ガンマ線バーストからの高エネルギー粒子

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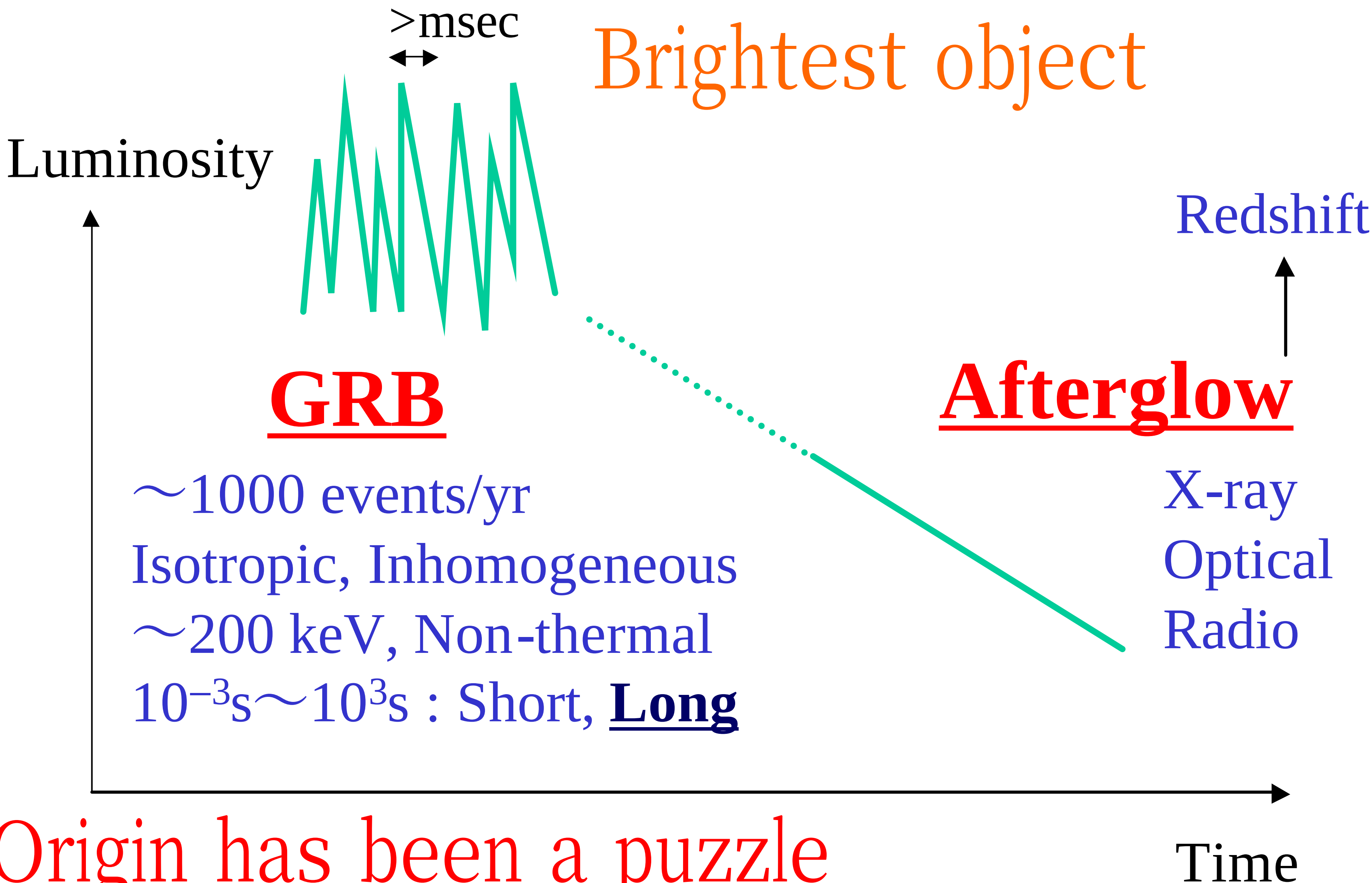
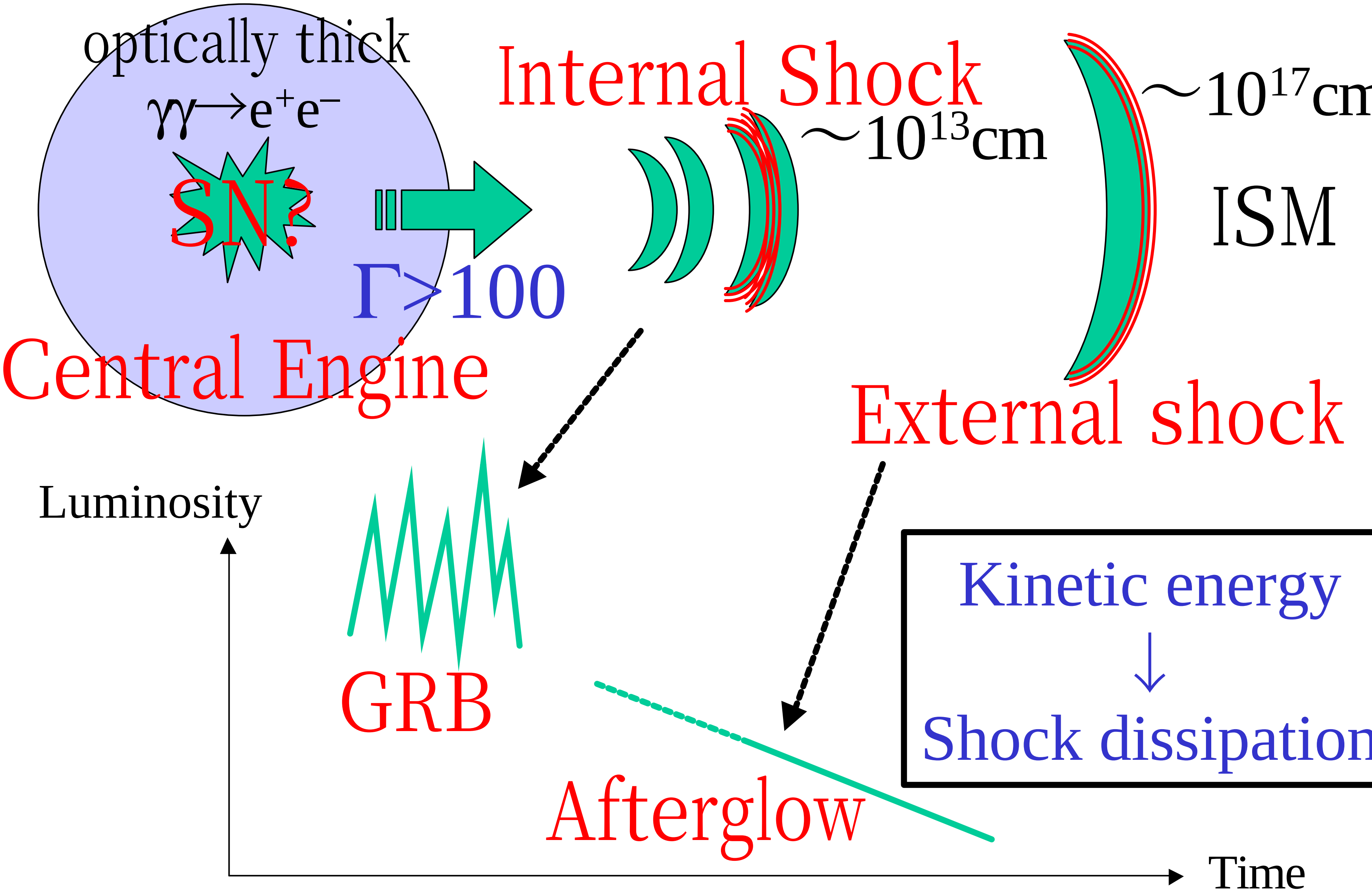
1. **Standard picture**
2. **Recent progress**
3. **UHECR, HEn, HEg, GW**
4. **Summary**

Summary of Observation

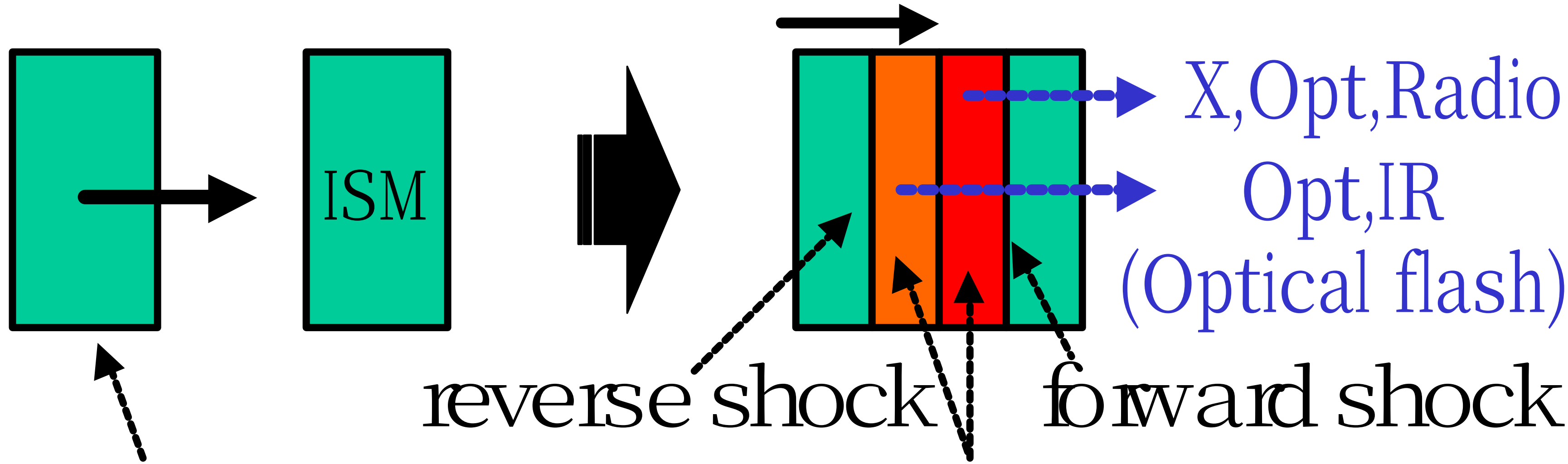


Origin has been a puzzle

Standard Model



Afterglow Model



Kinetic energy → Internal energy U_{int}

① Electron Fermi acceleration

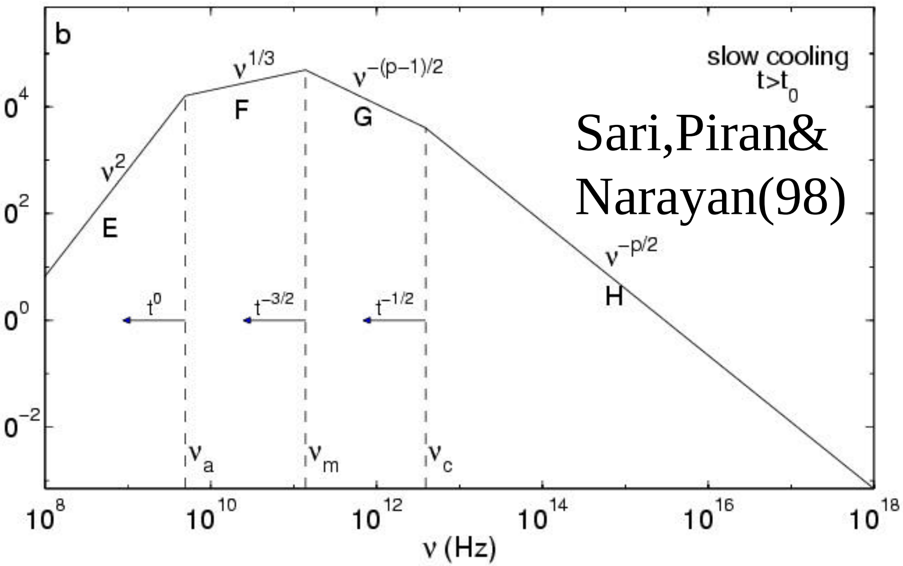
$$e_e = U_e / U_{\text{int}} \Box O(1), \quad N(g_e) \propto g_e^{-2} \; (g_e > 10^3 g)$$

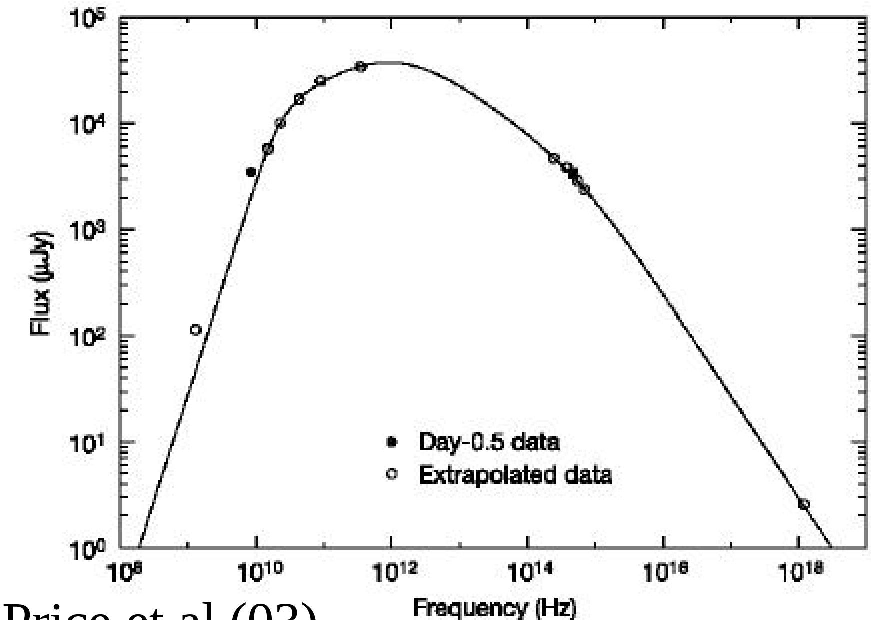
② Magnetic field $e_B = U_B / U_{\text{int}} \Box O(1)$

⇒ Synchrotron emission

Great Success of Model

Synchrotron shock model





Price et al.(03)

$$\{E,\ n,\ \varepsilon_e,\ \varepsilon_B\}$$

$$\Downarrow$$

$$\{\nu_c,\ \nu_m,\ \nu_a,\ F_{\nu,\max}\}$$

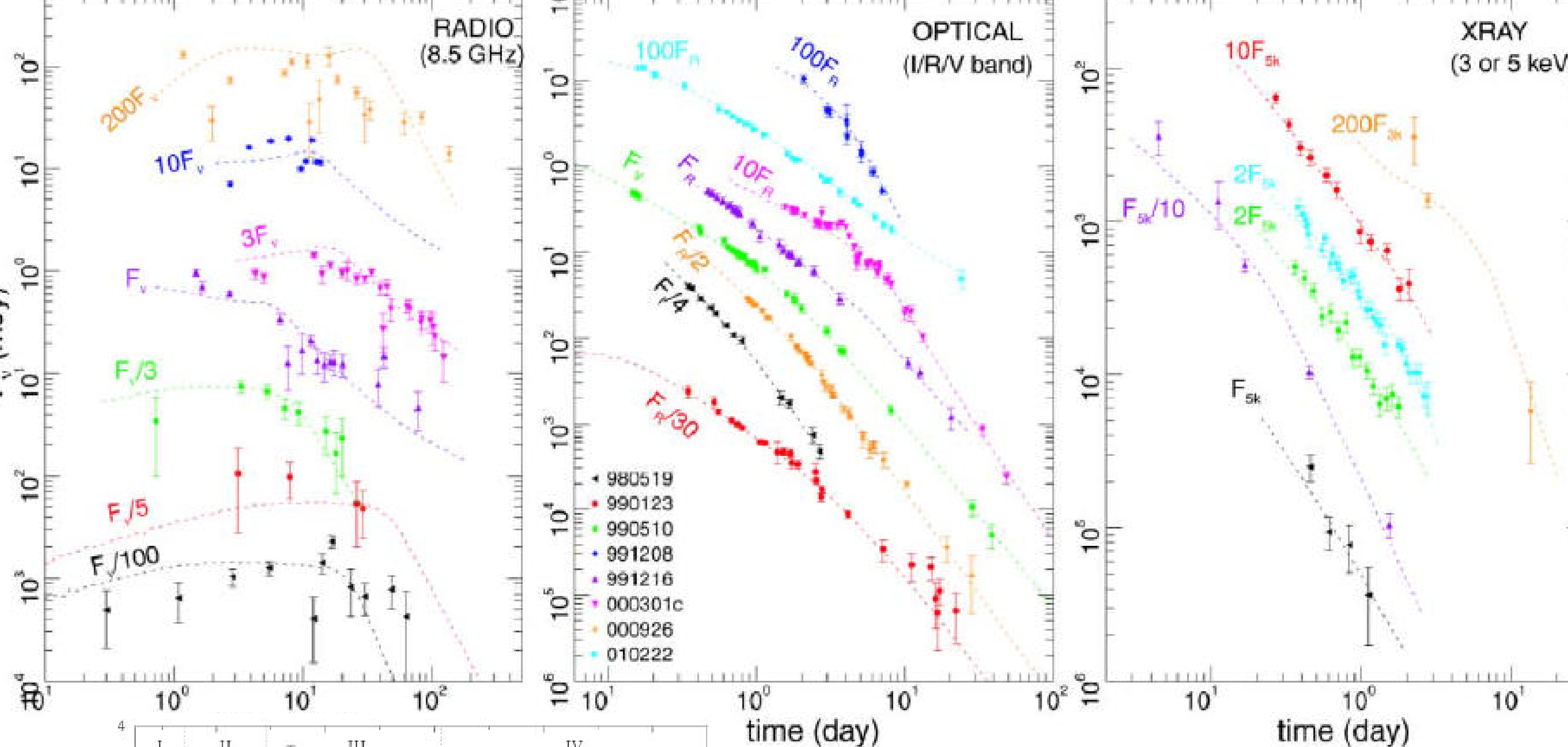
as functions of time

Fitting: $E \sim 10^{51\text{-}54}$ erg

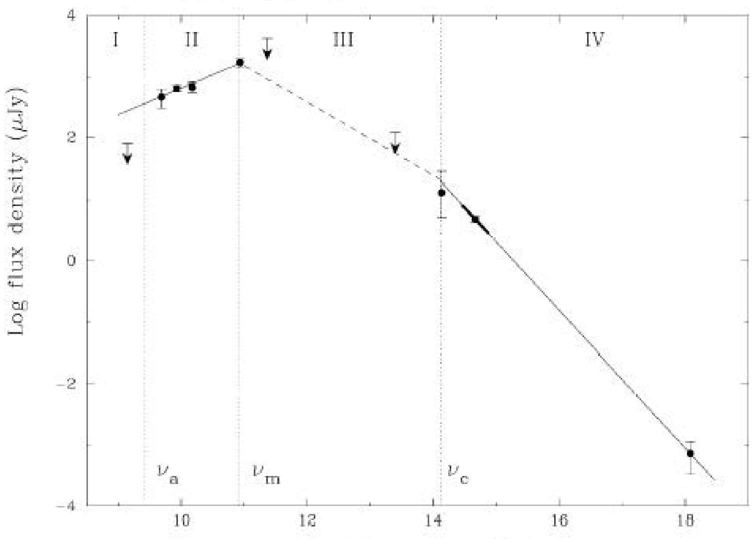
$n \sim 0.01-100\mathrm{cm}^{-3}$

$\varepsilon_e \sim 0.1$

$\varepsilon_B \sim 0.01$



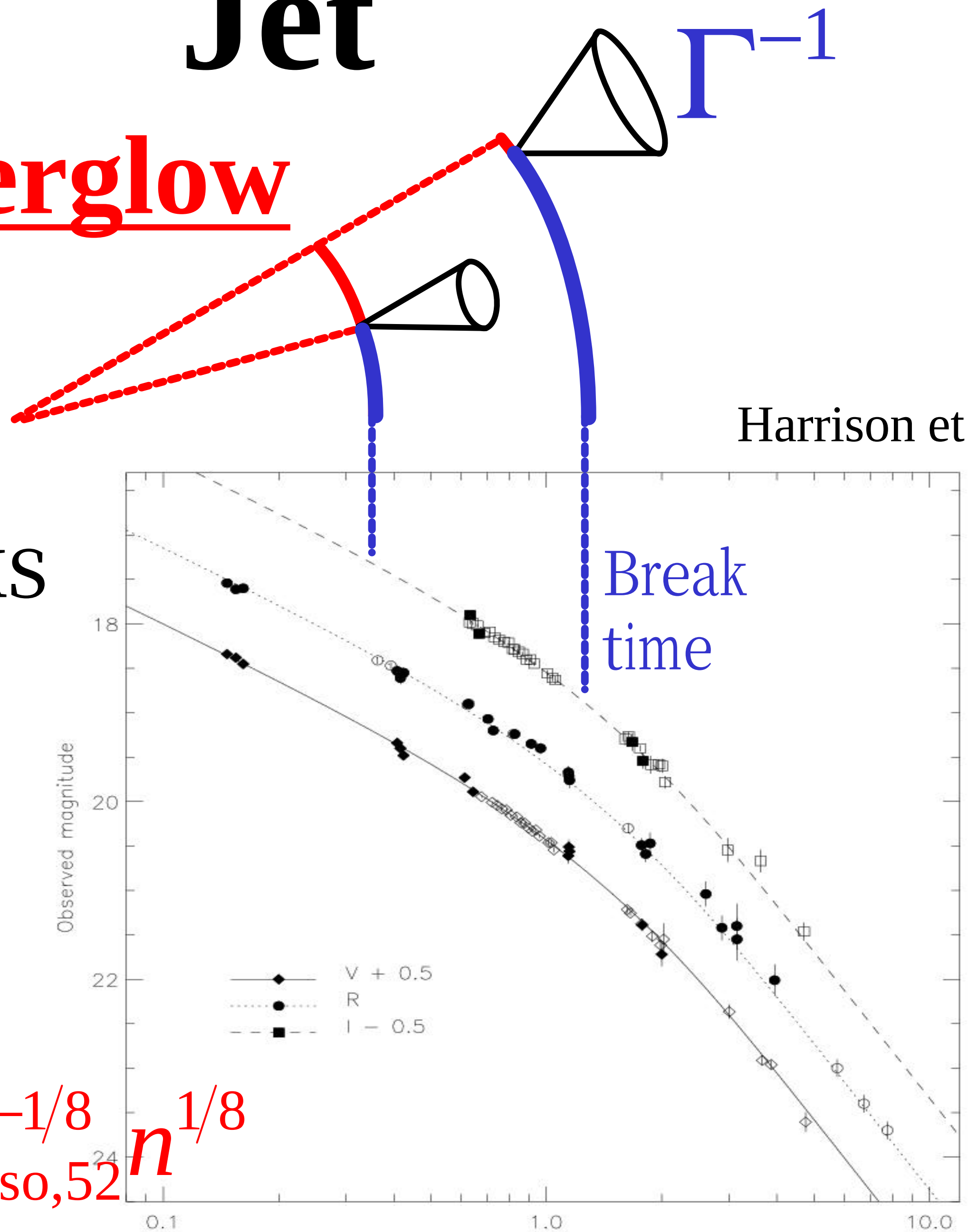
Panaitescu&Kumar(00)



Galama et al.(98)

Jet

Break in afterglow

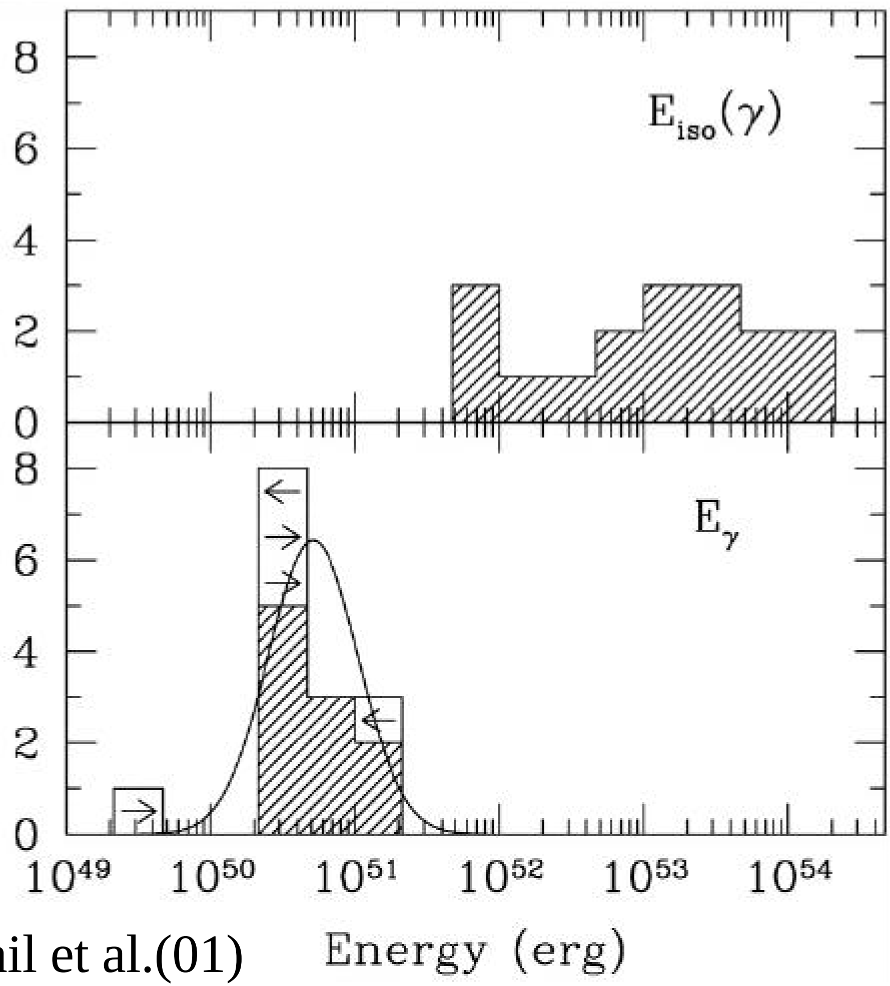


Afterglow breaks at $\theta \sim \Gamma^{-1}$

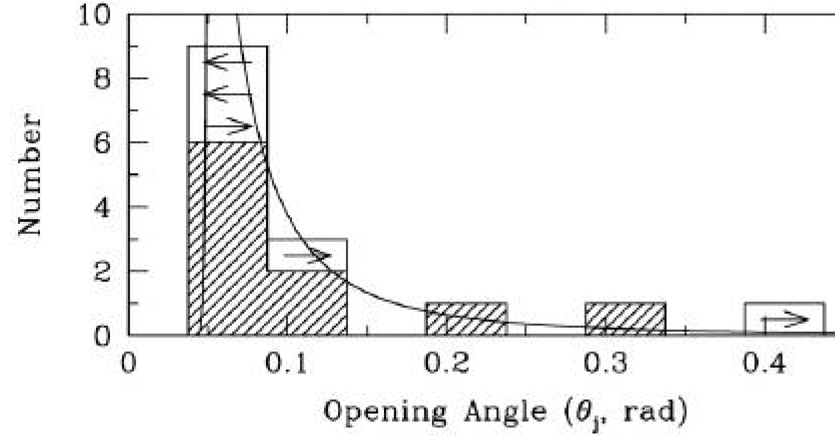
Break time
⇒ Jet angle

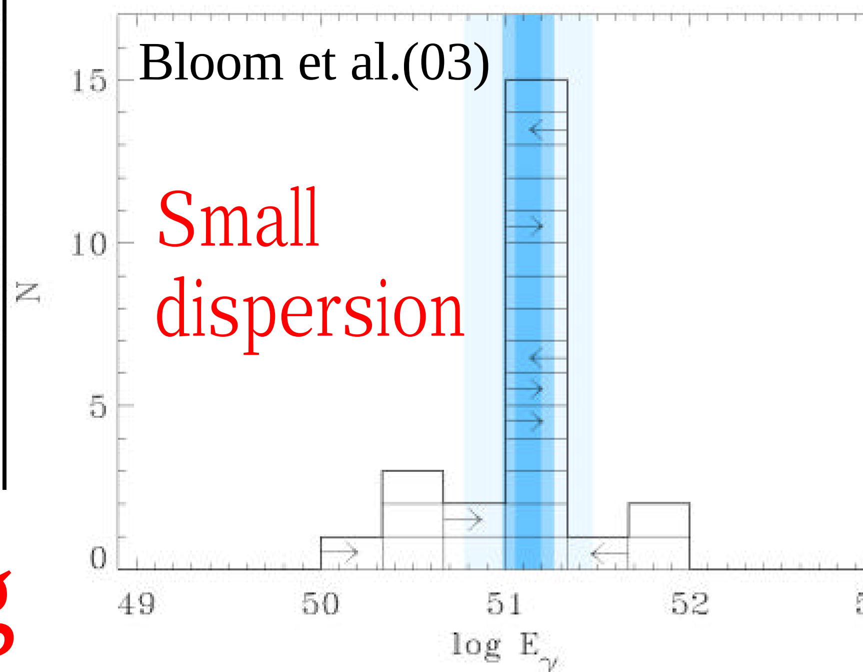
$$q \,\square\, 0.057\, t_{day}^{3/8} E_{iso,52}^{-1/8} n^{1/8}$$

Standard Total Energy



Frail et al.(01)



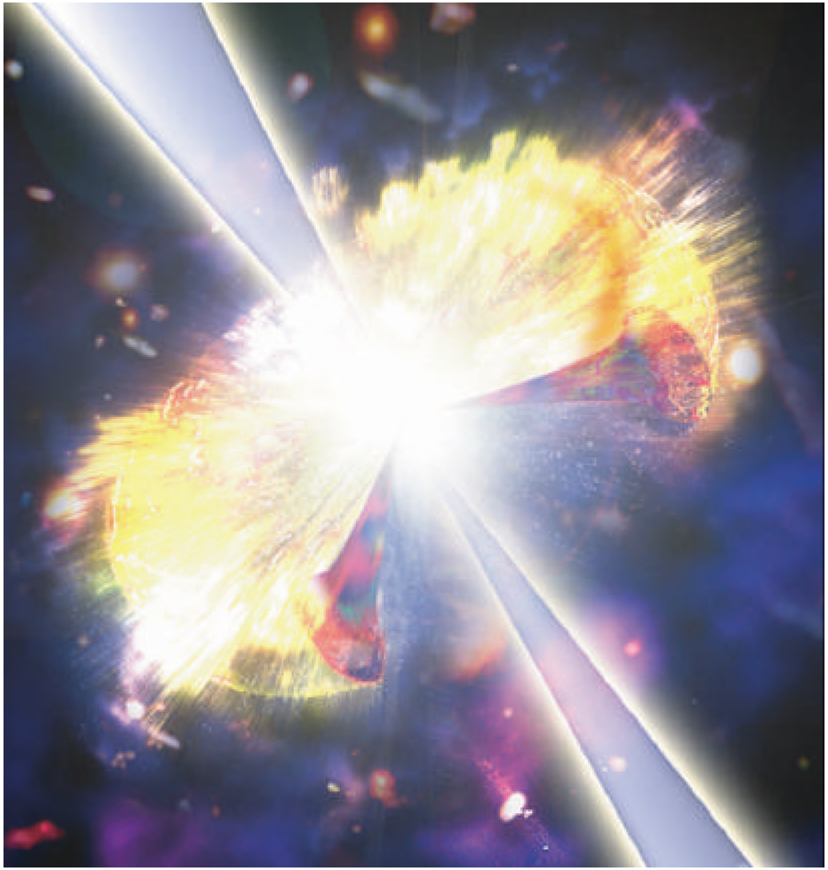


Bloom et al.(03)

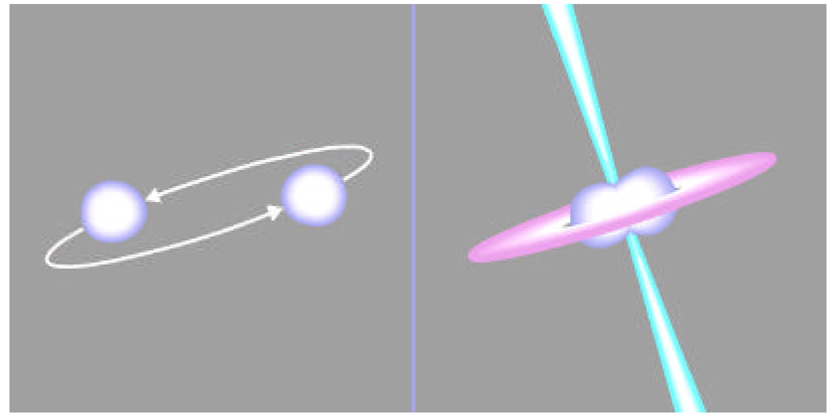
Small dispersion

$$E_\gamma \approx E_{iso}\theta^2 \approx 10^{51}\,\mathrm{erg}$$

Progenitor



Massive stellar collapse
(Hypernova, Collapsar)



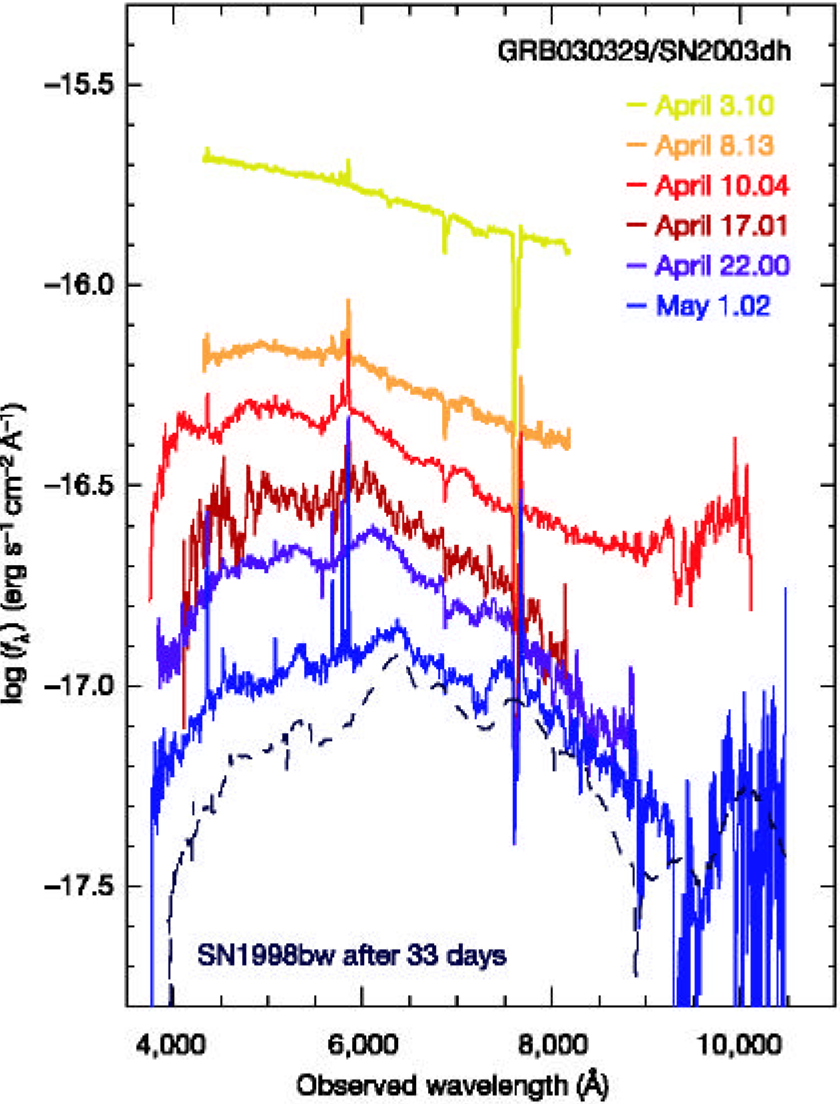
Binary NS merger

$R_{Ibc} \sim 6 \times 10^4$ Gpc^{-3}yr^{-1}

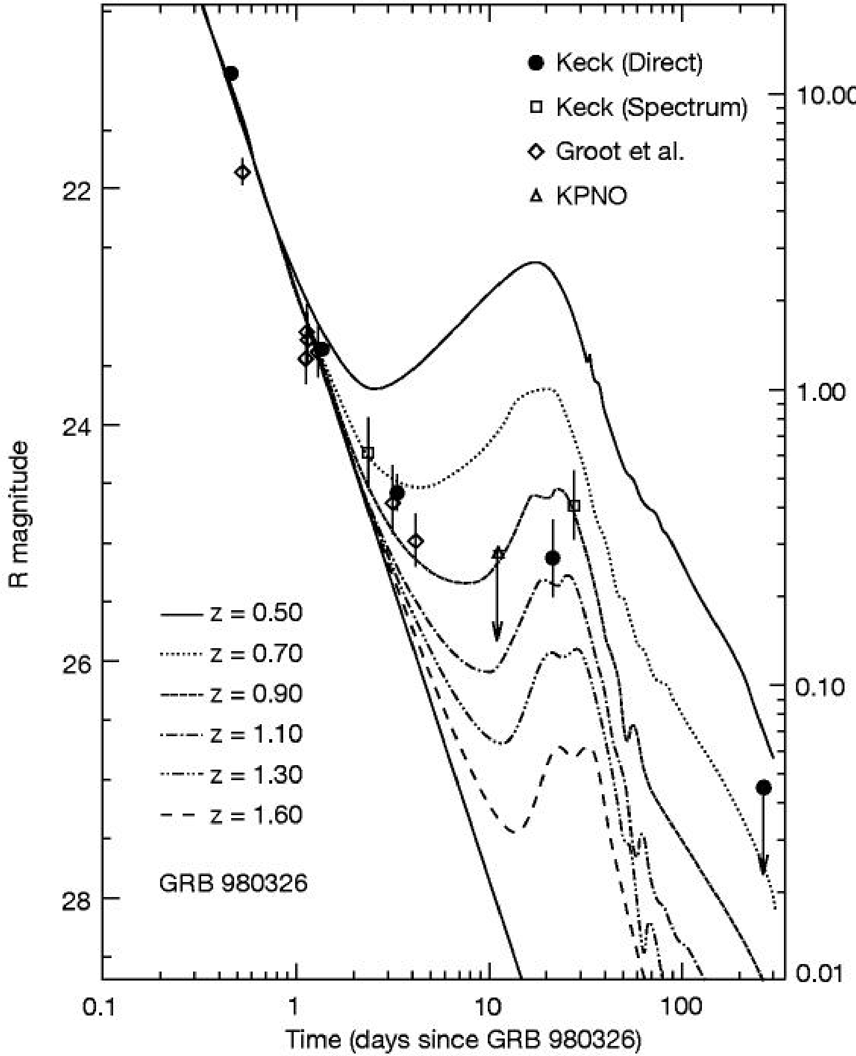
$R_m \sim 80$ Gpc^{-3}yr^{-1}($\times 7$)

$R_{GRB} \sim 0.5(250)$ Gpc^{-3}yr^{-1}

SN in afterglow



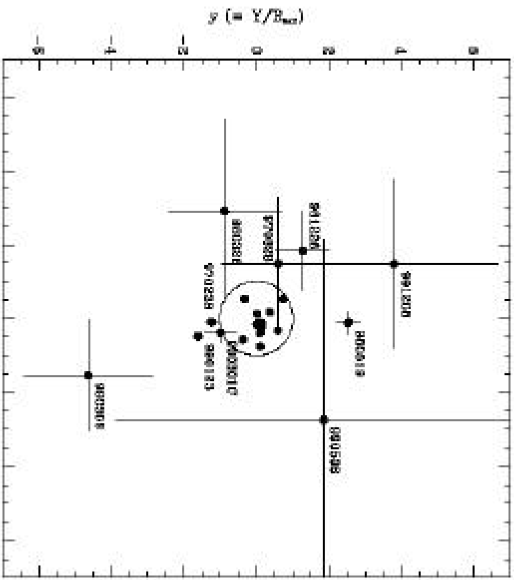
Hjorth et al.(03)

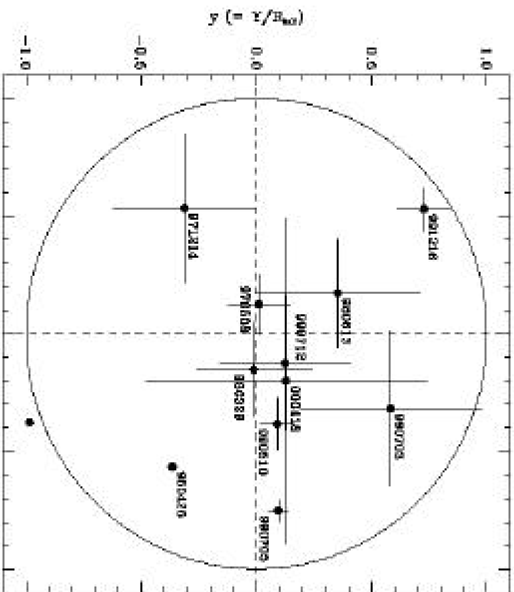


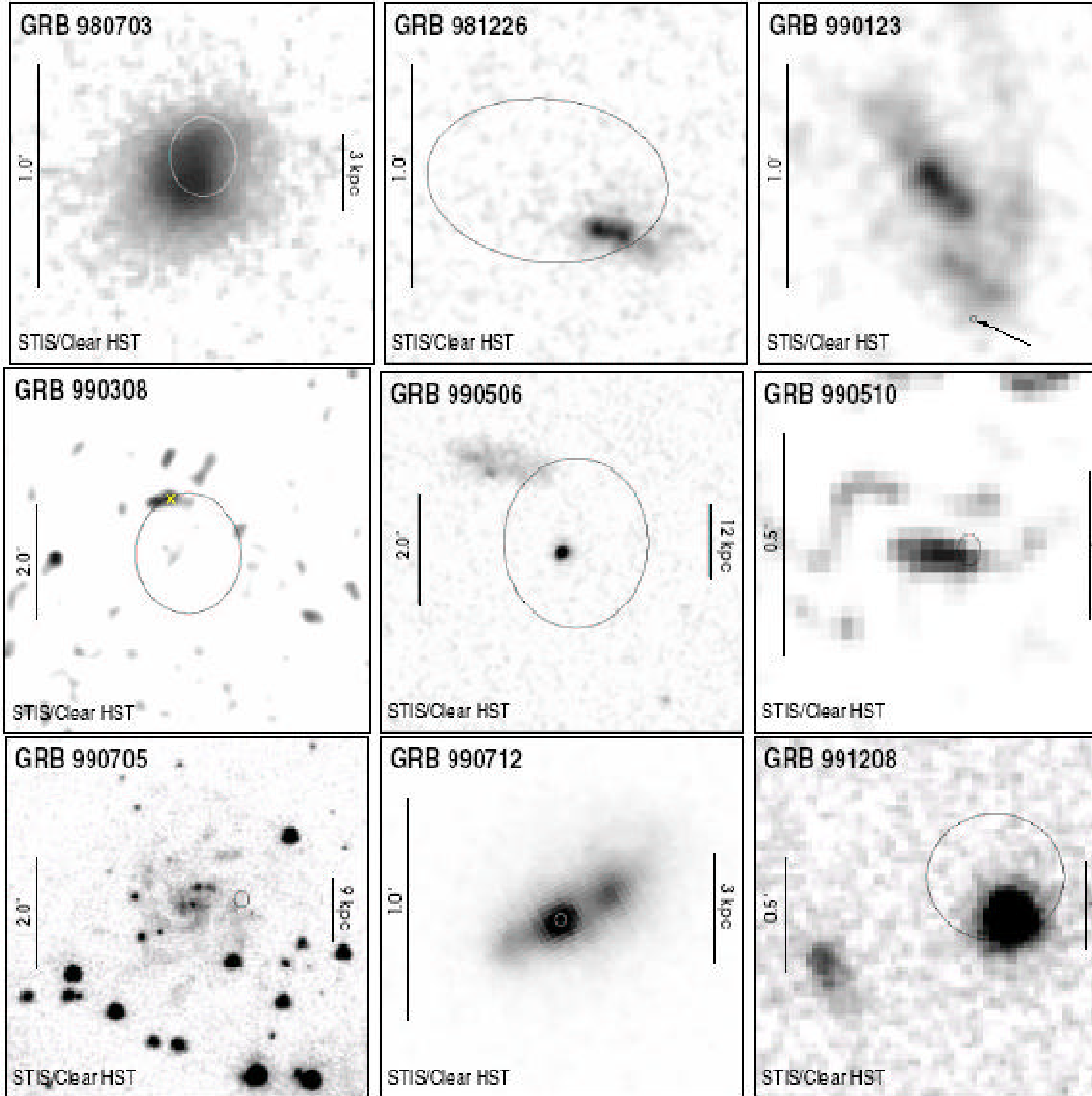
Bloom et al.(99)

Position in host galaxy

Bloom,Kulkarni&Djorgovski(02





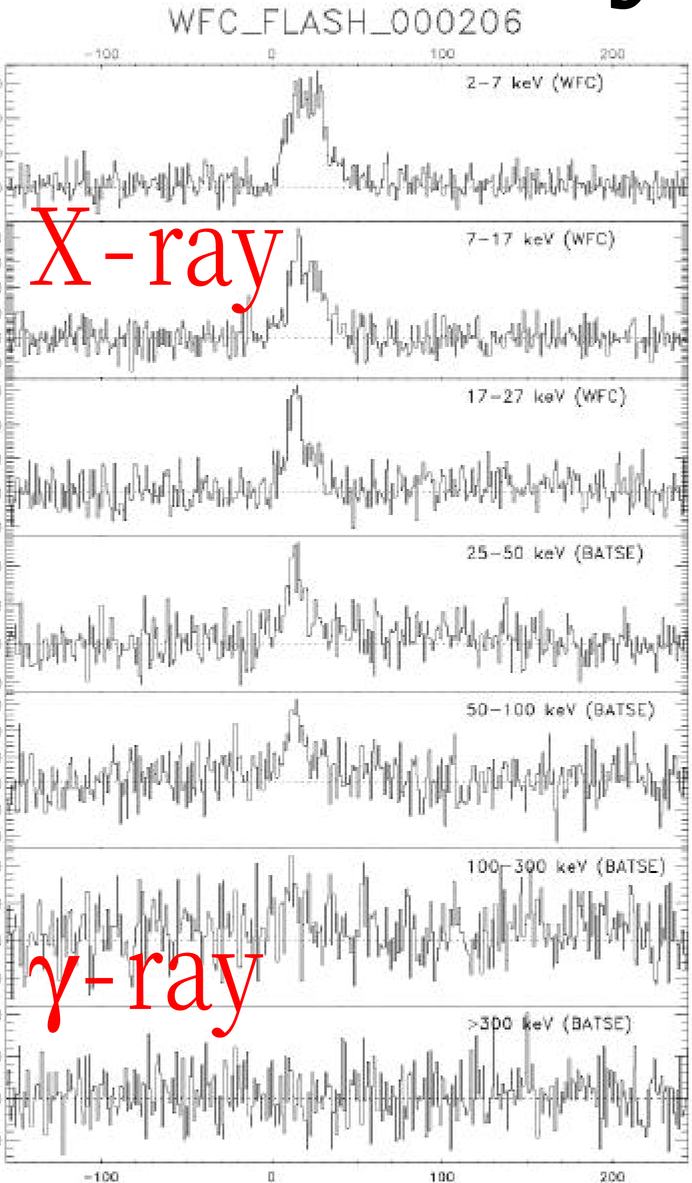


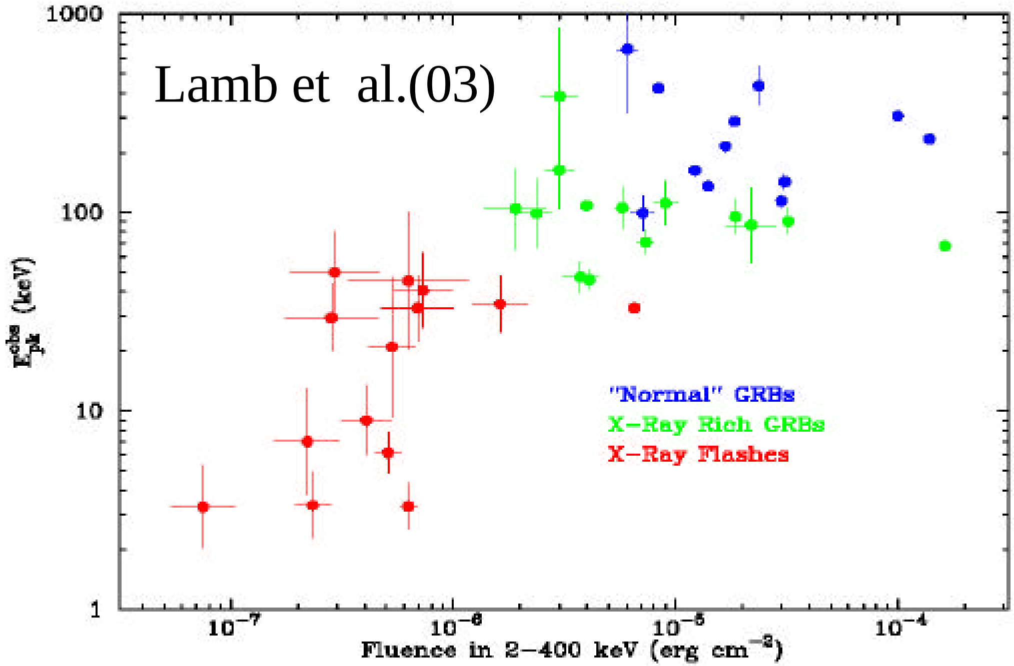
Standard Picture

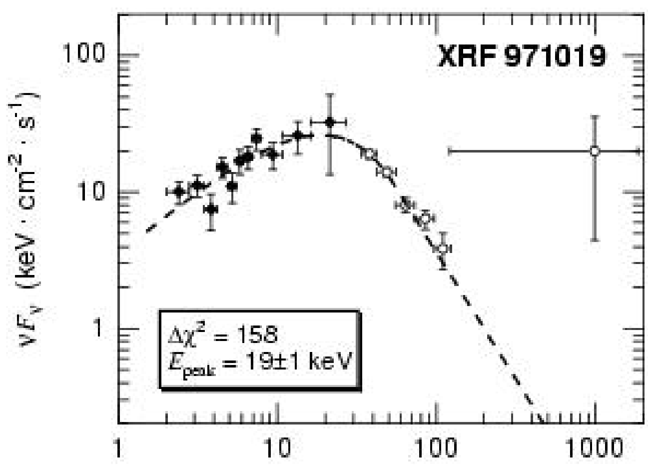
1. Cosmological (Long GRBs)
2. Relativistic jet is ejected: $\Gamma > 100$
3. Internal shock: GRB (?)
4. External shock: Afterglow
5. Synchrotron shock model succeeds
6. Standard total energy (?)
7. Massive star origin (Long GRBs)

But, …

X-Ray Flash (XRF)

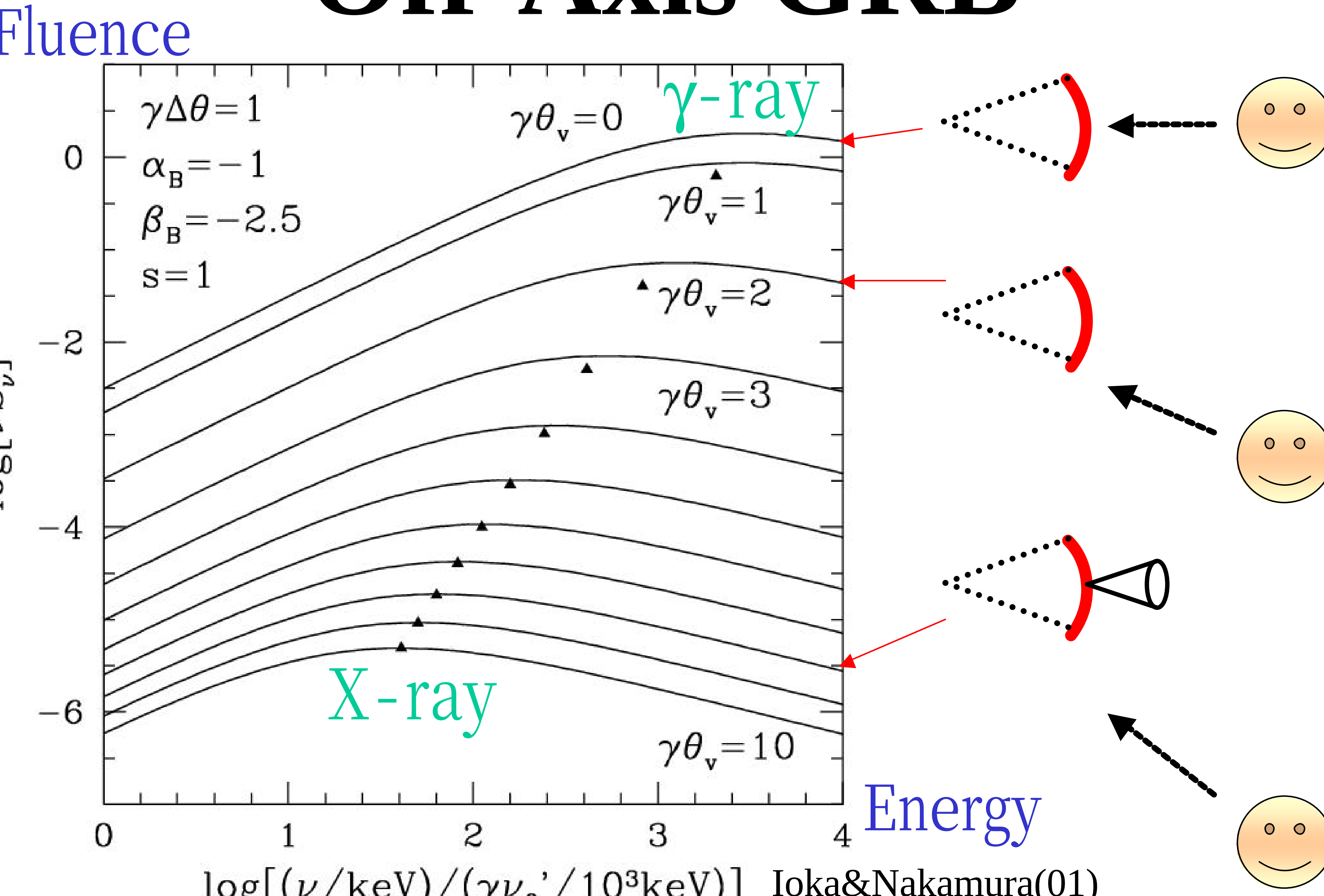






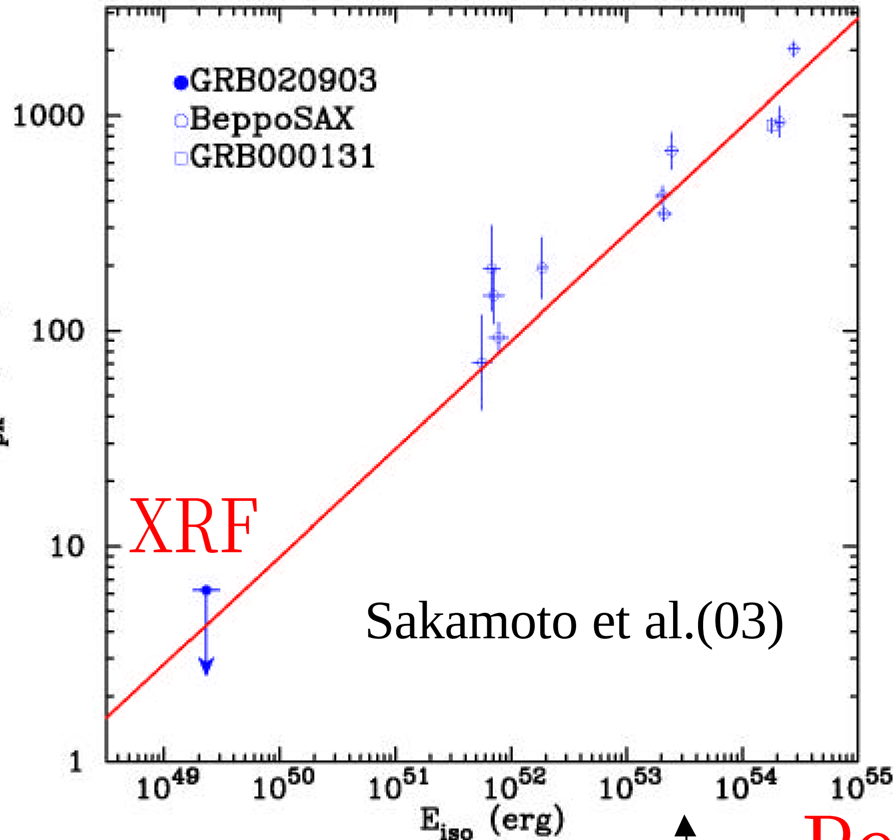
XRF～GRB except for small E_{peak} & fluence

Off-Axis GRB

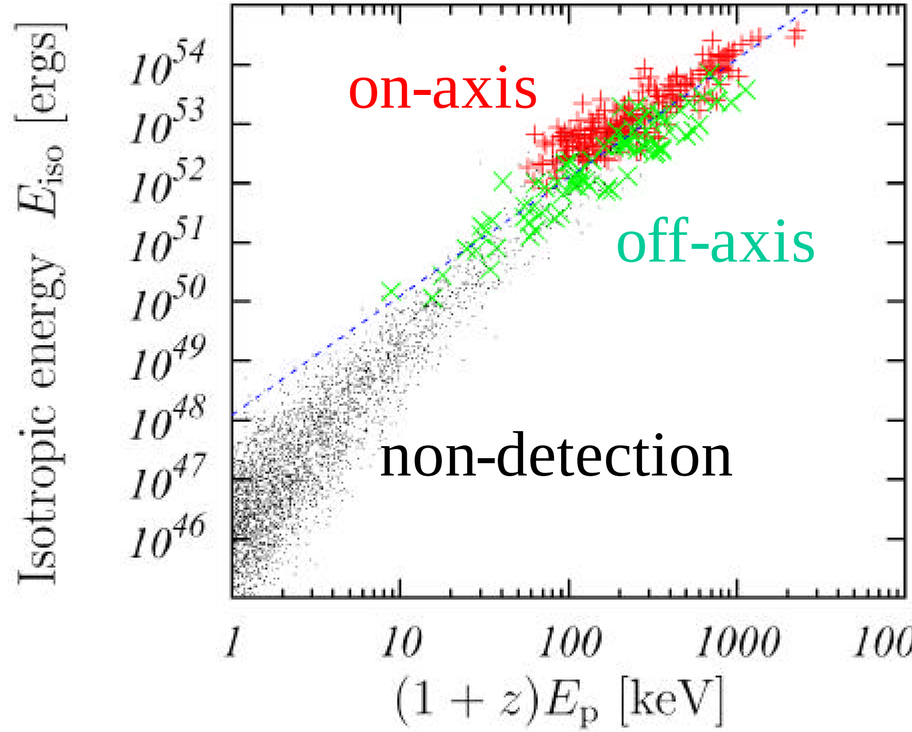


Ioka&Nakamura(01)

E_{iso}-E_{peak} relation

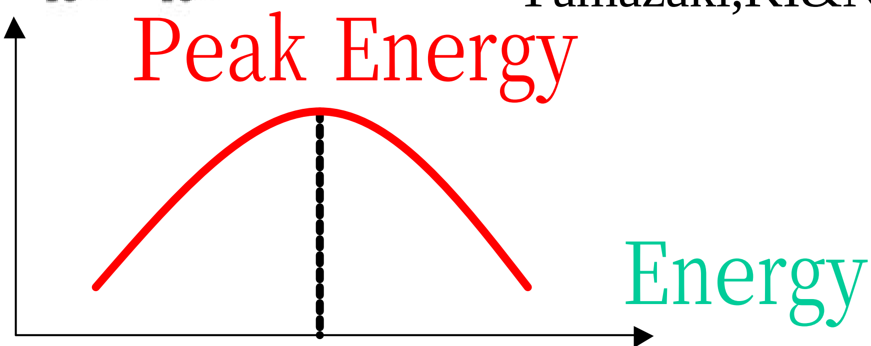


simulation



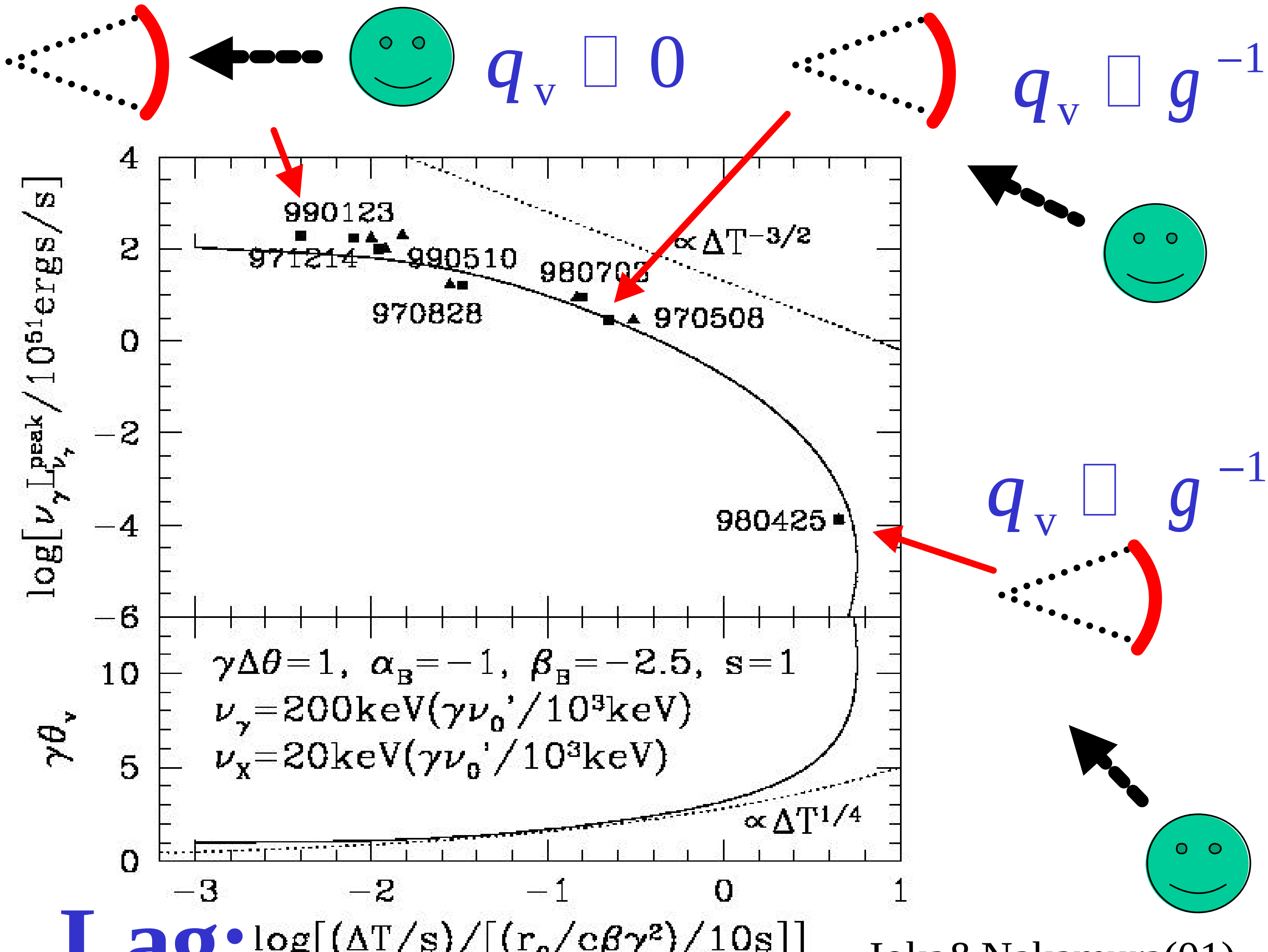
Yamazaki,KI&Nakamura(04)

GRB spectrum



Polarization ?

Lag-Luminosity

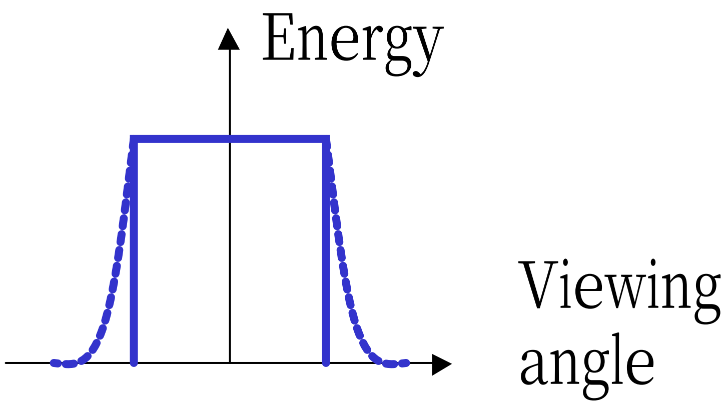


Lag:

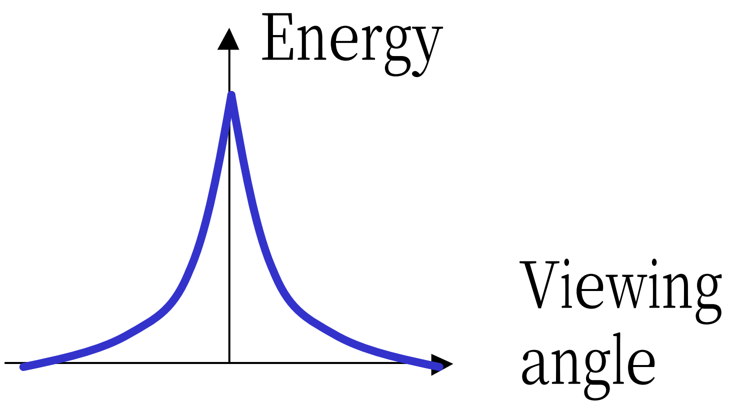
Ioka&Nakamura(01)

Jet Structure

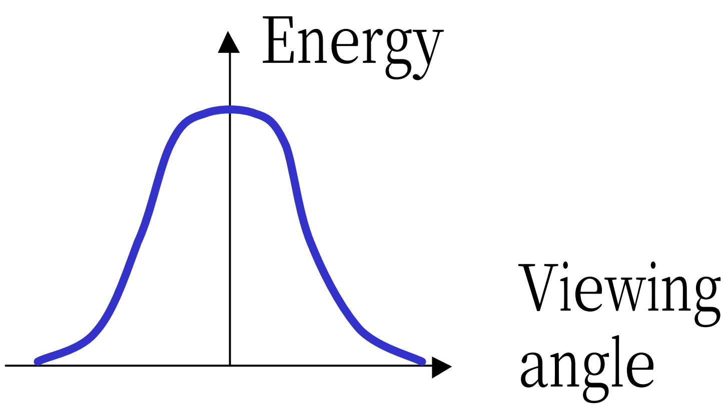
Uniform jet



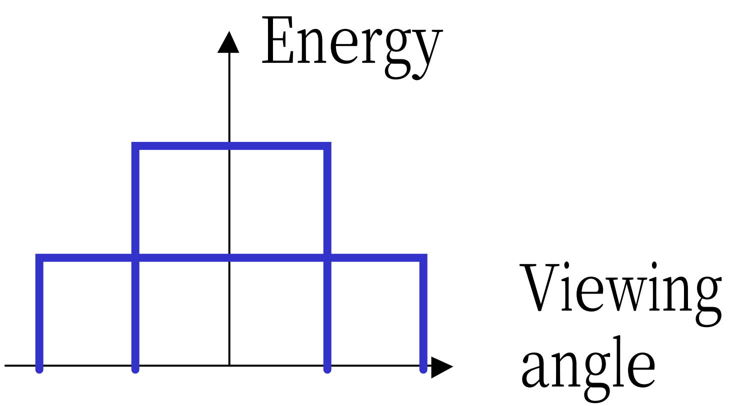
Power law jet



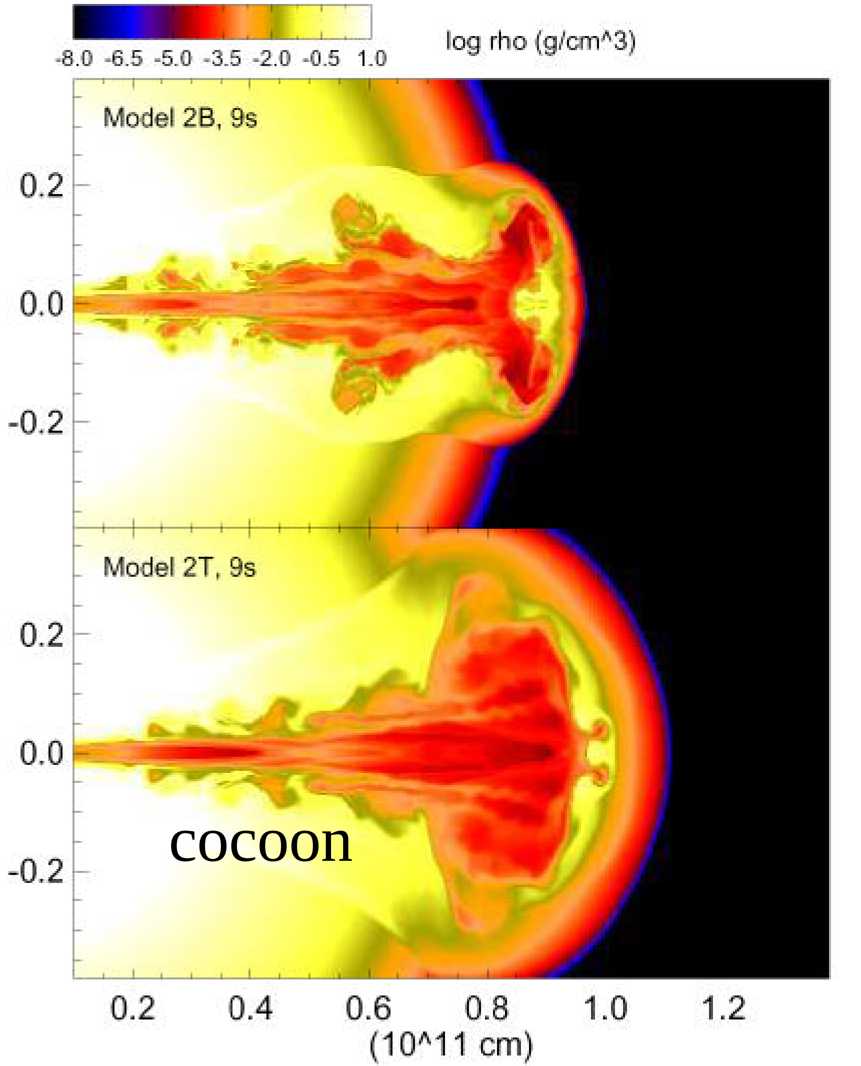
Gaussian jet

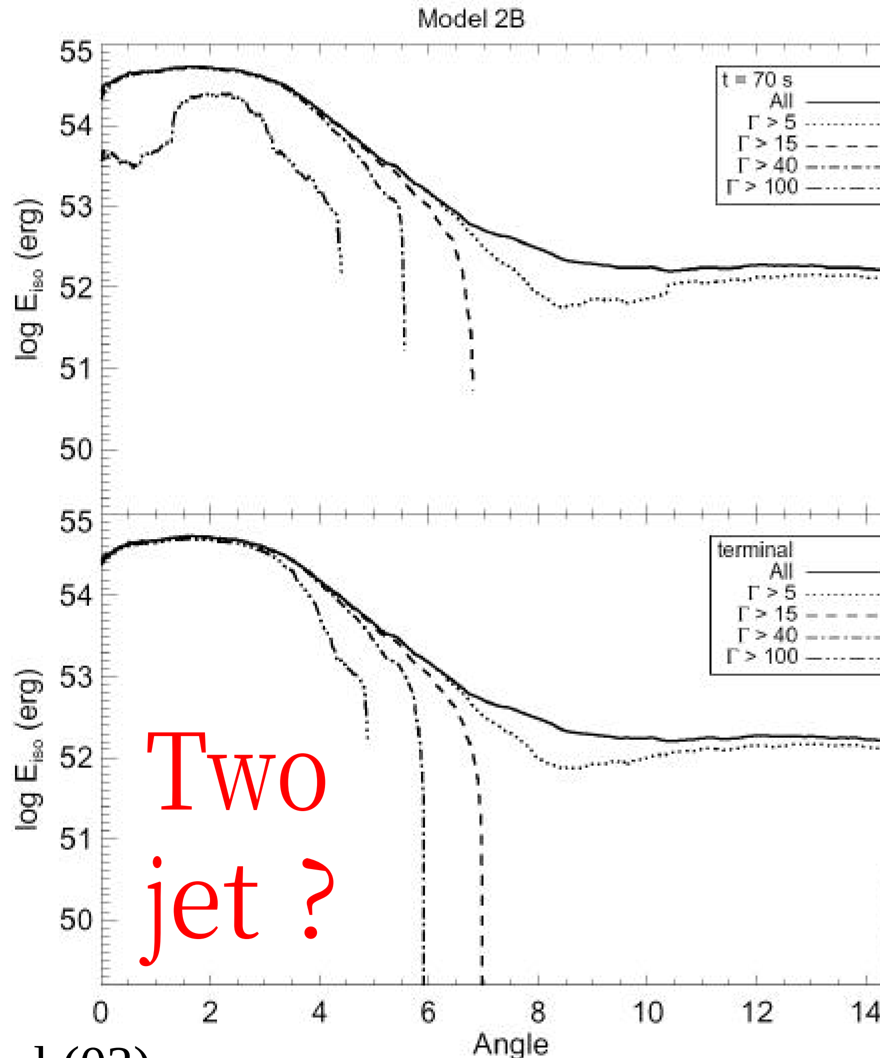


Two jet



Jet Breakout from Star



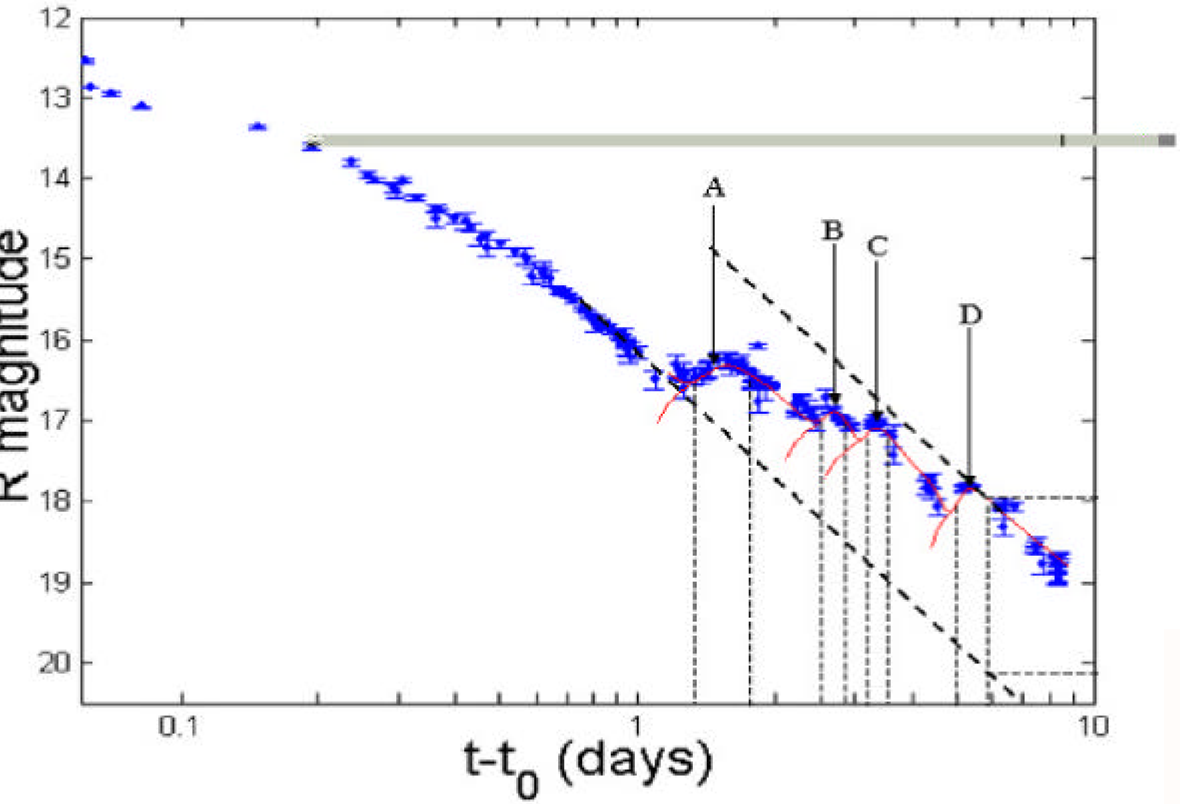


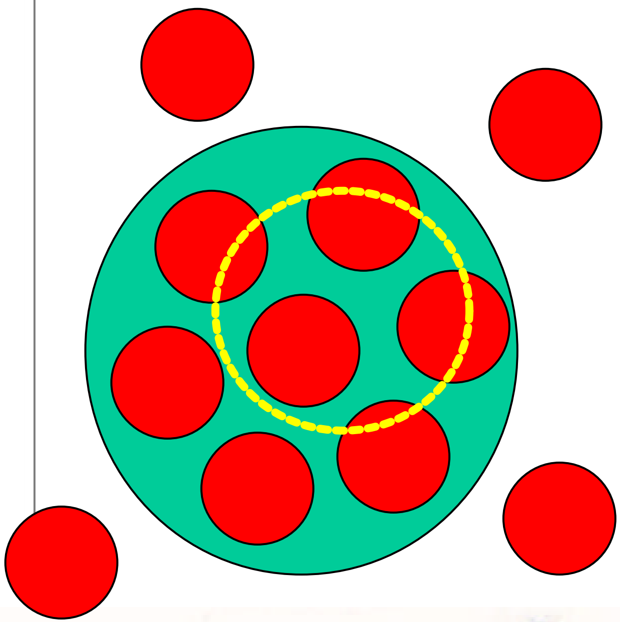
Zhang et al.(03)

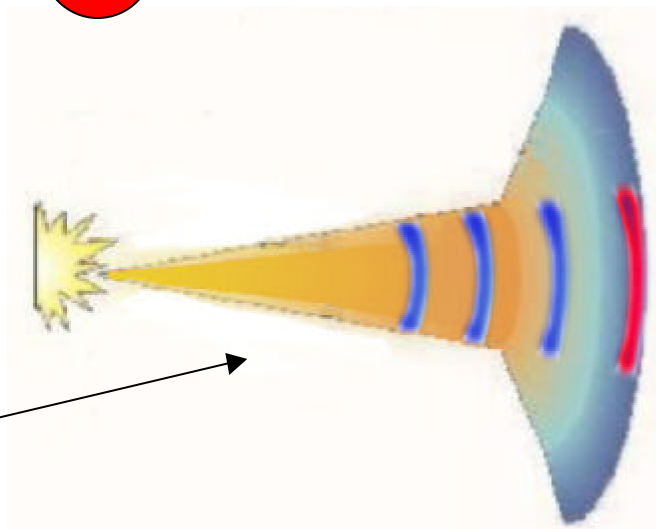
8.— Resolution study in two dimensions. The jets in Models 2B and 2T had identical
ameters, but the calculation was carried out in cylindrical grids having different resolution

Fig. 6.— Equivalent isotropic energy for Model 2B. See also Fig. 5.

Variable Light Curve





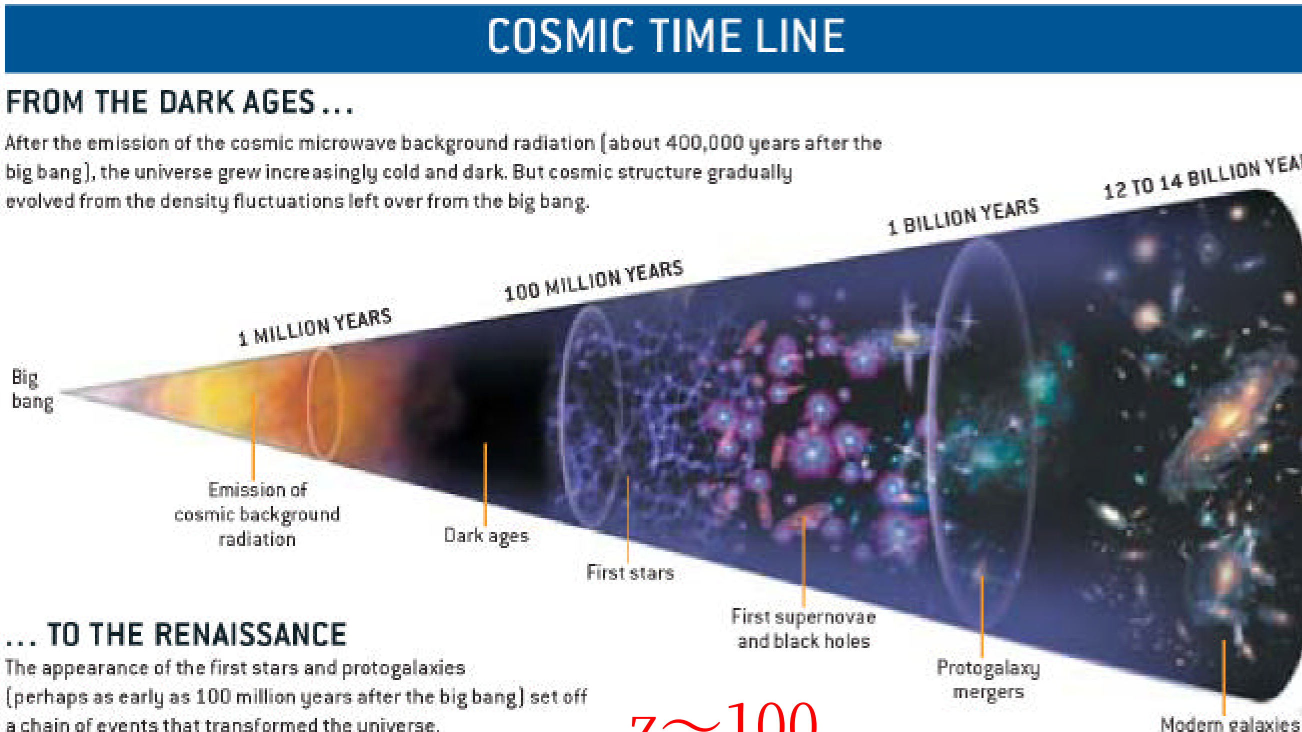


1. Variable external density
2. Patchy shell
3. Refreshed shock

GRB Cosmology

Massive star origin ⇒ High redshift GRBs

Like QSO
Like SN
Star formation
Microlensing
Reionization
…



z∼100

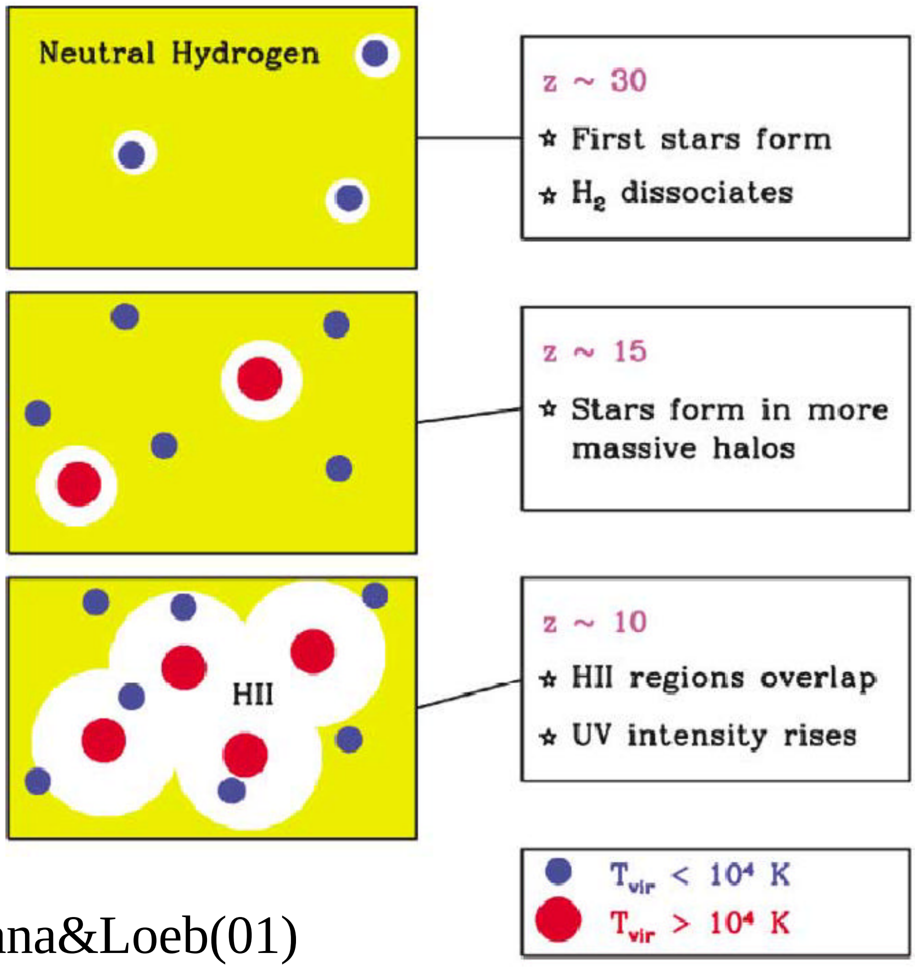
Larson&Bromm(02)

GRB

QSO, galaxy

GRBs are useful for probing high z

Cosmic Reionization



Barkana&Loeb(01)

ig. 4. Stages in the reionization of hydrogen in the intergalactic medium.

When reionized ?

$6<z_{reion}<1000$

$h\nu_{ion}=13.6$ eV

Important for star/galaxy formatio

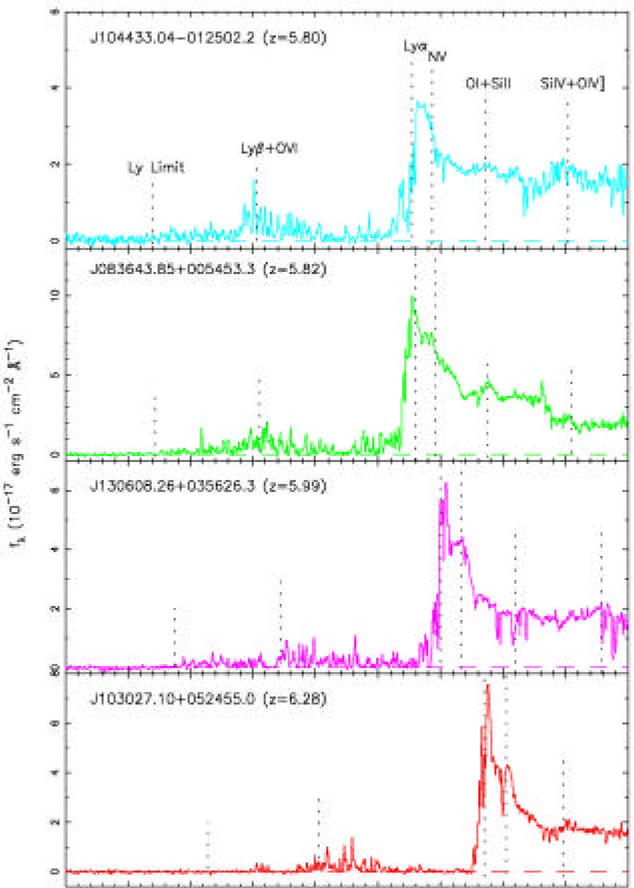
Reionization Redshift

Lyα absorption in QSO

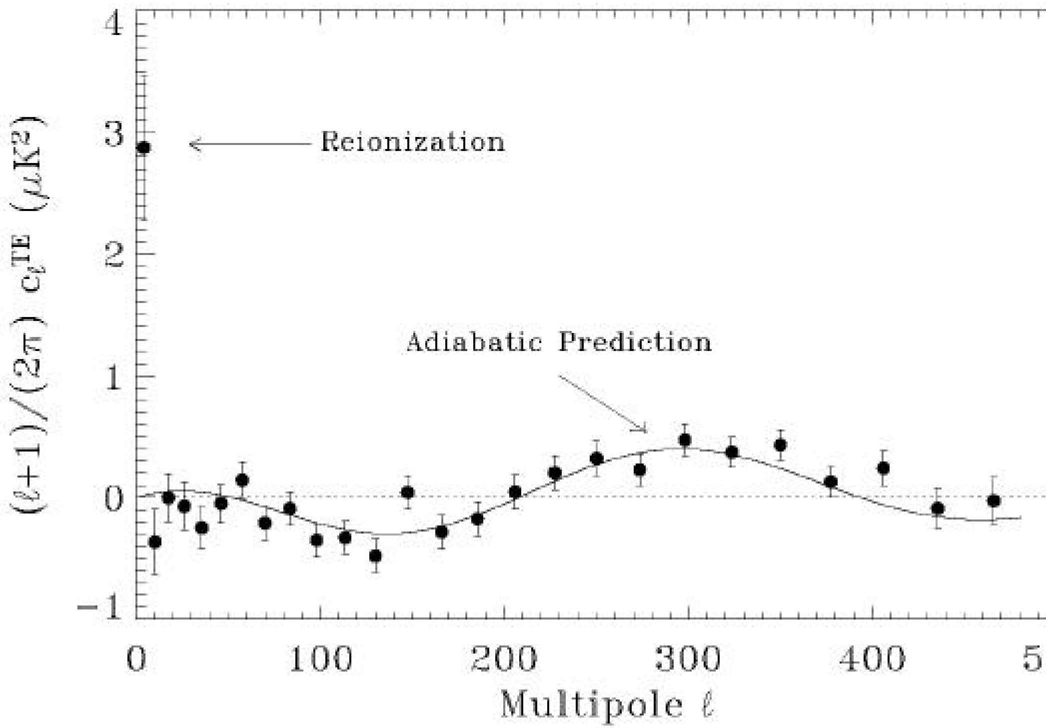
$\Rightarrow z_{reion} \sim 6$

WMAP polarization

$\Rightarrow z_{reion} \sim 17$



Fan et al.(02)

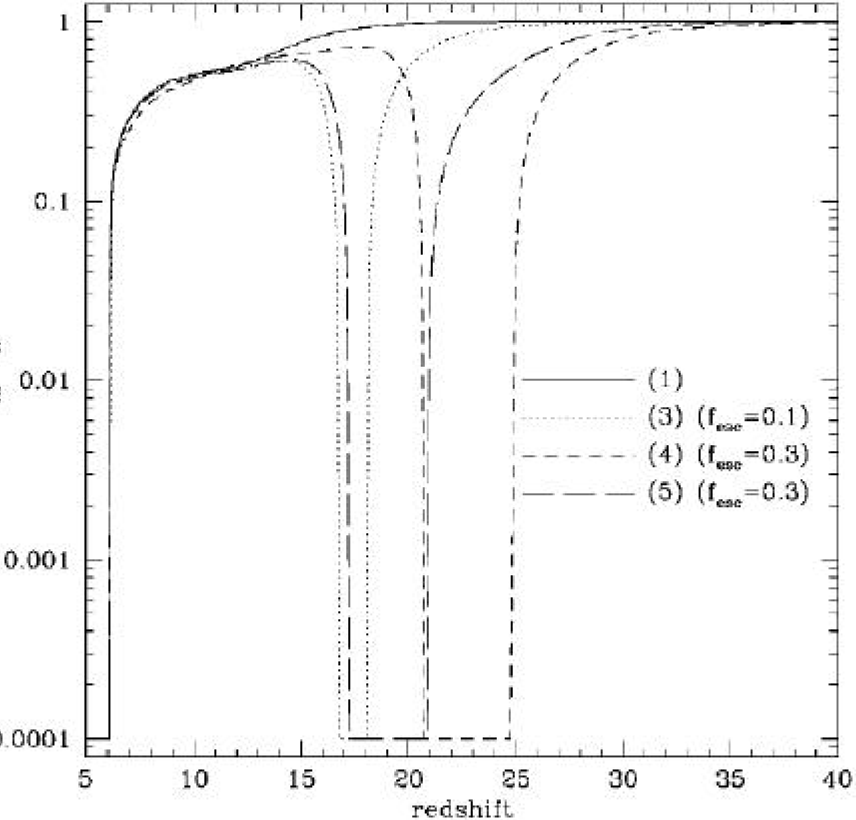


Spergel et al.(03

Kogut et al.(03)

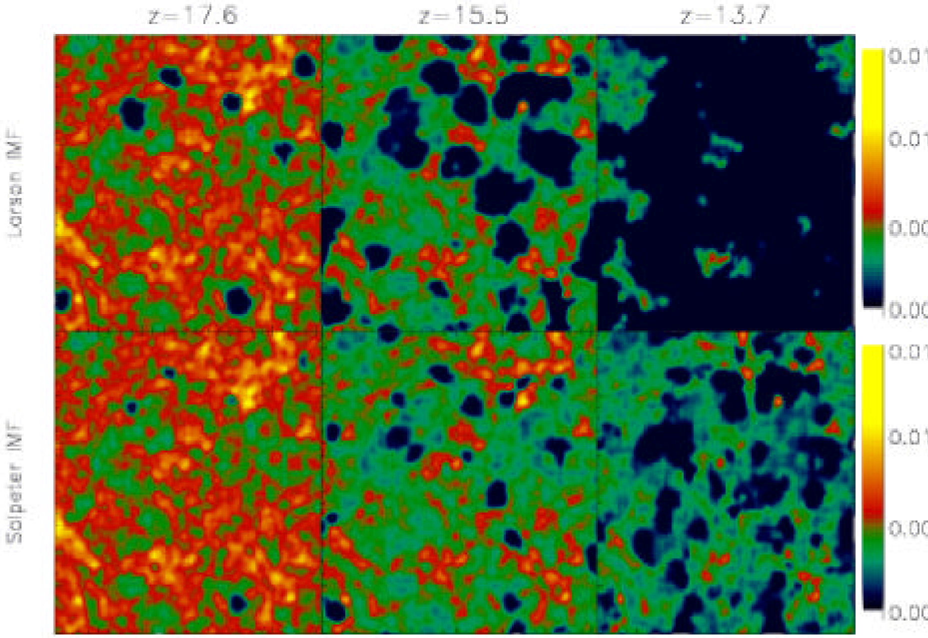
Complex Reionization

Double reionization



Cen(03)

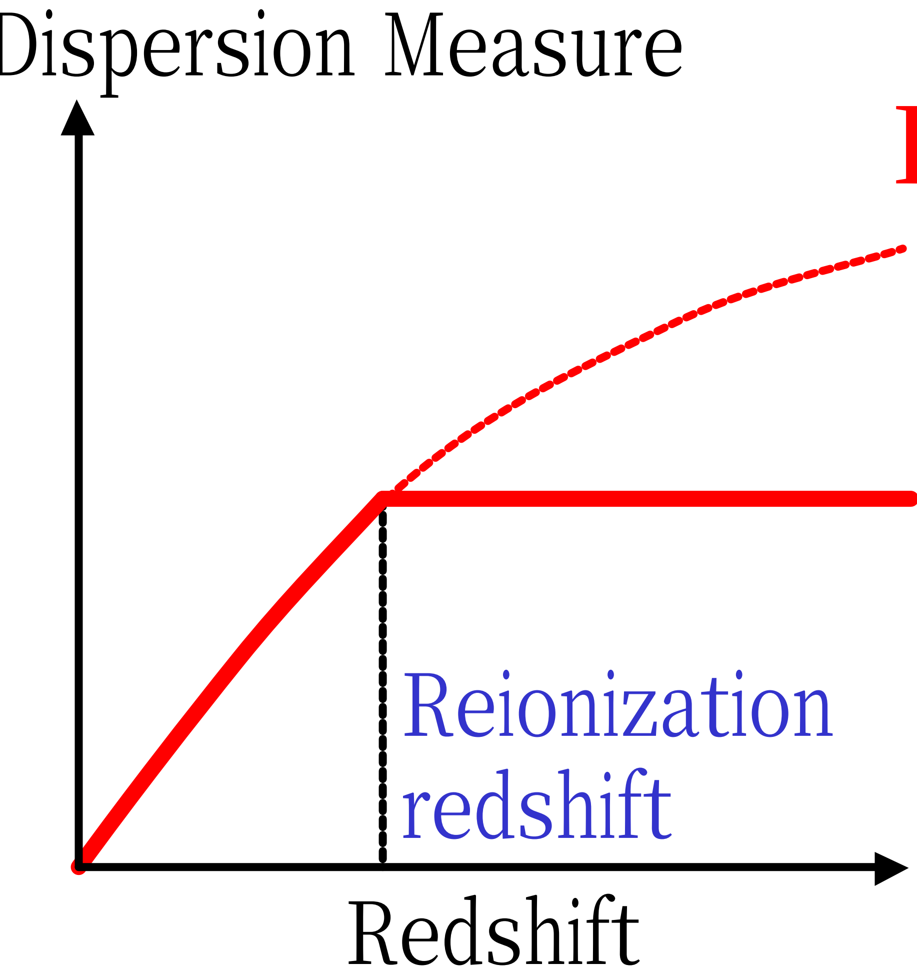
Inhomogeneous reionization



Ciardi,Ferrara&White(03)

Dispersion Measure (DM)

is the free electron column density along the light path



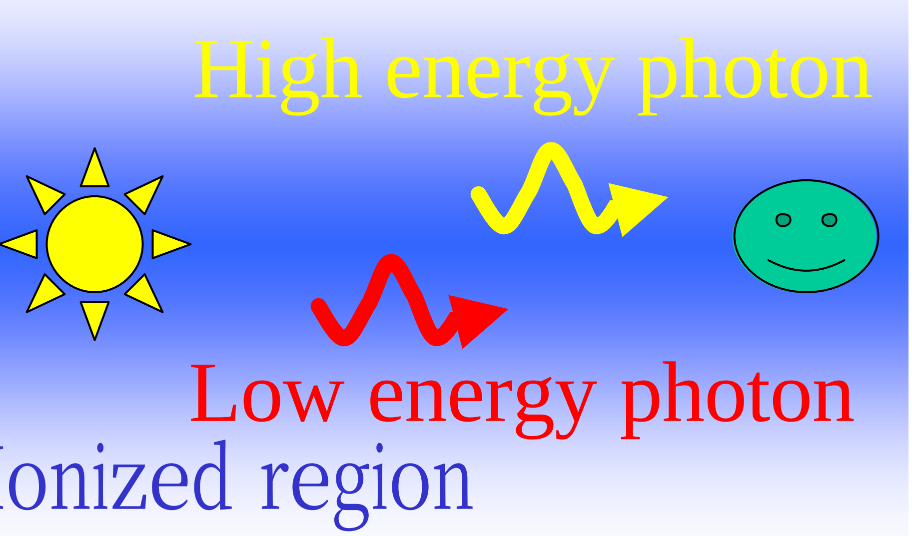
Dispersion Measure

↓

Reionization History

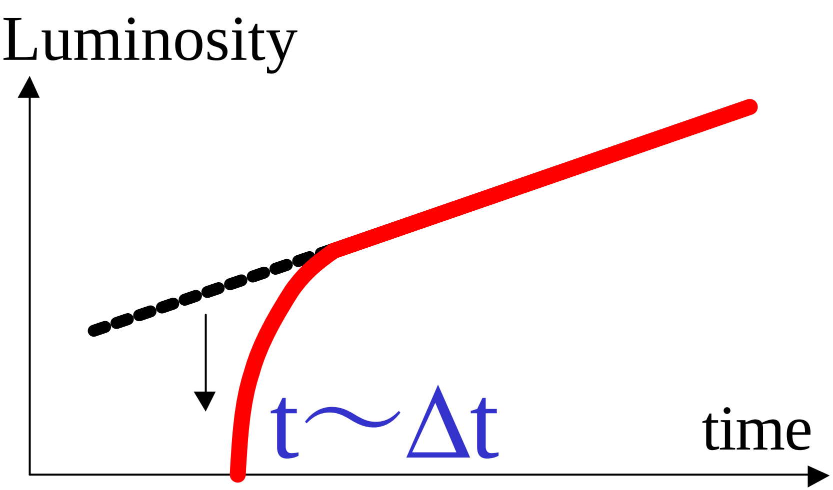
Recombined electrons provide no DM

DM from Afterglow



In a plasma, a light signal is delayed.

$$\Delta t = 415\ \mathrm{s} \left(\frac{n}{1\ \mathrm{GHz}}\right)^{-2} \left(\frac{\mathrm{DM}}{10^{5}\ \mathrm{pc\ cm}^{-3}}\right.$$



Distortion in light curve

⇒ DM

⇒ Reionization History

Ioka(03), Inoue(04)

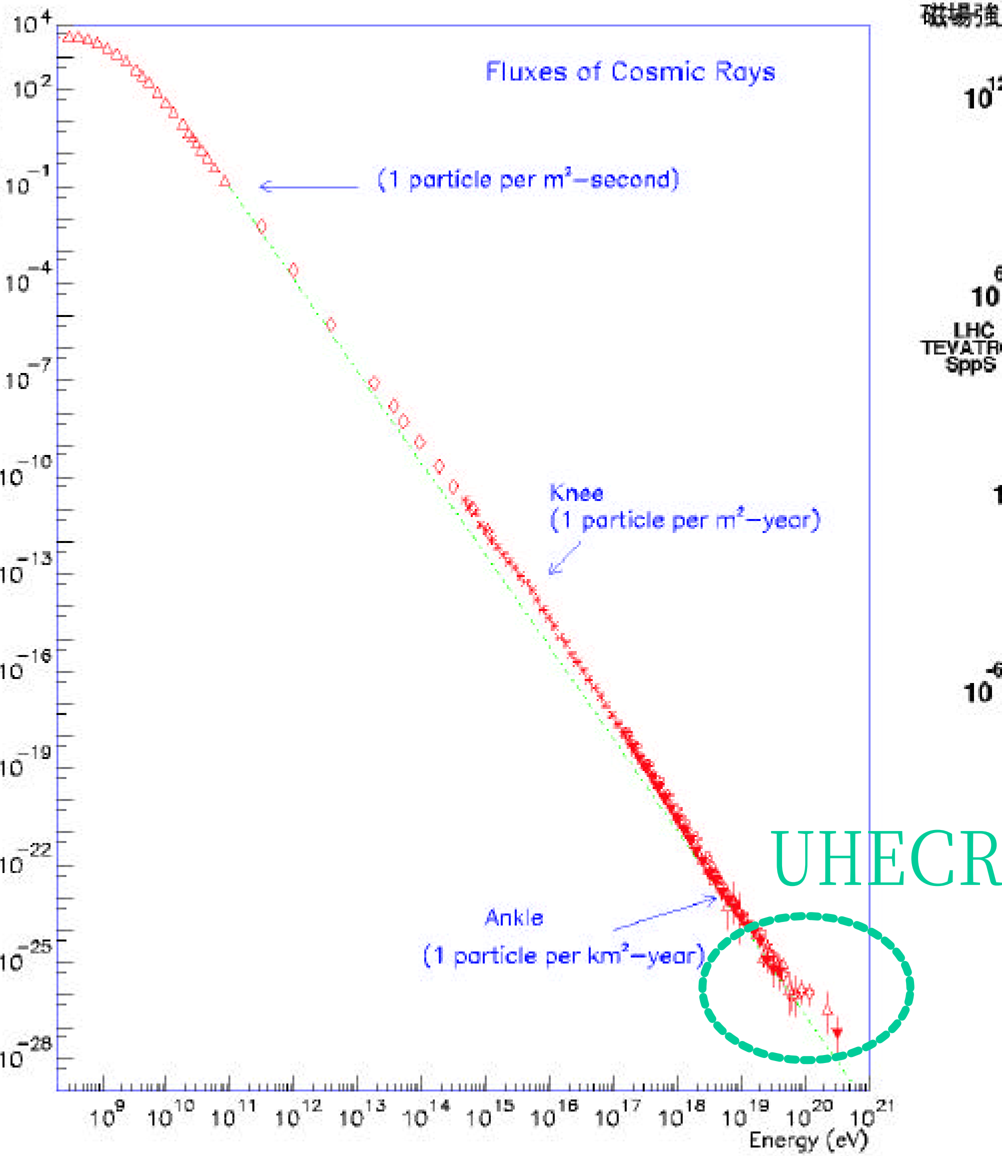
GRB cosmology

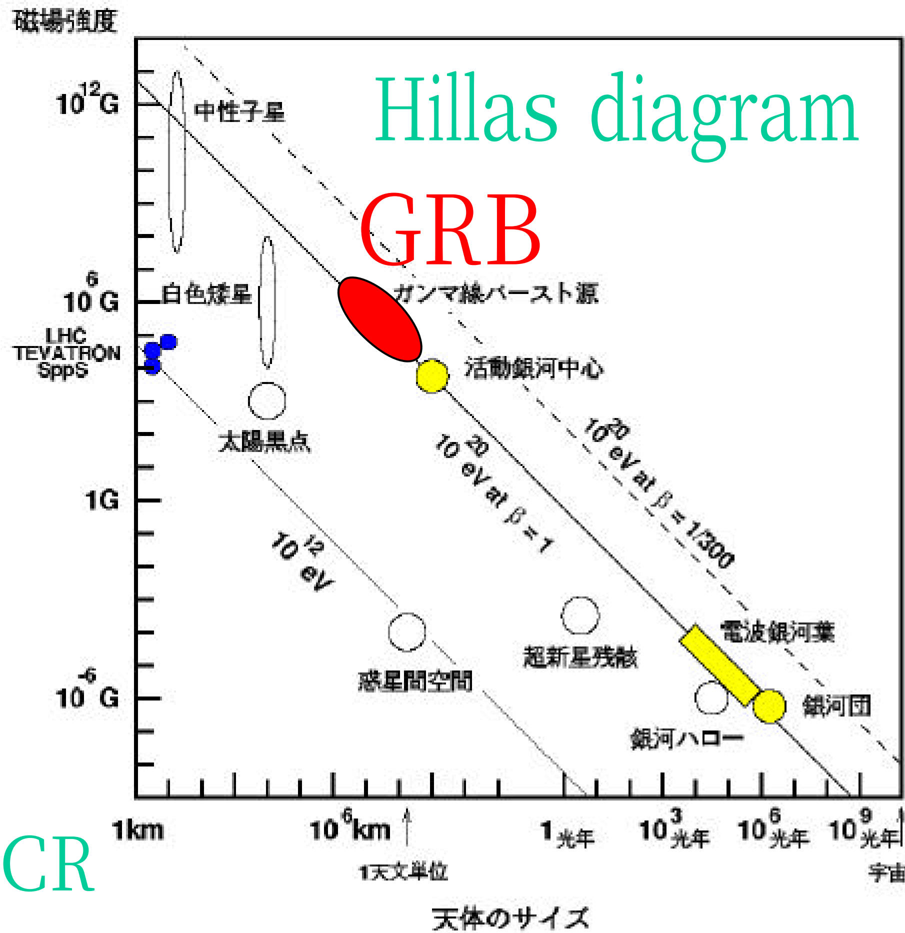
Problems

1. Fireball content: Kinetic or magnetic ?
2. GRB emission mechanism: Synchro or not
3. GRB jet structure: Uniform or not ?
4. Jet acceleration: How to launch ?
5. Environment: What is in front ?
6. Shock parameters: Universal or not ?
7. Short GRBs: What ?
8. Other emissions: UHECR, HEν, HEγ, GW ?
9. GRBs & cosmology: How to use ?

Etc…

UHECR





$\approx 10^{44}\ \mathrm{erg/Mpc^3/yr}$

$\approx$ UHECR

Event rate

10^3 events/(3Gpc)^3/yr

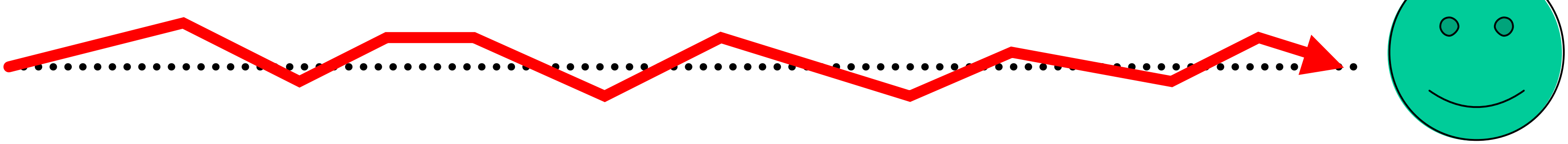
≈ 1 event/(100Mpc)^3/30yr

$\Rightarrow$ Dispersion ≥ 100yr in the arrival time

Time delay due to magnetic field

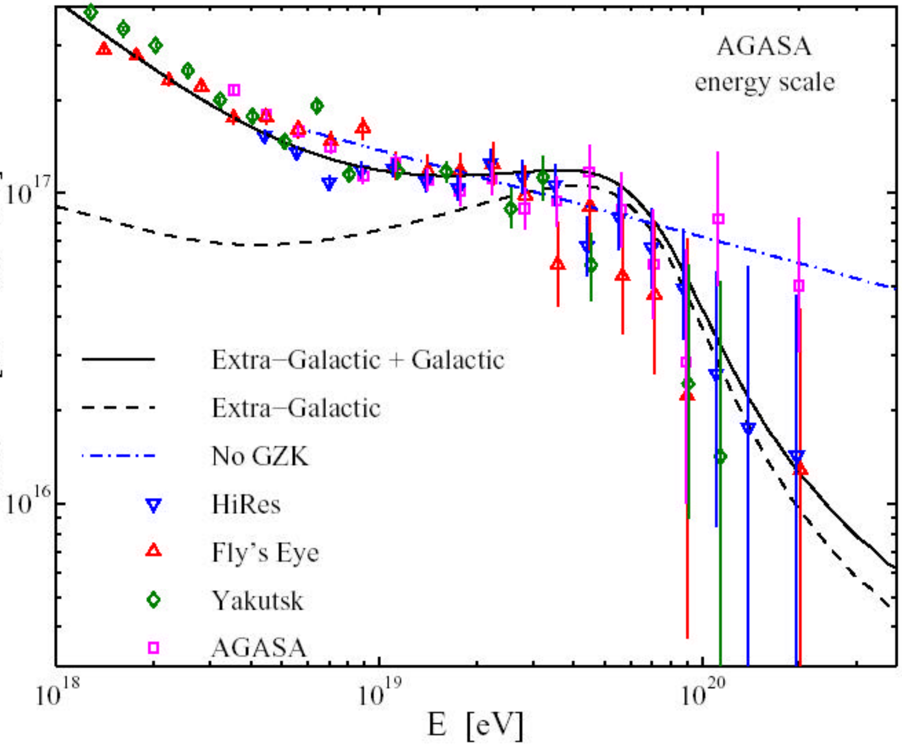
$$\tau(\varepsilon_p, D) \approx 10^5 \varepsilon_{p,20}^{-2} D_{100\mathrm{Mpc}}^2 \lambda_{\mathrm{Mpc}} B_{-9}^2 \,\mathrm{yr}$$

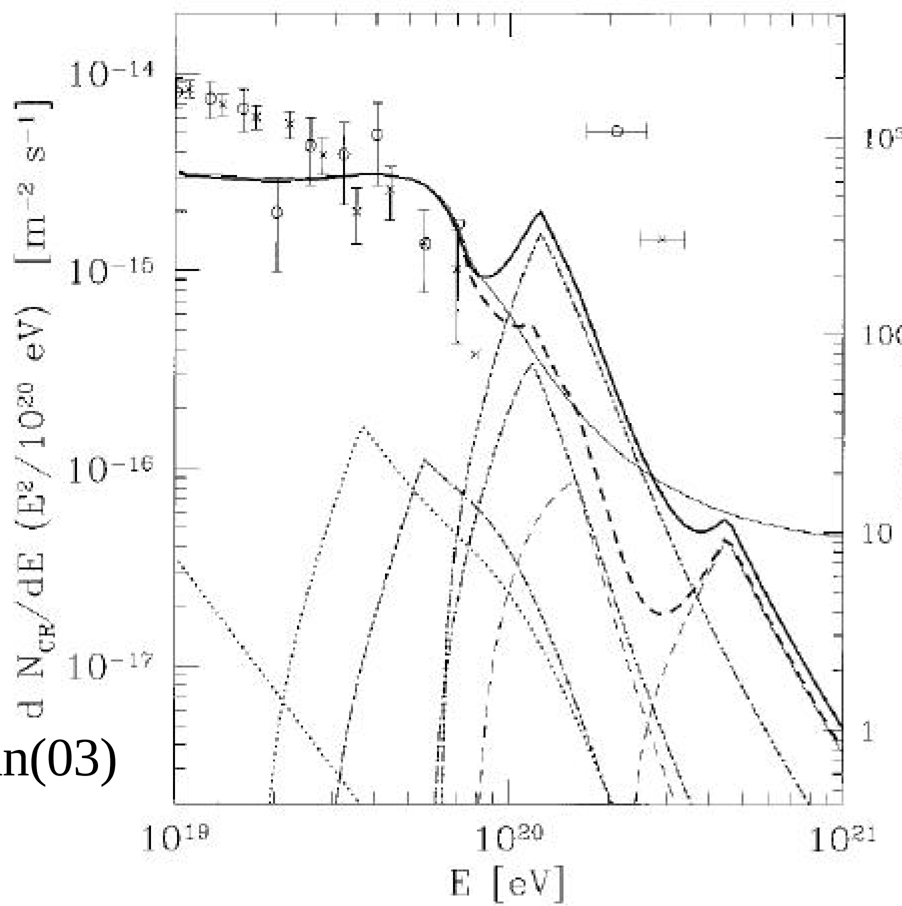
$\Delta\varepsilon_p / \varepsilon_p \approx 1$ for $\varepsilon_p \geq 10^{20}$ eV due to p-γ



GRB model prediction

Miralda-Escude&Waxman(96





Bahcall&Waxman(03)

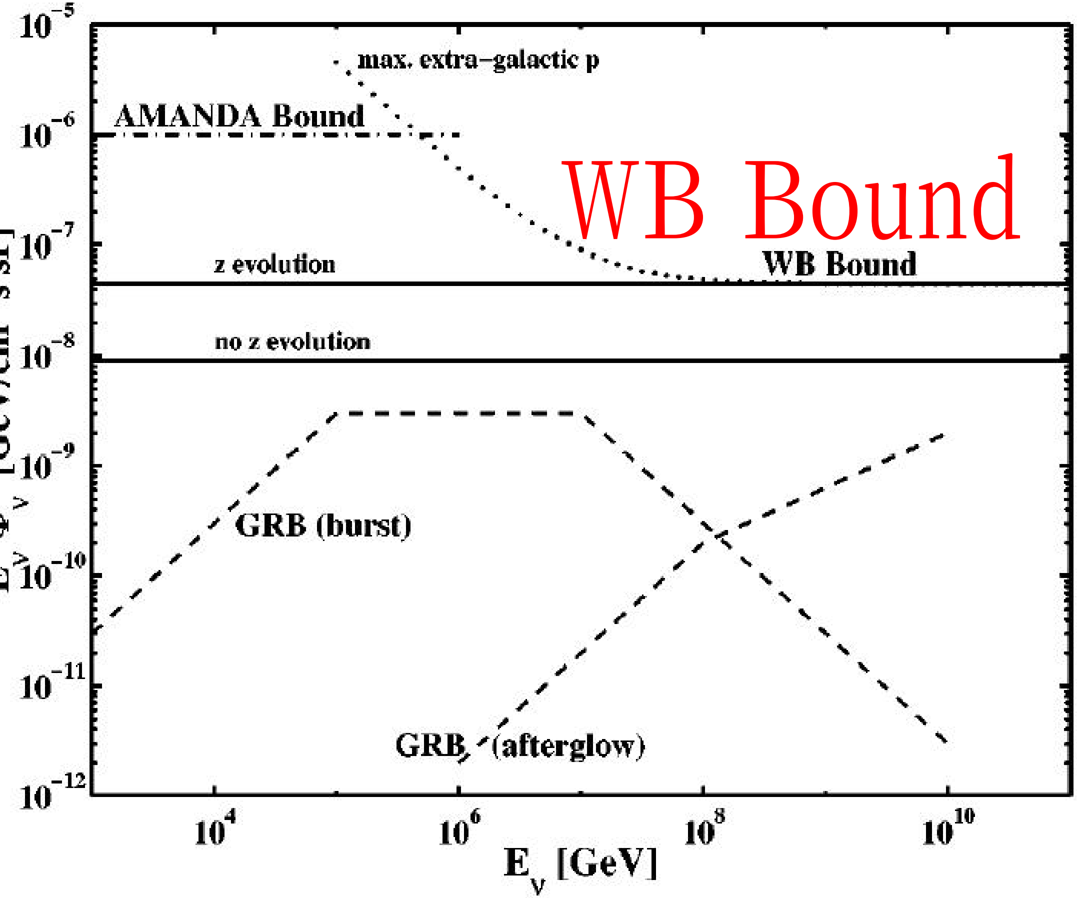
$$\text{Galactic:}\frac{dn}{de} \propto e^{-3.5}$$

$$\text{GRB:}\frac{dn}{de} \propto e^{-2}$$

$$e^2 \frac{d\dot{n}}{de} \approx 0.7\times10^{44} \text{erg Mpc}^{-3}\text{yr}^{-1}$$

Few sources at $>10^{20}$eV
$\Rightarrow$ spectral gap
anisotropy

High Energy n



Waxman&Bahcall(99)

Thin to π production

$dn_p/d\varepsilon_p \propto \varepsilon_p^{-2}$

$$pg \rightarrow np^+,\ pp^0$$

$$p^+ \rightarrow m^+ + n_m$$

$$\rightarrow e^+ + n_e + \bar{n}_m + n_m$$

$$p^0 \rightarrow gg$$

$$e_n^2 \Phi_n < e_n^2 \Phi_n^{WB} \approx 0.25 t_H \frac{c}{4p} e_p^2 \frac{d\dot{n}_p^{CR}}{de_p}$$

$\varepsilon_\nu \sim 0.05\varepsilon_p$

$\Rightarrow dn_\nu/d\varepsilon_\nu \propto \varepsilon_\nu^{-2}$

Photo-meson interaction

$$pg \to \Delta \to np^{+},\ pp^{0}$$

$$p^{+} \to m^{+} + n_{m} \to e^{+} + n_{e} + \bar{n}_{m} + n_{m},\quad p^{0} \to gg$$

$$e_{g} e_{p} \approx 0.2\Gamma^{2}\mathrm{GeV}^{2},\ e_{n} \approx 0.05 e_{p}$$

- Internal shock

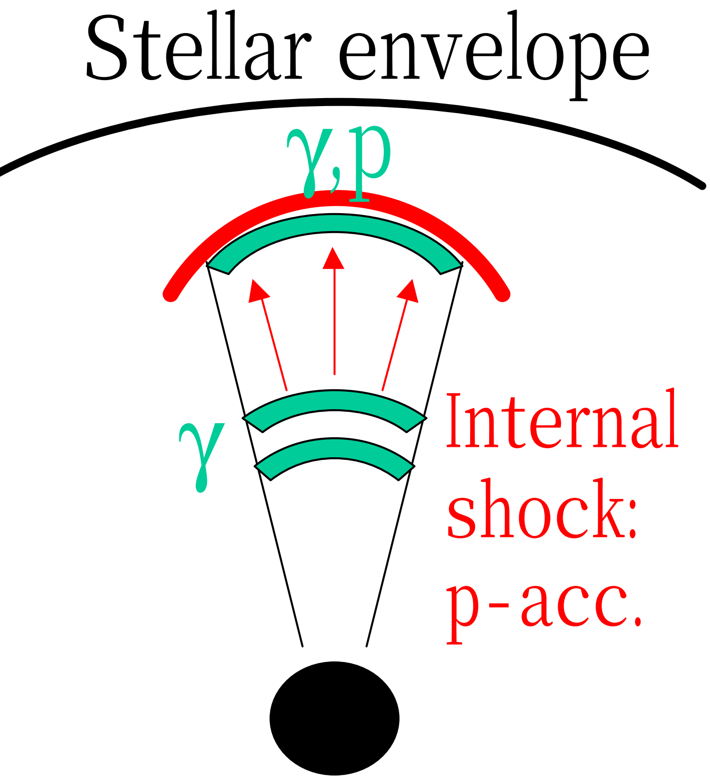
$$e_{g} \approx 1\mathrm{MeV}, \Gamma \approx 300 \Rightarrow e_{p} \approx 10^{16}\mathrm{eV} \Rightarrow e_{n} \approx 10^{14}\mathrm{eV}$$

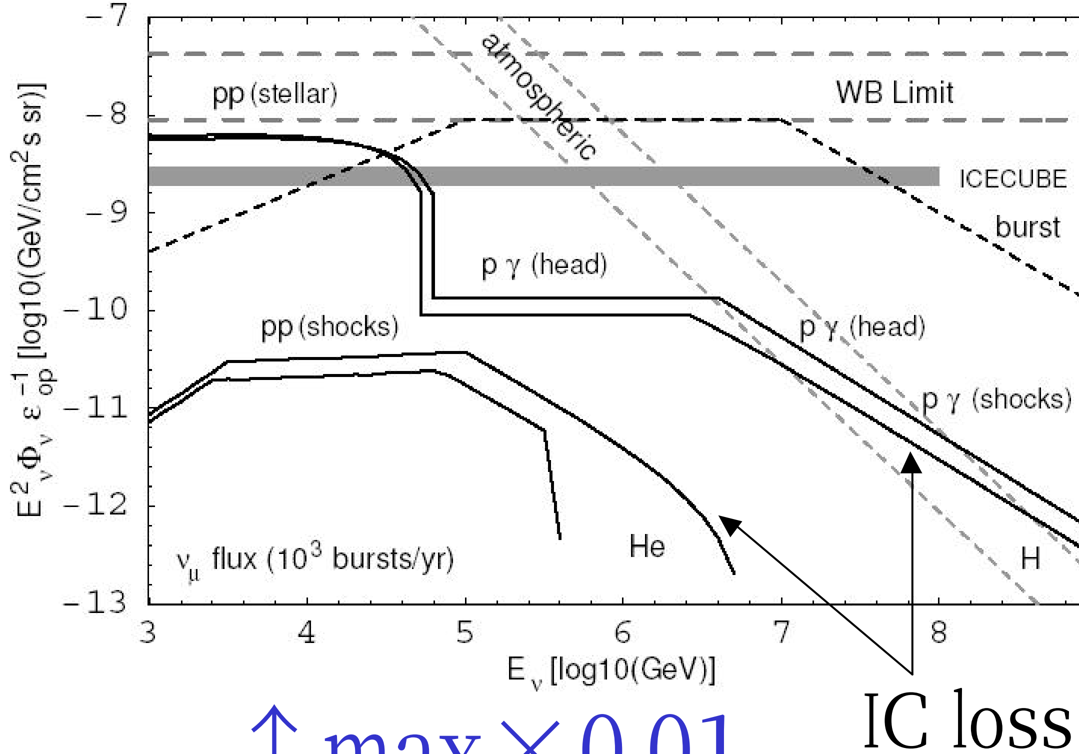
- External shock (reverse shock)

$$e_{g} \approx 1\mathrm{keV}, \Gamma \approx 250 \Rightarrow e_{p} \approx 10^{19}\mathrm{eV} \Rightarrow e_{n} \approx 10^{18}\mathrm{eV}$$

n from hypernova

Razzaque,Meszaros&Waxman(03)





↑max×0.01

if all SNe have GRB

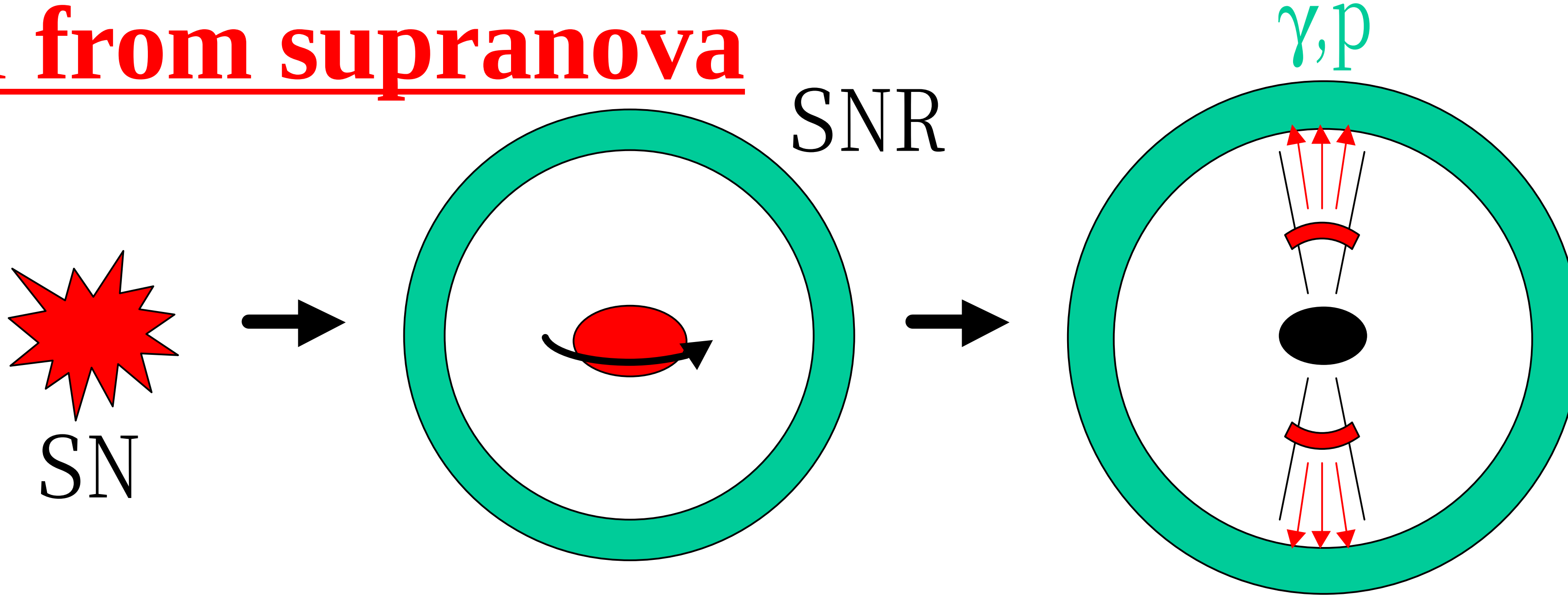
Constrain dark GRBs

10-100s before GRB

Probe outer envelope

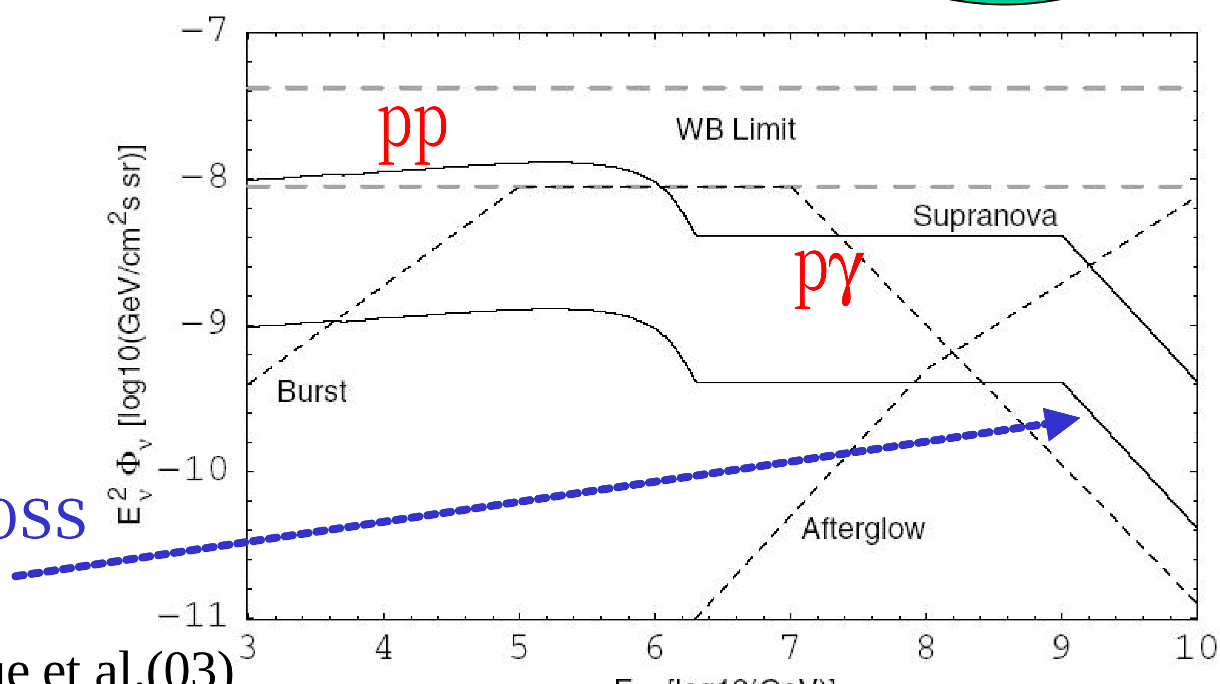
1st star may be very massive: Dark GRBs ?

n from supranova



Baryon free
Fe line

IC, Synchrotron loss
s small

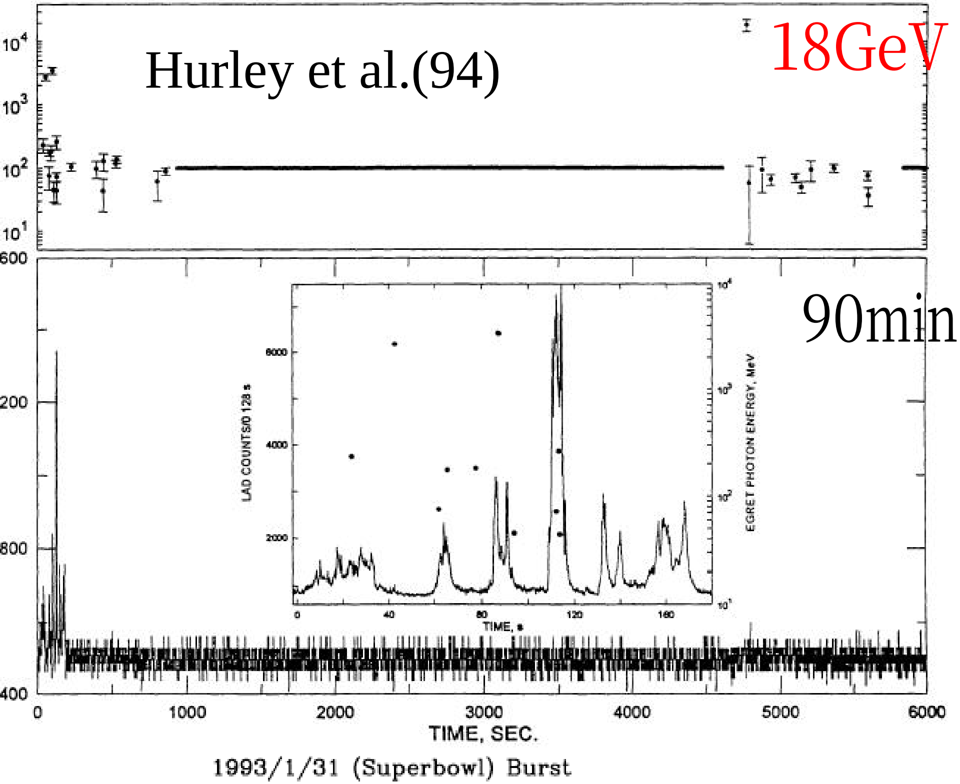


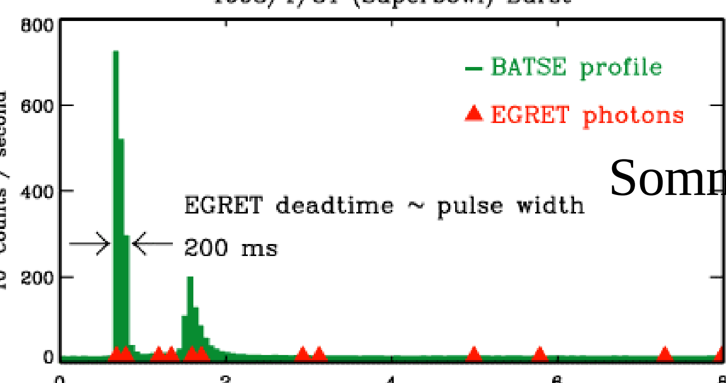
Razzaque et al.(03)

High Energy g

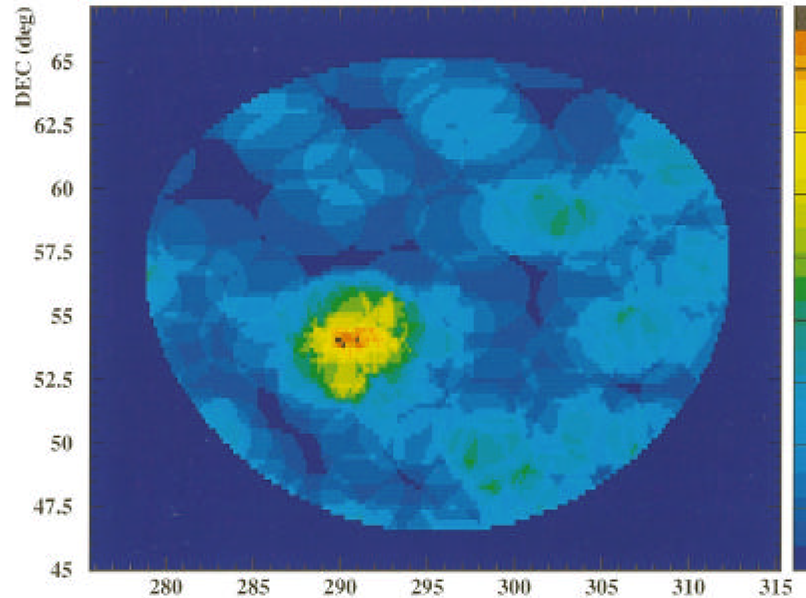
GeV γ

TeV γ

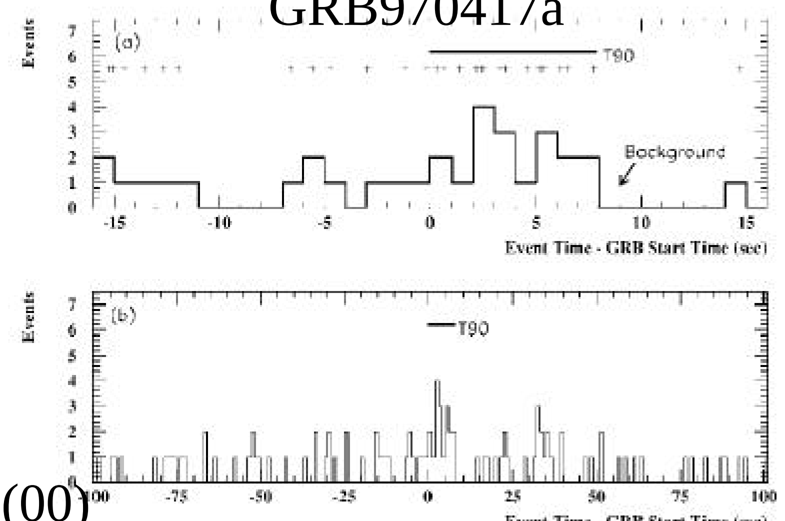




Sommer et al.(94)

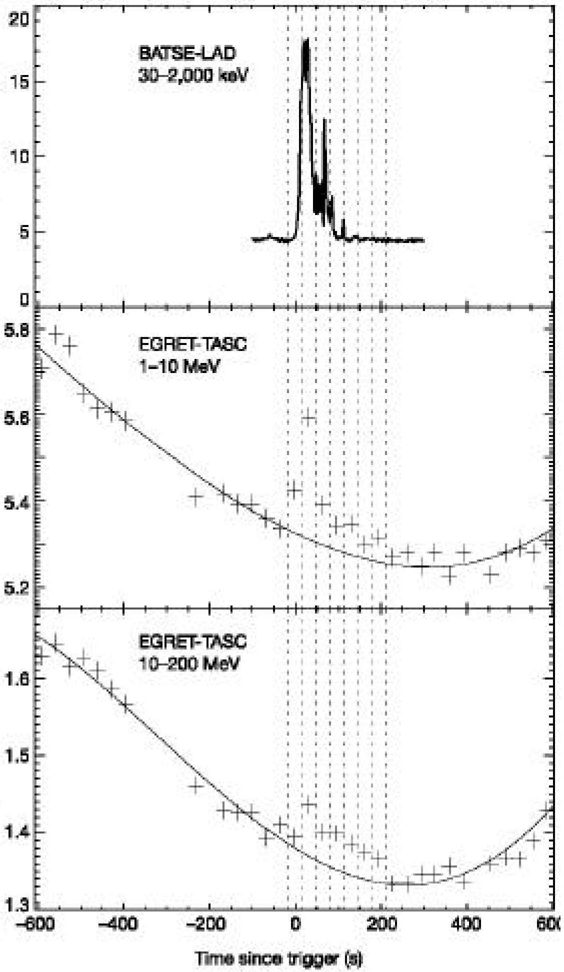


GRB970417a

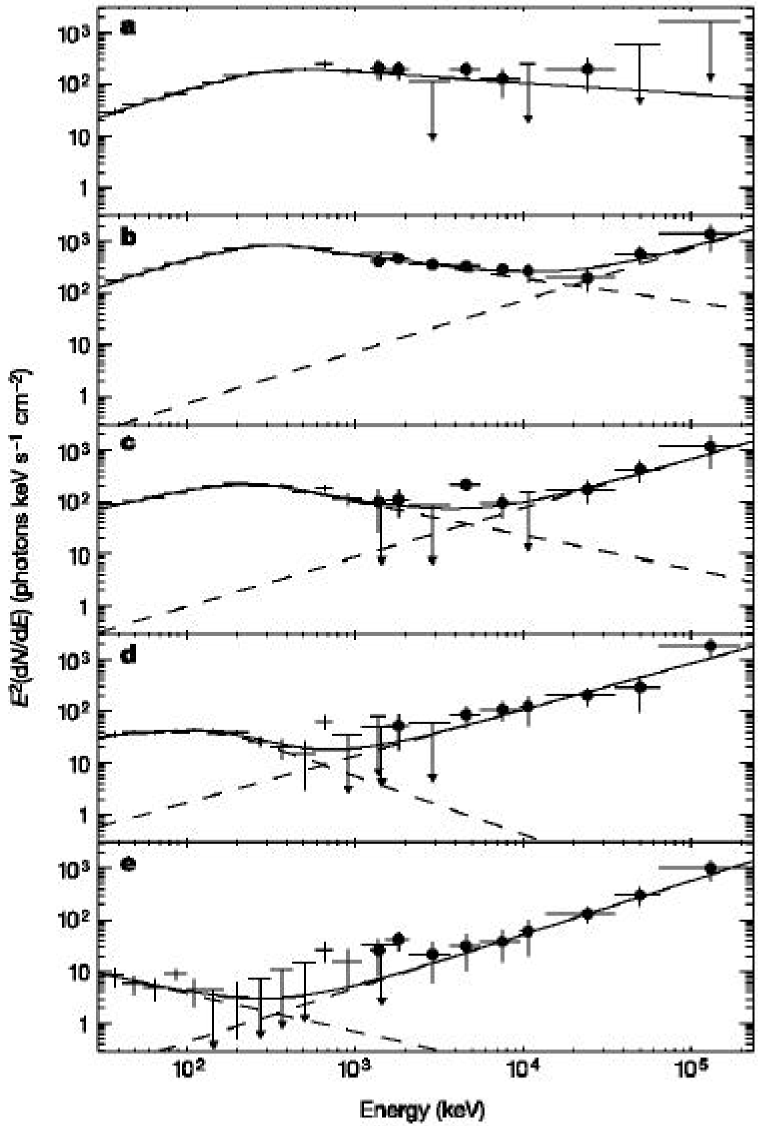


Atkins et al.(00)

>MeV Tail in GRB941017



Gonzalez et al.(03)

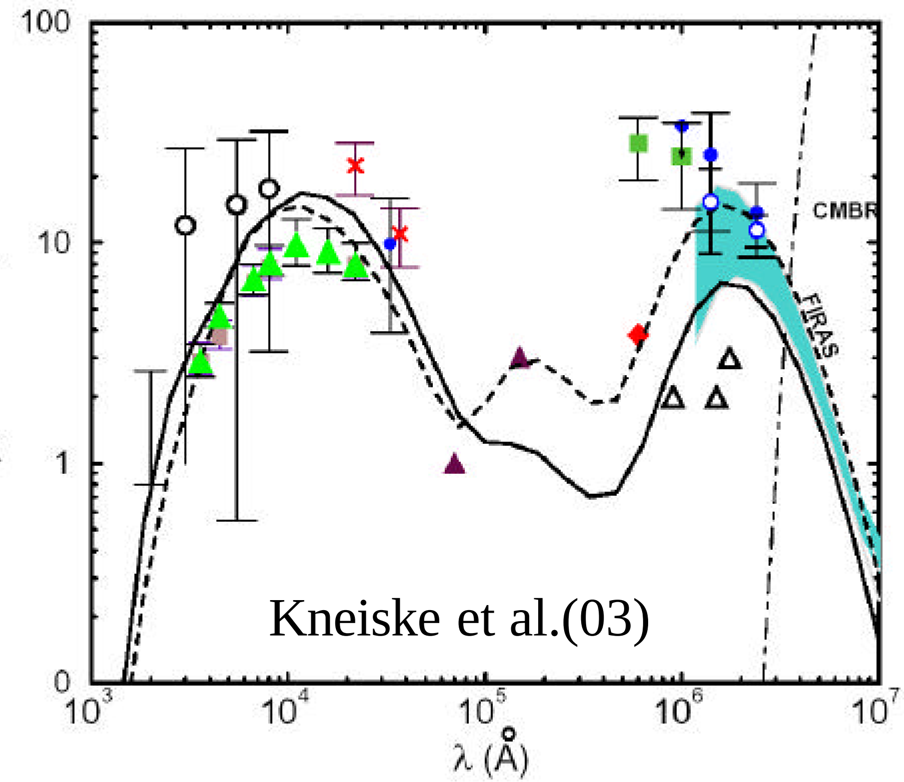


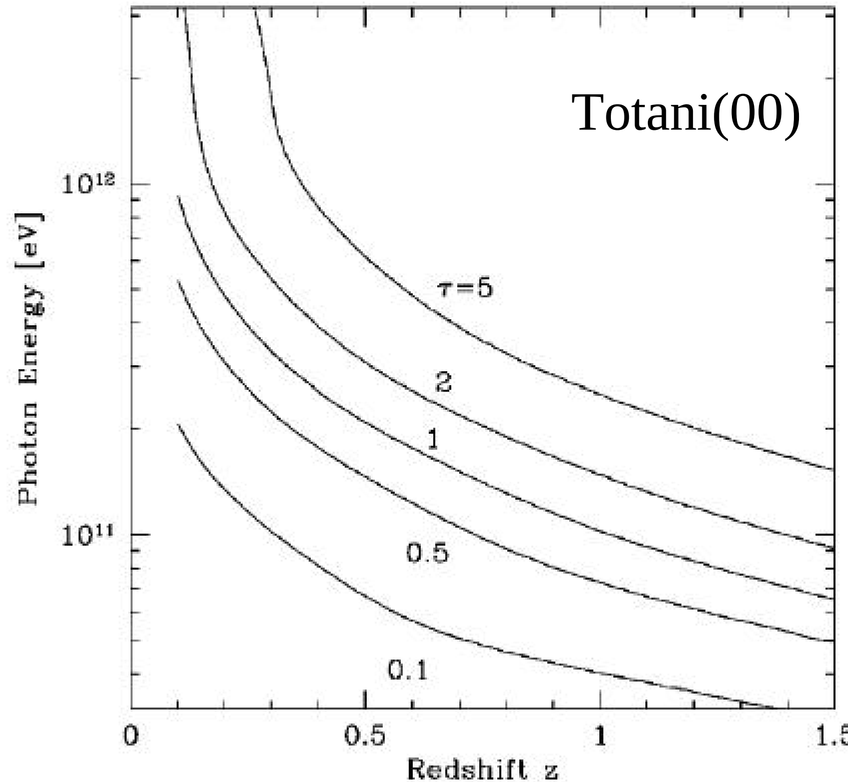
One of 26GRB

High energy decays more slowly

Photon numbe index: -1 (hard

IR Background





$.1\mathrm{eV}\times\mathrm{TeV}$ □ $\left(m_e c^2\right)^2$

$_{gg}$ □ $1/\sigma_T n_{\mathrm{IR}}$ □ $100\ n_{\mathrm{IR},-1}^{-1}$ Mpc

⇒ Nearby GRBs

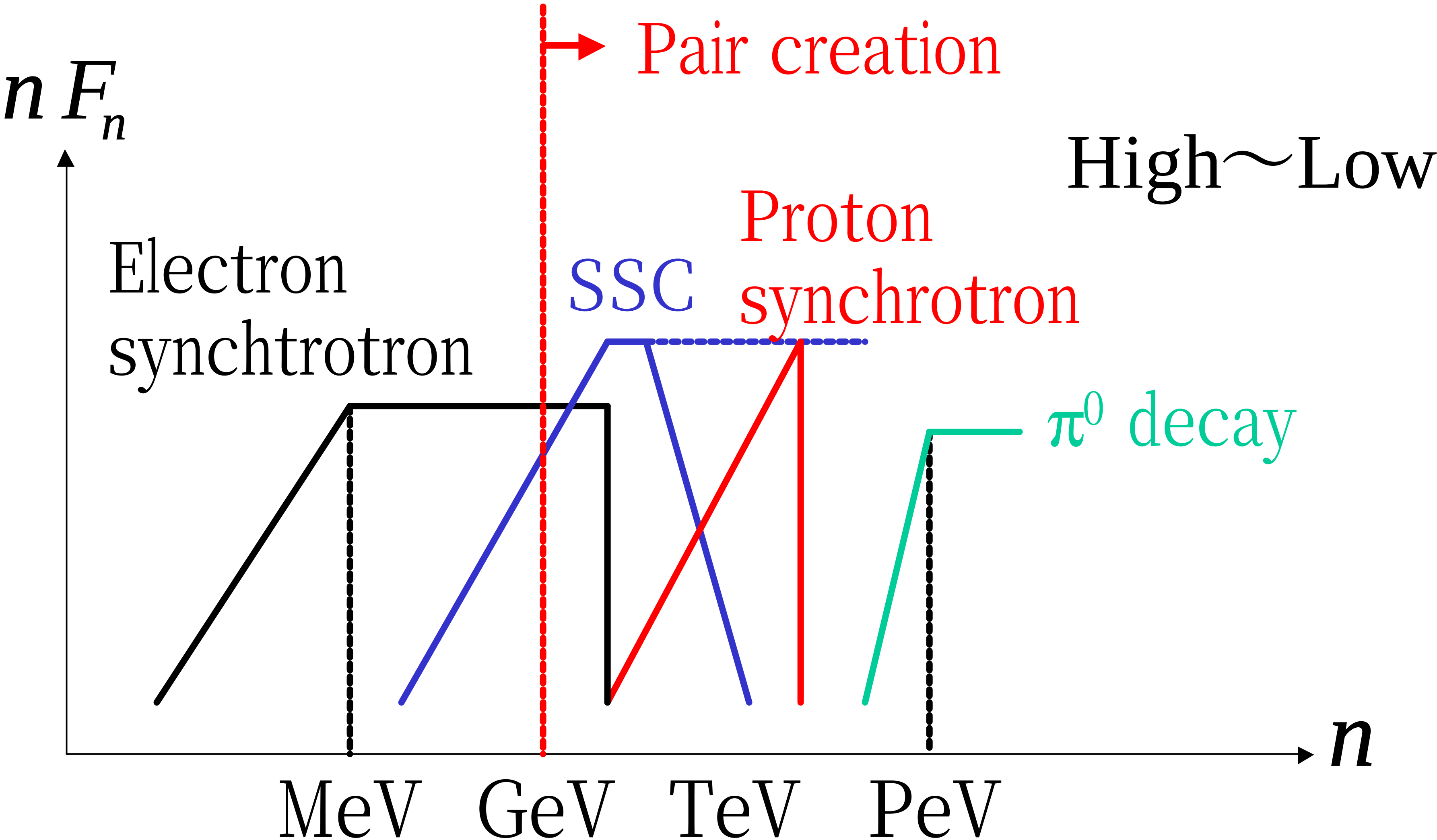
5GRB (z<0.5)

10^3events/(3Gpc)^3/yr

~1event/(100Mpc)^3/30yr

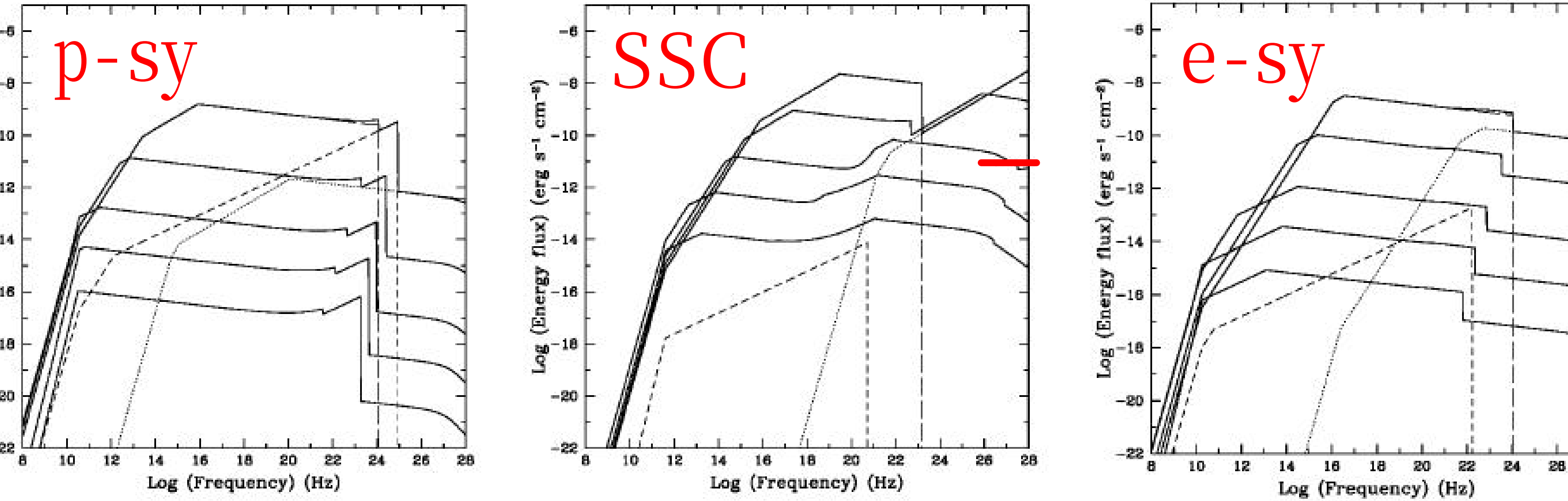
⇒ Off-axis GRB ?

HE g in GRB



n Fn
Pair creation
High～Low
Electron synchtrotron
SSC
Proton synchrotron
π0 decay
n
MeV
GeV
TeV
PeV

HE g in Afterglow



$\varepsilon_e=10^{-3}$, $\varepsilon_B=0.5$
$n=100\ cm^{-3}$

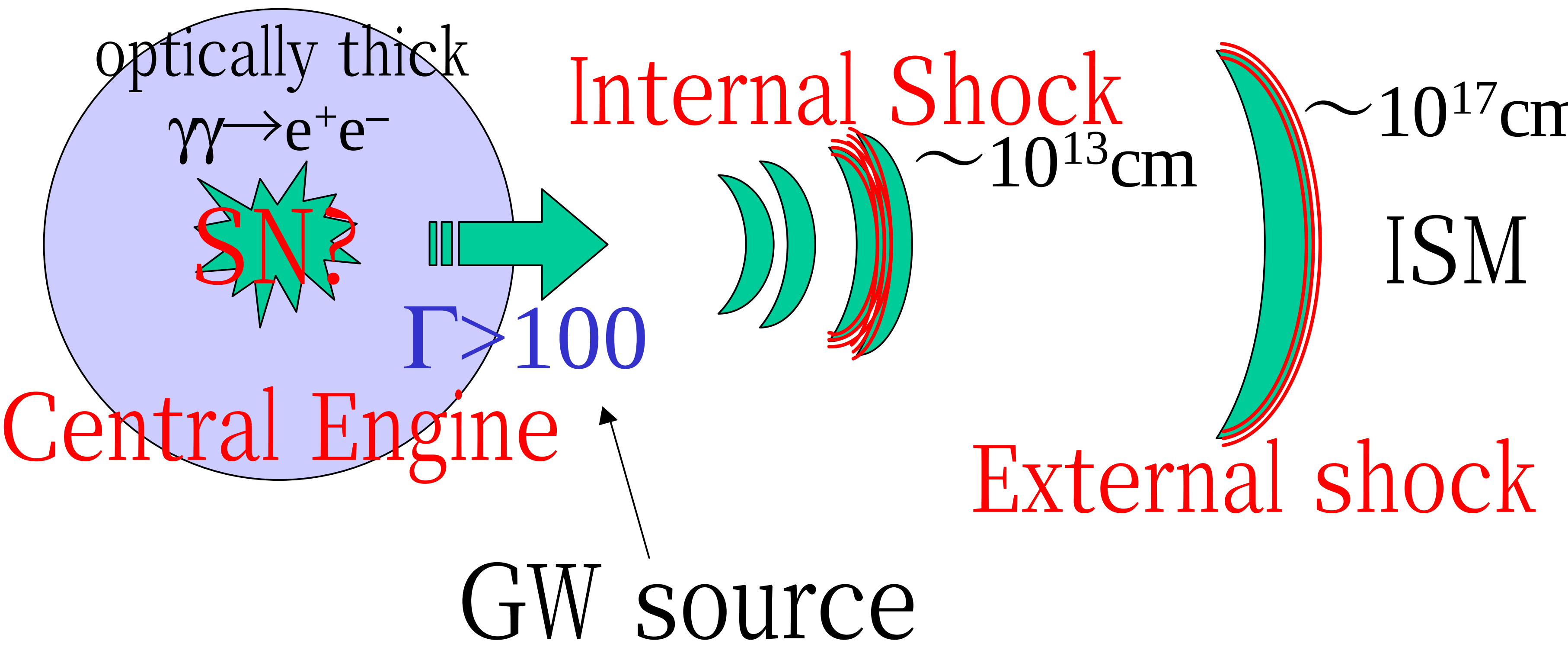
$\varepsilon_e=0.5$, $\varepsilon_B=0.01$
$n=1\ cm^{-3}$

$\varepsilon_e=0.01$, $\varepsilon_B=0.1$
$n=1\ cm^{-3}$

Long-dash: e-sy, short-dash: p-sy, dots: SSC
Times: trigger, 1 min, 1 hr, 1day, 1 month
$E_{52}=1$, $p=2.2$, $\varepsilon_p=1$, $\Gamma_0=300$, $z=1$ flat

Zhang&Meszaros(01

Gravitational Wave

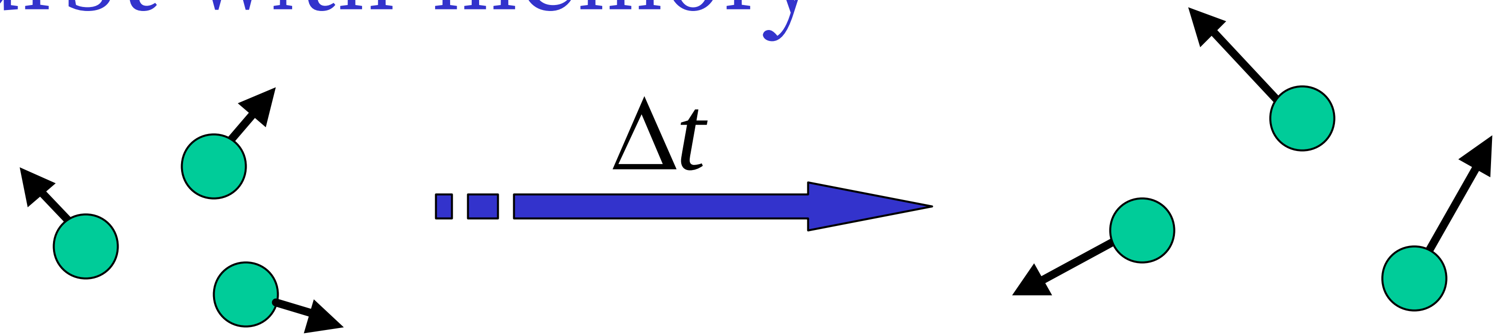


To see the center, ~~photon~~ but GW

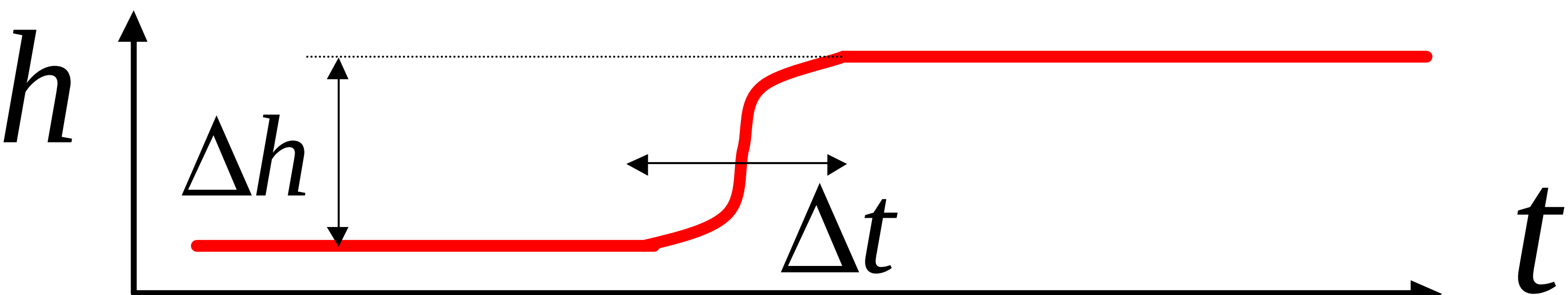
Guaranteed GW: Jet acceleration

GW Memory

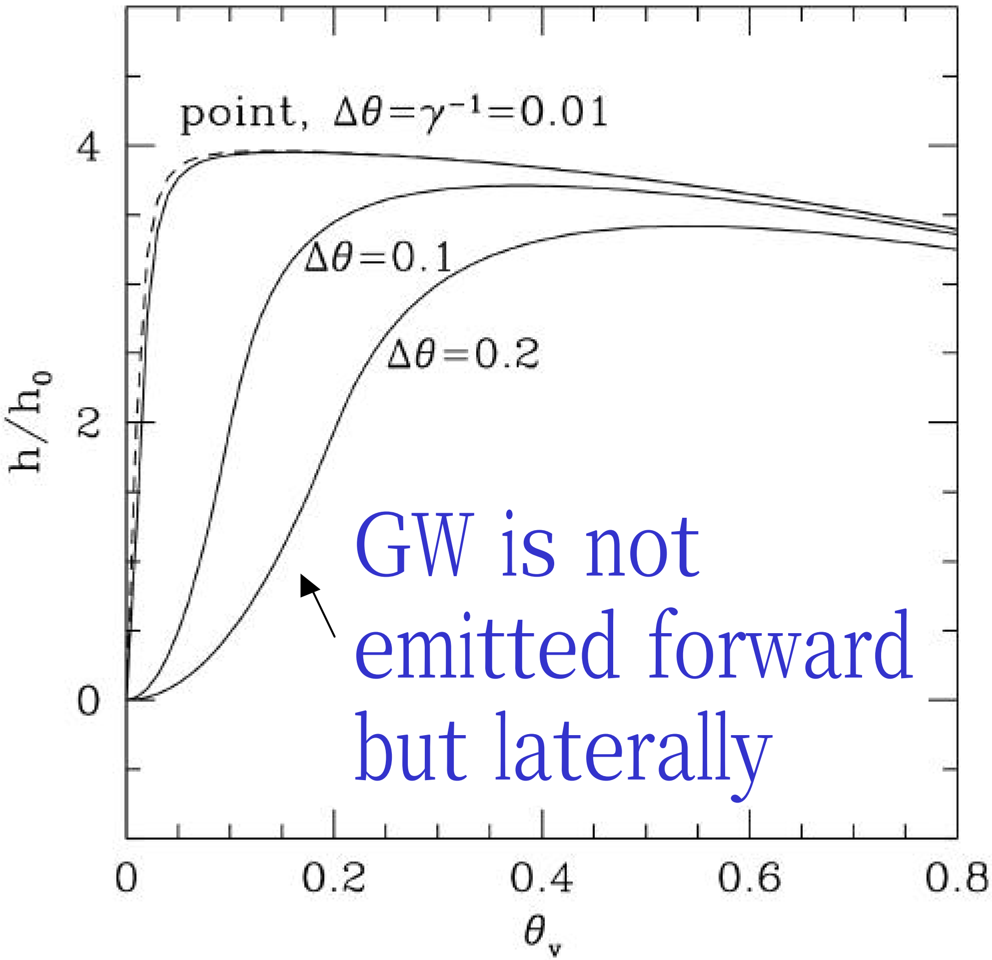
Burst with memory

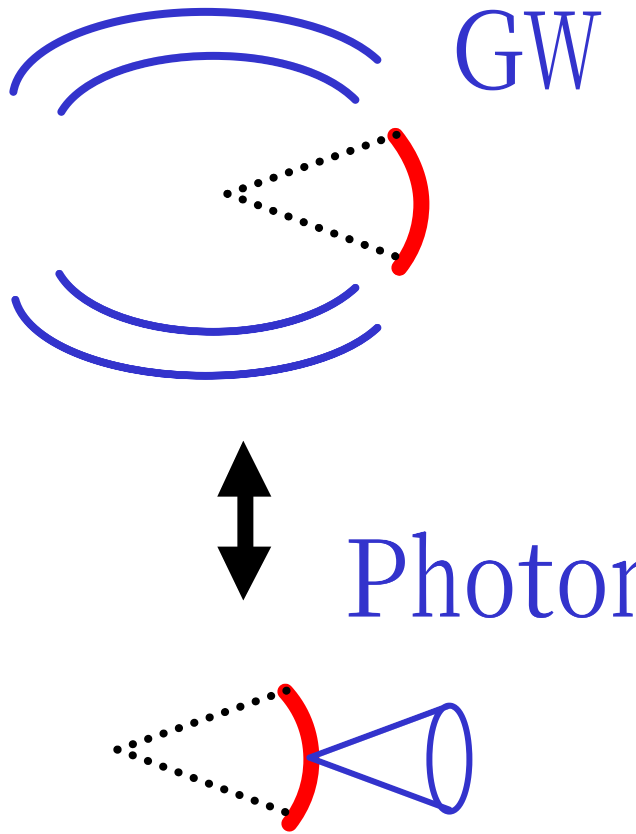


$$\Delta h_{jk}^{TT} = \Delta \sum_{A=1}^{N} \frac{4M_A}{r\sqrt{1-v_A^2}} \left[\frac{v_A^j v_A^k}{1 - v_A \cos\theta_A} \right]^{TT}$$



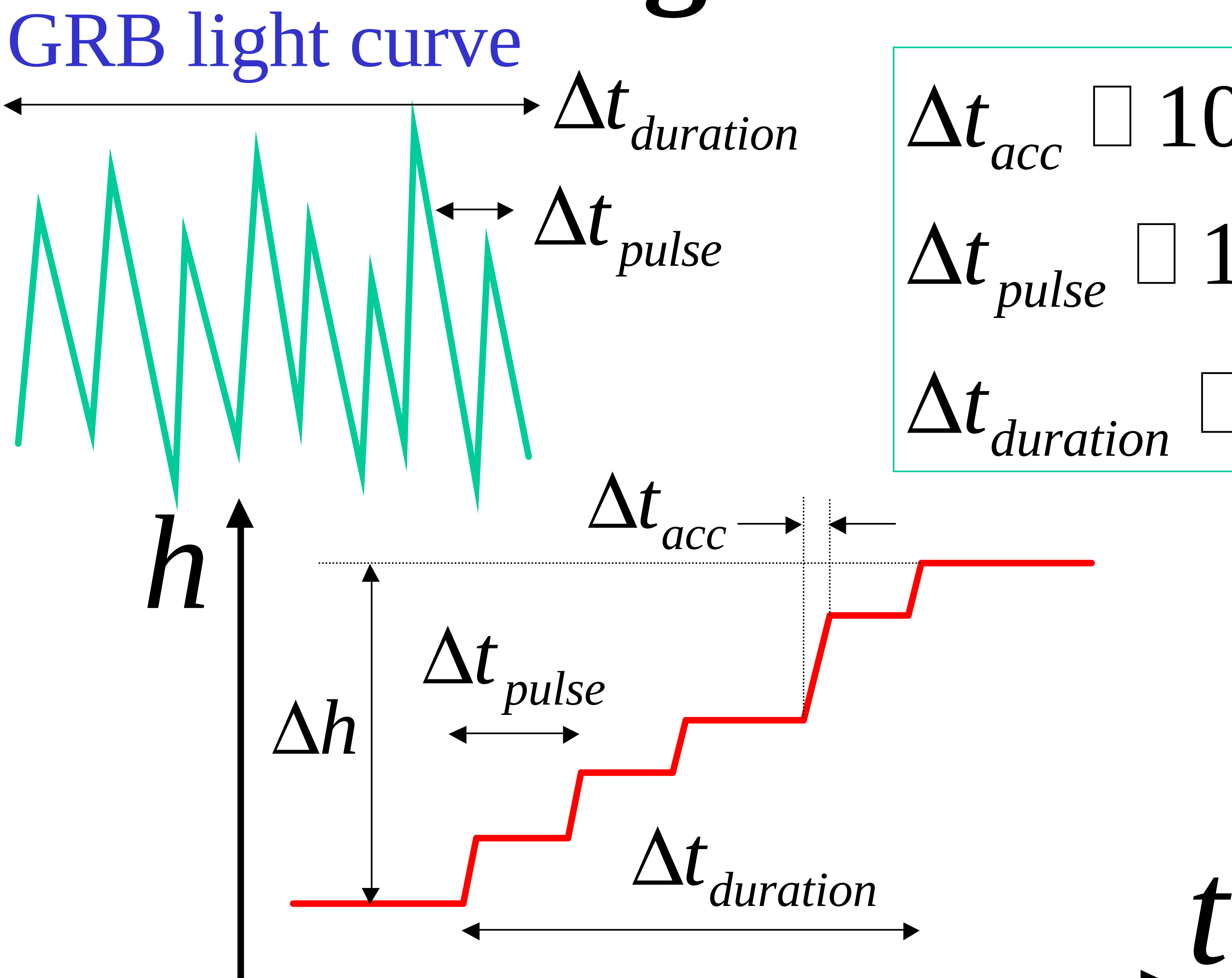
GW Memory of Jet





$$\Delta h \sim 2E/r \sim 8\times10^{-24} E_{51.5} r_{20\mathrm{Mpc}}^{-1}$$

GW Light curve



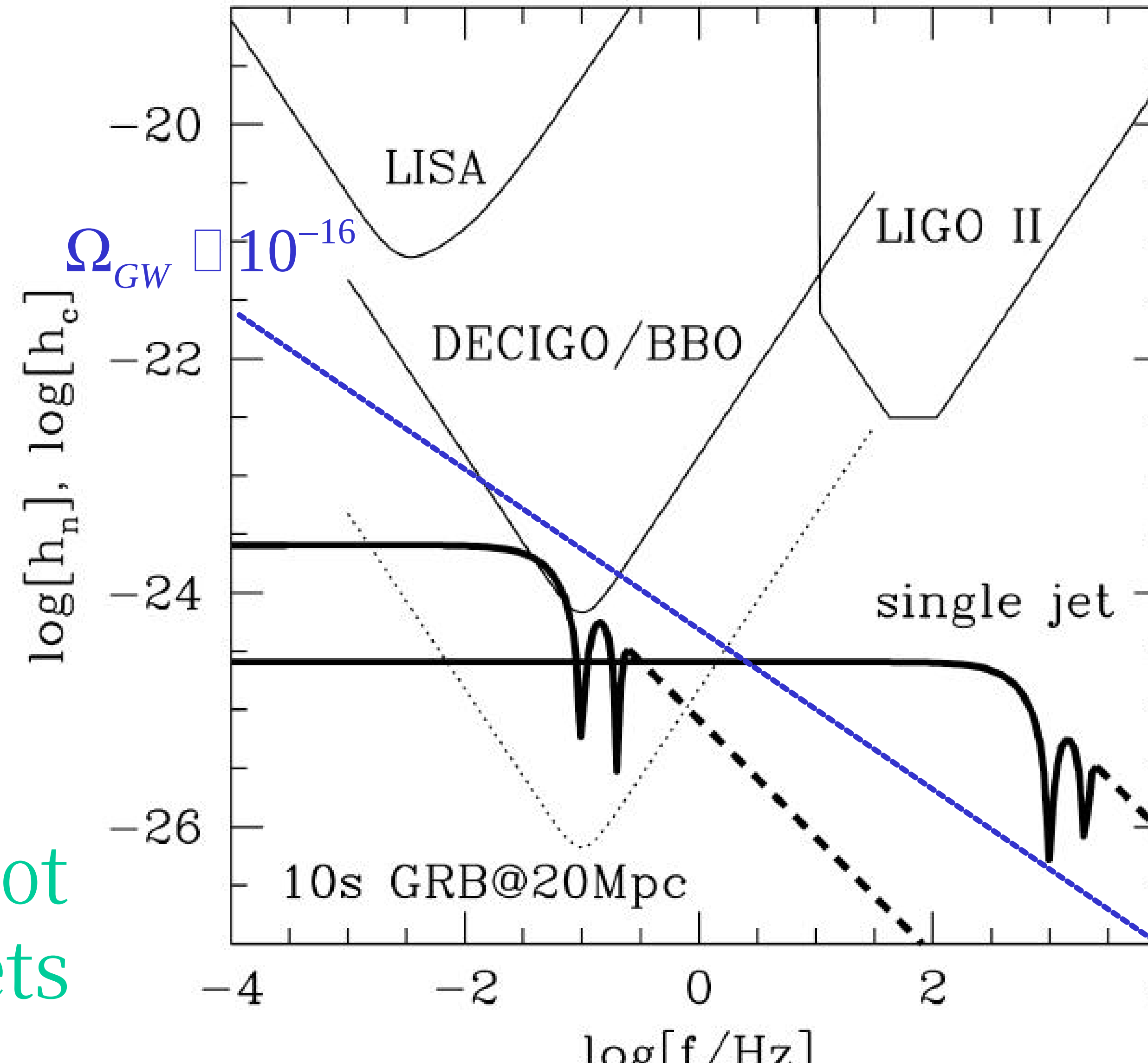
Δt_{acc} □ 10^{-3} s

Δt_{pulse} □ 1 s

$\Delta t_{duration}$ □ 10 s

Detectability

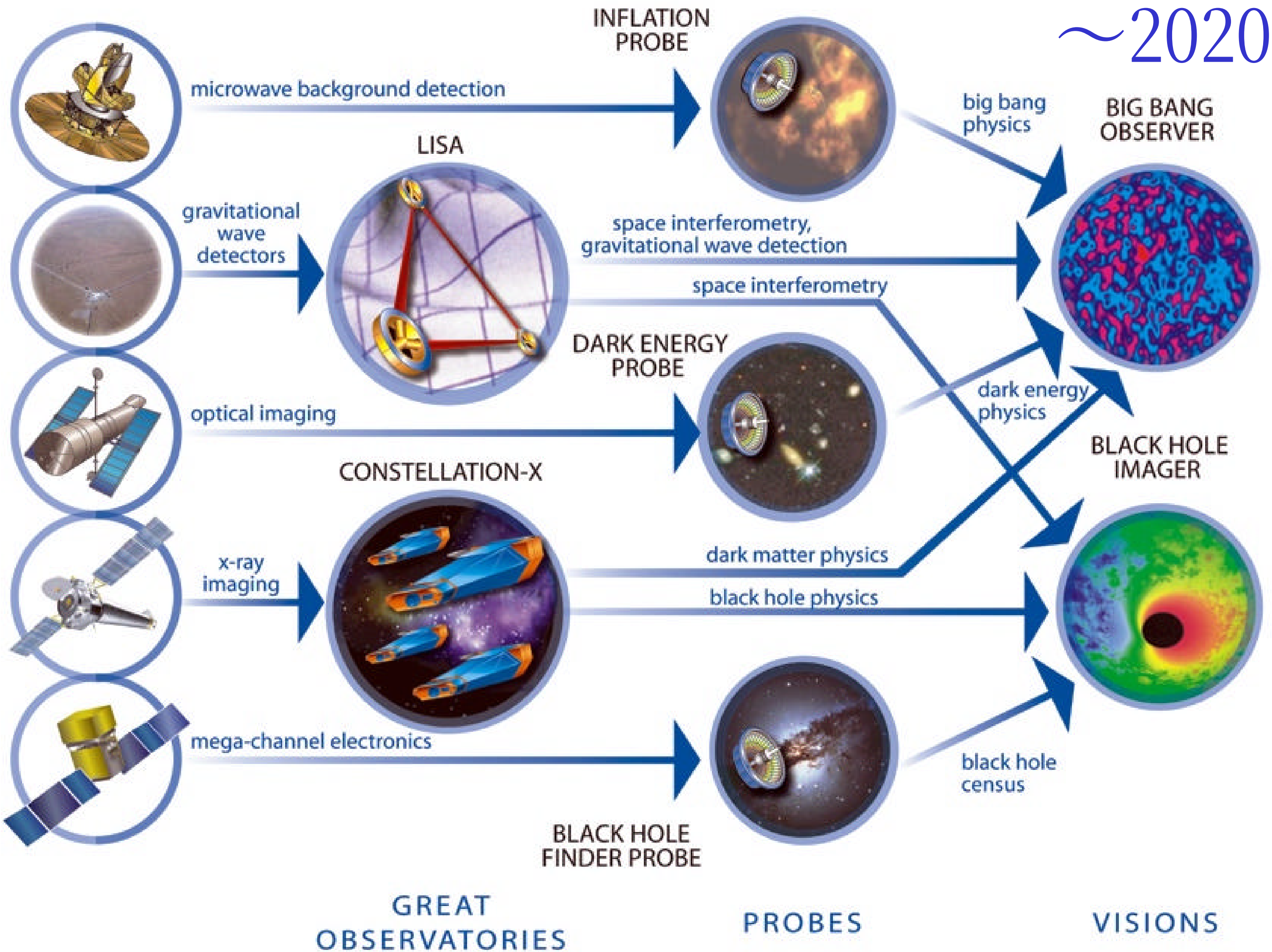
$\Delta t \sim 10s$
$\Rightarrow f \sim \Delta t^{-1}$
$\sim 0.1Hz$
$\Rightarrow$BBO
or DECIGO



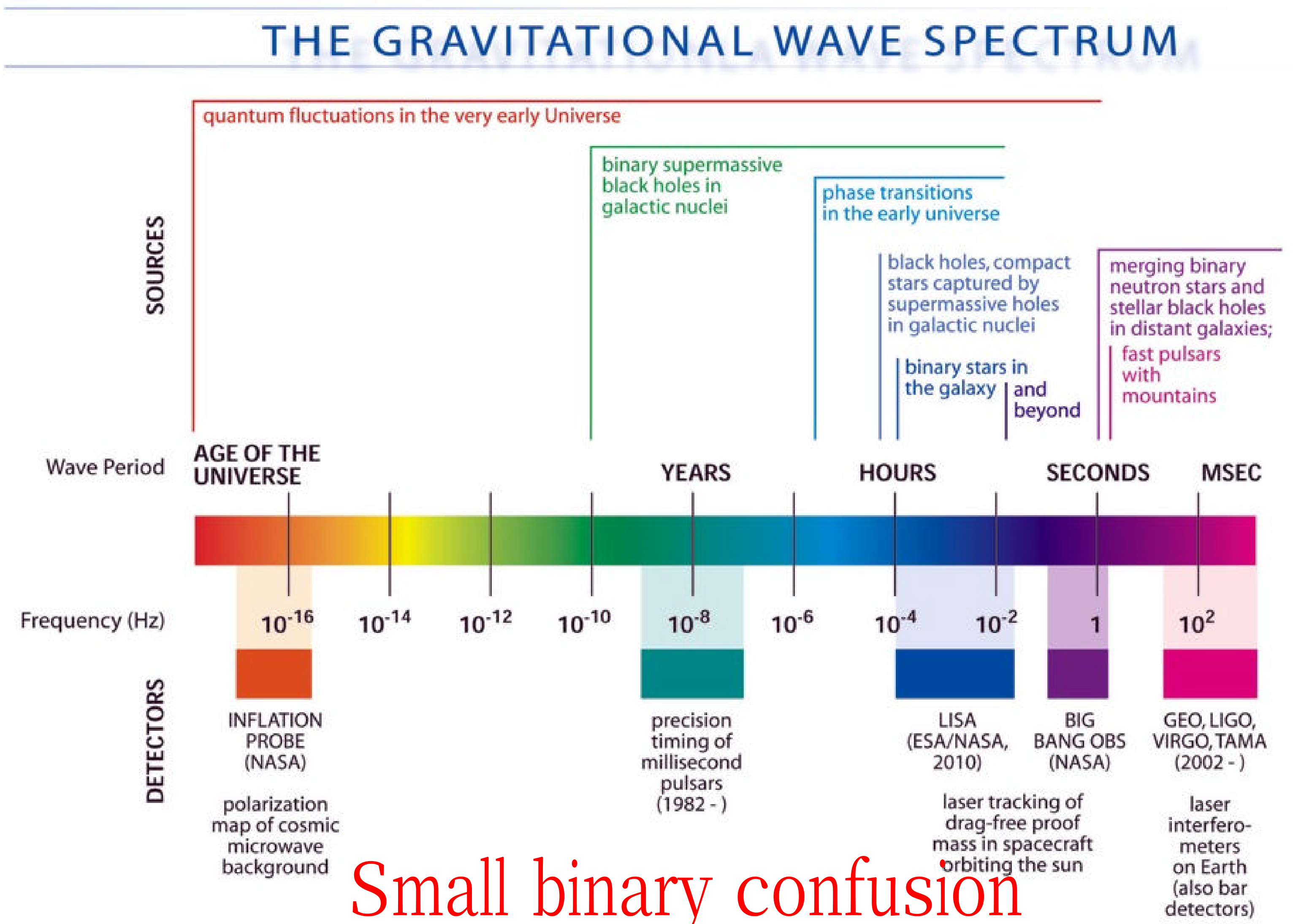
LIGO band cannot
see the whole jets

Beyond Einstein

~2020 ???



DECIGO/BBO



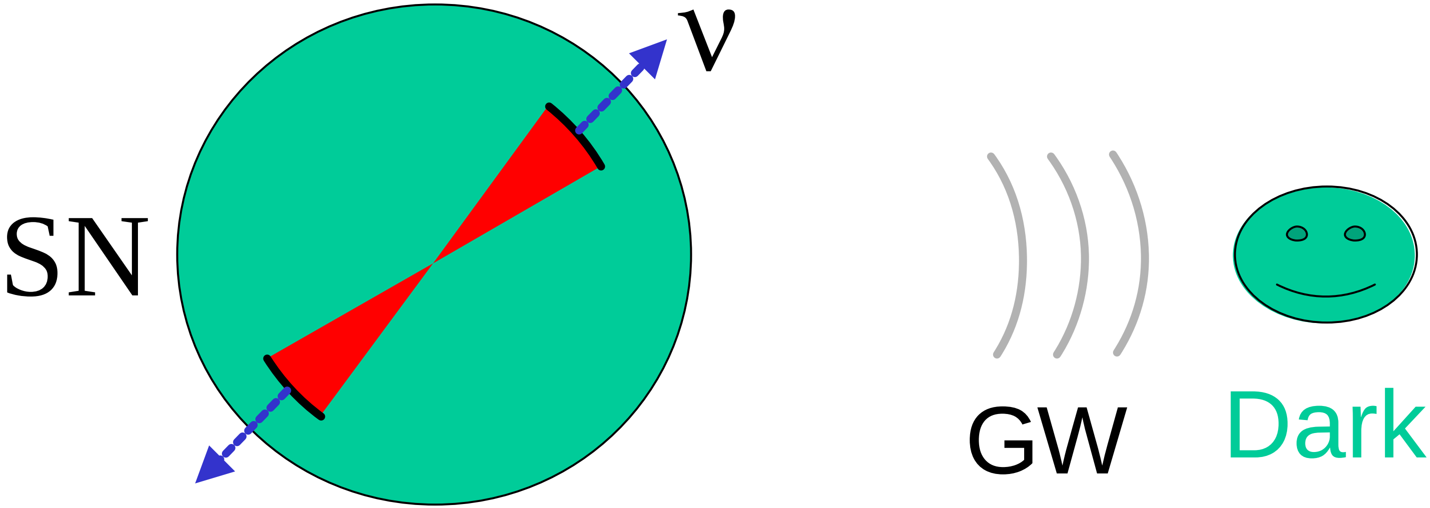
Small binary confusion

$\Rightarrow$ GW from inflation

Event Rate

1 GRB/yr within □ 300Mpc

1 SN/yr within □ 20Mpc



Dark GRBs are visible

SN1998bw: 40Mpc, SN2002ap: 10Mpc

Summary

A puzzle is being solved

Field structure: Polarization

Jet structure: X-ray flush, HEg

GRB cosmology: 1st star, z>10

UHECR, HEn, HEg: New frontier

GW: DECIGO/BBO

Swift satellite: Short GRB, 2004