MeV Gamma-Ray Bursts

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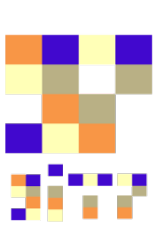
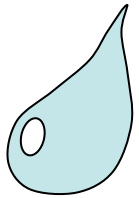


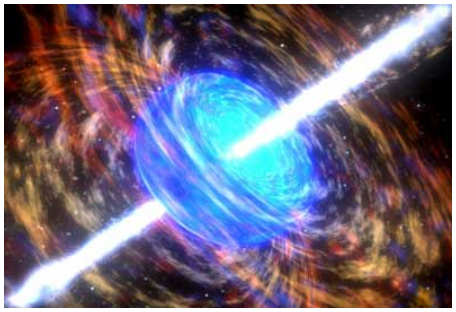
YITP
YUKAWA INSTITUTE FOR
THEORETICAL PHYSICS

Gamma-Ray Bursts

$E=mc^2$ (Einstein)

=





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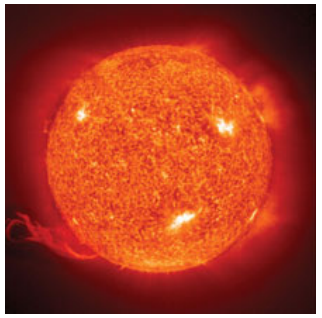
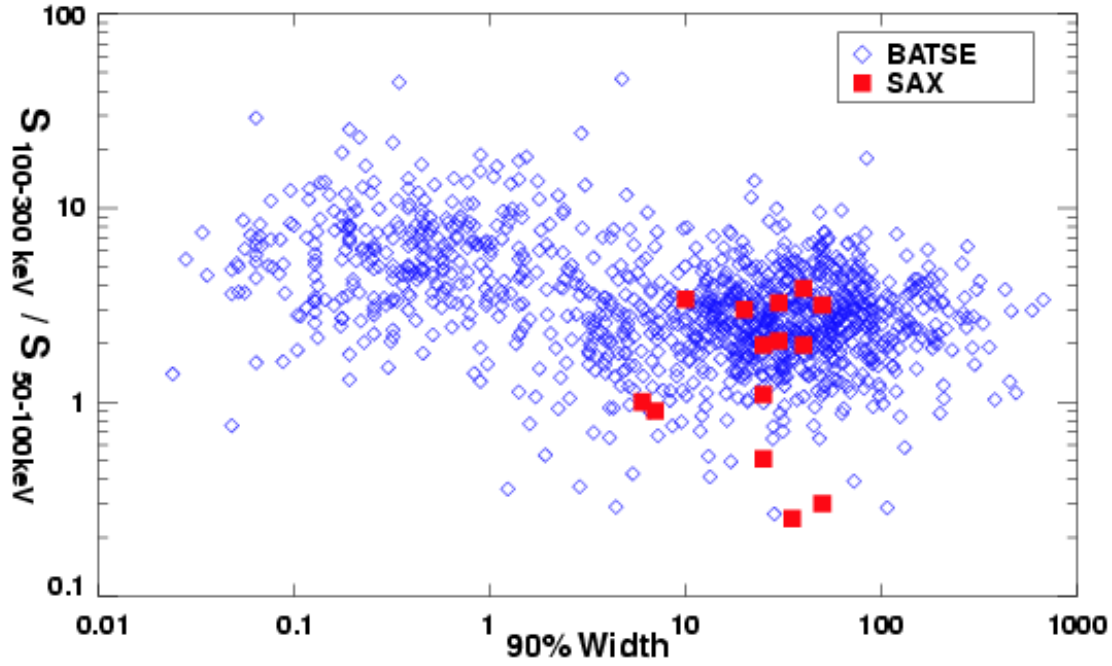


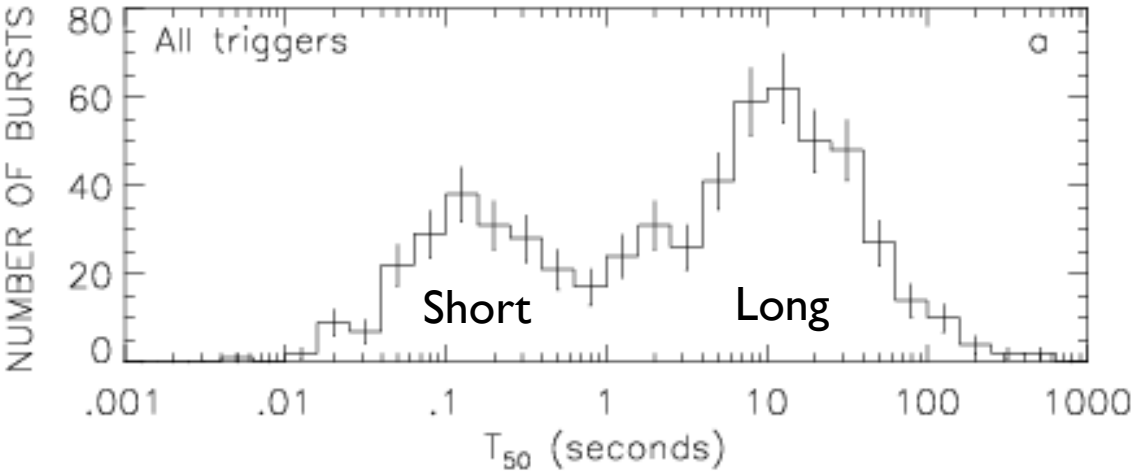
原子爆弾 ~1kg GRB ~10^{52}erg 太陽 ~10^{33}g

In ~sec, GRB release energy Sun emit over lifetime

The most luminous EM object

Duration





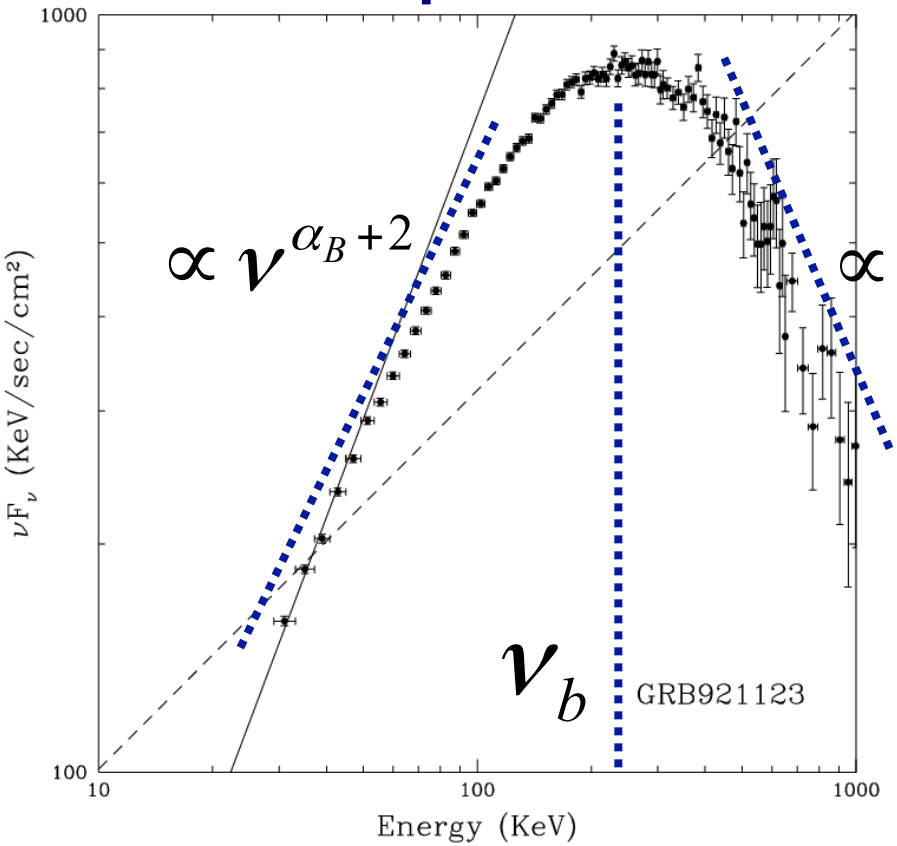
Long-soft
Short-hard

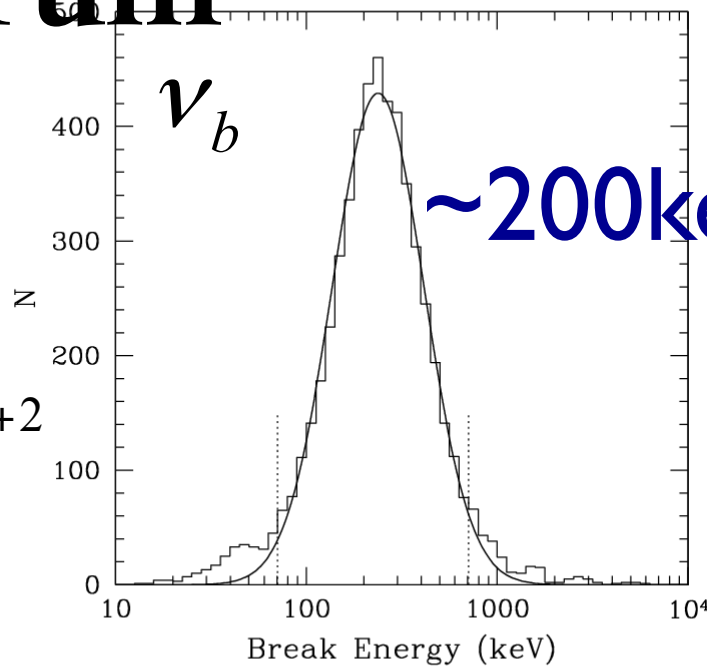
Long burst
Short burst

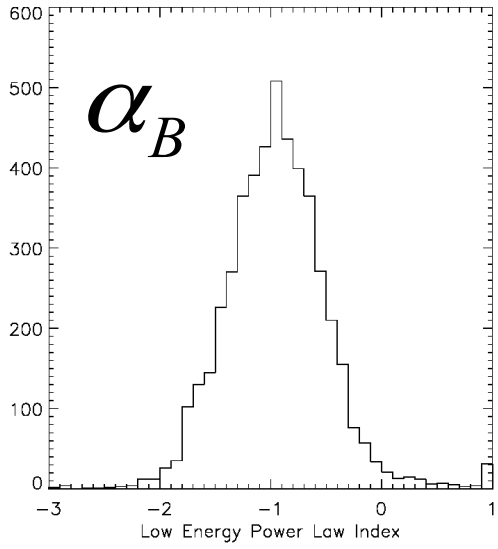
Hotokezaka's talk

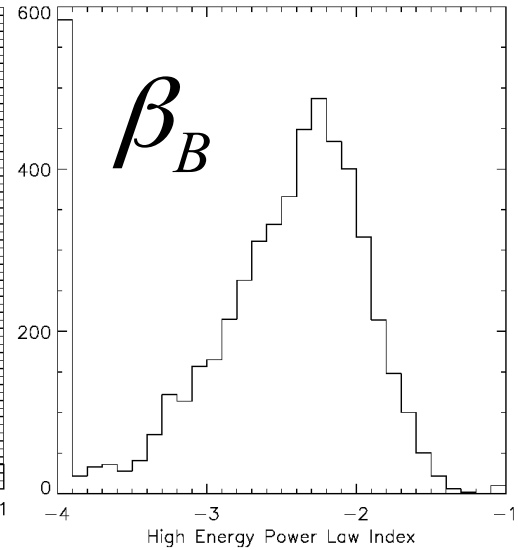
Spectrum

Band spectrum





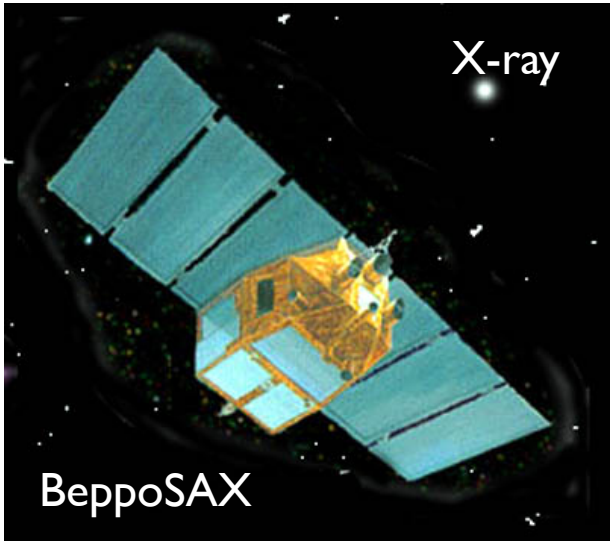


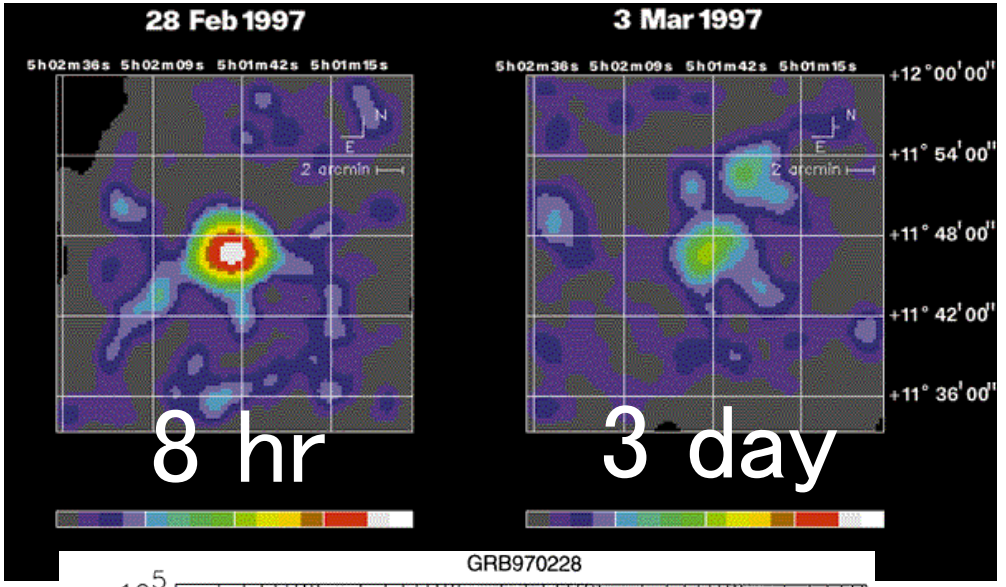


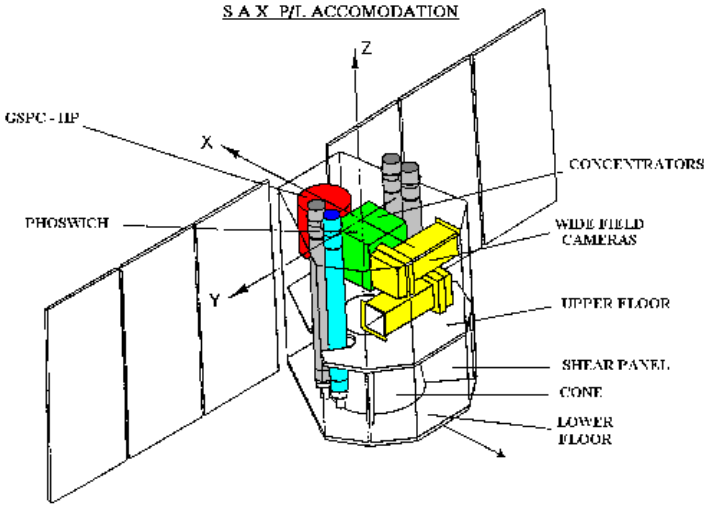
非熱的(≠黒体)

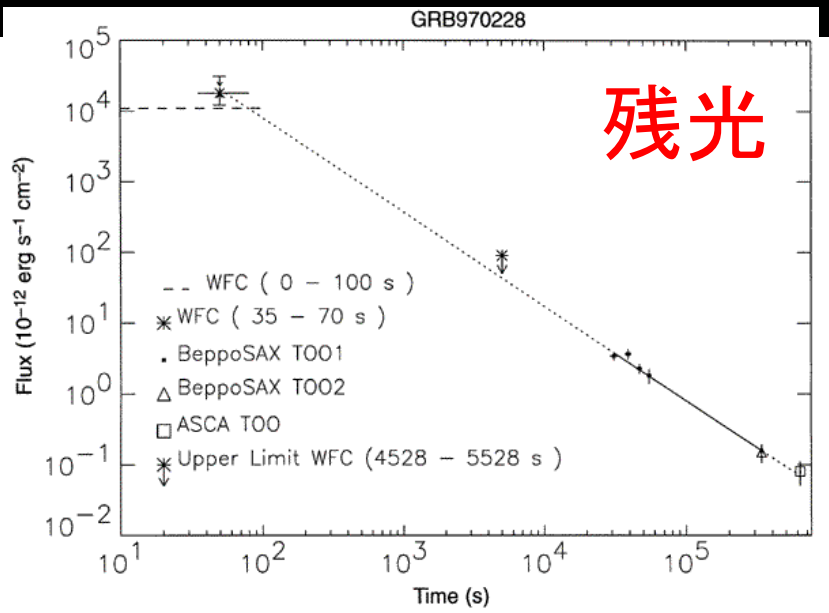
Preece+(00)

残光の発見@1997

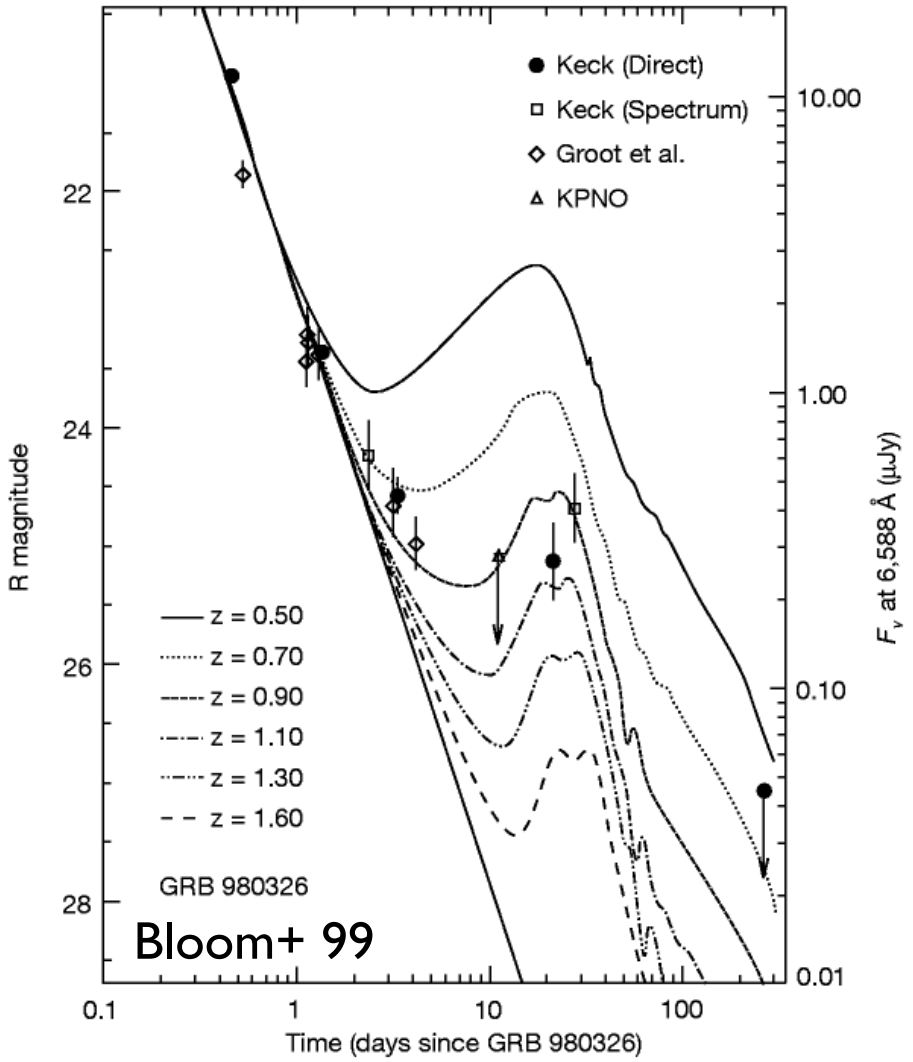

X-ray
BeppoSAX

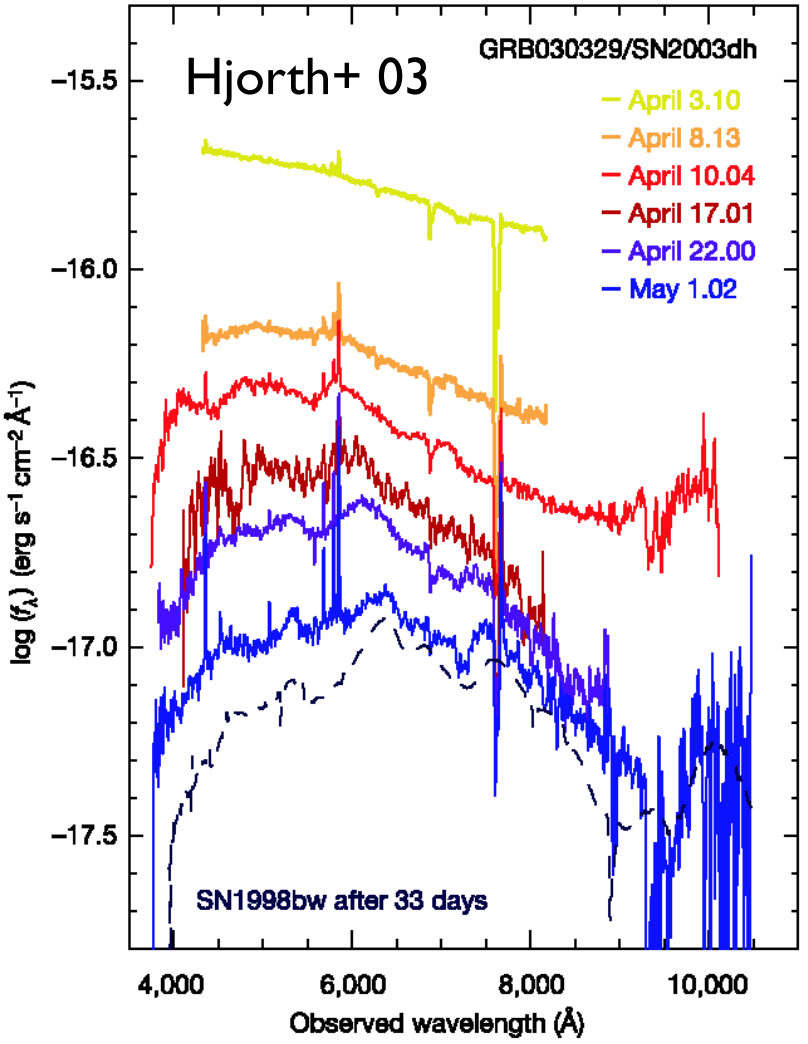

28 Feb 1997
3 Mar 1997
5h02m36s 5h02m09s 5h01m42s 5h01m15s
+12°00'00"
+11°54'00"
+11°48'00"
+11°42'00"
+11°36'00"
N
E
2 arcmin
8 hr
3 day


S A X P/L ACCOMODATION
Z
X
Y
GSPC - HP
PHOSWICH
CONCENTRATORS
WIDE FIELD CAMERAS
UPPER FLOOR
SHEAR PANEL
CONE
LOWER FLOOR

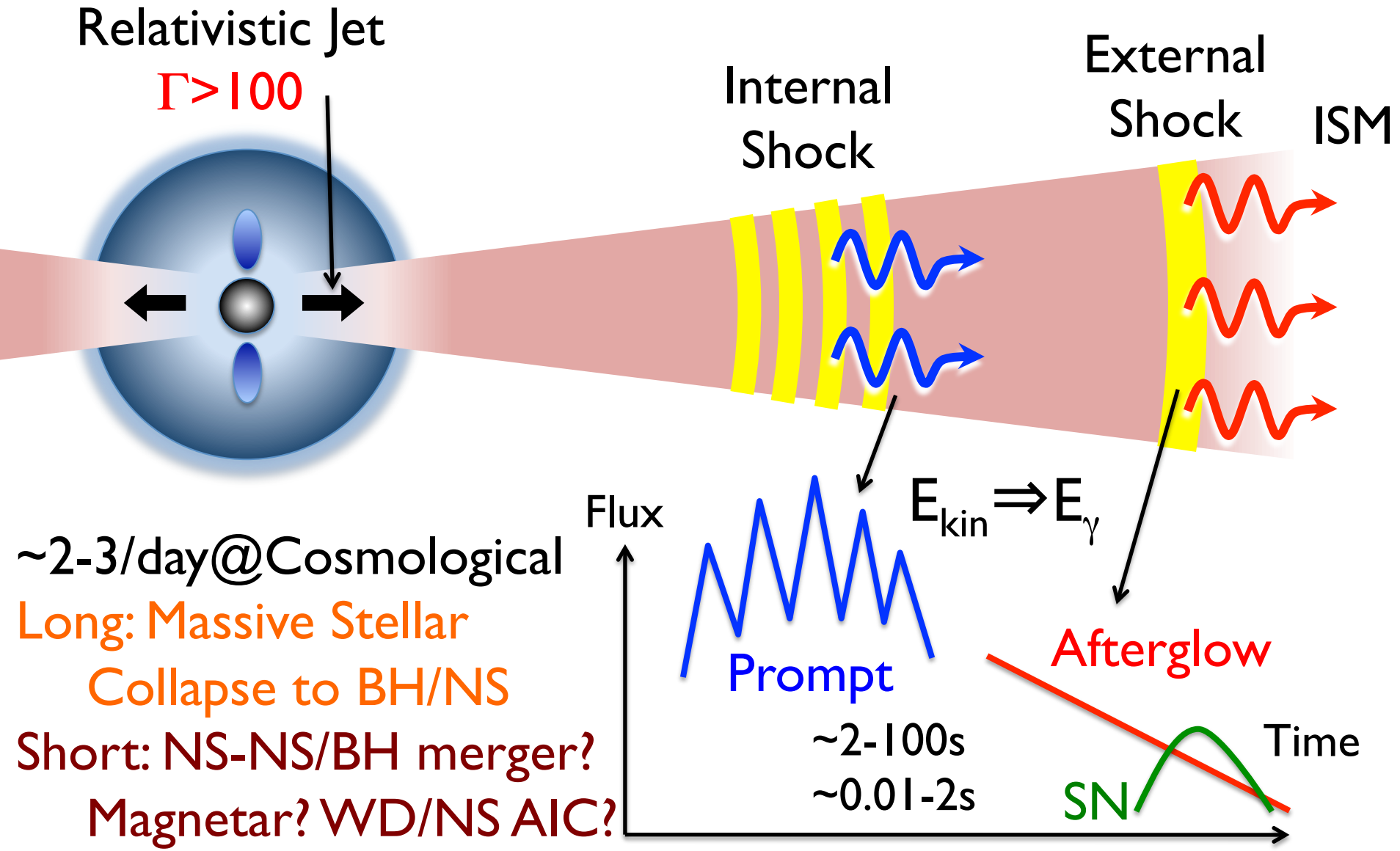

GRB970228
残光
Flux (10^{-12} erg s^{-1} cm^{-2})
Time (s)
WFC (0 – 100 s)
WFC (35 – 70 s)
BeppoSAX TOO1
BeppoSAX TOO2
ASCA TOO
Upper Limit WFC (4528 – 5528 s)

超新星爆発の発見@2003





Standard Model



~2-3/day@Cosmological

Long: Massive Stellar Collapse to BH/NS

Short: NS-NS/BH merger? Magnetar? WD/NS AIC?

Unresolved Big Problems

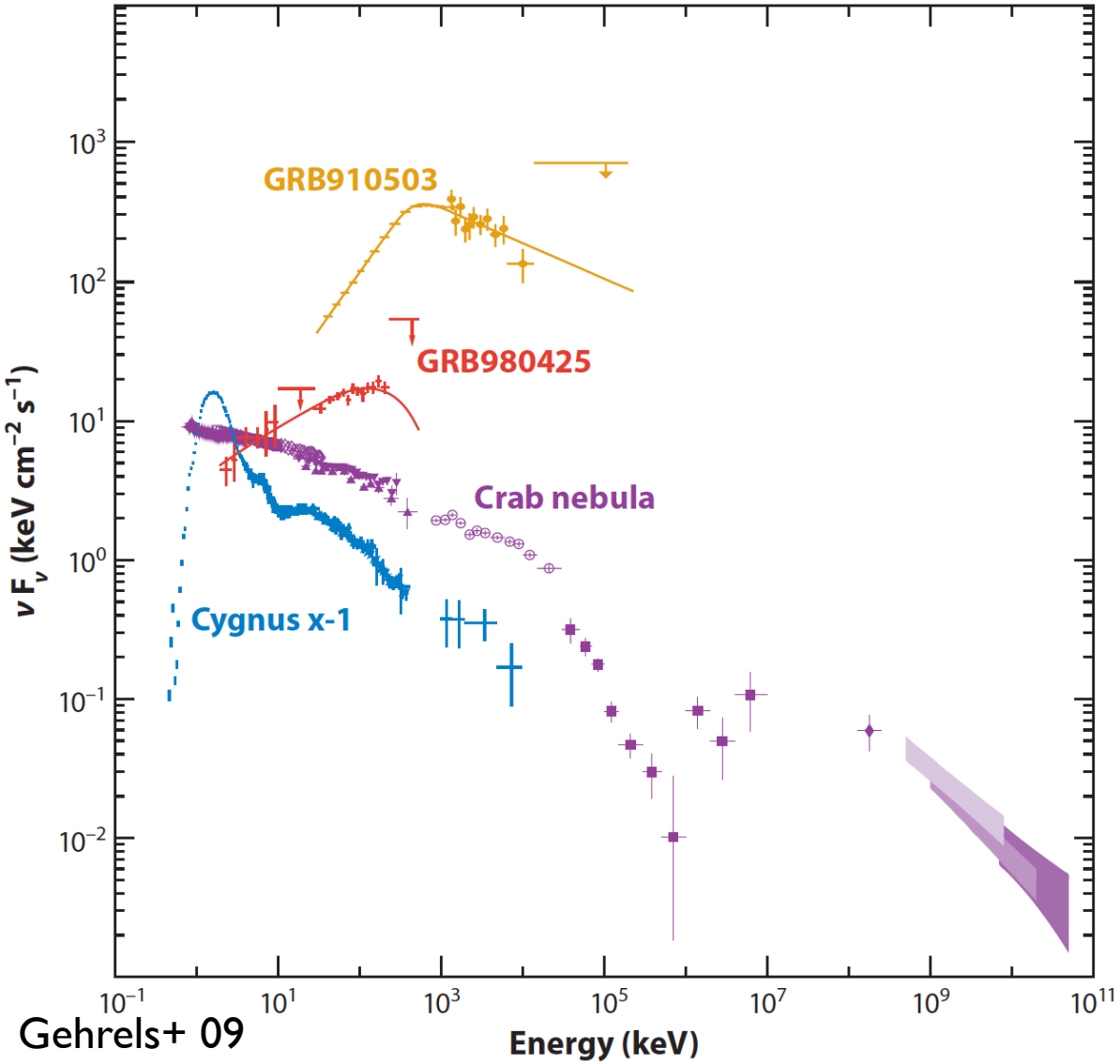
- ***Jet composition***
  - p, $e^{\pm}$, γ plasma? Poynting?
- ***Emission mechanism***
  - Synchrotron? Photosphere? Componized?
- ***Central engine***
  - Black hole? Neutron star?
- ***Jet acceleration mechanism***
  - ν? B?
- ***Progenitors***
  - Single? Binary? Metallicity?

MeV Physics

- ***Prompt emission***
  - Nonthermal, Thermal, High-energy
  - Polarization
- ***Afterglow***
  - Synchrotron, Reverse, Steep decay, Flare, Plateau
- ***Supernova***
  - ^{56}Ni
- ***Diverse populations***
  - llGRB, ulGRB, Pop III GRB, Shock breakout, TDE

Better than BATSE
Large FOV

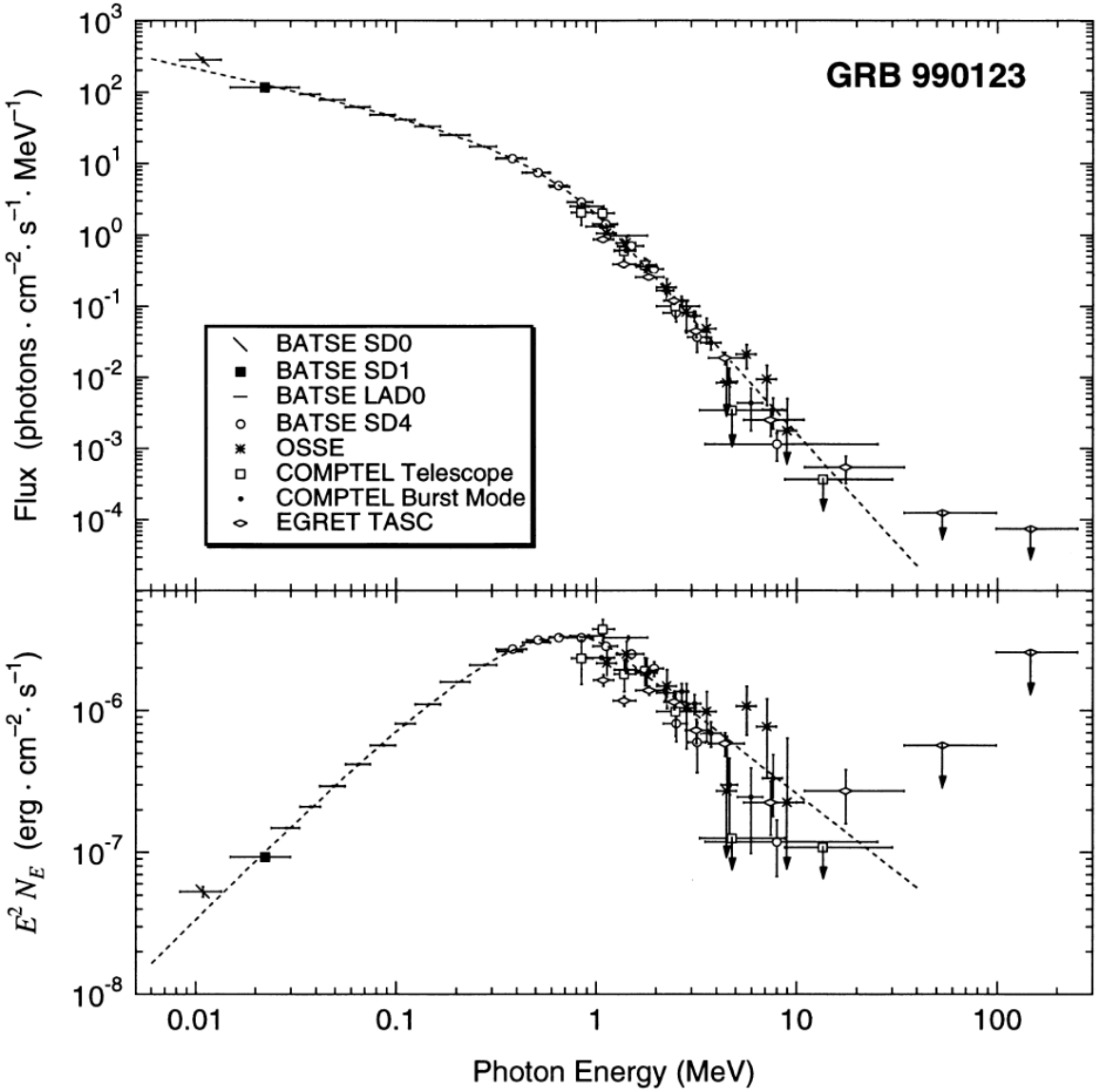
GRB Flux



Gehrels+ 09

Max sensitivity
~10mCrab@1Ms
by eASTROGAM
↓
~10Crab@1s
~1Crab@100s

Spectrum

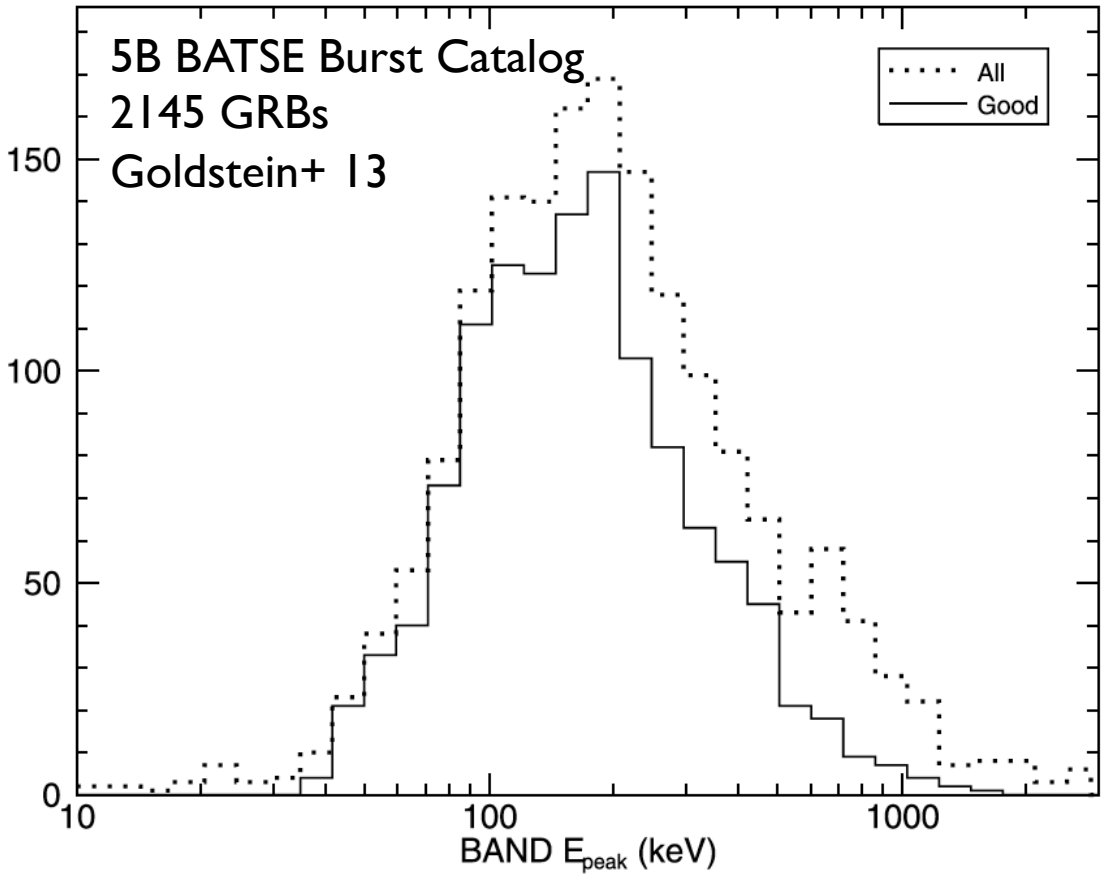


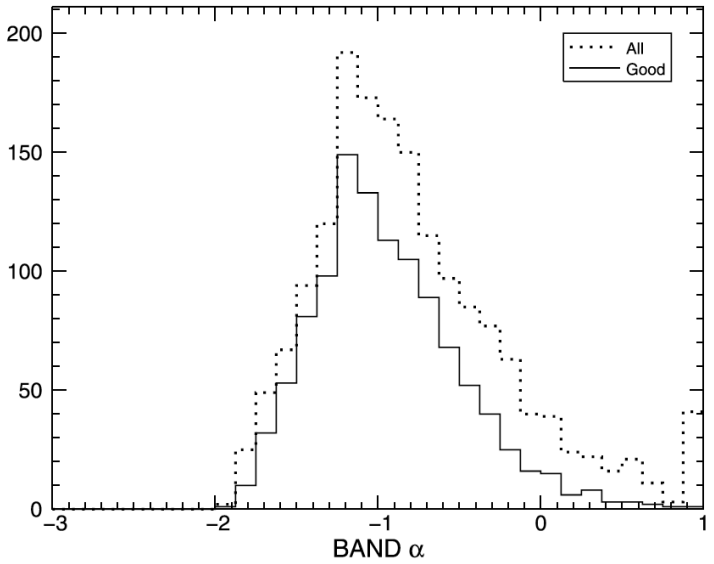
明るいGRB

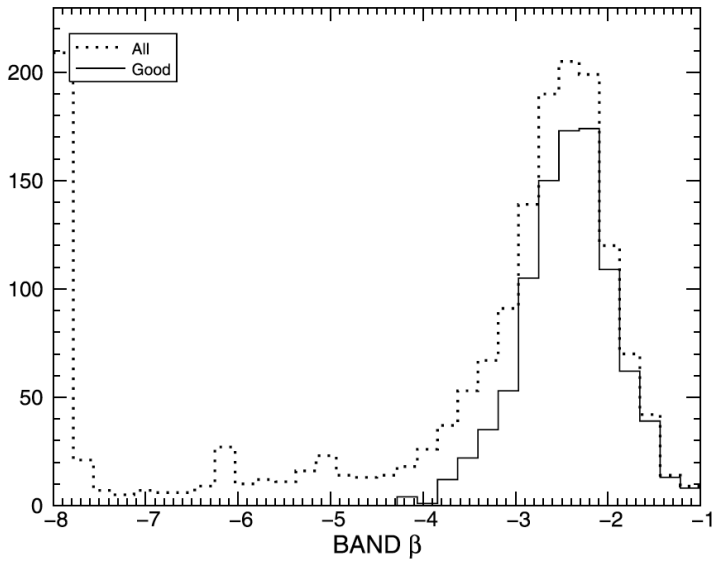
>MeV
はまだまだ

Briggs+ 99

Spectrum





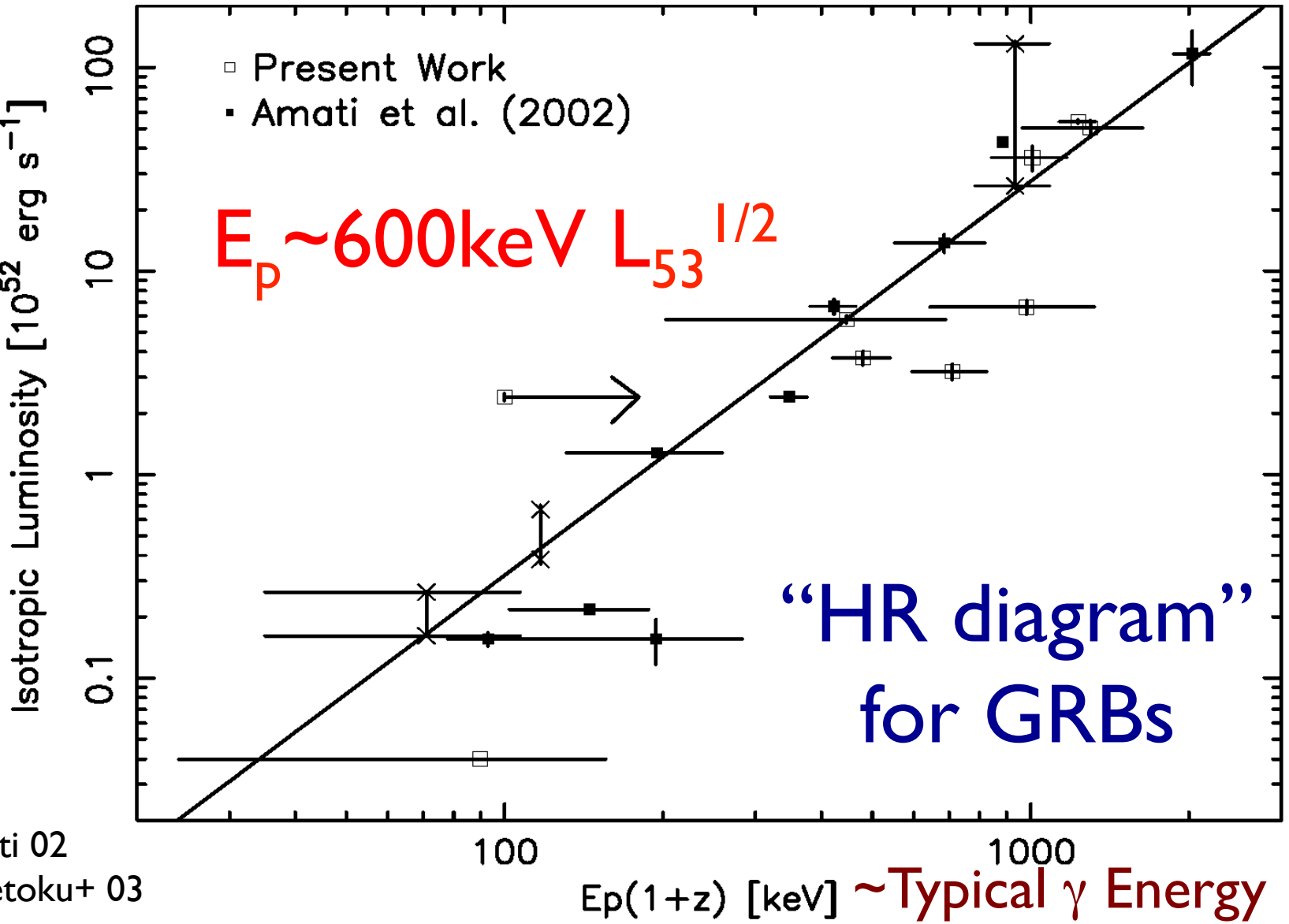


Sensitivity (50-300keV)

CGRO BATSE: ~0.2 cm^{-2} s^{-1}

Fermi GBM: ~0.5 cm^{-2} s^{-1}

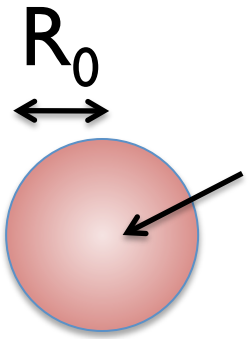
Amati/Yonetoku Relation



Amati 02
Yonetoku+ 03

Fireball Model

Paczynski 86
Goodman 86



- Initial Radius

$$R_0 \approx c\Delta t \sim 3\times10^7\,\mathrm{cm}\left(\frac{\Delta t}{1\ \mathrm{ms}}\right)$$

~10R_{BH}

- Optical Depth

$$\tau_{\gamma\gamma\rightarrow e^+e^-} >> 1 \Rightarrow \text{Thermalize}$$

- Temperature

$$L = 4\pi R_0^2 c a T_0^4$$

$$T_0 = \left(\frac{L}{4\pi R_0^2 c a}\right)^{\frac{1}{4}} \approx 1\ \mathrm{MeV}\left(\frac{L}{10^{52}\mathrm{erg\ s^{-1}}}\right)^{\frac{1}{4}}\left(\frac{R_0}{10^7\mathrm{cm}}\right)^{-\frac{1}{2}}$$

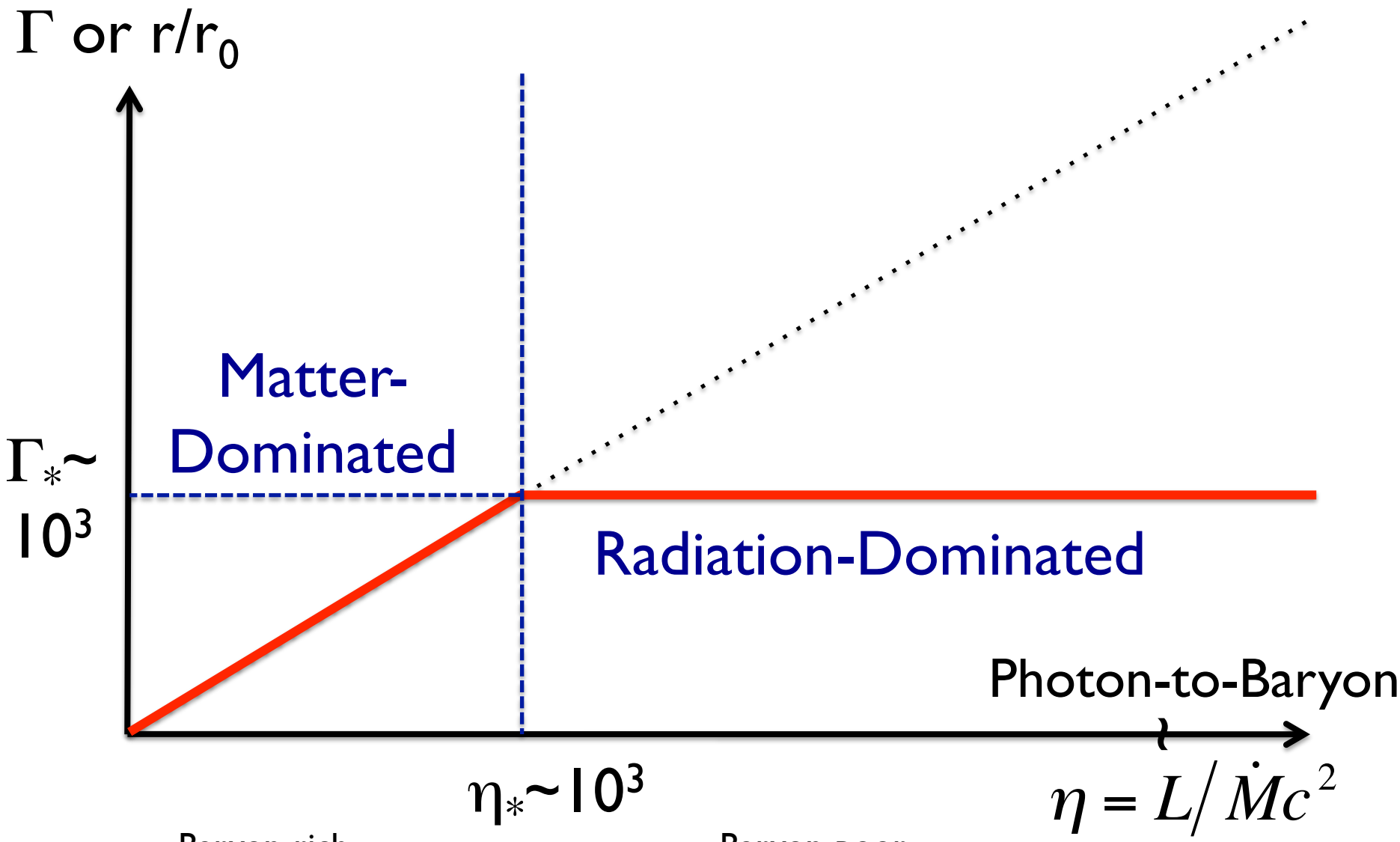
$$a = \frac{\pi^2 k_B^4}{15\hbar^3 c^3} = \frac{4\sigma_{SB}}{c}$$

$$= 7.6\times10^{-15}\mathrm{erg\ cm^{-3}\ K^{-4}}$$

Leptonic (γ, $e^{\pm}$) Fireball

Baryon Load

Shemi & Piran 90
Rees & Meszaros 94



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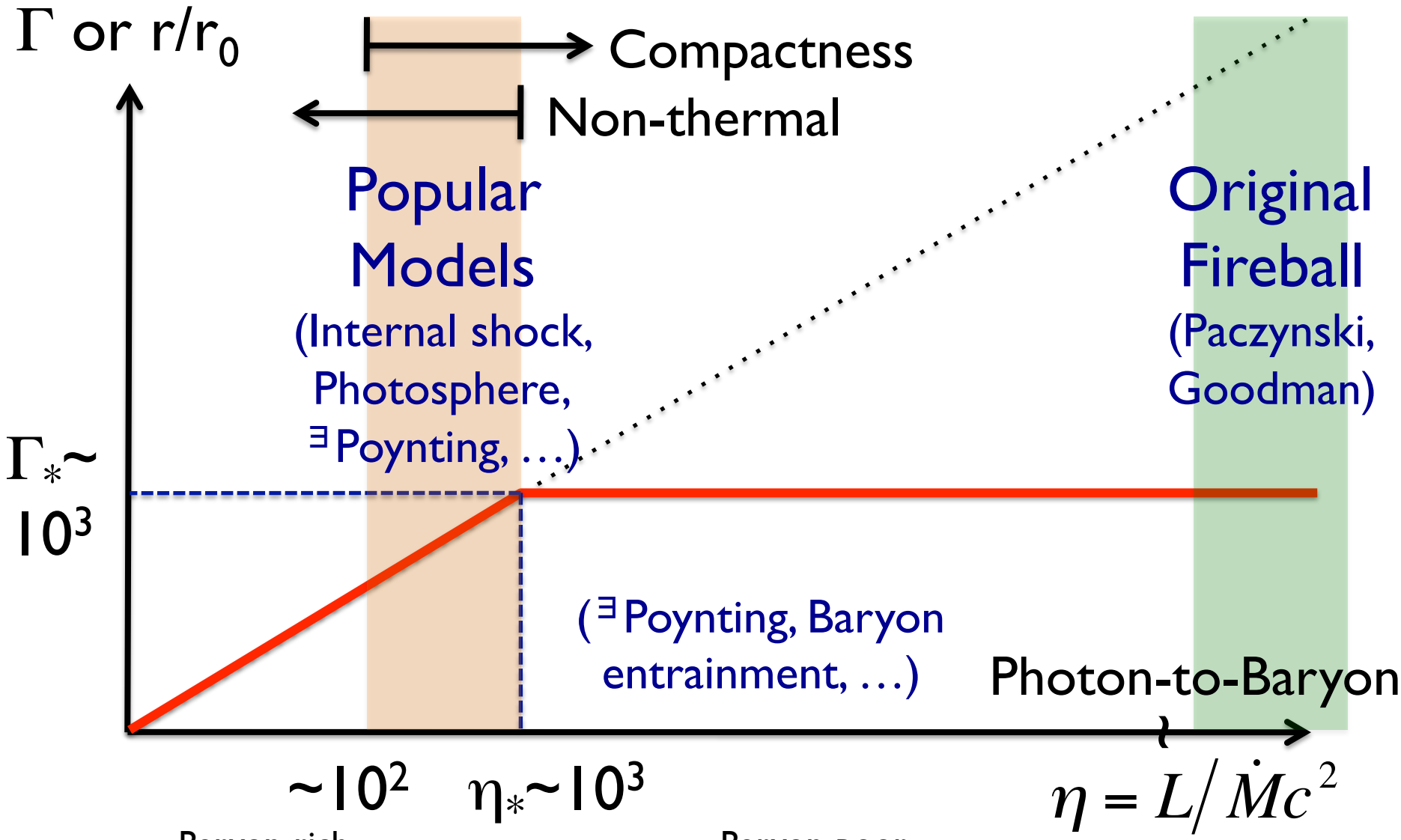


Internal Shock

$\Gamma_r > \Gamma_s$

Kinetic energy ⇒ Internal energy

Energy & Momentum conservation

⇒ η_γ~6% if $\Gamma_r=2\Gamma_s$, $m_r=m_s$

η_γ~43% if $\Gamma_r=10\Gamma_s$, $m_r=m_s$

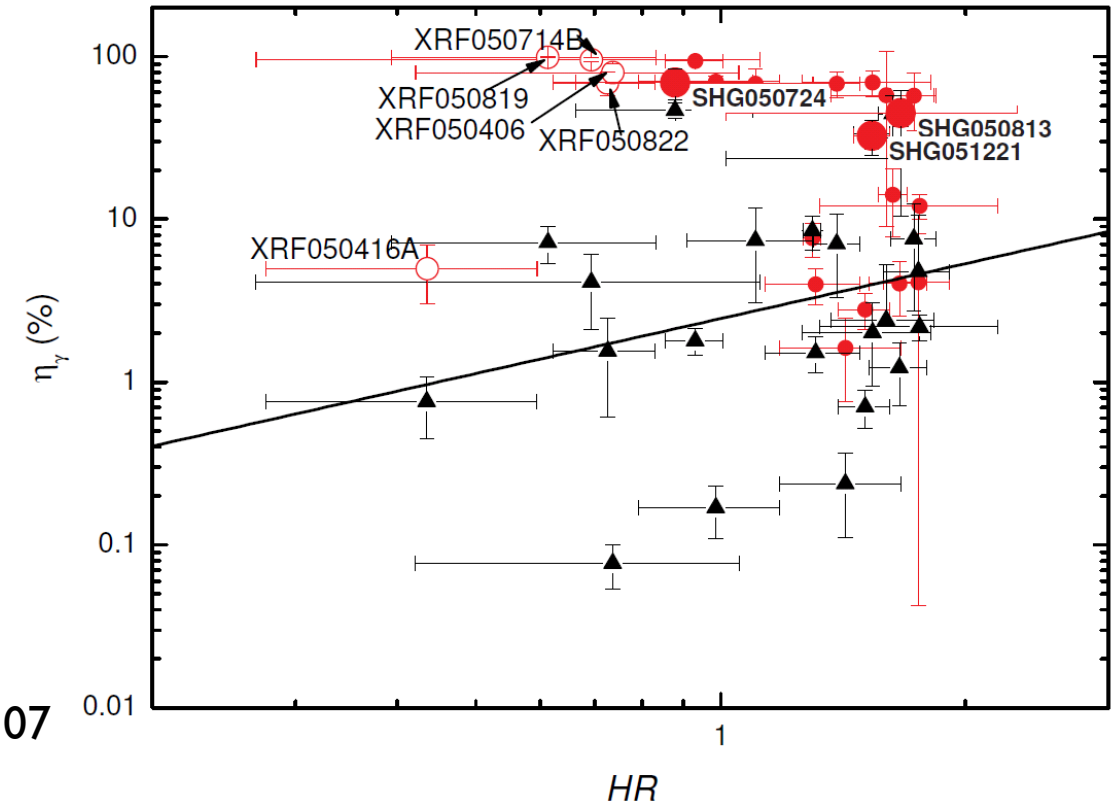
Kobayashi & Sari 01

Γの幅が小 ⇒
低効率 (<10%)

N	γ_{min}	γ_{max}	Efficiency ($\epsilon_e = 0.1$) (%)	Efficiency ($\epsilon_e = 0.5$) (%)
30	10^2	10^3	9.2 ± 2.3	16.2 ± 3.0
30	10	10^4	40.0 ± 9.2	67.5 ± 9.3
10^2	10^2	10^3	15.1 ± 1.5	17.7 ± 1.5
10^2	10	10^4	62.9 ± 4.8	72.4 ± 4.3

Radiative Efficiency

$$\frac{E_{GRB}}{E_{GRB}+E_{Afterglow}} > 50\%$$ for some bursts



▲: Pre-Swift

●: Swift

Large: Short

Open: XRF

Assuming ε_e=0.1

Zhang+ 07

KI+ 06

Synchrotron Shock Model

内部衝撃波

⇒1. 電子加速 $\gamma_m \approx \xi_e (m_p/m_e)$

2. 磁場増幅 $4\pi r_i^2 c\Gamma^2 B^2/8\pi = \xi_B L_{\rm int} \quad (L_{\rm int.} = L_\gamma/\xi_e)$

⇒シンクロトロン

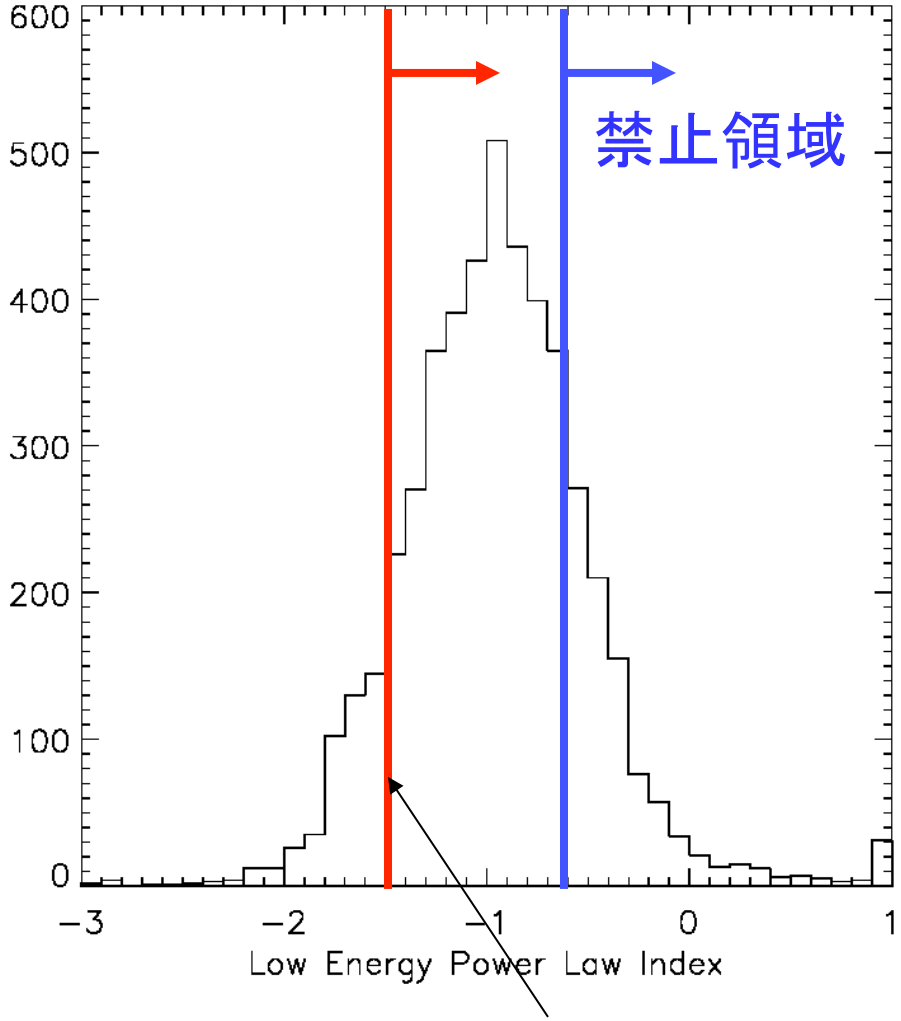
$$\epsilon_{\gamma b} = \Gamma\hbar\gamma_m^2 eB/m_e c$$

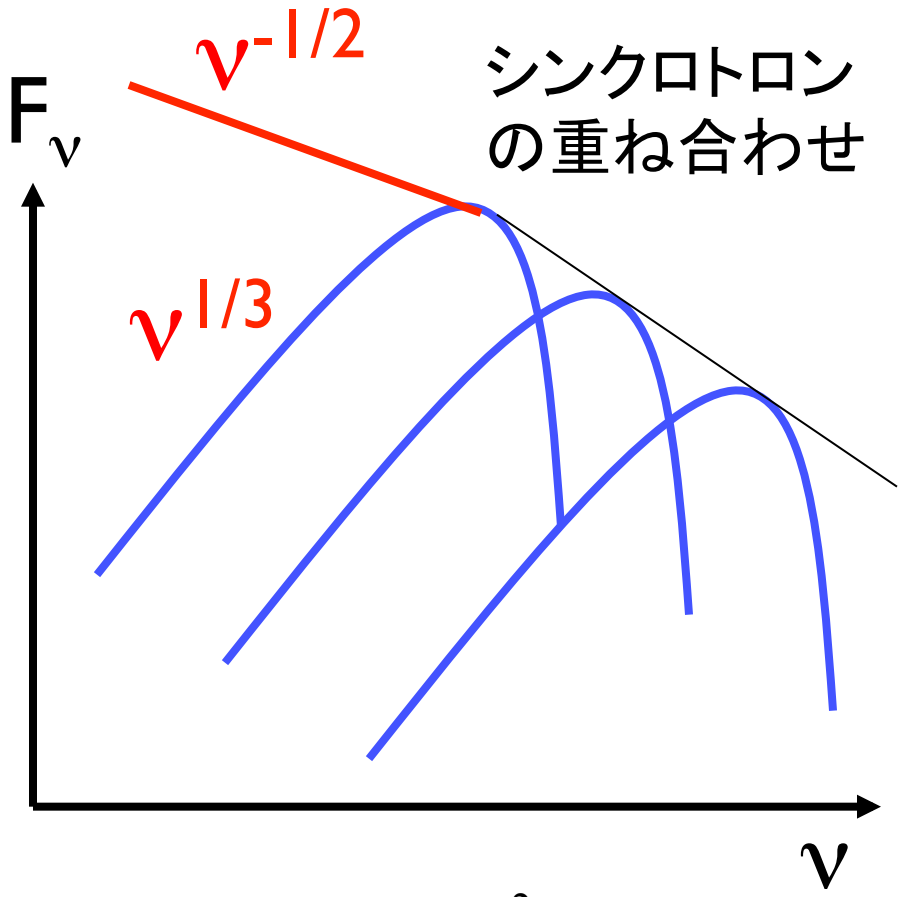
$$\epsilon_{\gamma b} \approx 1\xi_B^{1/2}\xi_e^{3/2}\frac{L_{\gamma,52}^{1/2}}{\Gamma_{2.5}^2\Delta t_{-2}}{\rm MeV}.$$ with $r_i \sim c\Gamma^2\Delta t$

一応、米徳相関 $E_p \sim L^{1/2}$ はでる

Γは幅を持つ⇒通常相関は崩れる

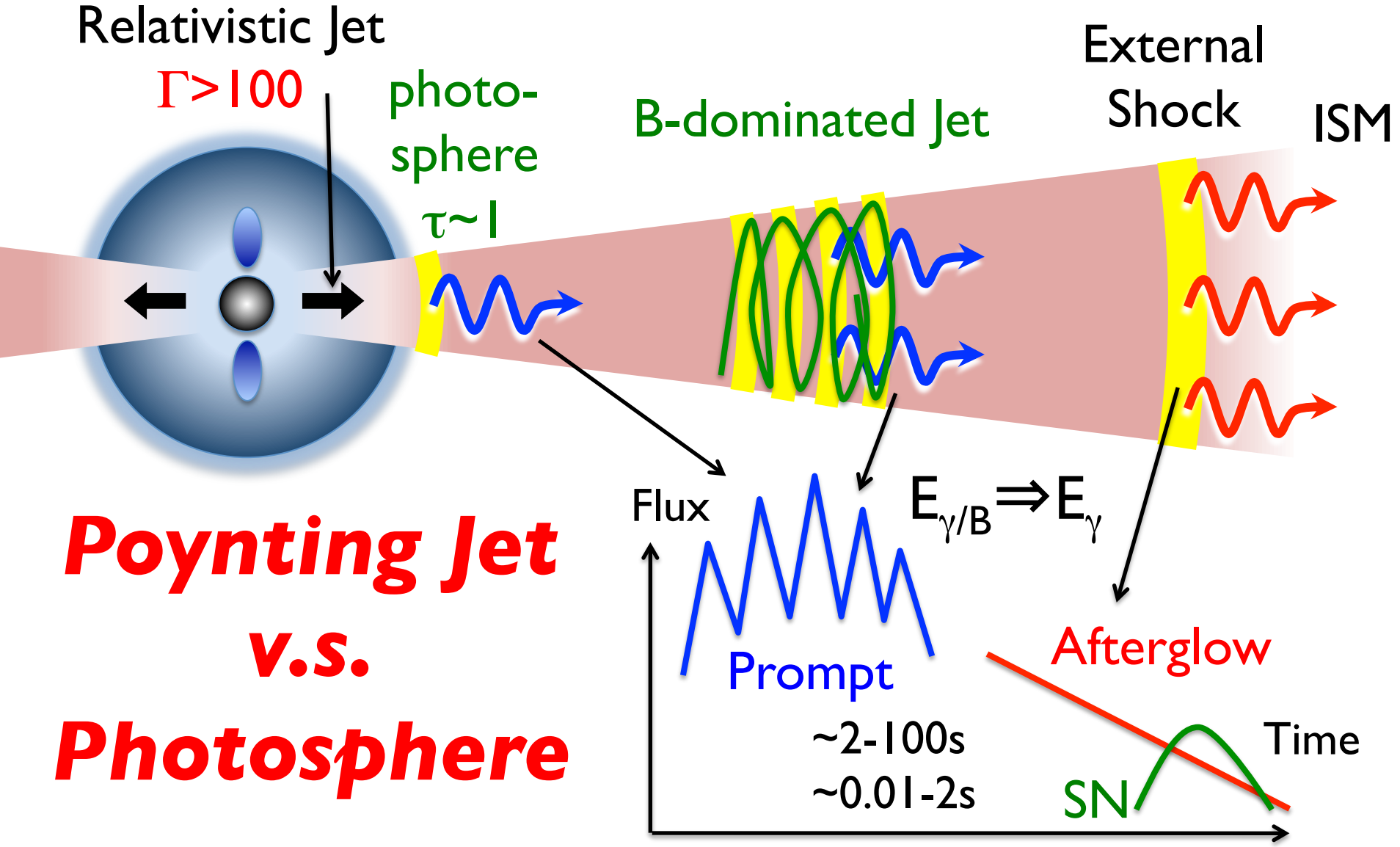
Death Line



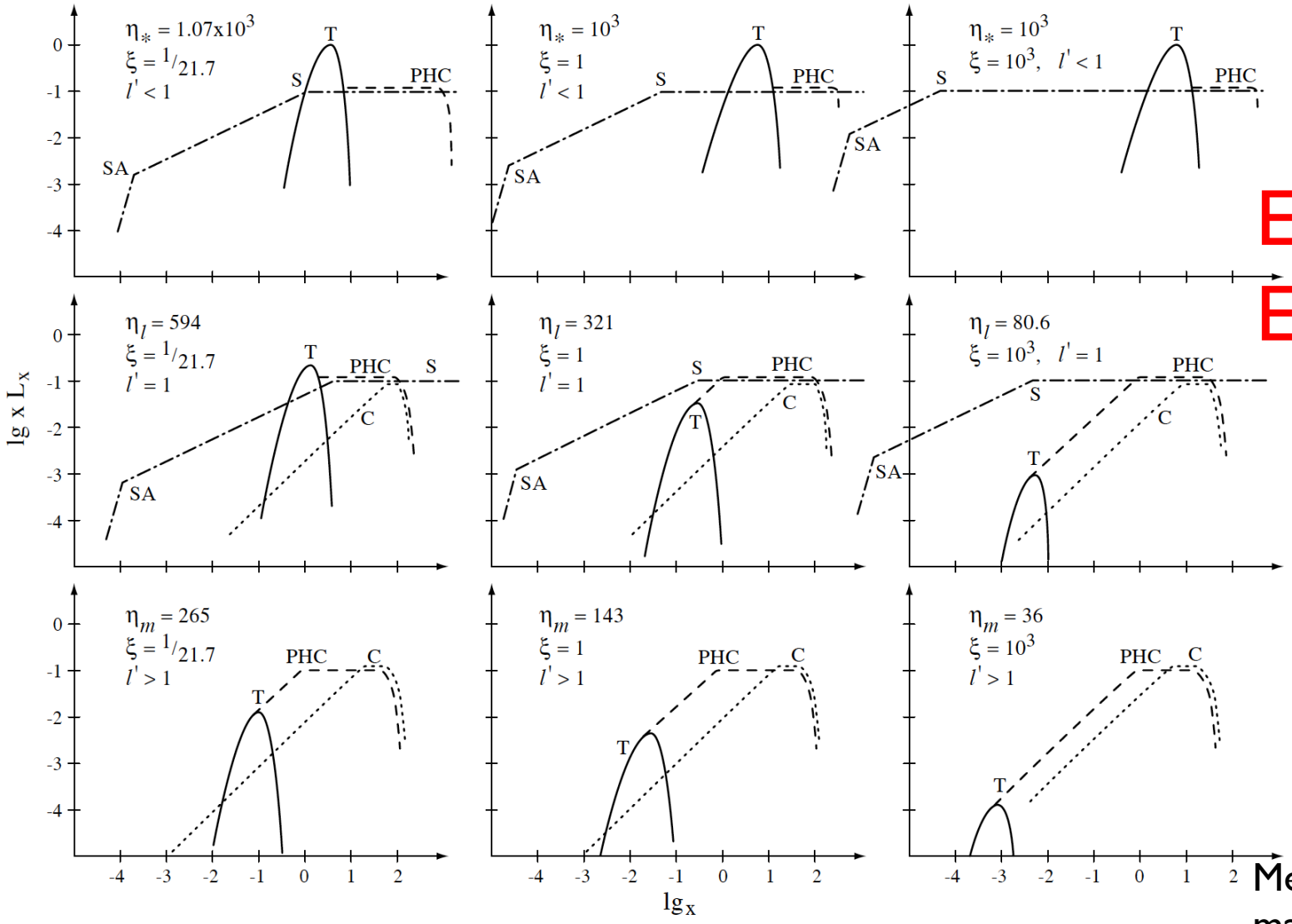


電子の冷却時間 $t_{cool} = \dfrac{\gamma_e m_e c^2}{P_{synchrotron}} << t_{dyn}$

Beyond Standard Model



Photosphere Model



$E_{peak}=E_{th}$?

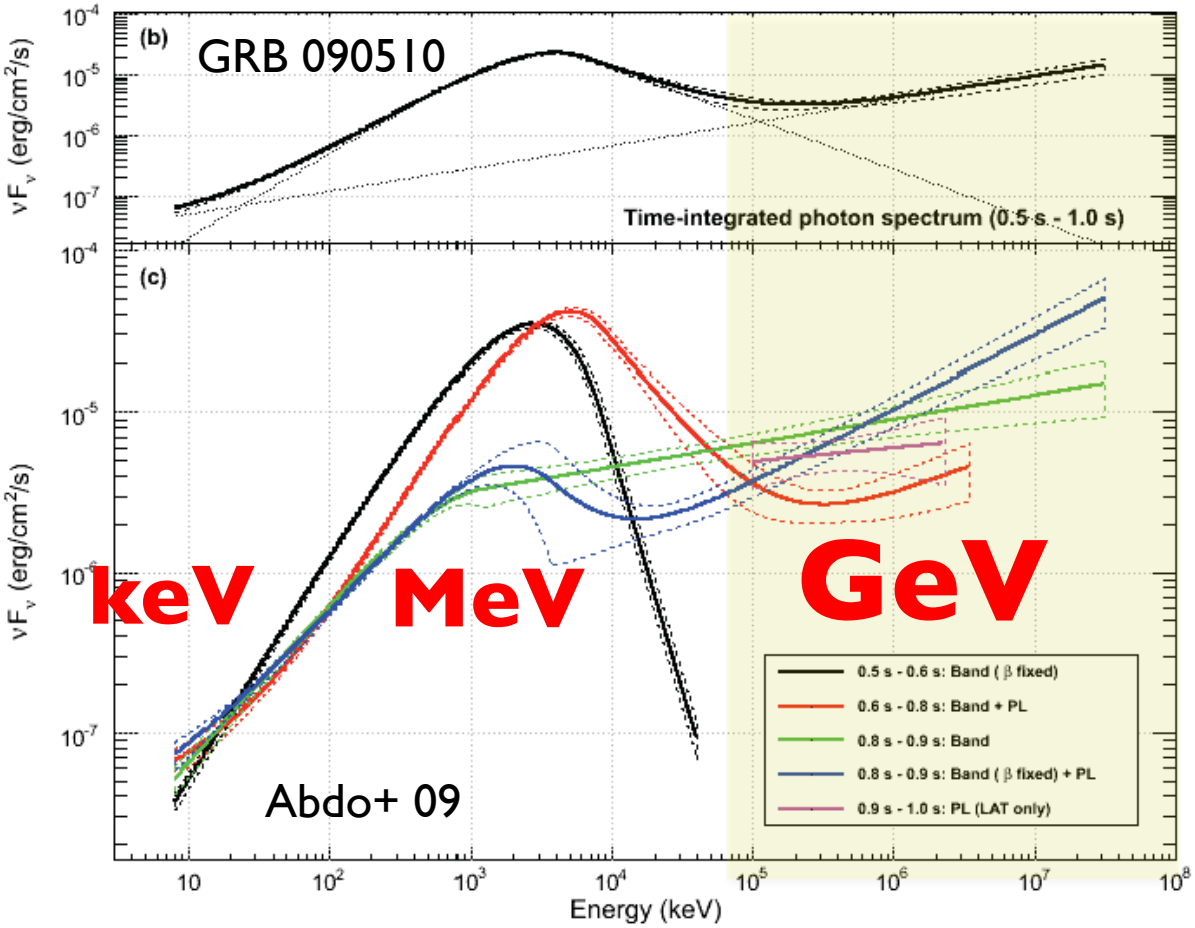
$E_{peak}=E_{syn}$?

Meszaros & Rees 00
many papers

Tanaka's talk

Fermi Revolution

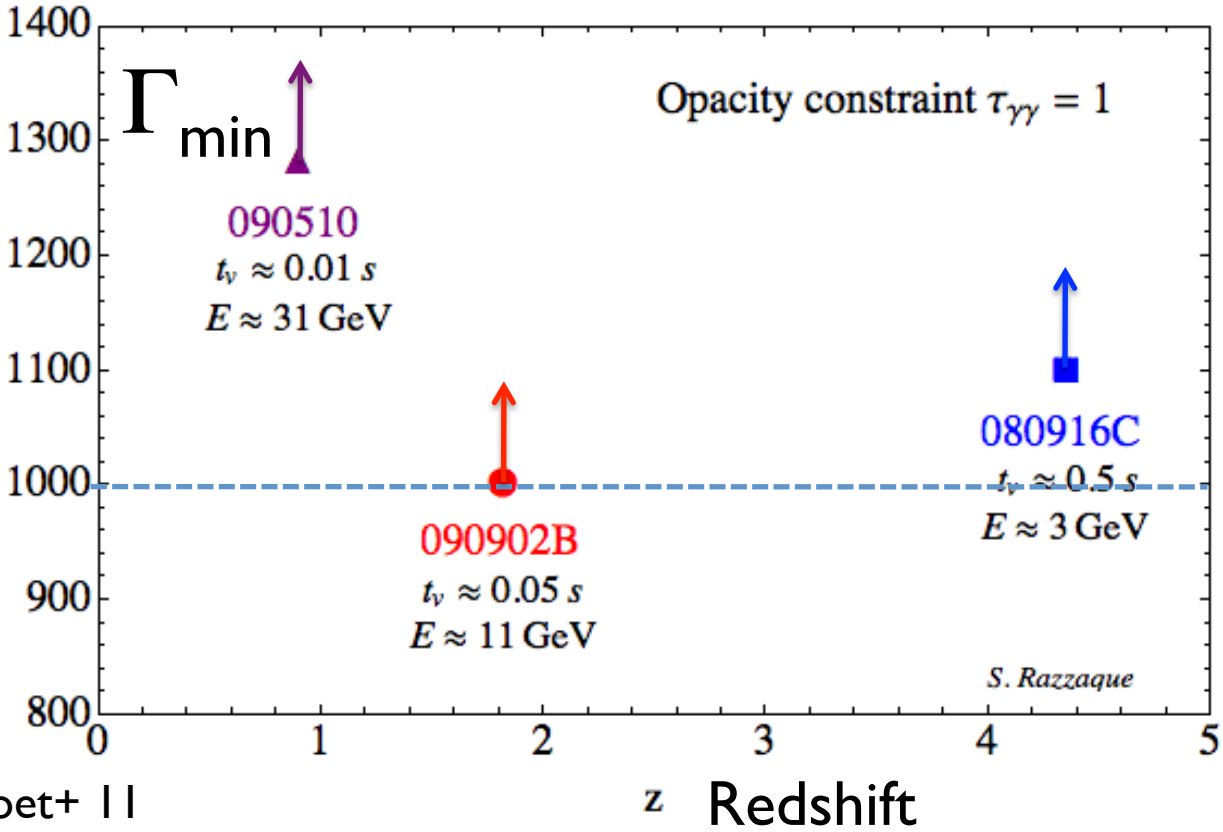
GeV γ from GRBs



High Lorentz Factor?

- $\gamma\gamma \rightarrow e^+e^-$ (ε_{th}~MeV)
  - $R \sim c\Delta t \Rightarrow \tau \sim \sigma_T N_\gamma / 4\pi R^2 \gg 1$ (γ-ray cannot escape)
- **Relativistic**
  - $R \sim \Gamma^2 c\Delta t$
  - Blueshift
  - $\tau \sim \Gamma^{2\beta-2} \sim \Gamma^{-6}$
- **$\Gamma > 10^3$!**

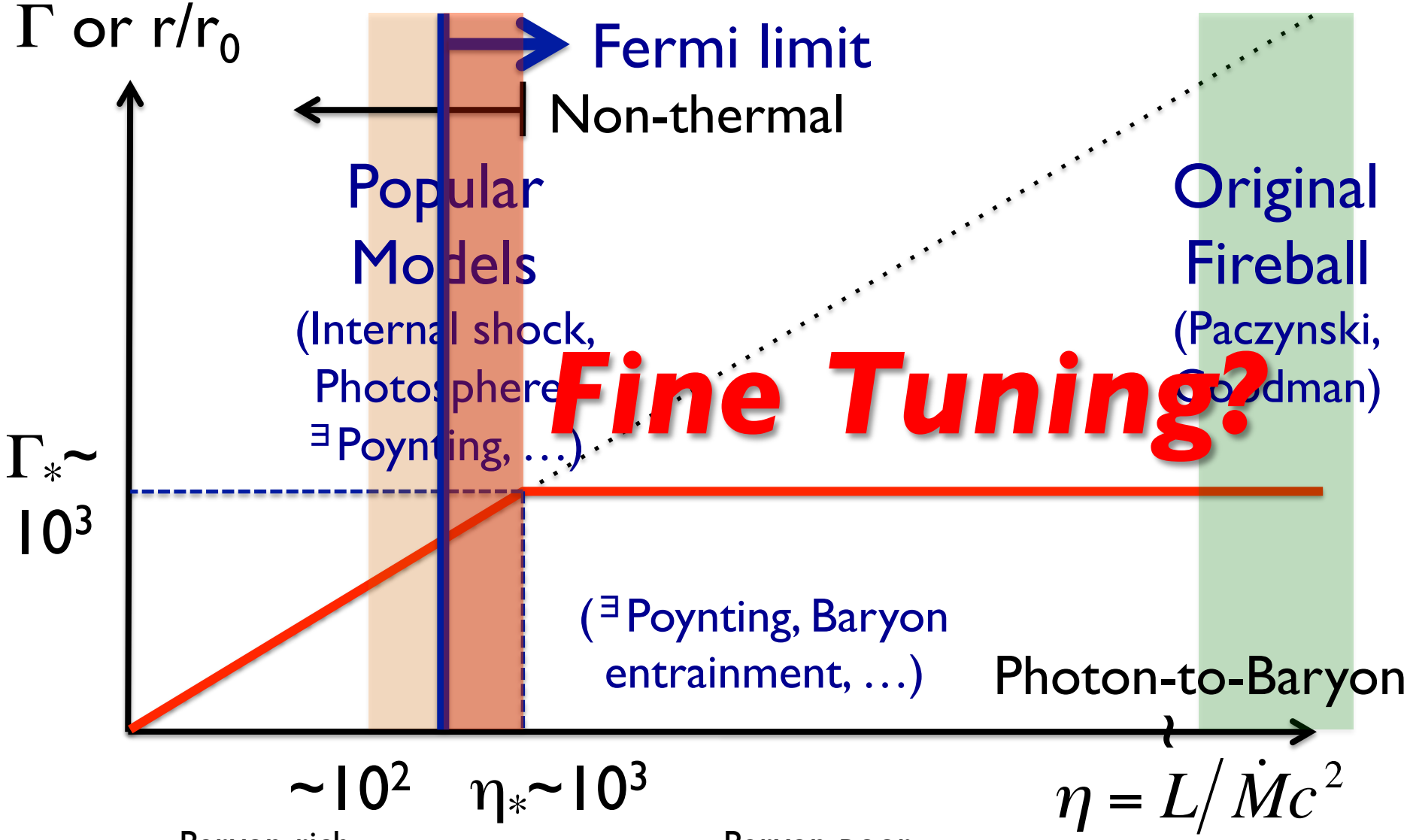
$v > 0.999999 \times c$



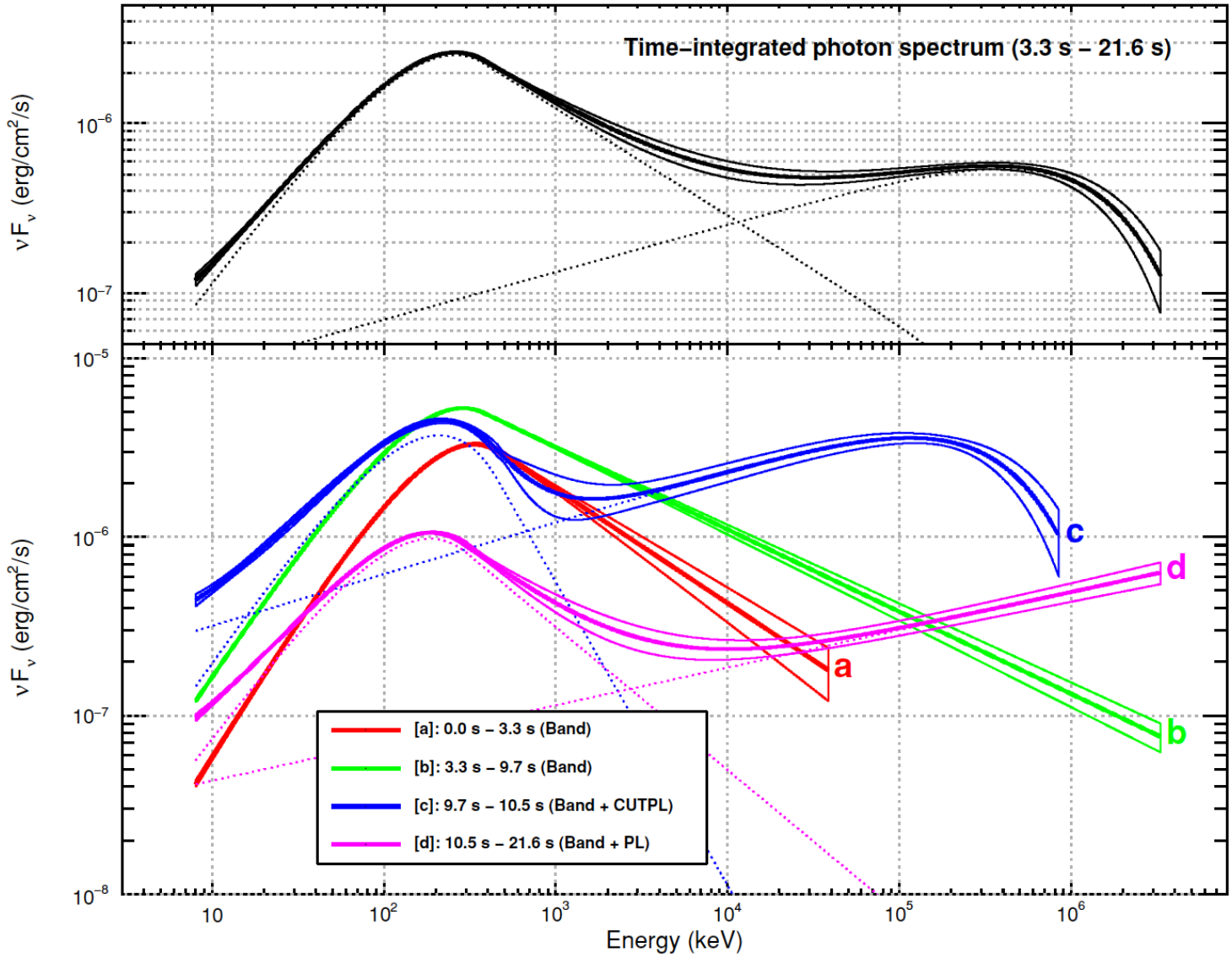
But Li 08, Granot+08, Bosnjak+09, Aoi+ 10, Zou+11, Zhao+ 11, Hascoet+ 11

Fine-tuning Problem?

KI+ 11



$\gamma\gamma \rightarrow e^+e^-$ Cutoff?

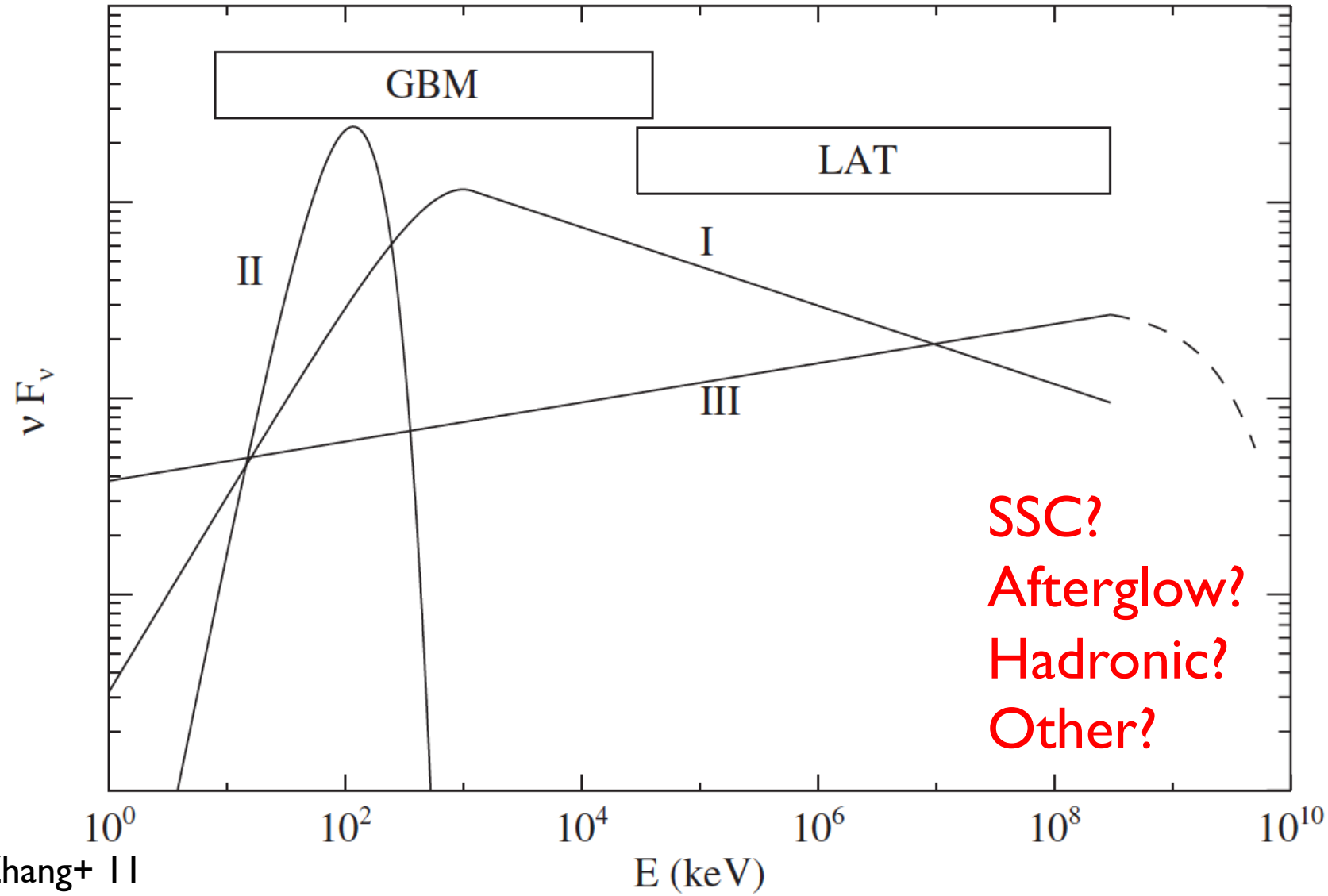


$$\frac{\varepsilon_{\rm cut}}{\rm MeV} \sim \left(\frac{\Gamma}{100}\right)^5$$

Fermi GRB は明るい

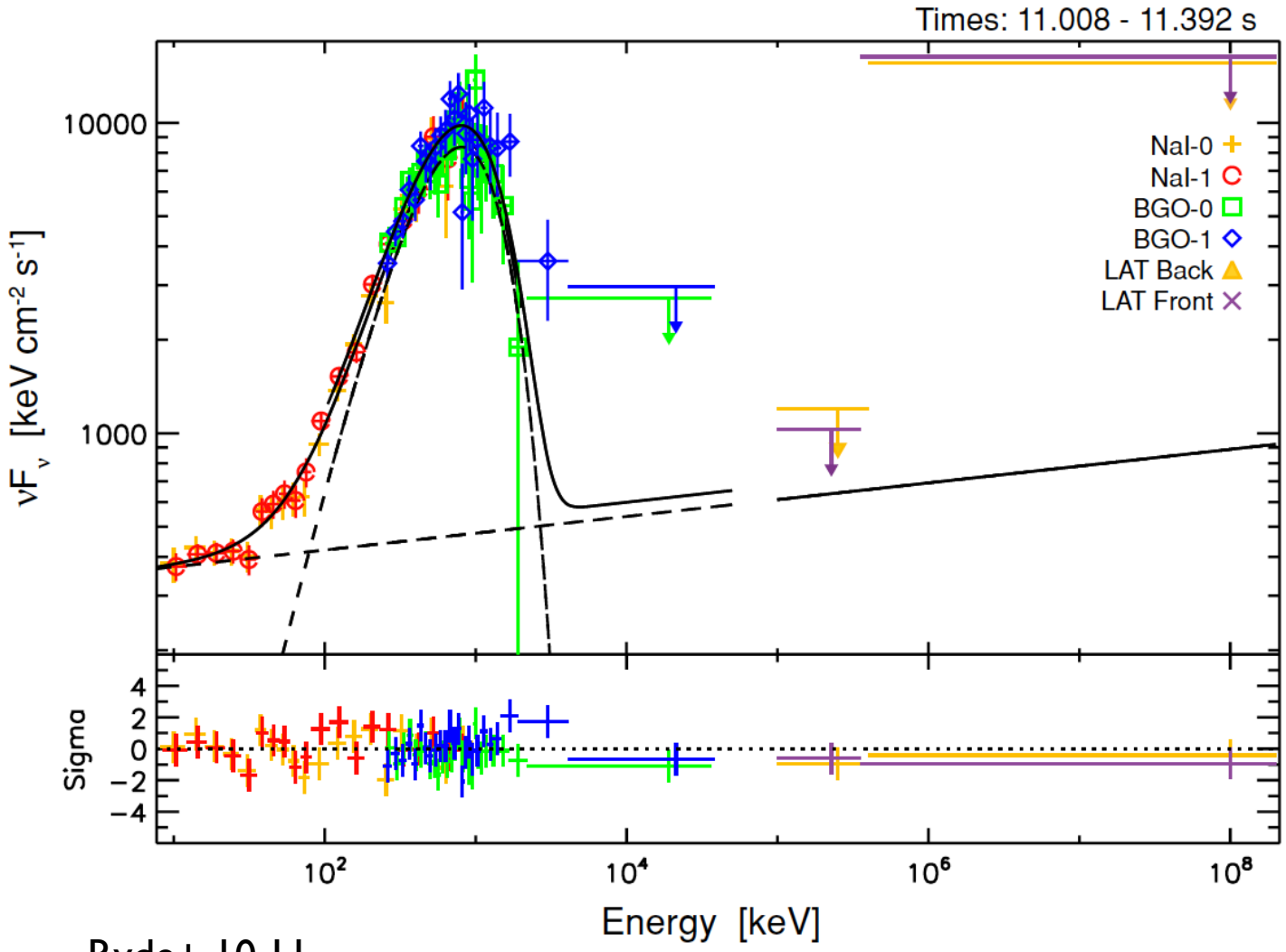
MeV γ for low Γ GRBs

3 Prompt Components?



Zhang+ 11

Photospheric Emission?



Ryde+ 10,11

GRB090902B

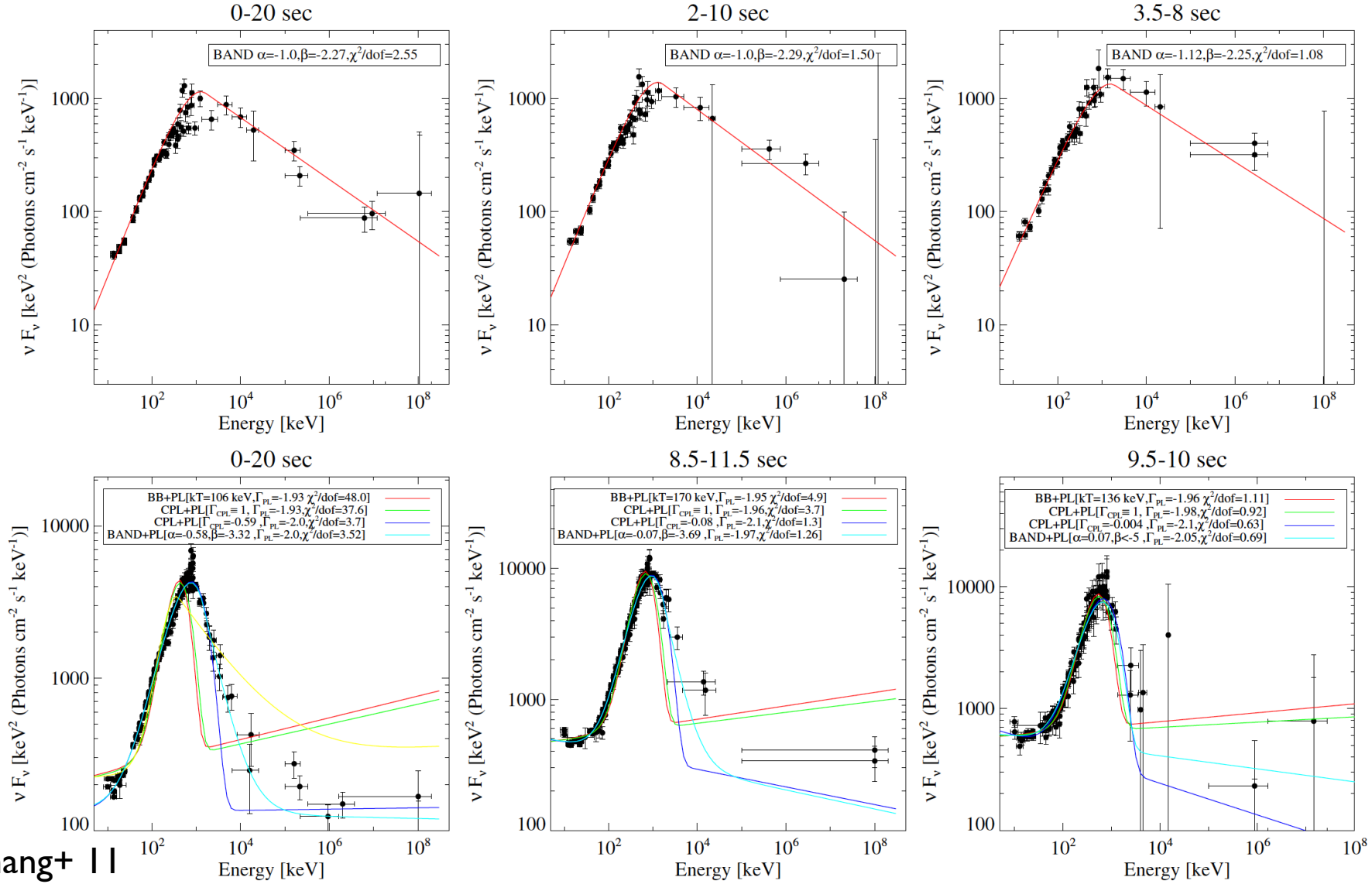
$R_{ph} \sim 10^{12} Y^{1/4}$ cm

$\Gamma \sim 750 Y^{1/4}$

$Y = E_{tot}/E_\gamma$

MeV $\gamma \Rightarrow$ Thermal or not?

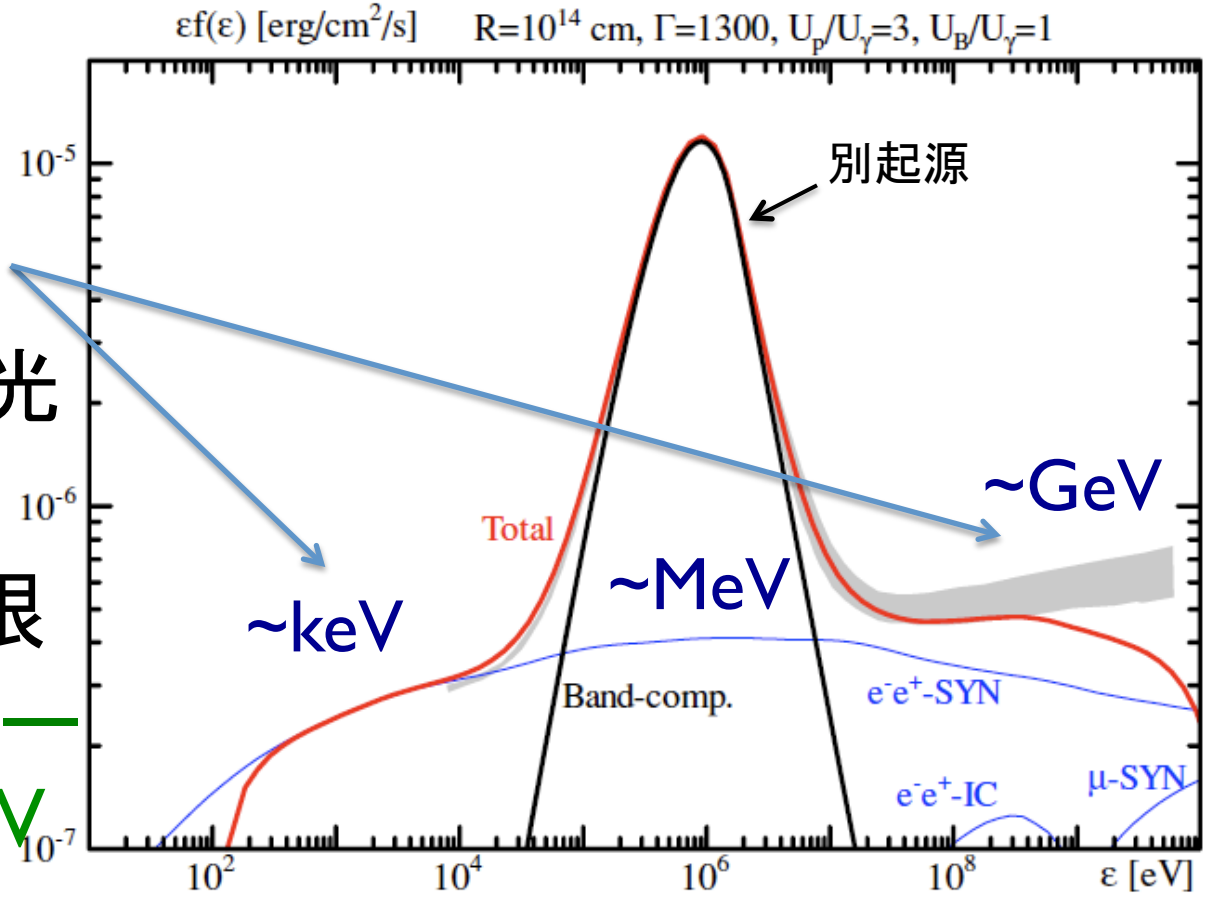
Different Component?



Zhang+ 11

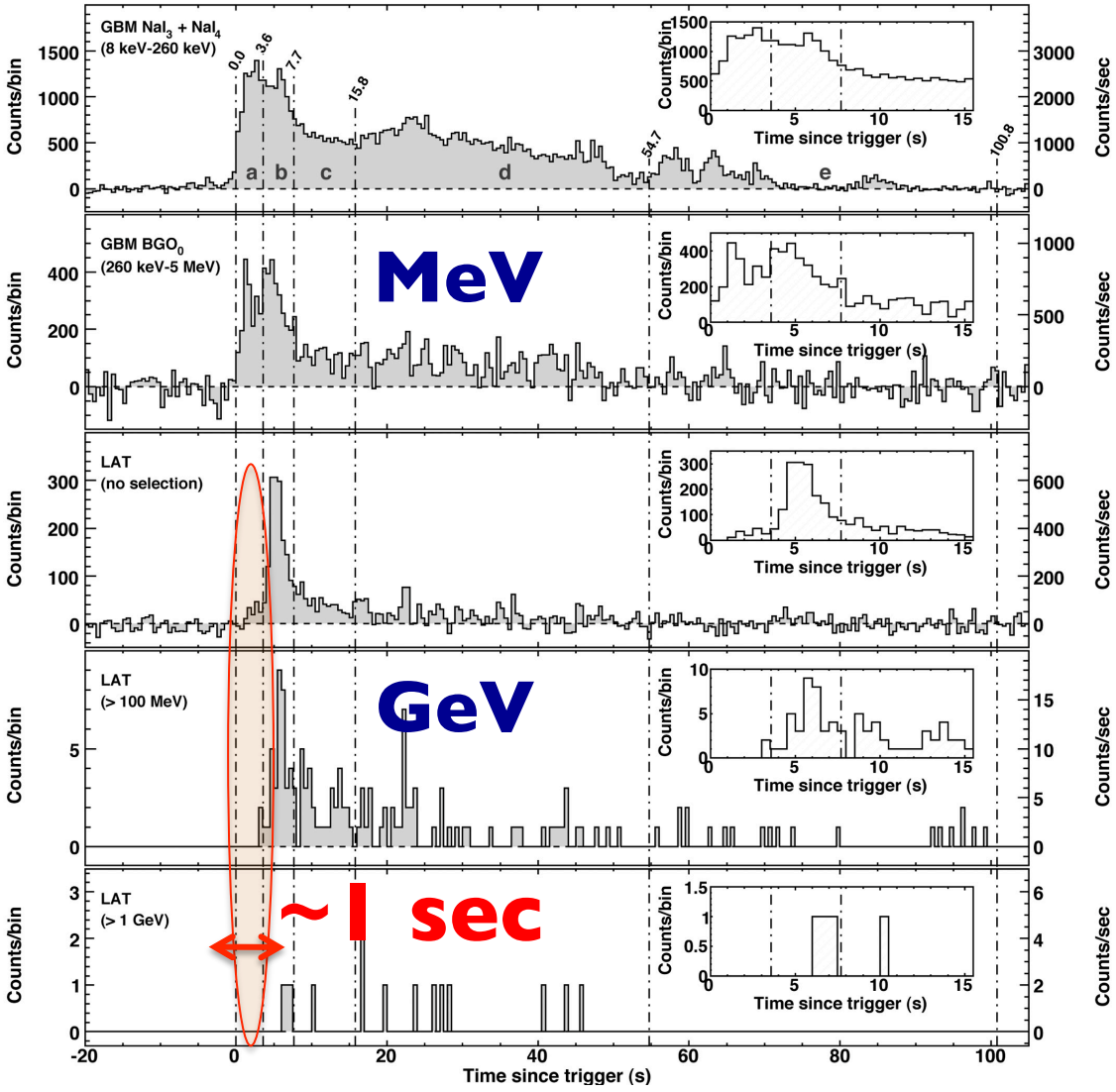
Hadronic Origin?

- $>10^{17}$eV p + γ → π → γ, $e^{\pm}$ カスケード シンクロ、IC
- to X線、可視光
- $E_p > E_\gamma \sim 10^{53}$erg
- IceCubeの制限
- 最高エネルギー宇宙線 $\sim 10^{20}$eV の起源?



Asano & Takahara 07
Asano, Inoue+ 10

GeV Onset Delay



t_{delay}

~1 sec (long)

~0.1 sec (short)

~0 sec in a few

$>> t_{variability}$

Afterglow?	$\sim R_{sh}/c\Gamma_j^2$
$\gamma\gamma$-break shift?	$\sim R_\gamma/c\Gamma_j^2$
Progenitor?	$\sim R_*/c$
Unconfined jet?	$\sim R_\gamma/c\Gamma_c^2$

Toma+ 11, Li 10,
Bosnjak+ 11, KI 10,11

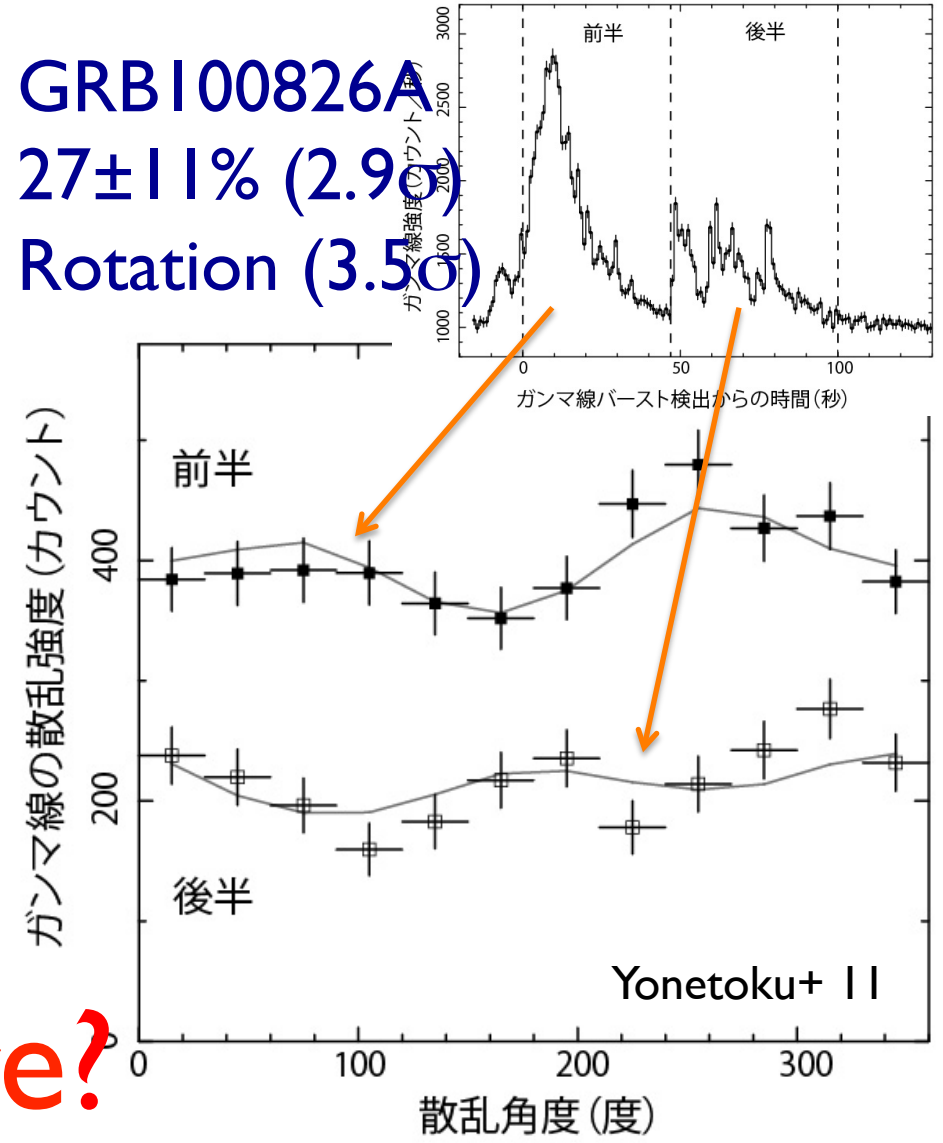
MeV Physics

- ***Prompt emission***
  - Nonthermal, Thermal, High-energy
  - Polarization
- ***Afterglow***
  - Synchrotron, Reverse, Steep decay, Flare, Plateau
- ***Supernova***
  - ^{56}Ni
- ***Diverse populations***
  - llGRB, ulGRB, Pop III GRB, Shock breakout, TDE

Better than BATSE
Large FOV

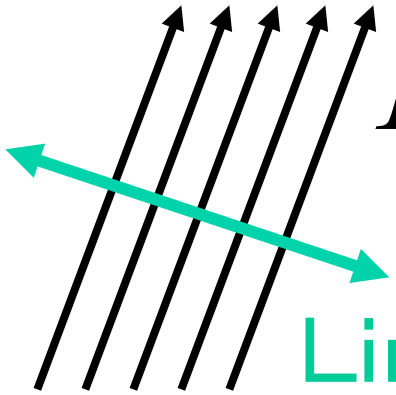
γ-ray Polarization

GRB100826A
27±11% (2.9σ)
Rotation (3.5σ)



Patchy B? γ-shere?

Uniform Magnetic Field?



Linear polarization

$$\Pi_{\max} = \frac{p+1}{p+7/3} \simeq 70\%$$

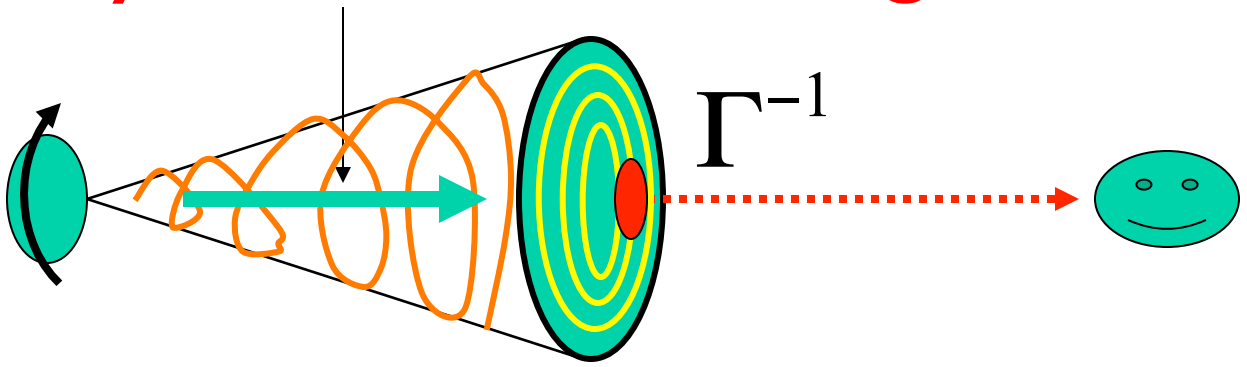
$$N_e(\gamma_e)d\gamma_e \propto \gamma_e^{-p} d\gamma_e$$

Theoretical maximum

⇒ Uniform, large scale magnetic field?

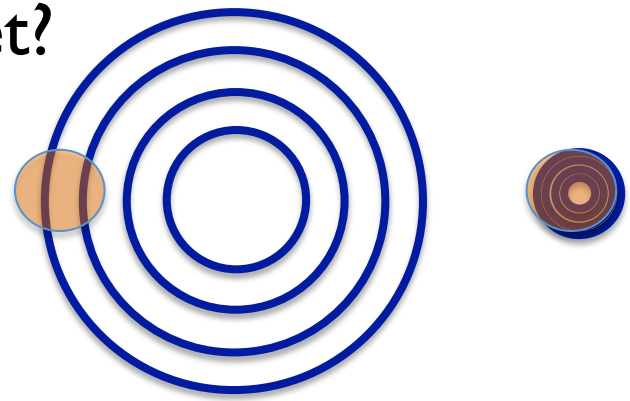
⇒ Magnetically driven GRB? Magnetar?

B~10^{15}G



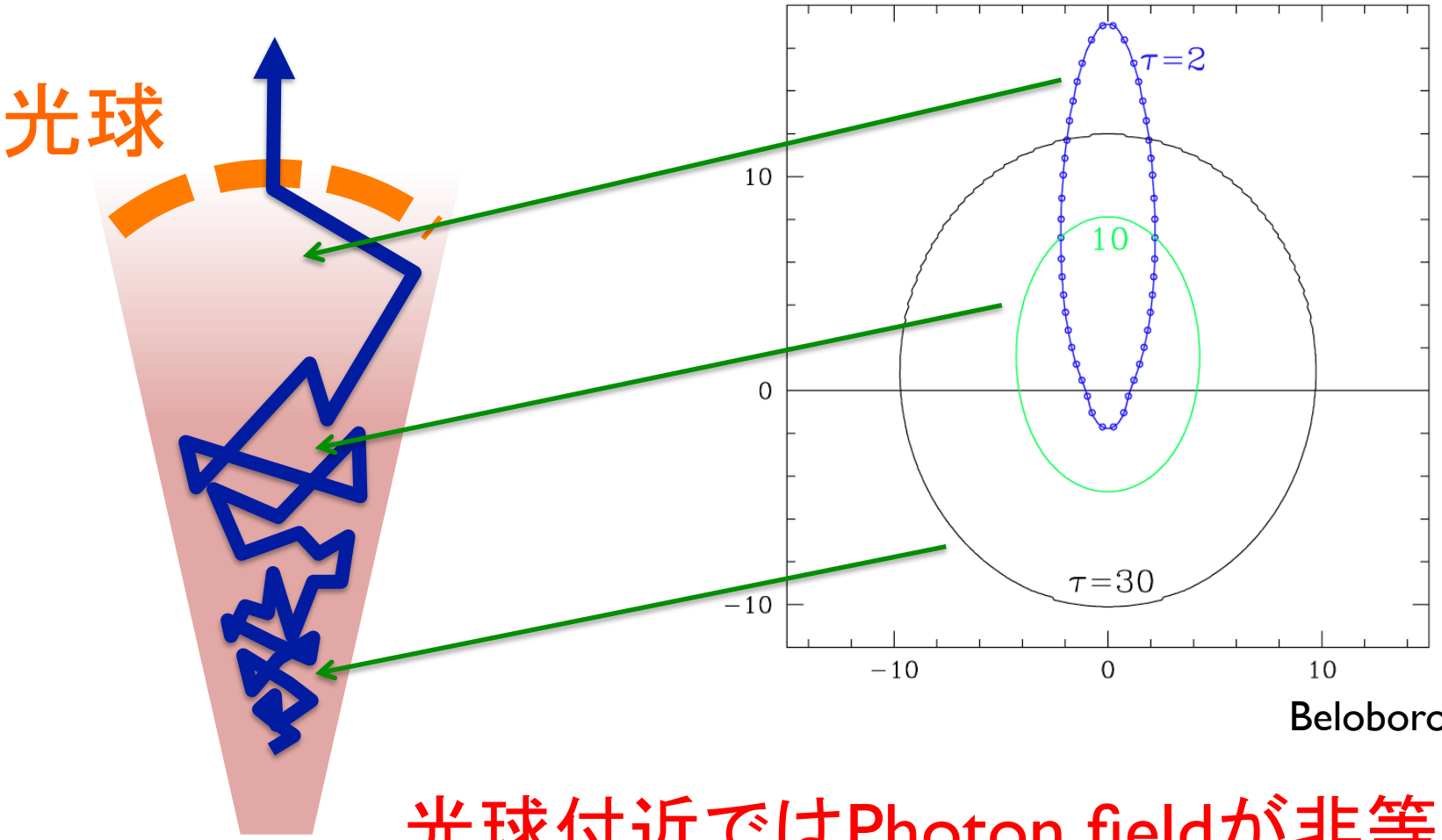
磁場ジェット？

- ヘリカル磁場の場合、偏光は変動しない
  - Patchy or 細いJet?



- 偏光しているものはどれも明るい
  - 放射効率を>50%とすると、Π<50%になる?
- シンクロトロンの場合、E_{peak}より下では50%
  - E_{peak}をまたいで偏光度に変化はあるのか?

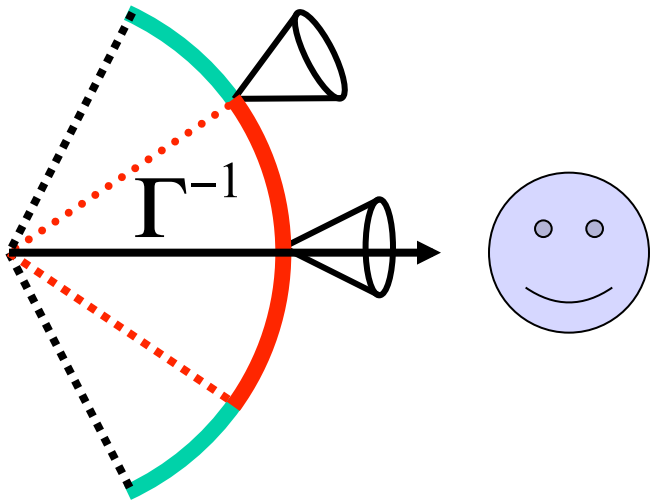
光球も偏光?

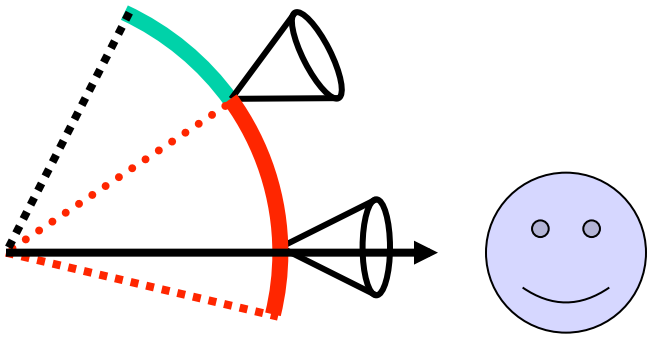


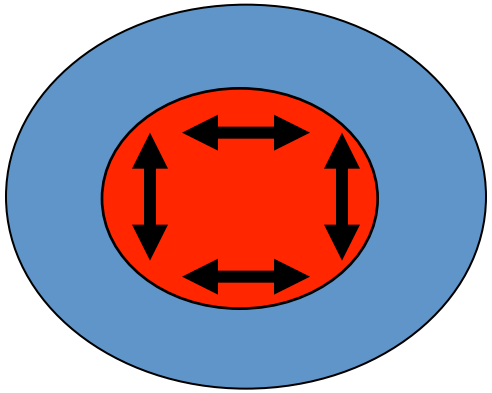
Beloborodov 11

光球付近ではPhoton fieldが非等方
⇒ 最後のThompson散乱で偏光

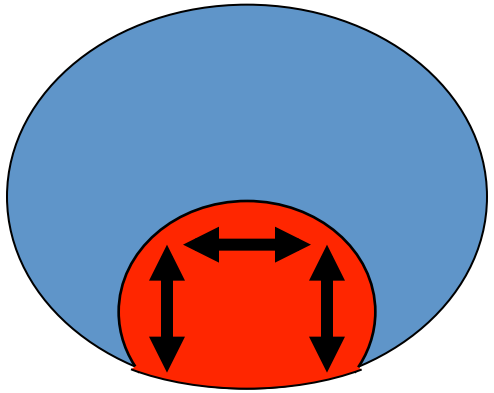
Patchy γ-sphere?





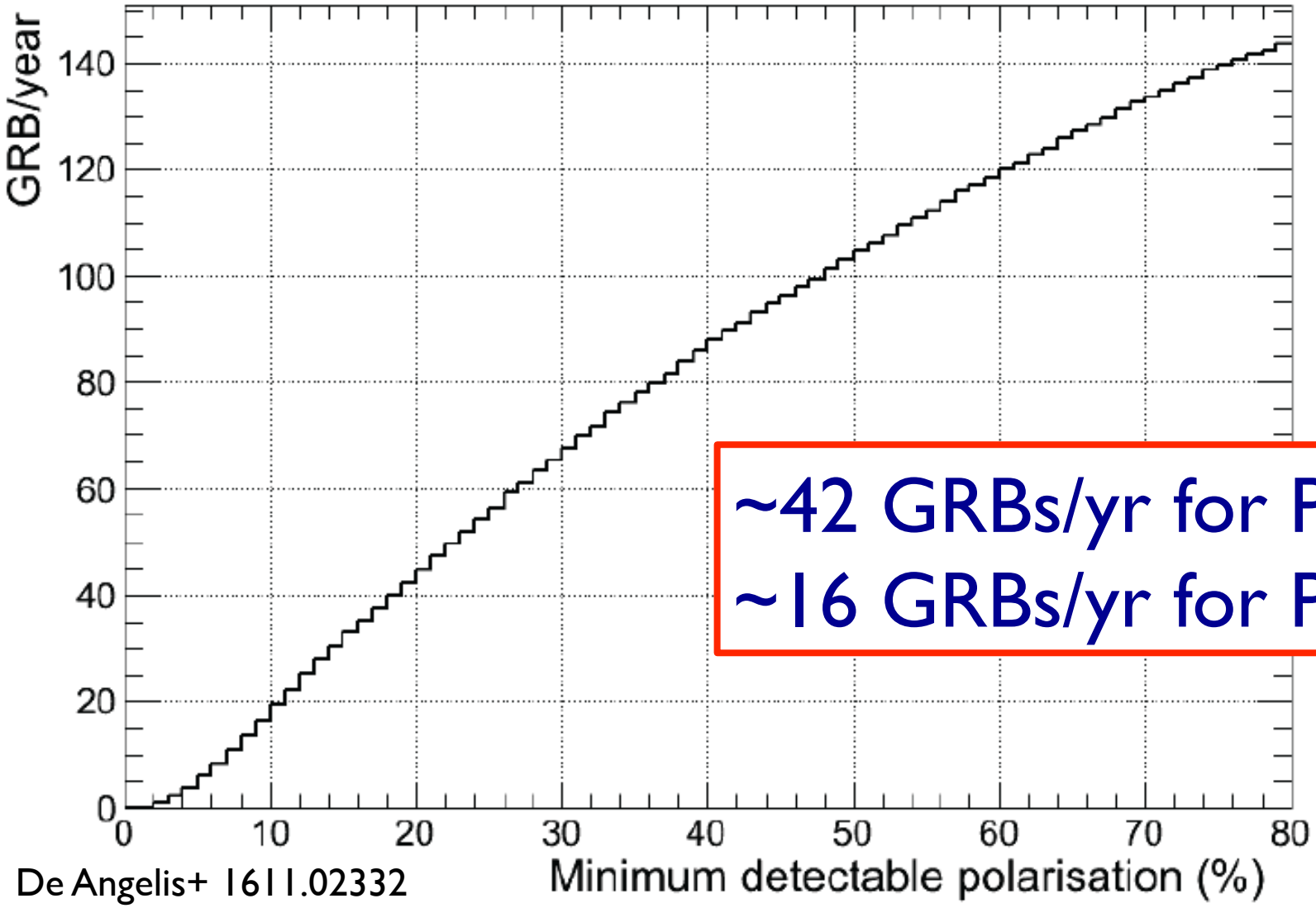


Total
0



Total

e-ASTROGAM



~42 GRBs/yr for P~20%
~16 GRBs/yr for P~10%

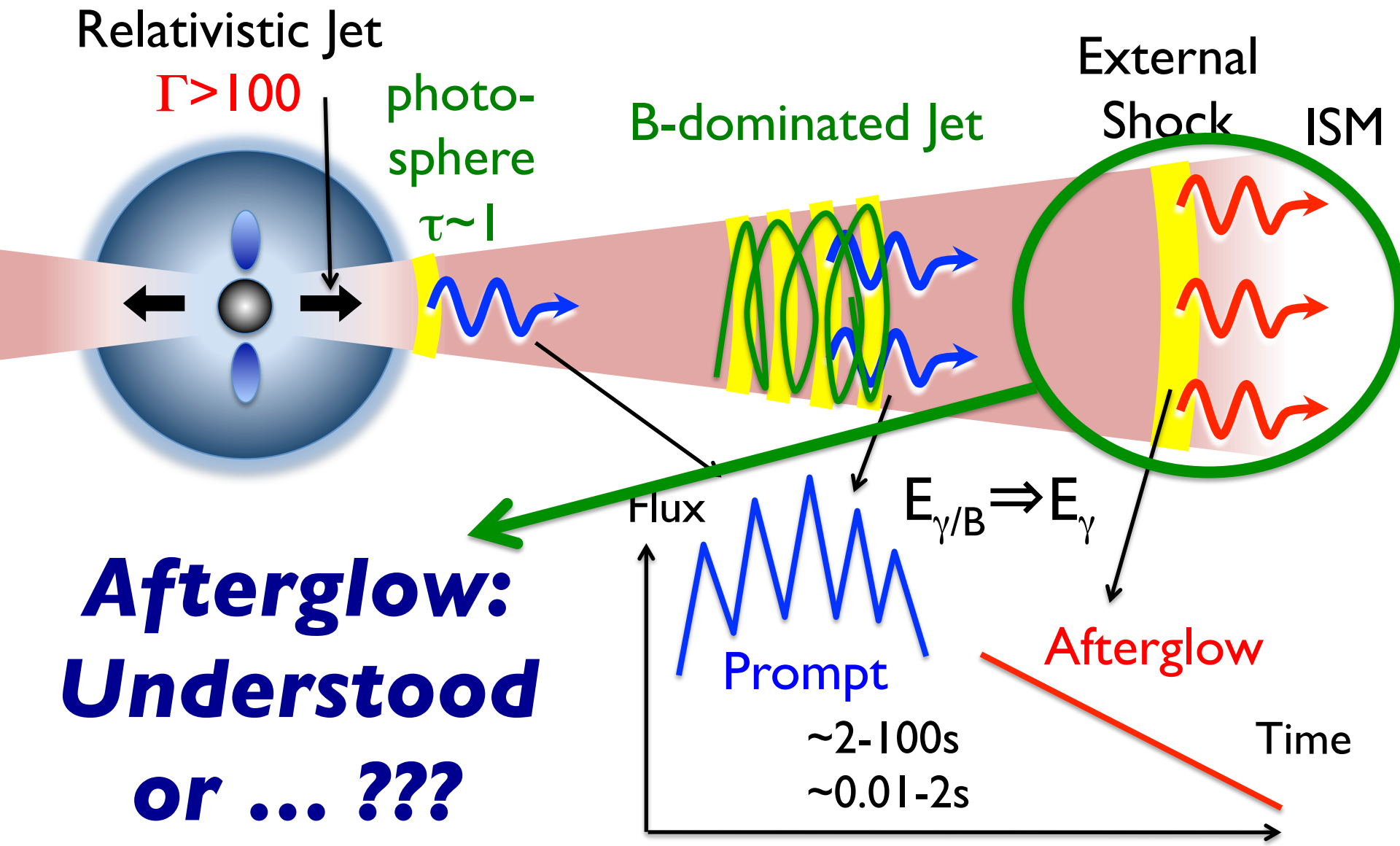
De Angelis+ 1611.02332

MeV Physics

- ***Prompt emission***
  - Nonthermal, Thermal, High-energy
  - Polarization
- ***Afterglow***
  - Synchrotron, Reverse, Steep decay, Flare, Plateau
- ***Supernova***
  - ^{56}Ni
- ***Diverse populations***
  - llGRB, ulGRB, Pop III GRB, Shock breakout, TDE

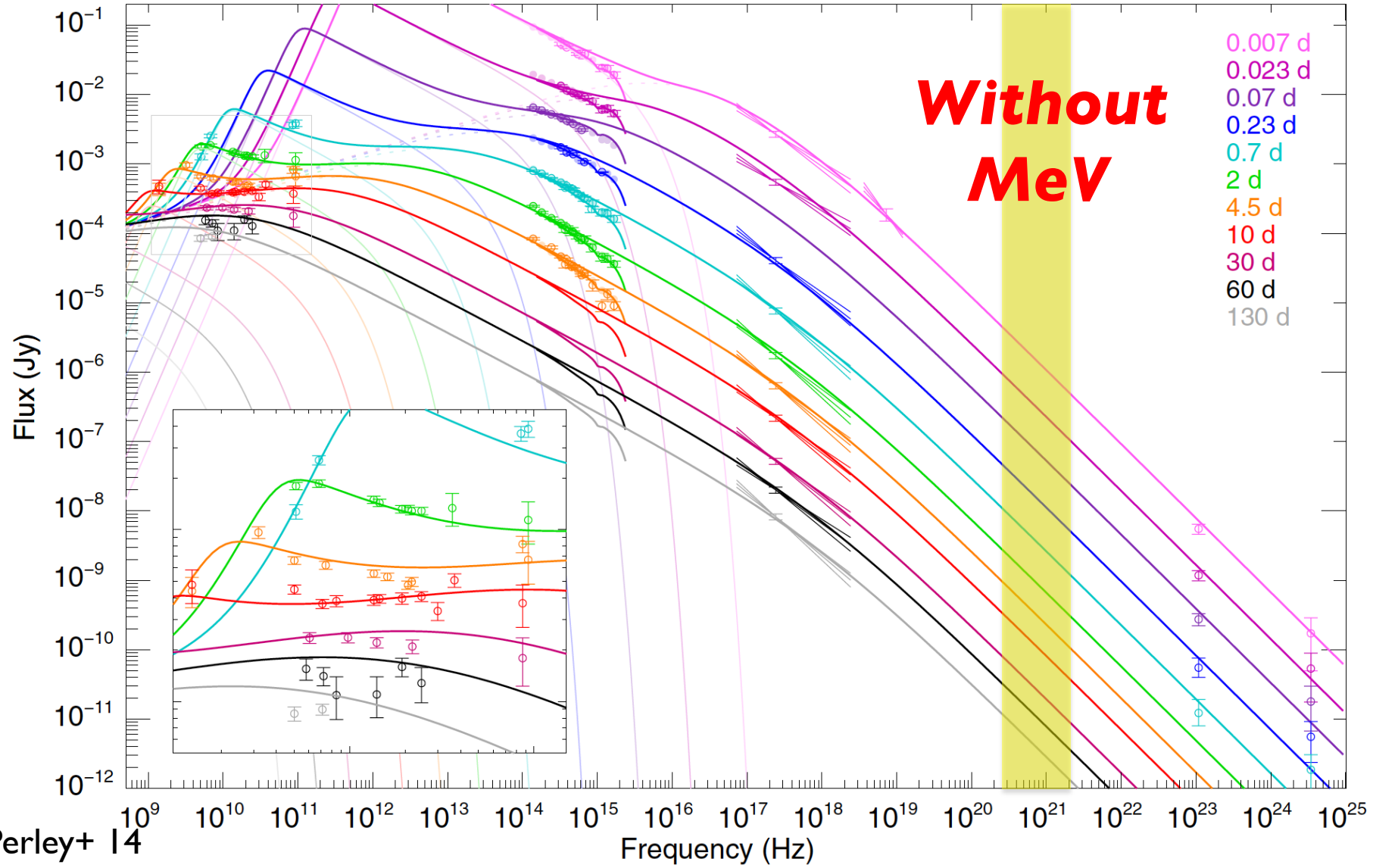
Better than BATSE
Large FOV

標準モデル?



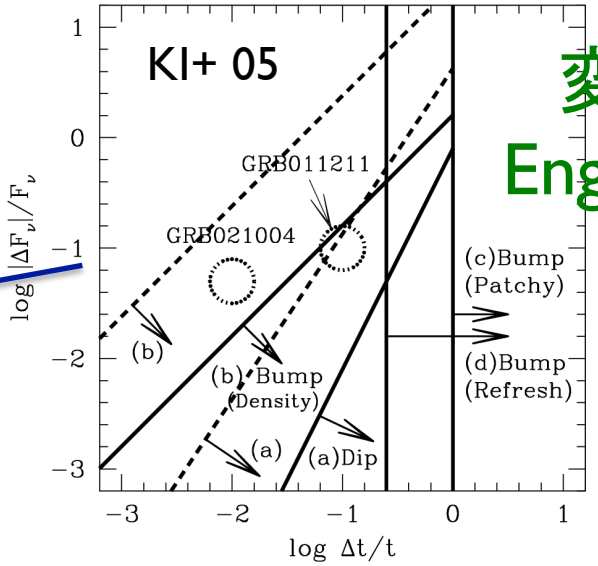
Afterglow: Understood or … ???

All-Band Spectrum



Perley+ 14

X-ray Afterglow



0

~ -3

Steep Decay

I

Flare

V

変動大 ⇒ Engine-Driven

How?

Curvature?

Decaying?

II

~ -0.5

Plateau

What?

III

~ -1.2

t_{b3}:10^4–10^5 s

t_{b1}:10^2–10^3 s

t_{b2}:10^3–10^4 s

~ -2

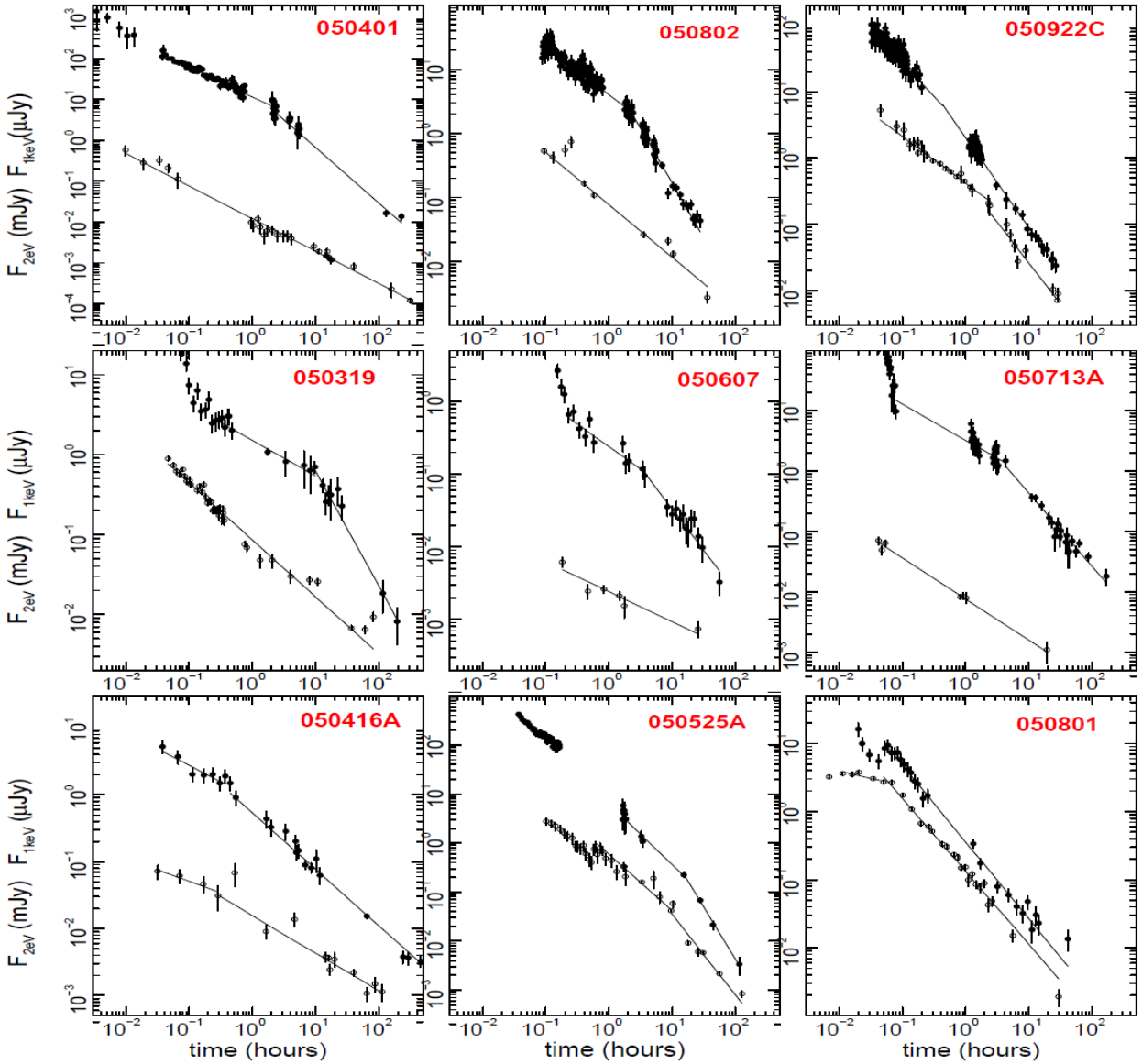
IV

Jet Break

When?

Zhang+ 06

Chromatic Break



Plateau phase
の起源が謎

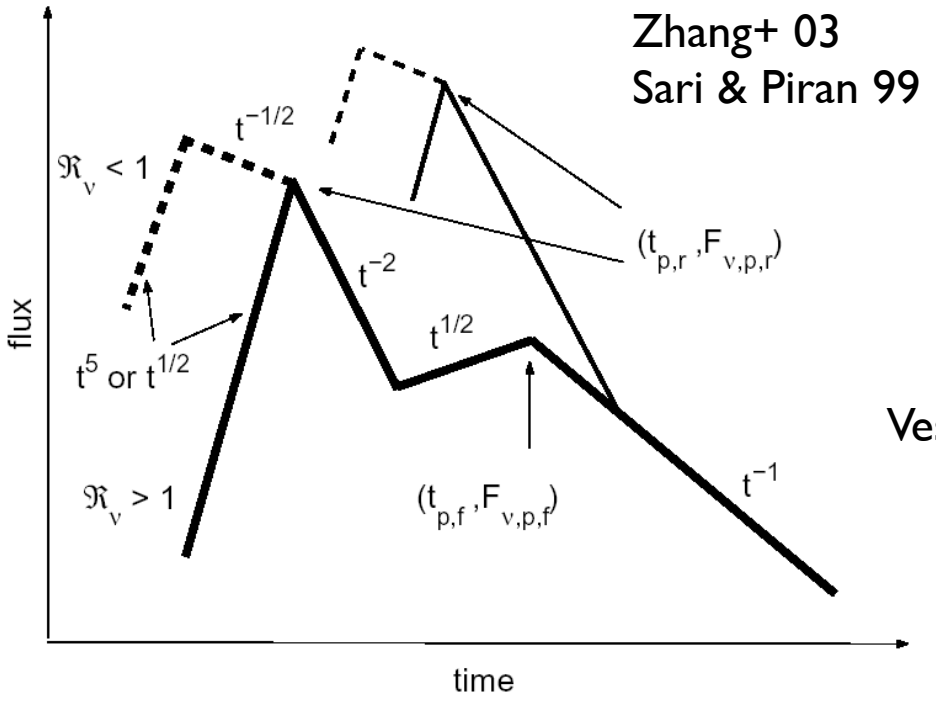
X線ブレーク
without
光学ブレーク

X-ray: Engine
Opt: Afterglow?

Panaitescu(06)

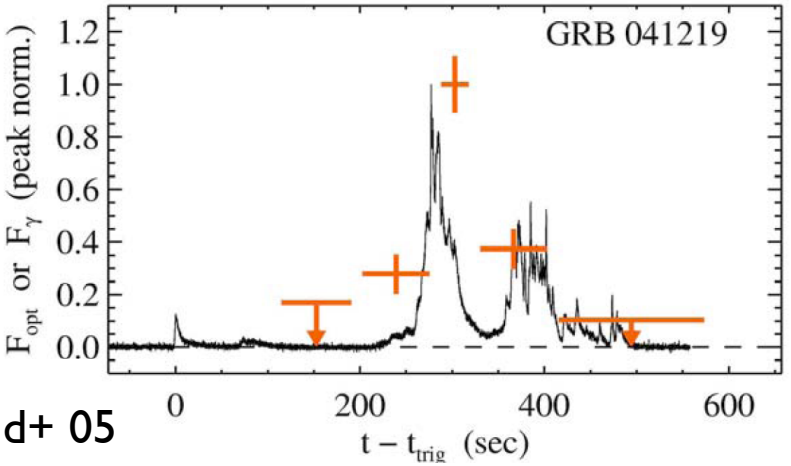
Optical Flash

Reverse Shock

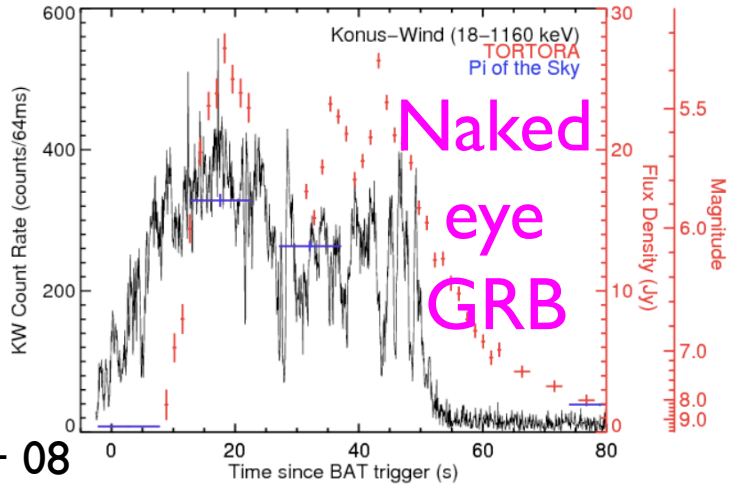


Zhang+ 03
Sari & Piran 99

Prompt Optical



Vestrand+ 05

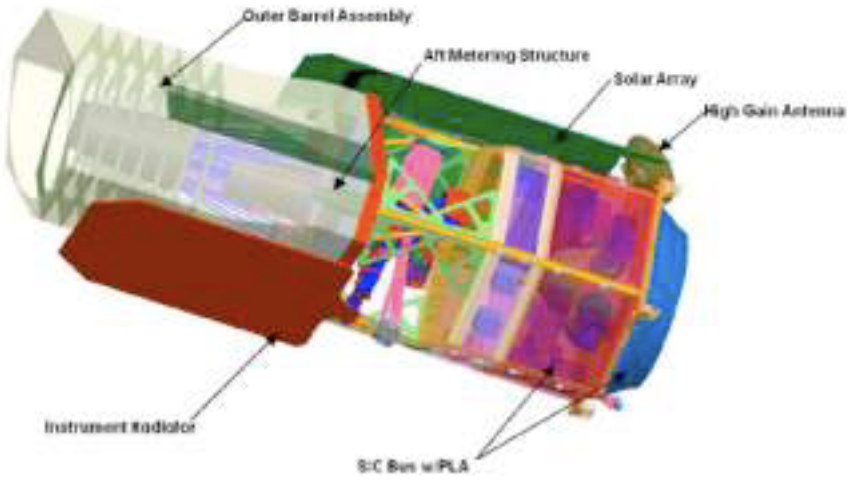


Racusin+ 08

Why so paucity?
B-? or $e^{\pm}$-dominated?

Deep, Wide, Fast

IR-Opt Big Survey Era



LSST

3.5 deg FOV

WFIRST

Near IR wide-field

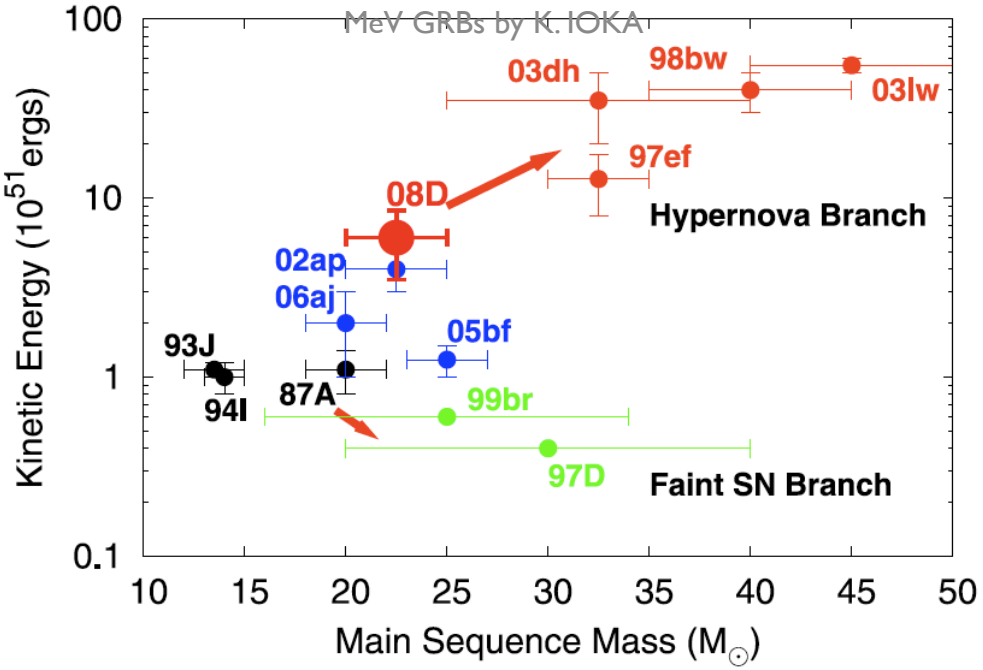
MeV survey than MeV follow-up?

MeV Physics

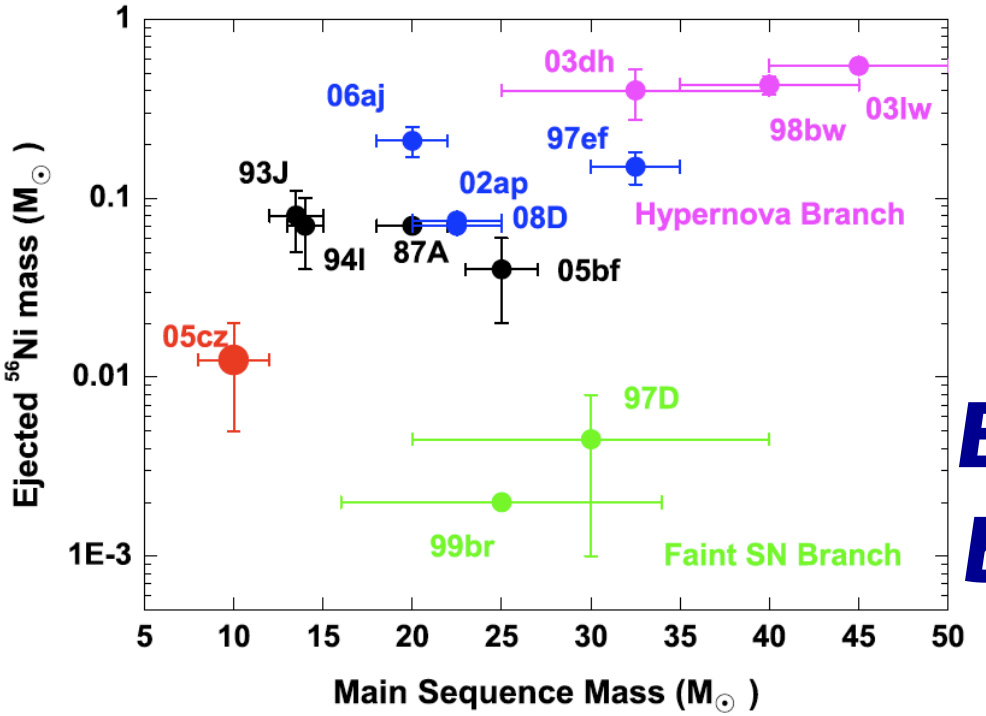
- ***Prompt emission***
  - Nonthermal, Thermal, High-energy
  - Polarization

Better than BATSE
Large FOV

- ***Afterglow***
  - Synchrotron, Reverse, Steep decay, Flare, Plateau
- ***Supernova***
  - ^{56}Ni
- ***Diverse populations***
  - llGRB, ulGRB, Pop III GRB, Shock breakout, TDE



Maeda's talk
Terada's talk

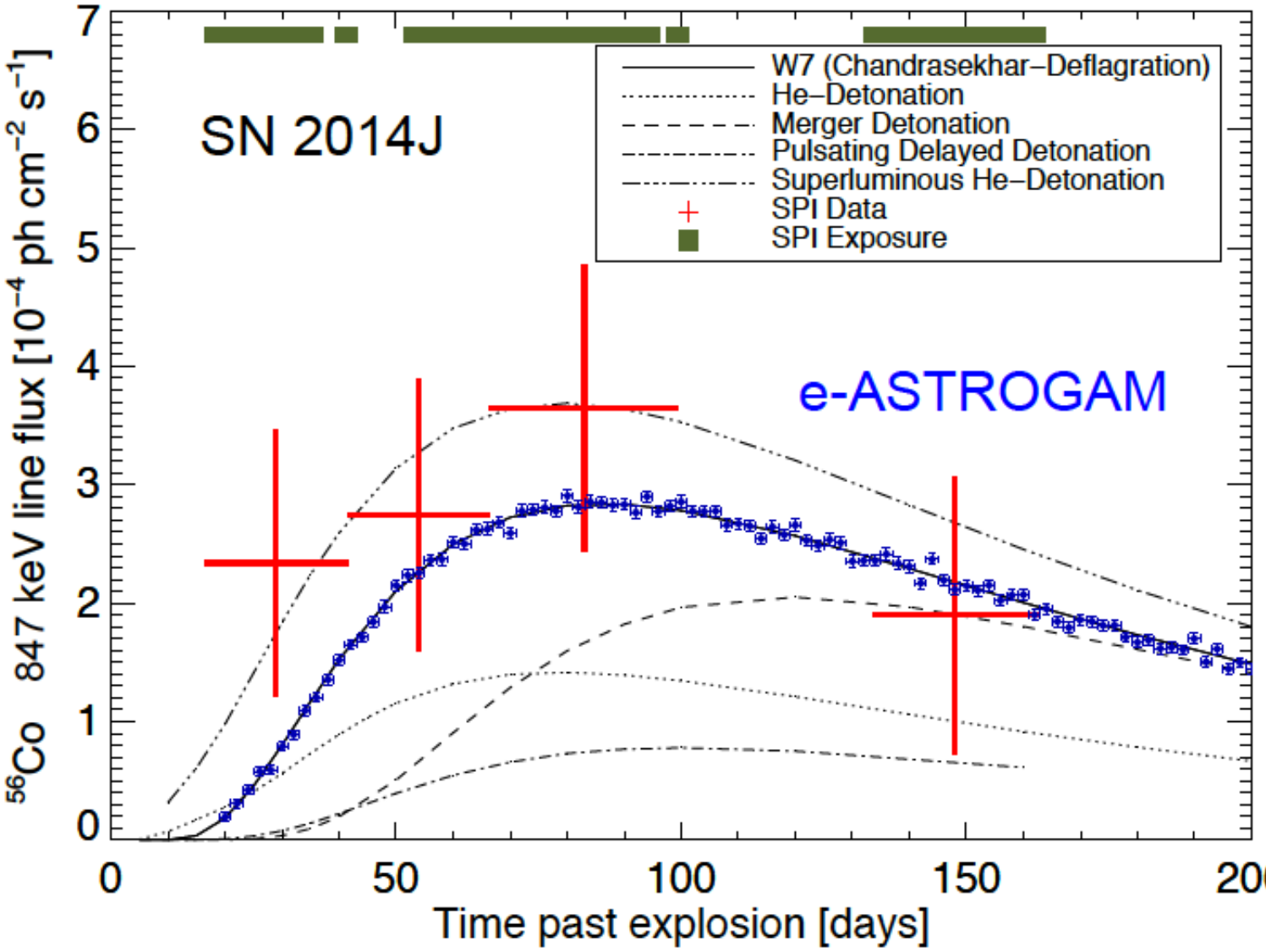


Huge Nickel mass

E injection by Central Engine?

Nomoto+ 11

Supernova Ia 2014J



^{56}Co lines

$M_{Ni} \sim 0.6 M_\odot$

D=3.5Mpc

$R \sim R_{SN}/10^3$

$D \sim D_{SN} \times 10$

$F \sim F_{SN}/10^2$

Churazov+ 14

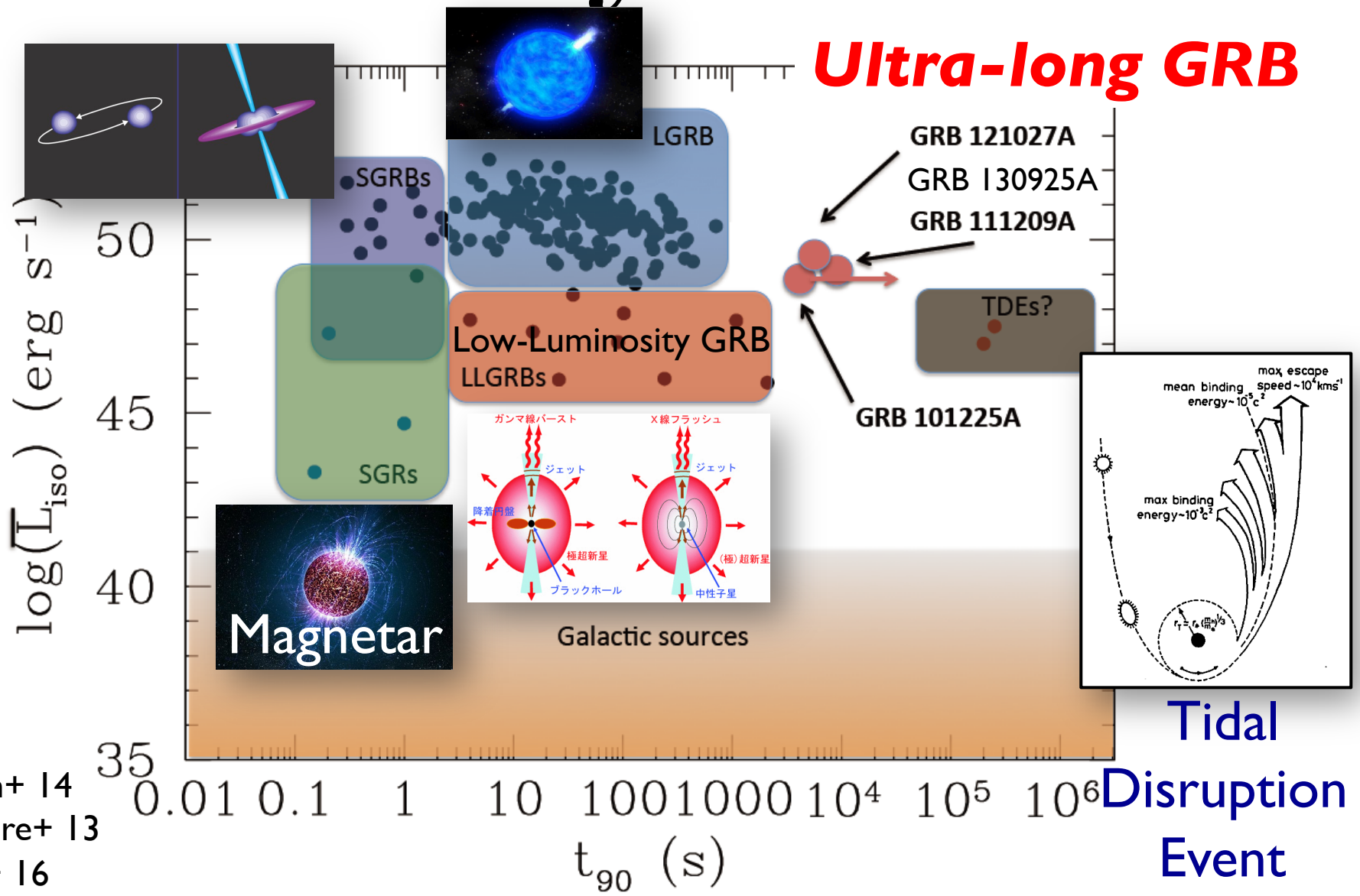
De Angelis+ 16

MeV Physics

- ***Prompt emission***
  - Nonthermal, Thermal, High-energy
  - Polarization
- ***Afterglow***
  - Synchrotron, Reverse, Steep decay, Flare, Plateau
- ***Supernova***
  - ^{56}Ni
- ***Diverse populations***
  - llGRB, ulGRB, Pop III GRB, Shock breakout, TDE

Better than BATSE
Large FOV

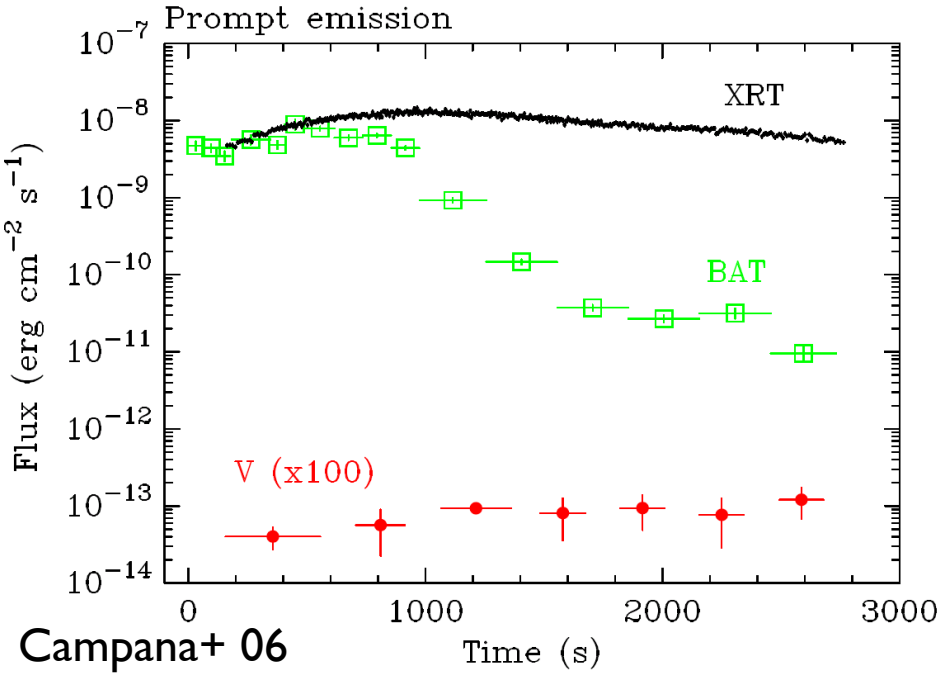
Diversity of GRB



Levan+ 14
Gendre+ 13
Lien+ 16

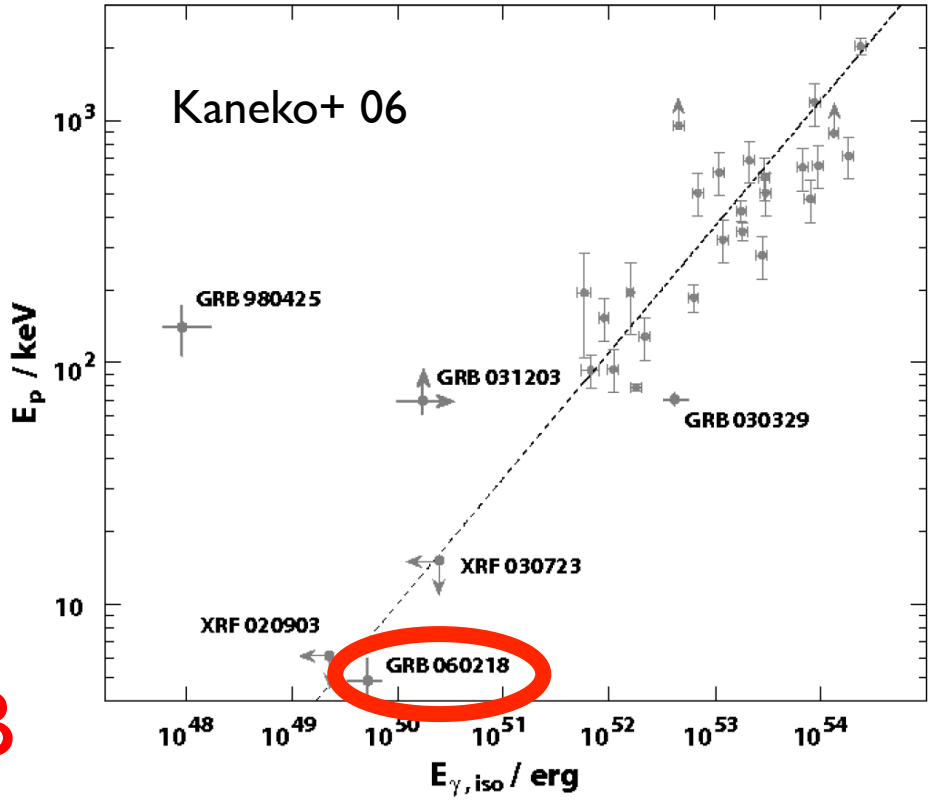
低光度GRB

>1000 sec Duration



Campana+ 06

Low E_{iso}

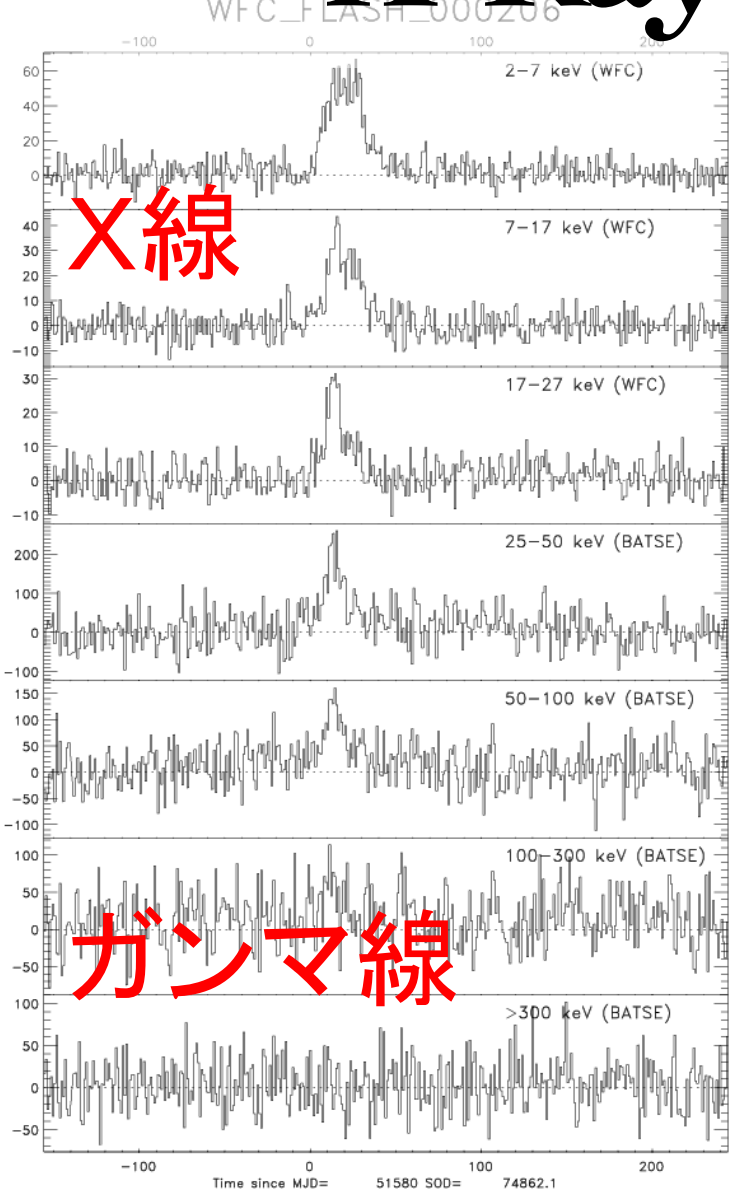


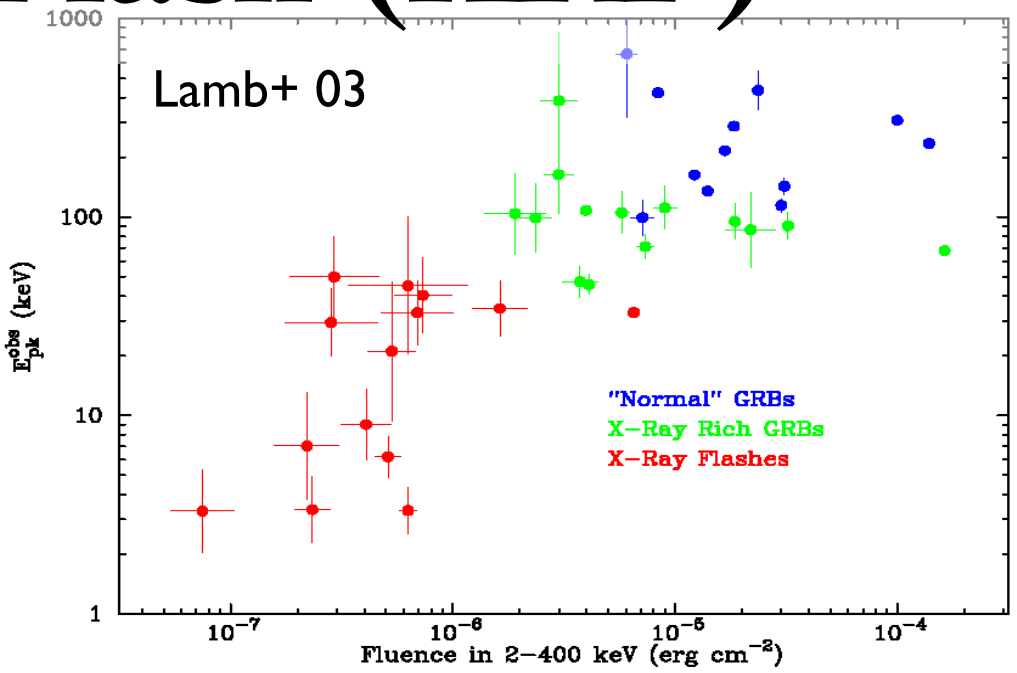
⇒ Low luminosity GRB

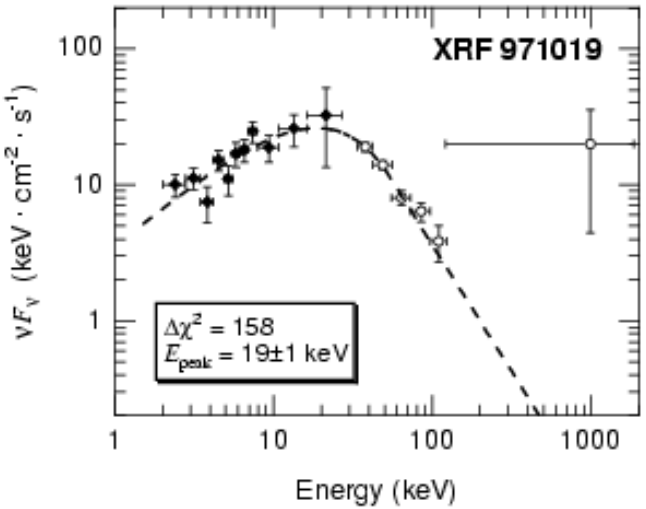
z=0.033, 0.059: 遠くは見えていない

実際のEvent rateは~**10倍**かも

X-Ray Flash (XRF)





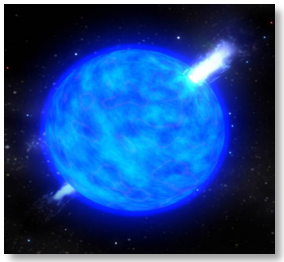


XRF~GRB except for small E_{peak} & fluence

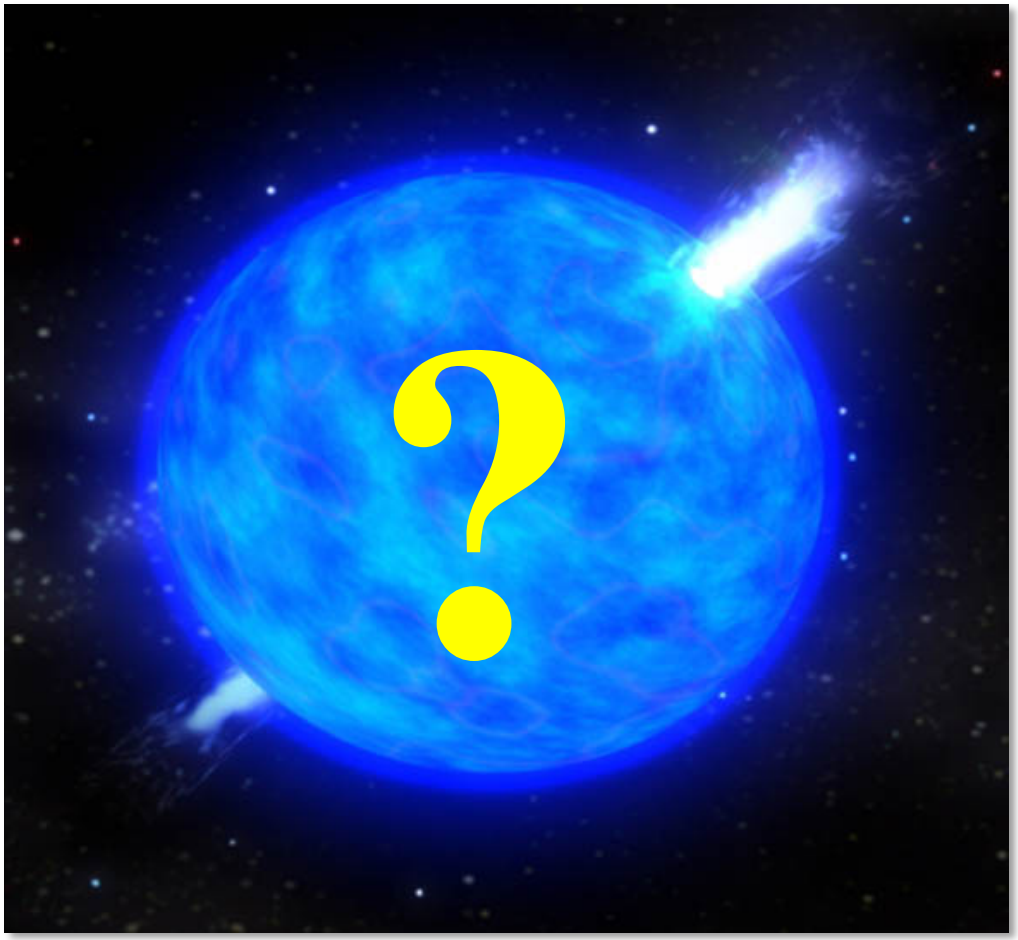
Pop III GRB?

Matsumoto's talk

Present Day GRB

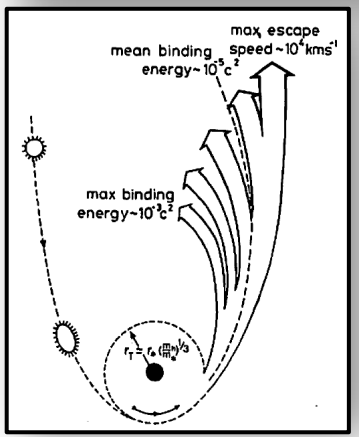


Komissarov & Barkov 10
Meszaros & Rees 10
Suwa & KI 11
Nagakura, Suwa & KI 12

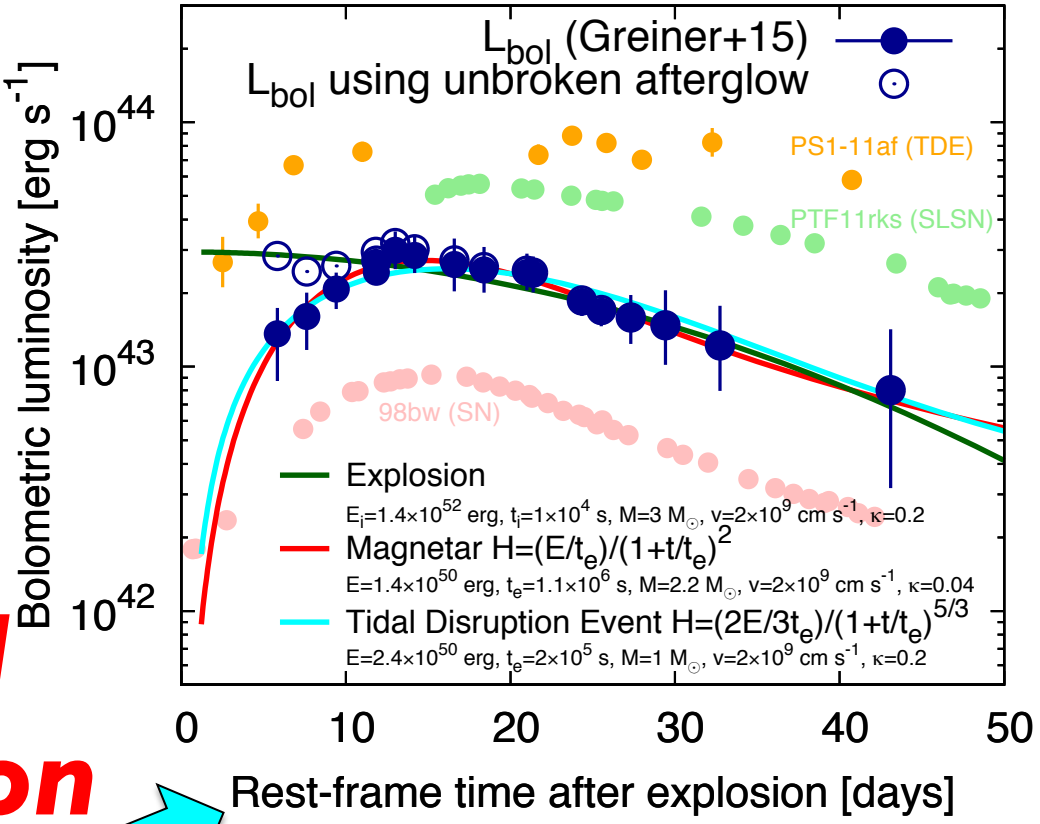


Envelope accretion ⇒ Ultra-long

Ultra-Long GRBs

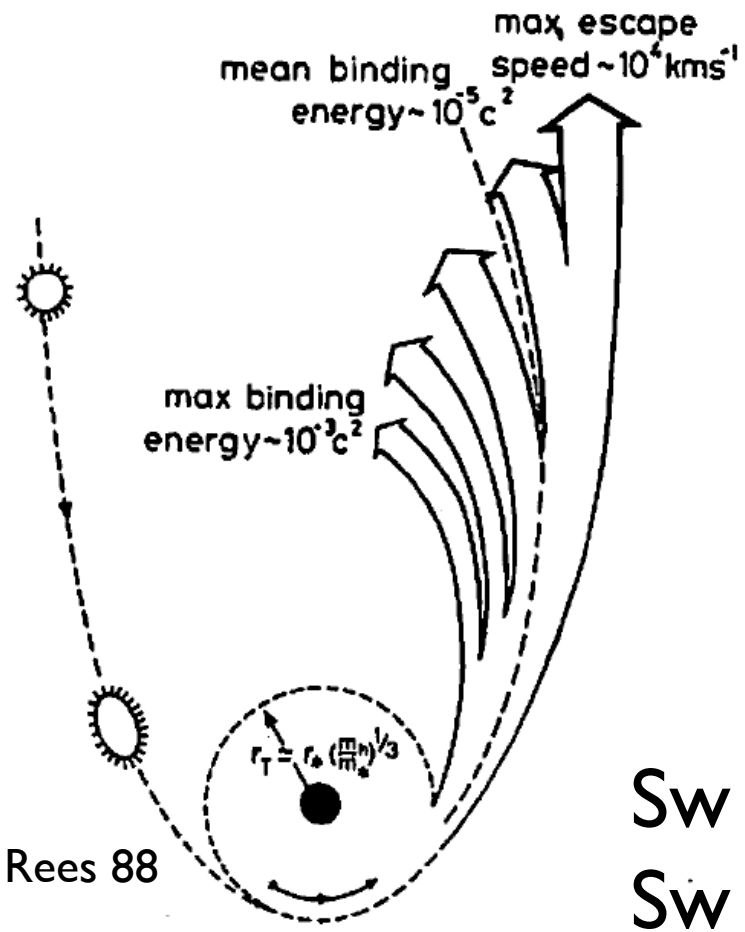


Supernova(-like Event)

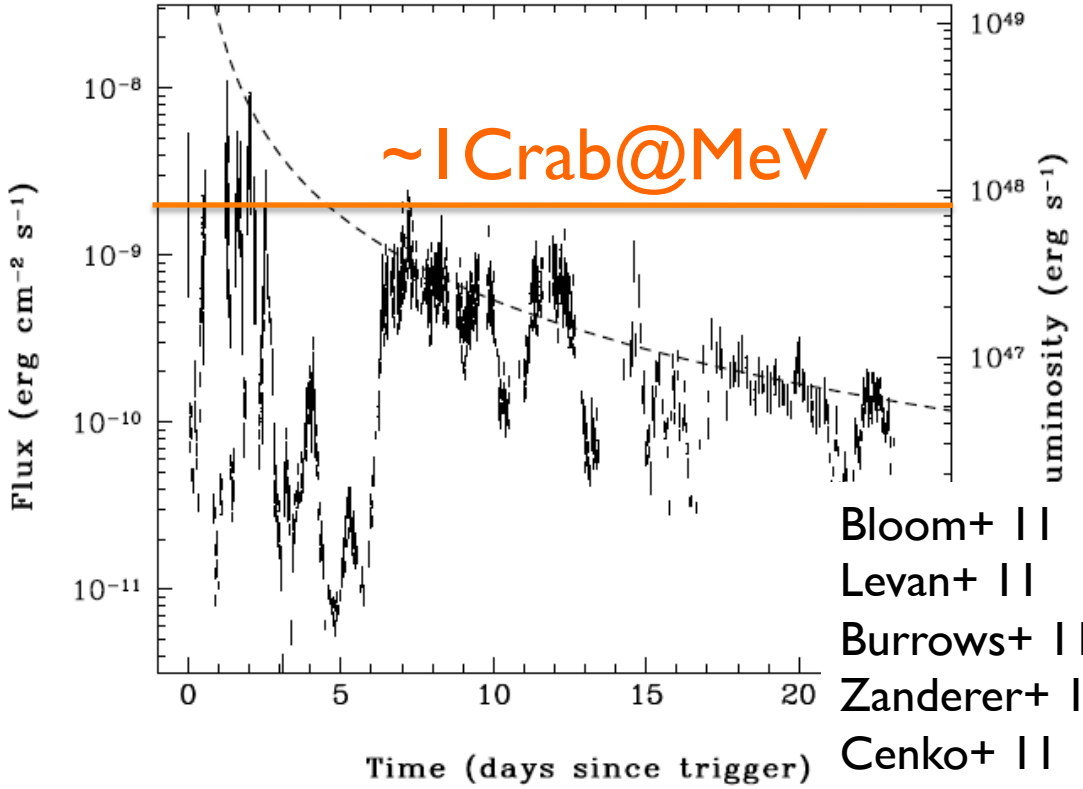


+ Tidal Disruption Event

Tidal Disruption Event



Rees 88



Bloom+ 11
Levan+ 11
Burrows+ 11
Zanderer+ 11
Cenko+ 11

Sw J1644+57 @z~0.35 (d_L~1.8Gpc)
Sw J2058+05 @z~1.19 (d_L~8.2Gpc)

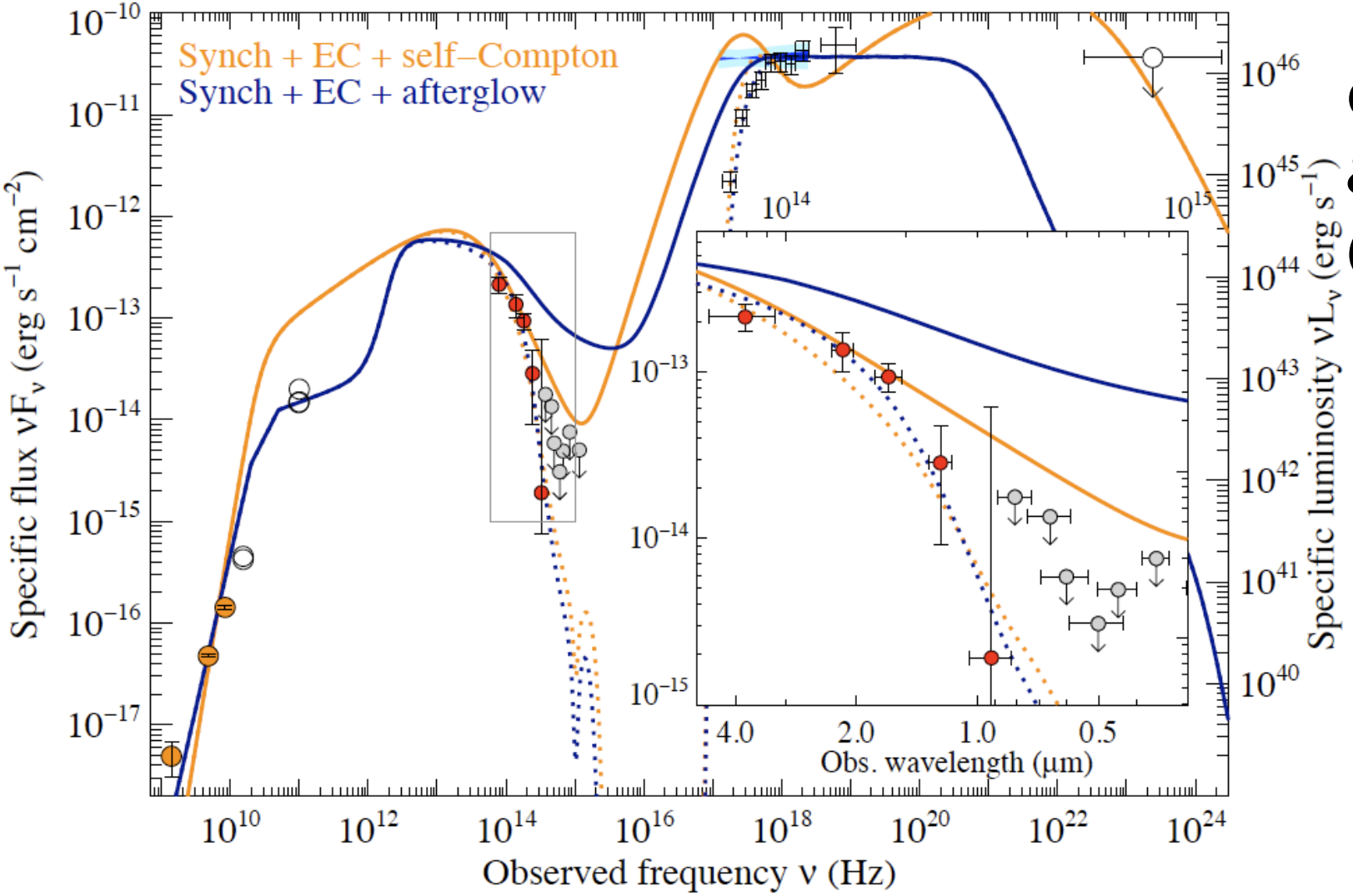
TD ⇒ Jet

~1/yr (all-sky)

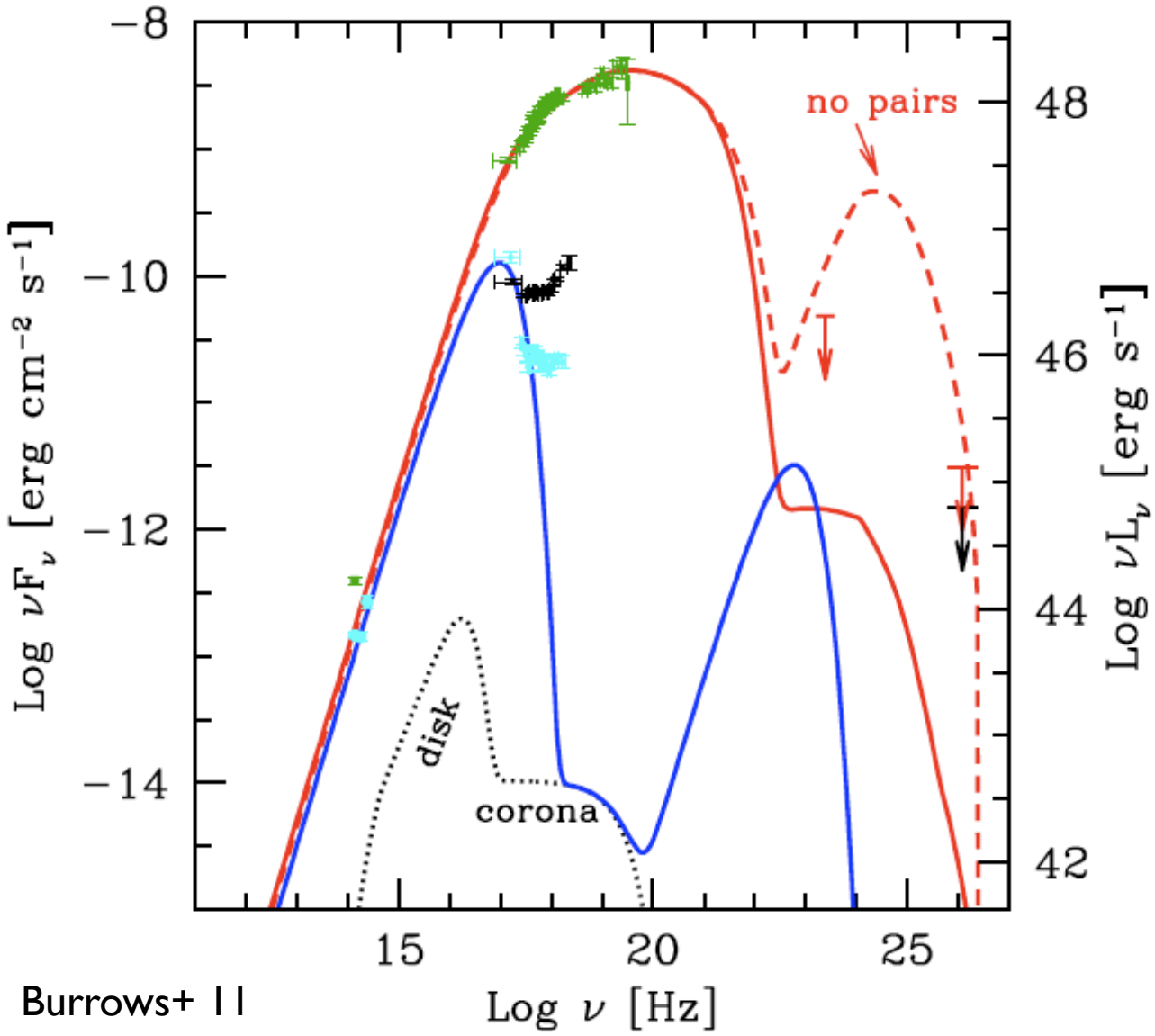
TDE Jet Spectrum

@2.9day

Galaxy
& A_V~3-5
@opt



TDE Jet Spectrum



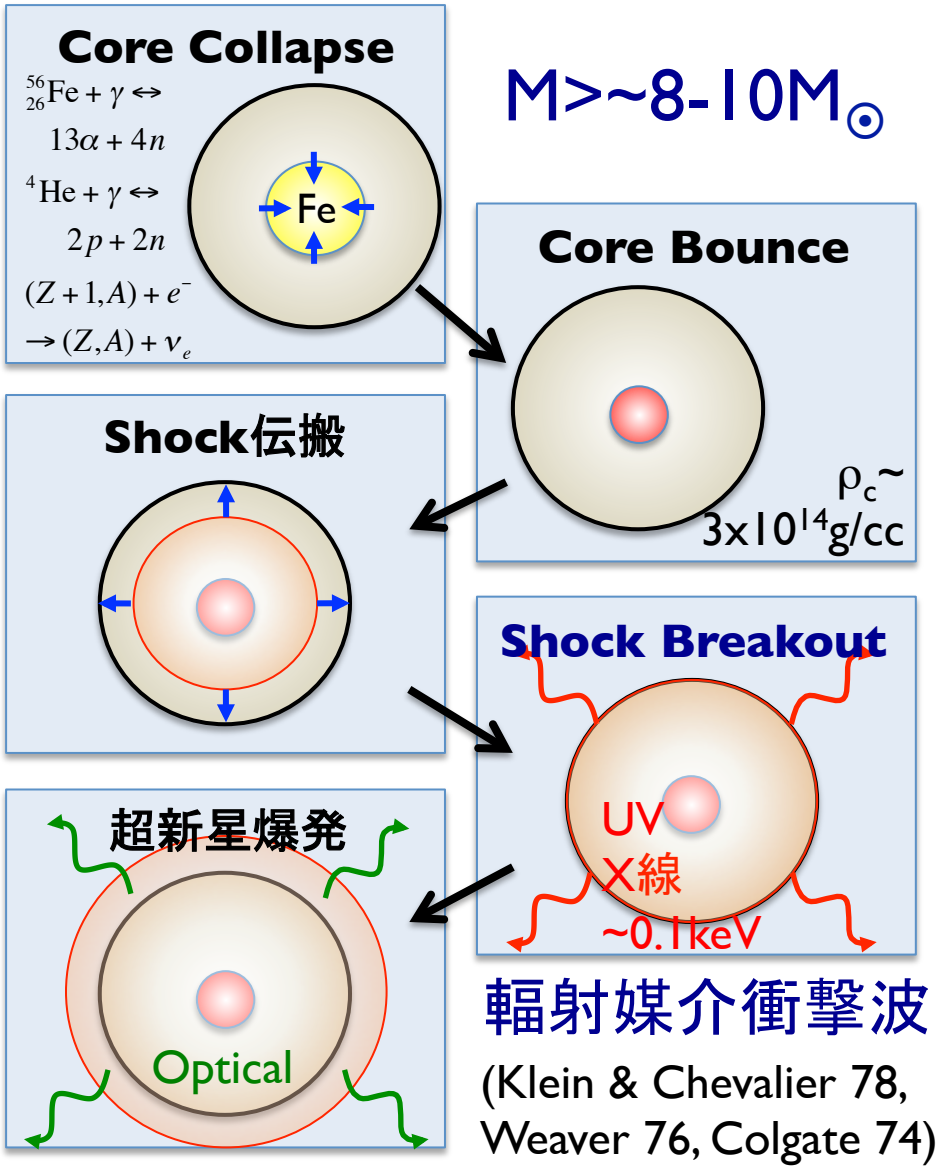
Burrows+ 11

green: a few days
cyan: 4.5 days
black: 6.5-9.5 days

X: NH=2×10^{22}cm^{-2}
NIR: A_V=4.5
γ: Fermi, VERITAS
Γ<10

Suppression of low energy electrons?
⇒ B-dominated?
(⇔ IR less variable)

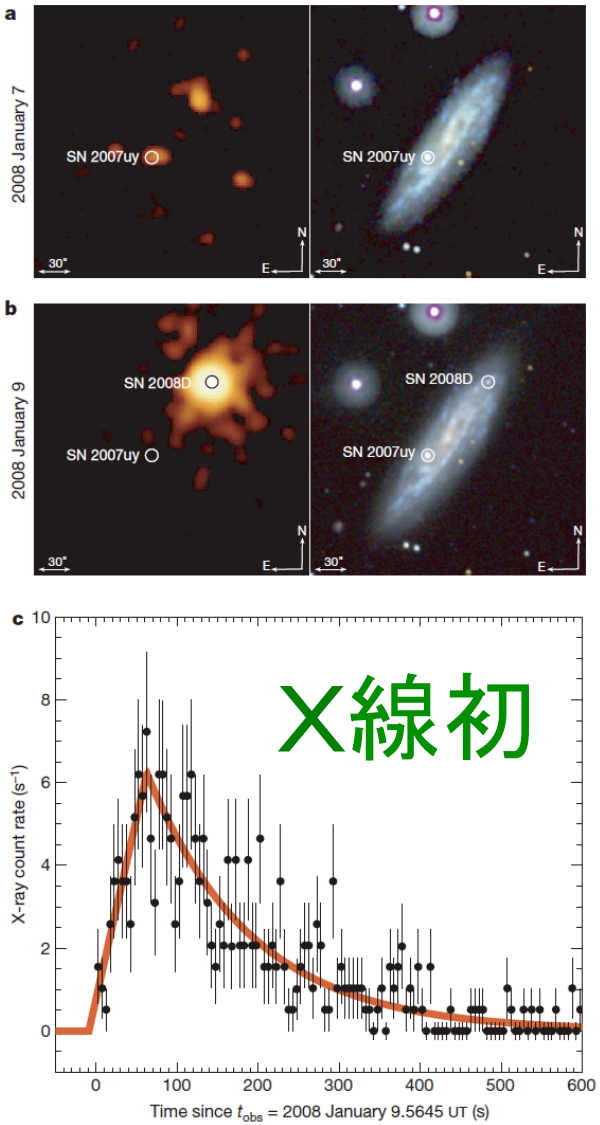
SN Shock Breakout



M>~8-10$M_\odot$

輻射媒介衝撃波

(Klein & Chevalier 78, Weaver 76, Colgate 74)



XRF080109/ SN2008D (Ib/c) @27Mpc

Single PL or PL+BB

Γ~-2.3

T~0.1keV

非熱的成分

Soderberg+ 08

MeV Physics

- ***Prompt emission***
  - Nonthermal, Thermal, High-energy
  - Polarization
- ***Afterglow***
  - Synchrotron, Reverse, Steep decay, Flare, Plateau
- ***Supernova***
  - ^{56}Ni
- ***Diverse populations***
  - llGRB, ulGRB, Pop III GRB, Shock breakout, TDE

Better than BATSE
Large FOV

Thank You

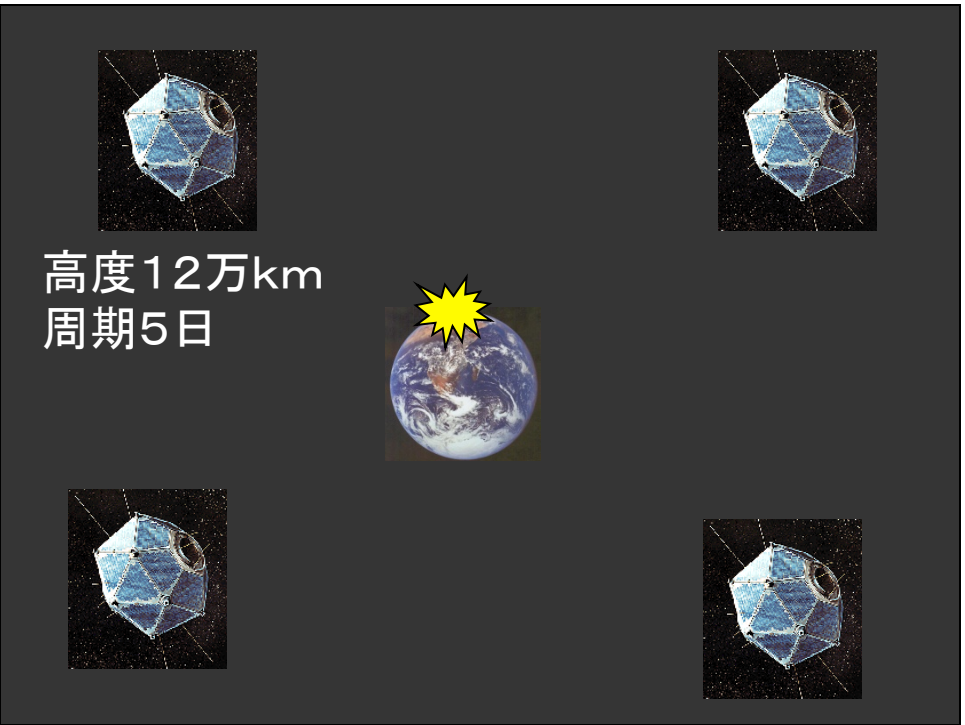
発見は偶然から

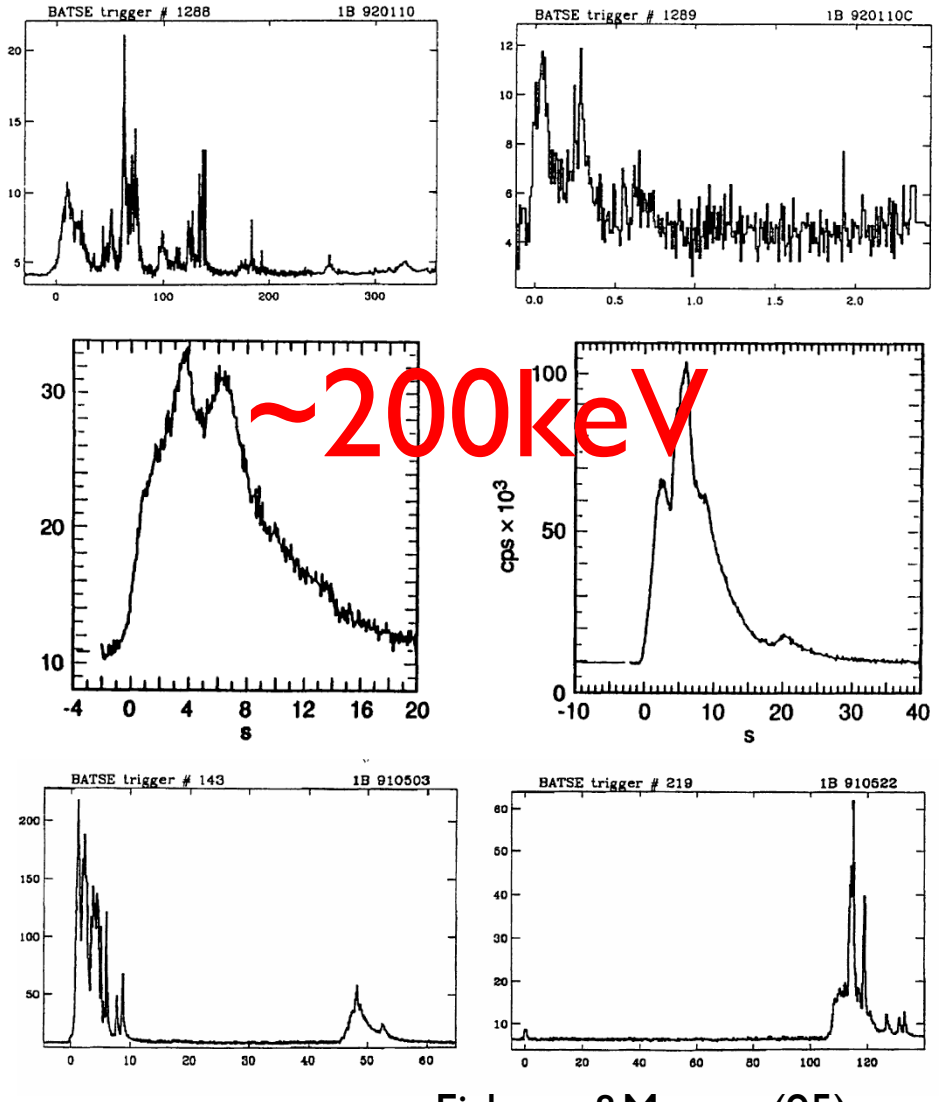
1967　Vela衛星が発見

核実験の監視衛星

ところがγ線は地球外から！

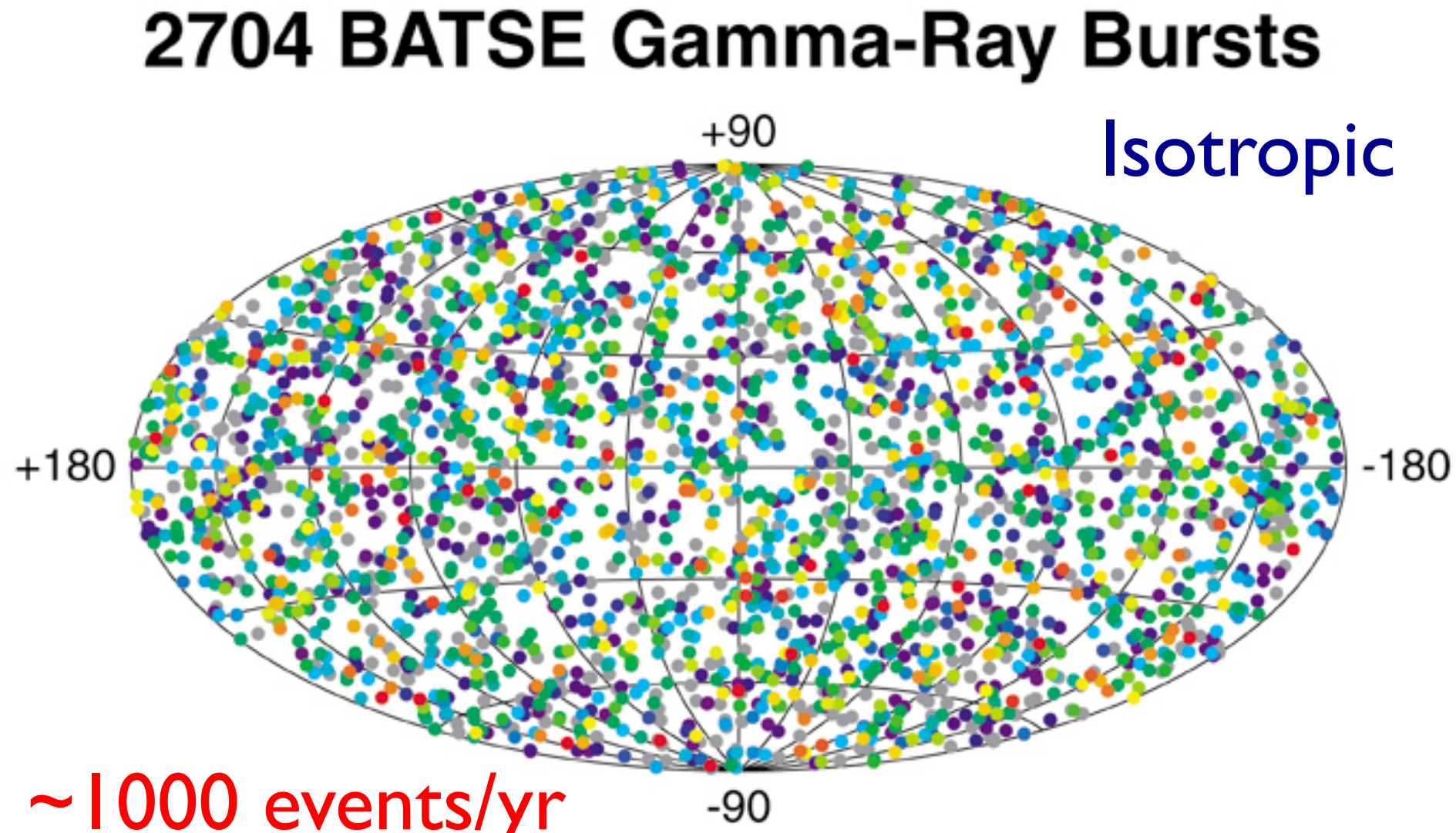
1973　発表





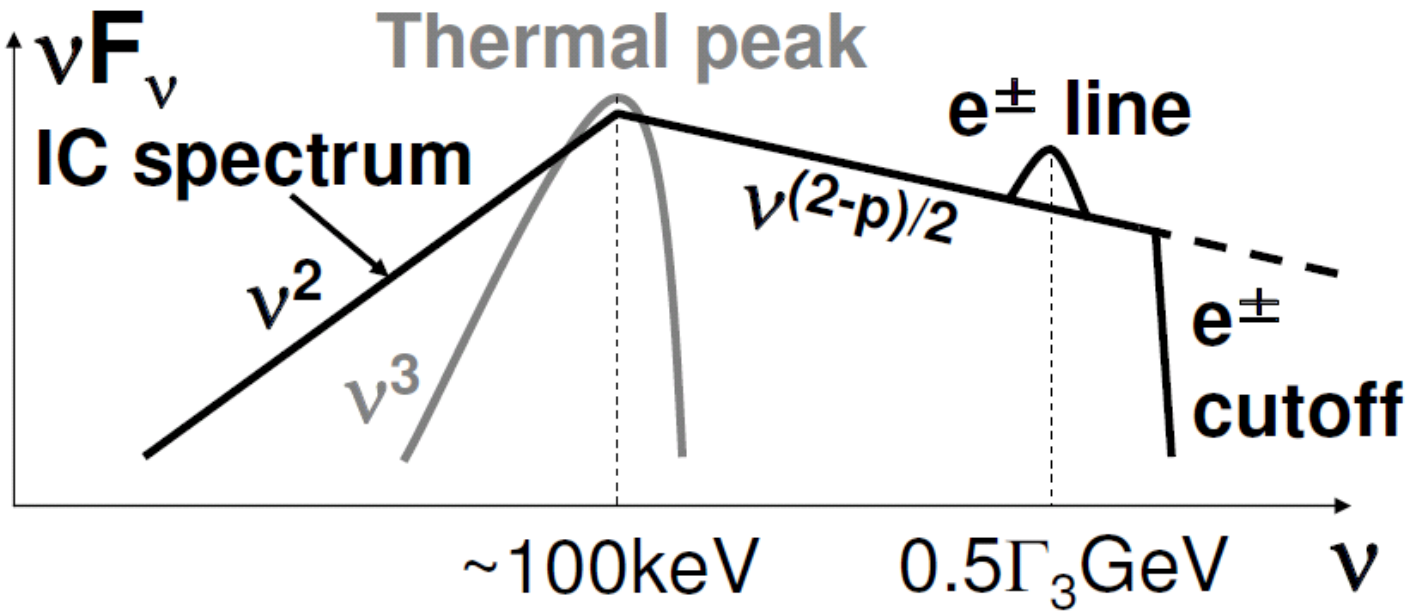
Fishman&Meegan(95)

天空分布

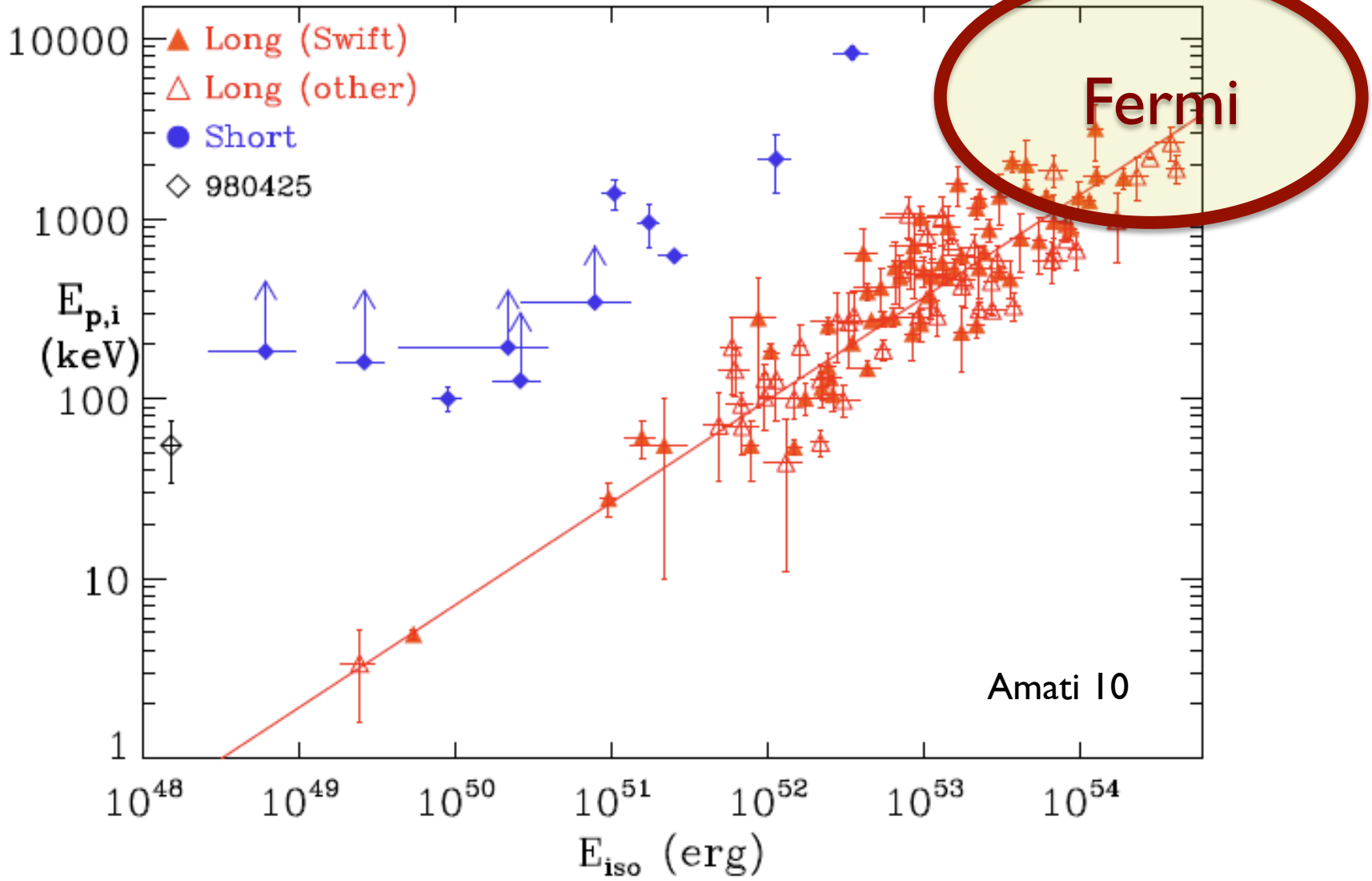


Isotropic

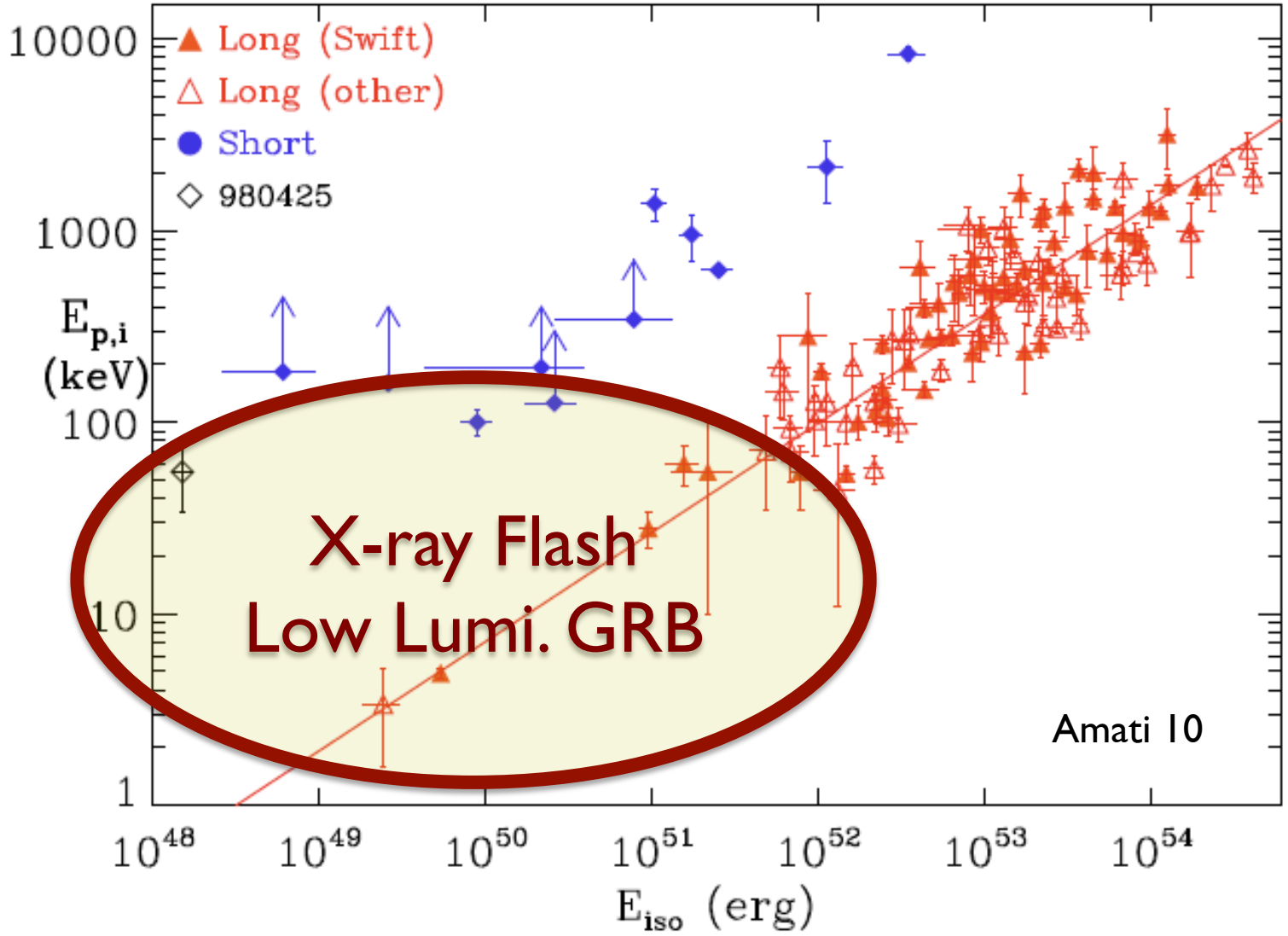
~1000 events/yr


νF_ν
Thermal peak
IC spectrum
e± line
ν^(2-p)/2
ν^2
ν^3
e±
cutoff
~100keV
0.5Γ_3GeV
ν

High E_{peak}

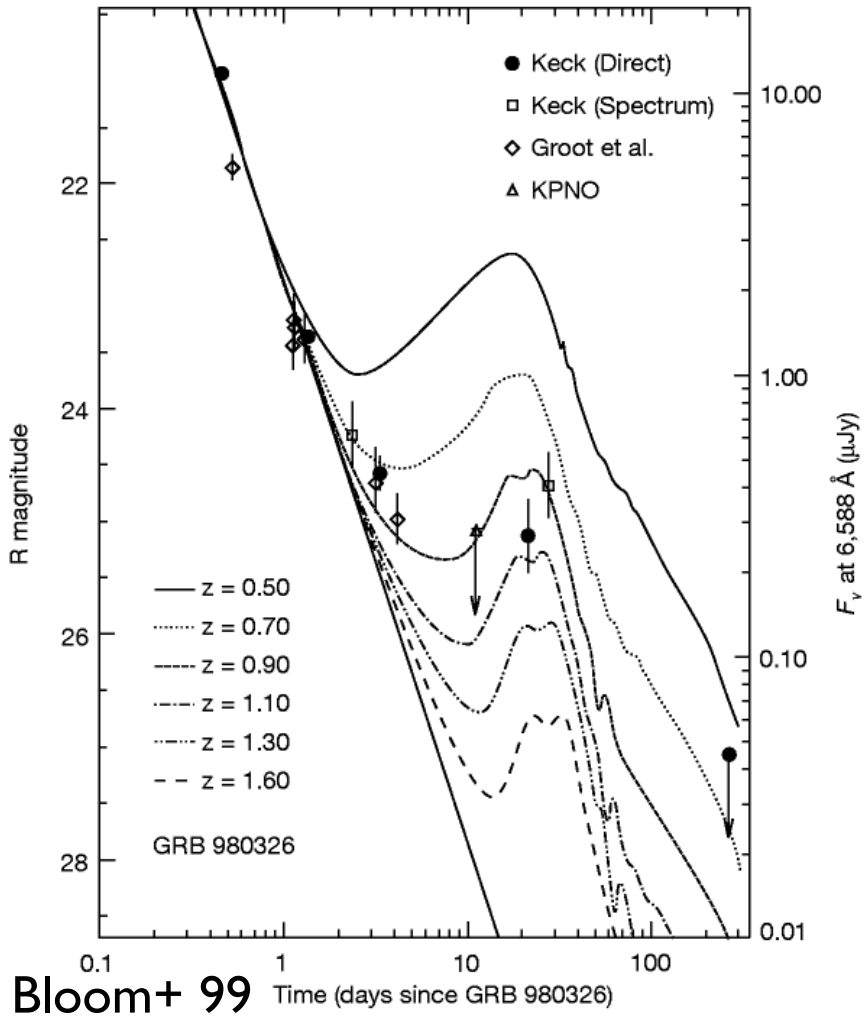

Long (Swift)
Long (other)
Short
980425
10000
1000
100
10
1
$E_{p,i}$ (keV)
10^{48}
10^{49}
10^{50}
10^{51}
10^{52}
10^{53}
10^{54}
E_{iso} (erg)
Fermi
Amati 10

Low E_{peak}


Long (Swift)
Long (other)
Short
980425
10000
1000
100
10
1
$E_{p,i}$ (keV)
10^{48}
10^{49}
10^{50}
10^{51}
10^{52}
10^{53}
10^{54}
E_{iso} (erg)
X-ray Flash
Low Lumi. GRB
Amati 10

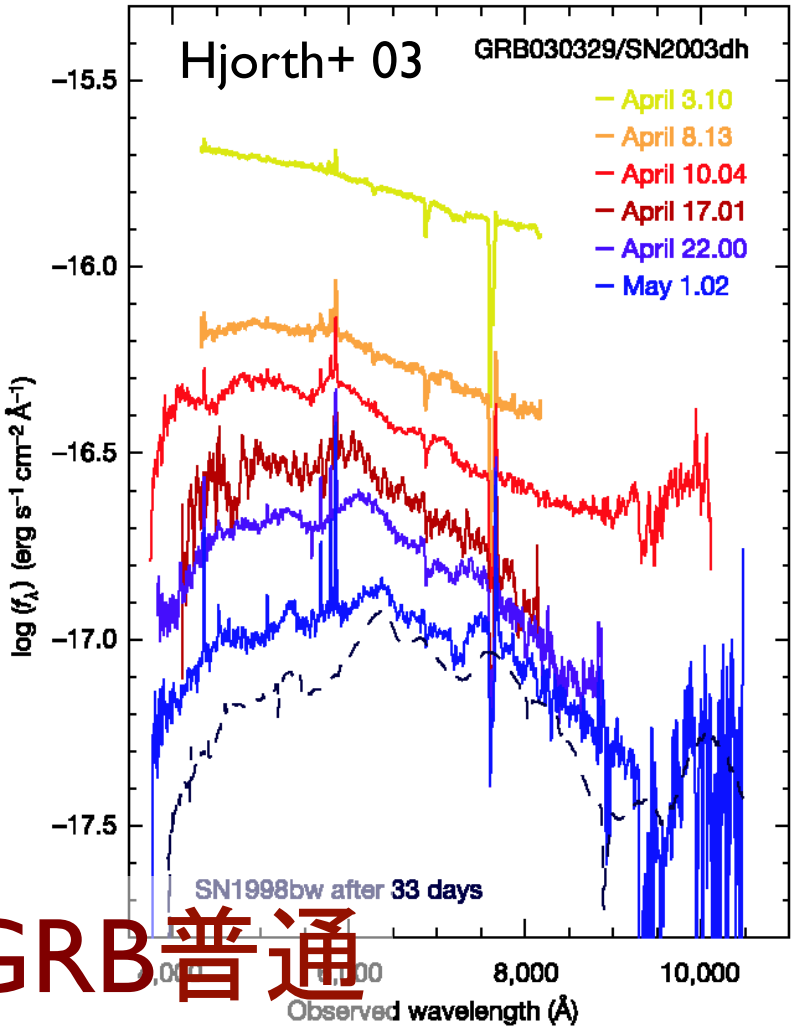
SN-GRB Connection

残光中の増光



Bloom+ 99

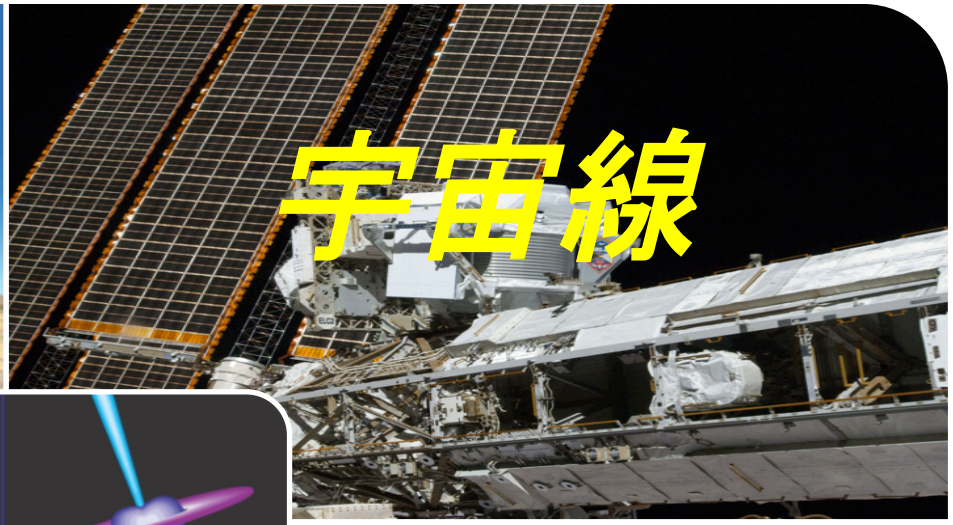
SN2003dh-GRB030329



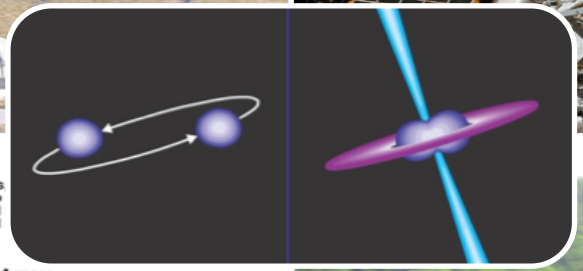
GRB普通

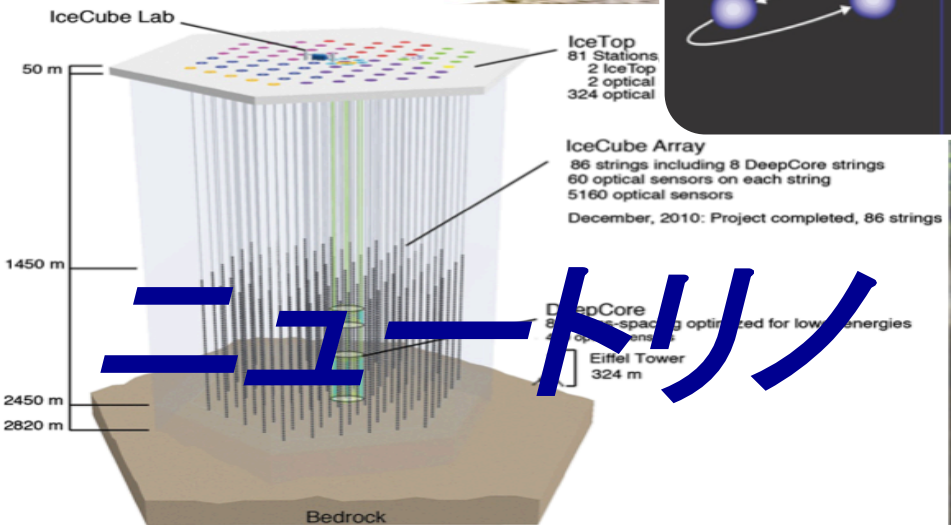
マルチメッセンジャー

電磁波



宇宙線

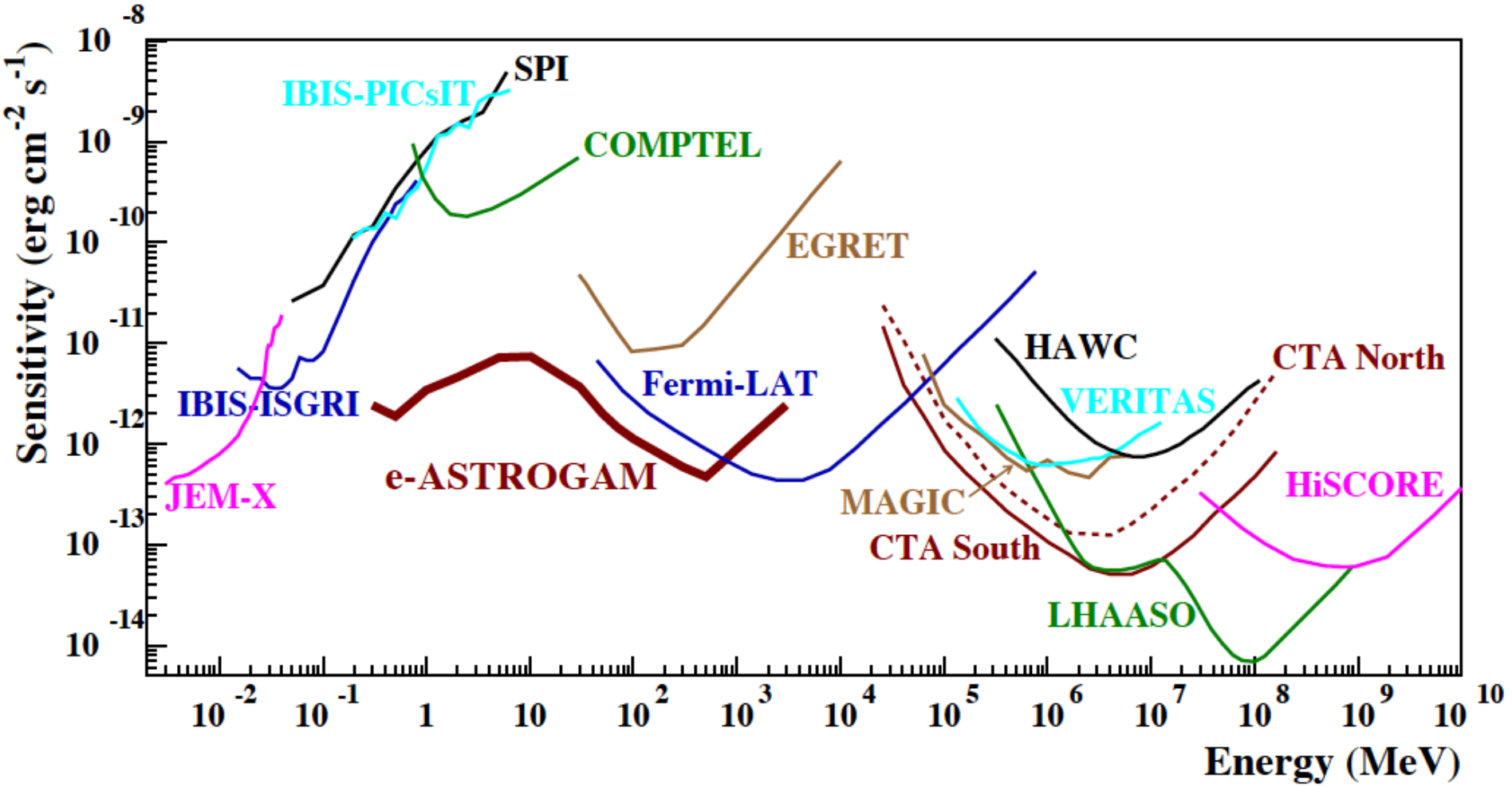




ニュートリノ

重力波

20世紀: 全波長 ⇒ 21世紀: 全粒子


Sensitivity (erg cm^{-2} s^{-1})
Energy (MeV)
SPI
IBIS-PICsIT
COMPTEL
EGRET
HAWC
CTA North
VERITAS
Fermi-LAT
IBIS-ISGRI
e-ASTROGAM
JEM-X
MAGIC
CTA South
HiSCORE
LHAASO