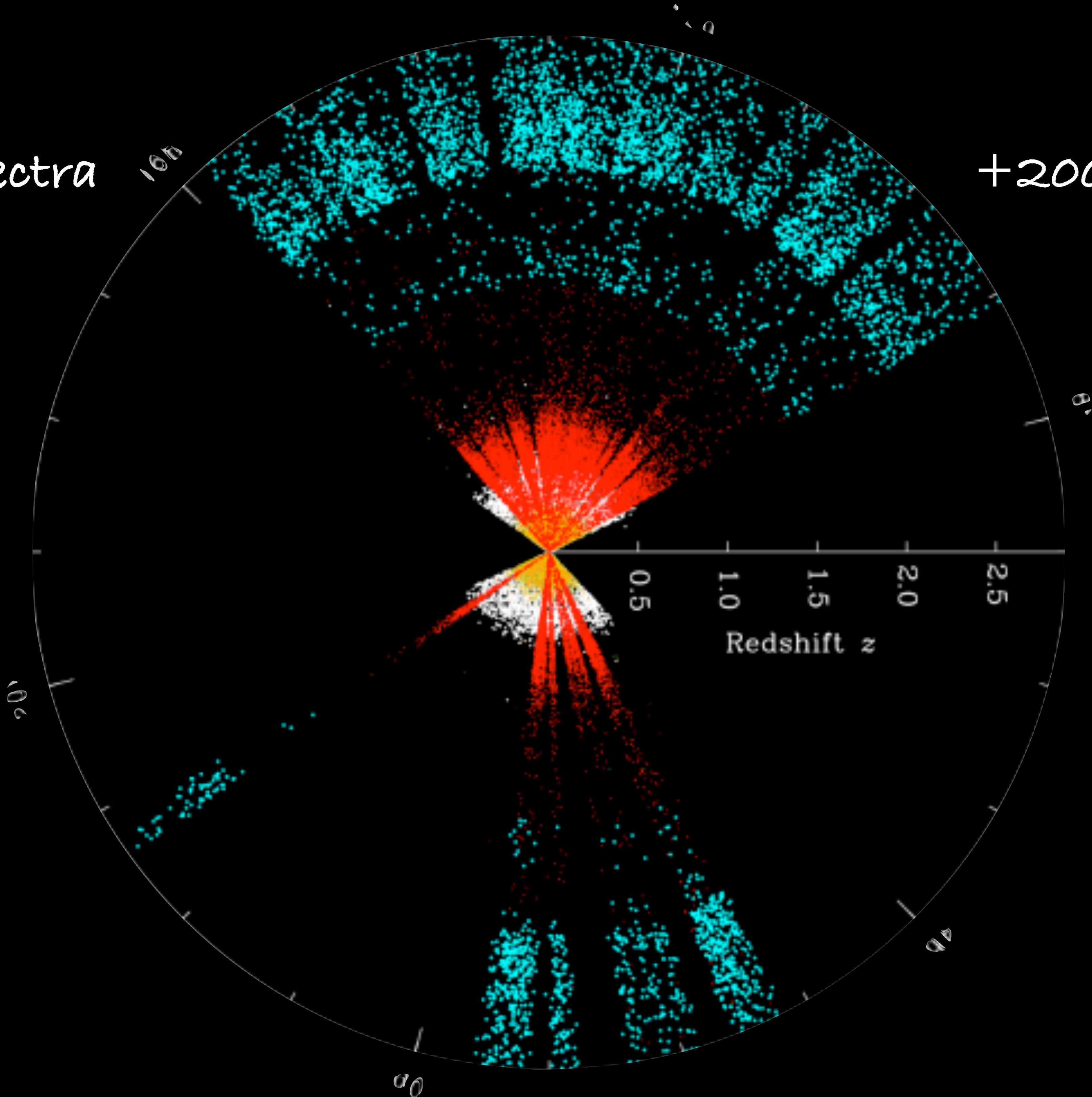


LARGE SCALE STRUCTURE

2006:
350000 spectra

2010:
+200000 spectra

SDSS +
SDSS LRGs +
BOSS



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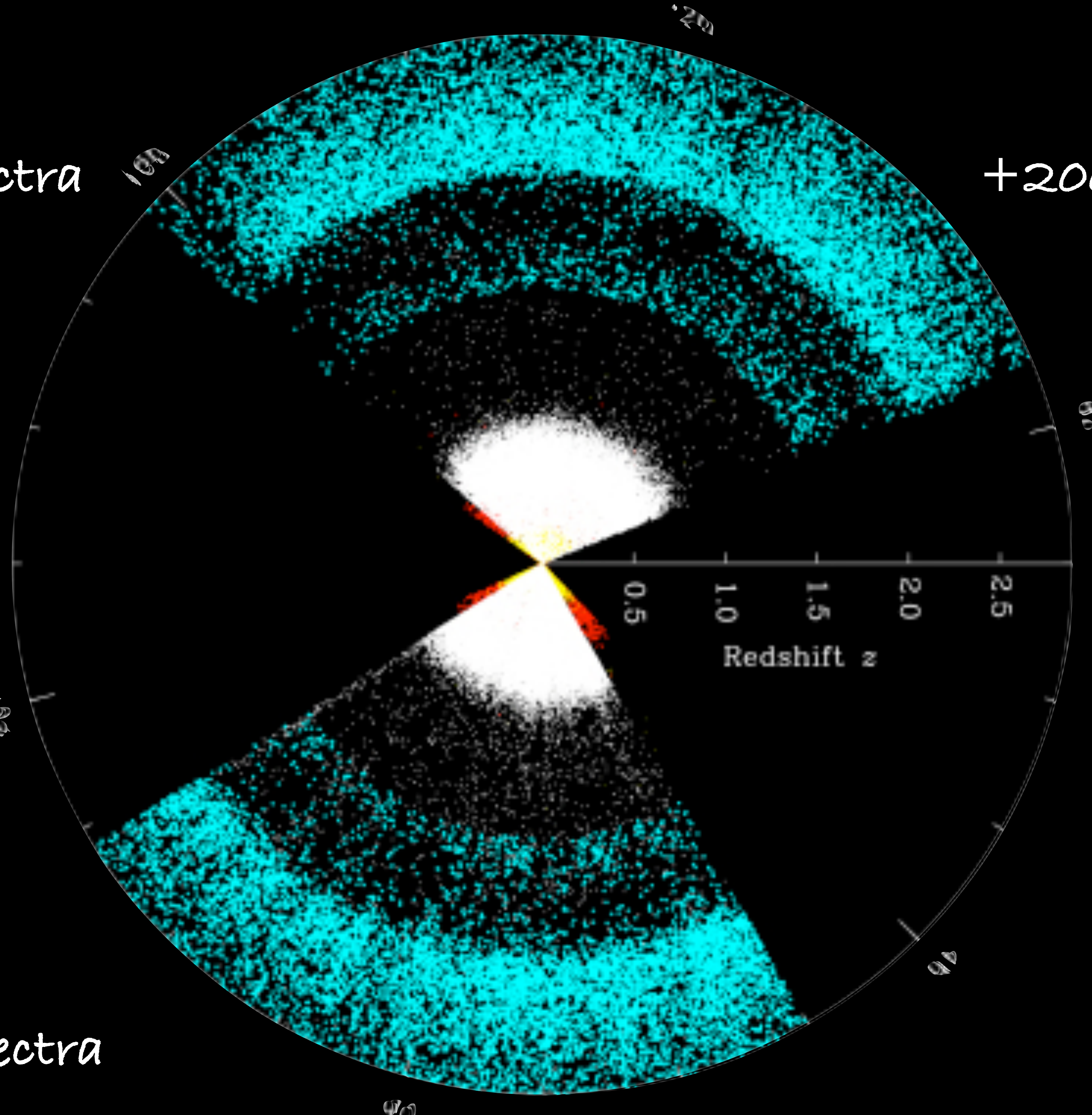

2011
+300000 spectra

LARGE SCALE STRUCTURE

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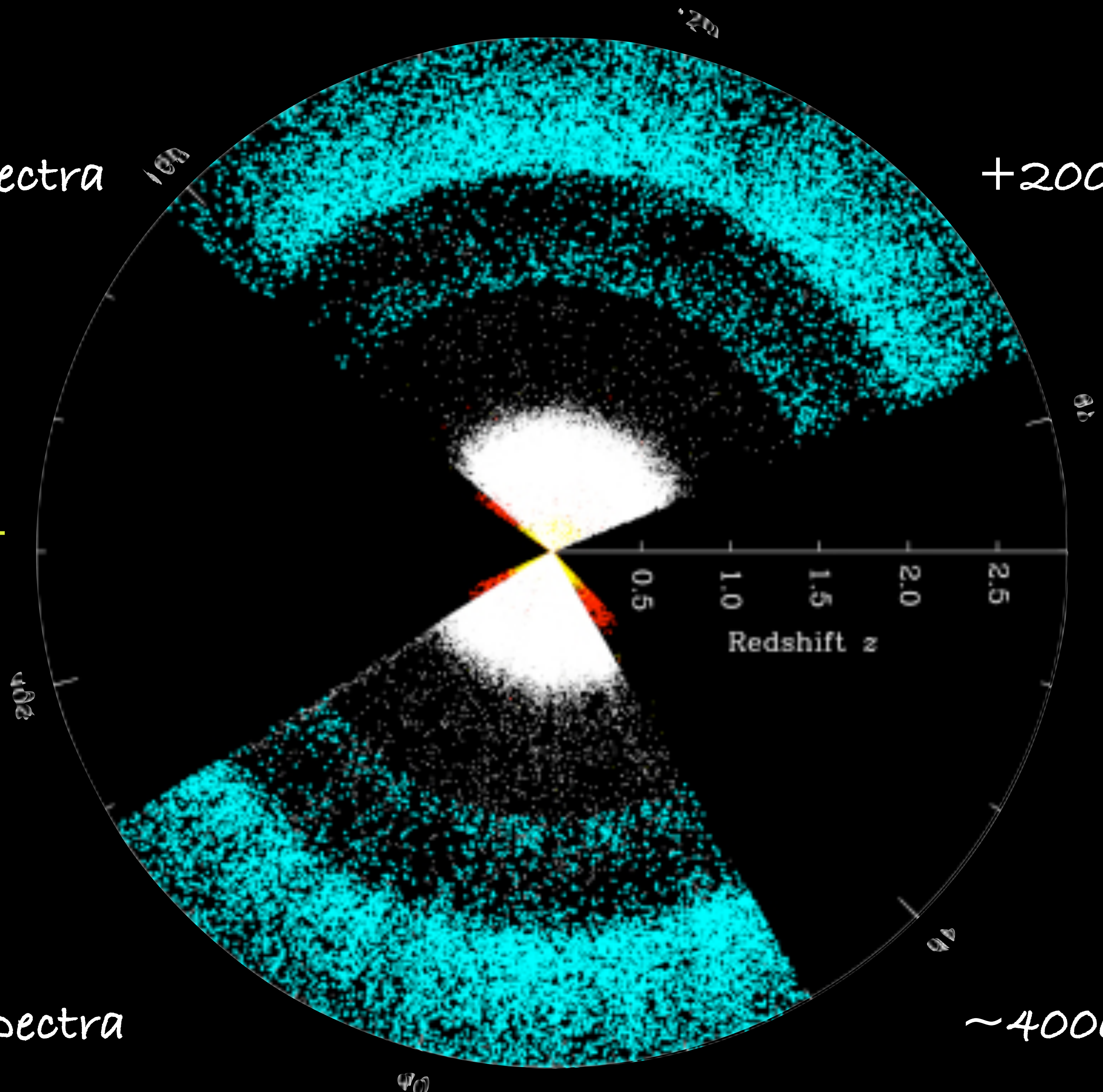
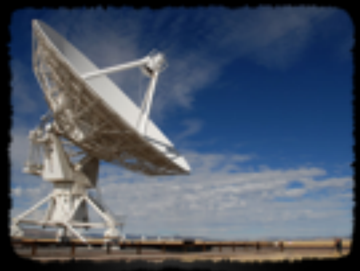


2011
+300000 spectra

2015
~4000000 spectra

GRAVITATIONAL LENSING



GRAVITATIONAL LENSING

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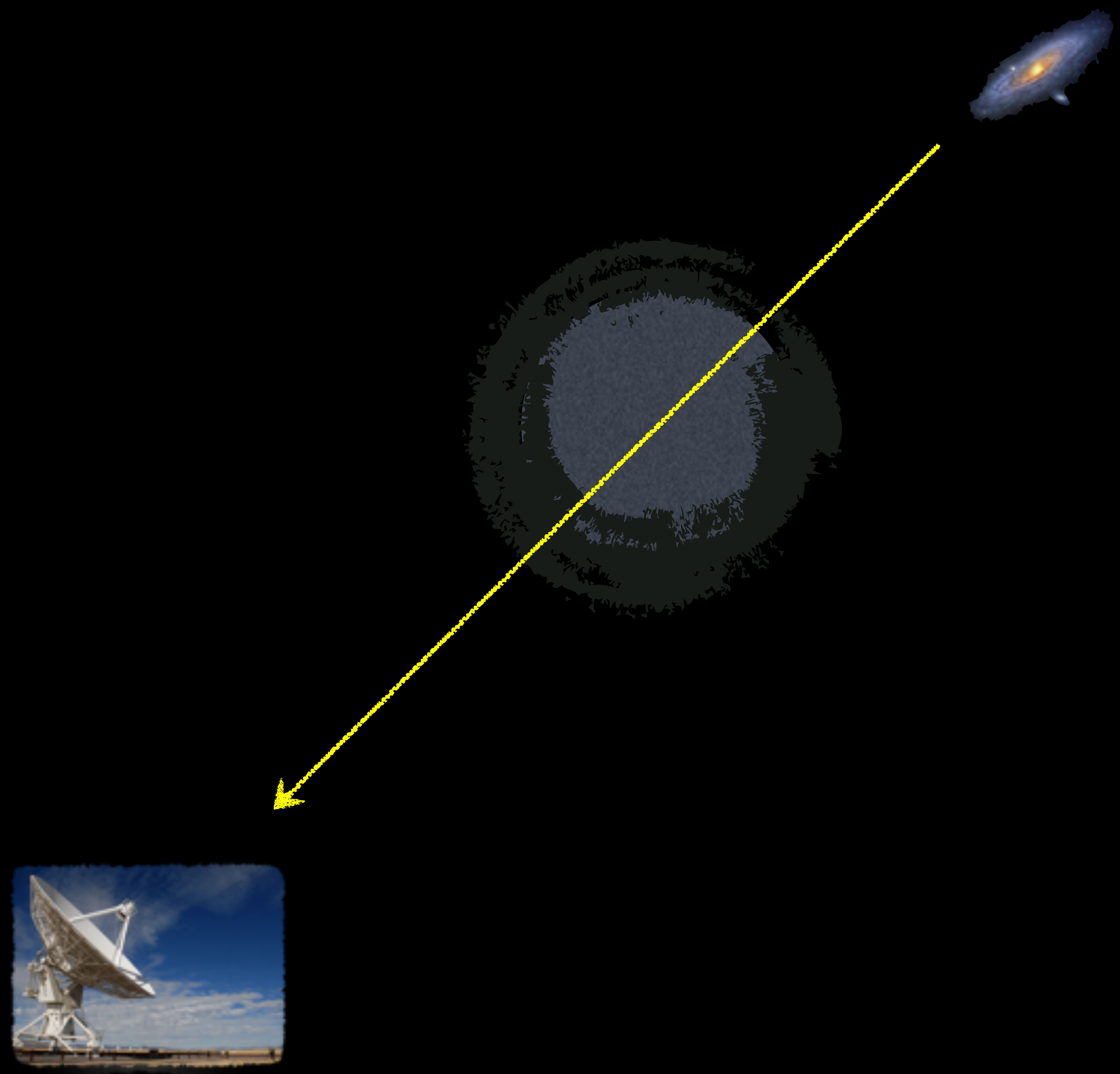
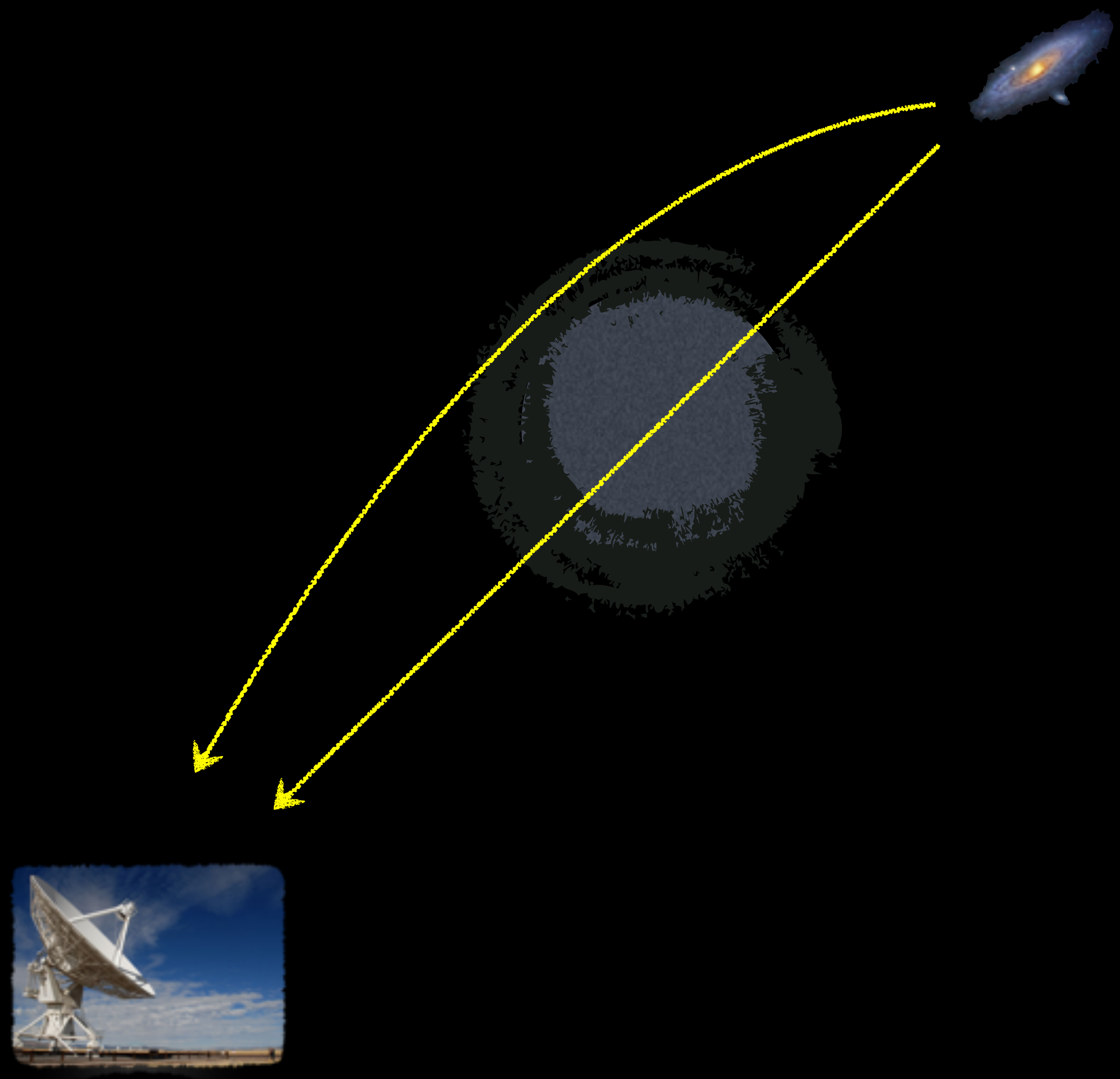


GRAVITATIONAL LENSING

Light bends after passing through a gravitational potential well



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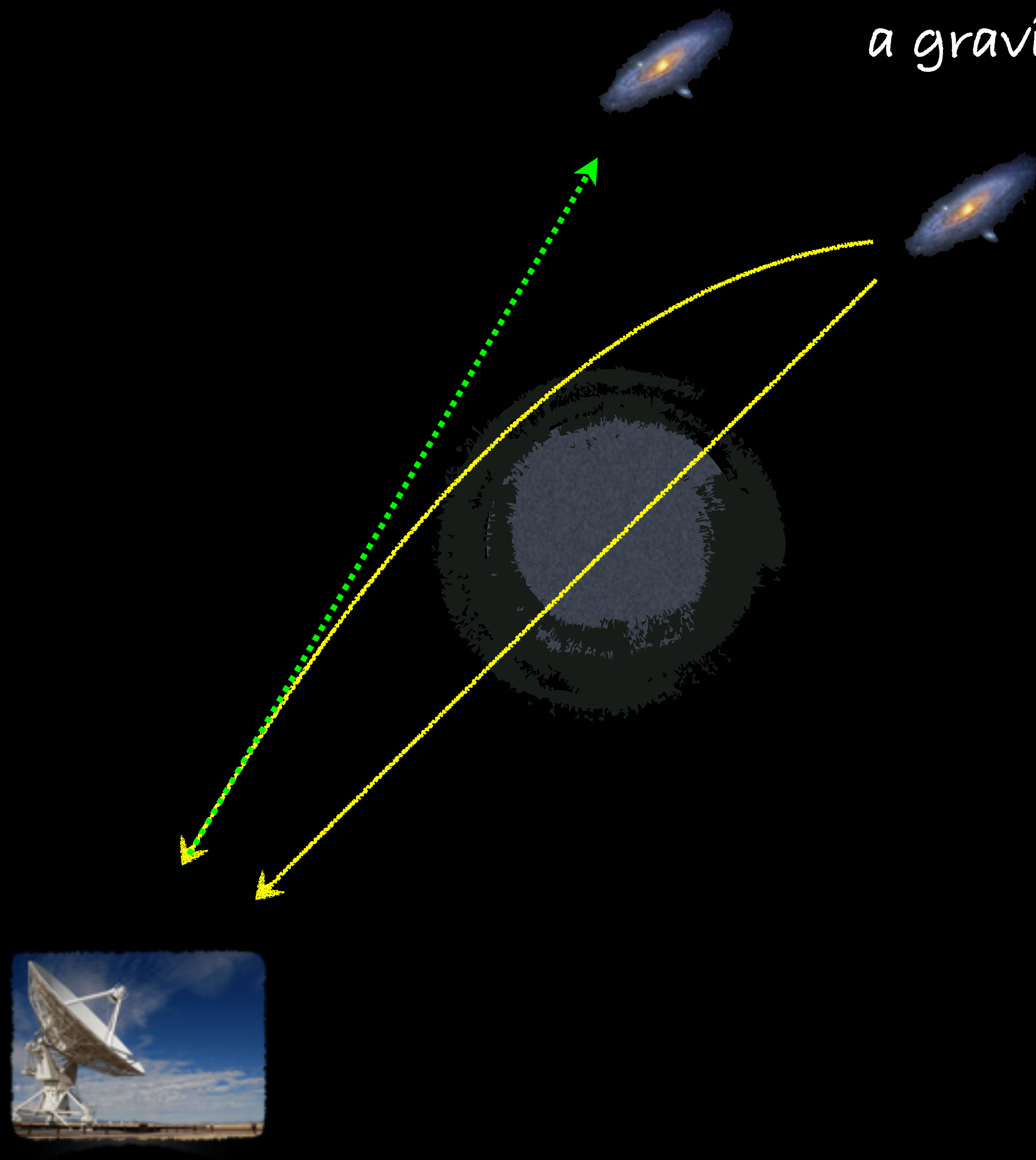

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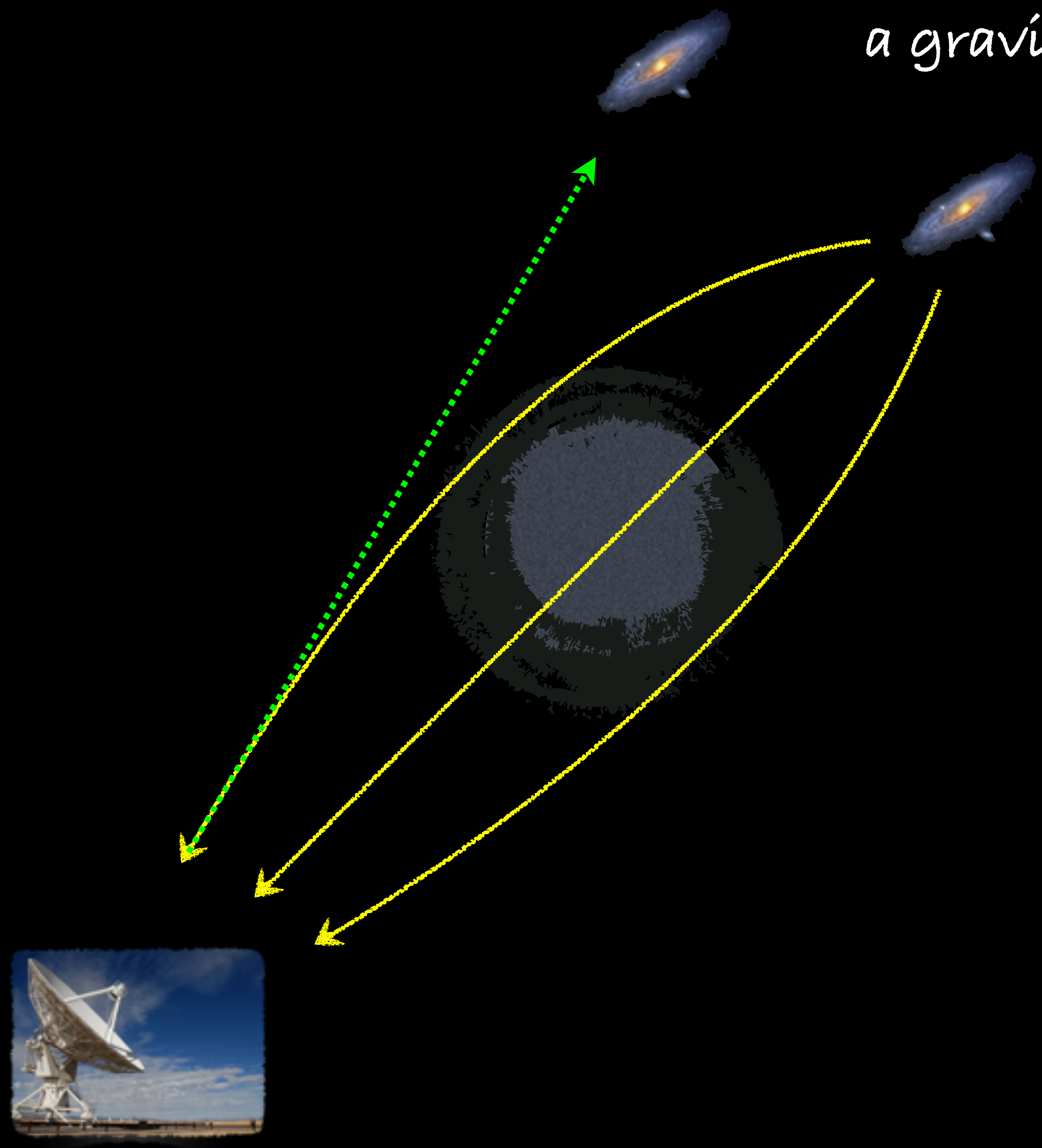

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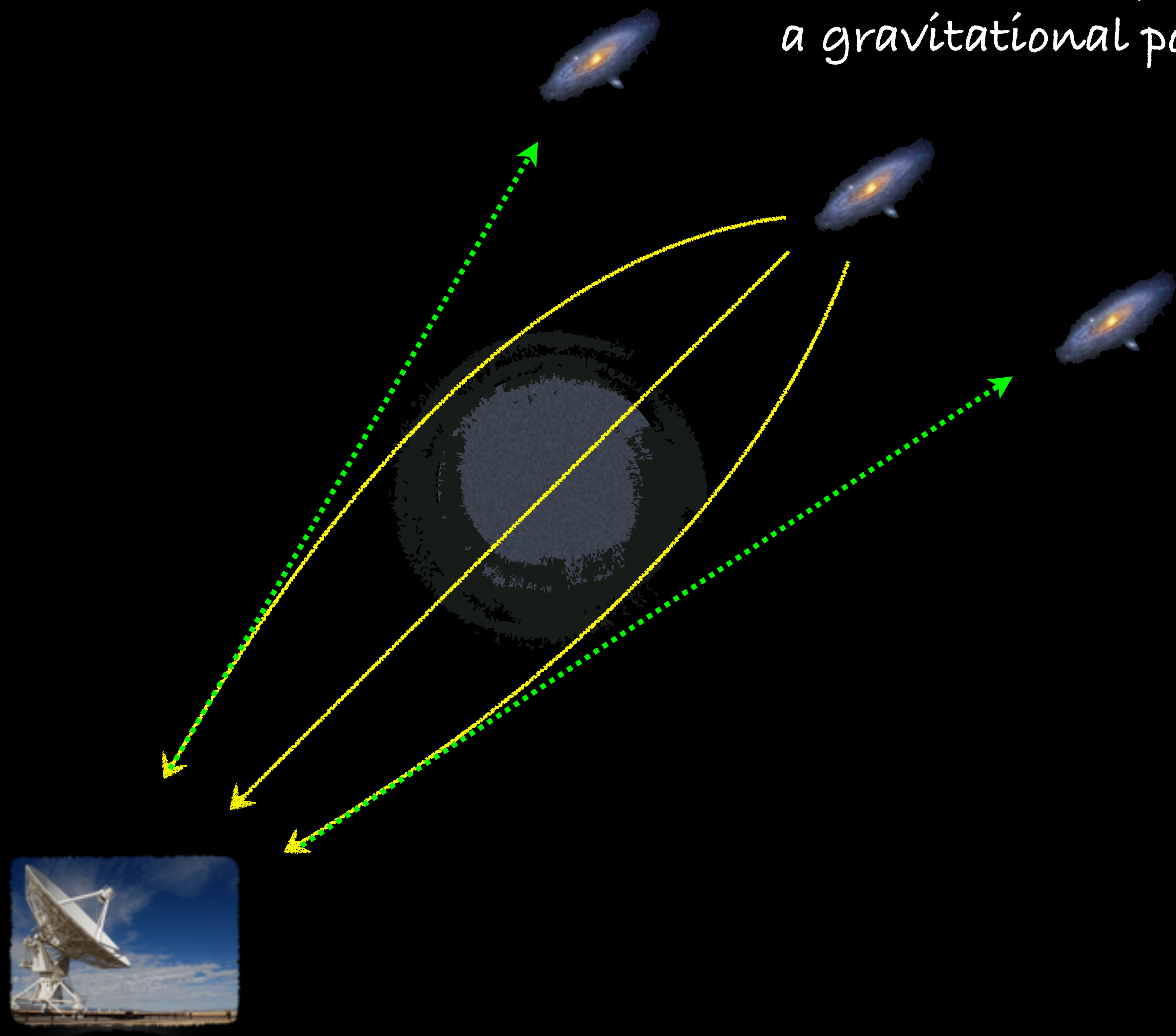

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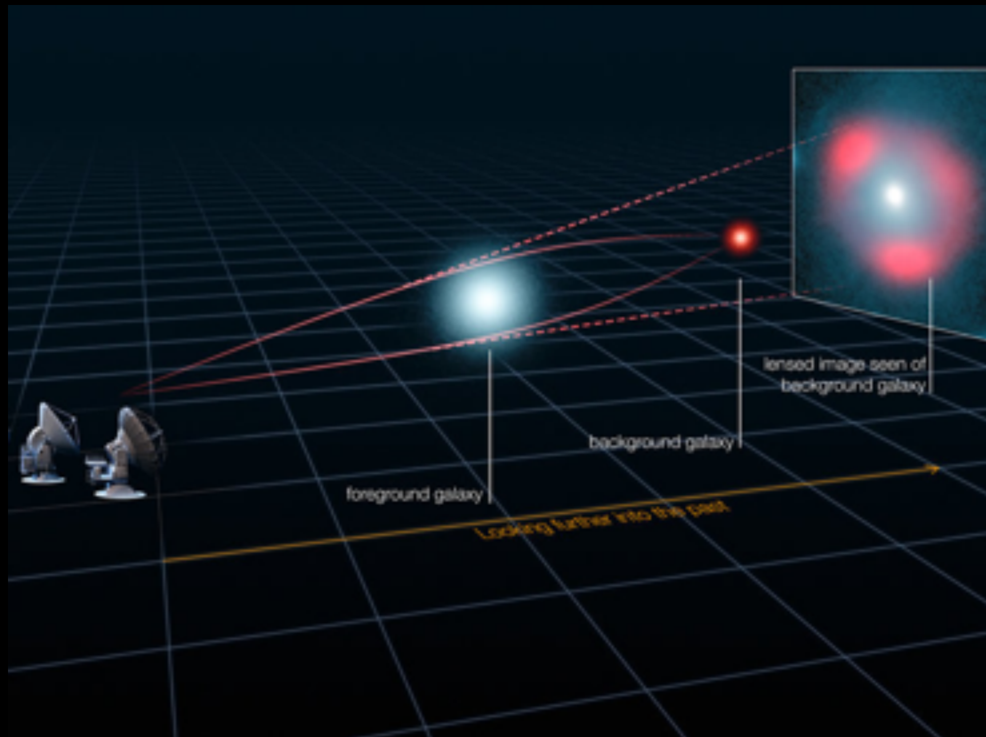

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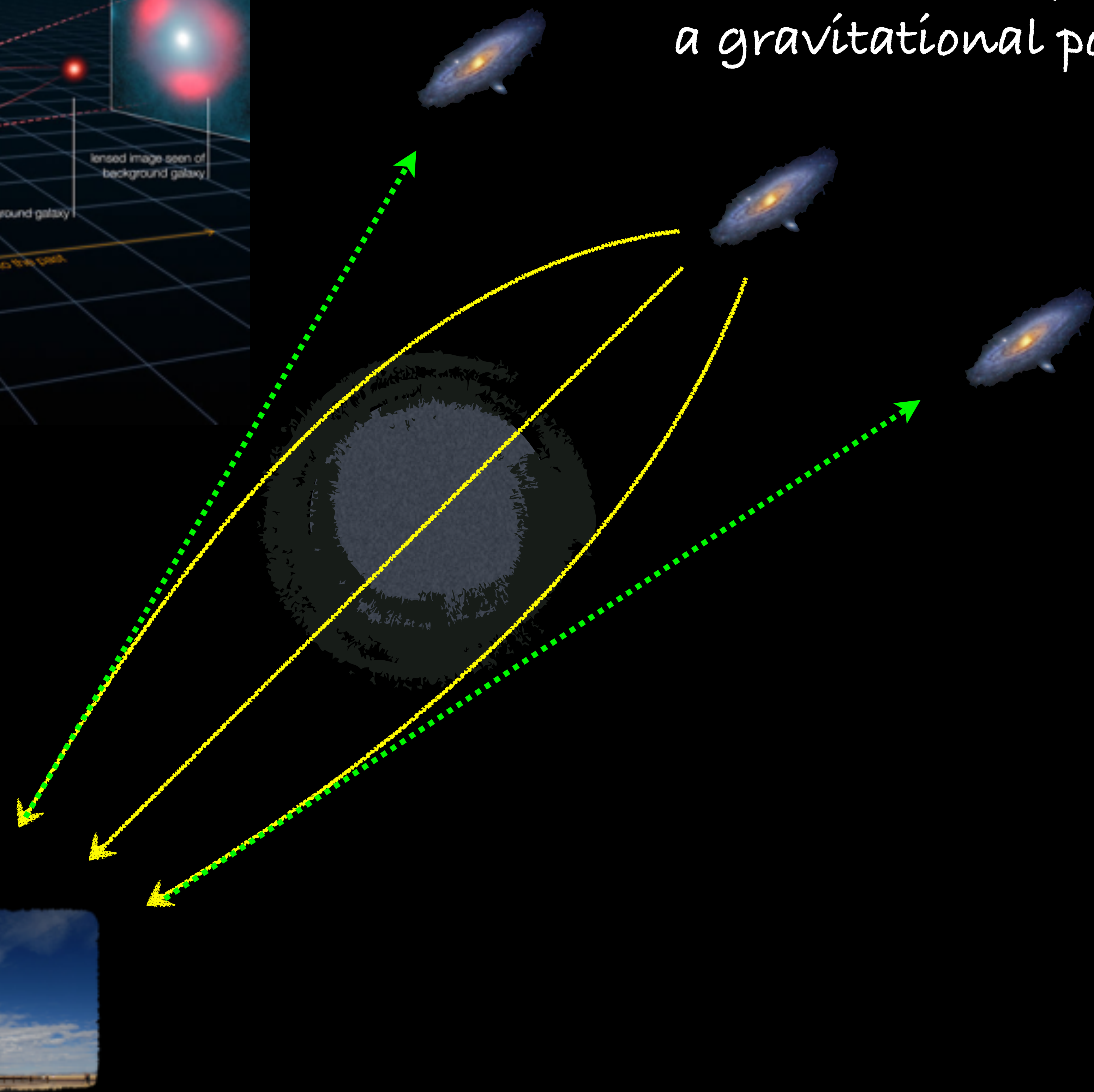

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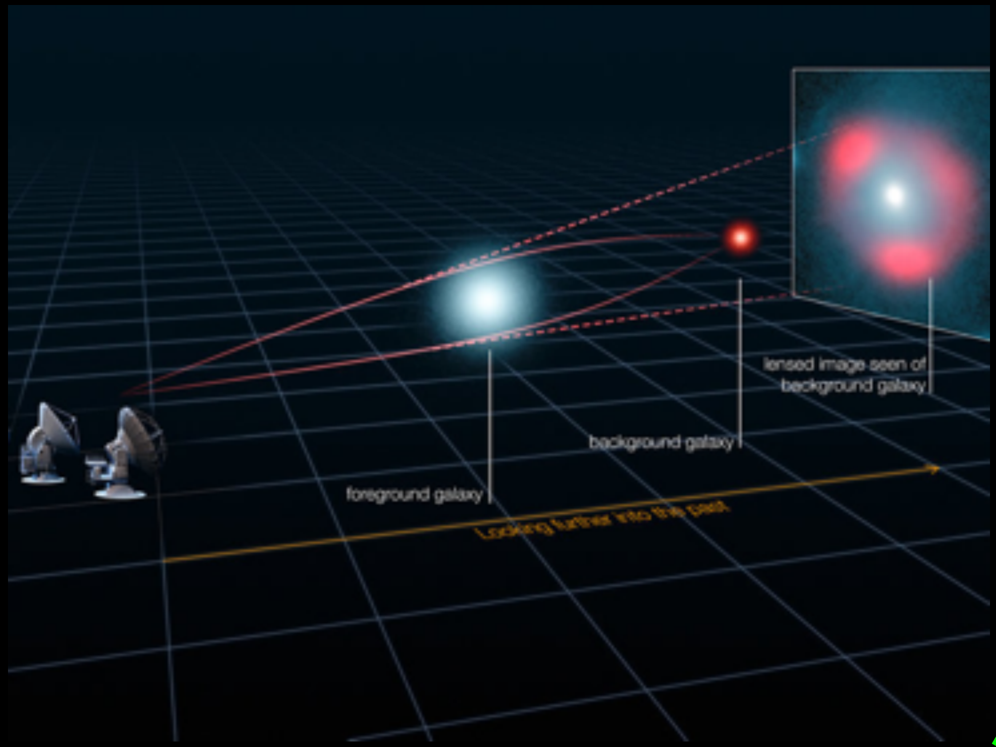

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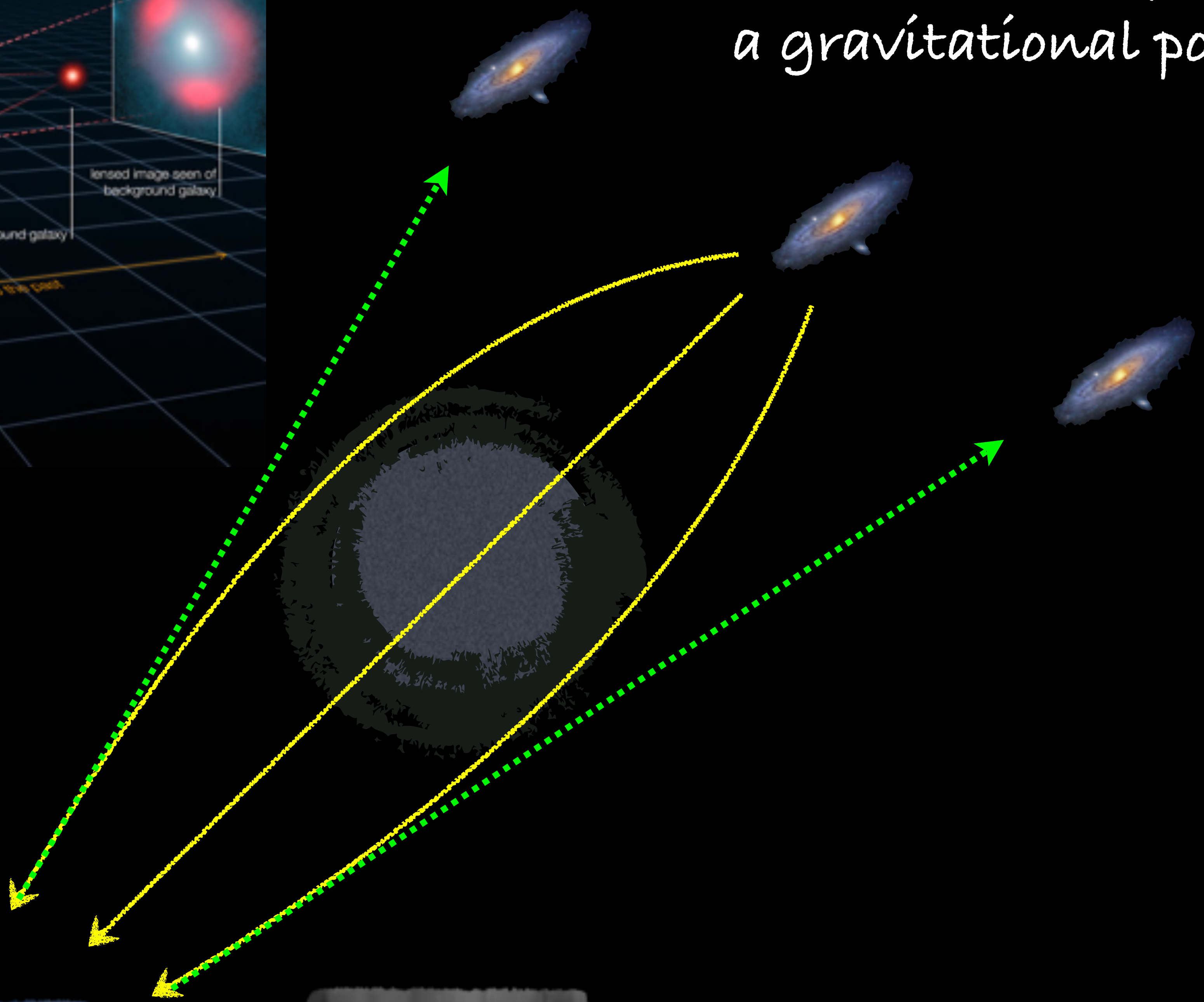

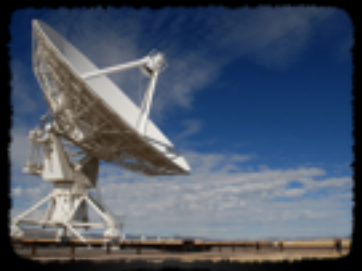

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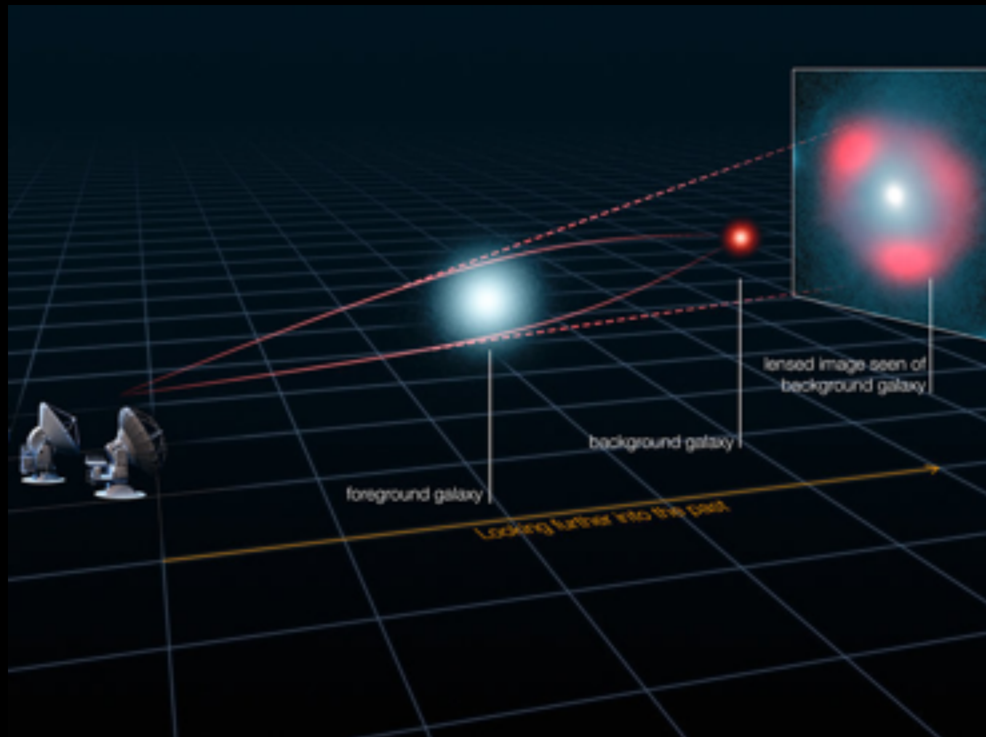

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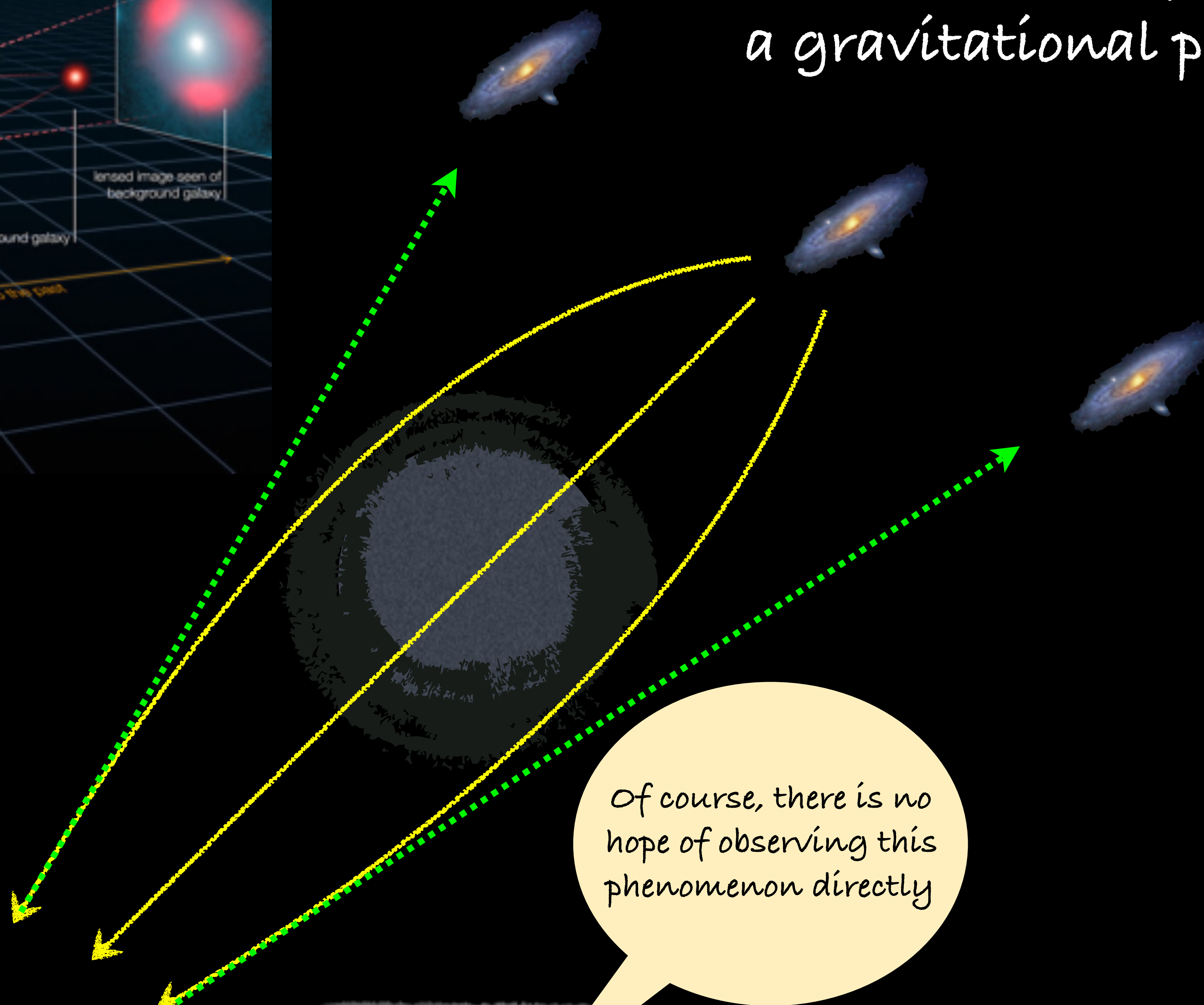
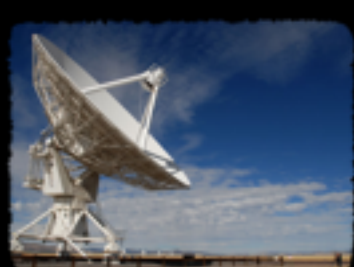
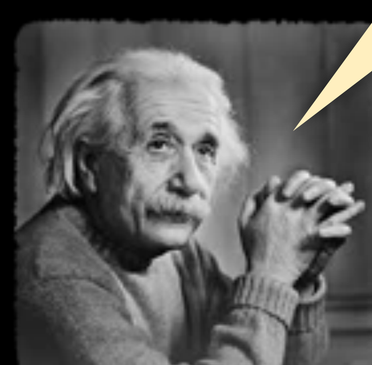


Of course, there is no hope of observing this phenomenon directly





A. Einstein, Science 84:506, 1936

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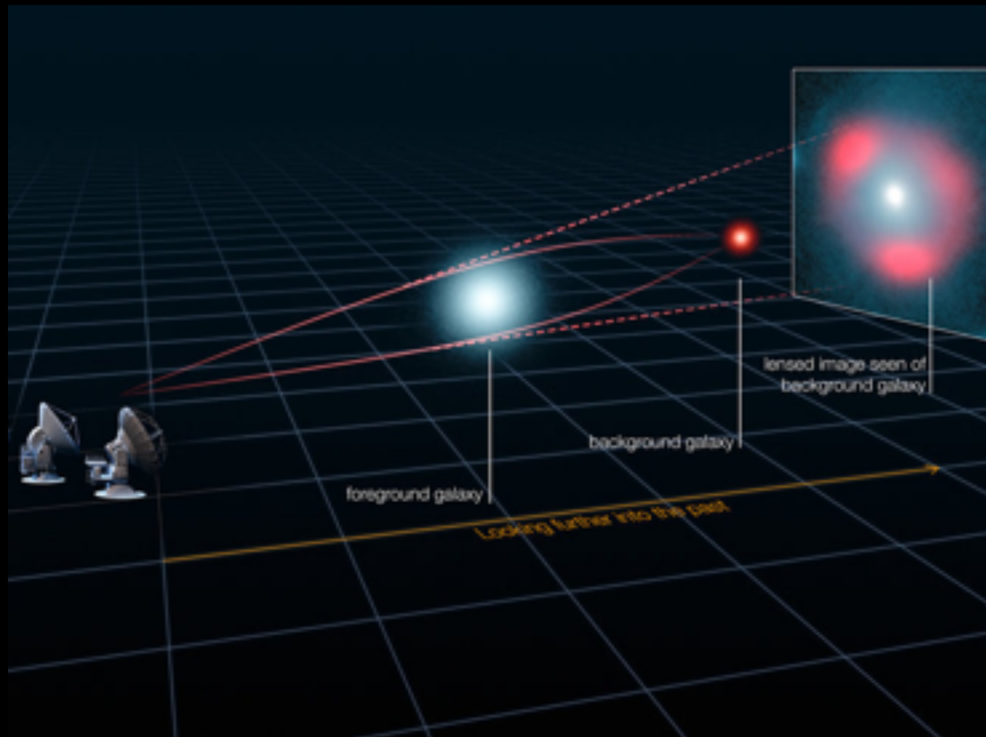

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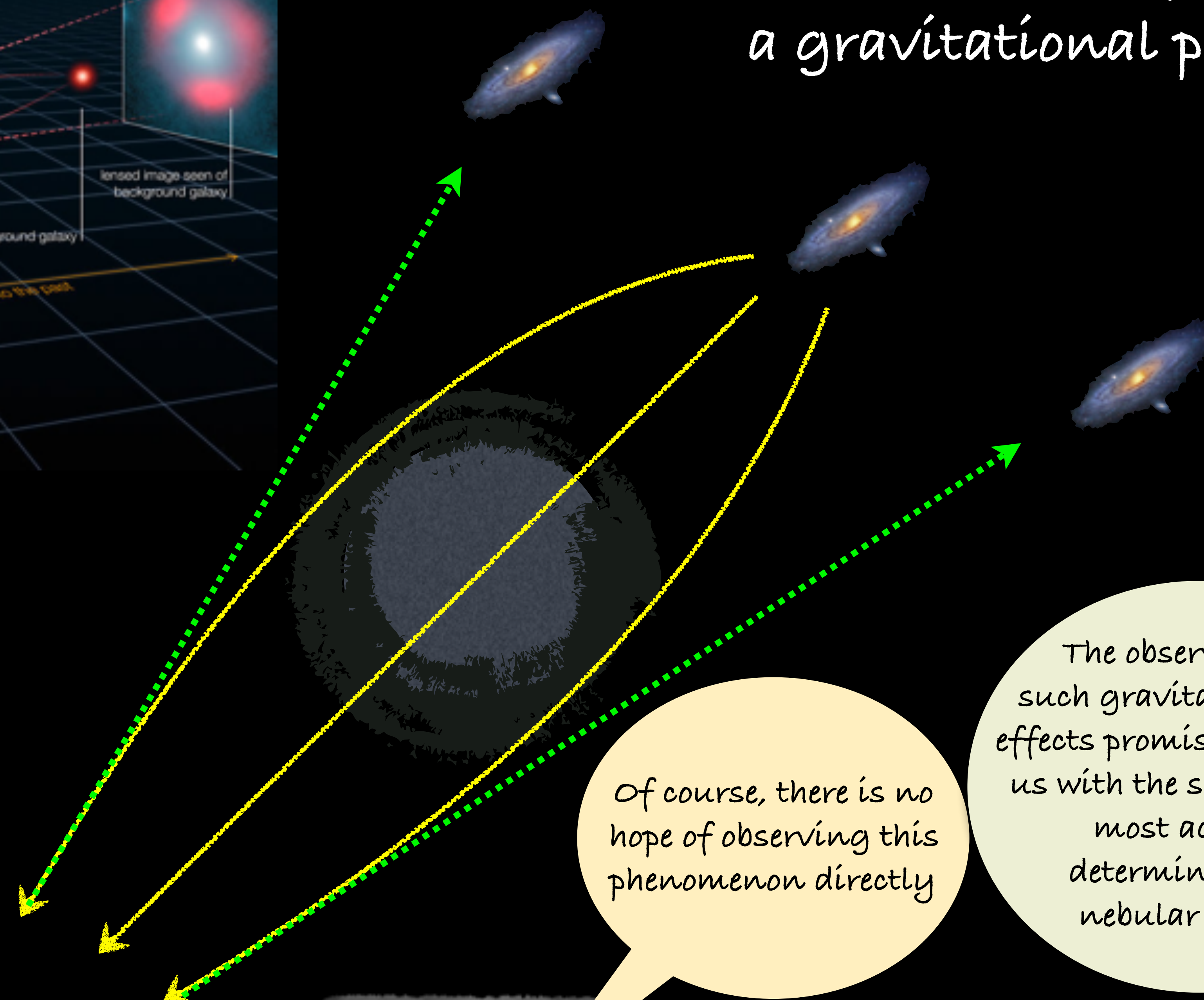

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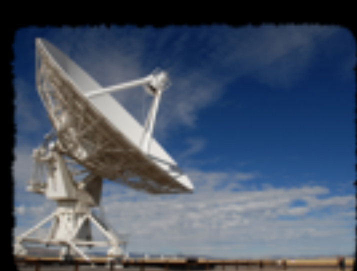
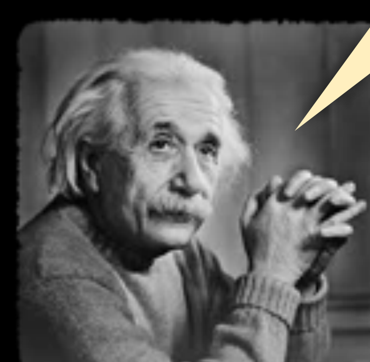
The observation of such gravitational lens effects promises to furnish us with the simplest and most accurate determination of nebular masses





A. Einstein, Science 84:506, 1936

F. Zwicky, Astrophys. J. 86:217, 1937

GRAVITATIONAL LENSING

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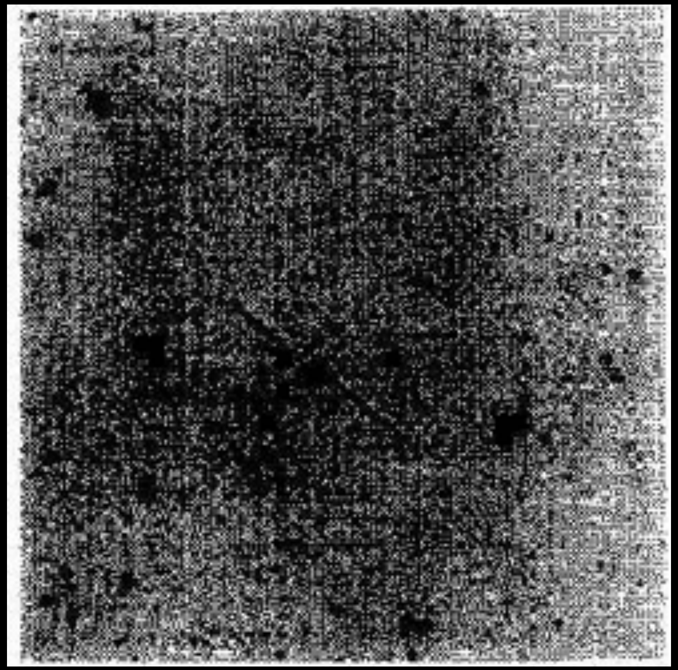
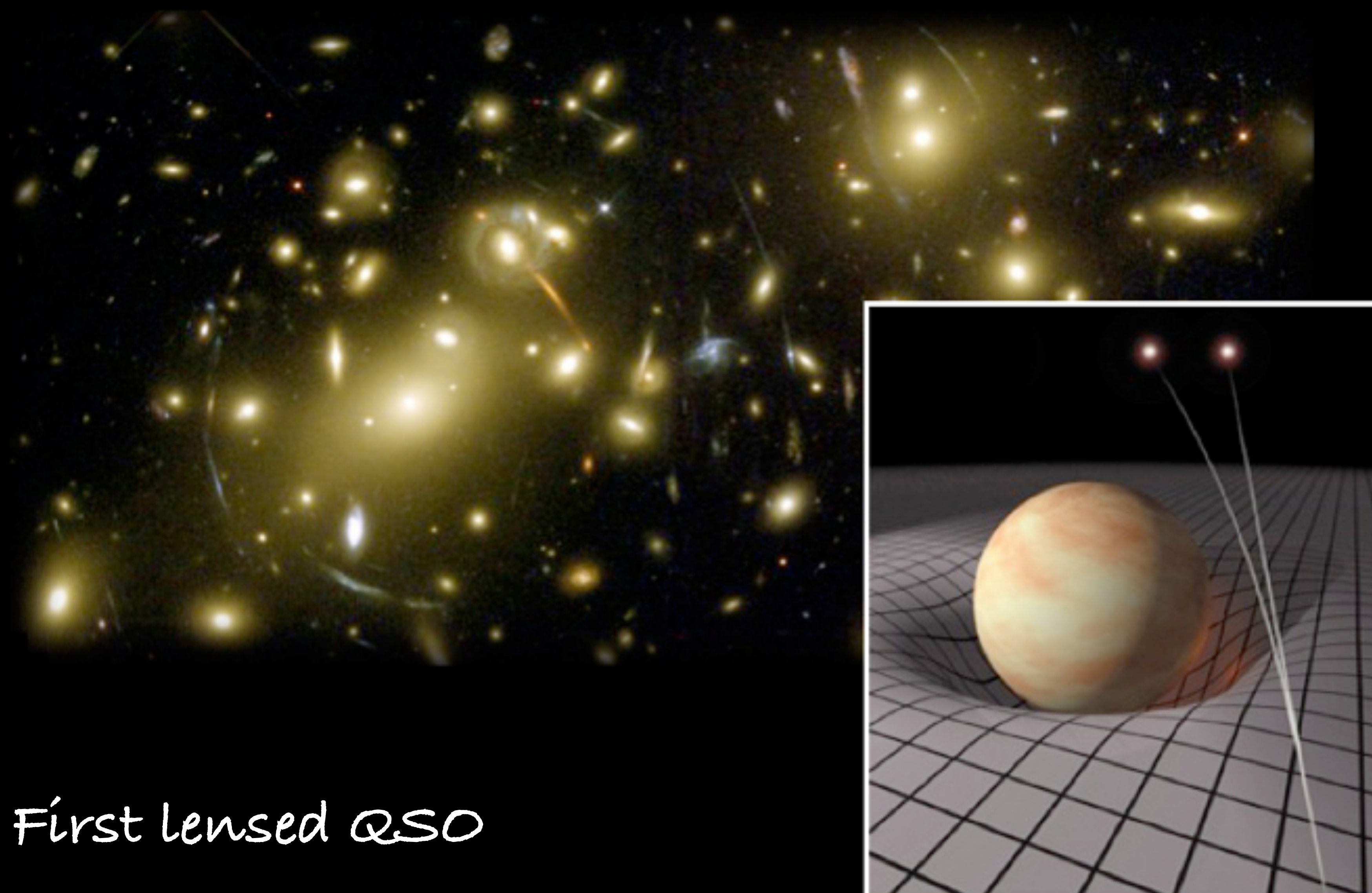


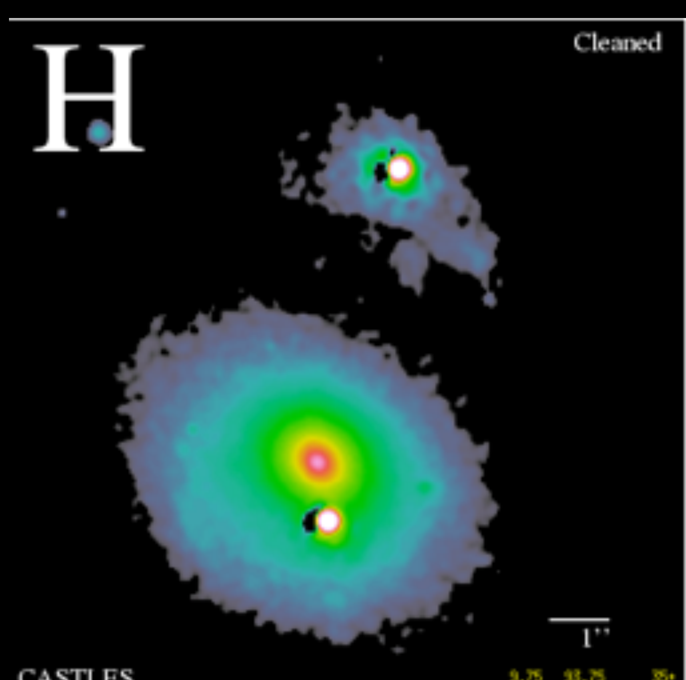
First lensed QSO

D. R. Walsh, R. Carswell and R. Weymann,
Nature 279:38, 1979

GRAVITATIONAL LENSING

Abell Cluster 2218





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COLLIDING CLUSTERS

BULLET CLUSTER

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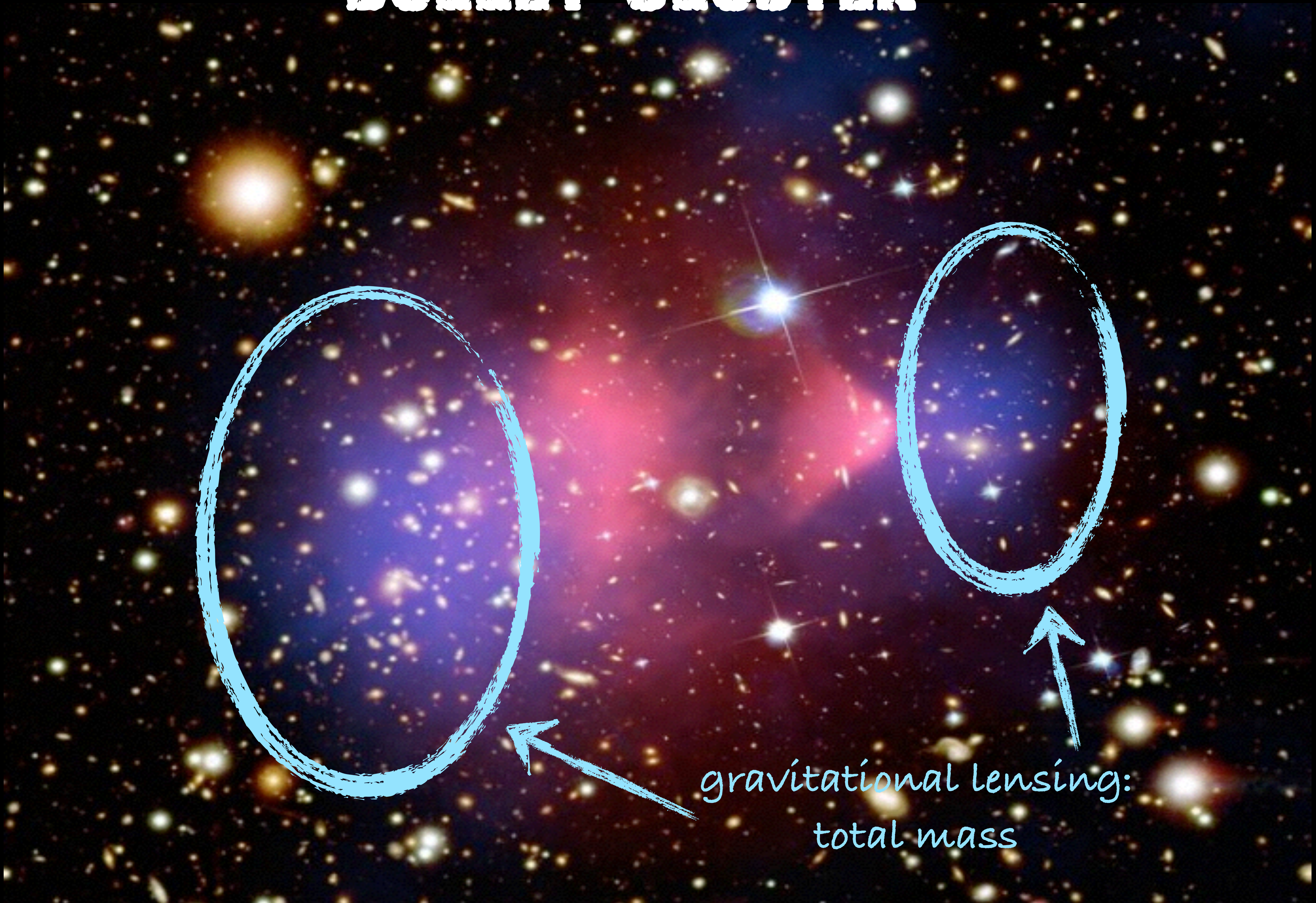

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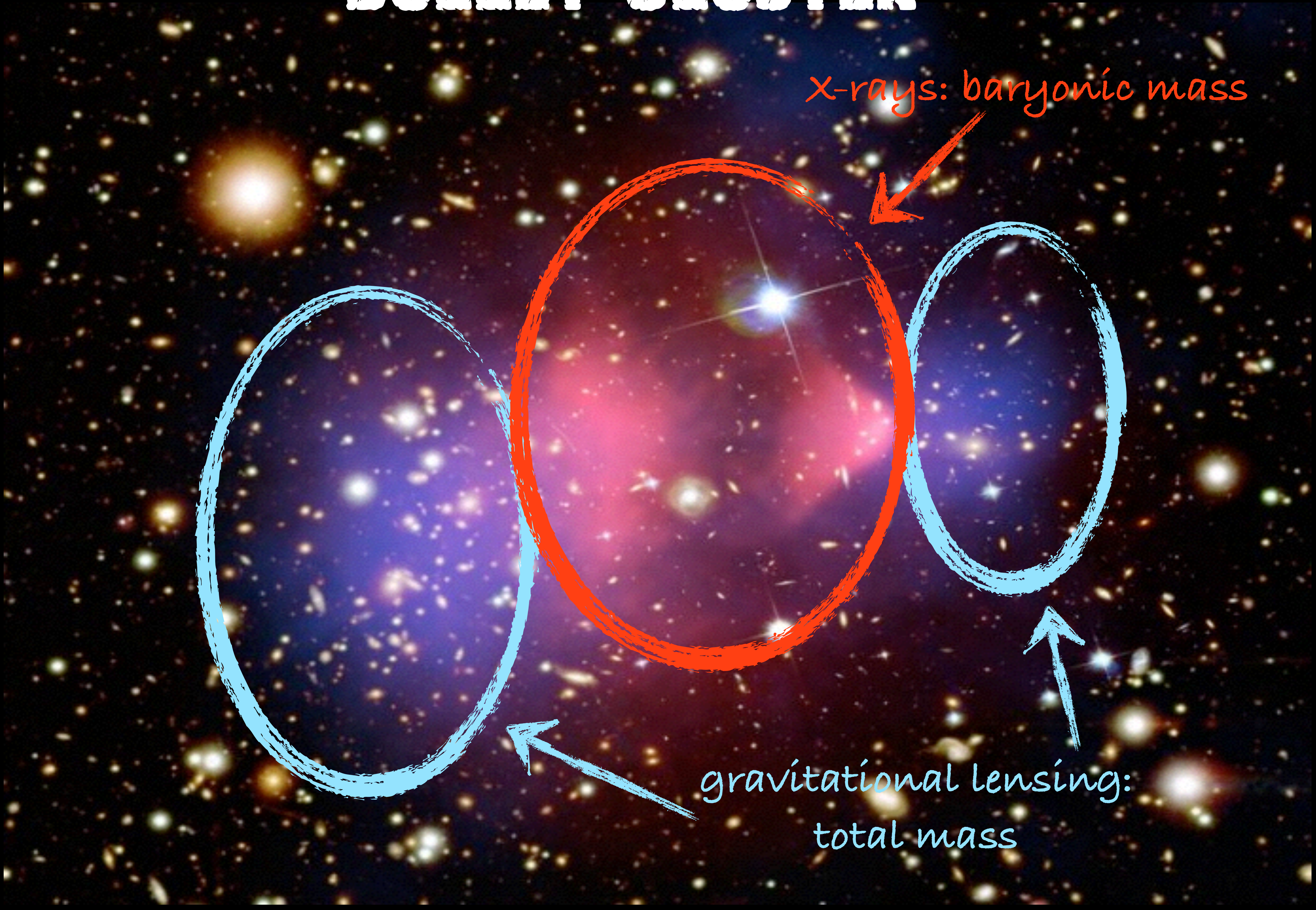


BUT ... WHAT ABOUT THE PARTICLE PROPERTIES?

Simply requiring DM to form halos and using Spin statistics

Boson

$$\Delta x \, \Delta p \geq 1$$

$$R_{halo}\left(m_{boson} v\right) \geq 1$$

$$m_{boson} \geq 10^{-22} \text{ eV}$$

Fermion (Pauli exclusion principle)

$$M_{halo} = m_{fermion} V \int f(p) \, d^3 p <$$

$$m_{fermion} V \int d^3 p \sim m_{fermion} R_{halo}^3 \left(m_{fermion} v\right)^3$$

$$m_{fermion} \geq 100 \text{ eV}$$

TREMAINE-GUNN BOUND

S. Tremaine and J. E. Gunn, Phys. Rev. Lett. 42:407, 1979

Folding in assumptions about the evolution in the Early Universe, sets more restrictive scales

DARK MATTER PRODUCTION

Thermal production

In thermal equilibrium with the SM particles

Non-thermal production

very weak couplings, phase transition, particle decays...

Candidates must:

Be stable on cosmological scales

Interact weakly or very weakly

Be neutral

Have the right relic density

Be warm or cold

EQUILIBRIUM DENSITIES

At high temperatures, DM interactions with SM particles keep DM in thermal equilibrium

$$n_{eq} = \frac{g}{(2\pi\hbar)^3}\int \frac{4\pi p^2 dp}{e^{E/kT} \pm 1} = \begin{cases} \text{Fermions} & \begin{cases} \dfrac{3\varsigma(3)}{4\pi^2} g T^3 & \text{if} \quad m \ll T \\ g\left(\dfrac{mT}{2\pi}\right)^{3/2} e^{-m/T} & \text{if} \quad m \gg T \end{cases} \\ \text{Bosons} & \begin{cases} \dfrac{\varsigma(3)}{\pi^2} g T^3 & \text{if} \quad m \ll T \\ g\left(\dfrac{mT}{2\pi}\right)^{3/2} e^{-m/T} & \text{if} \quad m \gg T \end{cases} \end{cases}$$

THERMAL FREEZE-OUT

Boltzmann equation:

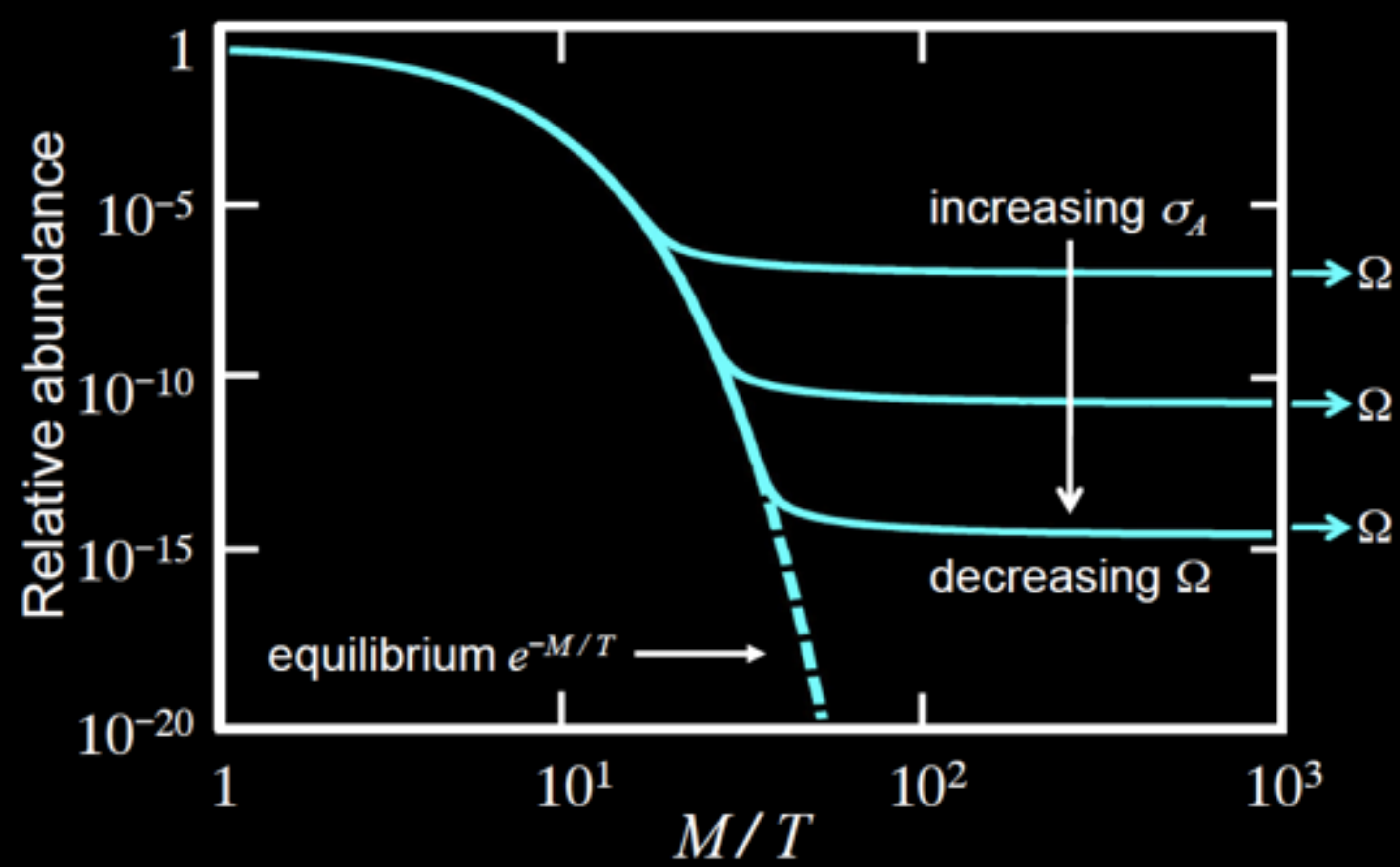
$$\int L[f]\frac{d^3p}{(2\pi)^3} = \int C[f]\frac{d^3p}{(2\pi)^3}$$

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

$$Y \equiv n/s \qquad x \equiv m/T$$

$$\frac{x}{Y_{eq}}\frac{dY}{dx} = -\frac{n_{eq}\langle\sigma v\rangle}{H}\left(\left(\frac{Y}{Y_{eq}}\right)^2 - 1\right)$$

$$Y(x) \simeq \begin{cases} Y_{eq}(x) & x \le x_f \\ Y_{eq}(x_f) & x \ge x_f \end{cases}$$



THERMAL RELICS

Hot relics

$$n_0 = s_0 Y_\infty$$

Cold relics $Y \gg Y_{eq}$

$$\Omega_{\rm HDM} h^2 = \frac{m\, n_0\, h^2}{\rho_c^0} = 0.076 \frac{g_n}{g_{*S}(T_F)} \left(\frac{m}{\rm eV}\right) \leq 1$$

For a fermion with g=2 and decoupled at T~MeV

$$m \leq 94.1 \text{ eV}$$

COWSIK-MCCLELLAND BOUND

G. Gerstein and Ya. B. Zeldovich, Zh. Eksp. Teor. Fiz. Pis'ma Red. 4:174, 1966

R. Cowsik and J. McClelland, Phys. Rev. Lett. 29:669, 1972

$$Y_\infty \simeq \frac{H(T=m)}{\langle \sigma v \rangle g_{*S}(T_F) m^3} x_F$$

$$\Omega_{\rm CDM} h^2 \approx 0.1 \left(\frac{\langle \sigma v \rangle}{3\times 10^{-26}\,{\rm cm}^3/{\rm s}}\right)^{-1} \left(\frac{x_F}{20}\right) \left(\frac{7}{g_{*S}(T_F)/g_*(T=m)^{1/2}}\right)$$

with weak interactions: $\langle \sigma v \rangle \simeq G_F^2 m^2$

$$m \geq 2 \text{ GeV}$$

LEE-WEINBERG BOUND

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

P. Hut, Phys. Lett. B69:87, 1977

K. Sato and M. Kobayashi, Prog. Theor. Phys. 58:1775, 1977

M. I. Vysotskii, A. D. Dolgov and Ya. B. Zeldovich, JETP Lett. 26:188, 1977

D. A. Dicus, E. W. Kolb and V. L. Teplitz, Phys. Rev. Lett. 39:168, 1977

CAVEATS

K. Griest and D. Seckel, Phys. Rev. D43: 3191, 1991

Resonances

Existence of a particle with twice the DM mass

Thresholds

Contribution at freeze-out from "forbidden" channels

Co-annihilations

Existence of particles with similar mass as DM

CANDIDATES

General requirement for theoretical models

Lightest (neutral) particle in the new sector needs to be stable: how?

by adding a discrete D-symmetry, such that

D=+1 SM sector
D=-1 new sector

Particles in one sector can only be annihilated or produced in pairs
When particles in one sector decay, they have to produce one of the same sector:

the lightest particle with D=-1 is stable

KINETIC DECOUPLING

Sets minimum size of structures

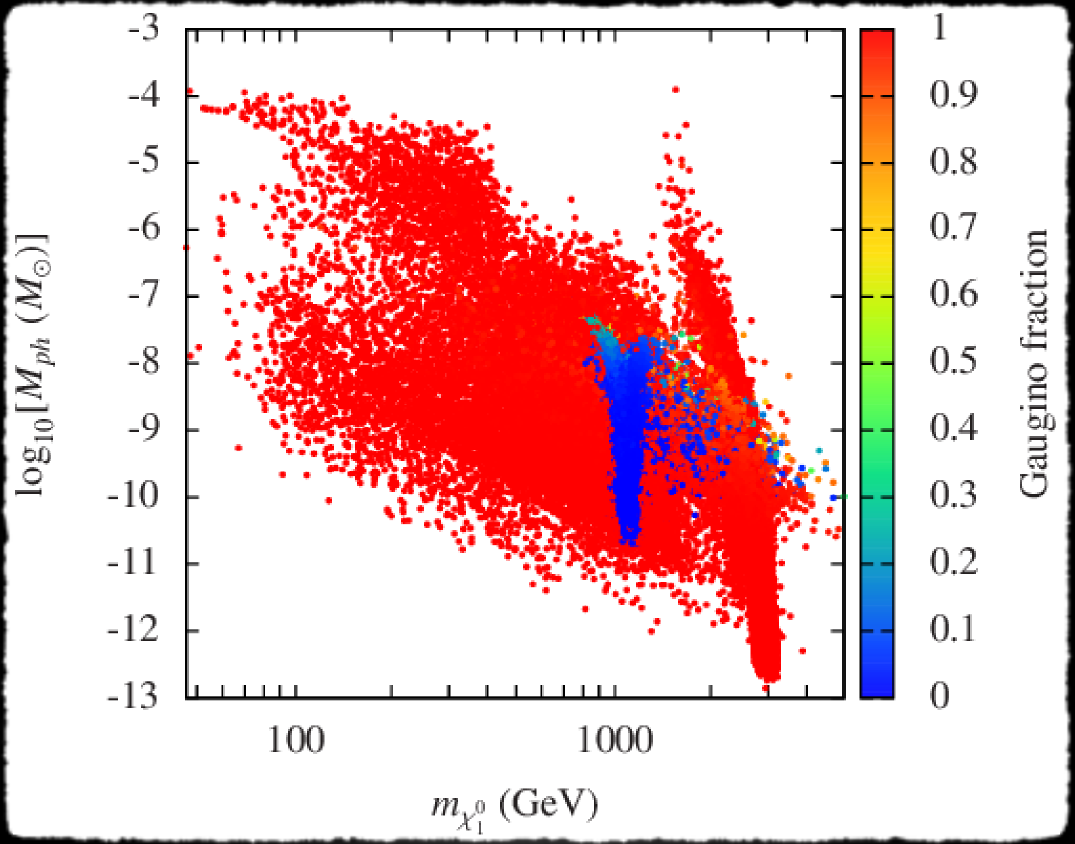
$$n_{SM}\sigma_{DM-SM}v_{DM} \sim H(T_{kd})$$

free-streaming (after decoupling) and collisional damping (before decoupling)

A. M. Green, S. Hofmann, D. Schwarz, JCAP 08:003, 2005

C. Boehm, P. Fayet and R. Schaeffer, Phys. Lett. B518:8, 2001

A. Loeb and M. Zaldarriaga, Phys. Rev. D71:103520, 2005



Large range of possible values depending on the properties of the particle physics model

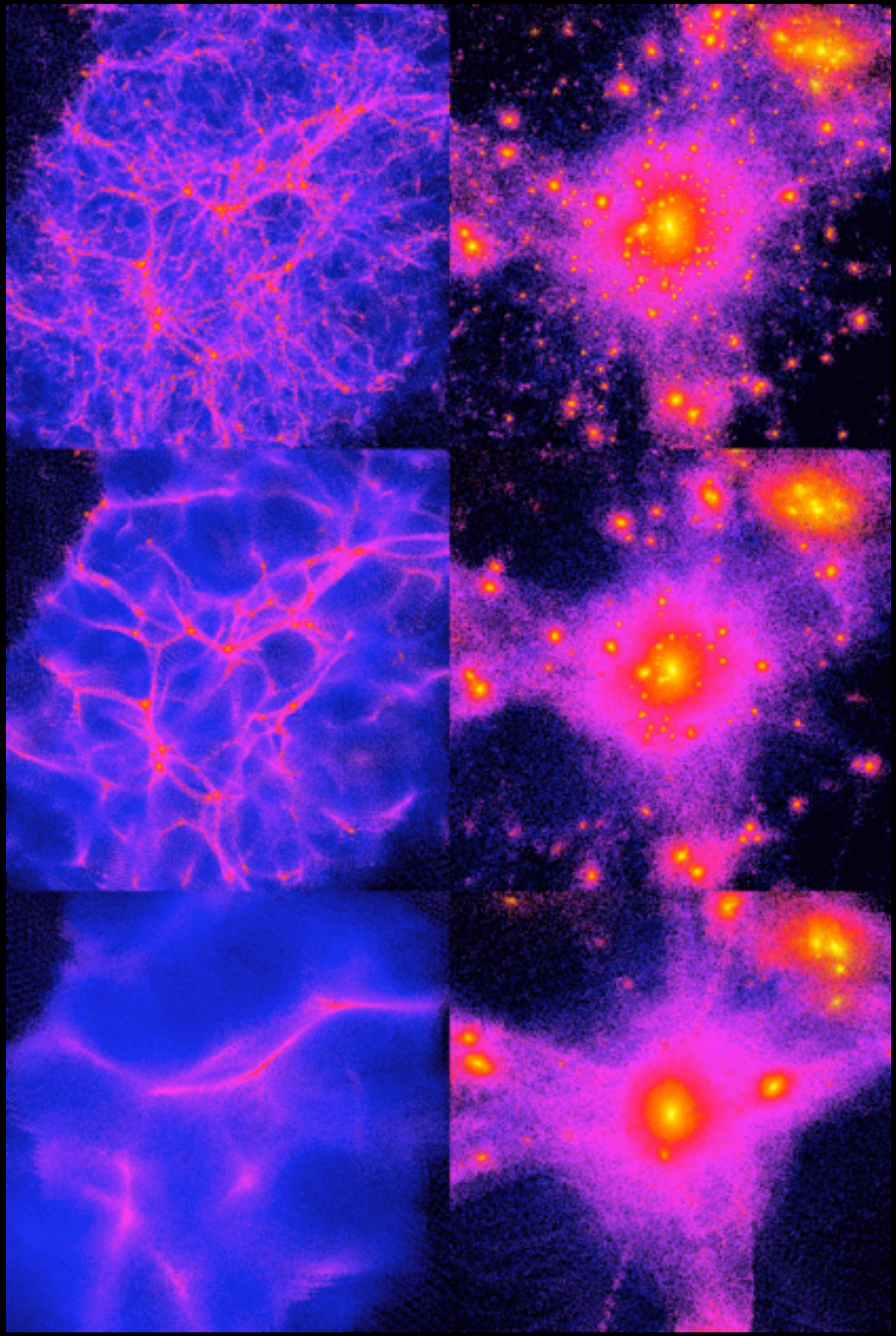
R. Diamanti, M. E. Cabrera-Catalán and S. Ando, Phys. Rev. D92:065029, 2015

KINETIC DECOUPLING

CDM (v<0.1c)
WIMPs, axion, SuperWIMPs...

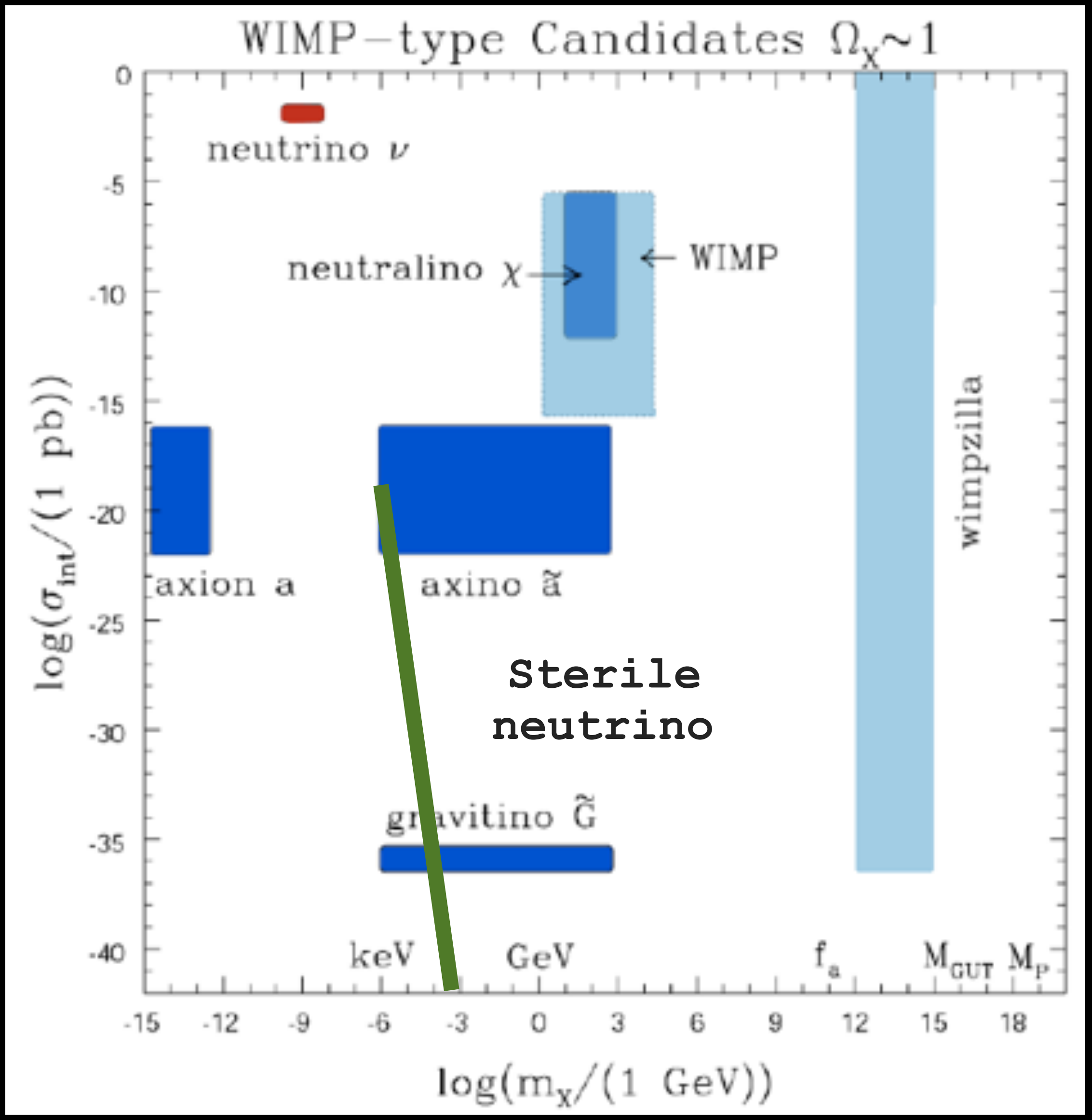
WDM (0.1c < v <0.95 c)
sterile neutrinos, gravitinos

HDM (v>0.95c)
Light neutrinos



ITP, Zurich

CANDIDATES



L. Roszkowski, Pramana 62:389, 2004

SUSY WIMPs

(sneutrino, gravitino, neutralino)

double the particle content and
add R-parity (to avoid proton decay)

Extra-D WIMPs

every field corresponds to a tower of 4-D particles:
the lightest one is a DM candidate (KK parity)

Inert Higgs

extra Higgs doublet with Z_2 symmetry

Axion (non-thermal)

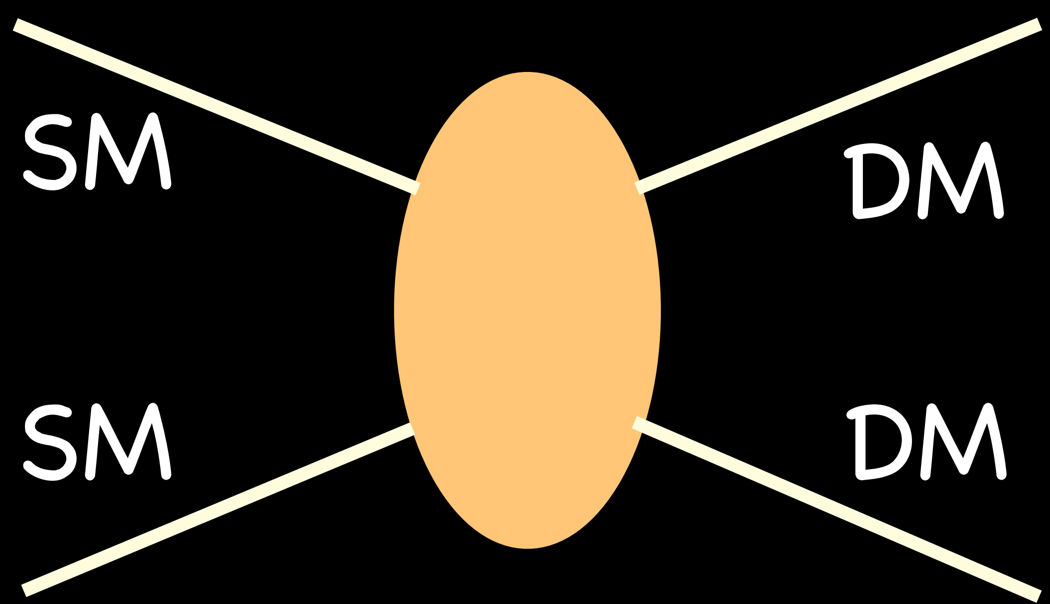
to solve the strong CP problem (no CP violation in strong interactions): add U(1) symmetry

Sterile neutrinos (non-thermal)

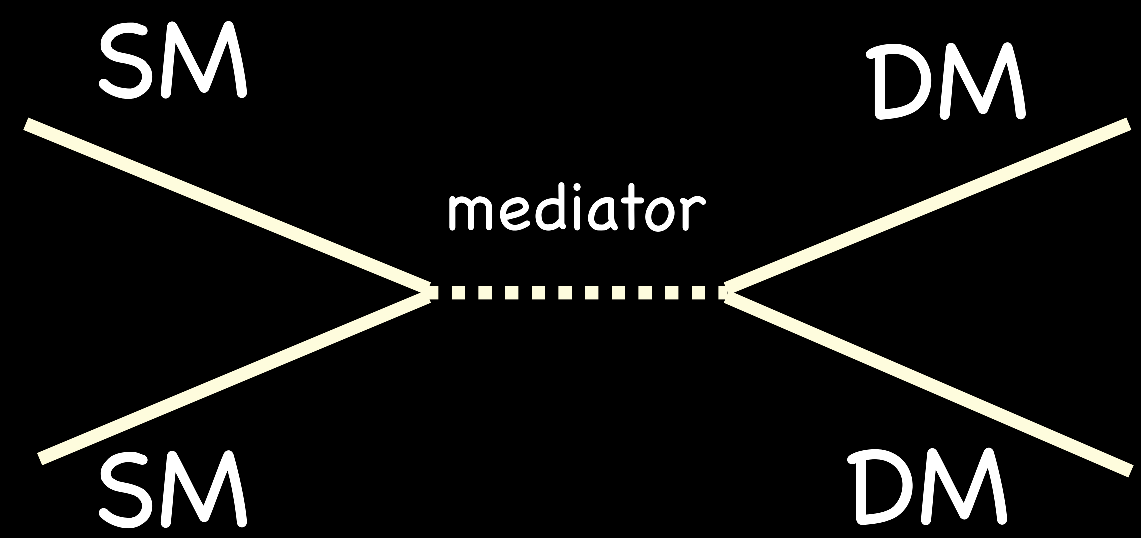
neutrinos have mass: heavy partners?
If m~keV WDM (e.g., produced via oscillations)

THEORETICAL APPROACHES

EFFECTIVE FIELD THEORY



SIMPLIFIED MODELS



COMPLETE MODELS

SUSY, 2HDM, UED...

THEORETICAL APPROACHES

EFFECTIVE FIELD THEORY

it is the most simplified description to study models in general and links different searches with a single operator

its range of validity is limited (mainly at colliders)

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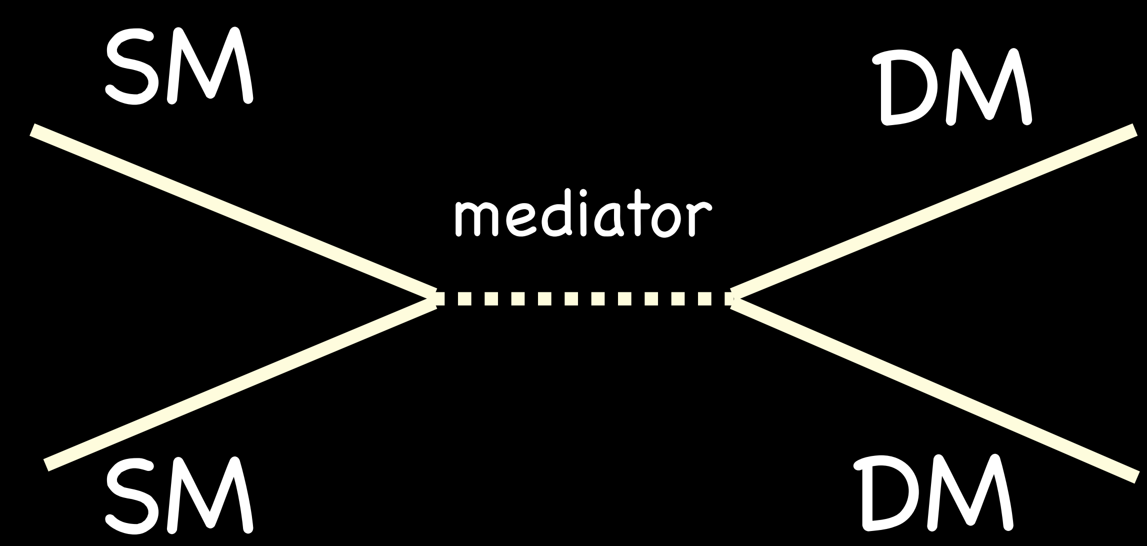

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SIMPLIFIED MODELS

simple, but renormalizable, closer to realistic (UV-completed) models mediator searches

yet, quite academic

COMPLETE MODELS

SUSY, 2HDM, UED...

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COMPLETE MODELS

full-fledged models (solving other problems)

many parameters → degeneracies