ガンマ線バーストで
読み解く太古の宇宙

井岡　邦仁

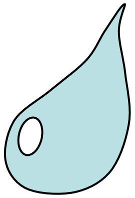
(Cosmophysics Group, IPNS, KEK)

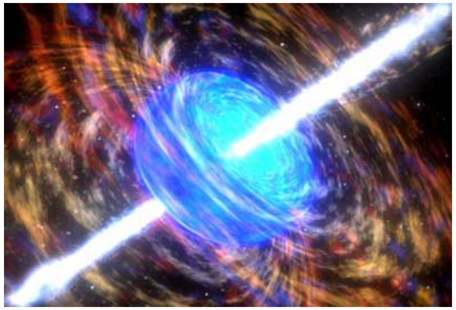
GRBとは

$E=mc^2$

原子爆弾

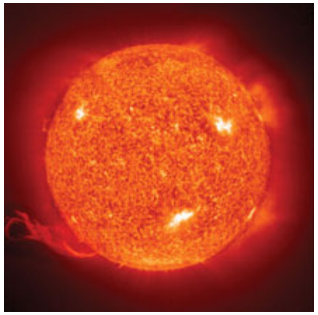
=





GRB
~10^{52}erg

=

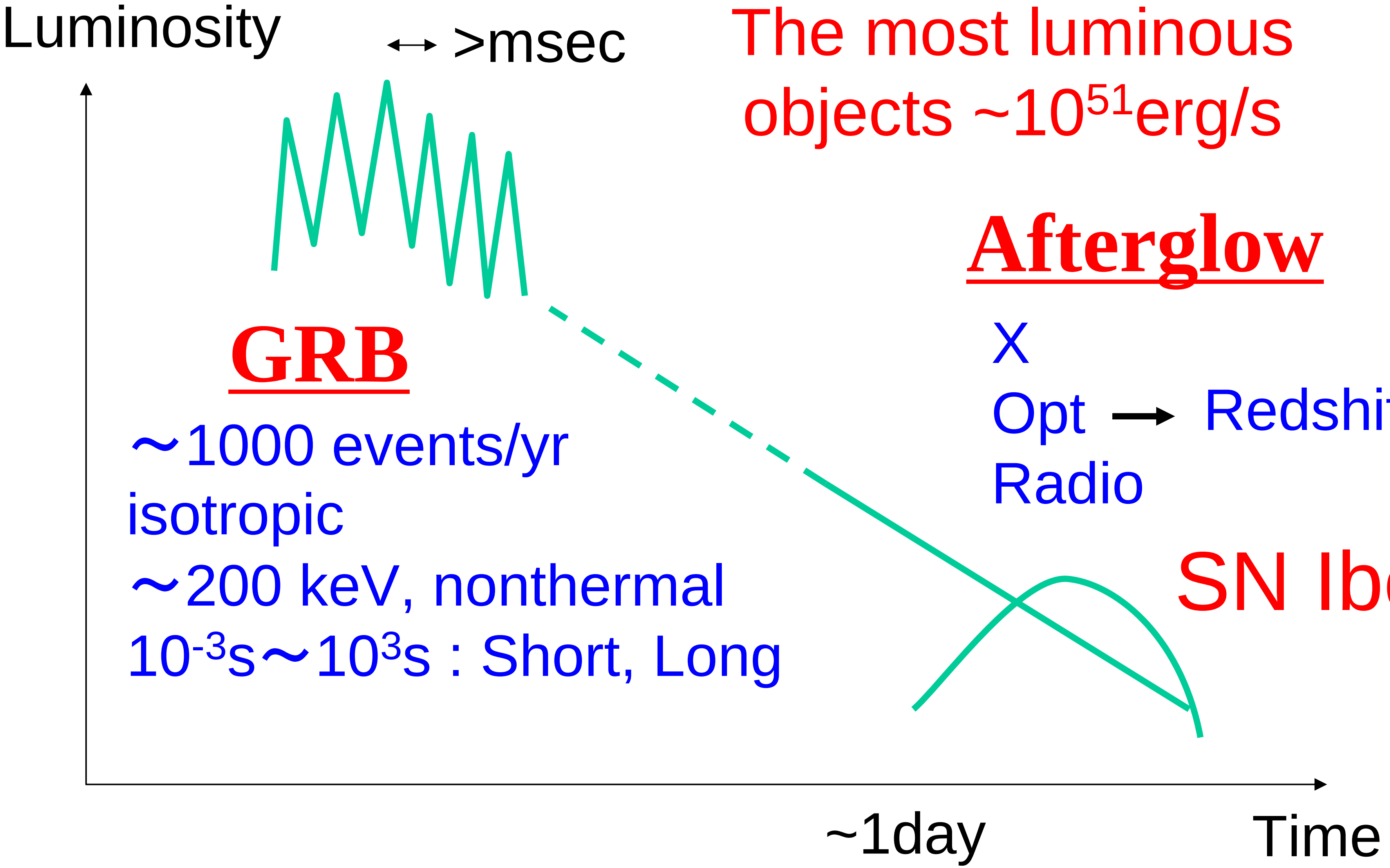


太陽
~10^{33}g

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

GRB



The most luminous objects ~10^{51}erg/s

GRB

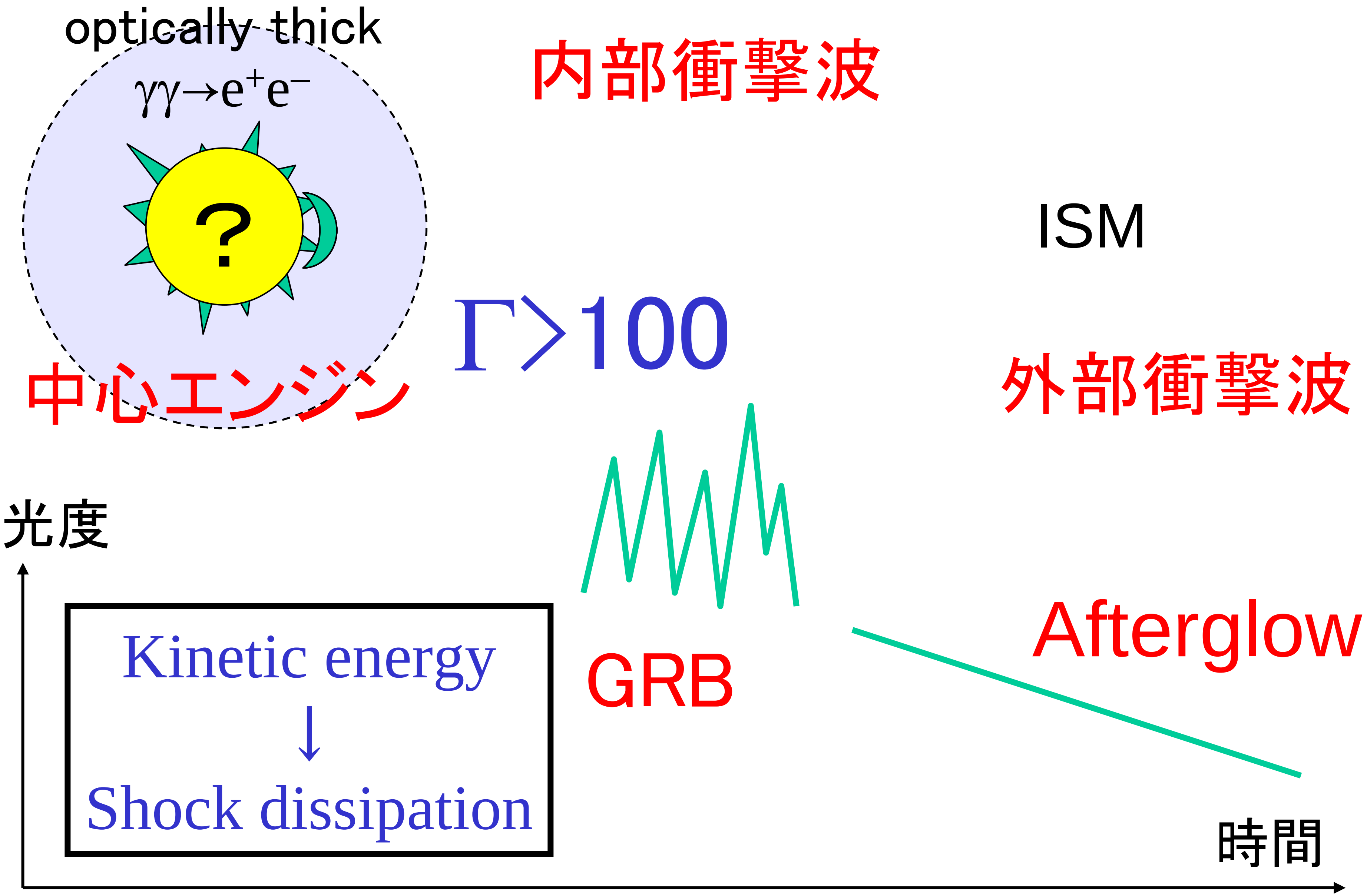
～1000 events/yr
isotropic
～200 keV, nonthermal
10^{-3}s～10^{3}s : Short, Long

Afterglow

X
Opt → Redshift
Radio

SN Ibc

Standard model



optically thick

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

中心エンジン

内部衝撃波

$\Gamma > 100$

ISM

外部衝撃波

光度

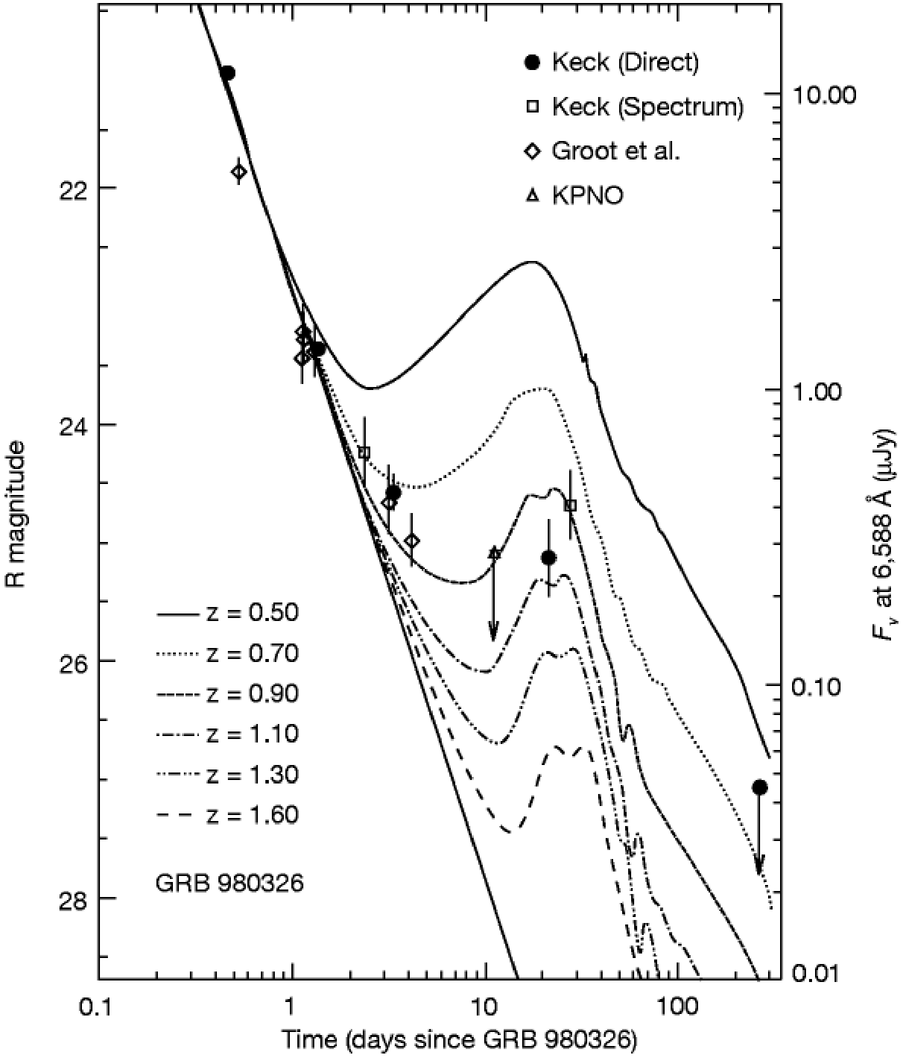
Kinetic energy
↓
Shock dissipation

GRB

Afterglow

時間

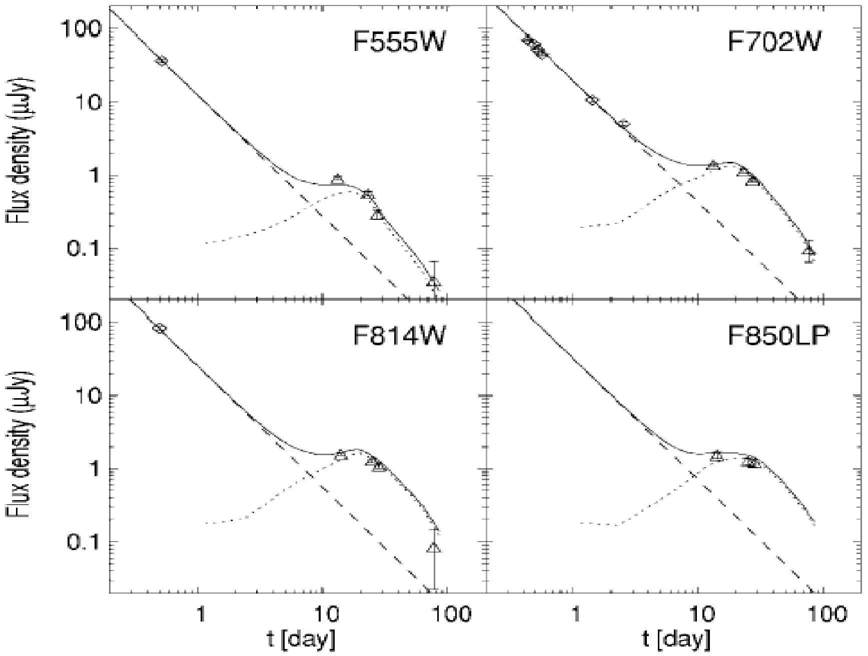
残光中の超新星



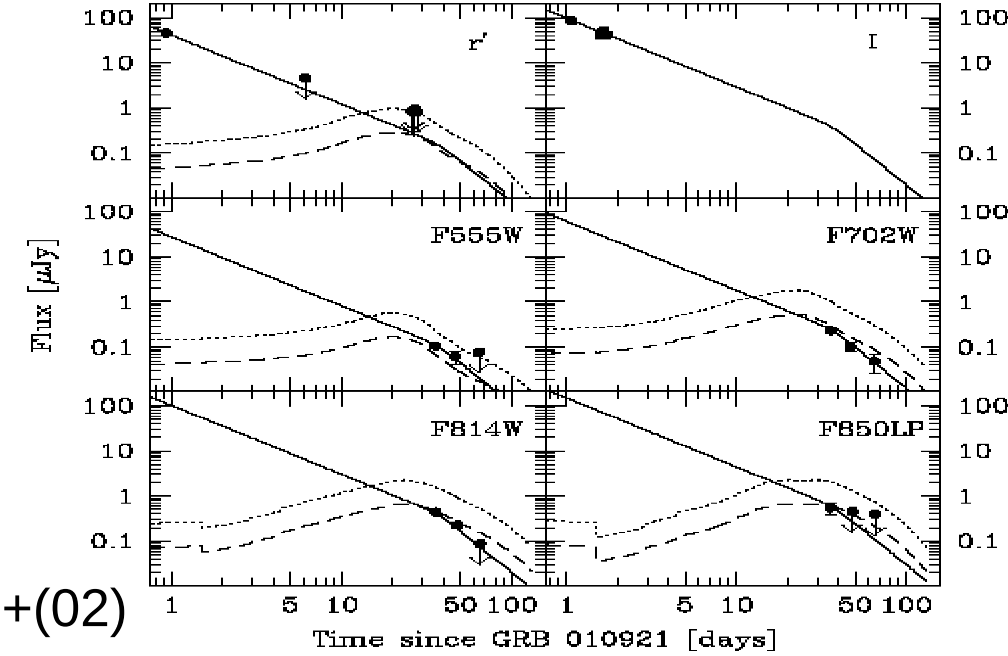
Bloom+(99)

他のモデルもありえる

GRB011121,Bloom+(02)

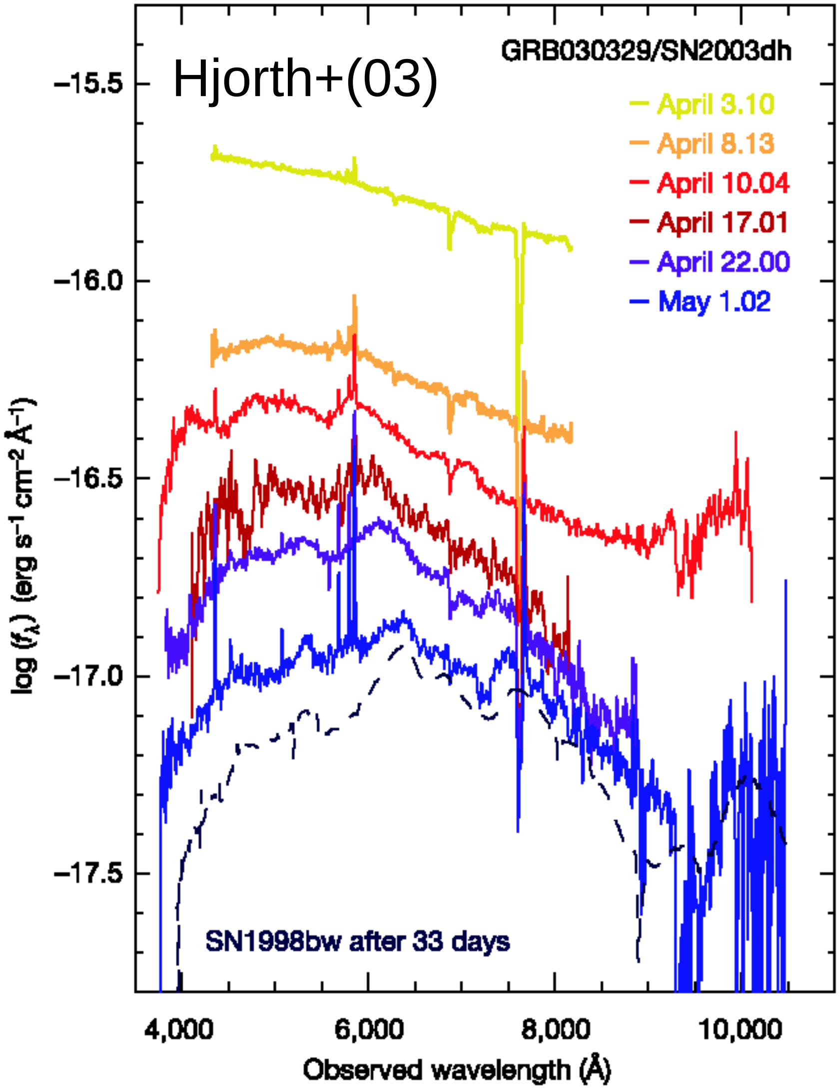


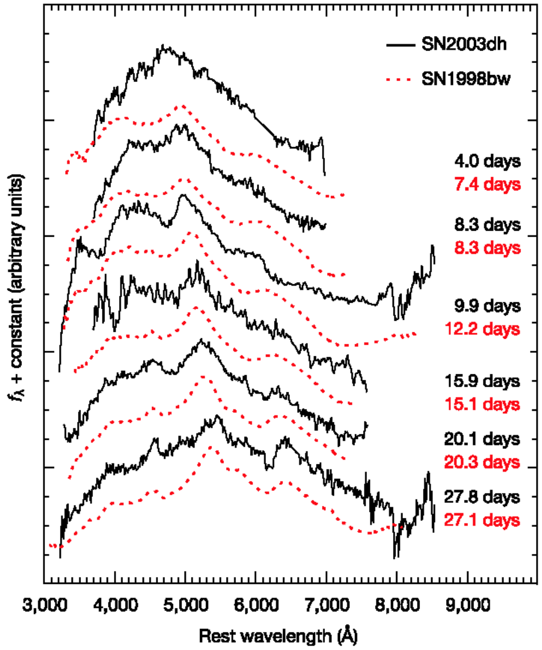
Price+(02)



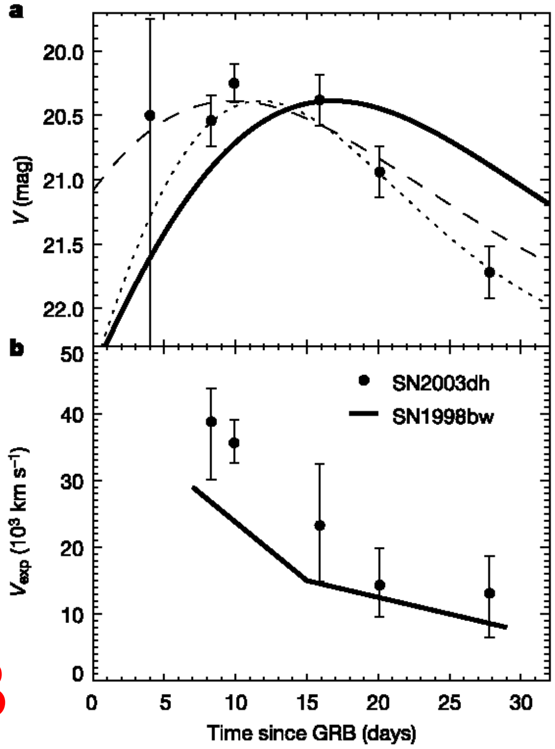
GRB030329

普通の明るさ


Hjorth+(03)



Broad line

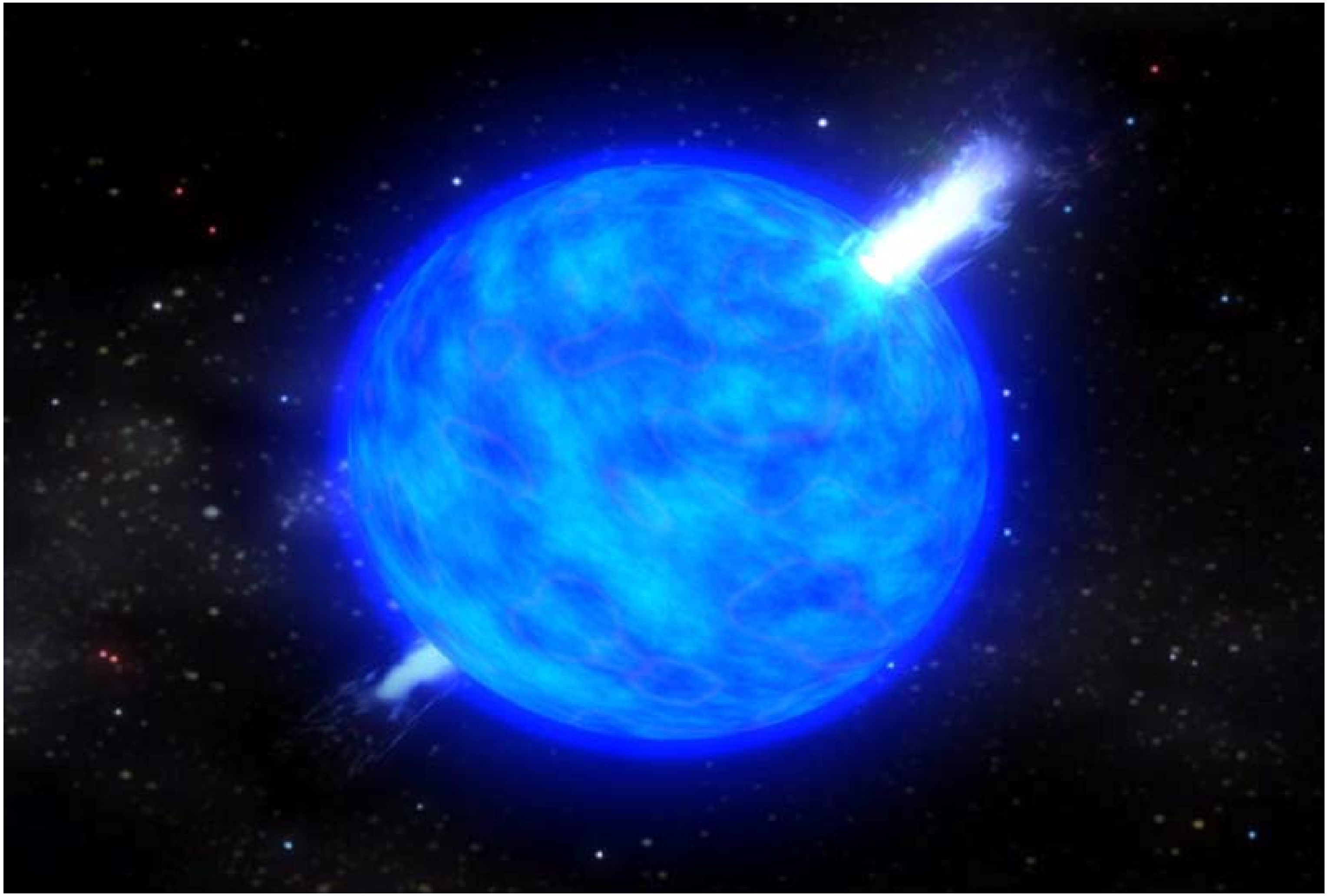


Within a few days

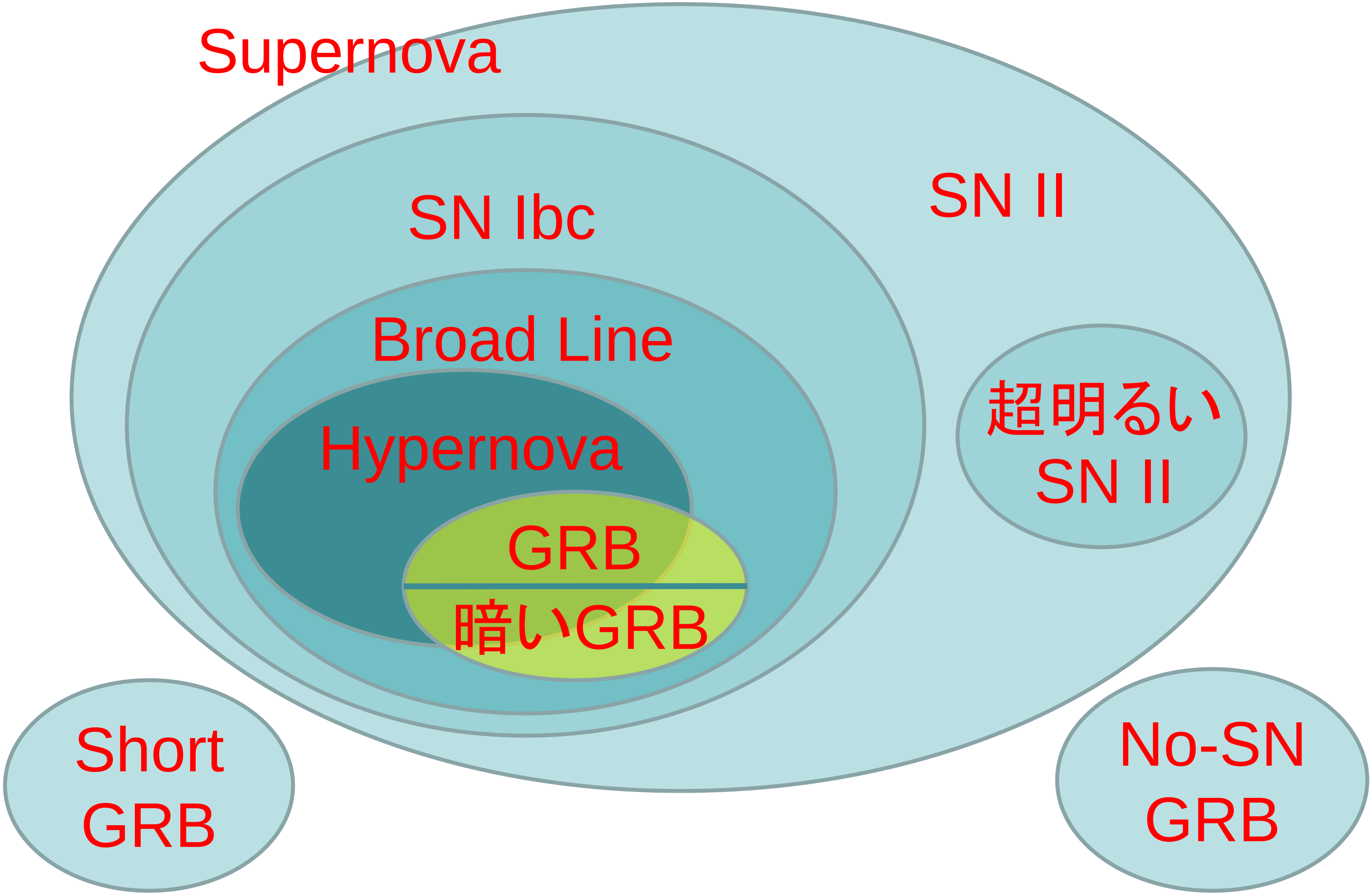
⇒超新星と同時に起こるGRB

Collapsar

GRBのジェットが外層を突き破っているはず



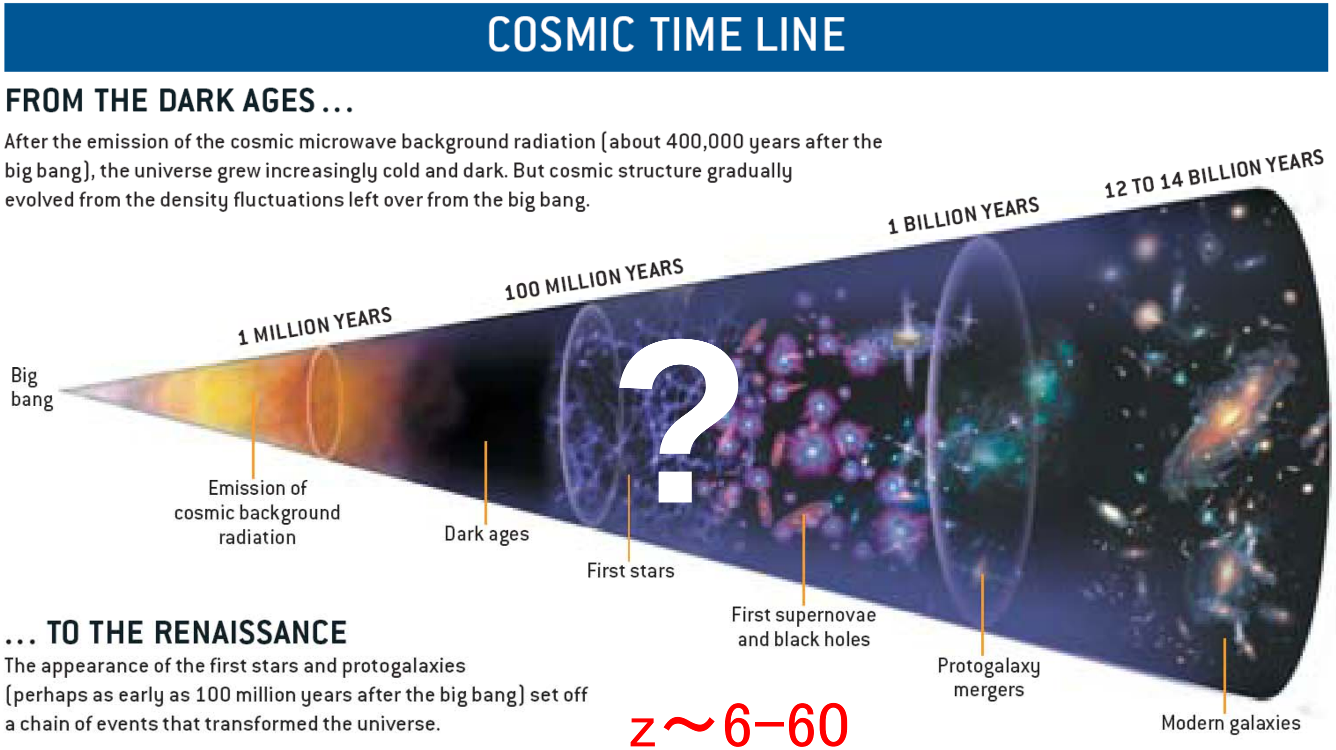
Zoo of Bursts



GRB Cosmology

Massive star origin ⇒ High redshift GRBs

Like QSO
Like SN
Star formation
Reionization
Metal
Dark energy
…



COSMIC TIME LINE

FROM THE DARK AGES …

After the emission of the cosmic microwave background radiation (about 400,000 years after the big bang), the universe grew increasingly cold and dark. But cosmic structure gradually evolved from the density fluctuations left over from the big bang.

… TO THE RENAISSANCE

The appearance of the first stars and protogalaxies (perhaps as early as 100 million years after the big bang) set off a chain of events that transformed the universe.

Larson&Bromm 02

z～6–60

GRB ⟷

z~7

QSO, galaxy ⟷

GRBs are useful for probing high z

Detectability

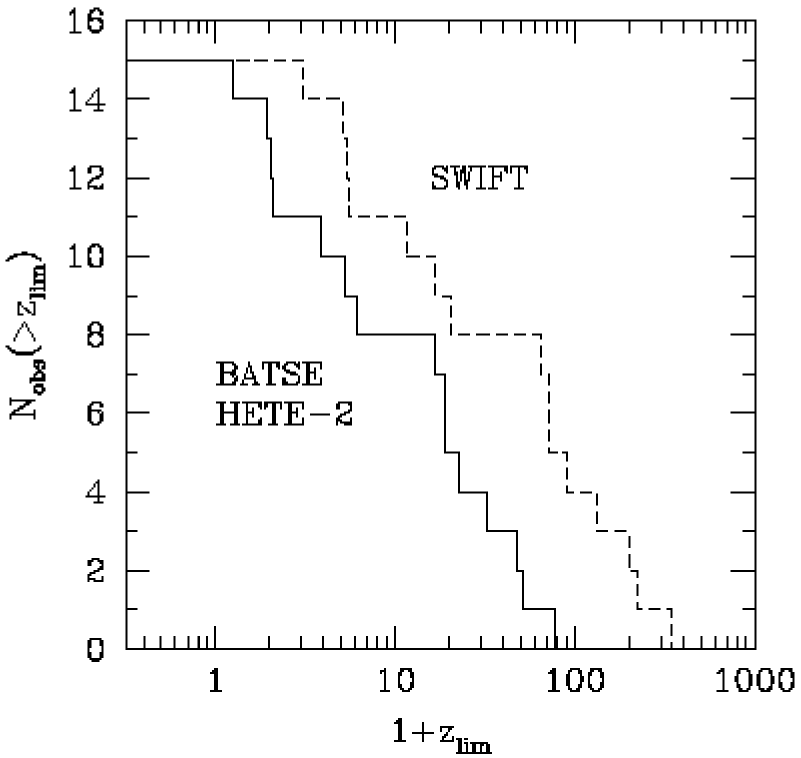
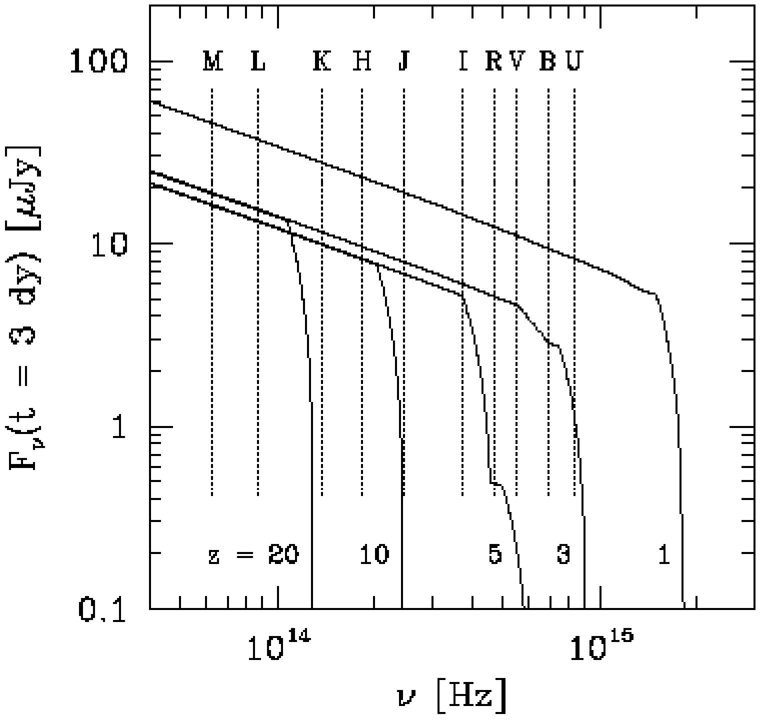


FIGURE 1. Cumulative distributions of the limiting redshifts at which the 15 GRBs with well-determined redshifts and published peak photon number fluxes would be detectable by BATSE and HETE-2, and by *Swift*.



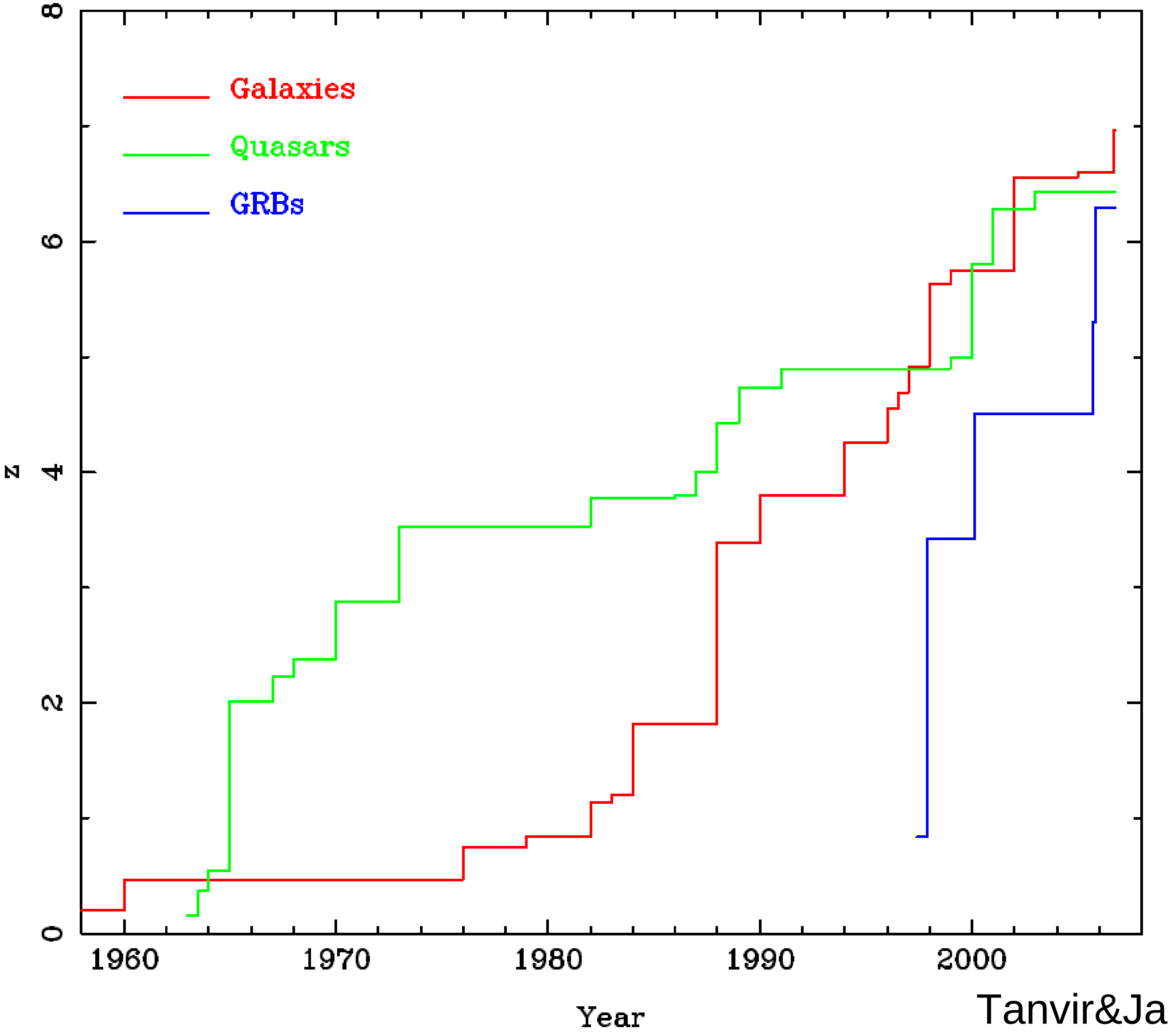
Lamb&Reichart 01, Ciardi&Loeb 00

Time dilation+L$\propto t^{-1}$⇒

High-zでも暗くならない

Lyα trough⇒Redshift

最高赤方偏移

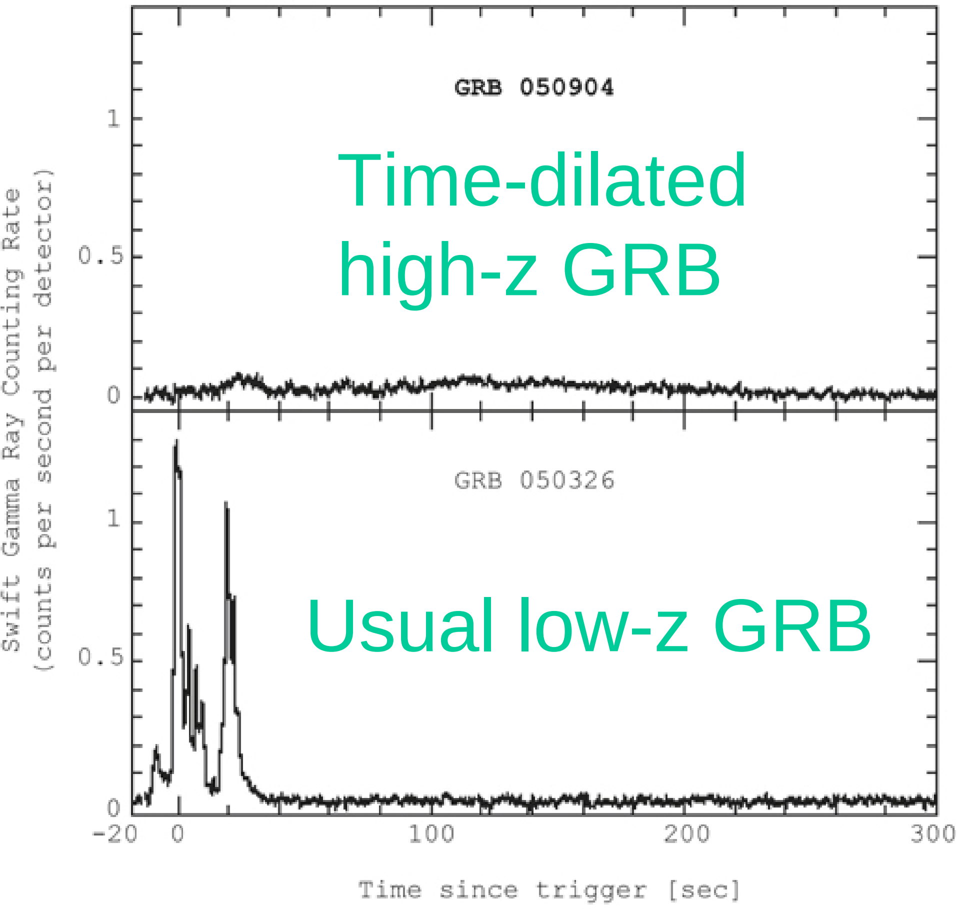


z_{max}~6.3
すばる

z>6 fraction:
~1%(GRB)
~10^{-3}%(QSO)

Tanvir&Jakobsson 07

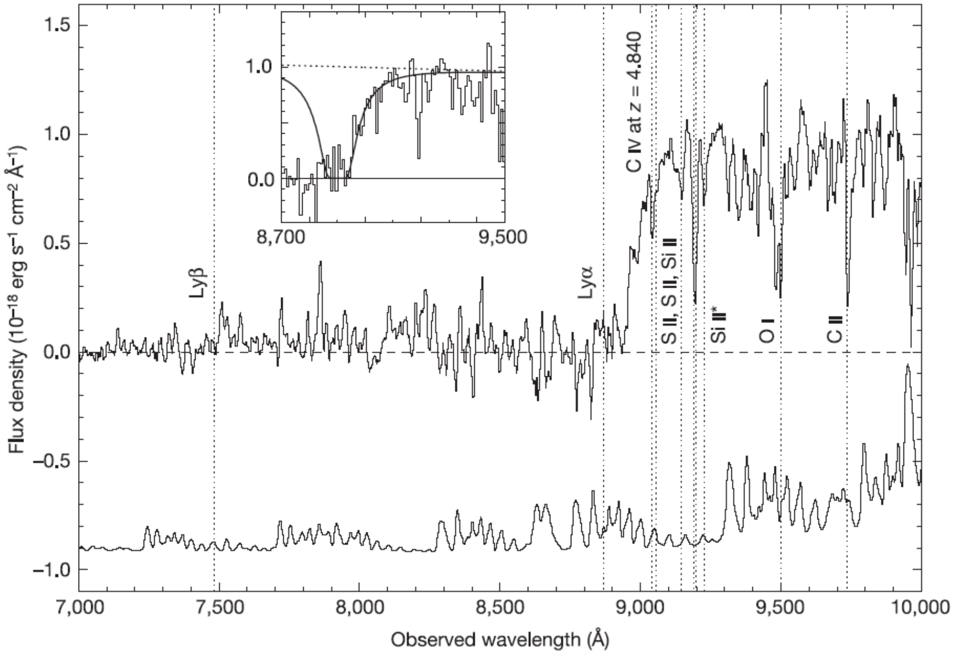
GRB 050904 @z~6.3



Time-dilated high-z GRB

Usual low-z GRB

Swift
T90~225s

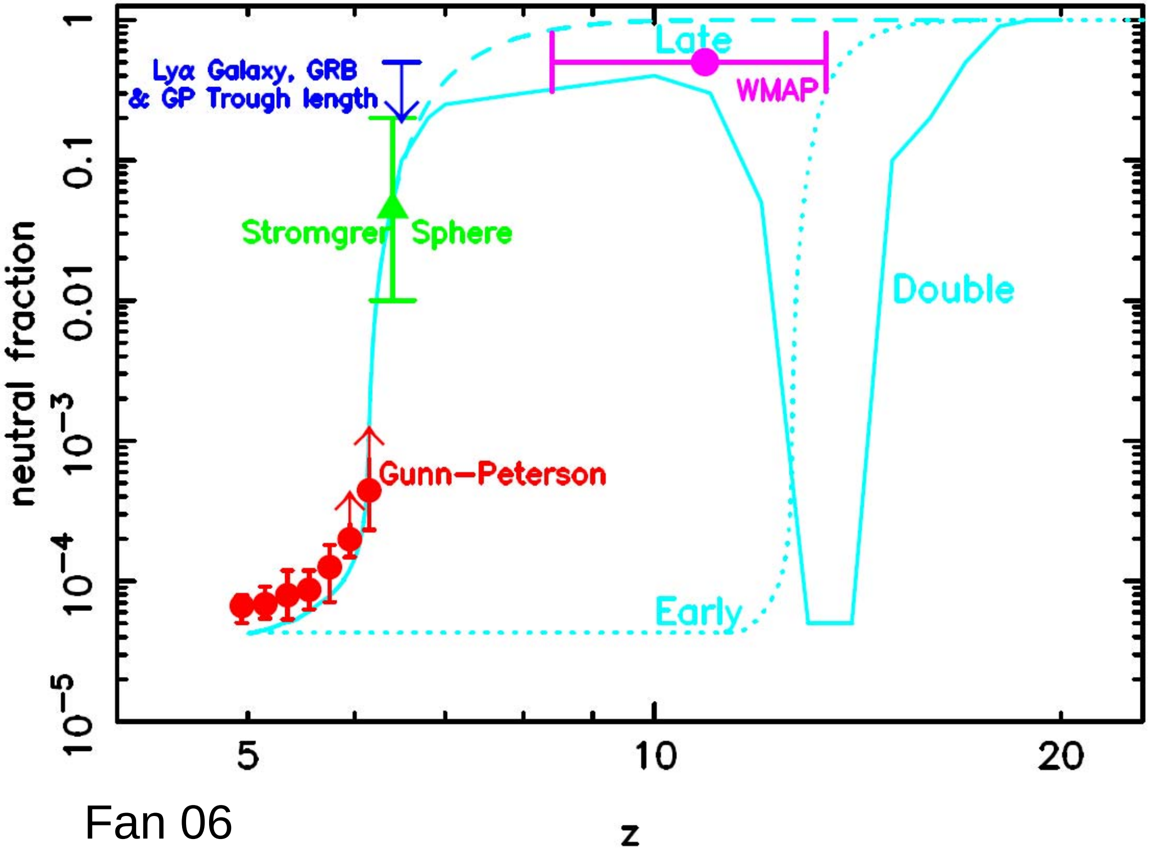


Kawai+ 06
Totani+ 06

すばる@3.4day
⇒Lyα Damping wing
z=6.295±0.002
中性度 $x_{HI}<0.60$ (95%CL)
母銀河DLA $\log[N_{HI}]\sim21.6$
重元素 [C/H]=-2.4,[O/H]=-2.3,
[Si/H]=-2.6,[S/H]=-1.0

Reionization History

$$\tau_s = \frac{\pi e^2 f_\alpha \lambda_\alpha n_{HI}(z_s)}{m_e c H(z_s)} \approx 6.5\times10^5 x_{HI}\left(\frac{\Omega_b h}{0.03}\right)\left(\frac{\Omega_m}{0.3}\right)^{-1/2}\left(\frac{1+z_s}{10}\right)^{3/2}$$



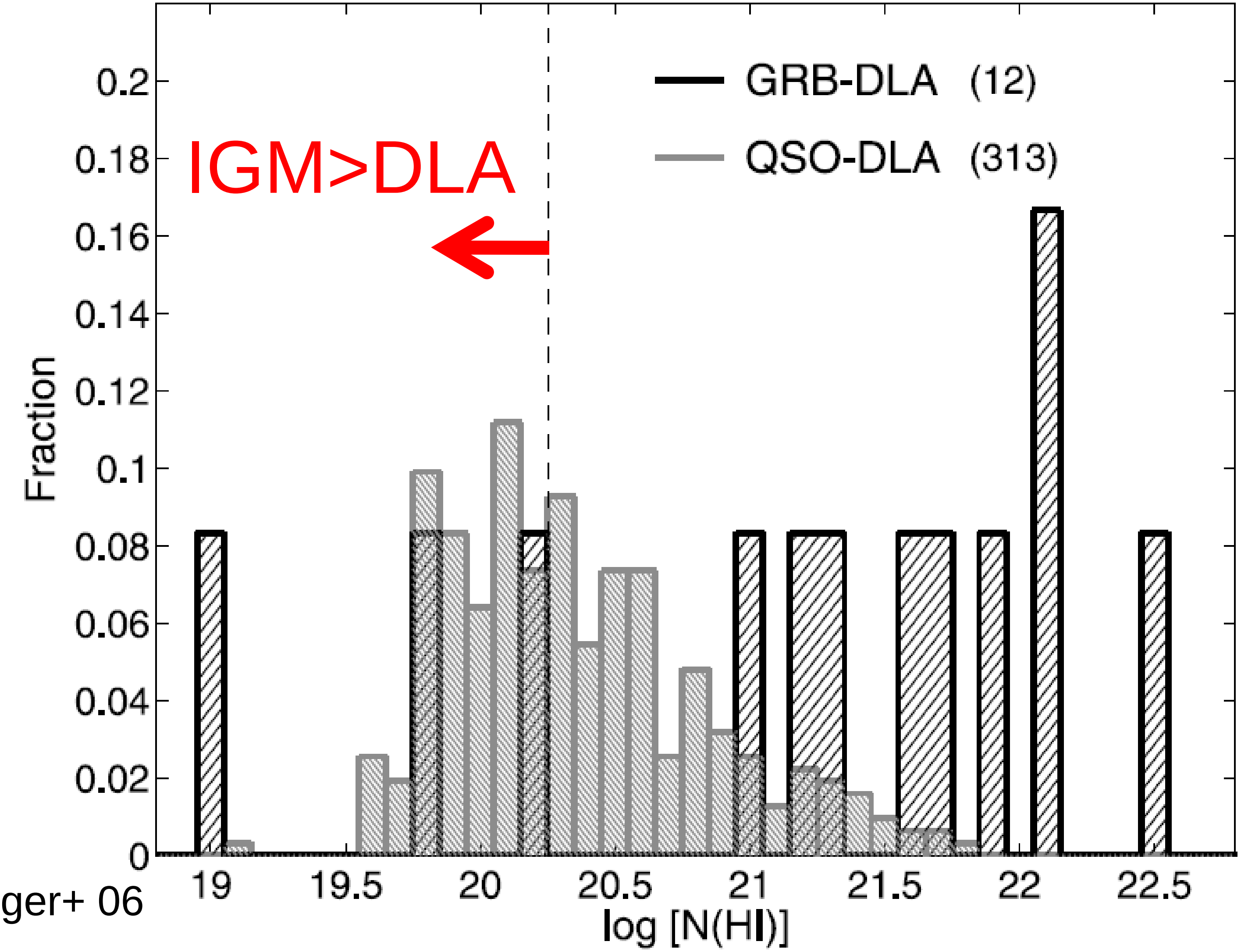
Fan 06

Damping Wing
⇒x_{HI}の下限ではなく値が分かる

1. GRBは明るい
2. No proximity effect（電離領域が小さい）
3. 母銀河は暗くてよい（バイアスが少ない）
4. 冪的スペクトル

将来的には色々な視線方向⇒Topology

Column Density

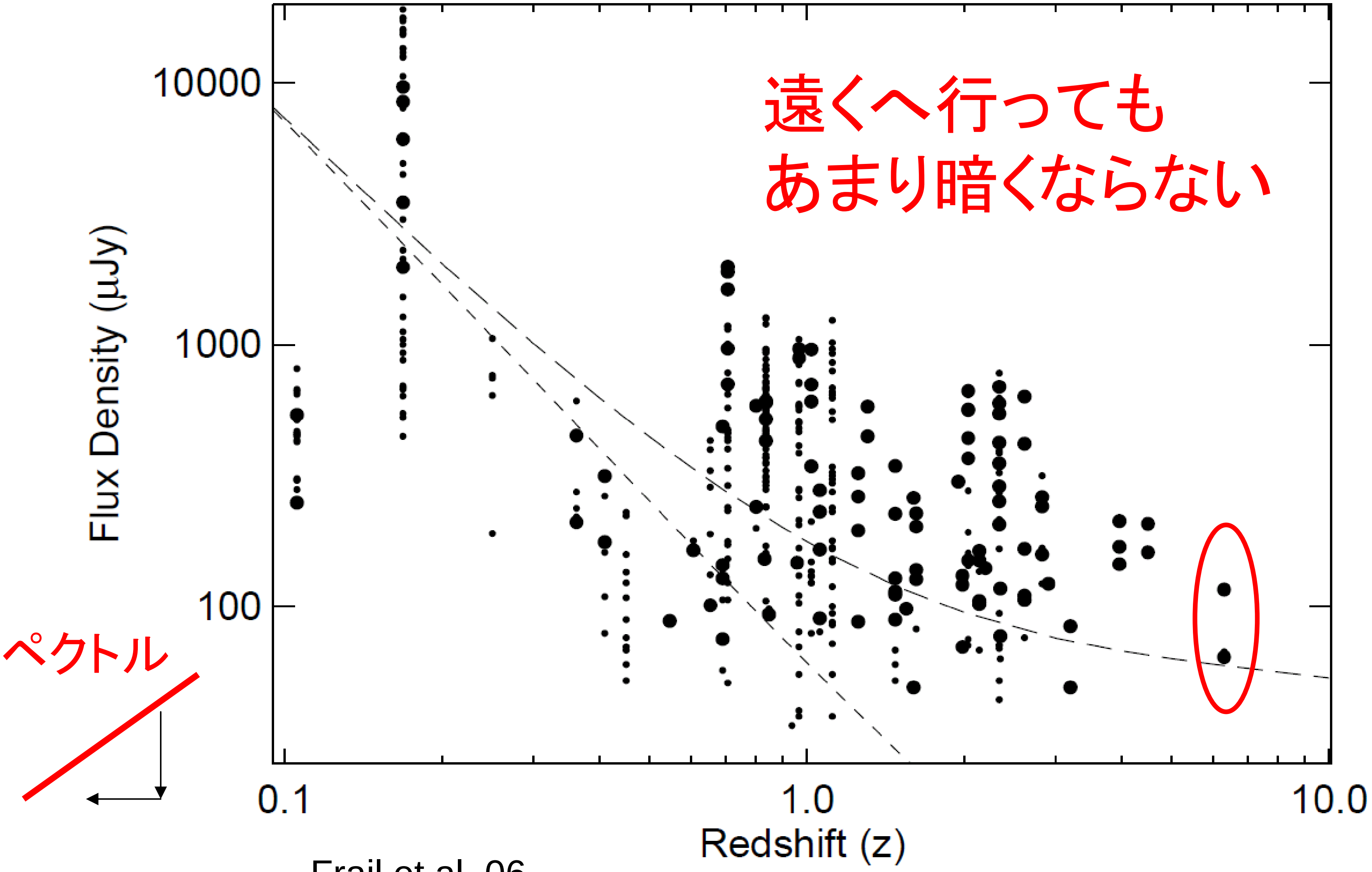


IGM>DLA

Berger+ 06

ちなみに N(HI) ⇒ Escape fraction ~ 0.02±0.02 Chen+ 07

電波残光 @z~6.3

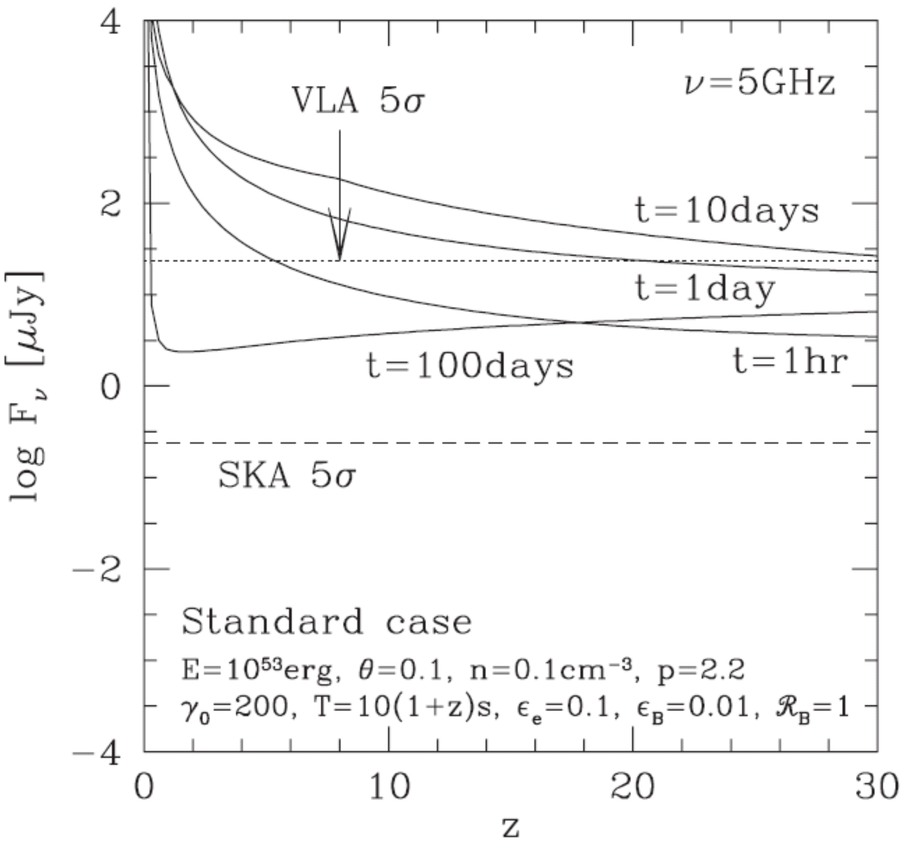


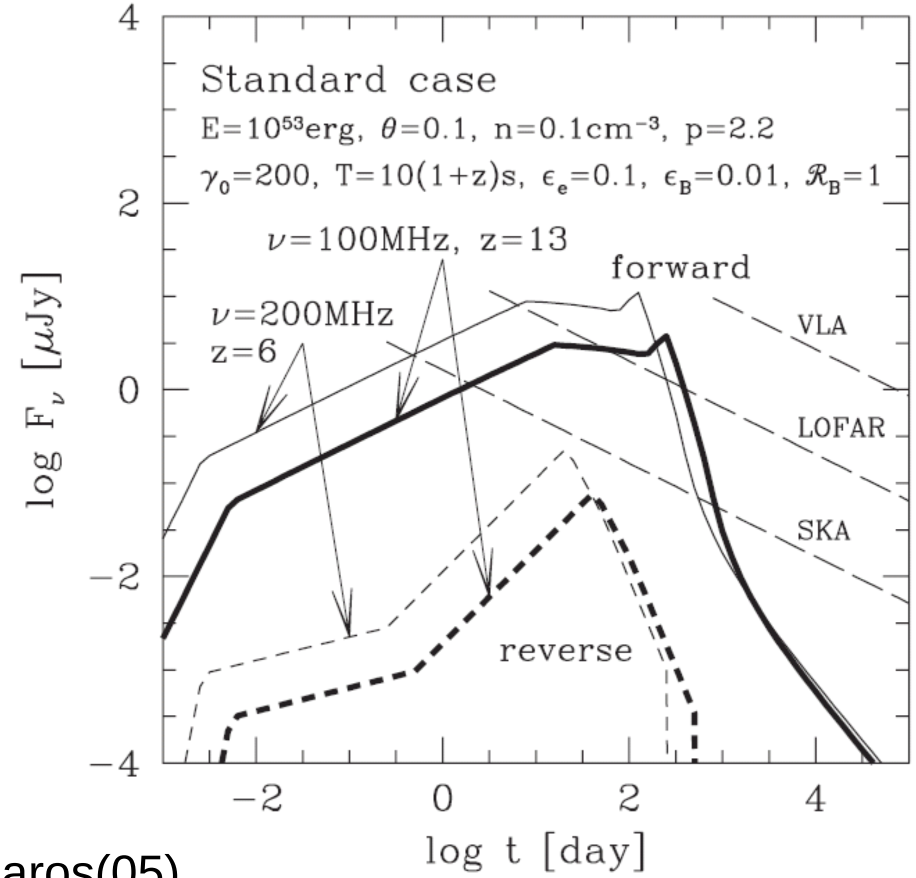
遠くへ行っても
あまり暗くならない

スペクトル

Frail et al. 06

電波残光の予想

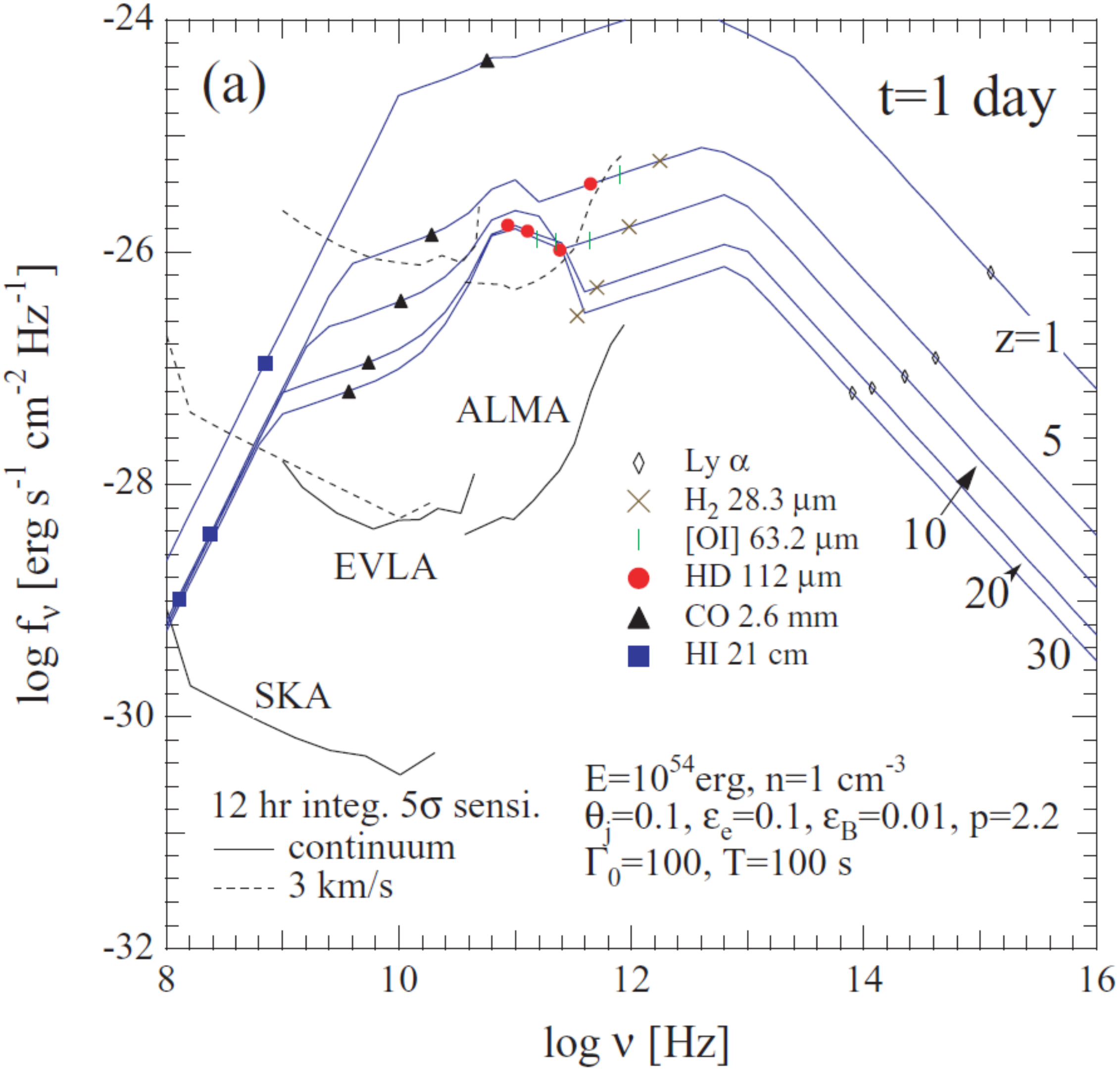




Ioka&Meszaros(05)

暗くならないことは予想通り

Atomic/Molecular Lines



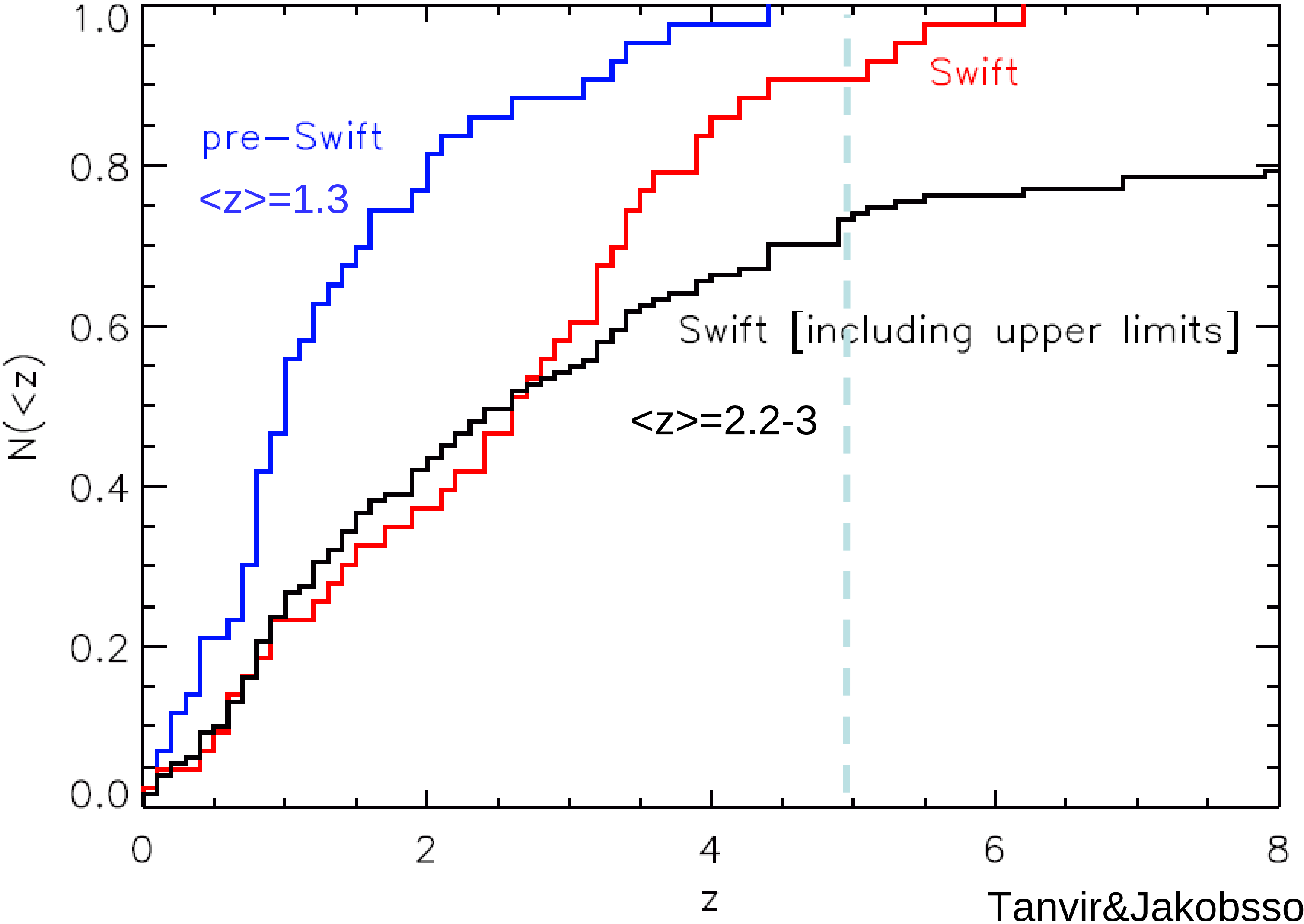
SKA
CO (low)

ALMA
HD
CO (high)
[OI]

⇒Physical conditions in PopIII & early PopII, although challenging

Inoue+ 07

赤方偏移分布



~10%@z>5

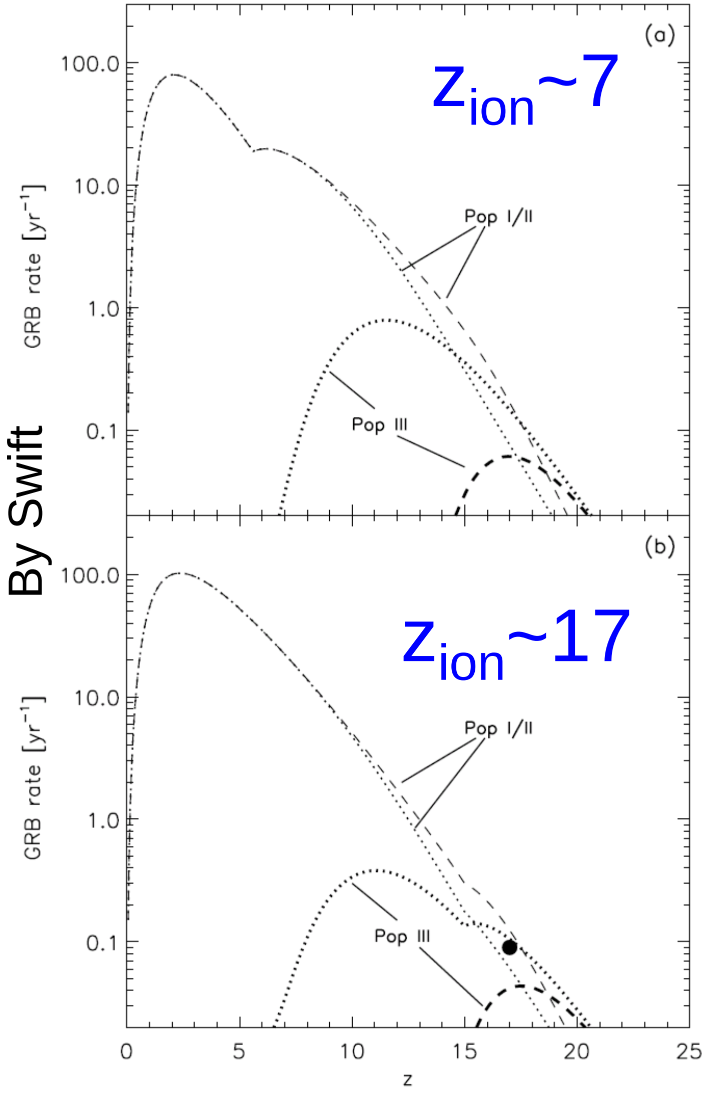
Potentially
High-z

~50% are
dark GRBs

Tanvir&Jakobsson(07)

理論的予想

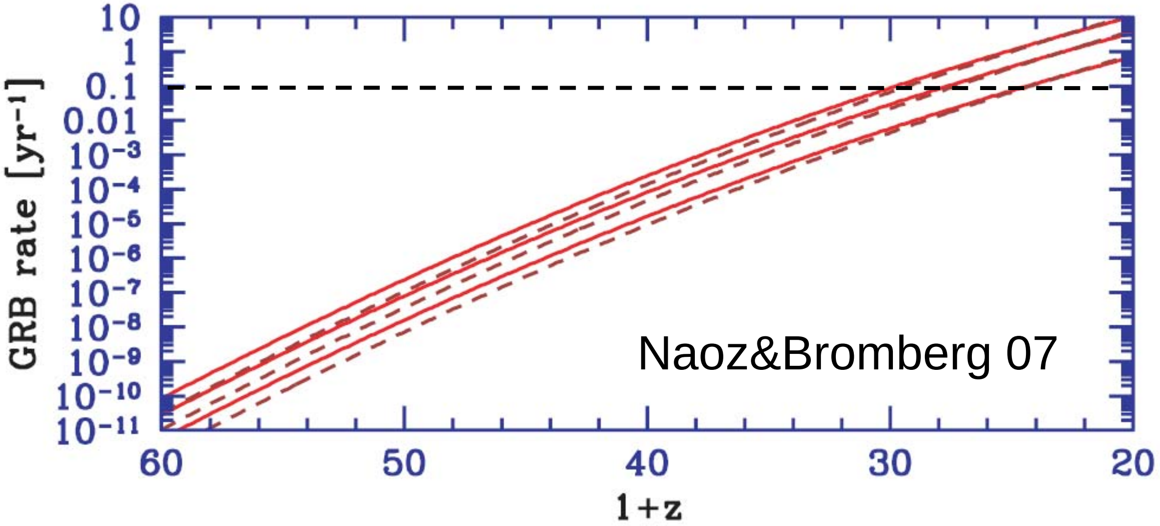
Bromm&Loeb 06



z_{ion}~7

z_{ion}~17

(Strong chemical feedback ---)



Naoz&Bromberg 07

Salvaterra+ 07,08, Daigne+06

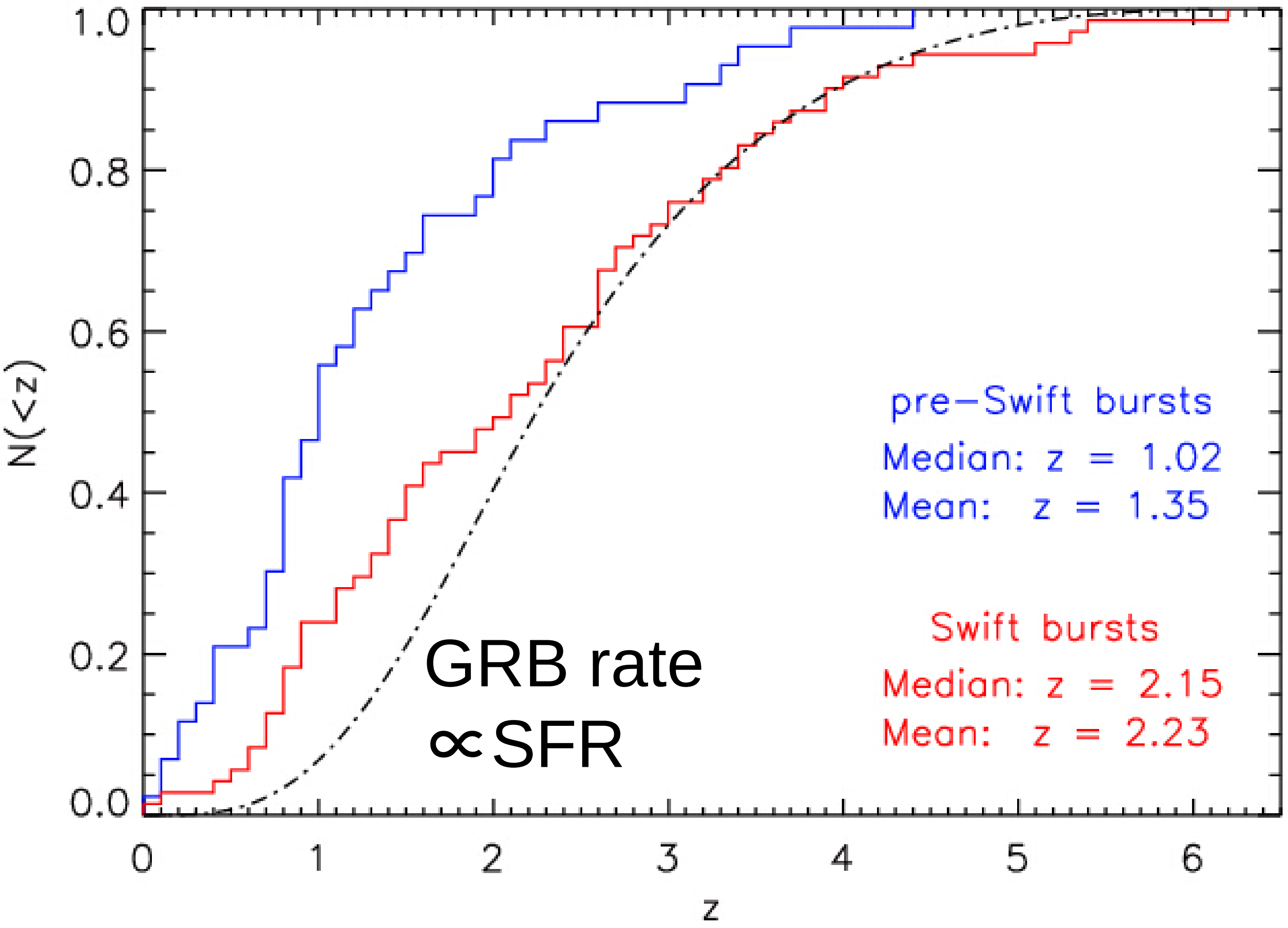
~10% @z>5

0.1GRB/yr ⇒ z~30

First GRB @z~60

Depend on SFR, L-function, spectrum, efficiency, feedback

Latest z-distribution

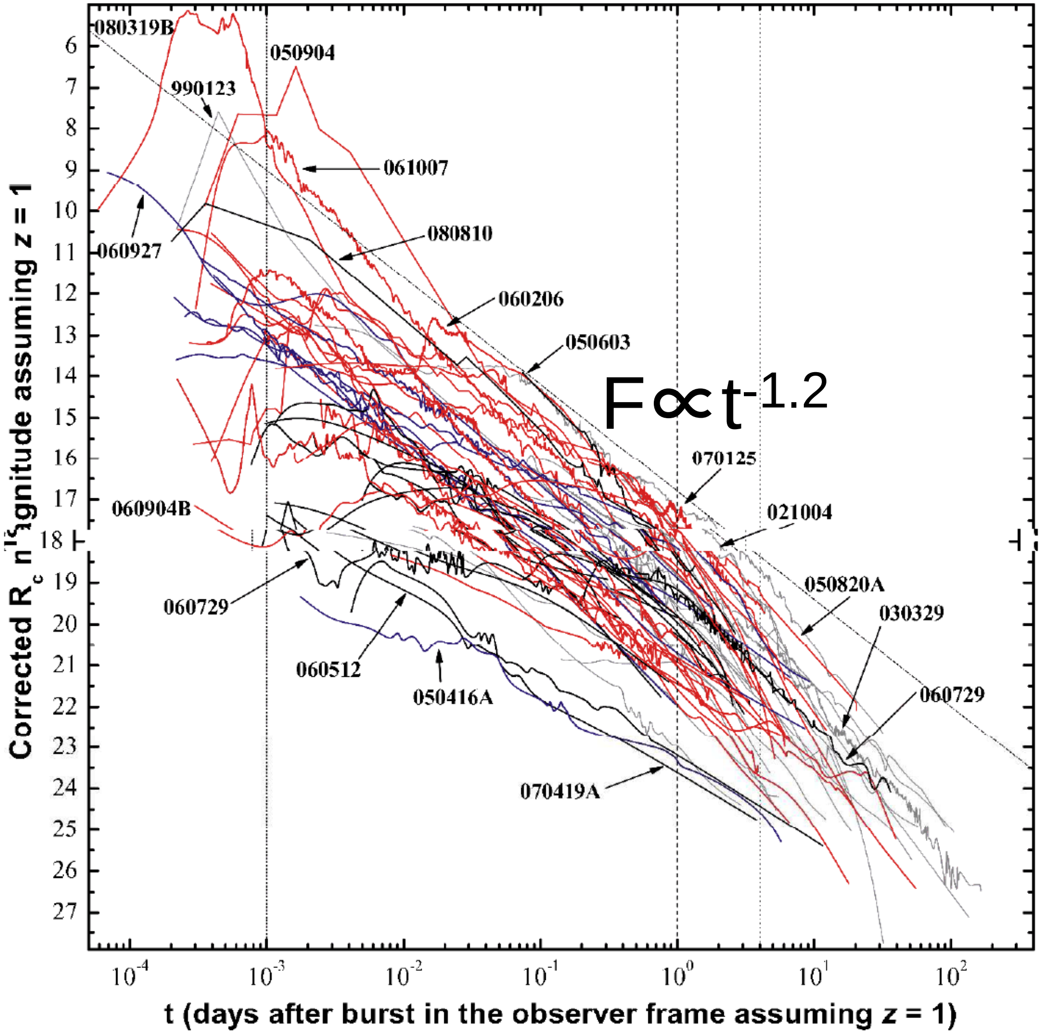


GRB rate
$\propto$SFR

3%(4/163)
@z>5

http://raunvis.hi.is/~pja/GRBsample.html

Optical Afterglow



$F \propto t^{-1.2}$

Bad news:

・初期明るいものでも1日後には皆と同じ

・No reverse shock?

Good news:

・Naked-eye burst

Extinction corrected. Thin gray: the pre-Swift sample
Red: Golden Sample; Blue: Silver Sample; Black: Bronze Sample
Vertical lines: time where the optical luminosity was examined

Need for 8-10m telescope

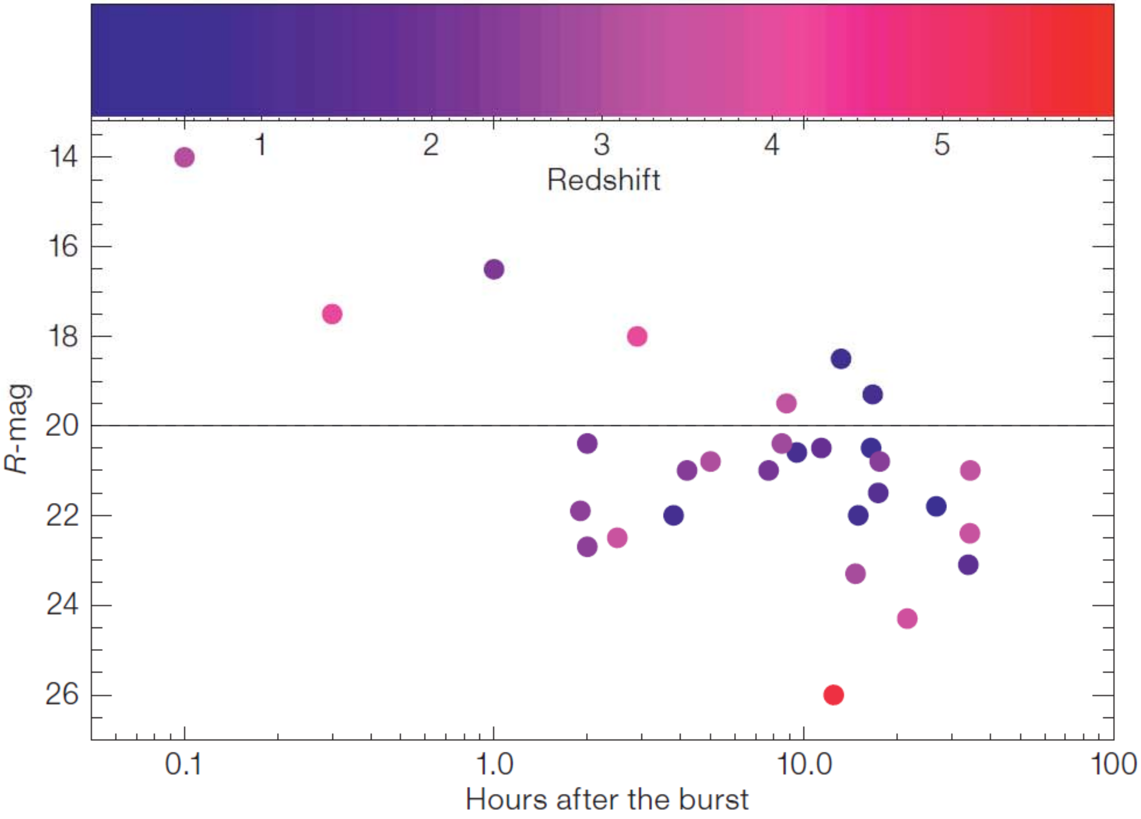


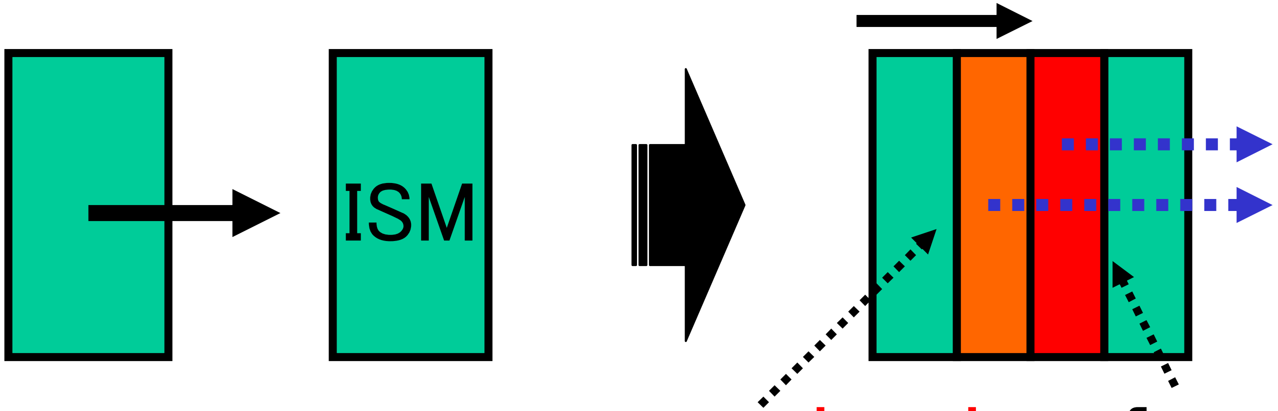
Figure 3: The *R*-band magnitude of the optical afterglows as a function of the time after the burst at which the spectroscopic observations were obtained. Only included are *Swift* bursts for which we have measured the redshift (using primarily the VLT, but also NOT, WHT and GEMINI). The colour bar at the top indicates the colour code for the measured redshifts. The dashed line marks a magnitude of R = 20 which is roughly the spectroscopic limit for 2–4-m telescopes for detecting absorption lines. As seen, most afterglows are fainter than this limit when observable.

Fynbo+ 07

数時間でR>20: 2-4m望遠鏡は無力に

NIR robotic telescope (REM, PAIRITEL…)

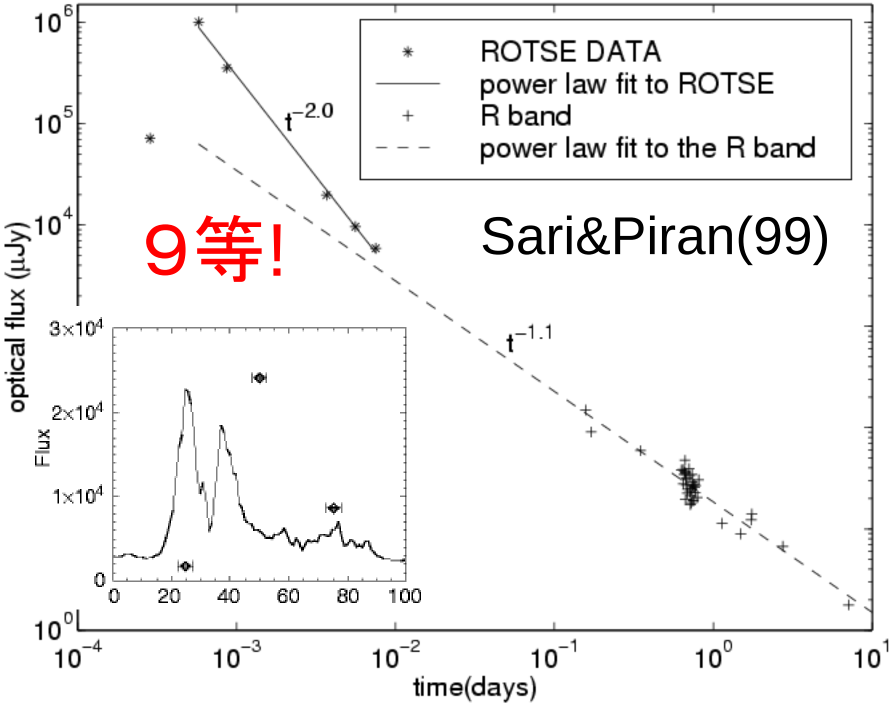
Reverse shock emission



Shock emission

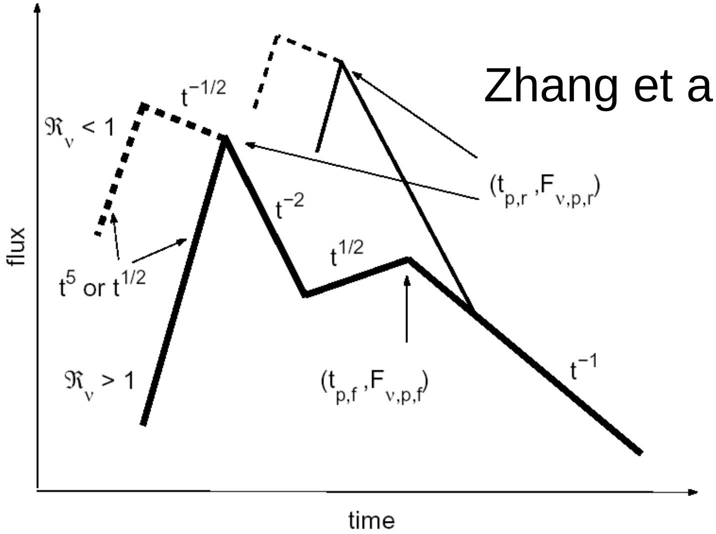
reverse shock

forward shock



９等!

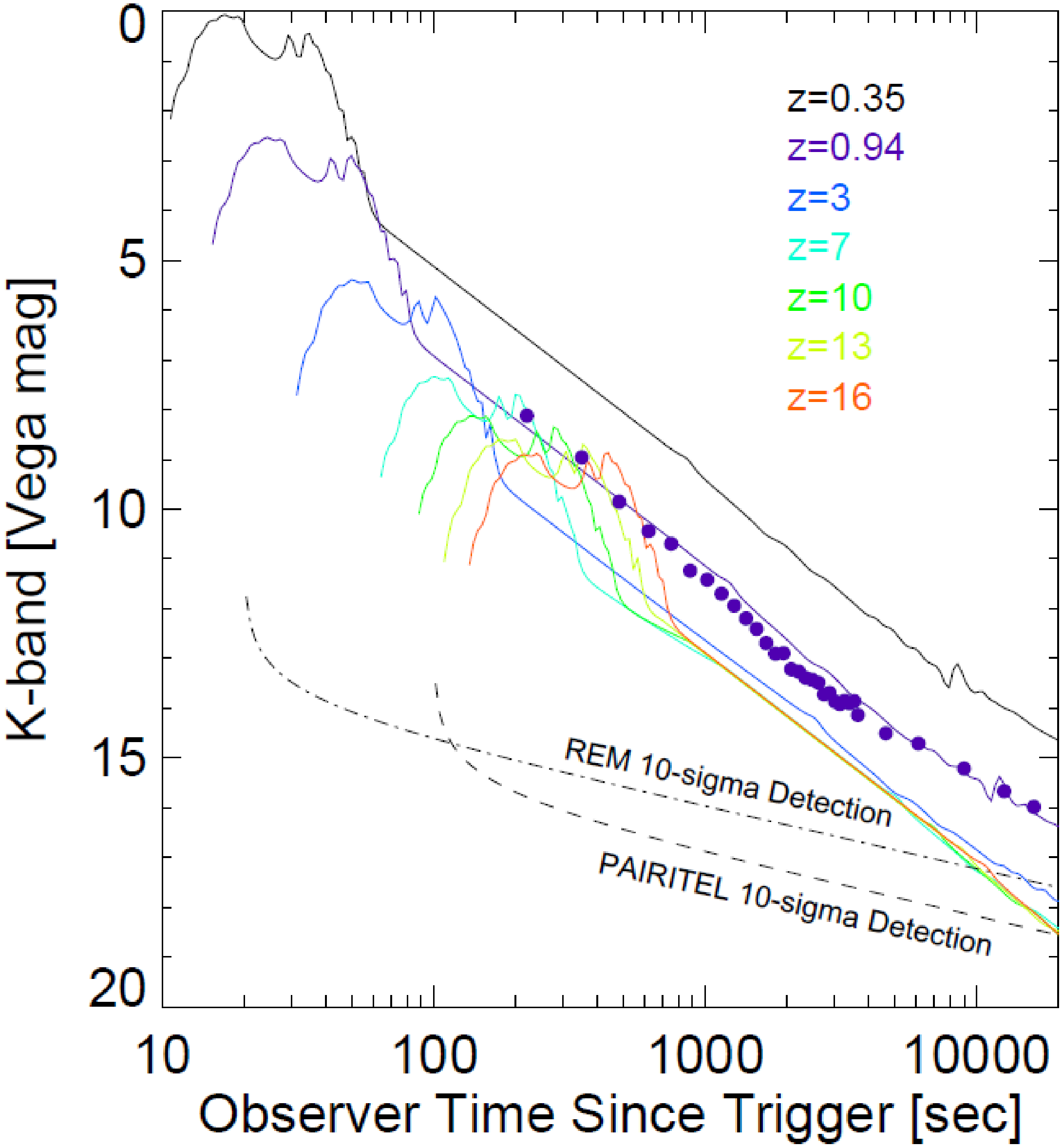
Sari&Piran(99)



Zhang et al.(03)

なぜかあまり受かっていない
B dominated? IR flash?

裸眼GRB



GRB080319B
peaked at V_{mag}~5.3
: Naked-eye GRB
(裸眼GRB)

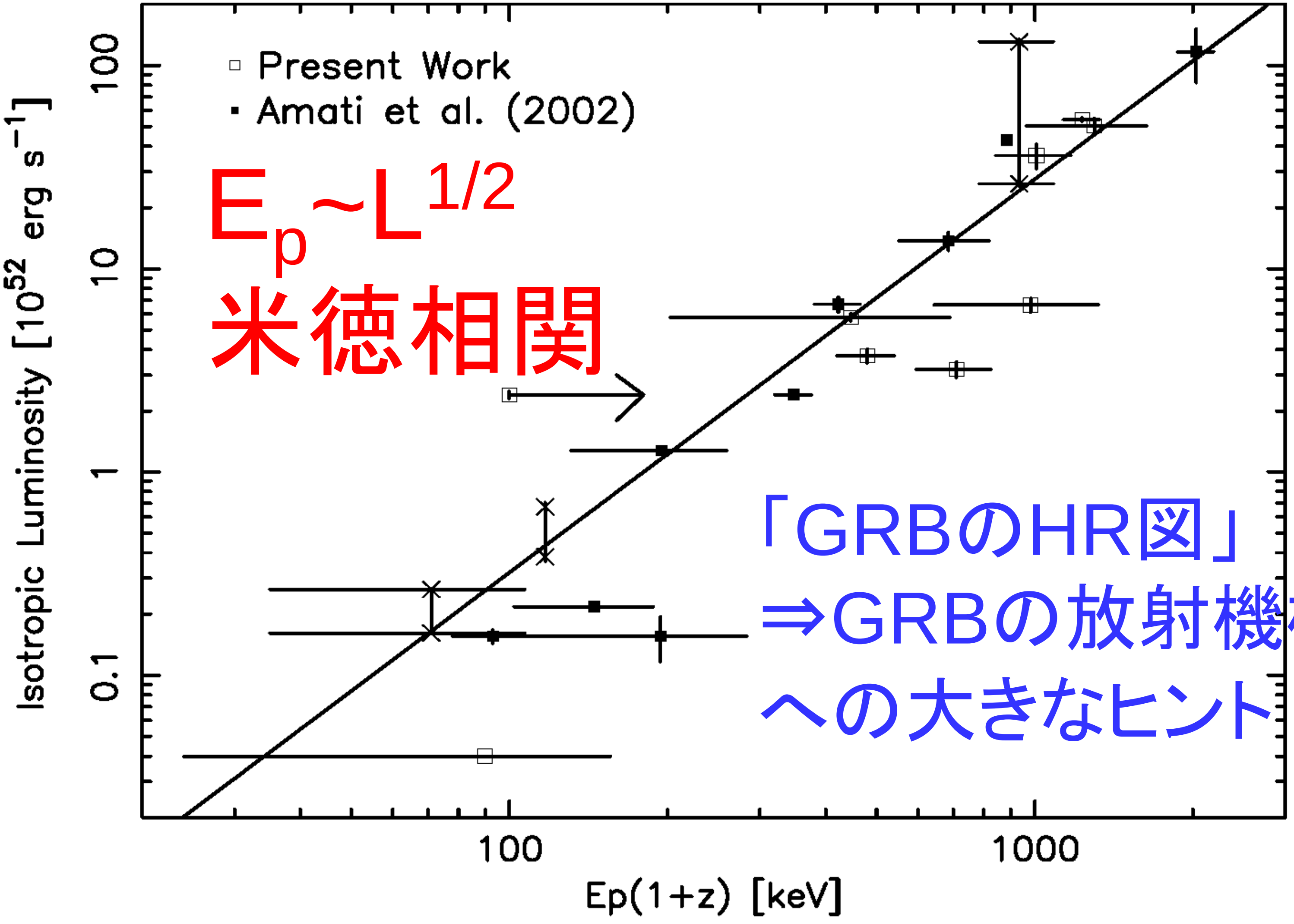
Time-dilation+L∝t^{-2}
High-zでも明るい

7時間後には
大きな望遠鏡でも
スペクトルが
取れなくなった

E_{peak}-L_{iso} Correlation

Typical GRB photon energy

Yonetoku+KI(03)



$E_p \sim L^{1/2}$

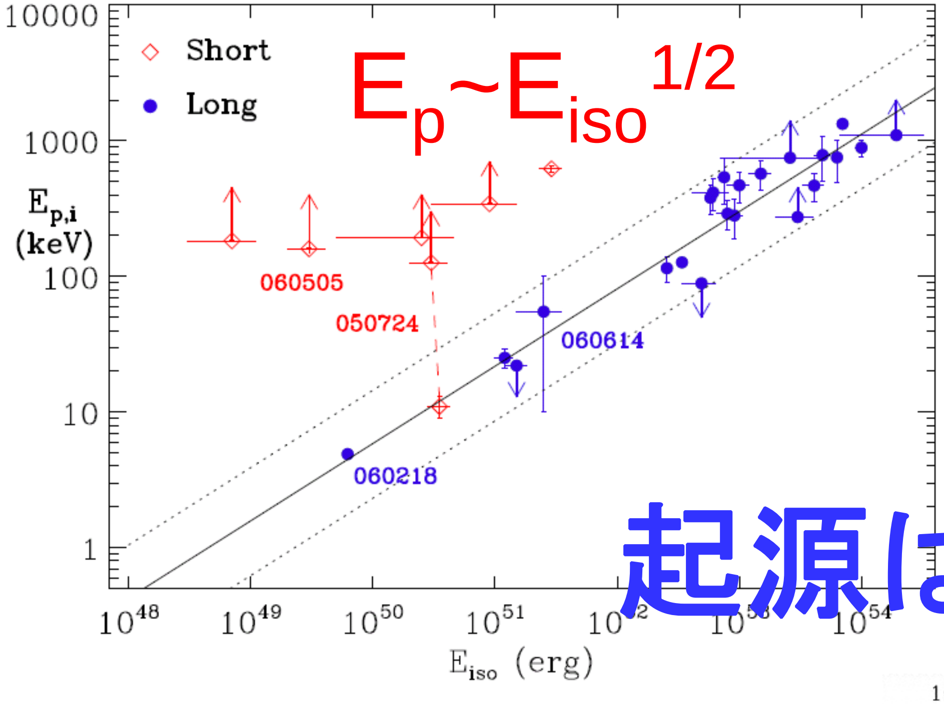
米徳相関

「GRBのHR図」

⇒GRBの放射機構

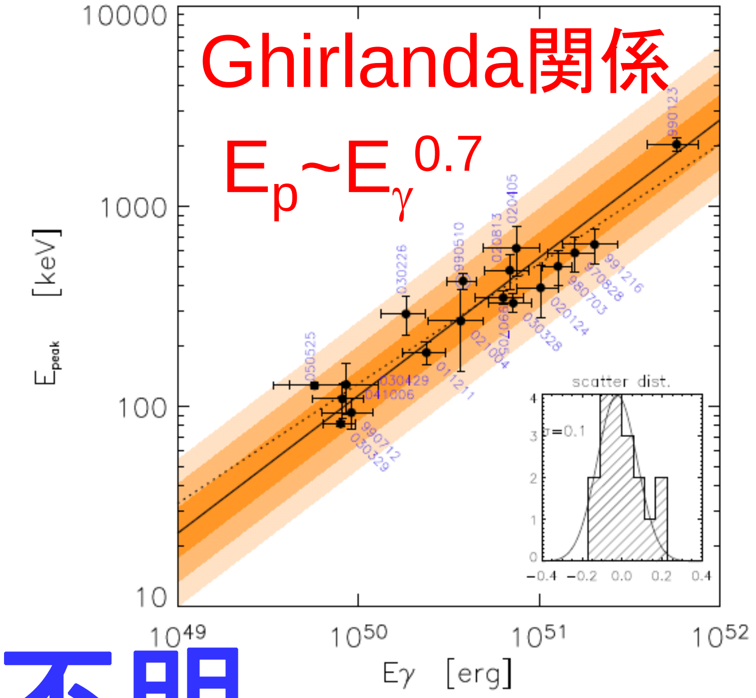
への大きなヒント

Amati関係



$E_p \sim E_{iso}^{1/2}$

Ghirlanda関係



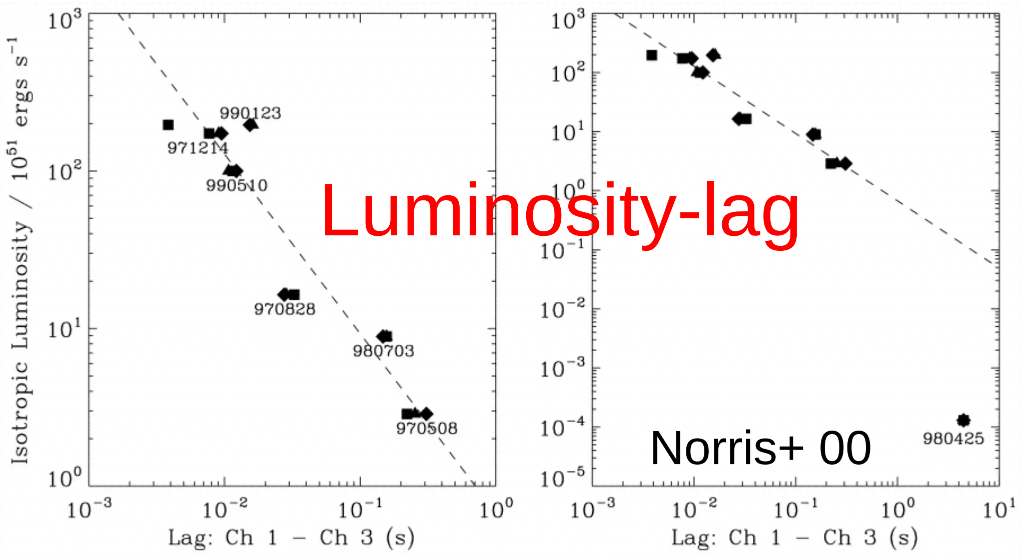
$E_p \sim E_\gamma^{0.7}$

起源は不明

Liang-Zhang関係

$E_{iso} \sim E_p^{1.94}\ t_b^{-1.24}$

Luminosity-variability

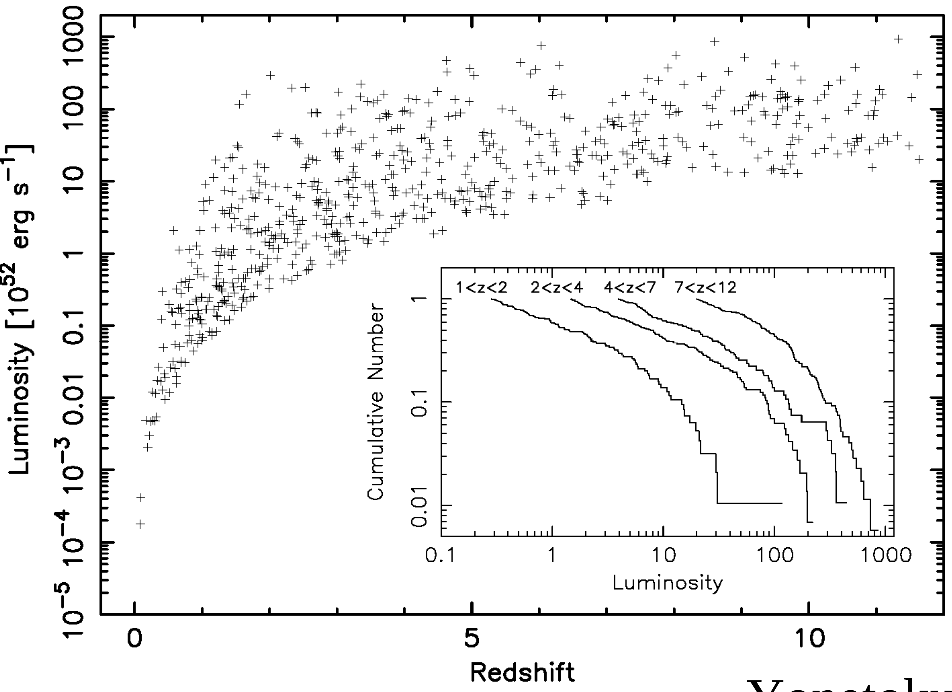


Luminosity-lag

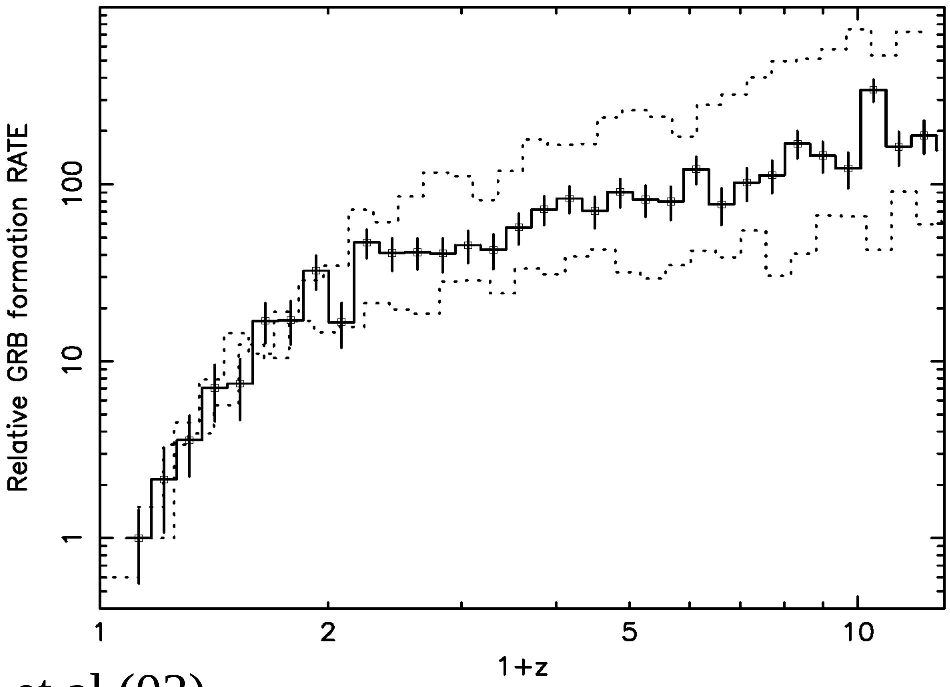
Norris+ 00

E_p-L相関⇒L⇒距離(z)

z-distribution



星形成率(SFR)

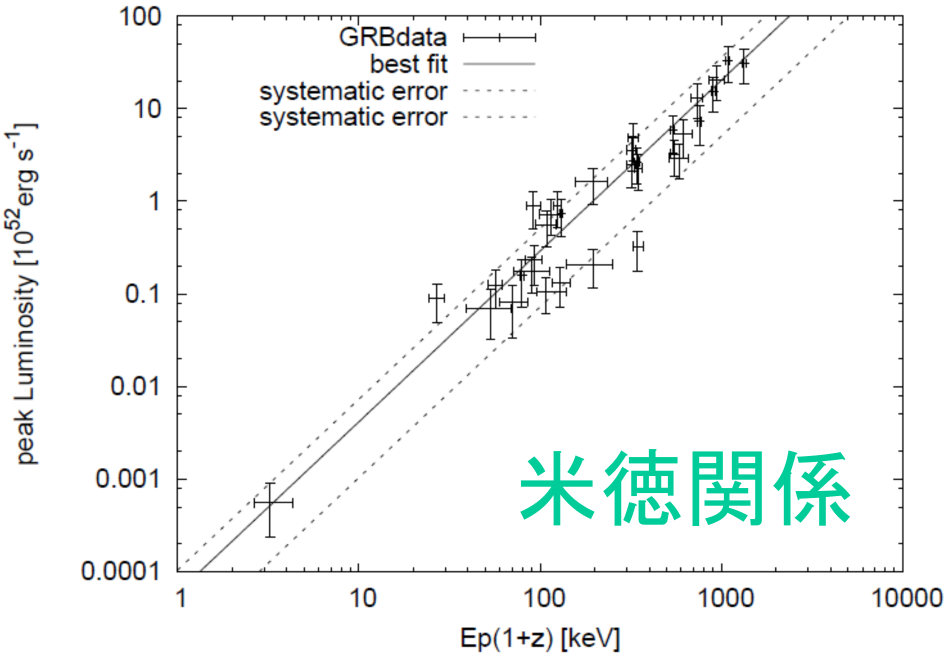


Yonetoku et al.(03)

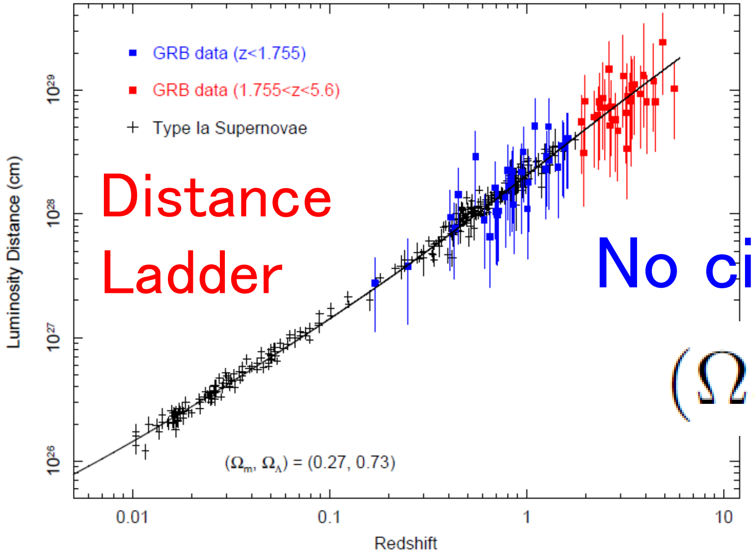
z>10 GRBs have been detected

SFR continues to increase until z～10

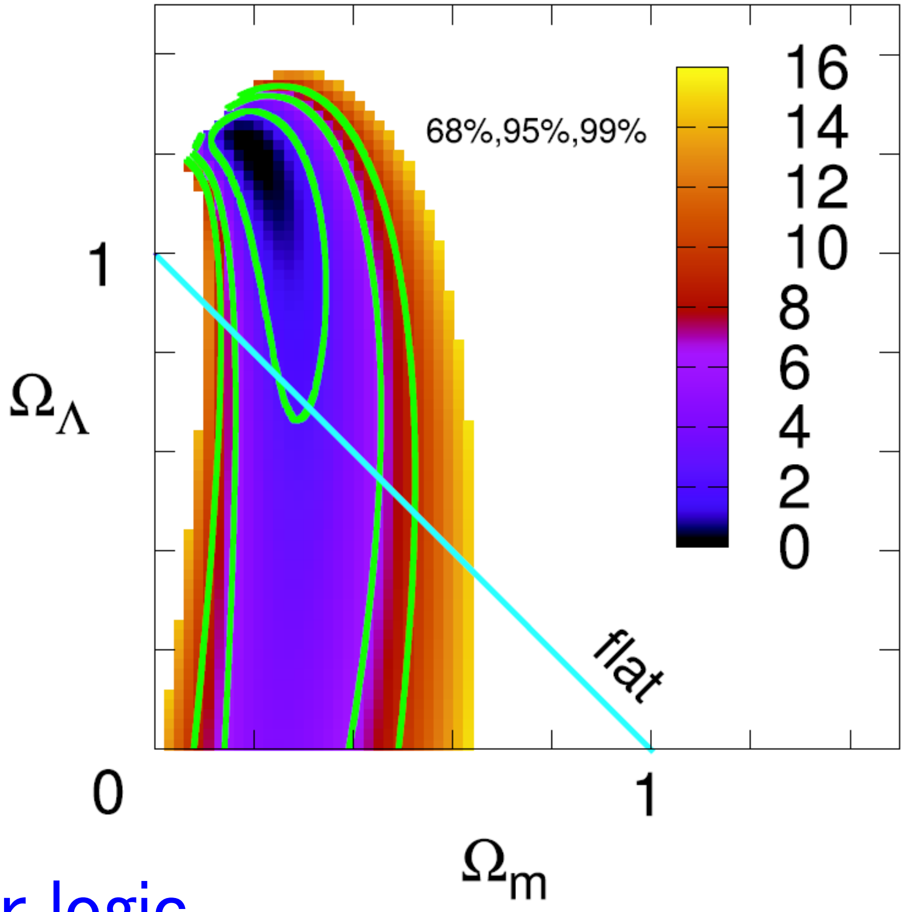
Dark Energy



米徳関係



Distance Ladder

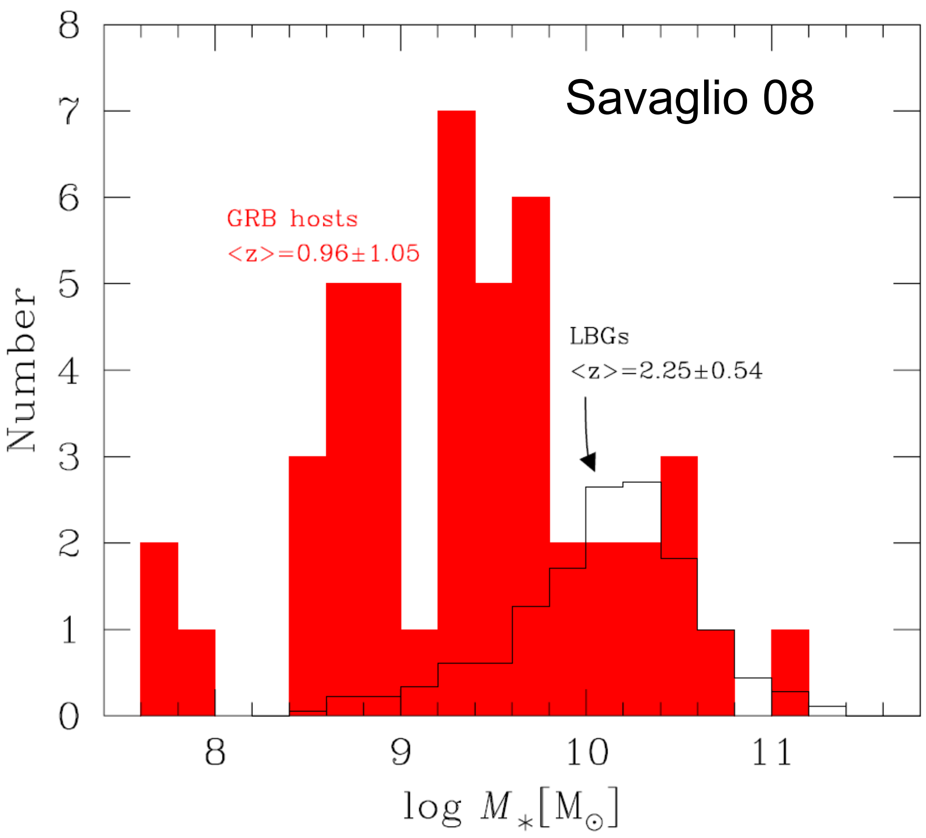


No circular logic

$$(\Omega_m, \Omega_\Lambda) = (0.26^{+0.05}_{-0.01}, 0.74^{+0.01}_{-0.05})$$

Kodama+08, Liang+ 08, Tsutsui+ 08

GRB Host



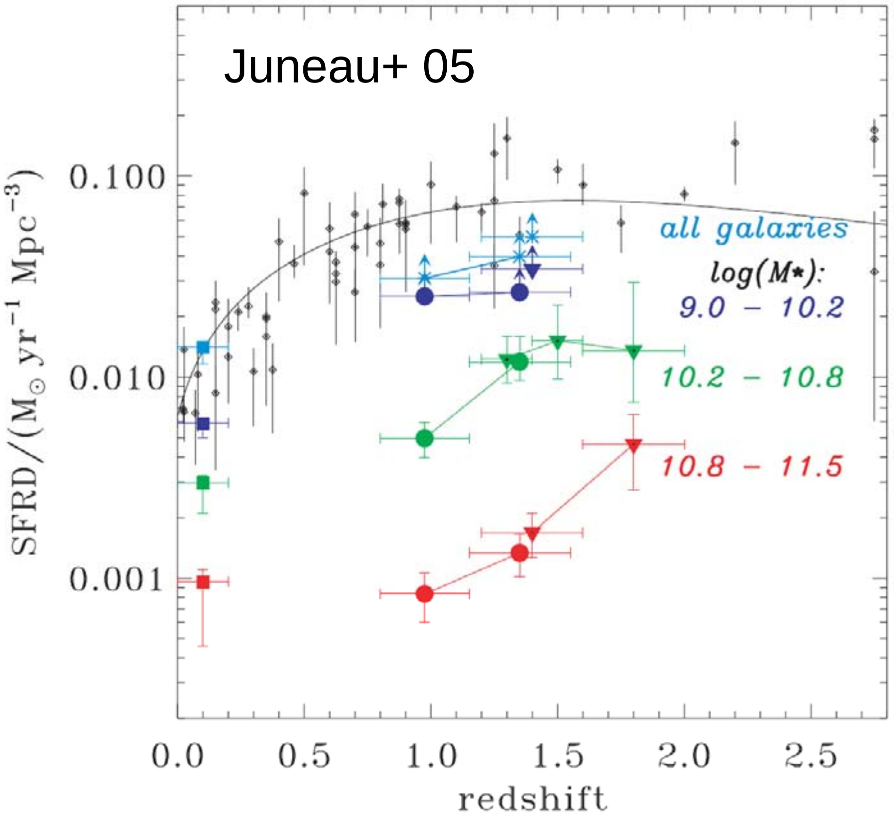
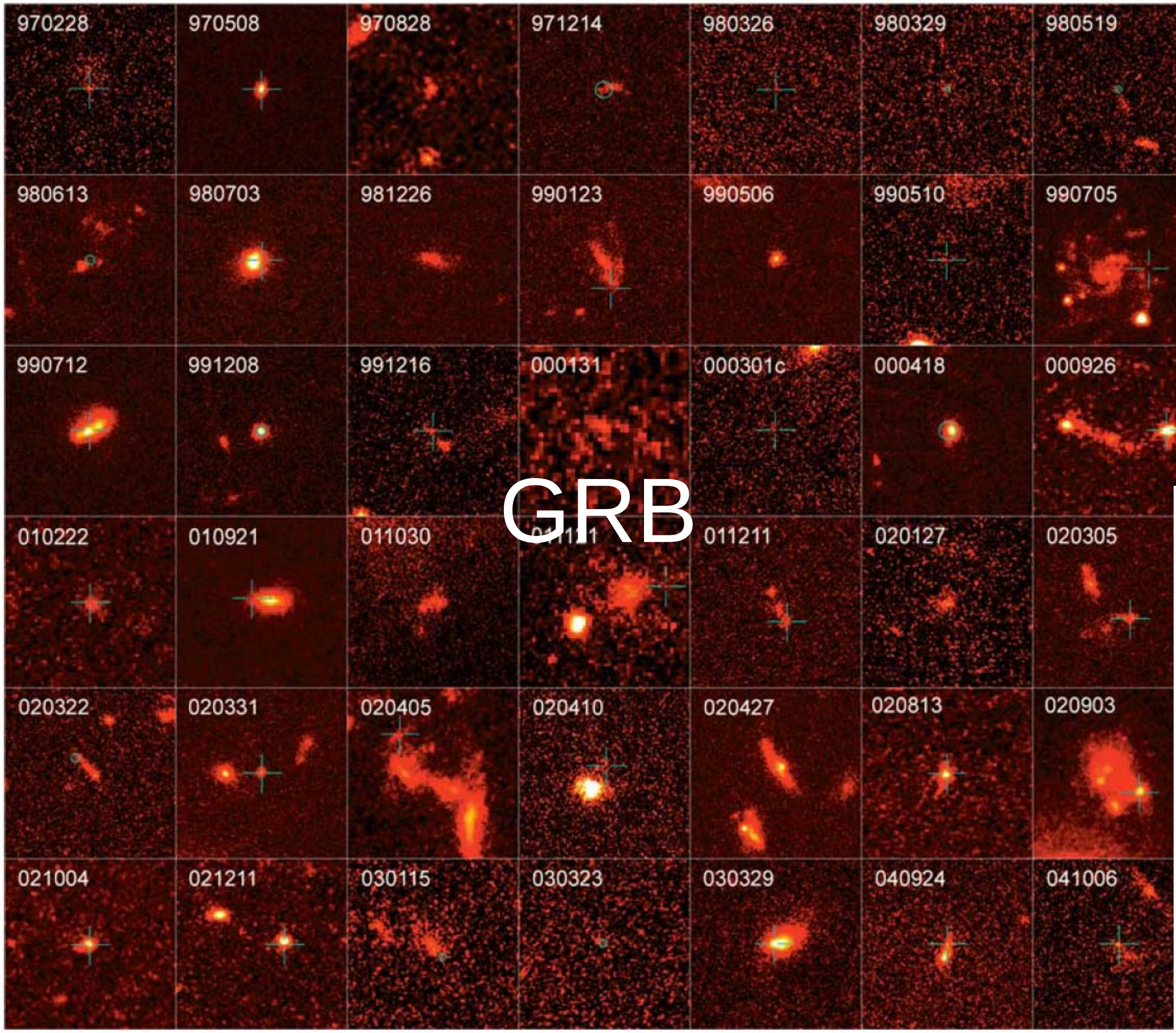


FIG. 2.—SFRD derived from L([O II]) (*circles*) and from L(2000 Å) (*triangles*). The symbols are color-coded with the mass ranges as in Fig. 1. The error bars in redshift show the width of the redshift bins used. The error bars in the SFRD combine shot noise and mass-completeness corrections. Both the sampling and the spectroscopic completeness corrections were applied. The squares are the values found locally by Brinchmann et al. (2004) converted according to our assumed IMF and dust correction. The compilation made by Hopkins (2004), where all the values are converted to a ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$) cosmology, are overplotted with diamonds. The solid line is the fit derived by Cole et al. (2001) assuming $A_V = 0.6$.

GRBの母銀河～LMC

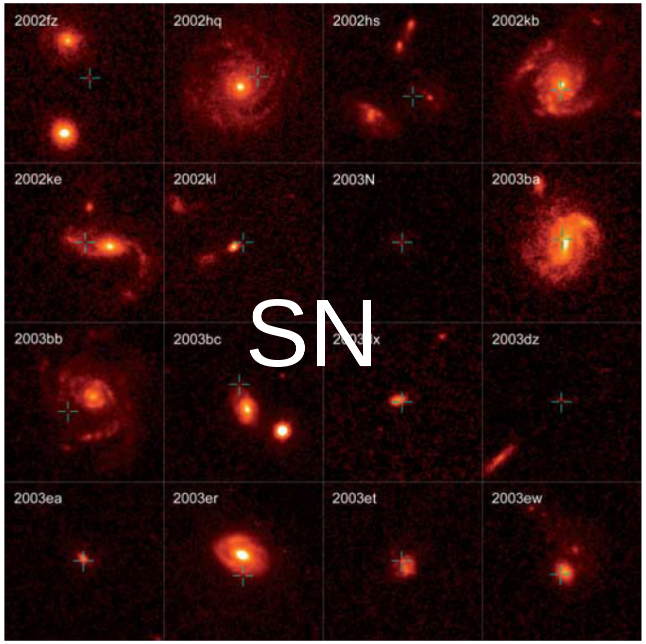
~Star formationを担う銀河

Host galaxy

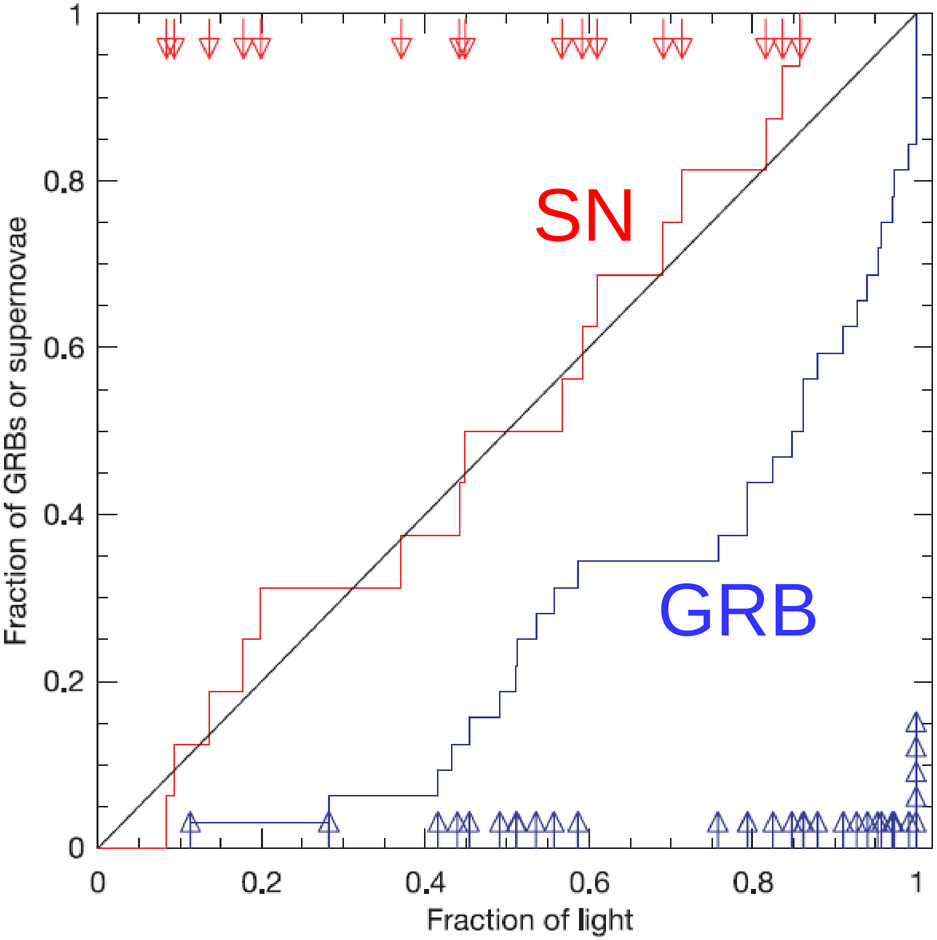


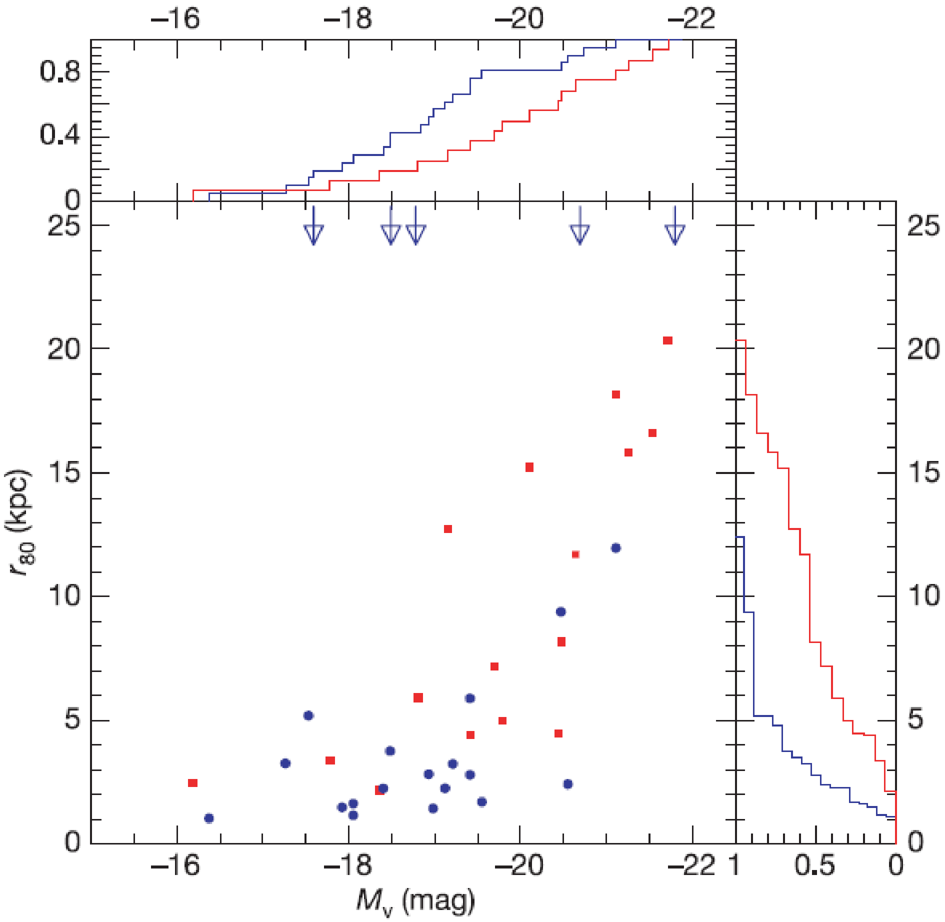
Fruchter+(06)

star forming
blue
faint
small
irregular
low metallicity



GRB≠SN

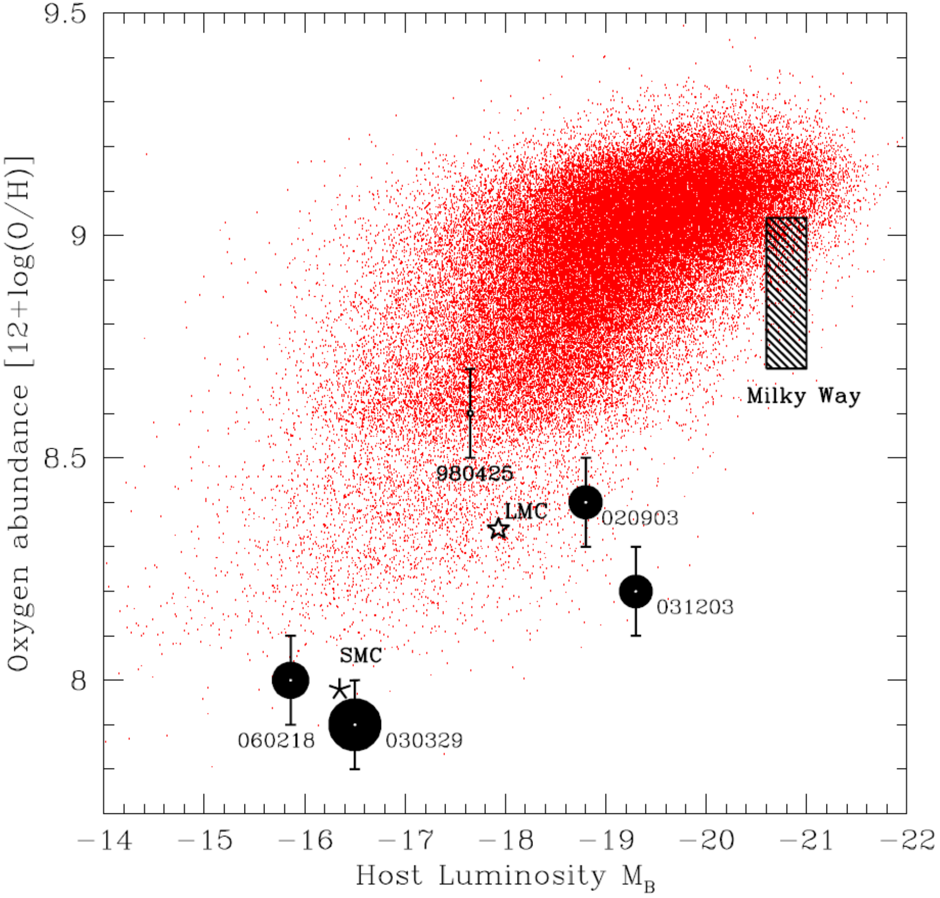


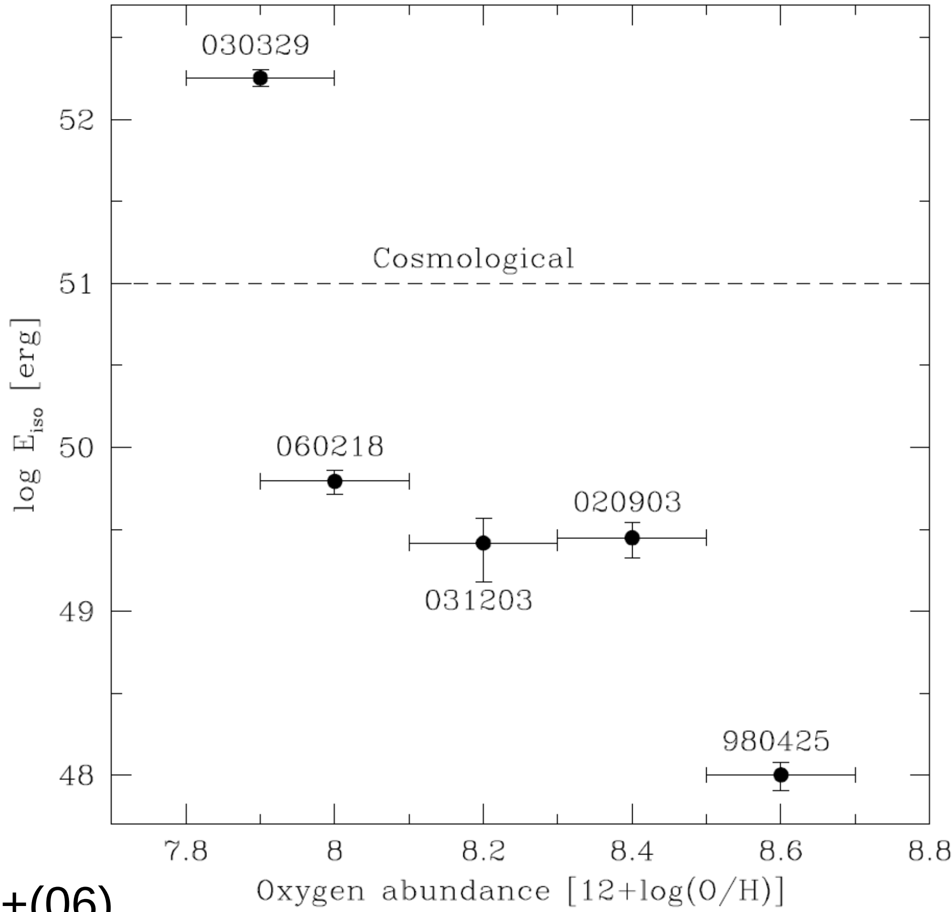


GRBは銀河のより明るい所で
⇒より重い星(O stars)

GRB Hostは小さく暗い
⇒低金属?

Low metallicity





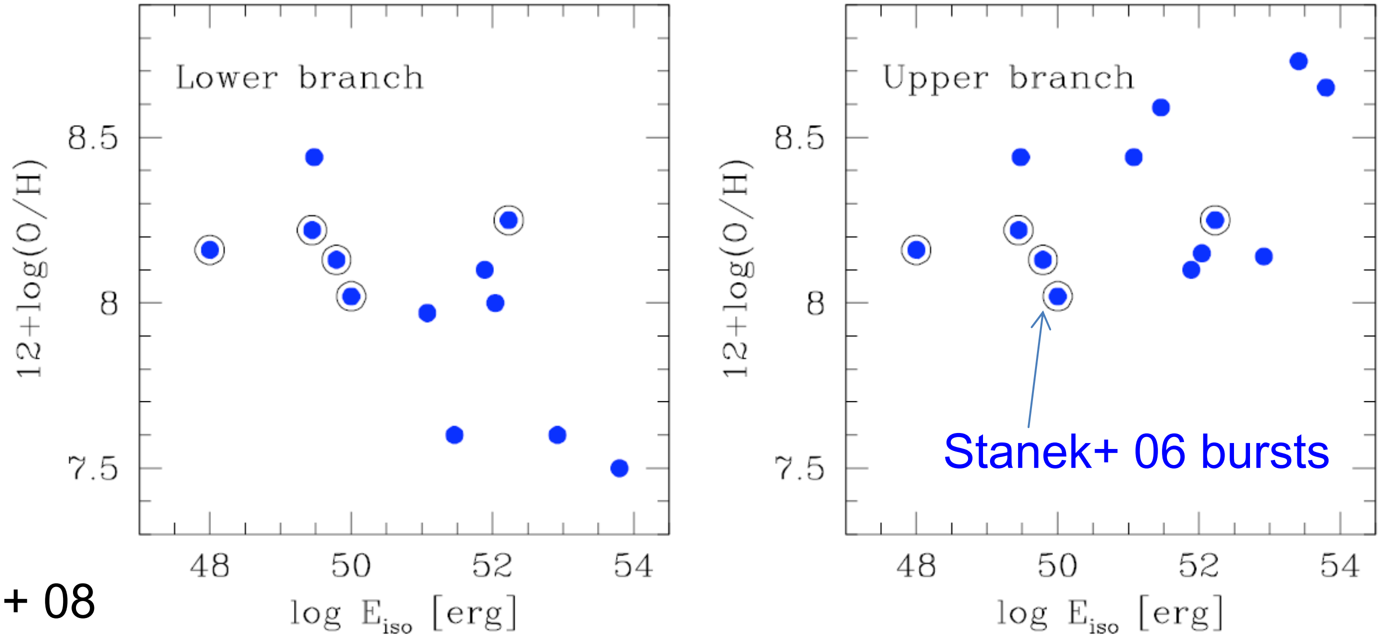
Stanek+(06)

Low metallicity

(⇒small, faint & irregular)

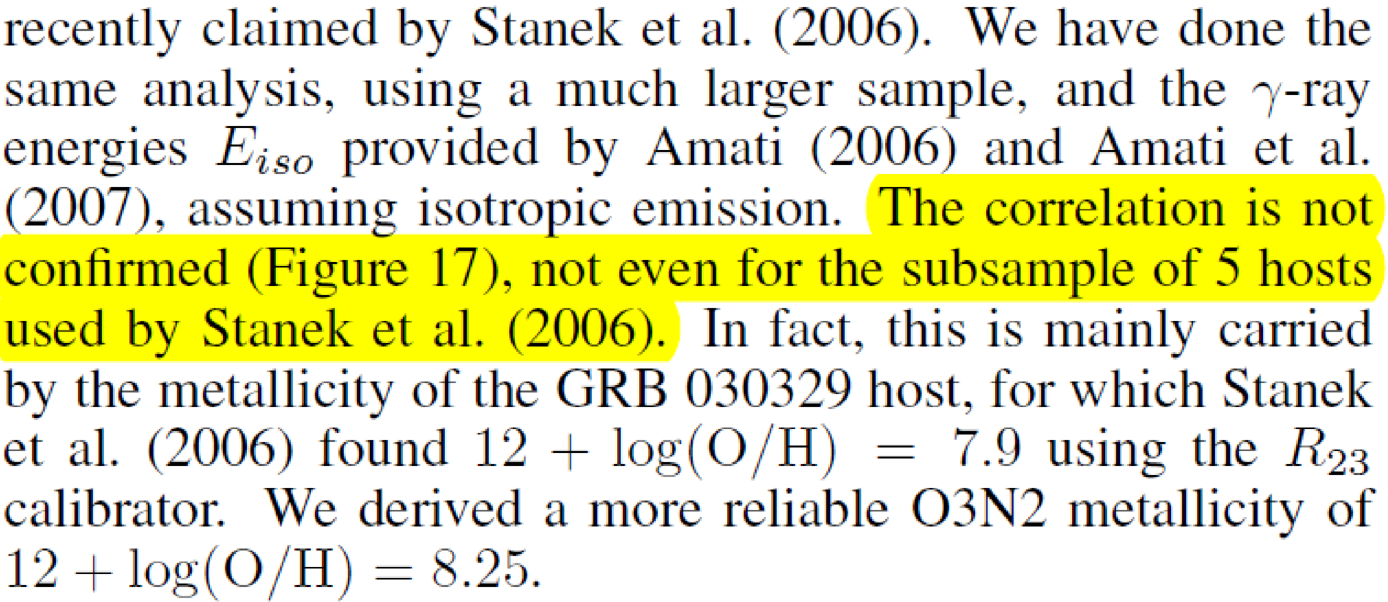
$Z_{crit} \sim 0.15 Z_{\odot}$?

We are safe



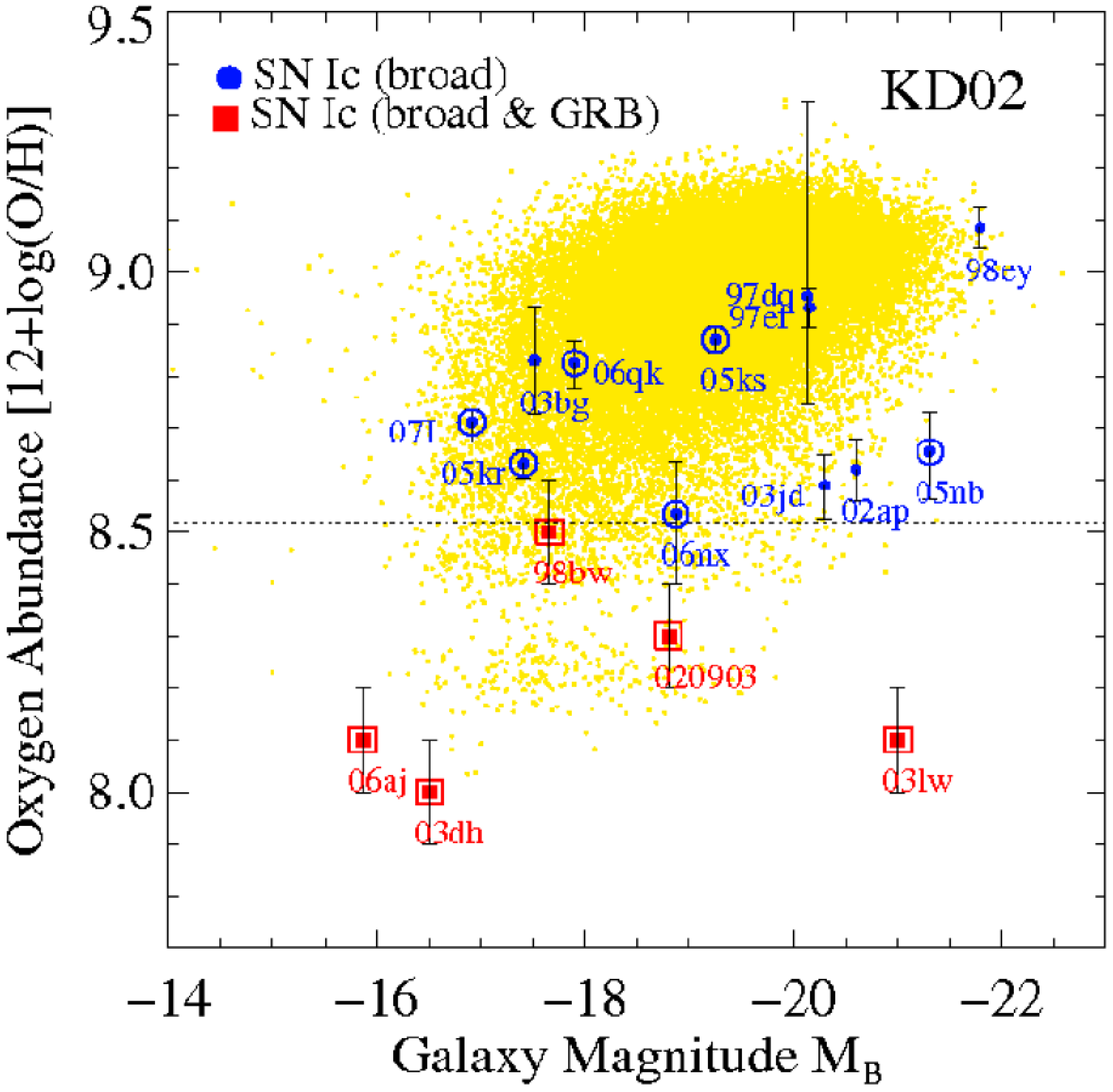
Savaglio+ 08

FIG. 17.— Metallicity as a function of the isotropic emission in γ-rays E_{iso}, for 12 GRBs. In the left and the right panels, the lower and upper branch solutions for metallicity in a GRB-host subsample is shown, respectively. GRB energies are taken from Amati (2006) and Amati et al. (2007). Circled GRBs are those used by Stanek et al. (2006) to identify a possible correlation between the two parameters. This was mainly due to the low metallicity used by Stanek et al. (2006) for the most-right circled point, which is GRB 030329.



recently claimed by Stanek et al. (2006). We have done the same analysis, using a much larger sample, and the γ-ray energies E_{iso} provided by Amati (2006) and Amati et al. (2007), assuming isotropic emission. The correlation is not confirmed (Figure 17), not even for the subsample of 5 hosts used by Stanek et al. (2006). In fact, this is mainly carried by the metallicity of the GRB 030329 host, for which Stanek et al. (2006) found $12 + \log(O/H) = 7.9$ using the R_{23} calibrator. We derived a more reliable O3N2 metallicity of $12 + \log(O/H) = 8.25$.

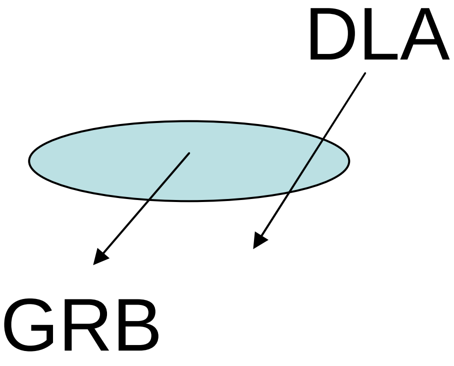
We are not safe!?

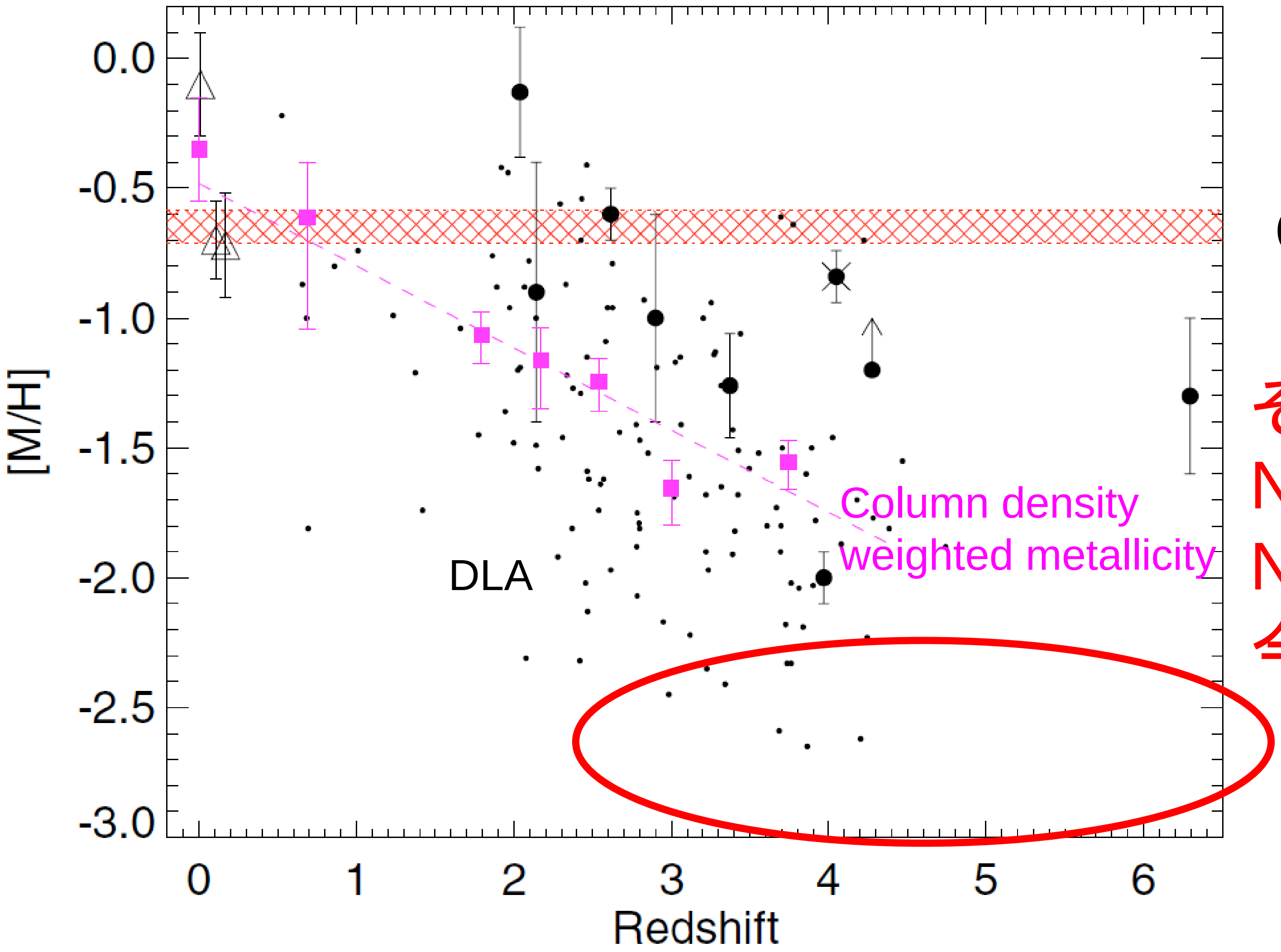


SN Ic (broad)
SN Ic (broad & GRB)
KD02
Oxygen Abundance [12+log(O/H)]
Galaxy Magnitude M_B
9.5
9.0
8.5
8.0
−14
−16
−18
−20
−22
98ey
97dq
97ef
05ks
06qk
03bg
07I
05kr
03jd
02ap
05nb
06nx
98bw
020903
06aj
03dh
03lw

Modjaz+(07)

Metallicity-Redshift





それとも本当に
No metalでは
No GRBか？
今後のテーマ

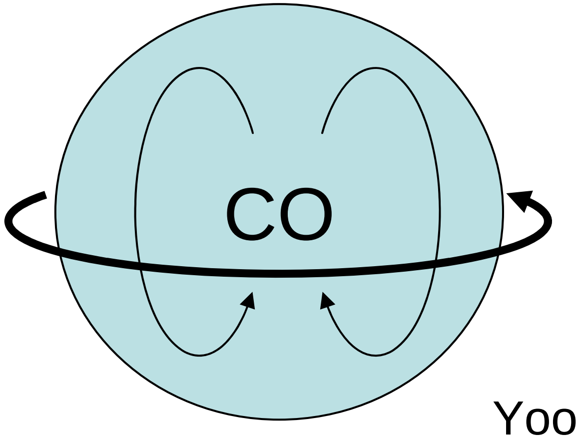
Fynbo+(06)

角運動量と親星

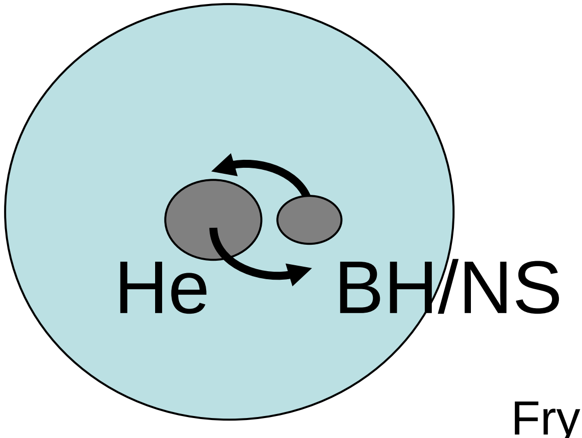
SN Ic ⇒ H, He外層がない

外層を星風で飛ばすと回転が落ちる

しかし回転はジェット生成に必要（だろう）



Yoon+ 06



Fryer 02

低金属⇒星風少

高速回転⇒子午面対流

により全体がCOコアに

連星⇒伴星が外層を

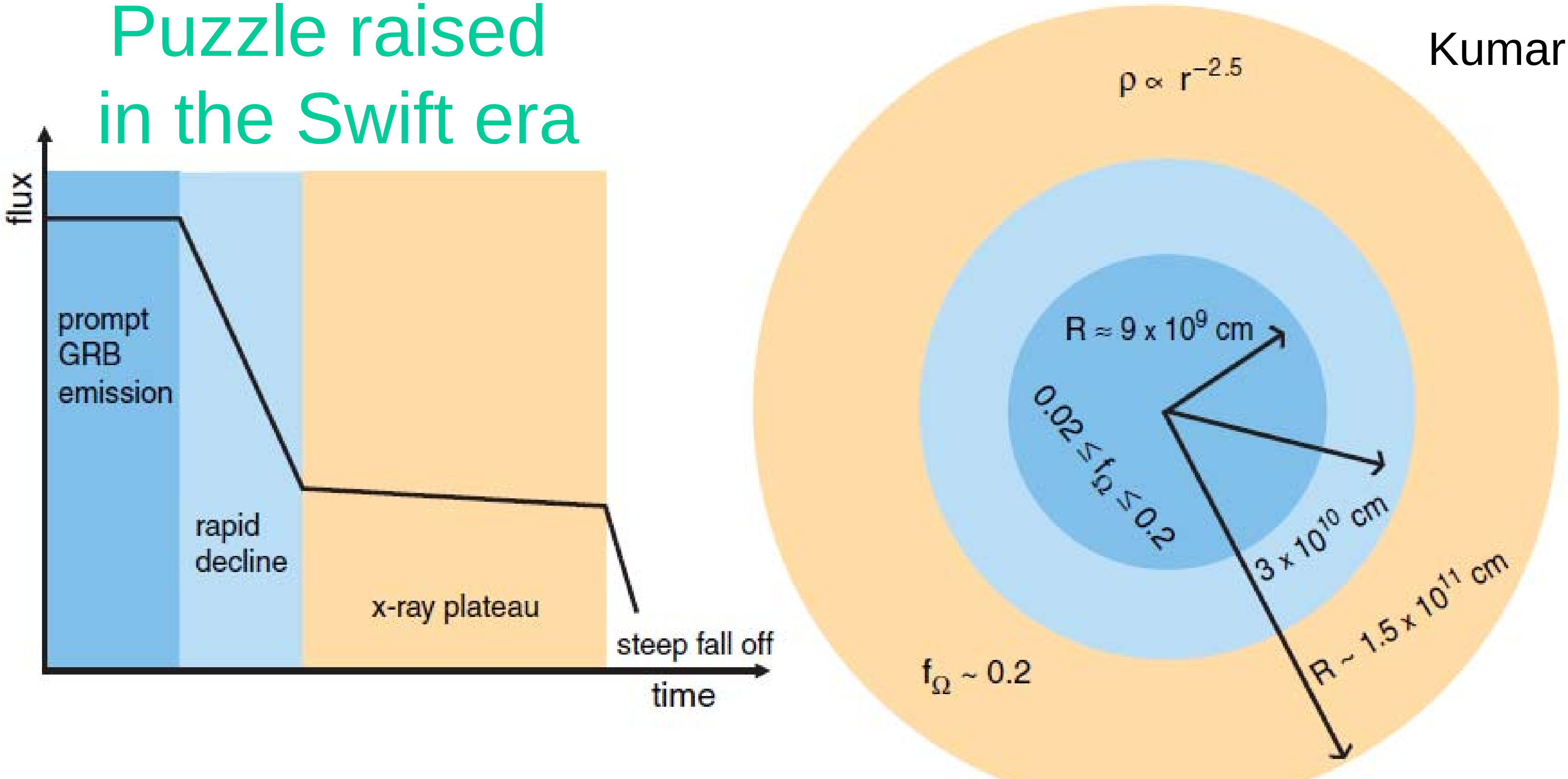
はがし，合体時に

角運動量を与える

外層とX-ray Afterglow

Puzzle raised
in the Swift era

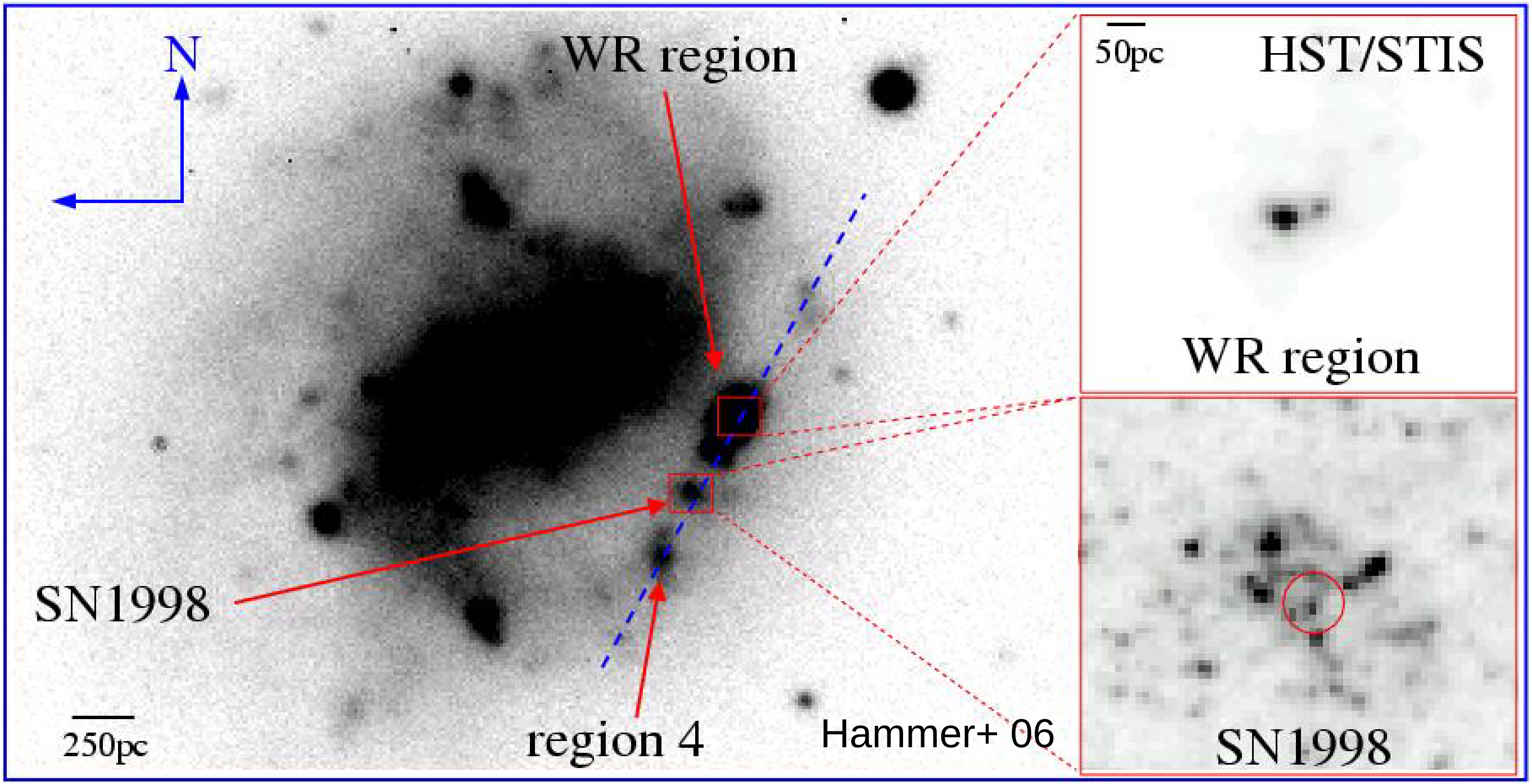
Kumar+ 08



外層の構造⇒Puzzling X-ray Afterglow?

Figure 2: The panel on the left shows a schematic x-ray lightcurve with the following four segments: a prompt emission phase, a steep decline phase, a plateau phase, and a post-plateau phase. For the three GRBs considered in this work, the last phase has a steep and sudden decline. The panel on the right outlines our proposal for how the different segments in the LC are related to the accretion of corresponding zones in the progenitor star. The radii (r) and spin parameters ($f_\Omega \equiv \Omega/\Omega_k$) of the various zones are estimated from the x-ray data.

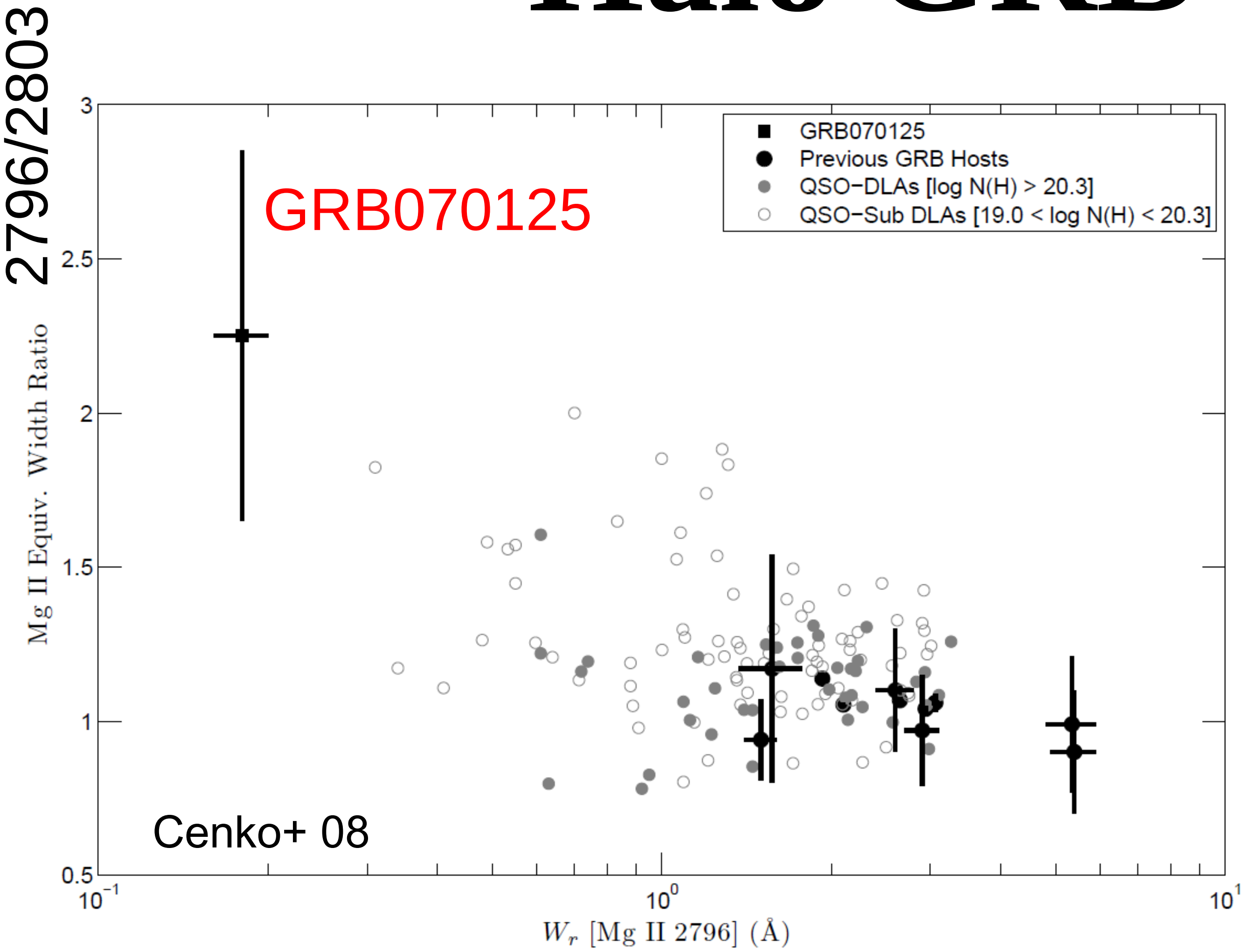
Runaway massive star?



Hammer+ 06

GRBは大質量星団から~400-800pc離れたところ
⇒ ~100km/sで飛び出た?

Halo GRB



Equivalent width

GRB070125
Low Mg II and
inferred HI is
in typical halos

Offset d>27kpc

In a compact
star-forming
cluster?

GRB071003
(Perley+ 08)

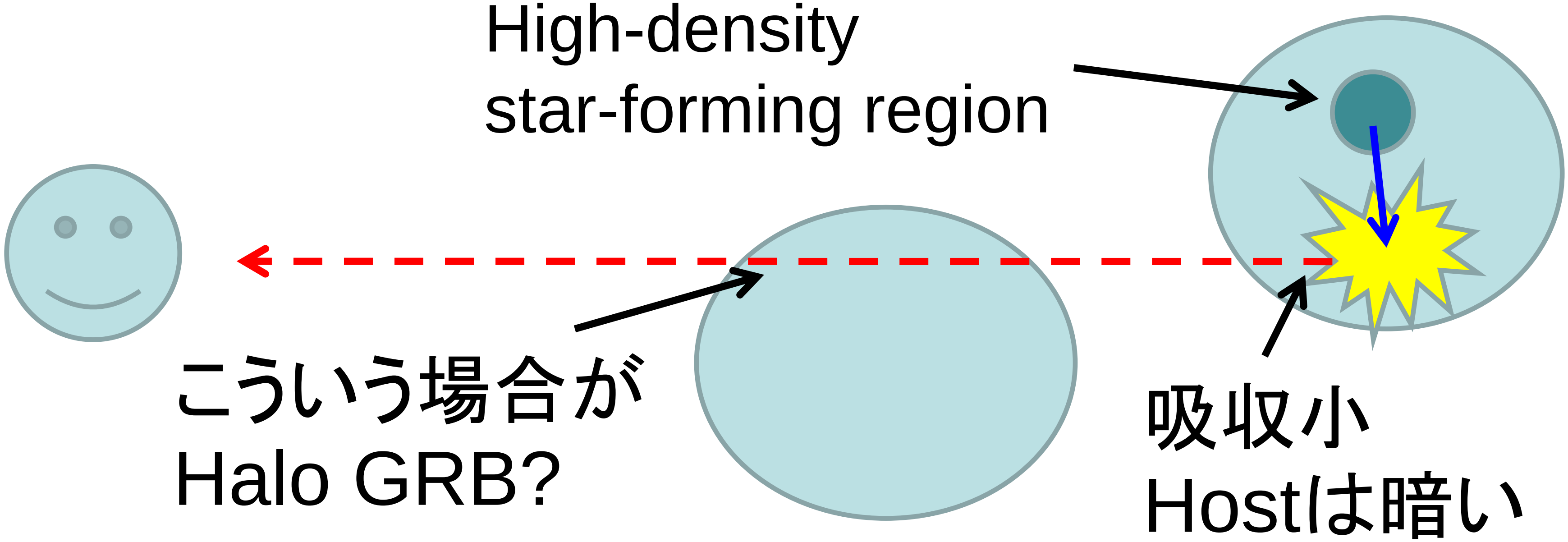
Zero-metal host

そもそもZero-metal hostは観測できるのか？

金属-質量関係 ⇒ ホストはlow mass

⇒ 吸収小、しかも暗い

z~a fewでもfollow upできない?



Zero-metal host

High-density
star-forming region

こういう場合が
Halo GRB?

吸収小
Hostは暗い

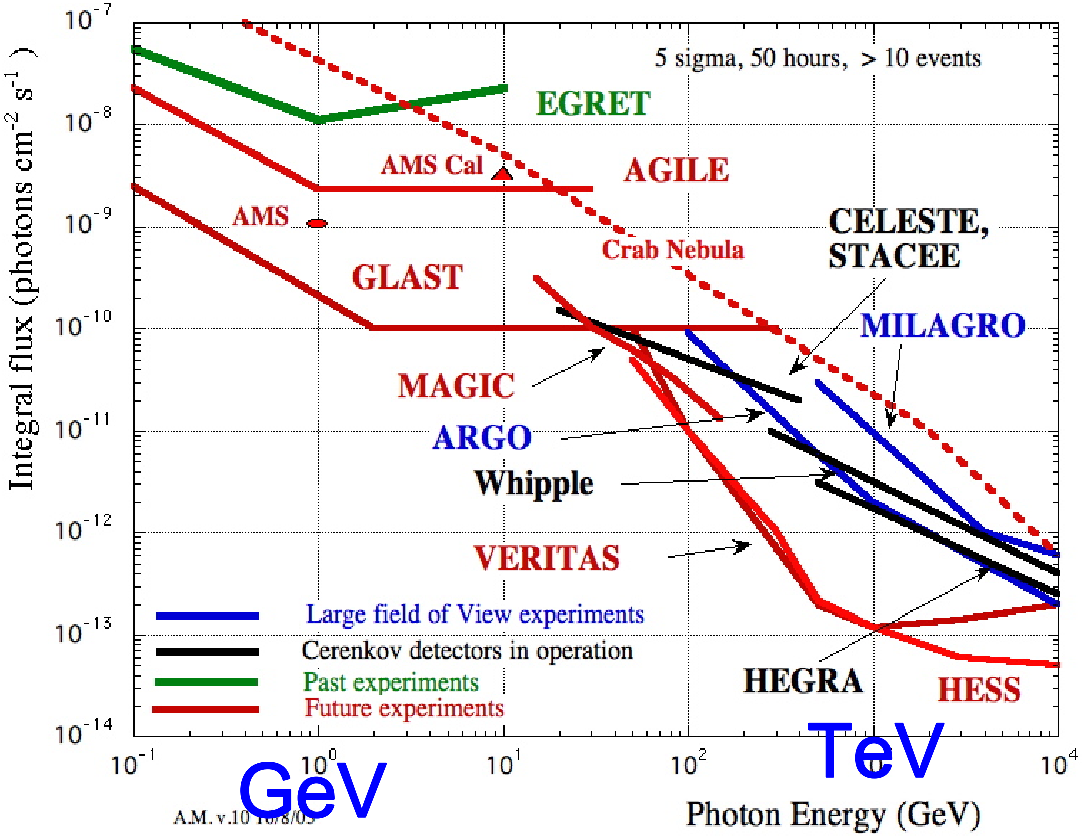
Zero-metal hostがLAEだった場合も気になる

GLAST has launched!

11 Jun 2008

GBM: 0.008-30MeV, 8sr, 1°res

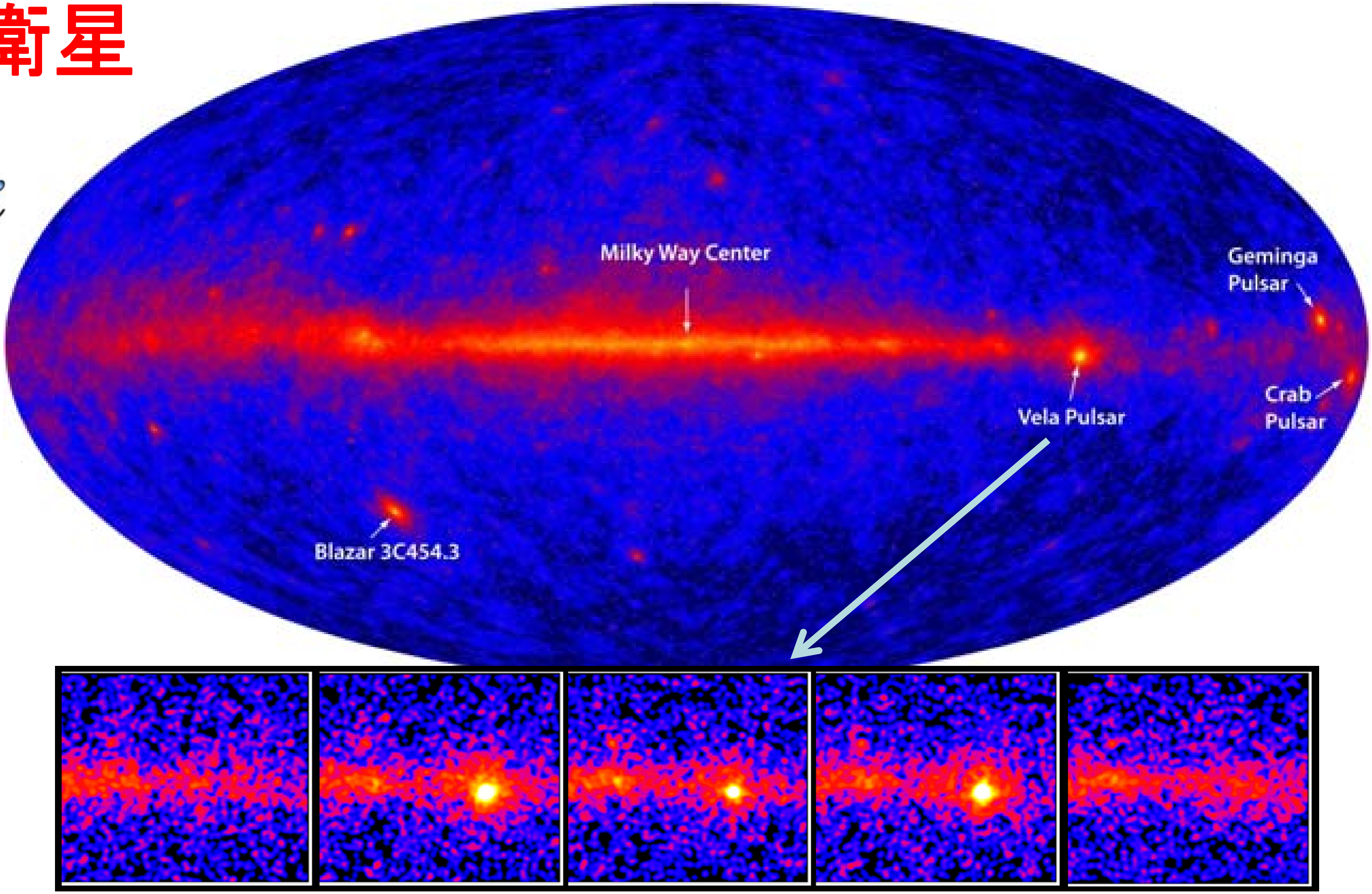
LAT: 0.02-300GeV, 2.5sr, 5°-5’res



LAT First All-Sky Map

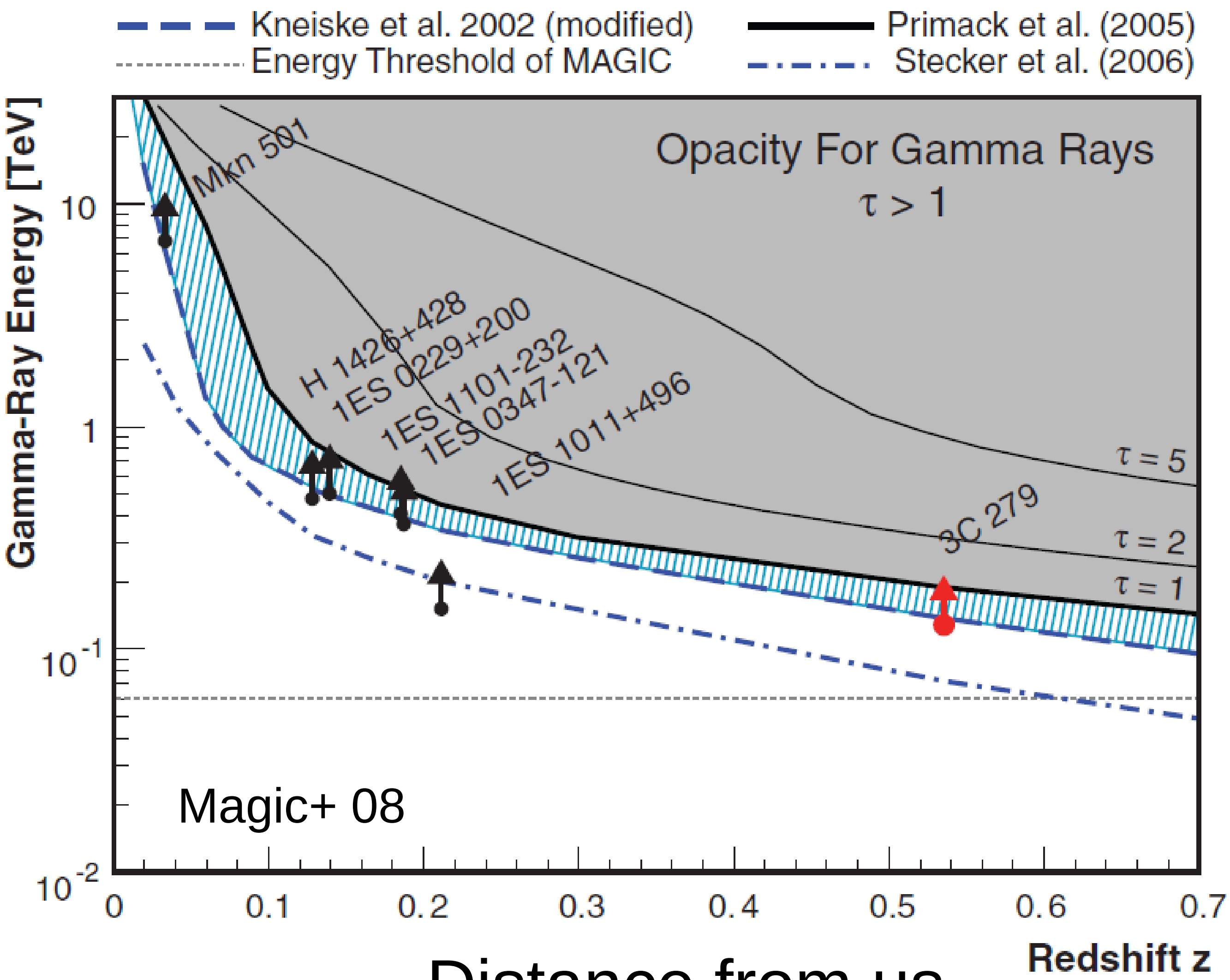
Fermi衛星

Fermi
Gamma-ray
Space Telescope



たった４日でEGRET１年分！

IR Background γ



Magic+ 08

Distance from us

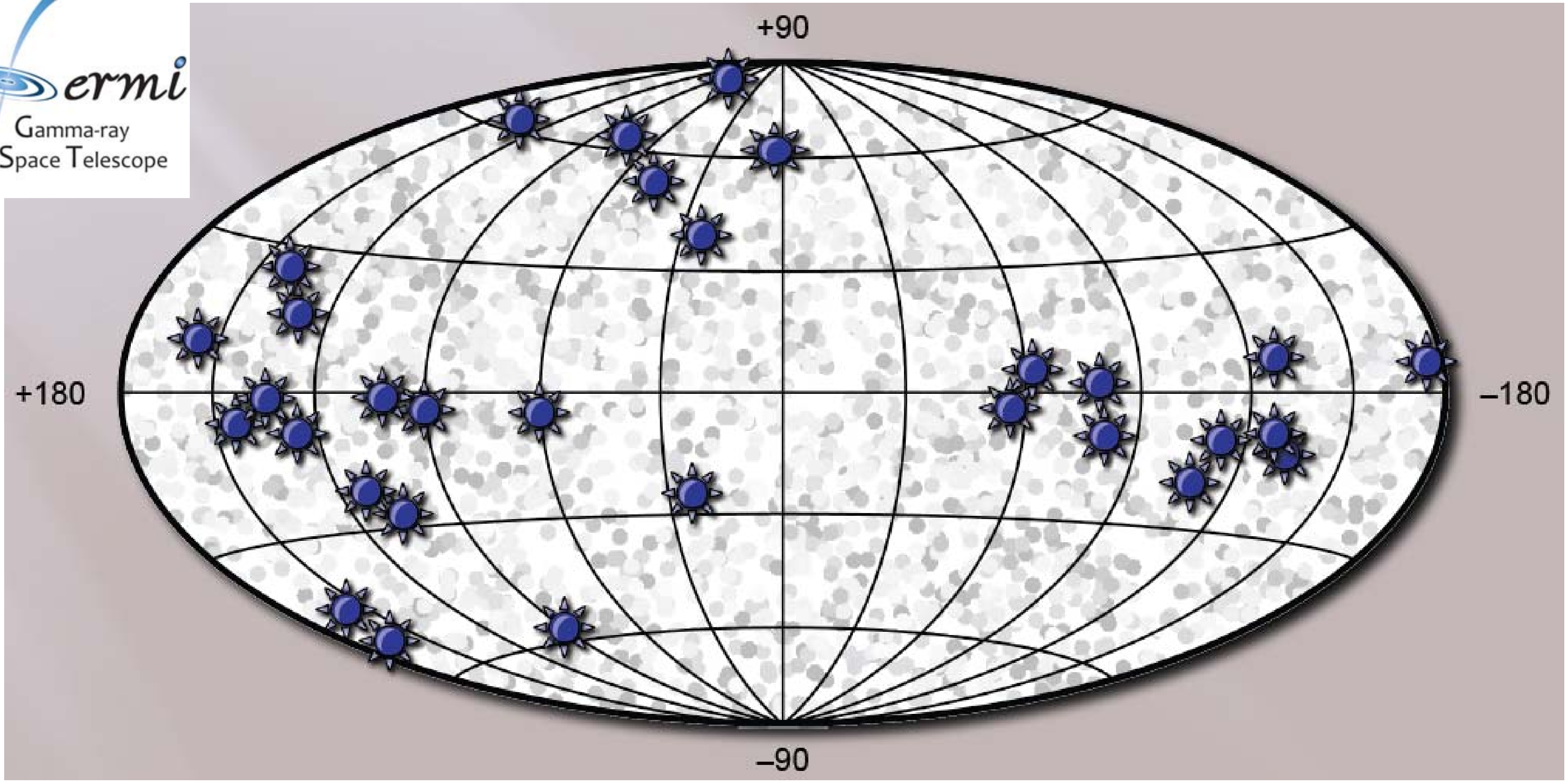
GRB γ-ray

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

Infra Red Background γ

Can measure the amount of IR bg γ up to cosmological distance

GBM First GRBs



31 GRBs per 1st month (⇒ 372/yr)

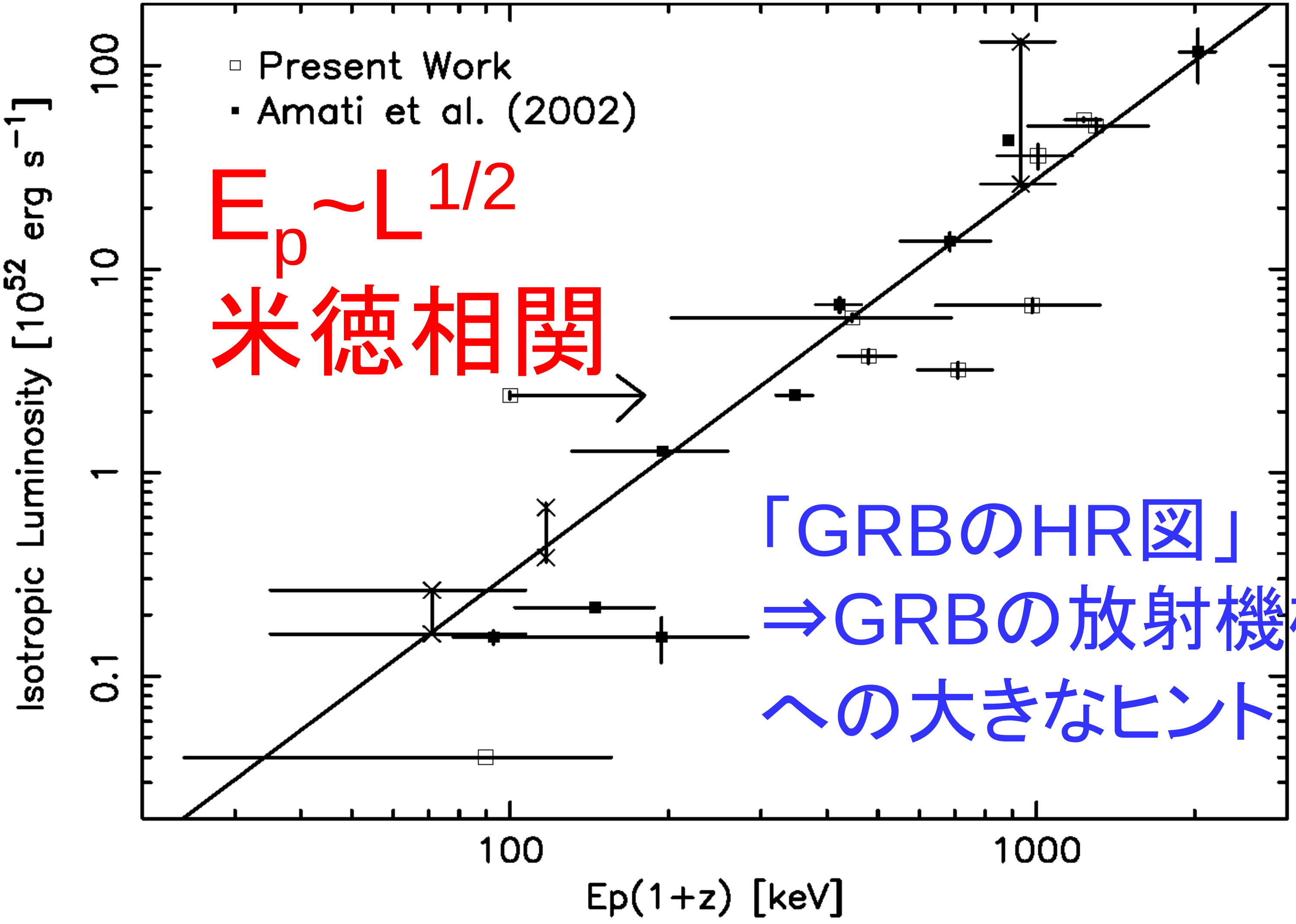
Sensitivity as predicted (若干多い？)

Within a few degrees of Swift calculations

E_{peak}-L_{iso} Correlation

Typical GRB photon energy

Yonetoku+KI(03)



$E_p \sim L^{1/2}$

米徳相関

「GRBのHR図」
⇒GRBの放射機構
への大きなヒント

GZK neutrino

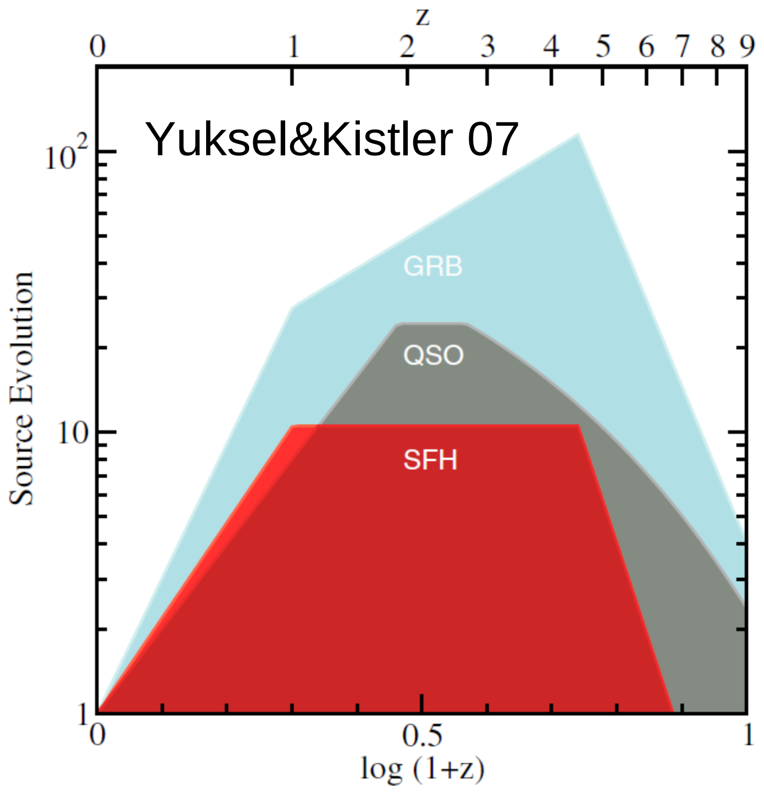


FIG. 1 (color online). Models of cosmic-ray source evolution (i.e. yield vs z, normalized to 1 at $z = 0$). From top-to-bottom, the metallicity-dependent GRB rate density (this work), the quasar (QSO) evolution model used in Refs. [11,55], and the fit to the cosmic star formation history (SFH) of Ref. [19]. Models similar to the latter two have been frequently used in cosmic-ray studies.

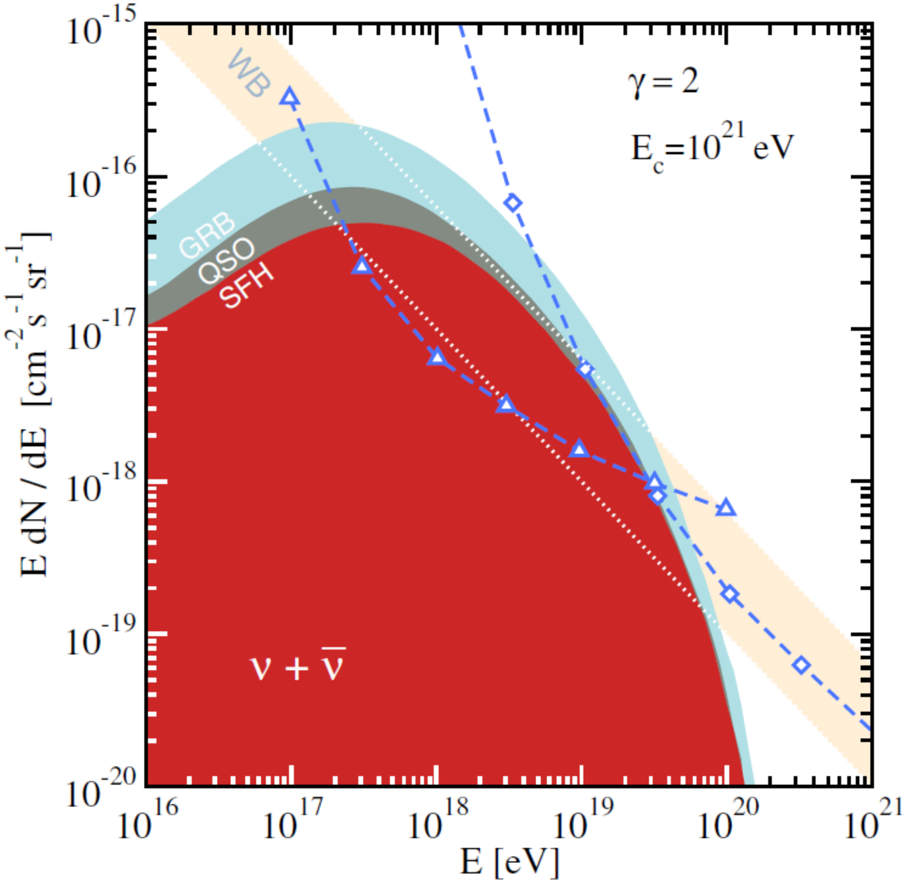


FIG. 4 (color online). Expected (all-flavor) cosmogenic neutrino fluxes assuming various evolution scenarios. From top-to-bottom, are the fluxes resulting from the strongly evolving (metallicity-dependent) GRB rate density, QSO-like evolution, and the SFH. Shown for comparison are the Waxman-Bahcall bound (shaded band) and the expected sensitivities for ANITA (diamonds) and ARIANNA/SalSA (triangles).

ν flux depends on GRB rate

まとめ

Developments in the Swift era

- GRB 050904 @ z=6.3
- z-distribution ⇒ ~10%? @z>5
- Distance indicators
- Afterglow (Naked-eye GRB, Few optical flashes)
- Low metal host

GRB cosmology in the Fermi+Swift era

- Star formation rate
- Reionization
- Chemical evolution (atom, molecule, dust)
- Dark energy
- IR background
- Magnetic field (Faraday rotation, Pair echo), …