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Gamma ray bursts

1. Observations
2. Theories
3. Magnetic fields

History
- first found by gamma-detectors in bomb monitors
- astronomy: late ‘70s
- positions in sky by IPN-timing
- found to be isotropic on sky (Konus satellites)
  distance still unknown

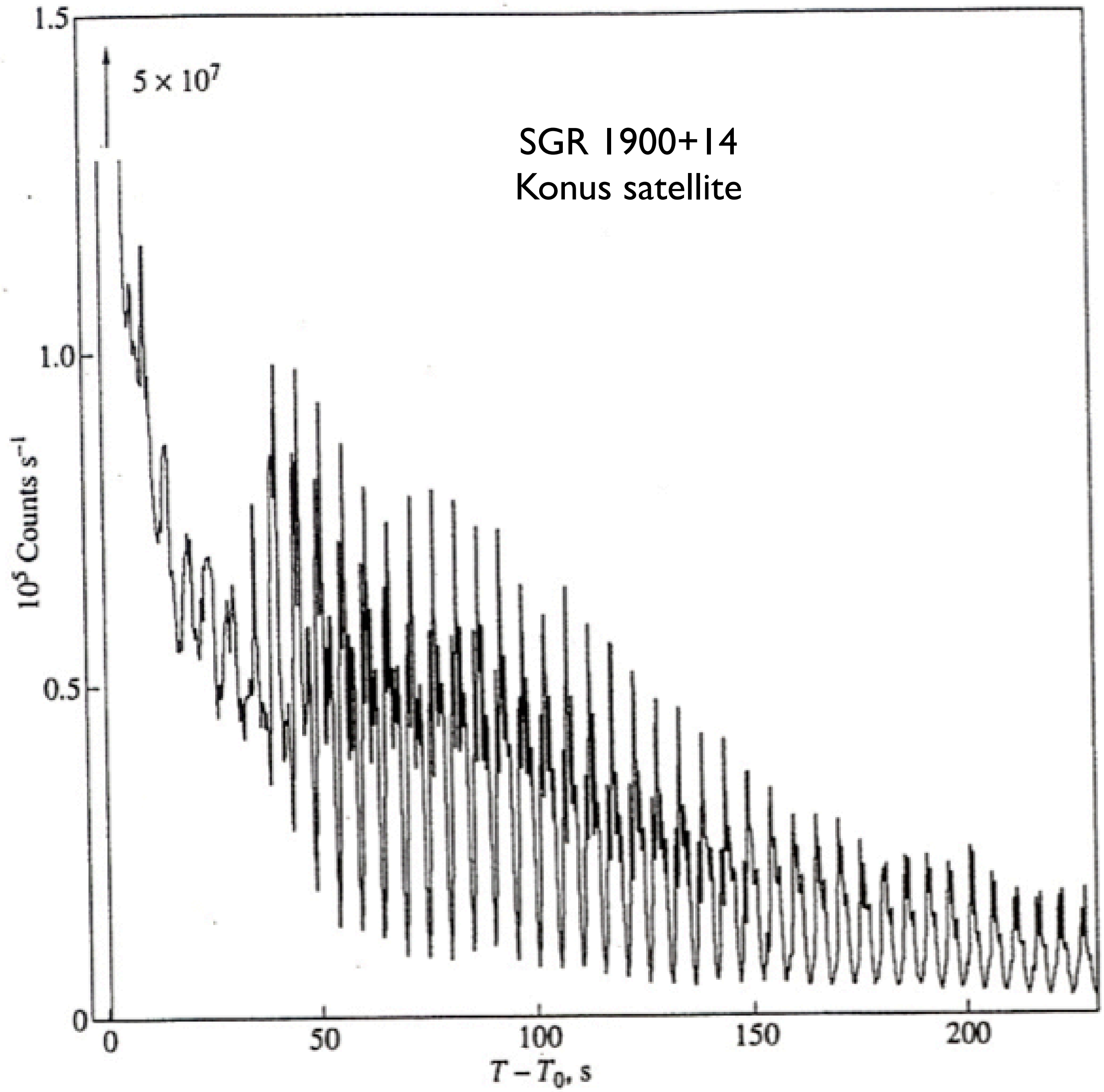
BATSE all sky monitor confirms isotropy (1994)
- 1997 optical identification w distant galaxies
- afterglows
- predicted supernova connection found (1997)

current instumentation: Fermi (formerly GLAST), SWIFT, Agile, INTEGRAL

2 types of gamma-ray burst:

1. soft gamma repeaters (SGR)
2. classical GRB

SGR: local (in the galactic plane, 1 in MC)
outbursts from supermagnetic ($B \sim 10^{15}$ G)
neutron stars ('magnetars')



SGR 1900+14
Konus satellite

Fig. 1. Giant August 27, 1998 outburst. The intensity of the $E_\gamma > 15$ keV radiation.

end of the universe

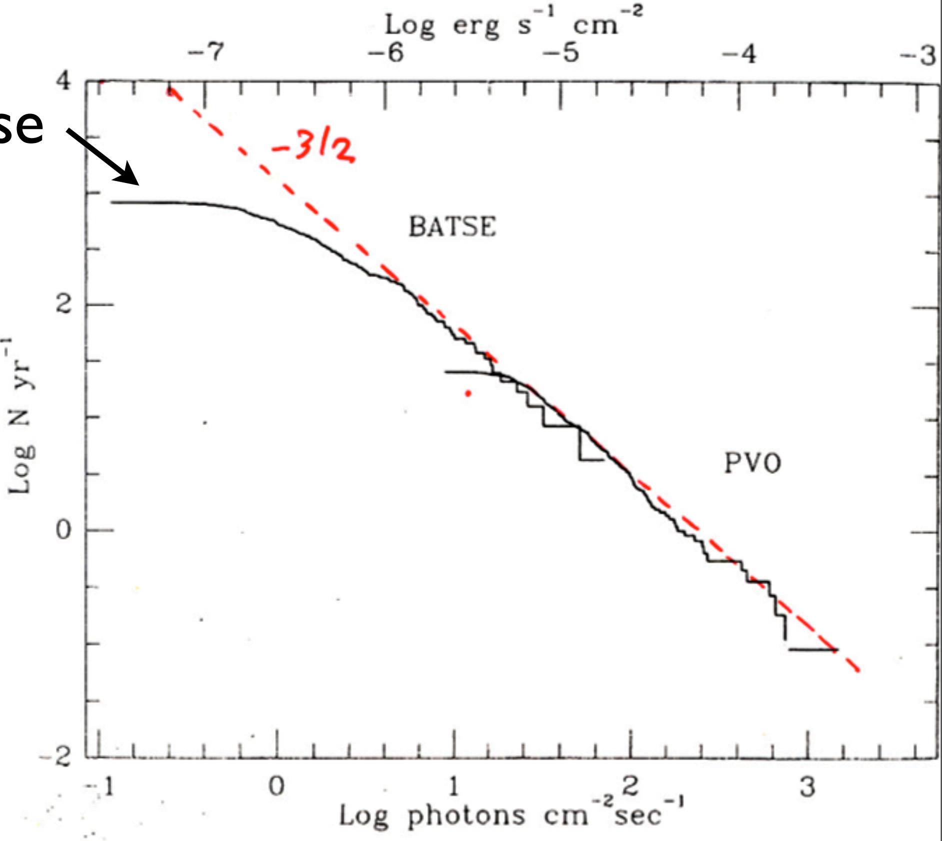
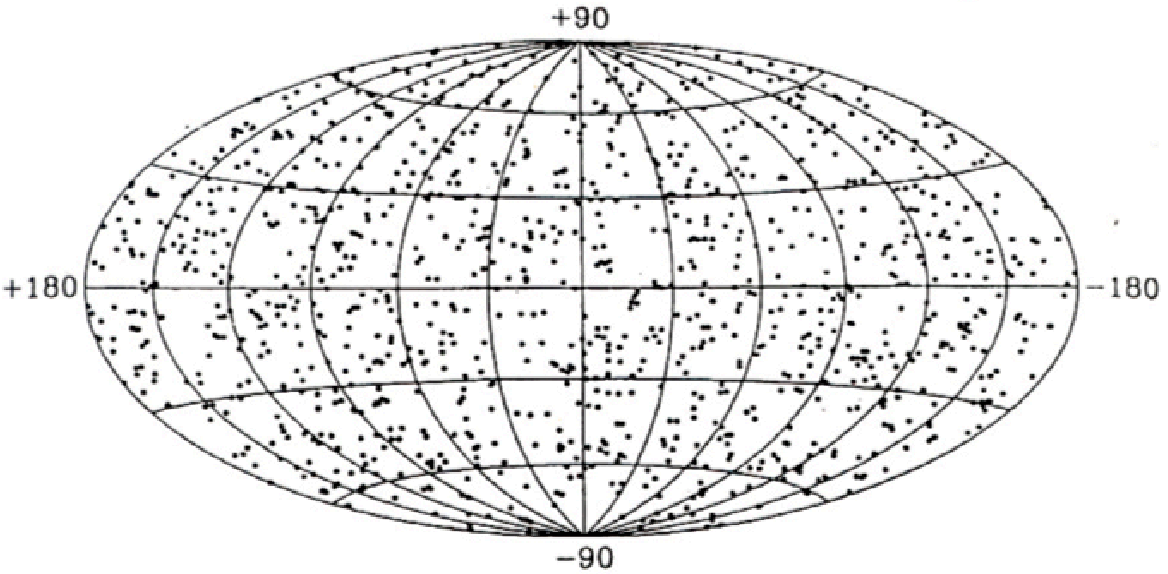


Figure 13 The log *N*–log *P* distribution from combined BATSE and *PVO* data (adapted from Fenimore et al 1993). The distributions match well in the overlap region. The *PVO* data, which has recorded more strong bursts than BATSE during its long lifetime, is seen to follow a −3/2 power law for strong bursts.



Galactic Coordinates

Figure 14 The celestial distribution of 1121 gamma-ray bursts as seen by BATSE over a three-year period, plotted in Galactic coordinates. No clustering or anisotropies are seen (Briggs et al 1995, Meegan et al 1995, Hartmann et al 1995).

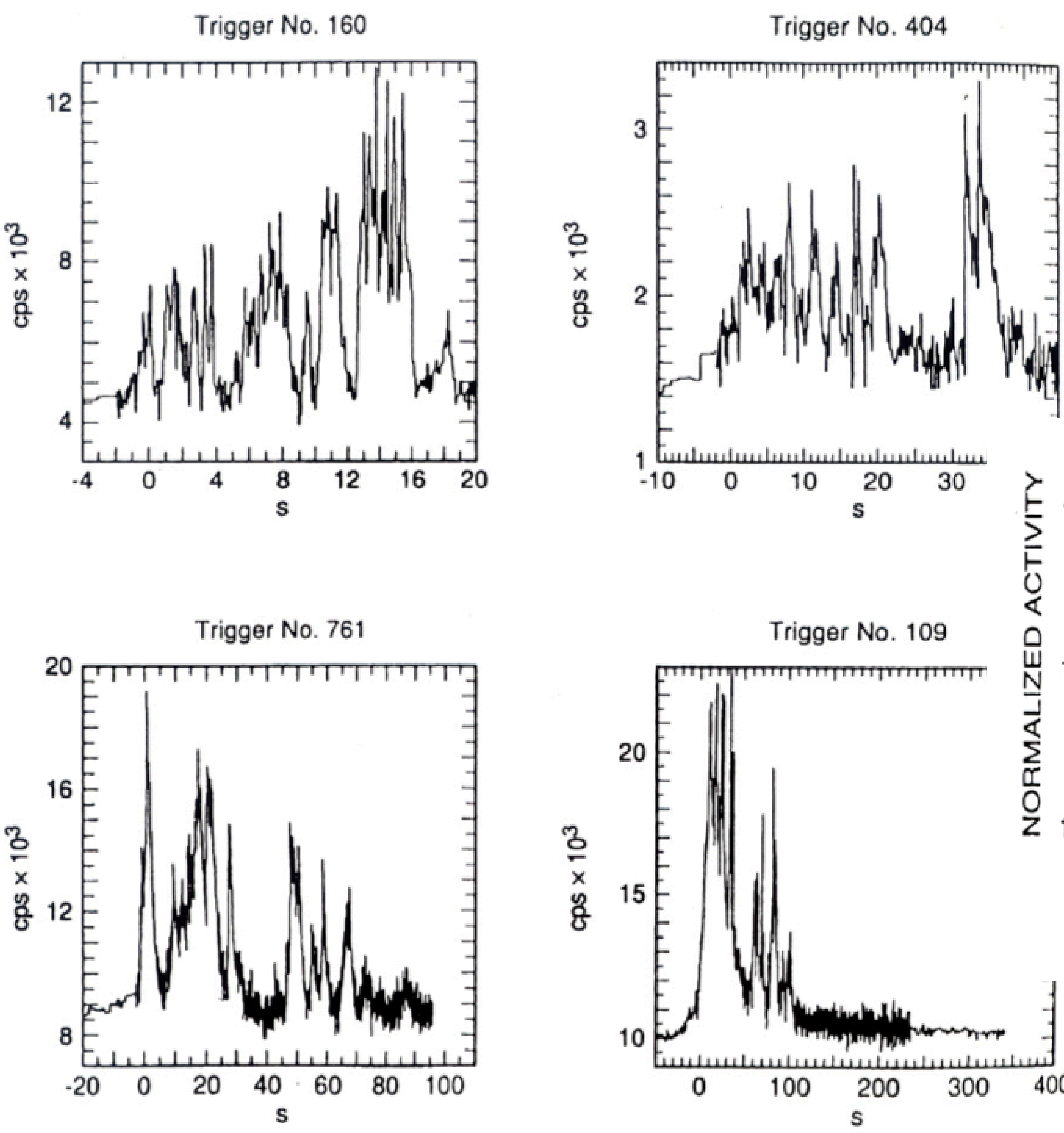
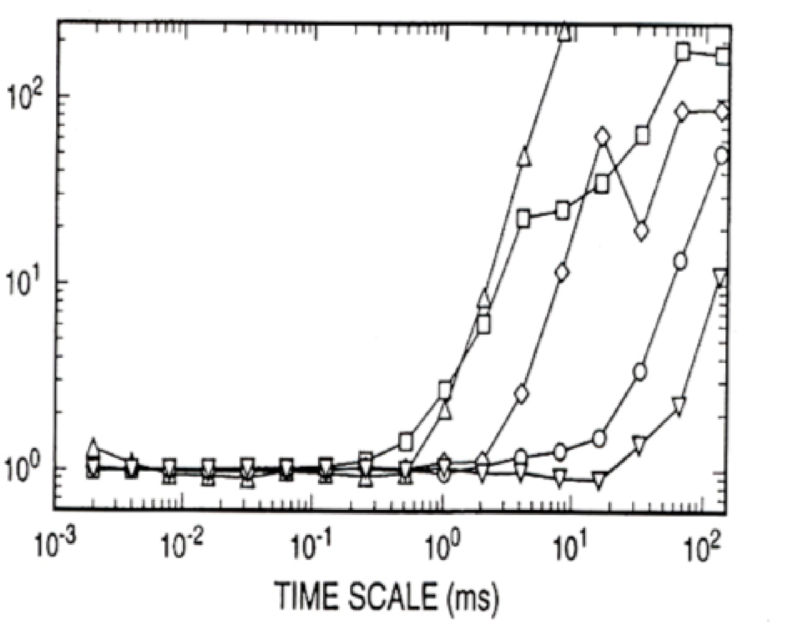
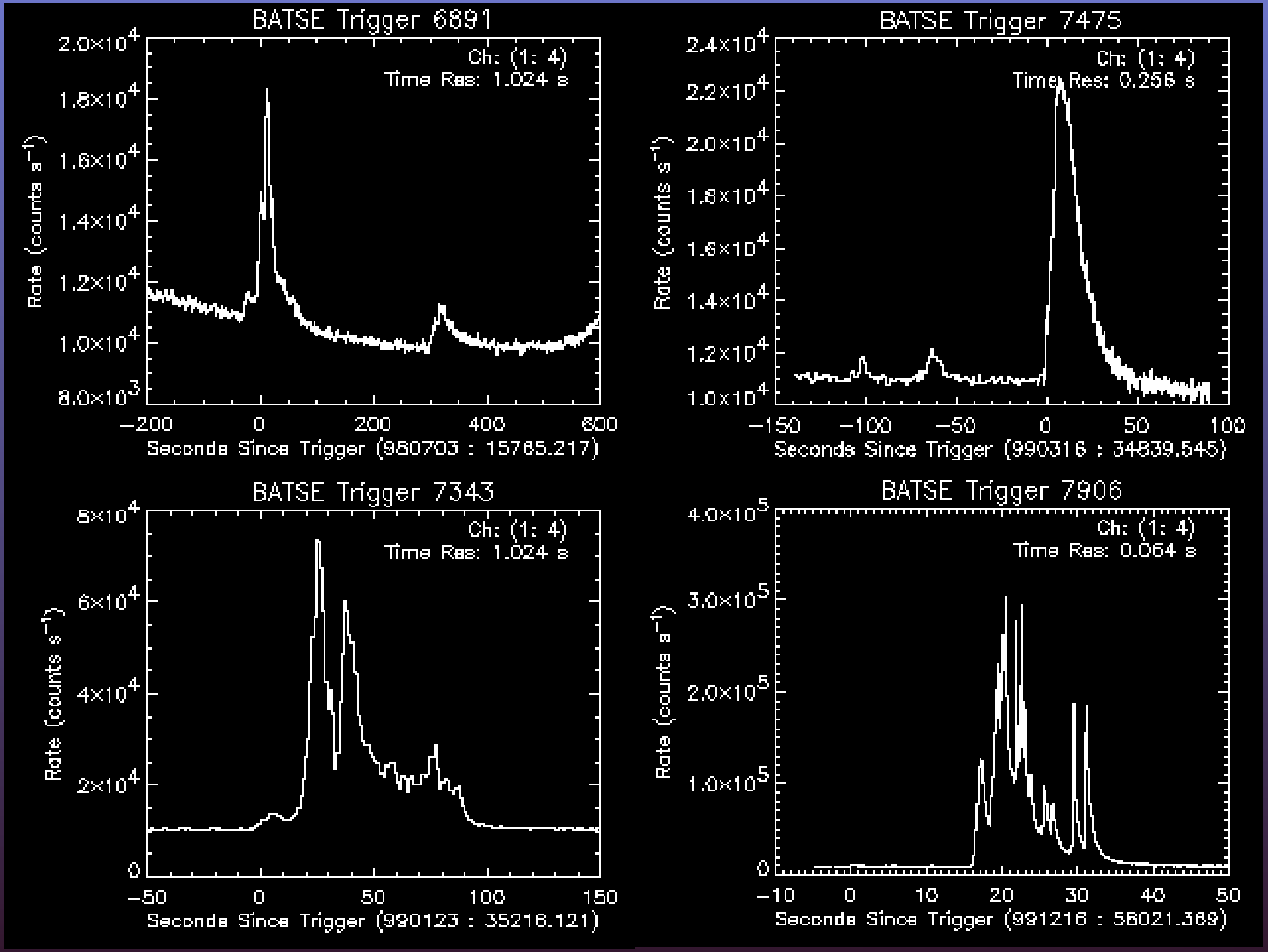
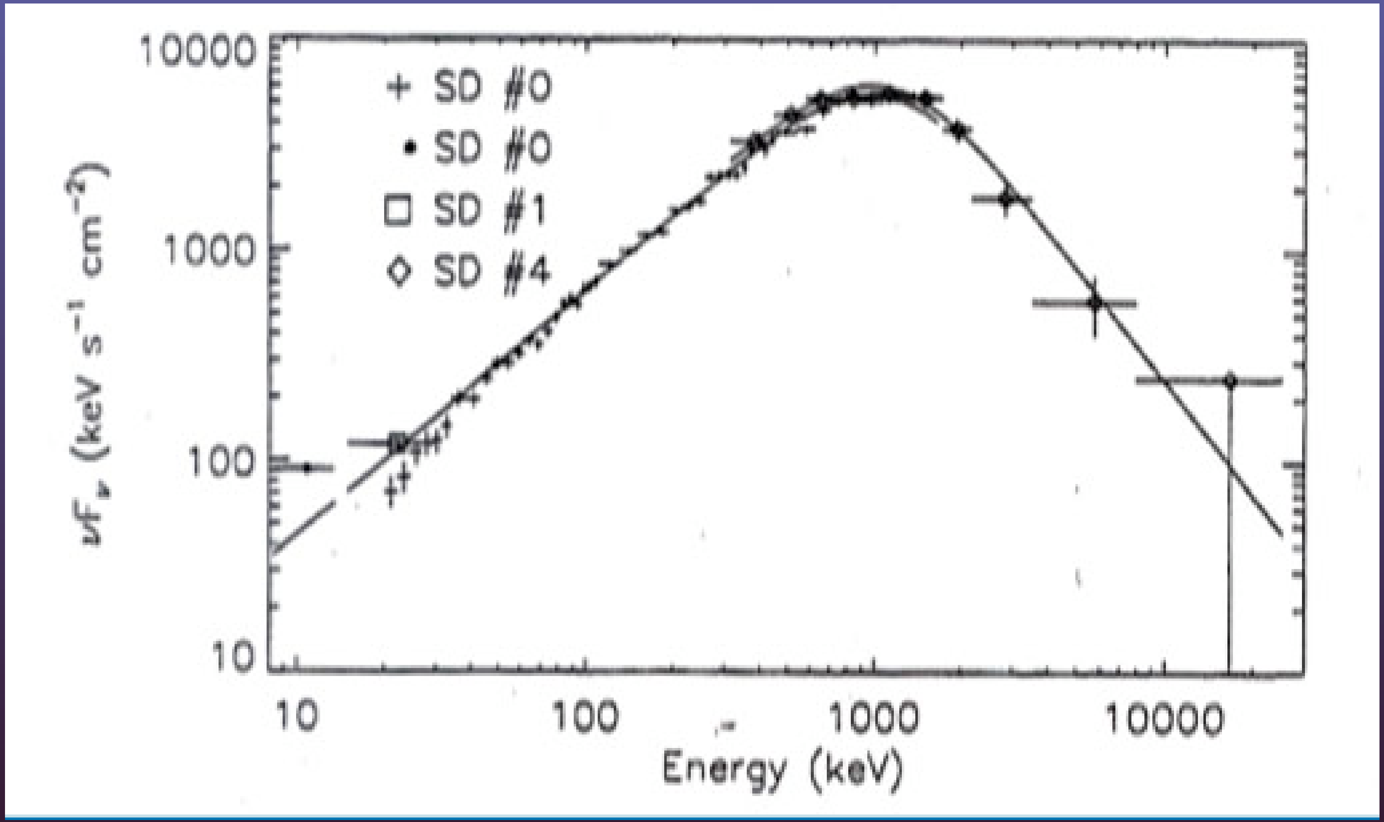


Figure 4 Examples of gamma-ray bursts with extremely complex temporal structures.




BATSE Trigger 6891
Ch: (1: 4)
Time Res: 1.024 s
Rate (counts s^{-1})
2.0×10^4
1.8×10^4
1.6×10^4
1.4×10^4
1.2×10^4
1.0×10^4
8.0×10^3
−200
0
200
400
600
Seconds Since Trigger (980703 : 15765.217)
BATSE Trigger 7475
Ch: (1: 4)
Time Res: 0.256 s
Rate (counts s^{-1})
2.4×10^4
2.2×10^4
2.0×10^4
1.8×10^4
1.6×10^4
1.4×10^4
1.2×10^4
1.0×10^4
−150
−100
−50
0
50
100
Seconds Since Trigger (990316 : 34839.545)
BATSE Trigger 7343
Ch: (1: 4)
Time Res: 1.024 s
Rate (counts s^{-1})
8×10^4
6×10^4
4×10^4
2×10^4
0
−50
0
50
100
150
Seconds Since Trigger (990123 : 35216.121)
BATSE Trigger 7906
Ch: (1: 4)
Time Res: 0.064 s
Rate (counts s^{-1})
4.0×10^5
3.0×10^5
2.0×10^5
1.0×10^5
0
−10
0
10
20
30
40
50
Seconds Since Trigger (991216 : 58021.369)

X-ray spectral energy distribution peaks at 0.1-1 MeV



Light-travel-time argument

$R \sim \Delta t = \frac{R}{c}$

→ Even if brightness of surface varies coherently on short time scales, obs time scale

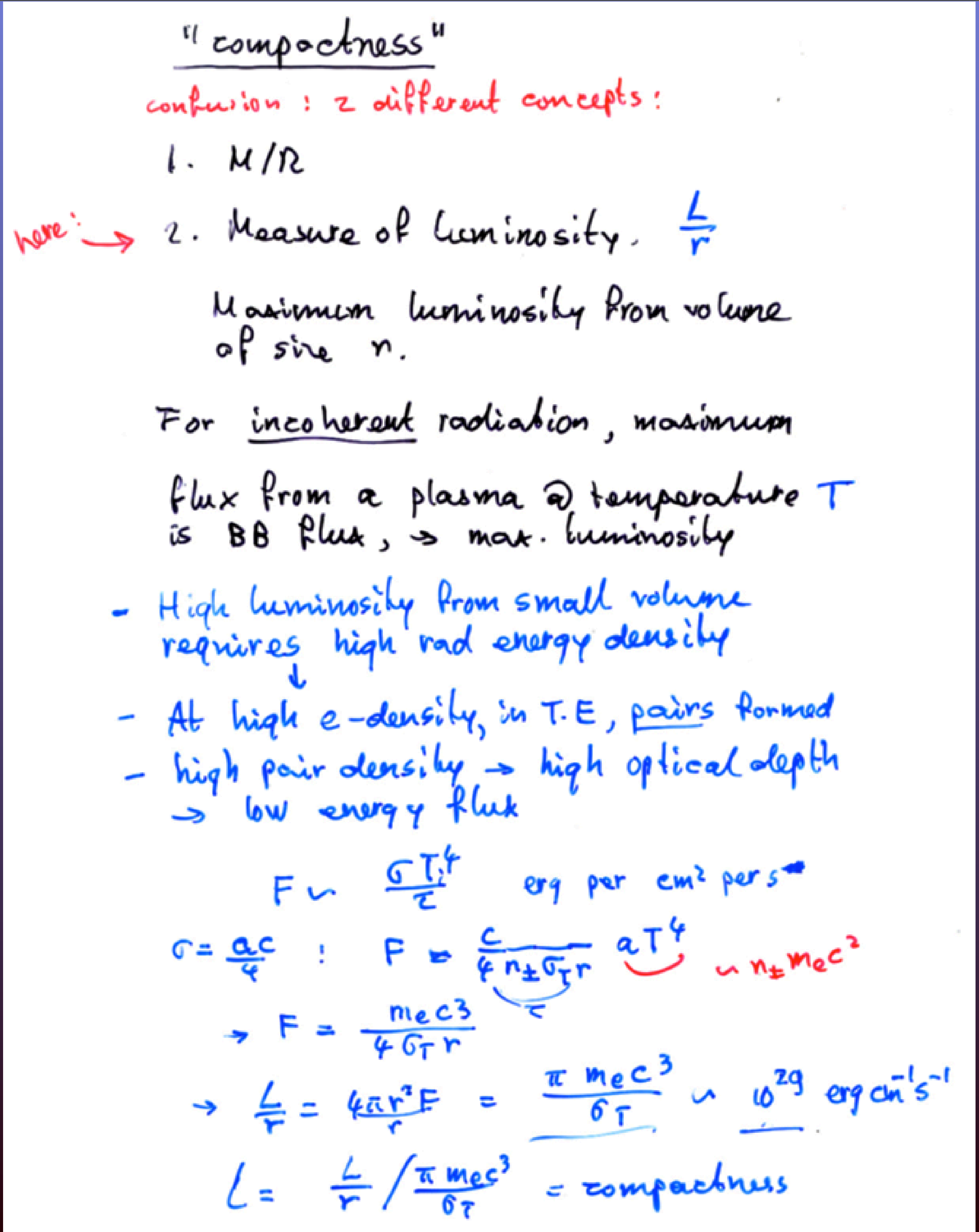
$$\Delta t \gtrsim \frac{R}{c}$$

GRB : $E \sim 10^{52}$ erg

time scales $\Delta t \gtrsim 1$ msec } →

compactness problem

Assuming *incoherent* radiation from a *static* object, observed time scale of variation sets a maximum to the size of the object



"compactness"

confusion : 2 different concepts :

1. M/R

here: → 2. Measure of luminosity. $\frac{L}{r}$

Maximum luminosity from volume of size r.

For incoherent radiation, maximum flux from a plasma @ temperature T is BB flux, → max. luminosity

- High luminosity from small volume requires high rad energy density ↓
- At high e-density, in T.E, pairs formed
- high pair density → high optical depth → low energy flux

$$F \sim \frac{\sigma T_i^4}{\tau} \text{ erg per cm}^2 \text{ per s}$$

$$\sigma = \frac{ac}{4} \;!\quad F \approx \frac{c}{\underbrace{4 n_\pm \sigma_T r}_{\tau}} \underbrace{aT^4}_{\sim n_\pm m_e c^2}$$

$$\rightarrow F = \frac{m_e c^3}{4 \sigma_T r}$$

$$\rightarrow \frac{L}{r} = \frac{4\pi r^2 F}{r} = \underline{\frac{\pi m_e c^3}{\sigma_T}} \sim \underline{10^{29}} \text{ erg cm}^{-1} \text{s}^{-1}$$

$$l = \frac{L}{r} \Big/ \frac{\pi m_e c^3}{\sigma_T} = \text{compactness}$$

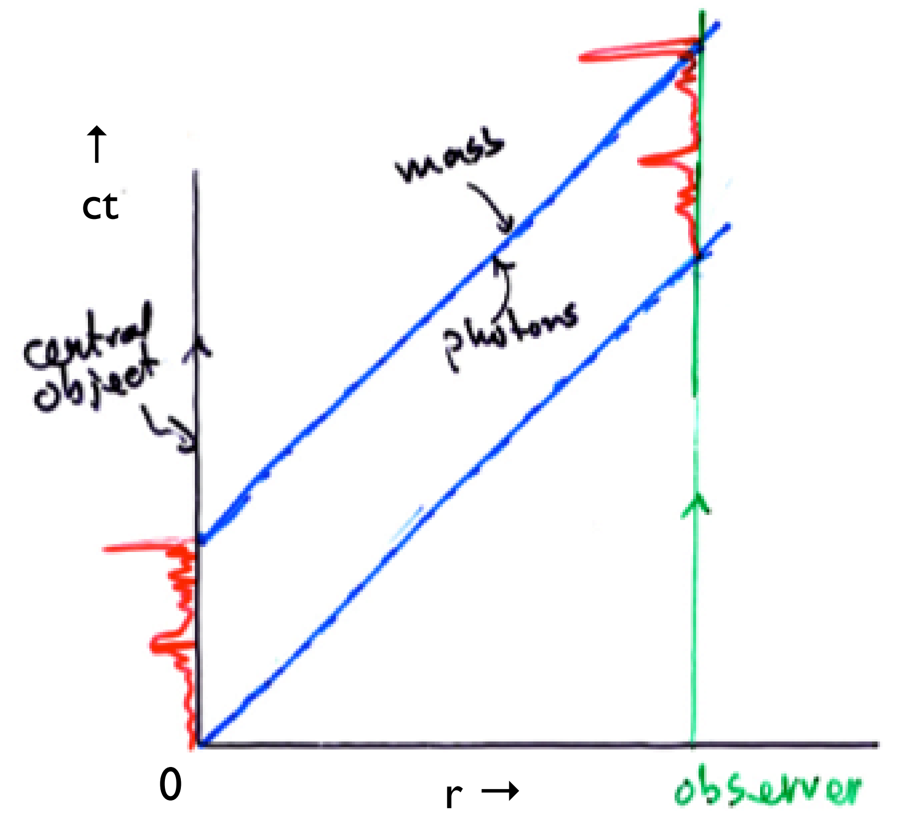
$L = 10^{50}$ erg/s,

$R = c\delta t = 10^8$ cm

$\rightarrow L/r \sim 10^{42}$

$\rightarrow l = 10^{13}$

For $\Gamma \gg 1$: variability intrinsic variability of the central object translates directly to the observer:



In the following:

Γ: Lorentz factor of the relativistic flow

M: ejected mass (not central mass)

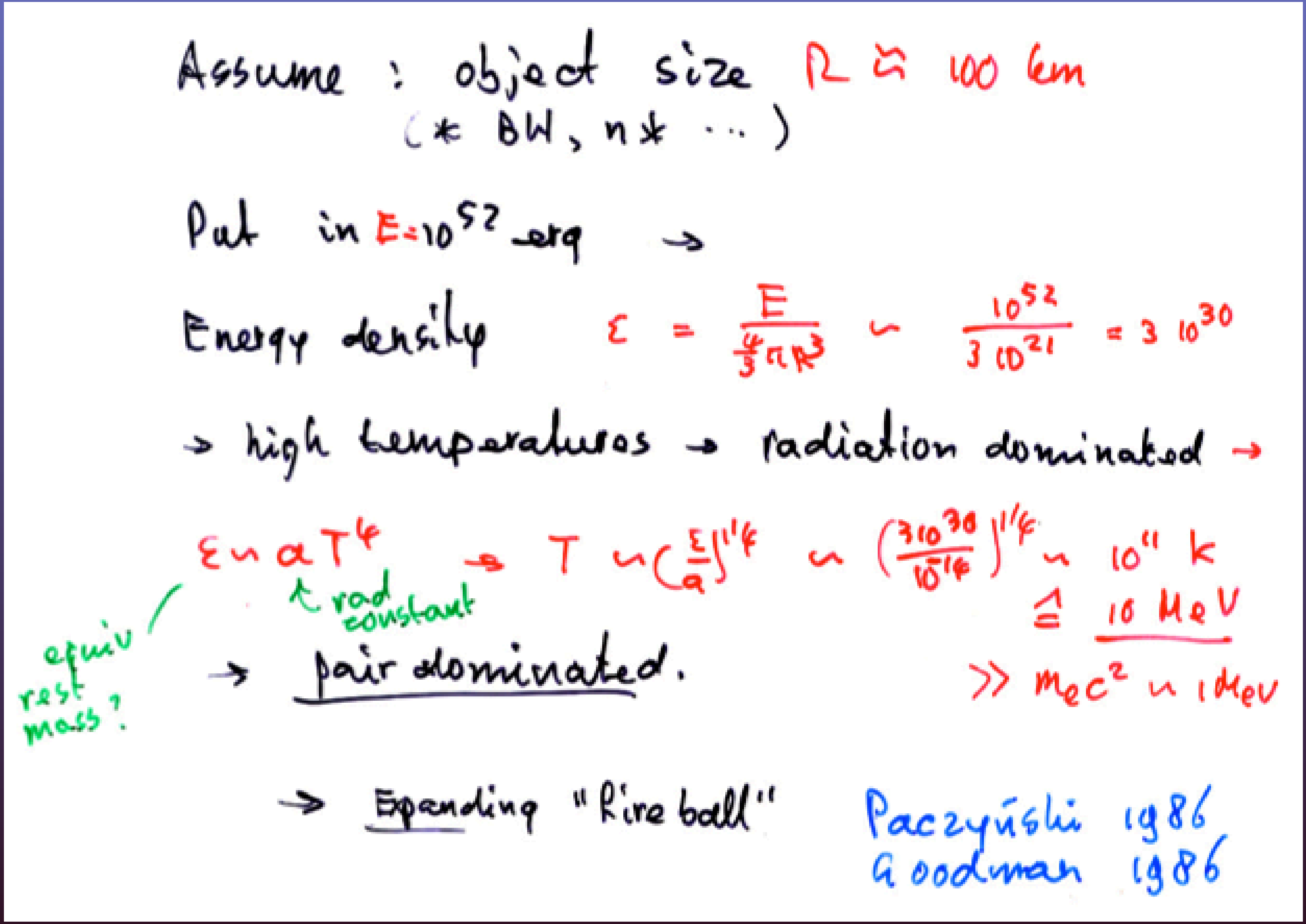
wide variation!

Characteristic values for GBR parameters

total energy	$E = 10^{51}$ erg
ejected mass	$M = 10^{-4} M_\odot$
Lorentz factor of flow	$\Gamma \sim 100$
size (radius of photosphere)	$r_{\rm phot} = 10^{11}$ cm
duration	$t = 1 - 1000$ s
shortest time scale	$1 - 100$ ms

assume these for the moment, justification for $M, \ \Gamma, \ r_{\rm phot}$ to follow.

conditions in central engine, for assumed energy deposition near a stellar mass black hole



Assume : object size $R \simeq 100$ km
($*$ BH, $n*$ ...)

Put in $E = 10^{52}$ erg →

Energy density $\varepsilon = \frac{E}{\frac{4}{3}\pi R^3} \sim \frac{10^{52}}{3\,10^{21}} = 3\,10^{30}$

→ high temperatures → radiation dominated →

$\varepsilon \sim a T^4 \rightarrow T \sim \left(\frac{\varepsilon}{a}\right)^{1/4} \sim \left(\frac{3\,10^{30}}{10^{-14}}\right)^{1/4} \sim 10^{11}$ K

↑ rad constant

$\triangleq \underline{10 \text{ MeV}}$

equiv rest mass ? /

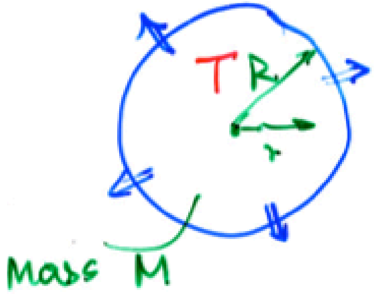
→ pair dominated.

$\gg m_e c^2 \sim 1$ MeV

→ Expanding "fire ball"

Paczyński 1986
Goodman 1986

Nonrelativistic fireball



Adiabatic expansion into vacuum.

Q: Velocity v_∞ of expansion ?

$P = k\rho^\gamma$ Ionized hydrogen:

$\gamma = \frac{c_p}{c_v} = 5/3$

Initial state : $\rho(r) = cst$

Homologous expansion (assume)

$\vec{v} : v_r \propto r$; $\operatorname{div} \vec{v} = cst\,(r)$

$\rightarrow \rho = \rho_0 \left(R_0/R(t)\right)^3$

Energy conservation : $\int (u + \frac{1}{2}\rho v^2) dV = cst = E$

$t=0 : v=0 \rightarrow E = \int u_0 \, dV$

$t \rightarrow \infty : u \rightarrow 0 \quad E = \left(\frac{1}{2}\int \rho v^2\right)_{t\rightarrow\infty}$

$v = q \cdot r$

$$\int_V \frac{1}{2}\rho v^2 = \frac{1}{2} q^2 \, 4\pi \rho \frac{1}{5} R^5 = \frac{3}{10} M \, v_\infty^2(R) = E$$

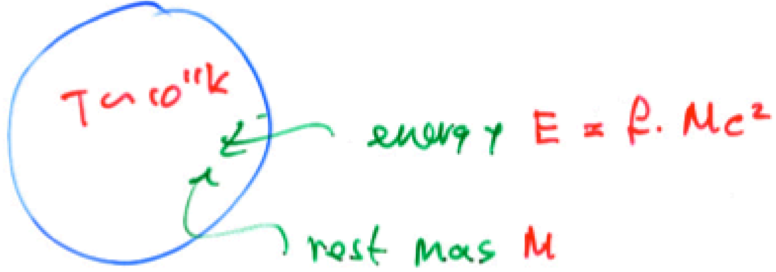
$$\int u_0 \, dV = \int \frac{P}{\gamma - 1} dV = V \frac{P_0}{\gamma - 1} = \rho V \left(\frac{P}{\rho}\right)_0 \frac{1}{\gamma - 1}$$

$$= M c_{s0}^2 \frac{1}{(\gamma-1)\gamma} \overset{\gamma = 5/3}{=} M c_{s0}^2 \frac{9}{10} = E$$

$$\boxed{c_s^2 = \frac{\gamma P}{\rho}}$$

$$\underline{v_\infty = 3\, c_{s0}}$$

Relativistic fireball



Energy conservation: kinetic energy at $t \to \infty$ equals initial energy E

$E_k = \overset{\Gamma}{\gamma_\infty} M c^2$ $(\overset{\Gamma}{\gamma_\infty} \gg 1)$

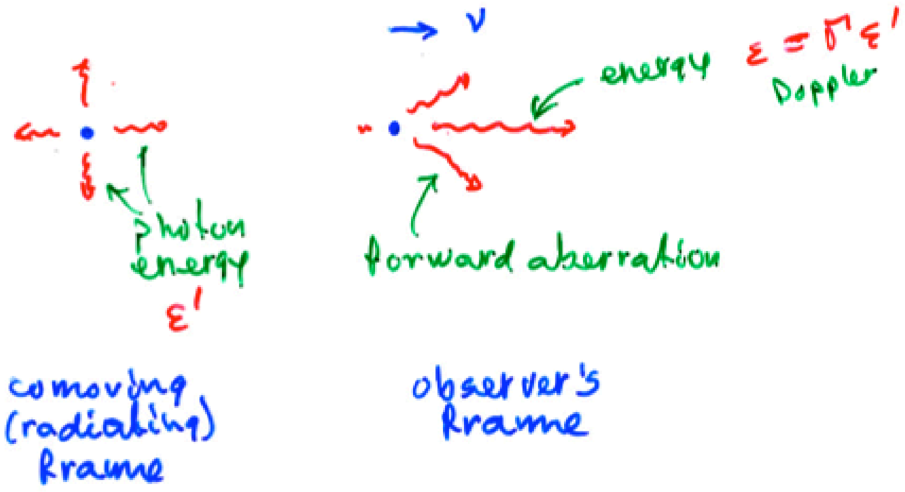
→ $\overset{\Gamma}{\gamma_\infty} = f.$ (GRB : aim for $\overset{\Gamma}{\gamma_\infty} \sim 100$)

Flow emits photons, observed phenomena to be treated with SR.

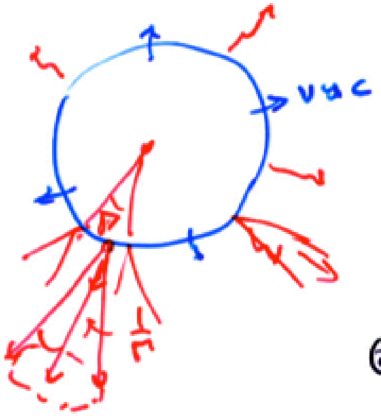
sequence of events :

- → energy released (somehow) in small volume
- → high T → pair dominated plasma + some baryons
- → expansion → cooling + conversion into K.E.
- → pairs annihilate, helps accelerate flow
- → end result : cold matter expanding relativistically

Relativistic beaming :
- doppler boosting +
- aberration



If $\Gamma >> 1$, radiation beamed into narrow forward cone opening angle ~ $\frac{1}{\Gamma}$



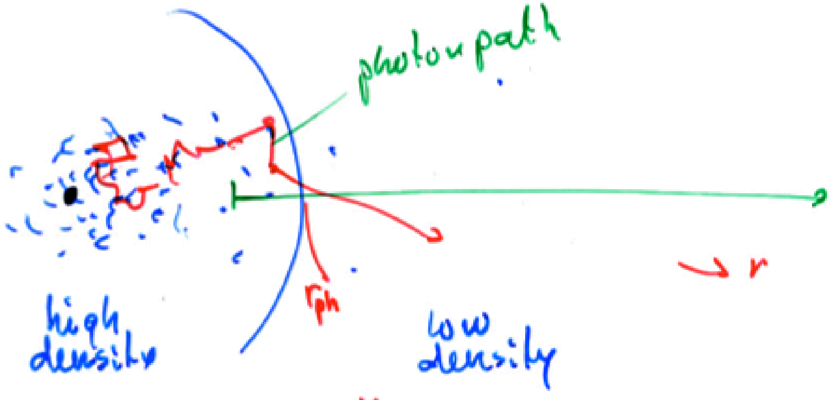
① observed energy flux Doppler-boosted by factor Γ

② Only a small part of the radiating surface visible

(↔ time scale problem)

light travel time limit on size does not apply to a relativistic fireball

Intermezzo : the photosphere



def : $\tau = \int_{r_{ph}}^{\infty} \kappa \rho \, dr = 1$

optical depth
$\tau(r)$

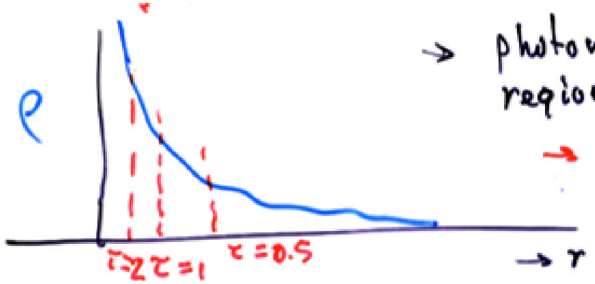
Steady outflow @ constant speed v :

$\dot{M} = \rho v r^2 = cst \rightarrow \rho \sim \frac{1}{r^2}$

κ : electron scattering (for example) :

$\kappa_{es} \simeq 0.3 \ cm^2 g^{-1}$

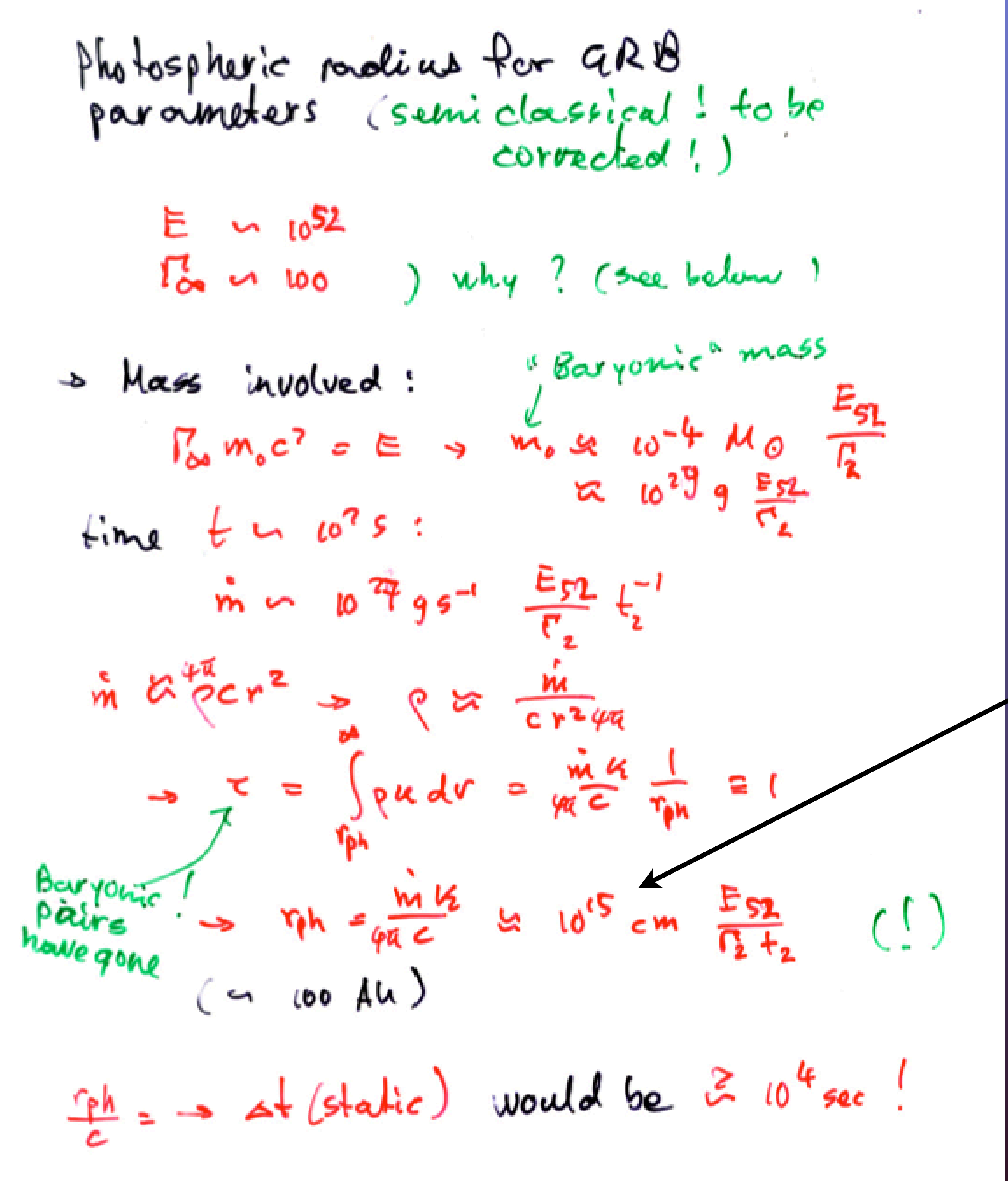
$\tau = \int_{r}^{\infty} \rho \kappa \, dr \sim \frac{1}{r}$



→ photons escape from region $\Delta\tau \lesssim 1$

$\rightarrow \Delta r \lesssim r_{ph}$

Where/when is radiation emitted?



Photospheric radius for GRB parameters (semiclassical ! to be corrected !)

$E \sim 10^{52}$

$\Gamma_\infty \sim 100$) why ? (see below)

→ Mass involved : "Baryonic" mass

$\Gamma_\infty m_0 c^2 = E \rightarrow m_0 \simeq 10^{-4} M_\odot \frac{E_{52}}{\Gamma_2}$

$\simeq 10^{29} g \frac{E_{52}}{\Gamma_2}$

time $t \sim 10^2 s$:

$\dot{m} \sim 10^{27} g s^{-1} \frac{E_{52}}{\Gamma_2} t_2^{-1}$

$\dot{m} \simeq 4\pi \rho c r^2 \rightarrow \rho \simeq \frac{\dot{m}}{c r^2 4\pi}$

$\rightarrow \tau = \int_{r_{ph}}^{\infty} \rho \kappa \, dr = \frac{\dot{m} \kappa}{4\pi c} \frac{1}{r_{ph}} \cong 1$

Baryonic pairs have gone !

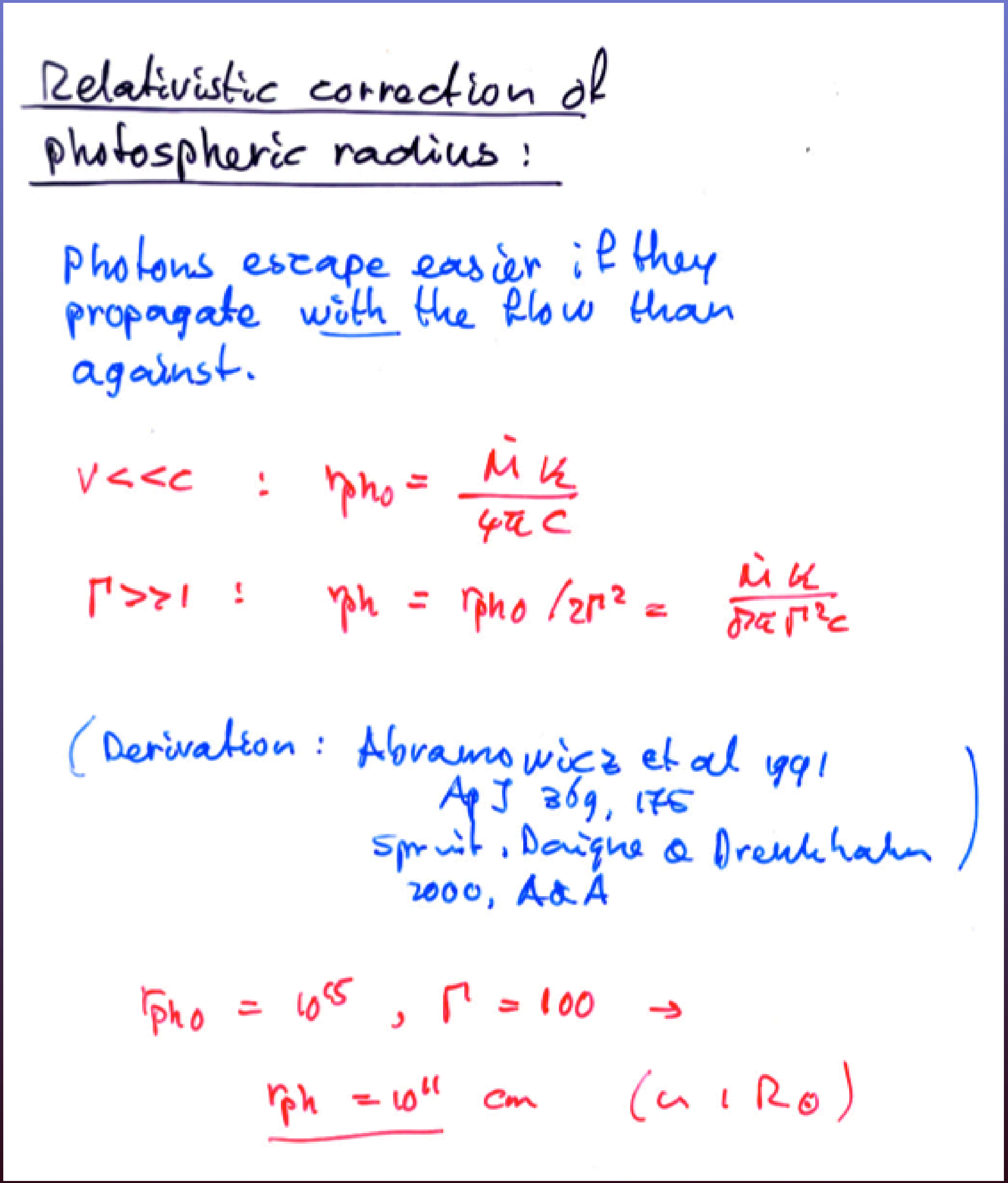
$\rightarrow r_{ph} = \frac{\dot{m} \kappa}{4\pi c} \simeq 10^{15} cm \frac{E_{52}}{\Gamma_2 t_2}$ (!)

(∼ 100 AU)

$\frac{r_{ph}}{c} = \rightarrow \Delta t$ (static) would be $\gtrsim 10^4$ sec !

too large,
does not fit
observations

relativistic
corrections



Relativistic correction of photospheric radius:

Photons escape easier if they propagate with the flow than against.

$v << c$: $r_{pho} = \frac{\dot{M} \kappa}{4\pi c}$

$\Gamma >> 1$: $r_{ph} = r_{pho} / 2\Gamma^2 = \frac{\dot{M} \kappa}{8\pi \Gamma^2 c}$

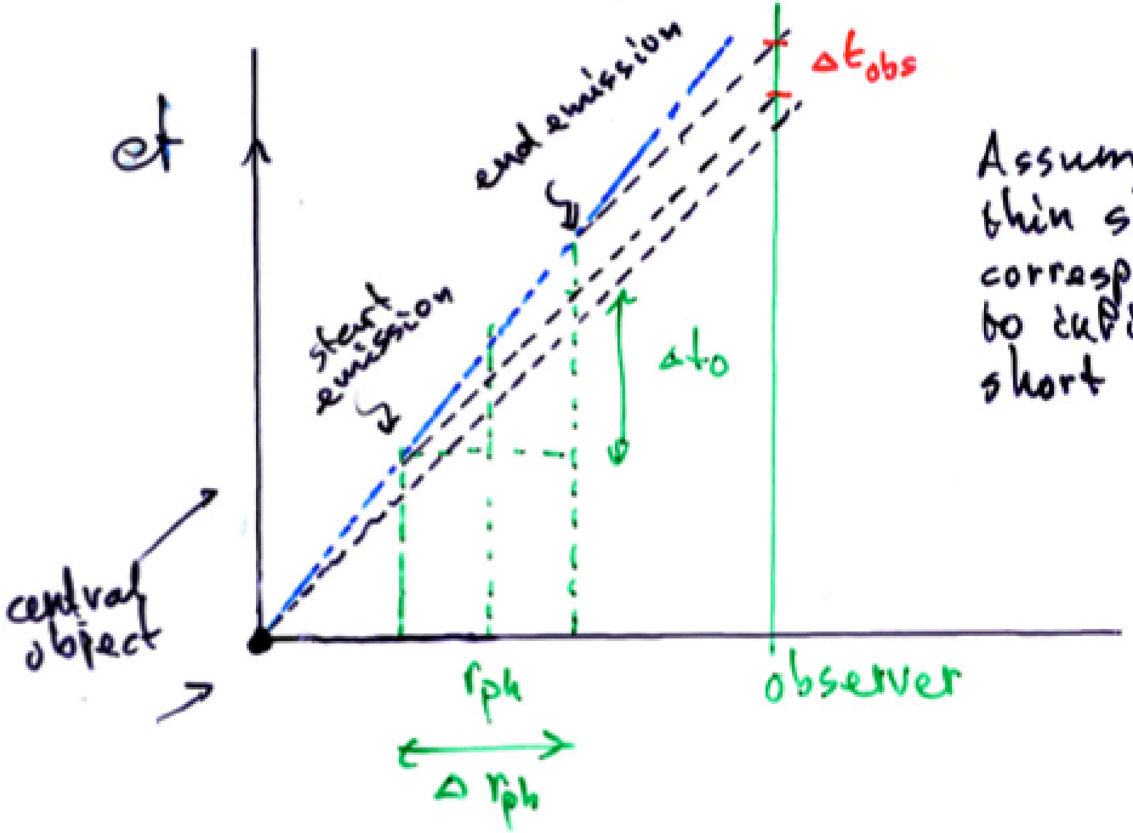
(Derivation : Abramowicz et al 1991
ApJ 369, 175
Spruit, Daigne & Drenkhahn
2000, A&A)

$r_{pho} = 10^{15}$, $\Gamma = 100$ →

$r_{ph} = 10^{11}$ cm ($\sim 1 R_\odot$)

Reduction of observed variability time scale by SR.

Minkowski diagram :



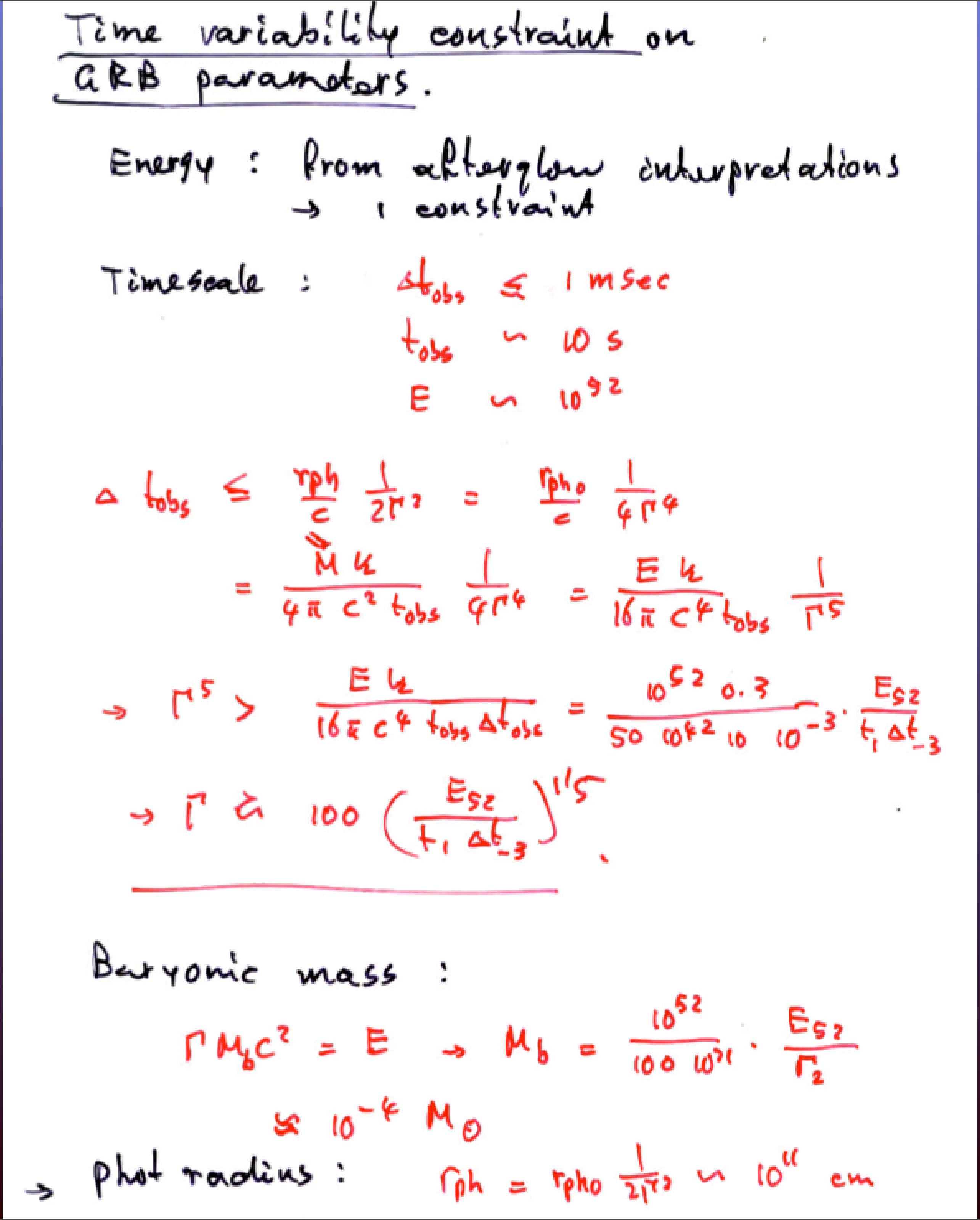
Assume :
thin shell,
corresponding
to infinitesimally
short burst @ t=0

$$\Delta t_{obs} = \frac{\Delta r_{ph}}{v} - \frac{\Delta r_{ph}}{c} = \underbrace{\frac{\Delta r_{ph}}{c}}_{\Delta t_0}\left(1-\frac{1}{\beta}\right)$$

$\Gamma >> 1$:

$\Gamma = (1-\beta^2)^{-1/2}$

$\beta \approx 1 - \frac{1}{2\Gamma^2} \rightarrow \underline{\Delta t_{obs} \approx \frac{\Delta r_{ph}}{c}\frac{1}{2\Gamma^2}}$



Time variability constraint on GRB parameters.

Energy : from afterglow interpretations
→ 1 constraint

Timescale : $\Delta t_{obs} \leq 1$ msec

$t_{obs} \sim 10$ s

$E \sim 10^{52}$

$$\Delta t_{obs} \leq \frac{r_{ph}}{c}\frac{1}{2\Gamma^2} = \frac{r_{pho}}{c}\frac{1}{4\Gamma^4}$$

$$= \frac{\dot{M}\kappa}{4\pi c^2 t_{obs}}\frac{1}{4\Gamma^4} = \frac{E\kappa}{16\pi c^4 t_{obs}}\frac{1}{\Gamma^5}$$

$$\rightarrow \Gamma^5 > \frac{E\kappa}{16\pi c^4 t_{obs}\Delta t_{obs}} = \frac{10^{52}\,0.3}{50\;10^{42}\;10\;10^{-3}}\cdot\frac{E_{52}}{t_1\,\Delta t_{-3}}$$

$$\rightarrow \Gamma \gtrsim 100\left(\frac{E_{52}}{t_1\,\Delta t_{-3}}\right)^{1/5}.$$

Baryonic mass :

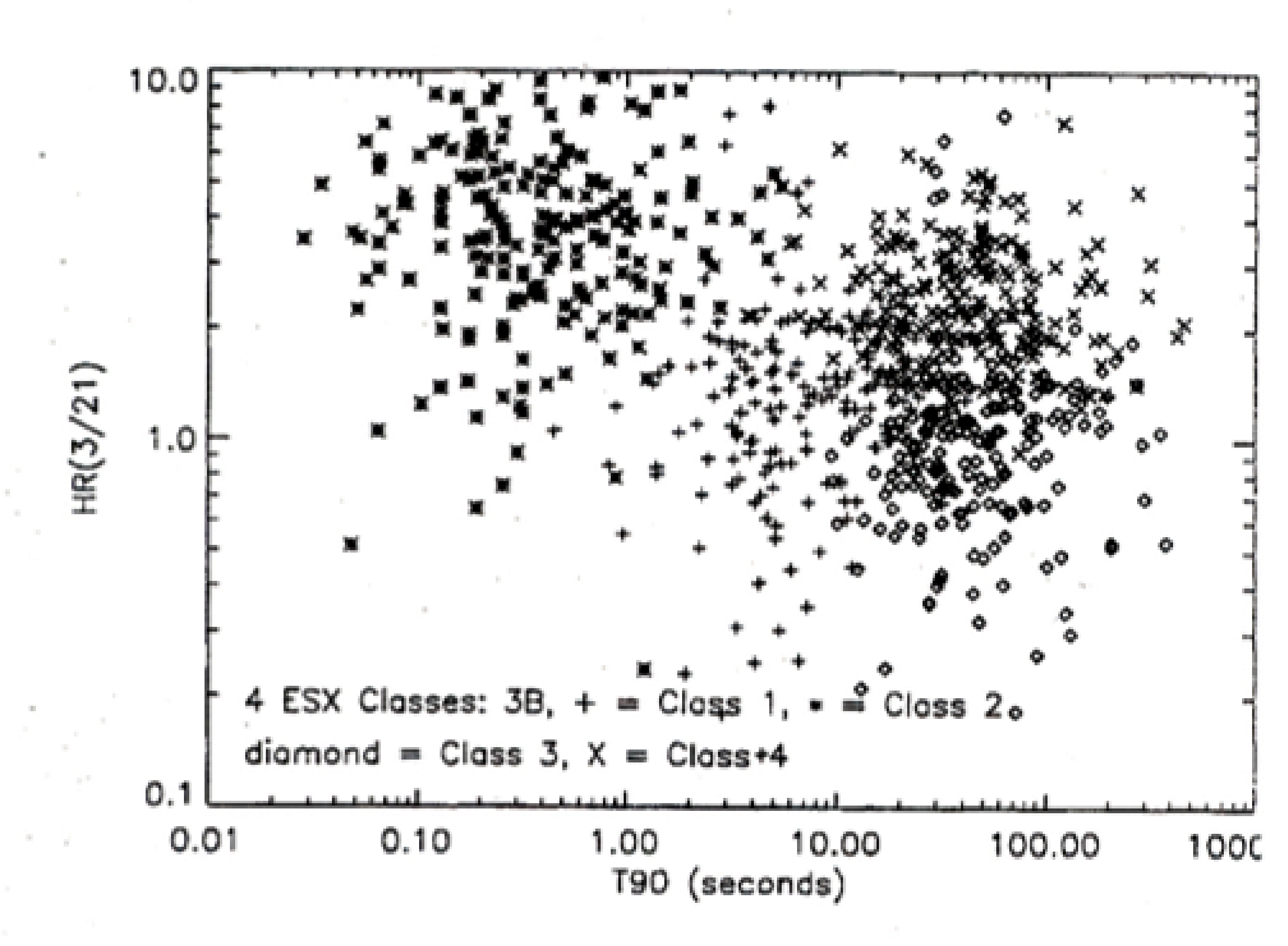
$$\Gamma M_b c^2 = E \rightarrow M_b = \frac{10^{52}}{100\;10^{21}}\cdot\frac{E_{52}}{\Gamma_2}$$

$$\lesssim 10^{-4}\,M_\odot$$

→ phot radius : $r_{ph} = r_{pho}\frac{1}{2\Gamma^2} \sim 10^{11}$ cm

Text

2 classes of GRB: 'short' and 'long'



Central engine ideas

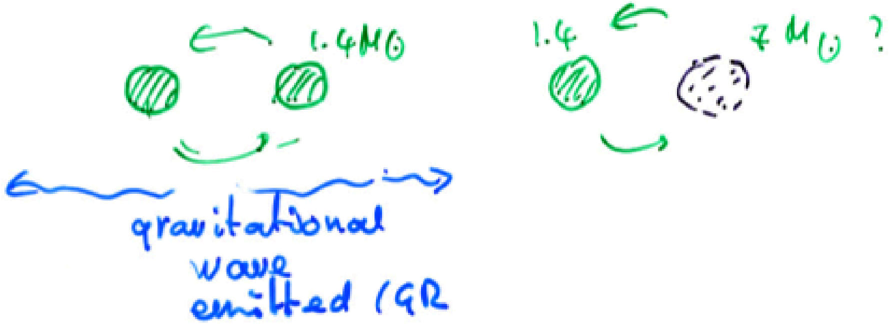
{ None of them worked out very well }

1 Merging neutron stars or
neutron star + BH

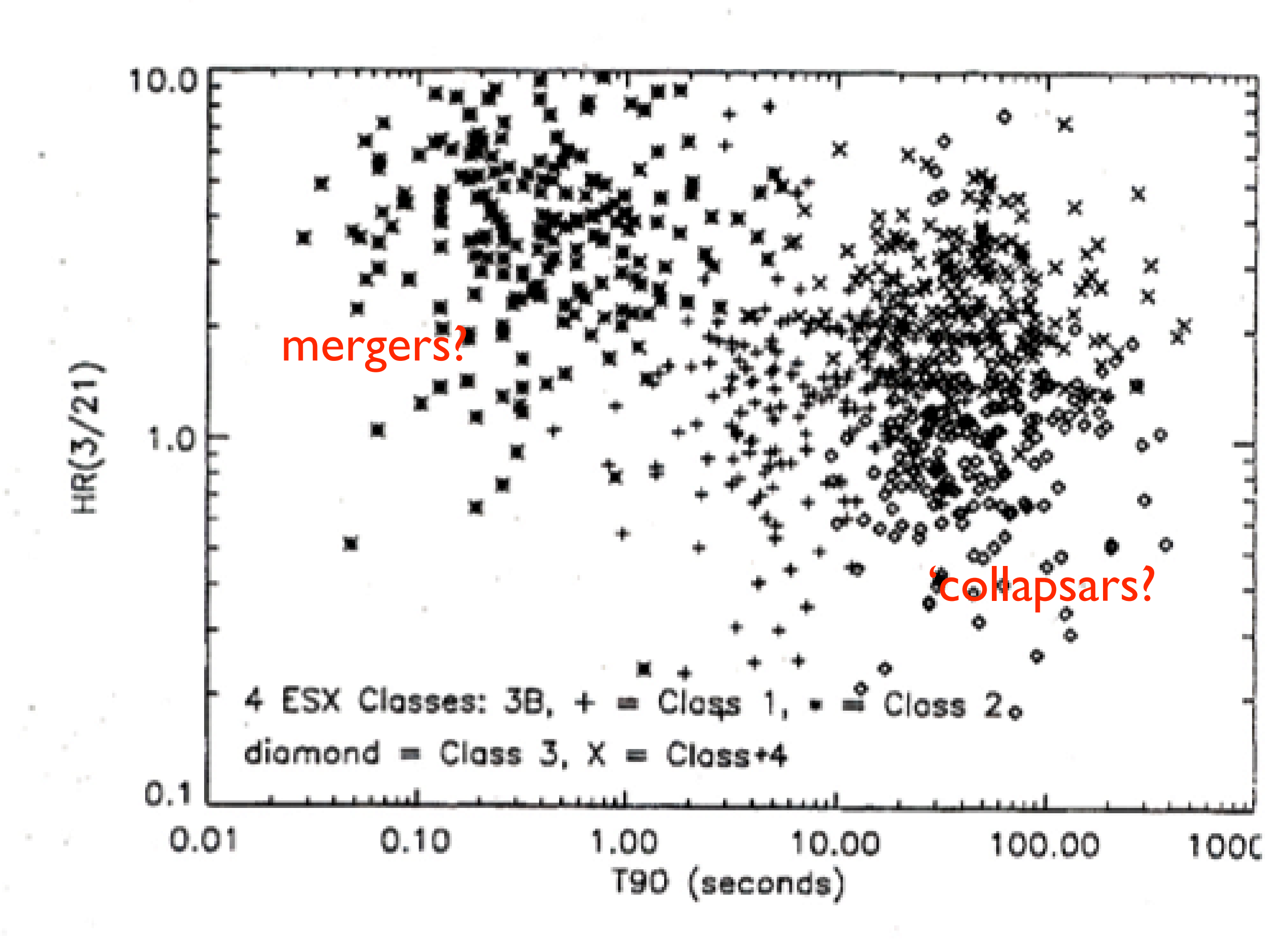
2 Rapidly rotating neutron star
with very strong B-field

3 Supernova ("collapsar")

1 Mergers



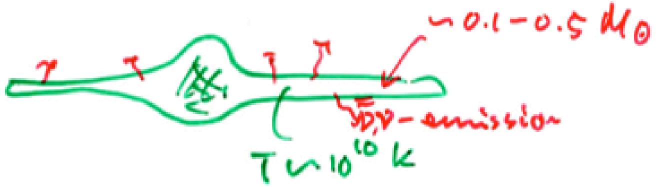
Final stages:


10.0
1.0
0.1
HR(3/21)
0.01
0.10
1.00
10.00
100.00
100(
T90 (seconds)
4 ESX Classes: 3B, + = Class 1, ▪ = Class 2,
diamond = Class 3, X = Class+4
mergers?
collapsars?

Mergers (ct'd)

Energy release : $\sim 0.1\ M_\odot c^2 \sim 10^{53} - 10^{54}$

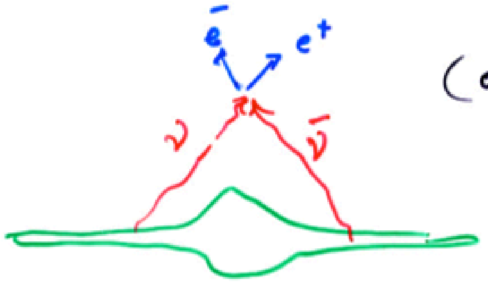
- Efficiency ?
- Baryon loading



- optically thick for all e.m. radiation
  $\tau \sim O(1)$ for neutrino emission

→ rapid cooling (seconds)

Idea : neutrino → pair conversion



$\nu\bar\nu \to e^+e^-$

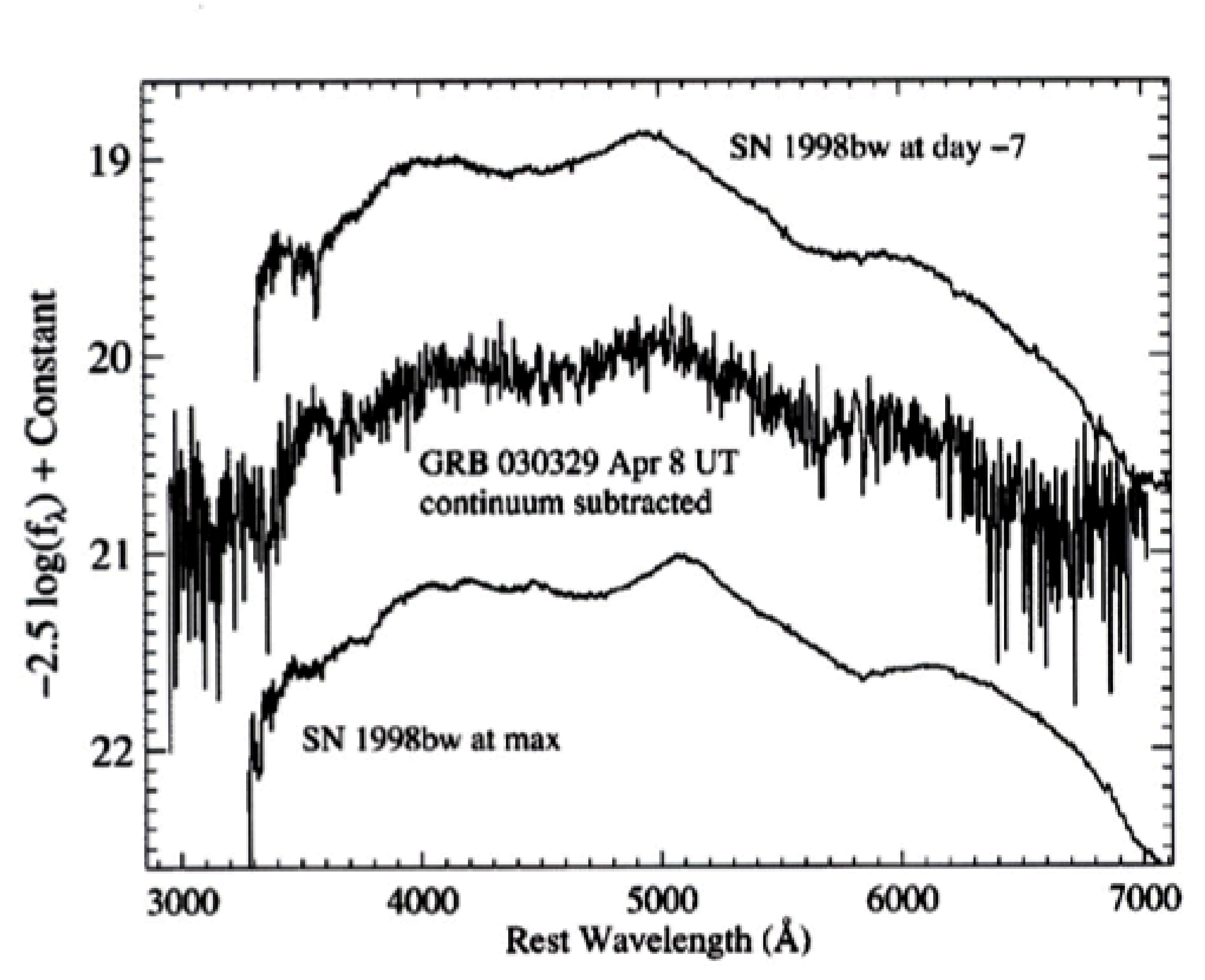
(also : $\nu\bar\nu \to 2\gamma$)

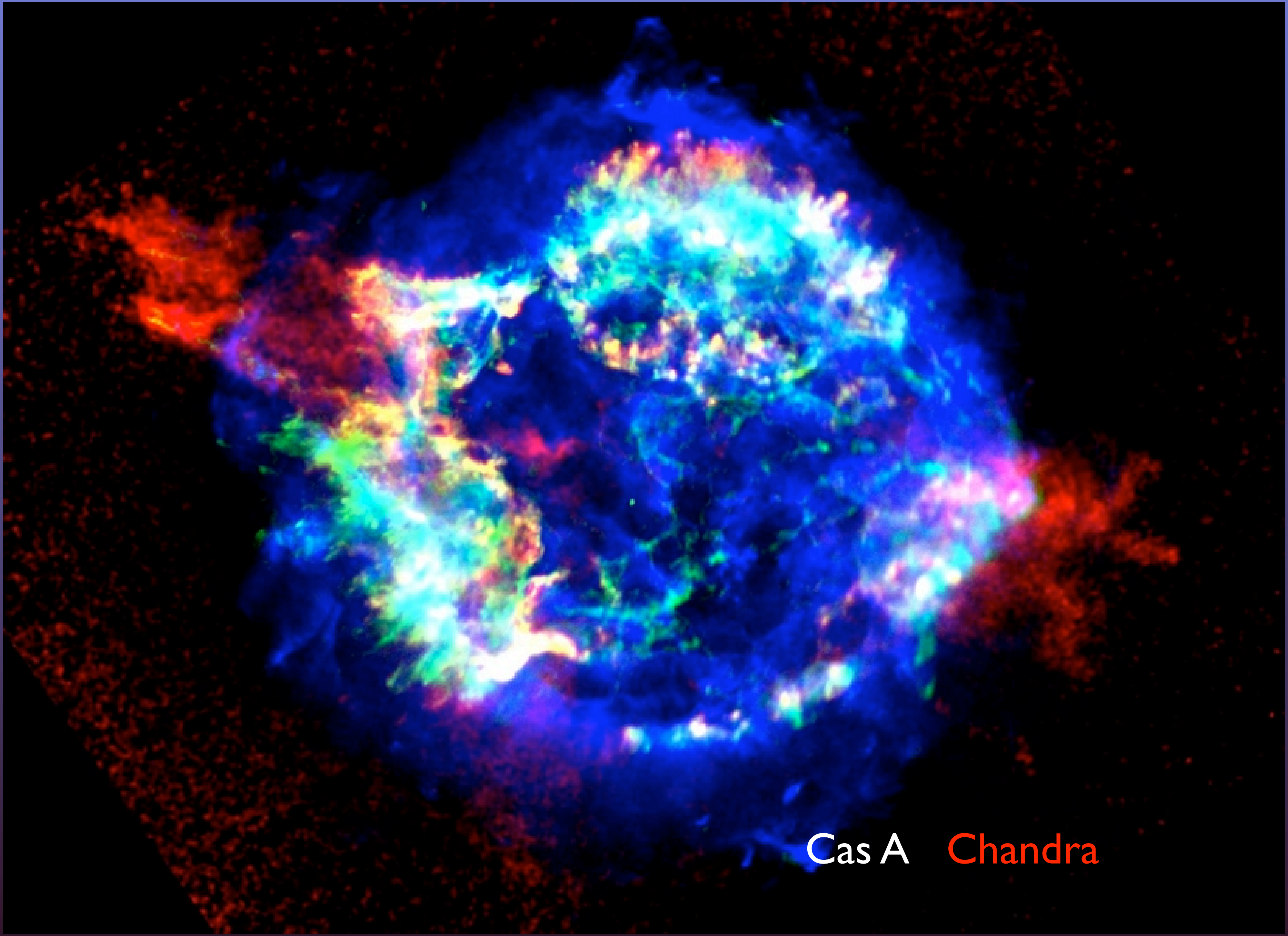
- Can take place in low density regions above disk

* But :- Efficiency low ($\lesssim 10^{49}$ erg) of conversion into pair plasma
- Baryon loading problem (neutrino-driven wind from disk)

Collapsars: GBR from supernovae
confirmation: GRB030329

Woosley 1993





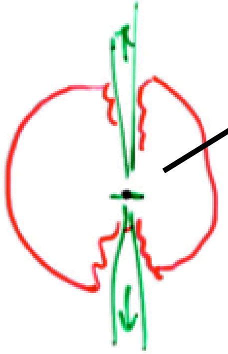
Cas A Chandra

collapsar (ct'd)

binary?

Scenario :

- pre-SN core with "just right" amount of rotation.
- collapse → black hole + spinning torus
- rotational energy "somehow" converted to directed outflow along axis
- Hole drilled through star



- Seen as GRB if "on axis"

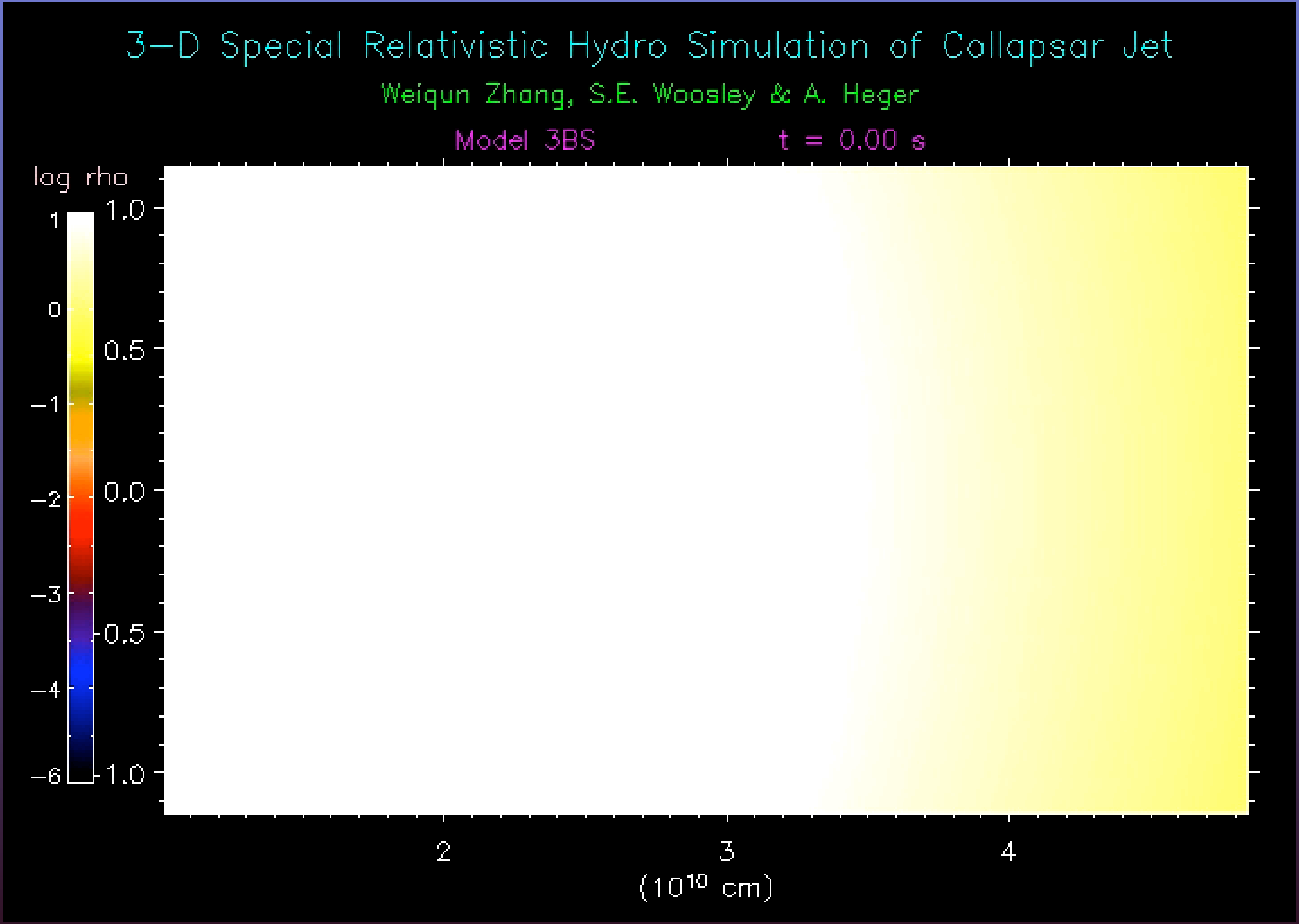
Questions:

- How is hole "drilled"?
- Why only some SN Ic ?
- What determines the "right" amount of rotation

GRB are rare:
10^{-7} yr^{-1} per galaxy
beaming factor 10^{-3}?
$\rightarrow \sim 10^{-4}$ yr^{-1}

supernova rate:
$\geq 10^{-2}$ yr^{-1}

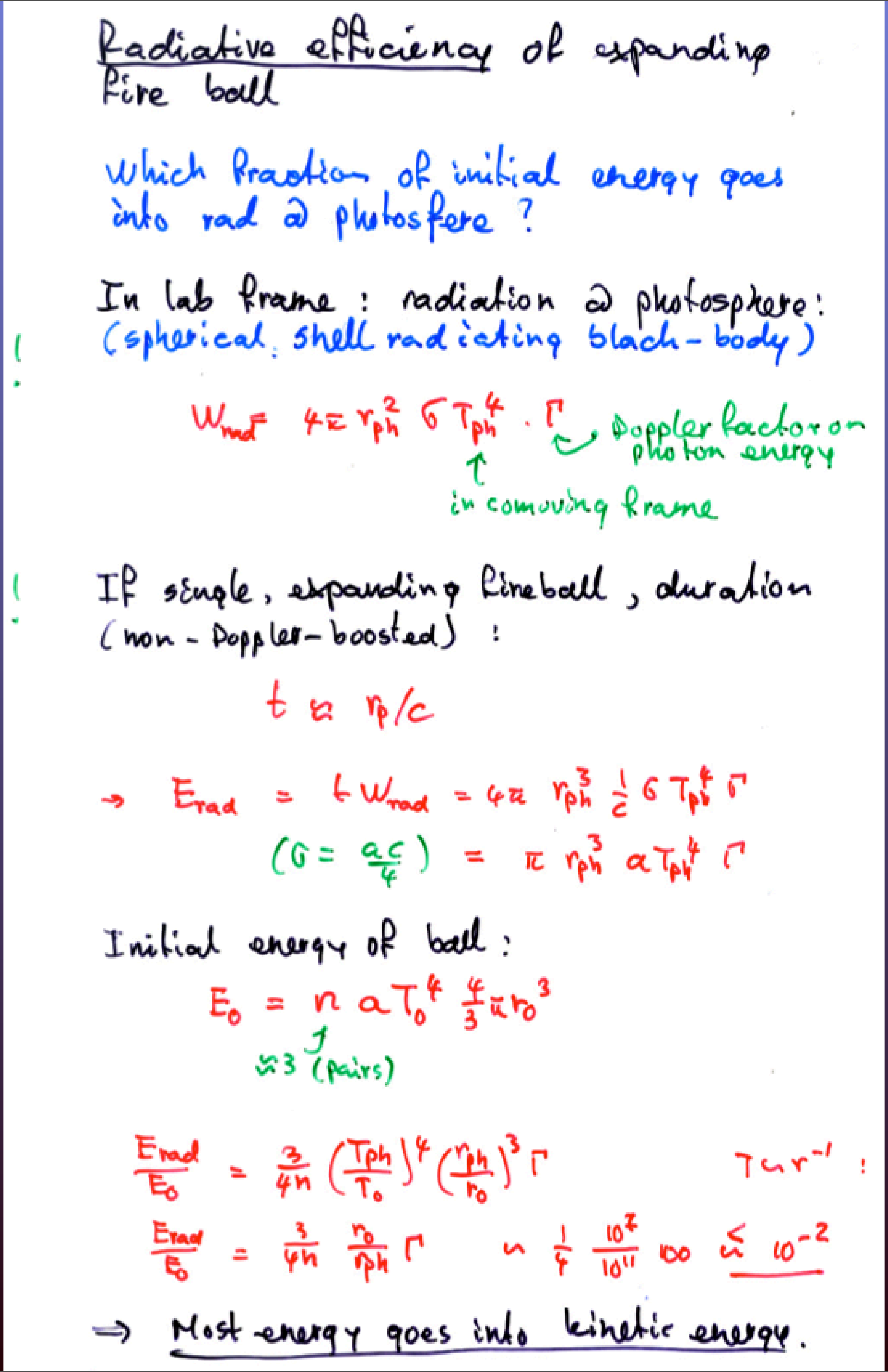
GRB-SN are some special subclass.
1998bw: SN 1c (exploding WR star)



3–D Special Relativistic Hydro Simulation of Collapsar Jet

Weiqun Zhang, S.E. Woosley & A. Heger

Model 3BS t = 0.00 s



Radiative efficiency of expanding fire ball

which fraction of initial energy goes into rad @ photosfere ?

In lab frame : radiation @ photosphere:
(spherical shell radiating black-body)

$$W_{rad} = 4\pi r_{ph}^2 \sigma T_{ph}^4 \cdot \Gamma$$

T_{ph}: in comoving frame

Γ: Doppler factor on photon energy

If single, expanding fireball, duration (non-Doppler-boosted) :

$$t \approx r_p/c$$

$$\rightarrow \quad E_{rad} = t W_{rad} = 4\pi r_{ph}^3 \frac{1}{c} \sigma T_{ph}^4 \Gamma$$

$$\left(\sigma = \frac{ac}{4}\right) = \pi r_{ph}^3 a T_{ph}^4 \Gamma$$

Initial energy of ball :

$$E_0 = \underset{\approx 3 \text{ (pairs)}}{n}\, a T_0^4 \frac{4}{3}\pi r_0^3$$

$$\frac{E_{rad}}{E_0} = \frac{3}{4n}\left(\frac{T_{ph}}{T_0}\right)^4 \left(\frac{r_{ph}}{r_0}\right)^3 \Gamma \qquad T \propto r^{-1} \;!$$

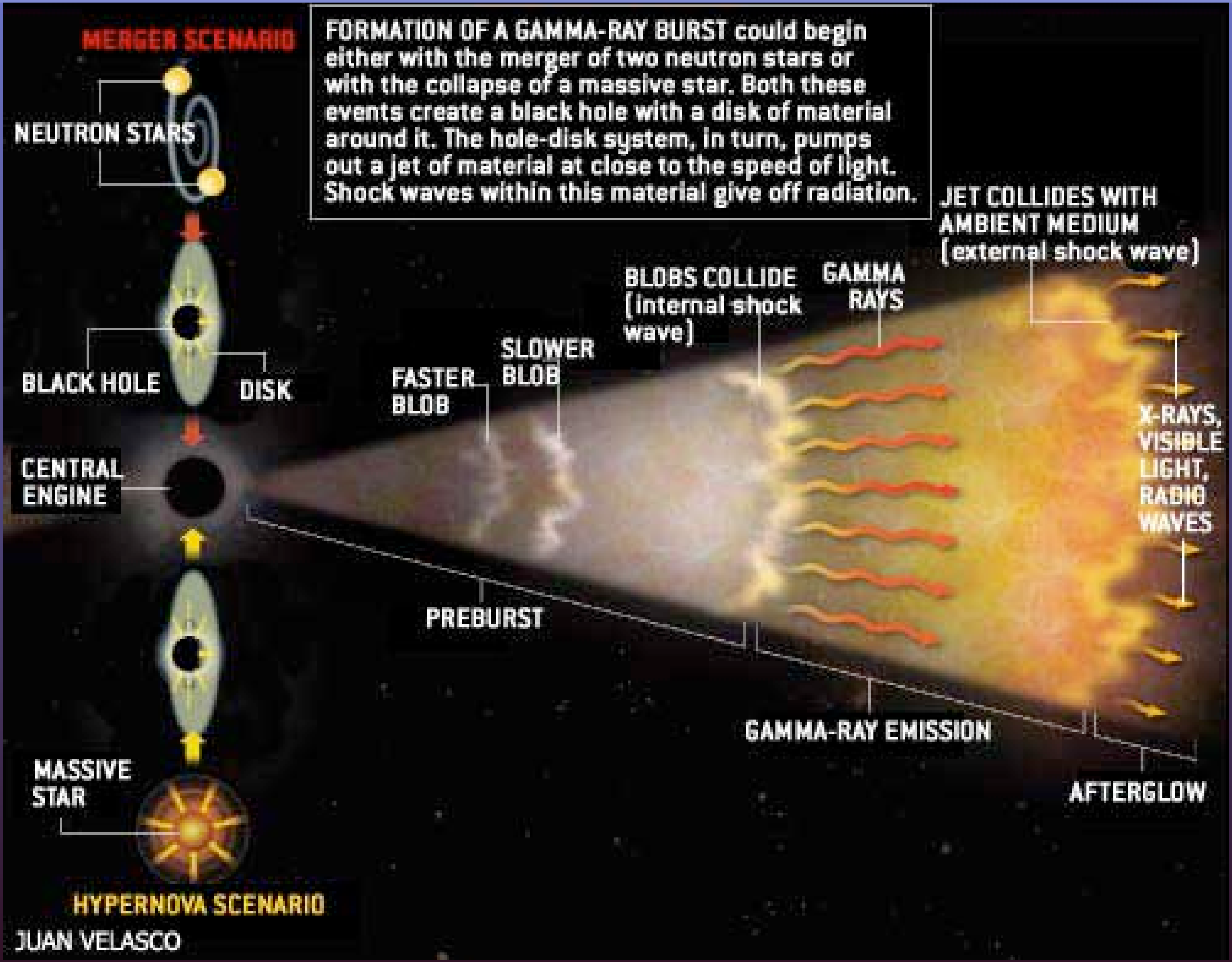
$$\frac{E_{rad}}{E_0} = \frac{3}{4n} \frac{r_0}{r_{ph}} \Gamma \quad \sim \frac{1}{4} \frac{10^7}{10^{11}} 100 \underline{\lesssim 10^{-2}}$$

$\Rightarrow$ Most energy goes into kinetic energy.

solution:
internal shock model

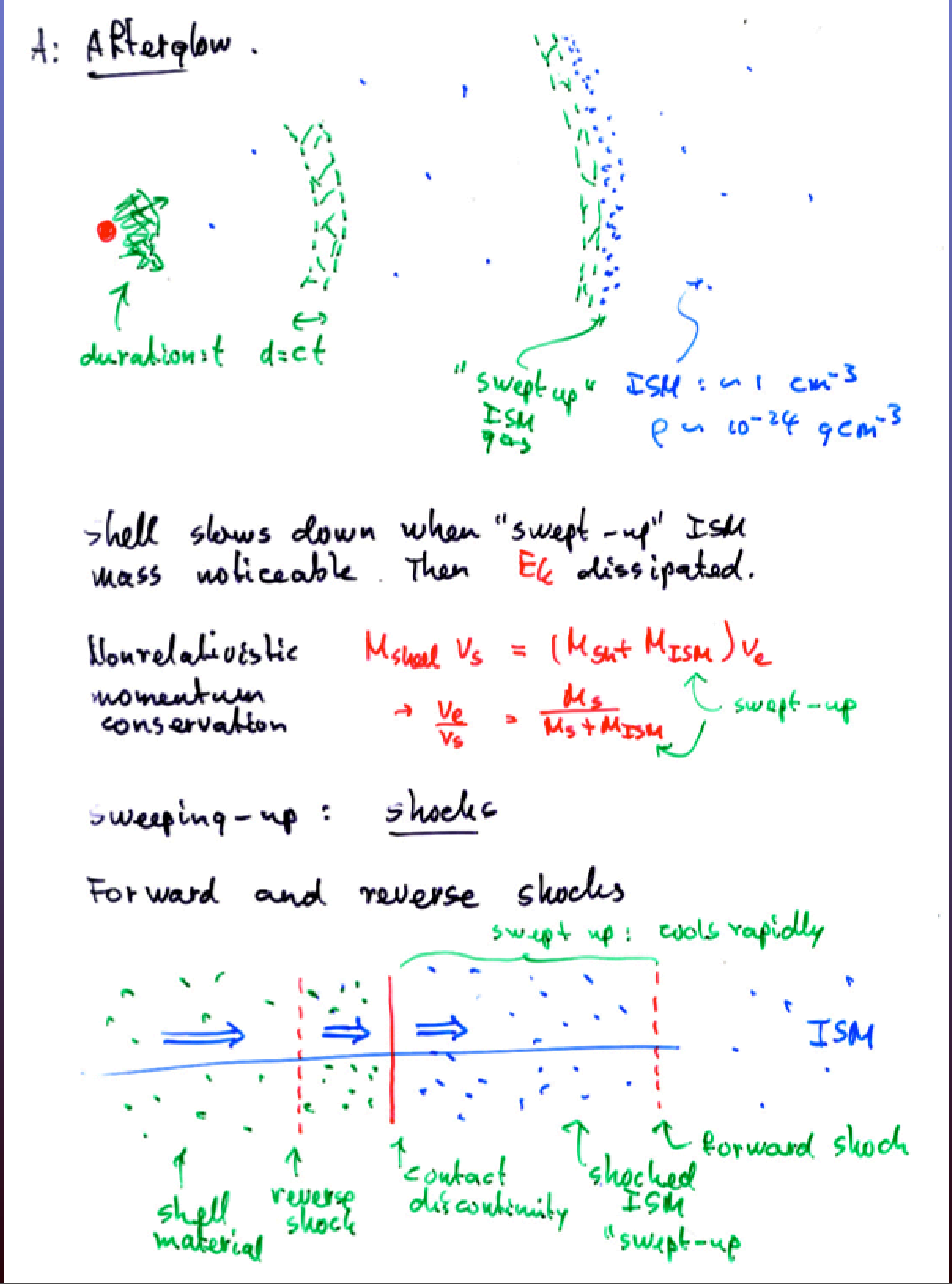
Meszaros & Rees 1992

Internal shock model of GRB radiation


FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.

JUAN VELASCO

where does remaining KE go?



A: Afterglow

duration: t

d = ct

"swept-up" ISM gas

ISM: ~ 1 cm^{-3}

$\rho \sim 10^{-24}$ g cm^{-3}

shell slows down when "swept-up" ISM mass noticeable. Then E_k dissipated.

Nonrelativistic momentum conservation

$$M_{shell} V_s = (M_{sh} + M_{ISM}) V_e$$

$$\rightarrow \frac{V_e}{V_s} = \frac{M_s}{M_s + M_{ISM}}$$

swept-up

sweeping-up: shocks

Forward and reverse shocks

swept up: cools rapidly

ISM

shell material

reverse shock

contact discontinuity

shocked ISM "swept-up"

forward shock

Only part of the kinetic energy dissipated in internal shocks problems with the internal shock scenario

- radiative efficiency: only differential energy between shells dissipated
- does not explain smooth light curves

Alternative: gradual internal dissipation of magnetic fields

Roles of magnetic fields in GRB

1 extraction of energy from rotating central engine

2 radiation from internal dissipation of magnetic energy in the flow

3 acceleration of the flow

Outflow dominated by a magnetic field

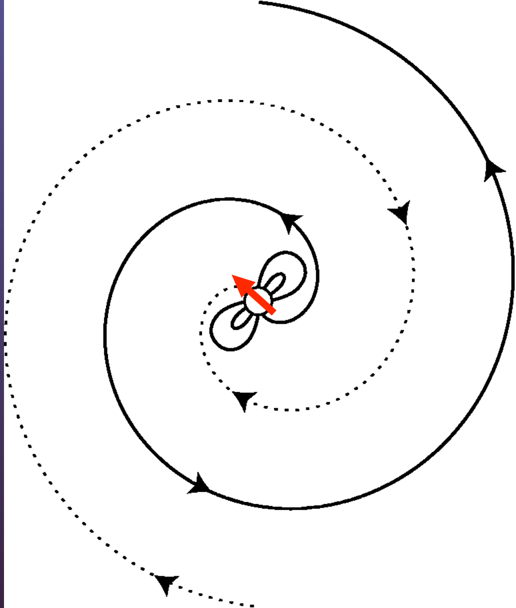
rotating engine ejects mass M with a
magnetic field B such that $B^2/8\pi \sim 100\,\rho c^2$

if all converted to KE: $\Gamma \sim 100$

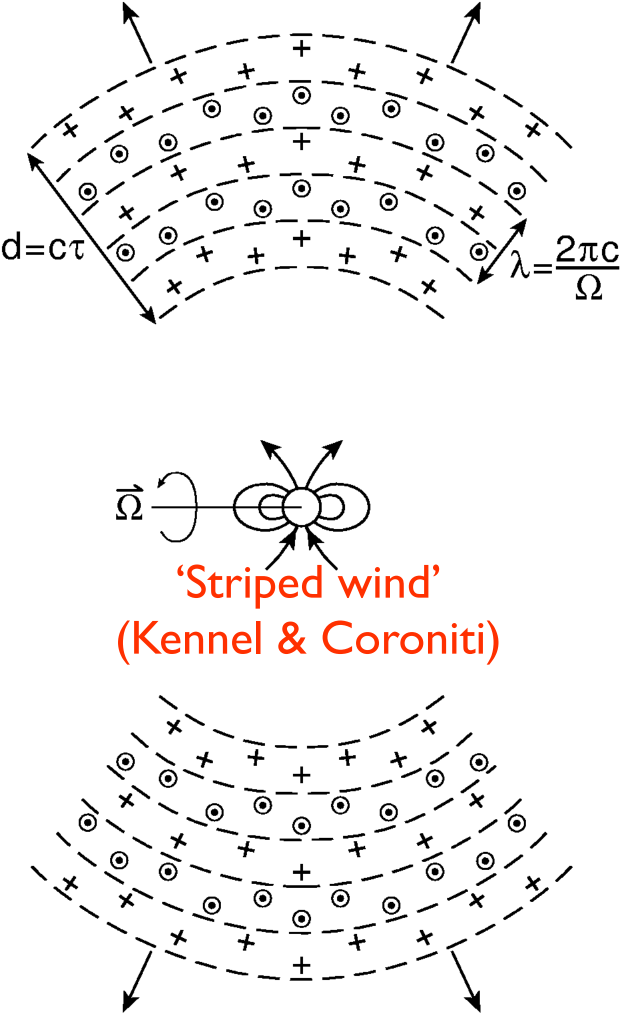
relativistic field strength
- internal dissipation → GRB radiation
- ‘Poynting flux conversion’ →acceleration

'AC' outflow

Nonaxisymmetric rotator



(top view)



'Striped wind'
(Kennel & Coroniti)

(side view)

Reconnection in an AC flow

prime: for quantities
in comoving frame

- Wavelength of striped wind (in lab frame)

$$\lambda \sim 2\pi v/\Omega \sim 2\pi r_{\rm L} \qquad \lambda' = \Gamma\lambda$$

Lyubarski 2005

- Reconnection speed (comoving frame) $v'_{\rm rec} \sim \epsilon v'_{\rm A} \sim \epsilon c$ (ϵ = 0.1?)
- Reconnection time (comoving fame) $\tau' = \lambda'/v' \sim \dfrac{\Gamma}{\epsilon\Omega}$
- Reconnection time (in lab frame) $\tau = \Gamma\tau'$ (time dilatation)

$$\tau_{\rm rec} \sim \frac{\Gamma^2}{\epsilon\Omega}$$

- → dissipation at `interesting' distances (photosphere, 10^{11} cm)
  (near photosphere for $\Gamma = 100$ *)*

Flow acceleration by dissipation

plane flow: $v(x), \quad B^2(x)$

dissipation: $\partial_x B^2(x) < 0$

→ pressure gradient accelerates in flow direction

faster dissipation → steeper gradient

hydro: Bernoulli: $\frac{1}{2}v^2 + w = E\,, \;\; w = p + e$

Poynting flux

$$S = \frac{c}{4\pi} E \times B$$

$$|S| = c(\frac{E^2}{8\pi} + \frac{B^2}{8\pi})$$

in MHD: $E = v \times B/c\,,\quad S = v_\perp \frac{B^2}{4\pi}$

magnetic energy flux: $F_{\rm m} = v_\perp \frac{B^2}{8\pi}$

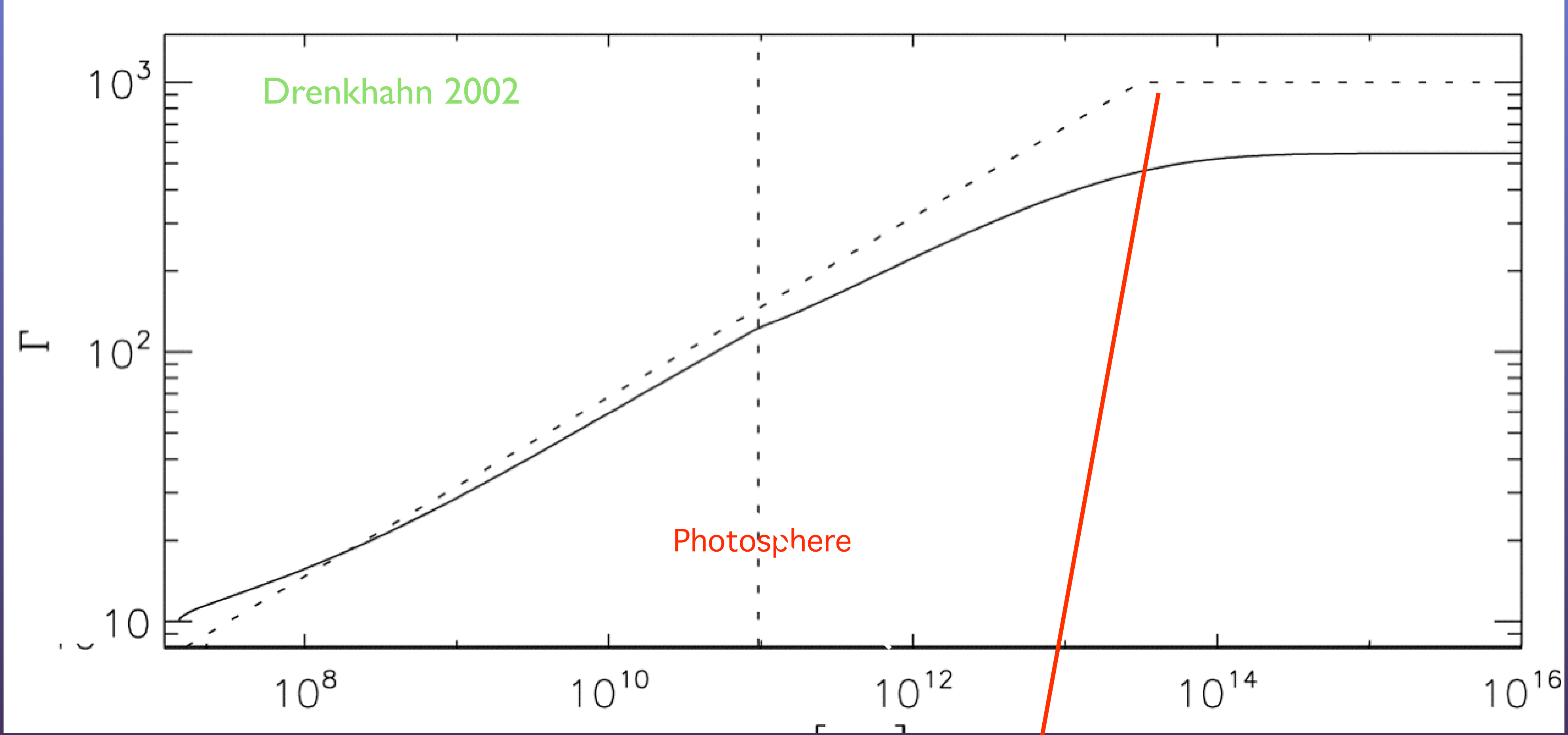
$$S = 2F_{\rm m} = v_\perp w_{\rm m}, \qquad w_{\rm m} = P_{\rm m} + e_{\rm m}$$

Calculations

- radially expanding flow
- relativistic
- dissipation of B^2 ($\epsilon \sim 0.1$) into radiation
- radiation loss in optically thin region

acceleration: $\Gamma \sim r^{1/3}$ Drenkhahn 2002

dependence on baryon loading, ϵ , Ω



$$\left.\begin{array}{ll} \Gamma \sim r^{1/3} & r < r_{\rm s} \\ \Gamma_\infty & r > r_{\rm s} \end{array}\right\}$$

Energy conversion in AC outflow

Optically thick (dissipation inside photosphere):

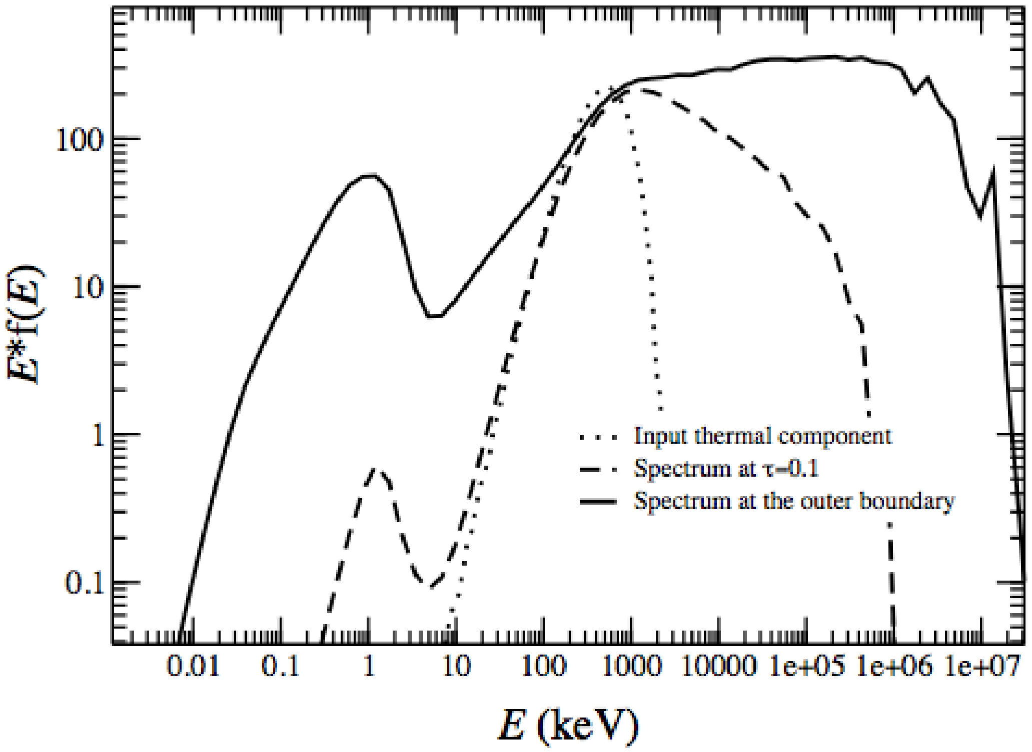
$S \longrightarrow$ radiation $\longrightarrow$ 100% KE

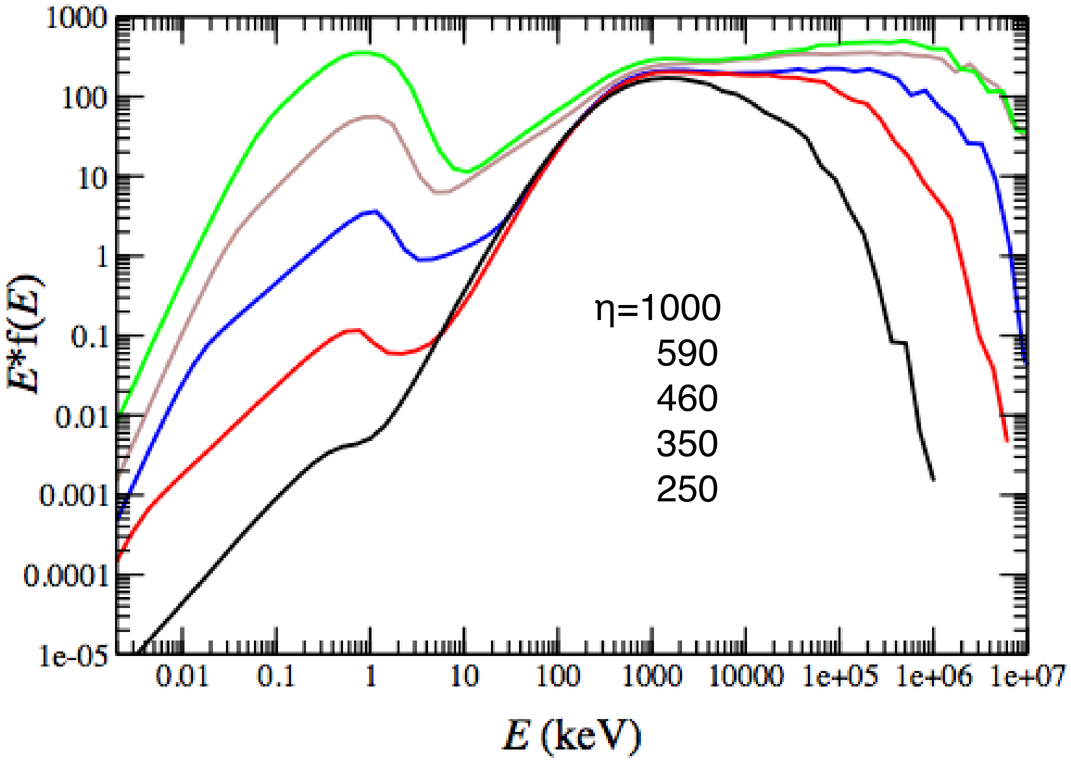
(as classical fireball)

Optically thin (dissipation outside photosphere):

radiation escapes, $S \longrightarrow$ 50% KE, 50% radiation.

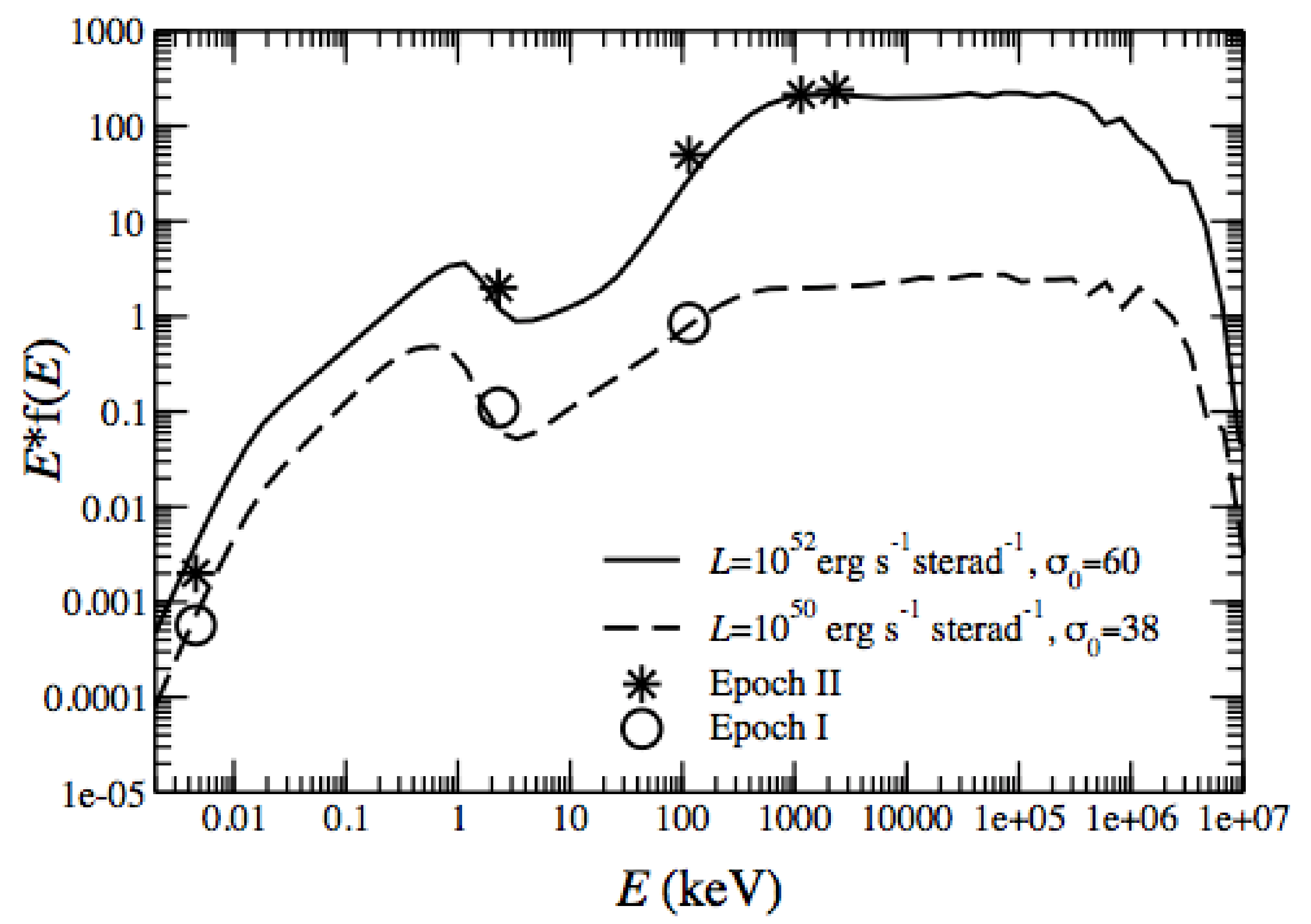
the gamma spectrum from (magnetically) dissipative flow





D. Giannios 2008, A&A 480, 305

prediction: lots of emission up to ~ 1 GeV



D. Giannios 2008, A&A 480, 305

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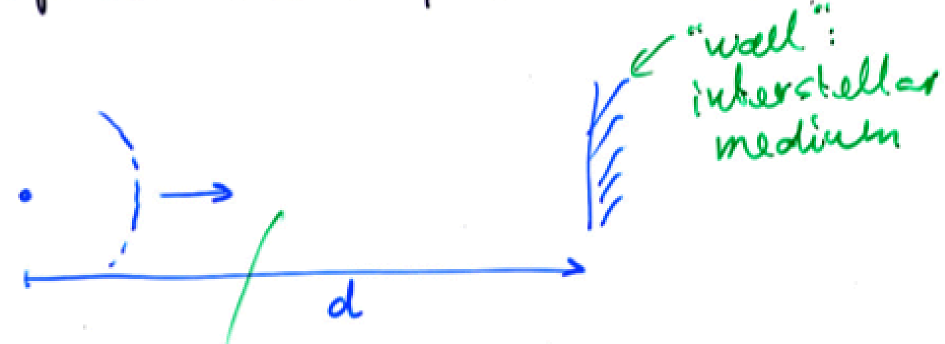
Spares

Special relativity of GRB outflow



Lorentz contraction & time dilatation

$\Gamma \gg 1$: (Bulk Lorentz factor)

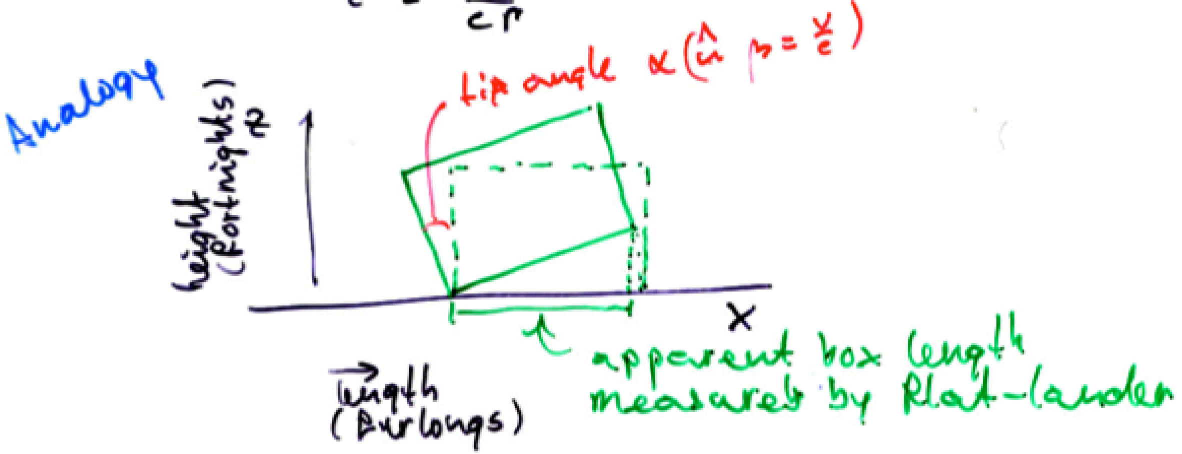
$v \approx c \rightarrow t \approx \frac{d}{c}$

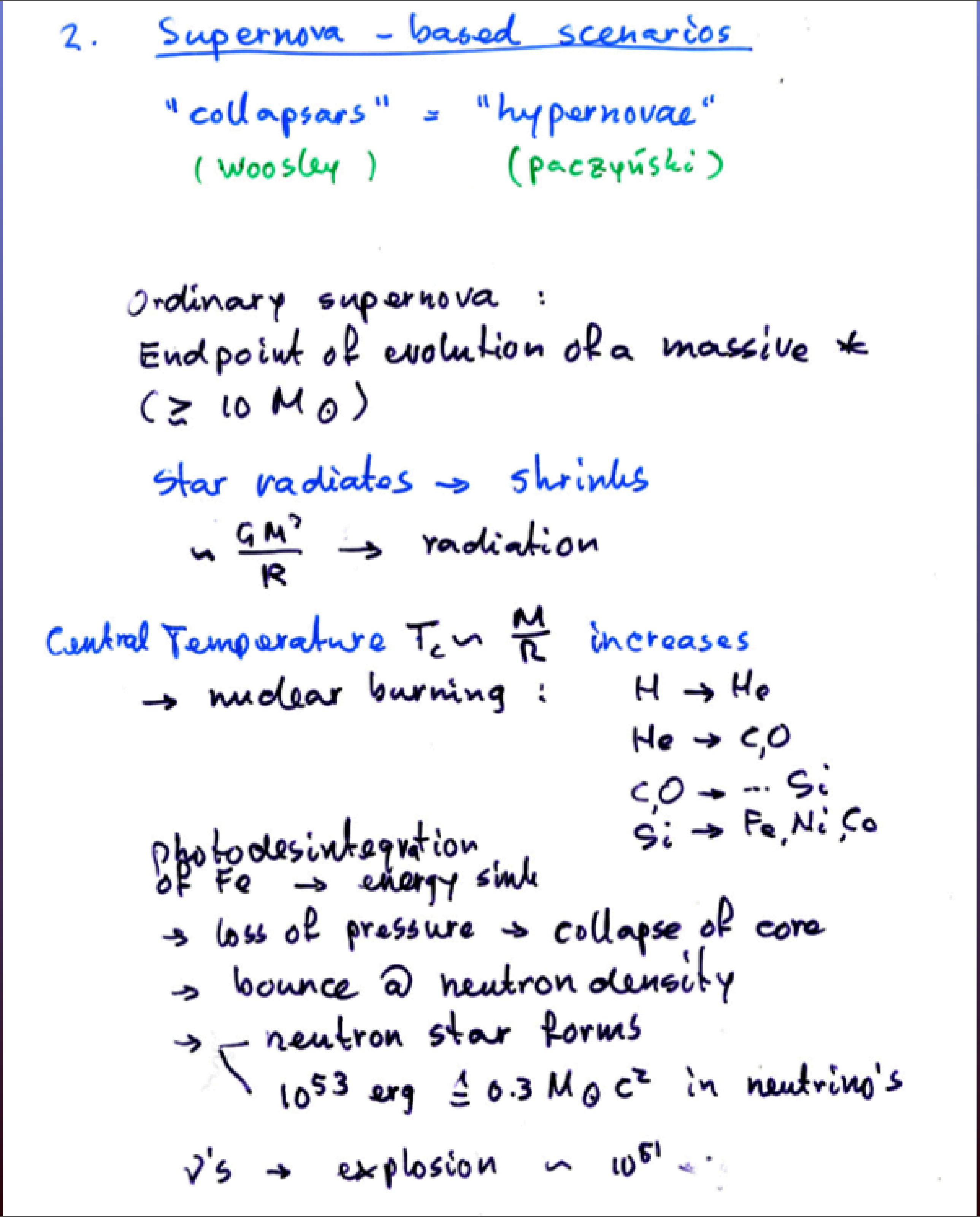
comoving : flow itself sees d contracted:

$$d' = \frac{d}{\Gamma} = \left(1 - \frac{v^2}{c^2}\right)^{1/2} d \ll d$$

Equivalent : time dilatation :
Clock moving w. flow is seen by a Laboratory observer as slow:

$$t' = \frac{d}{c\Gamma}$$





2. Supernova - based scenarios

"collapsars" = "hypernovae"
(woosley) (paczyński)

Ordinary supernova :
Endpoint of evolution of a massive ★
($\gtrsim 10\,M_\odot$)

Star radiates → shrinks

$\sim \frac{GM^2}{R}$ → radiation

Central Temperature $T_c \sim \frac{M}{R}$ increases

→ nuclear burning :

H → He
He → C,O
C,O → ... Si
Si → Fe, Ni, Co

photodesintegration of Fe → energy sink

→ loss of pressure → collapse of core

→ bounce @ neutron density

→ neutron star forms

10^{53} erg $\triangleq 0.3\,M_\odot c^2$ in neutrino's

ν's → explosion $\sim 10^{51}$

Will pair-annihilation be observed?

(no).

Look at photospheric temperature

Adiabatic expansion of radiation dominated ball:

$$\gamma = \frac{4}{3}$$

$$\rightarrow P_{rad} \sim \left(\frac{1}{V}\right)^{4/3} \sim \rho^{4/3}$$

$$\rightarrow \underbrace{n.a}_{\substack{O(1)\\ \text{pairs!}}} T^4 \sim \rho^{4/3} \sim r^{-4}$$

$$\rightarrow \underline{T \sim r^{-1}}$$

Initial temp $T_0 = 10^{11}$ (10 MeV)

initial radius $r = 10^7$ cm (BH)

photosphere $r = 10^{11}$

$$\rightarrow T_{phot} \cancel{\simeq} T_0 \frac{r_0}{r_{phot}} = 10^{-4}\, 10^{11} = 10^7$$

$$\lesssim 1 \text{ keV}$$

$$\ll m_e c^2$$

Observed thermal radiation:

$$\varepsilon_{phot} = \Gamma\, \varepsilon'_{phot} \sim 100 \text{ keV}$$