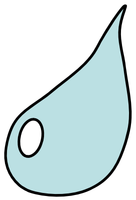
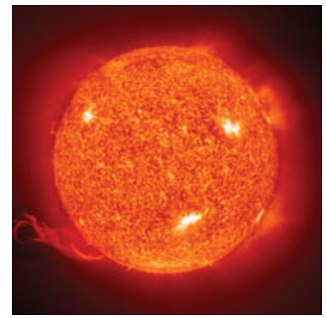
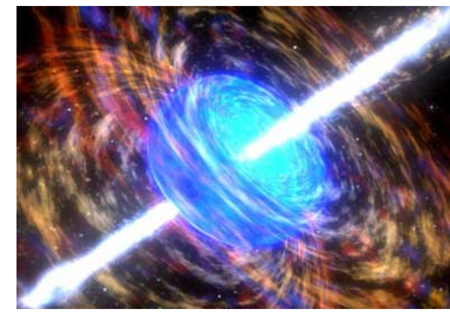
ガンマ線バースト:
ブラックホールの誕生

井岡　邦仁　（天体核）

$E=mc^2$

 = 

原子爆弾

 = 

太陽
~10^{33}g

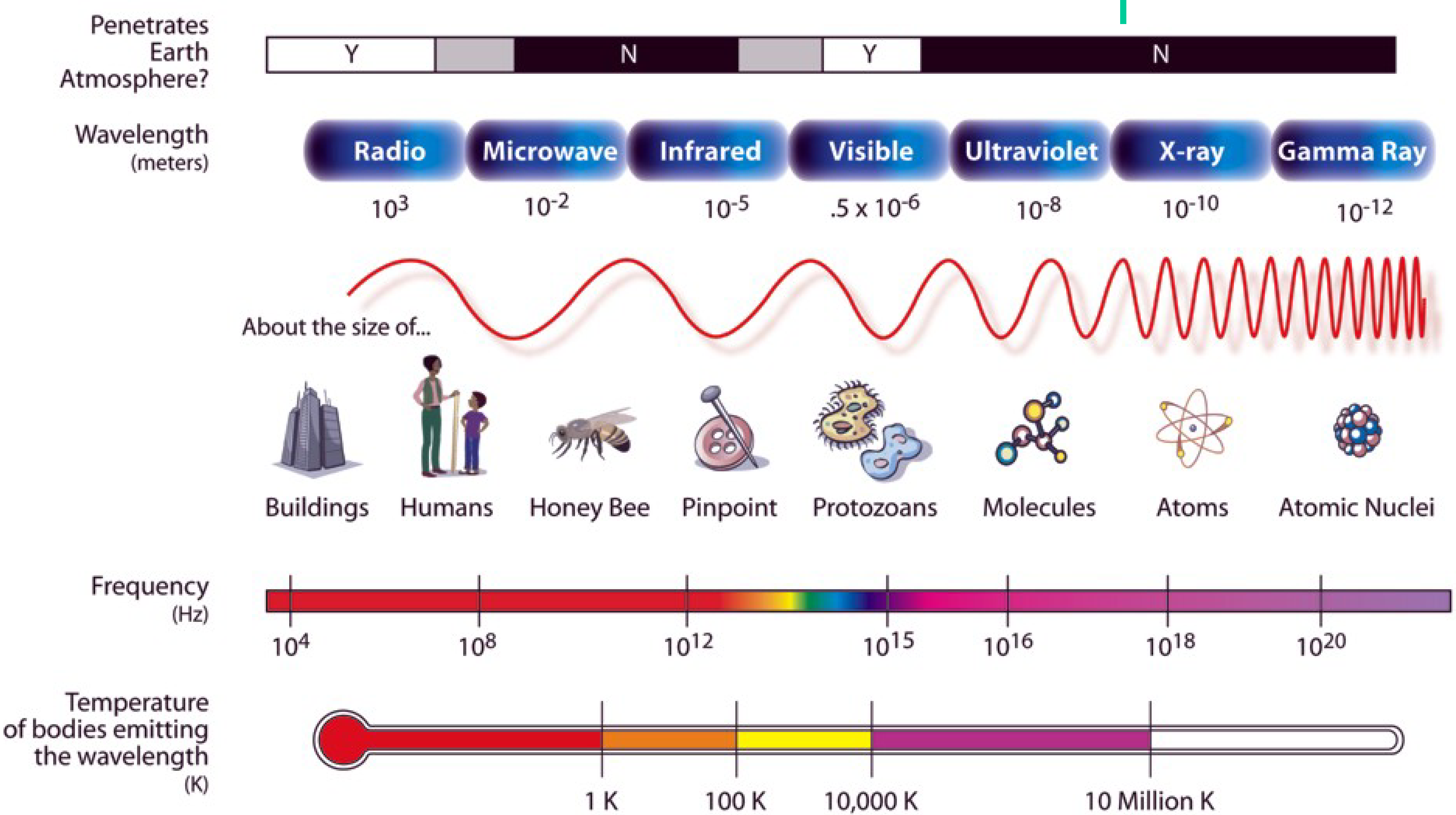
GRB
~10^{52}erg

太陽が一生かけて出すエネルギーを数秒で放出

GRBは宇宙一明るい謎の天体

電磁波

高エネルギー
宇宙物理



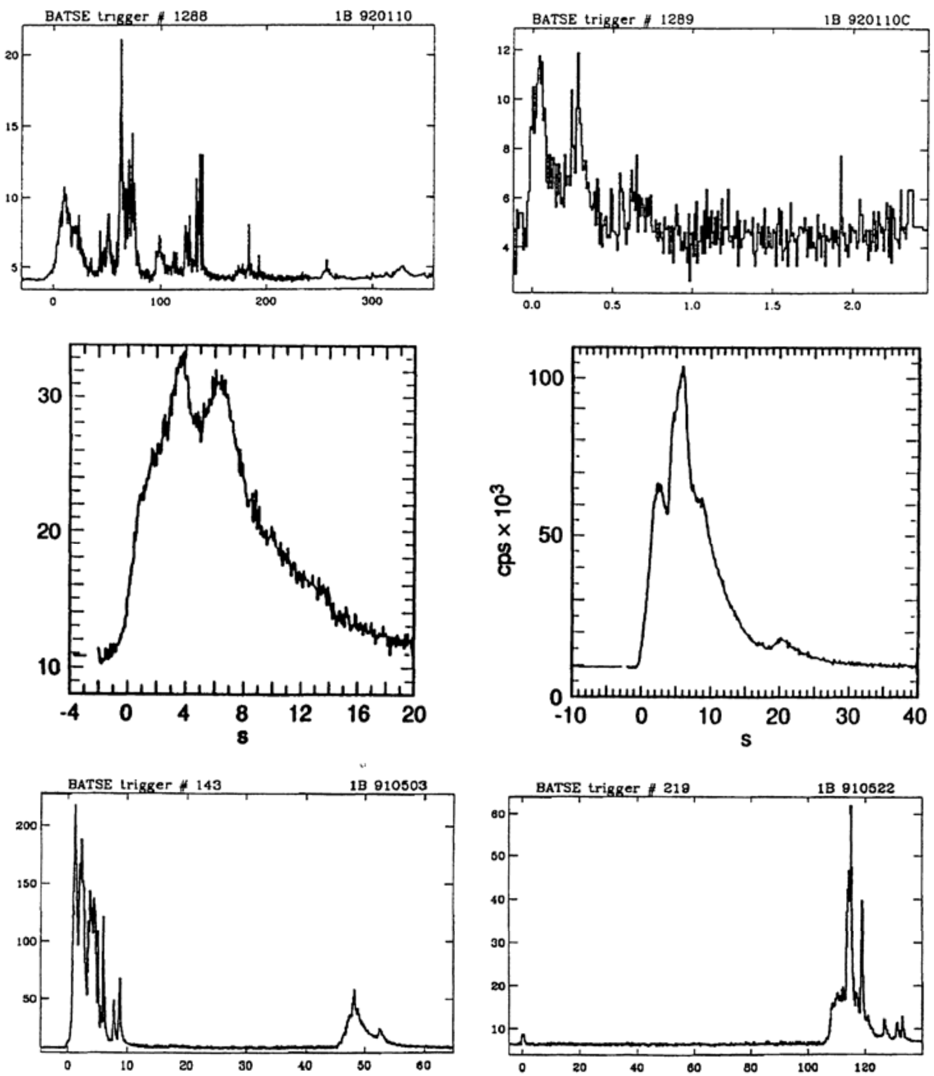
偶然の発見

1967　Vela衛星が発見

核実験の監視衛星

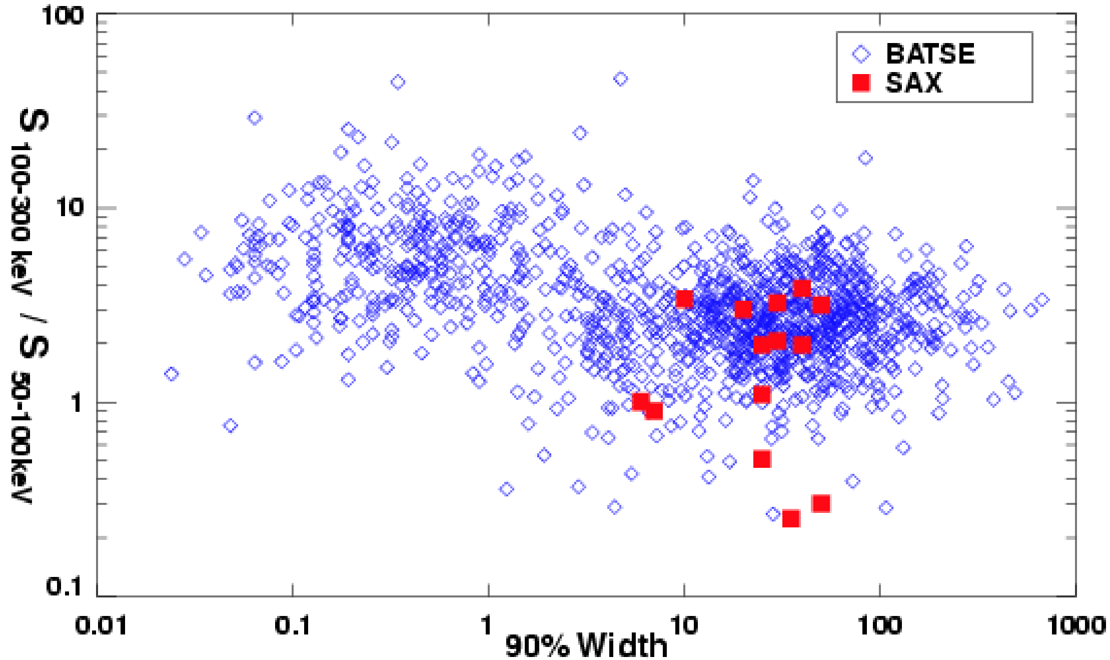
ところがγ線は地球外から！

1973　発表

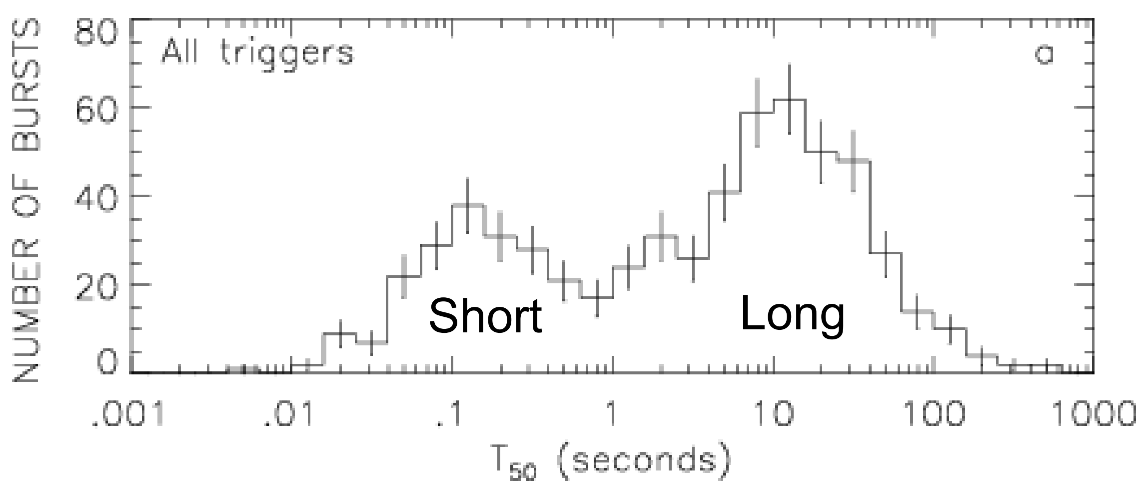


Fishman&Meegan(95)

継続時間



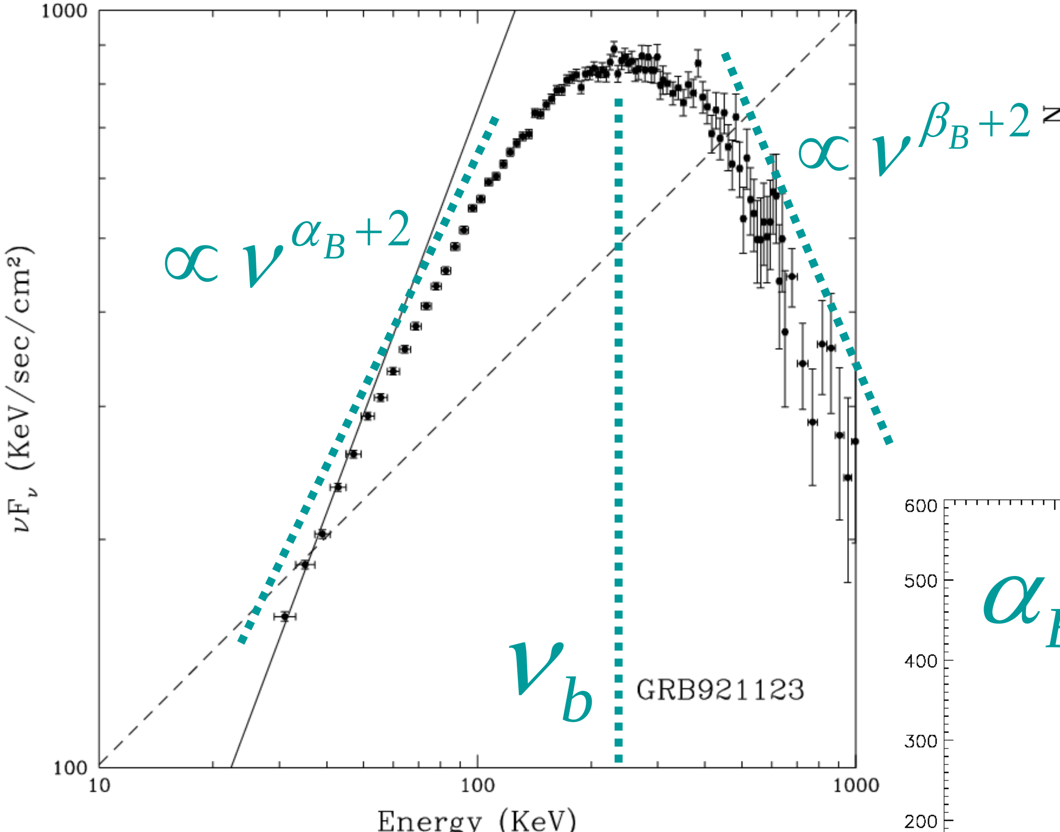
Long-soft
Short-hard

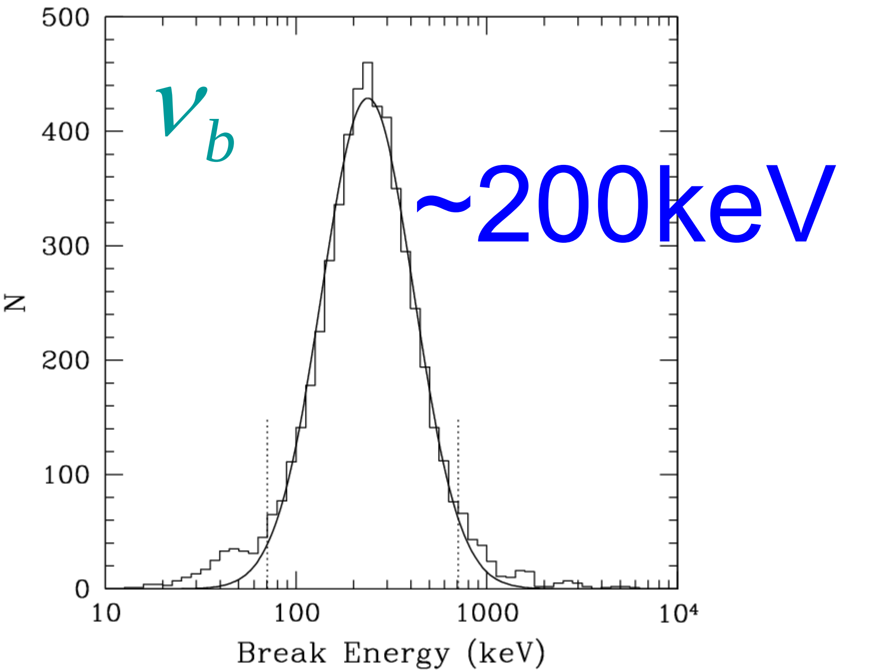


Long burst
Short burst

光子のエネルギー分布

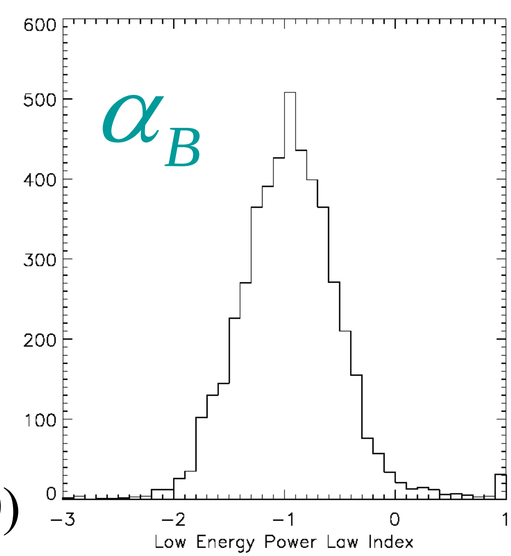
Band spectrum

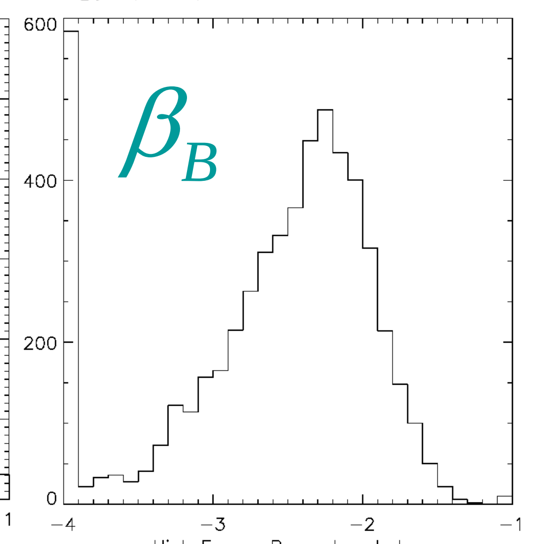




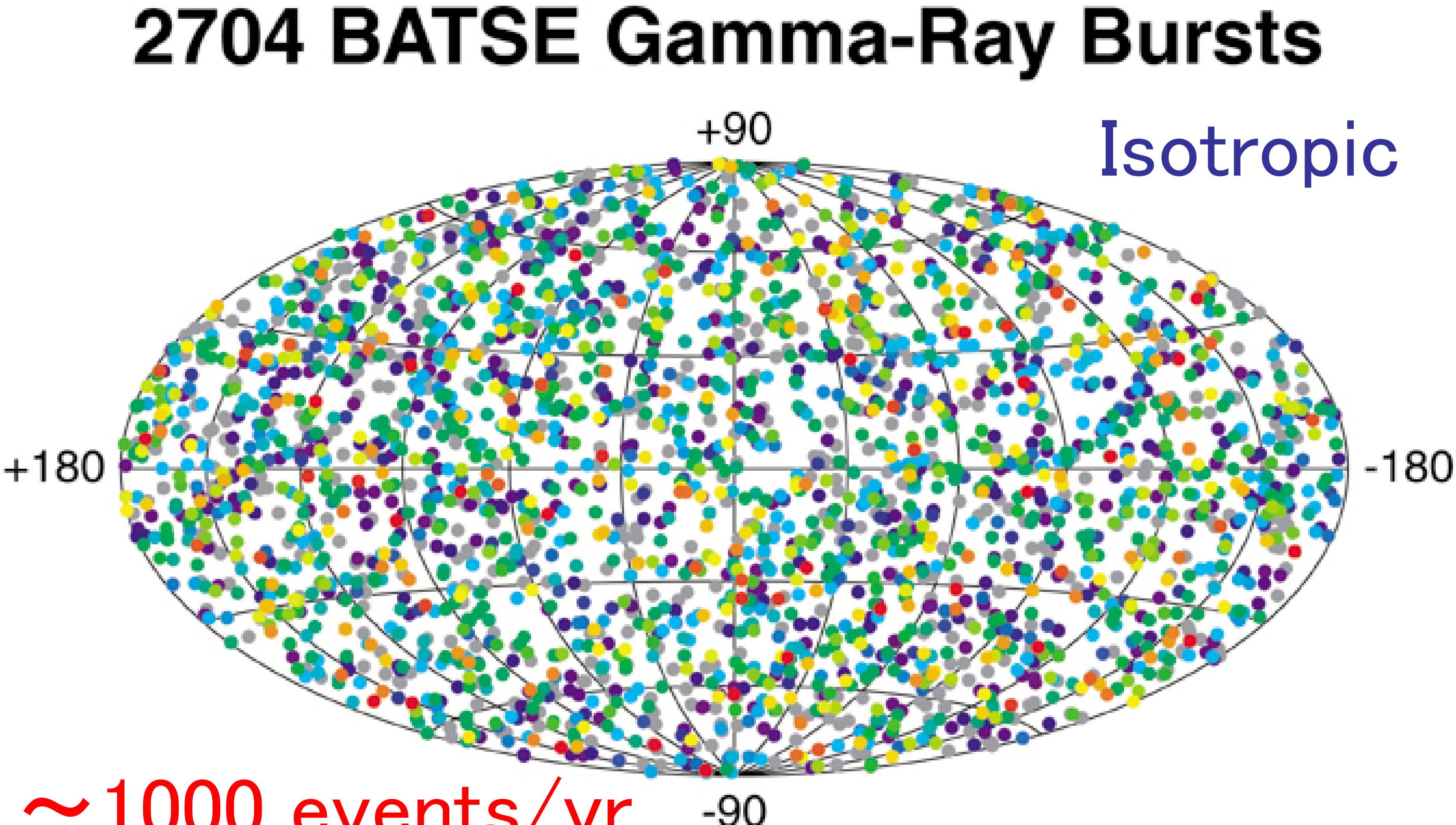
Non-thermal

Preece et al.(00)





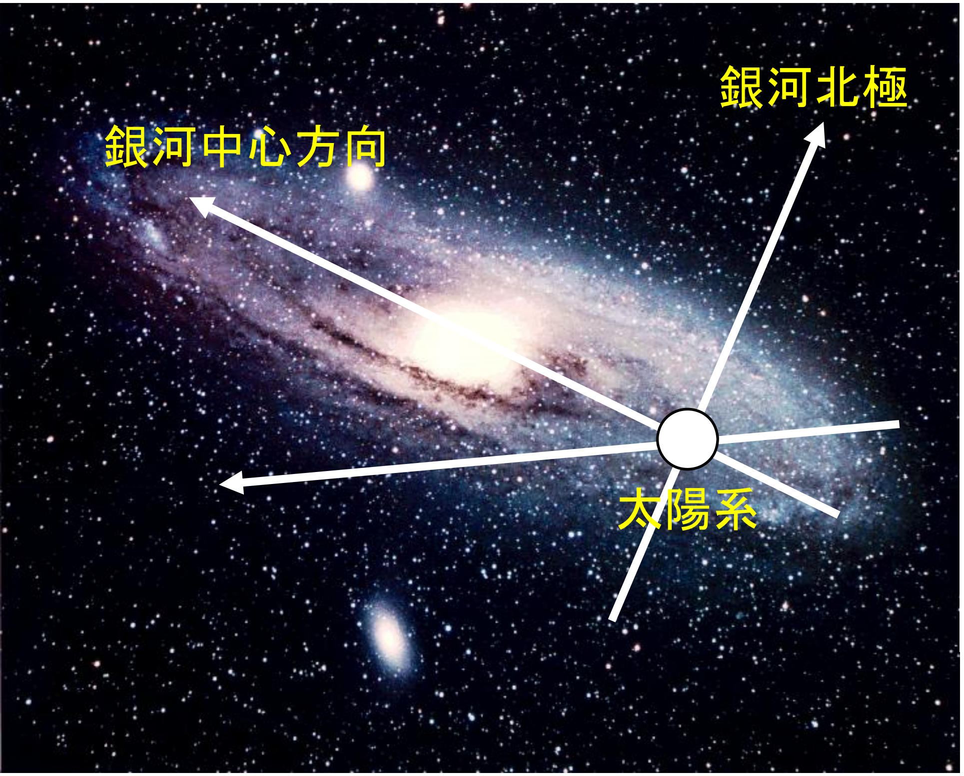
天空分布

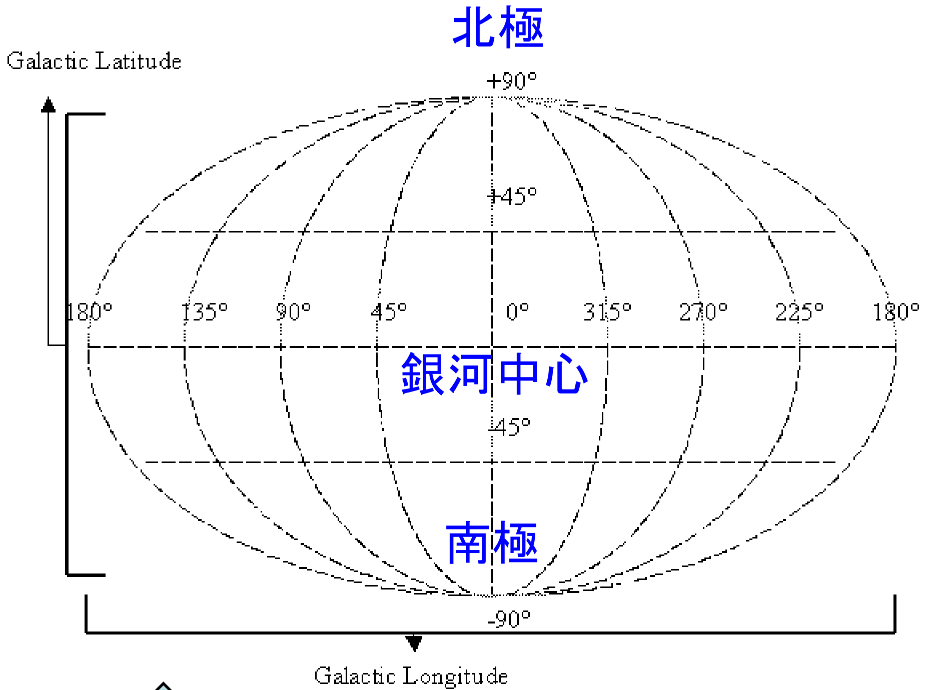


Isotropic

～1000 events/yr

銀河座標


銀河北極
銀河中心方向
太陽系


北極
Galactic Latitude
+90°
+45°
180°
135°
90°
45°
0°
315°
270°
225°
180°
銀河中心
-45°
南極
-90°
Galactic Longitude

平面に射影

GRBまでの距離は？

1967ー1997年の間、距離すら不明

⇒ エネルギー($\propto d^2$)も不明

距離の決定方法

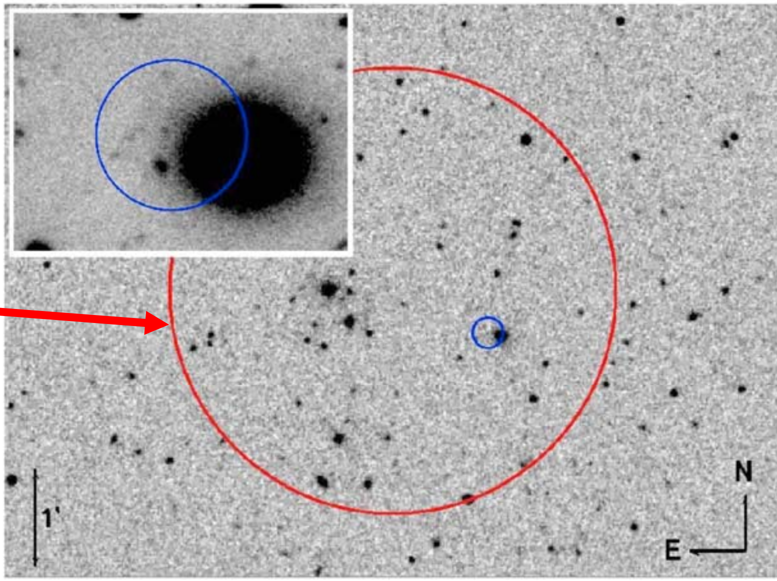
1.三角測量(~100光年が限度)

2.本当の明るさが分かれば　$F \sim L/4\pi d^2$

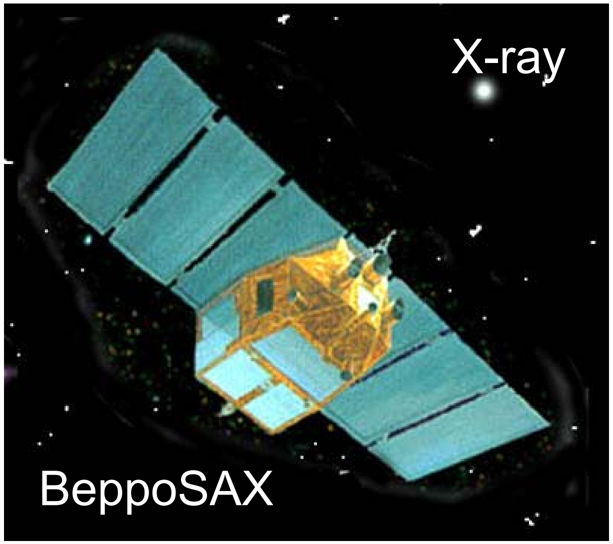
3.吸収線、放射線の赤方偏移

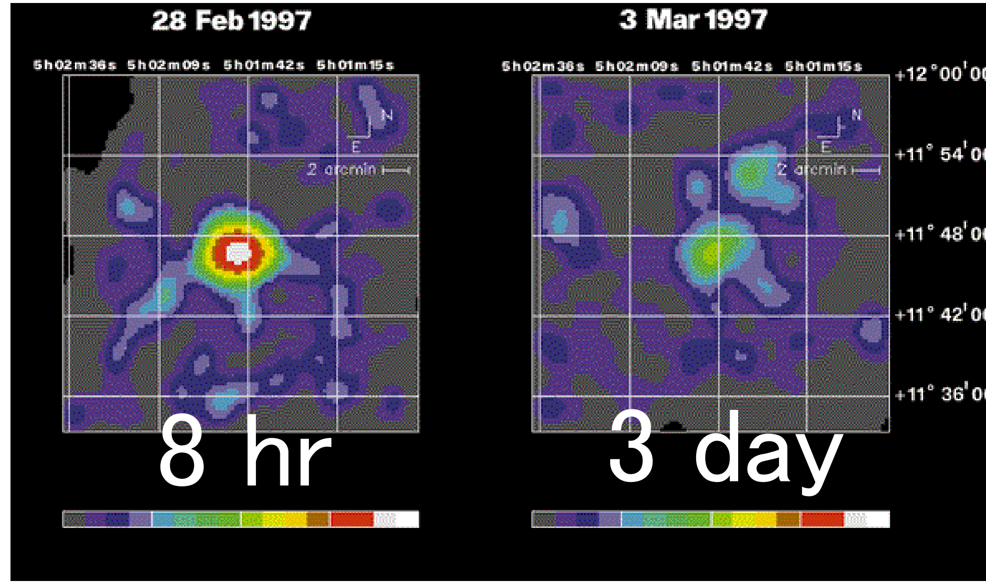
4.対応天体の距離

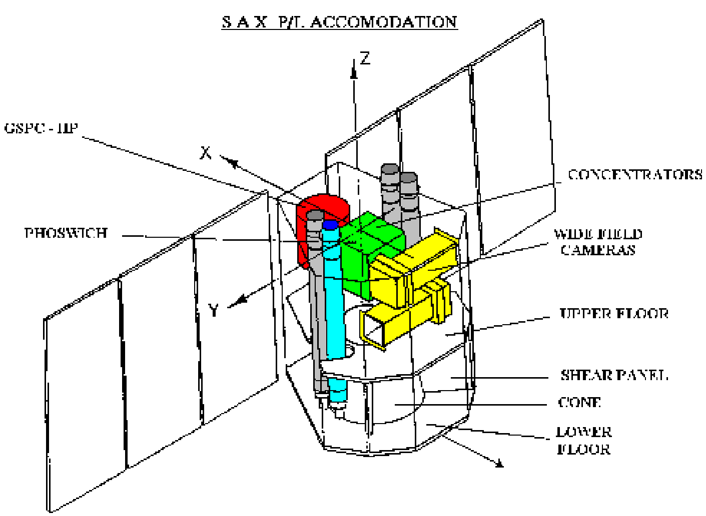
γ線の位置決定精度は悪い
その中には無数の天体

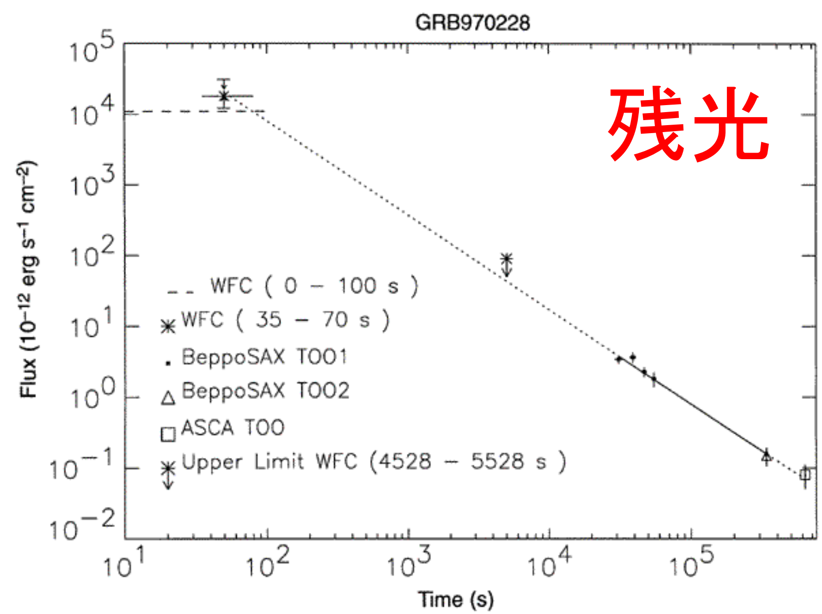


残光の発見 (Long GRB)



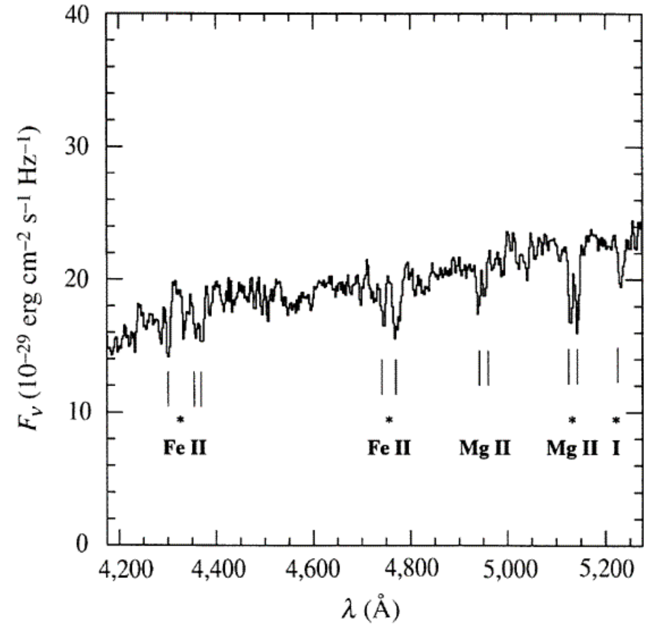






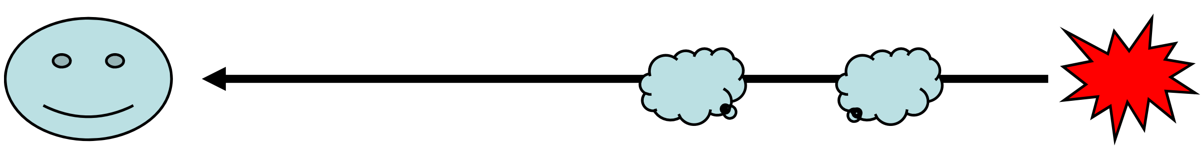
GRBは宇宙論的距離にあった！

X線望遠鏡の分解能は数分
⇒ 対応天体を探せる
⇒ 光学残光、母銀河の発見
⇒ スペクトルをとる
⇒ 赤方偏移している！

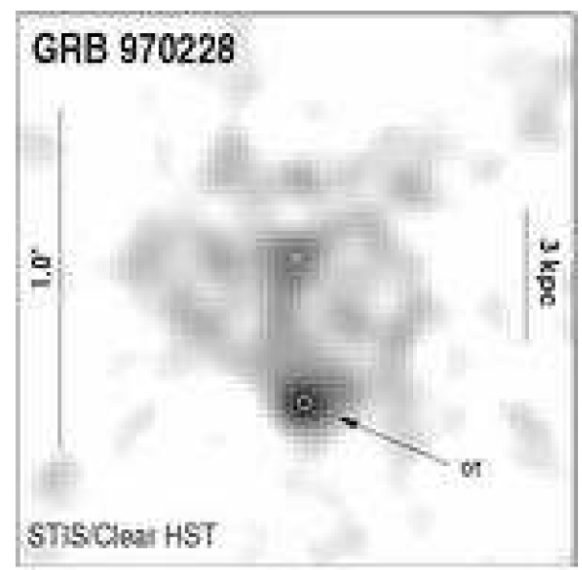


$$\lambda_{obs}/\lambda_0=1+z$$

z>0.835



z=0.768　0.835

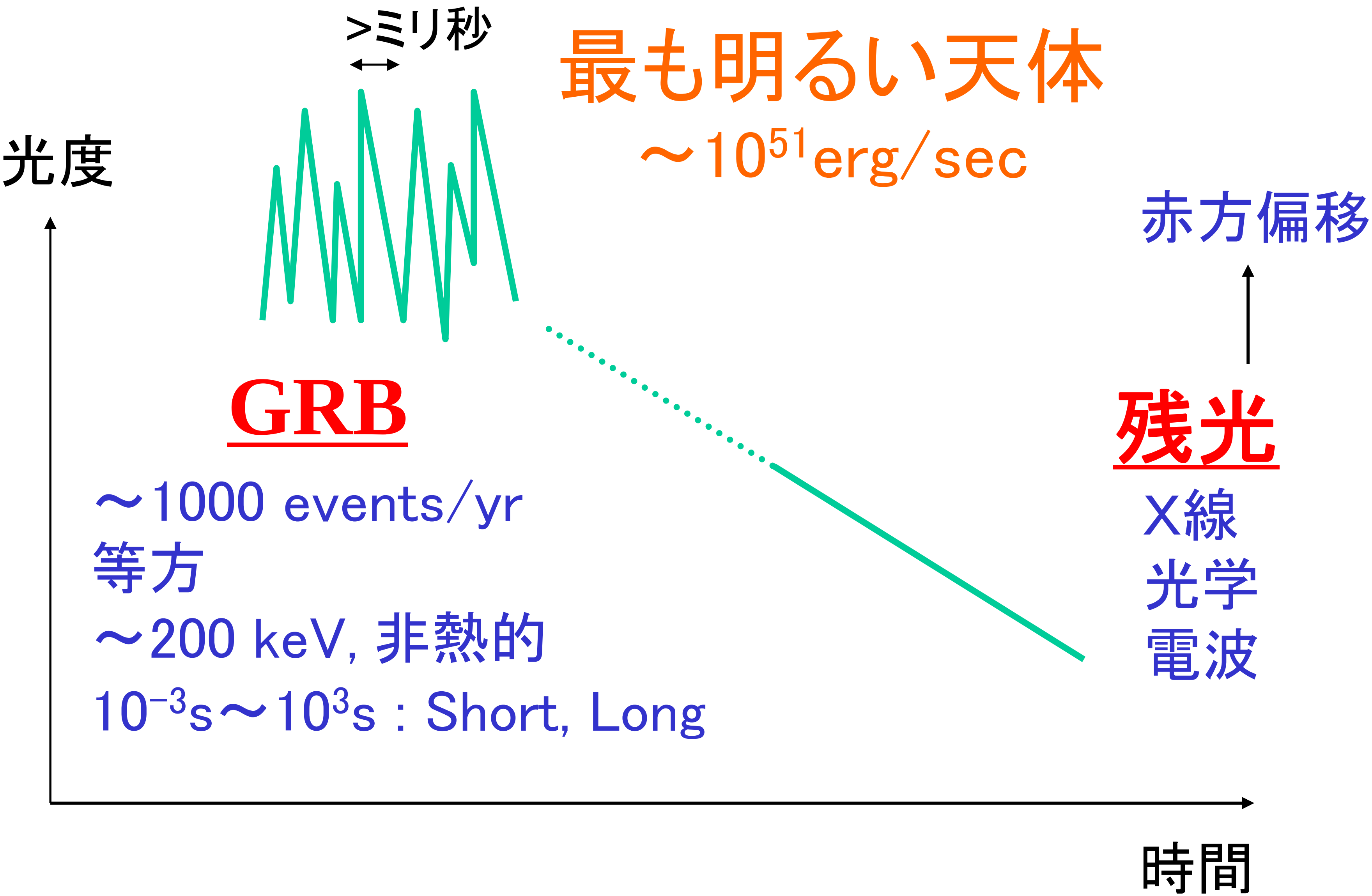


~1000近くの論文が死んだ

宇宙最大の爆発

- 宇宙論的距離：d~100億年×c~10^{28}cm
- 観測される典型的なガンマ線のFluxは
  F~10^{-6}erg/s/cm^2
- 等方的に放射していると
  $L=4\pi d^2 F \sim 10^{51}$erg/s
- 銀河: L~10^{43}erg/s
- つまり ~10^8 個の銀河のLuminosity
  ~宇宙の全銀河のLuminosity
- ⇒ 宇宙で最もViolentな現象

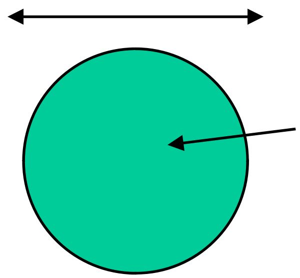
観測のまとめ



>ミリ秒
最も明るい天体
～10^51 erg/sec
光度
赤方偏移
GRB
残光
～1000 events/yr
等方
～200 keV, 非熱的
10^−3 s～10^3 s : Short, Long
X線
光学
電波
時間

一見矛盾

ミリ秒 x 光速 ~ 300km



10^{51}erg/s
x ミリ秒
~ 10^{48}erg

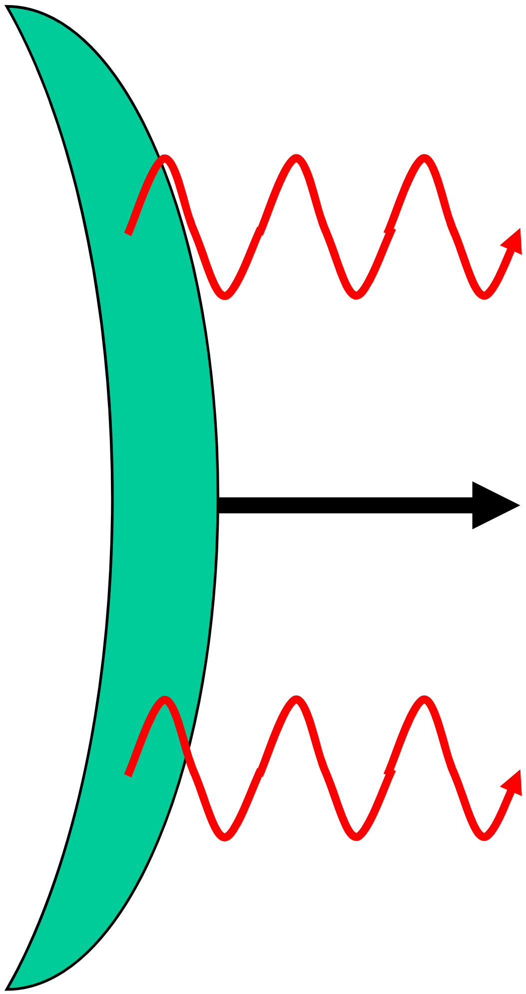
MeV以上の
光子密度>10^{29}cm^{-3}

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

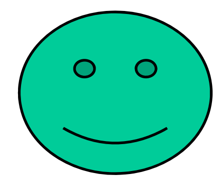
$(10^{-25}$x$10^{29})^{-1}$cm
~10^{-4}cmでe$^{\pm}$生成

ガンマ線が出てこれない！？

光の99．9999%の速さ



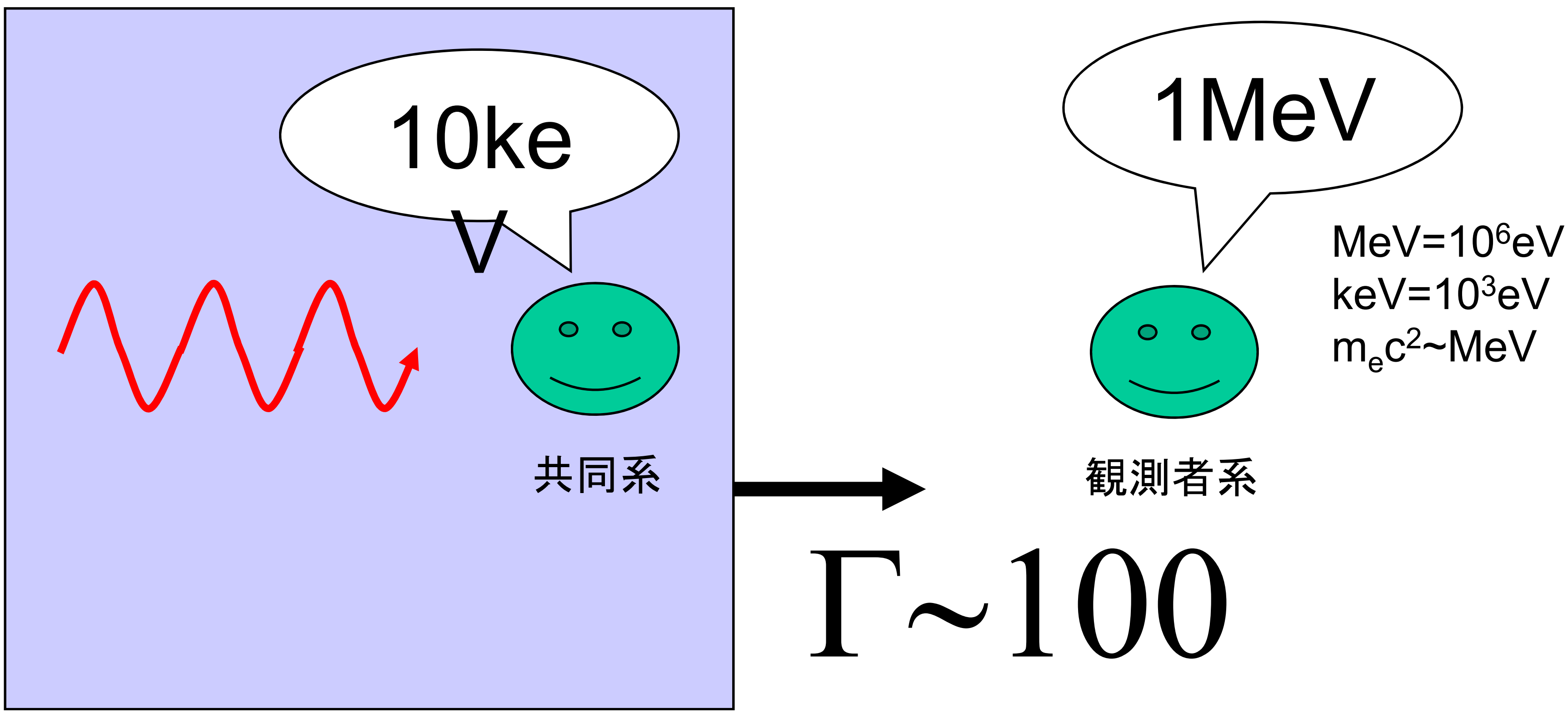
おそらく唯一の解決法



ローレンツ因子

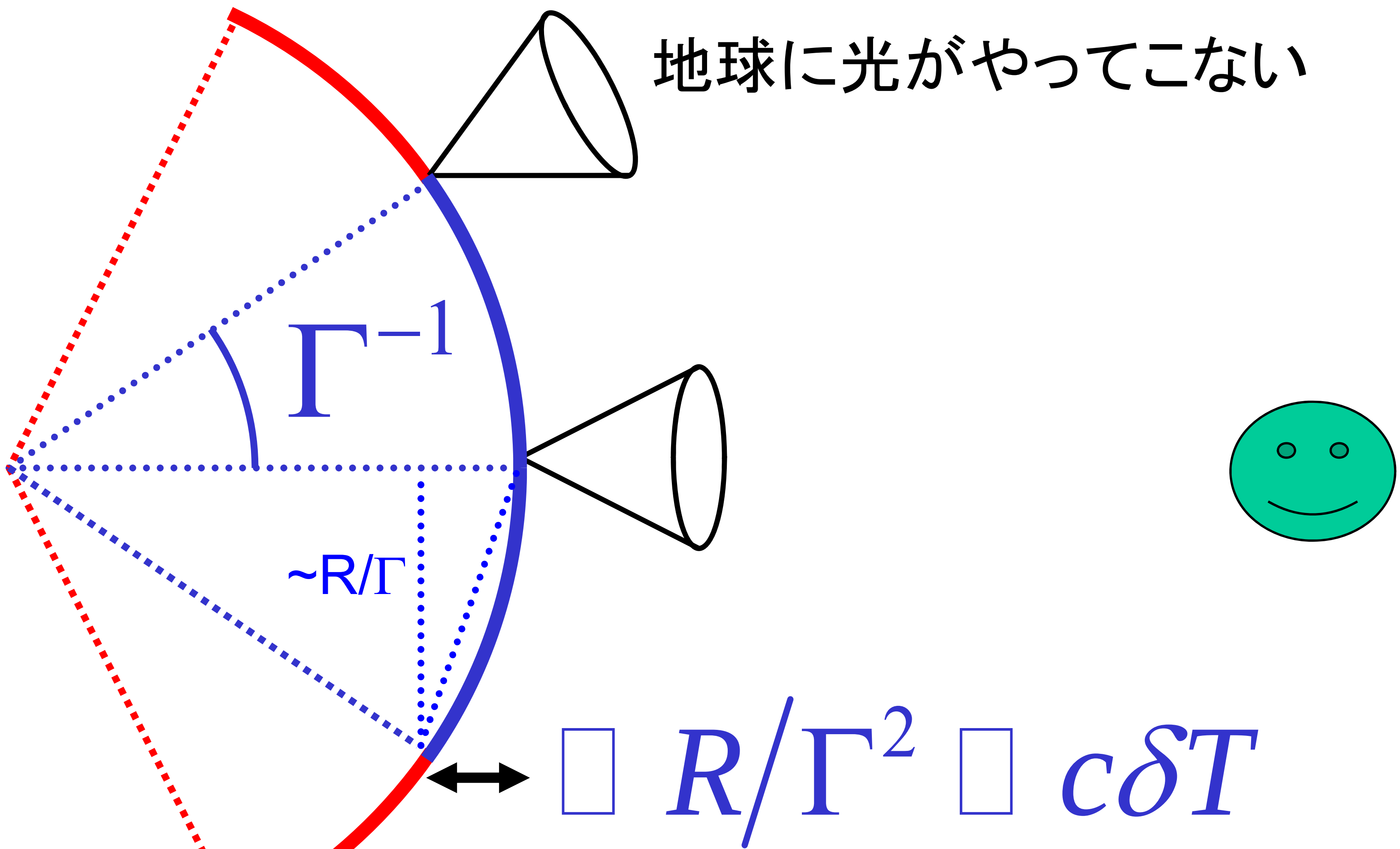
$$\Gamma = \frac{1}{\sqrt{1-(v/c)^2}} > 100$$

効果1：青方偏移



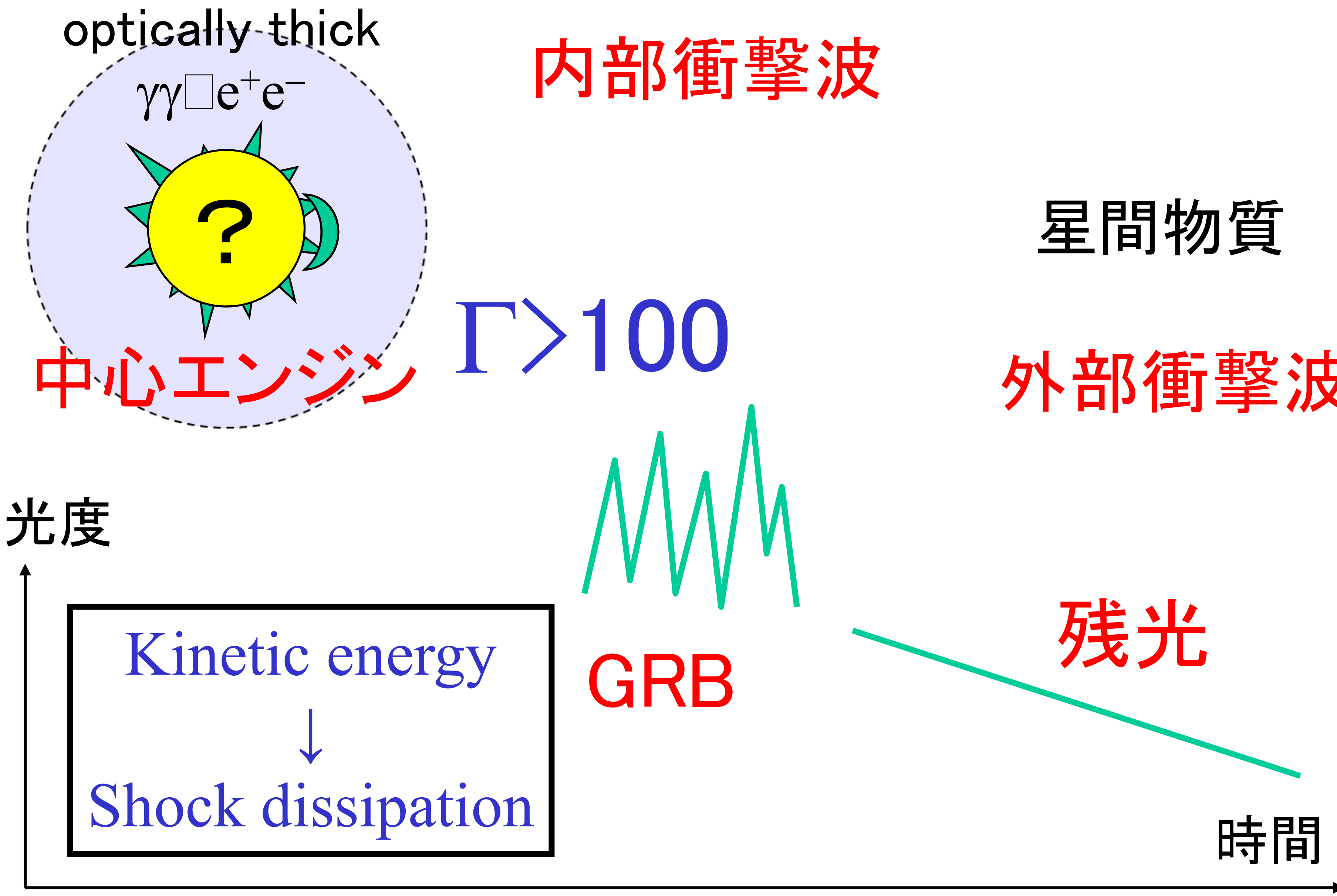
$e^{\pm}$を作れる光子を少なくできる

効果2:相対論的ビーミング



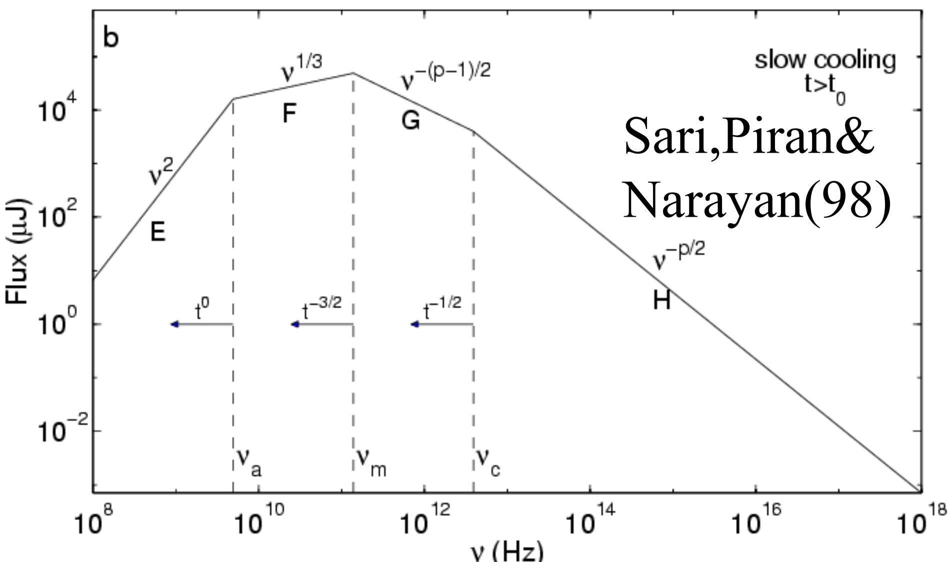
サイズを大きくできる

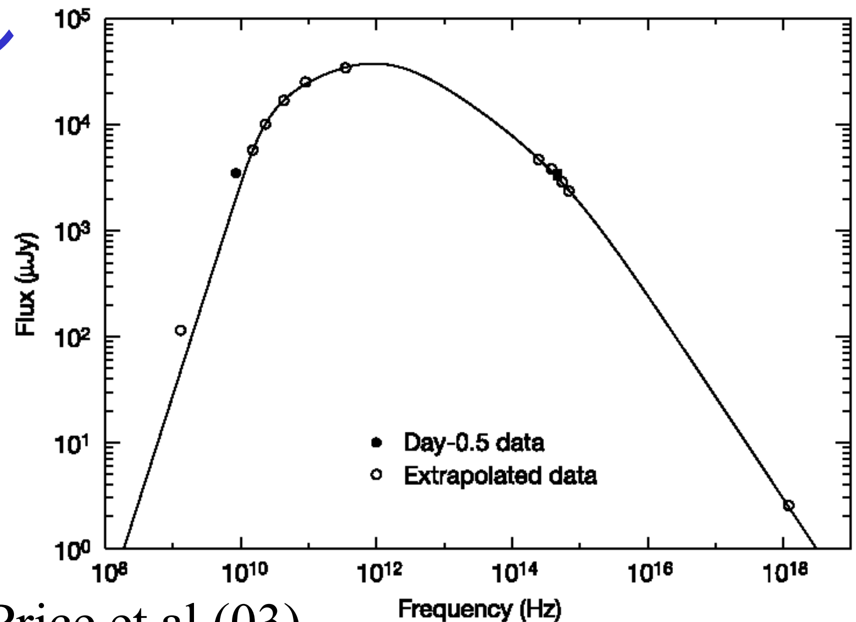
標準モデル


optically thick
γγ□e+e−
?
中心エンジン
内部衝撃波
星間物質
Γ>100
外部衝撃波
光度
Kinetic energy
↓
Shock dissipation
GRB
残光
時間

残光モデルの成功

シンクロトロン衝撃波モデル





Price et al.(03)

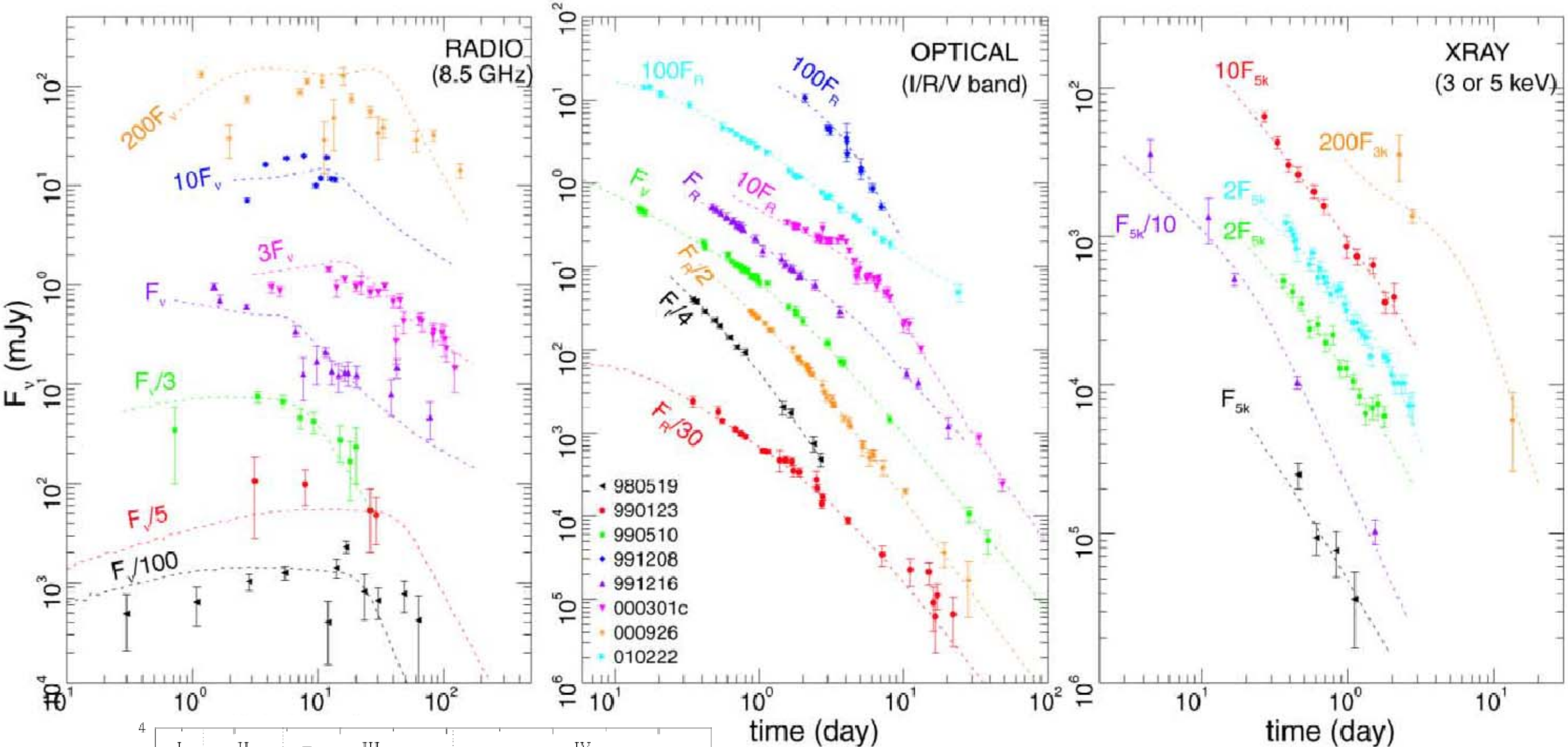
① 電子の加速
② 磁場の生成
⇒ シンクロトロン放射
数個のパラメータ
E, n, ε_e, ε_B, p

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

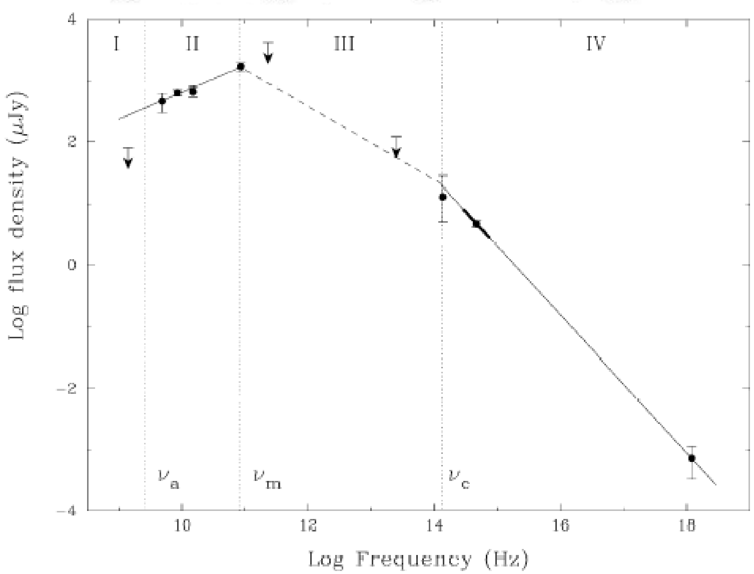
$n \sim 0.01 - 100\,\mathrm{cm}^{-3}$

$\varepsilon_e \sim 0.1$

$\varepsilon_B \sim 0.01$



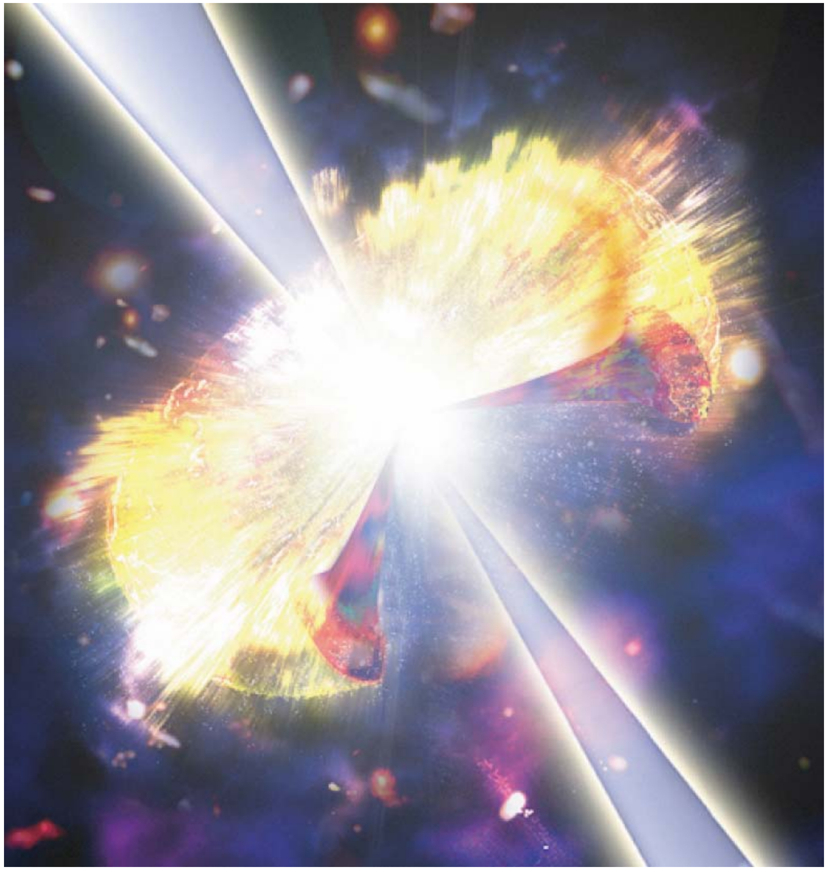
Panaitescu&Kumar(00)



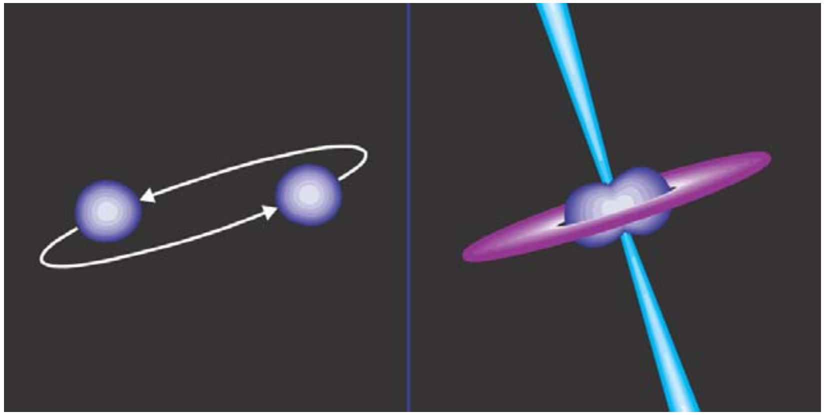
Galama et al.(98)

驚くほどよく合う

中心エンジンは何？



重い星の崩壊
（Hypernova, Collapsar）



連星中性子星の合体

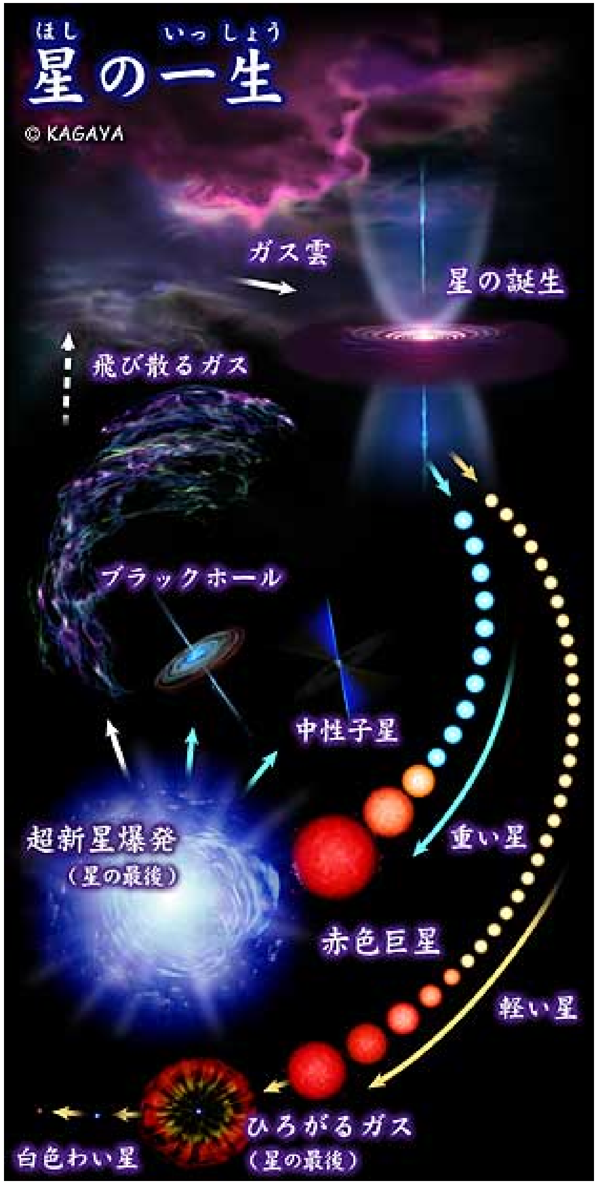
イベントレート

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

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

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

星の一生



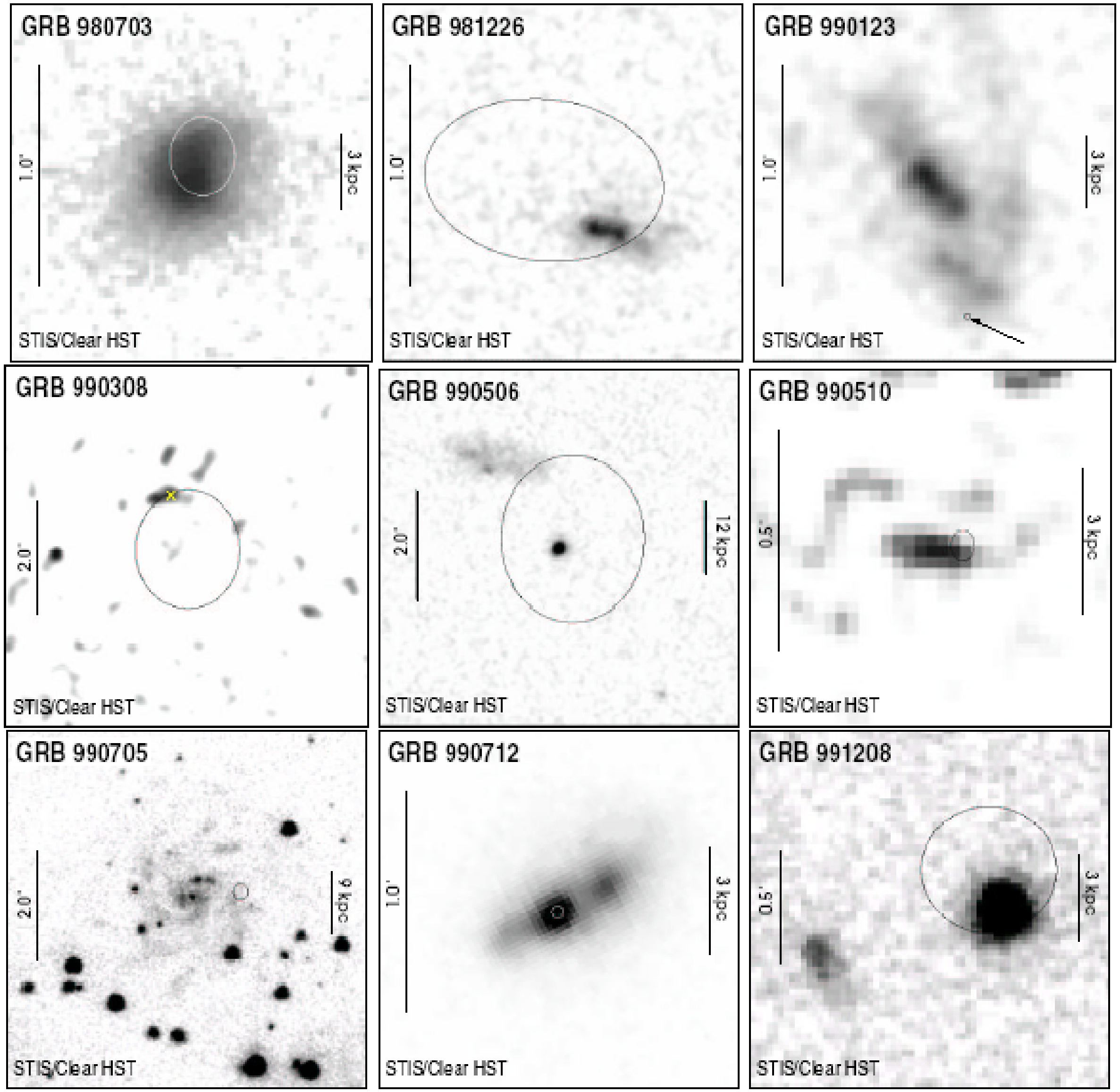
中心で核融合

水素→ヘリウム→炭素→･･･→鉄

星の進化は主に質量で決まる

$M<0.08M_{太陽}$	水素が燃えない → 褐色矮星
$0.08M_{太陽}<M<0.45M_{太陽}$	ヘリウムが燃えない →ヘリウムの白色矮星
$0.45M_{太陽}<M<8M_{太陽}$	炭素が燃えない → 炭素の白色矮星
$8M_{太陽}<M<13M_{太陽}$	Ne、Mgまで進む。電子捕獲後 超新星爆発して中性子星？
$13M_{太陽}<M$	鉄まで進み重力崩壊。 外層が飛べば中性子星？ 失敗すればブラックホール

母銀河



基本的に若くて星形成を活発に行っている銀河

⇒ 重い星を示唆

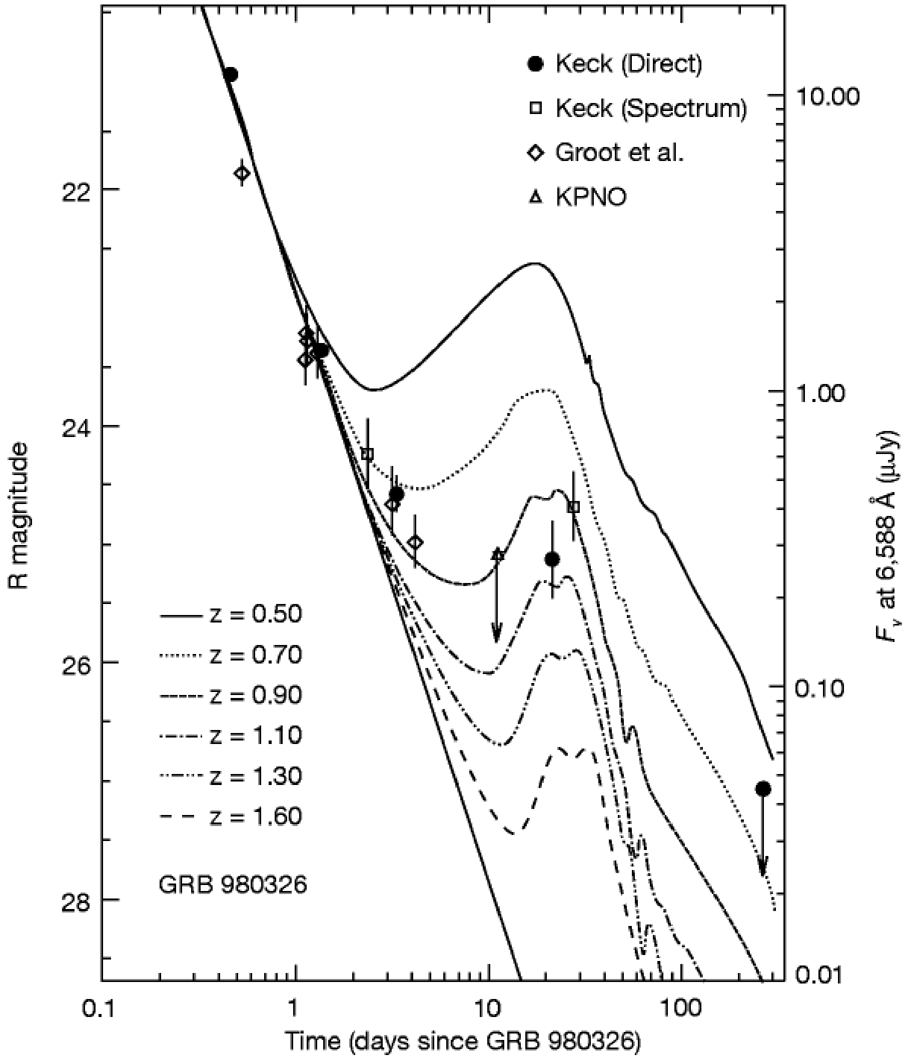
∵重い星は短命

これでは傍証

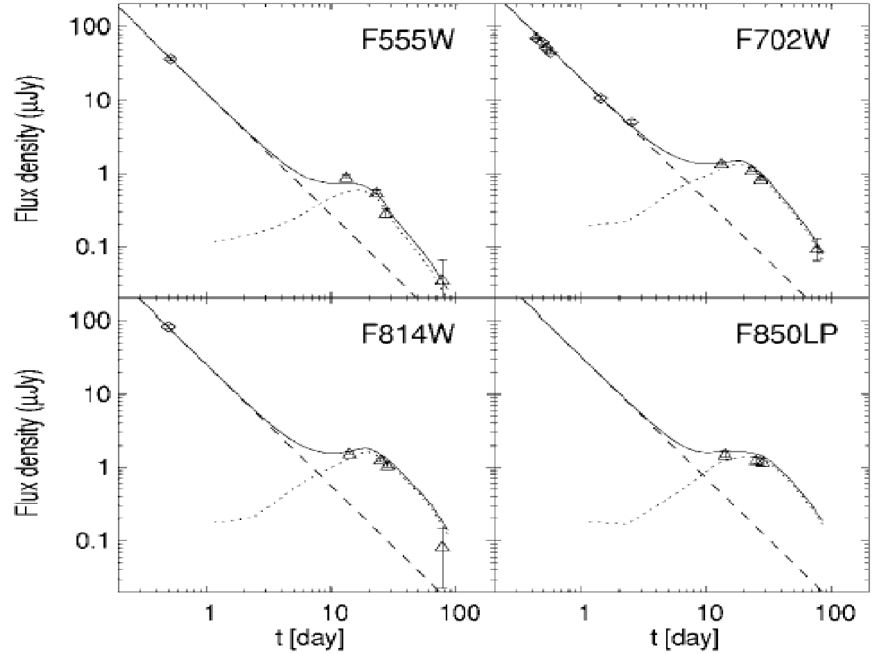
Bloom,Kulkarni&Djorgovski(02)

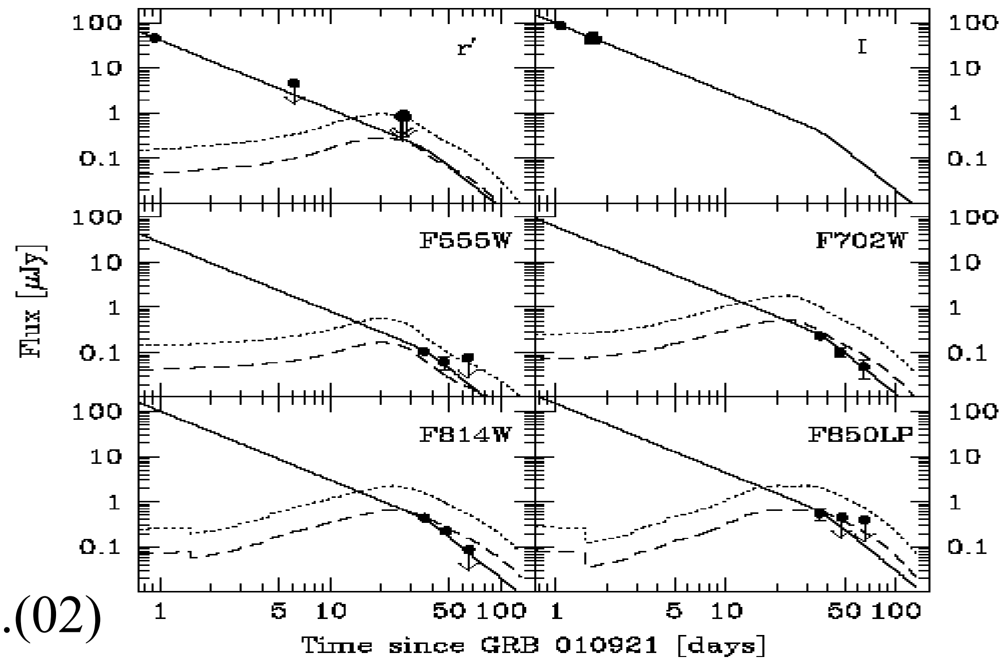
残光中の超新星

GRB011121,Bloom et al.(02)



Bloom et al.(99)



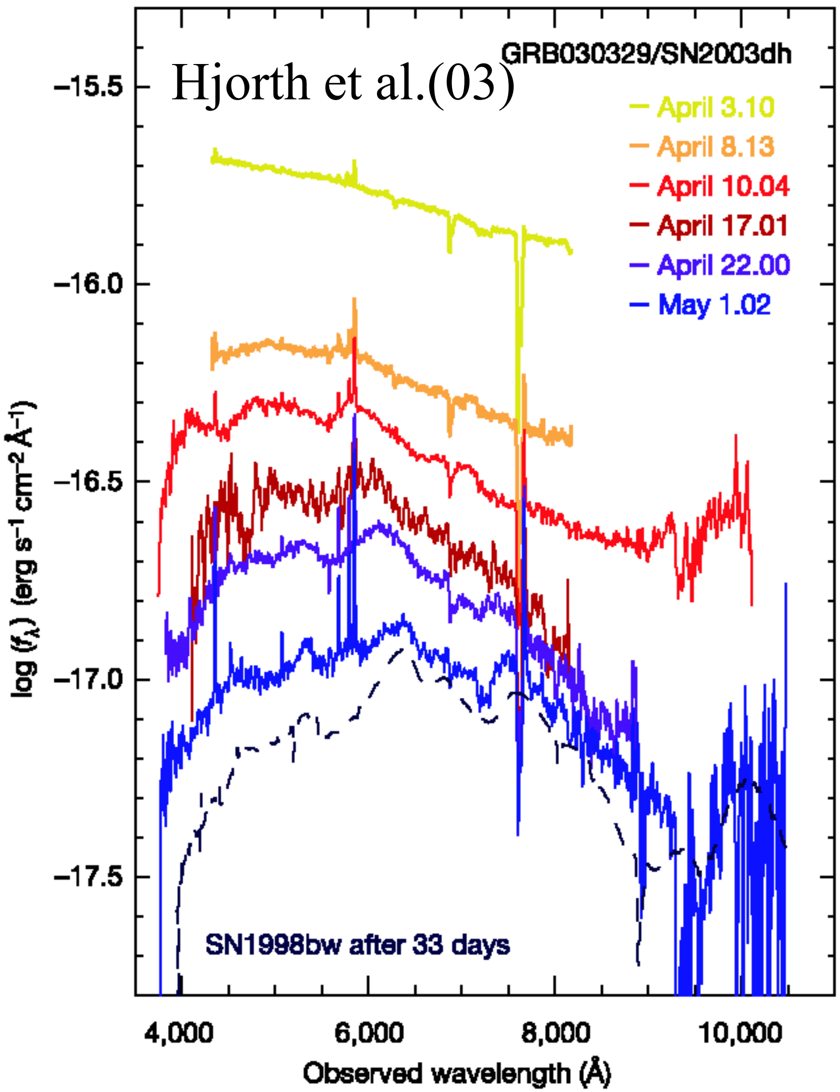


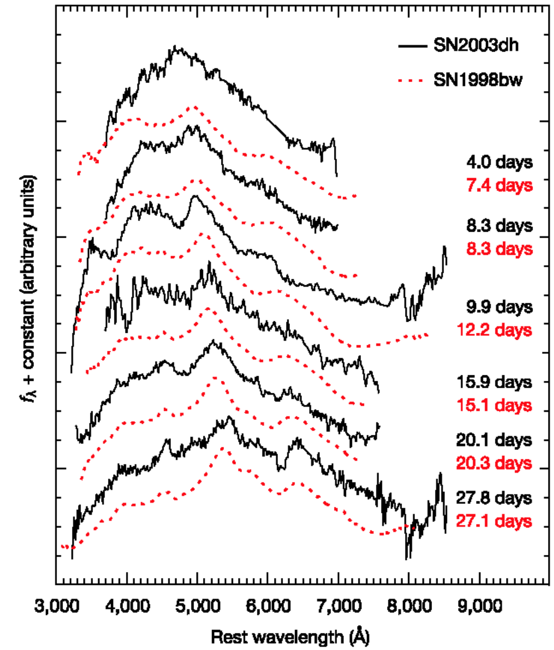
でも本当？

Price et al.(02)

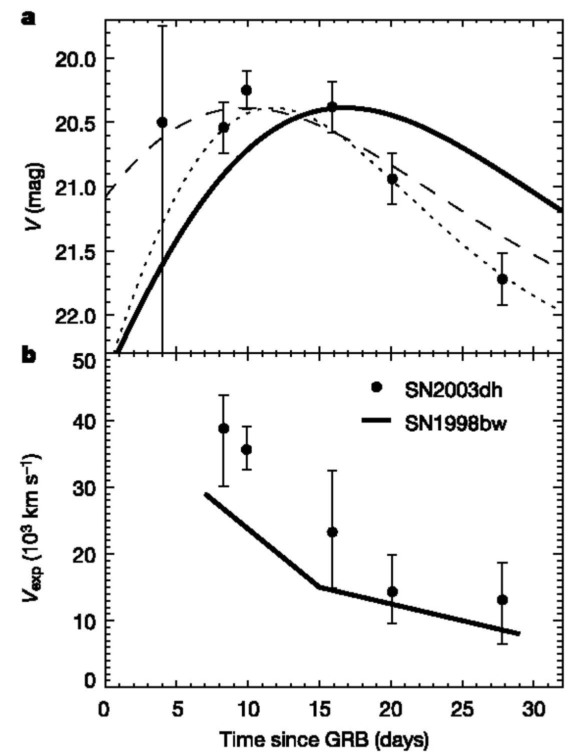
GRB030329

いままでで
2番目に近いGRB





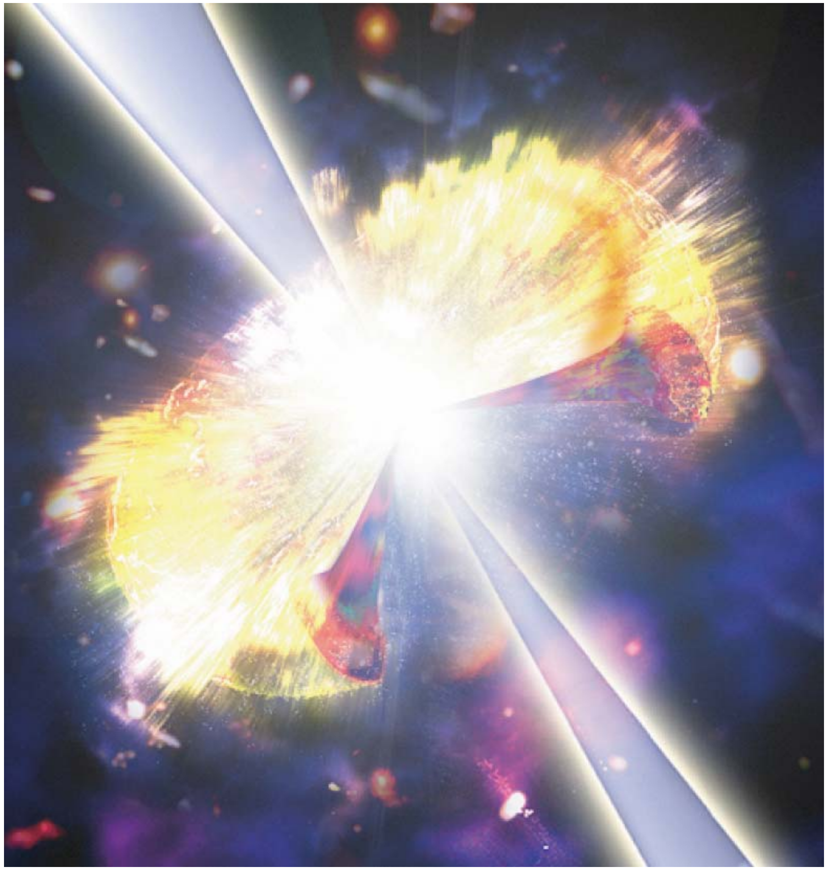
Wide
line



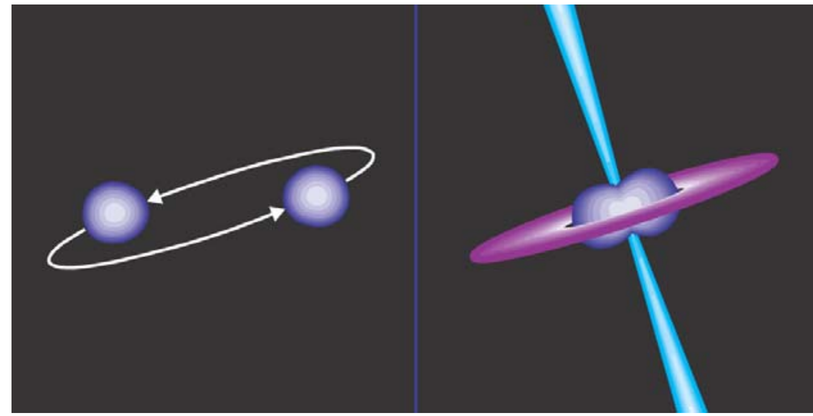
Within
a few
days

GRBは超新星とともに起こる

中心エンジンは何？



重い星の崩壊
（Hypernova, Collapsar）



連星中性子星の合体

イベントレート

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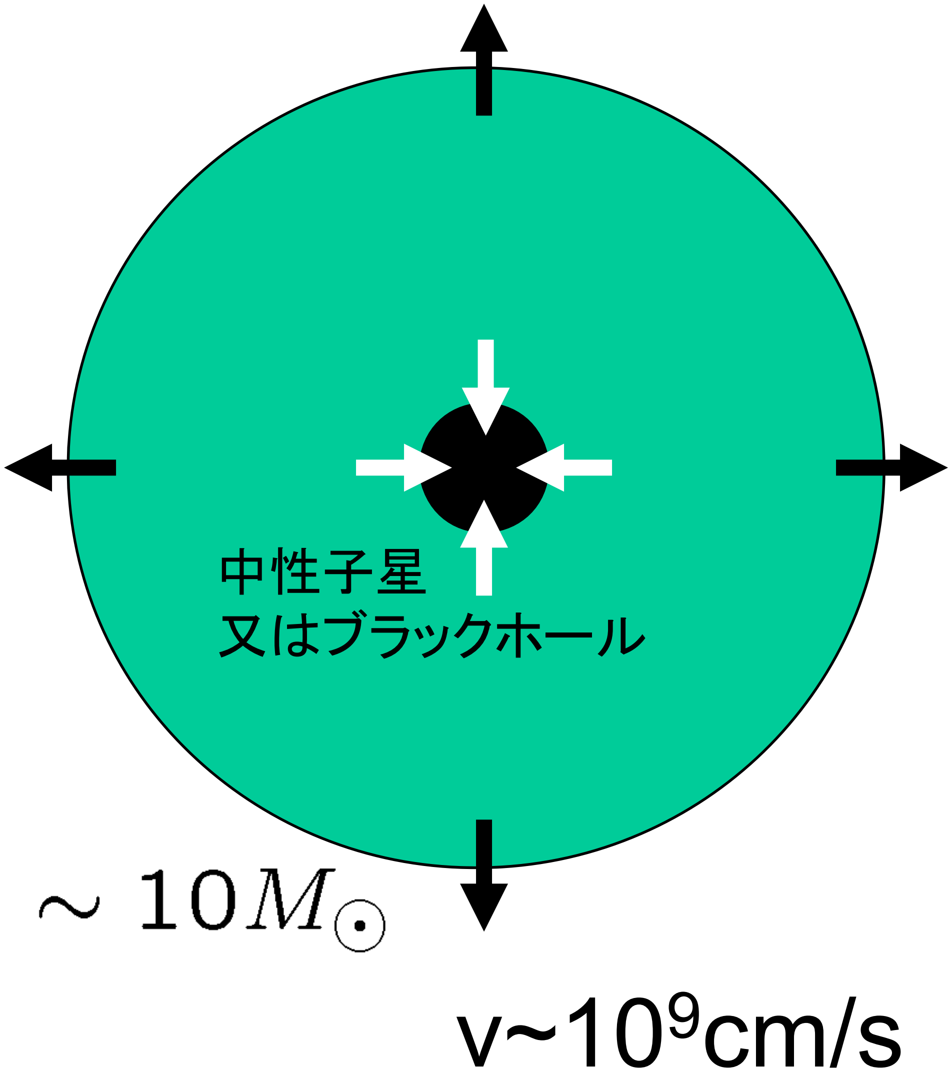
$R_m \sim 80\ \mathrm{Gpc^{-3}yr^{-1}}(\times 7)$

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

ガンマ線が出てくるために

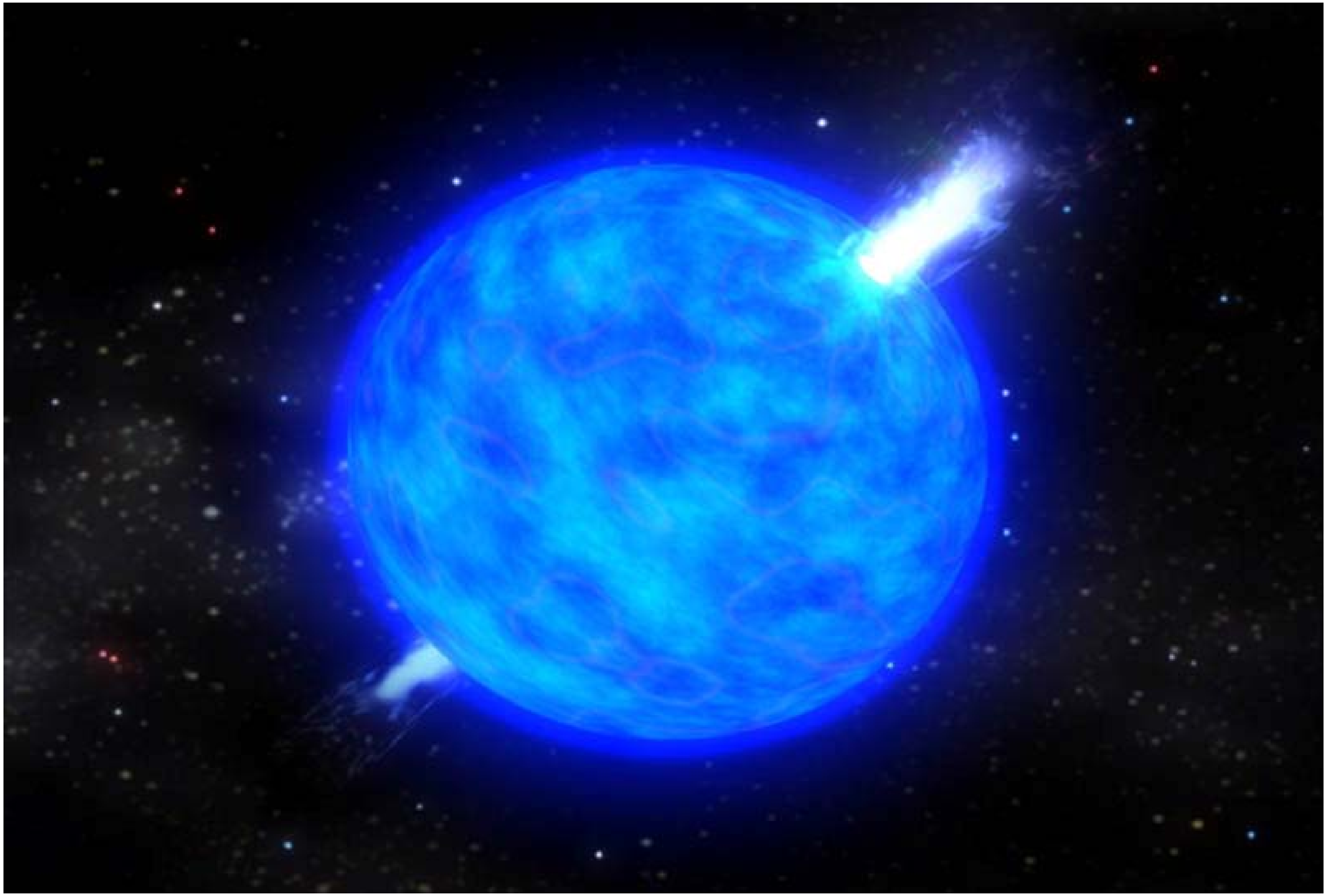


外層の質量:10^{34}g
一日後:R=cv=10^{14}cm
中心から外までの物質の量は10^6g/cm^2。
>>1g/cm^2

ガンマ線は外に出られない。
→ 穴が開いている
→ ジェット

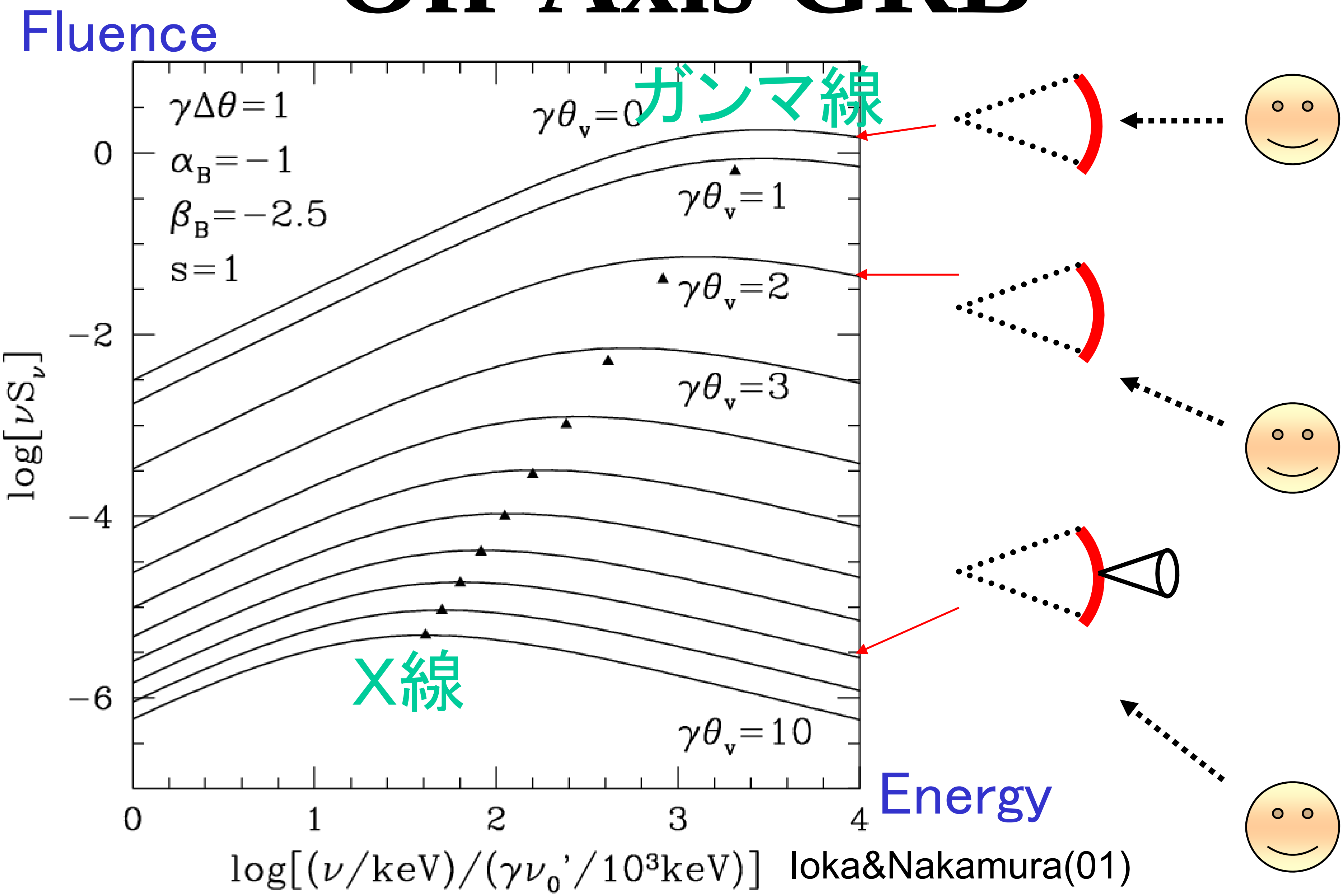
Collapsar

GRBのジェットが外層を突き破っているはず



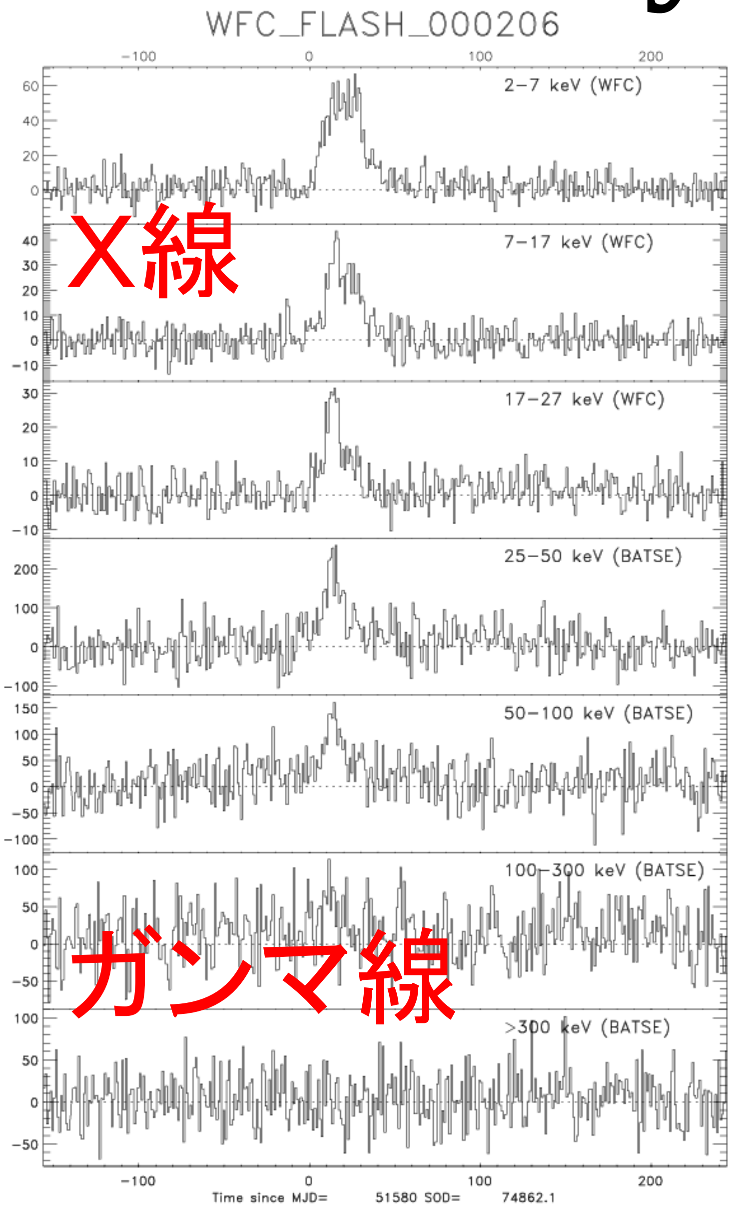
Zhang et al.(03)

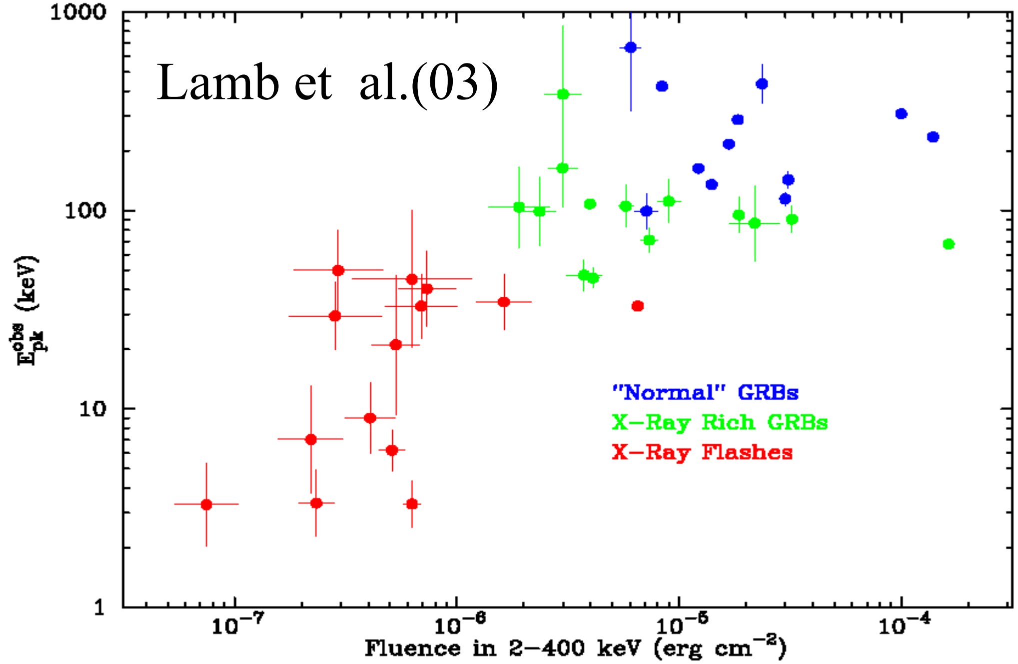
Off-Axis GRB

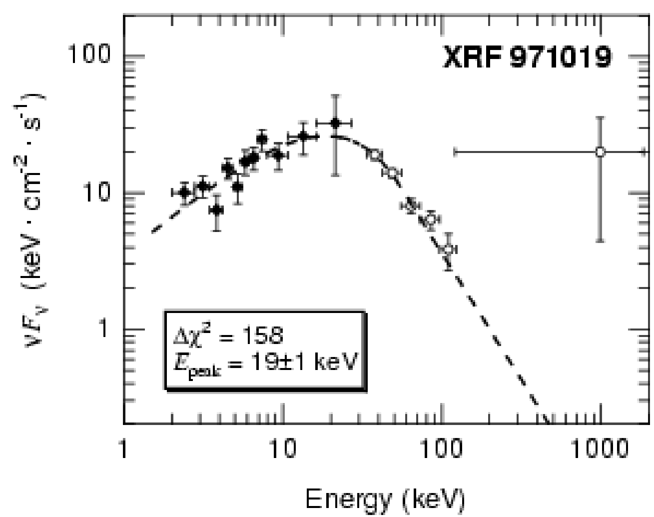


Ioka&Nakamura(01)

X-Ray Flash (XRF)





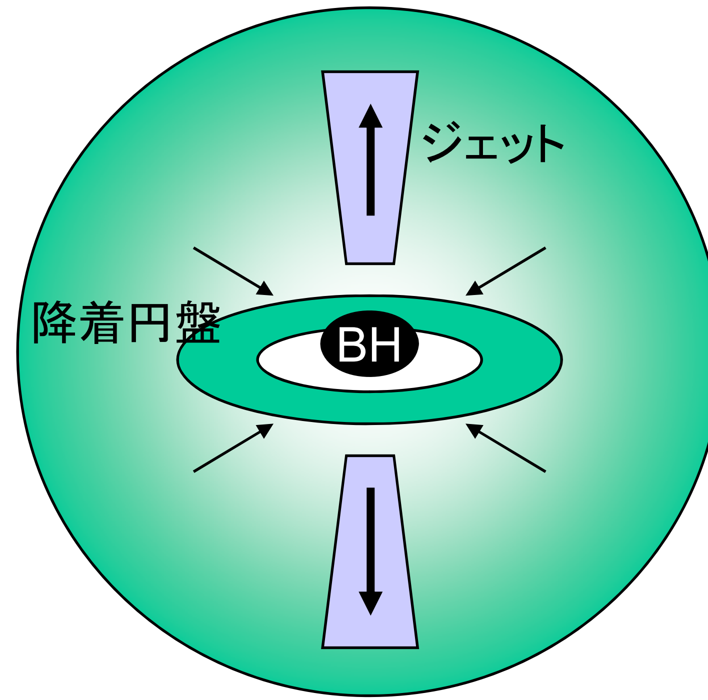


XRF〜GRB
except for
small E_{peak}
& fluence

ジェット形成機構は謎

一般相対性理論が中心では重要

ブラックホールの半径は
$R \sim 2GM/c^2 \sim 3\mathrm{km}(M/M_{太陽})$
~0.1ミリ秒~GRBの変動時間
中性子星の半径は約3倍
まわりに星の外層が降着

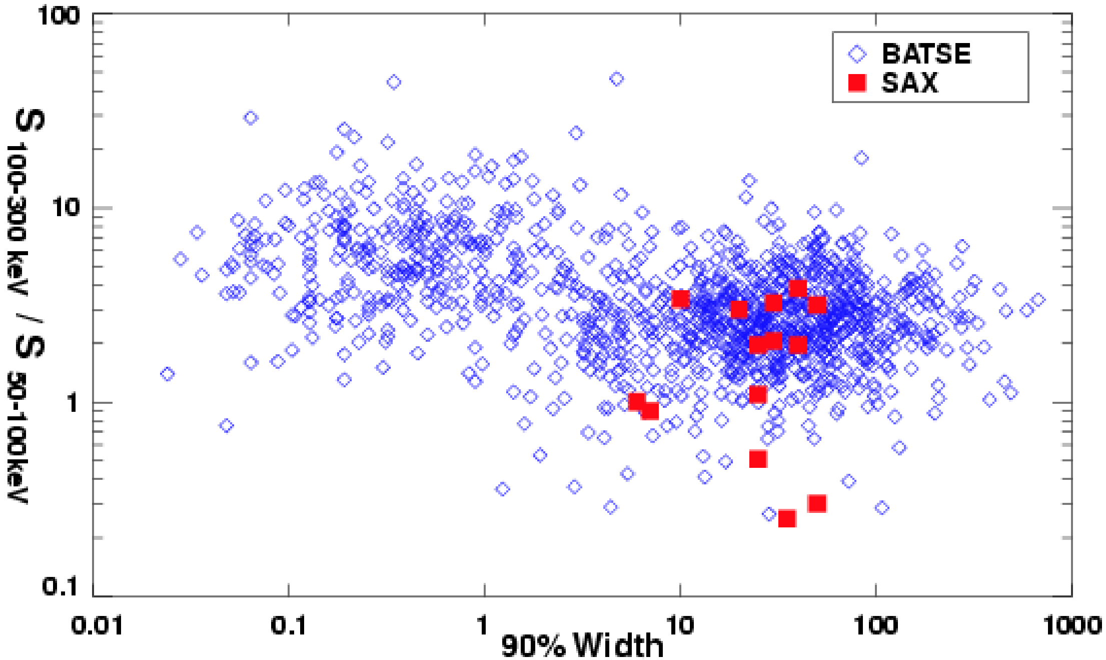


~10^{15}Gの強磁場が存在

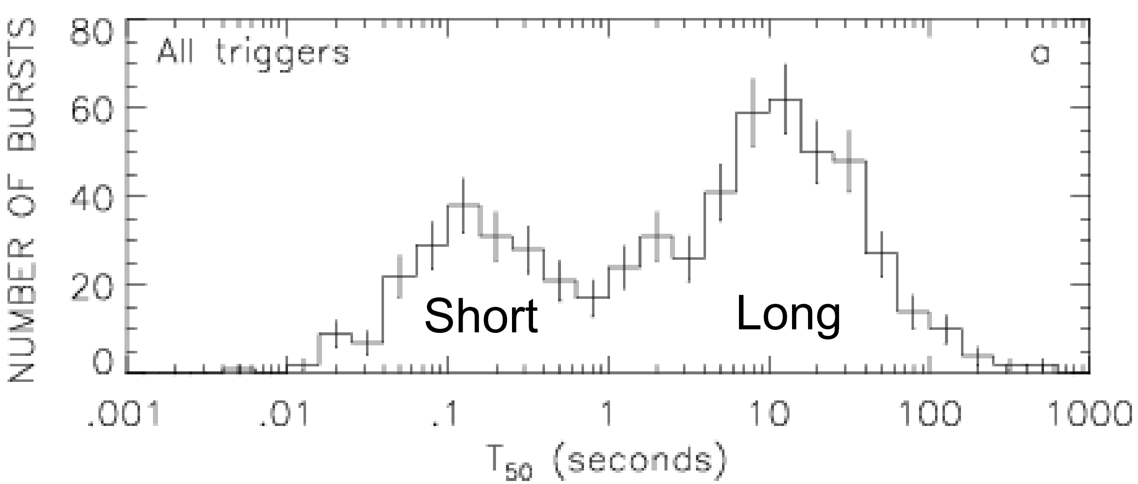
QEDの非線形性

なぜブラックホールからものが吹き出るのか？

継続時間



Long–soft
Short–hard



Long burst
Short burst

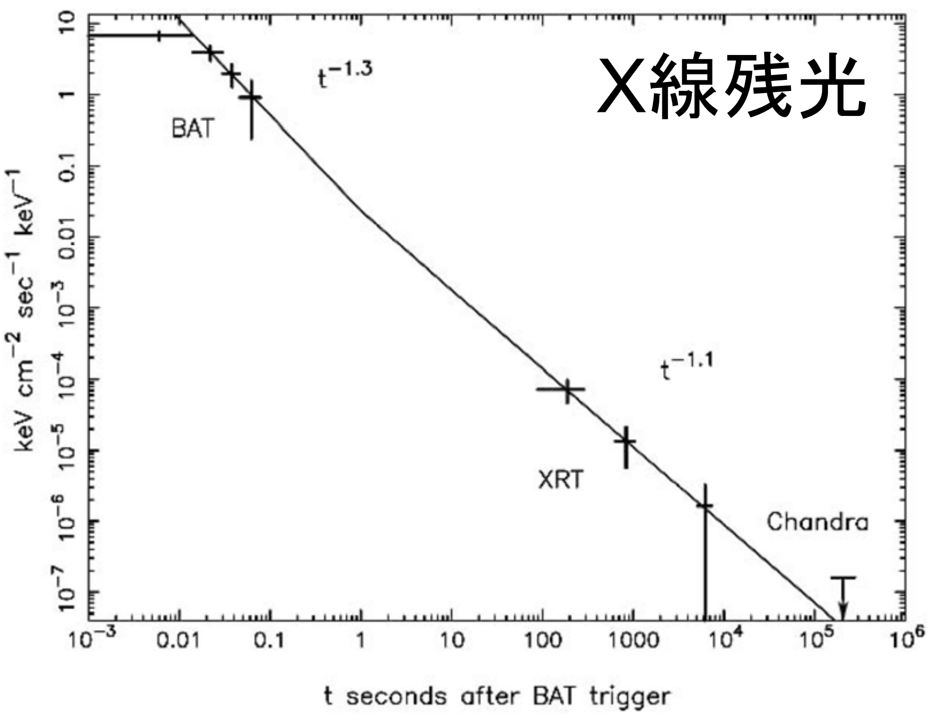
GRB専用衛星Swift

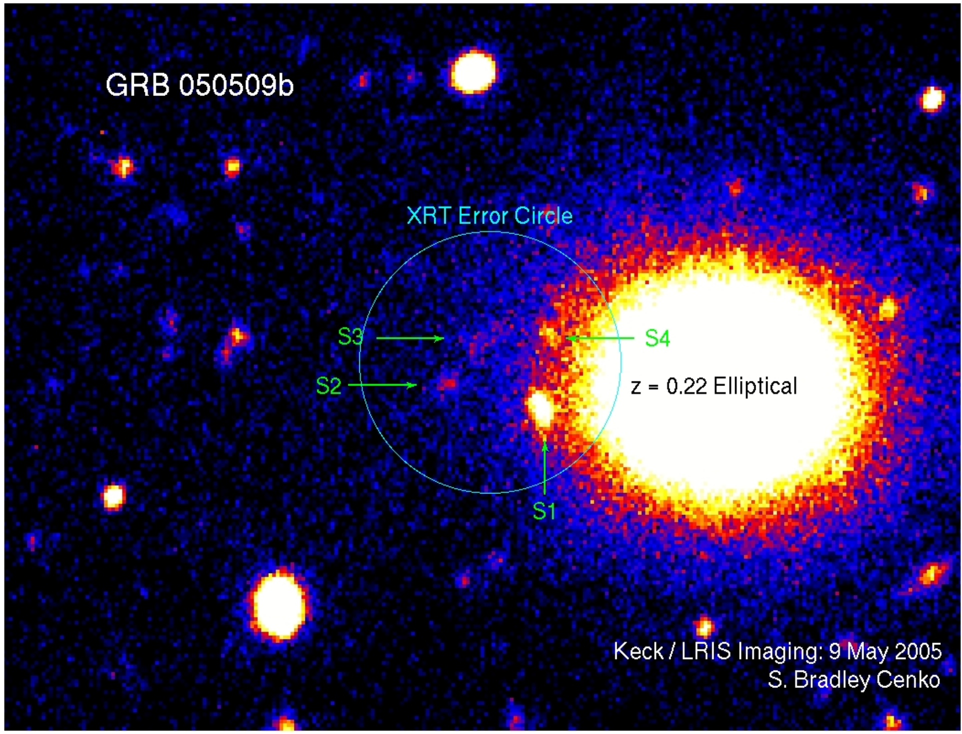
去年11月20日

ガンマ線、エックス線、光学検出器を積む
最強のGRB専用衛星

残光の発見 (Short GRB)

GRB050509b





Gehrels et al. (05)

ついにshort GRBの正体の手がかりが出始めた

エネルギーは小さい？

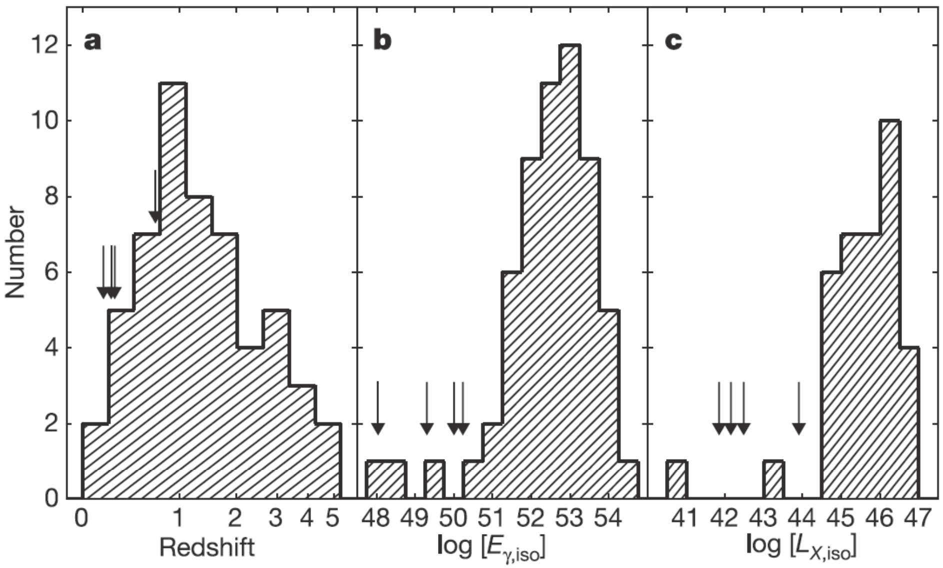


Figure 4 | Physical properties of the afterglows of long-duration GRBs (histograms) and SHBs (arrows). a–c, For GRBs with known redshifts, their distribution in redshift (**a**), isotropic-equivalent gamma-ray luminosity (log[$E_{\gamma,\mathrm{iso}}$], **b**), and isotropic-equivalent X-ray luminosity at 10 h after the burst (log[$L_{X,\mathrm{iso}}$], **c**) are shown. Arrows indicate the values of these properties for the four SHBs with afterglow detections, GRB 050509B, GRB 050709, GRB 050724 and GRB 050813 (ordered from lowest to highest, in each panel). The contrast between the physical properties of the two burst populations is noticeable. GRB properties are from refs 23 and 44–46. See Table 2 for SHB references.

Fox et al.(05)

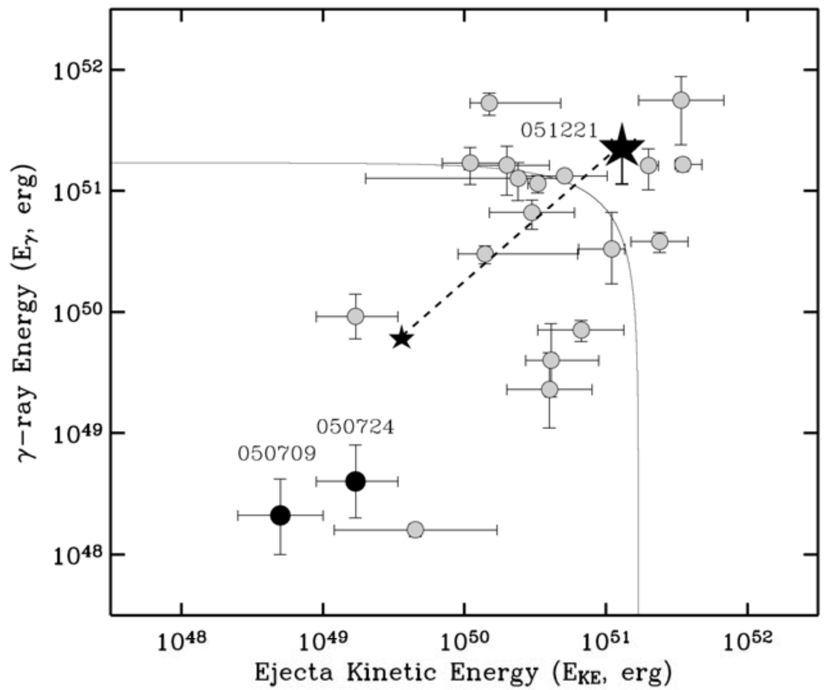
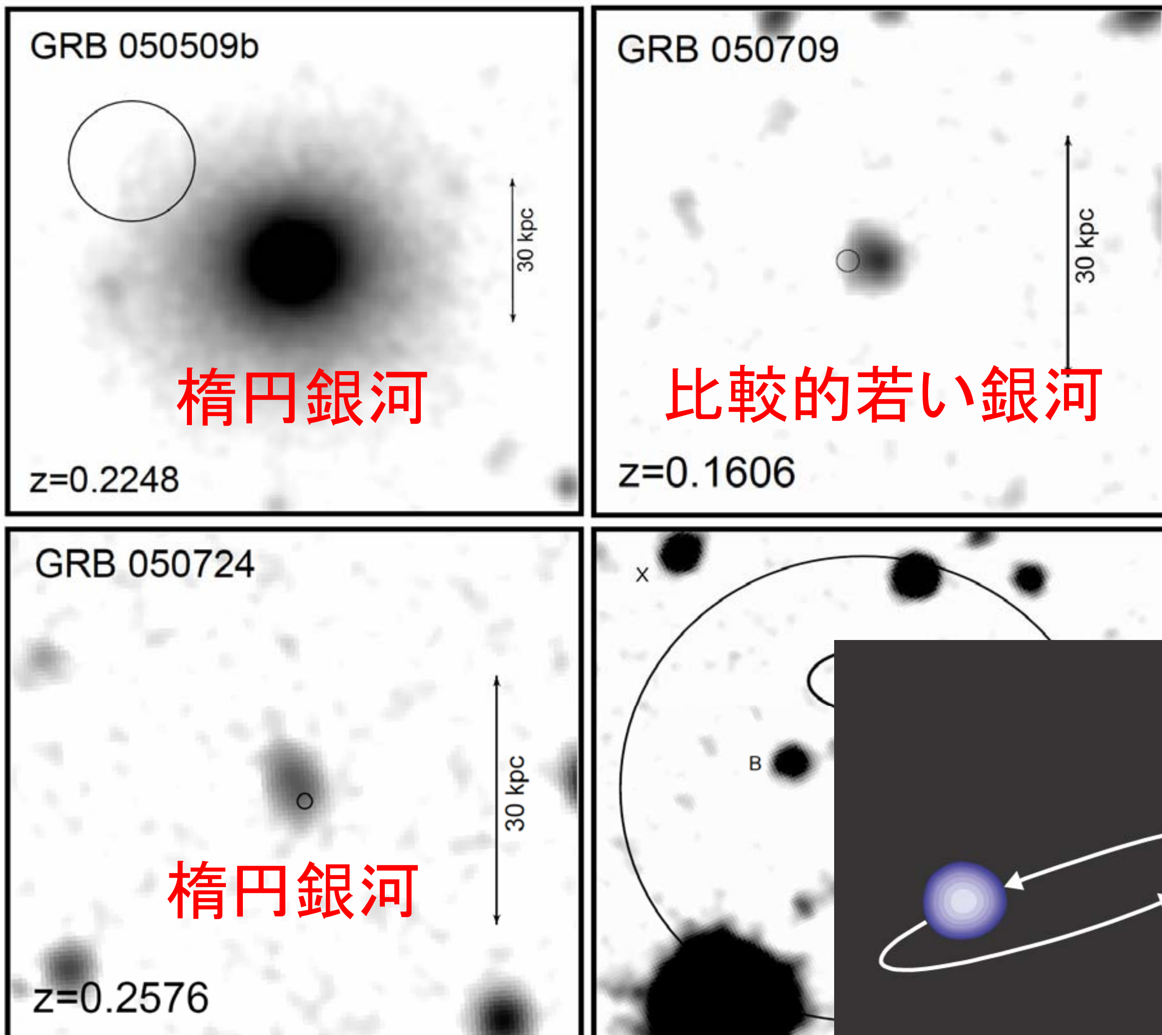


Fig. 8.— The energy release in prompt gamma-ray emission is plotted against the total kinetic energy of the ejecta for long GRBs (grey circles; Bloom, Frail & Kulkarni 2003; Ghirlanda, Ghisellini & Lazzati 2004; Sazonov, Lutovinov & Sunyaev 2004; Soderberg *et al.* 2005b and references therein) and short bursts (black circles; GRB 050709: Fox *et al.* 2005; GRB 050724: Berger *et al.* 2005). Both axes are corrected for collimation of the ejecta. The total energy release (prompt plus afterglow) of long bursts cluster near 1.7×10^{51} erg (black solid arc). For GRB 051221 (black stars) we show the full range of possible energies for $\theta_j \gtrsim 13°$.

Soderberg et al.(06)

母銀河

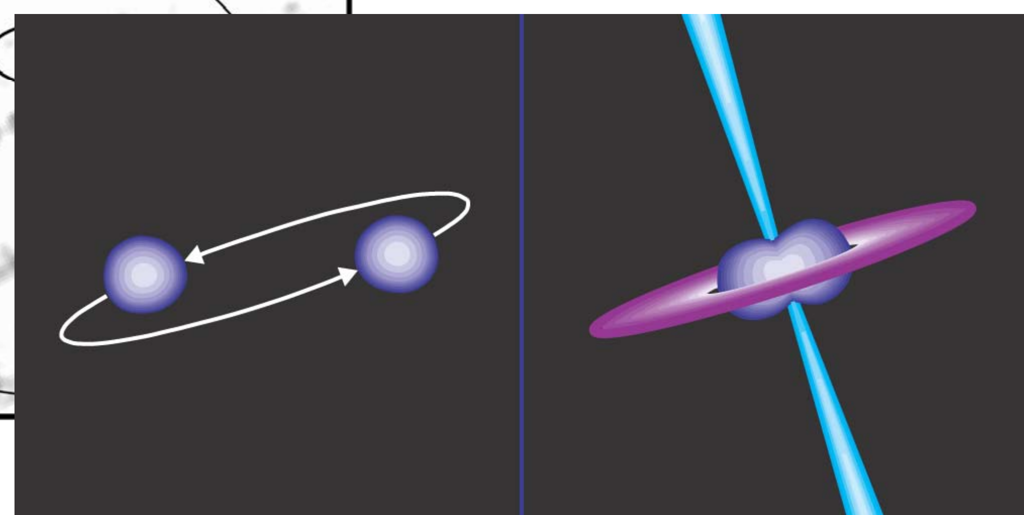


Prochaska et al. a-ph/0510022

楕円銀河(古い)
⇔ long GRBは
一つも楕円銀河で
起こっていない

↓

NS-NSの合体？

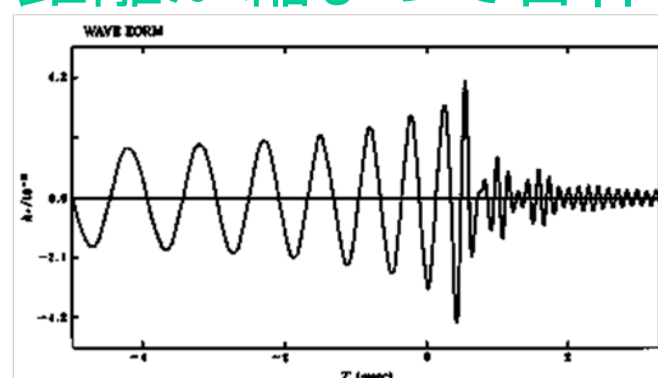


重力波

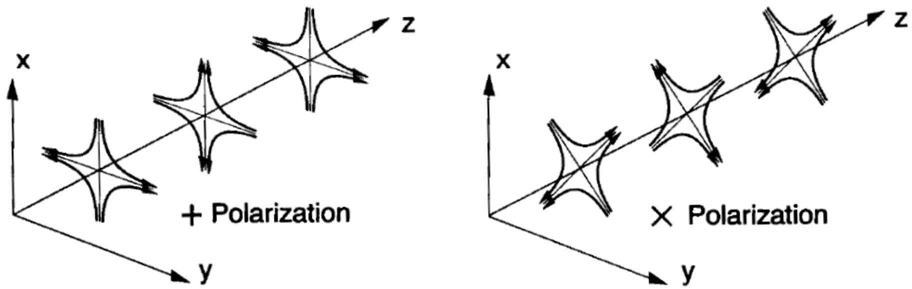
電荷が加速度運動⇒電磁波：真空中を光速で進む横波
質量が加速度運動⇒重力波：真空中を光速で進む横波
1918年に一般相対性理論にもとづいてアインシュタインが予言

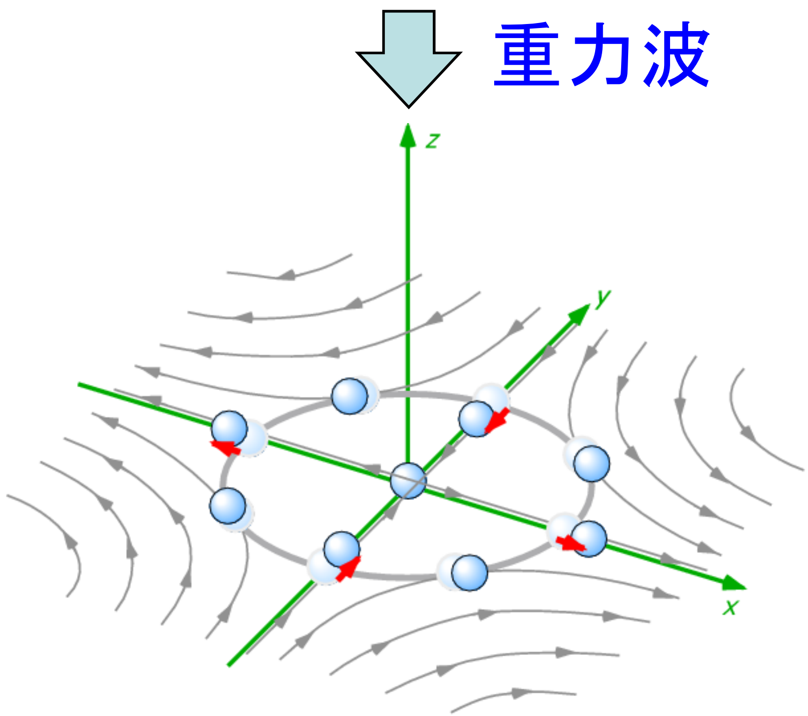
NS-NSやNS-BHの合体は重力波の強力な源

重力波を放出するとエネルギーを失う。重力エネルギーは$E=-GM^2/r$なので、距離が縮まって合体

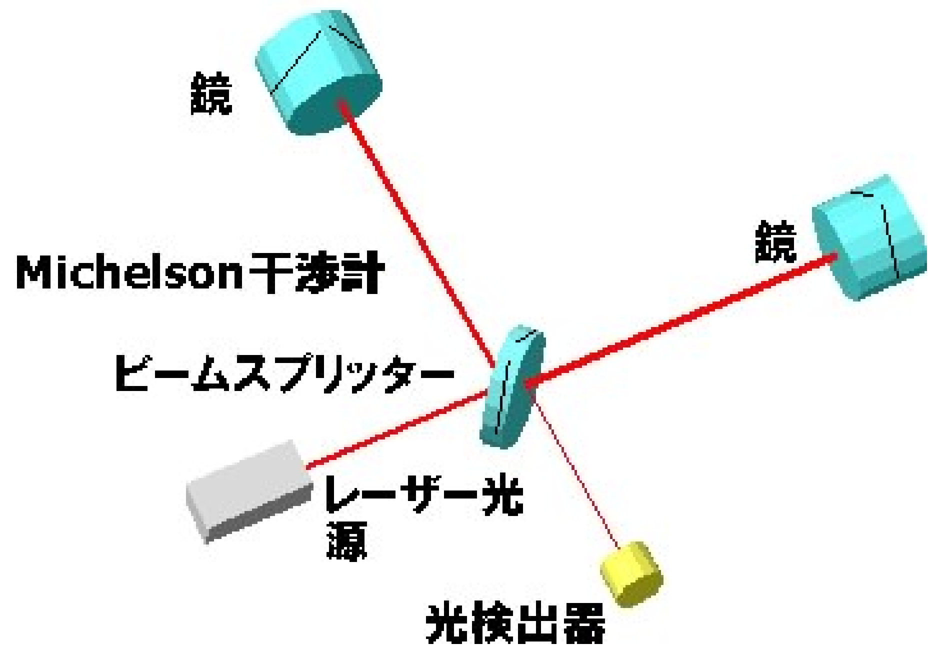


重力波の検出





自由質点間の距離が変化



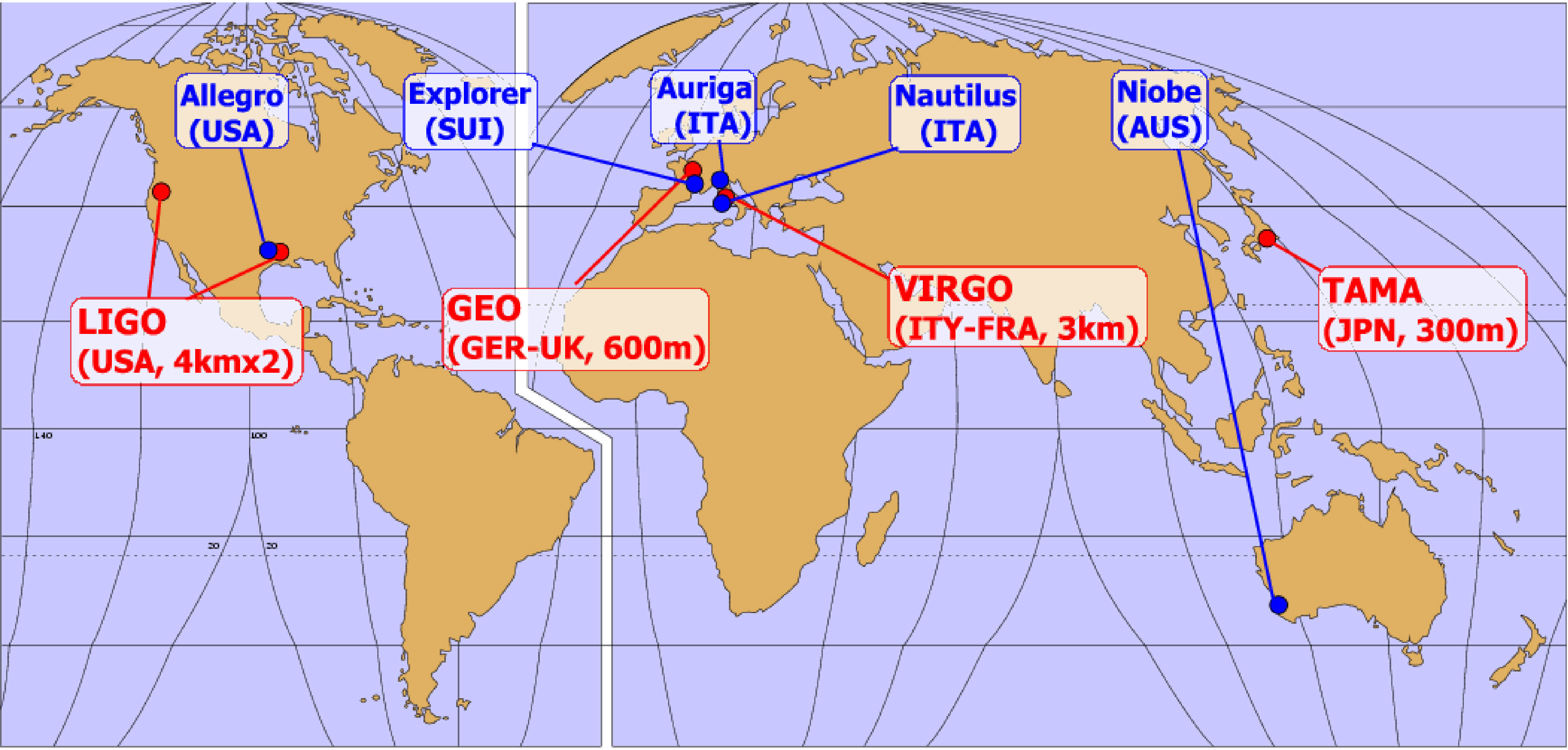
レーザー干渉計型検出器

$\Delta x/x \sim GM/r \sim 10^{-22}$

TAMA300

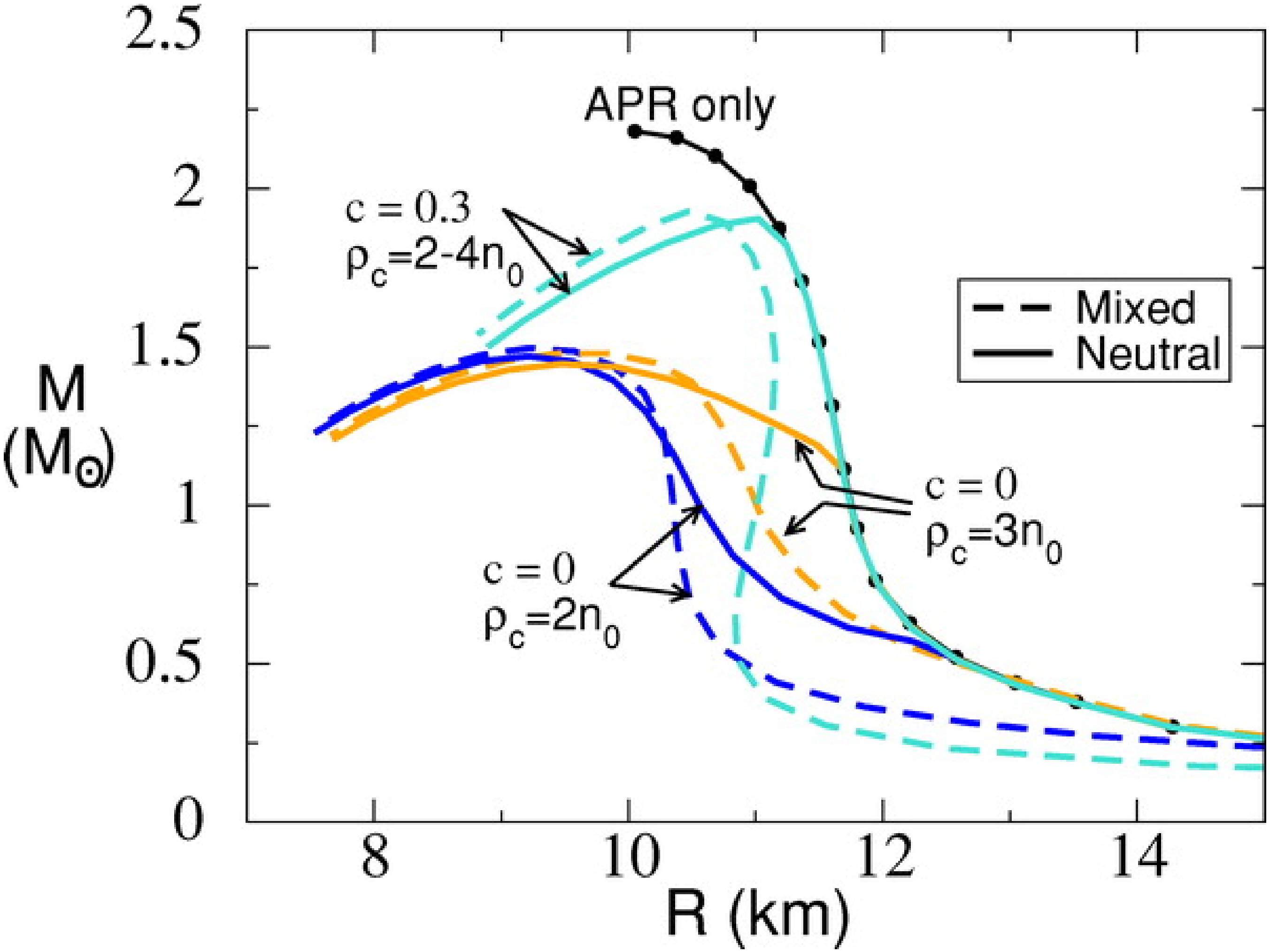
東京三鷹

世界の重力波検出器



初めて重力波を検出したらノーベル賞

中性子星の状態方程式



核密度での
状態方程式が
QCDからまだ
求まっていない

NSの半径が
状態方程式に
依存する

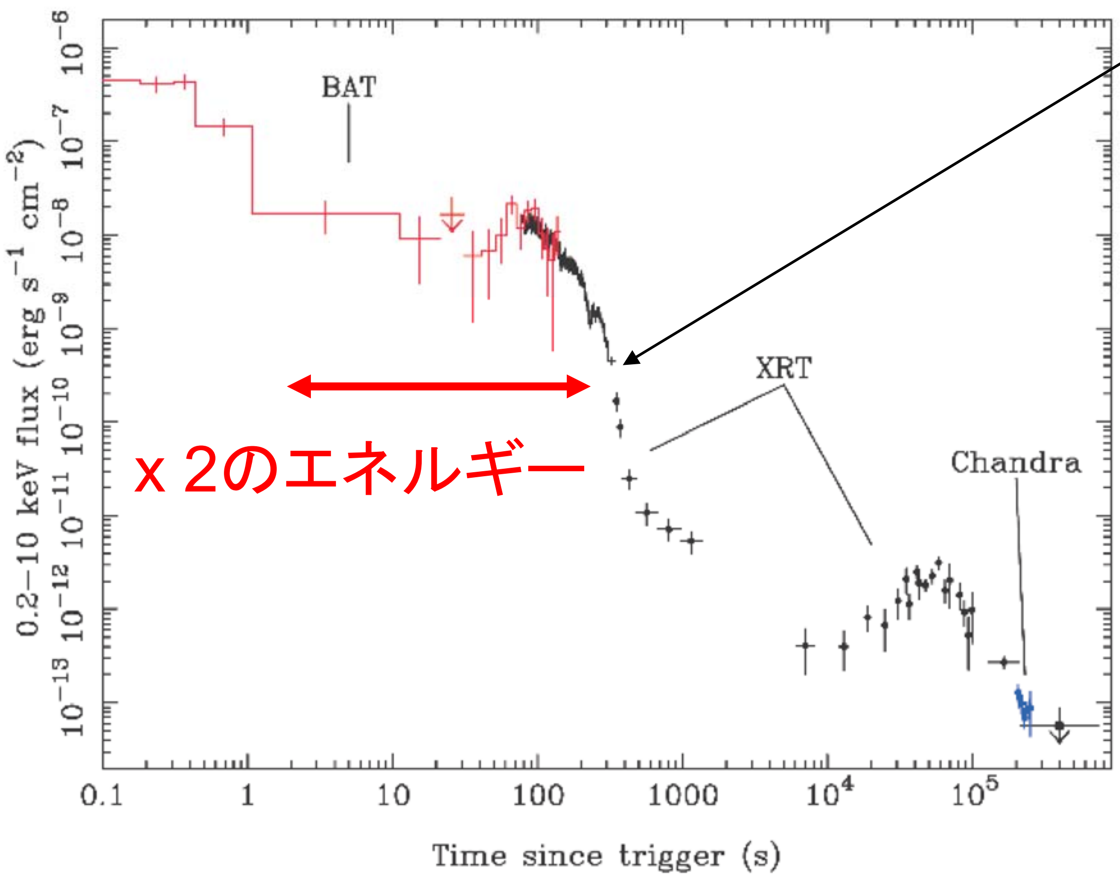
重力波の波形
にQCDの情報

Alford et al.(05)

長いshort GRBがある！

しかしそう単純じゃない

Short GRB



急激に落ちすぎている
⇒残光では説明できない
⇒中心エンジンは
100秒は動いている
⇒NS-NS, NS-BHの合体
ではここまで長くできない
R~GM/c^2~3km~0.1msec

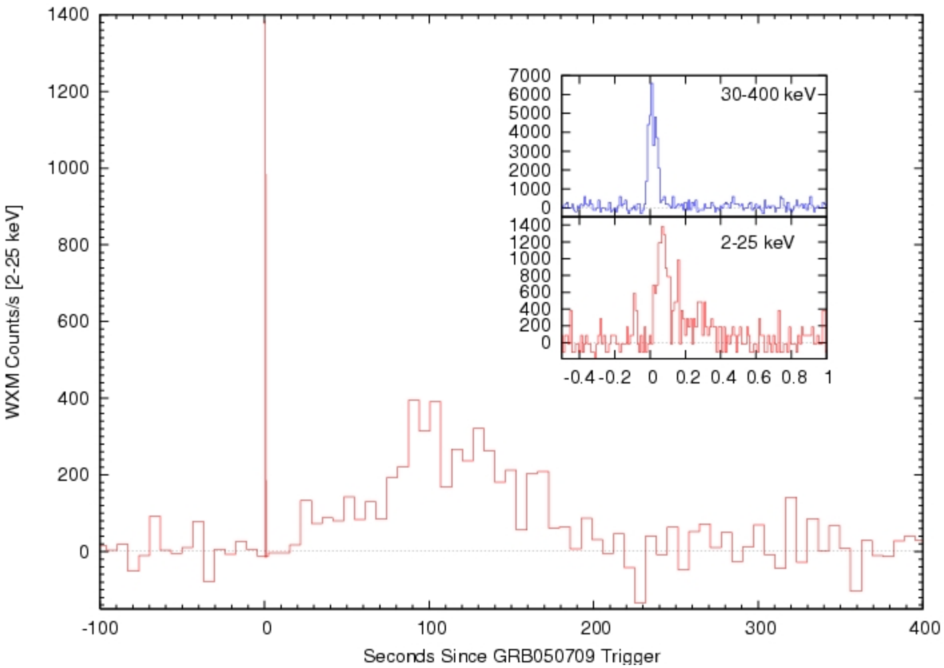
何らかの変更が必要

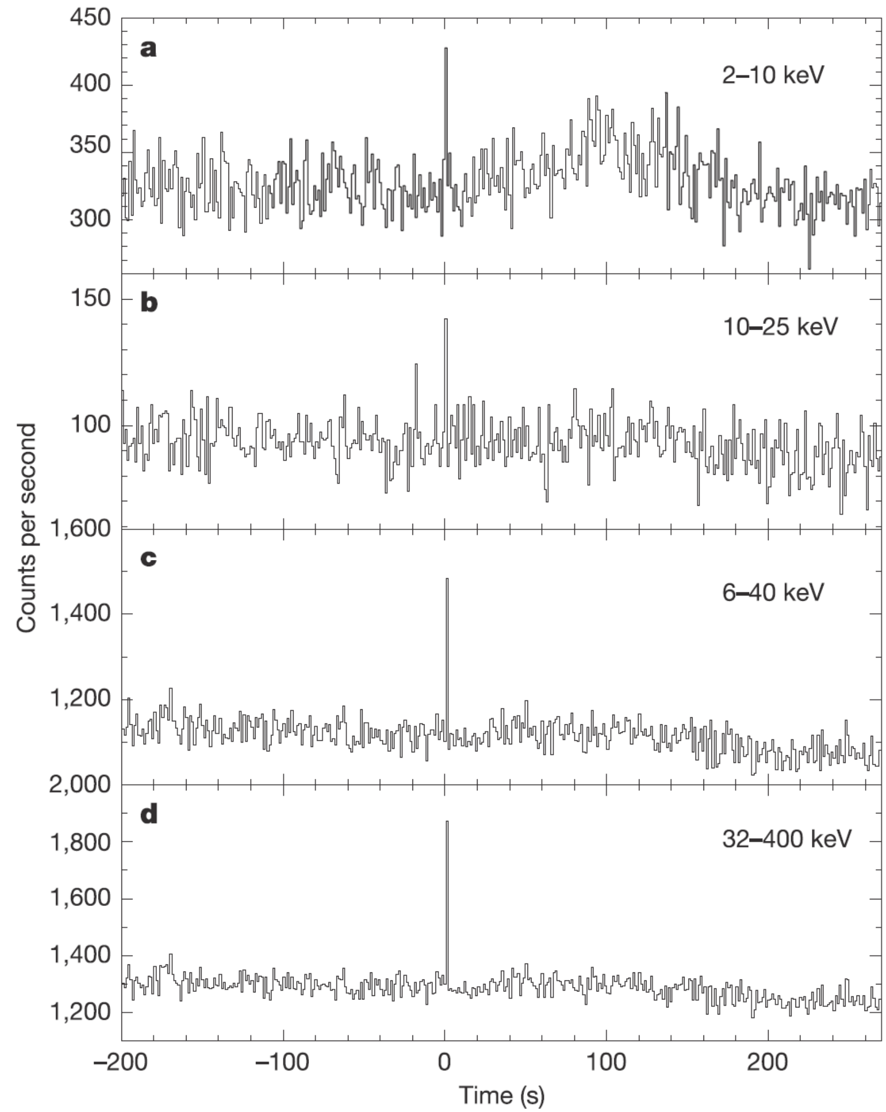
Barthelmy et al.
a-ph/0511579

GRB050724

その他の長いshort GRB

GRB 050709





Villasenar et al.(05)

GRB 051210

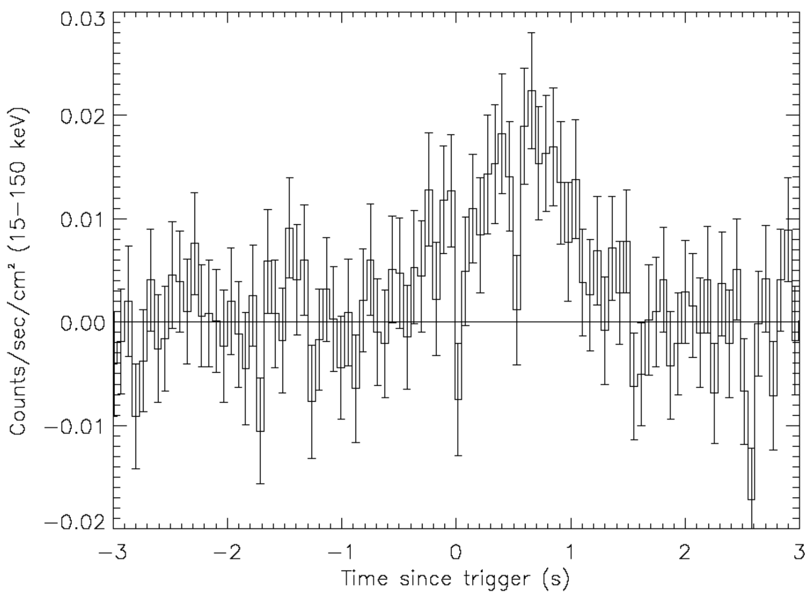


Fig. 1. BAT light curve of the prompt emission of GRB051210. Each time bin is 64 ms long.

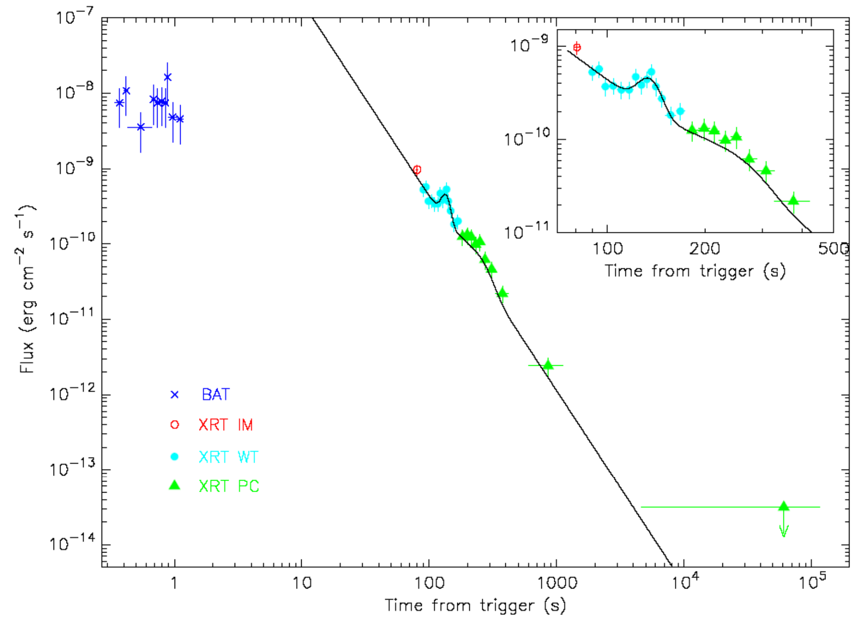


Fig. 2. XRT light curve decay of GRB 051210. The XRT count rate (0.2-10 keV) was converted into flux units by applying a conversion factor derived from the spectral analysis. The solid line represents the best fit model to the XRT data. The BAT light curve was extrapolated into the XRT energy band by converting the BAT count rate with the factor derived from the BAT spectral parameters.

~100ぐらいにx-ray flare

n<4x10^{-3} cm^{-3}

steep decayはcurvature emissionでOK

GRB 050911

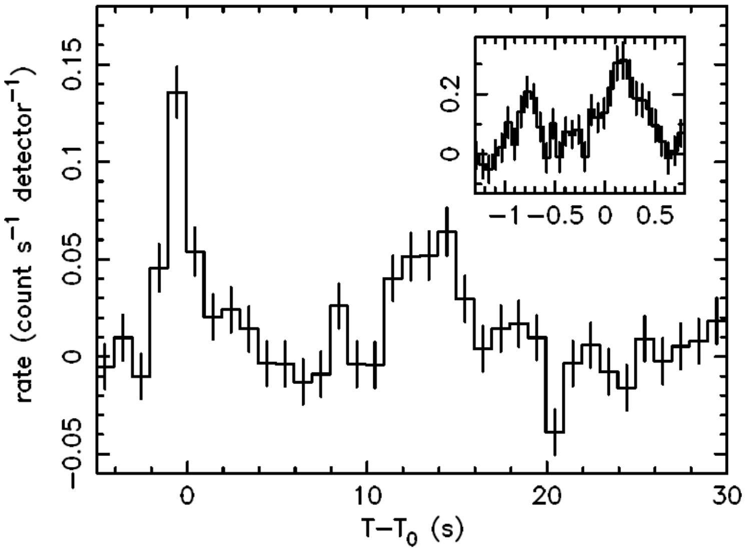


FIG. 1.— The BAT light-curve over 15–350 keV. The main plot shows both the initial short burst and the longer, later emission, while the inset zooms in on the two short peaks.

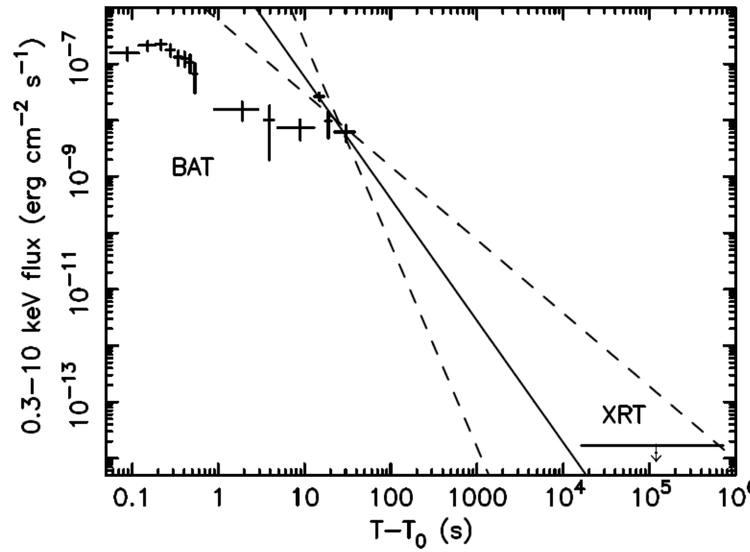
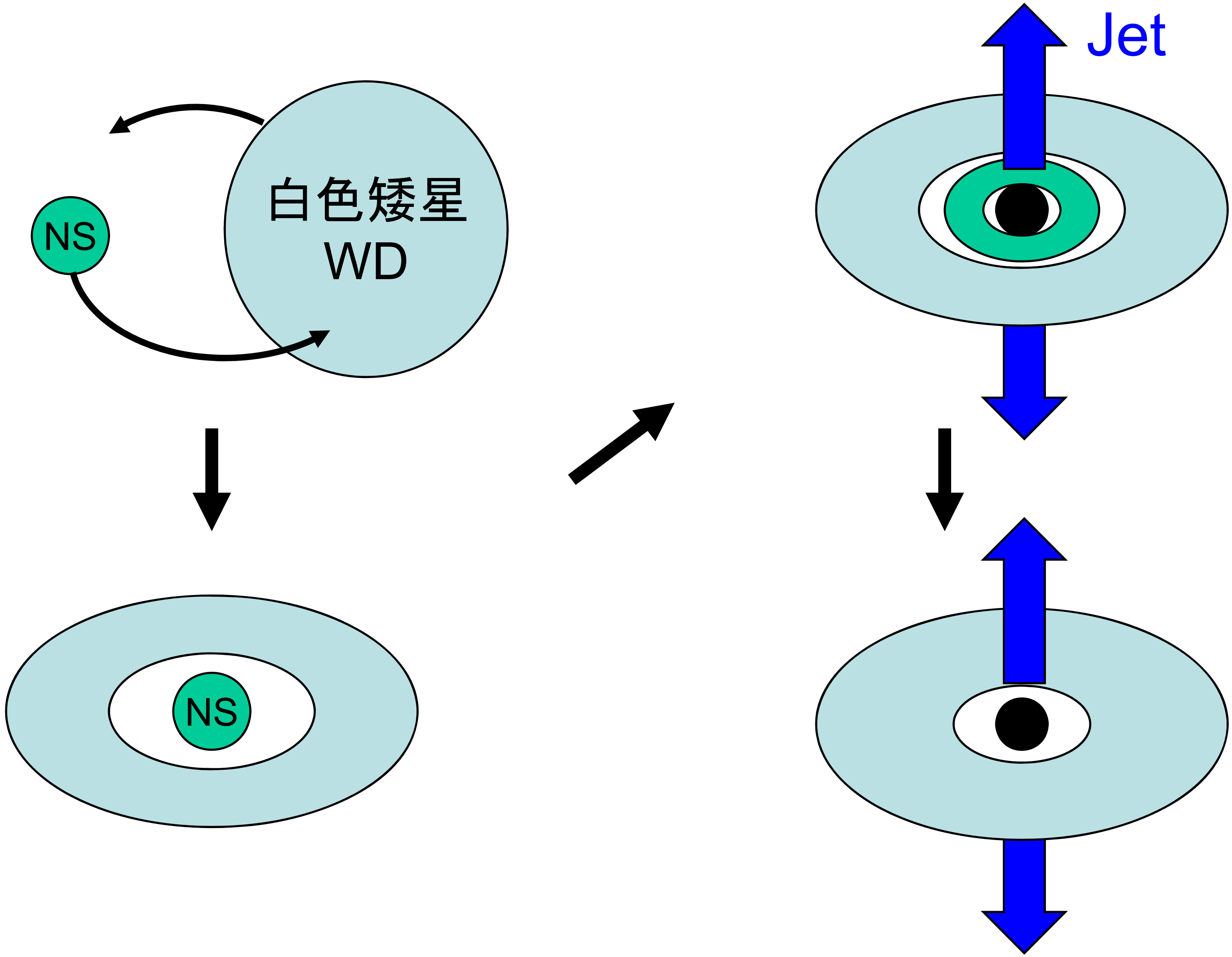


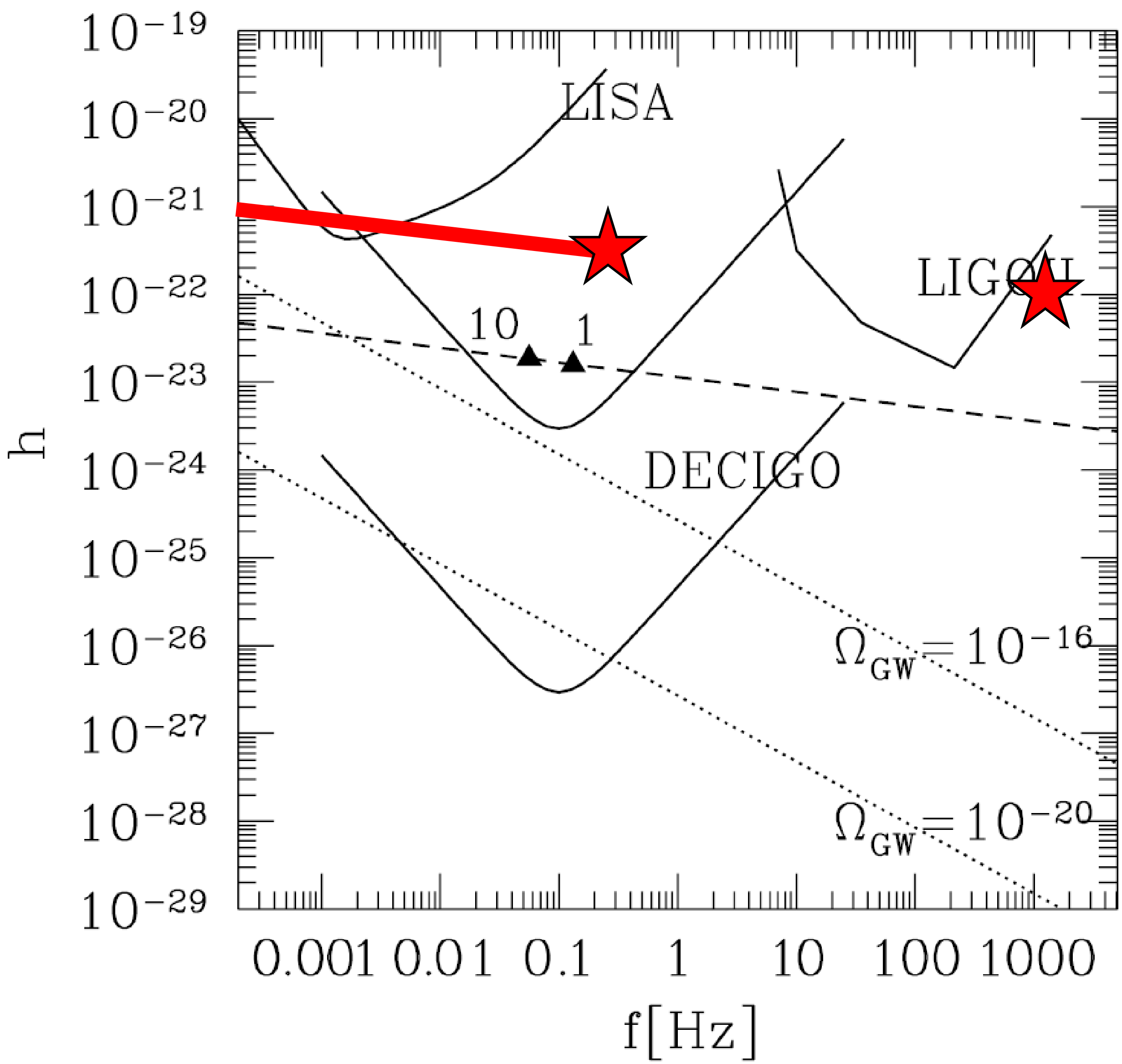
FIG. 2.— The BAT flux light-curve and XRT upper limit, showing an extrapolation of the power-law fit to the last peak in the BAT.

longに分類された
short GRB+ 10sec X-ray flareかも（lagは0とconsistent）
X-ray afterglowなし（α~2.2以上）
又は周りの密度小さい

NS-WDの合体？



多波長重力波天文学



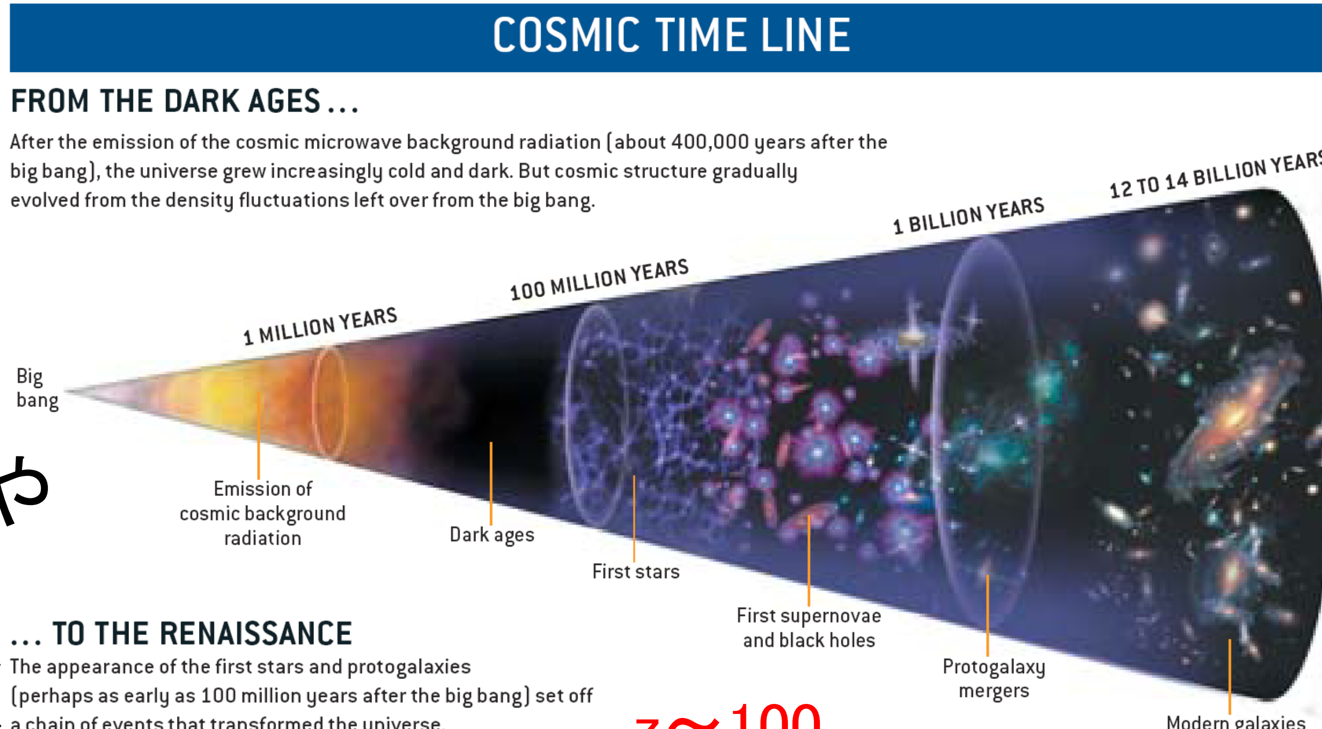
~Hz重力波の後
~10秒後ぐらいに
~kHz重力波

多波長重力波観測
が究極的な検証

GRB宇宙論

重い星起源 ⇒ High-z (遠い) GRBs

GRB 050904
@z~6.3
知られている
最も遠い銀河や
QSOに匹敵
すぐに追いつく



z～100

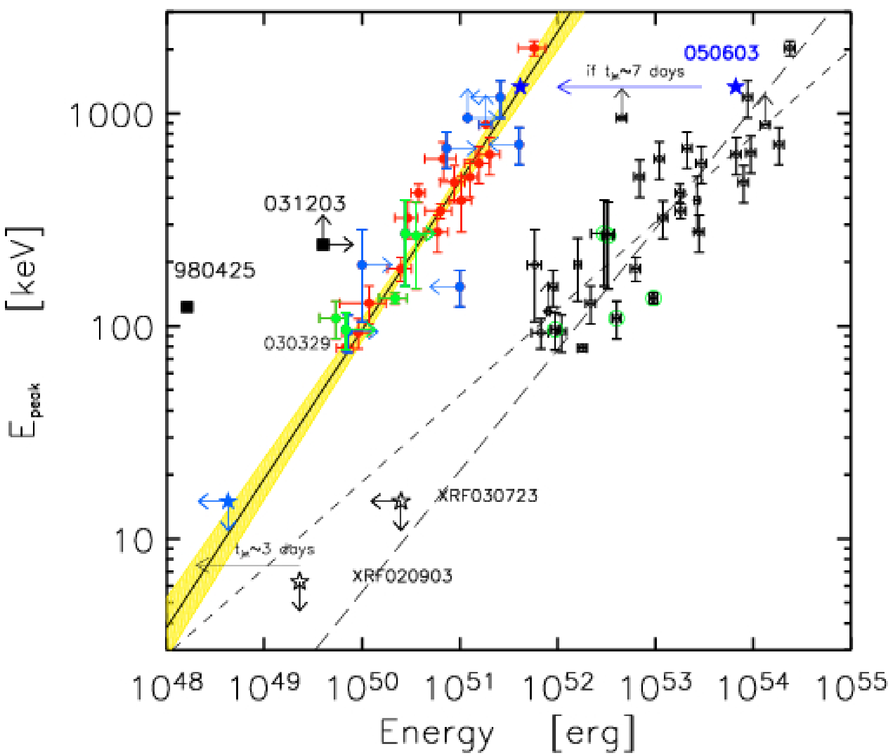
Larson&Bromm(02)

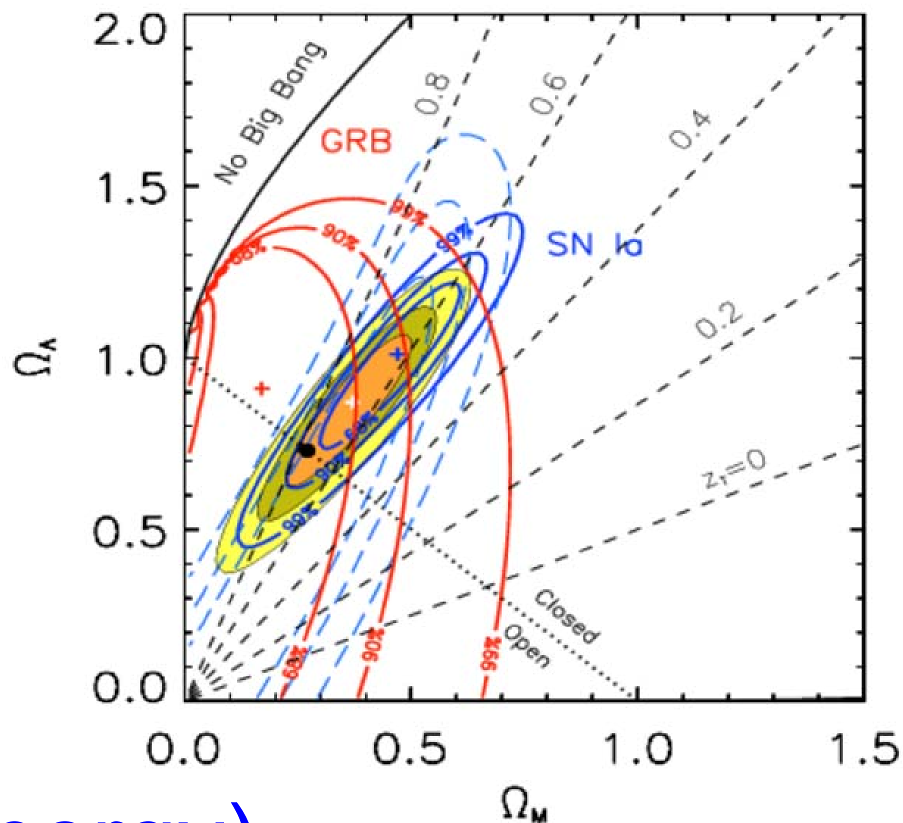
GRB

QSO, galaxy

GRBsを使った初期宇宙の研究が進むであろう

標準光源?



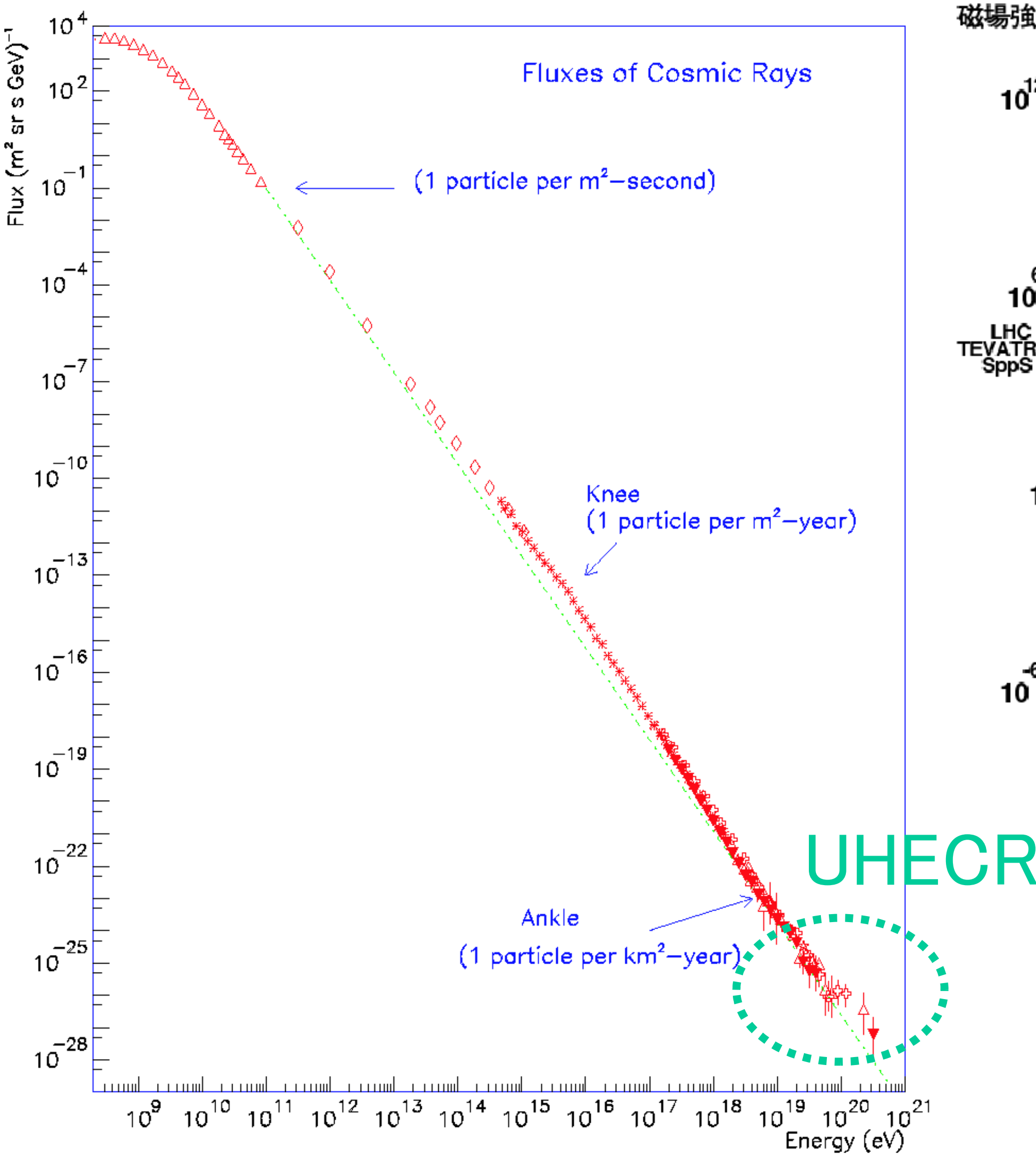


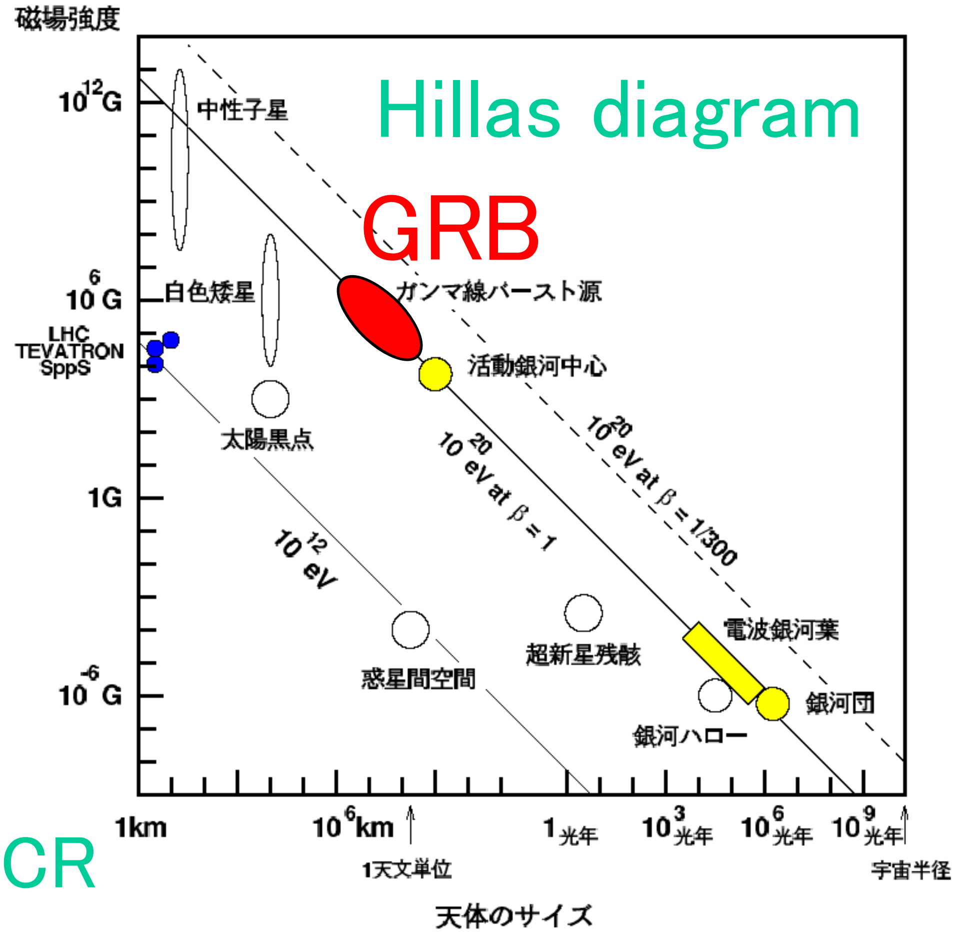
E_{peak}(γ線の典型的energy)

→Intrinsicな明るさ→距離→距離-z関係

→宇宙論(dark energy, dark matter)

最高エネルギー宇宙線





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

$$\approx \mathrm{UHECR}$$

Science 310(05)

Areas to Watch in 2006

Avian flu. Whether or not a pandemic kicks off in 2006, research on flu vaccines and drugs will expand—as will debates on who should get them first should a pandemic occur. Also look for a wealth of data on the molecular biology, evolution, epidemiology, and even the history of influenza. And keep your fingers crossed.

Gravity rules. After years of refinements, the first phase of the Laser Interferometer Gravitational-Wave Observatory (LIGO) has reached its promised sensitivity. LIGO's laser chambers in Louisiana and Washington state will monitor the sky during most of 2006—with a smaller facility in Germany, called GEO-600, joining the network later in the year. If two neutron stars merge within 50 million light-years or so, the devices could detect the death spiral. It's a long shot, but we're betting they will.

RNAi-based treatments. They're moving into human patients with startling speed, and 2006 should offer the first hints of how well the highly touted technique works. Company-funded trials in macular degeneration and the pediatric illness respiratory syncytial virus are under way; another targeting hepatitis C is supposed to launch soon, with some therapies for neurological diseases to follow. Oh, and another treatment that's coming down the pike: RNAi for permanent hair removal.

Catching rays. The speediest atomic nuclei in the universe, called ultrahigh-energy cosmic rays, may open a new frontier of physics. The sprawling Pierre Auger Observatory in Argentina will near completion in 2006, offering the best chance to explore those limits. Already, Auger's powerful combination of ultraviolet telescopes and water-tank detectors is measuring different aspects of the particle showers sparked by incoming rays. Early results affirm a theorized energy threshold, imposed by interactions in space, that cosmic rays rarely cross.

Small worlds. With ever-better methods of pulling DNA from environments such as soils and the human gut, researchers are documenting the incredible microbial diversity on this planet. In 2006, expect a flurry of papers detailing the evolution and molecular bases of microbial communities and the relationships, both beneficial and pathogenic, between microbes and their partners; more examples of lateral transfer of genes between species; and—just possibly—consensus about a microbial family tree and a much sharper picture of how eukaryotic cells arose.

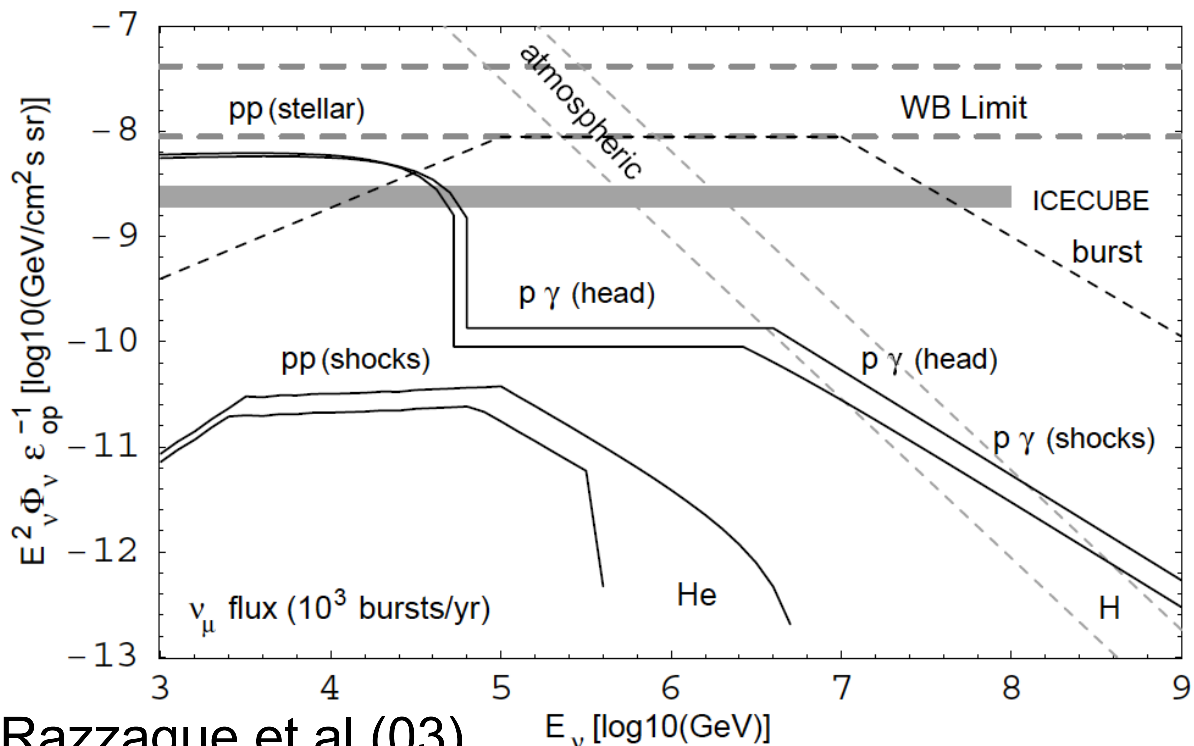
Seconding supersolidity. Two years ago, physicists reported that solidified helium appears to flow like a liquid without any viscosity. Theorists debate whether such "superflow" is possible in a well-ordered crystal, and no one has reproduced the result yet. Look for someone to confirm the observation—or shoot it down.

Homing in on high-T_c. In 1986, physicists discovered that certain compounds laden with copper and oxygen carry electricity without resistance, some now at temperatures as high as 138 kelvin. Twenty years later, researchers still aren't sure precisely how high-T_c superconductors work. But a variety of exquisitely sensitive experimental techniques should cull the vast herd of possible explanations.

Now you see it? A fleeting glimpse captured on video raised hopes that the ivory-billed woodpecker might not be extinct after all.

Bird to watch for. Early in 2005, a blurry video and new sightings of the ivory-billed woodpecker, considered extinct for the past 60 years, wowed conservationists and birders alike. Some skeptics remained unconvinced by the 1.2-second footage, but many later were swayed by audio tapes of the woodpecker's call and distinctive "tap, tap." Biologists are scouring the Arkansas bayou, where there have now been more than a dozen sightings, for more evidence that they are not seeing a ghost of a bird past. We're betting this "ghost" proves to be the real thing.

High Energy ν



Razzaque et al.(03)

$$p\gamma \to n\pi^+,\ p\pi^0$$

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^0 \to \gamma\gamma$$

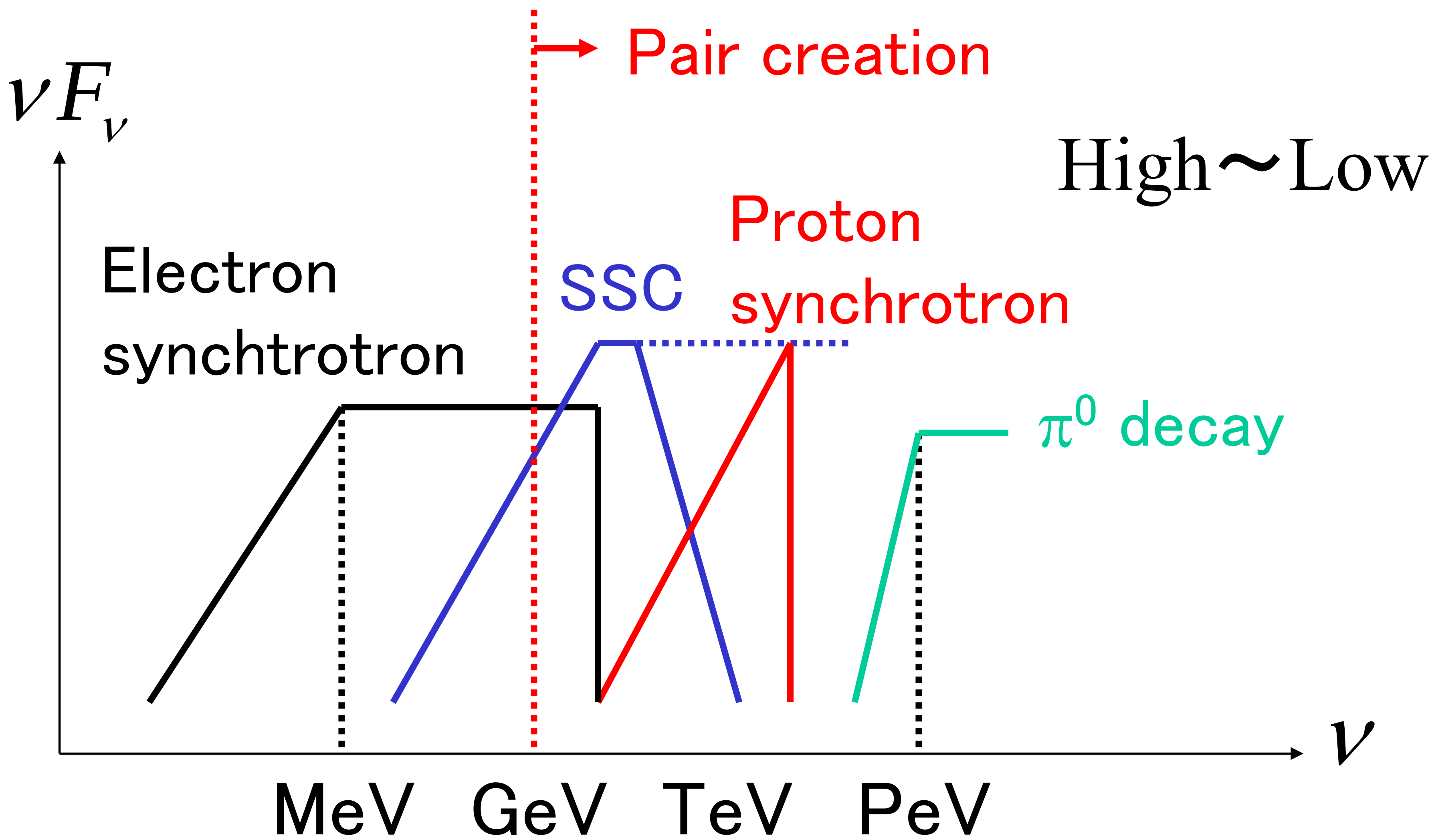
TeV-EeV ν

南極でAMANDA→ICECUBEが稼動中

ν振動の実験、弱い等価原理の実験、等

新しい宇宙への目

High Energy γ



まとめ

GRBは宇宙一明るい相対論的な爆発

Long GRBは重い星の崩壊
Short GRBはNS-NS連星合体？？？
⇒ BH or NSの誕生の産声

重力波、宇宙論
高エネルギー宇宙線、ν、γ
Suzaku, CANGAROO

高エネルギー宇宙物理は今後が楽しみ

最初の3時間