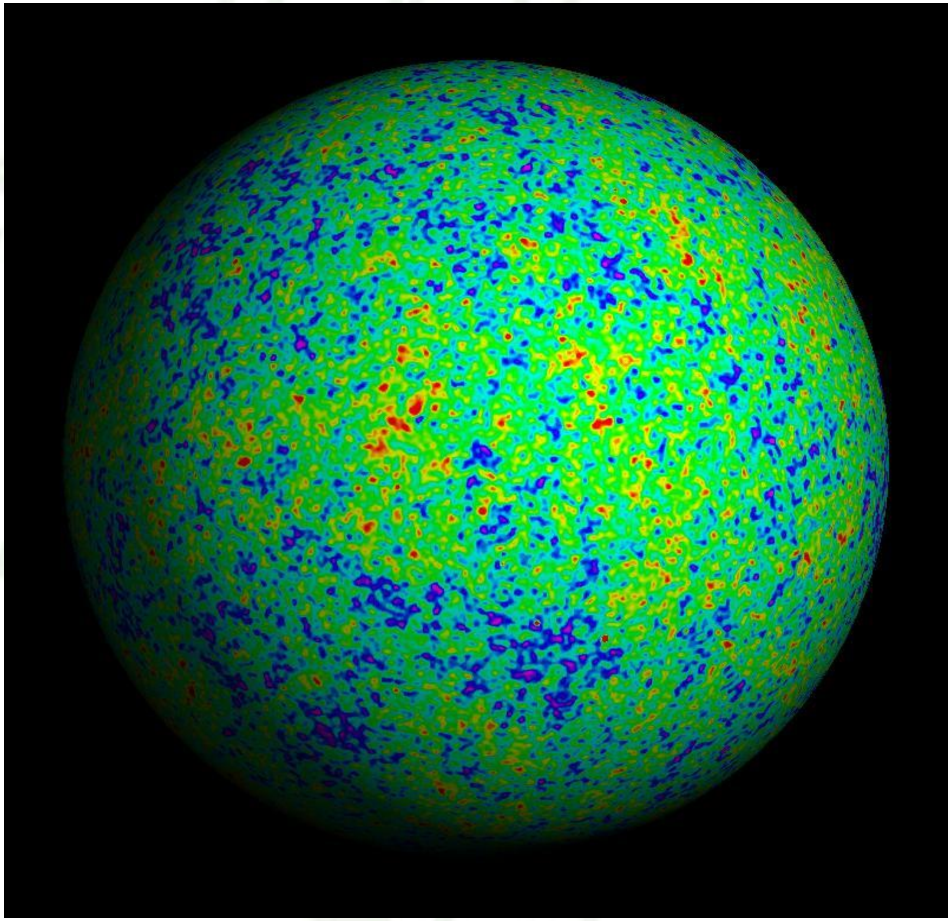
HOVO cursus Kosmologie

Voorjaar 2011



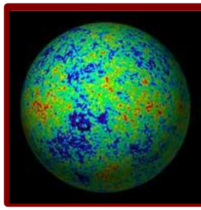
prof.dr. Paul Groot
dr. Gijs Nelemans

Afdeling Sterrenkunde,
Radboud Universiteit Nijmegen

HOVO cursus Kosmologie

Overzicht van de cursus:

• 17/1	Groot	Historische inleiding + afstandsladder
• 24/1	Nelemans	Observationele kosmologie, CMB
• 31/1	Nelemans	Friedmann vgl., Nucleosynthese
• *7/2*	*Nelemans*	*Donkere materie en Structuurvorming*
• 14/2	Nelemans	Supernovae, donkere energie, Inflatie
• 21/2	Groot	Weak lensing, EUCLID, toekomst



De wet van Hubble

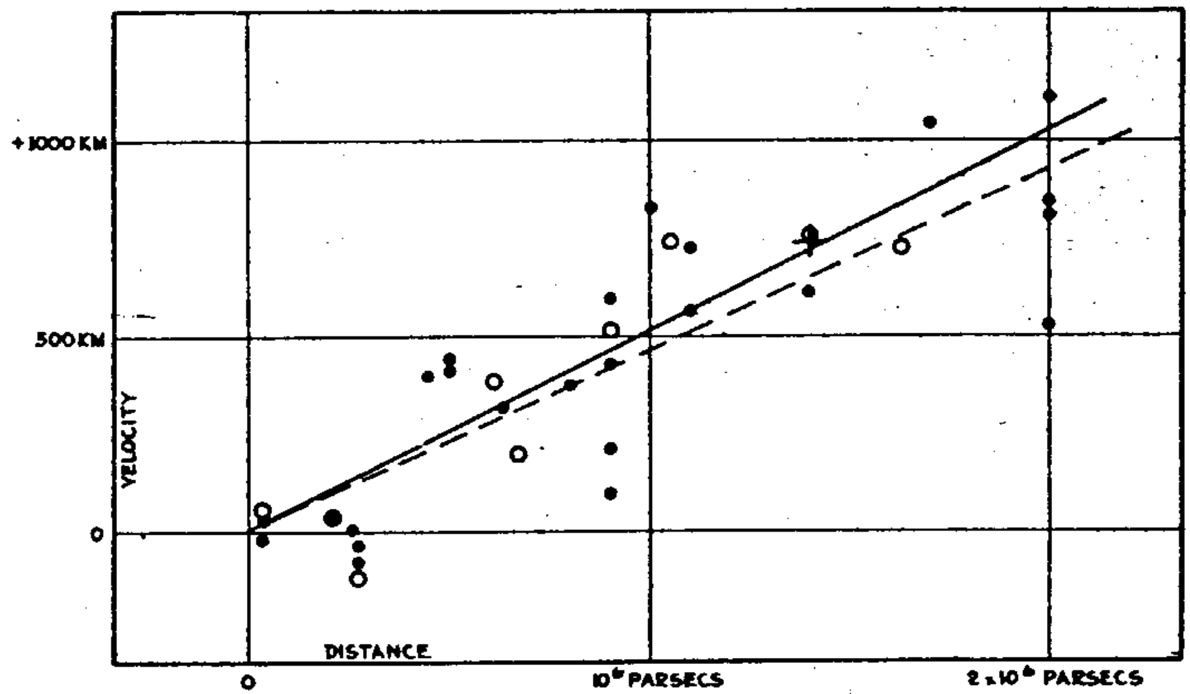
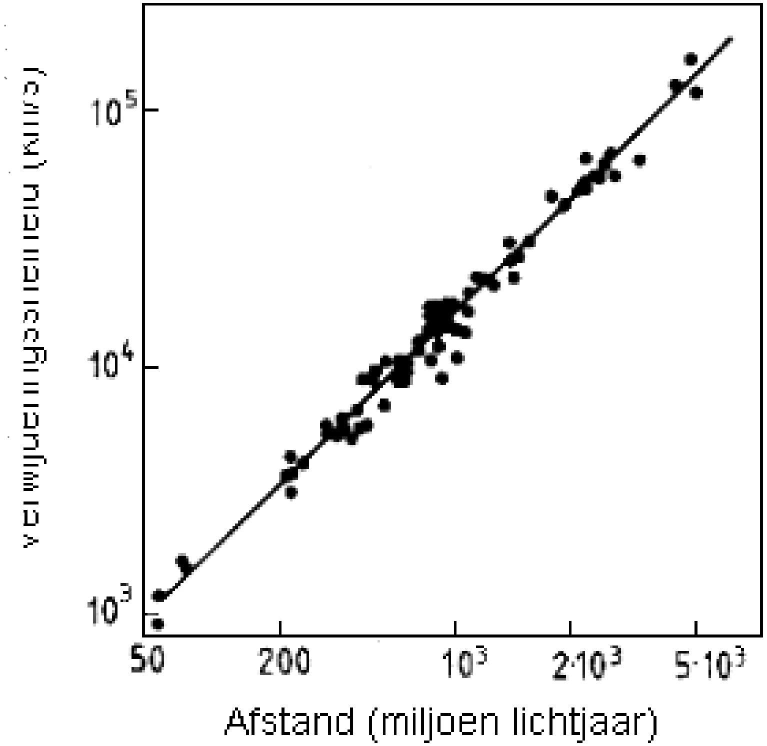
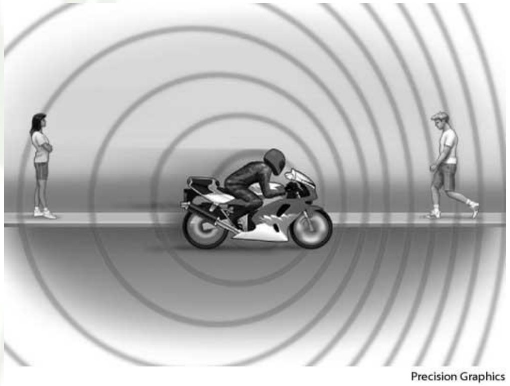


FIGURE 1

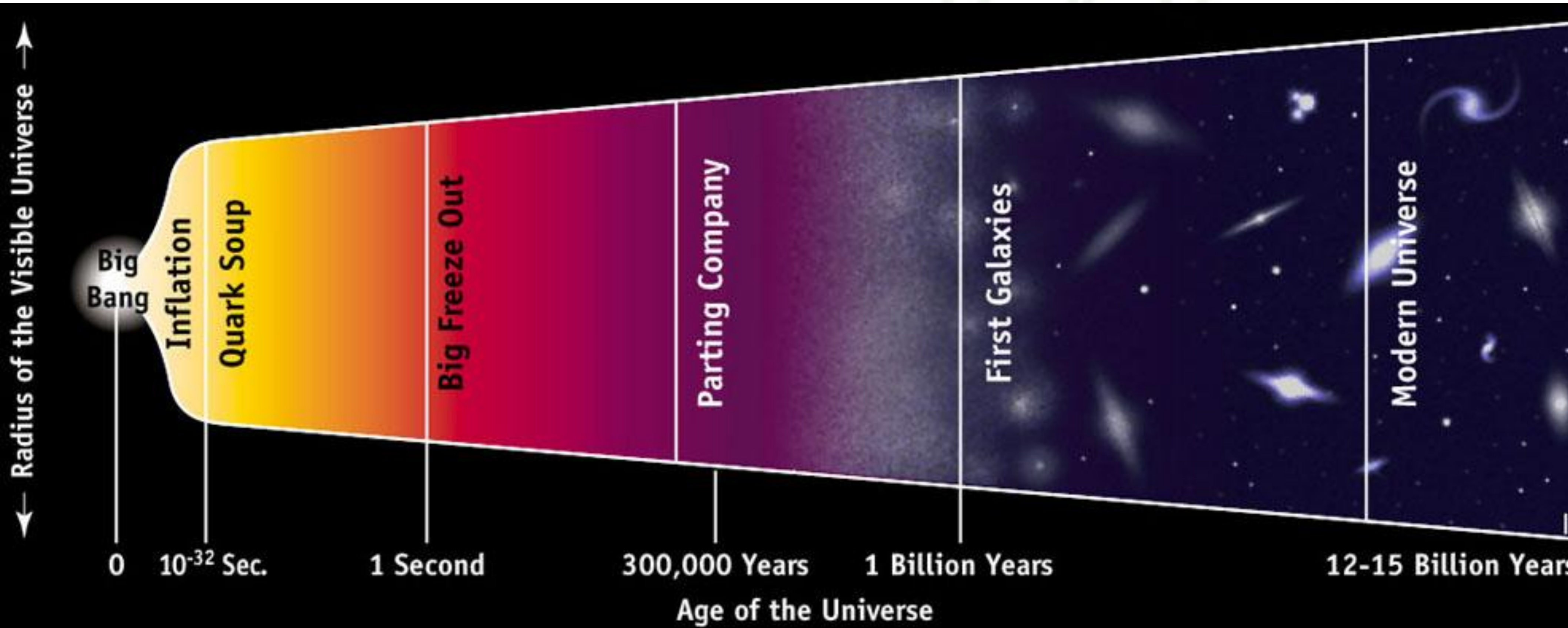


De wet van Hubble $v = H_0 d$

Doppler effect: $\dfrac{\Delta\lambda}{\lambda} = \dfrac{v}{c}$



Geschiedenis van het Heelal



T(K)	10^{10}	3000		2,726	
1+z	3×10^9	1000	10	1	
	n/p vast, helium	ontkoppeling	verste quasar	nu	

Theorie van het heelal is theorie van de zwaartekracht!

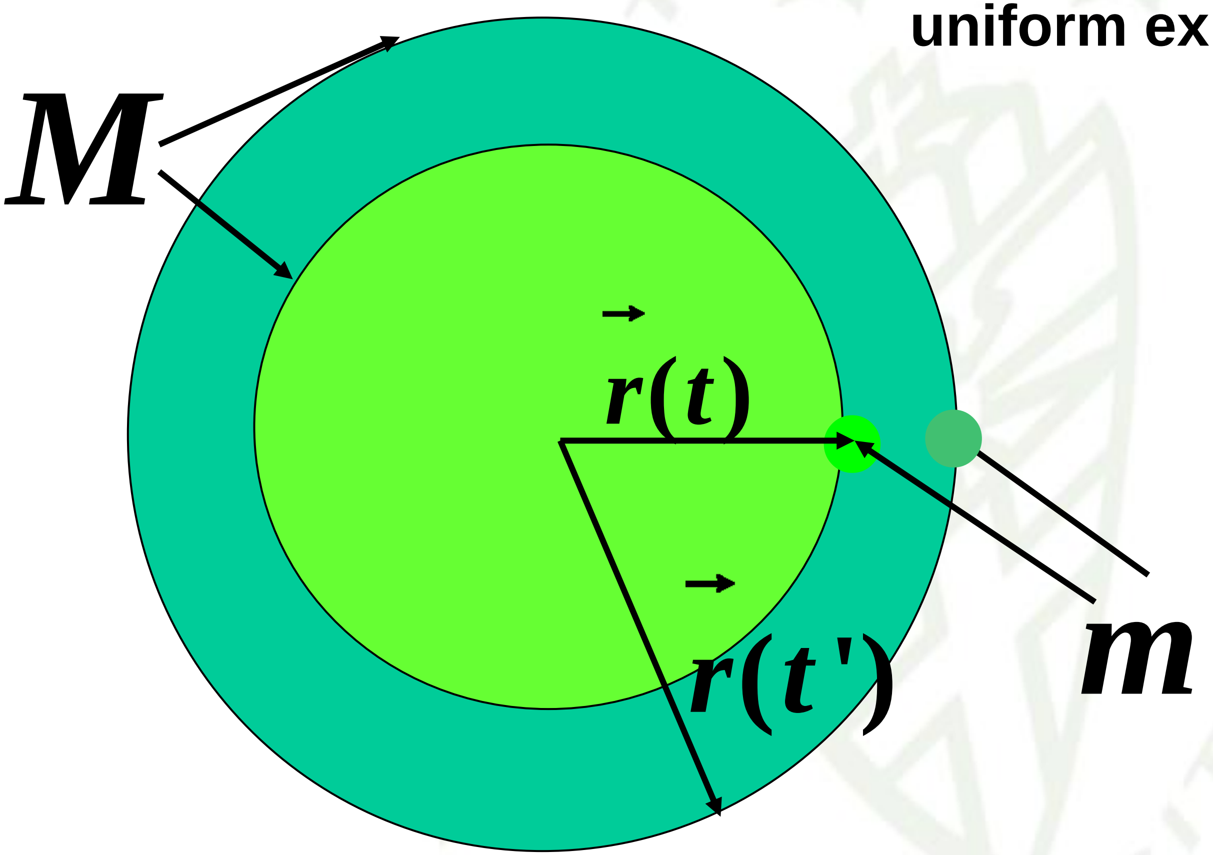
- Isaac Newton 1642 – 1727
- Albert Einstein 1875 - 1955:
  Algemene RelativiteitsTheorie 1915

Zolang $\boxed{v \ll c}$ en $\boxed{\sqrt{\frac{2GM}{R}} \ll c}$

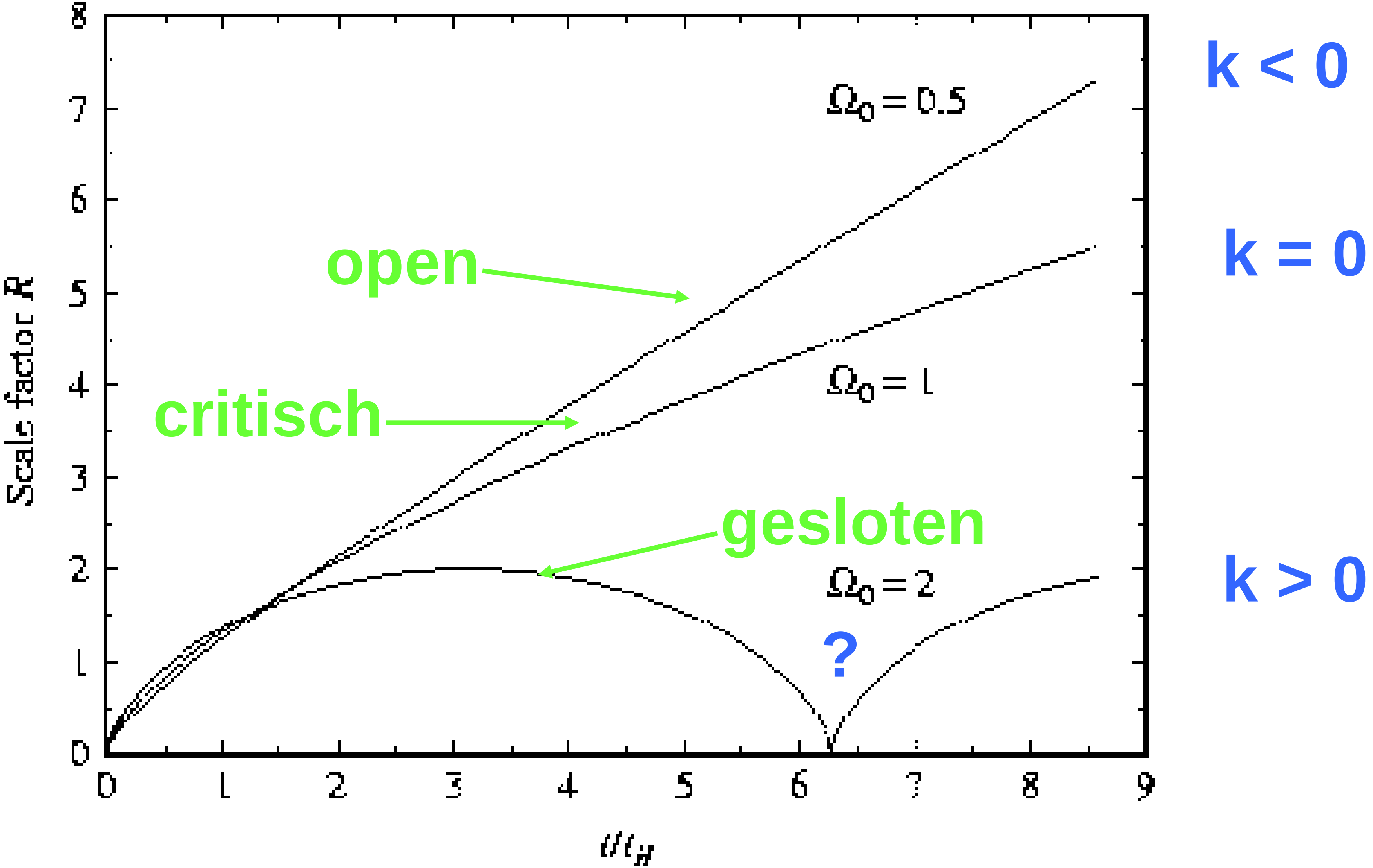
is Newton een goede benadering voor Einstein!

De Friedmannvergelijkingen

Homogeen koud gas,
uniform expanderend



Wat is de waarde van k?



$$\left(\frac{v}{R}\right)^2 - \frac{8\pi G\rho}{3} = -\frac{k}{R^2}$$

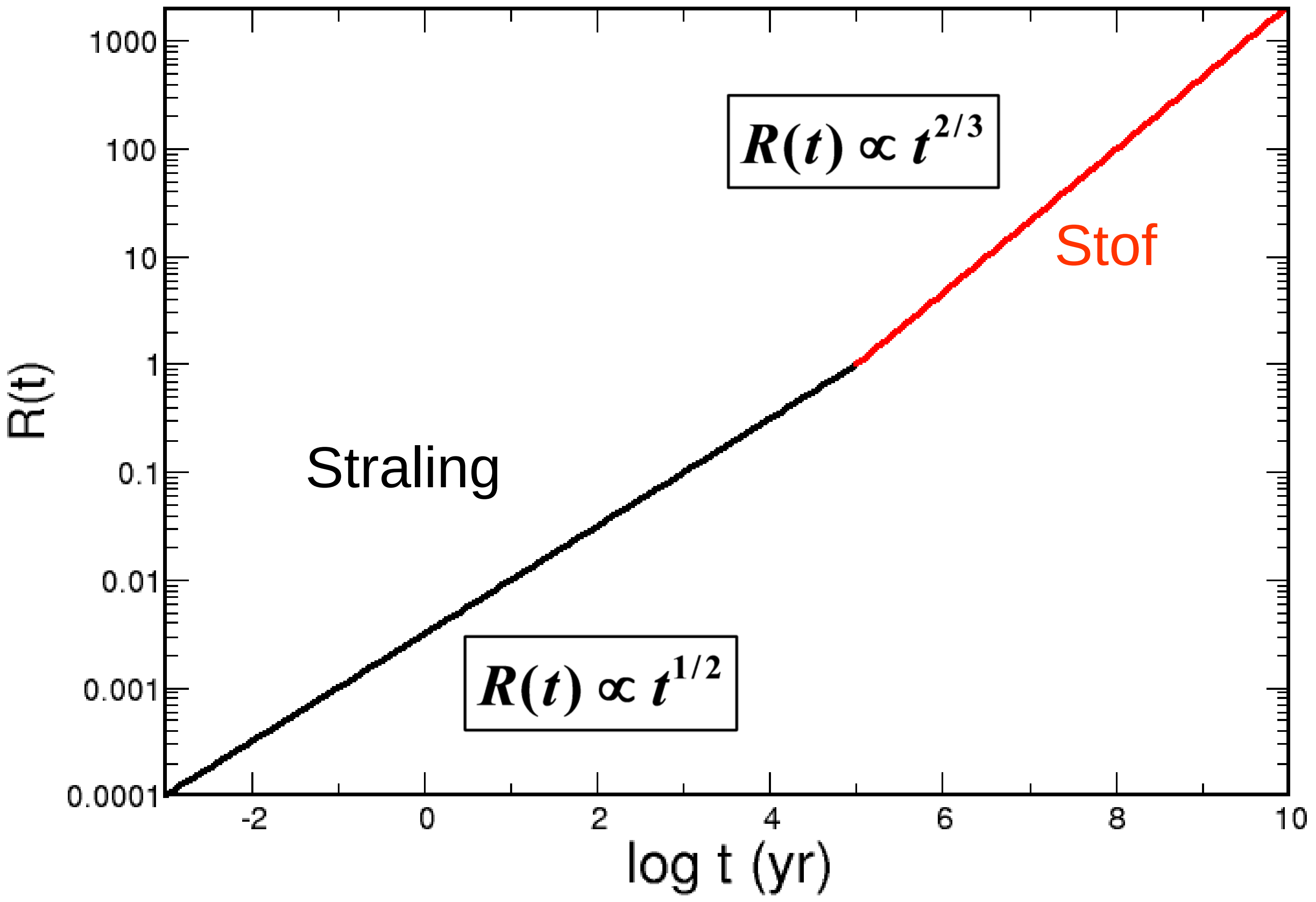
“Constante” van Hubble $H \equiv \frac{v}{R}$

Som geschreven in termen critische dichtheid

$$1 - \frac{\rho}{\rho_c} = -\frac{k}{H^2 R^2}$$

$$\boxed{1 - \Omega_M = -\frac{k}{H^2 R^2}}$$

Evolutie van dit heelal

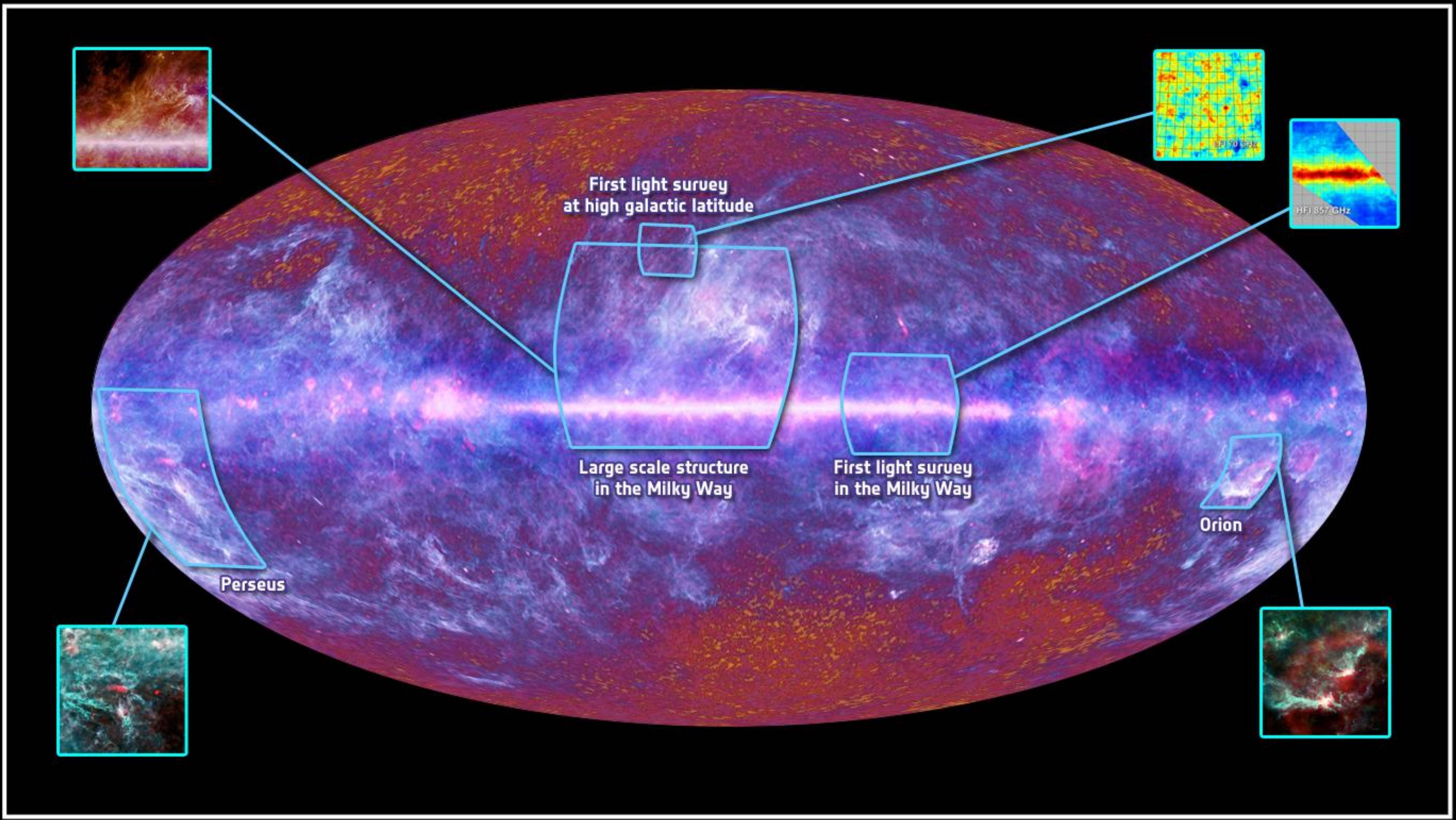


Leeftijd heelal

- Uit oplossing Friedmann vergelijking

$$R \sim t^{2/3} \rightarrow t = \frac{2}{3H_0} \approx 9\,\mathrm{Gyr}$$

- Oudste sterren zijn > 10 Gyr oud!



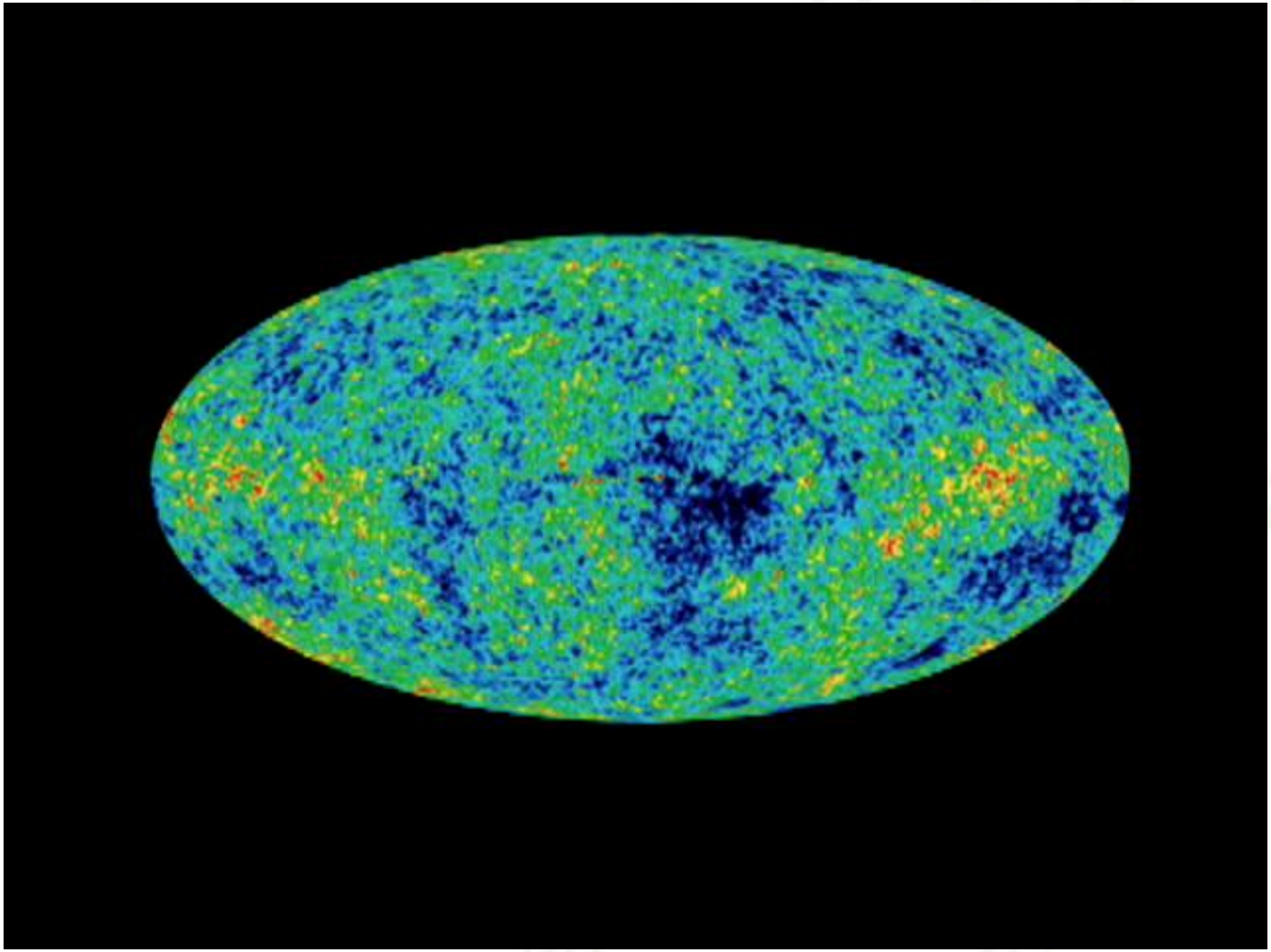
The Planck one-year all-sky survey

esa

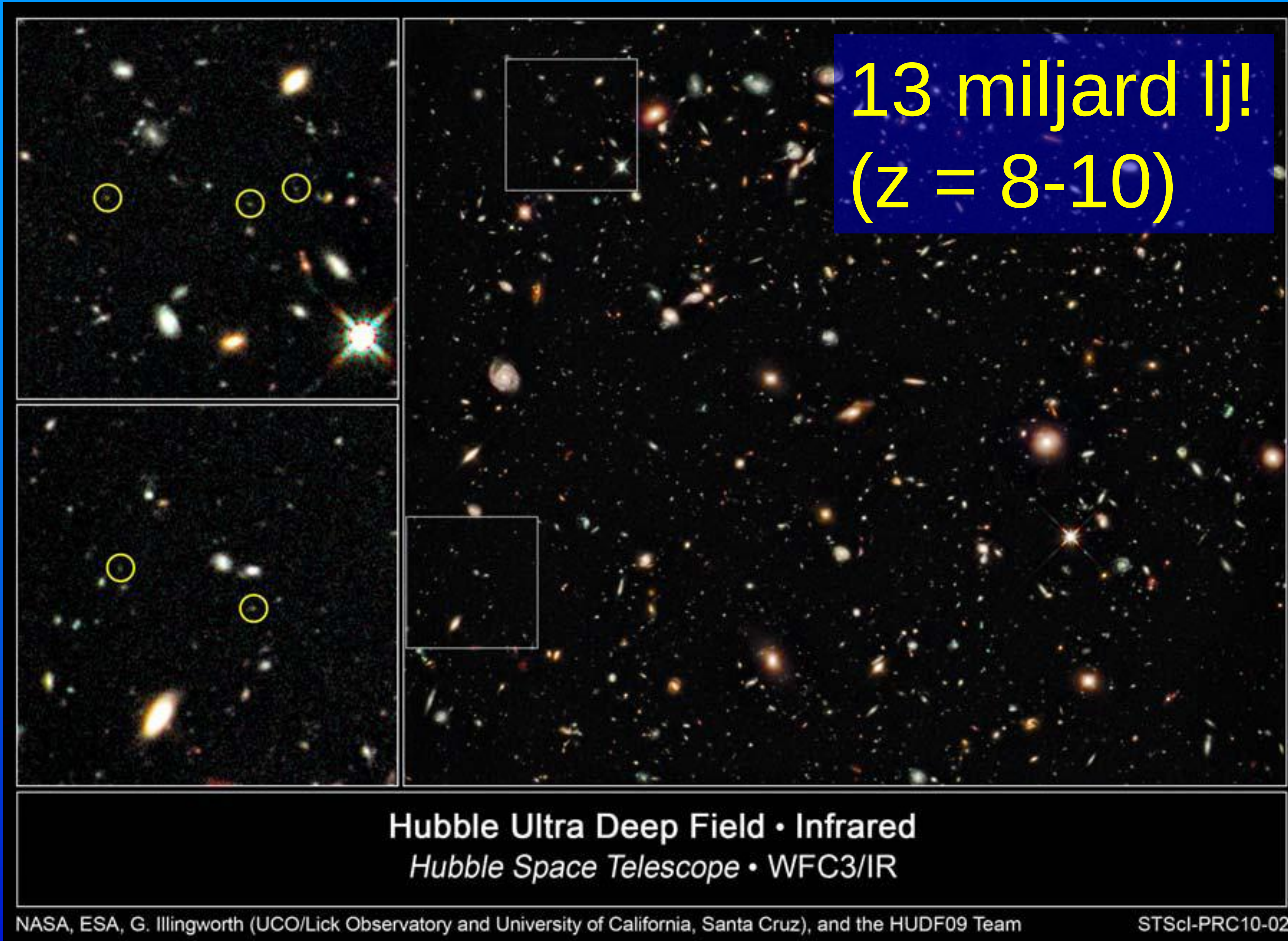
De problemen van ons model
(mogelijke oplossing: volgende week)

- Vlakheidsprobleem
  - Waarom leven we in een heelal met $k = 0$?
- Horizonprobleem
  - Heelal is niet oneindig oud → gebied dat we kunnen zien is eindig (horizon)
  - Heelal wordt steeds groter, maar horizon groeit sneller
  - Gebieden die we nu te zien krijgen (CMB) kunnen elkaar (nog) niet zien (en konden dat nooit!) maar zijn wel vrijwel identiek!
- Leeftijdsprobleem
  - Hoe kunnen oudste sterren ouder zijn dan heelal?

Structuurvorming



13 miljard lj!
(z = 8-10)

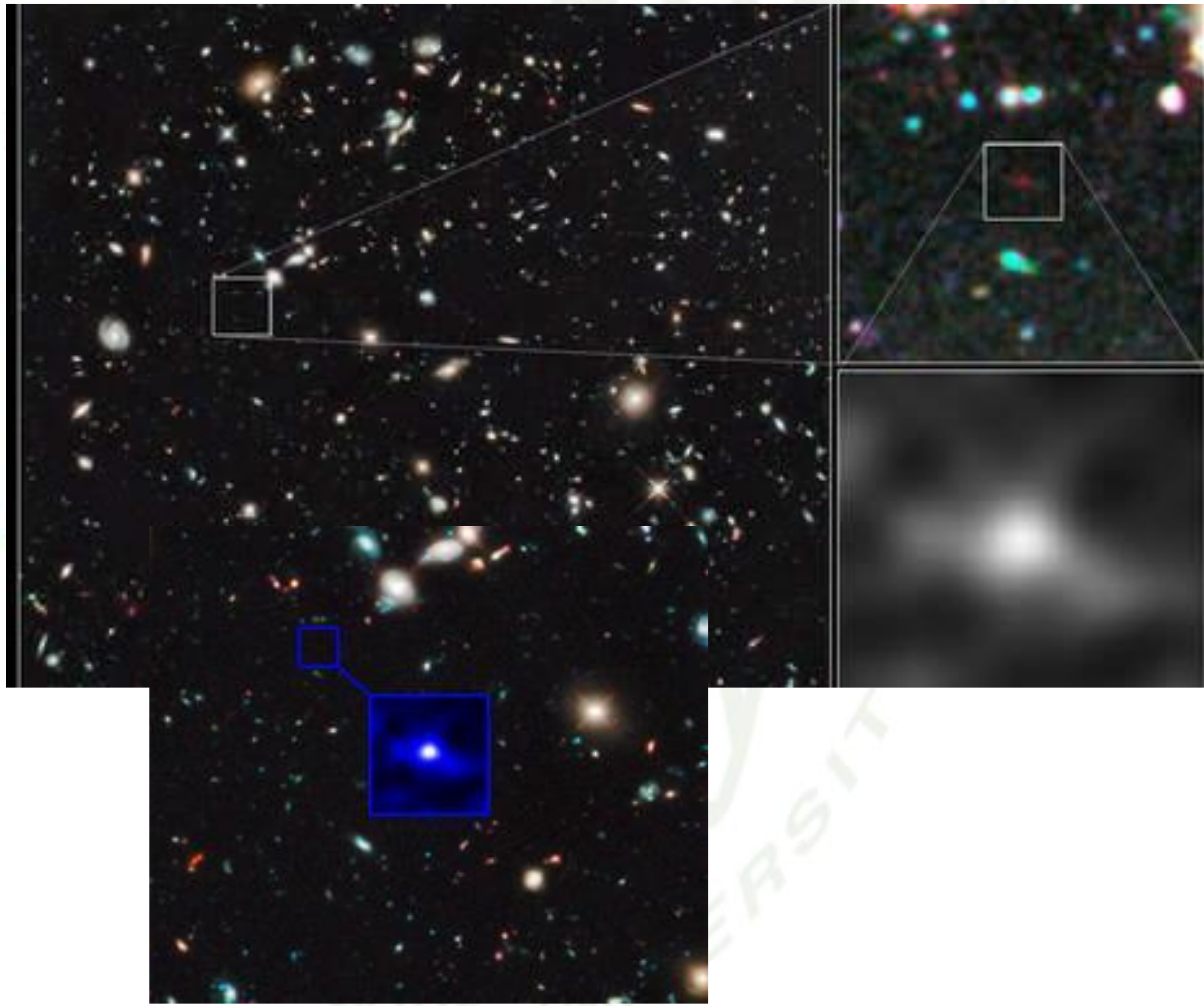


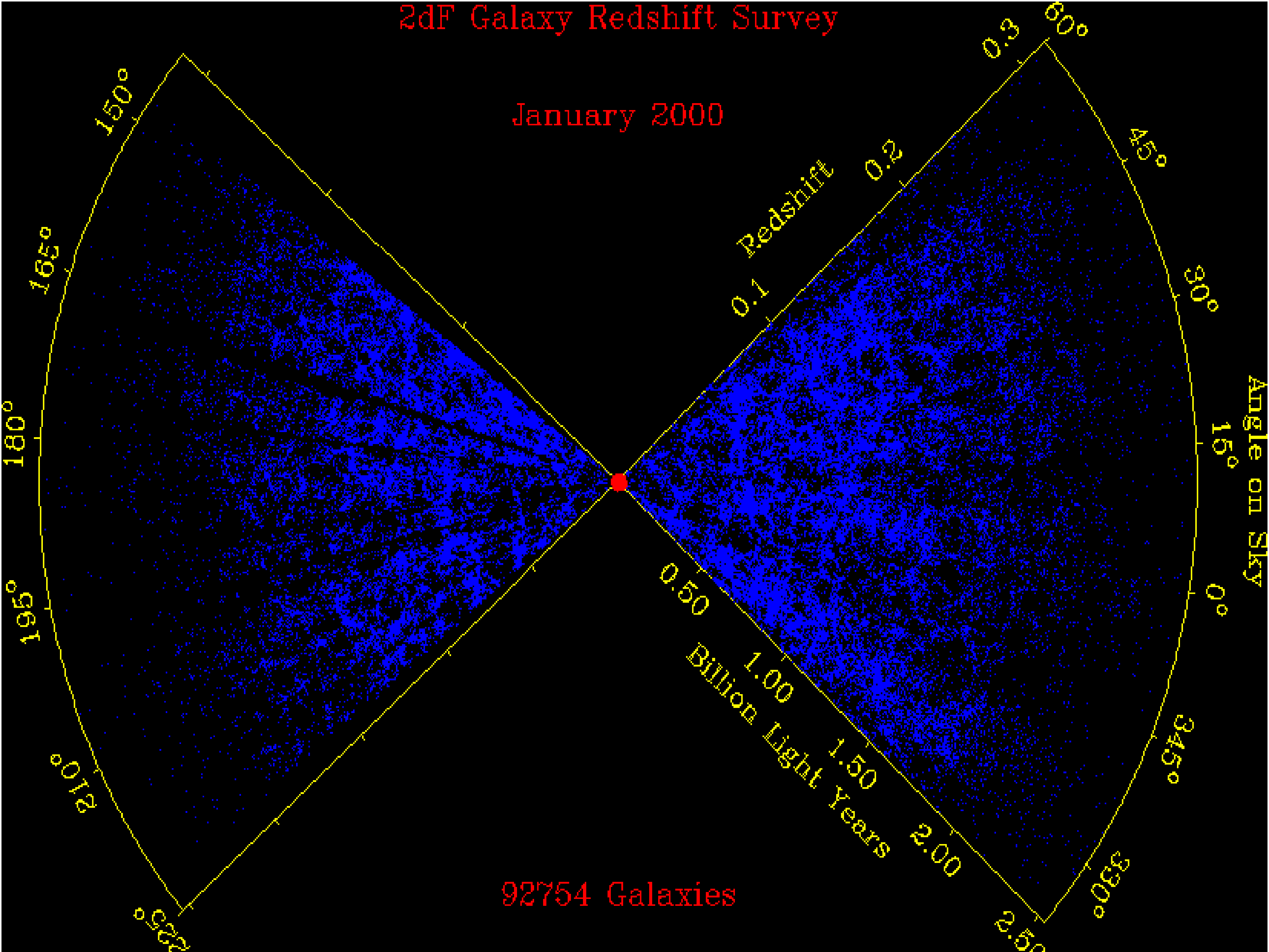
Vorige week in Nature

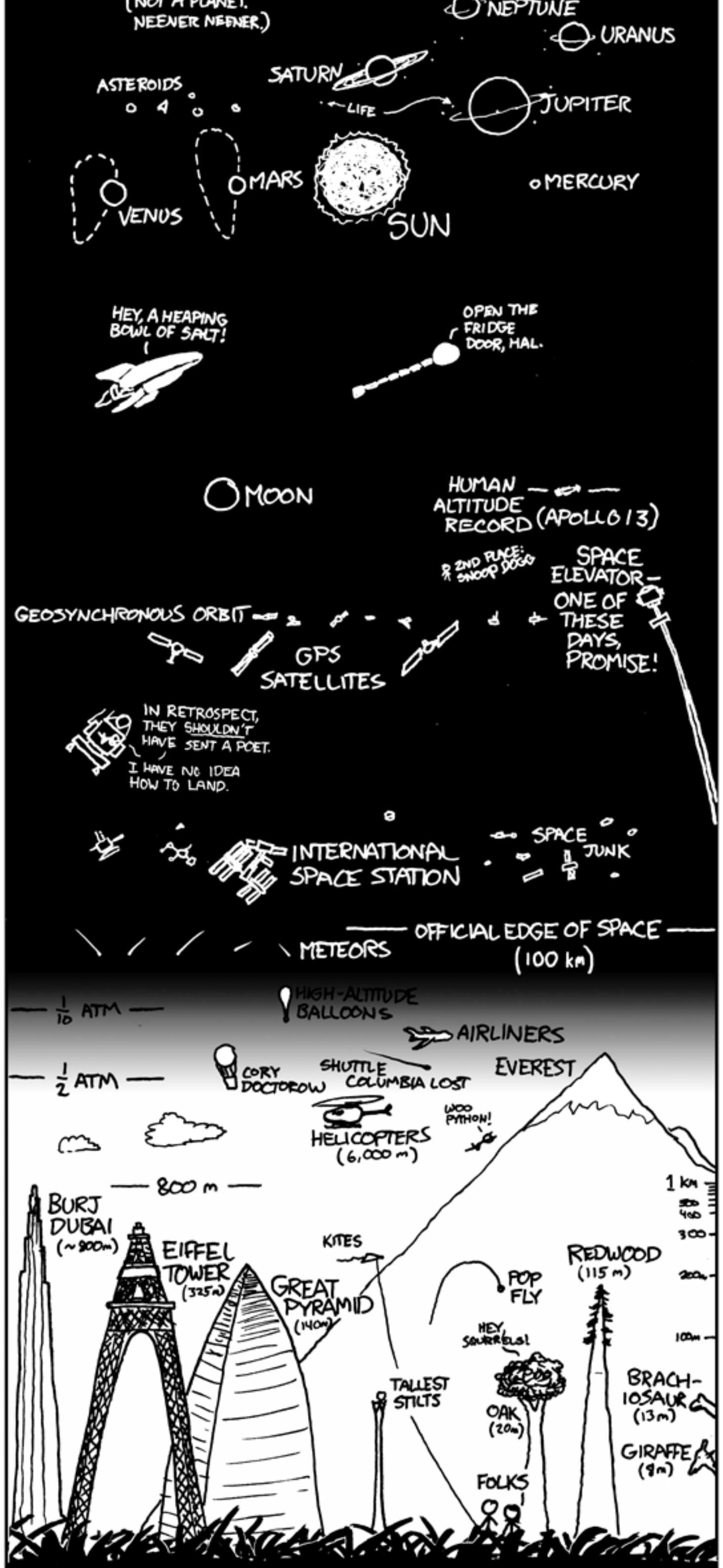
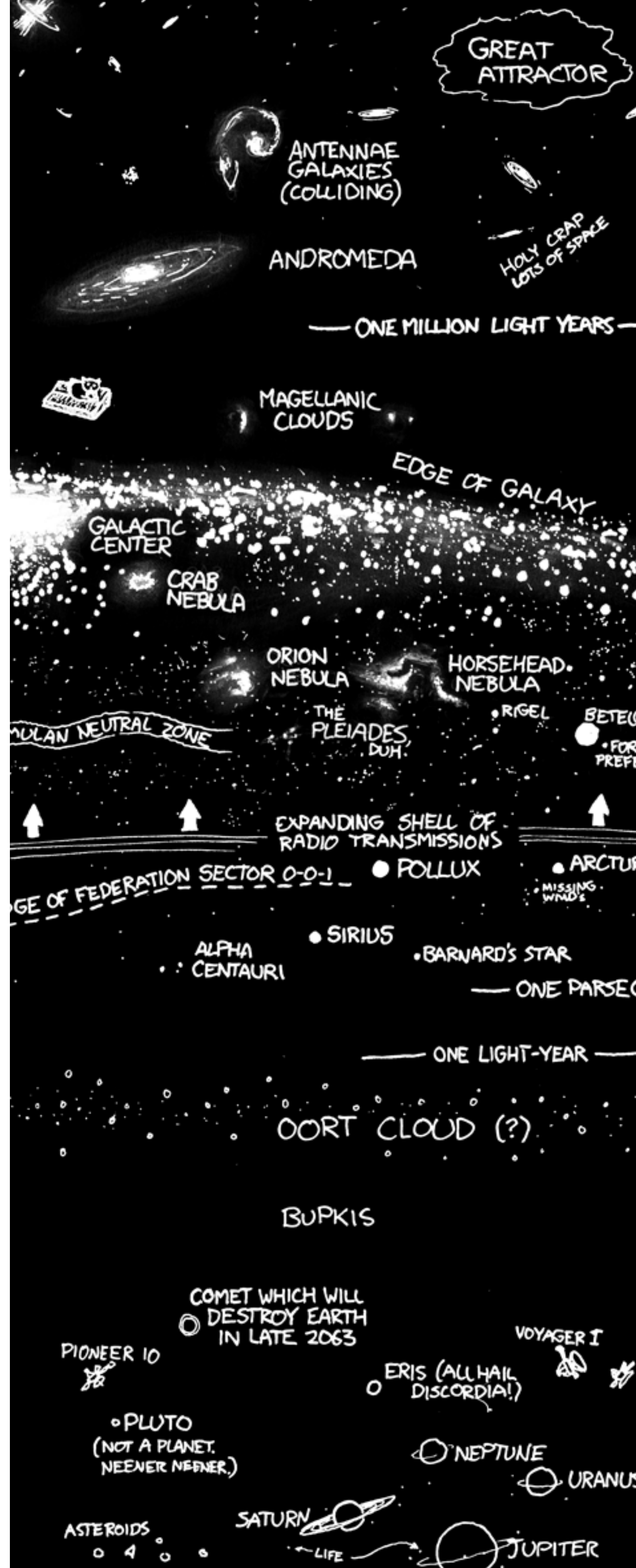
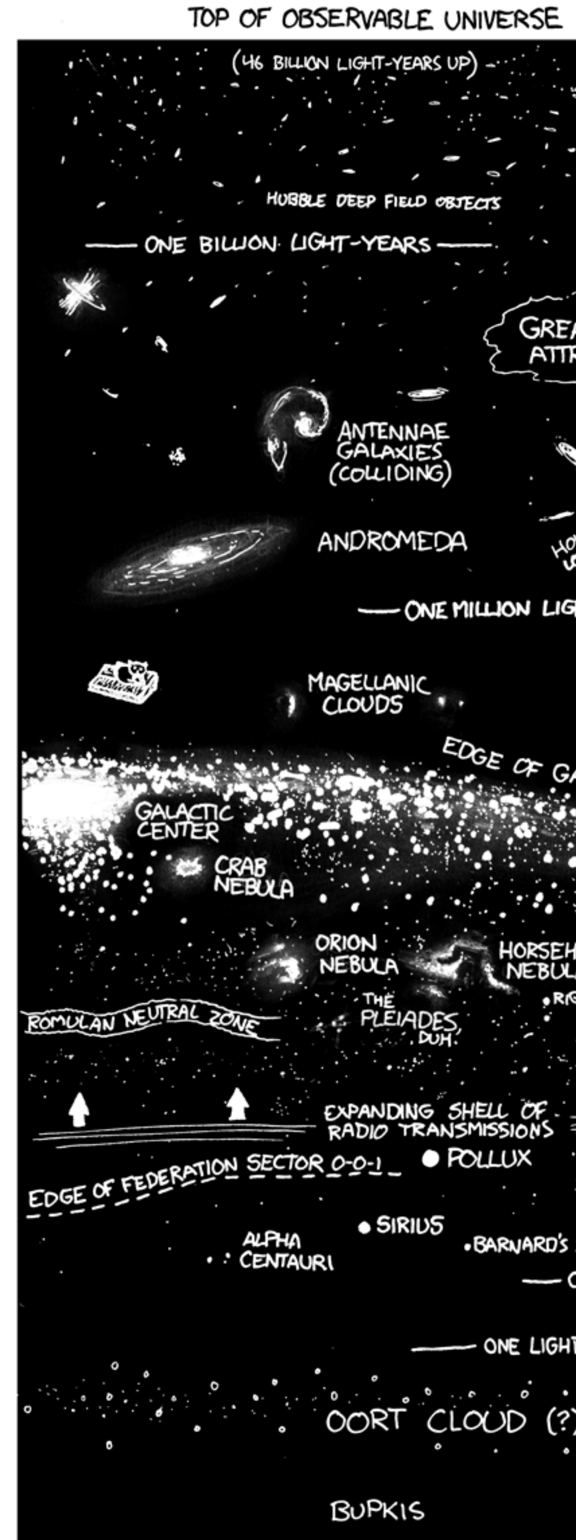
Bouwens, Franx

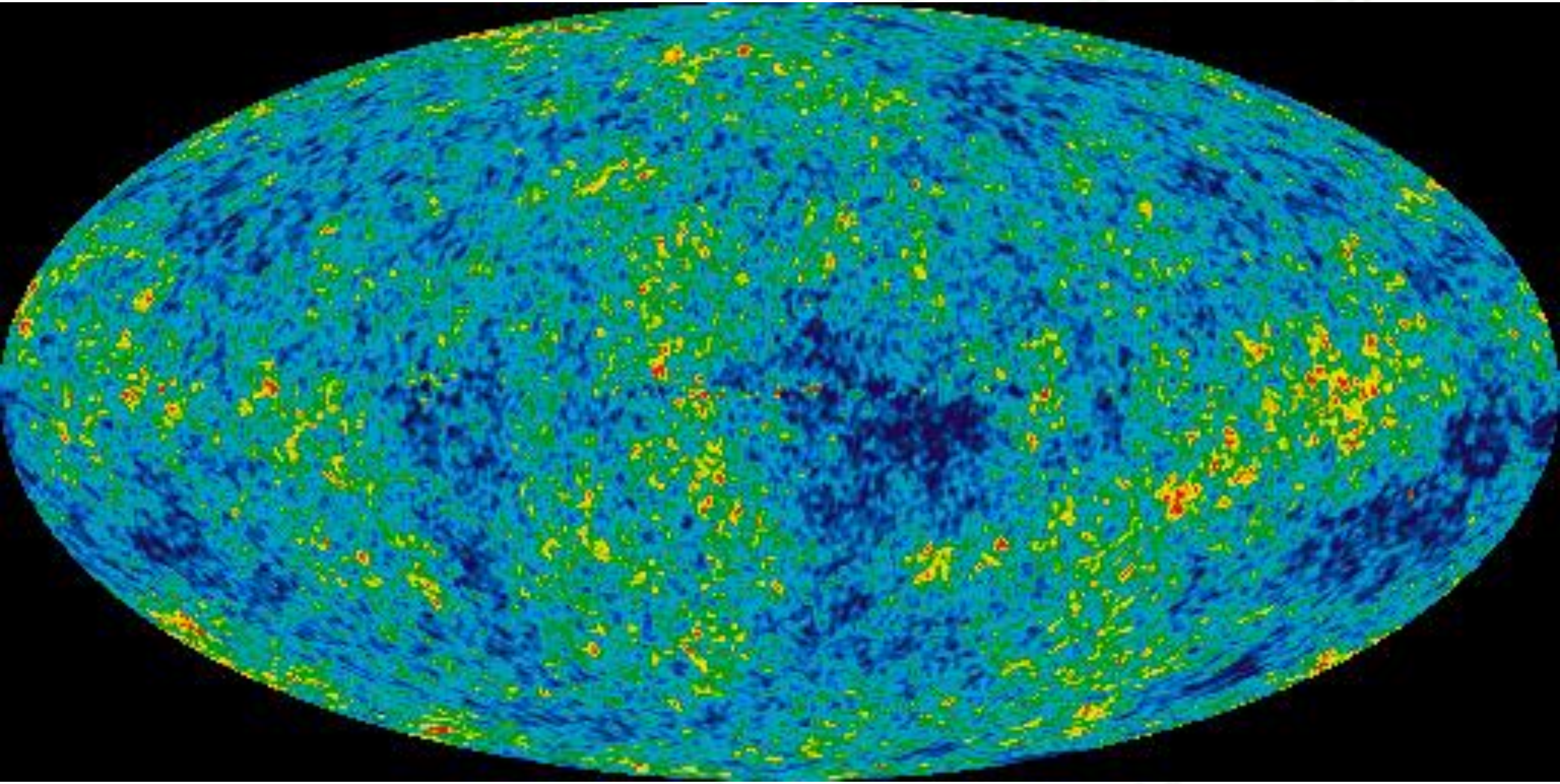
J-band drop outs toch niet echt

Maar 1 melkwegstelsel bij   z = 10

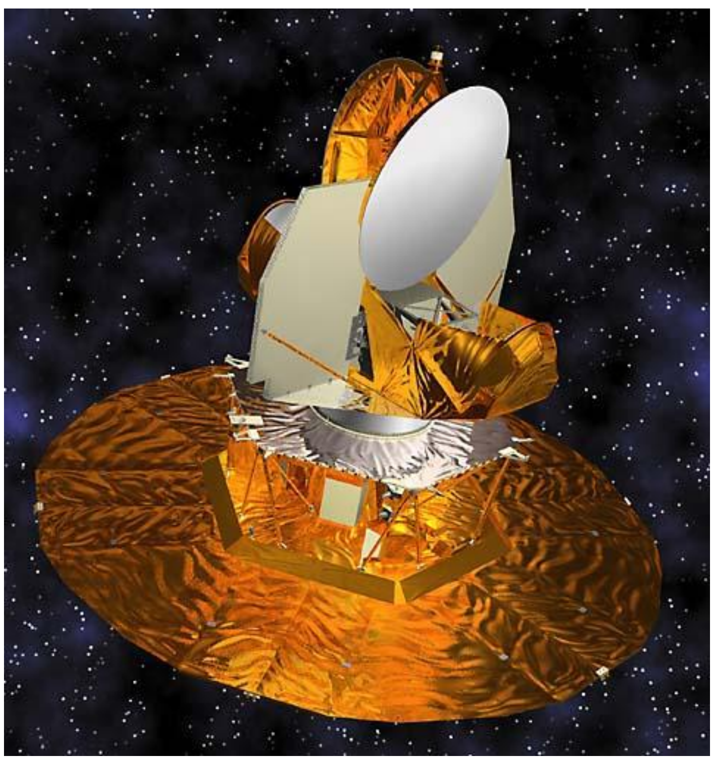


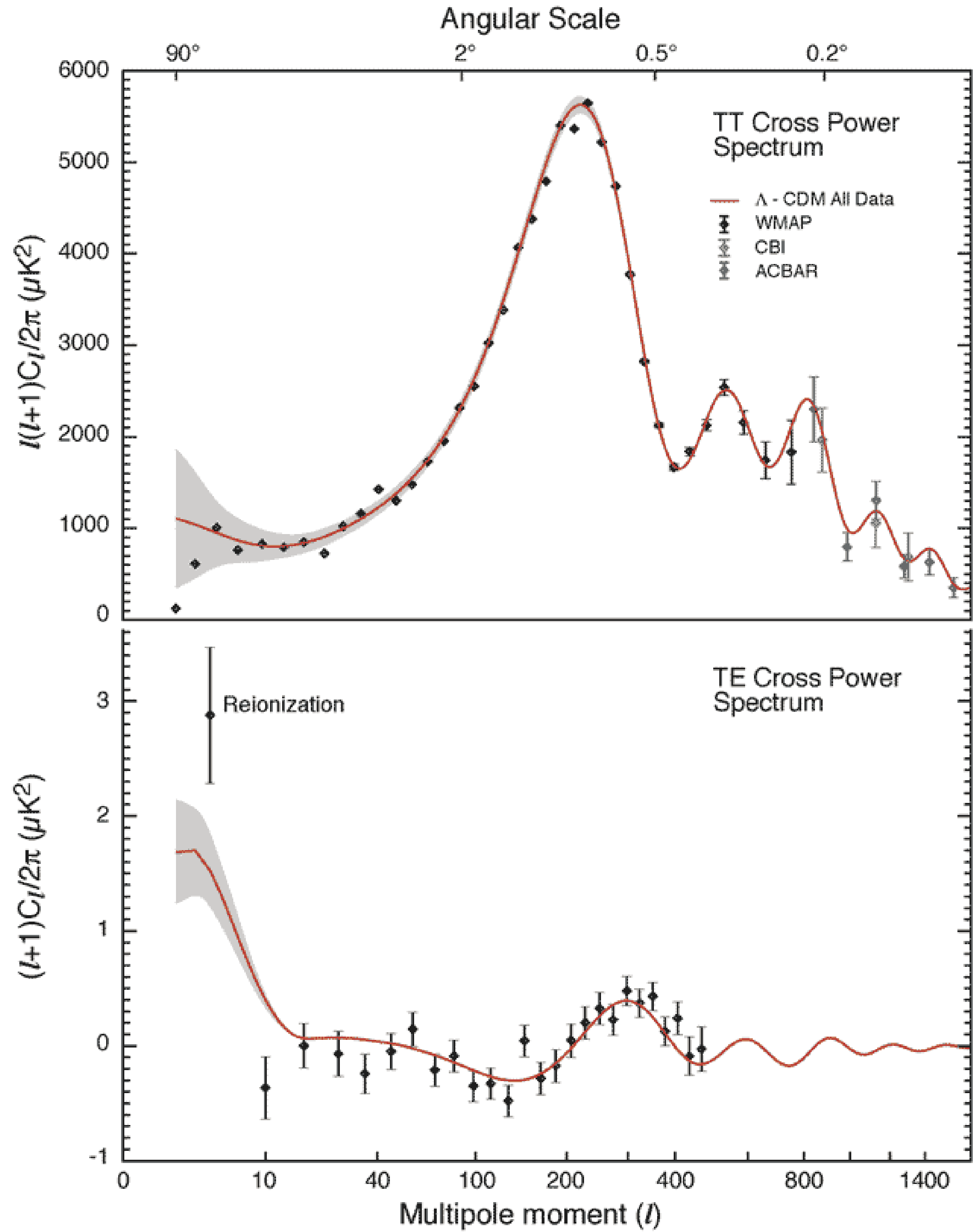

2dF Galaxy Redshift Survey
January 2000
92754 Galaxies
Redshift
0.1
0.2
0.3
Billion Light Years
0.50
1.00
1.50
2.00
2.50
Angle on Sky
150°
165°
180°
195°
210°
225°
60°
45°
30°
15°
0°
345°
330°


(NOT A PLANET. NEENER NEENER.)
NEPTUNE
URANUS
ASTEROIDS
SATURN
LIFE
JUPITER
VENUS
MARS
SUN
MERCURY
HEY, A HEAPING BOWL OF SALT!
OPEN THE FRIDGE DOOR, HAL.
MOON
HUMAN ALTITUDE RECORD (APOLLO 13)
2ND PLACE: SNOOP DOGG
SPACE ELEVATOR
ONE OF THESE DAYS, PROMISE!
GEOSYNCHRONOUS ORBIT
GPS SATELLITES
IN RETROSPECT, THEY SHOULDN'T HAVE SENT A POET.
I HAVE NO IDEA HOW TO LAND.
INTERNATIONAL SPACE STATION
SPACE JUNK
OFFICIAL EDGE OF SPACE (100 km)
METEORS
1/10 ATM
HIGH-ALTITUDE BALLOONS
AIRLINERS
1/2 ATM
CORY DOCTOROW
SHUTTLE COLUMBIA LOST
EVEREST
HELICOPTERS (6,000 m)
WOO PYTHON!
800 m
1 km
BURJ DUBAI (~800m)
EIFFEL TOWER (325m)
GREAT PYRAMID (140m)
KITES
POP FLY
REDWOOD (115 m)
HEY SQUIRRELS!
TALLEST STILTS
OAK (20m)
BRACHIOSAUR (13m)
GIRAFFE (8m)
FOLKS

GREAT ATTRACTOR
ANTENNAE GALAXIES (COLLIDING)
ANDROMEDA
HOLY CRAP LOTS OF SPACE
ONE MILLION LIGHT YEARS
MAGELLANIC CLOUDS
EDGE OF GALAXY
GALACTIC CENTER
CRAB NEBULA
ORION NEBULA
HORSEHEAD NEBULA
RIGEL
ROMULAN NEUTRAL ZONE
THE PLEIADES, DUH.
EXPANDING SHELL OF RADIO TRANSMISSIONS
EDGE OF FEDERATION SECTOR 0-0-1
POLLUX
MISSING WINDS
SIRIUS
ALPHA CENTAURI
BARNARD'S STAR
ONE PARSEC
ONE LIGHT-YEAR
OORT CLOUD (?)
BUPKIS
COMET WHICH WILL DESTROY EARTH IN LATE 2063
PIONEER 10
VOYAGER I
ERIS (ALL HAIL DISCORDIA!)
PLUTO (NOT A PLANET. NEENER NEENER.)
NEPTUNE
URANUS
SATURN
ASTEROIDS
LIFE
JUPITER

TOP OF OBSERVABLE UNIVERSE
(46 BILLION LIGHT-YEARS UP)
HUBBLE DEEP FIELD OBJECTS
ONE BILLION LIGHT-YEARS
ANTENNAE GALAXIES (COLLIDING)
ANDROMEDA
MAGELLANIC CLOUDS
GALACTIC CENTER
CRAB NEBULA
ORION NEBULA
ROMULAN NEUTRAL ZONE
THE PLEIADES, DUH.
EXPANDING SHELL OF RADIO TRANSMISSIONS
EDGE OF FEDERATION SECTOR 0-0-1
POLLUX
SIRIUS
ALPHA CENTAURI
OORT CLOUD (?)
BUPKIS



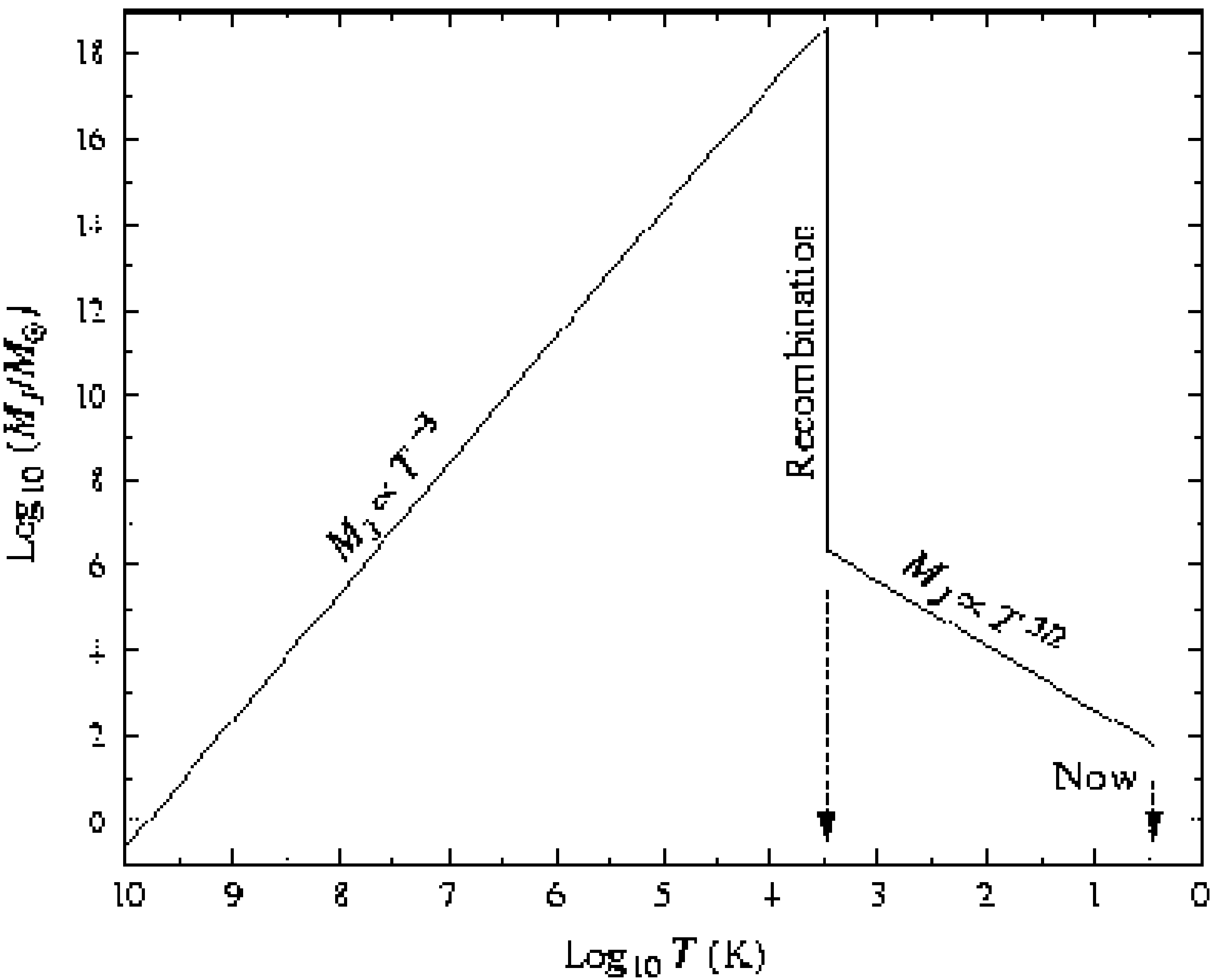
WMAP





Angular Scale
90°
2°
0.5°
0.2°
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
$l(l+1)C_l/2\pi\ (\mu K^2)$
6000
5000
4000
3000
2000
1000
0
TE Cross Power Spectrum
Reionization
$(l+1)C_l/2\pi\ (\mu K^2)$
3
2
1
0
-1
0
10
40
100
200
400
800
1400
Multipole moment (l)

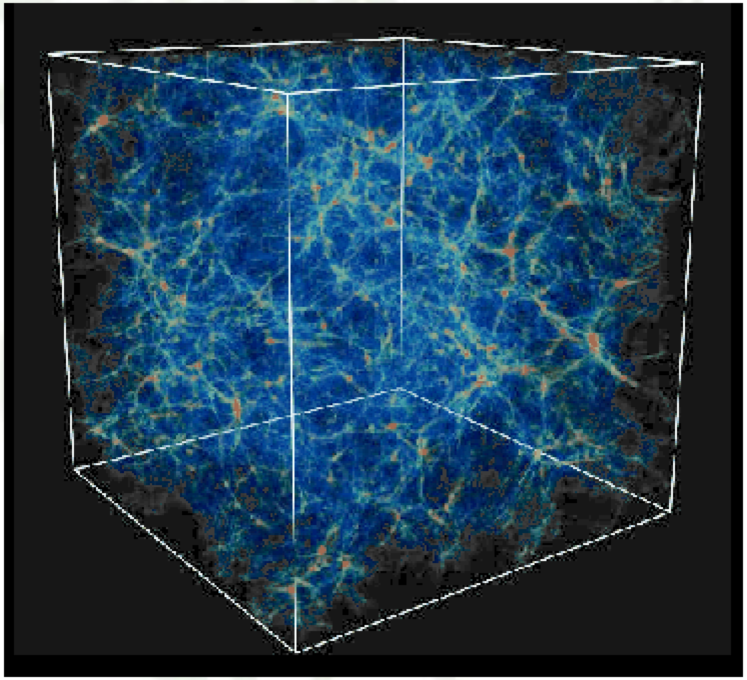
Jean Mass



18
16
14
12
10
8
6
4
2
0
$\mathrm{Log}_{10}\,(M_J/M_\odot)$
$M_J \propto T^3$
Recombination
$M_J \propto T^{-1/2}$
Now
10
9
8
7
6
5
4
3
2
1
0
$\mathrm{Log}_{10}\,T$ (K)

Probleem: uitdijing heelal!

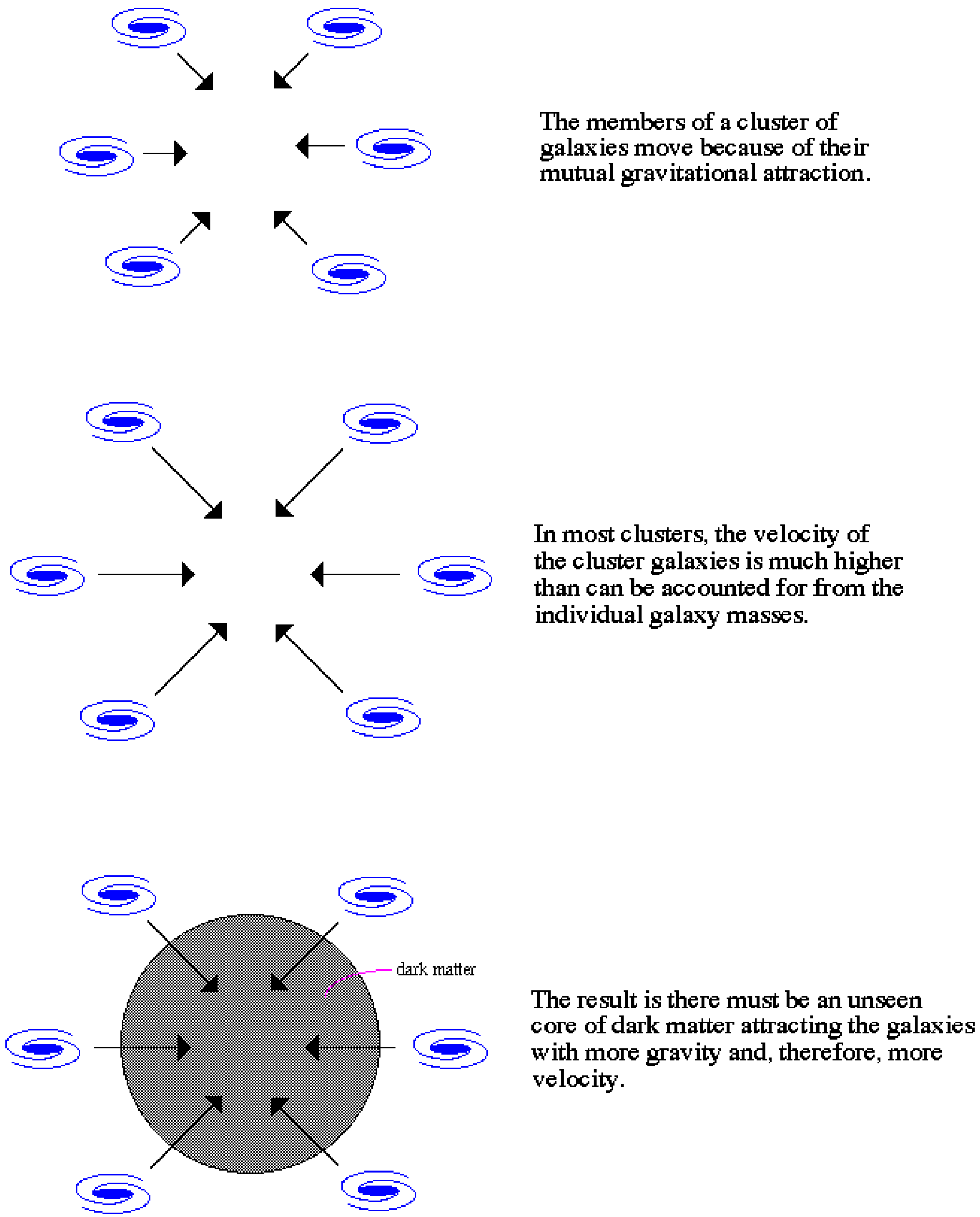
- “Normaal”
  - Als $M > M_J$: stort in elkaar
  - Duurt kort
  - Snel eerste structuur
- In uitdijend heelal
  - Inelkaarstorten vertraagd
  - Duurt lang voordat eerste structuur vormt
- Waarnemingen:
  - Structuur vormt snel!



Donkere Materie

Donkere materie

Zwicky (1898-1974):
"donkere materie" (1933)



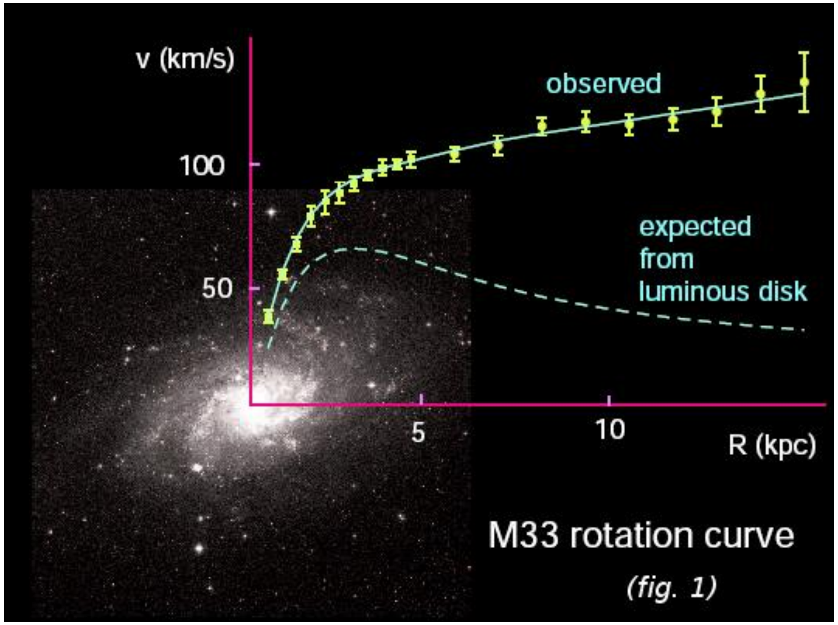
Massa meten: snelheden

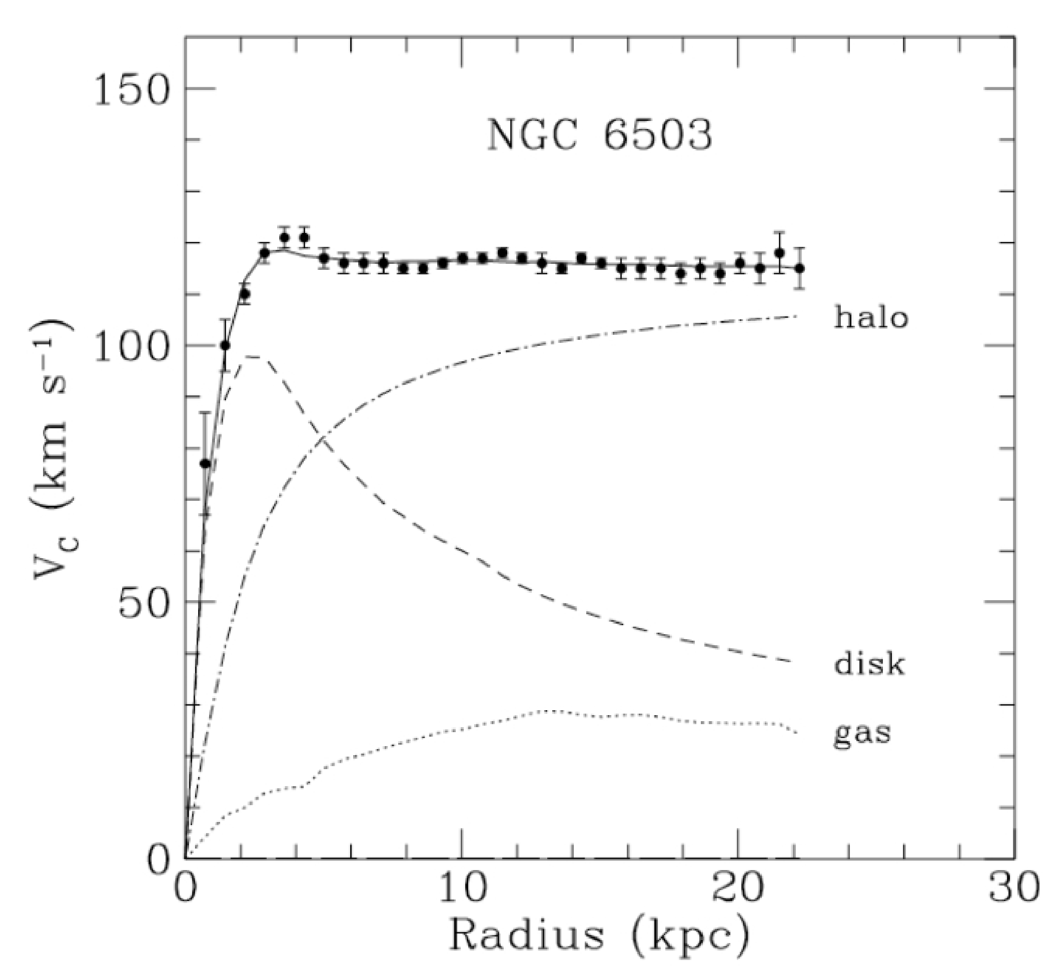
Kepler: cirkelbaan: $$2\frac{1}{2}mv^2 - \frac{GmM}{R} = 0$$

Algemeen voor een door de zwaartekracht gebonden systeem:

$$M \propto \frac{v^2 R}{G}$$

Rotatiekrommen van spiraalstelsels





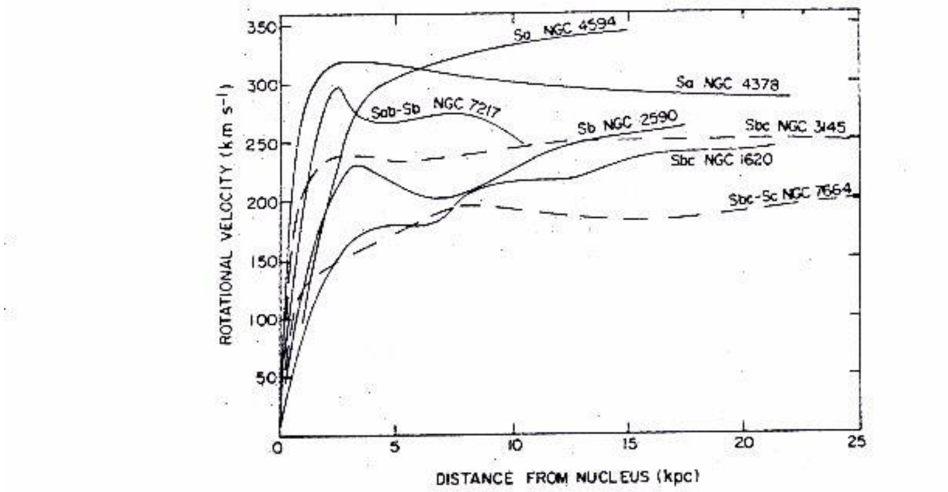
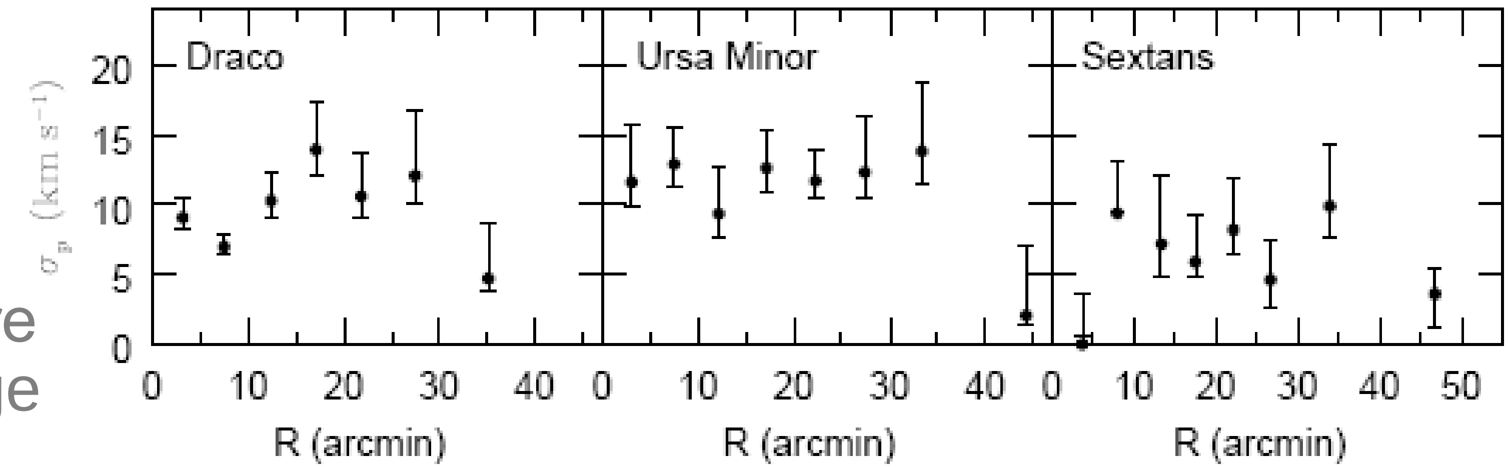
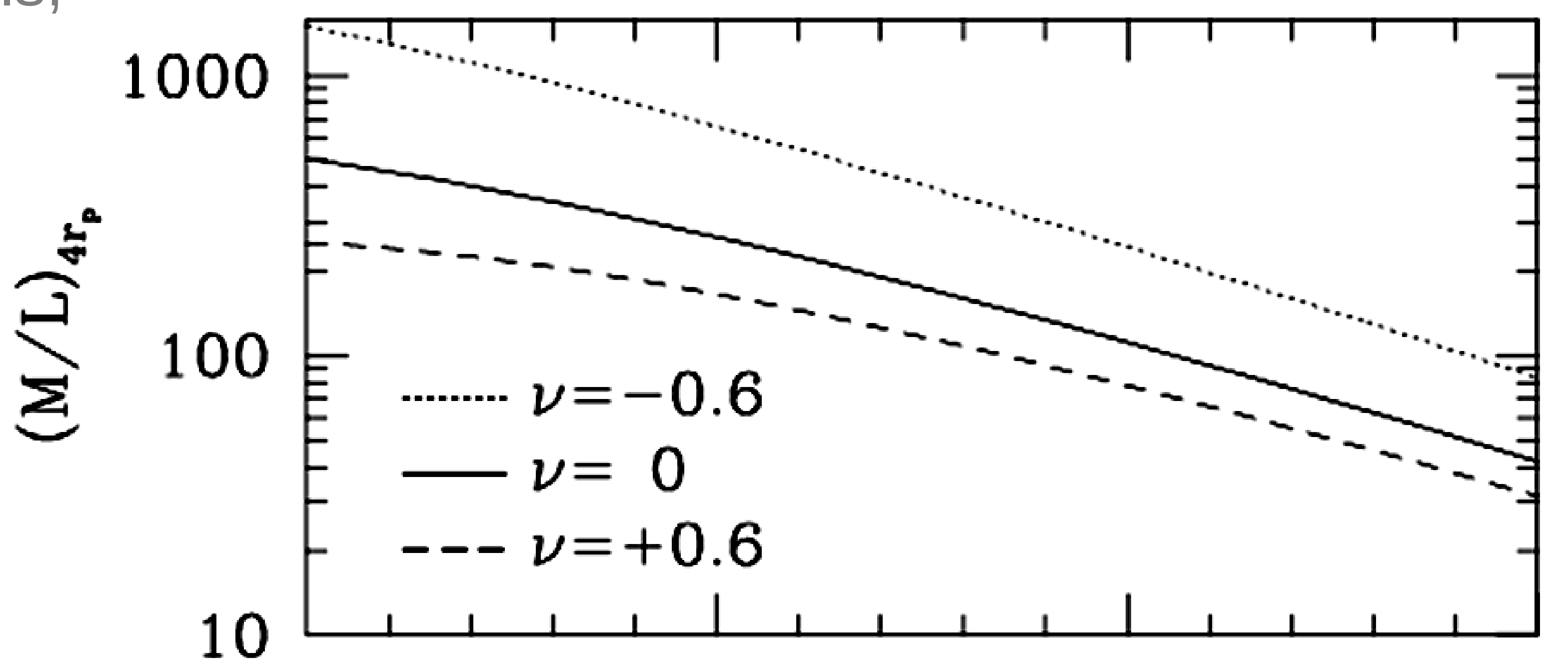


Figure 22.29 A series of rotation curves for spiral galaxies. (Figure from Rubin, Ford, and Thonnard, *Ap. J. Lett.*, *225*, L107, 1978.)

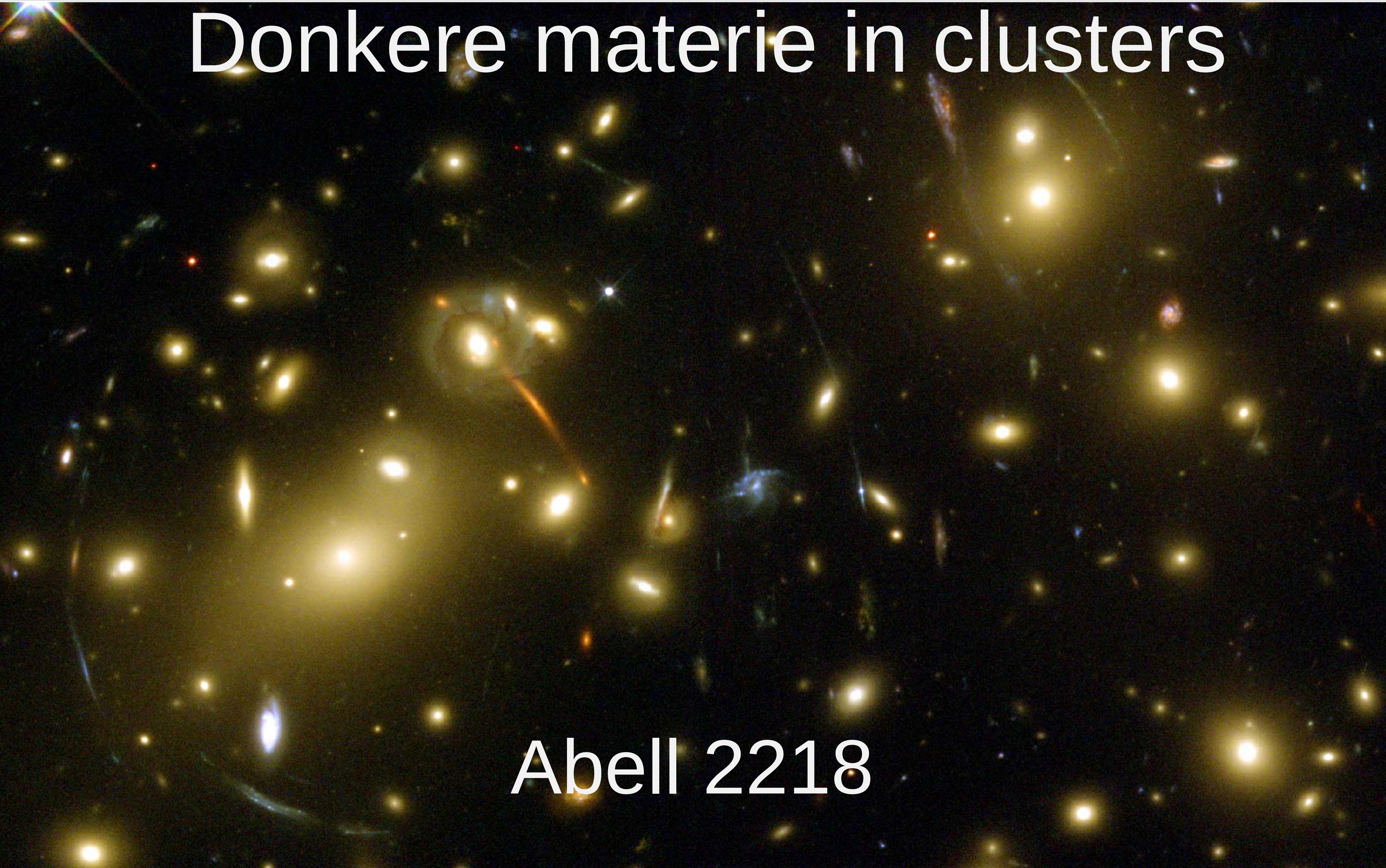
Snelheidsdispersie dwergstelsels

“Bewijs”donkere materie: hoge M/L in dwergstelsels, maar niet in bolvormige sterhopen

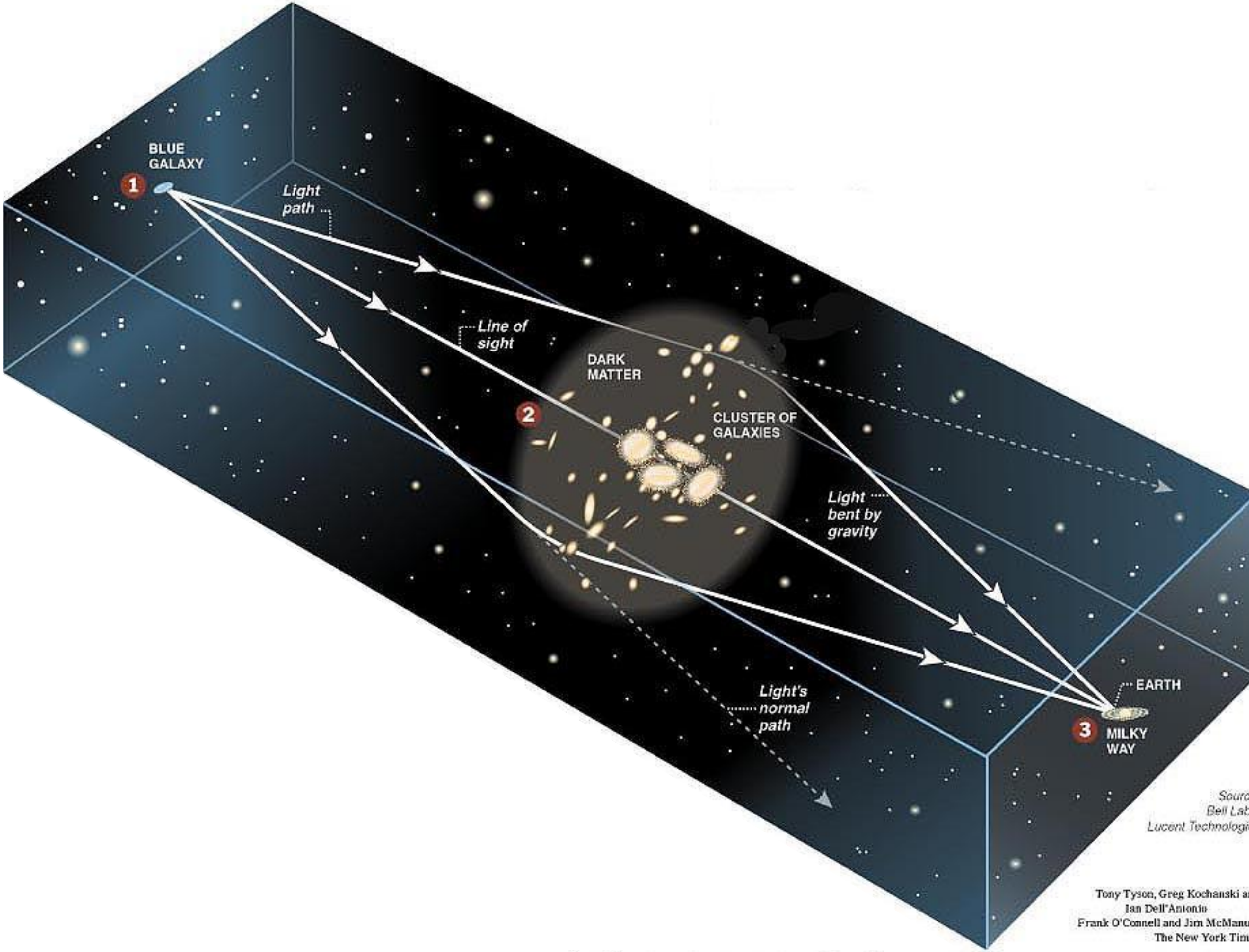




Gravitatielenzen:
Donkere materie in clusters



Abell 2218



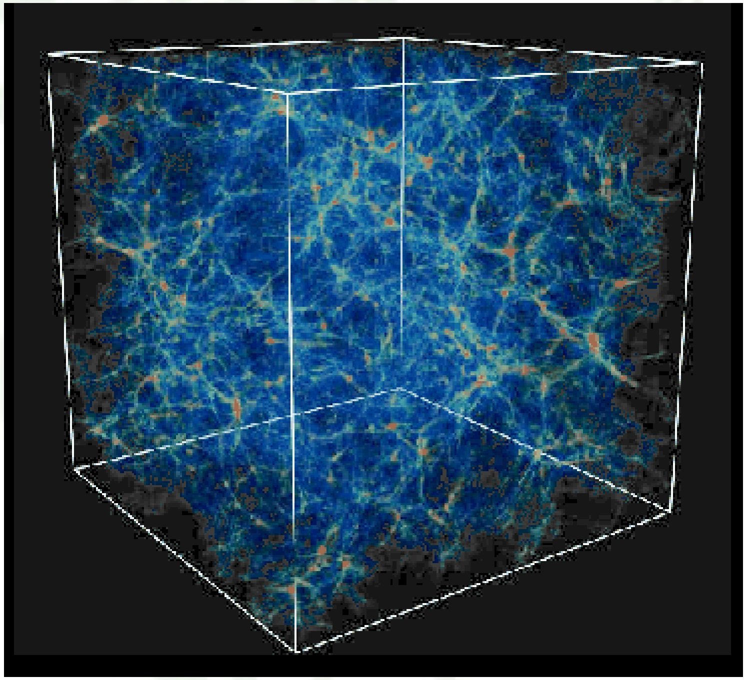
Source: Bell Labs, Lucent Technologies

Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/ The New York Times

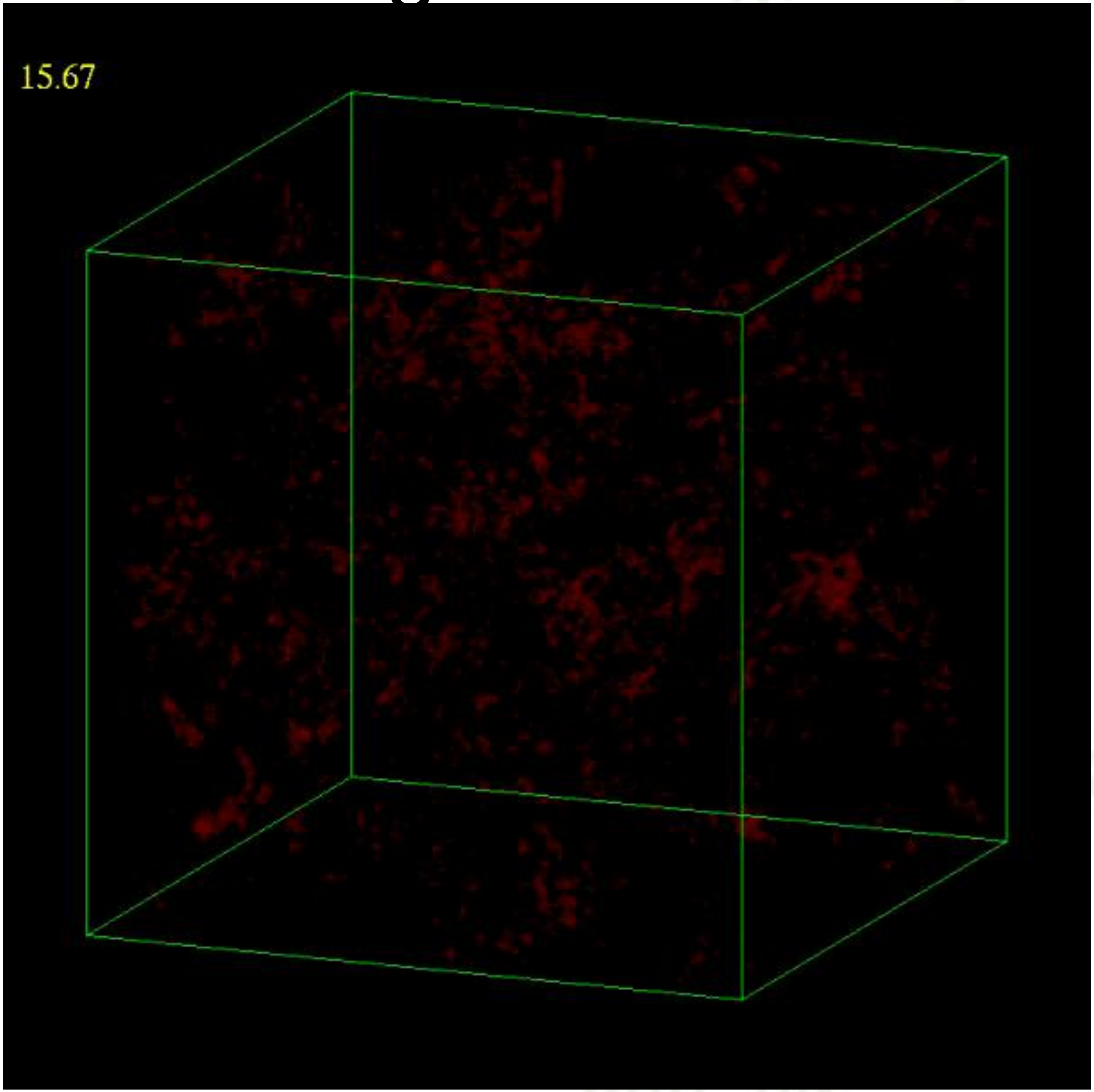

0024+1654

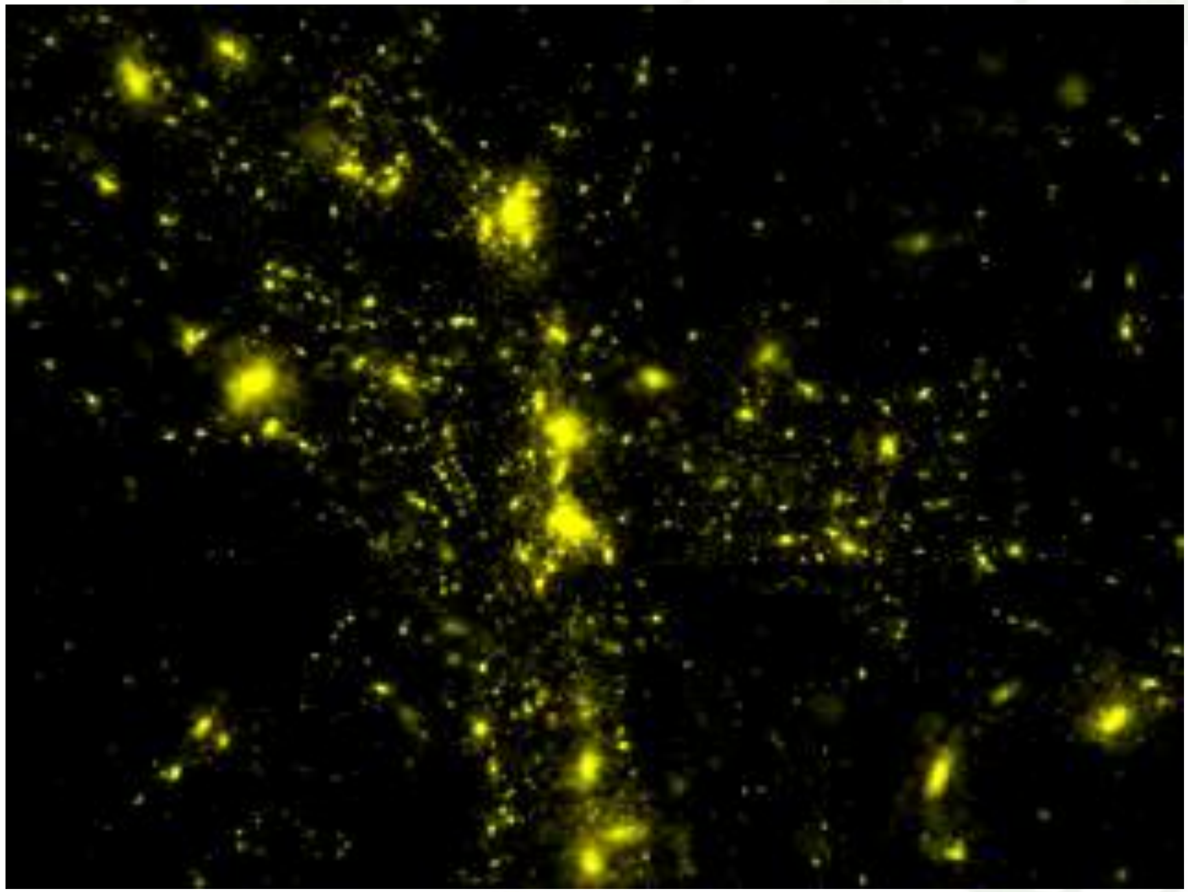
Structuurvorming met donkere materie

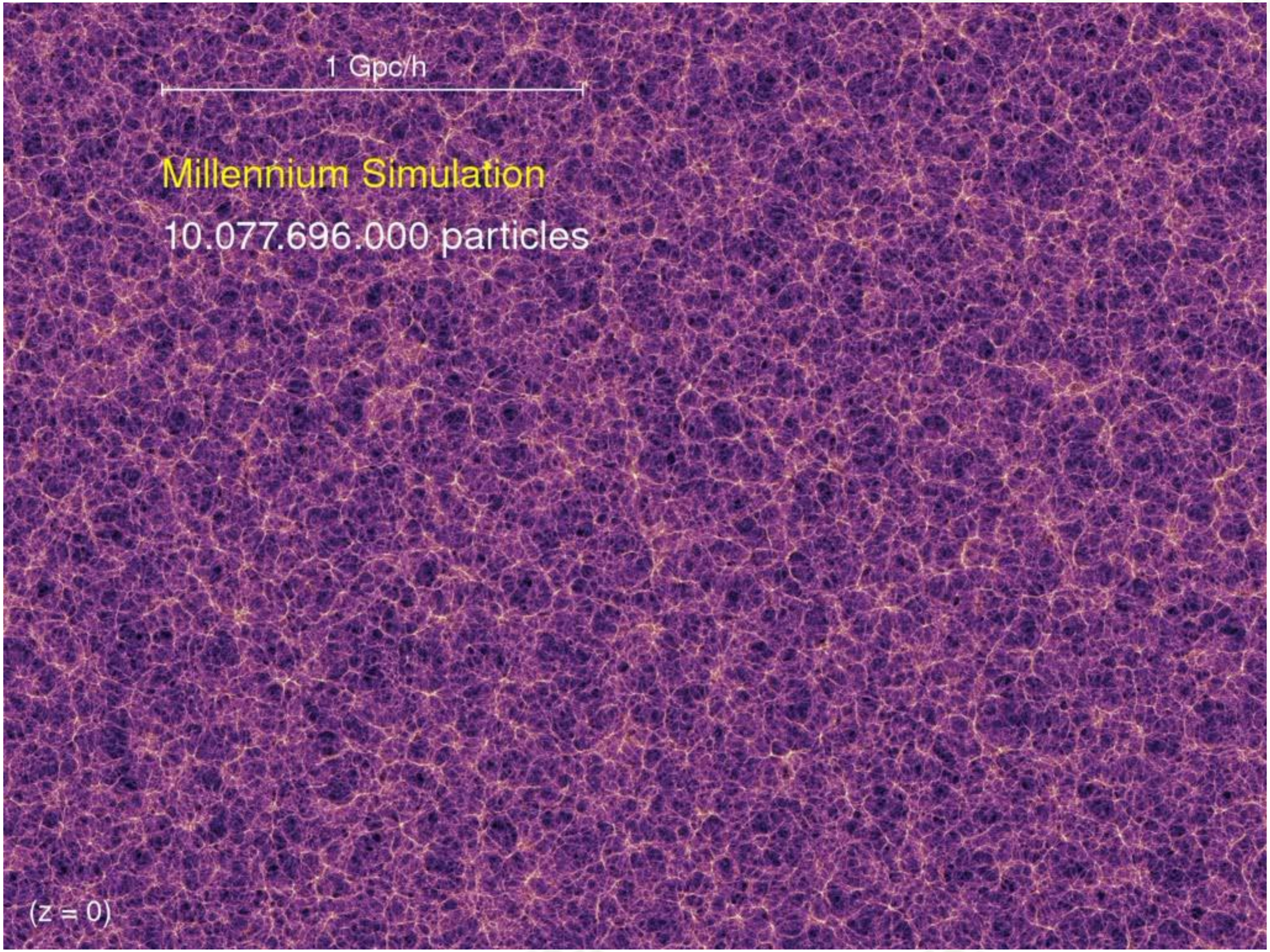
- Donkere materie domineert gravitatie (dus structuurvorming)
- DM ontkoppelt eerder van "straling" in het vroege heelal
- DM kan dus op moment CMB al meer structuur hebben!
- Probleem snelle structuurvorming opgelost



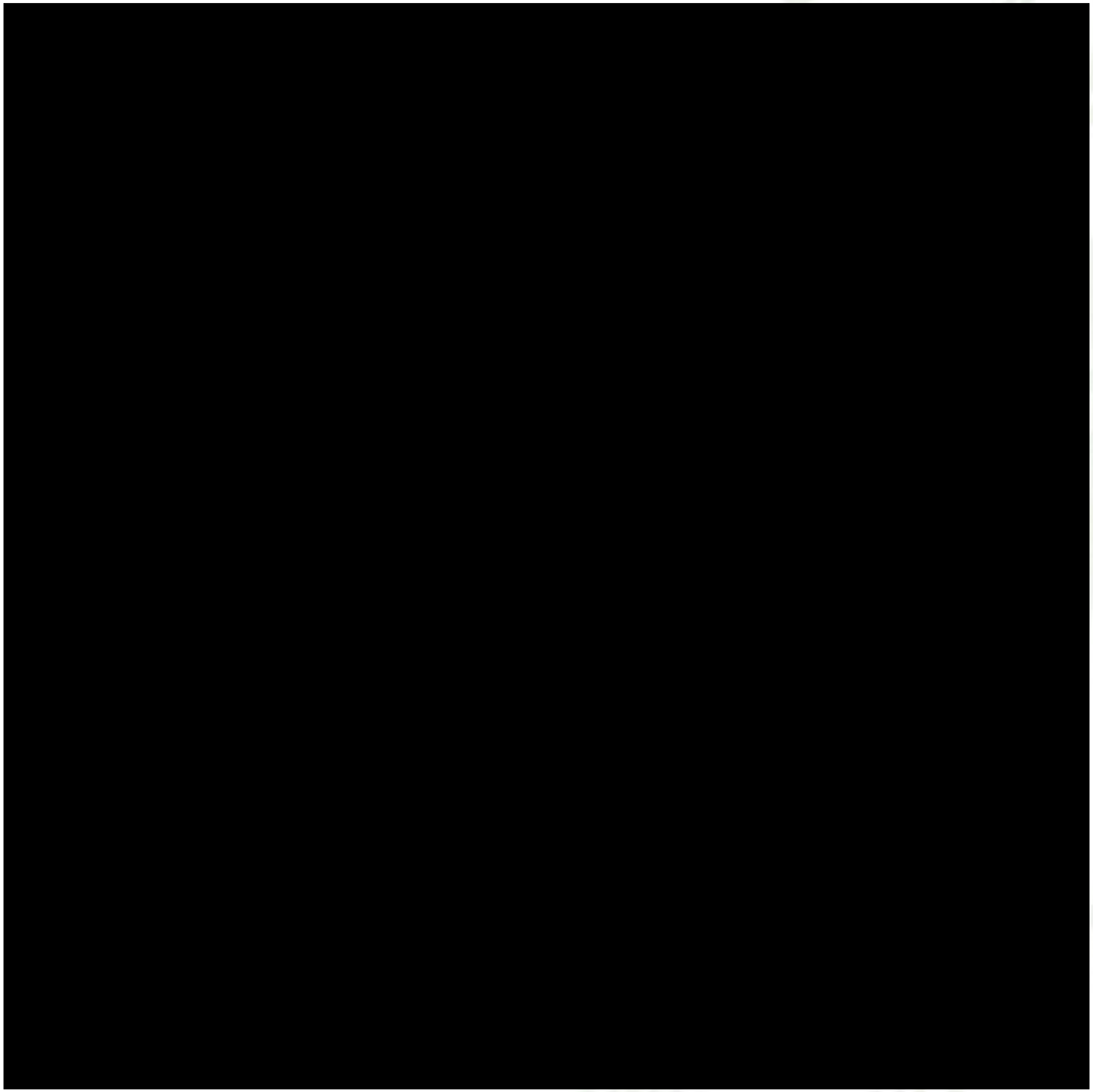
Het begin van structuur



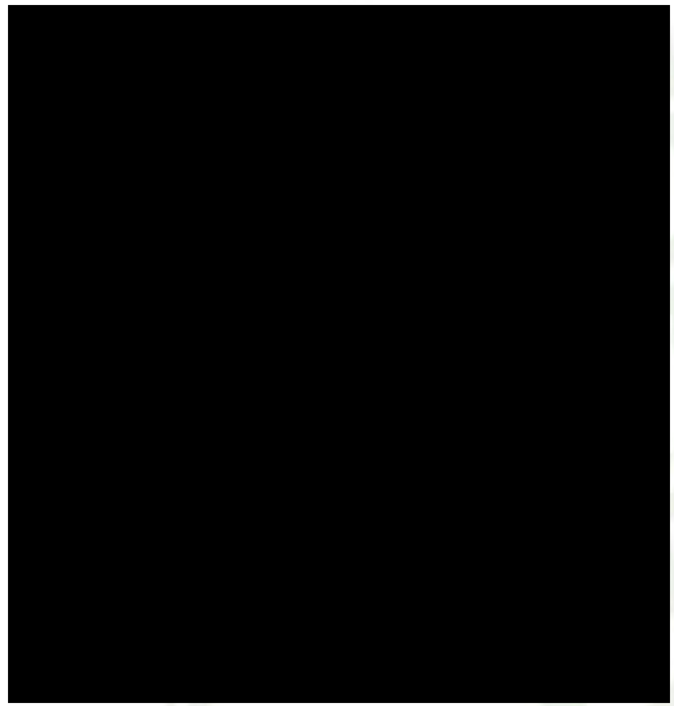



1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

De vorming van melkwegstelsels

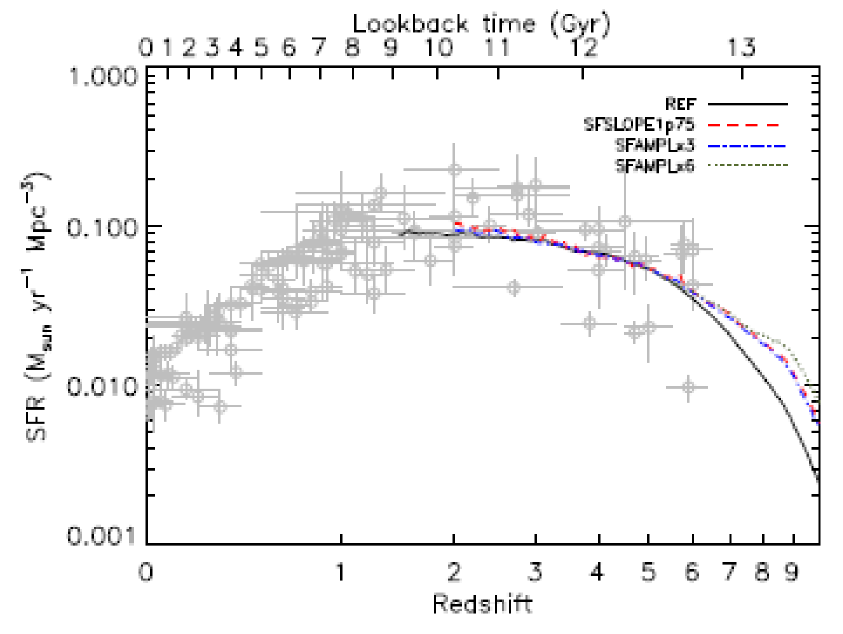


De eerste sterren

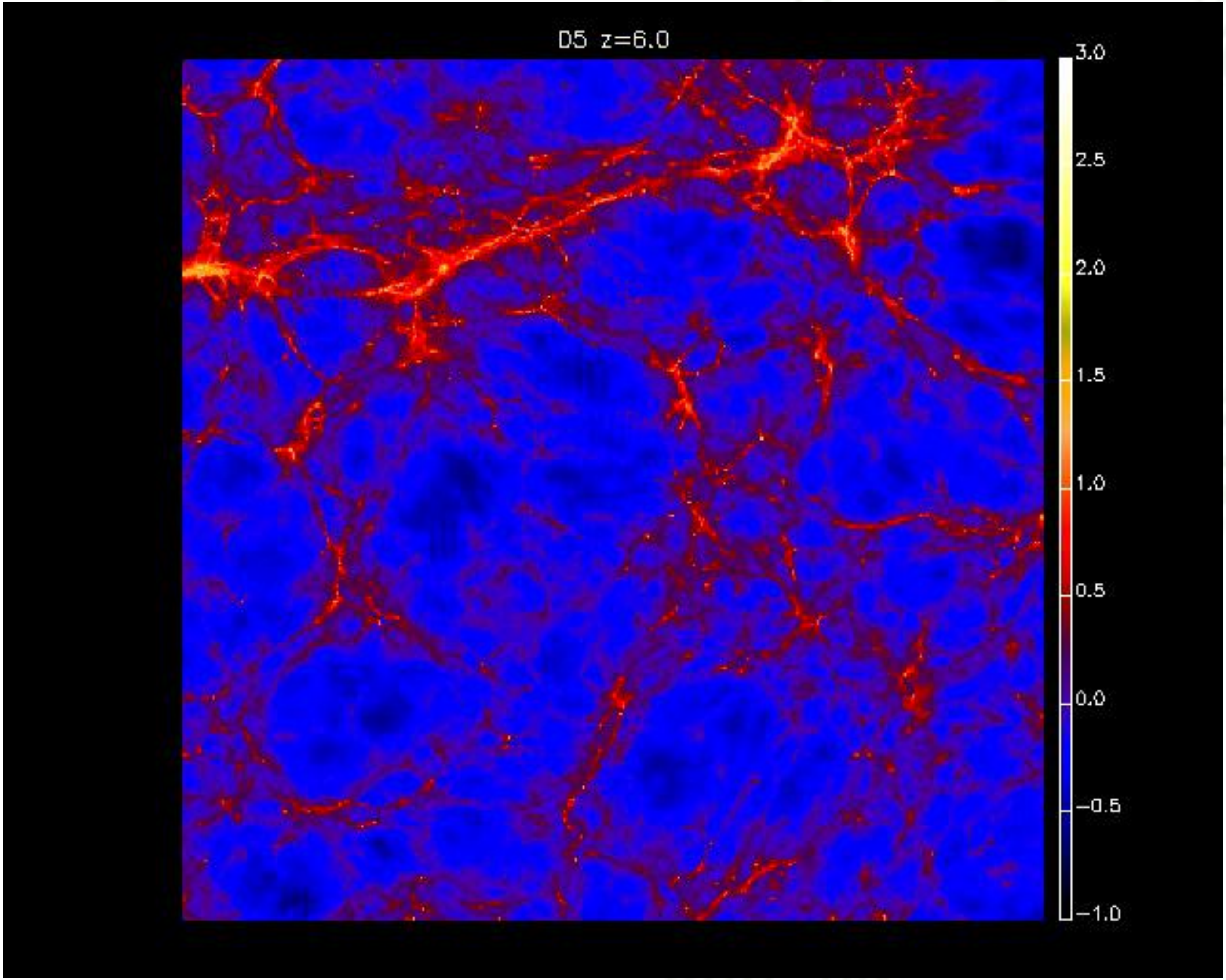


Feedback

- (Eerste) sterren geven feedback op hoe gas de DM volgt
- Nodig om simulaties met waarnemingen te vegelijken
- Ingewikkeld (supernova, sterrenwind, soorten sterren etc.)



Joop Schaye (Leiden)


D5 z=6.0
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0