

# Galaxies, Stars and Black Holes: Formation and Energy Budget

Martin Rees

*Cambridge University*

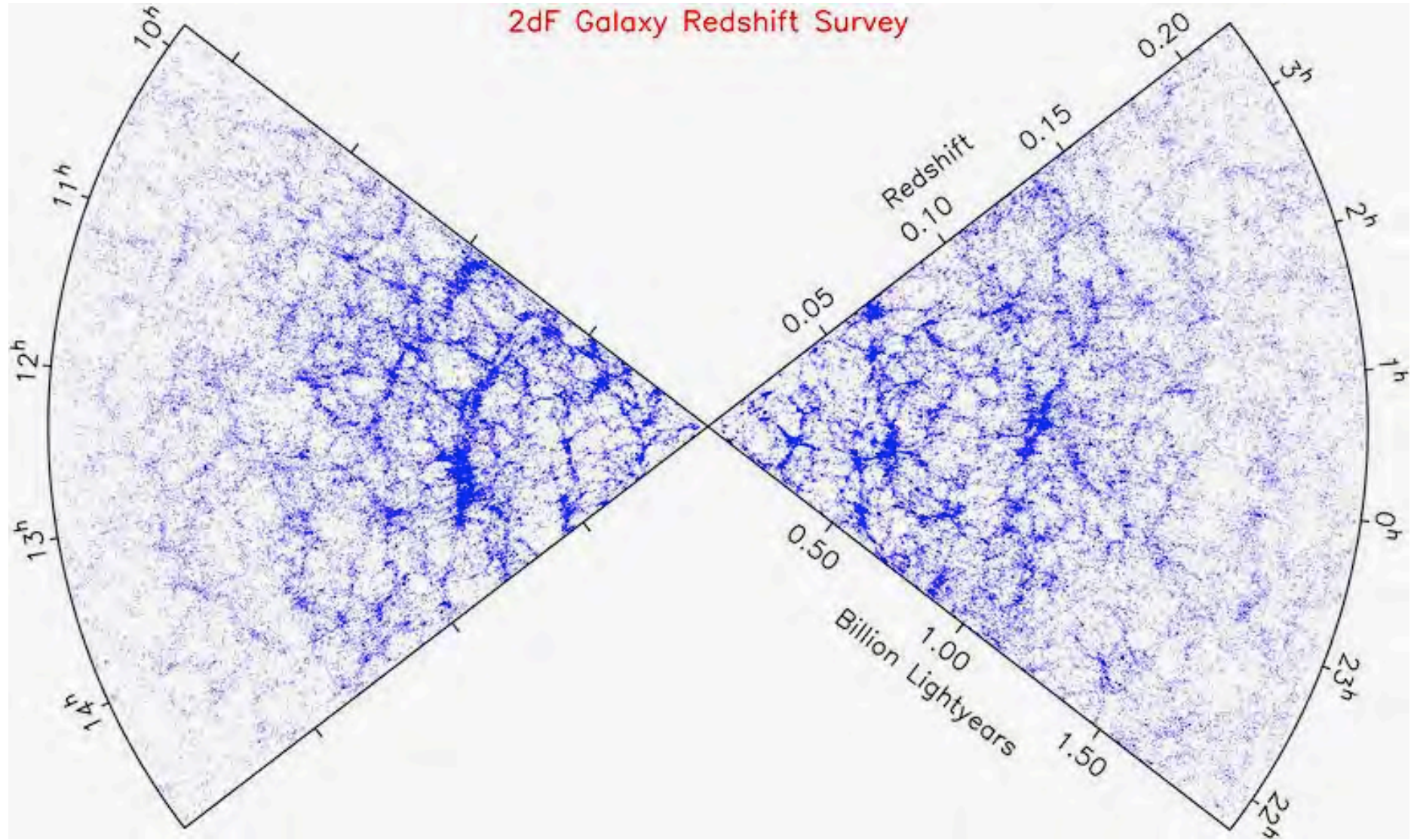




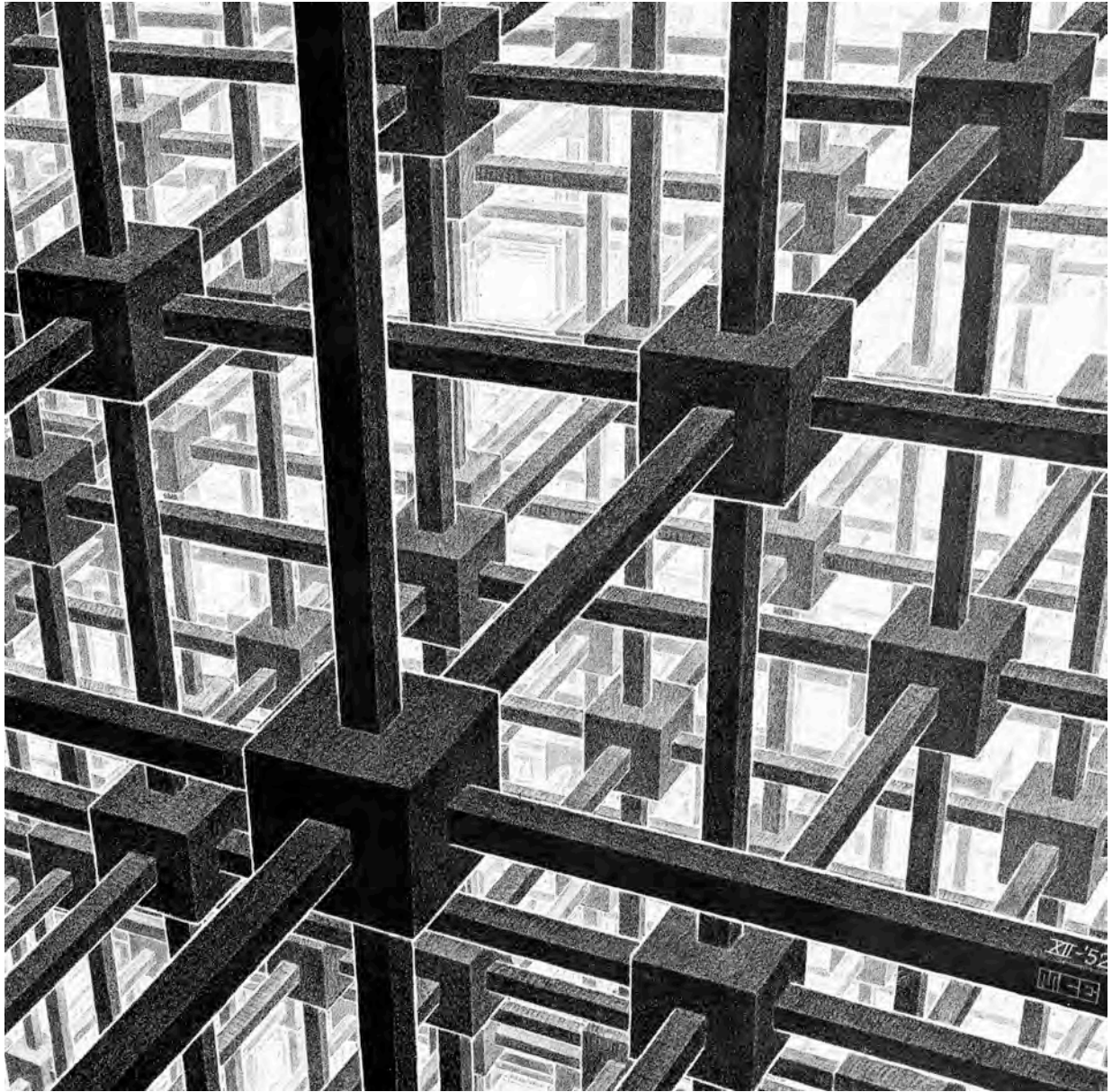


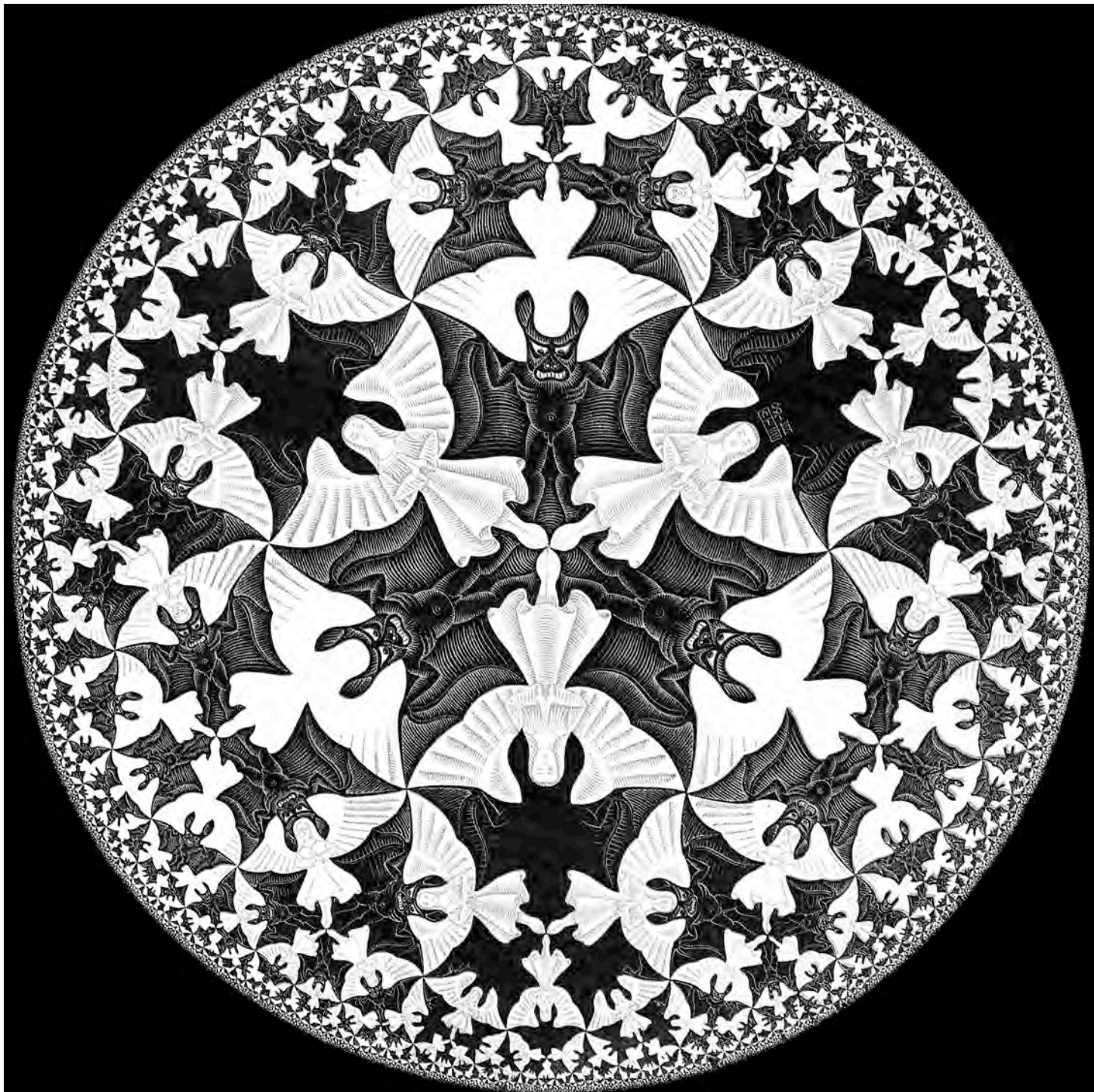


# 2dF Galaxy Redshift Survey



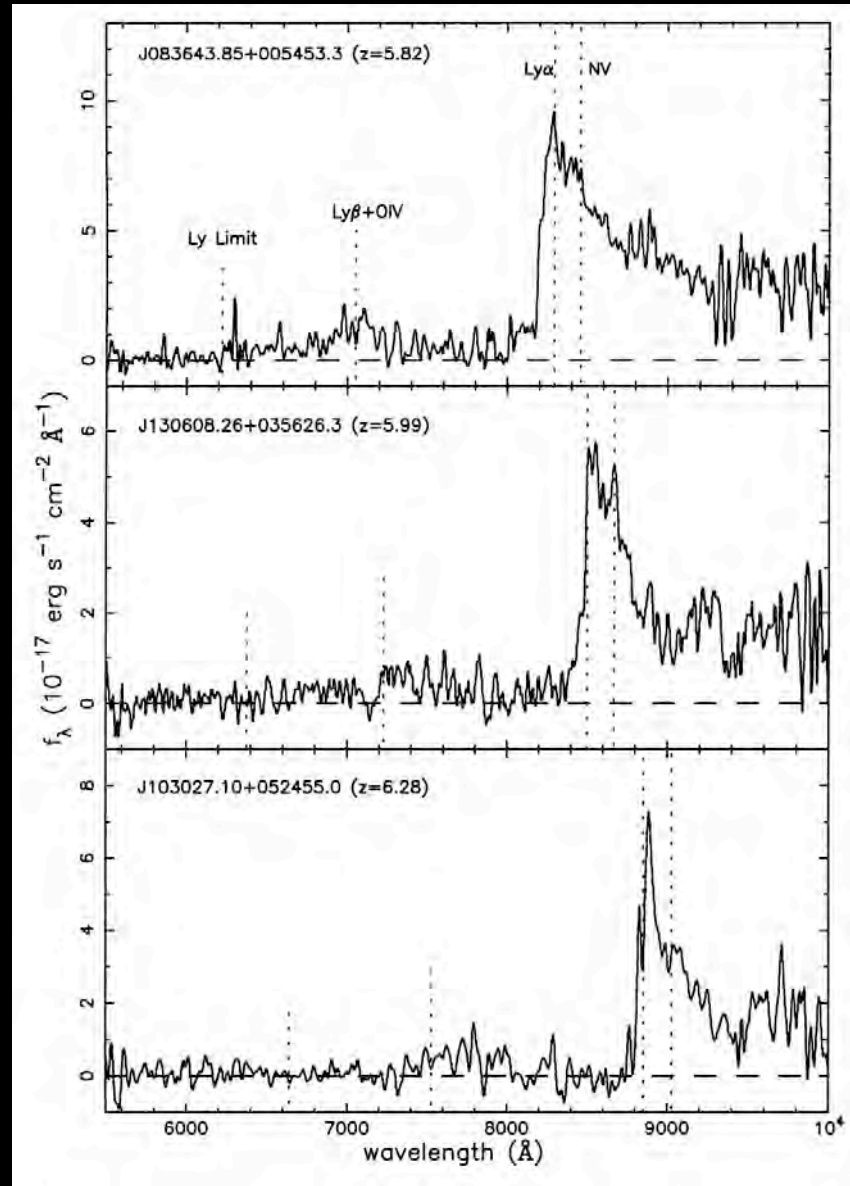




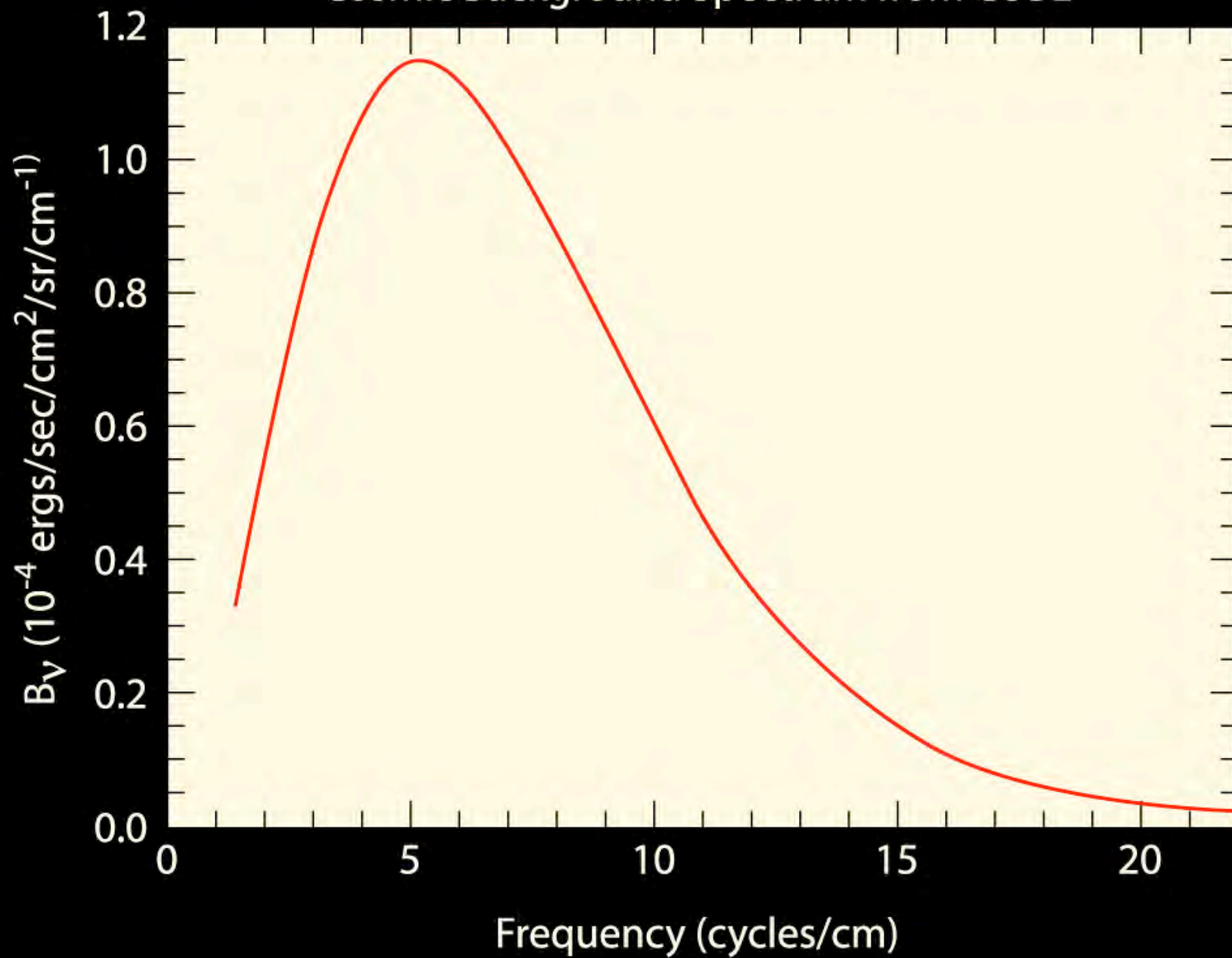




# THE HIGHEST-REDSHIFT QUASARS



# Cosmic Background Spectrum from COBE



Calculations of  
the primal  
“cooking” of  
the chemical  
elements predict  
Hydrogen  
Helium  
Lithium  
etc, correctly!

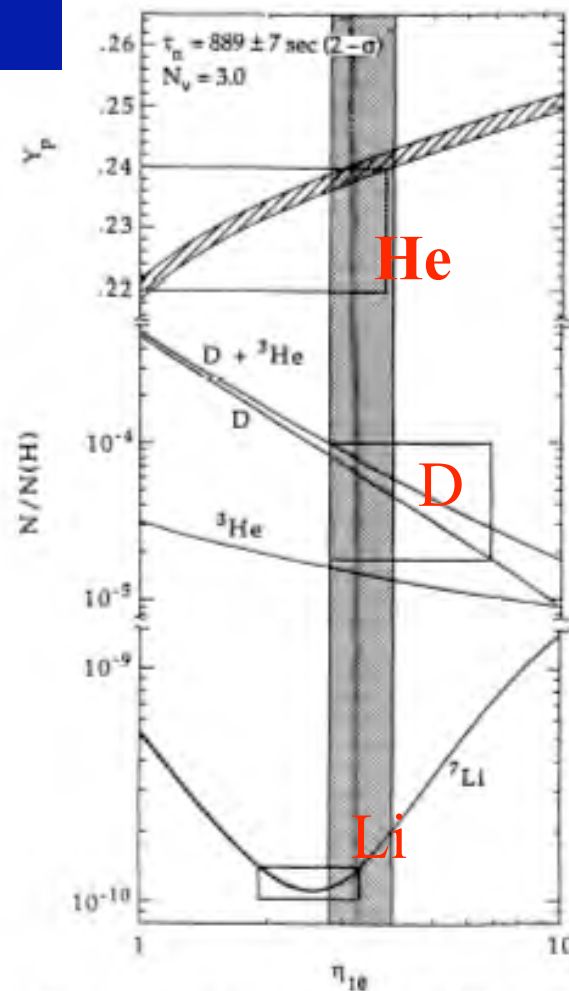
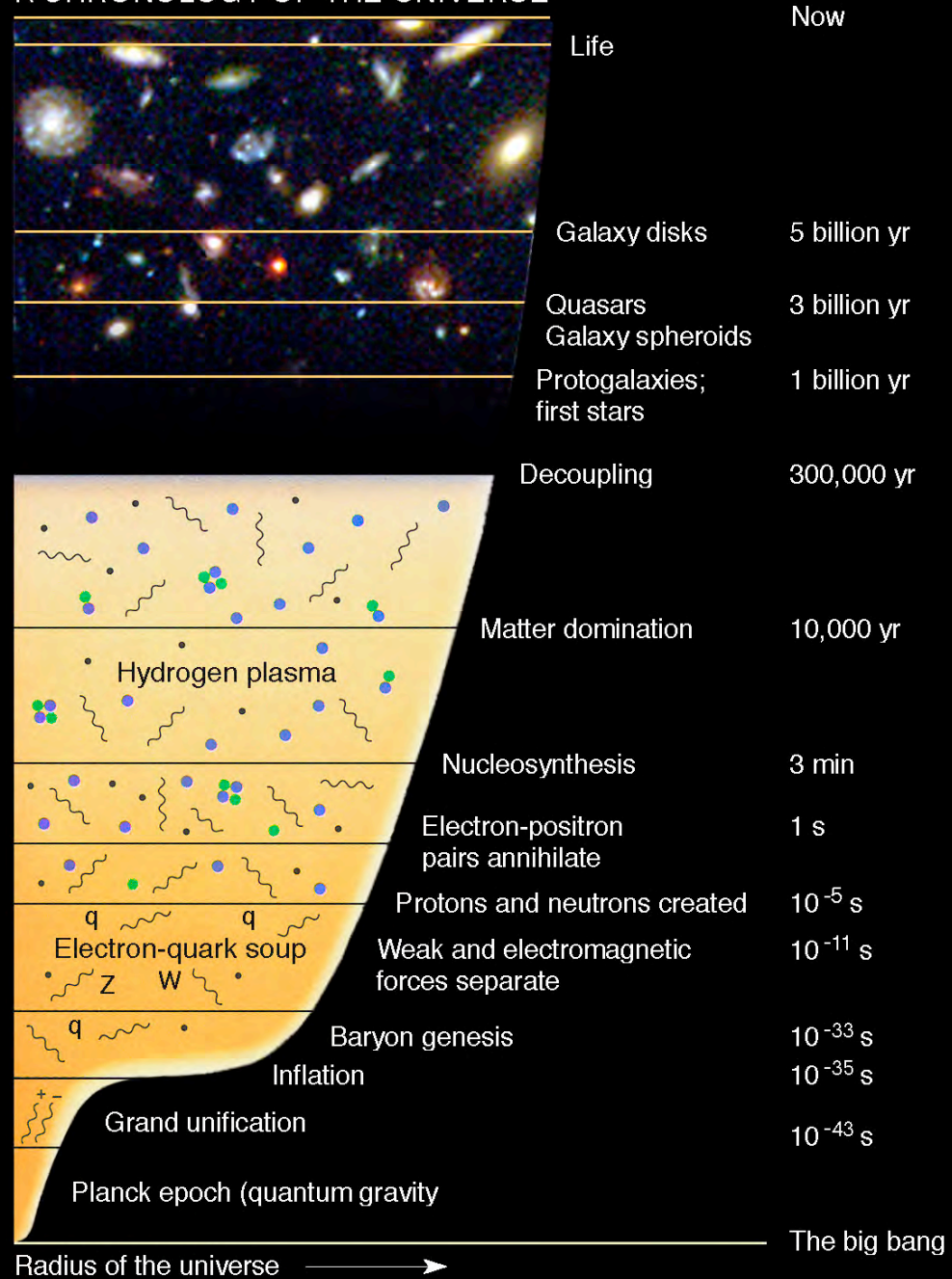


FIG. 13.—Predicted abundances (by number) of D,  ${}^3\text{He}$ ,  $D + {}^3\text{He}$ , and  ${}^7\text{Li}$ , and the  ${}^4\text{He}$  mass fraction as a function of  $\eta$  for  $N_\nu = 3$  and  $882 \leq \tau_n \leq 896 \text{ s}$ . The 95% CL bounds on the abundances (see text) are shown. The vertical band delimits the range of  $\eta$  consistent with the observations.

# A CHRONOLOGY OF THE UNIVERSE





# OUR UNIVERSE

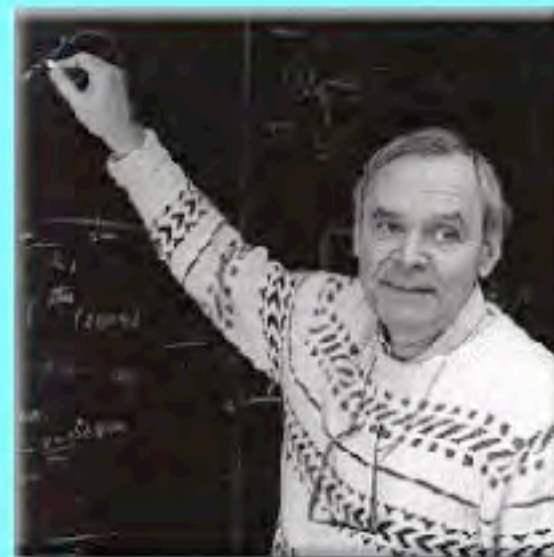
How did our complex cosmos --with huge contrasts in density and temperature -- emerge from near-uniform conditions at early times?



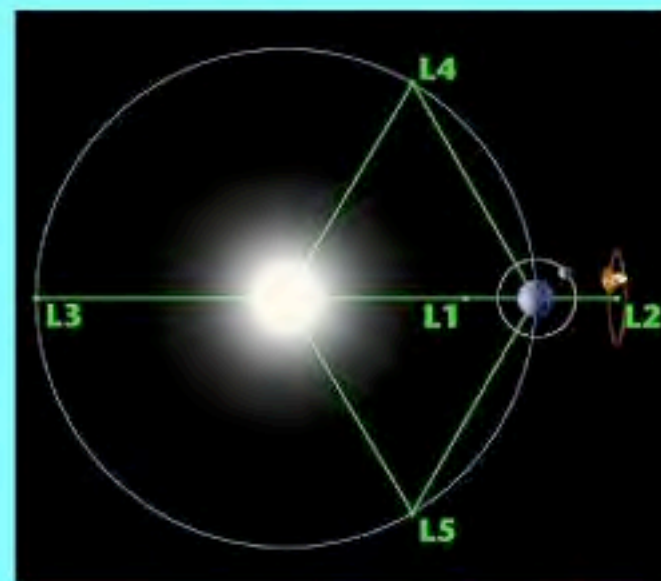
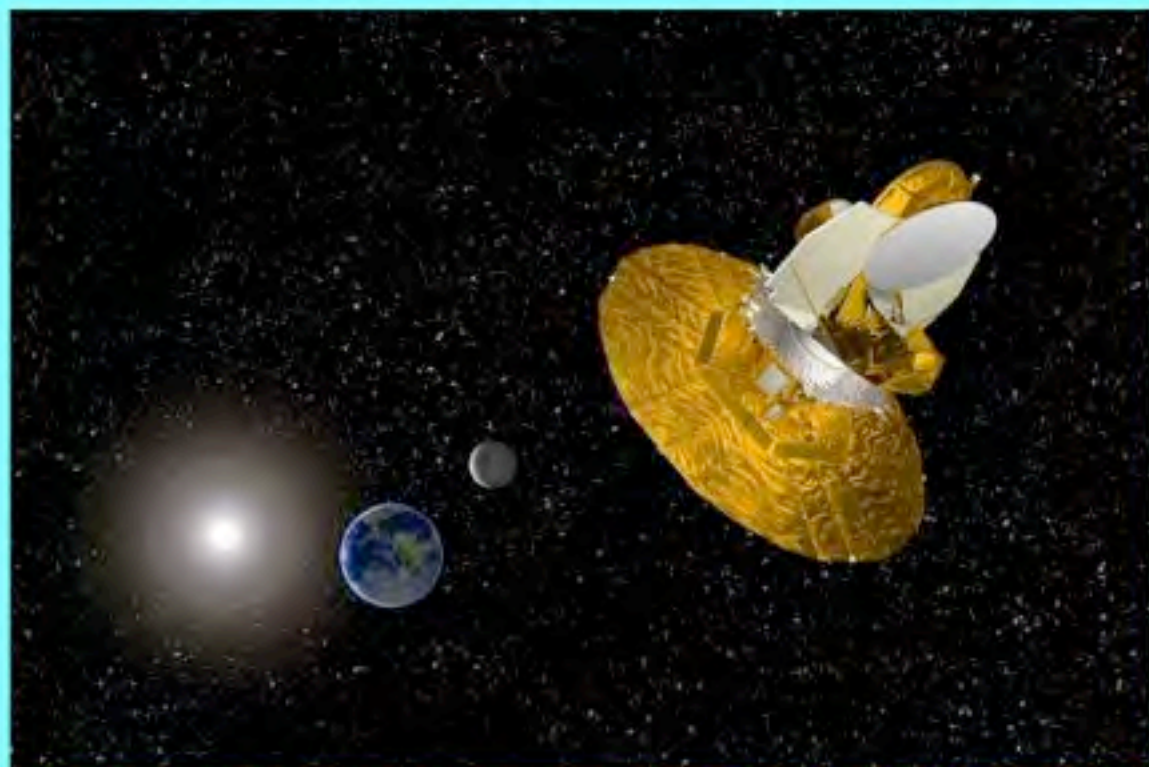
t = 0.06 Gyr

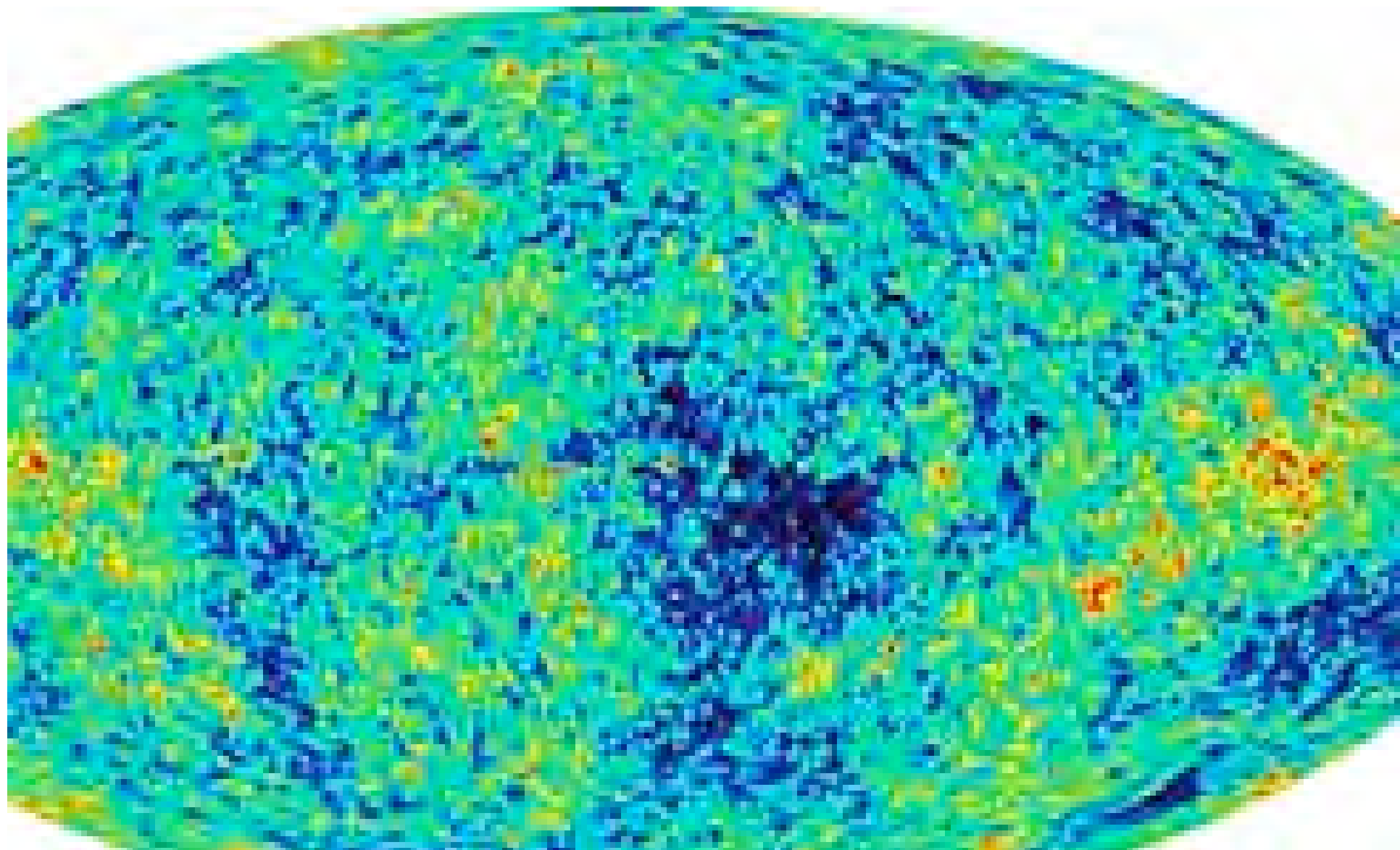
# WMAP: Wilkinson Microwave Anisotropy Probe

*Images courtesy of NASA/WMAP Science Team*



David T. Wilkinson







1 Gpc/h

Millennium Simulation

10,077,696,000 particles

( $z = 0$ )

## FLUCTUATION AMPLITUDE

$$Q \approx 10^{15} \frac{\delta T}{T}$$

→ Bound Systems\* with Gravitational Binding Energy  $QMc^2$   
(Virial Velocity  $Q^{1/2}c$ )

Max Non-Linear Scale

→  $Q^{1/2} \times$  (Hubble Radius).

\*Formation of Bound System Requires Expansion Factor of  $> \sim Q^{-1}$  After System Enters Horizon.

## AN ANAEMIC UNIVERSE ( $Q = 10^{-6}$ )

Small loosely-bound galaxies form later than in our universe; star formation is still possible, but processed material is likely to be expelled from shallow potential wells. There may be no second-generation stars containing heavy elements, and so no planetary systems at all.

If  $Q$  were significantly lower than  $10^{-6}$ , then gas would be unable to cool with a Hubble time.\*

*In a  $\Lambda$ -dominated universe, isolated clumps could survive for an infinite time without merging into a larger scale of hierarchy. So eventually, for any  $Q > 10^{-8}$ , a 'star' could form – but by that time there would be merely one minihalo within the entire event horizon!*

## POSSIBLE UNIVERSE WITH $Q = 10^{-4}$

*\*perhaps more interesting than ours!*

Masses  $>\sim 10^{14} M$  condense at  $3 \cdot 10^8$  yrs into huge disc galaxies with orbital velocity  $\sim 2000$  km/sec (gas would cool efficiently via Compton cooling, leading probably to efficient star formation).

These would, after  $10^{10}$  yrs, be in clusters of  $>\sim 10^{16} M$ .

There would be a larger range of non-linear scales than in our actual universe. Only possible 'disfavouring' feature is that stellar systems may be too packed together to permit unperturbed planetary orbits.

# 5 WAYS TO REFUTE "HOT BIG BANG"

Object with  $\ll 23\%$  helium

Millimetre-wave background below prediction

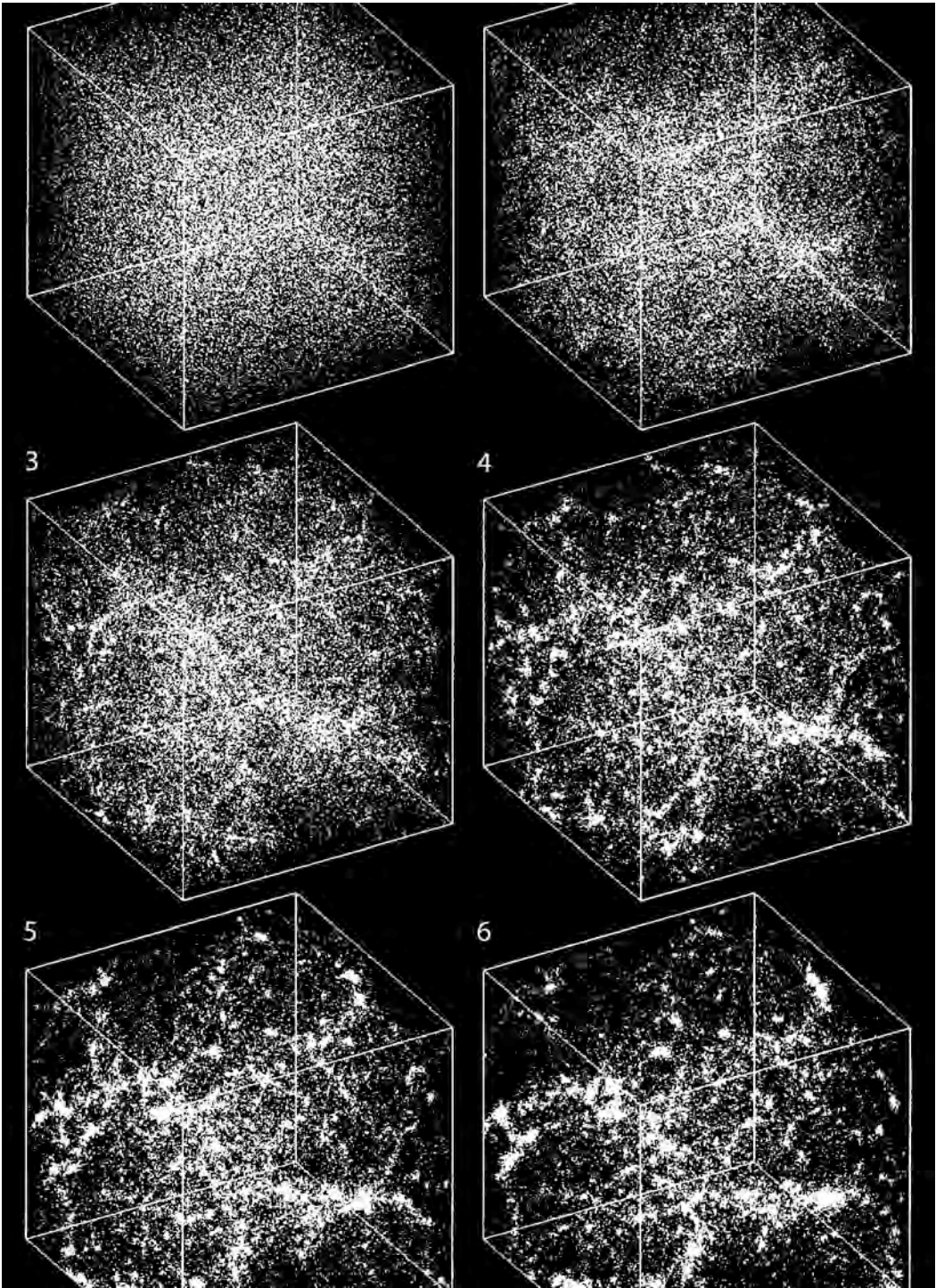
Stable neutrino with mass  $100 - 10^6$  eV

Too much deuterium to match baryon density

$\Delta T/T$  too small to account for present structure

When did the cosmic dark age  
end?

Formation of the first stars in  
'minihalos'

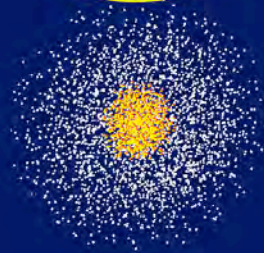


# FATE OF THE FIRST BOUND SYSTEMS

( $z \approx 20$ )

$$T_{\text{virial}} \propto M^{2/3} (1+z)_{\text{collapse}}$$

$10^4 M_{\odot}$



$T_{\text{virial}} \approx 50\text{K}$   
no cooling; no star formation

$10^6 M_{\odot}$



$T_{\text{virial}} \approx 10^3\text{K}$   
 $\text{H}_2$  cooling

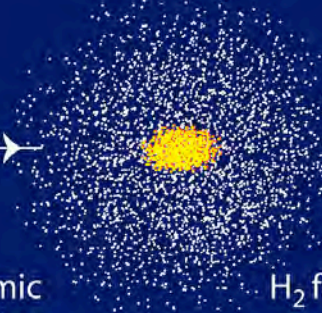


$10^8 M_{\odot}$

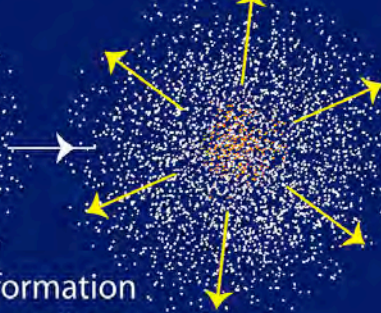


$T_{\text{virial}} \approx 20000\text{K}$

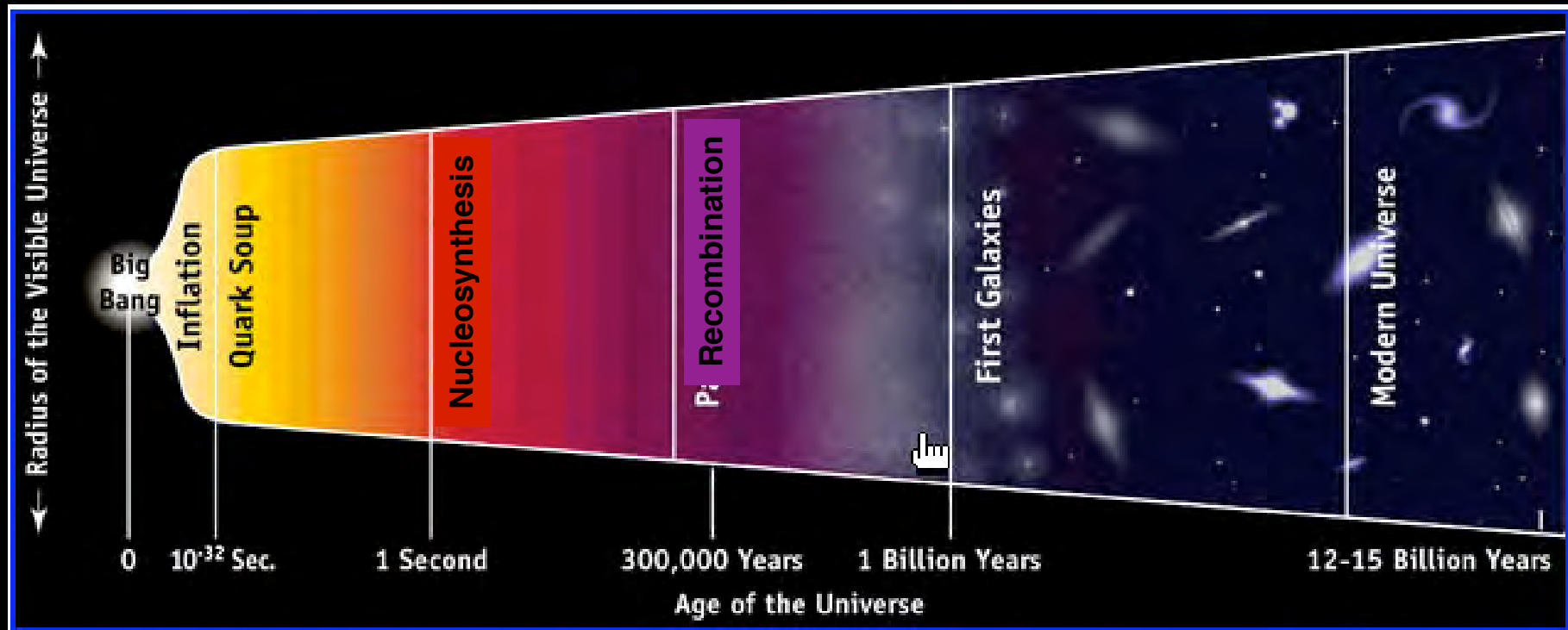
atomic cooling



$\text{H}_2$  formation & cooling



# Cosmic Structure Formation-Cartoon



linear perturbation theory

nonlinear simulations

# GALAXIES

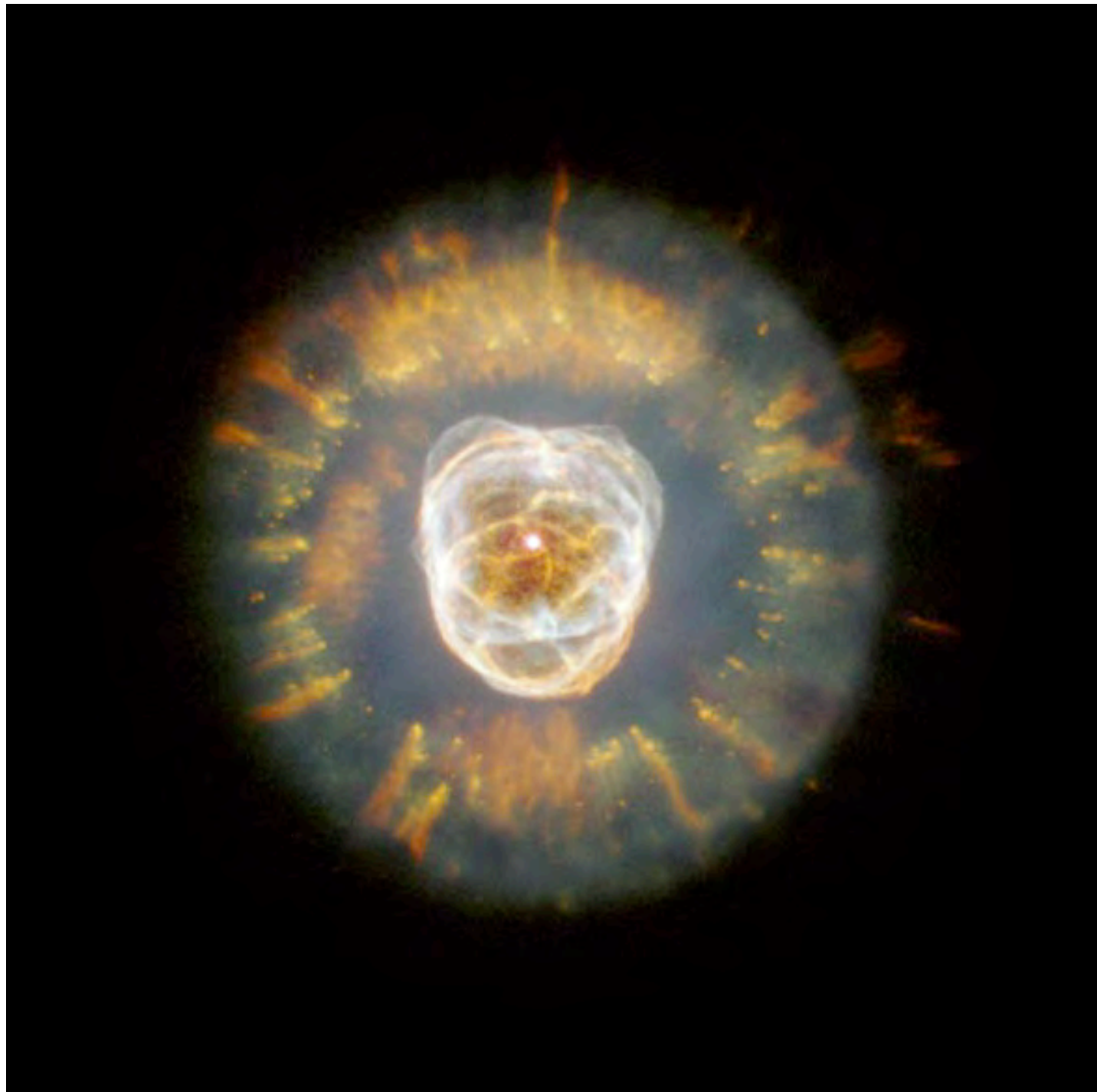
(i) Tracers of large-scale cosmic structure

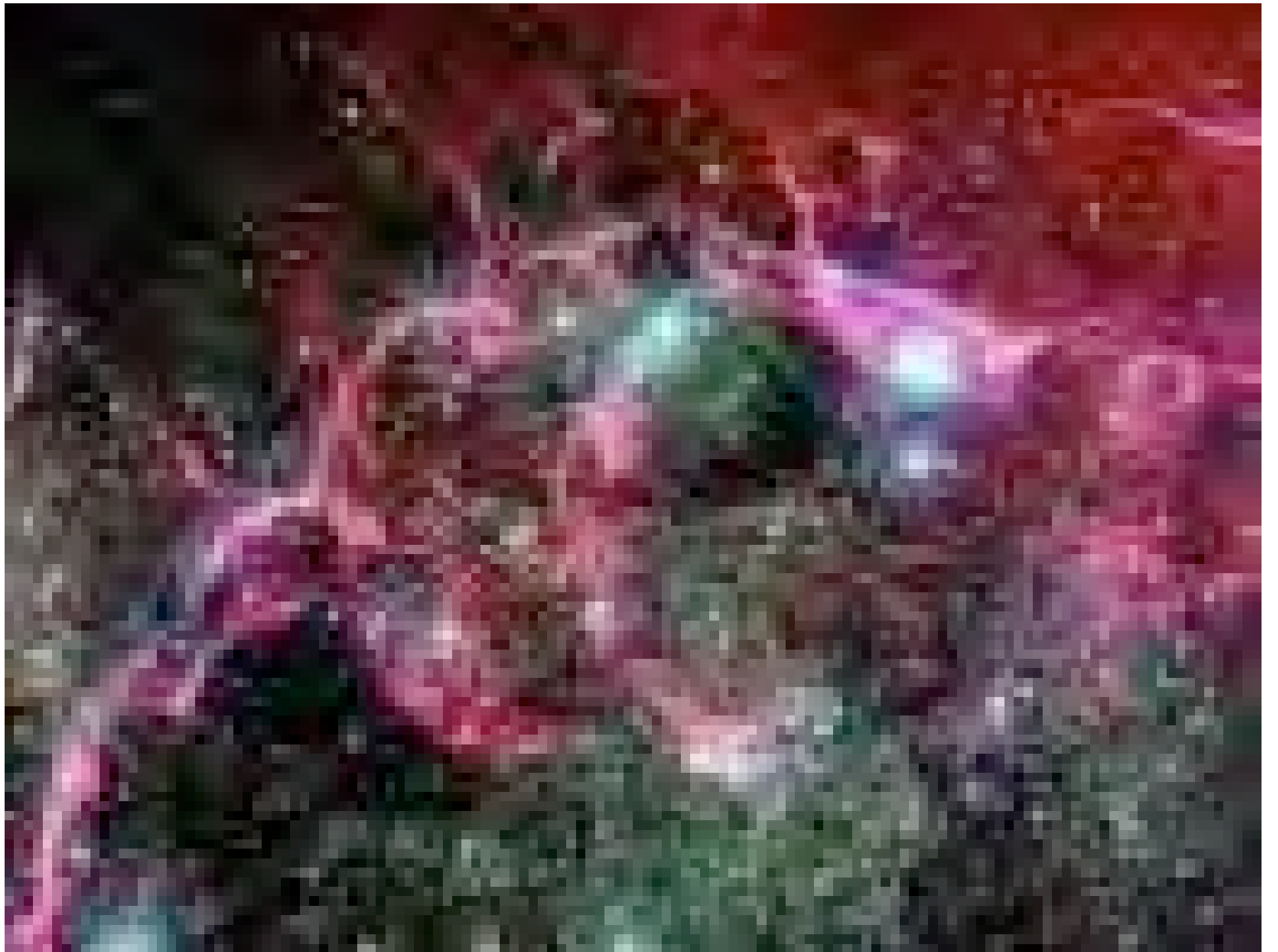
(ii) 'Ecosystems' of the cosmos  
(with central black holes)











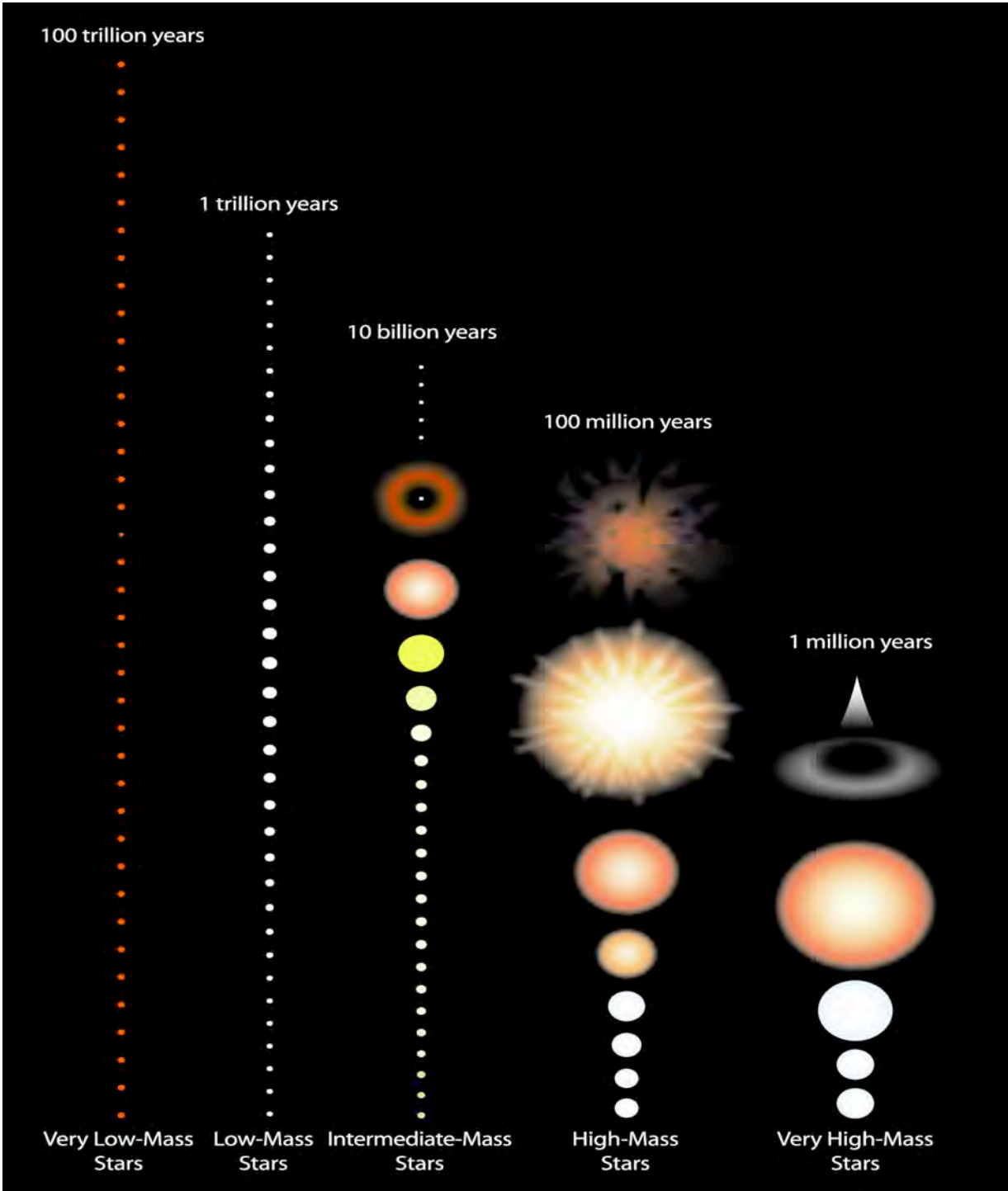


## STELLAR NUCLEAR ENERGY

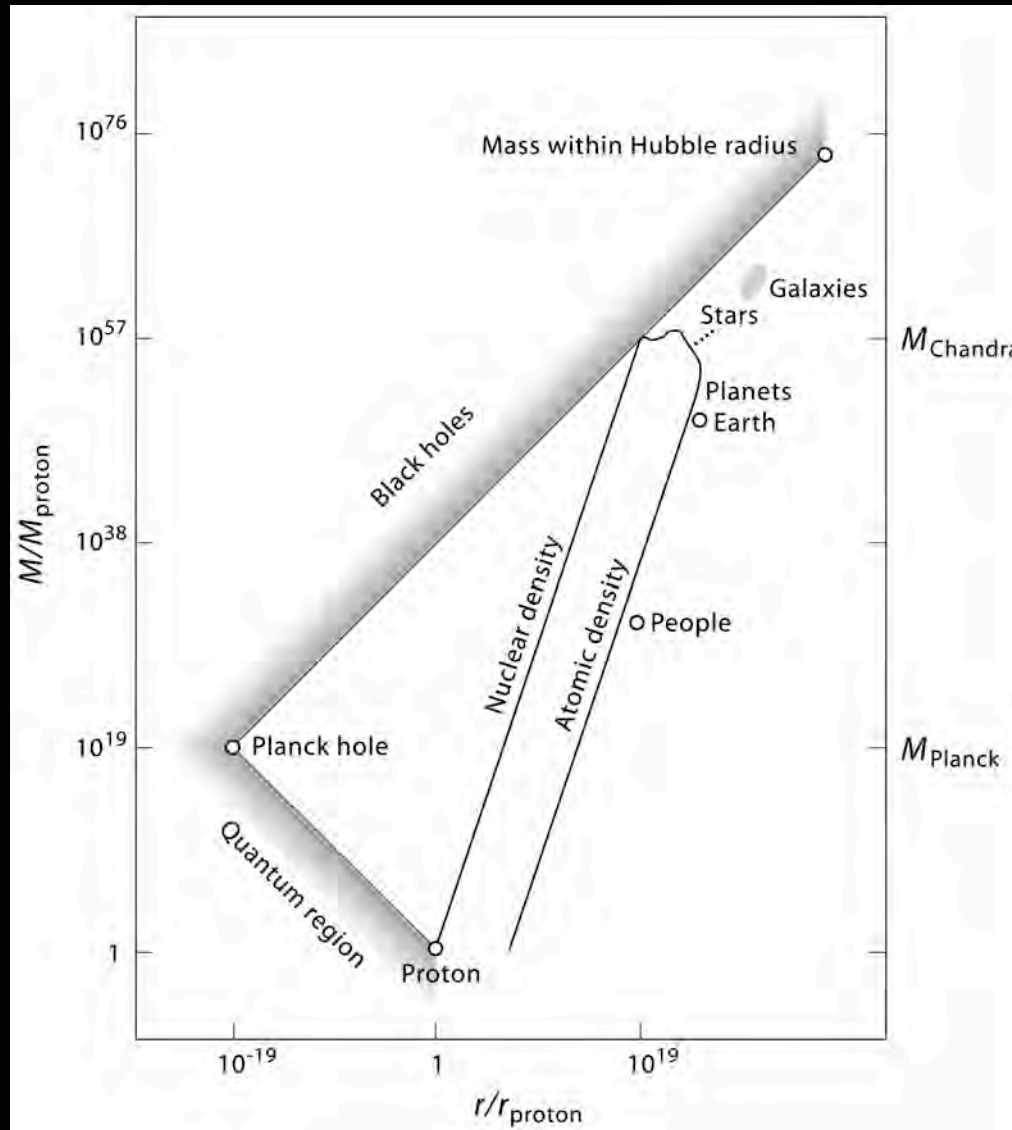
$$(\text{Efficiency}) = 0.0081 + 0.0071 \frac{\Delta Y}{\Delta Z}$$

Where  $\Delta Y$  is increment in He

$\Delta Z$  is increment in heavier elements







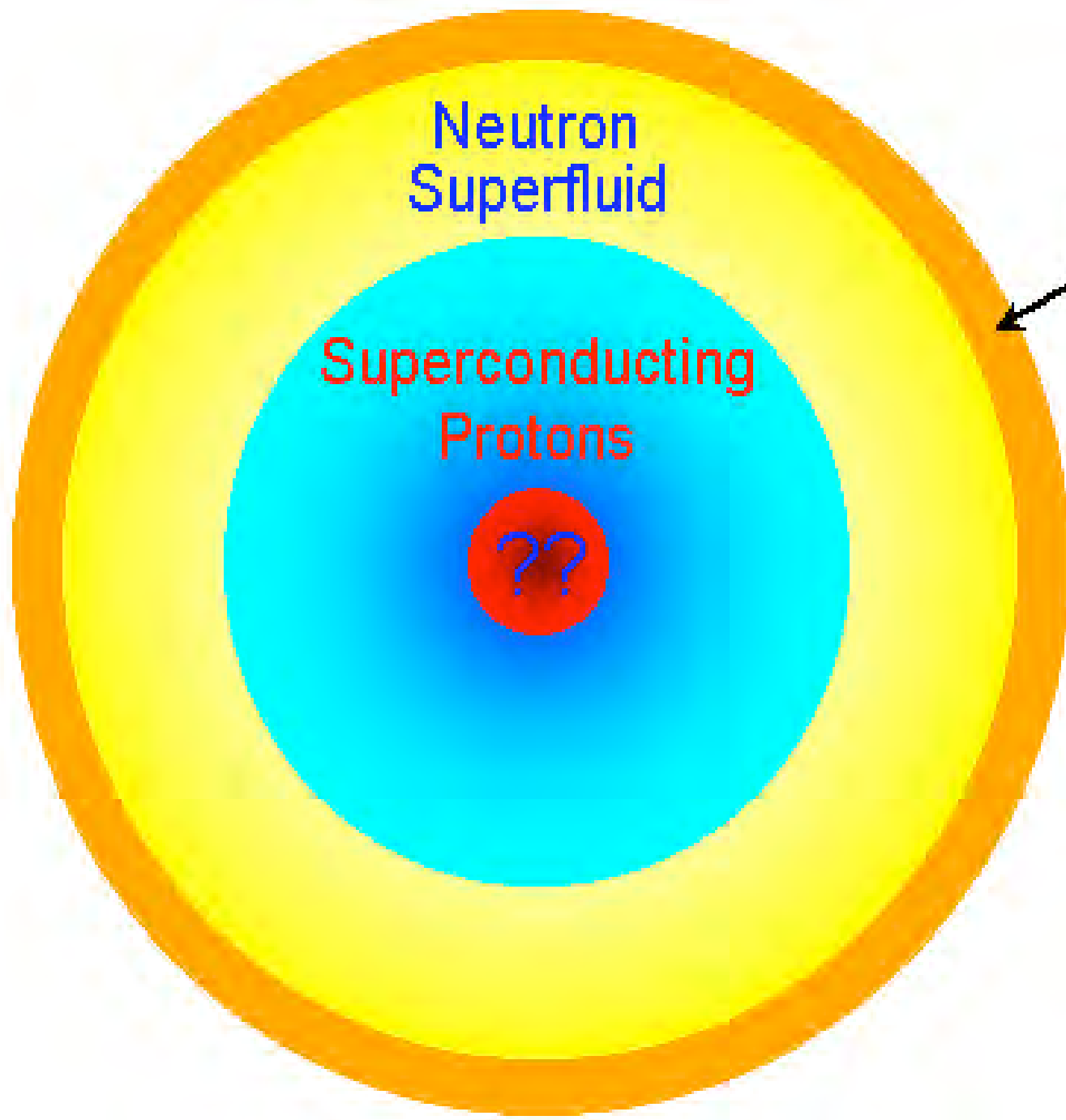
# GRAVITATIONAL ENERGY

In 'ordinary' stars, release of gravitational energy is *less* important than nuclear power (by factor 1000).

- *But*

When nuclear energy runs out, a star may contract so much that *more gravitational energy is released than ever came from nuclear reactions.*

*(STARS HAVE NEGATIVE SPECIFIC HEAT!)*

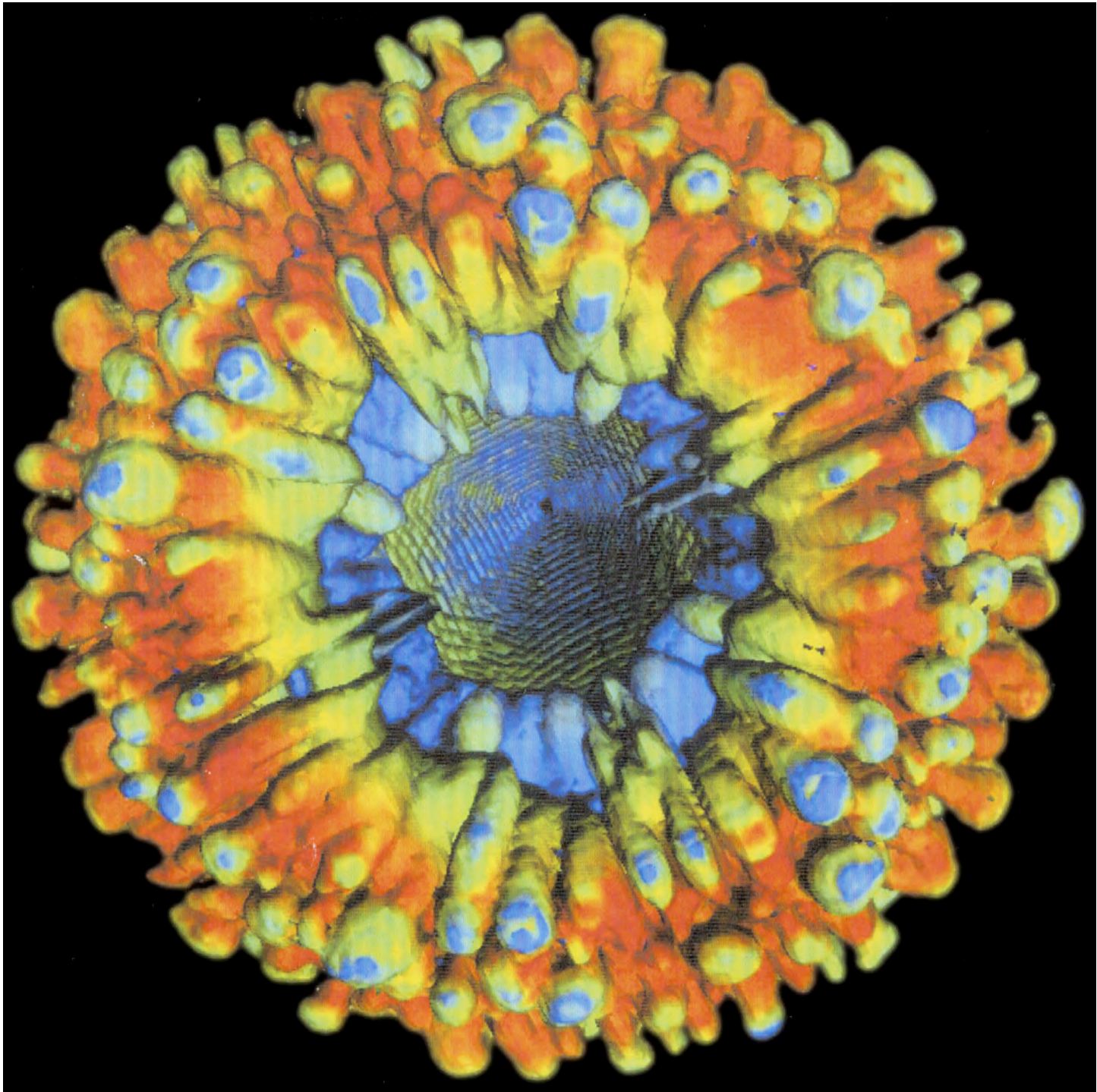


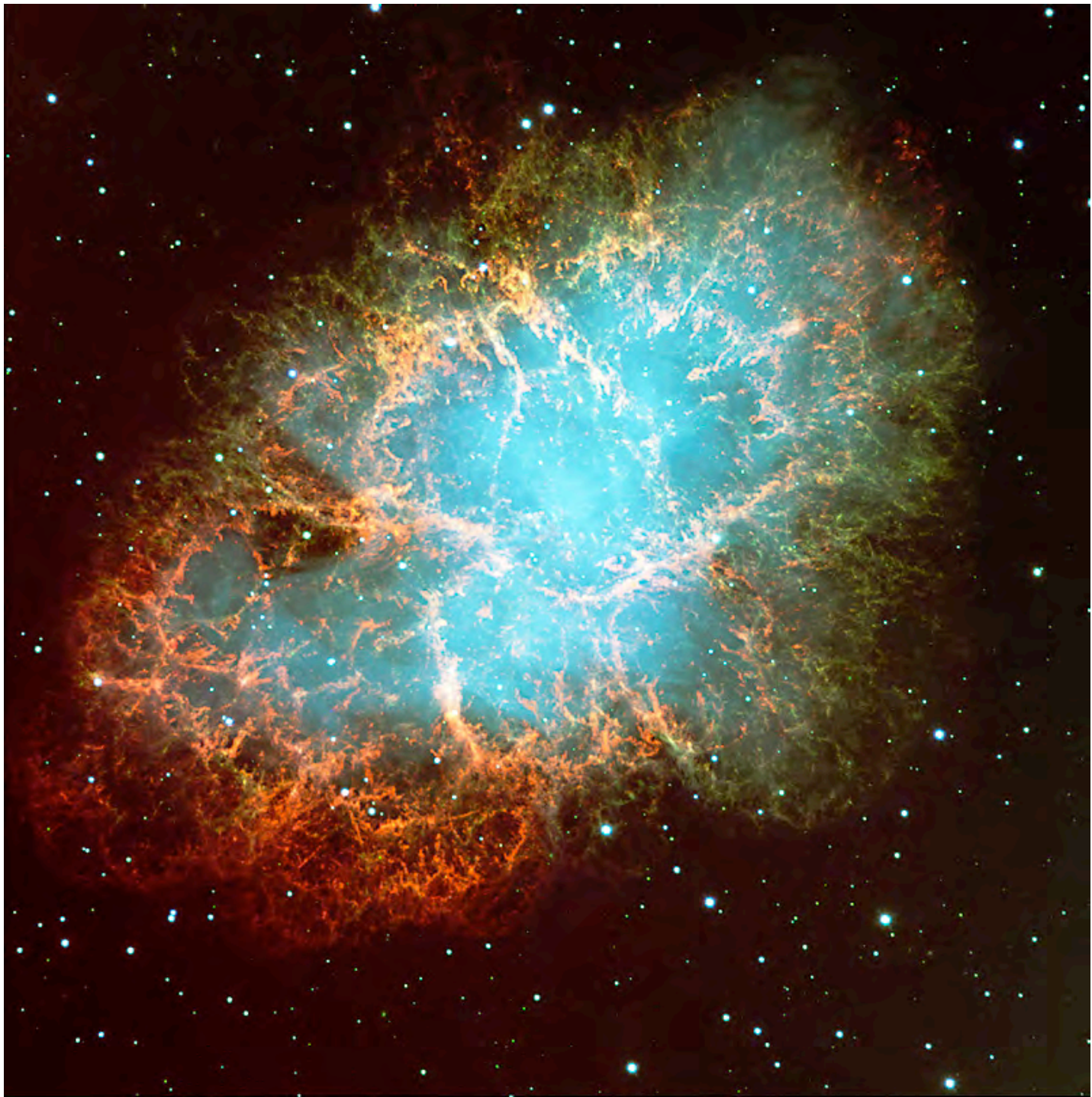
Neutron  
Superfluid

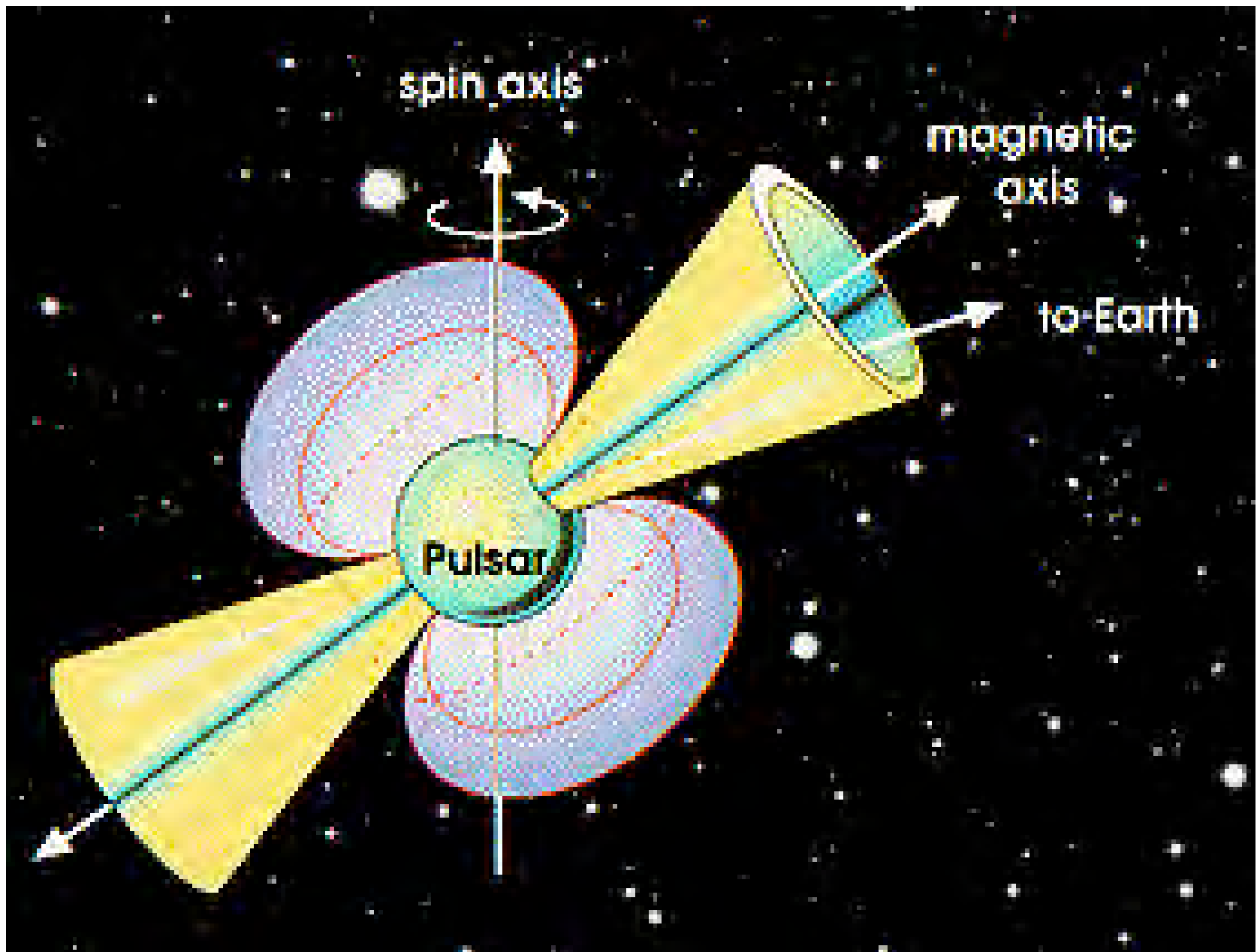
Superconducting  
Protons

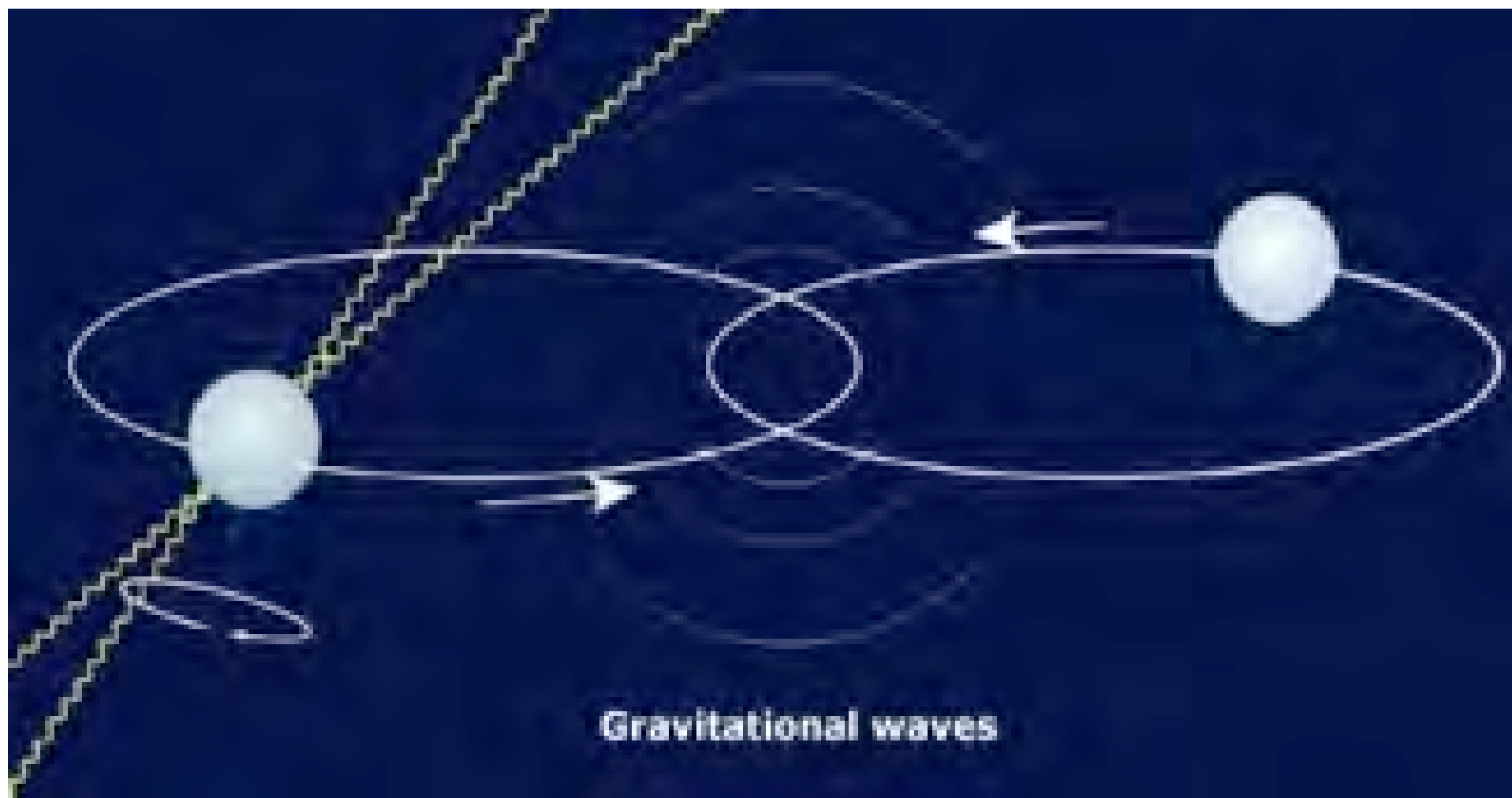
??

Crystalline  
Iron Crust

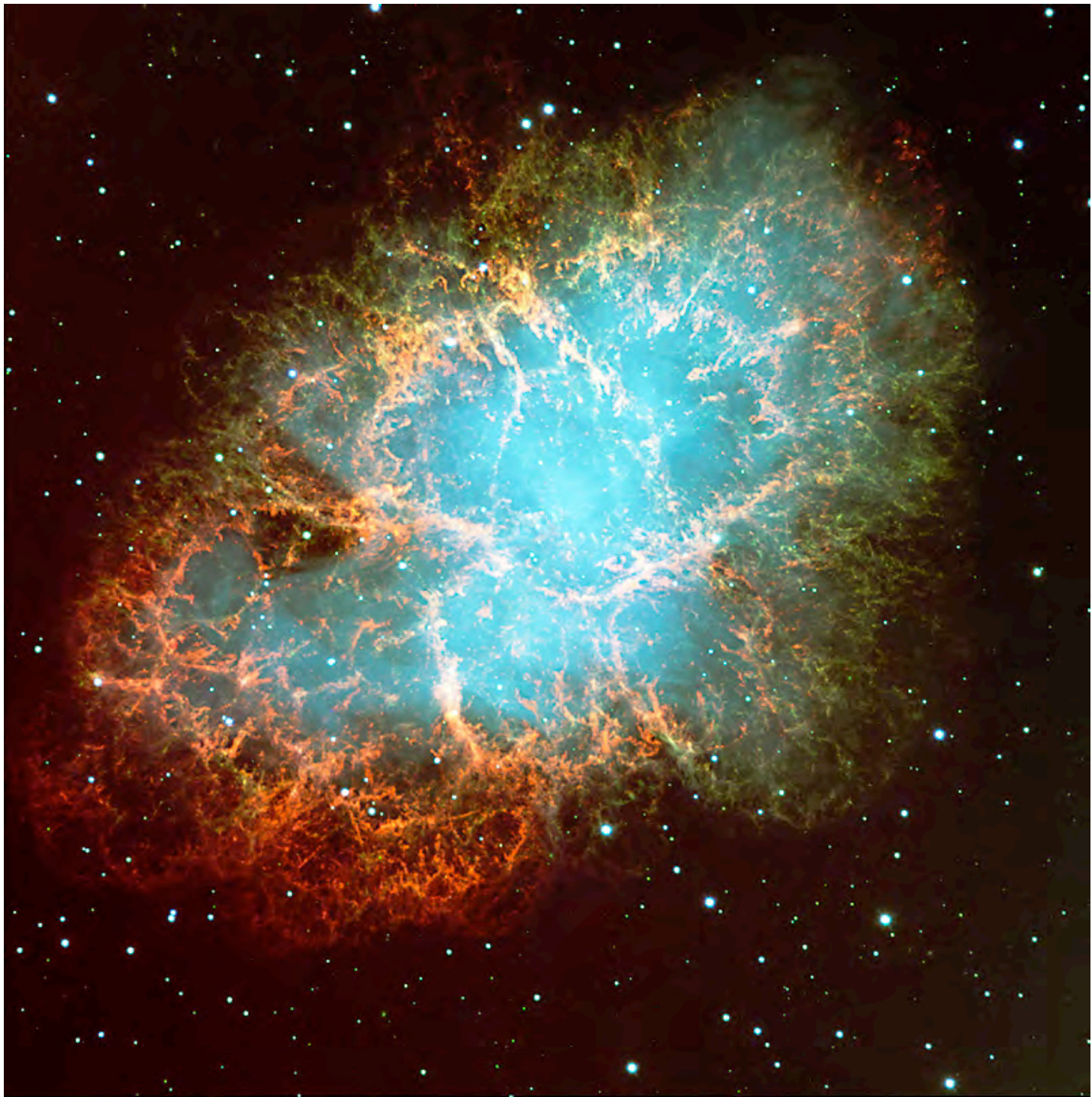




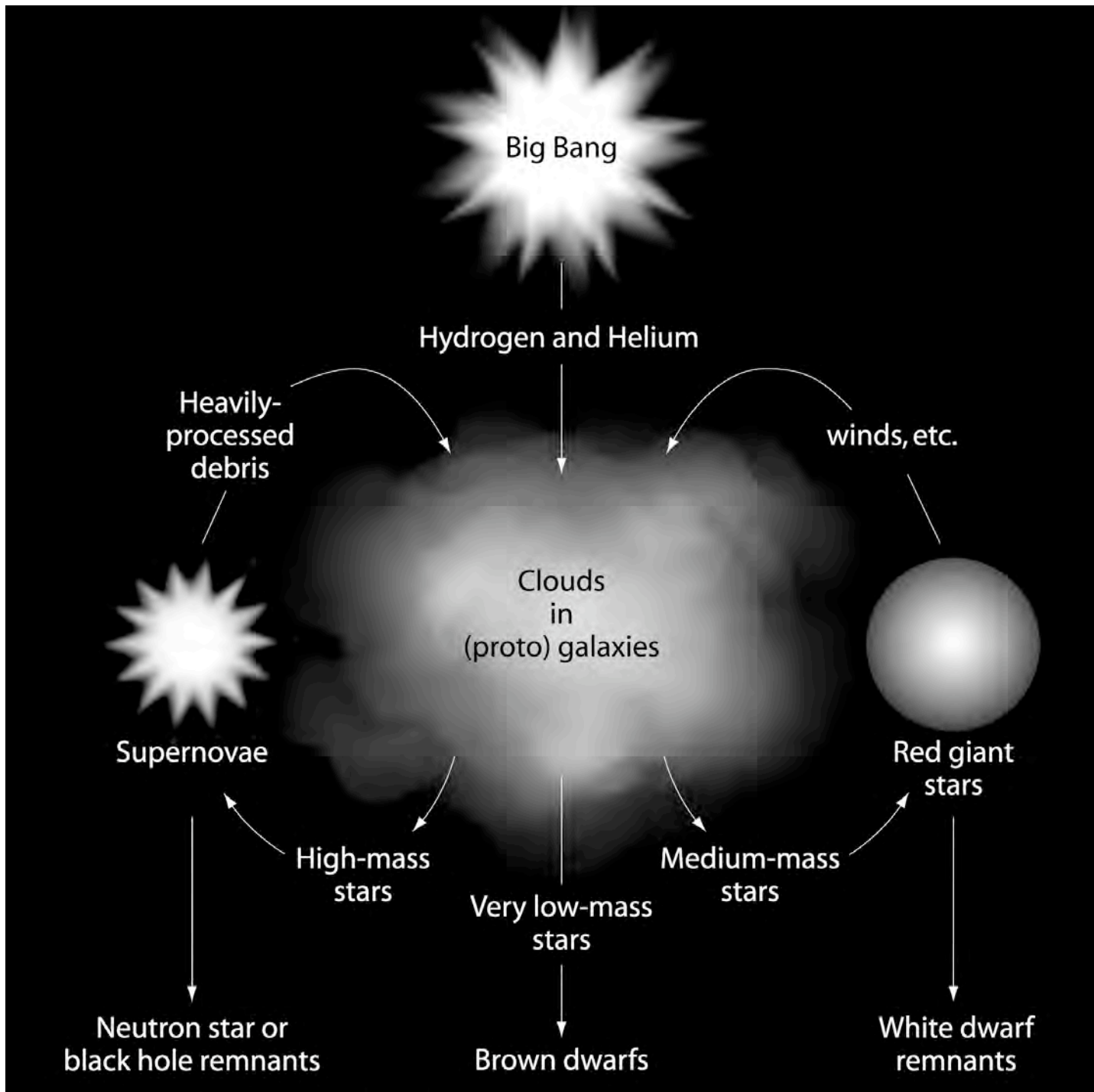








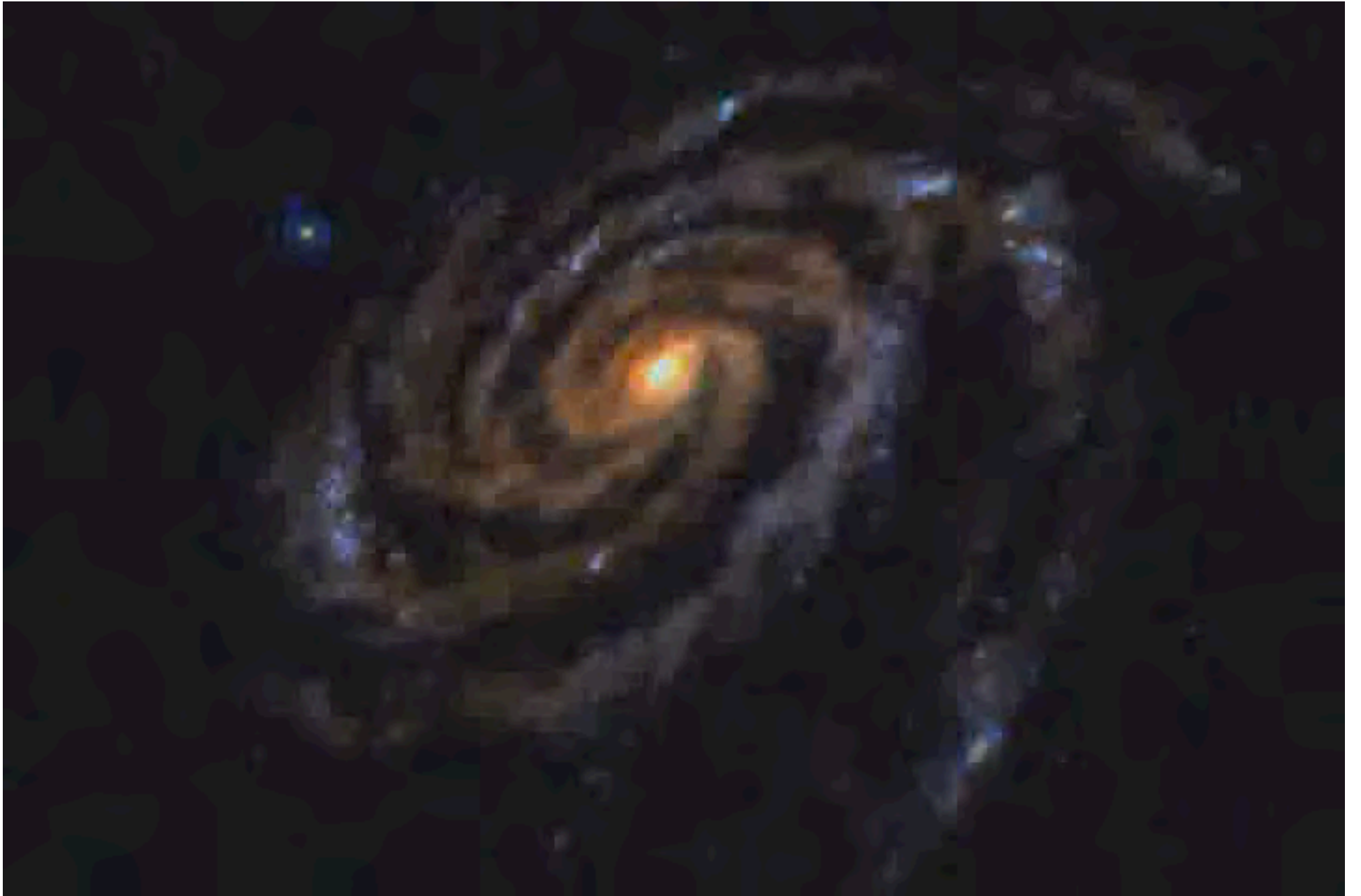


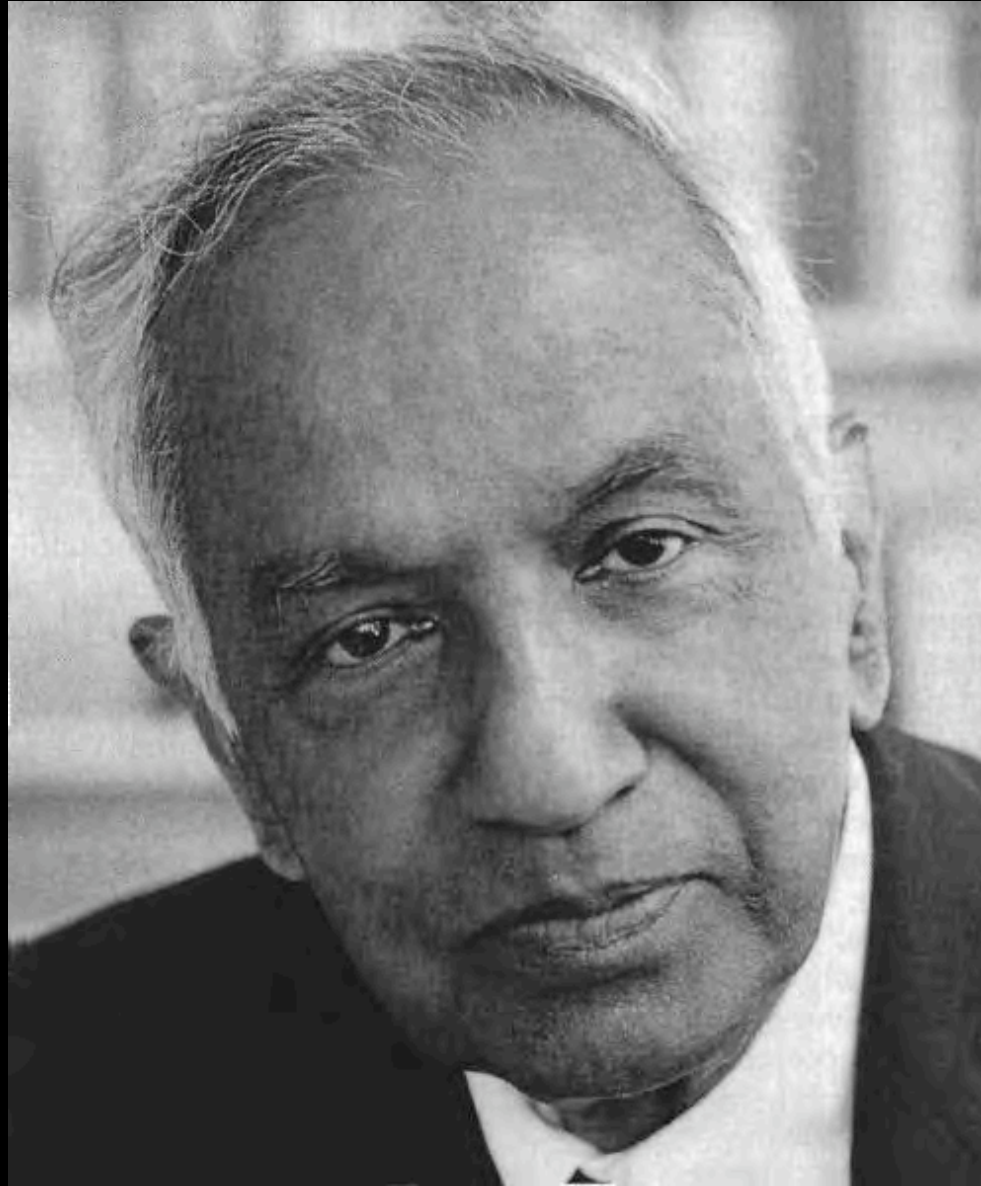




# BLACK HOLES

Gravity's final triumph over all other  
forces

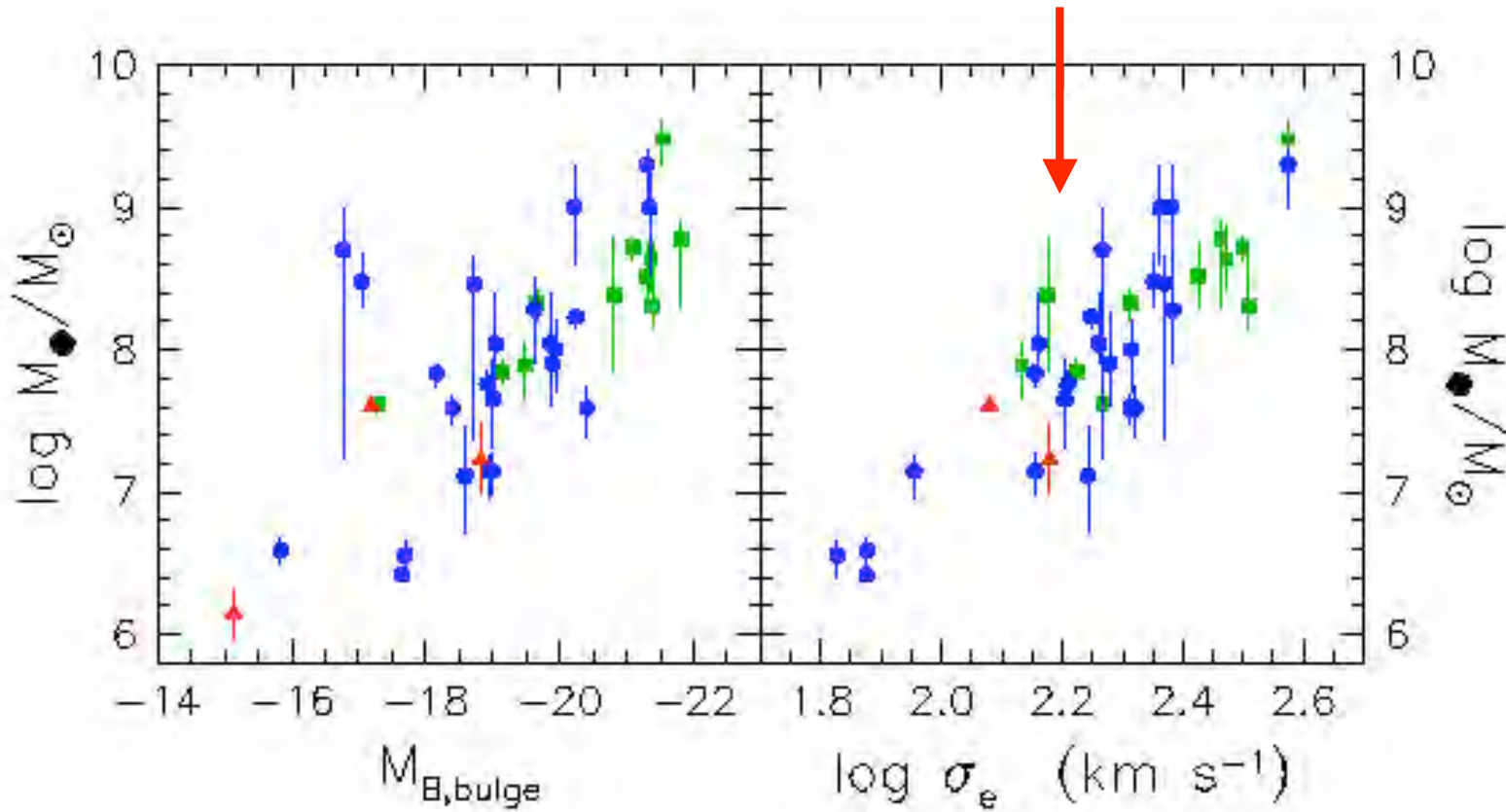




**"In my entire scientific life,... the most shattering experience has been the realisation that an exact solution of Einstein's equations..... provides the absolutely exact representation of untold numbers of massive black holes that populate the universe"**

**S. Chandrasekhar.**

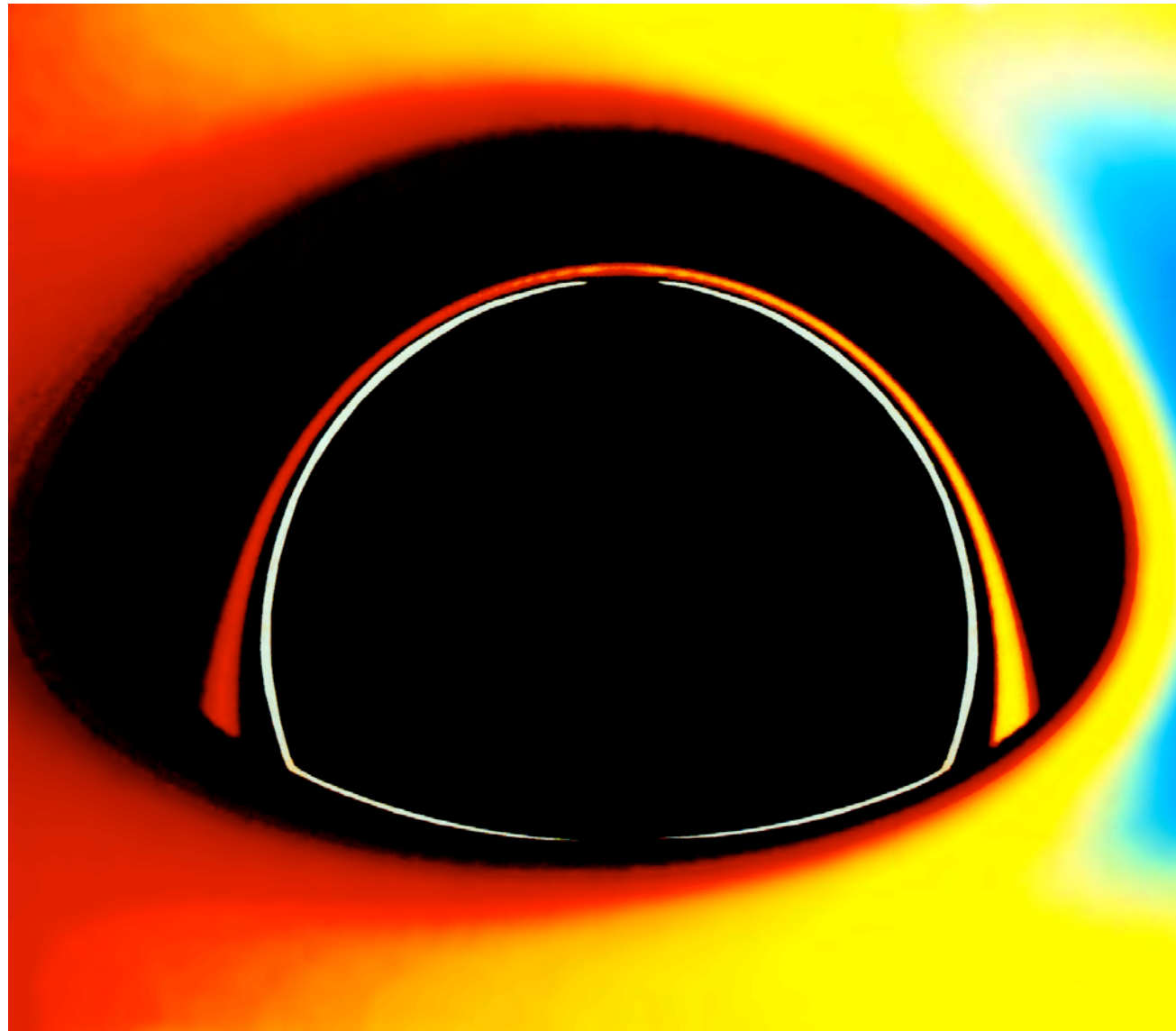
Is this really tighter?



Kormendy 2003

black hole mass scales with

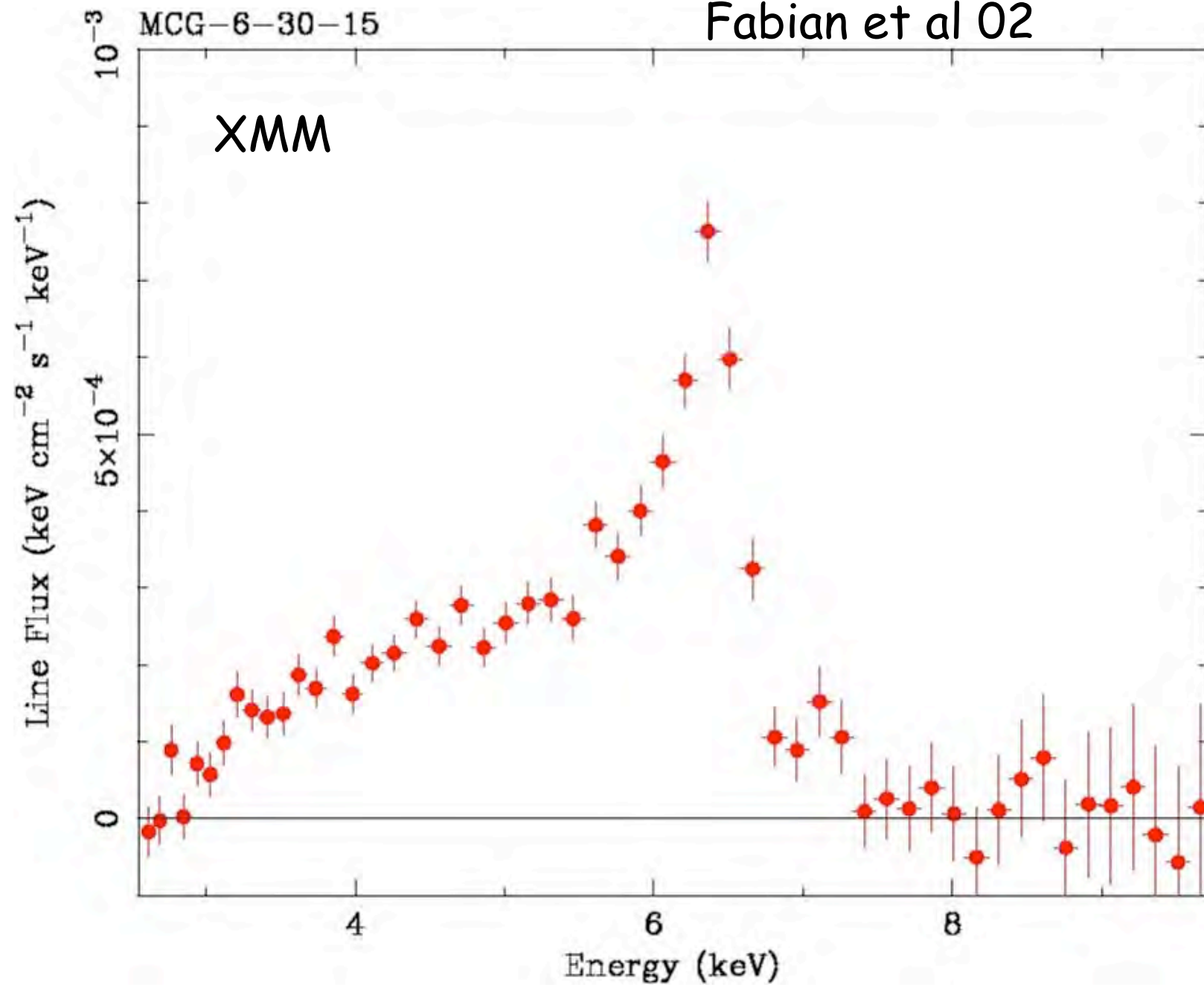
- bulge mass
- stellar velocity dispersion of the bulge

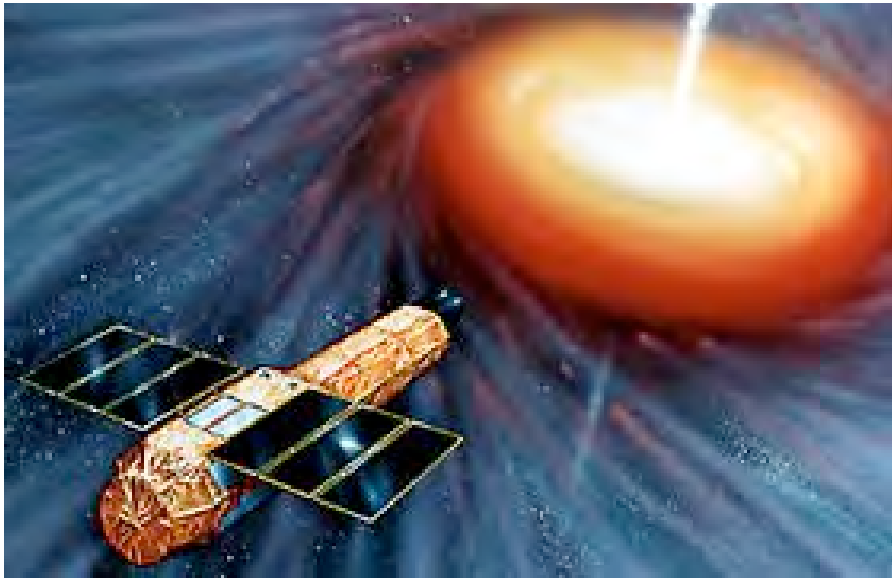


MCG-6-30-15

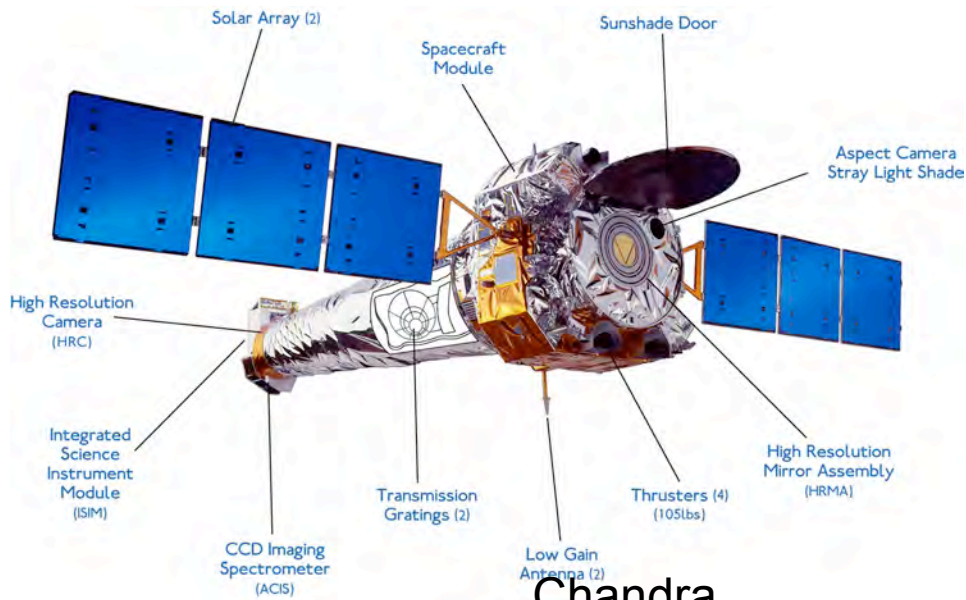
Fabian et al 02

XMM

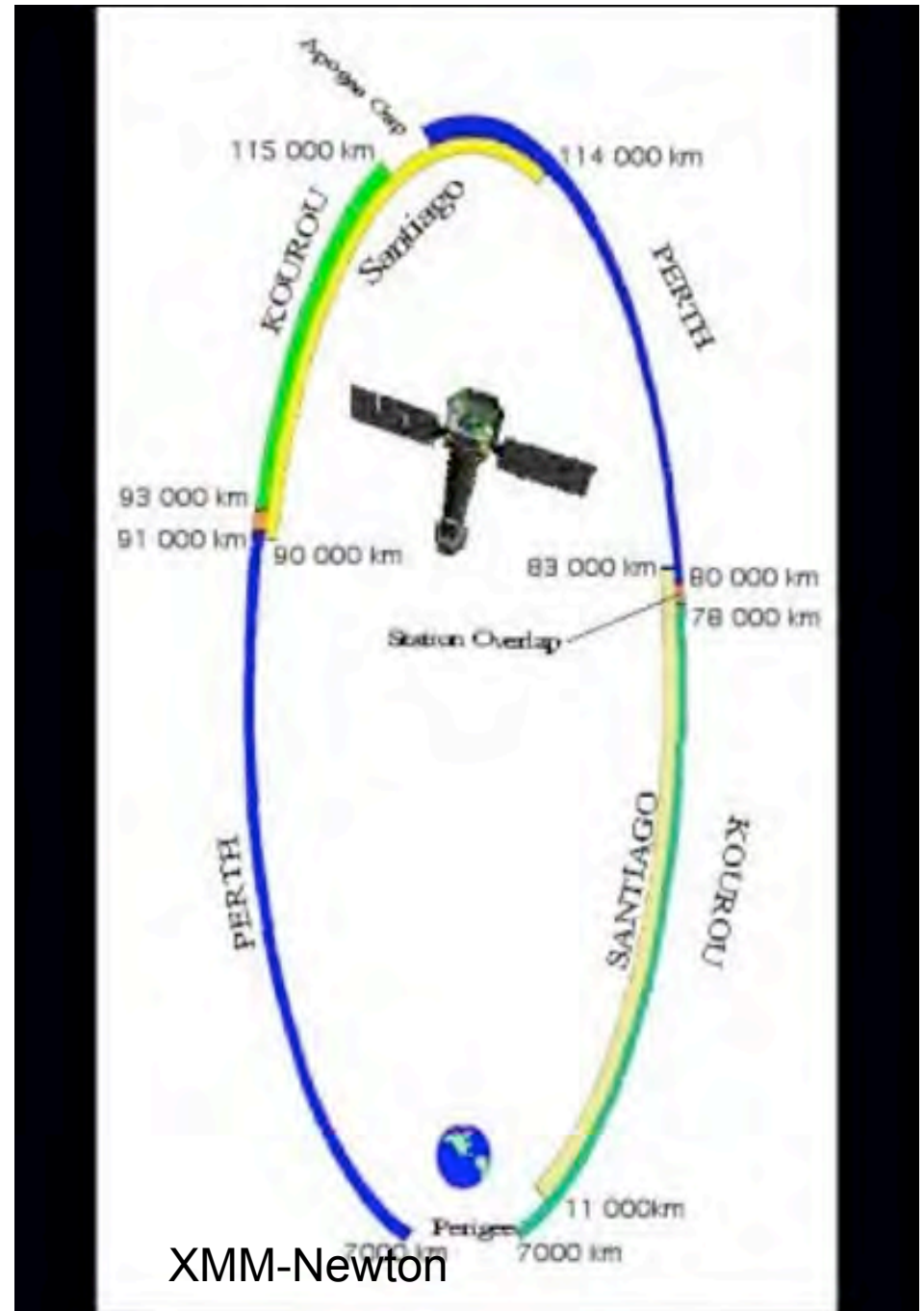




ASTRO-E2

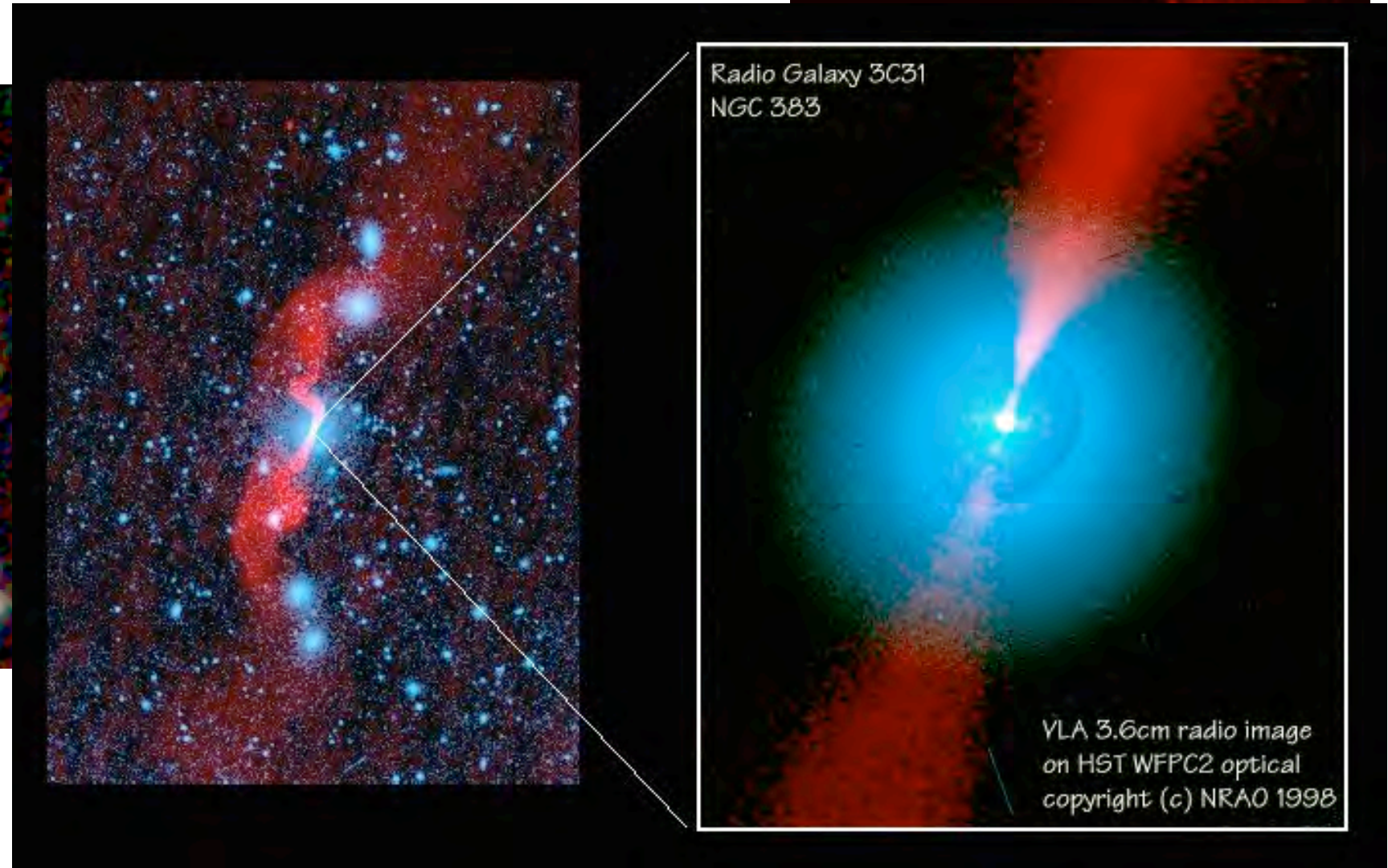


Chandra



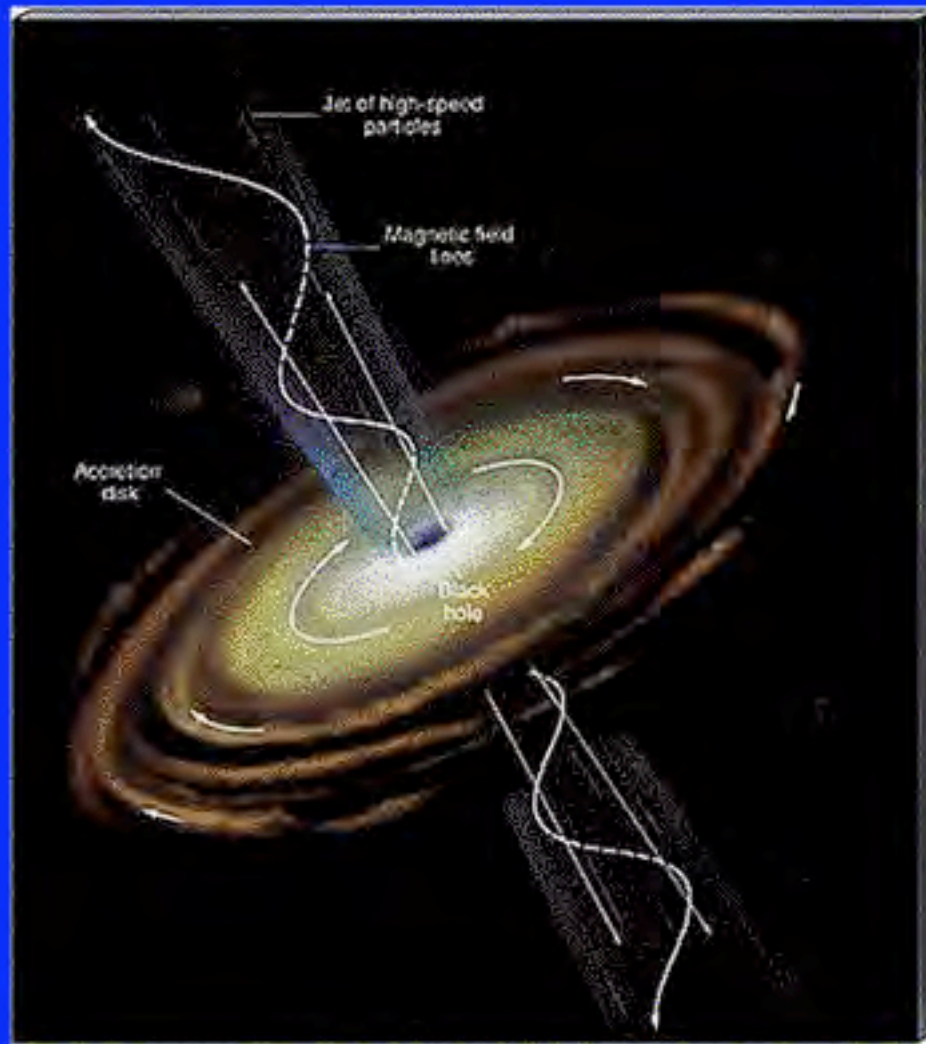
XMM-Newton

3C31:



radio

# Electromagnetic Formation of Jets



(Blandford-Znajek effect)

Corotating observer sees energy flow inwards at horizon; conserved energy flux in non-rotating frame is outward.

For a quasar jet:

$$B \sim 10^4 \text{ G}; M \sim 10^9 M_{\odot}$$

$$E \sim \Omega \Phi \sim 10^{20} \text{ V}$$

$$R_{\text{in}} \sim R_{\text{out}} \sim 100 \Omega$$

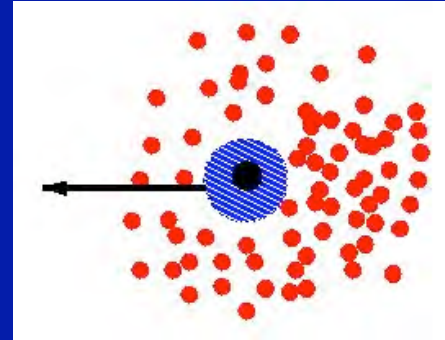
$$I \sim V / R \sim 10^{18} \text{ A}$$

$$P \sim E I \sim 10^{38} \text{ W}$$

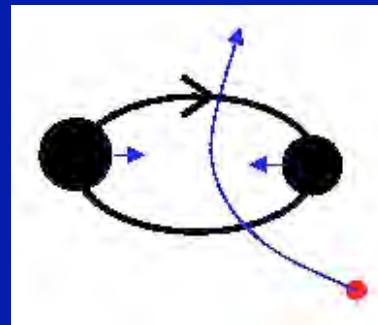
# Formation and evolution of supermassive binaries

1. Dynamical friction

$$t \propto a$$

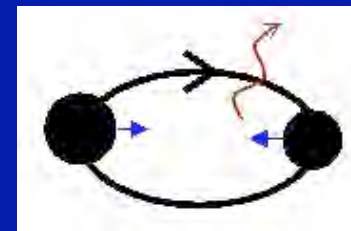


2. Binary hardening  
due to stars  
or  
accretion of gas

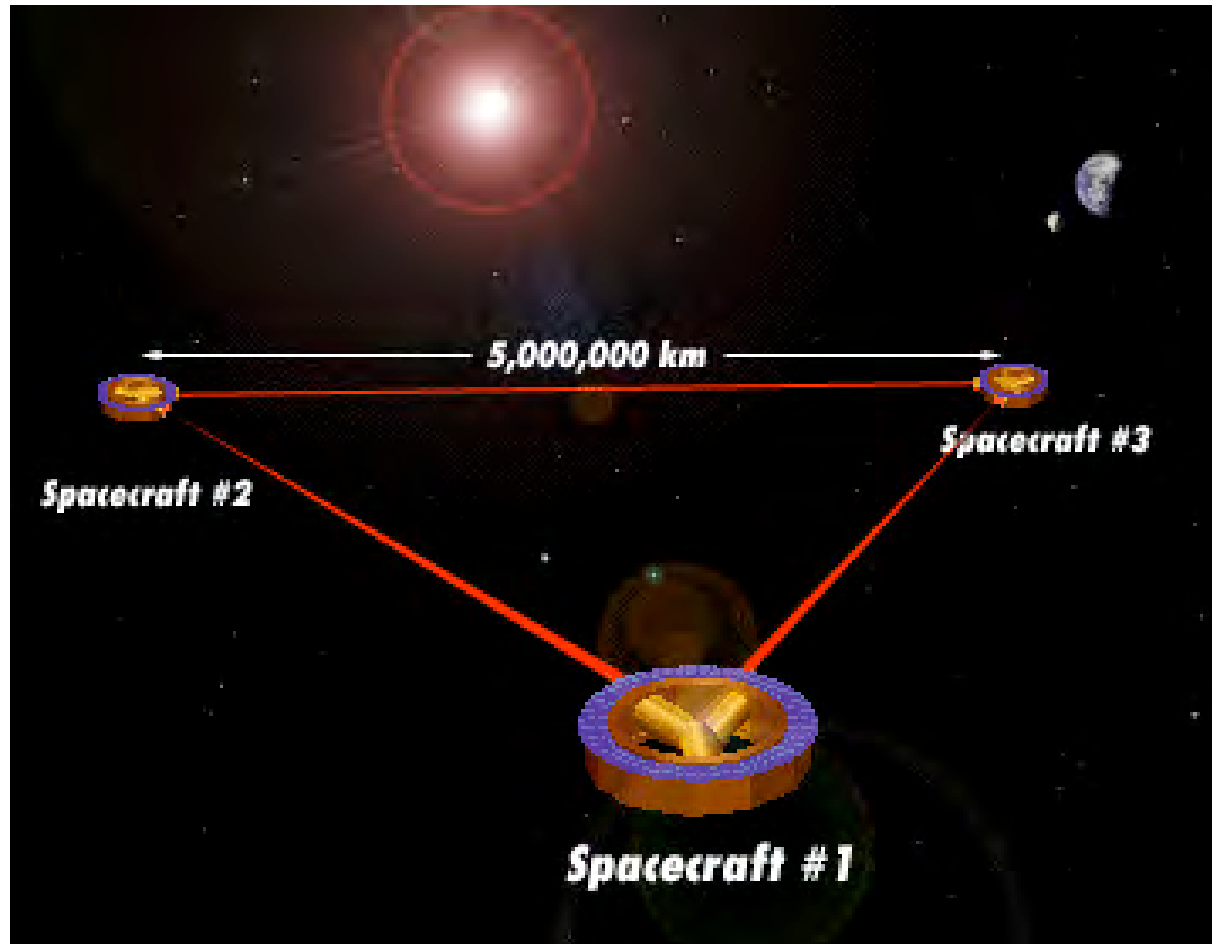


3. Gravitational radiation

$$t \propto a^4$$



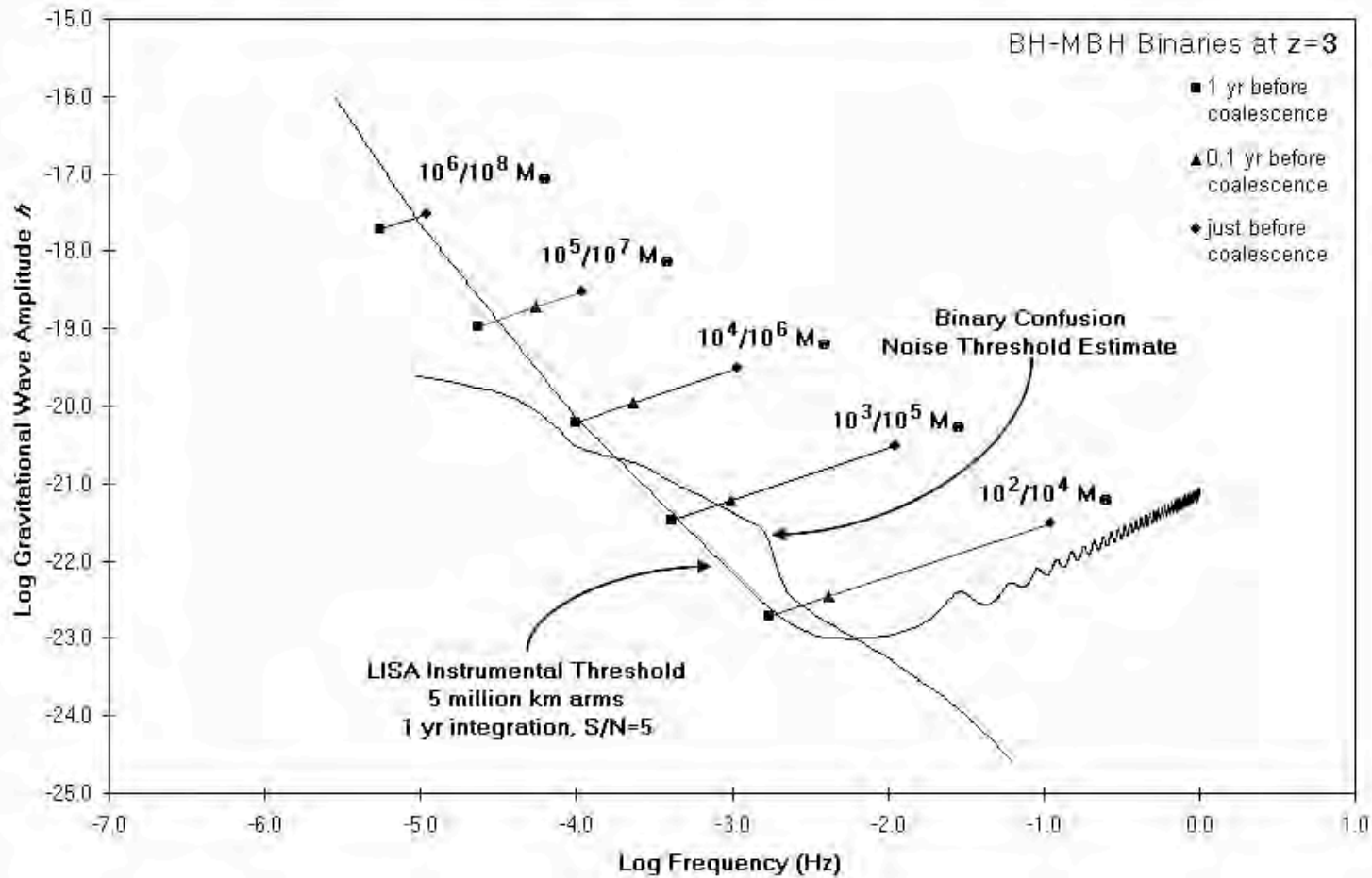
# LISA



Will see mergers  
of  $10^5 - 10^7$  Msol  
black holes

2011?

## Strain Amplitudes During Last Year Before BH-BH Coalescence



Lisa sensitivity to massive black hole binaries



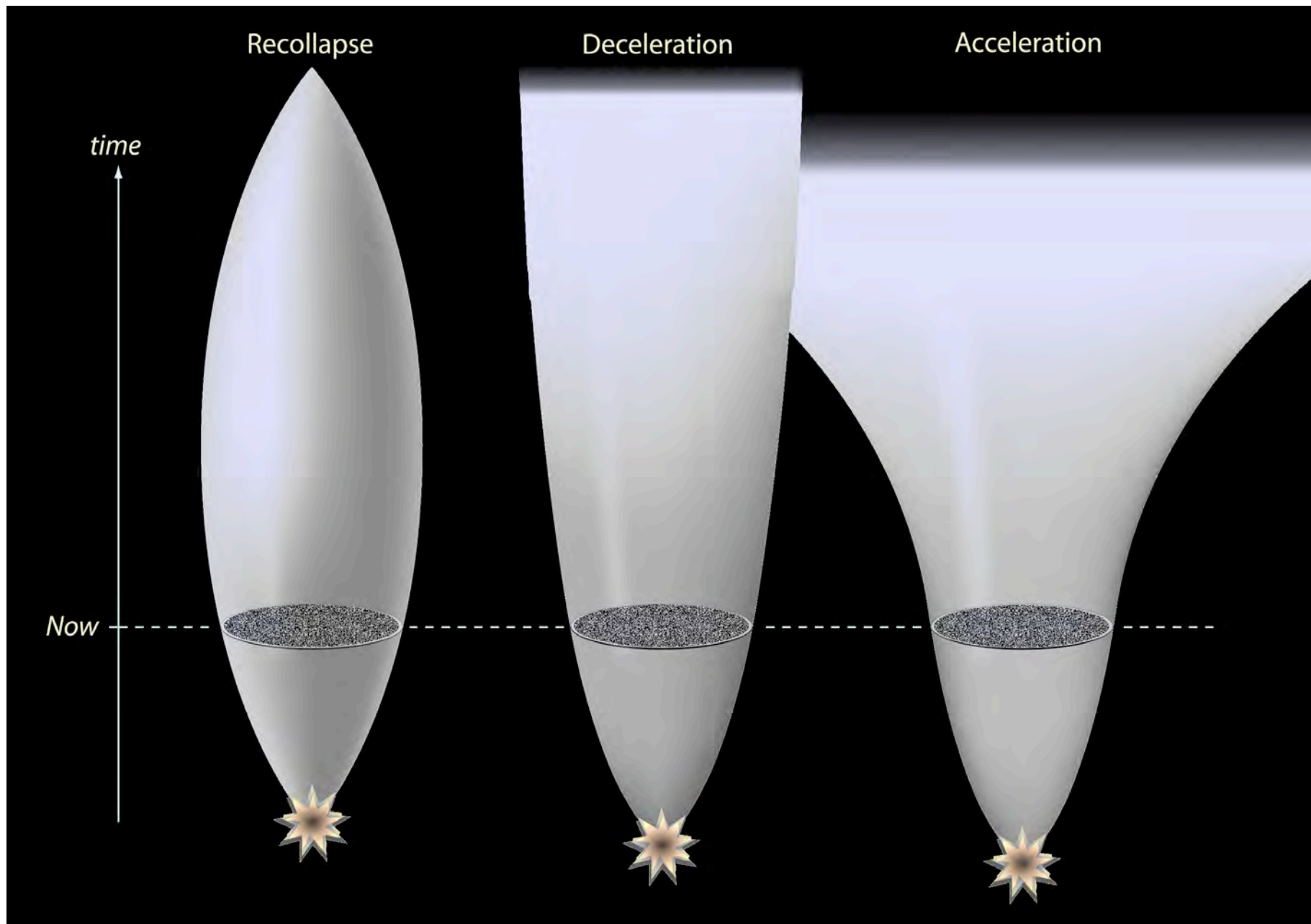
Recollapse

Deceleration

Acceleration

time

Now



$$\Omega = \frac{\text{DENSITY}}{\text{CRITICAL DENSITY}}$$

Direct observations  
+ He and D abundances

$$\Rightarrow \Omega_{\text{baryons}} \approx 0.04$$

Clustering models  
+ (baryon/dark matter) ratio

$$\Rightarrow \Omega_{\text{dark matter}} \approx 0.3$$

Angular scale of  
"Doppler peak"  
(implying flat universe)

$\Omega_{\text{dark matter}} \approx 0.3$



70% of mass-energy  
in uniform component  
with  $p < -\frac{1}{3} \rho c^2$



ACCELERATION



Hubble diagrams  
for supernovae



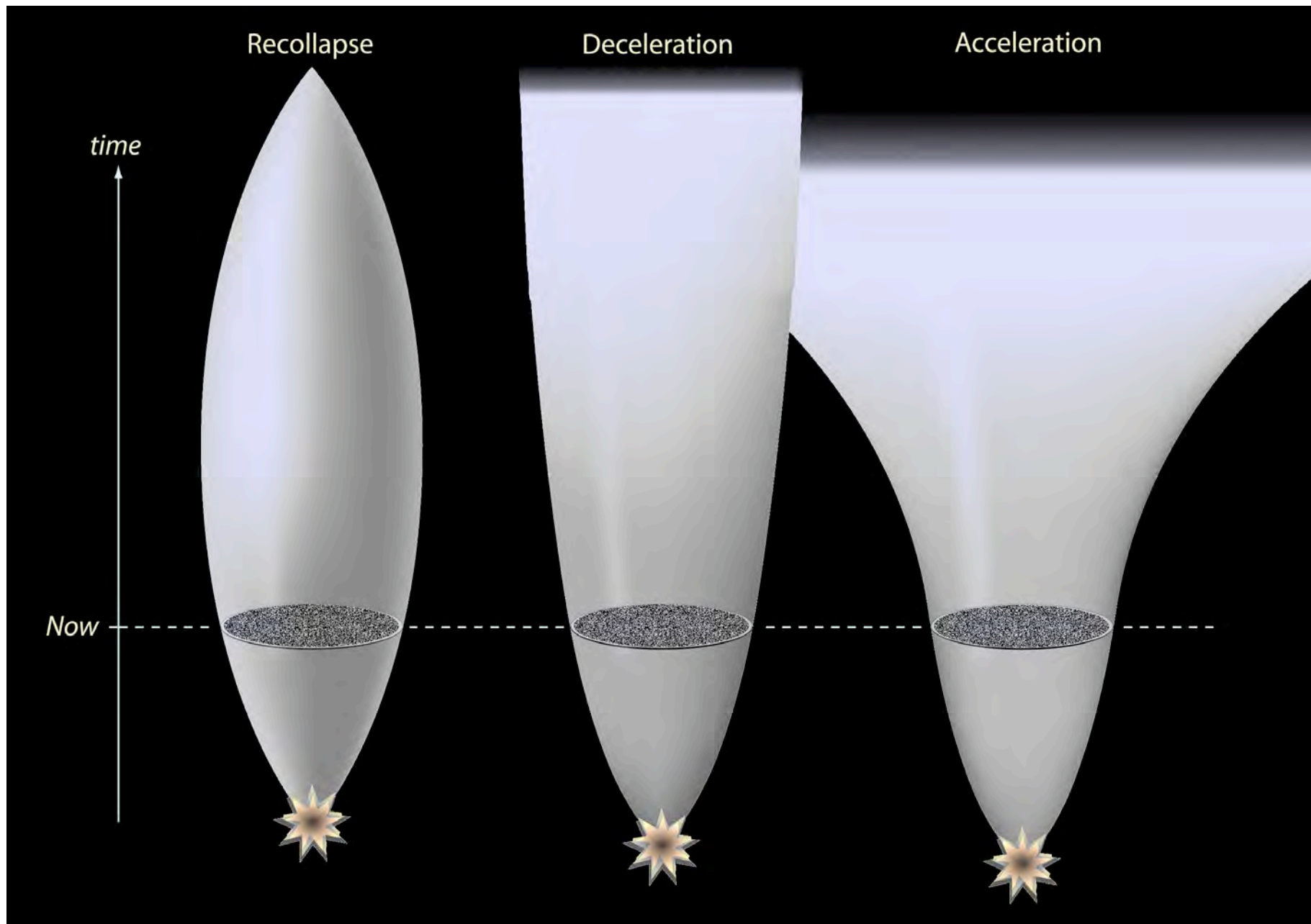
Recollapse

Deceleration

Acceleration

time

Now



## FAR FUTURE OF AN EVER-EXPANDING UNIVERSE

$10^{14}$ yr Ordinary stellar activity completed

$10^{17}$ yr Significant dynamical relaxation in galaxies

$10^{20}$ yr Gravitational radiation effects in galaxies

$10^{31}$ - $10^{36}$ yr Proton decay

$10^{64}$ (m/m.)<sup>3</sup>yr Quantum evaporation of black holes

$10^{1600}$ yr White dwarfs → iron\*

$10^{10^{26}}$ - $10^{10^{76}}$ yr Neutron stars undergo quantum\* tunnelling to black holes, which then “quickly” evaporate

\*If proton decay does not occur

## COUNTDOWN TO A “BIG CRUNCH”

t (yr)

$-10^9$  Clusters of galaxies merge

$-10^8$  Galaxies merge

$-10^6$  Stars moving relativistically

$-10^5$  Entire “night sky” hotter than  
stellar surface

$-10^3$  Stars destroyed  
Black holes grow catastrophically

-1 Temperature  $\geq 10^8$  K everywhere

# A NEW ESCHATOLOGY

(if  $\omega < -1$  for all future time)

## The countdown

$-10^9$ years	clusters disperse
$-10^8$ years	galaxies disperse
$-10^6$ years	Andromeda disappears beyond horizon
$-10$ years	nearest stars disappear beyond horizon outer planets move outward
$-1$ year	Sun* recedes from Earth*
$-1$ hour	Sun* goes beyond horizon Sun* and Earth* disrupt (post)humans levitate
$-1$ sec	(post)humans torn apart
$-10^{-20}$ sec	atoms torn apart

*\* Earliest this could happen is after 20 billion years  
(so actually not our Earth and our Sun!)*

