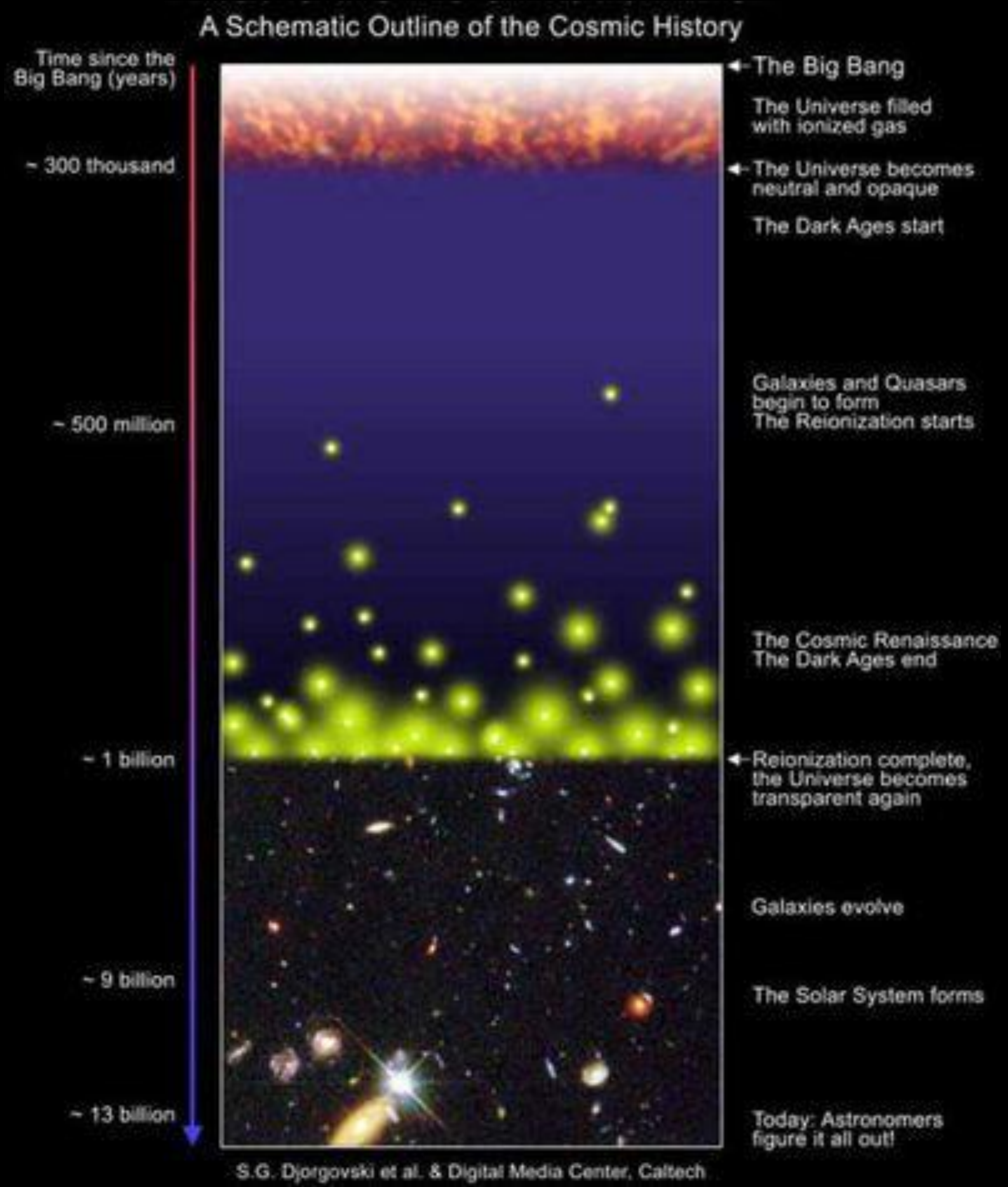
Formazione delle galassie

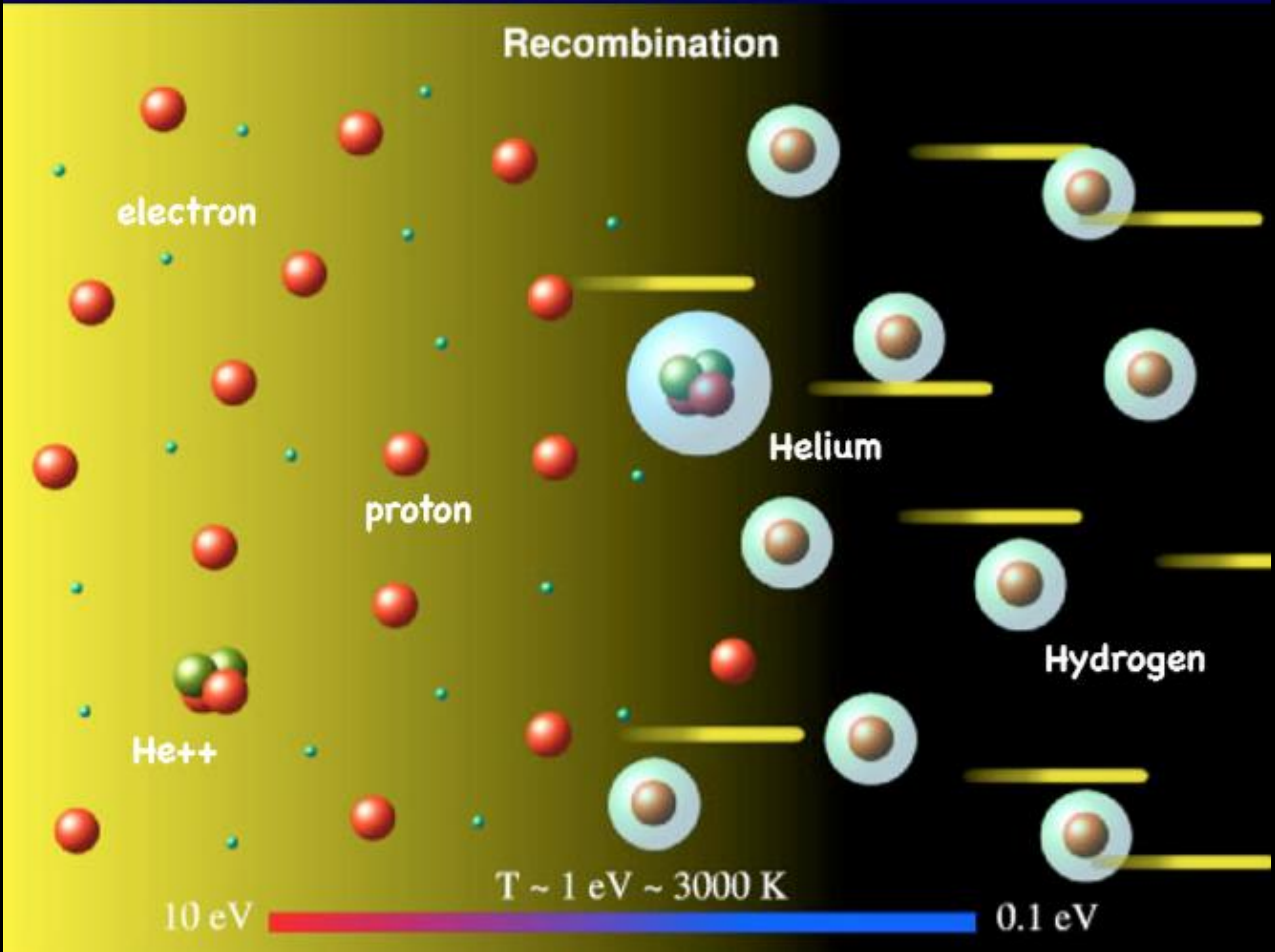
Dagli aloni di Materia Oscura ad oggi

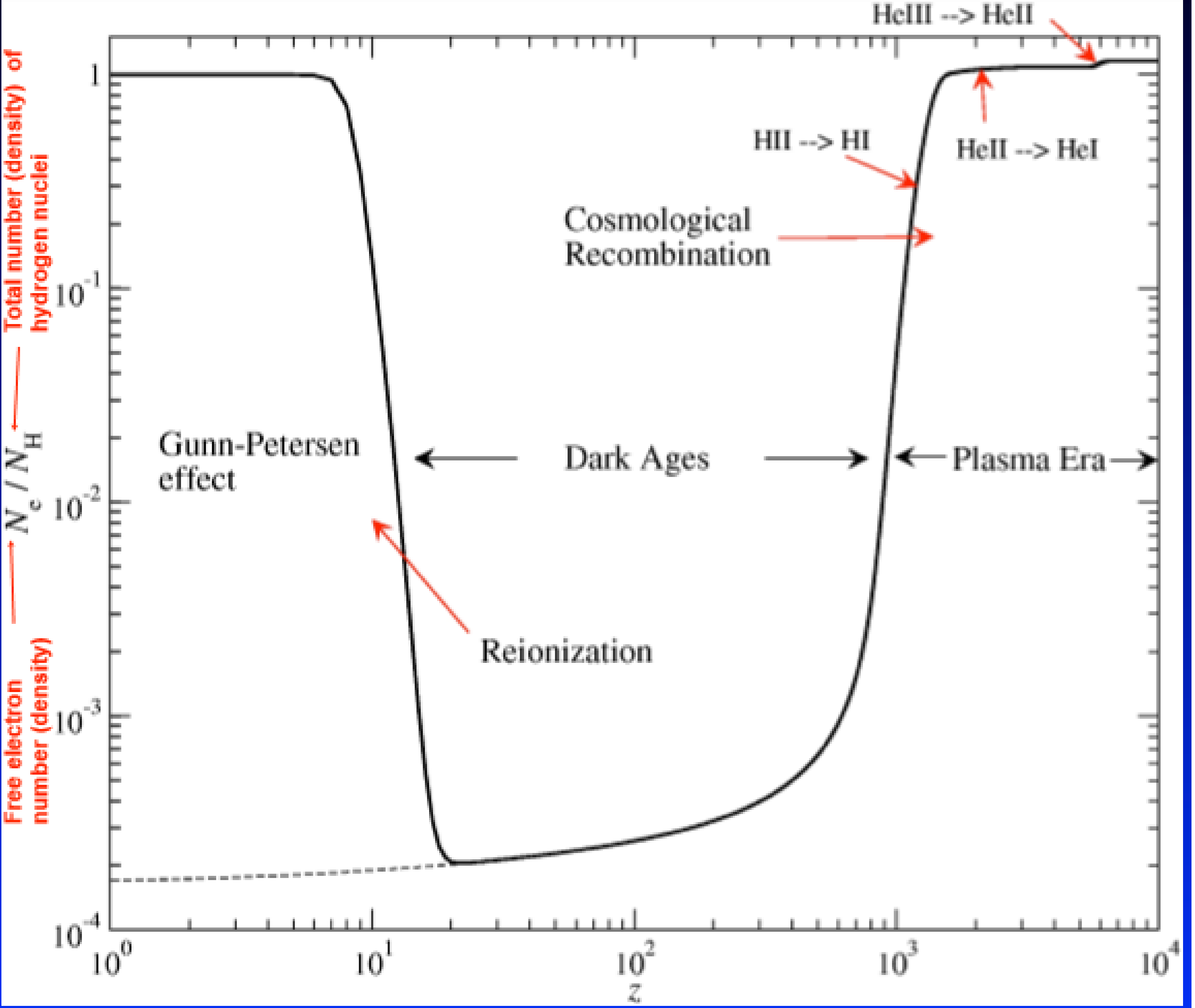
Massimiliano Matteuzzi

21/02/2020

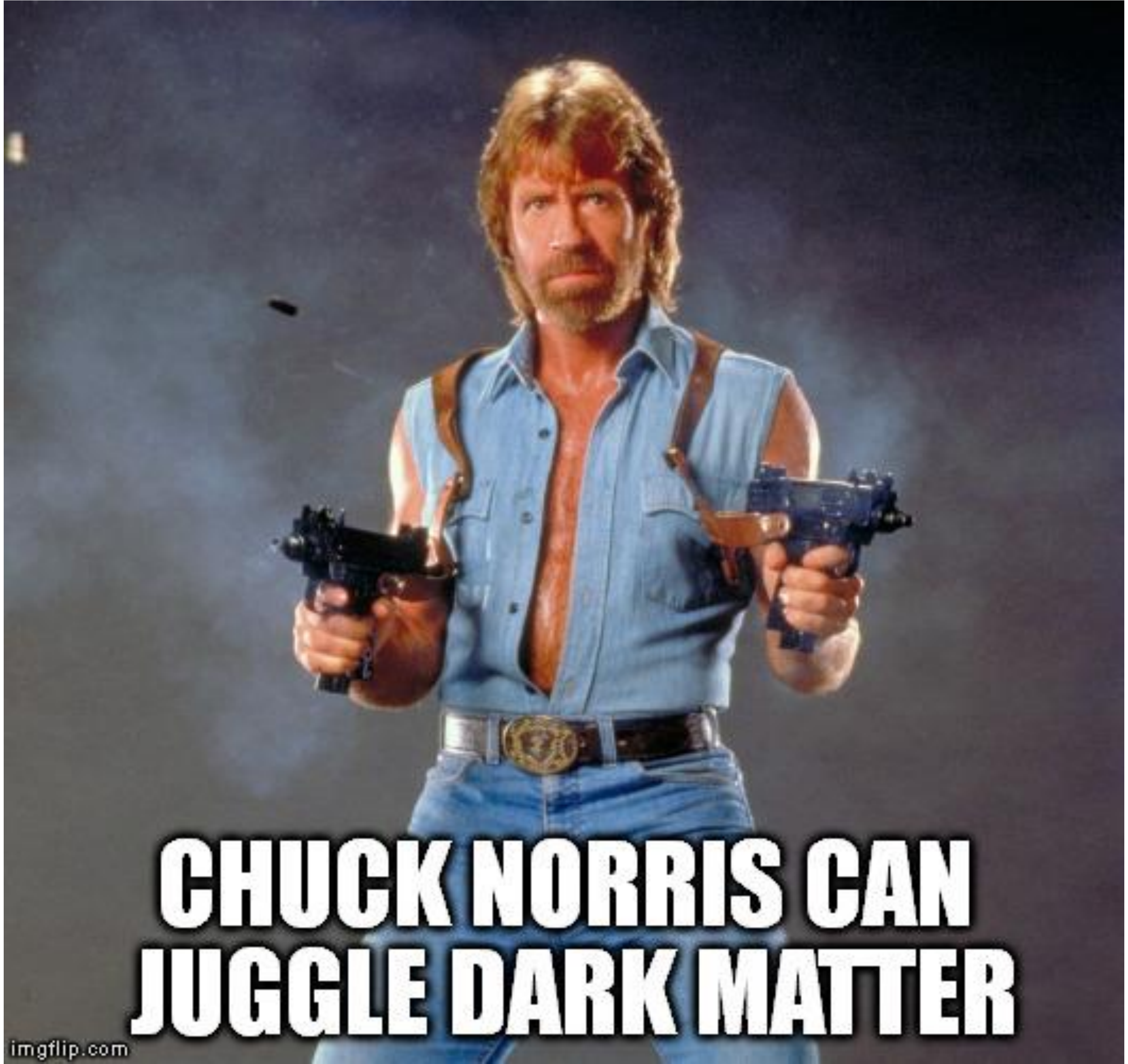

FORMAZIONE GALASSIE
imgflip.com

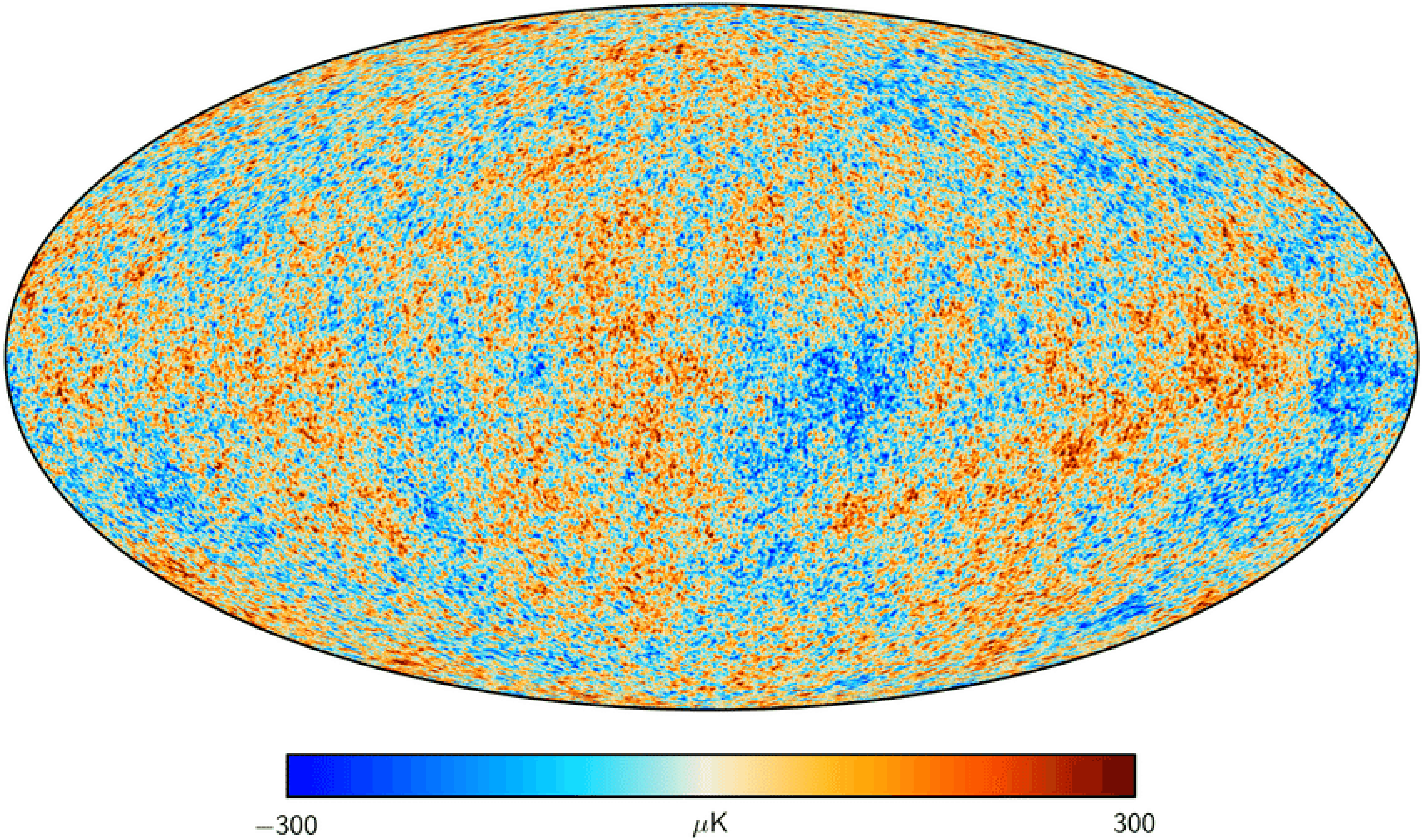

A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech

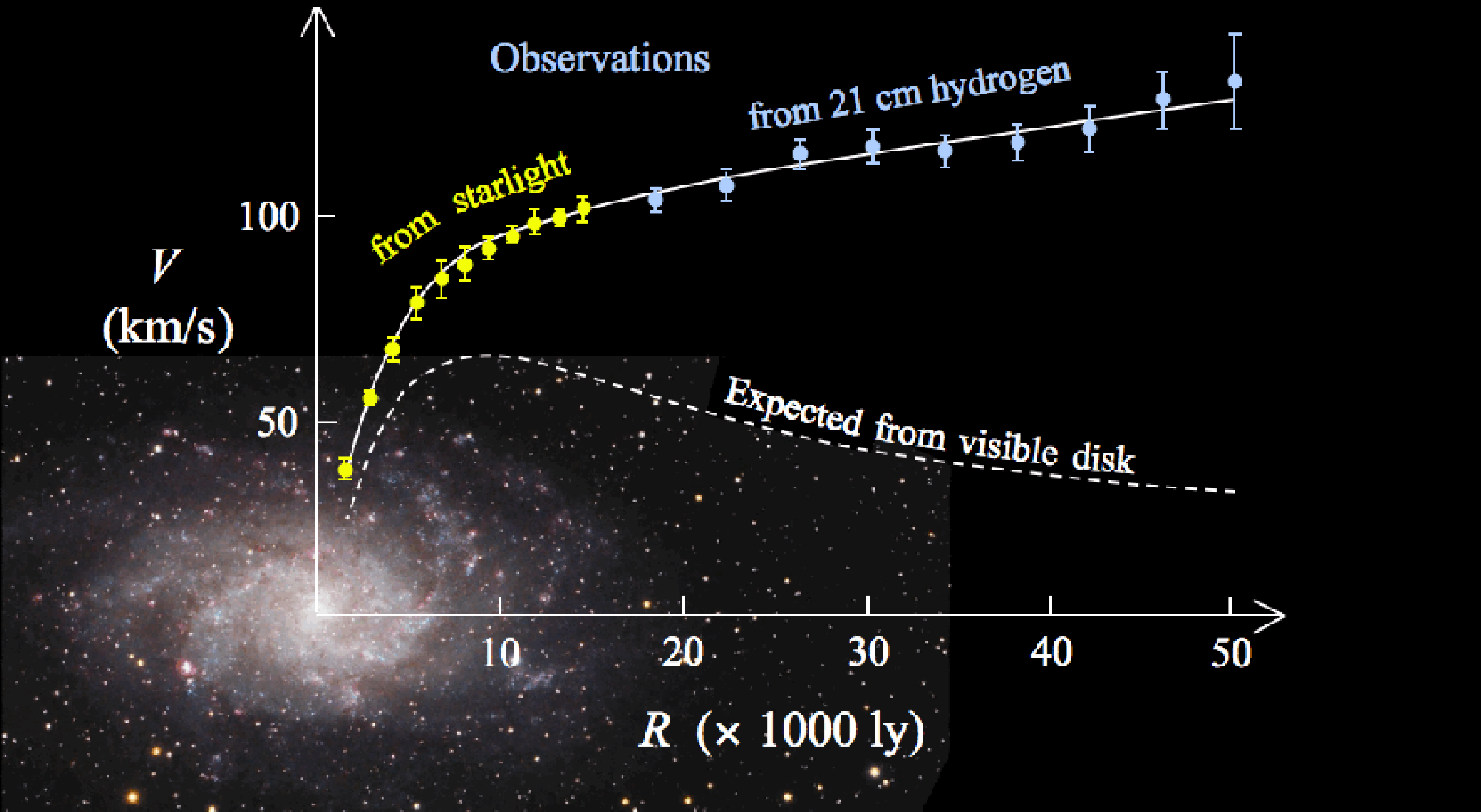

Recombination
electron
proton
He++
Helium
Hydrogen
T ~ 1 eV ~ 3000 K
10 eV
0.1 eV

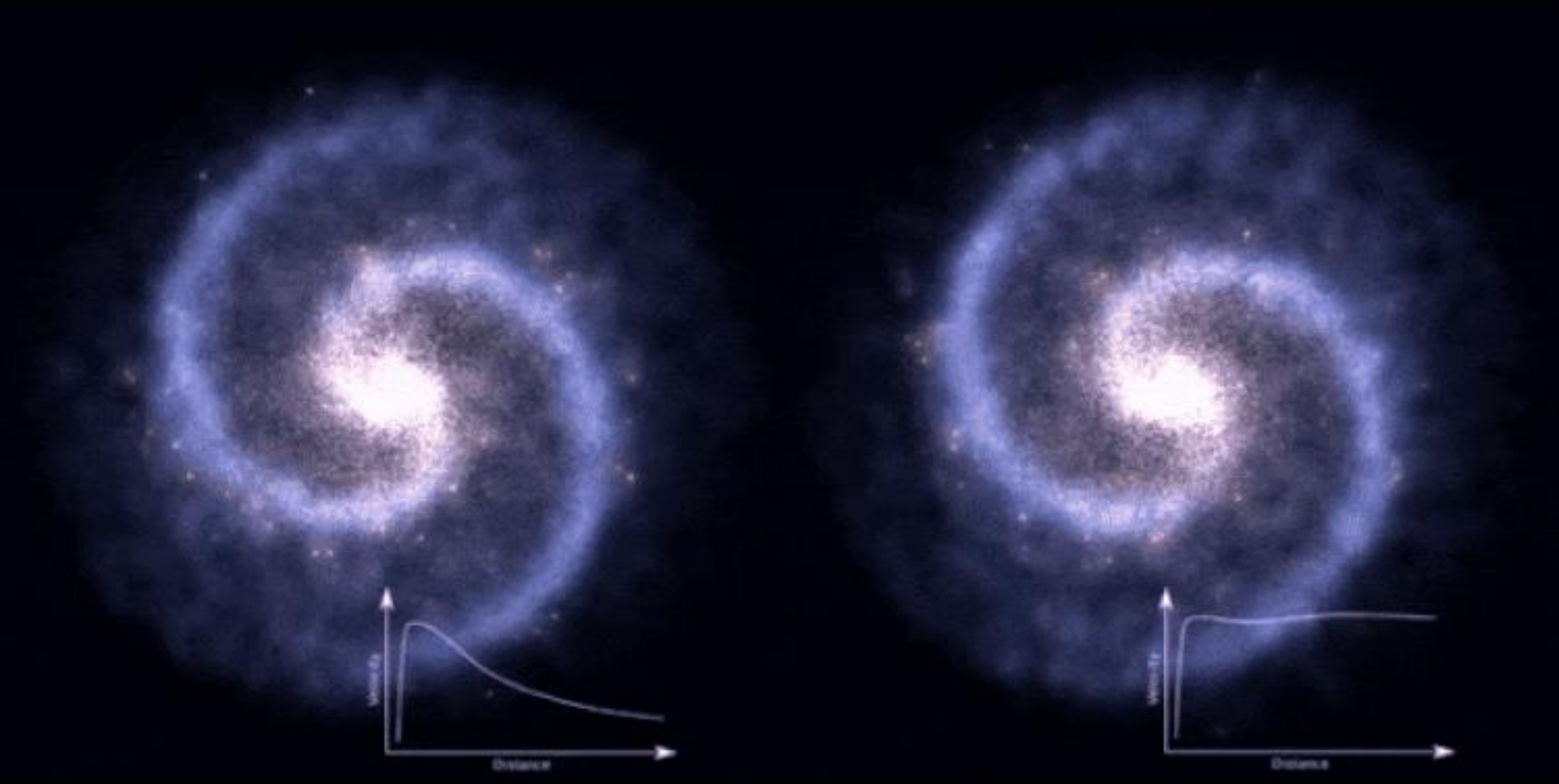


HeIII --> HeII
HII --> HI
HeII --> HeI
Cosmological Recombination
Gunn-Petersen effect
Dark Ages
Plasma Era
Reionization
Total number (density) of hydrogen nuclei
Free electron number (density)
N_e / N_H
z
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^0
10^1
10^2
10^3
10^4

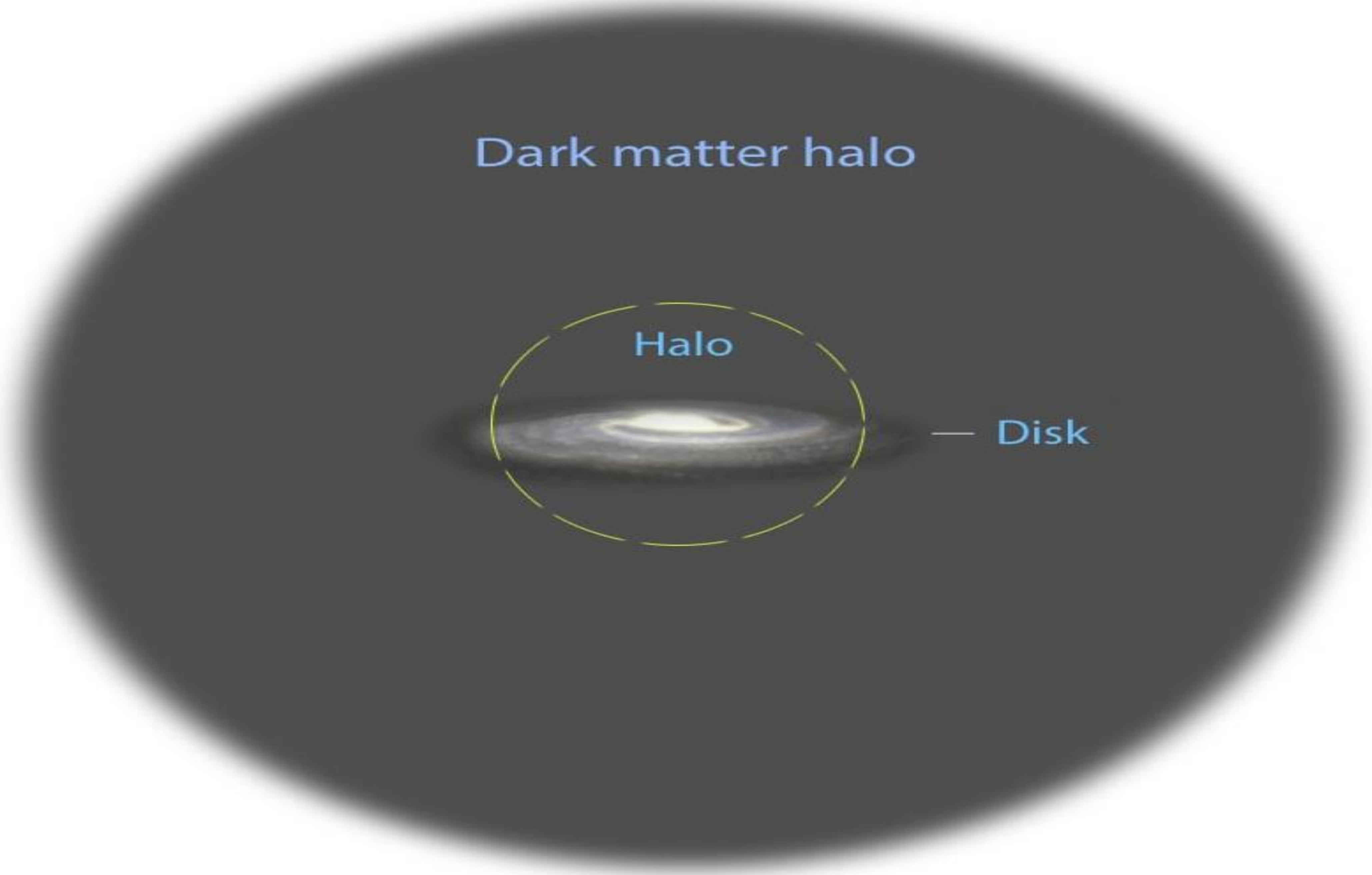

CHUCK NORRIS CAN
JUGGLE DARK MATTER
imgflip.com


−300
μK
300


Observations
from 21 cm hydrogen
from starlight
100
50
V
(km/s)
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)


Distance
Distance

imgflip.com



Milky Way model

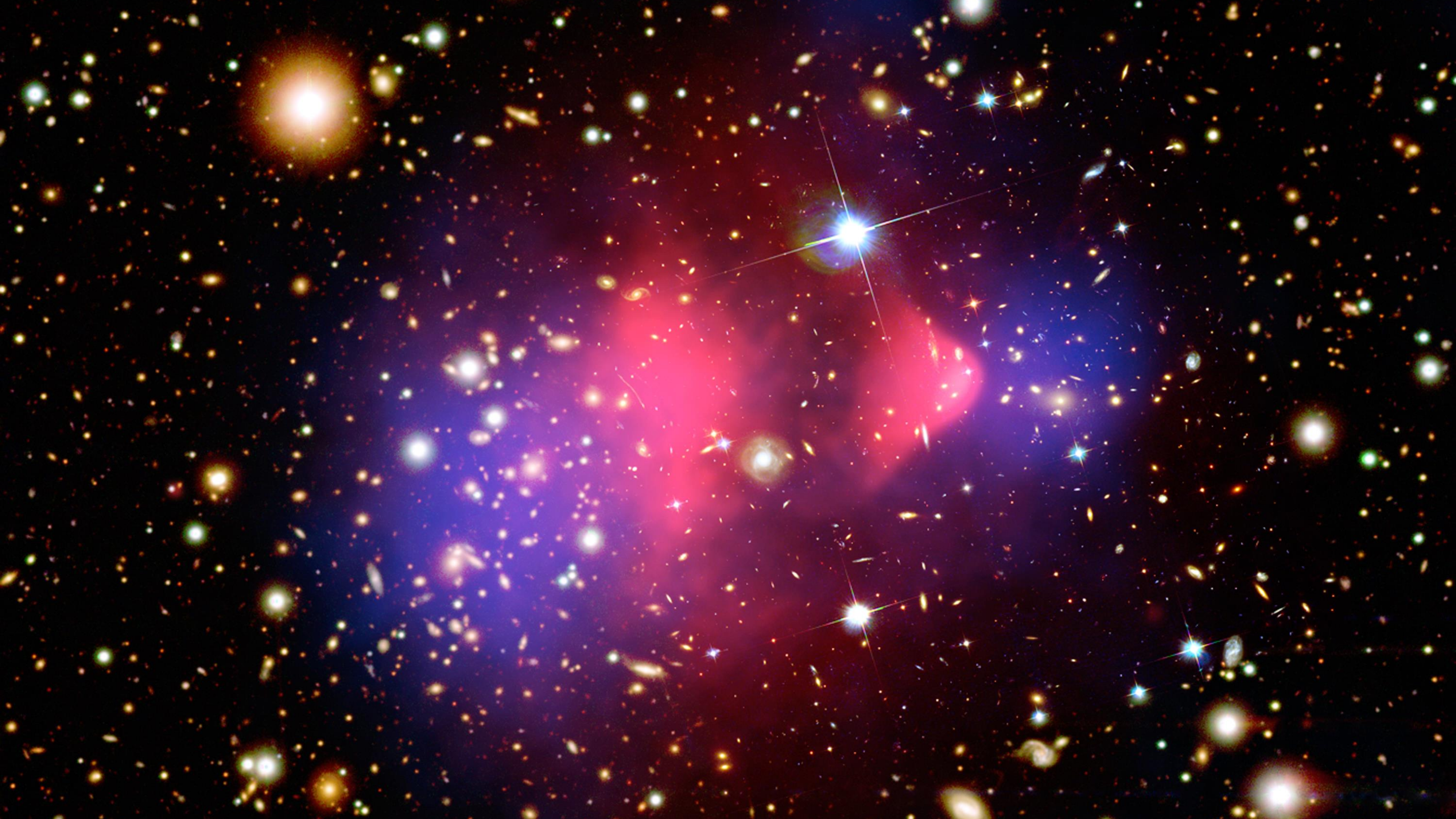
Die Rotverschiebung von extragalaktischen Nebeln

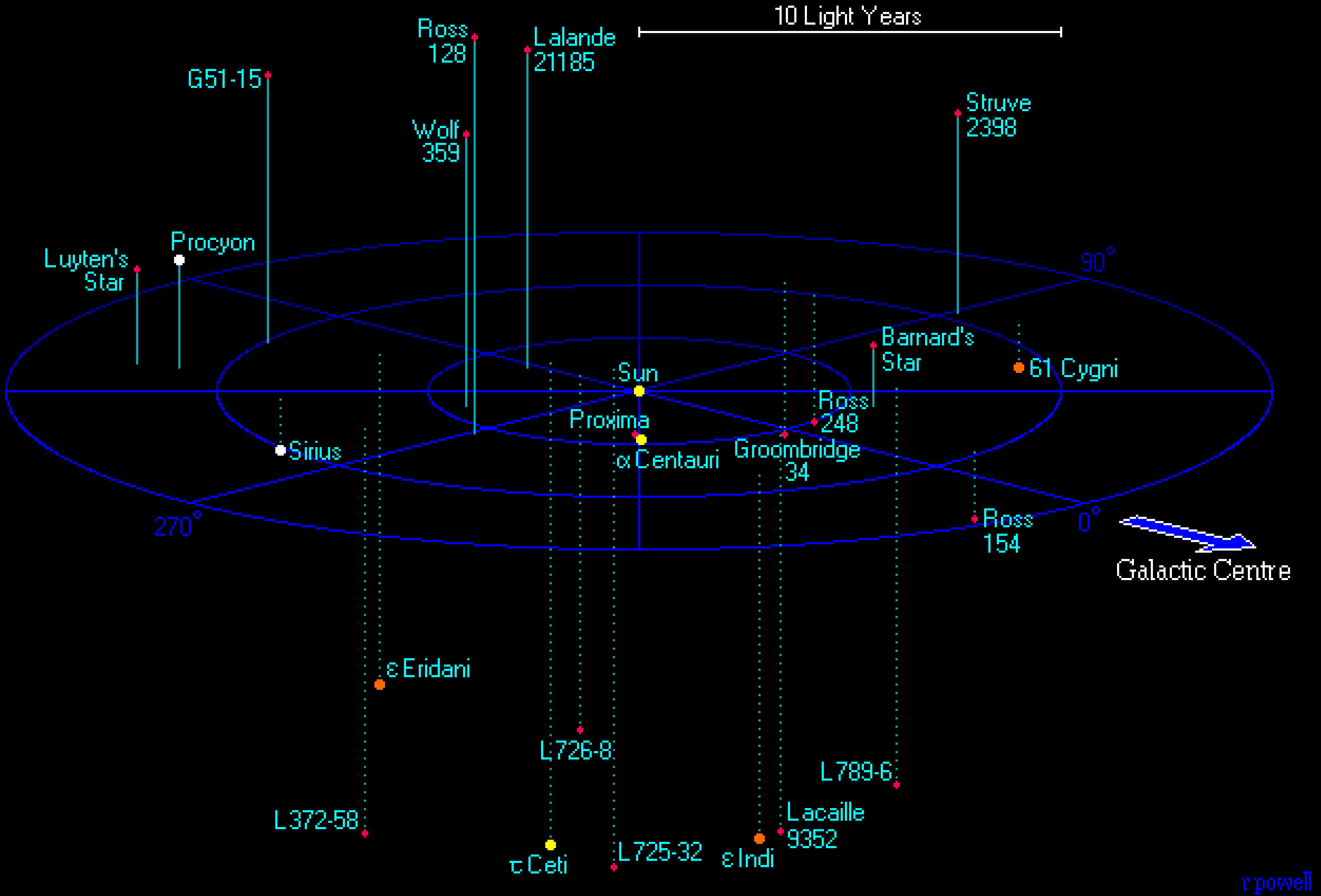
von **F. Zwicky.**

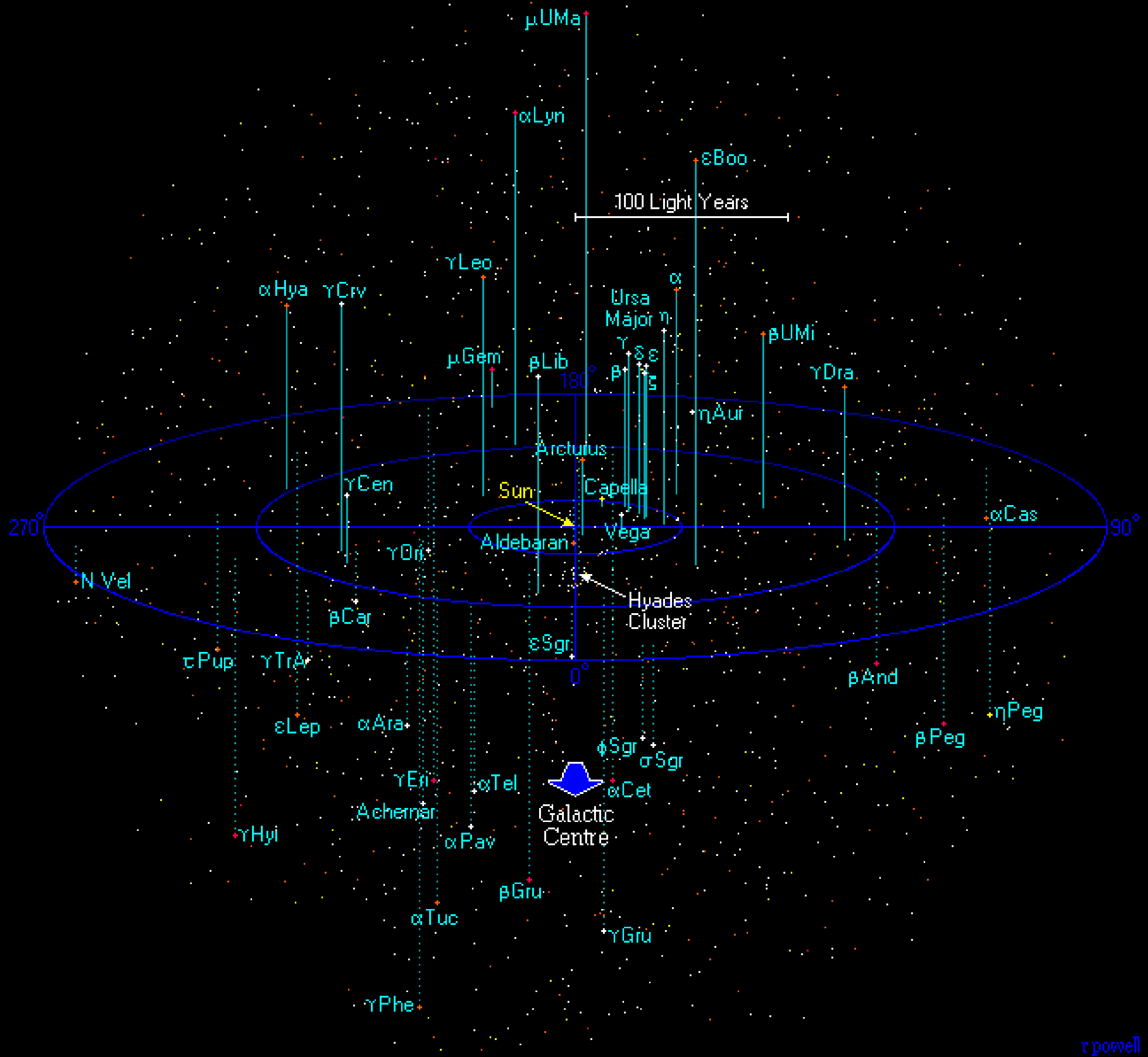
(16. II. 33.)

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.

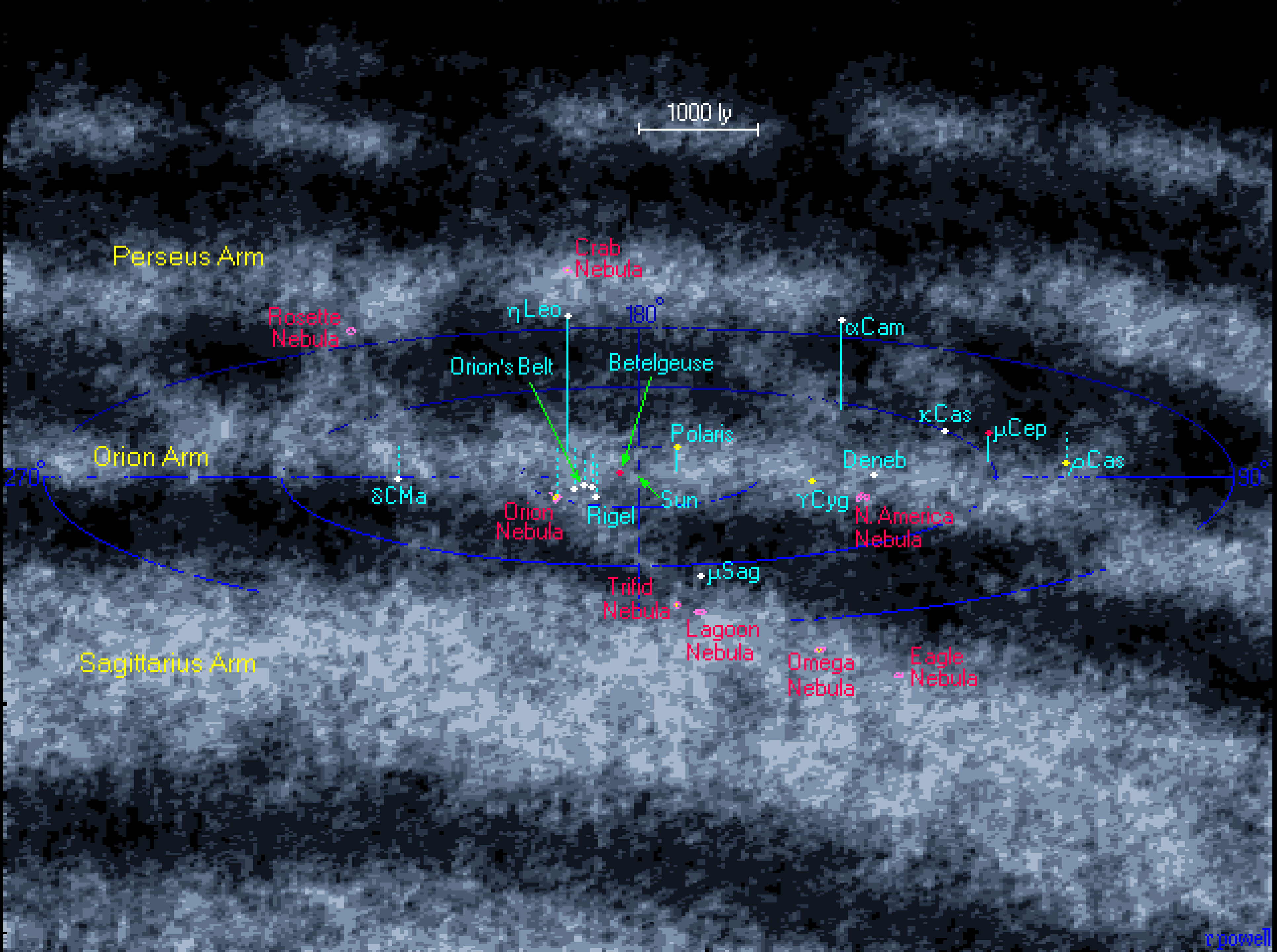
In order to obtain, as observed, a medium-sized Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times greater than that derived on the basis of observations of luminous matter. If this should be verified, it would lead to the surprising result that dark matter exists in much greater density than luminous matter.

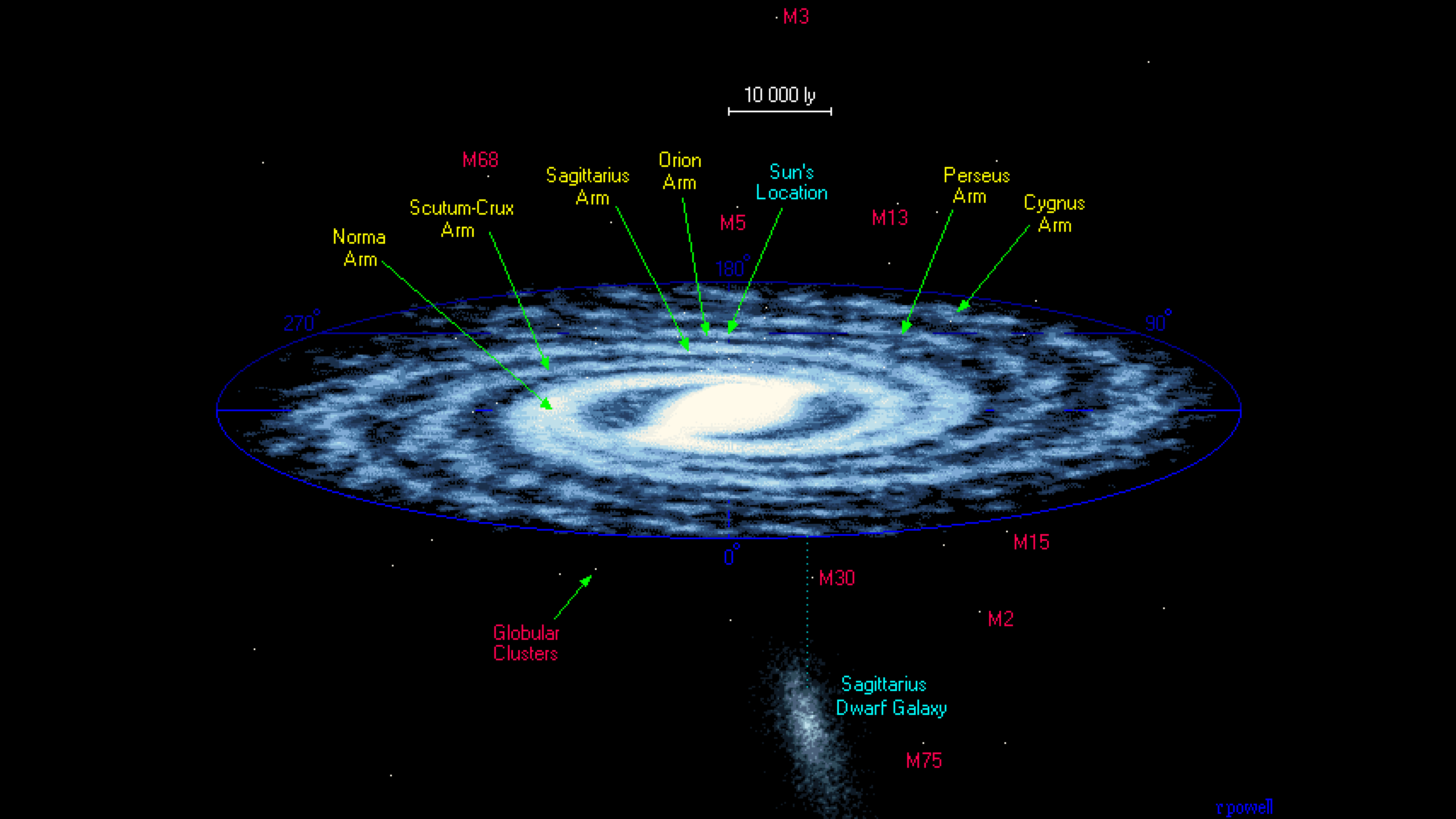


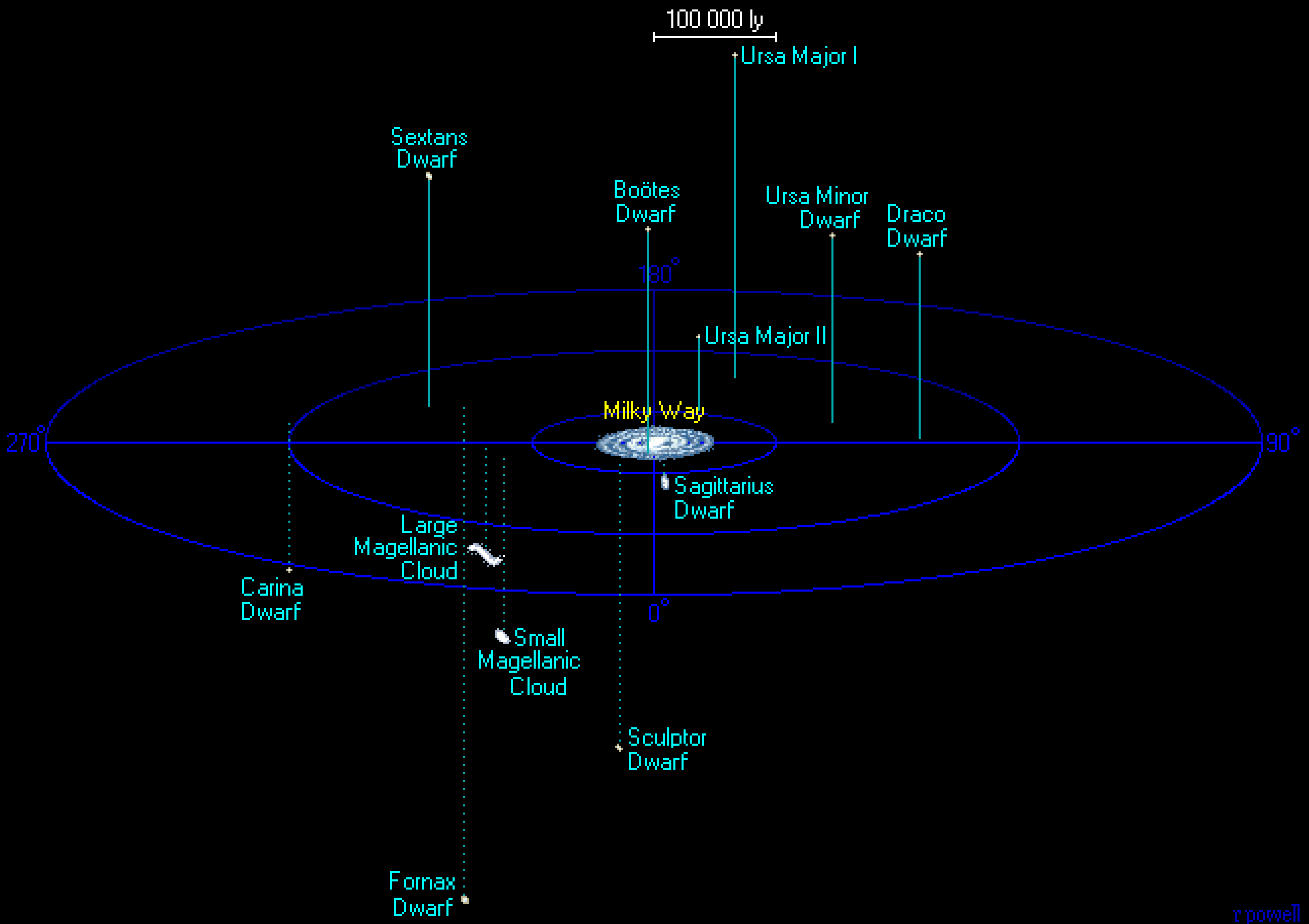

10 Light Years
Ross 128
Lalande 21185
G51-15
Wolf 359
Struve 2398
Luyten's Star
Procyon
90°
Barnard's Star
61 Cygni
Sun
Ross 248
Proxima
Sirius
α Centauri
Groombridge 34
270°
Ross 154
0°
Galactic Centre
ε Eridani
L726-8
L789-6
L372-58
Lacaille 9352
τ Ceti
L725-32
ε Indi
r powell

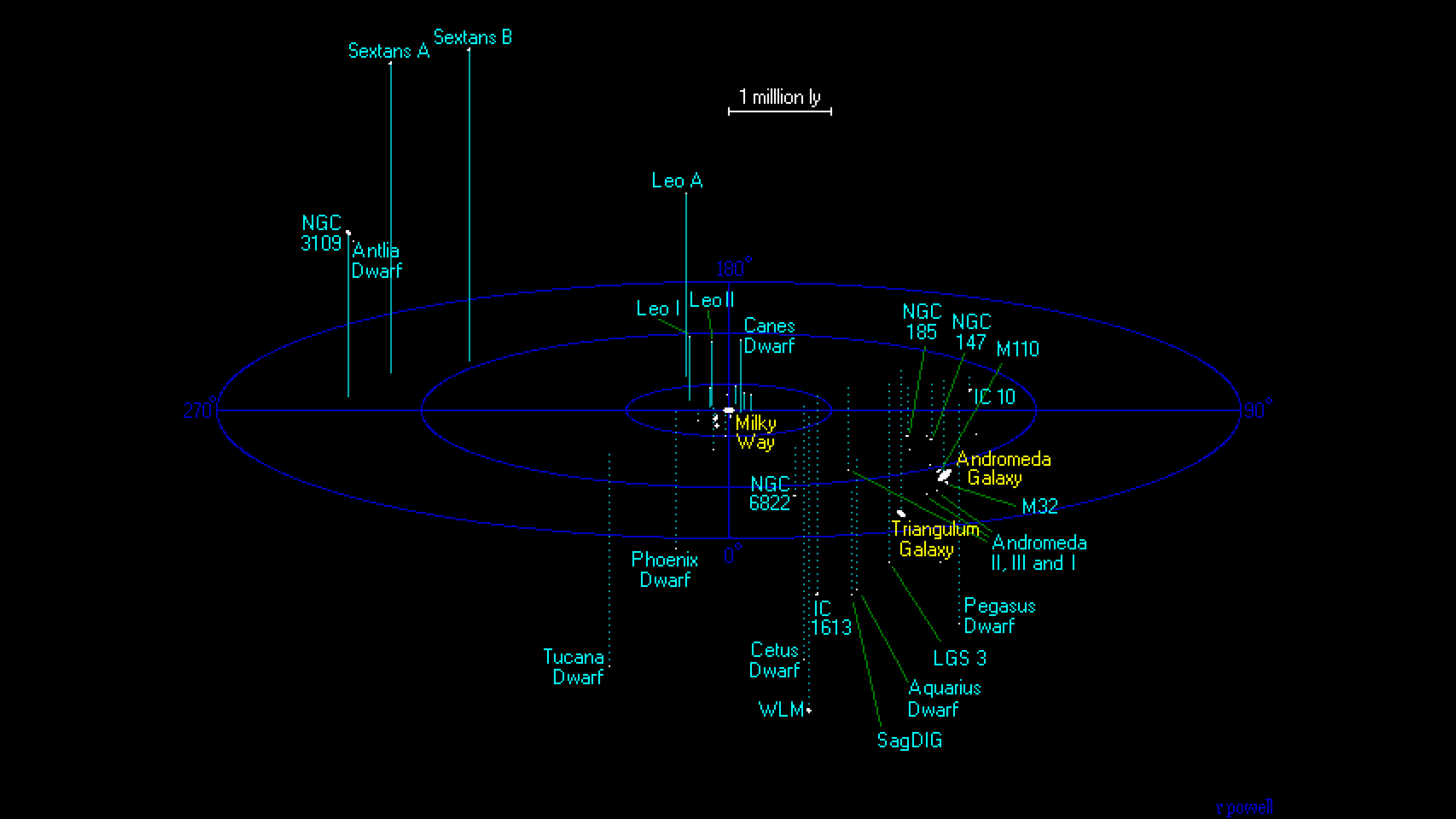


μUMa
αLyn
εBoo
100 Light Years
γLeo
αHya
γCrv
α
Ursa
Major
η
βUMi
γ
δ ε
μGem
βLib
β
ζ
γDra
180°
ηAql
Arcturus
Capella
γCen
Sun
270°
90°
αCas
Vega
Aldebaran
γOri
N Vel
Hyades
Cluster
βCar
εSgr
τPup
γTrA
0°
βAnd
ηPeg
εLep
αAra
φSgr
βPeg
σSgr
γEri
αTel
αCet
Galactic
Centre
Achernar
γHyi
αPav
βGru
αTuc
γGru
γPhe
r powell

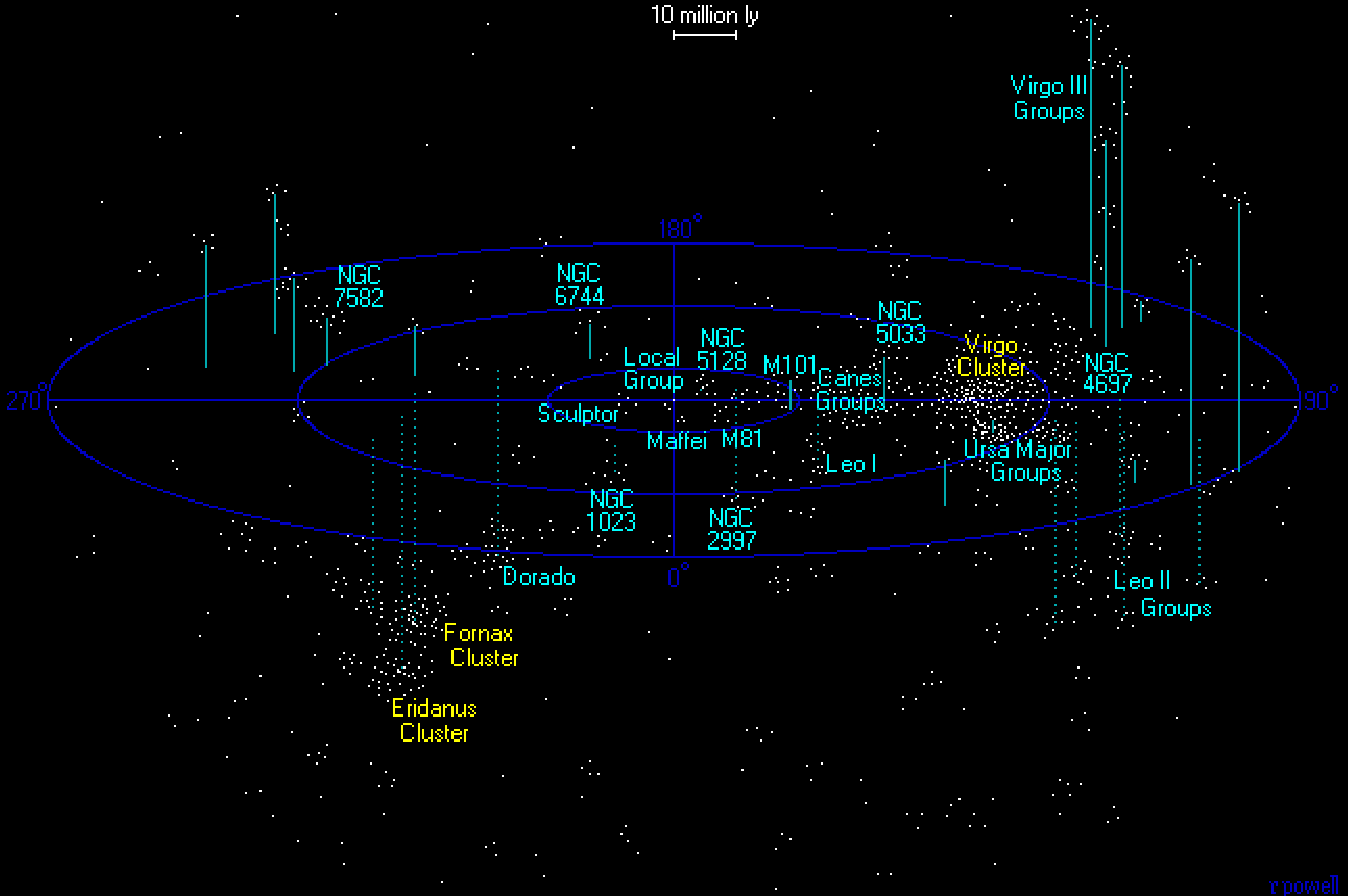

1000 ly
Perseus Arm
Crab Nebula
Rosette Nebula
ηLeo
180°
αCam
Orion's Belt
Betelgeuse
κCas
μCep
Polaris
Orion Arm
270°
Deneb
ρCas
90°
δCMa
Orion Nebula
Rigel
Sun
γCyg
N. America Nebula
μSag
Trifid Nebula
Lagoon Nebula
Omega Nebula
Eagle Nebula
Sagittarius Arm
c.powell


M3
10 000 ly
M68
Sagittarius Arm
Orion Arm
Sun's Location
Perseus Arm
Cygnus Arm
Scutum-Crux Arm
Norma Arm
M5
M13
180°
270°
90°
0°
M15
M30
M2
Globular Clusters
Sagittarius Dwarf Galaxy
M75
r powell

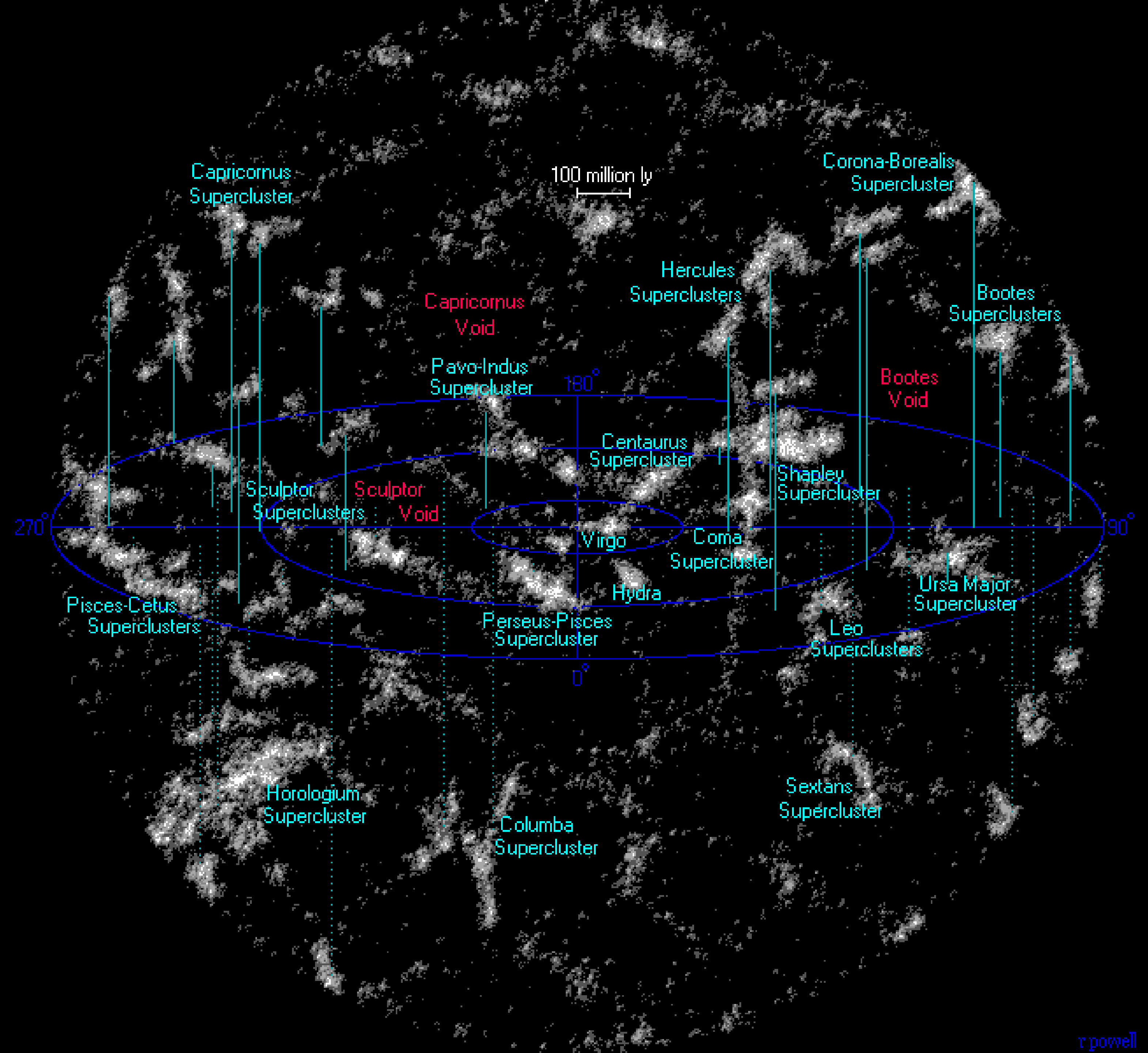

100 000 ly
Ursa Major I
Sextans Dwarf
Boötes Dwarf
Ursa Minor Dwarf
Draco Dwarf
180°
Ursa Major II
Milky Way
270°
90°
Sagittarius Dwarf
Large Magellanic Cloud
Carina Dwarf
0°
Small Magellanic Cloud
Sculptor Dwarf
Fornax Dwarf
r powell

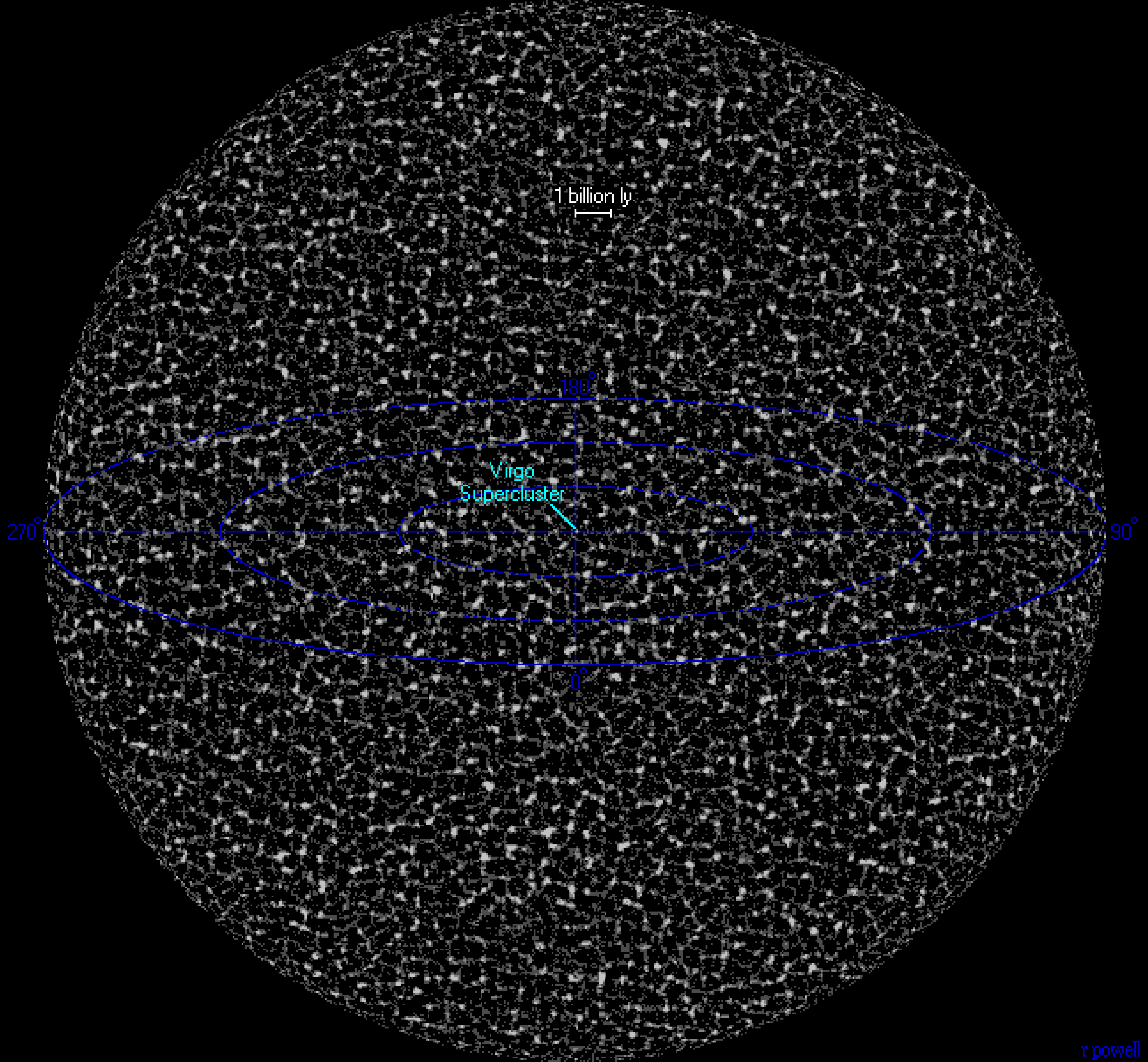


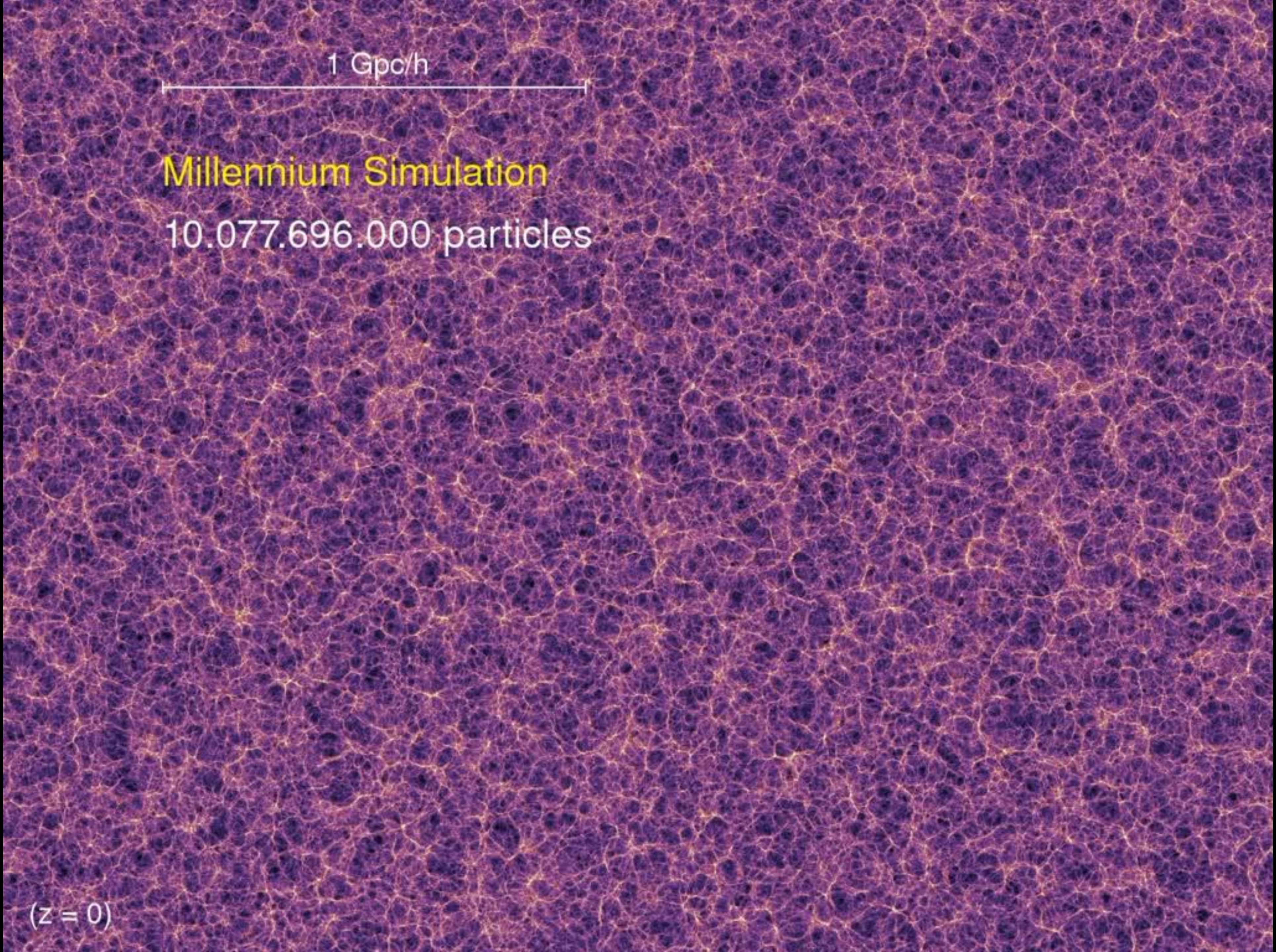
Sextans A
Sextans B
1 million ly
Leo A
NGC 3109
Antlia Dwarf
180°
Leo I
Leo II
Canes Dwarf
NGC 185
NGC 147
M110
IC 10
270°
90°
Milky Way
Andromeda Galaxy
NGC 6822
M32
Triangulum Galaxy
Andromeda II, III and I
0°
Phoenix Dwarf
IC 1613
Pegasus Dwarf
Tucana Dwarf
Cetus Dwarf
LGS 3
Aquarius Dwarf
WLM
SagDIG
r powell

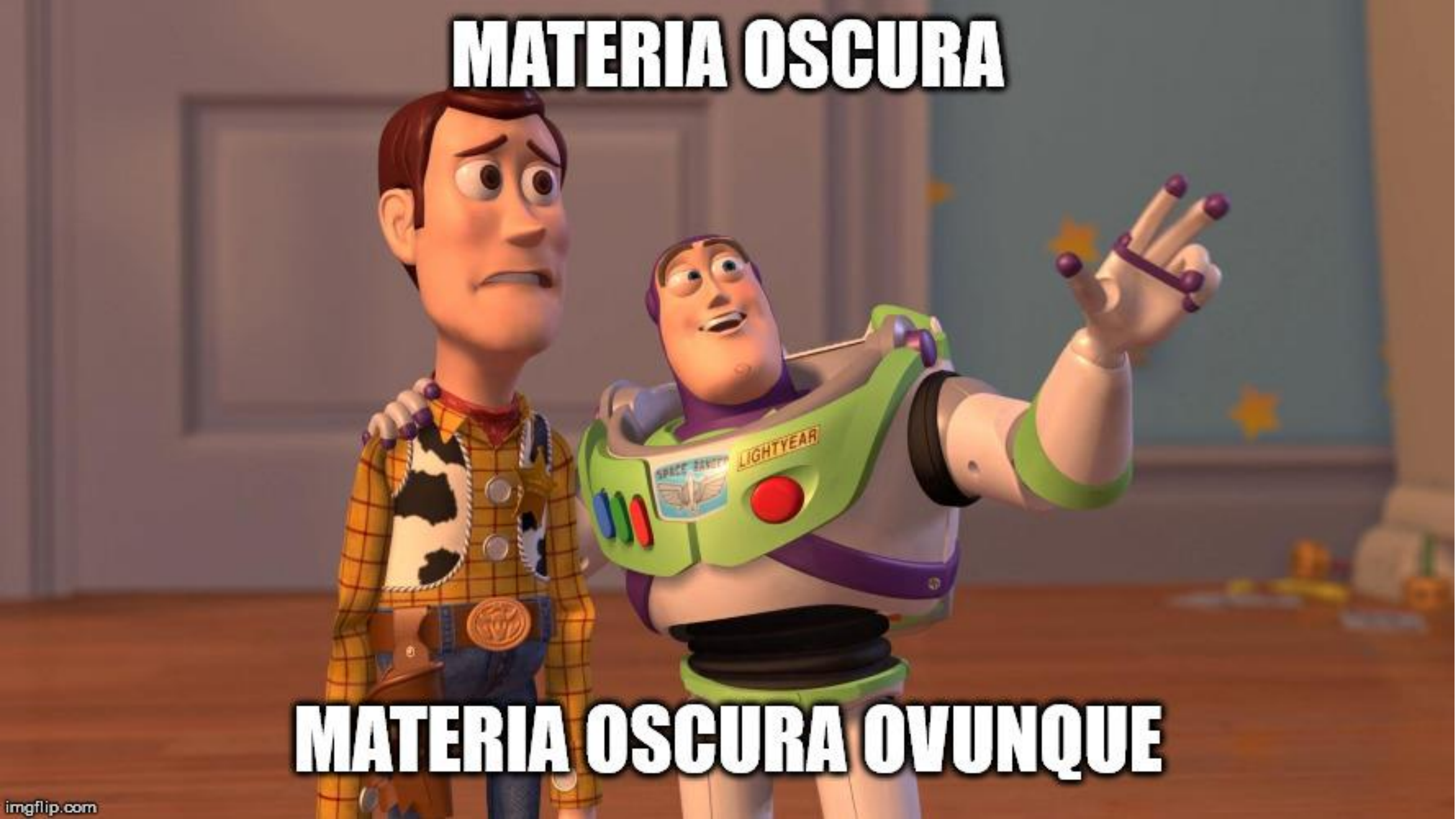


10 million ly
180°
270°
90°
0°
Virgo III
Groups
NGC
7582
NGC
6744
NGC
5033
NGC
5128
Local
Group
M101
Canes
Groups
Virgo
Cluster
NGC
4697
Sculptor
Maffei
M81
Leo I
Ursa Major
Groups
NGC
1023
NGC
2997
Dorado
Leo II
Groups
Fornax
Cluster
Eridanus
Cluster
r powell

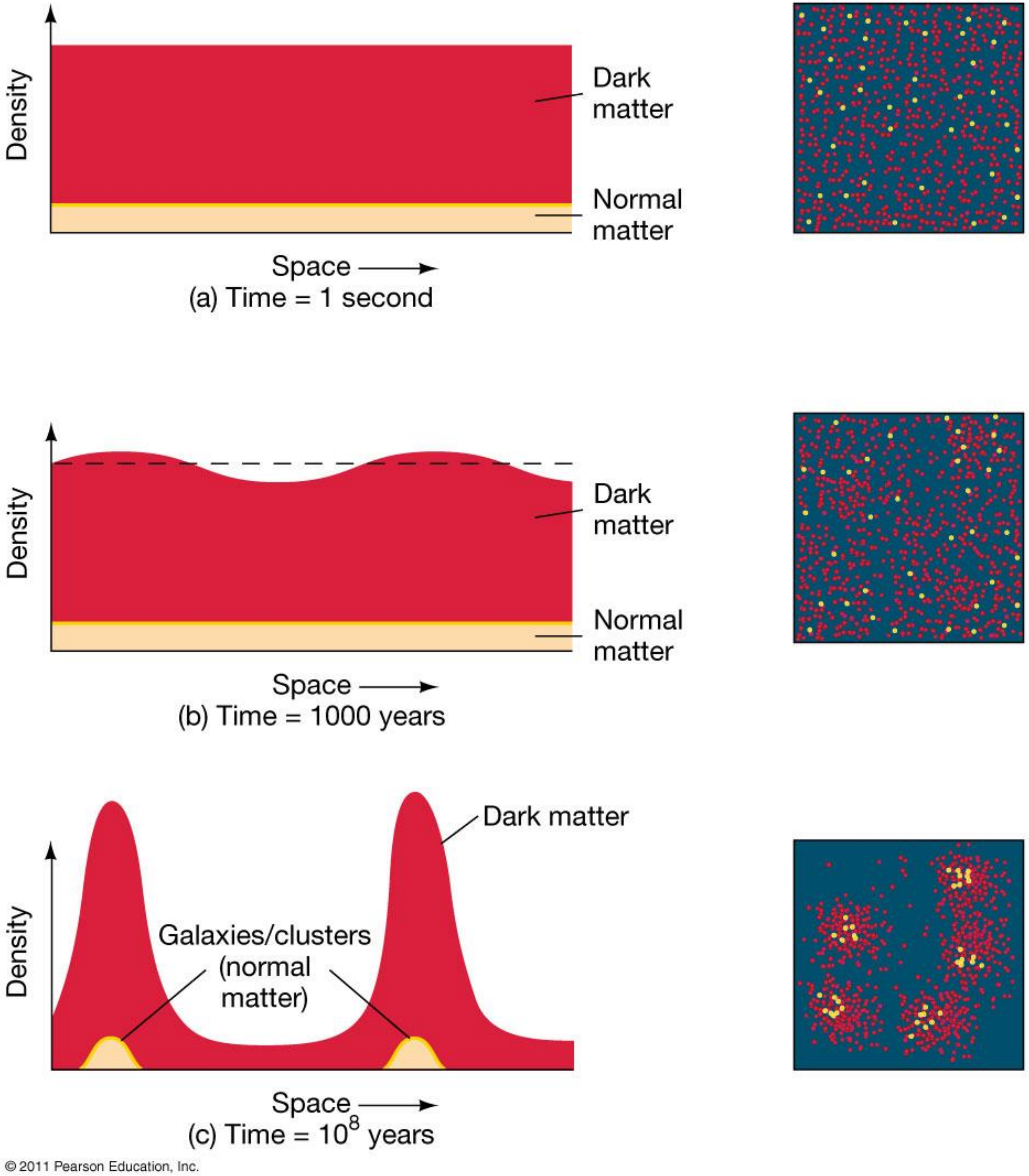

100 million ly
Capricornus Supercluster
Capricornus Void
Pavo-Indus Supercluster
Hercules Superclusters
Corona-Borealis Supercluster
Bootes Superclusters
Bootes Void
180°
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
270°
90°
Virgo
Coma Supercluster
Hydra
Ursa Major Supercluster
Pisces-Cetus Superclusters
Perseus-Pisces Supercluster
Leo Superclusters
0°
Horologium Supercluster
Columba Supercluster
Sextans Supercluster
r powell

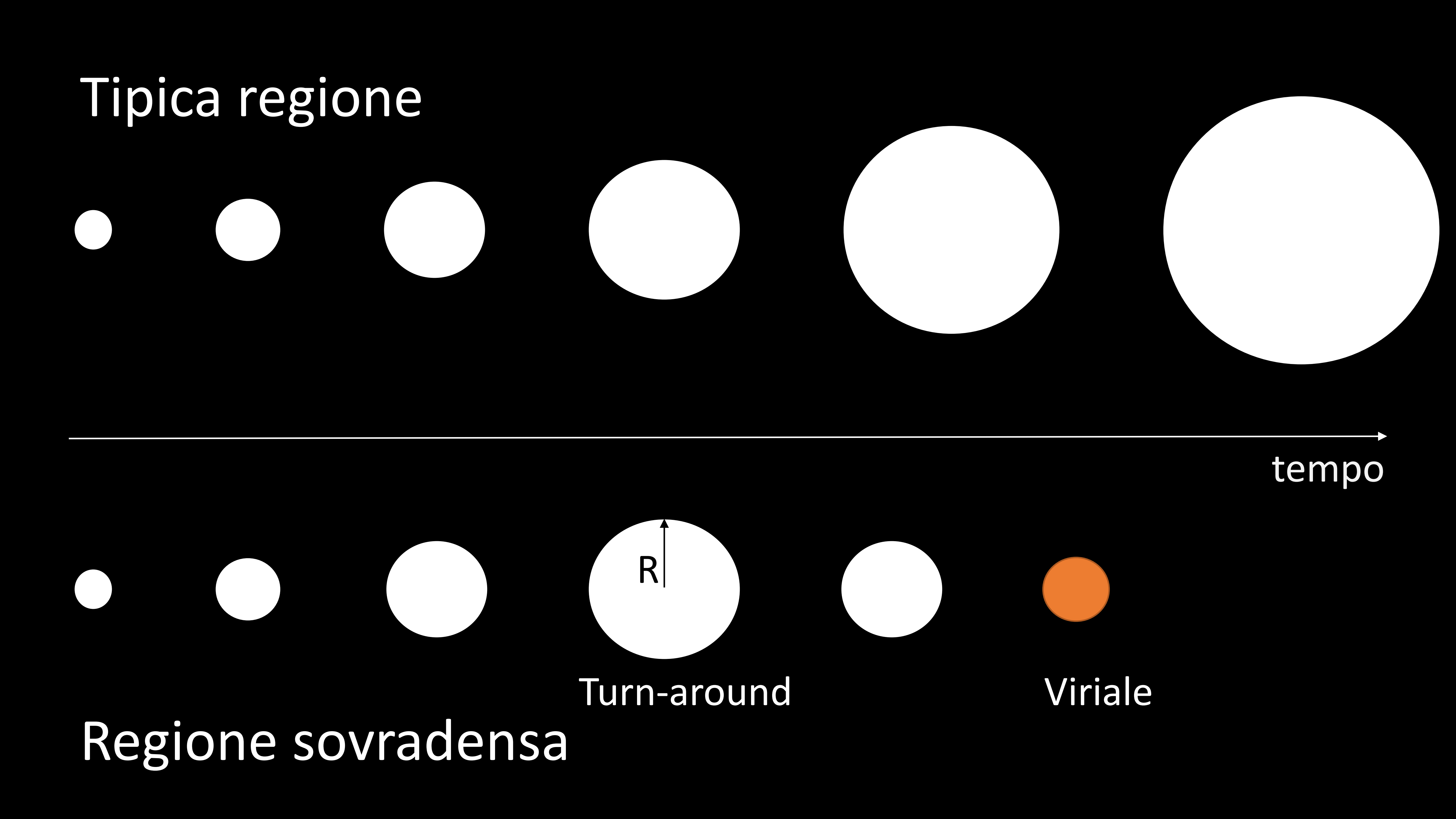

1 billion ly
180°
Virgo
Supercluster
270°
90°
0°
r powell


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

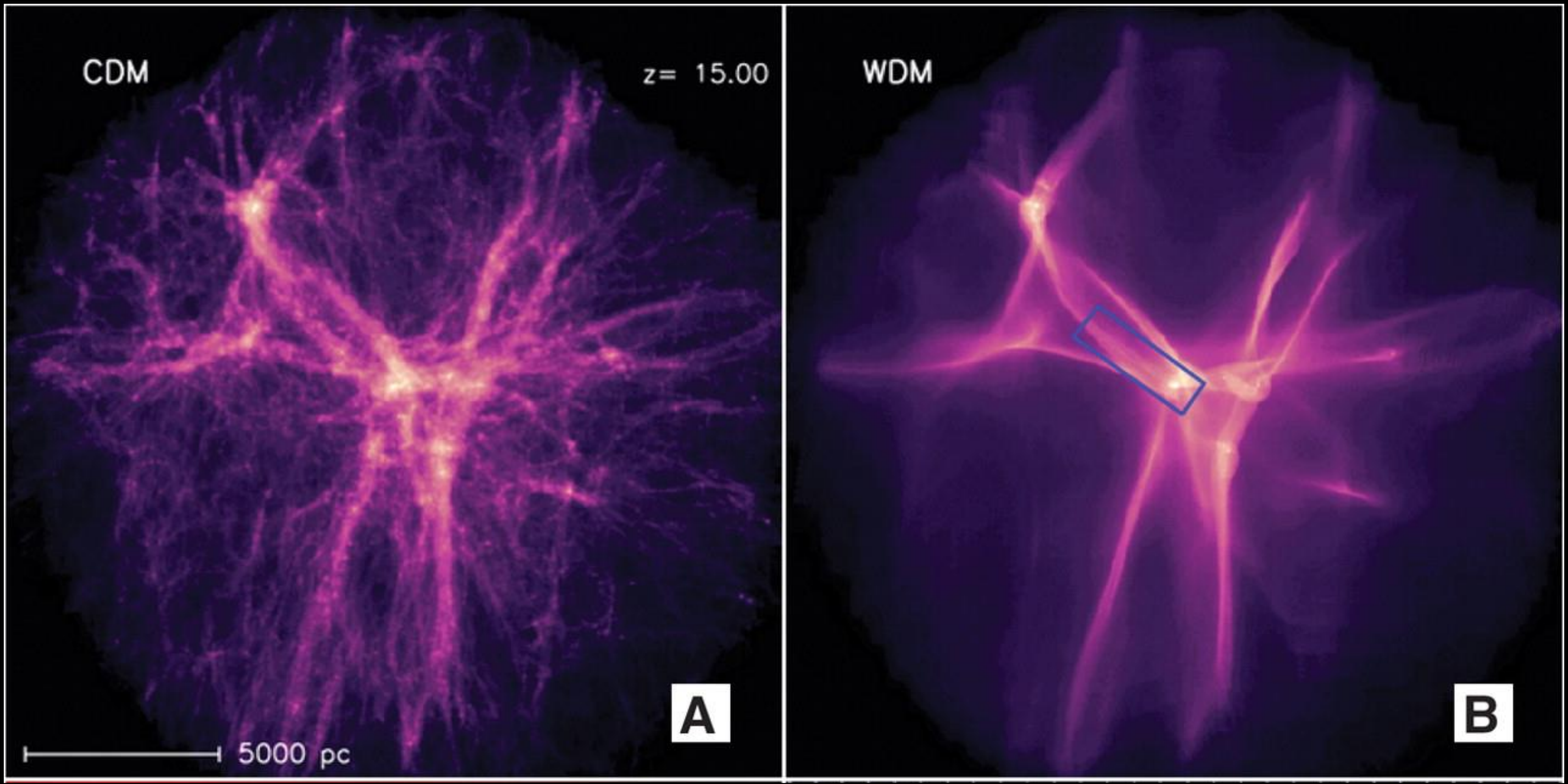

MATERIA OSCURA
MATERIA OSCURA OVUNQUE
imgflip.com

Massa di Jeans e Free streaming



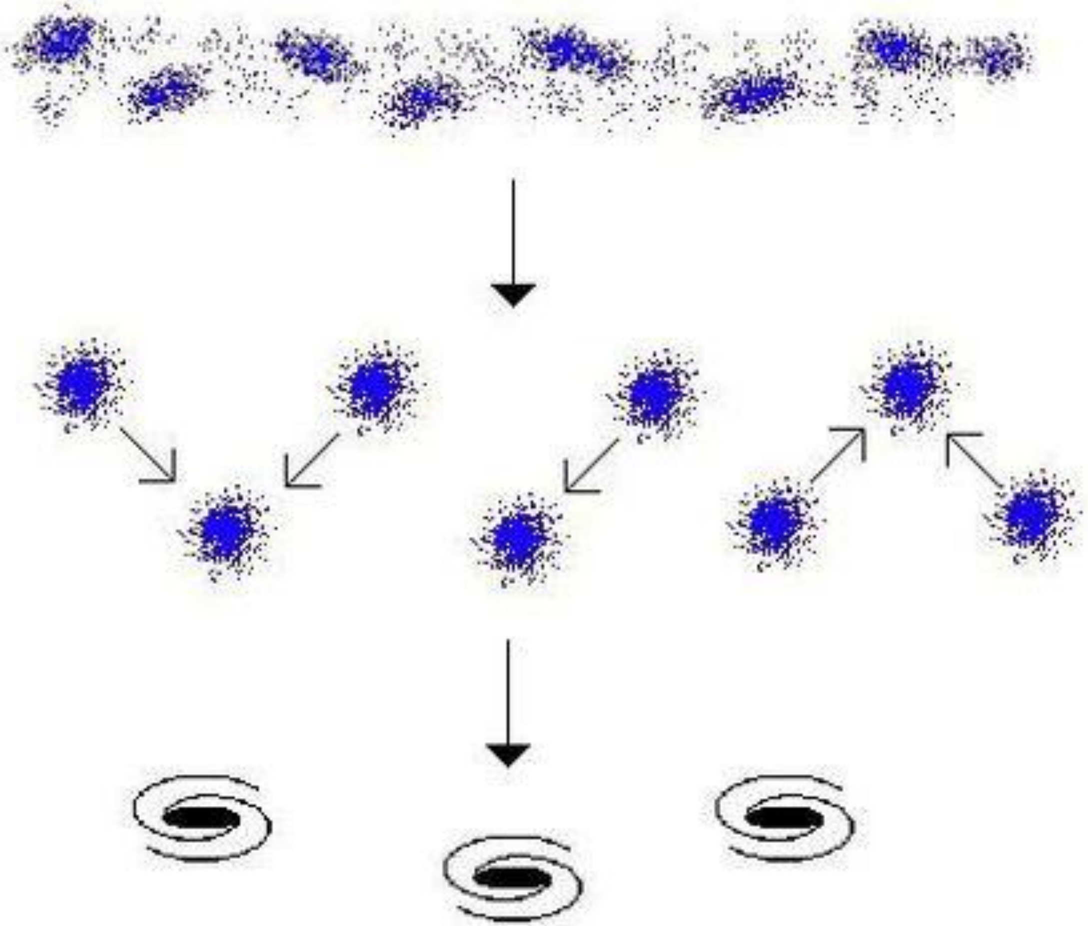

Tipica regione
tempo
R
Turn-around
Viriale
Regione sovradensa


MATERIA OSCURA CALDA
MATERIA OSCURA FREDDA
imgflip.com


CDM
z= 15.00
WDM
A
B
5000 pc

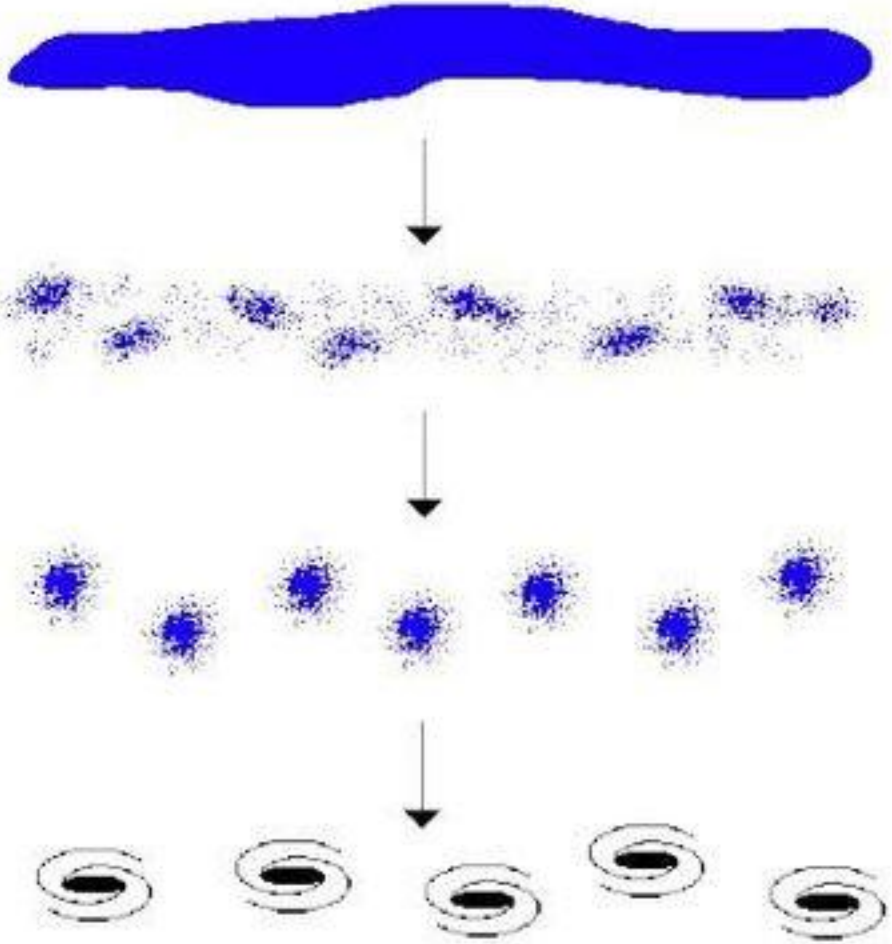
Bottom−Up Structure Formation

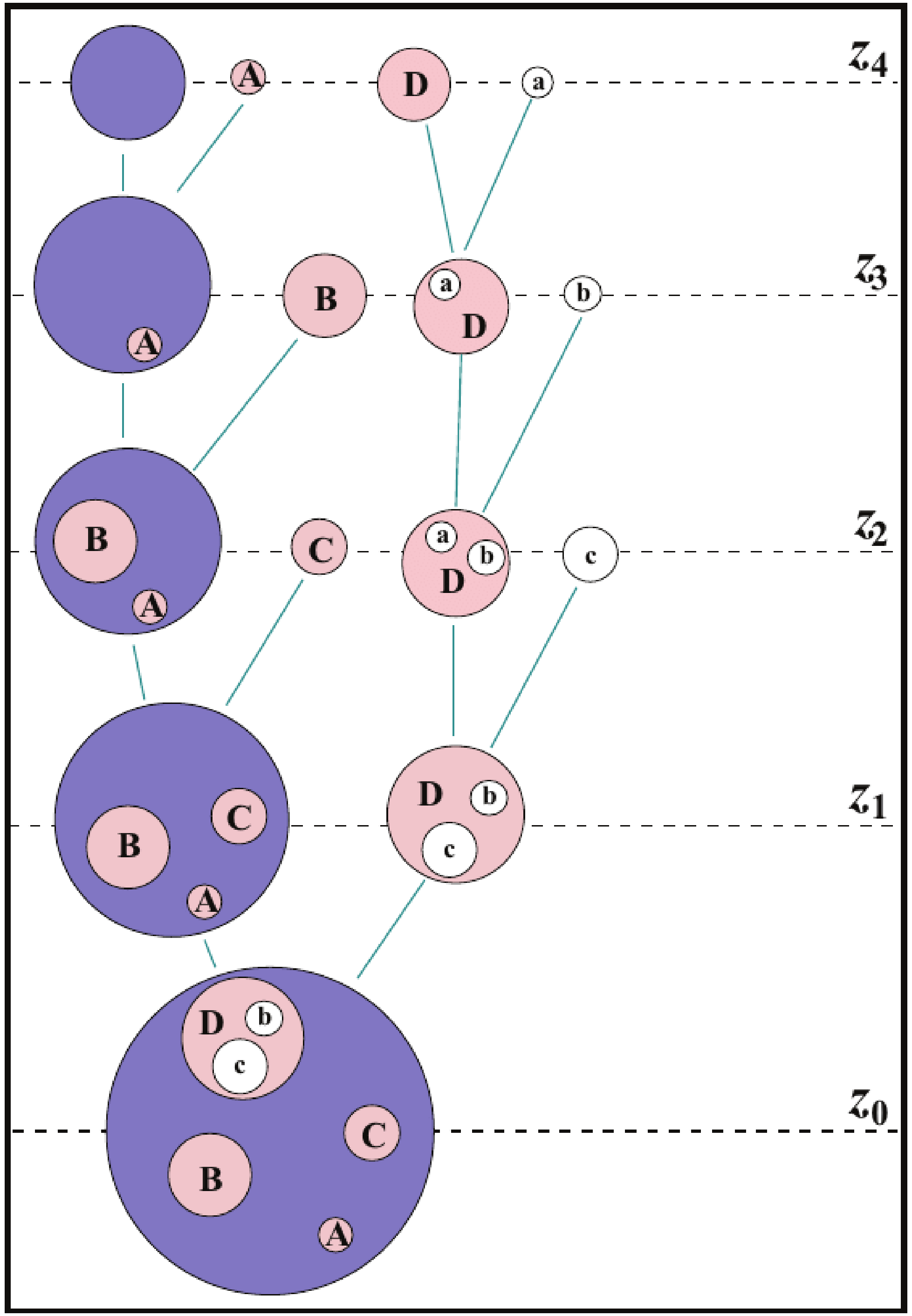
in a bottom−up scenario, small, dwarf galaxy−sized lumps form first, then merger to make galaxies and clusters of galaxies



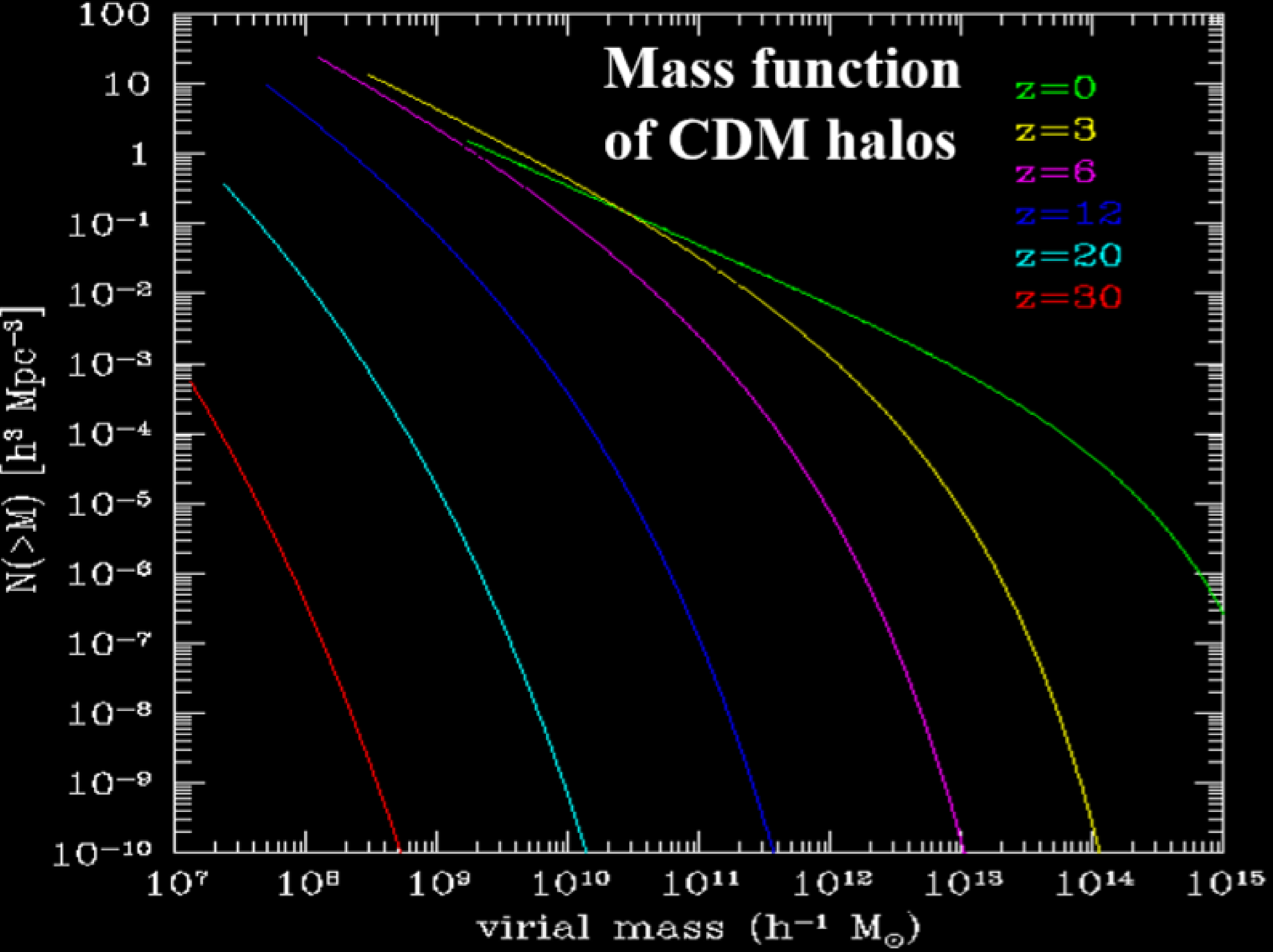
Top−Down Structure Formation

in a top−down scenario, large pancakes of matter form first, than fragment into galaxy−sized lumps



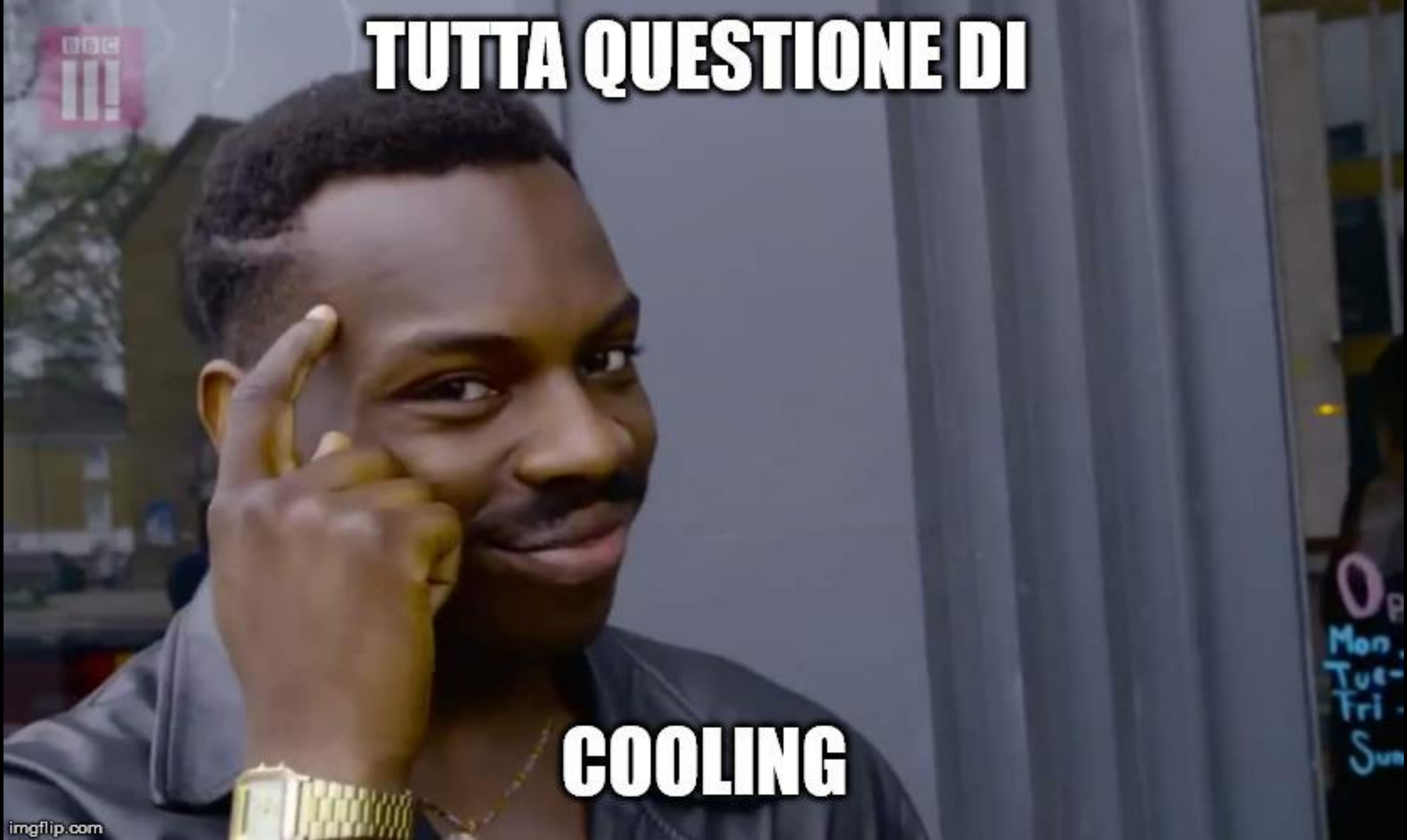


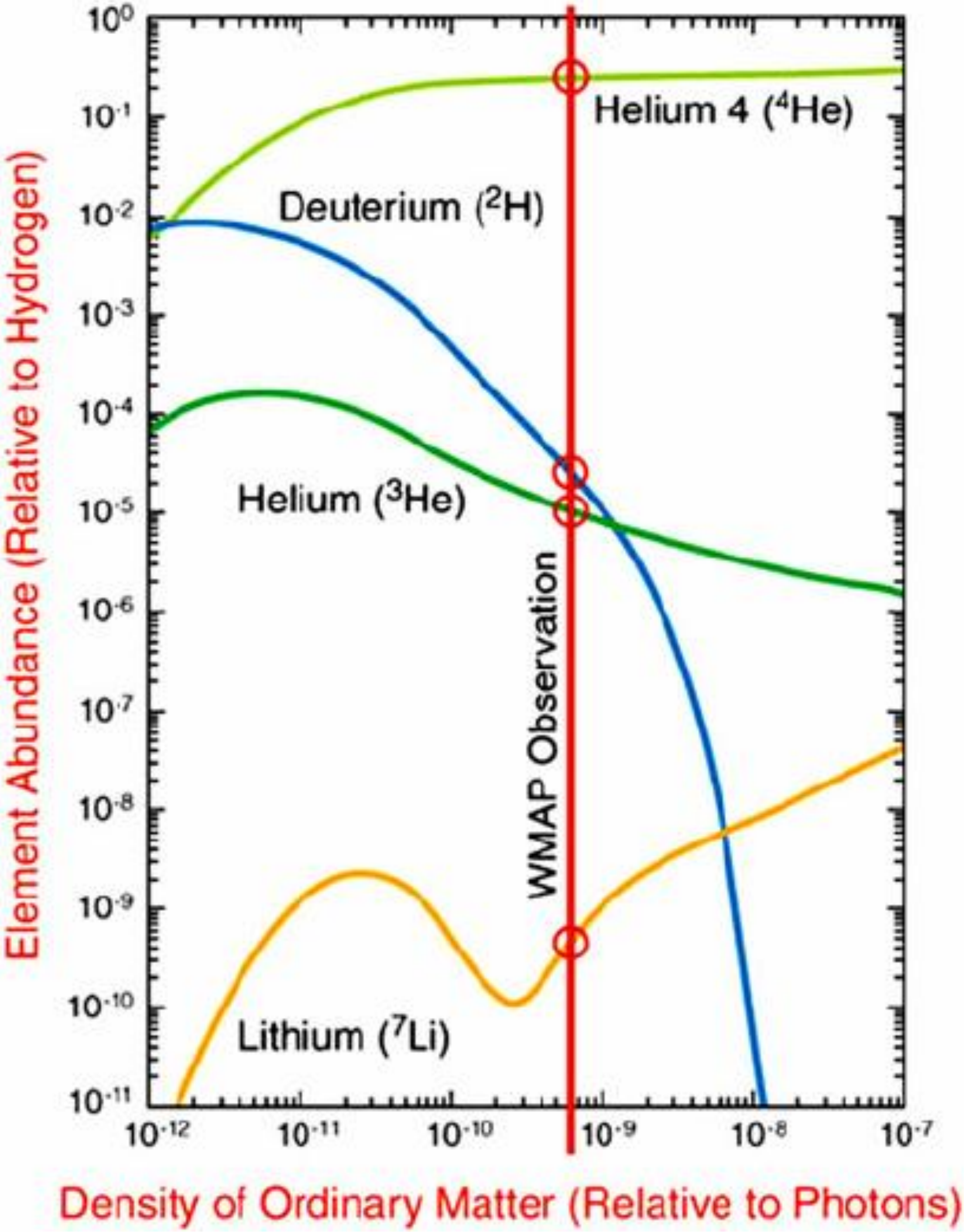
z_4
z_3
z_2
z_1
z_0
A
B
C
D
a
b
c



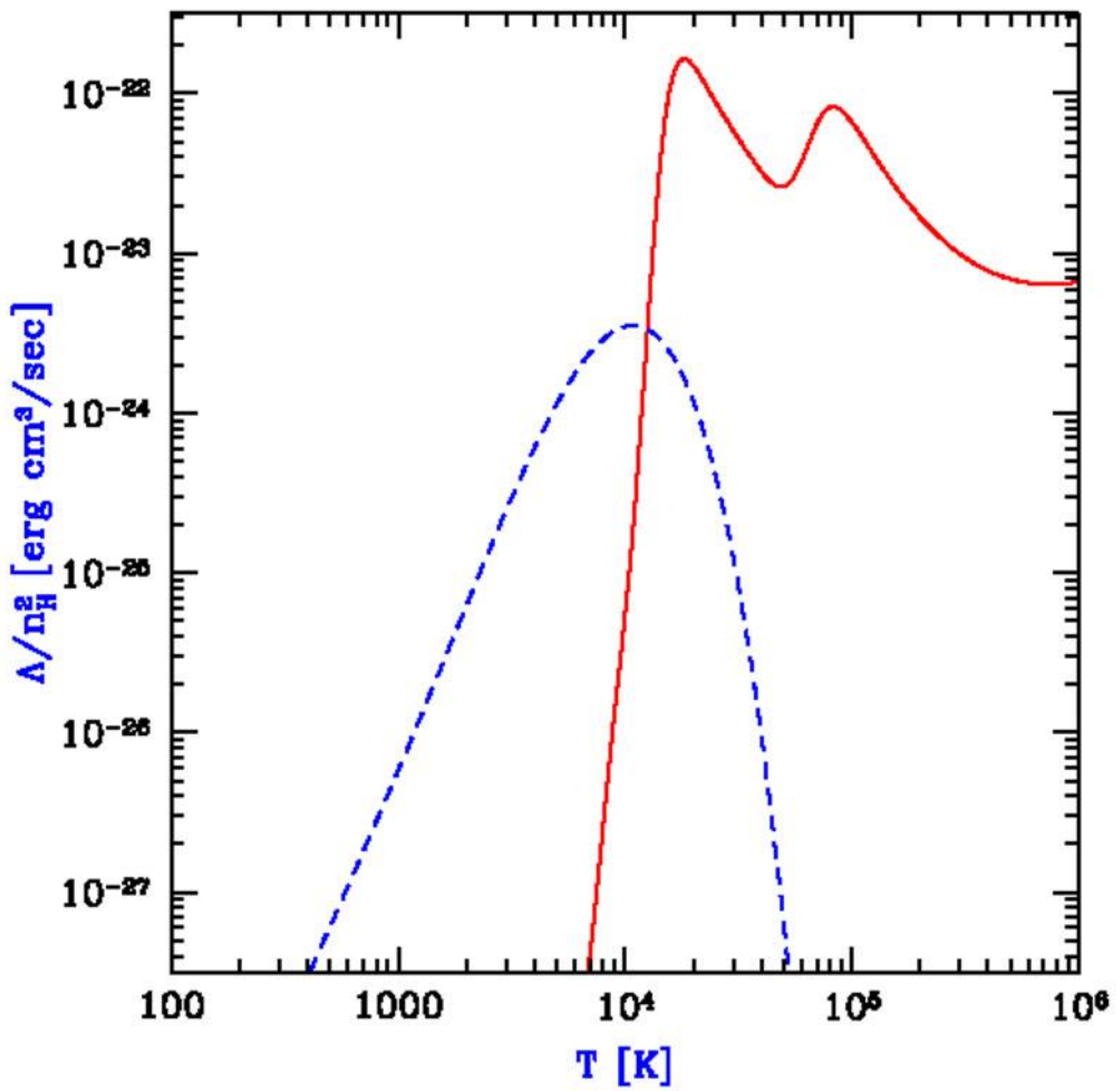
Mass function of CDM halos
z=0
z=3
z=6
z=12
z=20
z=30
N(>M) [h³ Mpc⁻³]
virial mass (h⁻¹ M☉)
100
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁷
10⁸
10⁹
10¹⁰
10¹¹
10¹²
10¹³
10¹⁴
10¹⁵


TROPPO CALDO!
imgflip.com


TUTTA QUESTIONE DI
COOLING
imgflip.com



Helium 4 (^{4}He)
Deuterium (^{2}H)
Helium (^{3}He)
Lithium (^{7}Li)
WMAP Observation
Element Abundance (Relative to Hydrogen)
Density of Ordinary Matter (Relative to Photons)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}



10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
Λ/n_H^2 [erg cm^3/sec]
100
1000
10^4
10^5
10^6
T [K]

Photoionization

(X-ray – UV radiation from stars, AGN, …)

$$A + h\nu \rightarrow A^{+} + e \quad \Rightarrow E_{kin}(e) = h\nu - E_{ionization}$$

High-energy photons: He has larger cross-section than H

Cosmic rays

(protons, nuclei, electrons with MeV energies)

example:

$p + H \rightarrow p' + H^{+} + e$

$e + H(1s) \rightarrow e + H(2p) \rightarrow e + H(1s) + h\nu$
(excitation)

$e + H(1s) \rightarrow e + H^{+} + e$
(ionization)

Molecule photodissociation

$$AB + h\nu \rightarrow A + B$$

Direct photo-dissociation
Molecule fragments carry away some of photon energy as kinetic energy

Dust grain heating

(1) Photoelectric emission of electrons (few eV). If efficient, one of the most important heating sources

$h\nu \rightarrow$ grain $\rightarrow e^{-}$

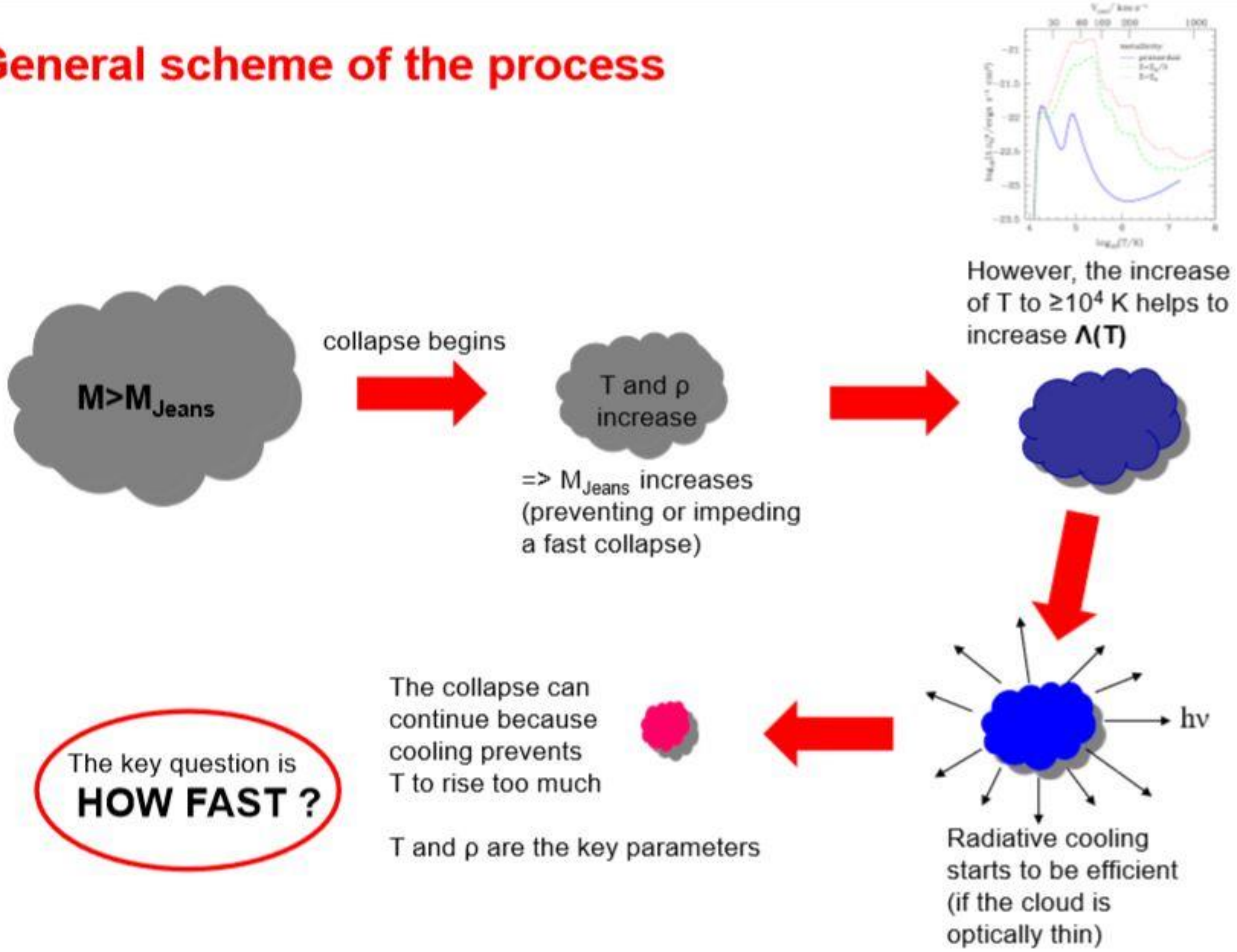
(2) If the dust is warmer than gas, atoms escaping from grains can heat the gas. Can be enhanced if dust grains move at high speed vs. gas (e.g. near a bright star where radiation pressure accelerates the dust grains)

Gas compression

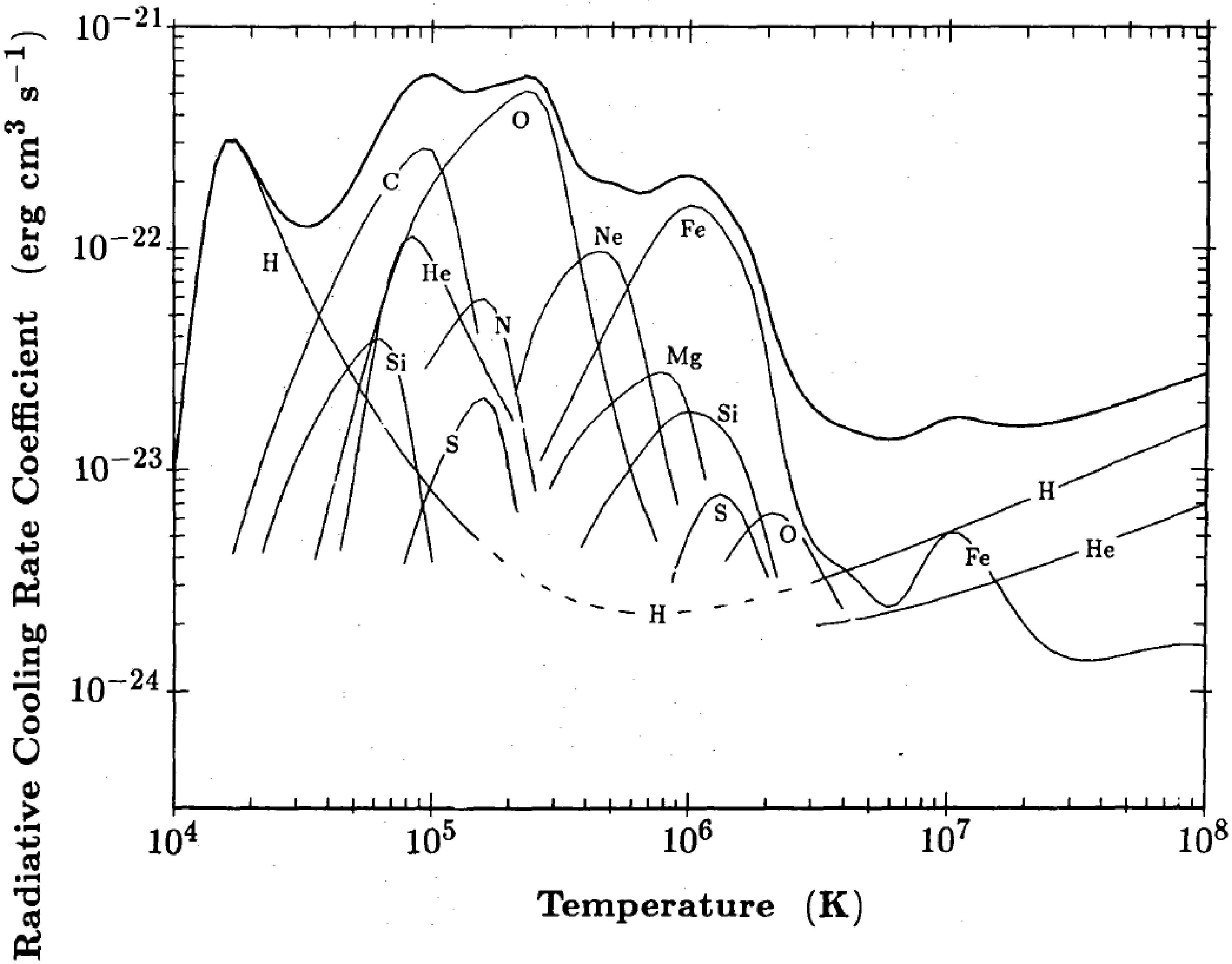
(e.g. during collapse, shocks, …)

Credit: Cimatti Andrea

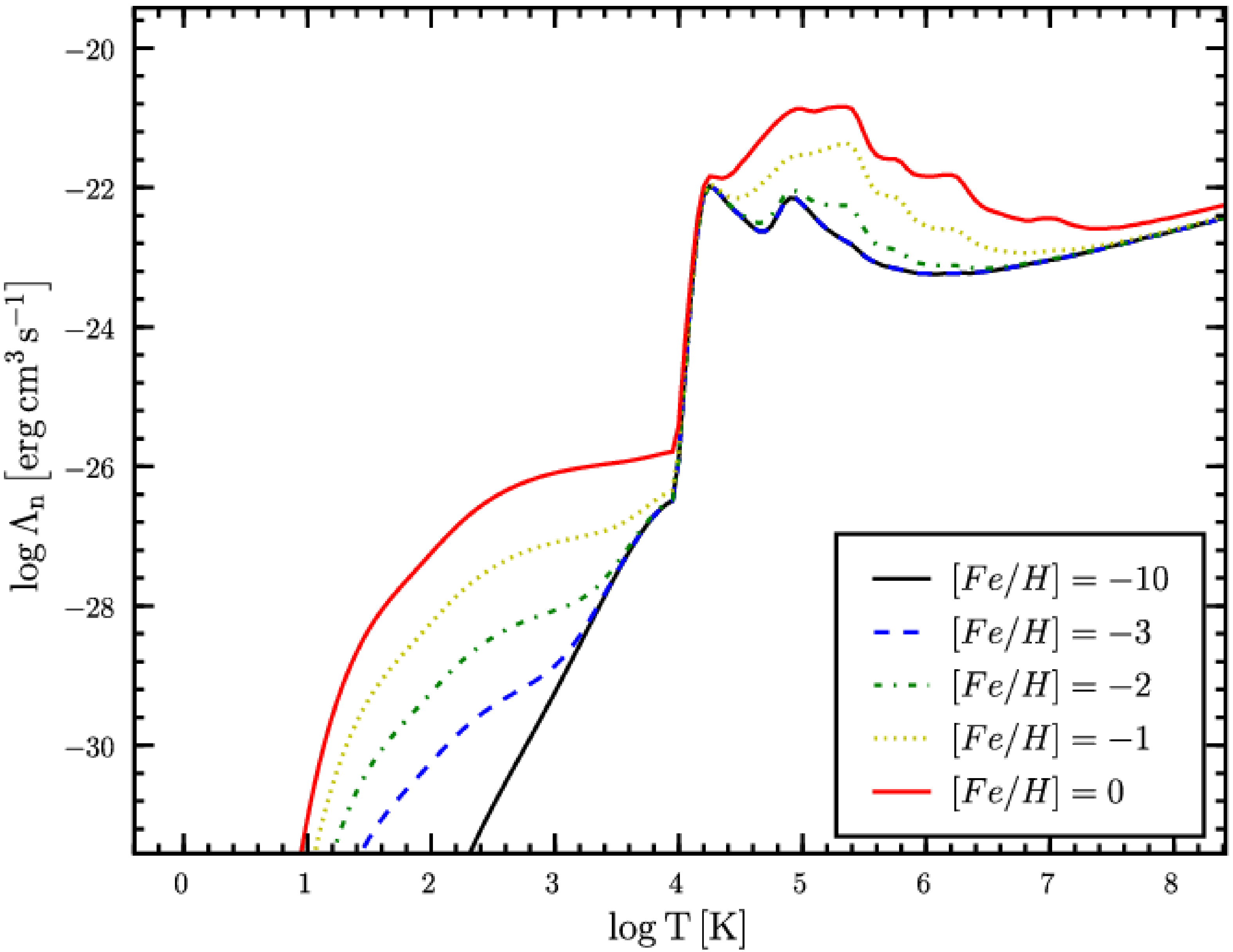
General scheme of the process



Credit: Cimatti Andrea

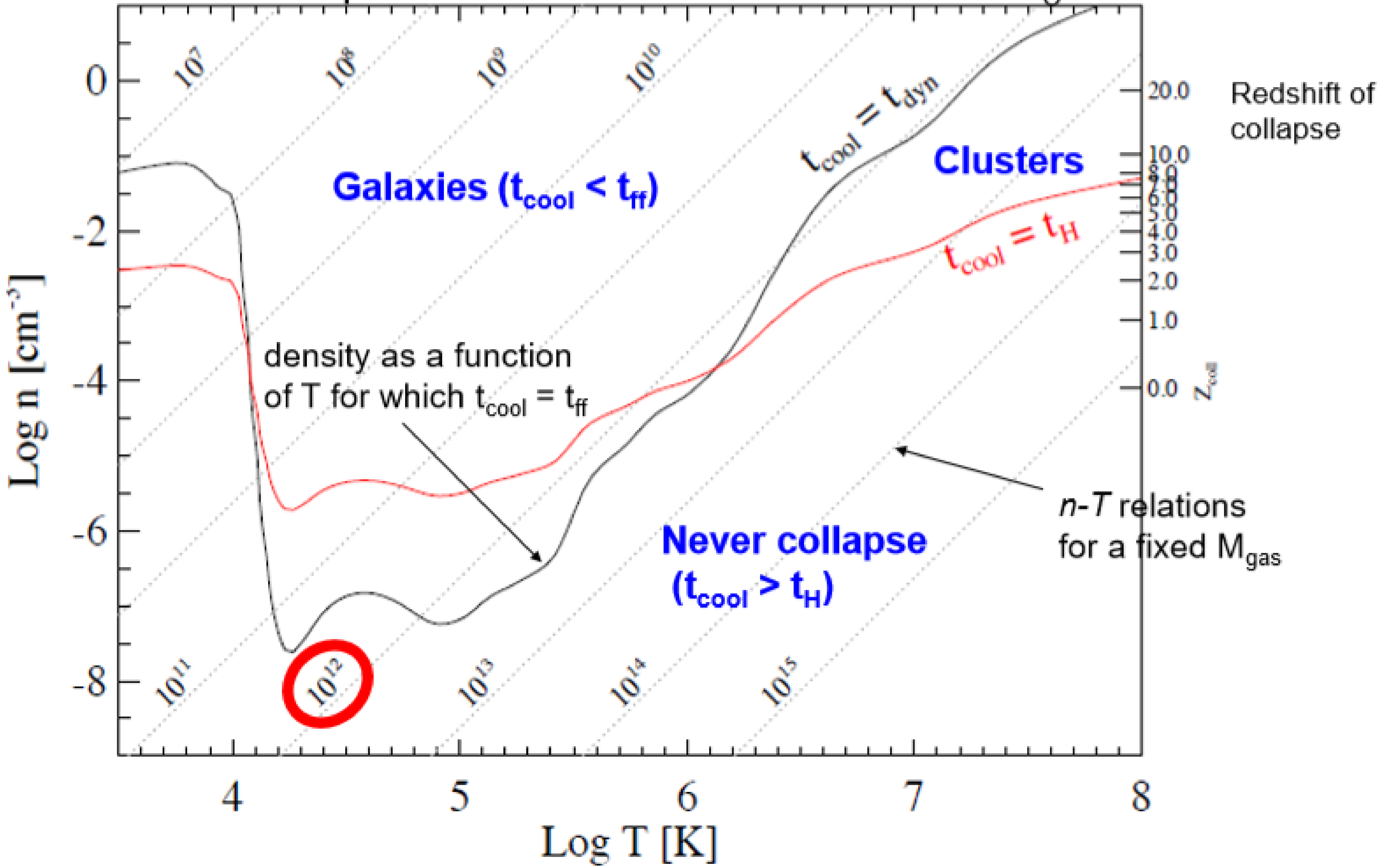


Radiative Cooling Rate Coefficient (erg cm^3 s^{-1})
10^{-21}
10^{-22}
10^{-23}
10^{-24}
Temperature (K)
10^4
10^5
10^6
10^7
10^8
H
C
O
He
N
Si
S
Ne
Fe
Mg
Si
S
O
H
H
Fe
He



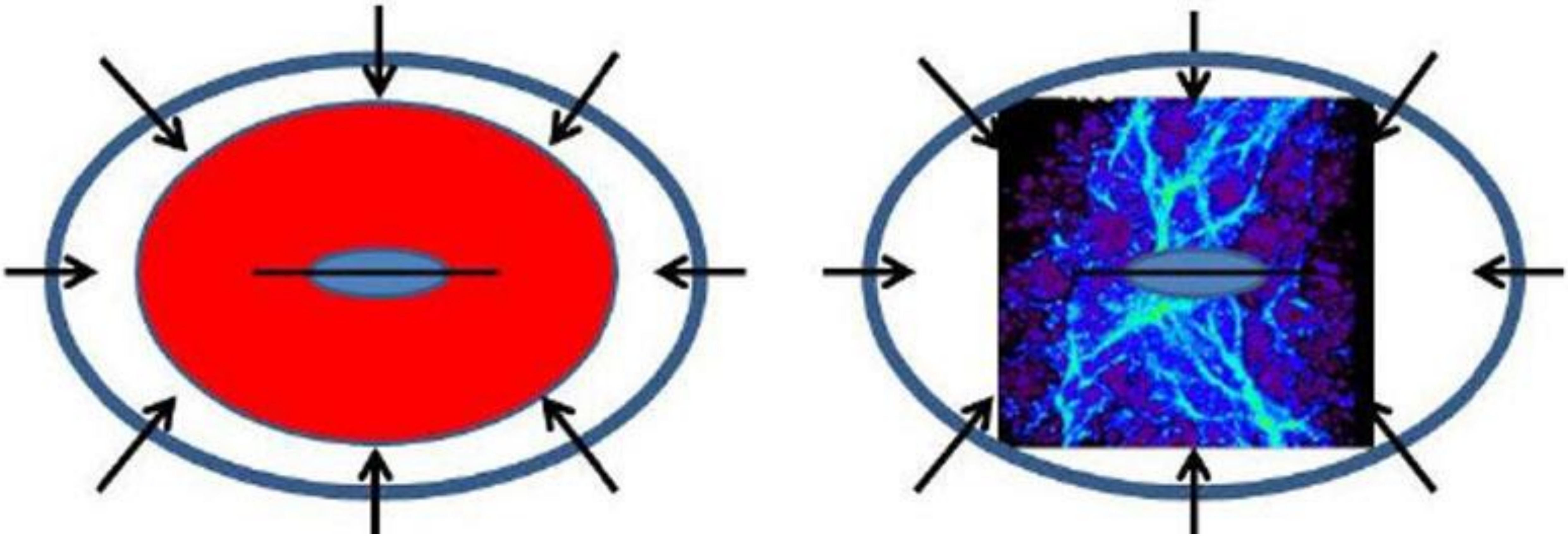
-20
-22
-24
-26
-28
-30
$\log \Lambda_{\rm n}\ [\rm erg\,cm^3\,s^{-1}]$
0
1
2
3
4
5
6
7
8
$\log \rm T\ [K]$
$[Fe/H] = -10$
$[Fe/H] = -3$
$[Fe/H] = -2$
$[Fe/H] = -1$
$[Fe/H] = 0$

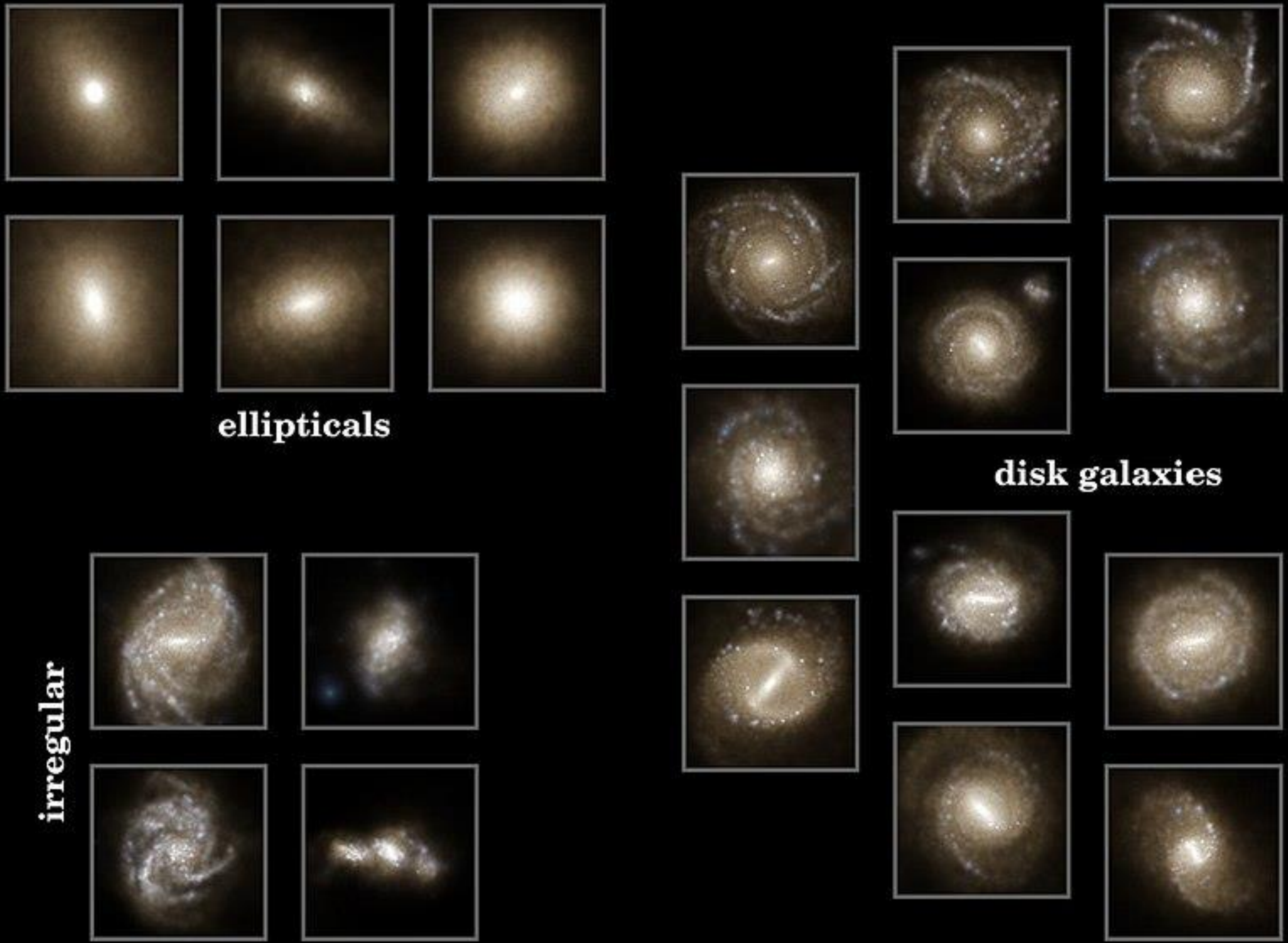
Example relative to redshift z=3 and $Z=Z_\odot$



Credit: Cimatti Andrea

Objects that lie above **both the red and black** curves are able to cool efficiently

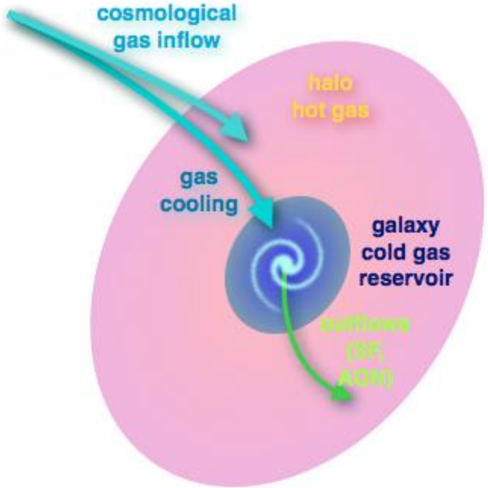


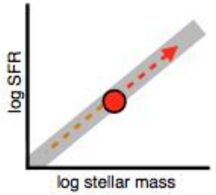


ellipticals
disk galaxies
irregular

Late-type galaxy star formation quenching schematic

(1) prior to t=0

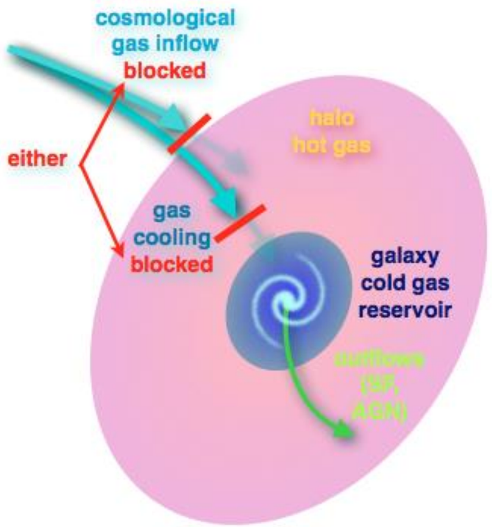


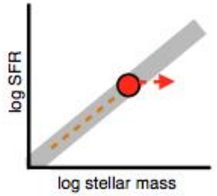


Galaxy is on main sequence
$M_{stellar} \sim SFR^{\beta}$

Inflows balance outflows: system in quasi-equilibrium (Bouche+10; Lilly+13)

(2) t=0, quenching event



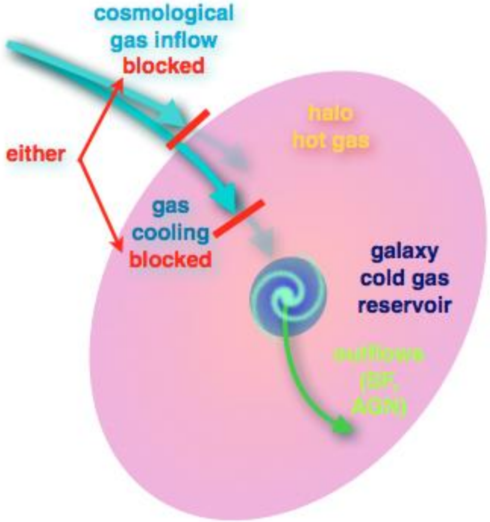


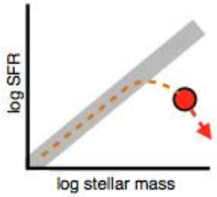
Either cosmological inflows or cooling from halo are stopped, galaxy gas reservoir is now no longer replenished

Galaxy leaves main sequence

SFR = εMgas/τdyn

(3) t~100-1000 Myr past quenching

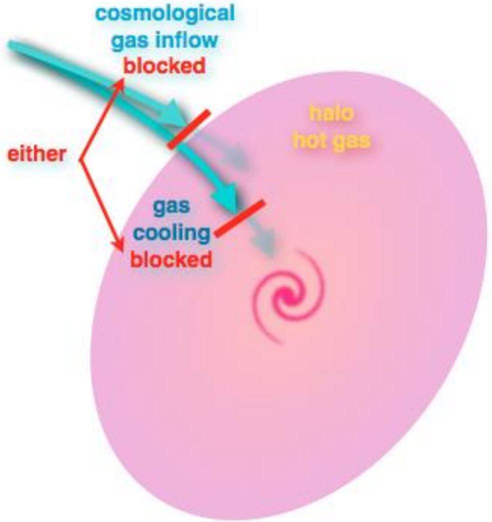


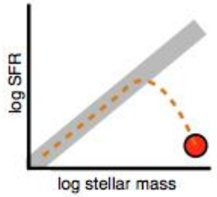


SFR goes into exponential decline, galaxy enters green valley

Gas reservoir is slowly used up

(4) t~ several Gyr past quenching



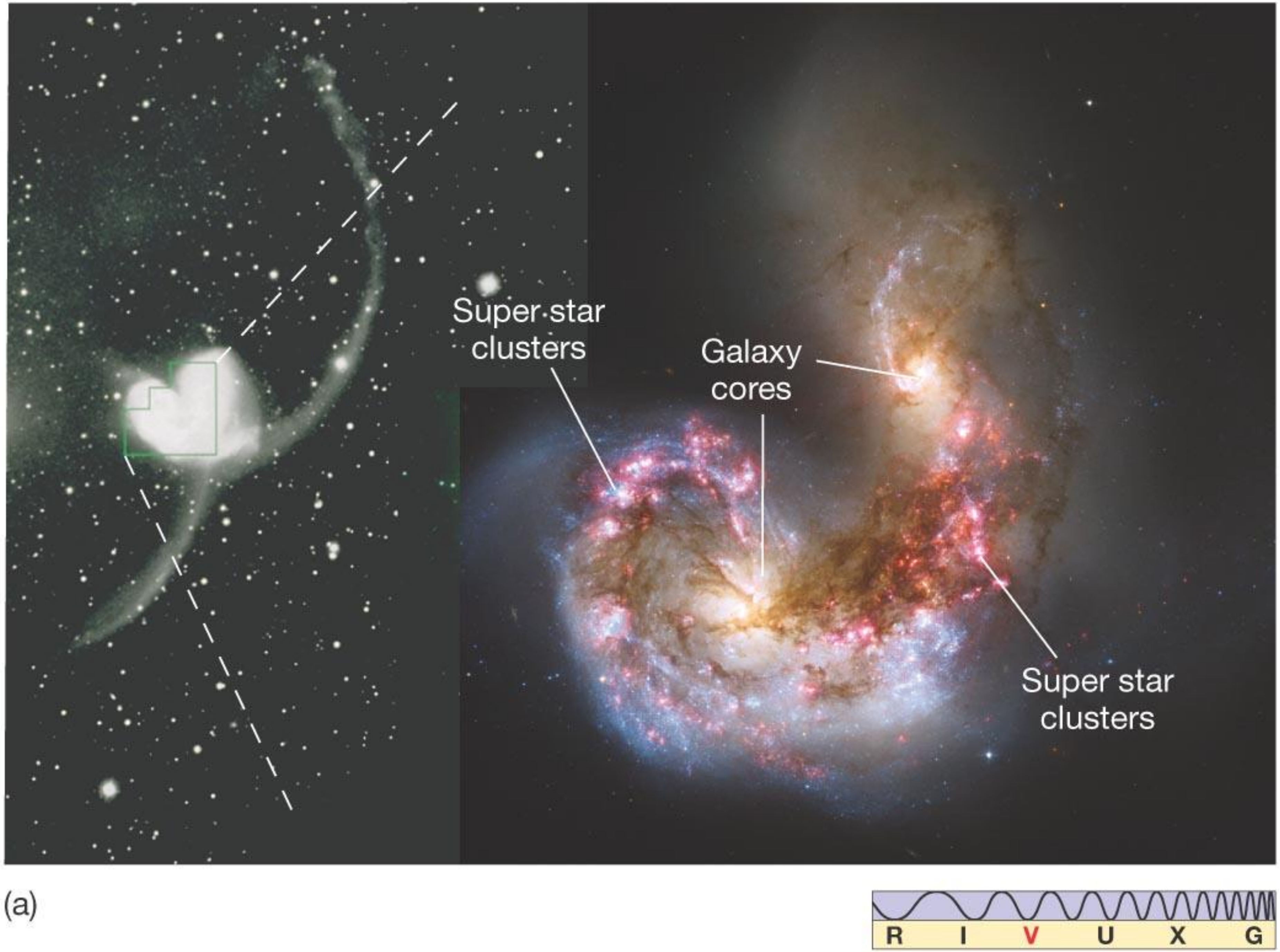


Several Gyr later...

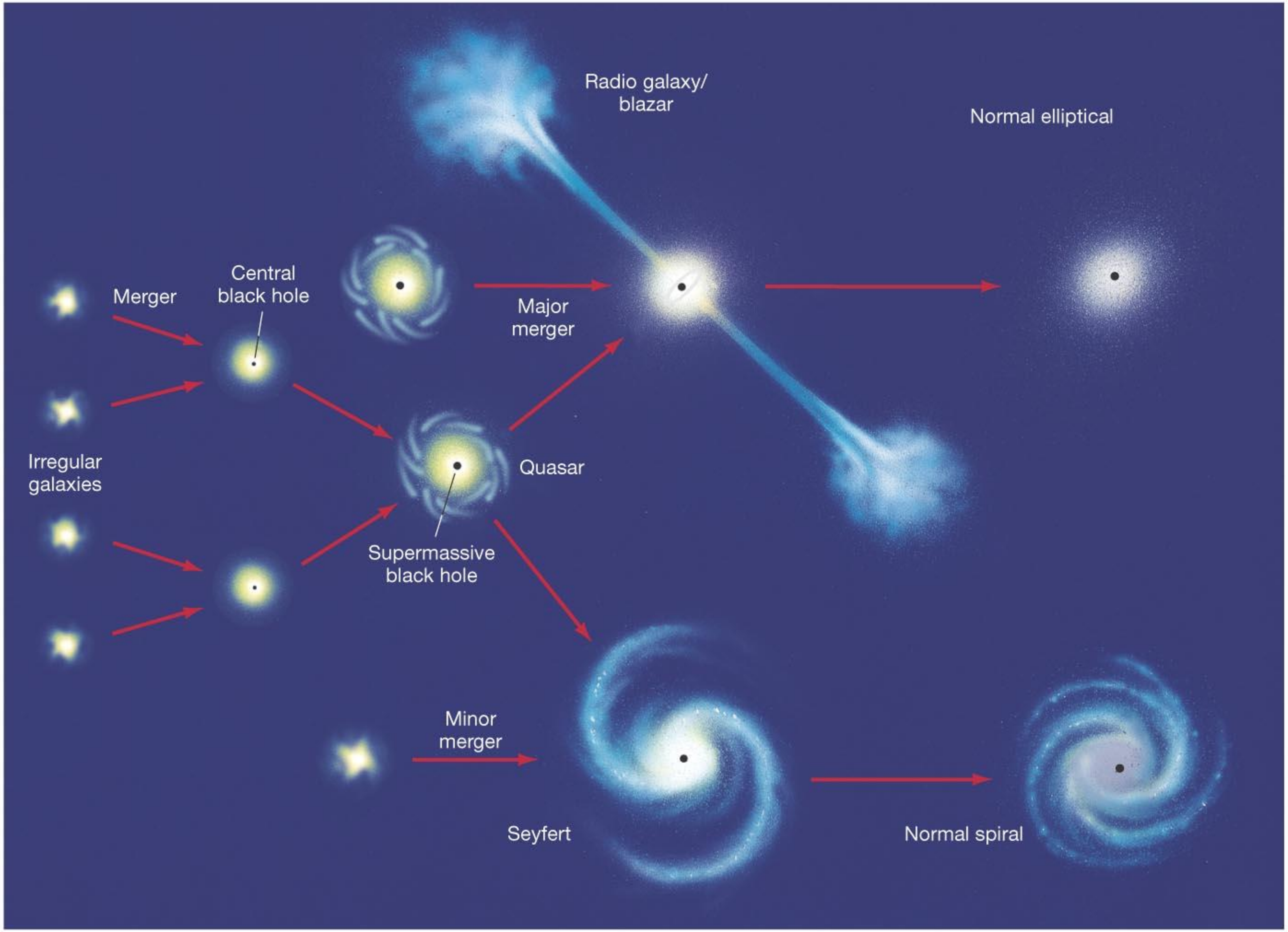
Passive, red spiral galaxy

No morphological transform-ation > “red spiral”

Very low SSFR

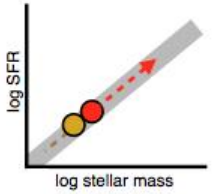

Super star
clusters
Galaxy
cores
Super star
clusters
R I V U X G

(a)


Radio galaxy/
blazar
Normal elliptical
Merger
Central
black hole
Major
merger
Irregular
galaxies
Quasar
Supermassive
black hole
Minor
merger
Seyfert
Normal spiral

Early-type galaxy star formation quenching schematic

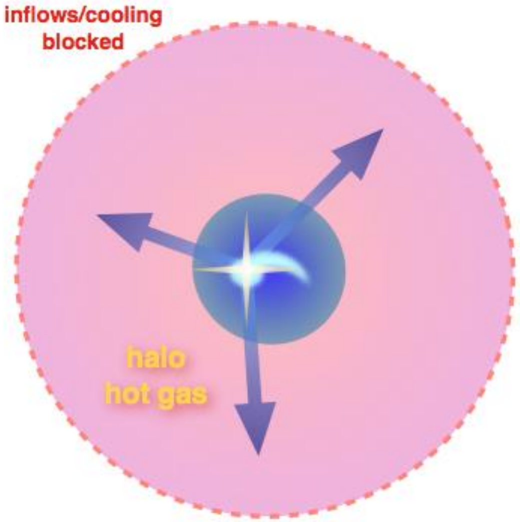
(1) ~100s Myr prior to quenching (t=0)

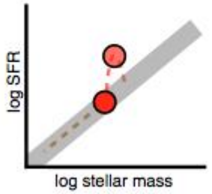


Two galaxies on main sequence are about to merge

Both bring in gas reservoir and are connected to cosmic gas inflow

(2) quenching time (t=0)





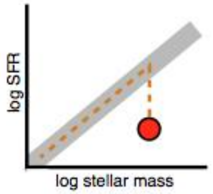
Merger may drive SFR above main sequence, or not.

Morphology is transformed to spheroid

Some process drives outflows of gas to rapidly deplete the cold gas reservoir, perhaps AGN feedback?

Further cosmological inflows and/or cooling stopped?

(3) t~100s Myr post quenching

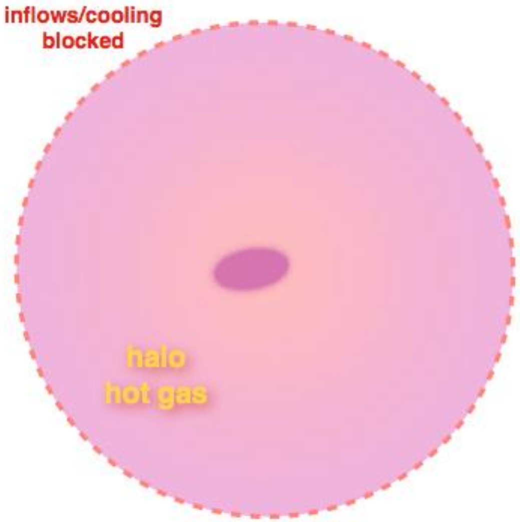


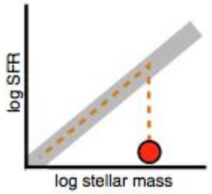
SFR drops rapidly to zero, galaxy moves to green valley

Gas reservoir is destroyed, further inflows not allowed to replenish

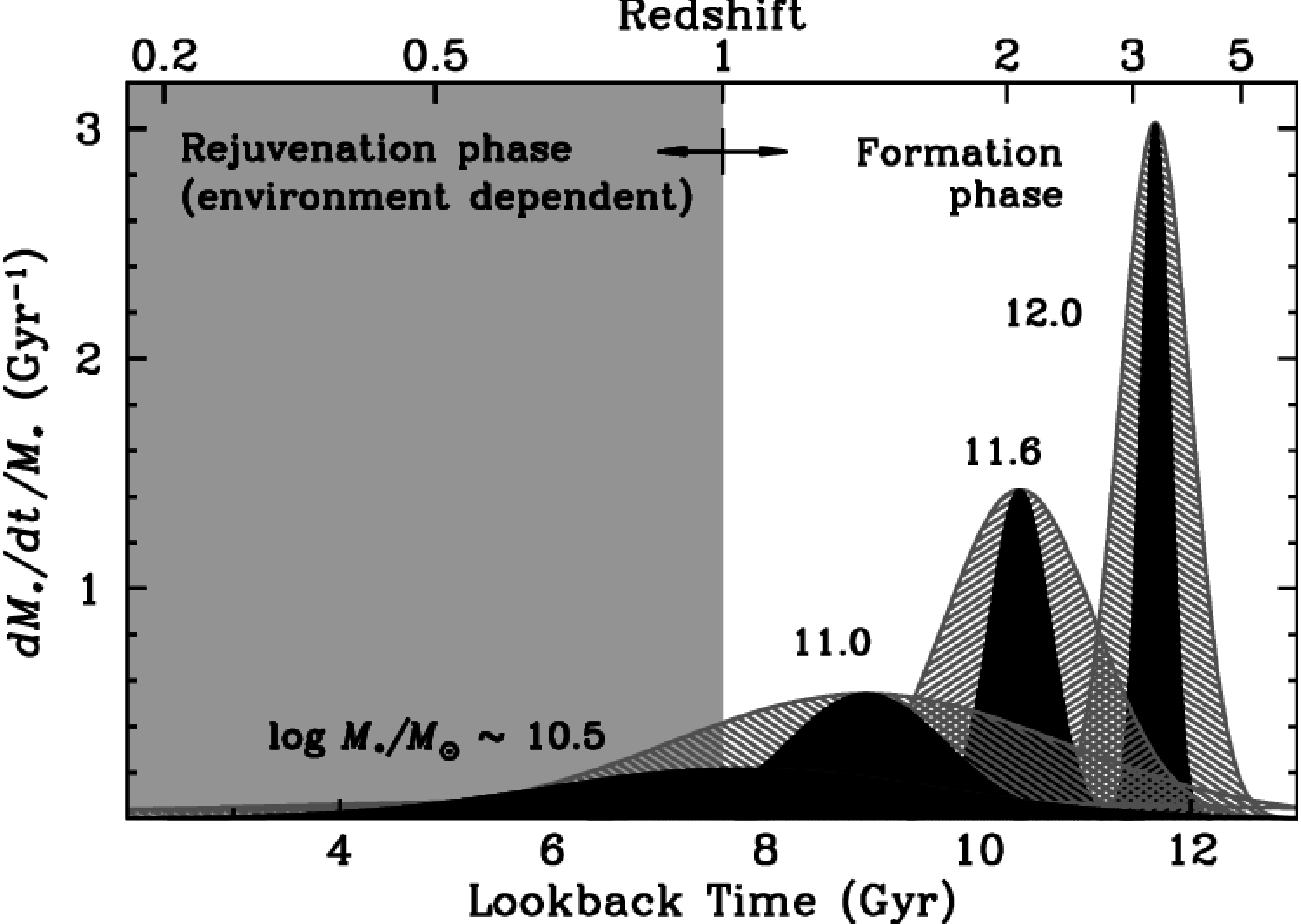
AGN active

(4) t~1-2 Gyr post quenching

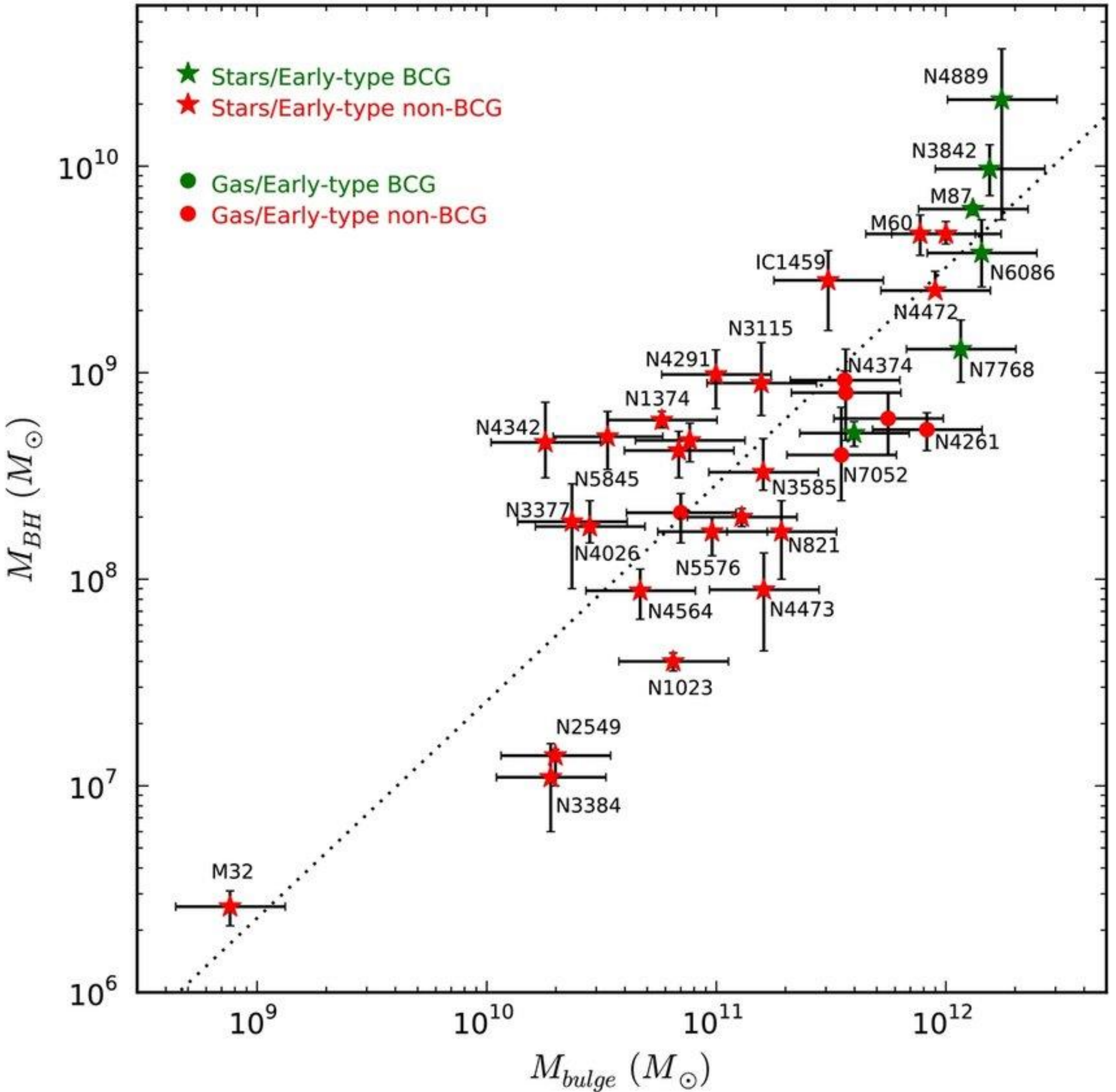




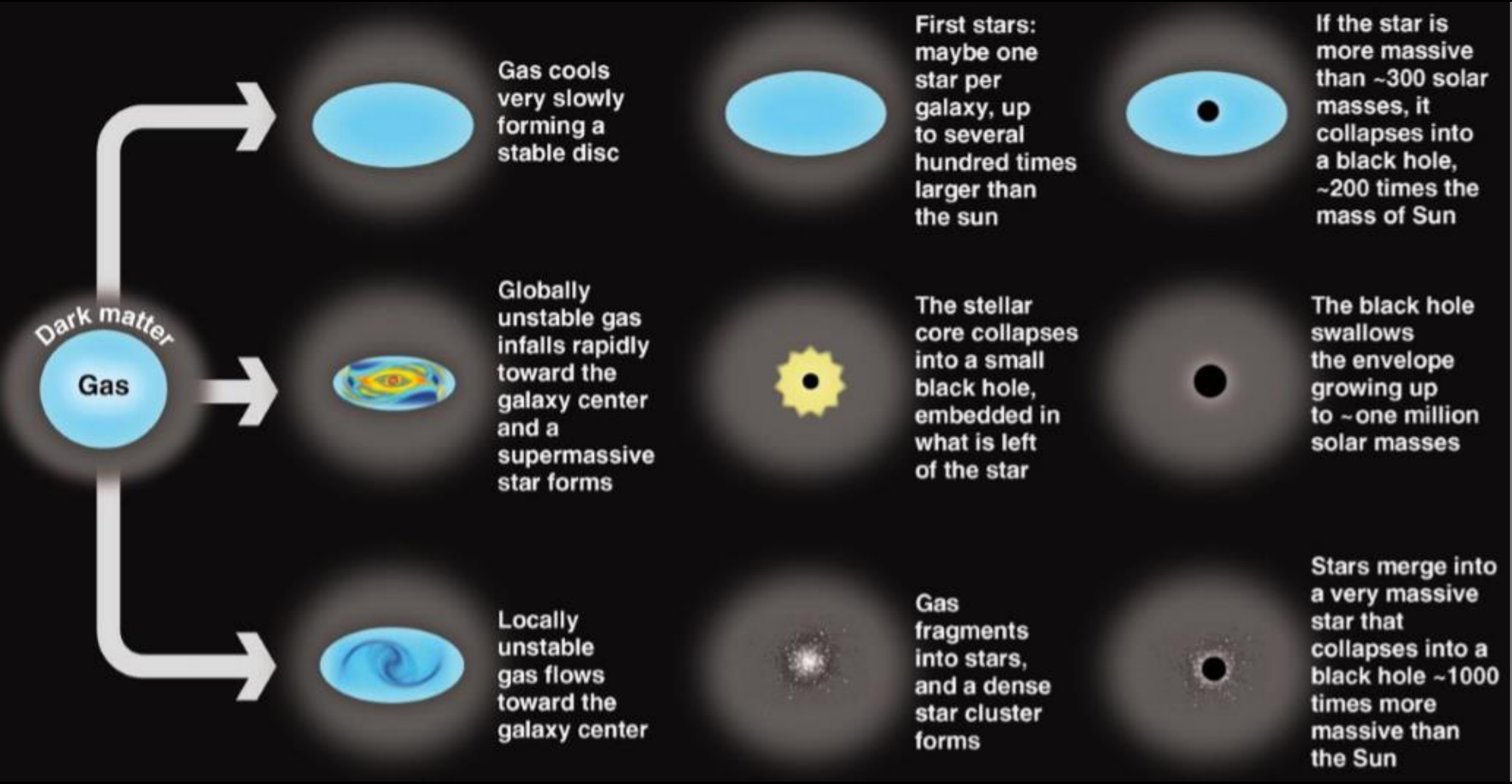
With no gas reservoir and no further gas inflows, new early-type becomes passive red sequence galaxy.



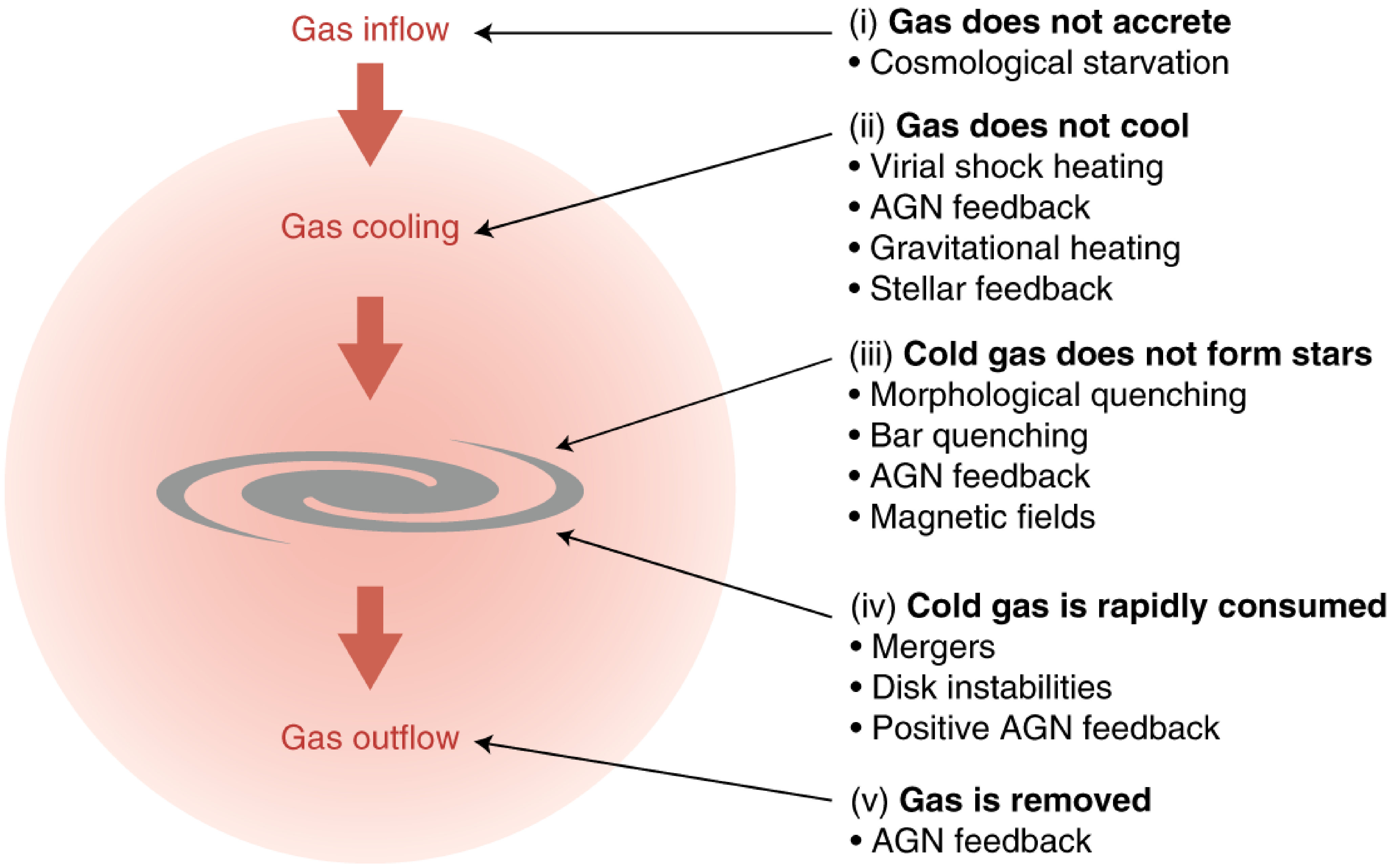
Redshift
0.2
0.5
1
2
3
5
3
2
1
Rejuvenation phase
(environment dependent)
Formation
phase
12.0
11.6
11.0
log $M_*/M_\odot \sim 10.5$
$dM_*/dt/M_*$ (Gyr^{-1})
4
6
8
10
12
Lookback Time (Gyr)



Stars/Early-type BCG
Stars/Early-type non-BCG
Gas/Early-type BCG
Gas/Early-type non-BCG
N4889
N3842
M87
M60
N6086
IC1459
N4472
N3115
N4291
N4374
N7768
N1374
N4342
N4261
N7052
N5845
N3585
N3377
N821
N4026
N5576
N4564
N4473
N1023
N2549
N3384
M32
M_{BH} $(M_\odot)$
M_{bulge} $(M_\odot)$
10^6
10^7
10^8
10^9
10^{10}
10^9
10^{10}
10^{11}
10^{12}


Dark matter
Gas
Gas cools very slowly forming a stable disc
First stars: maybe one star per galaxy, up to several hundred times larger than the sun
If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of Sun
Globally unstable gas infalls rapidly toward the galaxy center and a supermassive star forms
The stellar core collapses into a small black hole, embedded in what is left of the star
The black hole swallows the envelope growing up to ~one million solar masses
Locally unstable gas flows toward the galaxy center
Gas fragments into stars, and a dense star cluster forms
Stars merge into a very massive star that collapses into a black hole ~1000 times more massive than the Sun

What causes quenching in massive galaxies?



- Distribuzione della Materia Oscura
- Distribuzione del Gas
- Tasso di raffreddamento del Gas
- Formazione stellare
- AGN e altri Feedback
- Merging di galassie

- Luminosità e colori
- Morfologia
- Dinamica
- Età e metallicità
- Tasso di formazione stellare
- Posizioni e velocità


0.000 billion years

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- https://www.nasa.gov/mission_pages/hubble/science/milky-way-collide.html
- Livello avanzato: “Introduction to Galaxy Formation and Evolution: From Primordial Gas to Present-Day Galaxies” di Cimatti, Fraternali e Nipoti