Less Travelled Path of Dark Matter: Axions and PBHs

ICTS-TIFR, Bengaluru

INTRODUCTION TO DARK MATTER

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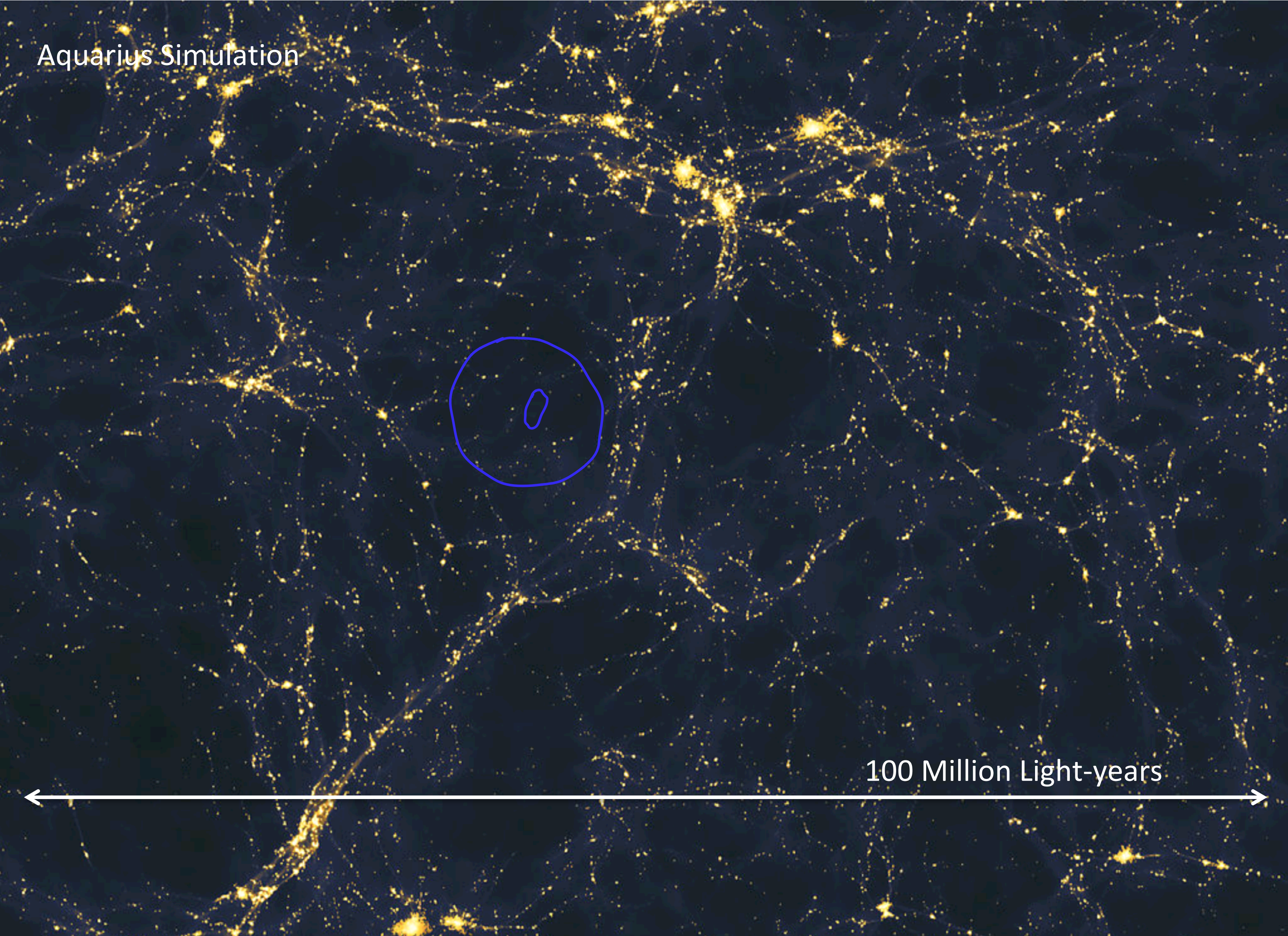
TIFR, Mumbai


Aquarius Simulation
100 Million Light-years

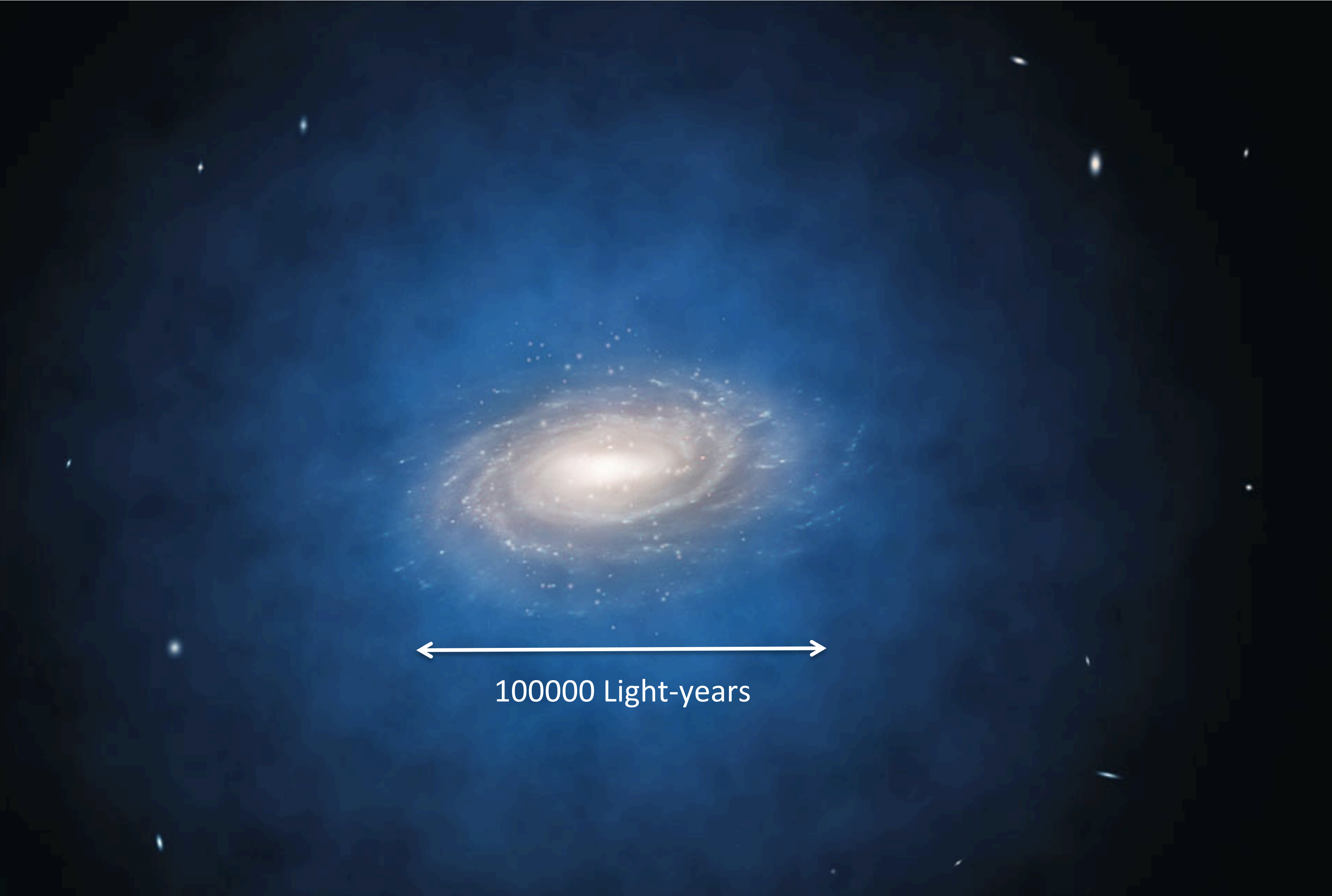


Image: Artist’s composition of Hubble image and Via Lactea simulation

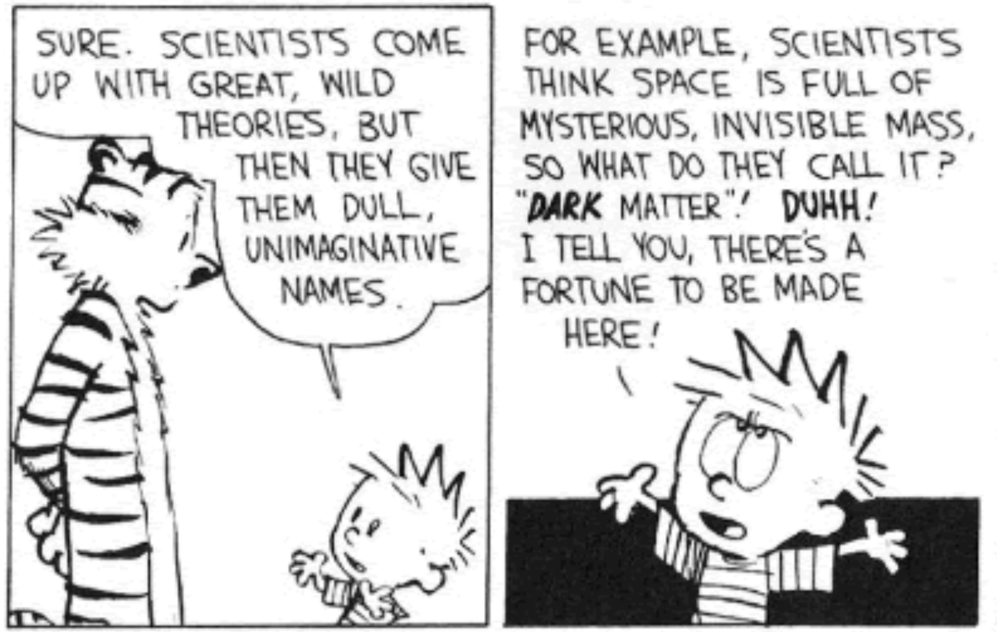


Image: Bill Watterson

HOW DO WE KNOW DM EXISTS?
WHAT IS IT ?

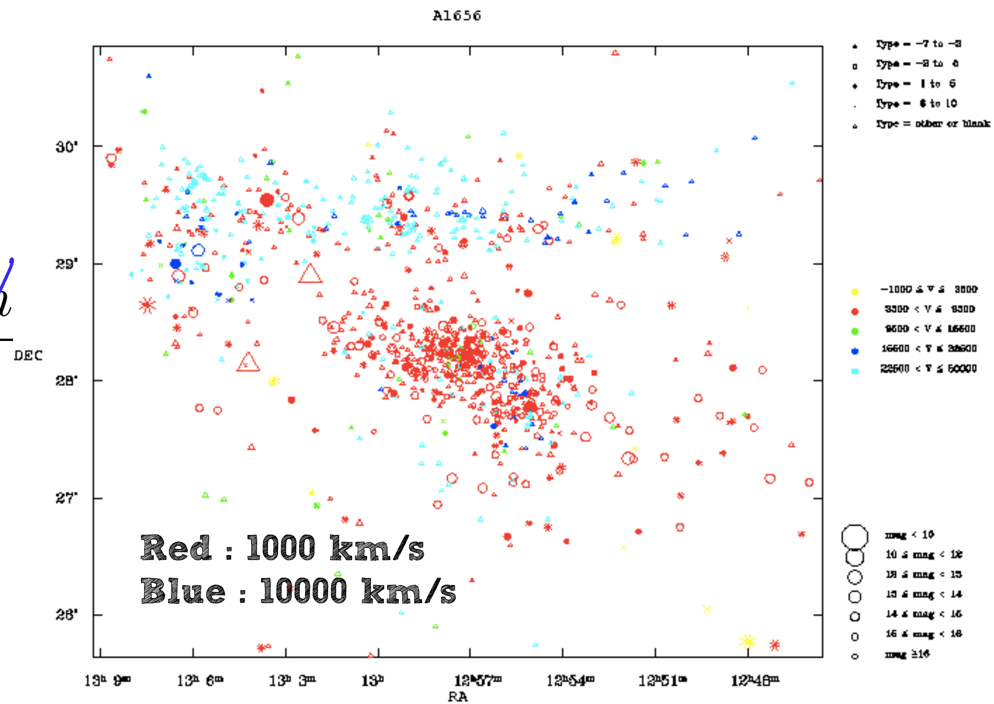
MOTION MEASURES MASS

1. VIRIAL VELOCITY IN CLUSTERS

$$\langle K.E.\rangle = -\frac{1}{2}P.E.$$

$$\frac{1}{2}\cancel{m}\langle v^2\rangle = \frac{+GM\cancel{m}}{2R}$$

$$M_{\text{cluster}} = \frac{R_{\text{cluster}}\langle v^2\rangle}{2G_N}$$



Mass inferred >> Mass seen

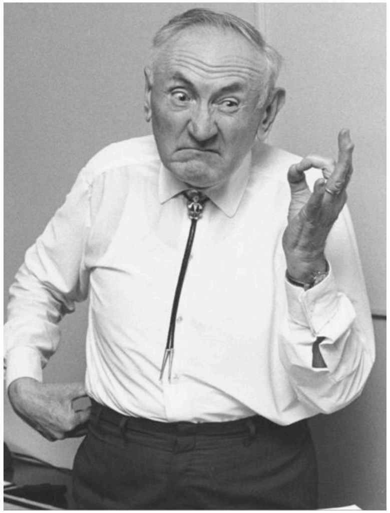


Image: Caltech

Fritz Zwicky, 1930s

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

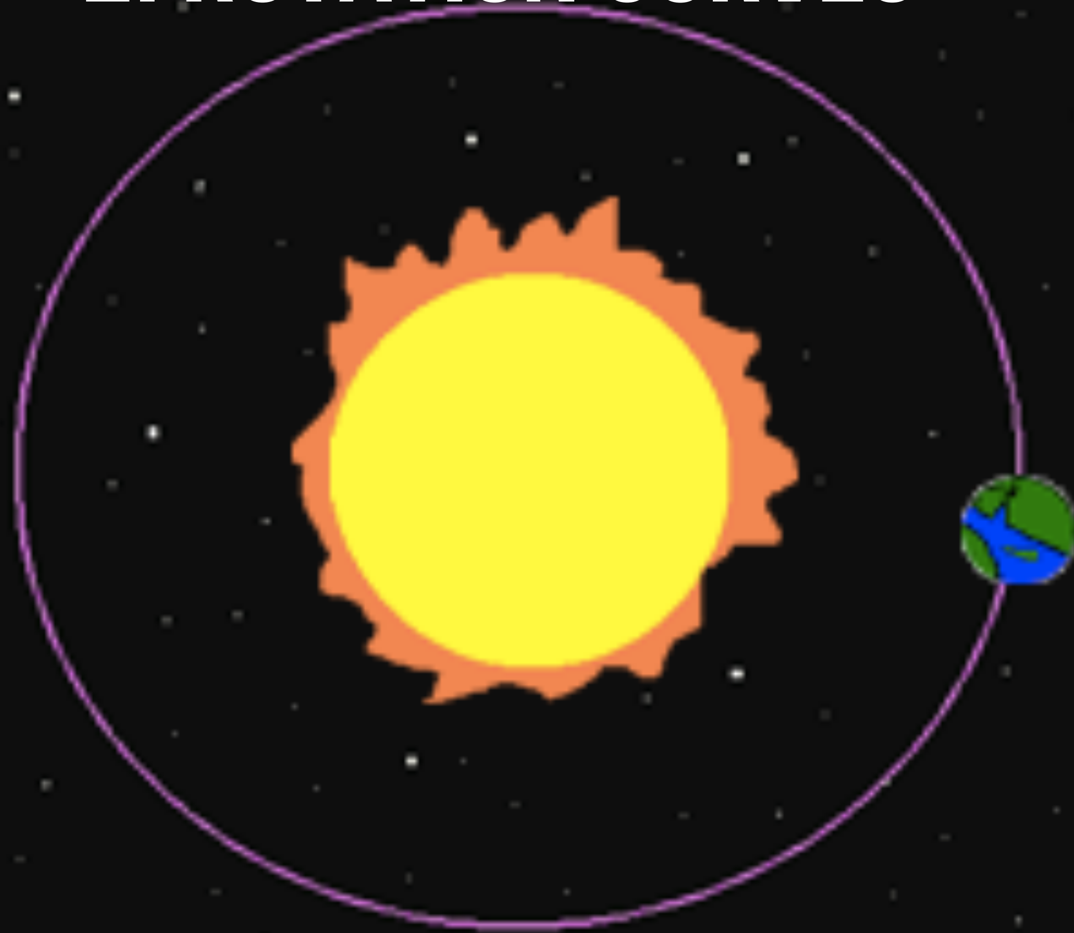
(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

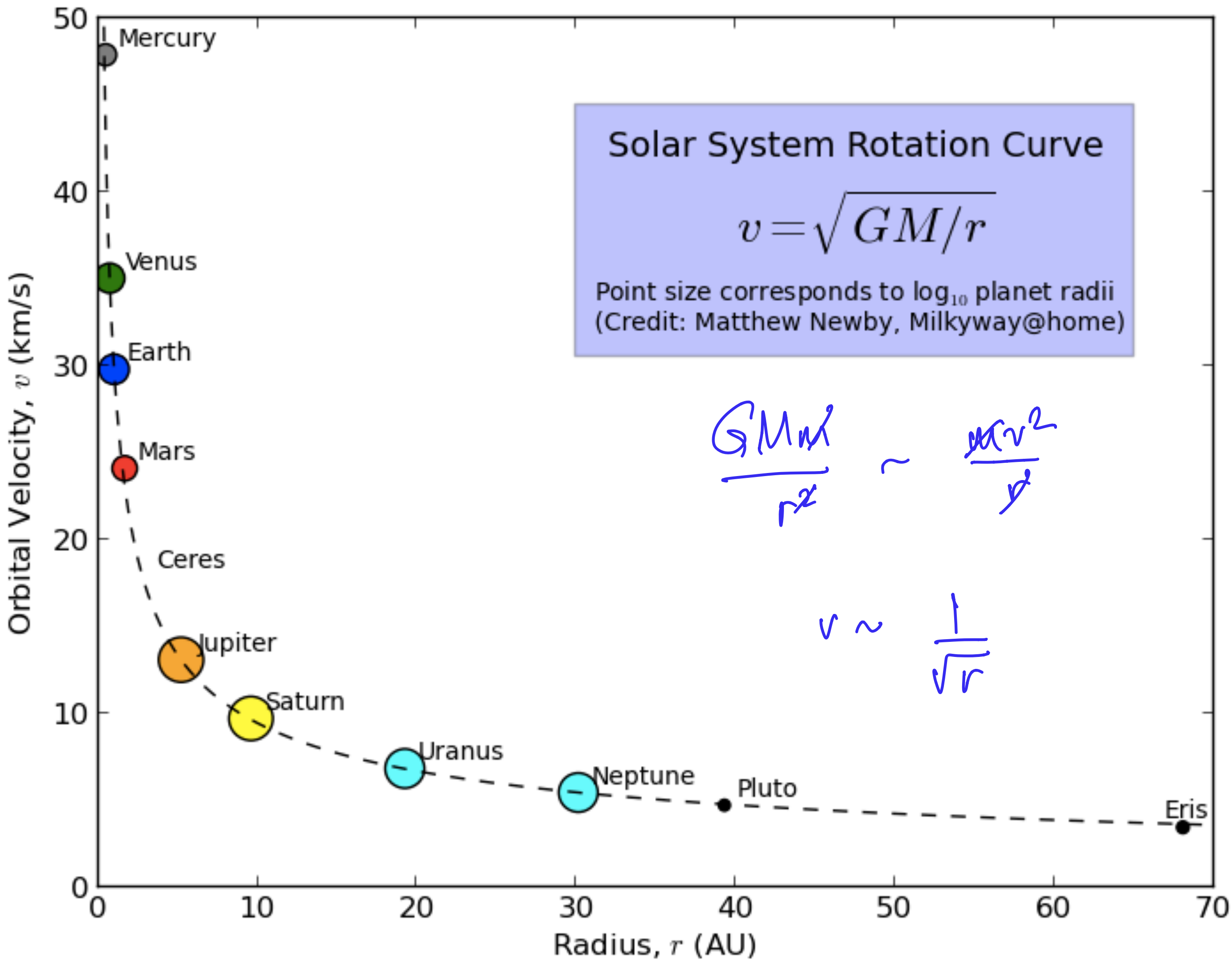
Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

2. Man kann auch annehmen, dass das Comasystem sich nicht im stationären Gleichgewicht befindet, sondern dass die ganze verfügbare potentielle Energie als kinetische Energie er-

2. ROTATION CURVES



Not to scale. Obviously!



$$\frac{GM\cancel{m}}{r^{\cancel{2}}} \sim \frac{\cancel{m}v^2}{\cancel{r}}$$

$$v \sim \frac{1}{\sqrt{r}}$$

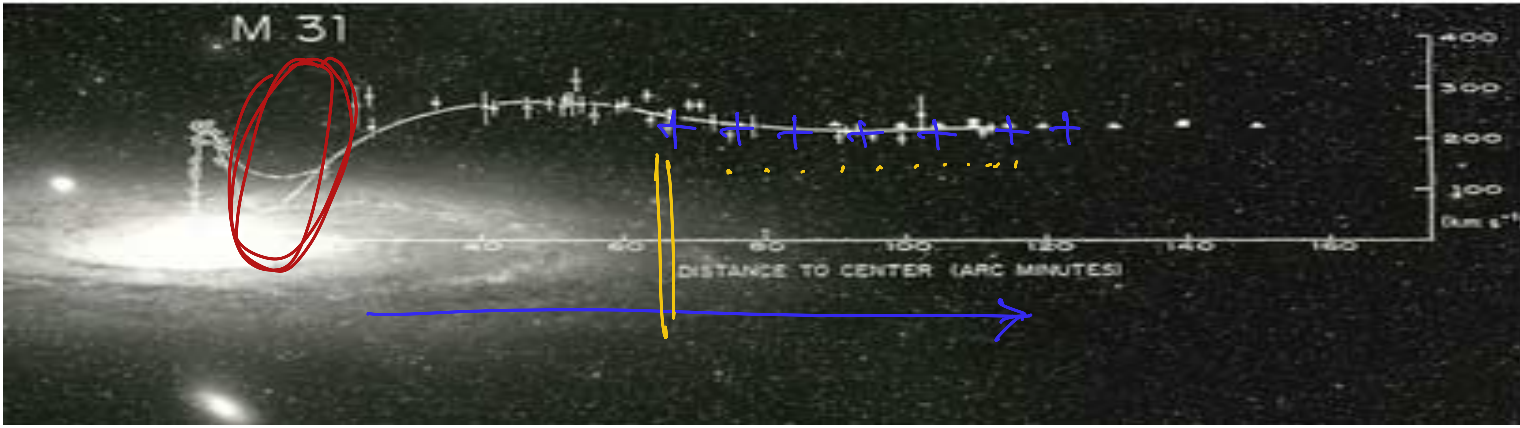


Image: Vassar College

There is mass beyond the Galaxy

- Vera Rubin

FLAT ROTATION CURVES

$$F_C \approx F_G$$

$$\frac{\cancel{m} v^2}{\cancel{r}} \sim \frac{G_N M(r) \cancel{m}}{r^{\cancel{2}}}$$

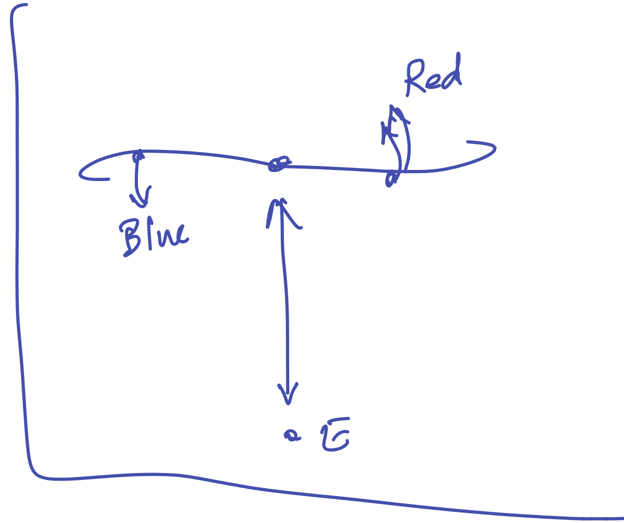
$$v^{\parallel}_{obs} - v_{\substack{known \\ rel}} = v_{circ}$$

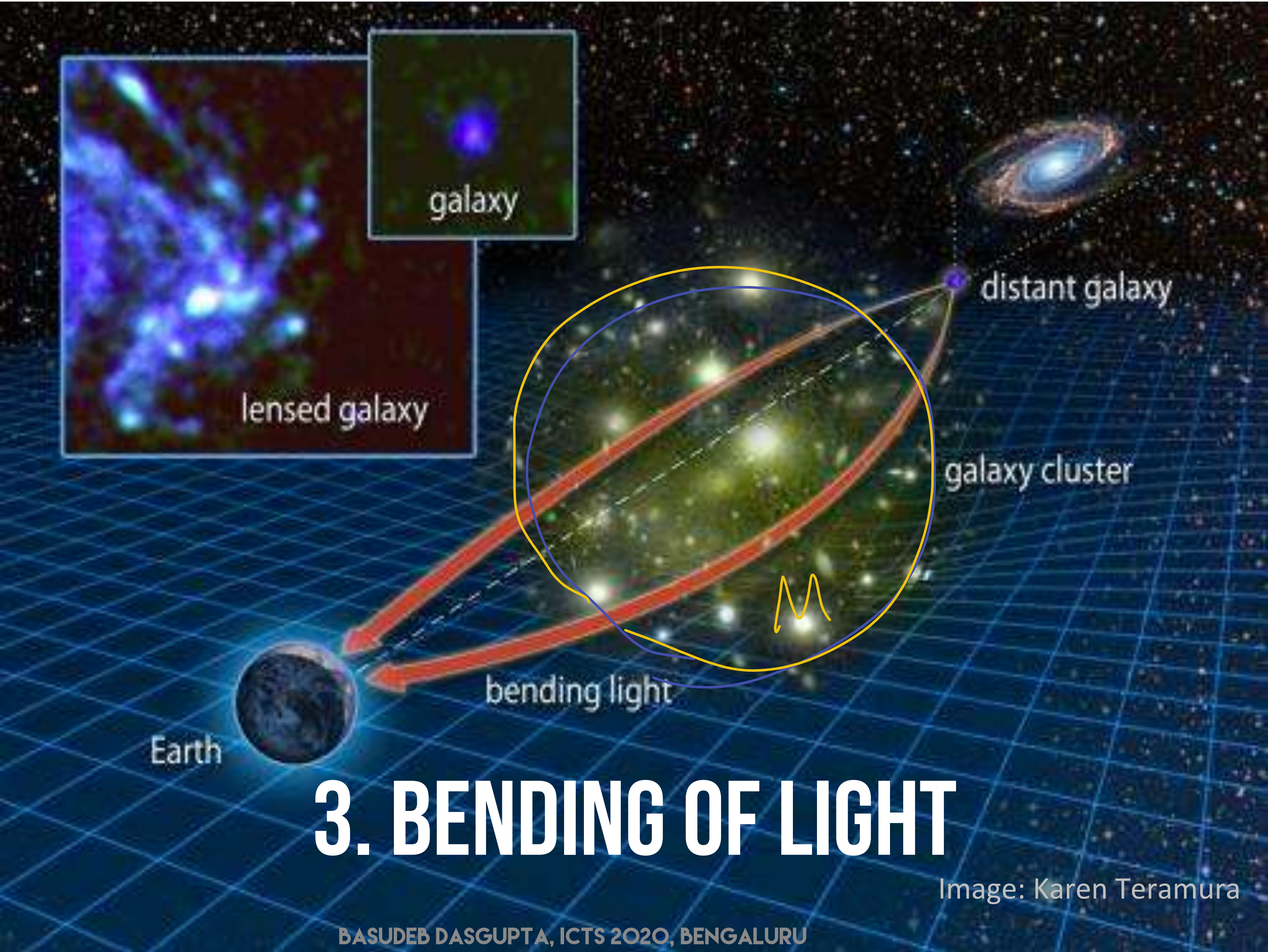
$$v^2 \sim \frac{G M(r)}{r}$$

$$\text{Const} \approx \frac{G M(r)}{r} \Rightarrow M(r) \simeq k\, r$$

$$M(r) = \int d^3r\, \rho(r) \simeq r^3 \rho(r) = kr$$

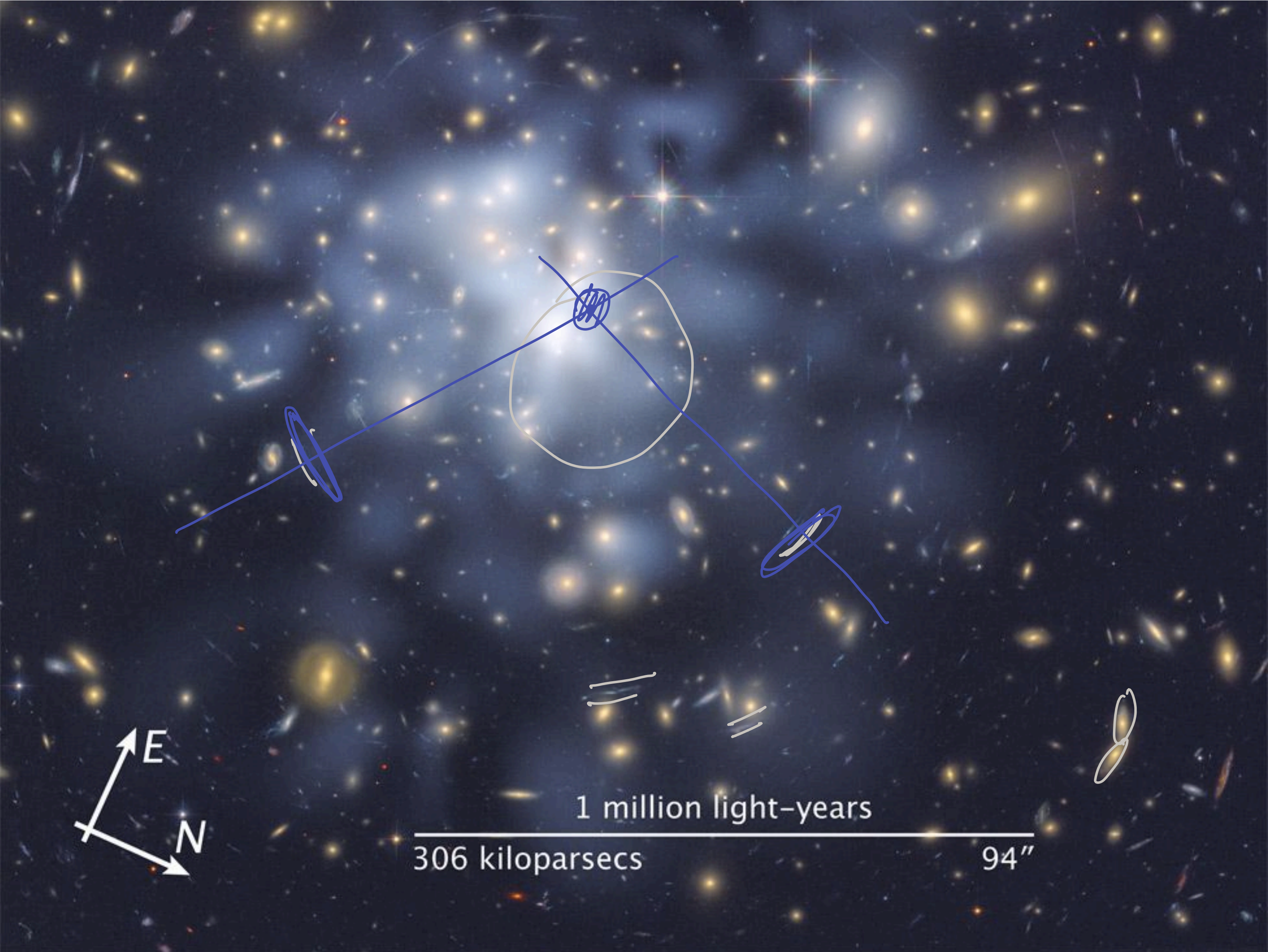
$$\Rightarrow \rho(r) \sim \frac{1}{r^2}$$



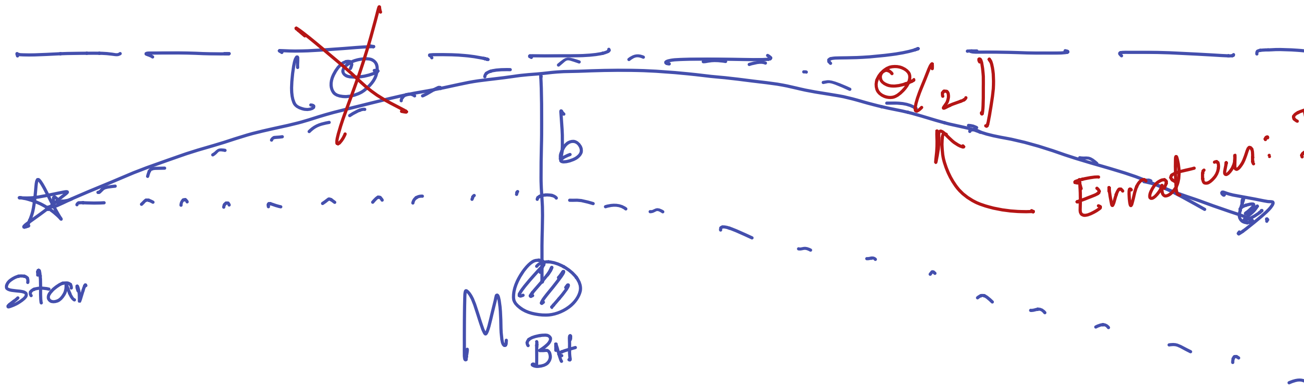


3. BENDING OF LIGHT

Image: Karen Teramura


E
N
1 million light-years
306 kiloparsecs
94″

GRAVITATIONAL LENSING



Erratum: In class this was stated as θ

$$\theta = \frac{4 G_N M_{BH}}{\cancel{4} b}$$

$$G_N \sim \frac{1}{M_{Pl}^2}$$

$$b \sim [M^{-1}]$$

BULLET CLUSTER

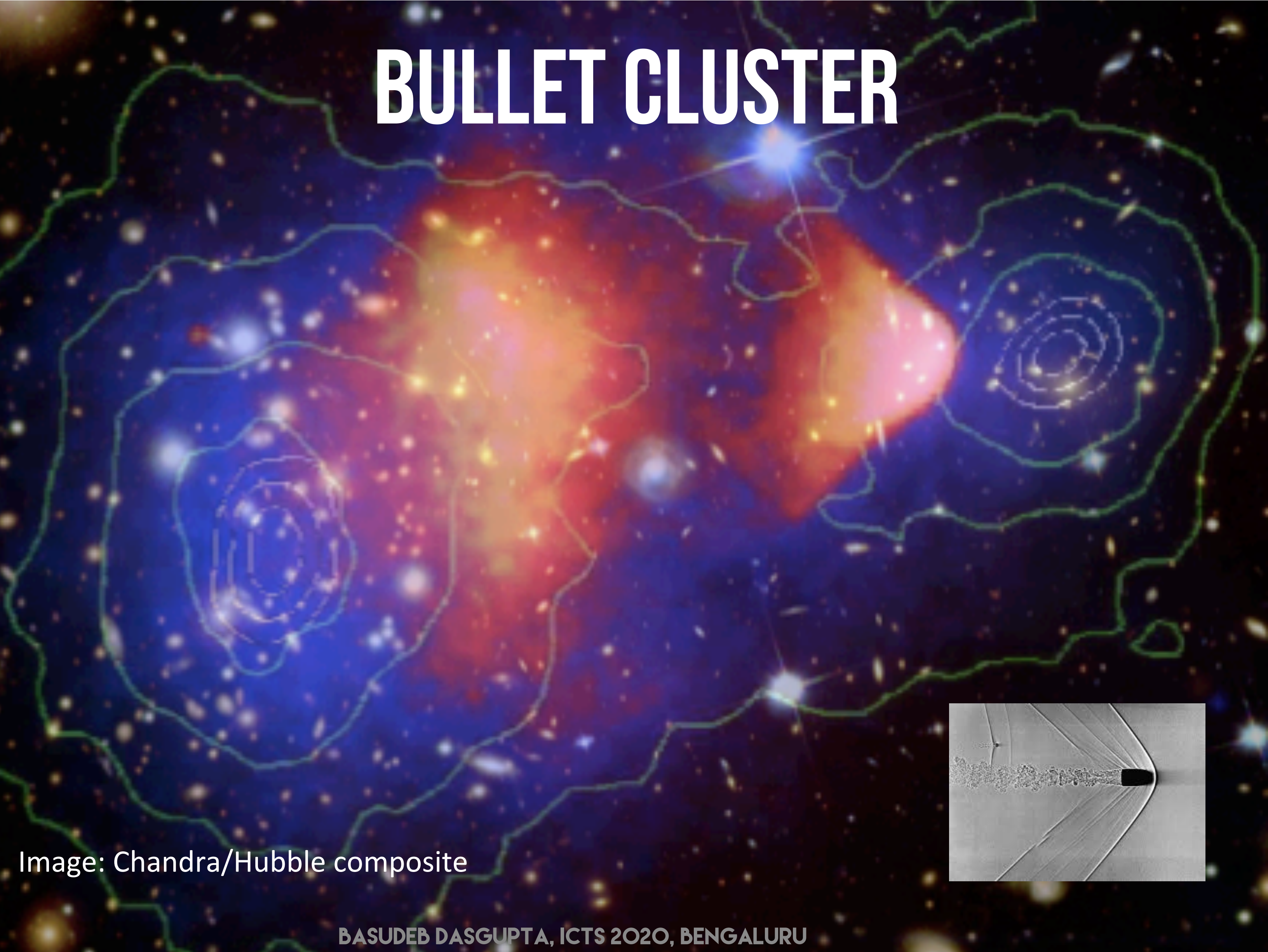
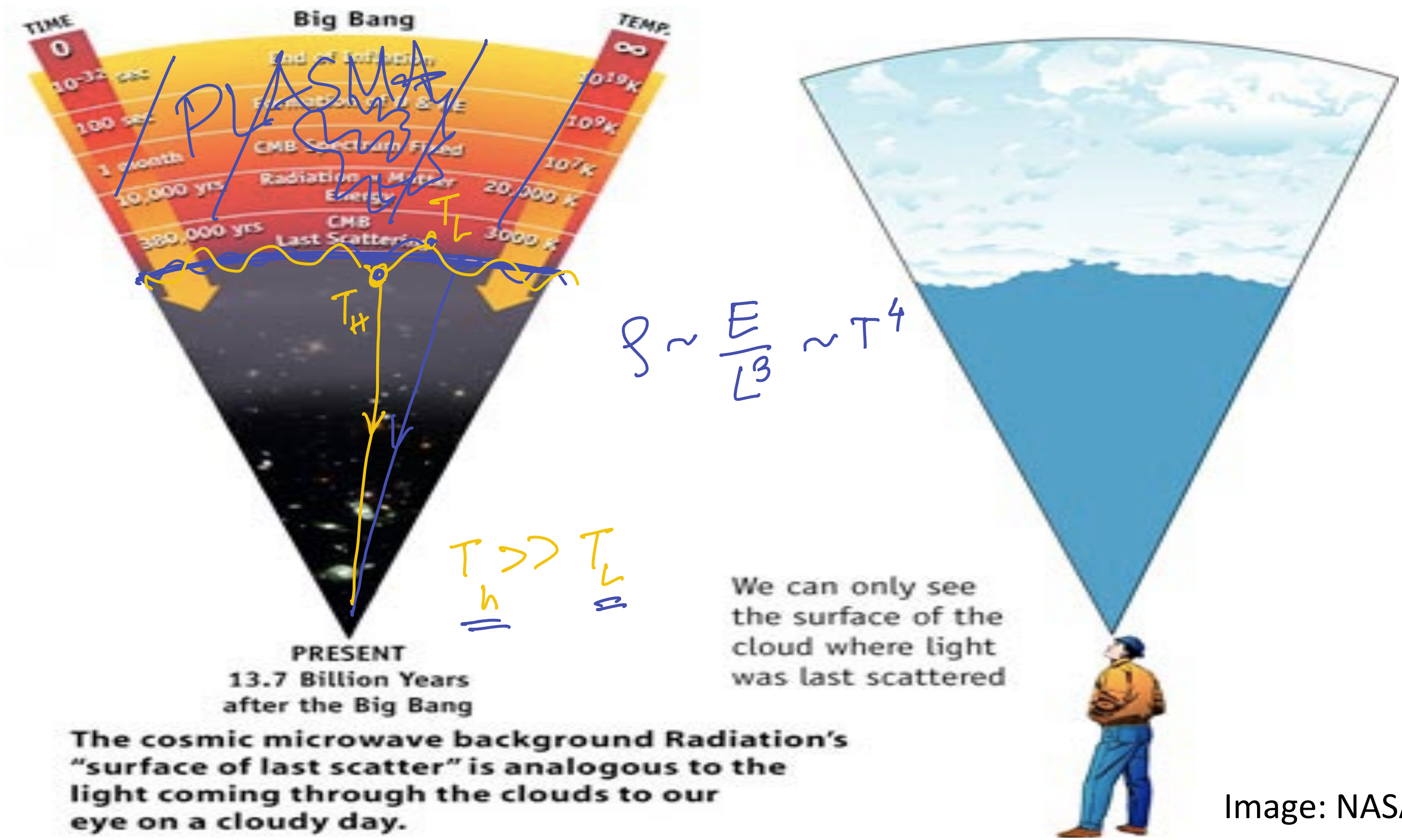


Image: Chandra/Hubble composite

4. LOOKING AT THE BIG BANG

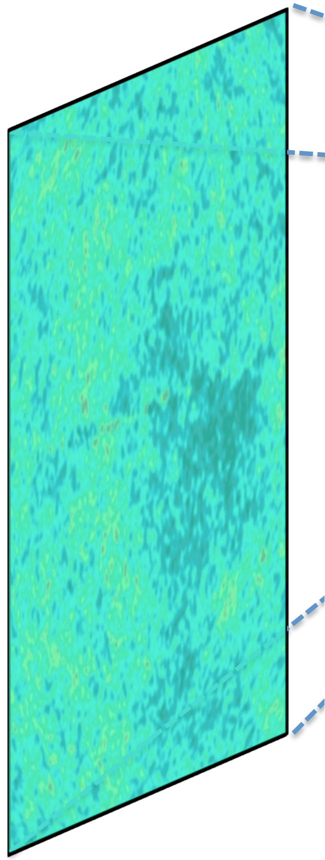


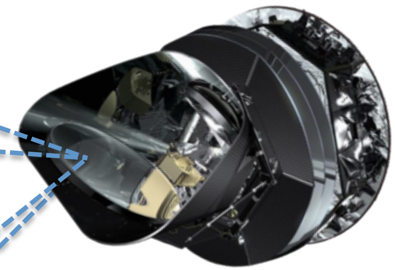
$$\rho \sim \frac{E}{L^3} \sim T^4$$

$$T_h >> T_L$$

Image: NASA

COSMIC MICROWAVE BACKGROUND





$$\frac{\Delta T}{T} \approx \frac{\Delta \rho}{\rho} \lesssim 1/10^4$$

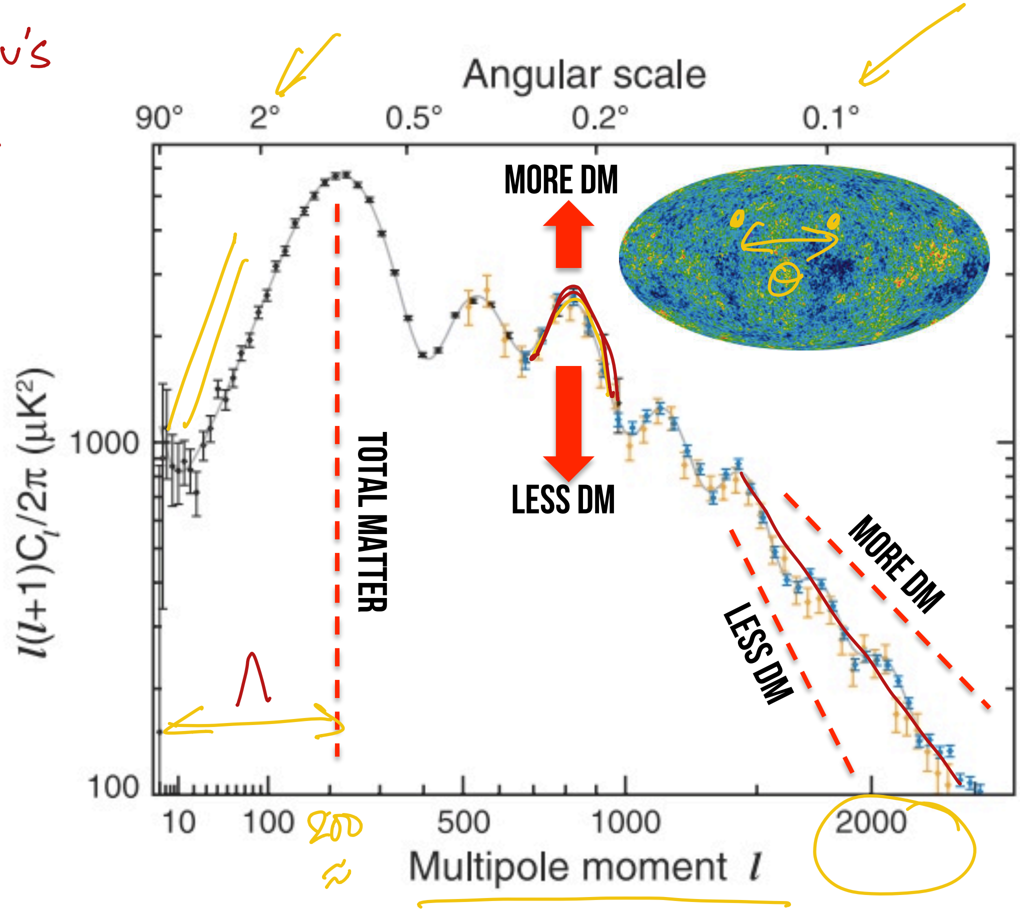
Gravity Pulls + Radiation Pushes

=

Primordial Plasma Oscillates

RIPPLES IN THE COSMIC POND

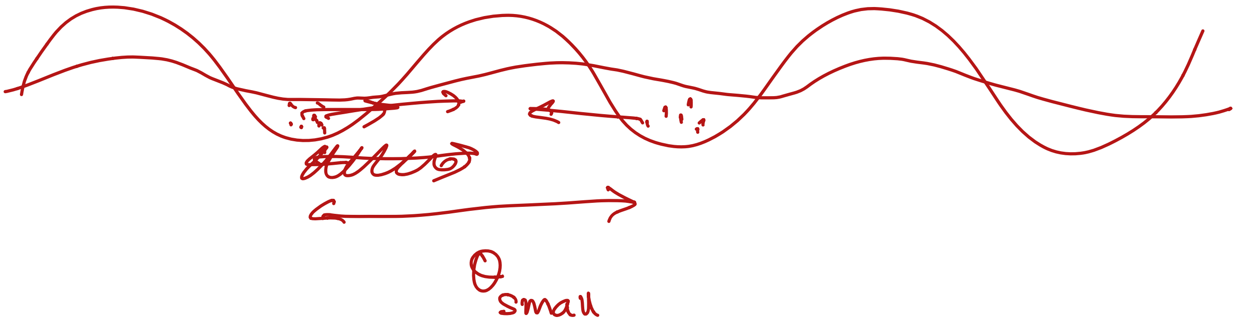
Wayne Hu's tutorial



$\theta \sim \frac{1}{l}$

$\Omega h^2 \simeq 0.12$

PERTURBATIONS



5. THE COSMIC NET

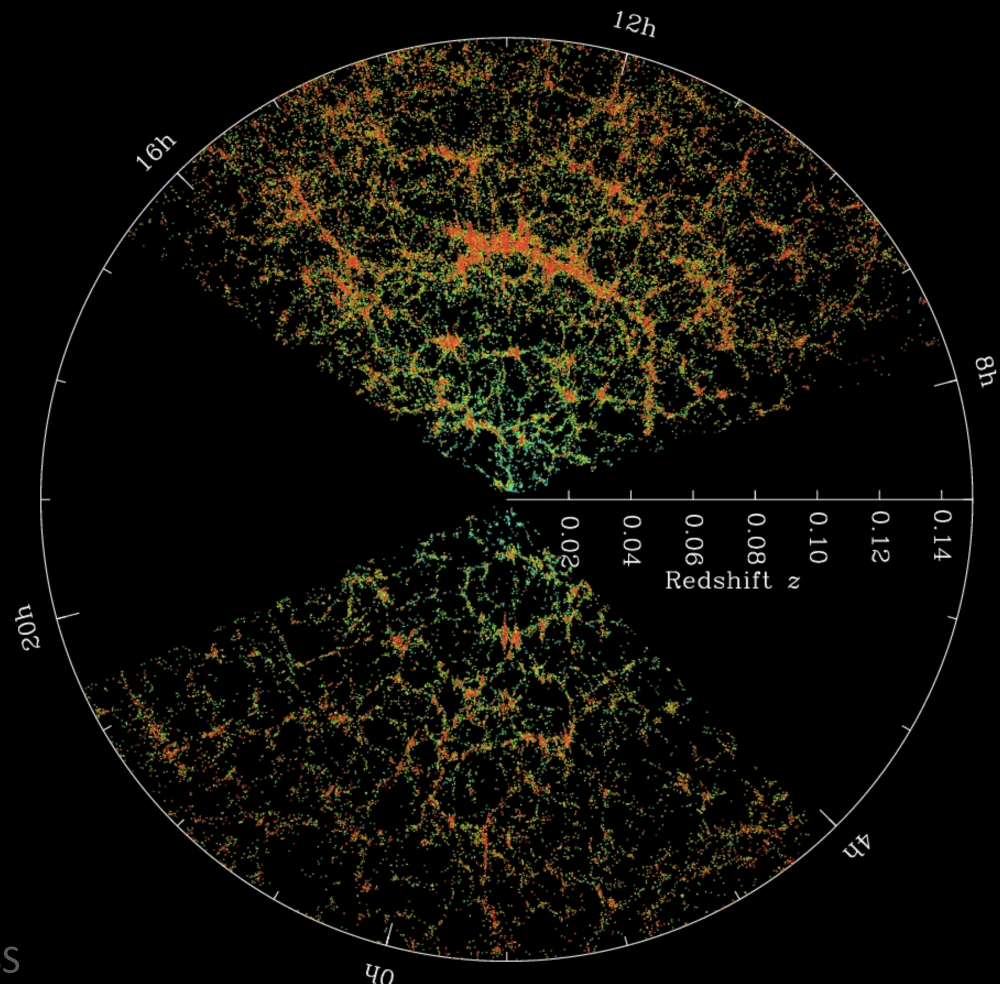


Image: SDSS

GROWTH OF STRUCTURES

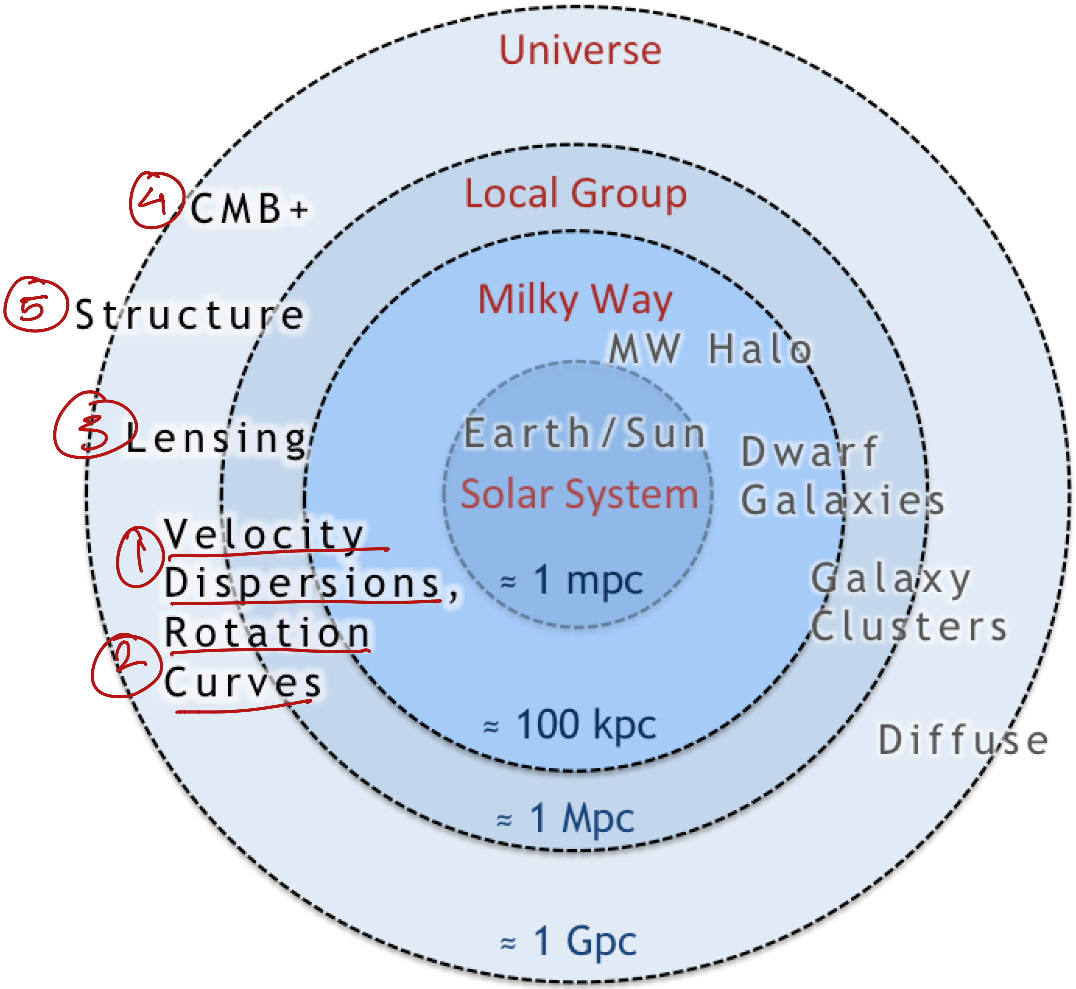
$\delta_m \approx \frac{\delta\rho_m}{\rho}$ grow after matter-radiation eq.

$\propto a$

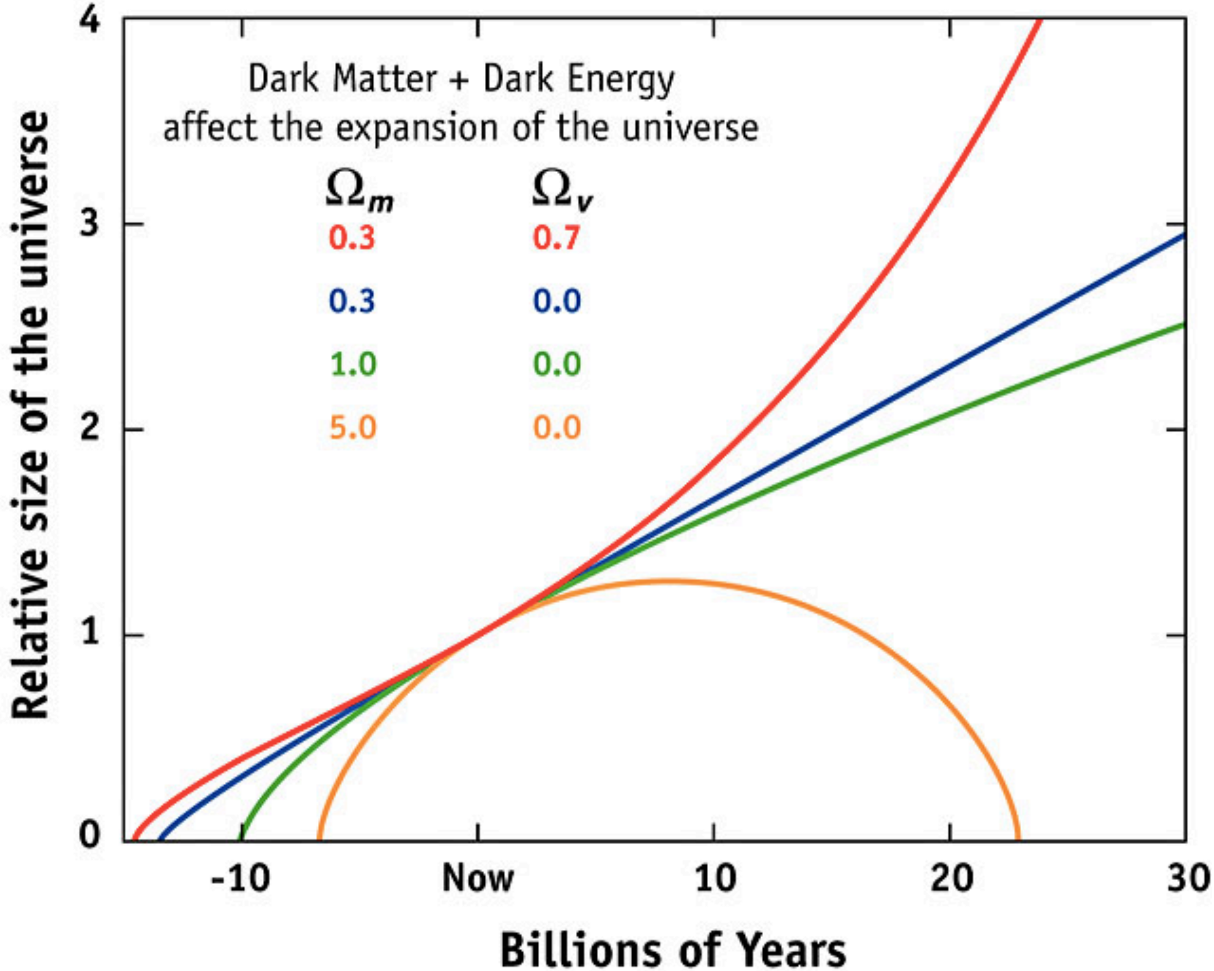
at most factor of $\frac{a}{a_{eq}} \approx \frac{1+z_{eq}}{1+z_{today}} \approx \frac{1100}{1} \simeq 10^3$

$\underline{\underline{\delta^{CMB}_{max} \sim 10^{-4}}} \longrightarrow 0.1$ vs $\delta^{clusters} \gtrsim 1$

(AT LEAST 5) REASONS FOR DM

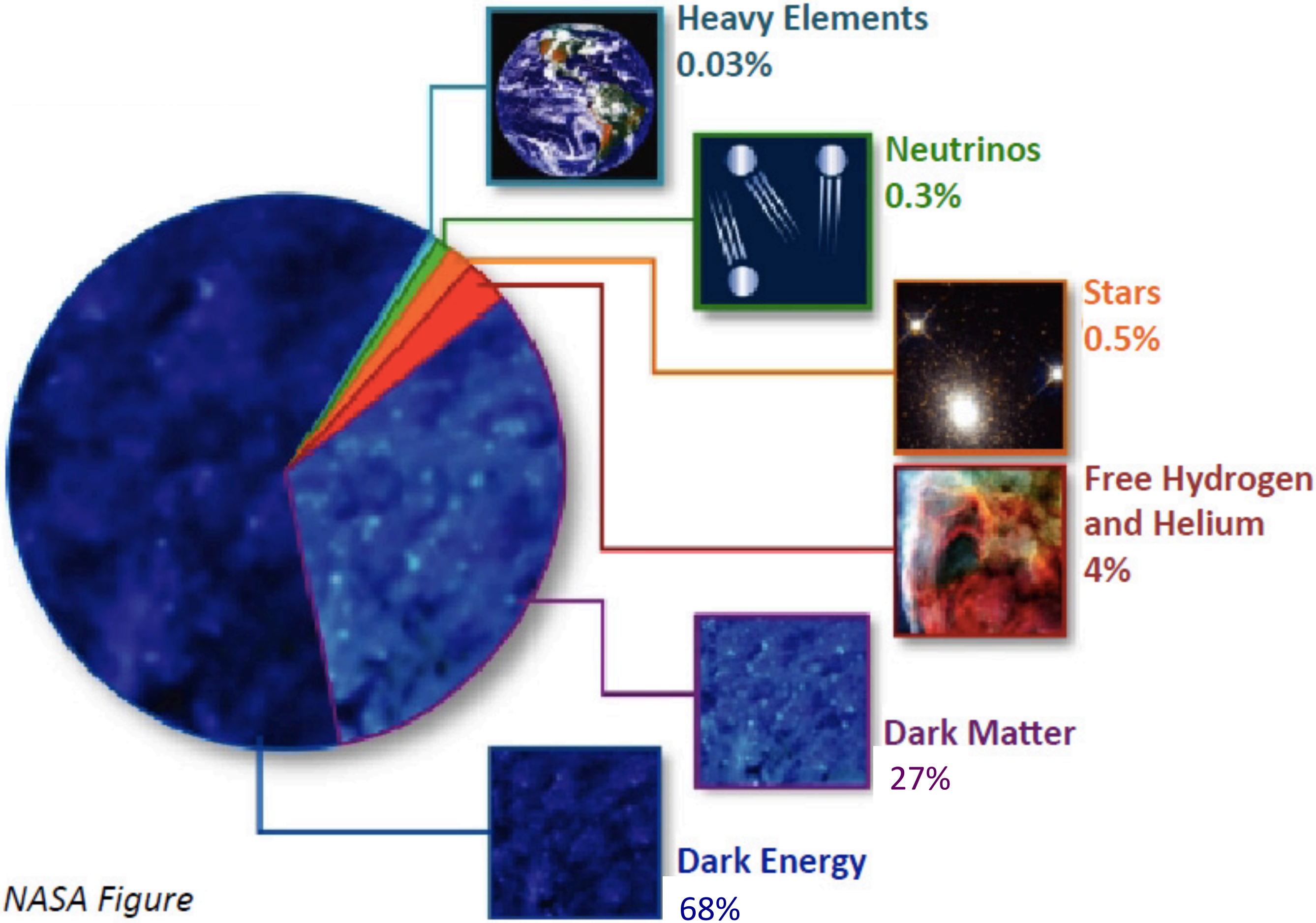


DARK ENERGY



Dark Matter + Dark Energy
affect the expansion of the universe
Ω_m Ω_v
0.3 0.7
0.3 0.0
1.0 0.0
5.0 0.0
Relative size of the universe
0
1
2
3
4
-10
Now
10
20
30
Billions of Years

OUR COSMIC RECIPE



NASA Figure

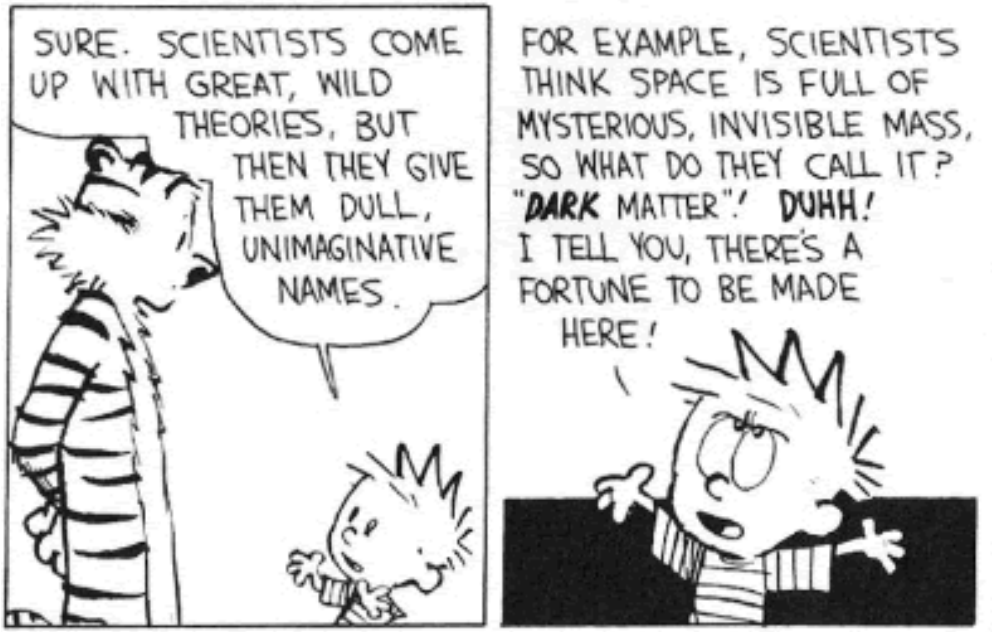


Image: Bill Watterson

✓HOW DO WE KNOW DM EXISTS?

WHAT IS IT ?

WHAT IS THE UNIVERSE MADE OF?

MODIFIED NEWTONIAN DYNAMICS

Mordehai Milgrom

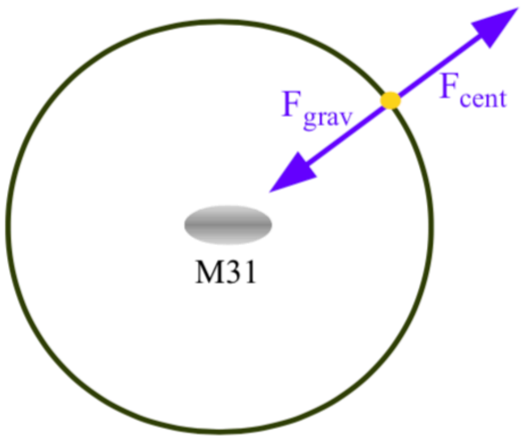
$$F = ma\left(1 + \frac{a_0}{a}\right)^{-1}$$

MOND explains rotation curves

"Not a "Theory" but "Parametrization"

Does not eliminate need for Dark Matter

MOND AND GALAXIES



$$\vec{F}_{\text{cent}} = \vec{F}_{\text{grav}}$$

$$\boxed{F = \begin{cases} ma & \text{if } a \gg a_0 \\ m\dfrac{a^2}{a_0} & \text{if } a \ll a_0 \end{cases}}$$

For small acceleration (expected at large distances).

$$m\frac{1}{a_0}\frac{v(r)^4}{\cancel{r^2}} = \frac{GMm}{\cancel{r^2}}$$

$$\boxed{v(r) = (GMa_0)^{1/4}}$$

$$a \sim \frac{v^2}{r}$$

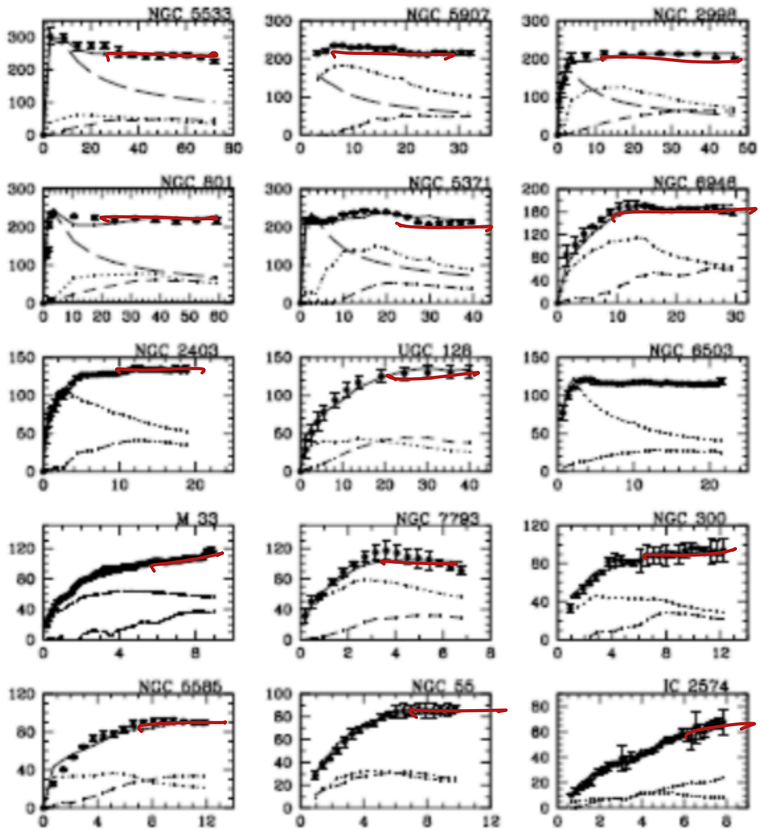
$$m\frac{a^2}{a_0} \simeq \frac{GMm}{r^2}$$

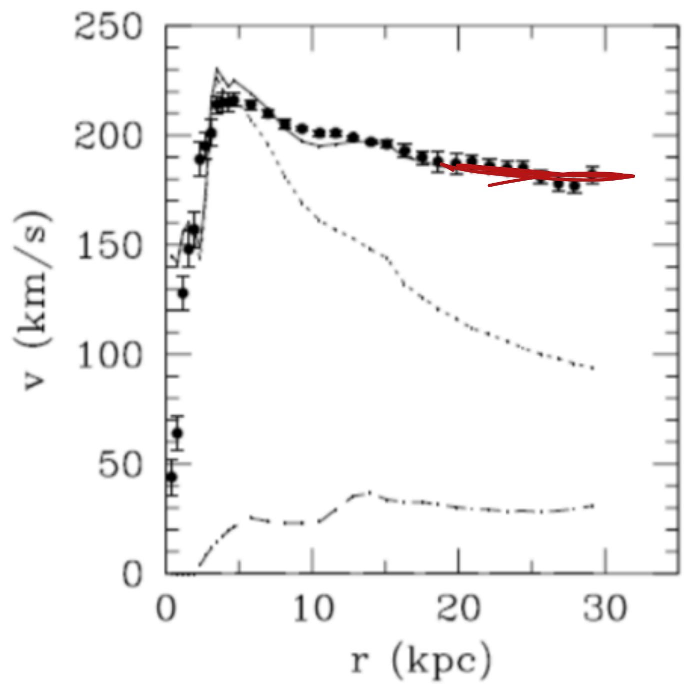
$$\frac{\cancel{m}\,v^4}{a_0\,\cancel{r^2}} \simeq \frac{GM\cancel{m}}{\cancel{r^2}}$$

$$v \simeq (GMa_0)^{1/4}$$

Credit: Ibarra

SPECTACULAR SUCCESS





$$a_0 \simeq 10^{-8}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$$

McGaugh and Sanders

MORE ABOUT MOND

$$F = m\left(\frac{d^2x}{dt^2}\right)^2 \frac{1}{a_0}$$

$$\frac{1}{\sqrt{a_0}}\frac{d^2x}{dt^2} = \sqrt{\frac{F}{m}}$$

BULLET CLUSTER

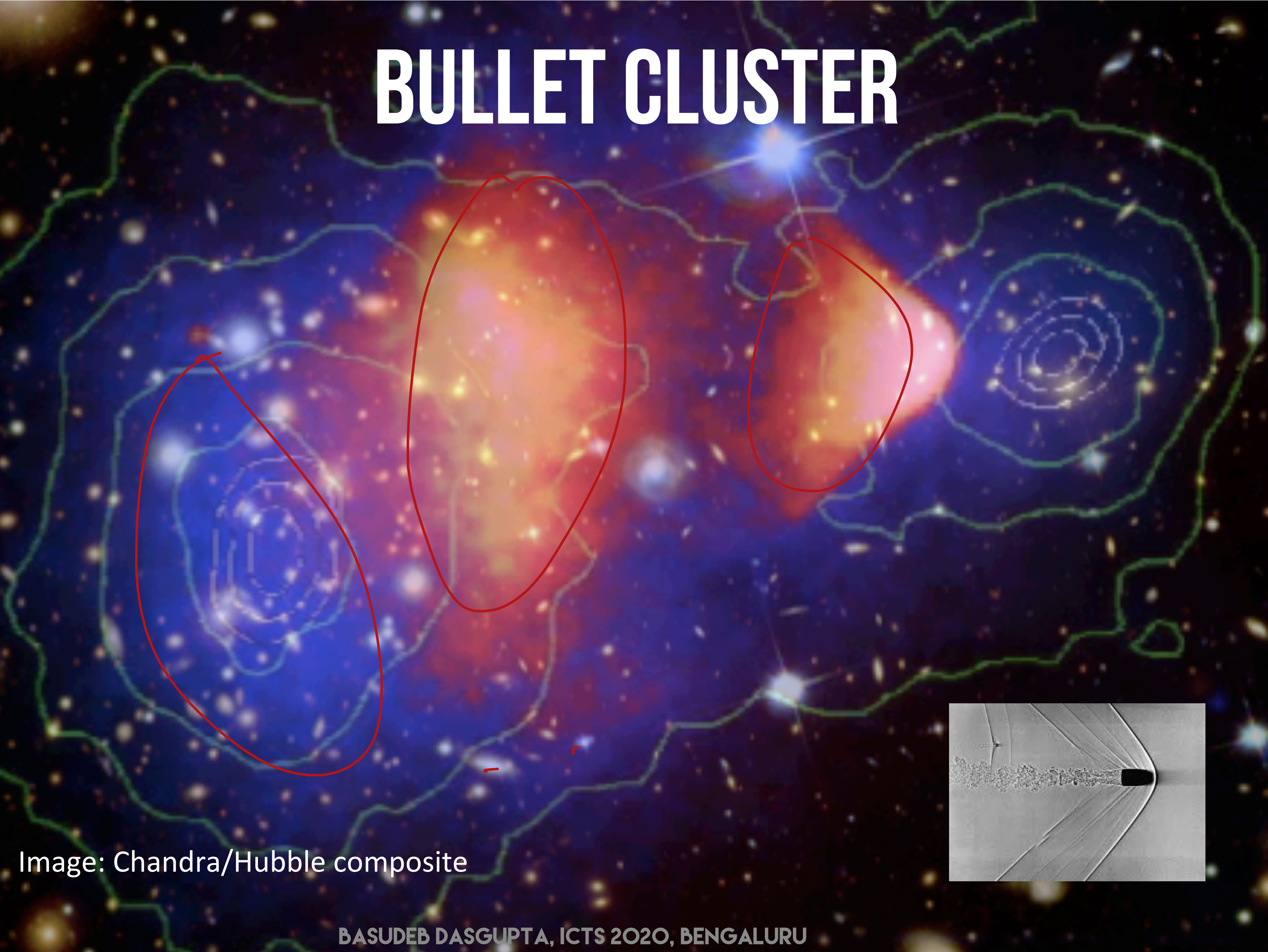
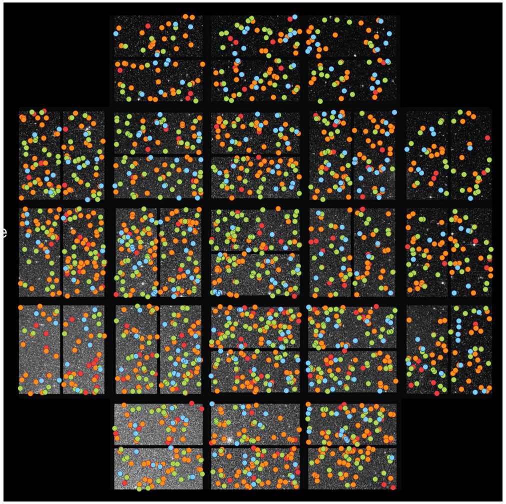
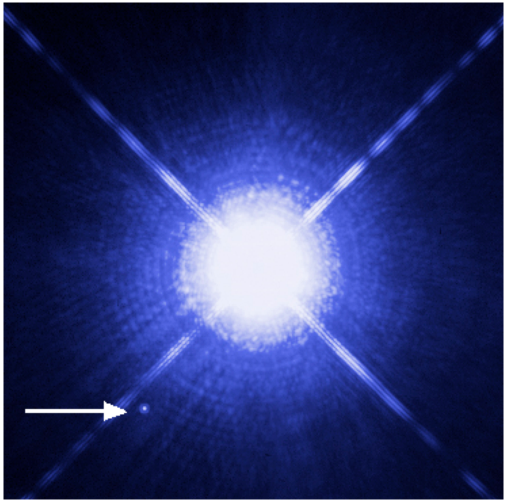


Image: Chandra/Hubble composite



Planets (Jupiters)

Old Neutron Stars



Old White Dwarf Stars

Black Holes

Not a

Massive
Astrophysical
Compact
Halo
Object*

* Terms and conditions apply

Primordial BHs

WHAT DO WE KNOW?

No electric charge (else forms anomalous atoms)

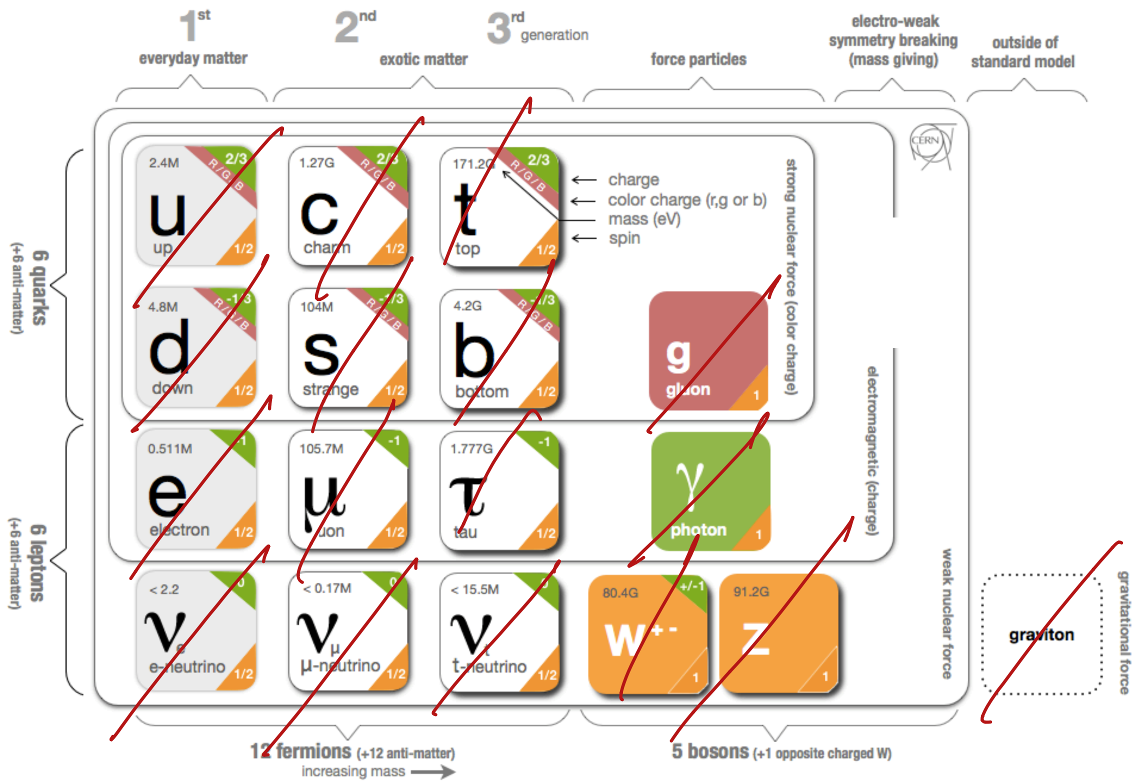
No baryonic interactions (else screws up CMB, BBN)

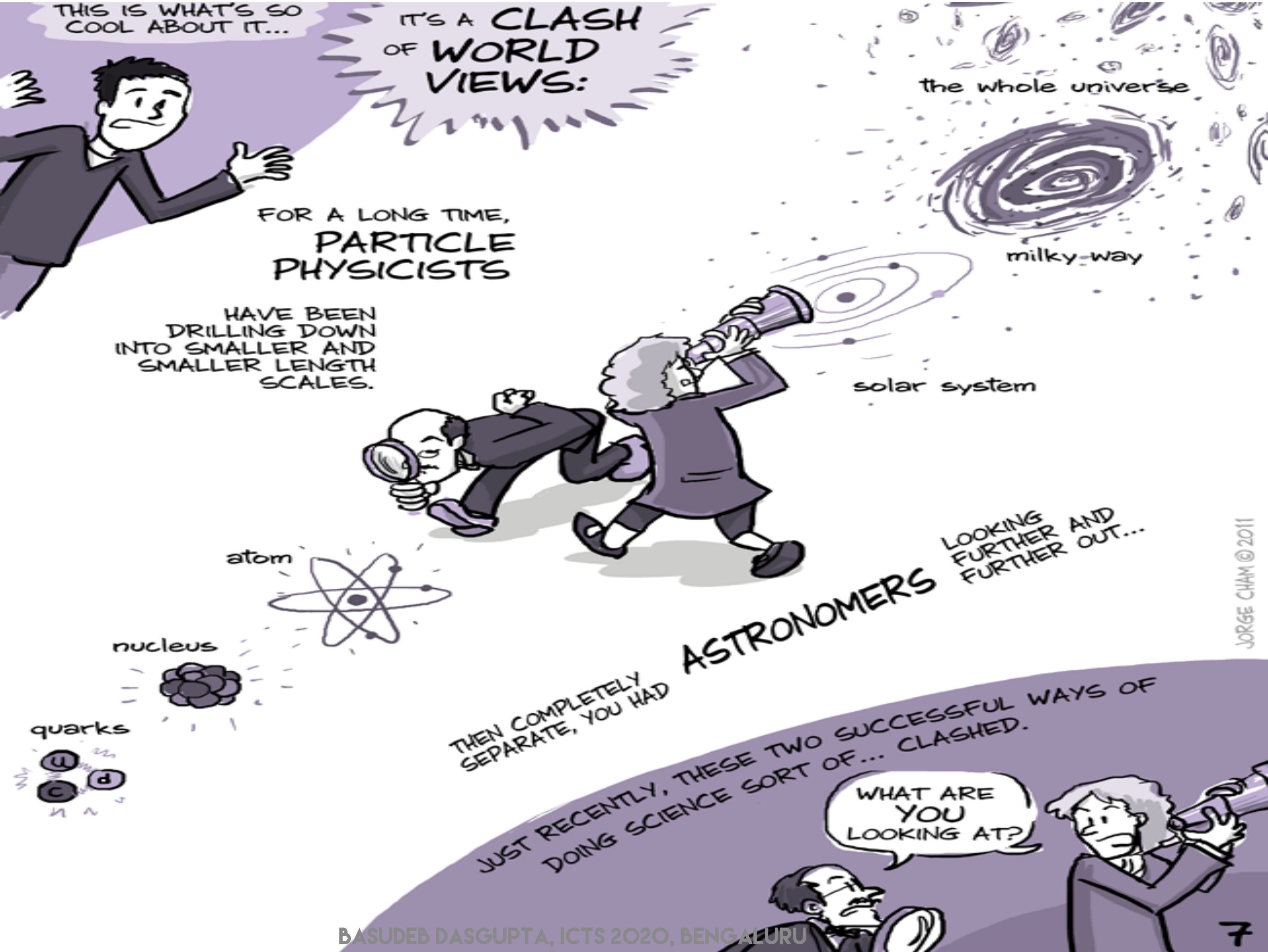
Slow speeds at the time it was created (else smears out cosmic structures)

Long-lived (else we won't see DM in galaxies today)

WHICH PARTICLE IS DARK MATTER ?

WHICH PARTICLE IS DARK MATTER ?




THIS IS WHAT'S SO COOL ABOUT IT...
IT'S A CLASH OF WORLD VIEWS:
FOR A LONG TIME, PARTICLE PHYSICISTS
HAVE BEEN DRILLING DOWN INTO SMALLER AND SMALLER LENGTH SCALES.
the whole universe
milky way
solar system
atom
nucleus
quarks
u
d
c
THEN COMPLETELY SEPARATE, YOU HAD ASTRONOMERS LOOKING FURTHER AND FURTHER OUT...
JORGE CHAM © 2011
JUST RECENTLY, THESE TWO SUCCESSFUL WAYS OF DOING SCIENCE SORT OF... CLASHED.
WHAT ARE YOU LOOKING AT?
7

More about models in Lectures by Neal Weiner