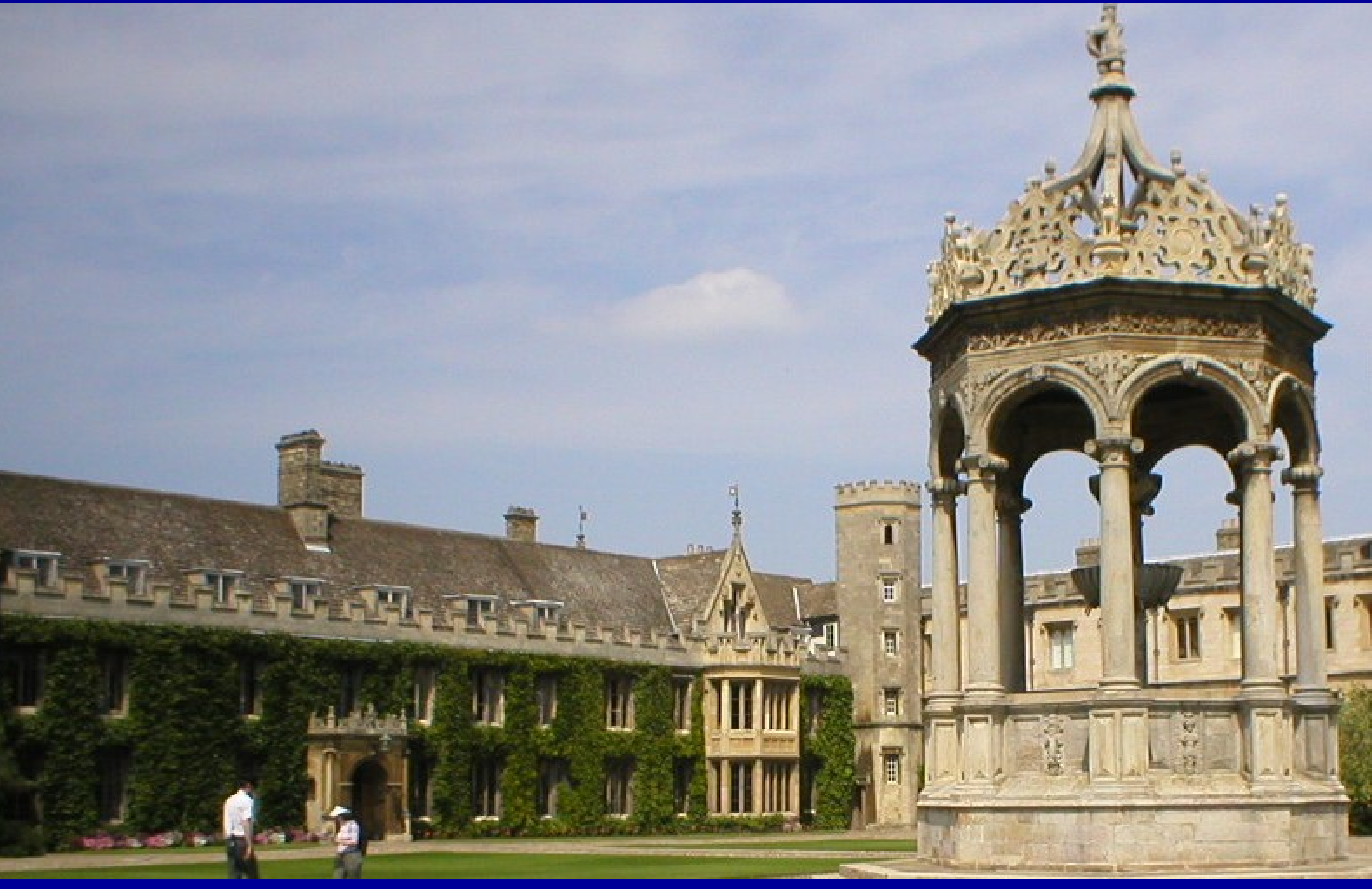
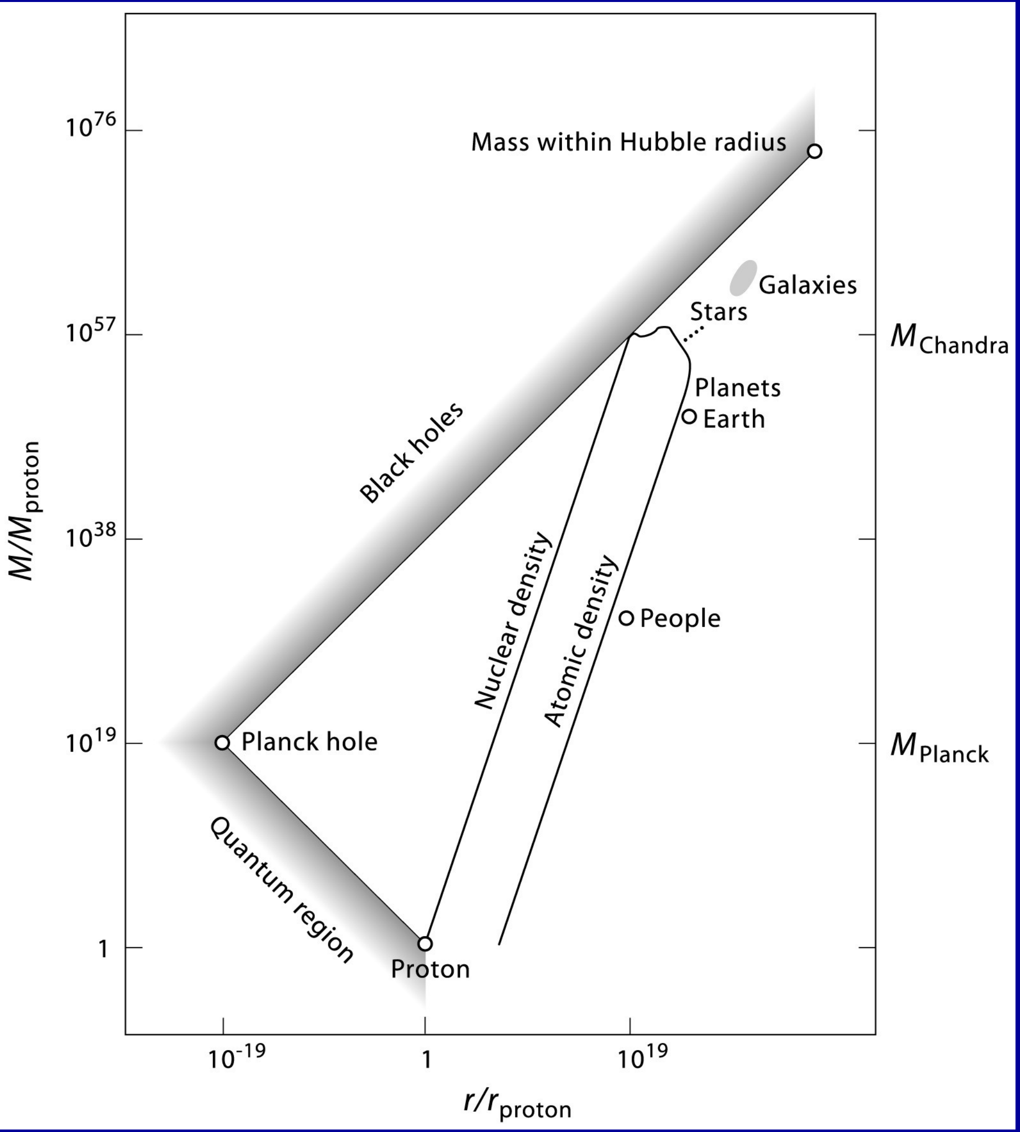
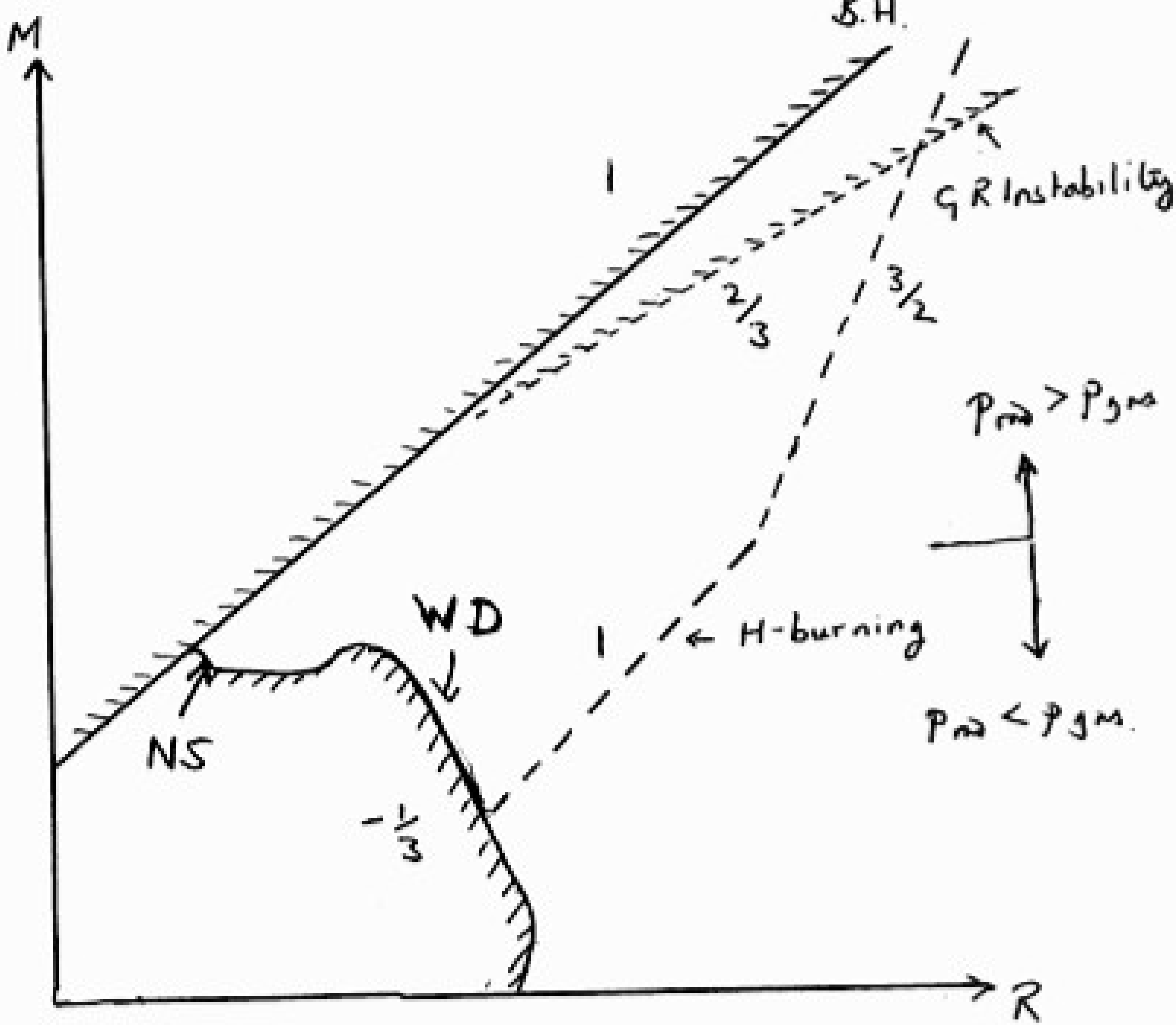
Chandra's Scientific Legacy

Martin Rees
Trinity College, Cambridge

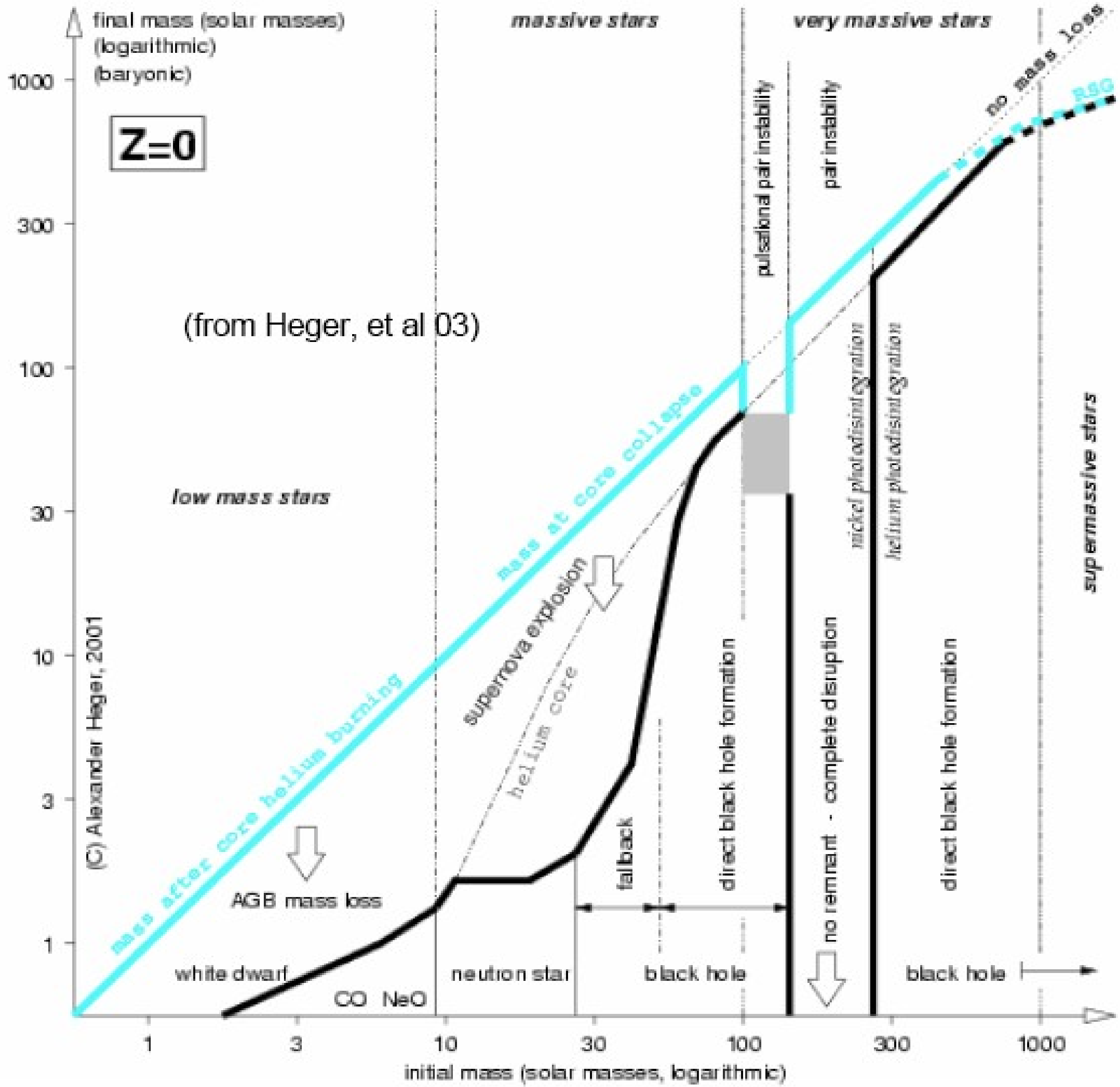




10^{76}
10^{57}
10^{38}
10^{19}
1
M/M_{proton}
Mass within Hubble radius
Galaxies
Stars
$M_{Chandra}$
Planets
Earth
Black holes
Nuclear density
Atomic density
People
Planck hole
M_{Planck}
Quantum region
Proton
10^{-19}
1
10^{19}
r/r_{proton}

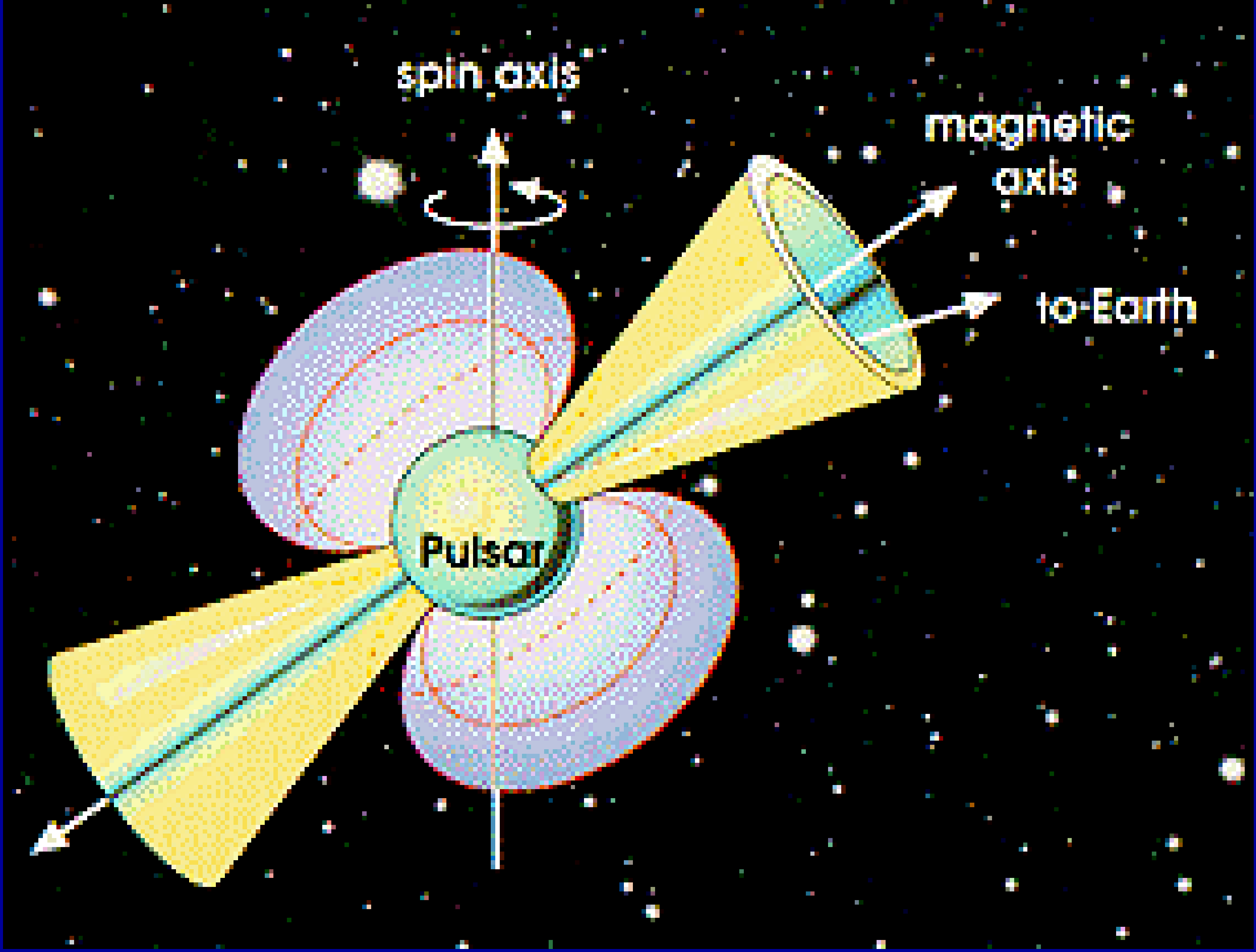


M
B.H.
1
GR Instability
2/3
3/2
$p_{rad} > p_{gas}$
$p_{rad} < p_{gas}$
WD
1
← H-burning
NS
-1/3
R



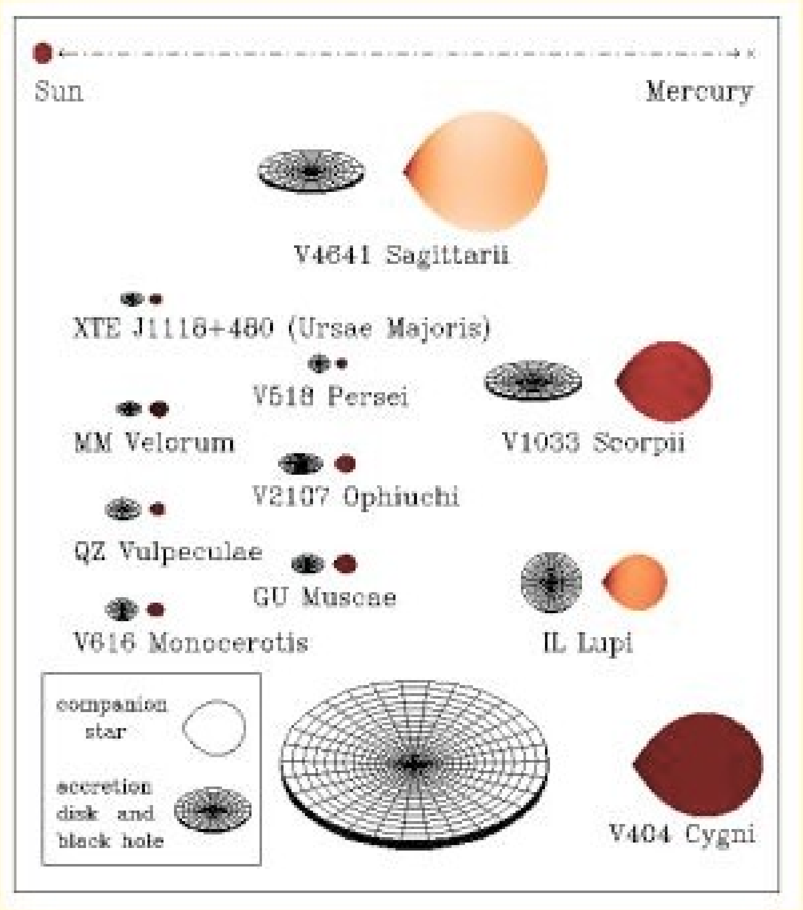
$M_{remn.}$ vs. $M_{\star ms}$

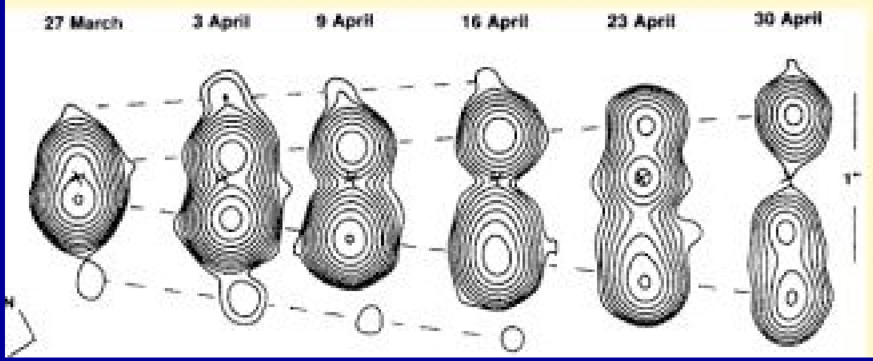
- Non-rotating single ms ⋆
- Mass-loss simplified
- Metallicity dependence?
- Core rotation, binary evol'n?
- etc

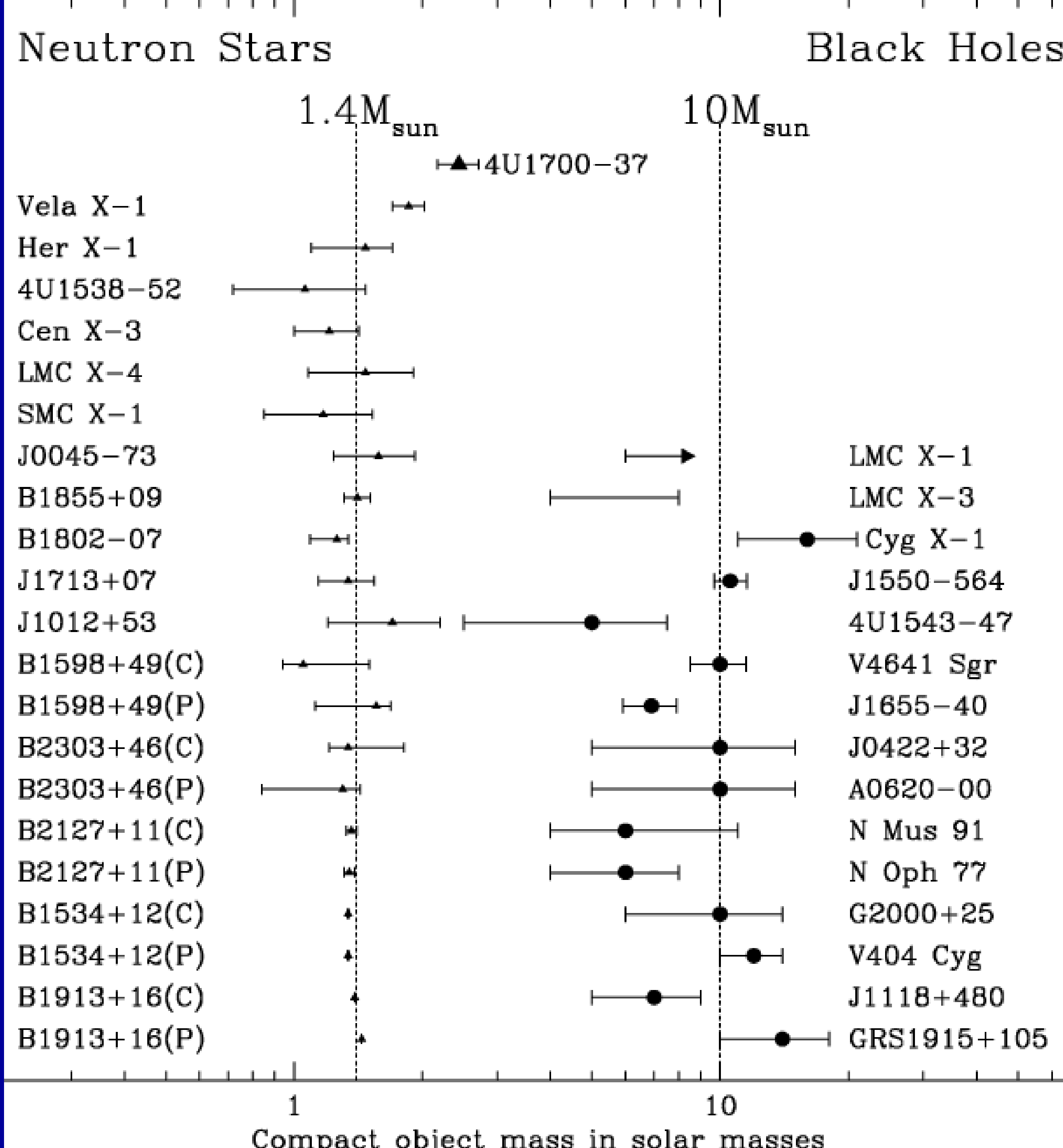

spin axis
magnetic axis
to Earth
Pulsar

X-ray binary black holes

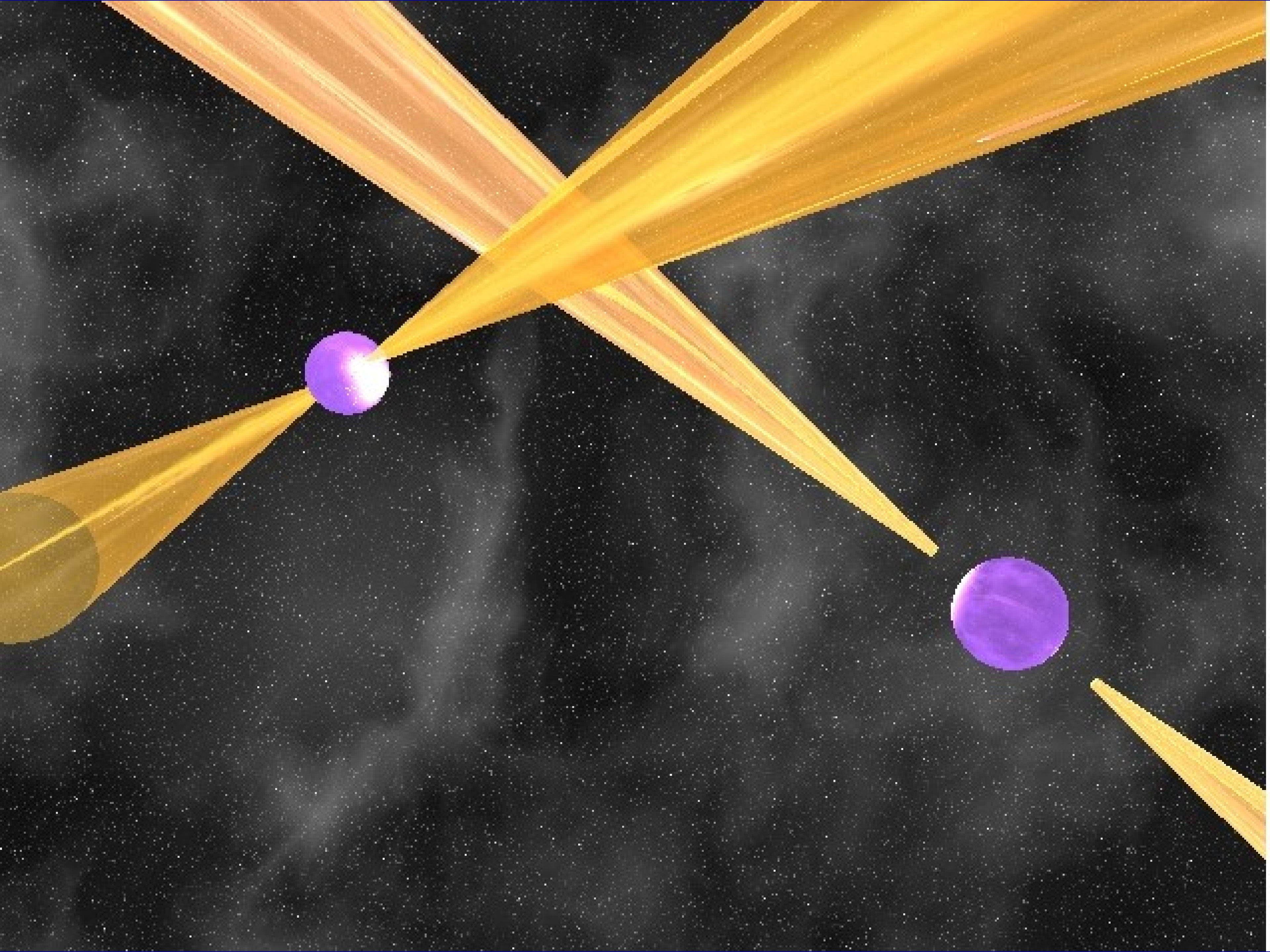
- Mass transfer of gas from companion star
- Accretion disks
- Release of gravitational binding energy of inflowing gas as radiation or wind



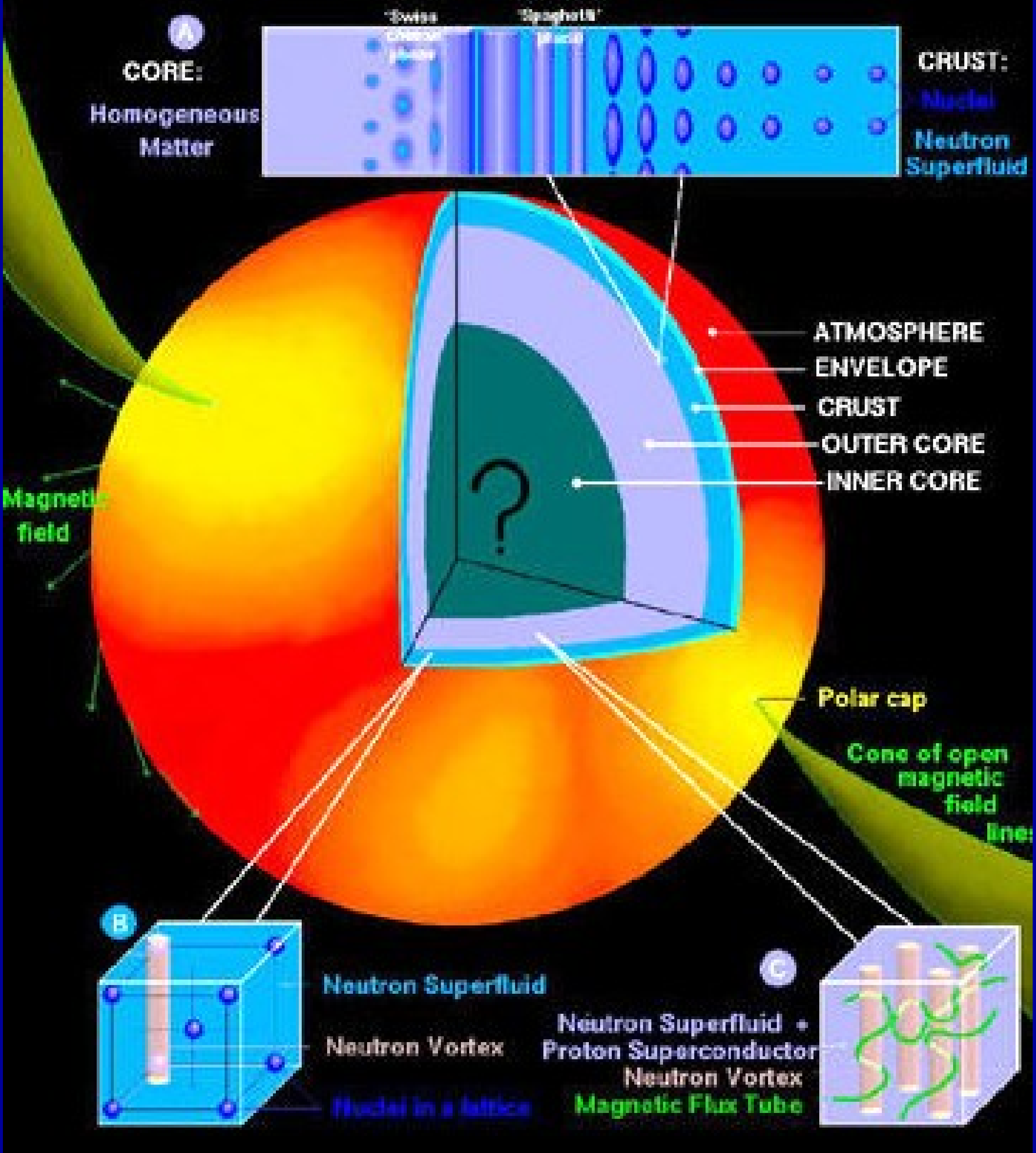




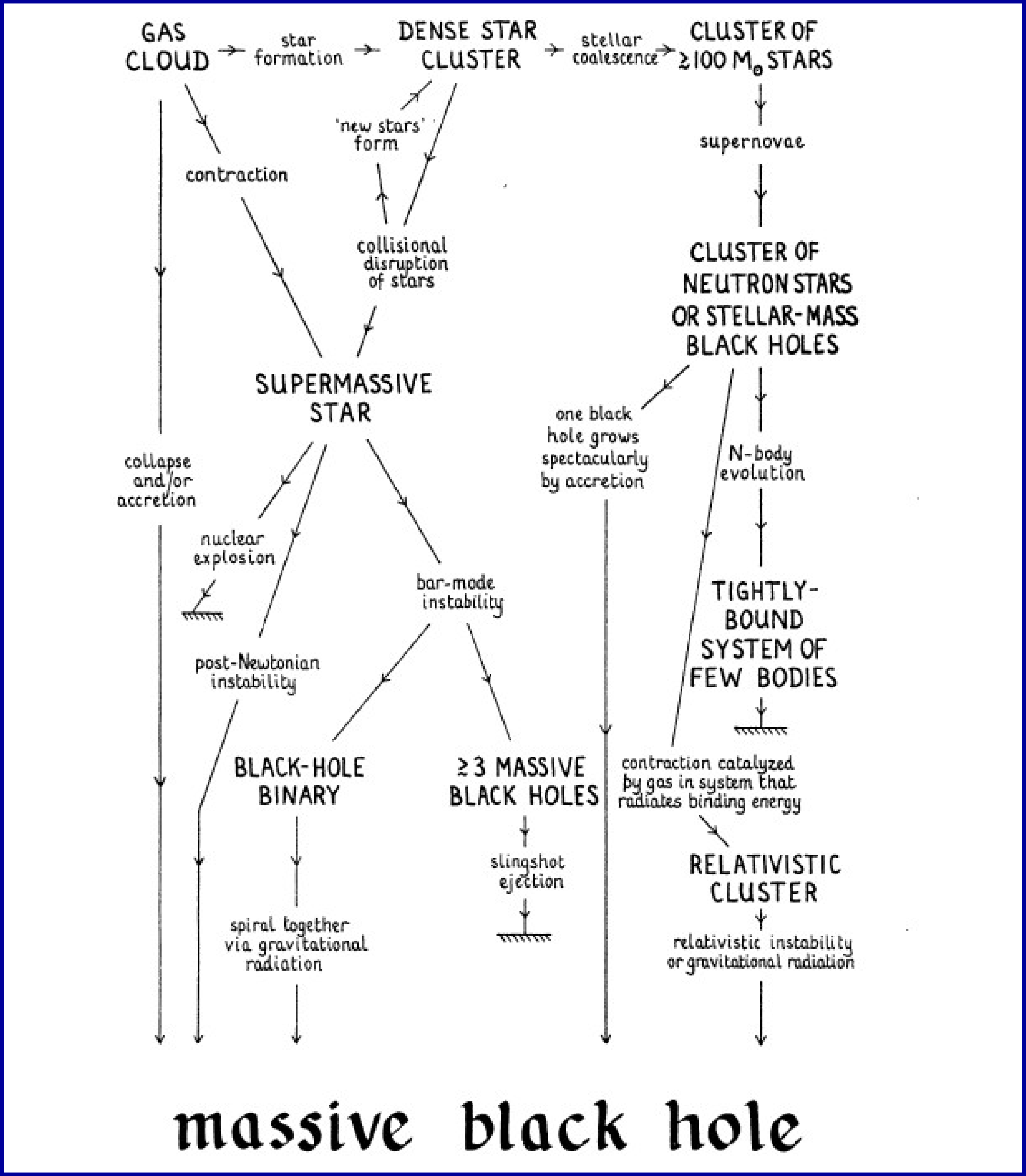
Neutron Stars
Black Holes
1.4M_sun
10M_sun
4U1700-37
Vela X-1
Her X-1
4U1538-52
Cen X-3
LMC X-4
SMC X-1
J0045-73
B1855+09
B1802-07
J1713+07
J1012+53
B1598+49(C)
B1598+49(P)
B2303+46(C)
B2303+46(P)
B2127+11(C)
B2127+11(P)
B1534+12(C)
B1534+12(P)
B1913+16(C)
B1913+16(P)
LMC X-1
LMC X-3
Cyg X-1
J1550-564
4U1543-47
V4641 Sgr
J1655-40
J0422+32
A0620-00
N Mus 91
N Oph 77
G2000+25
V404 Cyg
J1118+480
GRS1915+105
1
10
Compact object mass in solar masses



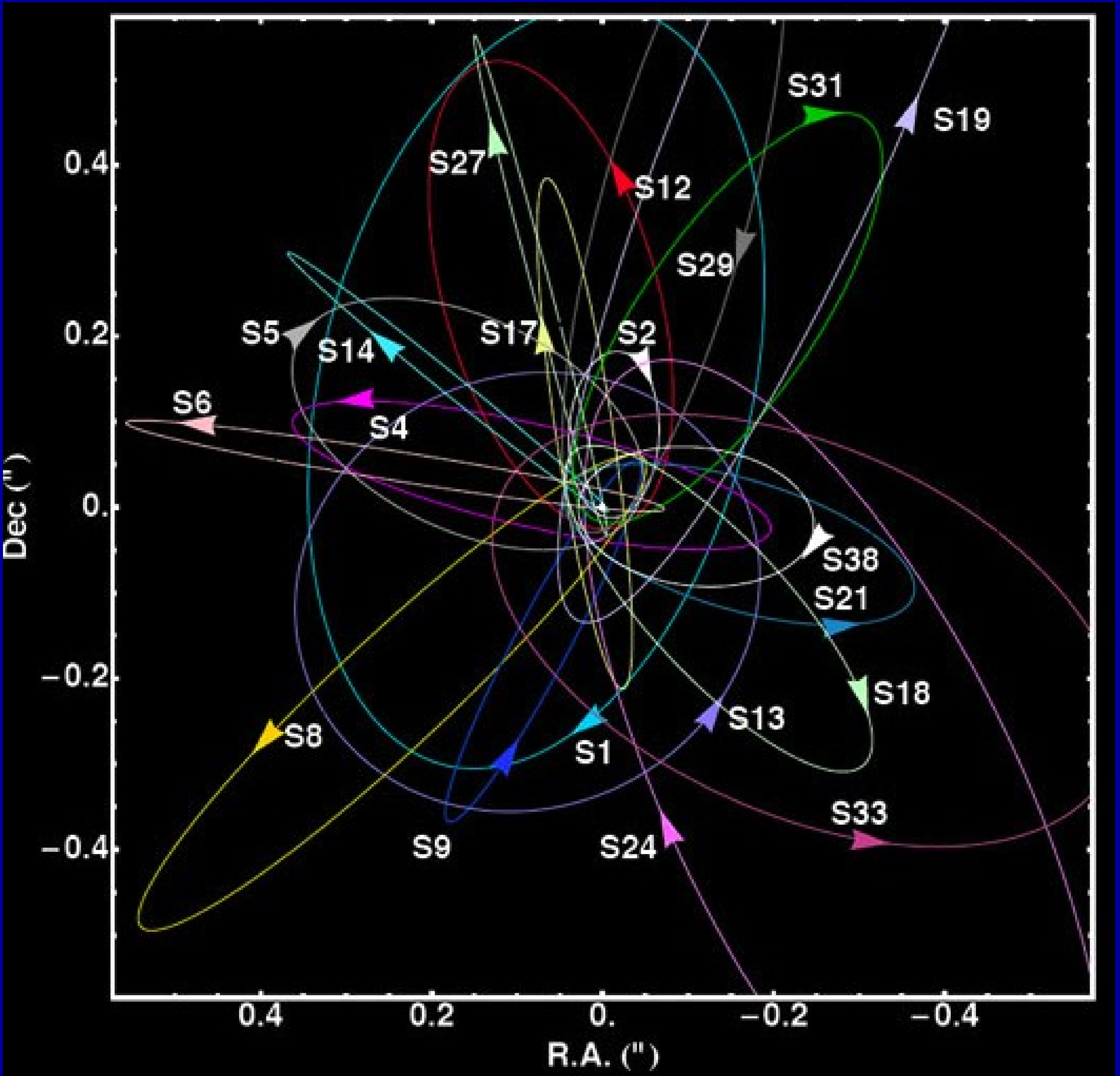
A NEUTRON STAR: SURFACE and INTERIOR

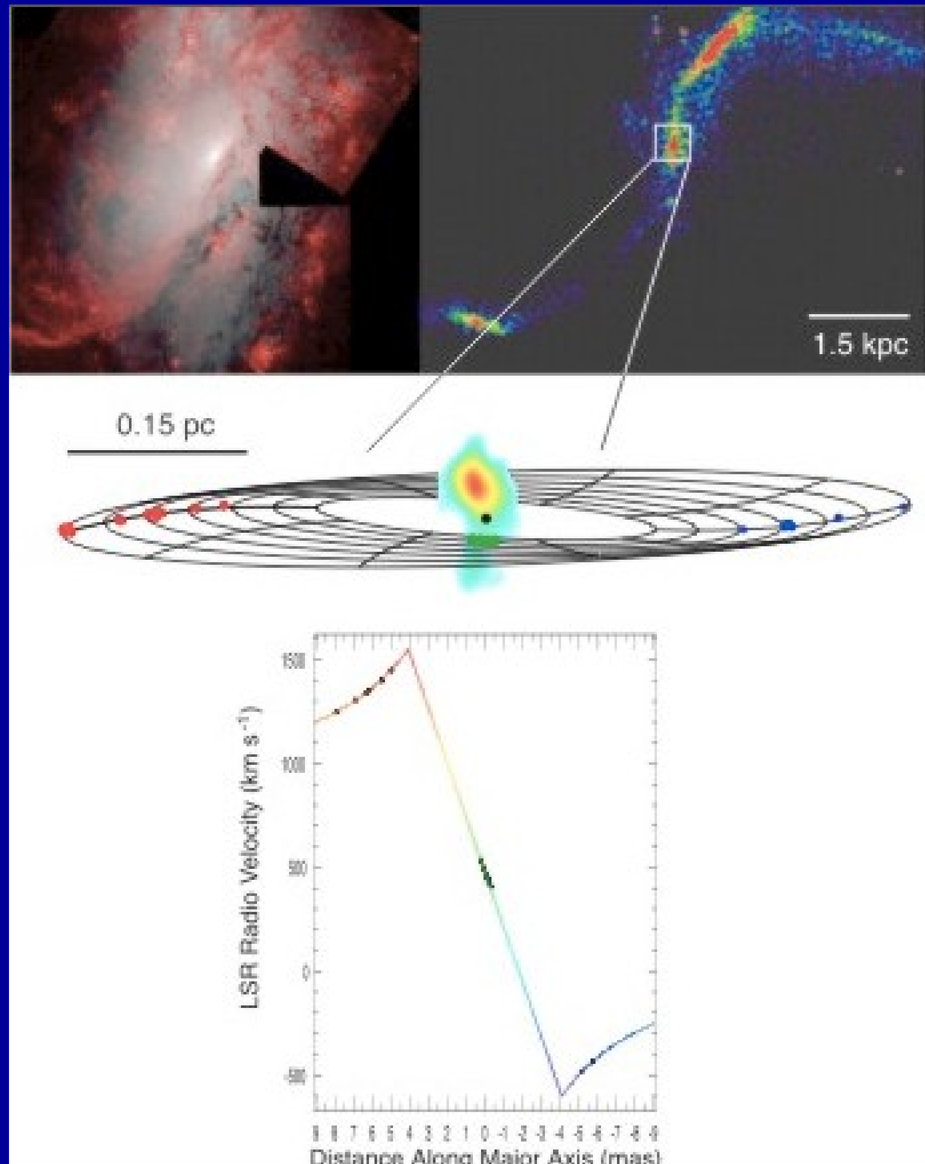


HOW can you make a massive black hole?



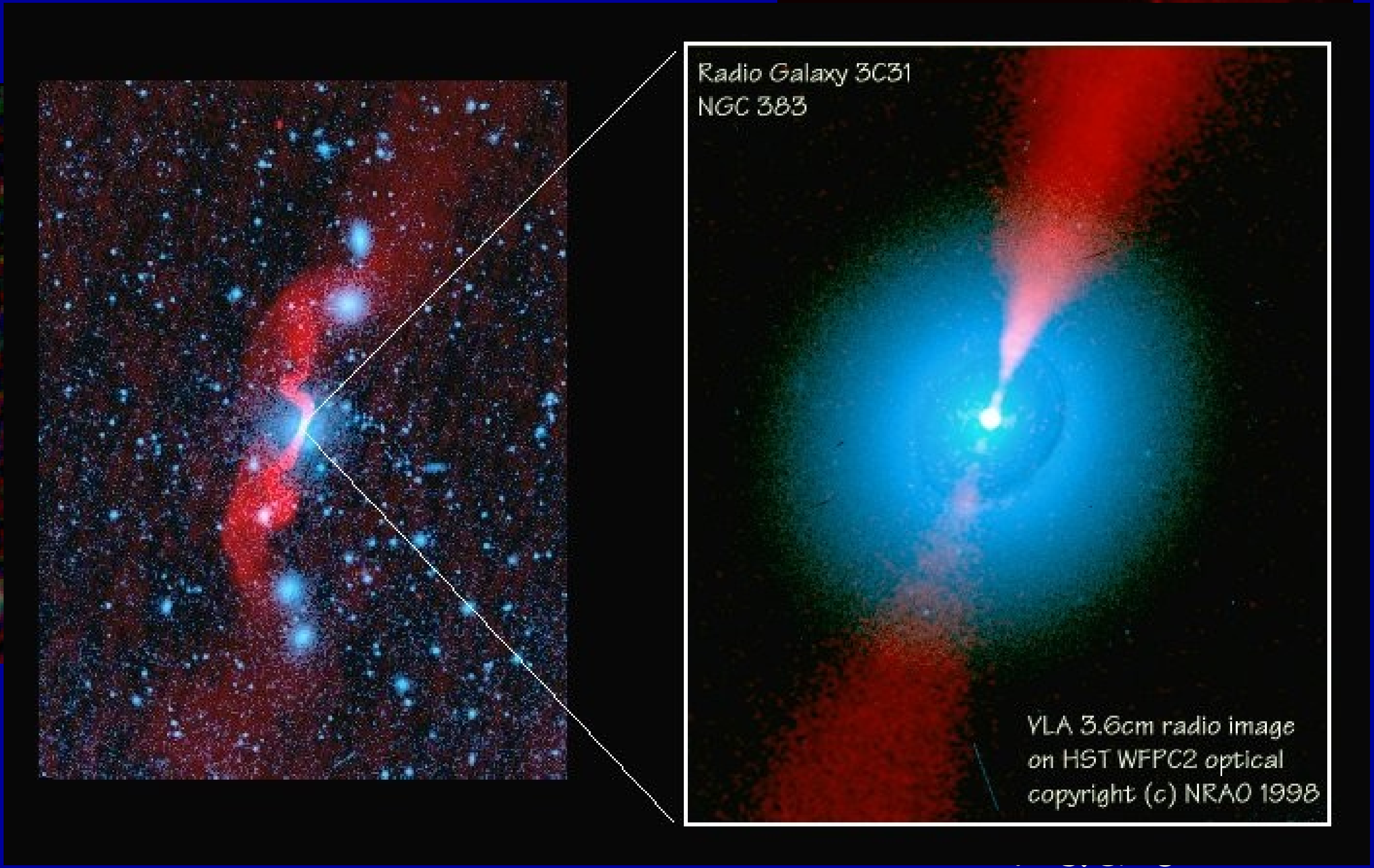
from Rees 1977


S31
S19
S27
S12
S29
S5
S14
S17
S2
S6
S4
S38
S21
S18
S13
S8
S1
S33
S9
S24
0.4
0.2
0.
−0.2
−0.4
Dec (")
R.A. (")



1.5 kpc
0.15 pc
LSR Radio Velocity (km s^{-1})
Distance Along Major Axis (mas)

3C31:


Radio Galaxy 3C31
NGC 383
VLA 3.6cm radio image
on HST WFPC2 optical
copyright (c) NRAO 1998

QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

What is likely spin (a/m)?

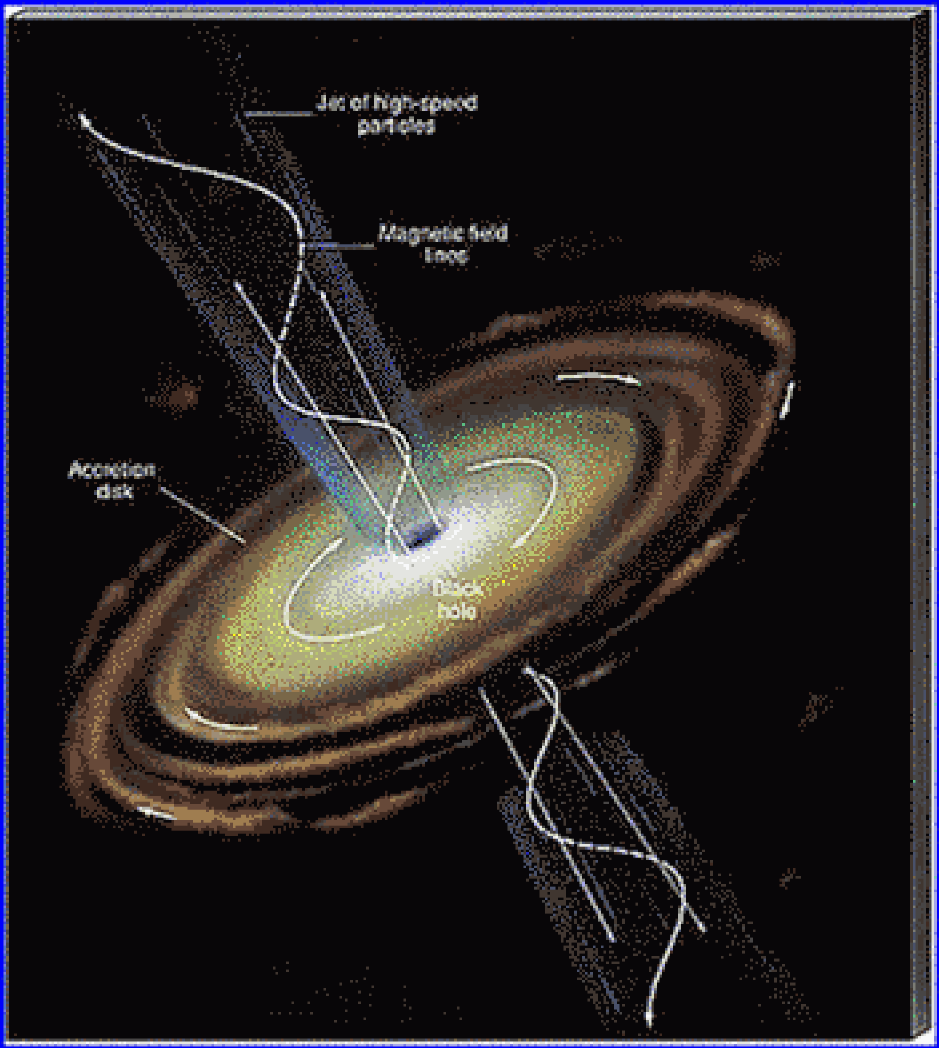
(determines accretion efficiency, minimum variability timescale, importance of B-Z energy extraction, etc)

Affected by: coalescence/mergers

spin-up by disc

etc

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:

$B \sim 10^4$ G; $M \sim 10^9 M_O$

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

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

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

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

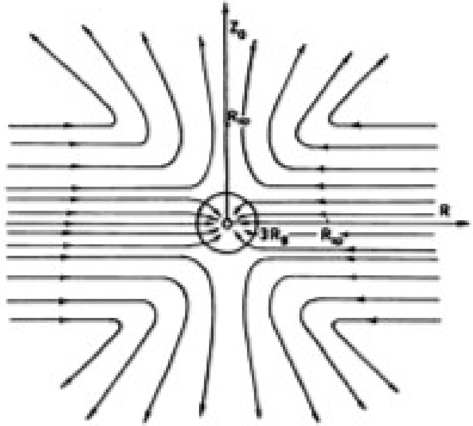


Fig. 8. Lines of matter flow at supercritical accretion (the disk section along the Z-coordinate). When $R < R_{sp}$ spherization of accretion takes place and the outflow of matter from the collapsar begins

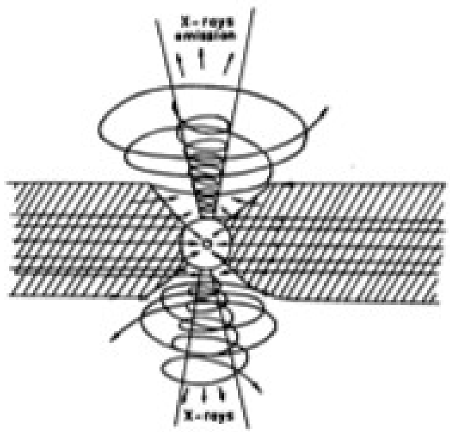


Fig. 9. The outflow of the matter from the collapsar at the supercritical regime of accretion

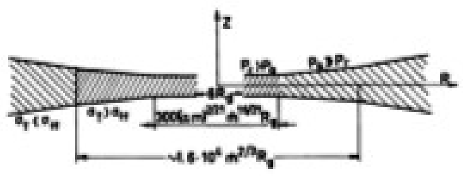


Fig. 10. The regions of disk having different physical conditions

The temperature does not vary much at low

$$u = \int_0^z \varrho\, dz \ll \frac{u_0}{2} = \int_0^\infty \varrho\, dz$$

and correspondingly at low optical depths $\tau = \sigma_T u(z)$ and low Z. Therefore, the disk structure may be characterized by a central temperature depending only on the coordinate R, and the dependence on the coordinate Z may be neglected. However, the outgoing radiation spectrum, formed in the upper layer of the disk is strongly dependent on the density and temperature distribution along the coordinate z.

In the region a) (closest to the collapsar) radiation pressure $P_r = \frac{\varepsilon}{3}$ dominates. According to (2.21) and (2.23)

$$q(z) = \frac{c}{\sigma_T} \frac{GM}{R^3} z\,. \tag{2.26}$$

Furthermore, $q(u) = 2Q \frac{u}{u_0}$ and $\varrho = \frac{du}{dz}$, and therefore the disk must be homogeneous with a sharp (depending only on the temperature of the plasma, the turbulent and magnetic pressure) decrease of matter density at $z > z_0$.

In regions b) and c) the gas pressure $p = \varrho \frac{kT}{m_p}$ dominates.

For $\frac{u}{u_0} \ll \frac{1}{2}$, the temperature in the disk is practically constant (2.25), and the density decreases according to a gaussian curve $\varrho = \varrho_0 \exp\left[-\left(\frac{z}{z_0}\right)^2\right]$. With increasing z and u, the temperature rapidly decreases and, according to (2.21), the density drops more rapidly.

In zone b), the outgoing radiation spectrum is formed at the depth defined by the condition $\tau^* = \int_0^{\infty} \sqrt{\sigma_T \sigma_{ff}} \cdot du \sim 1$. At $z > z_1$ the plasma temperature is practically constant. Therefore, according to (2.25), at $z > z_1$ we can assume the density profile

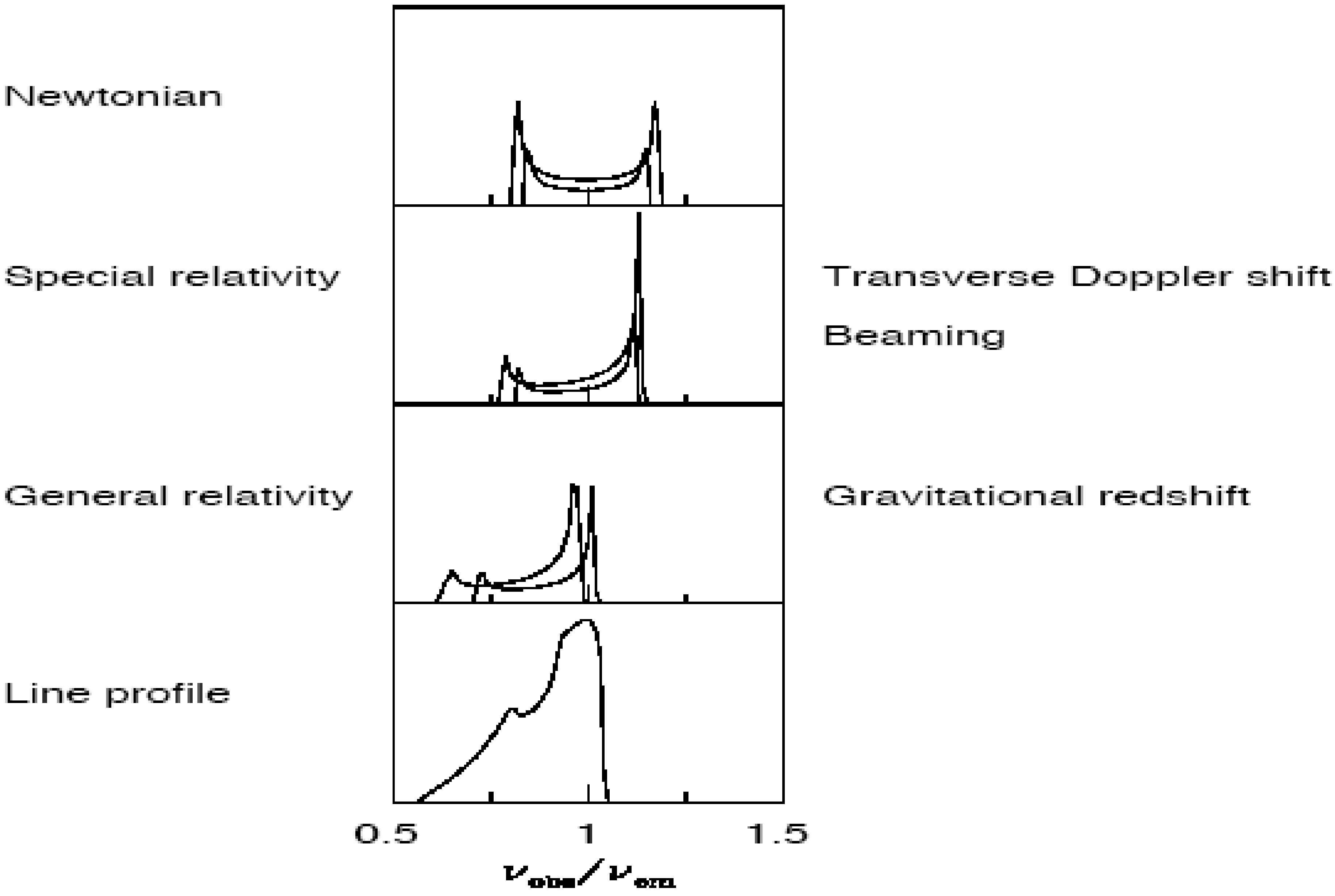
$$\varrho = \varrho(z_1) \exp\left(-\frac{z}{H_0}\right) \tag{2.28}$$

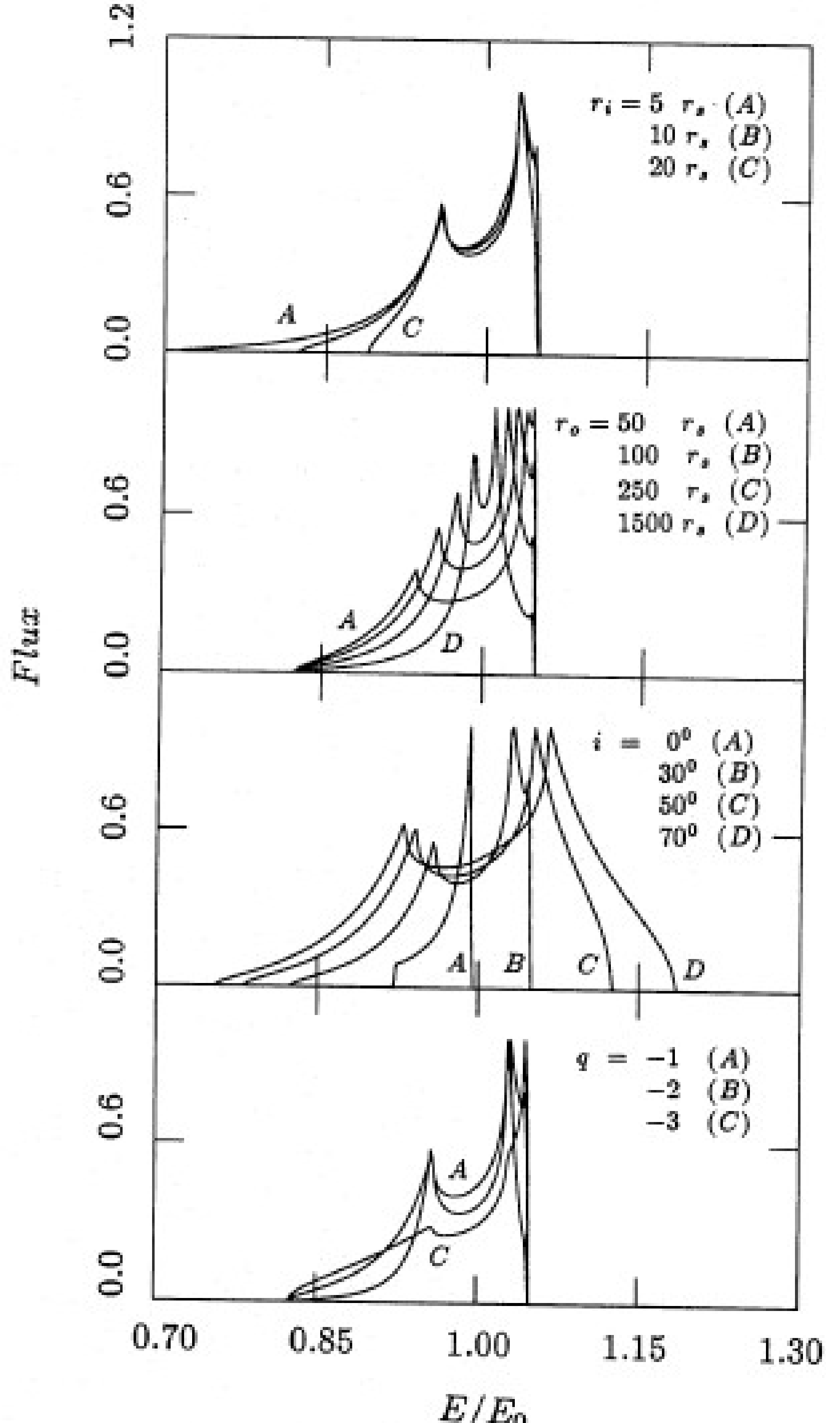
where $H_0 = \frac{R^3 kT(z_1)}{GM m_p z_1}$. The numerical solution of the system of equations (2.21 ÷ 2.23) showed that because of the rapid decrease of the temperature at $z > z_0$ for any conditions $z_1 \approx 1.2 - 1.5 z_0$. In the estimates below we shall assume $z_1 \simeq z_0$.

3. *Radiation Spectrum of the Disk*

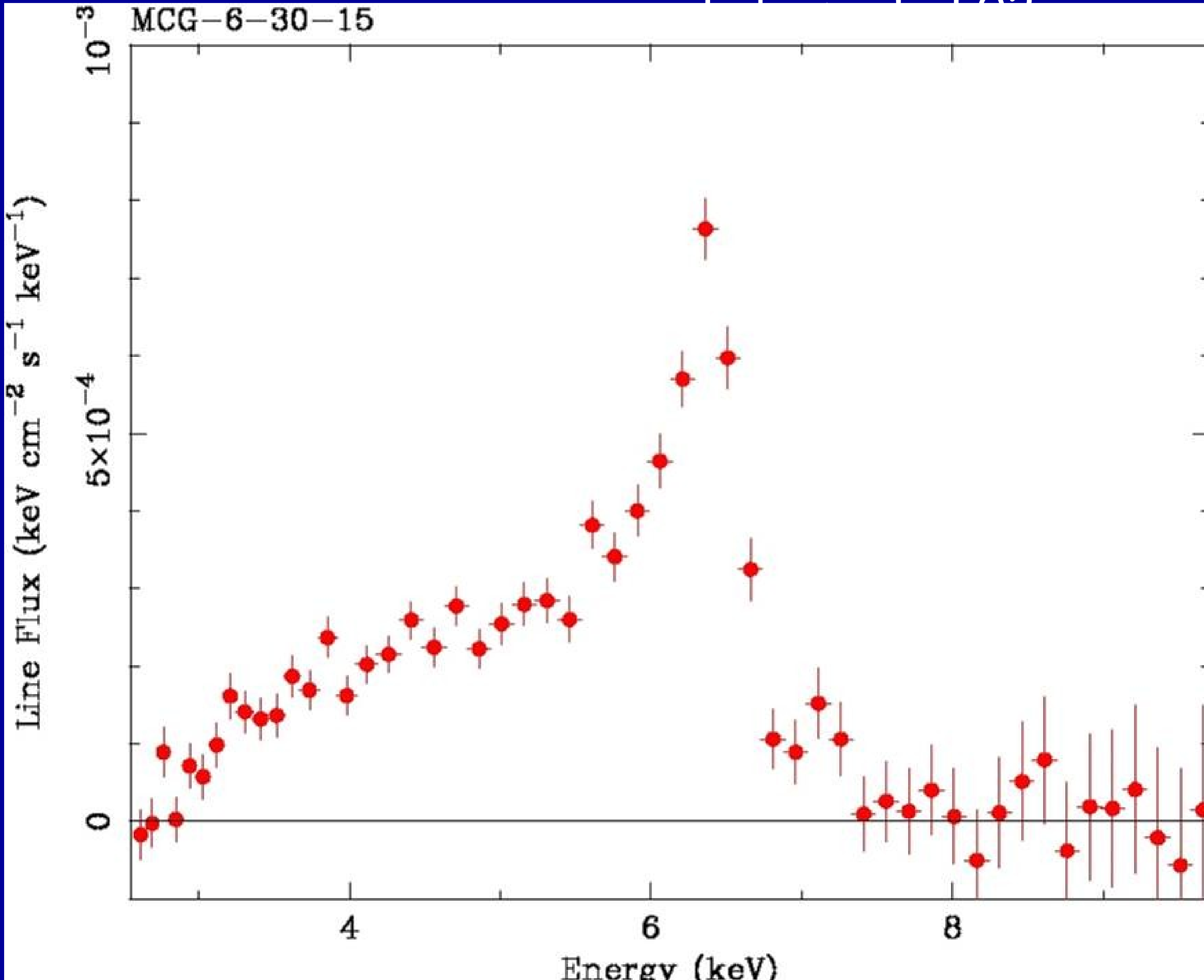
a) Local Radiation Spectrum

The spectrum shape formed at the disk surface depends on its structure and temperature (which was calculated

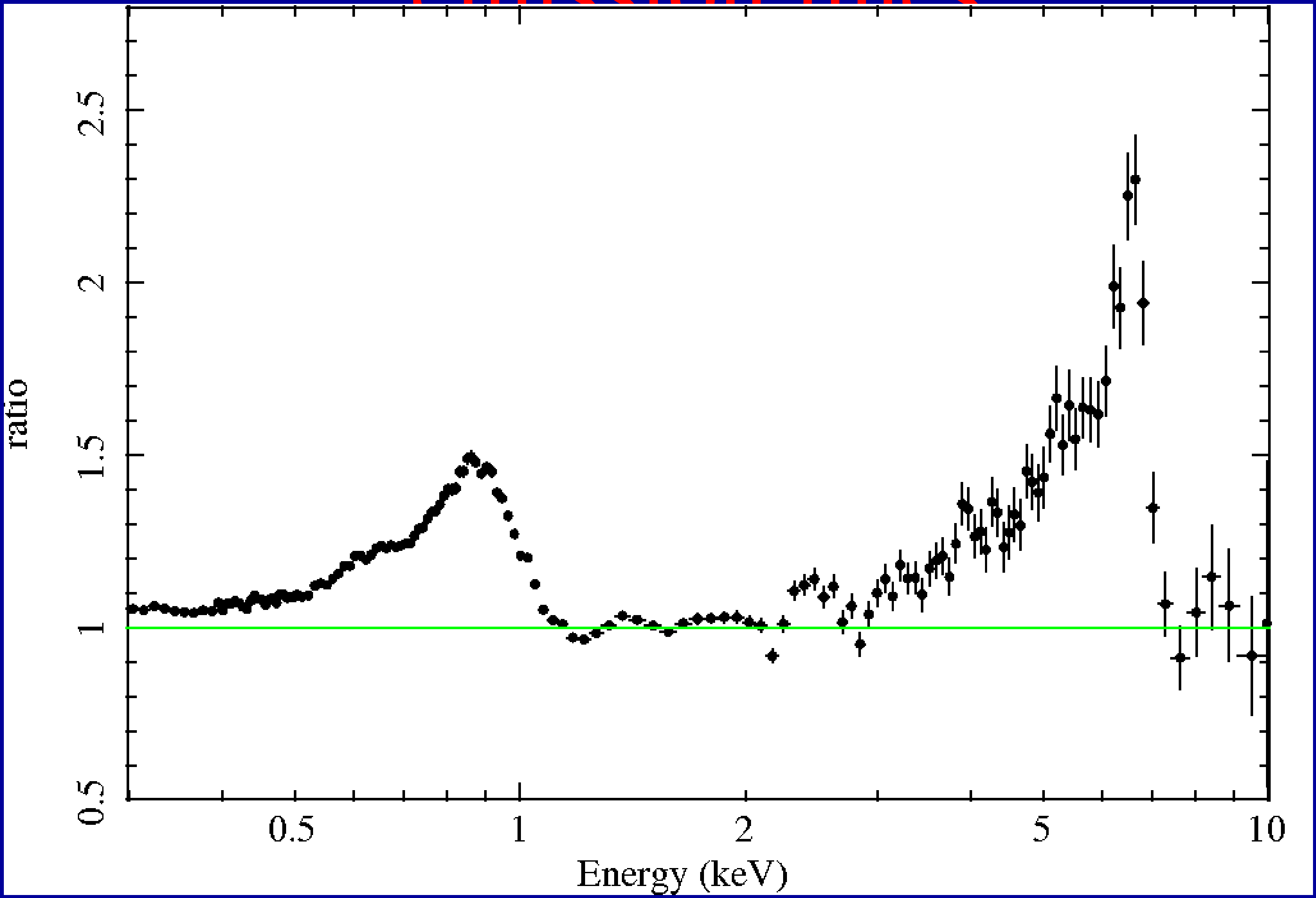

Newtonian
Special relativity
Transverse Doppler shift
Beaming
General relativity
Gravitational redshift
Line profile
0.5
1
1.5
ν_{obs}/ν_{em}



$r_i = 5\ r_s\ (A)$
$10\ r_s\ (B)$
$20\ r_s\ (C)$
$r_o = 50\ r_s\ (A)$
$100\ r_s\ (B)$
$250\ r_s\ (C)$
$1500\ r_s\ (D)$
$i = 0^0\ (A)$
$30^0\ (B)$
$50^0\ (C)$
$70^0\ (D)$
$q = -1\ (A)$
$-2\ (B)$
$-3\ (C)$
A
B
C
D
1.2
0.6
0.0
0.70
0.85
1.00
1.15
1.30
$Flux$
E/E_0


MCG−6−30−15
10^{-3}
5×10^{-4}
0
Line Flux (keV cm^{-2} s^{-1} keV^{-1})
4
6
8
Energy (keV)

Broad iron-L and iron-K emission lines



NATURE, VOL. 223, AUGUST 16, 1969

Galactic Nuclei as Collapsed Old Quasars

by

D. LYNDEN-BELL

Royal Greenwich Observatory,
Herstmonceux Castle, Sussex

Powerful emissions from the centres of nearby galaxies may represent dead quasars.

RYLE gives good evidence[1] that quasars evolve into powerful radio sources with two well separated radio components, one on each side of the dead or dying quasar. The energies involved in the total radio outbursts are calculated to be of the order of 10^{61} erg, and the optical variability of some quasars indicates that the outbursts probably originate in a volume no larger than the solar system. Now 10^{61} erg have a mass of 10^{40} g or nearly 10^7 Suns. If this were to come from the conversion of hydrogen into helium, it can only represent the nuclear binding energy, which is 3/400 of the mass of hydrogen involved. Hence 10^9 solar masses would be needed within a volume the size of the solar system, which we take to be 10^{15} cm (10 light h). But the gravitational binding energy of 10^9 solar masses within 10^{15} cm is GM^2/r which is 10^{62} erg. Thus we are wrong to neglect gravity as an equal if not a dominant source of energy. This was suggested by Fowler and Hoyle[2], who at once asked whether the red-shifts can also have a gravitational origin. Greenstein and Schmidt[3], however, earlier showed that this is unlikely because the differential red-shift would wash out the lines. Attempts to avoid this difficulty have looked unconvincing, so I shall adopt the cosmological origin for quasar red-shifts. Even with this hypothesis the numbers of quasar-like objects are very large, or rather they were so in the past.

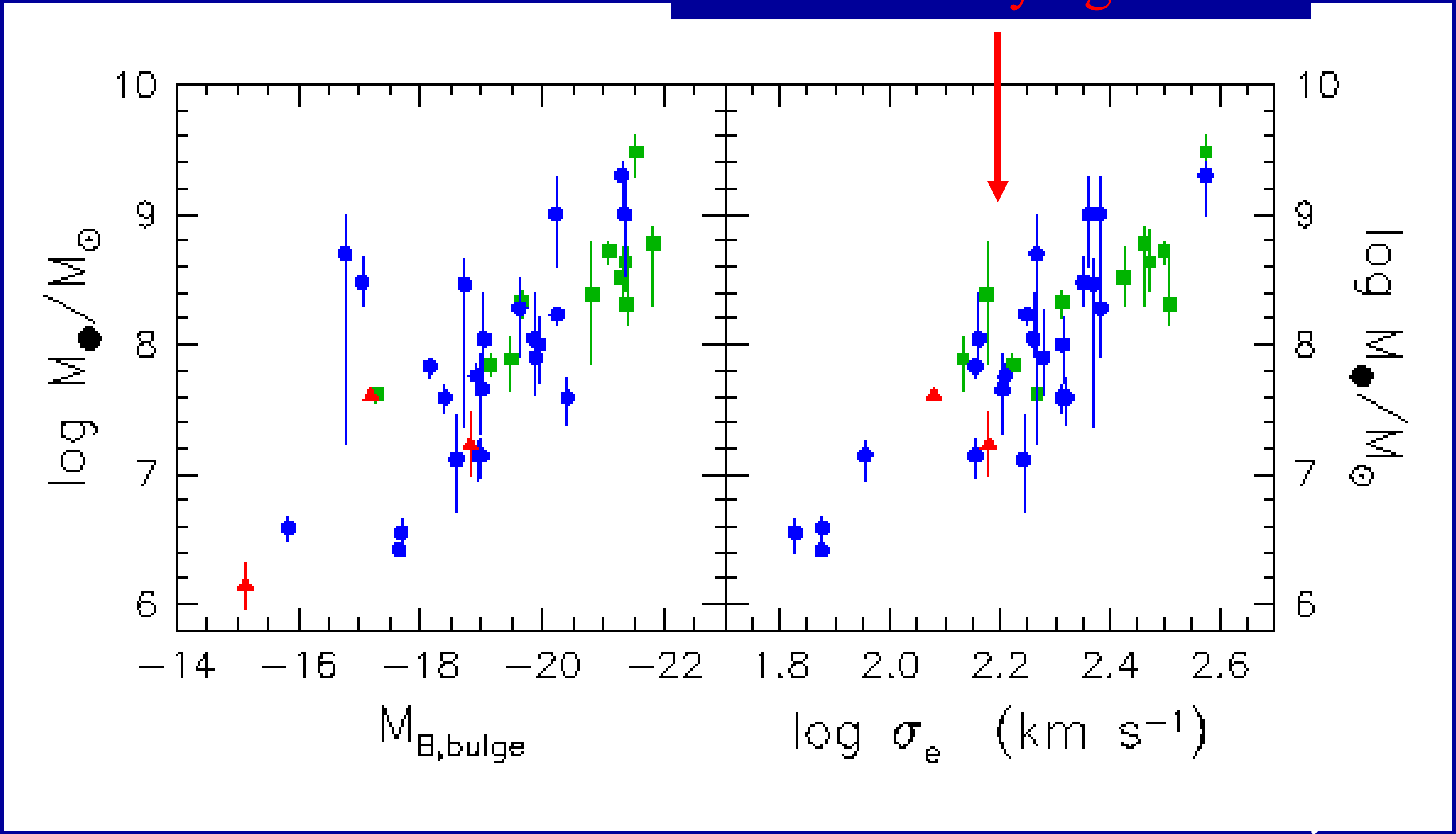
which we shall call the Schwarzschild throat. We would be wrong to conclude that such massive objects in space-time should be unobservable, however. It is my thesis that we have been observing them indirectly for many years.

Effects of Collapsed Masses

As Schwarzschild throats are considerable centres of gravitation, we expect to find matter concentrated toward them. We therefore expect that the throats are to be found at the centres of massive aggregates of stars, and the centres of the nuclei of galaxies are the obvious choice. My first prediction is that when the light from the nucleus of a galaxy is predominantly starlight, the mass-to-light ratio of the nucleus should be anomalously large.

We may expect the collapsed bodies to have a broad spectrum of masses. True dead quasars may have 10^{10} or 10^{11} $M_\odot$ while normal galaxies like ours may have only 10^7–10^8 $M_\odot$ down their throats. A simple calculation shows that the last stable circular orbit has a diameter of $12\ GM/c^2 = 12m$ so we shall call the sphere of this diameter the Schwarzschild mouth. Simple calculations on circular orbits yield the following results, where M_7 is the mass of the collapsed body in units of 10^7 $M_\odot$, so that M_7 ranges from 1 to 10^4.

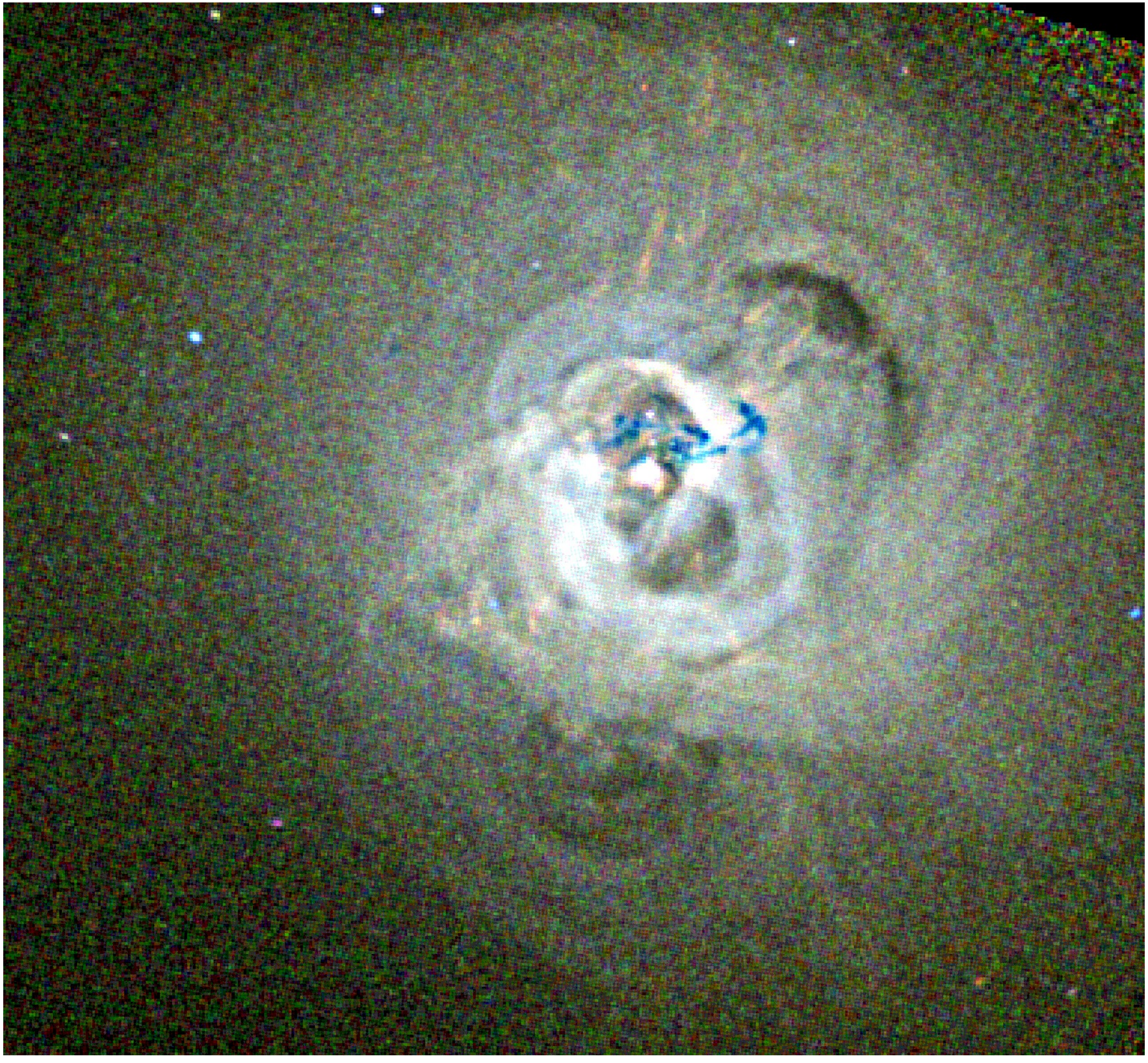
Is this really tighter?



black hole mass scales with

bulge mass

stellar velocity dispersion of the bulge



Massive black holes?

Giant Ellipticals/S0s

Yes

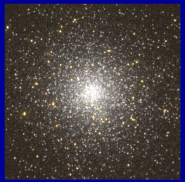
Spirals

Yes but black hole mass scales with bulge mass not total mass

Dwarfs

Some at least

Globular Clusters



Maybe

"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"

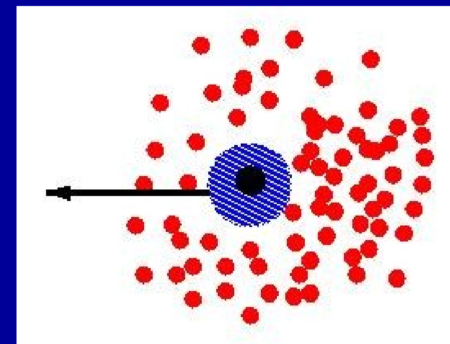
S. Chandrasekhar.

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

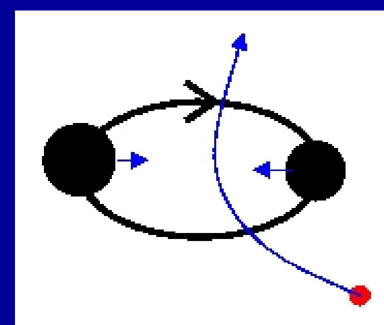
Formation and evolution of supermassive binaries

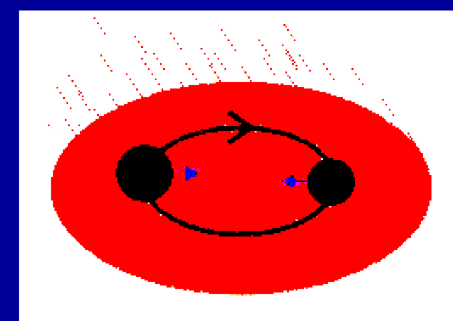
1. Dynamical friction

$t \propto a$



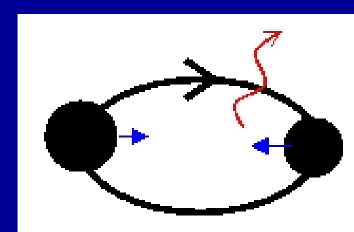
2. Binary hardening due to stars or accretion of gas



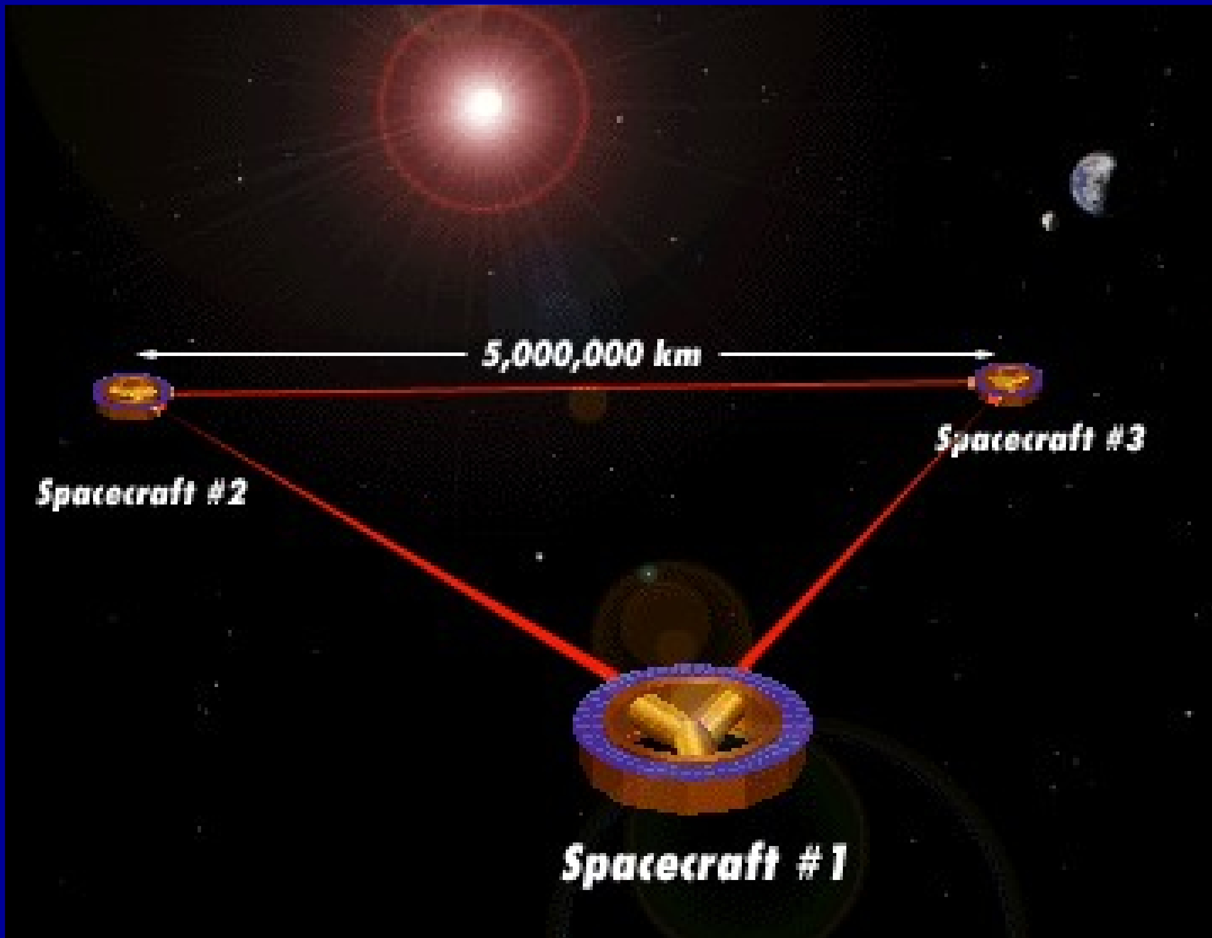


3. Gravitational radiation

$t \propto a$

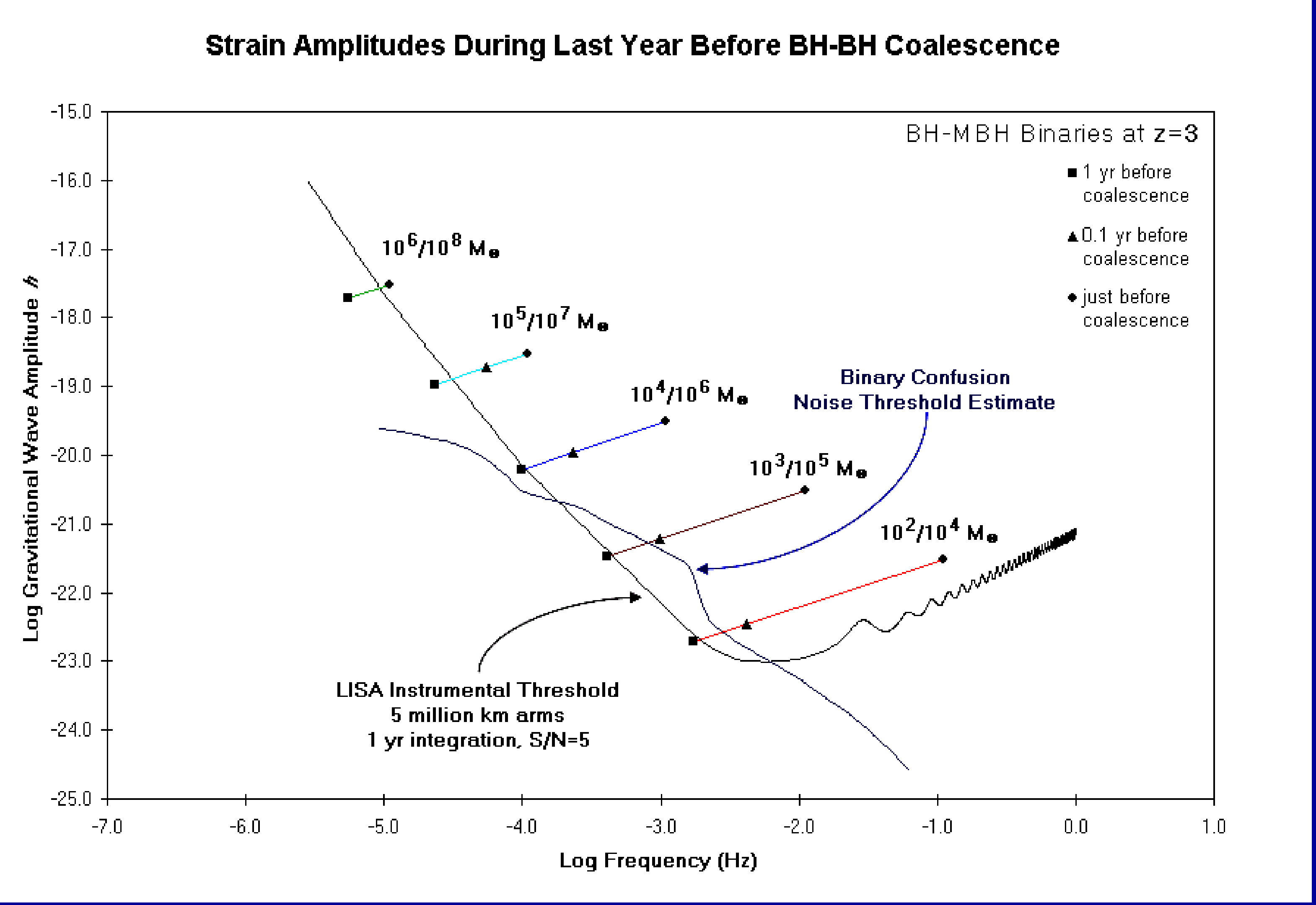


LISA

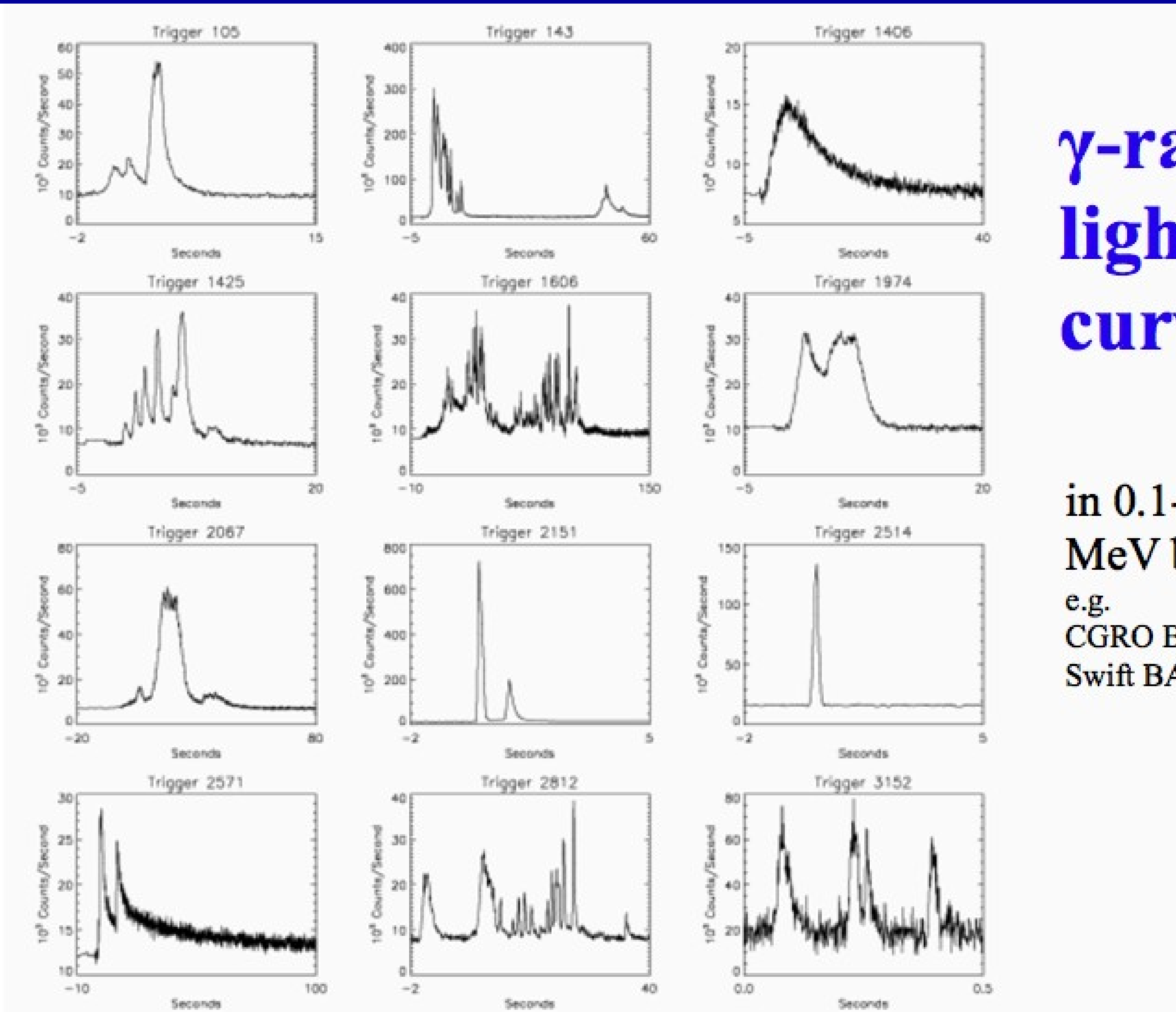


Will see mergers of 10 –10 Msol

2025?



Lisa sensitivity to massive black hole binaries



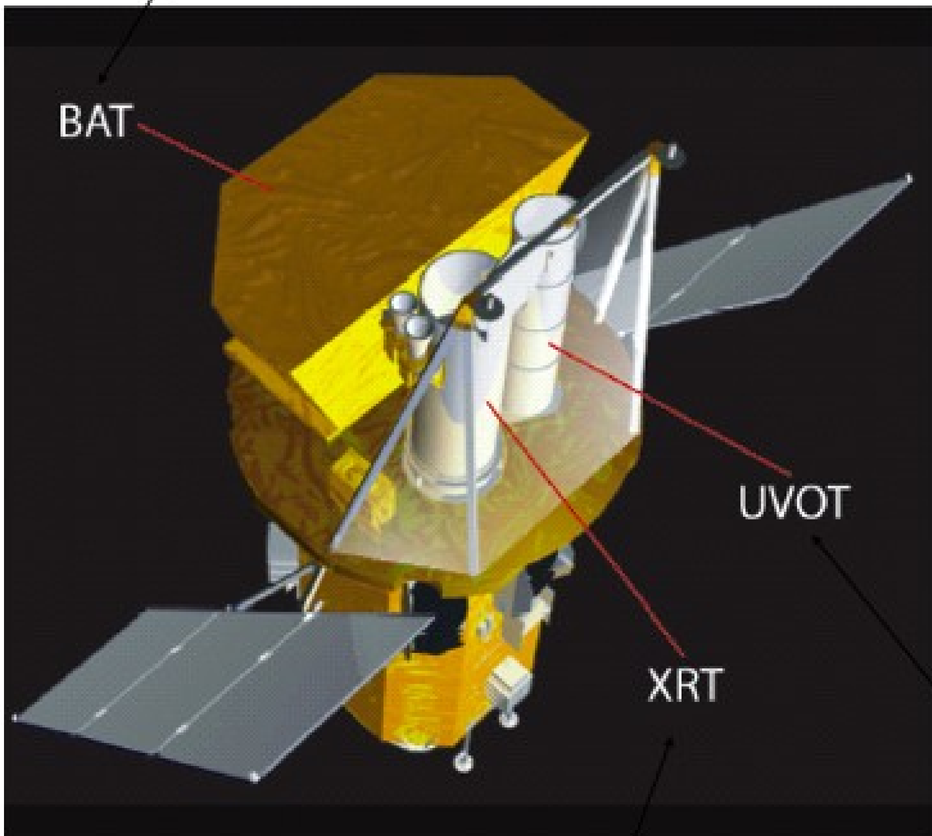
γ-ray light-curves

in 0.1-2 MeV band,

e.g.
CGRO BATSE,
Swift BAT

BAT: Energy Range: 15-150kev
FoV: 2.0 sr
Burst Detection Rate: 100 bursts/yr

SWIFT



Three instruments

Gamma-ray, X-ray and optical/UV

Slew time: 20-70 s !

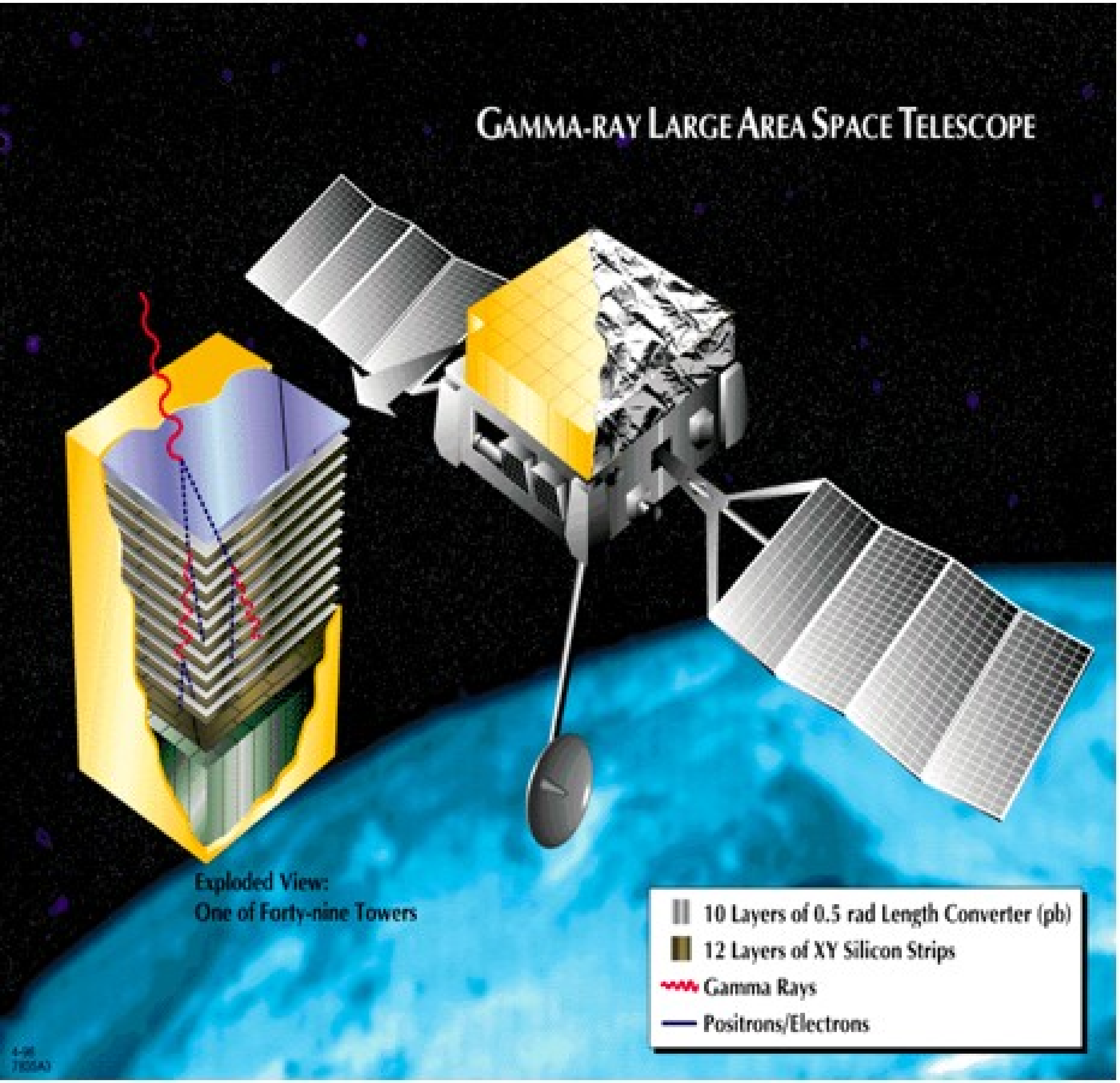
>95% of triggers yield XRT det
>50% triggers yield UVOT det.

UVOT: Wavelength Range: 170-650nm

XRT: Energy Range: 0.2-10 keV

Launched Nov 04

Mission Operations Center: @ PSU

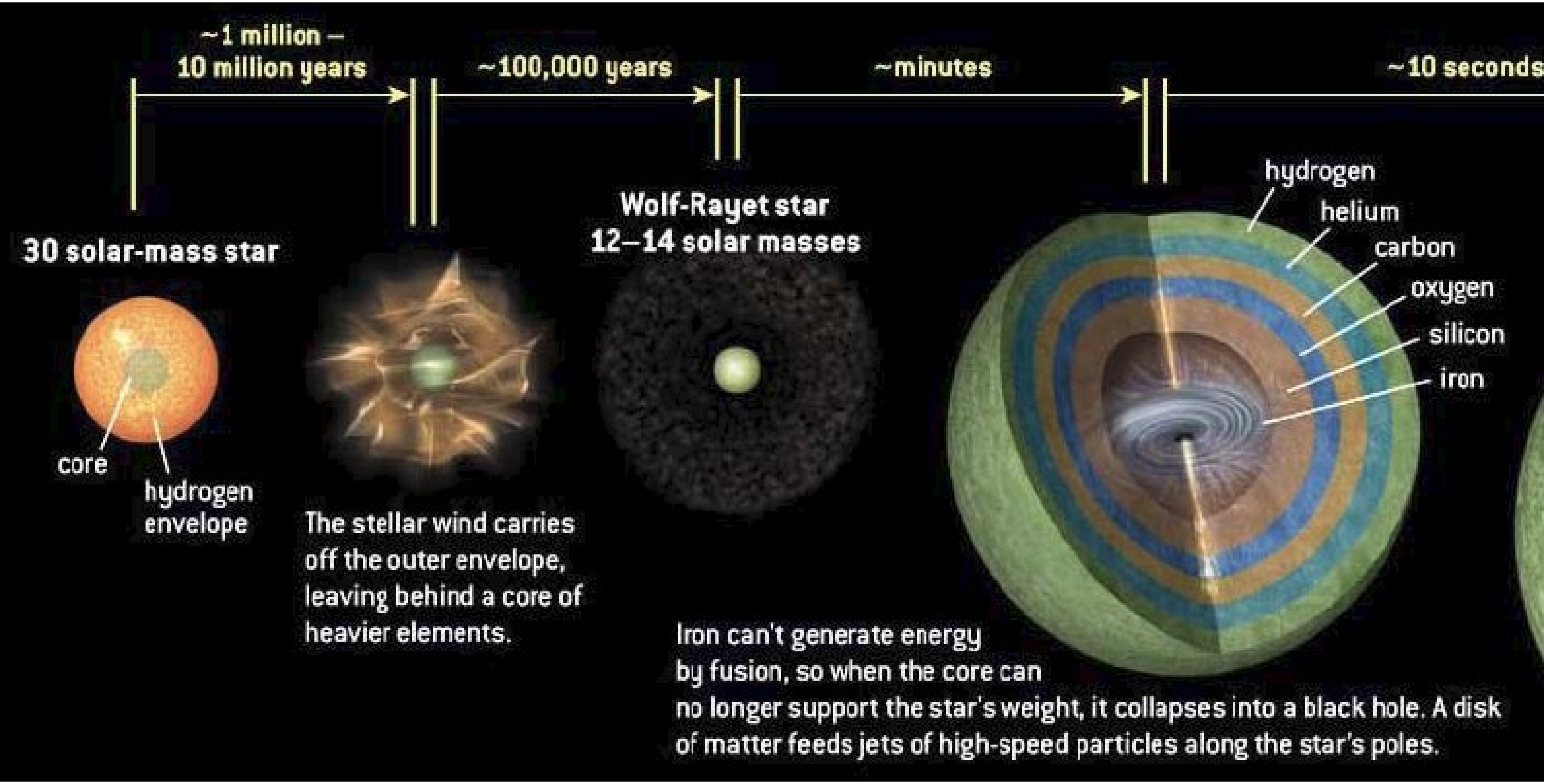


Fermi

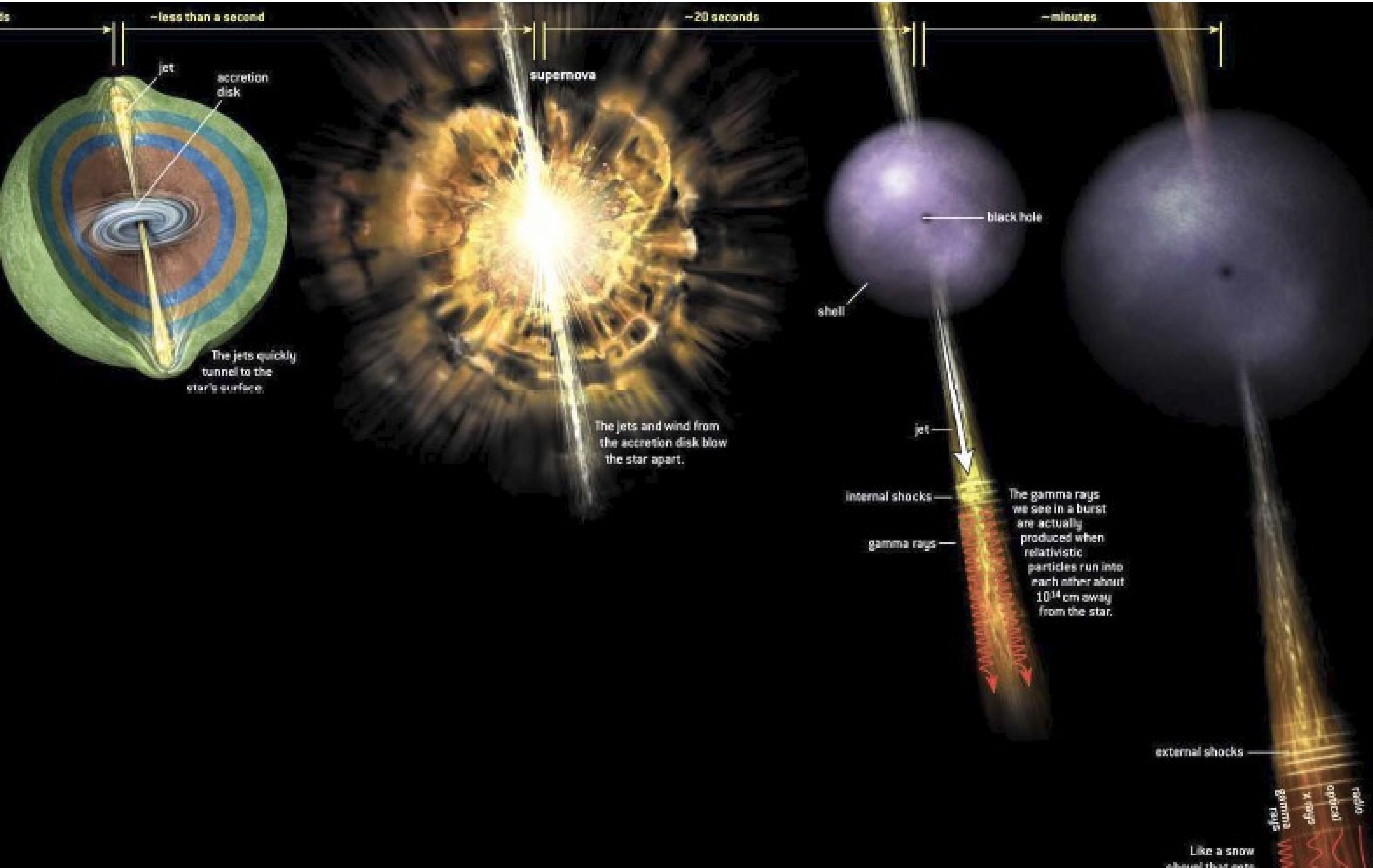
- Launched June 11 2008
- **LAT**: Pair-conv.modules + calorimeter
- 20 MeV-300 GeV, $\Delta E/E \sim 10\%$@1 GeV
- FoV = 2.5 sr (2xEgret), ang.res. θ~30”-5’ (10GeV)
- Sensit. $\sim 2.10^{-9}$ ph/cm^2/s (2 yr; > 50xEgret)
- GBM: FoV 4π, 10keV-30MeV
- 2.5 ton , 518 W
- det ~300 GRB/yr (GBM); simult. w. Swift : 30/yr; LAT: 1-2/month

Also on Fermi : **GBM** (~BATSE range) ;
12 NaI: 10keV-3 MeV; 2 BGO: 150 keV-30 MeV

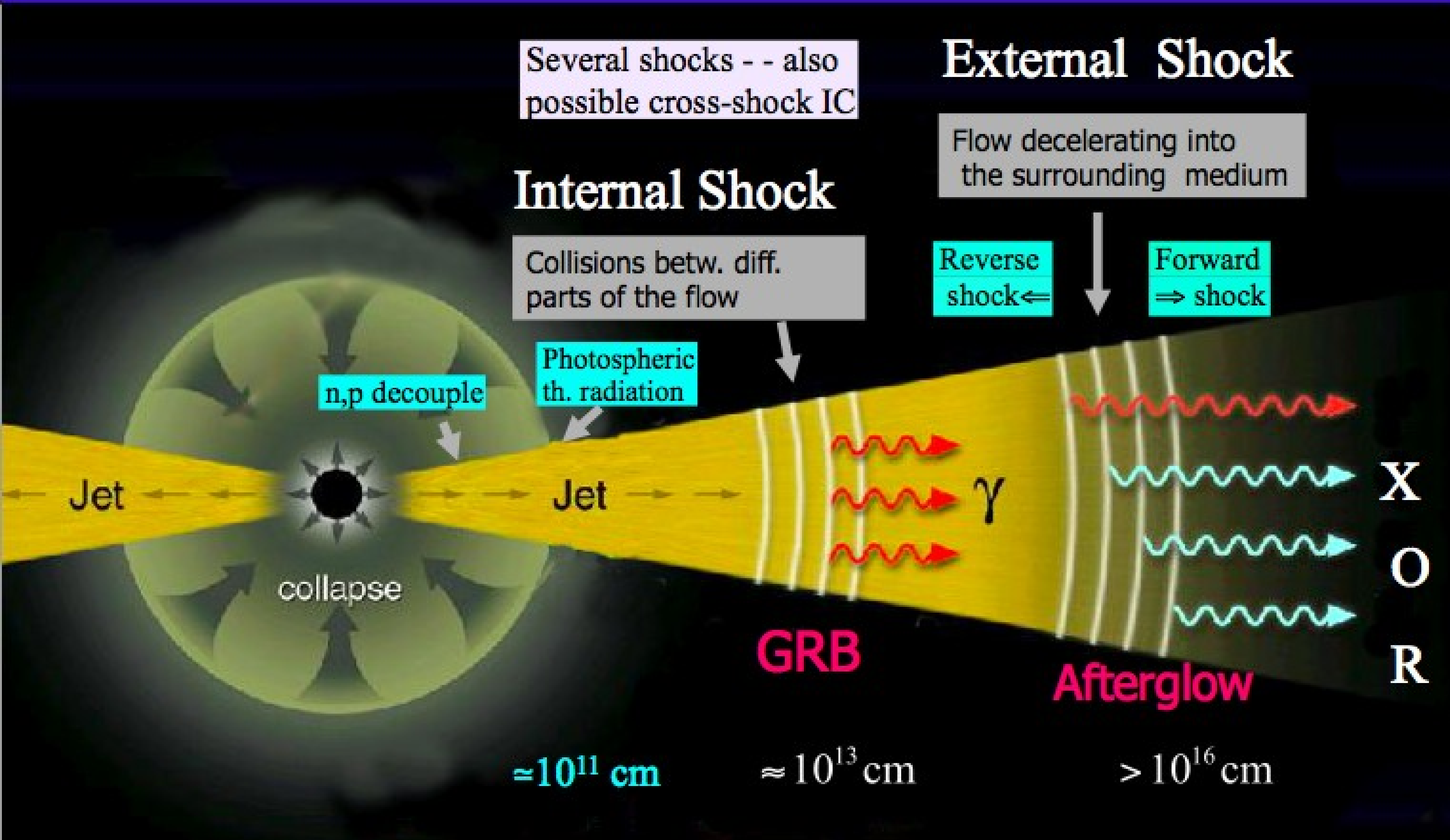
“long” GRB from “collapsars”



Collapsar GRB (cont.)



Fireball Shock Model of GRBs



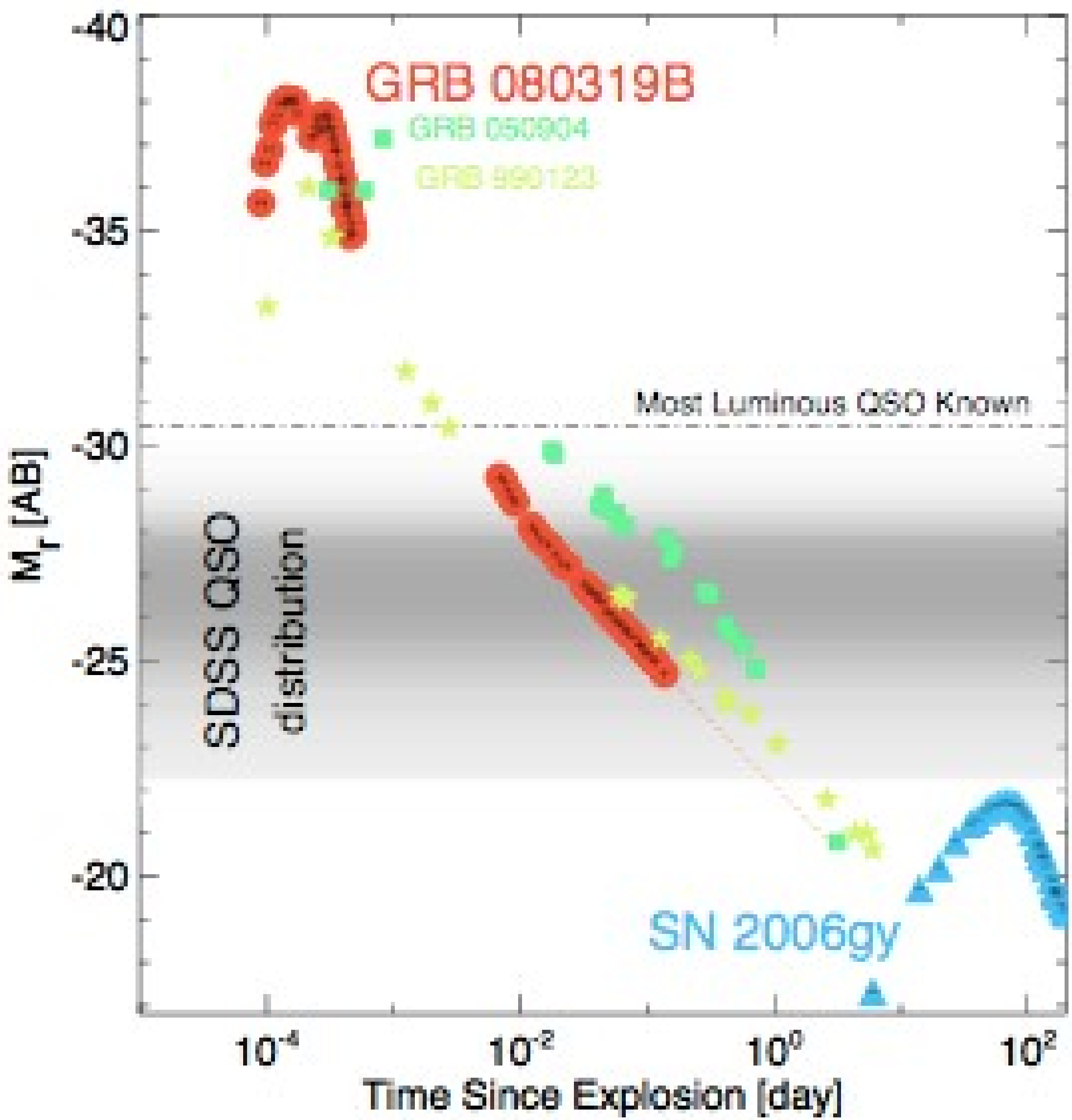
Letter

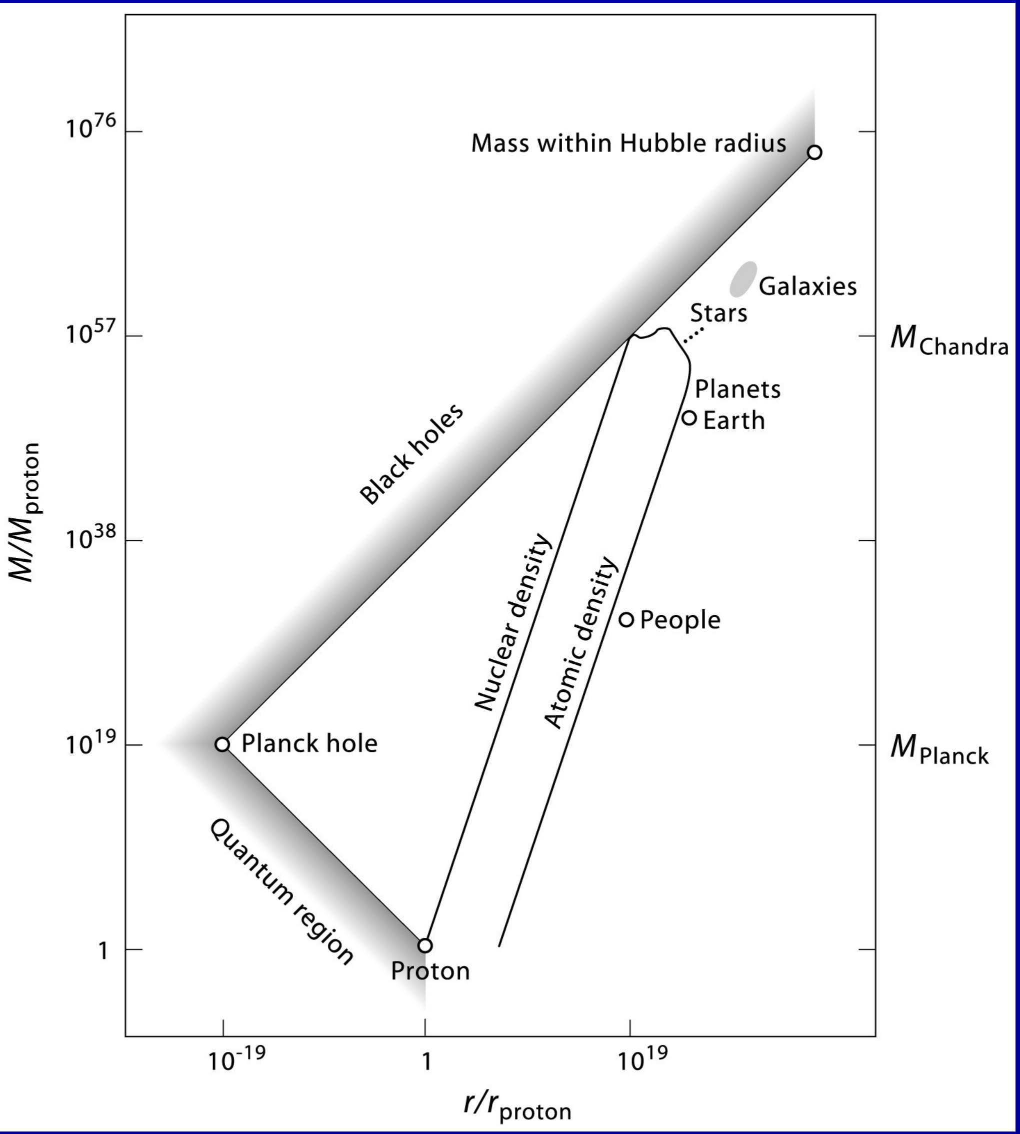
Nature **461**, 1254-1257 (29 October 2009) | doi:10.1038/nature08459; Received 3 June 2009; Accepted 19 August 2009

A γ-ray burst at a redshift of $z \approx 8.2$

N. R. Tanvir[1], D. B. Fox[2], A. J. Levan[3], E. Berger[4], K. Wiersema[1], J. P. U. Fynbo[5], A. Cucchiara[2], T. Krühler[6,7], N. Gehrels[8], J. S. Bloom[9], J. Greiner[6], P. A. Evans[1], E. Rol[10], F. Olivares[6], J. Hjorth[5], P. Jakobsson[11], J. Farihi[1], R. Willingale[1], R. L. C. Starling[1], S. B. Cenko[9], D. Perley[9], J. R. Maund[5], J. Duke[1], R. A. M. J. Wijers[10], A. J. Adamson[12], A. Allan[13], M. N. Bremer[14], D. N. Burrows[2], A. J. Castro-Tirado[15], B. Cavanagh[12], A. de Ugarte Postigo[16], M. A. Dopita[17], T. A. Fatkhullin[18], A. S. Fruchter[19], R. J. Foley[4], J. Gorosabel[15], J. Kennea[2], T. Kerr[12], S. Klose[20], H. A. Krimm[21,22], V. N. Komarova[18], S. R. Kulkarni[23], A. S. Moskvitin[18], C. G. Mundell[24], T. Naylor[13], K. Page[1], B. E. Penprase[25], M. Perri[26], P. Podsiadlowski[27], K. Roth[28], R. E. Rutledge[29], T. Sakamoto[21], P. Schady[30], B. P. Schmidt[17], A. M. Soderberg[4], J. Sollerman[5,31], A. W. Stephens[28], G. Stratta[26], T. N. Ukwatta[8,32], D. Watson[5], E. Westra[4], T. Wold[12] & C. Wolf[27]

1. Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH, UK


GRB 080319B
GRB 050904
GRB 990123
Most Luminous QSO Known
SDSS QSO
distribution
SN 2006gy
-40
-35
-30
-25
-20
M_r [AB]
10^{-4}
10^{-2}
10^{0}
10^{2}
Time Since Explosion [day]



Mass within Hubble radius
Galaxies
Stars
Planets
Earth
Black holes
Nuclear density
Atomic density
People
Planck hole
Quantum region
Proton
10^{76}
10^{57}
10^{38}
10^{19}
1
$M_{Chandra}$
M_{Planck}
M/M_{proton}
10^{-19}
1
10^{19}
r/r_{proton}

$$e^2 / G m_p^2$$

The Cosmological Constants

PROF. P. A. M. DIRAC's recent letter in NATURE[1] encourages me to direct attention to certain 'coincidences' which I had noticed some years ago, but which I have been hesitating to publish from the conviction that purely 'dimensional arguments' will not lead one very far.

If we consider the natural constants h (Planck's constant), c (velocity of light), H (mass of the proton), G (the constant of gravitation), we can form the following combination M_α which is of the dimension of mass:

$$M_\alpha = \left(\frac{hc}{G}\right)^\alpha \frac{1}{H^{2\alpha-1}}. \qquad (1)$$

where α is an arbitrary numerical constant. Now a particular case of the above occurs in the theory of stellar interiors, namely, when $\alpha = 3/2$. Then

$$M_{3/2} = \left(\frac{hc}{G}\right)^{3/2} \frac{1}{H^2} \doteqdot 5\cdot76 \times 10^{34} \text{ gm.}, \qquad (2)$$

which is about thirty times the mass of the sun. Now, the apparent success of steady state considerations in 'explaining' the observed order of stellar masses can be traced to the circumstance that the above combination (2) of the natural constants gives a mass of the correct order. It may be noticed that apart from numerical constants, (2) is the same as the upper limit to the mass of completely degenerate (degenerate in the sense of the Fermi-Dirac statistics) configurations[2]. The occurrence of (2) in stellar structure equations need not cause any surprise, since one can easily convince oneself by considering two homologous stellar configurations that if a formula for mass exists, it must contain the mean molecular weight μH with an inverse power 2, and this would, according to (1), fix the value of the exponent α as 3/2.

It is of interest to see what (1) leads to for other values of α. If $\alpha = 2$, then

$$M_2 = \left(\frac{hc}{G}\right)^2 \frac{1}{H^3} \doteqdot 9\cdot5 \times 10^{55} \text{ mass of sun} \qquad (3)$$

If we divide M_2 by H, then we get for the corresponding 'number of protons or/and neutrons',

$$N = \left(\frac{hc}{G}\right)^2 \frac{1}{H^4} \doteqdot 1\cdot1 \times 10^{79}, \qquad (4)$$

which is of the right order as the 'number of particles in the universe'. We may notice that if $G \sim t^{-1}$ (t is Milne's cosmological time), then $N \sim t^2$, which agrees with Dirac's speculation.

It may be further pointed out that if $\alpha = 1\frac{3}{4}$, then

$$M_{1\frac{3}{4}} = 1\cdot7 \times 10^{11} \text{ mass of sun}, \qquad (5)$$

which is of the same order as the mass of our Milky Way system. If we 'identify' $M_{1\frac{3}{4}}$ as representing the mass of a galaxy (external or otherwise), then we should have, according to Dirac's ideas, that the 'number of particles in the galaxy' should vary as $t^{1\cdot75}$. Similarly, the number of particles in a star should vary as $t^{1\cdot5}$.

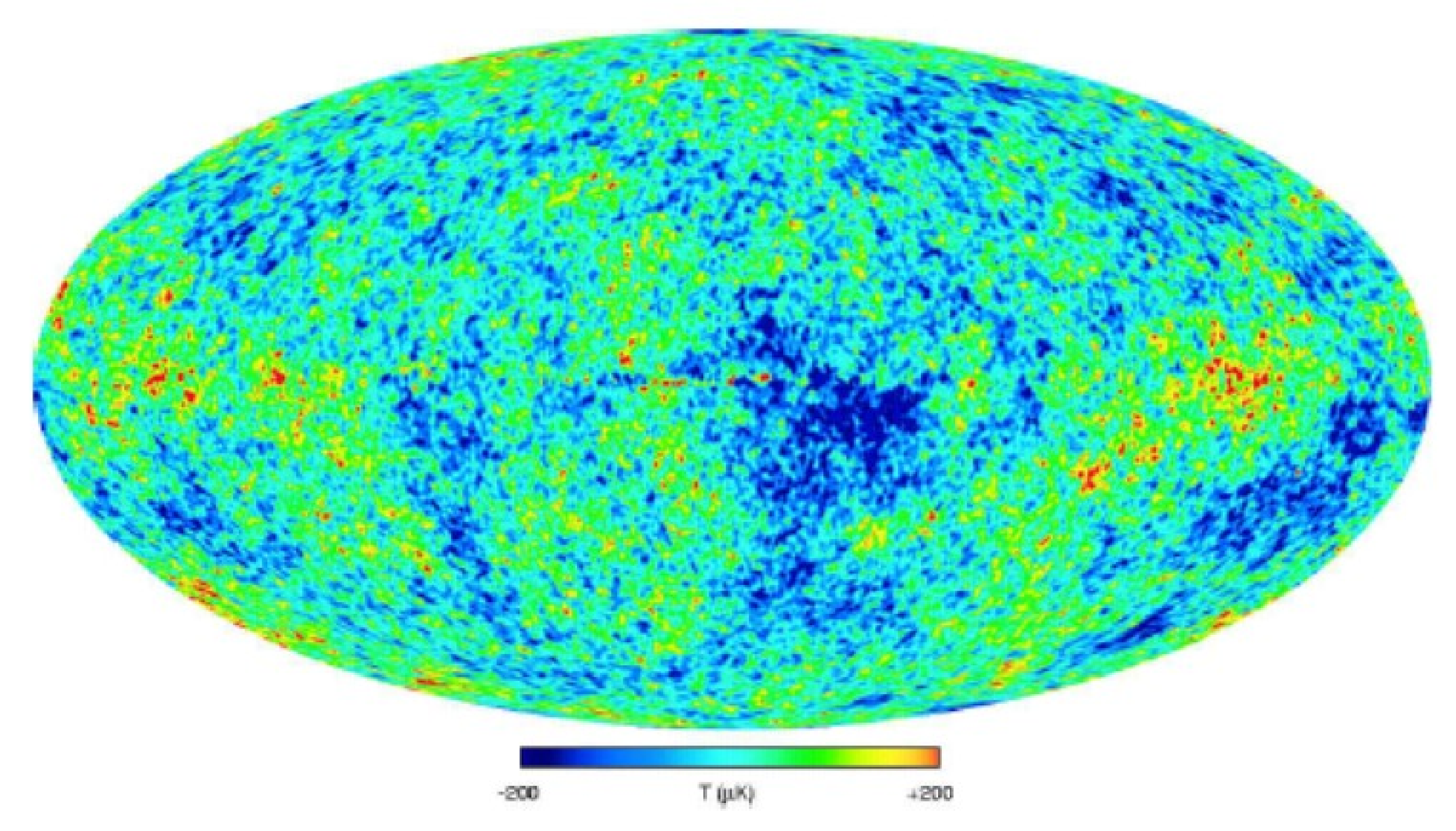
S. CHANDRASEKHAR.

Yerkes Observatory,
Wisconsin.

[1] NATURE, 139, 323 (Feb. 20, 1937).
[2] Chandrasekhar, S., *Mon. Not. Roy. Ast. Soc.*, 91, 456 (1931).

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

WMAP CBR SKY



Page et al; 2003

FLUCTUATION AMPLITUDE

$$Q \cong 10^{-5} \left(\sim \frac{\Delta T}{T} \right)$$

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

Max Non-:Linear Scale

→ $Q^{1/2}$ x (Hubble Radius).

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

POSSIBLE UNIVERSE WITH *Q* = 10-4

**perhaps* *<u>more interesting than ours!</u>*

Masses >~ 1014 M⊙ condense at 3.108 yrs into huge disc galaxies with orbital velocity ~2000 km/sec (gas would cool efficiently via Compton cooling, leading probably to efficient star formation).

These would, after 1010 yrs, be in clusters of

>~ 1016 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.

UNIVERSE WITH *Q* > 10-3

Monster overdensities (up to 1018 M$_\odot$) condense out early enough that they trap the CMB radiation, and collapse as radiation-pressure-dominated hypermassive objects unable to fragment*. This leads to universe of vast holes, clustered on scales up to several percent of Hubble radius (and probably pervaded by intense ‘hard’ radiation).

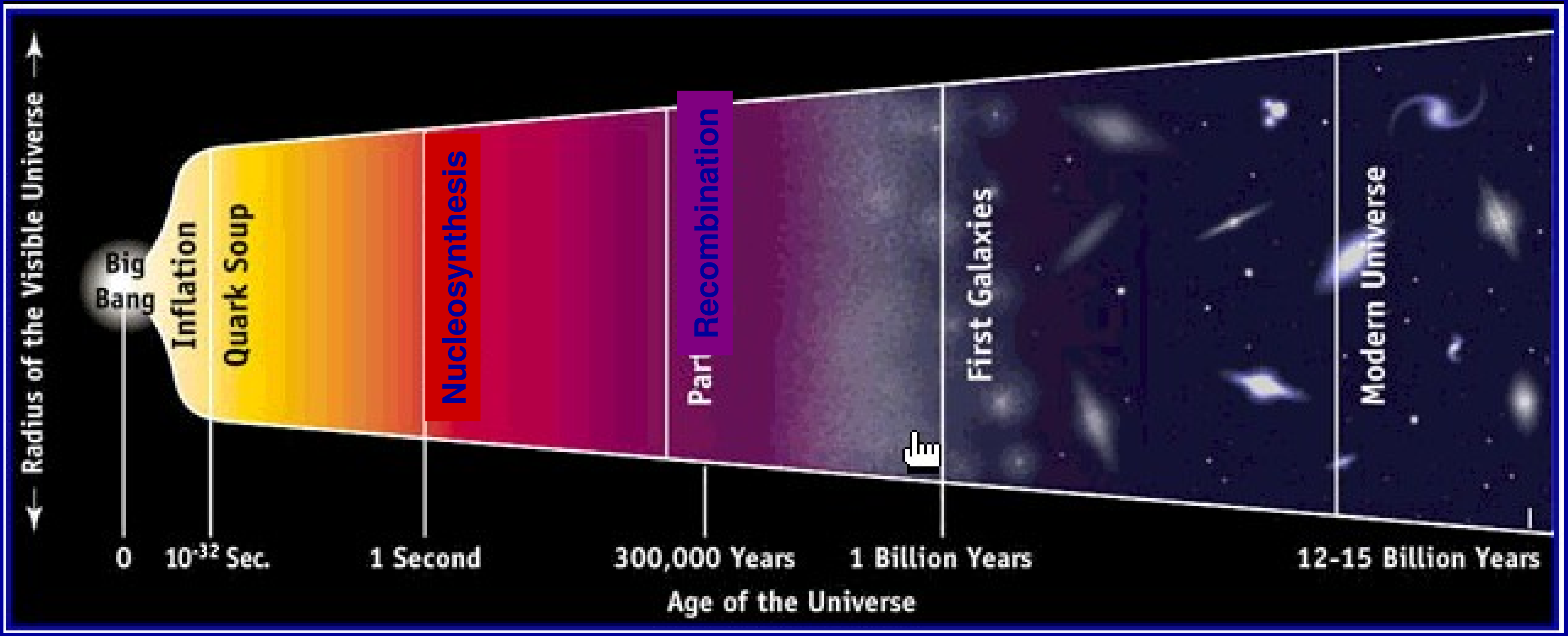
It isn’t obvious that much baryonic material would ever go into stars. (If so they would be in very compact highly bound systems.)

**This does not require pre-combination collapse. Collapse at (say)* 107 *years would lead to sufficient partial reionization (via strong shocks) to recouple the baryons and CMB.*

AN ANAEMIC UNIVERSE (Q = 10)

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.

Cosmic Evolution -Cartoon

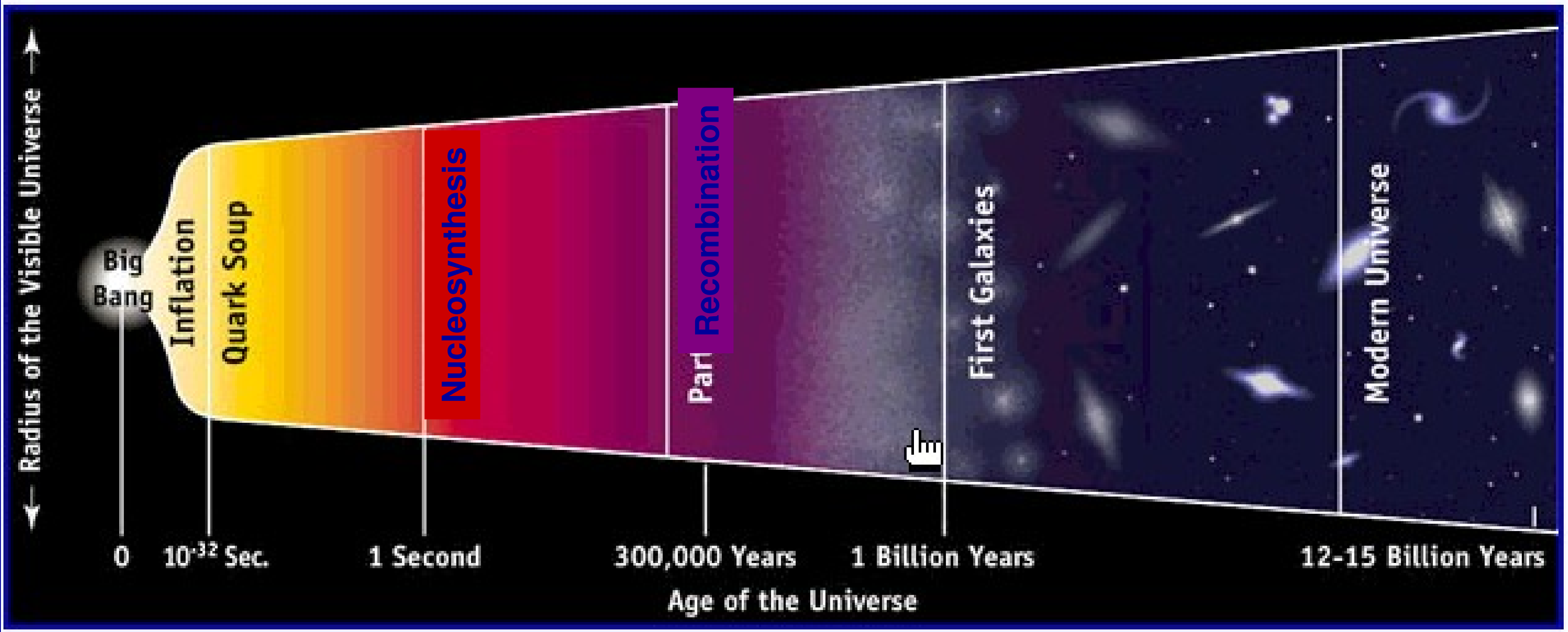


Well-understood

nonlinear simulations

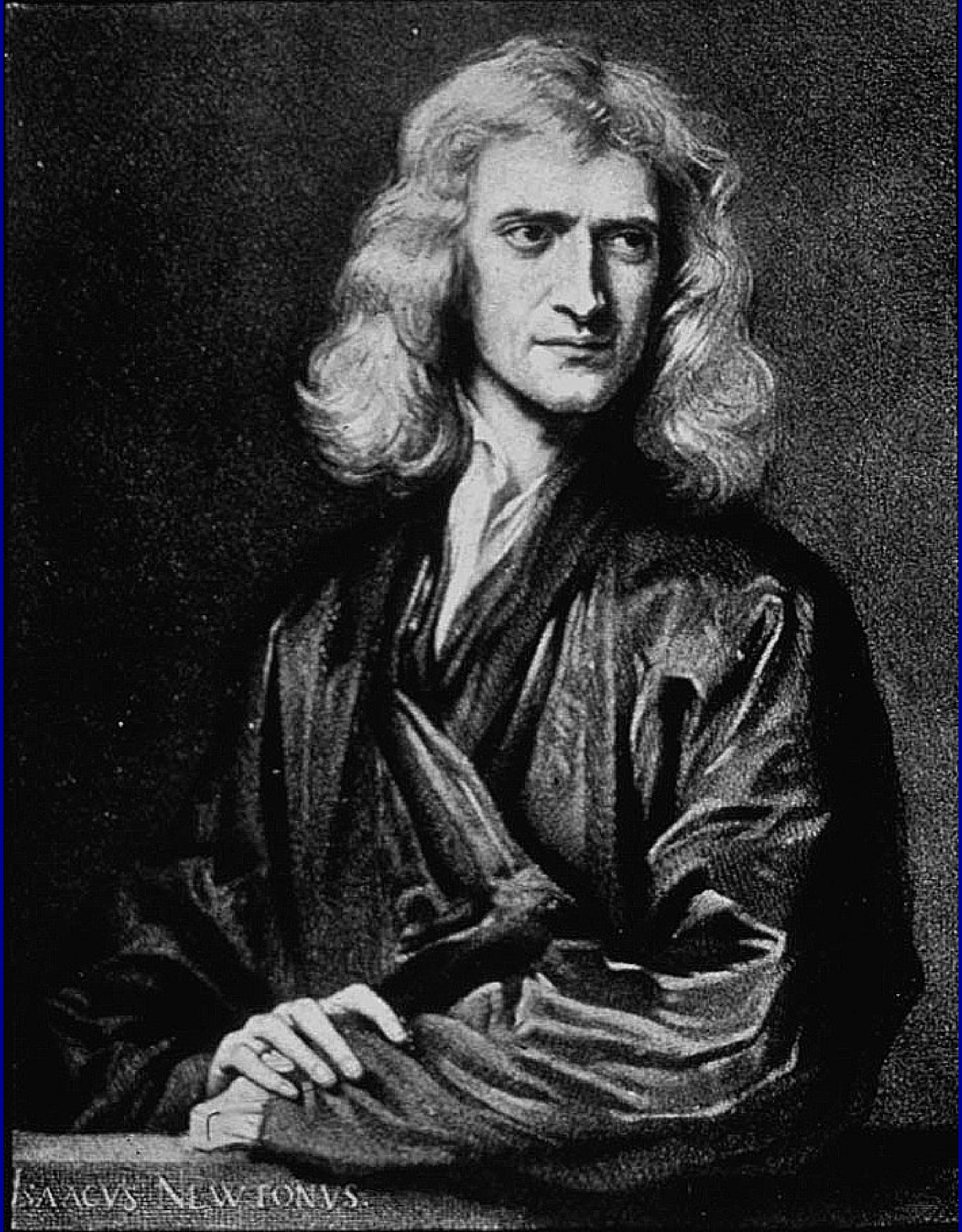

The Year in Science
Discover
SCIENCE, TECHNOLOGY, AND MEDICINE
The Very
Early
Real size!

Cosmic Evolution -Cartoon



Well-understood

nonlinear simulations

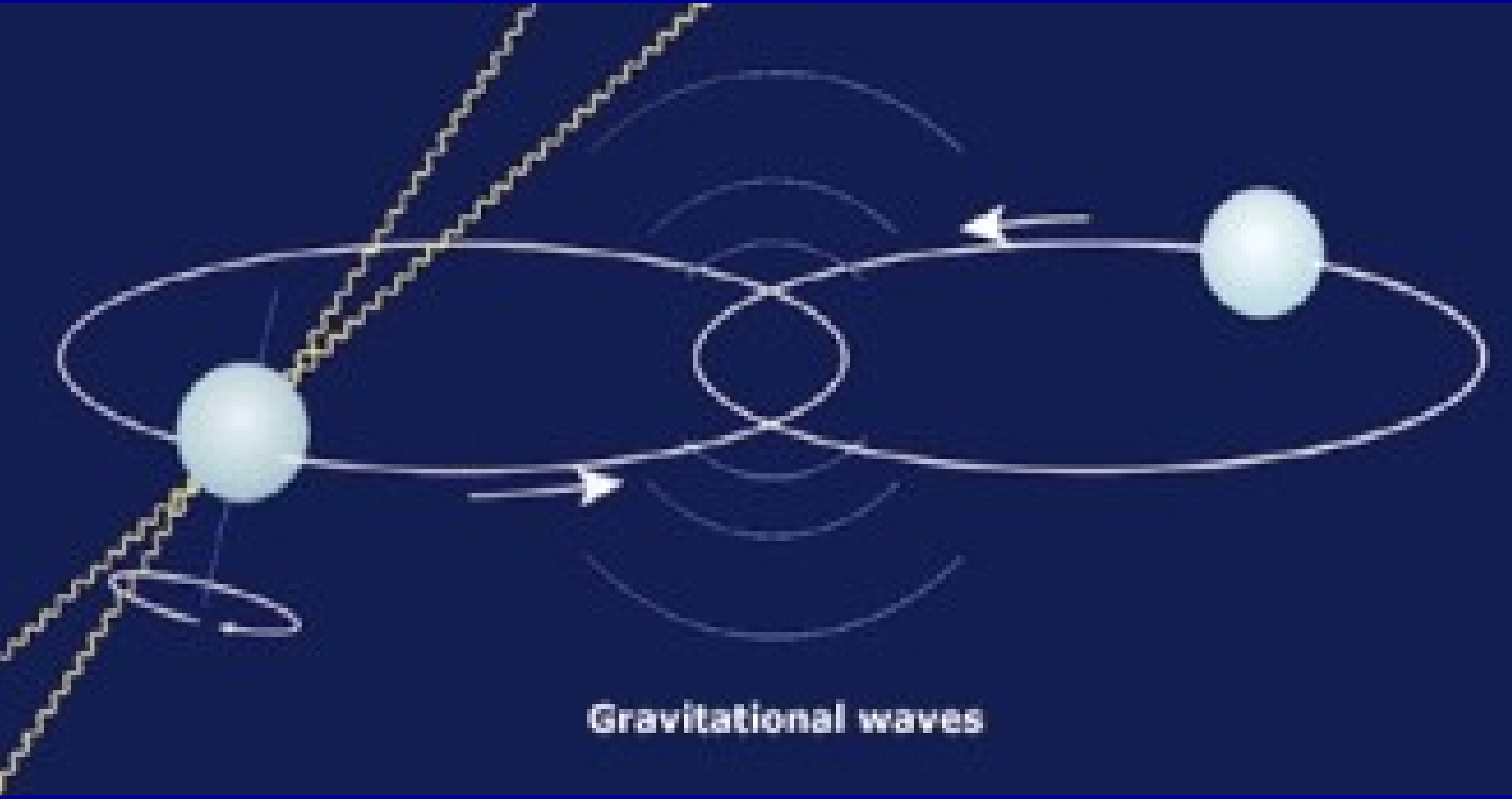

ISAACVS NEWTONVS.

QuickTime™ and a
decompressor
are needed to see this picture.

Observational progress in demography and evolution of holes

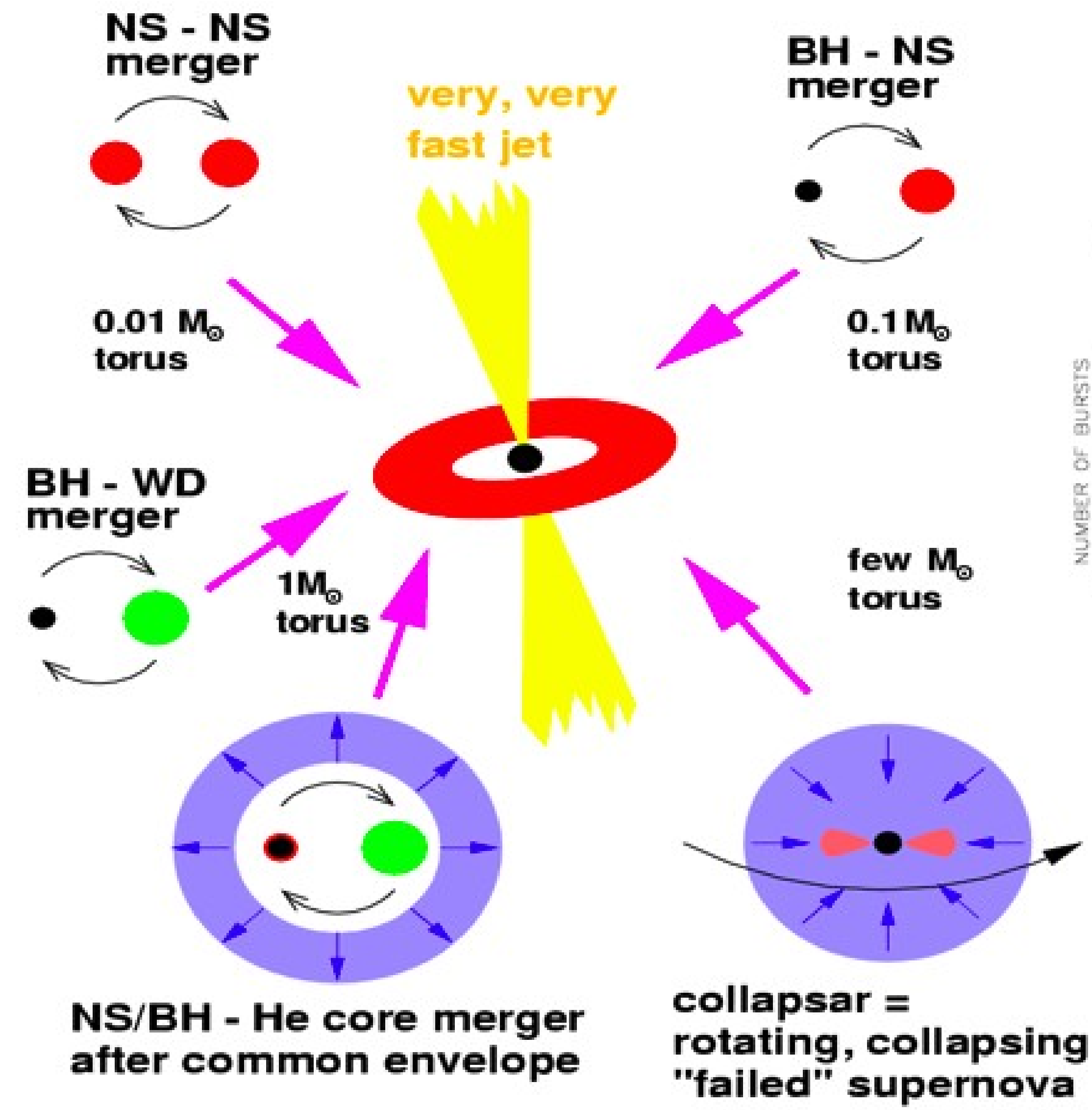
(I) Ubiquity of holes in galaxies

(II) Feedback from hole to galaxy


Gravitational waves

GRB: standard paradigm

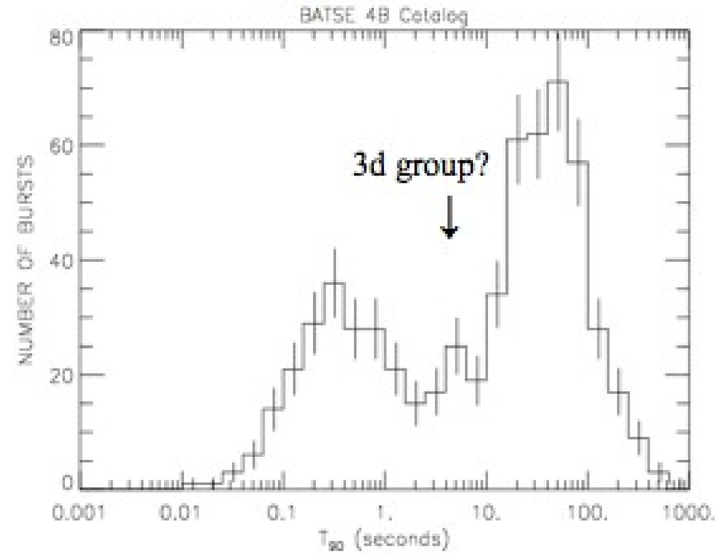
Hyperaccreting Black Holes



Bimodal distribution of t_γ duration

←↓**Short**

(t_g< 2 s)



→↑**Long**

(t_g >2 s)

Astrophysical questions about black holes

1. Radiation, ,accretion jets, winds, etc --- phenomenology and models.

1. Do ‘holes’ obey the Kerr metric (testing strong-field GR, etc)?

2. Population and demography of supermassive holes: how do they form and evolve?

* * *straightforward scaling laws between*

stellar-mass and supermassive holes

ROTATIONAL ENERGY

Gravitational contraction

$\Rightarrow$ spin-up
$\Rightarrow$ increase in rotational energy

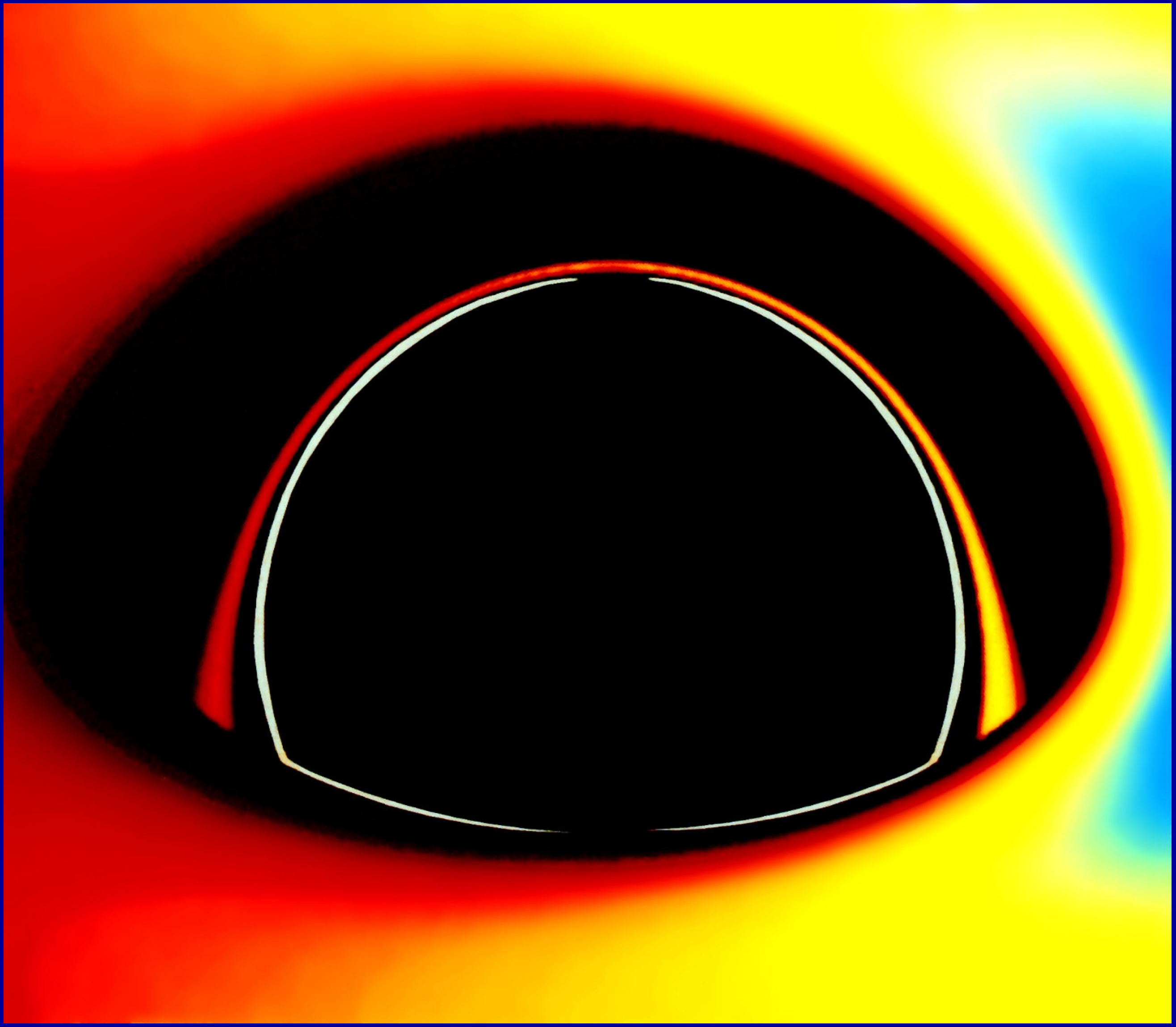
(c.f. pulsars: observed spin rates $\omega/2\pi$ up to 600 Hz)

$$\left(\begin{array}{c} \text{Spin} - \text{down} \\ \text{luminosity} \end{array} \right) \propto \omega^4 \times \left(\begin{array}{c} \text{mag. dipole} \\ \text{moment} \end{array} \right)^2 + \omega^6 \times \left(\begin{array}{c} \text{grav. quadrupole} \\ \text{moment} \end{array} \right)^2$$

↑ ELECTROMAGNETIC (mag. dipole moment term)

⇡ GRAVITATIONAL (grav. quadrupole moment term)

NOTE Gravitational radiation important in compact binaries

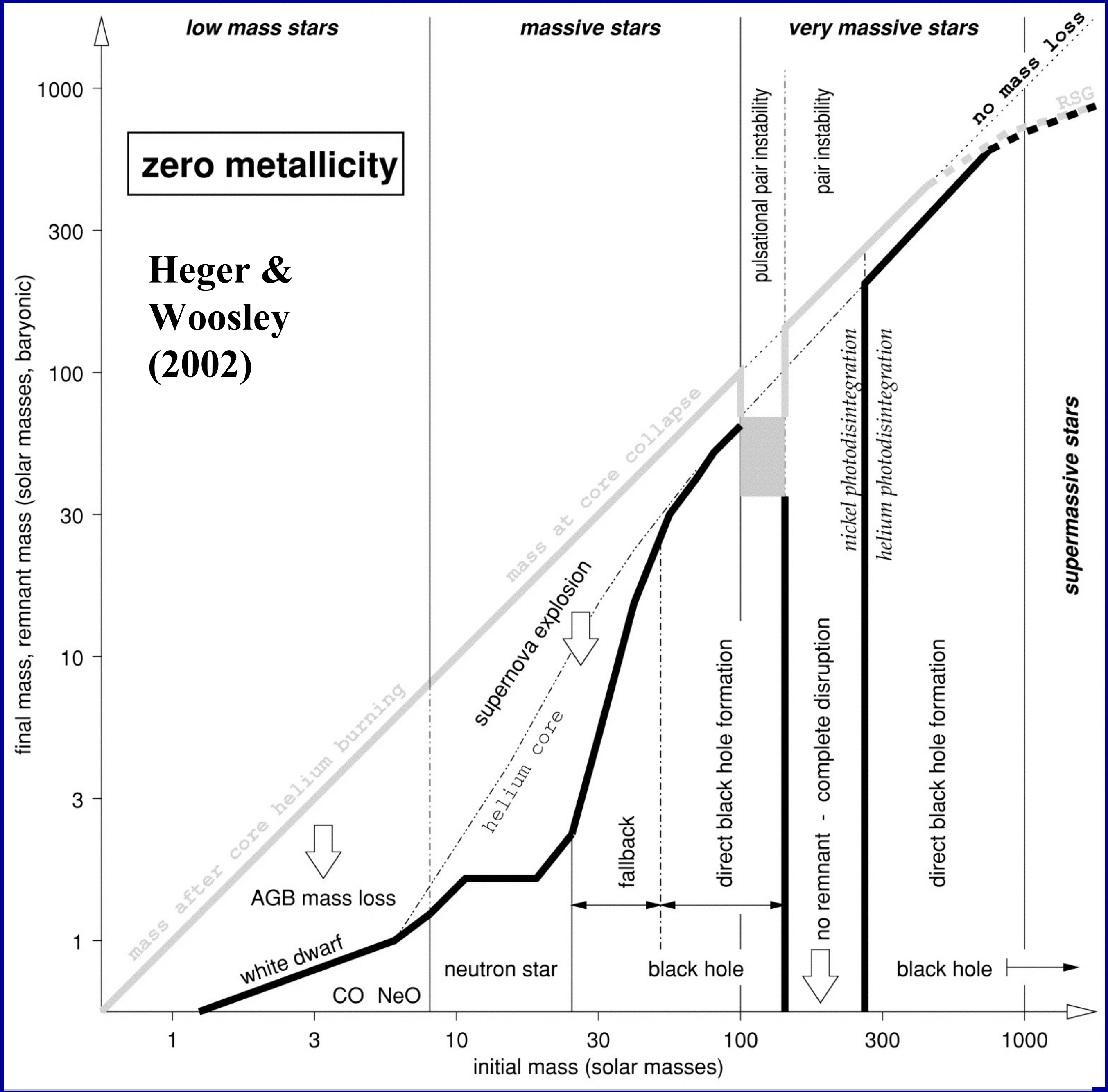


Just six numbers

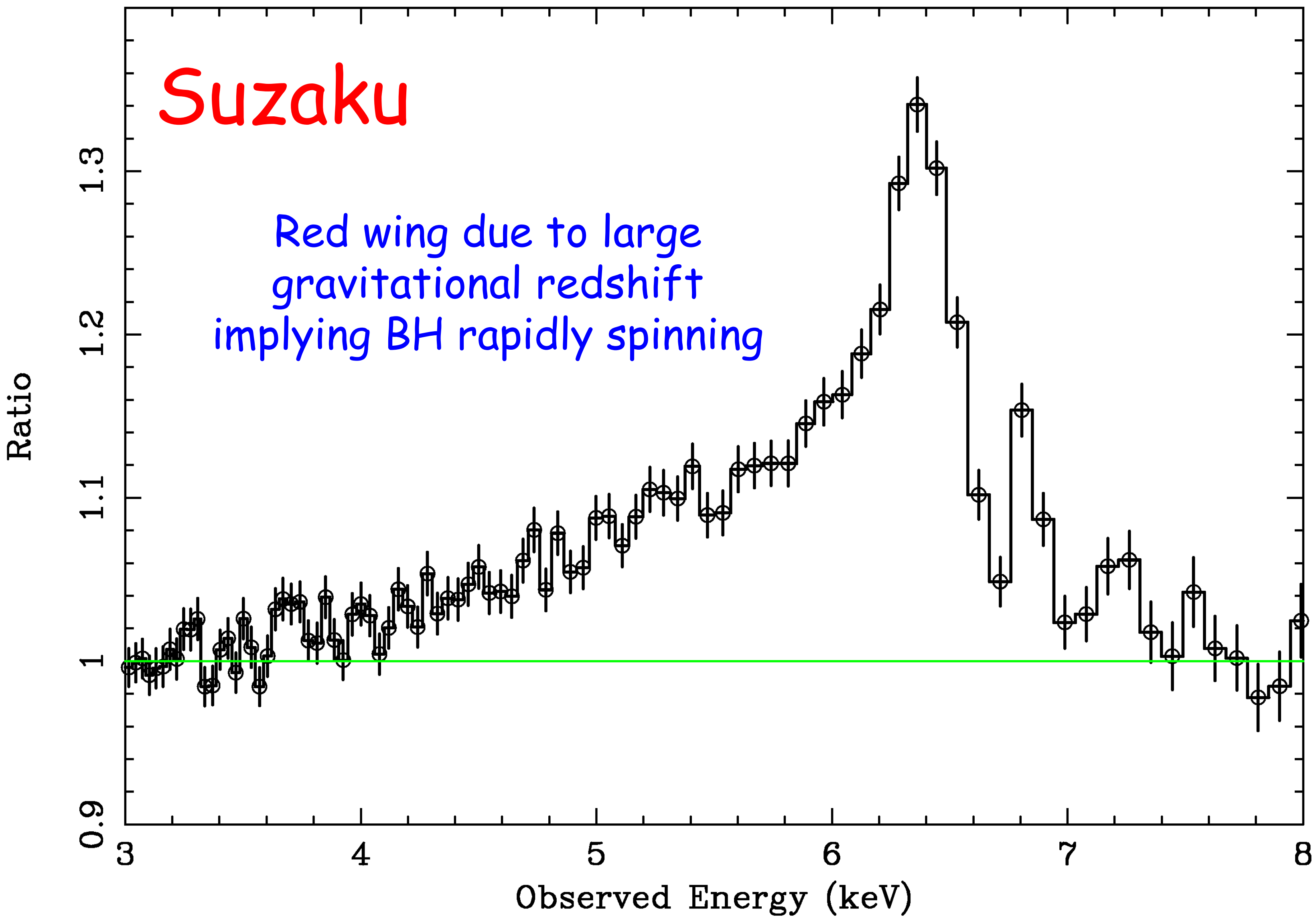
Six constants of nature whose values must lie in an ‘anthropic’ range for life to emerge

1. D = 3 The number of spatial dimensions
2. $G/E = 10^{-36}$ The ratio of gravitational to electrostatic force
3. S = 0.007 A measure of the strong force that binds nuclei
1. $\Omega_{Total} = 1$ The density of matter/energy in space
1. Q= 0.00001 The scale of fluctuations in the microwave background
1. $\Omega_{\Lambda} = 0.7$ Omega lambda, a measure of the vacuum energy of the universe

- Coincidence?
- Consequence?
- Multiverse?


zero metallicity
Heger & Woosley (2002)
low mass stars
massive stars
very massive stars
supermassive stars
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)
1000
300
100
30
10
3
1
1
3
10
30
100
300
1000
no mass loss
RSG
pulsational pair instability
pair instability
nickel photodisintegration
helium photodisintegration
mass at core collapse
mass after core helium burning
supernova explosion
helium core
AGB mass loss
white dwarf
CO NeO
neutron star
fallback
direct black hole formation
no remnant - complete disruption
direct black hole formation
black hole
black hole

MCG-6-30-15



Suzaku
Red wing due to large
gravitational redshift
implying BH rapidly spinning
Ratio
0.9
1
1.1
1.2
1.3
3
4
5
6
7
8
Observed Energy (keV)

MAXIMUM POWER OF ANY COSMIC SOURCE

(rest mass energy)

(light travel time across
Schwarzschild radius)

$$= C^5 / G$$

STELLAR NUCLEAR ENERGY

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

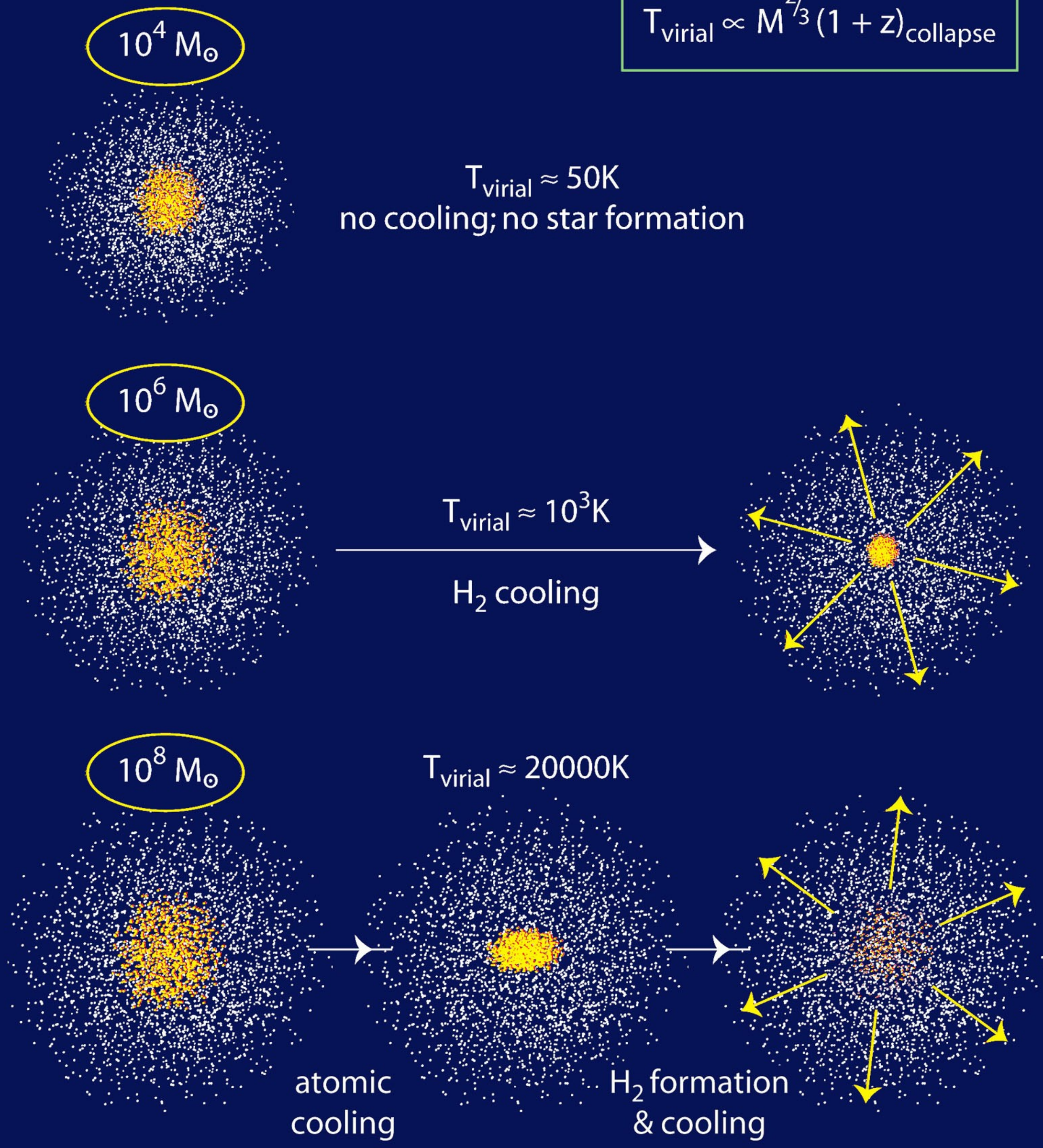
Where ΔY is increment in He

ΔZ is increment in heavier elements

FATE OF THE FIRST BOUND SYSTEMS

($z \approx 20$)

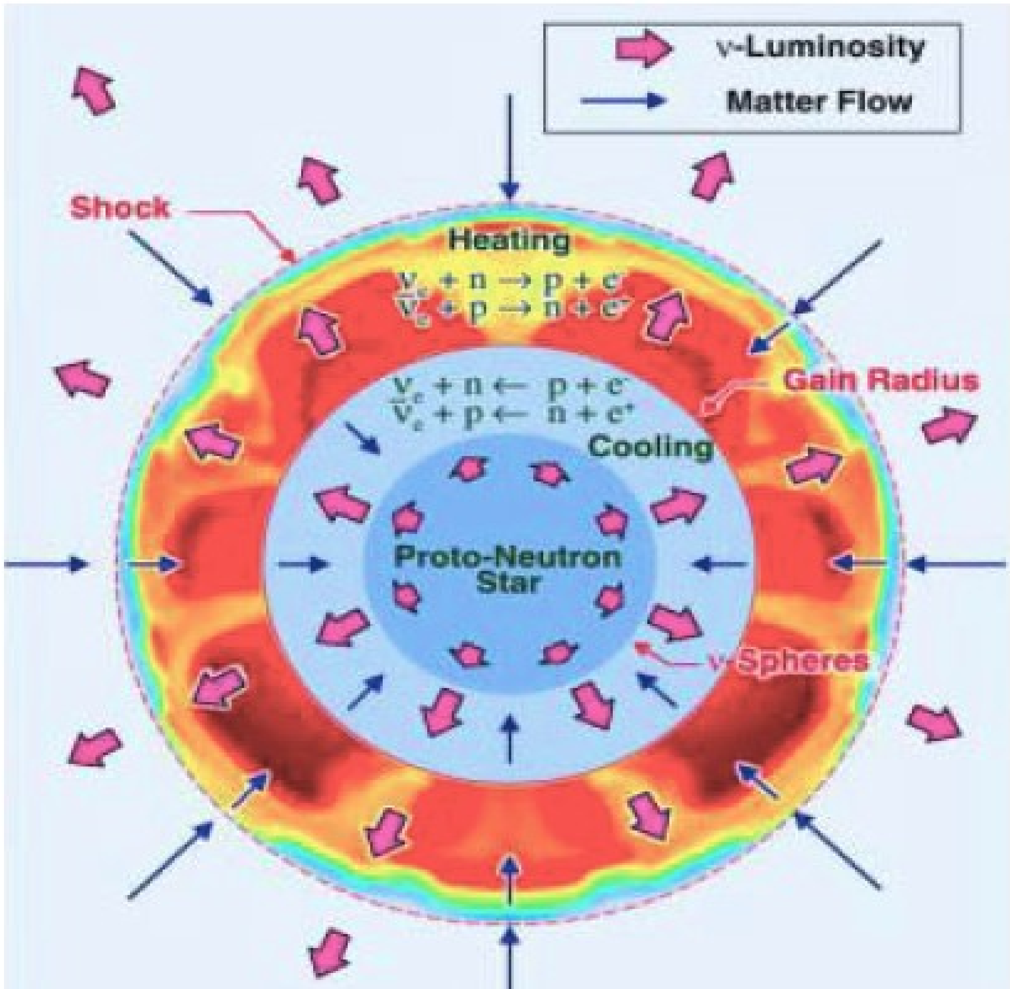
$$T_{virial} \propto M^{2/3} (1 + z)_{collapse}$$

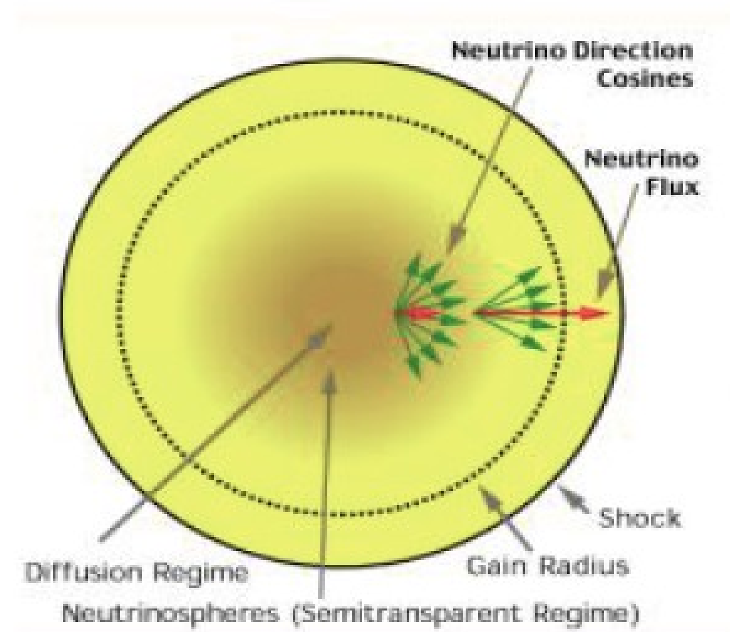


STARS

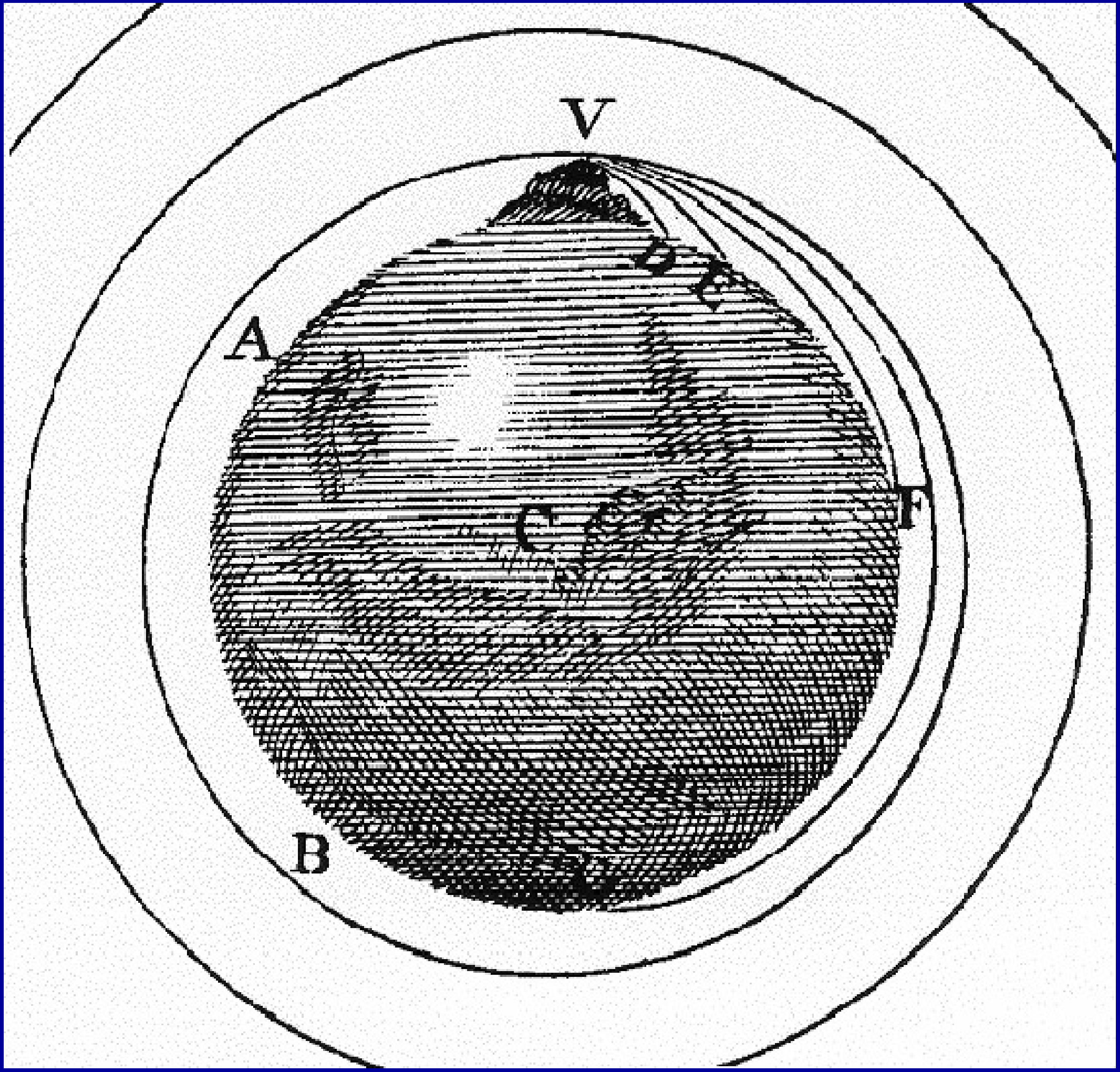
Gravitationally-bound systems
with *negative* specific heat

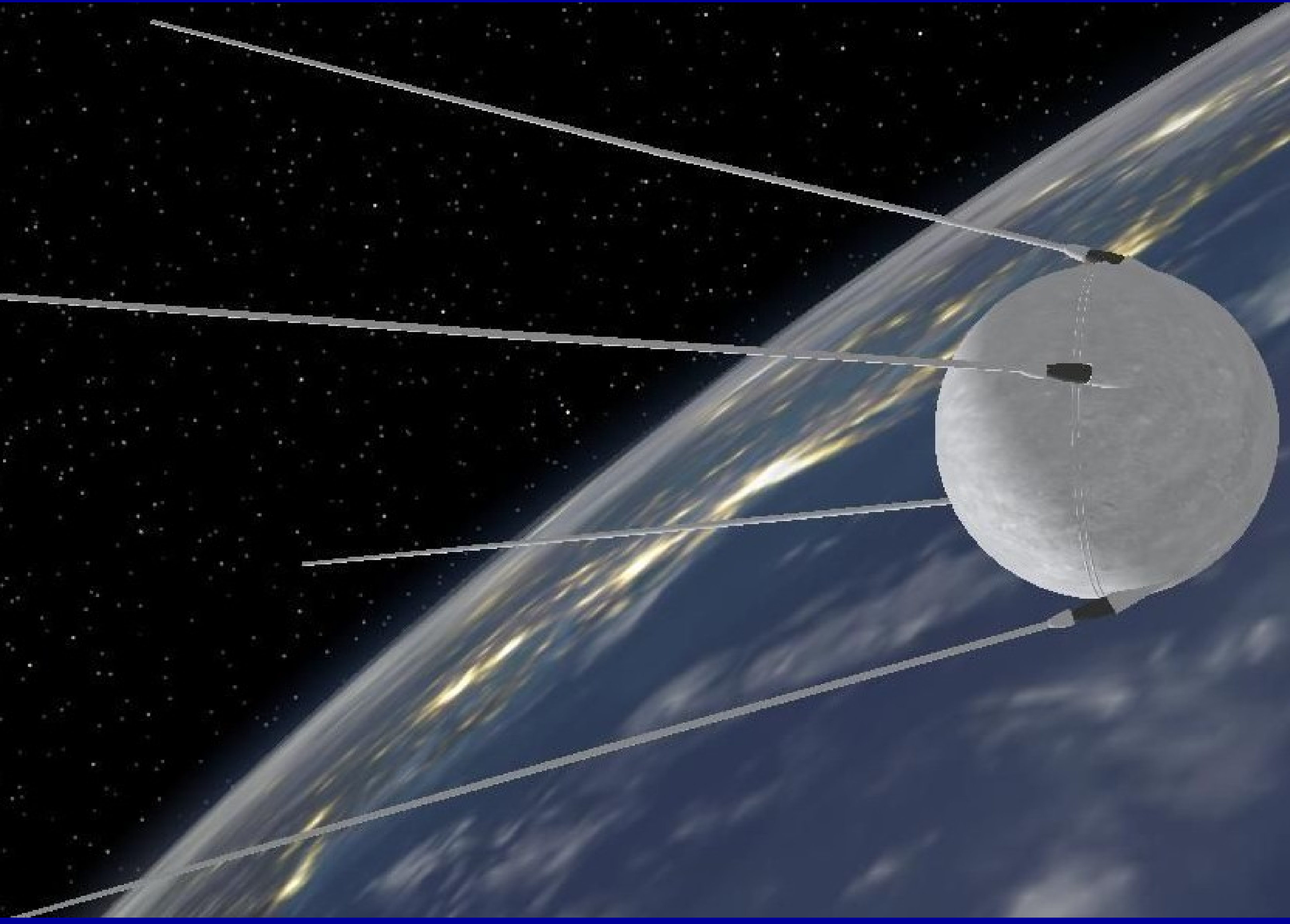
Core-collapse SN bounce, shock & thermal ν (10-30 MeV) production

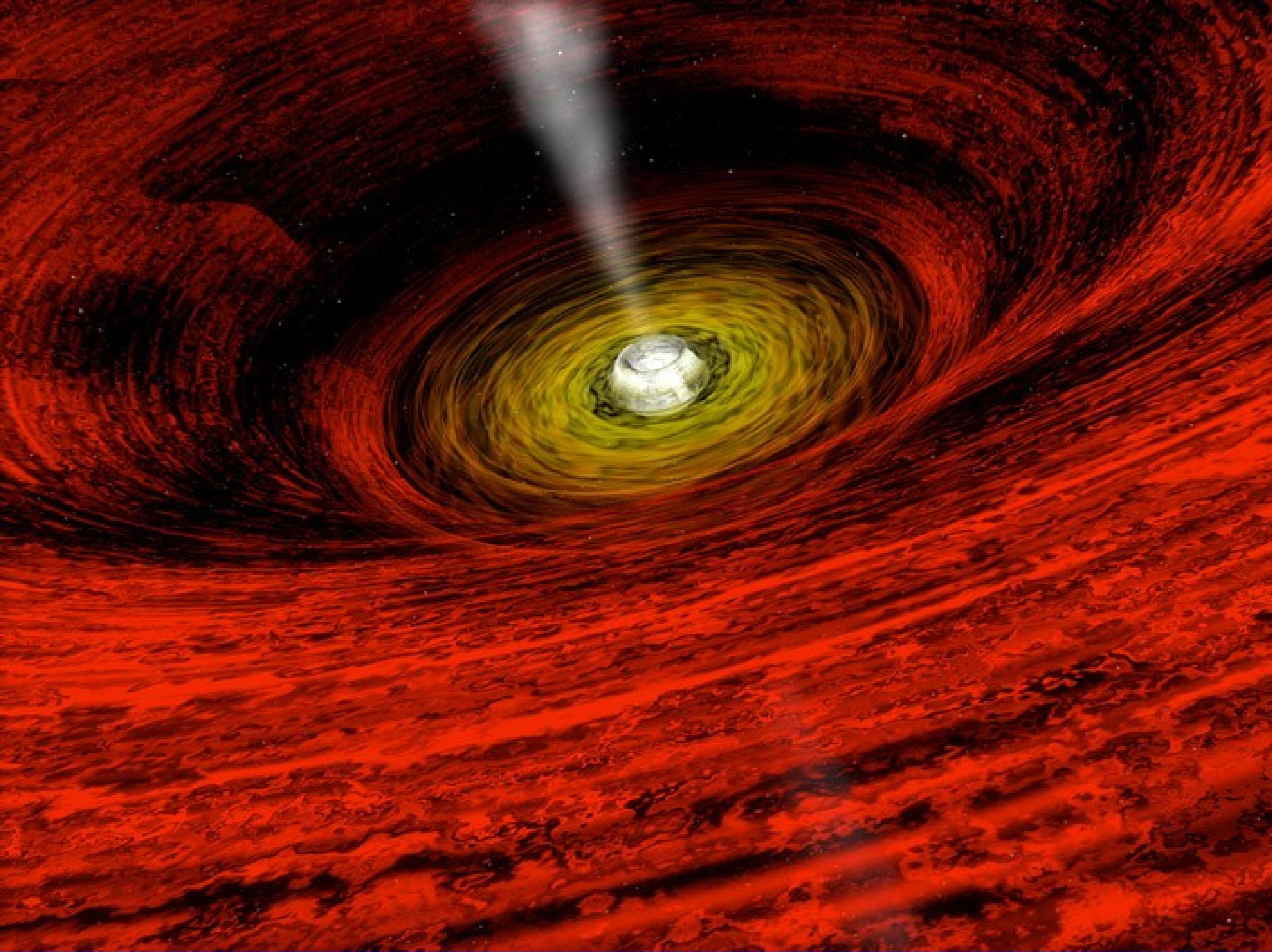




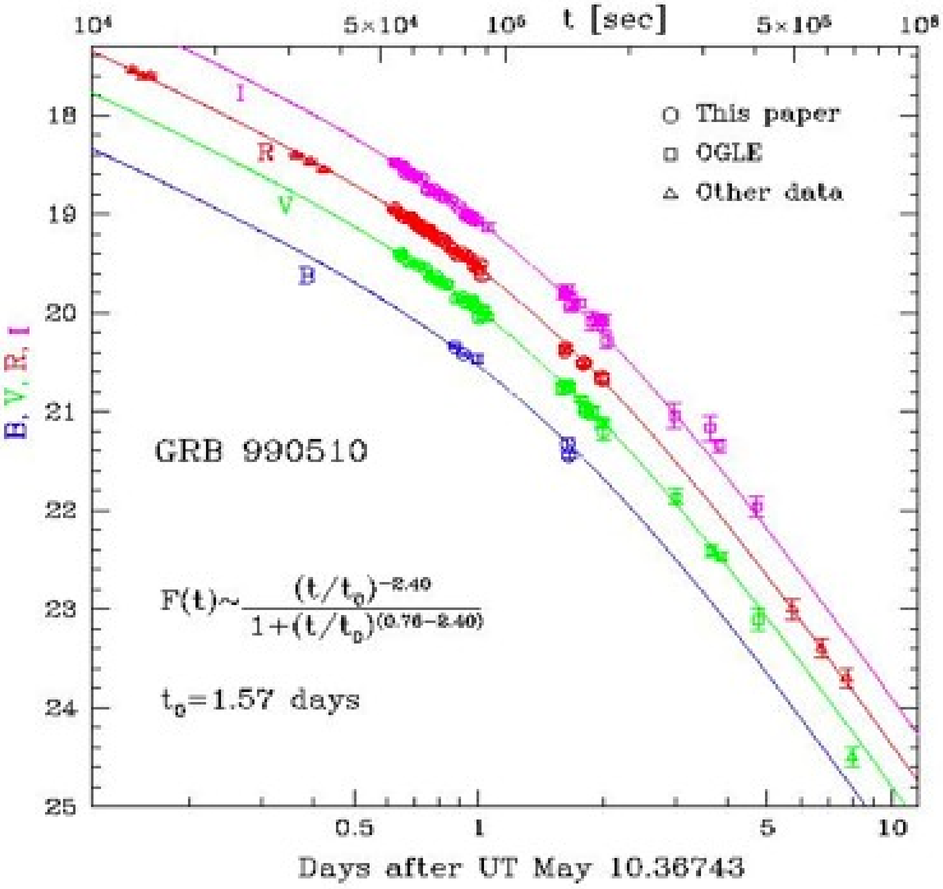
(Cardall 03 & Terascale Supernova Initiative)


V
D
E
A
F
C
B





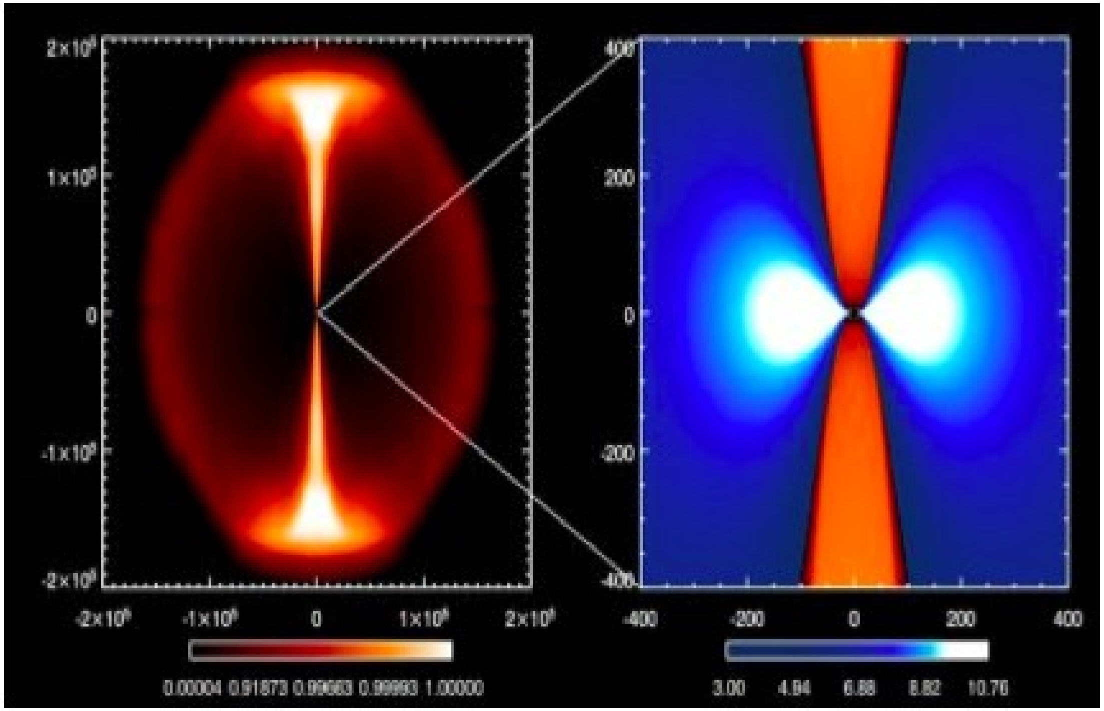
Light curve break: Jet Edge Effects



- Monochromatic break in light curve time power law behavior
- expect $\Gamma \propto t^{-3/8}$, as long as $\vartheta_{\text{light cone}} \sim \Gamma^{-1} < \vartheta_{jet}$, (spherical approx is valid)
- "see" jet edge at $\Gamma \sim \vartheta_{jet}^{-1}$
- Before edge, $F_\nu \propto (r/\Gamma)^2 . I_\nu$
- After edge, $F_\nu \propto (r\,\vartheta_{jet})^2 . I_\nu$,

  $\rightarrow F_\nu$ steeper by $\Gamma^2 \propto t^{-3/4}$
- After edge, also side exp.

  $\rightarrow$ further steepen $F_\nu \propto t^{-p}$



Short burst paradigm: NS-NS or NS-BH merger

↓

BH + accretion

- Paradigm seems compatible with hosts, and (for Kerr BH-NS) some simulations suggest extended activity & flares ⇒

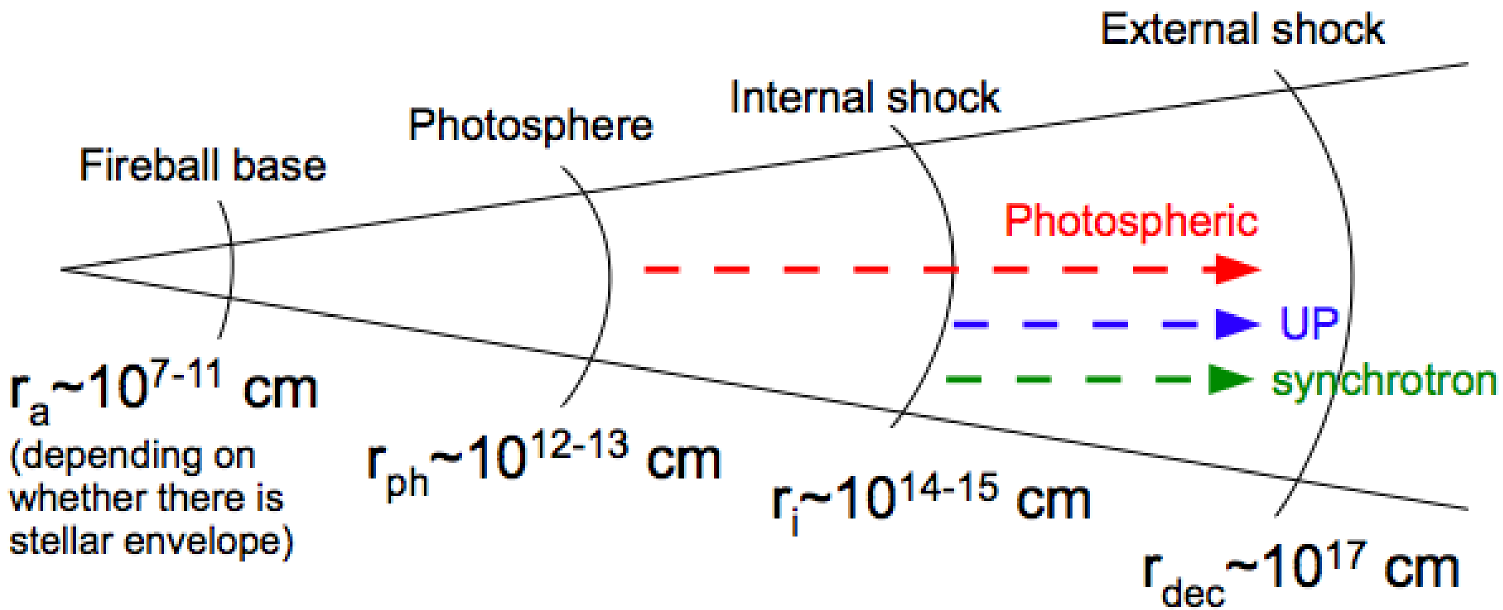
simulation

Laguna, Rasio 06;
(Preliminary)

Photosphere + IS model

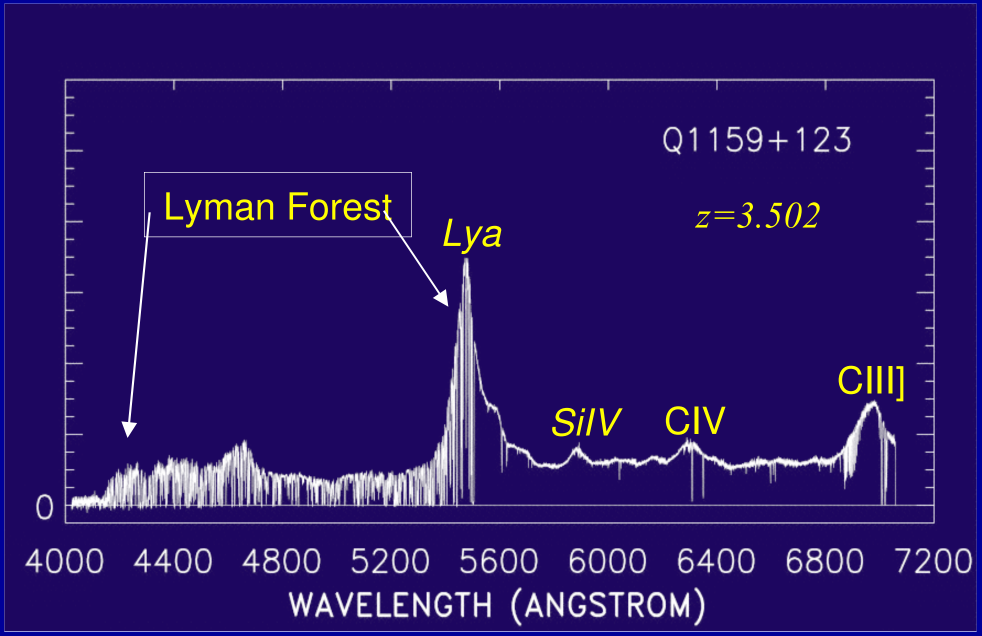
Toma, Wu, Mészáros, arX:1002.2634

Photosphere and internal shock of the GRB jet



- Photosphere: prompt, variable MeV
- IS occur at $r \gtrsim 10^{15}$ cm (high Γ) : Sy=XR, IC(UP)=GeV

Lyα forest



probes matter distribution on galactic scales and measures slope of power spectrum of density fluctuations in early Universe

probes galaxies as they form from the Intergalactic Medium

ANTHROPIC REQUIREMENTS FOR A UNIVERSE

Large amplitude inhomogeneities. *(almost certainly?)*
Some baryons *(very probably?)*
At least one star *(probably?)*
Some second-generation stars *(probably – unless heavy elements are primordial?)*

WHAT ARE THE CONSEQUENT CONSTRAINTS ON:

- Fluctuation amplitude *Q*? *($\sim 10^{-5}$ in our universe)*
- Λ *(maybe 70% of present critical density in our universe)*
- Baryon/photon ratio n_b/n_γ? *($\sim 10^{-9}$ in our universe)*
- [Baryon/(cold) dark matter] ratio? *($\sim 10^{-1}$ in our universe)*

Note: constraints are correlated, so should really consider these (and maybe other) parameters *together.*

THEN

NOW

Planetary orbits

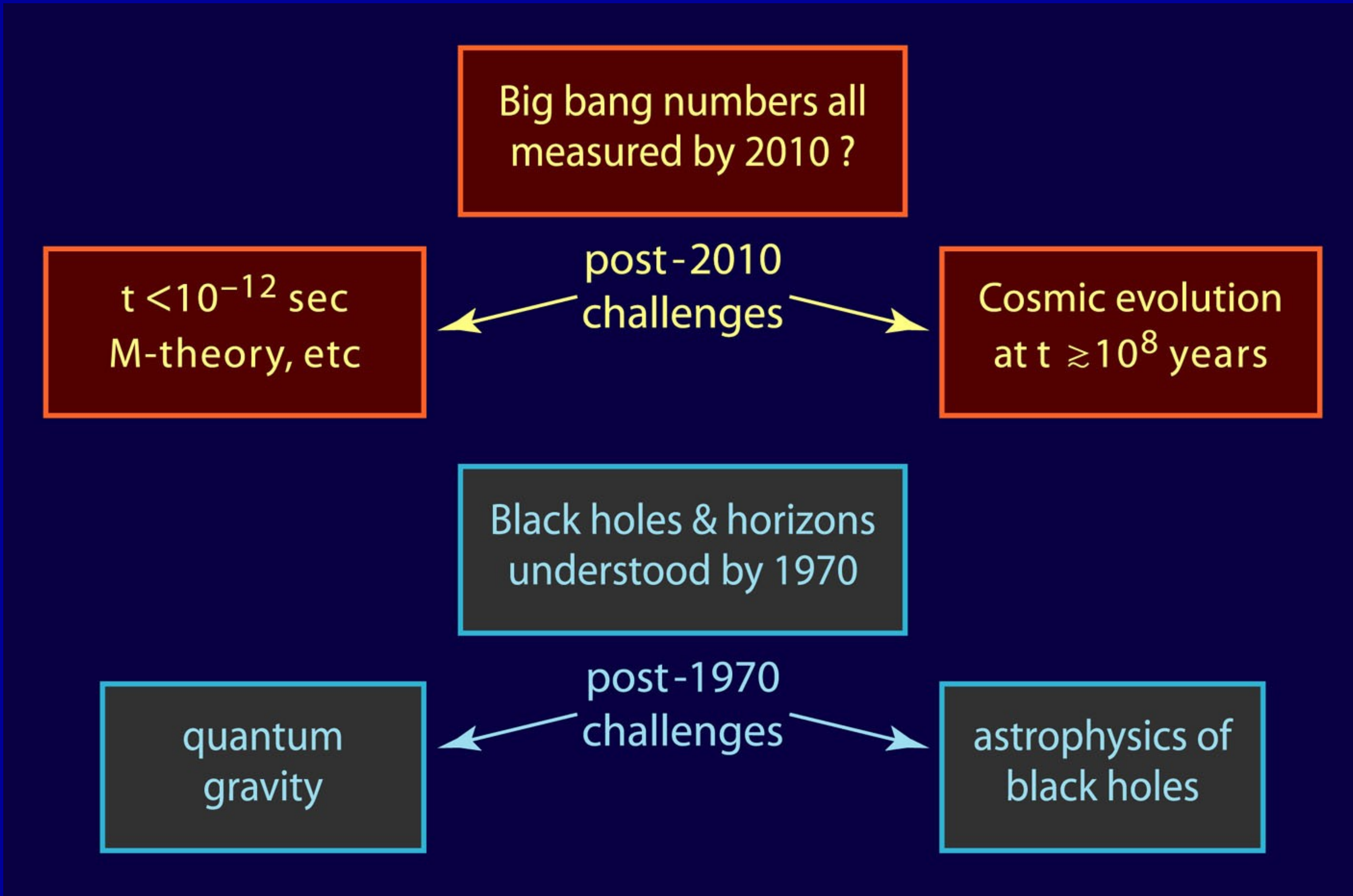
Perfect circles
Simple ratios (Kepler)

"Typical" life-supporting orbit

Big bang parameters

Simplest model
$\Omega = 1, \Lambda = 0$

"Typical" anthropically allowed model



Big bang numbers all measured by 2010 ?
post-2010 challenges
$t < 10^{-12}$ sec
M-theory, etc
Cosmic evolution
at $t \gtrsim 10^{8}$ years
Black holes & horizons understood by 1970
post-1970 challenges
quantum gravity
astrophysics of black holes

HOW can you make a (super)massive black hole @ z≈10-30?

M ~100-600 M

BH sun

PopIII stars remnants

✓ Simulations suggest that the first

sun

stars are massive M ~100-600 M

✓ Metal free dying stars with $M>260M_{sun}$ leave remnant BHs with

seed sun

M ≥100M

M ~10 -10 M

BH sun

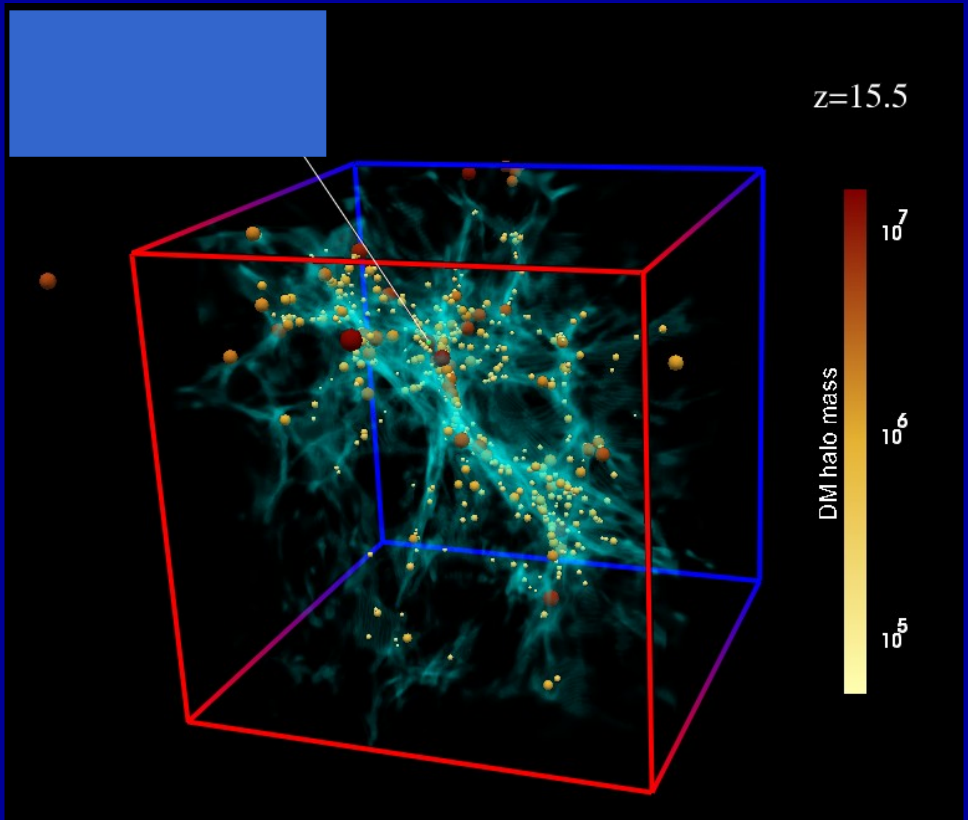
Quasistars

✓ Efficient viscous angular momentum transport + efficient gas confinement

First ‘seed’ black holes?

Hierarchical Galaxy Formation:
small scales collapse first and merge later to form more massive systems

BARYONS: need to COOL
First ‘action’ happens in the smallest halos with deep enough potential wells to allow this
(at z~20-30)



courtesy of M. Kuhlen

What happens earlier?

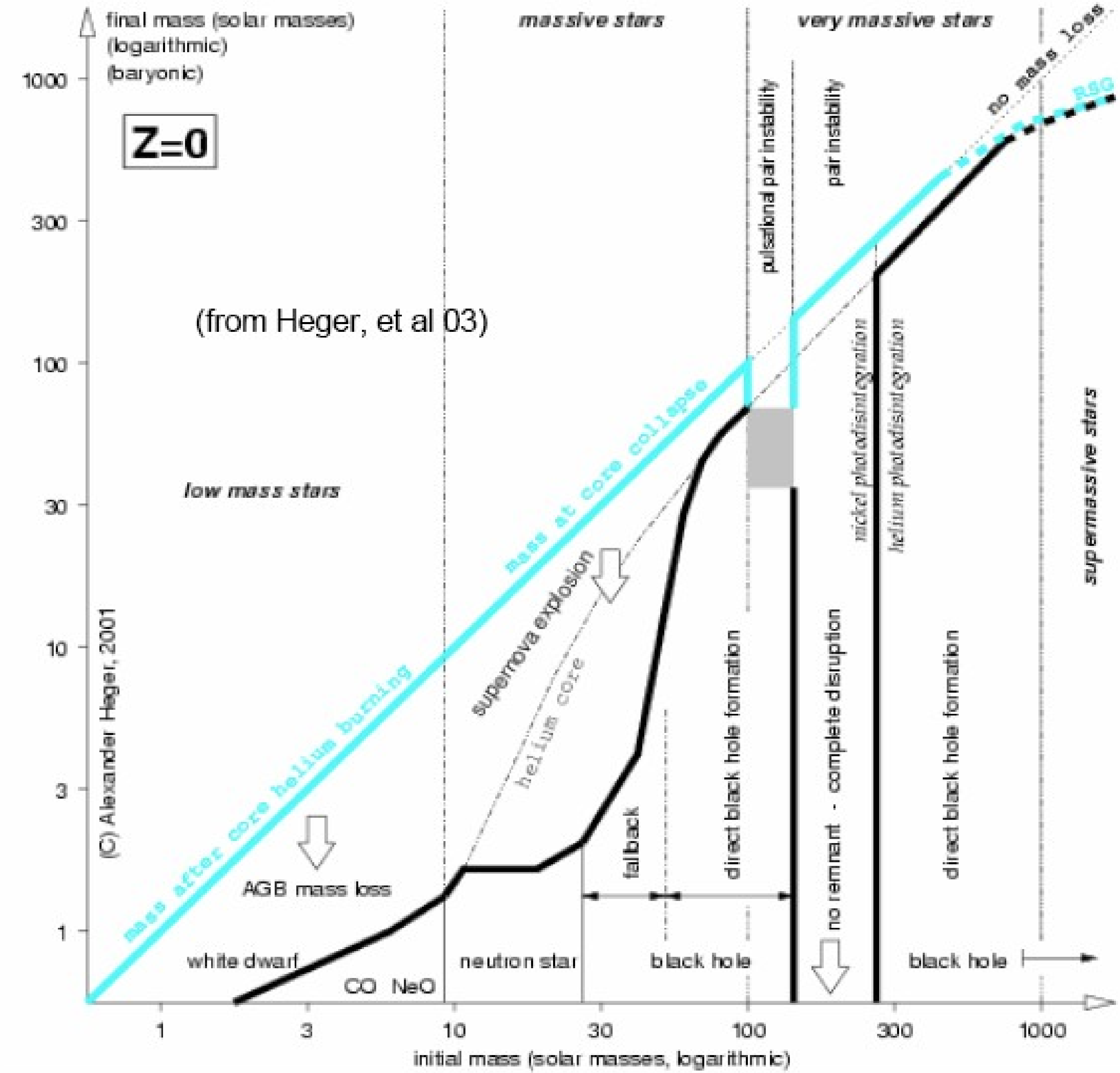
- What are the ‘hosts’ of the first holes?
- How massive are these ‘seed holes’ (stellar --- Pop III remnants -- or ‘intermediate’) ?
- How fast can they grow via:

  (a) accretion?

  (b) mergers?

How can we probe the highest redshifts (detection, environmental impact, ‘fossils’)?

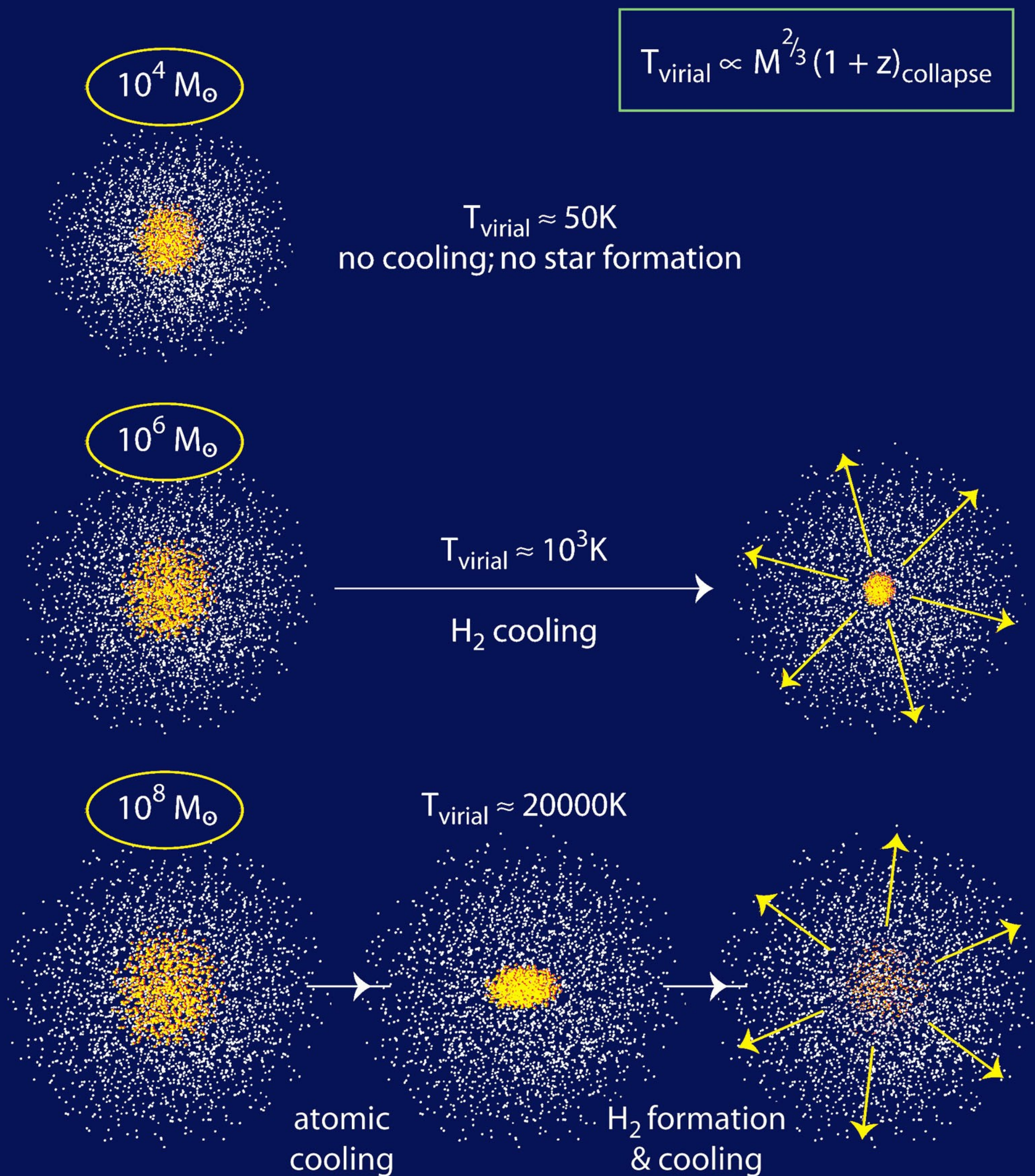
$M_{remn.}$ vs. $M_{\star ms}$



- Non-rotating single ms ★
- Mass-loss simplified
- Metallicity dependence?
- Core rotation, binary evol'n?
- etc

FATE OF THE FIRST BOUND SYSTEMS

($z \approx 20$)



Just six numbers

Six constants of nature whose values must lie in an 'anthropic' range for life to emerge

1. $D = 3$ The number of spatial dimensions
2. $G/E = 10^{-36}$ The ratio of gravitational to electrostatic force
3. $S = 0.007$ A measure of the strong force that binds nuclei
1. $\Omega_{Total} = 1$ The density of matter/energy in space
1. $Q = 0.00001$ The scale of fluctuations in the microwave background
1. $\Omega_{\Lambda} = 0.7$ Omega lambda, a measure of the vacuum energy of the universe

- Coincidence?
- Consequence?
- Multiverse?

Summary

SMBHs can be built up from seeds dating back to the end of the cosmological dark ages

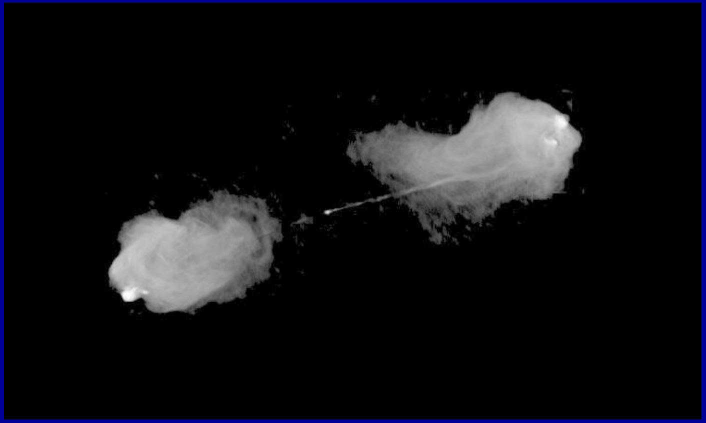
- seed MBHs in biased proto-galaxies

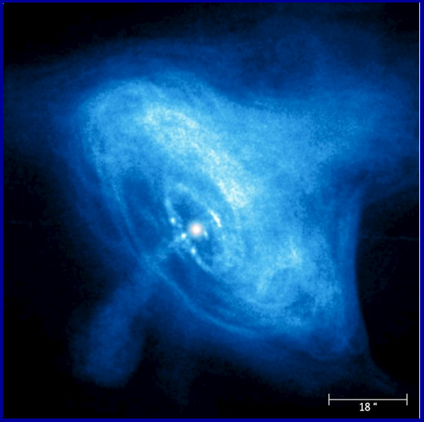
- MBHs evolve through mergers and accretion

- accretion: leads mass (and spin) evolution

- GWs to detect “black” black holes

Diffusion of flux?



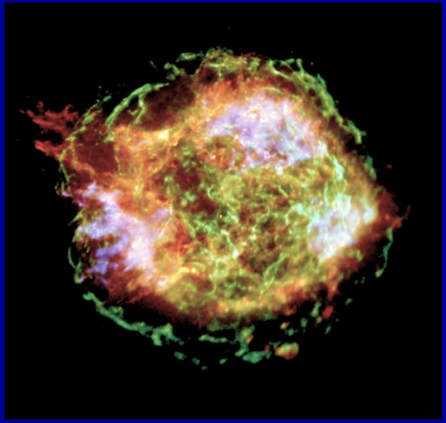


Electron-ion coupling

When there is shear but no streaming, are there collective processes that couple electrons and ions?

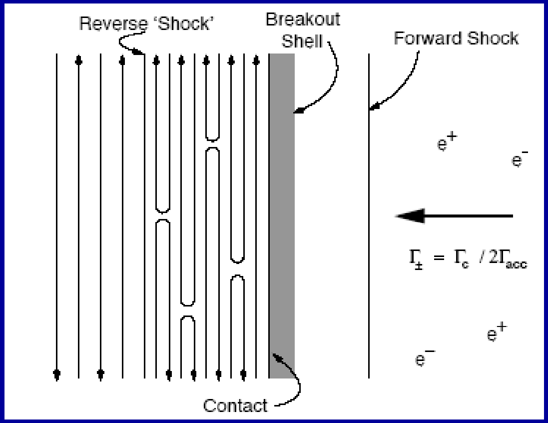
(Non-thermal tail?cf fusion research)

Field generation and particle acceleration by shocks?

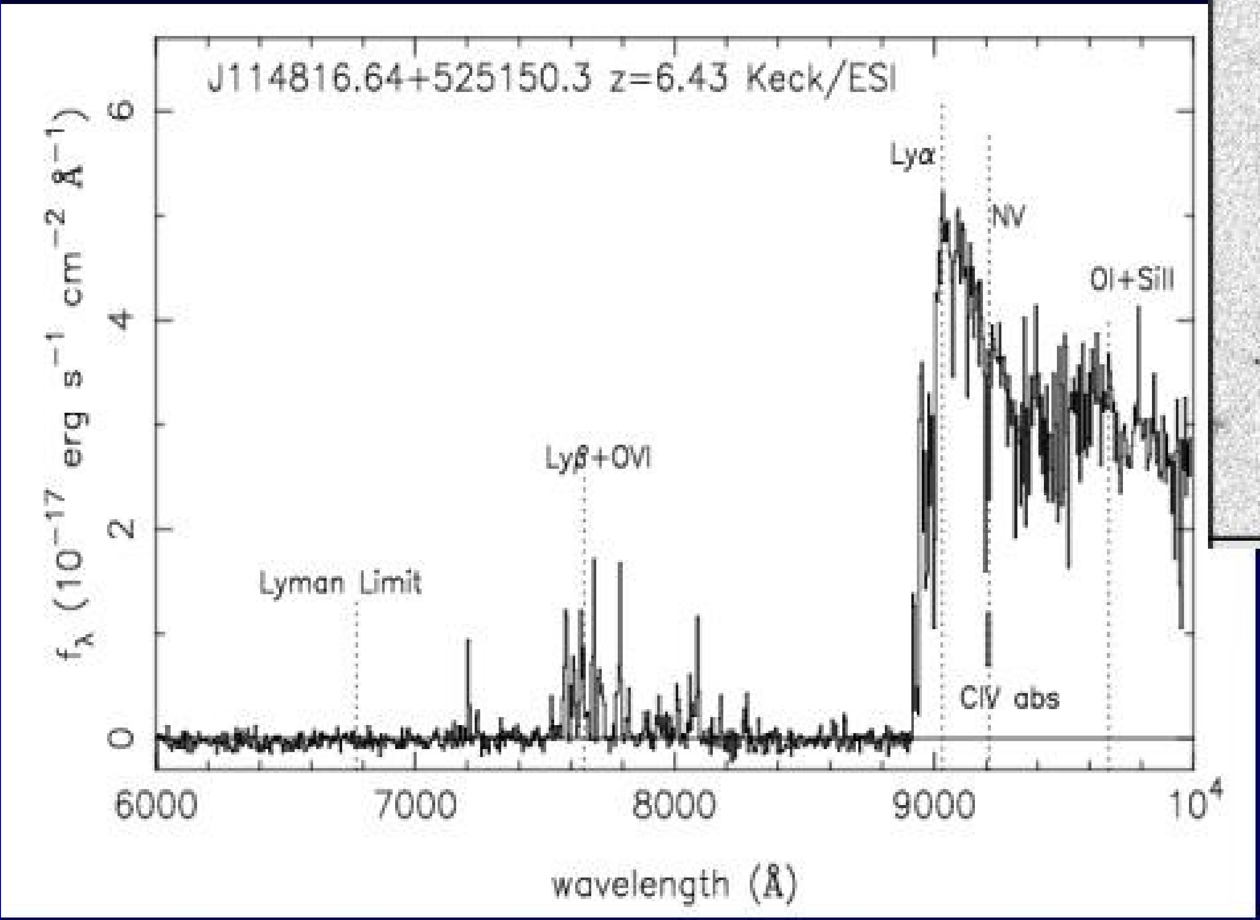


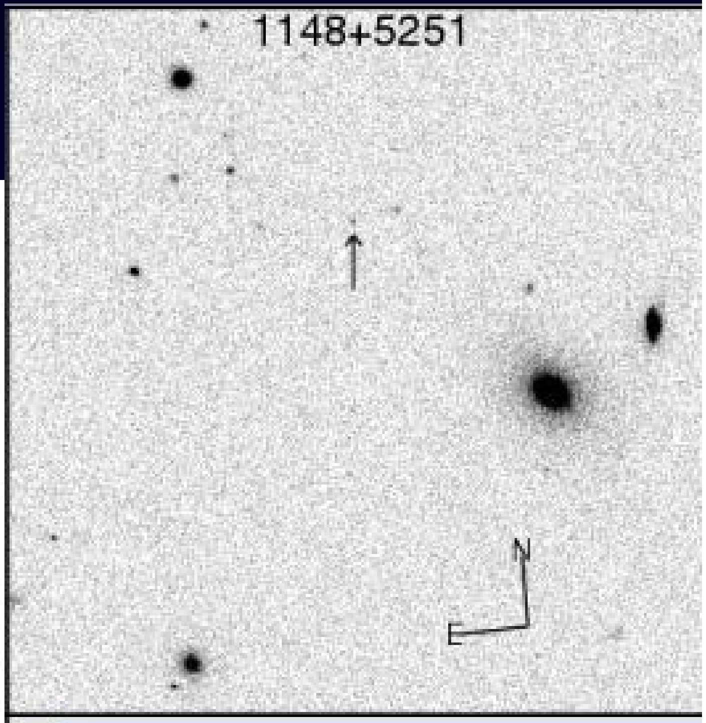
Does the field generated by Wrubel-type mechanisms lead to a large-scale and persistent component?

Particle acceperation in ultrarelativistlc shocks?



The Earliest Quasar Detected: z=6.4





Fan et al. 2002

First black holes in pregalactic halos z≈10-30

M_{BH} ~100-600 M_{sun}

PopIII stars remnants

(Madau & Rees 2001, Volonteri, Haardt & Madau 2003)

✓ Simulations suggest that the first stars are massive M~100-600 M_{sun} (Abel et al., Bromm et al.)

✓ Metal free dying stars with $M>260M_{sun}$ leave remnant BHs with

$M_{seed} \geq 100 M_{sun}$ (Fryer, Woosley & Heger)

M_{BH} ~10 -10 M_{sun}

Viscous transport + supermassive star

(e.g. Haehnelt & Rees 1993, Eisenstein & Loeb 1995, Bromm & Loeb 2003, Koushiappas et al. 2004)

✓ Efficient viscous angular momentum transport + efficient gas confinement

Bar-unstable self-gravitating gas + large "quasistar"

(Begelman, Volonteri & Rees 2006)

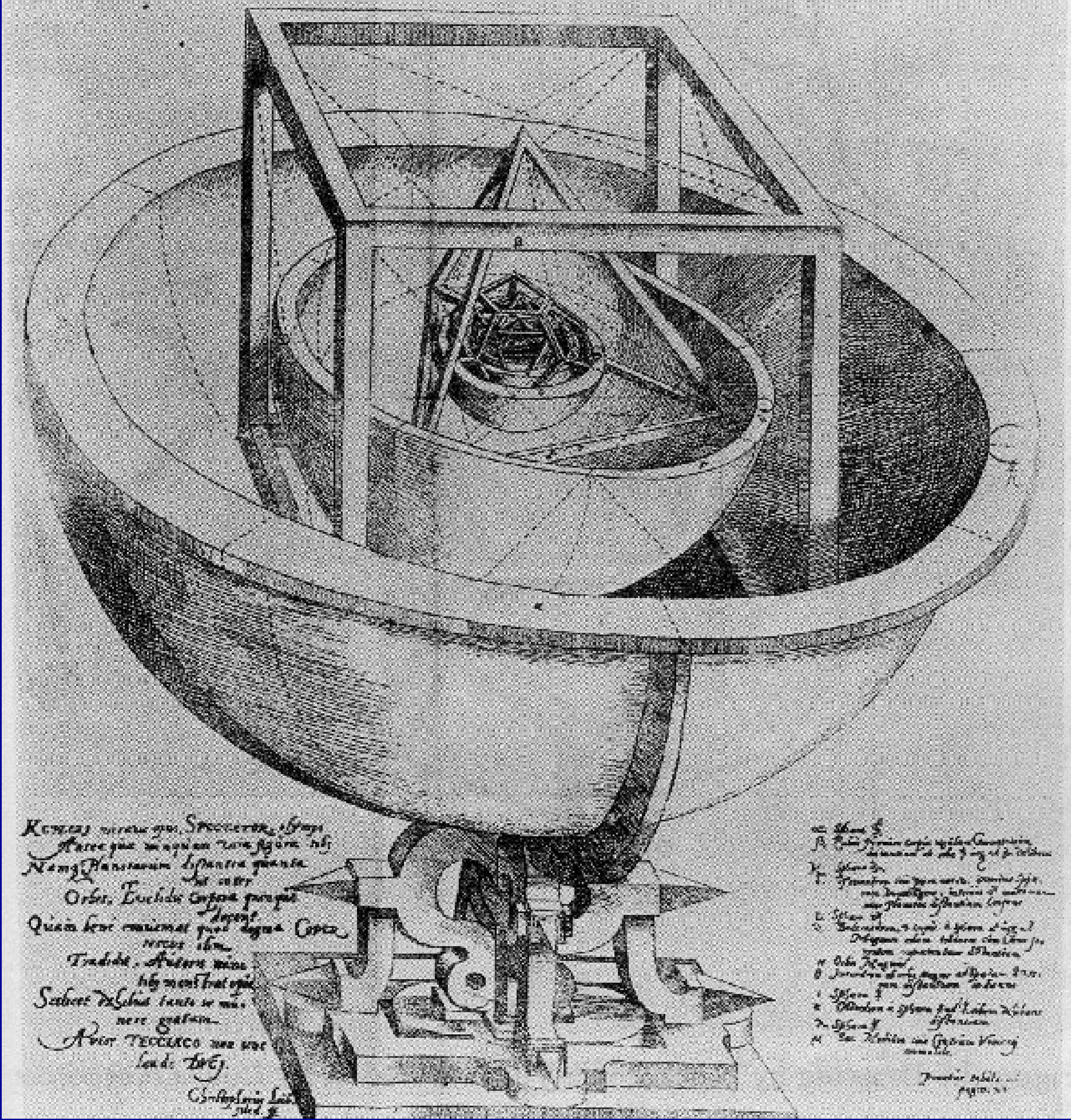
✓ Transport angular momentum on the dynamical timescale, process cascades

✓ Formation of a BH in the core of a low entropy quasistar ~10^4-10^6 Msun

✓ The BH can swallow the quasistar

TABVLA III. ORBIVM PLANETARVM DIMENSIONES, ET DISTANTIAS PER QVINQVE REGVLARIA CORPORA GEOMETRICA EXHIBENS.

ILLVSTRISS^{o}. PRINCIPI, AC DNO. DNO. FRIDERICO, DVCI WIRTENBERGICO, ET TECCIO, COMITI MONTIS BELGARVM, ETC. CONSECRATA.



TWO 'ASTROPHYSICAL' OPTIONS FOR GENERATING 'SEED' FIELD FOR GALACTIC DYNAMO

I. Biermann battery + dynamo within pop III stars

magnetised stellar wind

------> or

SN with Crab-like remnant.

Protogalaxy contains debris from > 10^5 Pop III stars; the large-scale component is amplified by galactic dynamo.

II Battery + dynamo in first AGNs

-------> jets

-------> extended radio lobes

Protogalaxy forms from infalling matter 'contaminated' by early-forming radio lobes

WAS THE B-FIELD ALREADY DYNAMICALLY IMPORTANT WHEN GALAXIES (AND THEIR DISCS) FIRST FORMED?

Magnetic fields play a key role in protostars *(modifying Jeans mass, transferring angular momentum, etc)*

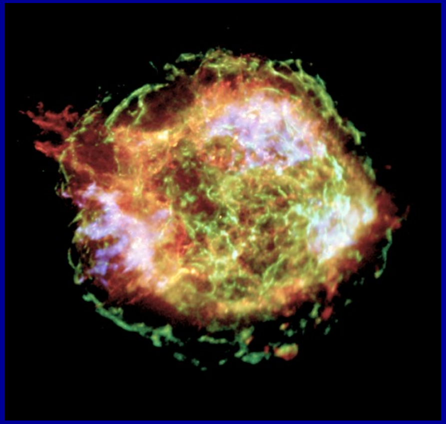
If a dynamically-important field builds up <u>only after several rotations of a galactic disc</u>, then this in itself may render the **IMF** different for the oldest stars*

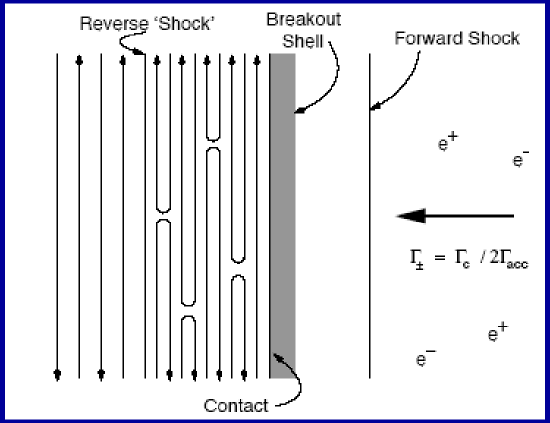
***cf the effect of removing heavy elements or of the higher CMB temperature at large z**

Note: *even a much weaker (dynamically trivial)* ***B-field*** *can inhibit thermal conductivity, confine cosmic rays, etc*

Field generation by shocks?

Does the field generated by Wrubel-type mechanisms lead to a large-scale and persistent component?

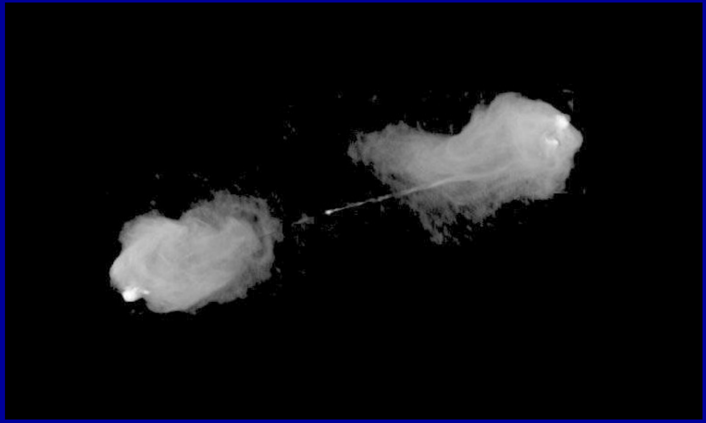


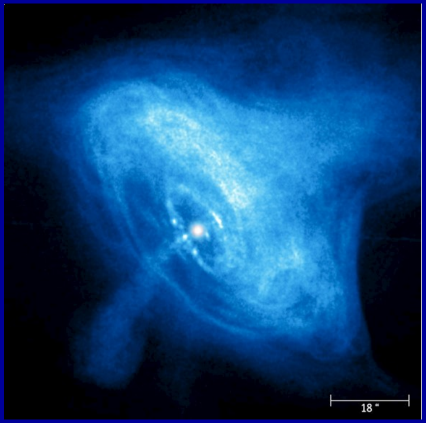


How do MBHs grow into superMBHs?

Mergers + accretion?
Is there enough time?
Effects of radiative and dynamical feedback?
Gravitatational wave recoil?

Diffusion of flux?





Key issues

- Were SMHs ‘seeded’ by Pop III remnants, or by ‘intermediate mass’ holes?
- How can we detect individual objects out to z=20?
- What is the ‘environmental impact’? *(first ‘metals’, magnetic fields, ionization, etc etc)*
- What is relative importance of mergers and accretion (GR very important!)?

TWO 'ASTROPHYSICAL' OPTIONS FOR GENERATING 'SEED' FIELD FOR GALACTIC DYNAMO

I. Biermann battery + dynamo within pop III stars

magnetised stellar wind
------> or
SN with Crab-like remnant.

Protogalaxy contains debris from > 10^5 Pop III stars; the large-scale component is amplified by galactic dynamo.

II Battery + dynamo in first AGNs
-------> jets
-------> extended radio lobes

Protogalaxy forms from infalling matter 'contaminated' by early-forming radio lobes

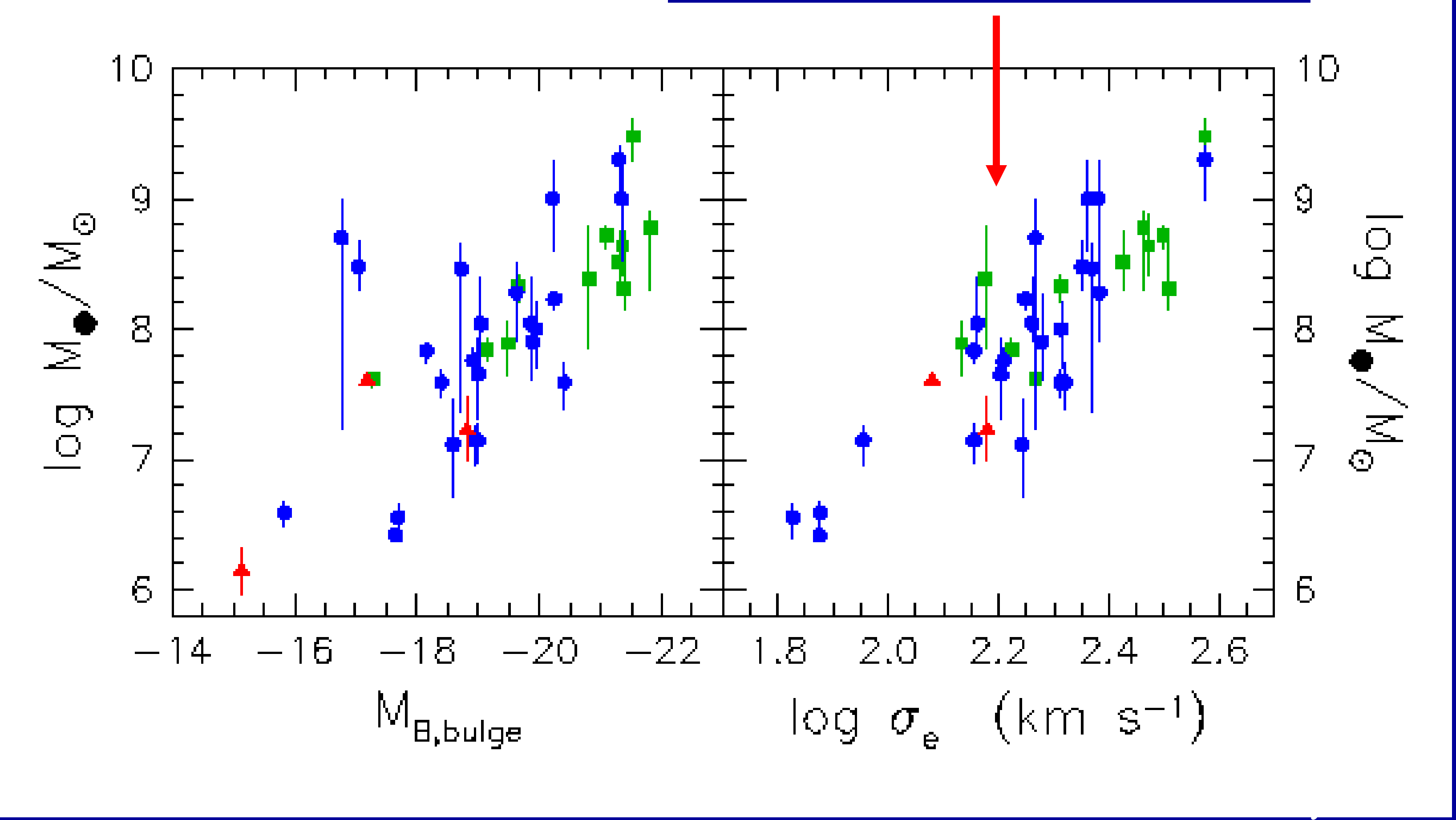
Build-up of holes by accretion

(a) Is there a **continuous gas supply** from host halo?
Johnson & Bromm 2007, Pelupessy et al. 2007

(b) When supply is **super-critical**: is 'excess' radiation trapped and/or accretion inefficient, allowing rapid growth in hole's mass ? Volonteri & Rees 2005
Or is there a radiation-driven outflow? Wang et al. 2006

(c) What is the **influence of spins**? affect maximal accretion efficiency, importance of Blandford-Znajek energy extraction, etc

Is this really tighter?



black hole mass scales with

bulge mass

stellar velocity dispersion of the bulge

1. Mass of the BH seed

PopIII stars remnants
M_{BH}~100-600 M_{sun}

Gas collapse via Post-Newtonian instability M_{BH}~10^5-10^6 M_{sun}

2. BH mergers

Positive contribution

Negative contribution

3. Accretion rate

Eddington-limited

Super-Eddington

Stellar hole birth

- Massive star supernova?
  - Neutron star collapse?
- Conjecture: Stellar Hole Birth accompanied by Gamma Ray Burst
  - Release of 10^{45}J of high entropy or electromagnetic energy by gas swirling around star
  - Escapes in a pair of exhausts (ultrarelativistic jets) along stellar rotation axis
  - Creates pulse of gamma rays for 0.1-100s
  - Followed by afterglow lasting for months to years

The hierarchical evolution predicts typical BH spins close to maximal

The radiative efficiency is consequently high:

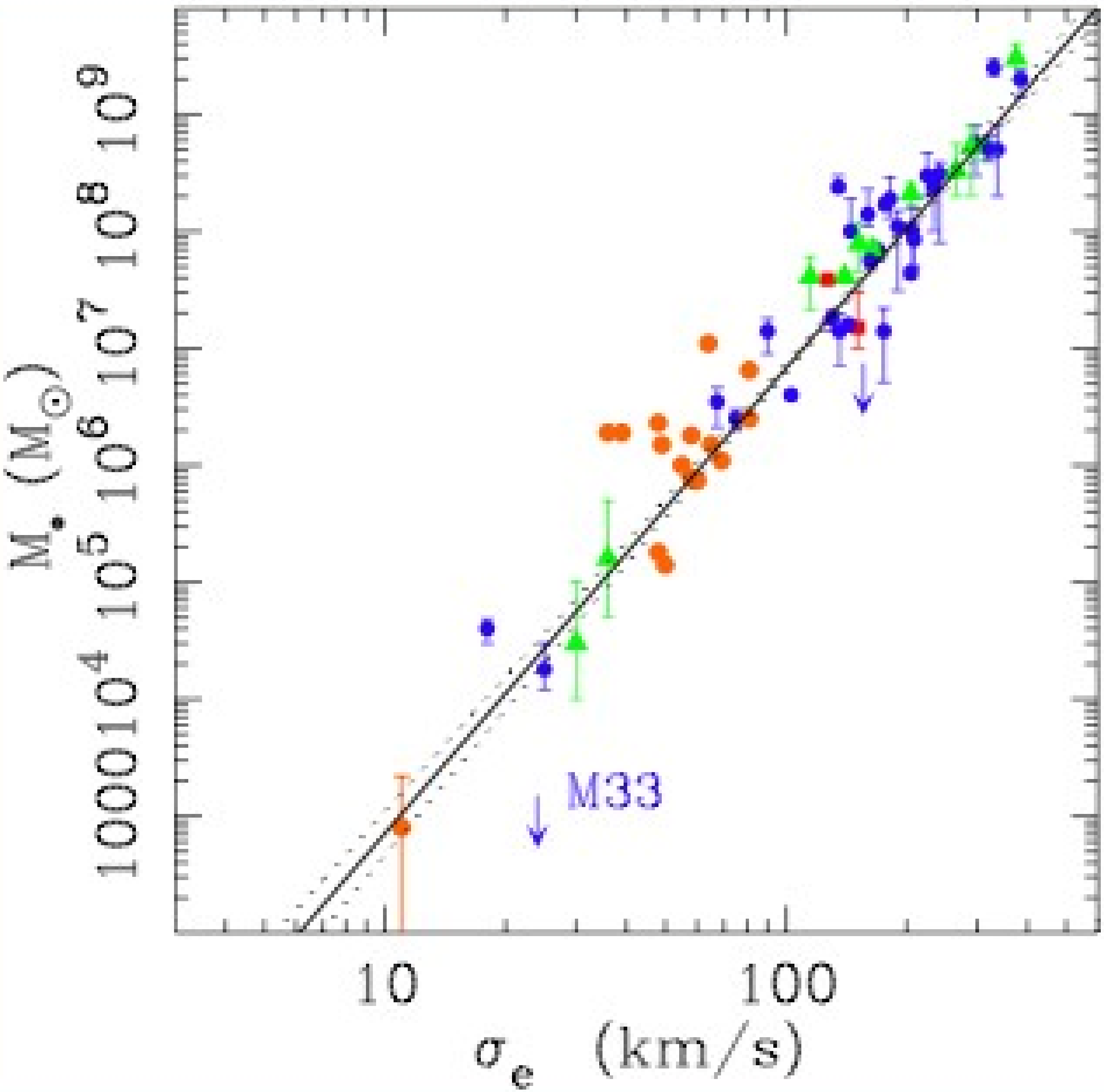
> 0.1

BHs spin is modified by BH mergers and coupling with the accretion disc

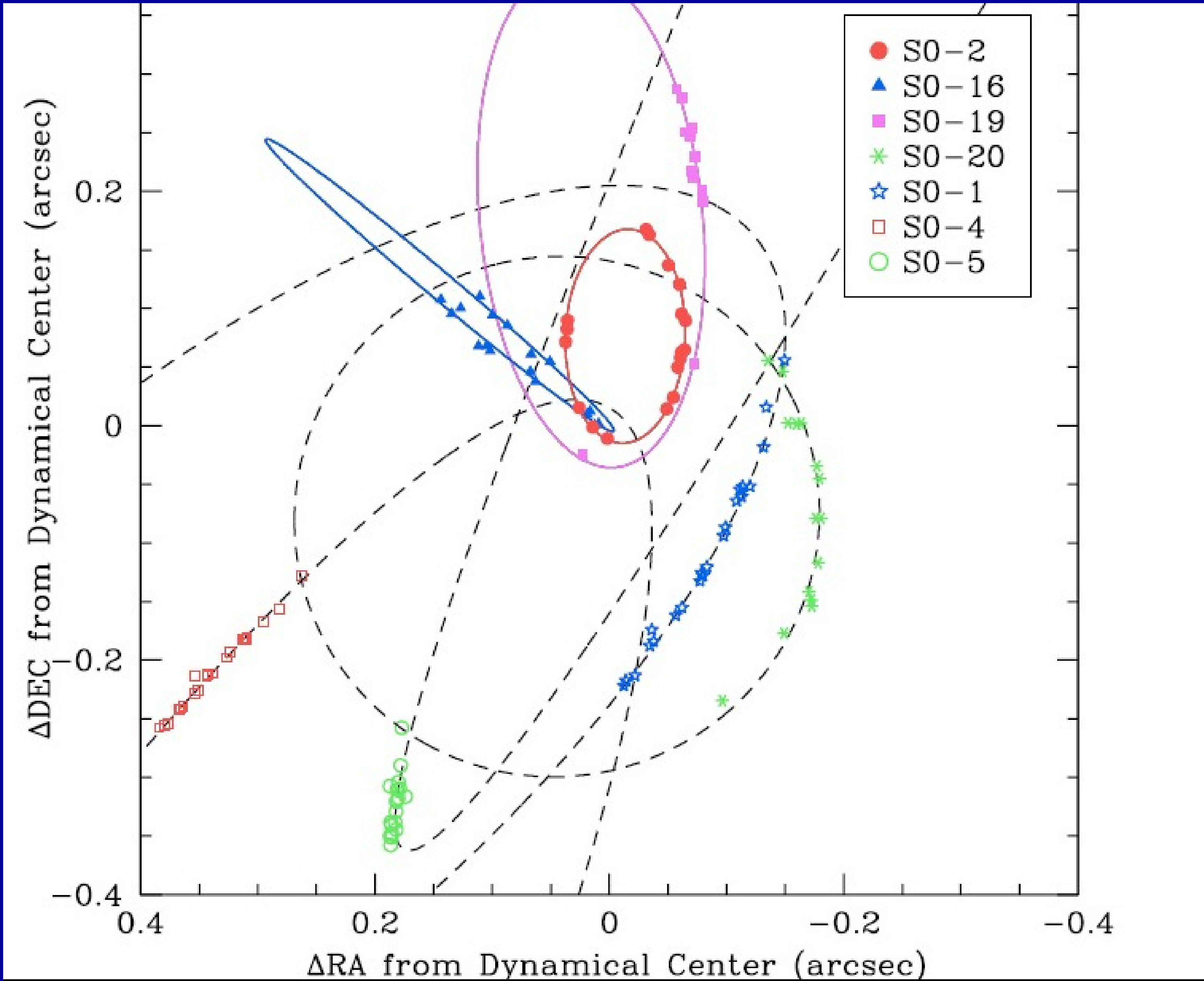
Hughes & Blandford 2003, Moderski & Sikora 1996

- ✔ mergers can spin BHs either up or down in a random walk - mainly depending on MBH mass ratio
- ✔ alignment with a thin disc spins up efficiently on short timescales.

Volonteri, Madau, Quataert & Rees 2005



M• (M⊙)
1000
10^4
10^5
10^6
10^7
10^8
10^9
M33
10
100
σe (km/s)



S0−2
S0−16
S0−19
S0−20
S0−1
S0−4
S0−5
0.2
0
−0.2
−0.4
0.4
0.2
0
−0.2
−0.4
ΔDEC from Dynamical Center (arcsec)
ΔRA from Dynamical Center (arcsec)