Gamma-Ray Bursts

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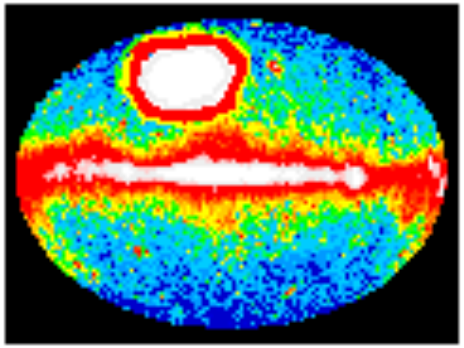
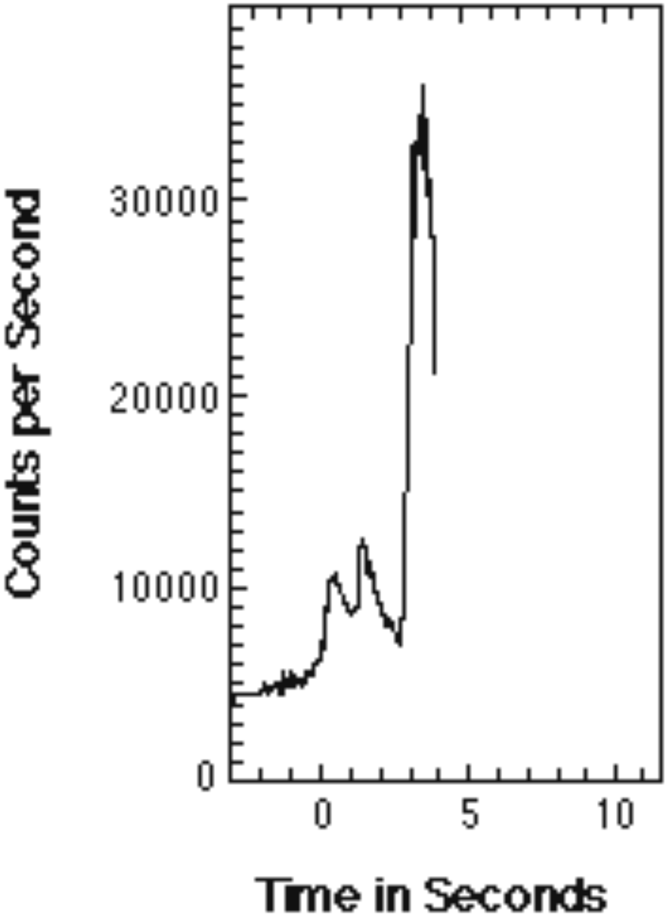
Séminaire du SPP – lundi 12 septembre 2016

GRBs: observations

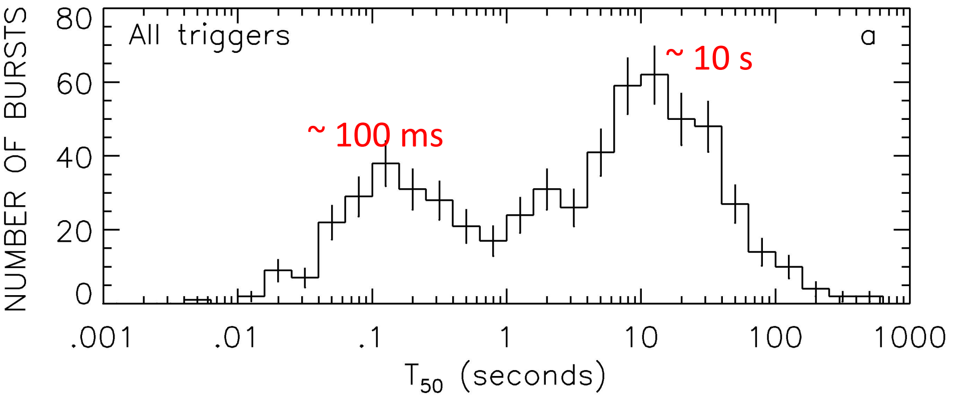




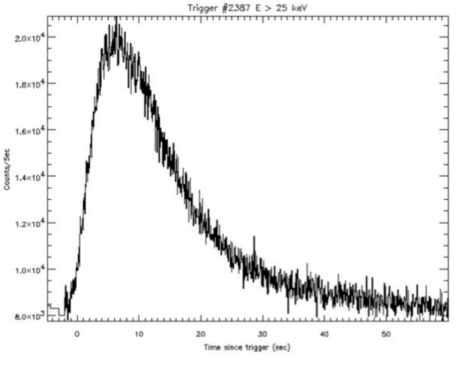
Gamma-ray bursts: prompt emission

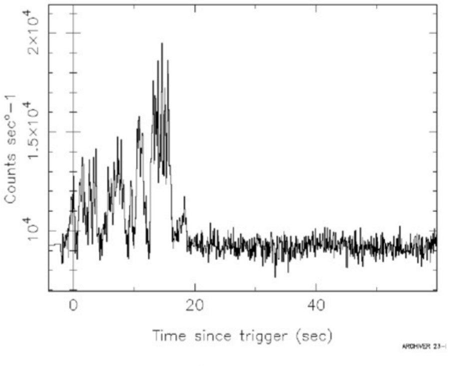
CGRO/BATSE

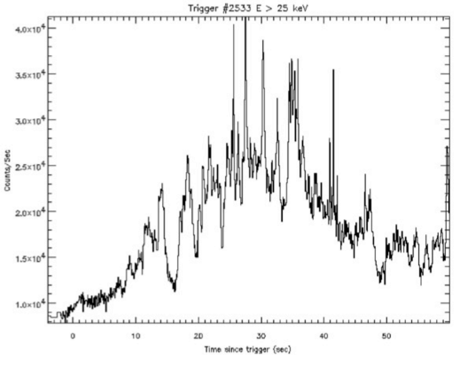
- Apparent rate:
  ~ 1 GRB / day
- Duration:
  two groups

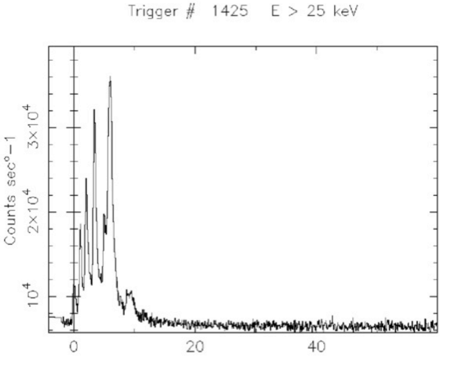


- Lightcurves :
  variability
  diversity



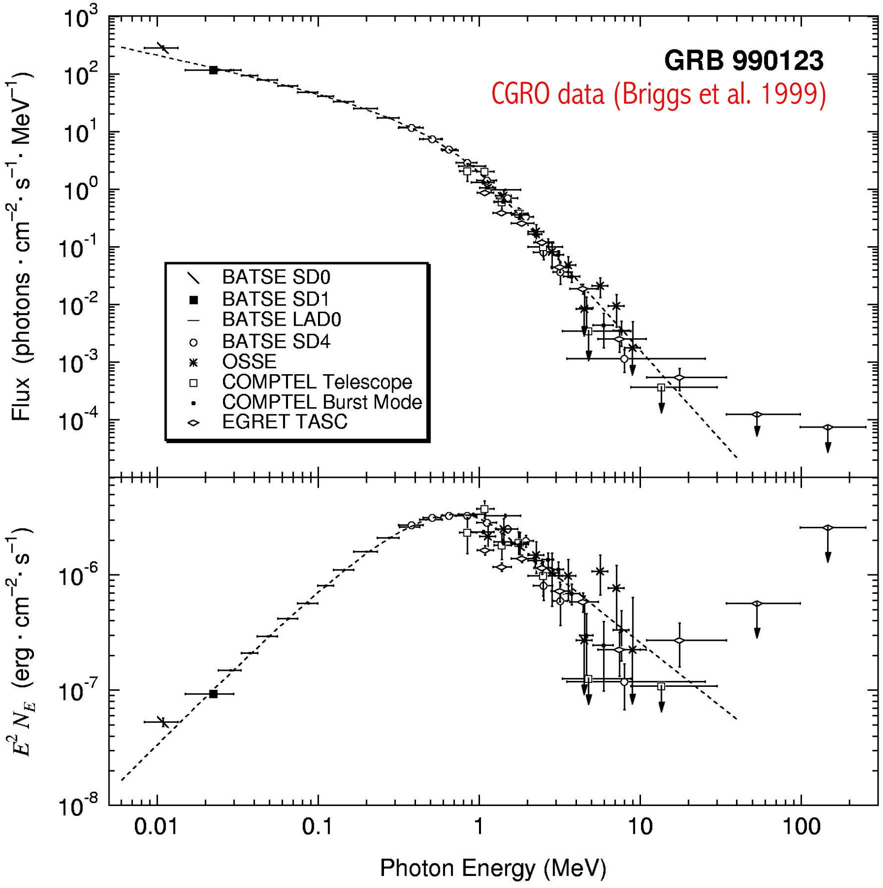






Gamma-ray bursts: prompt emission

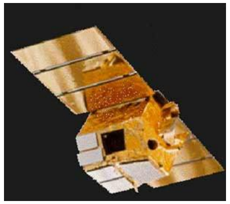
- Spectrum: non-thermal



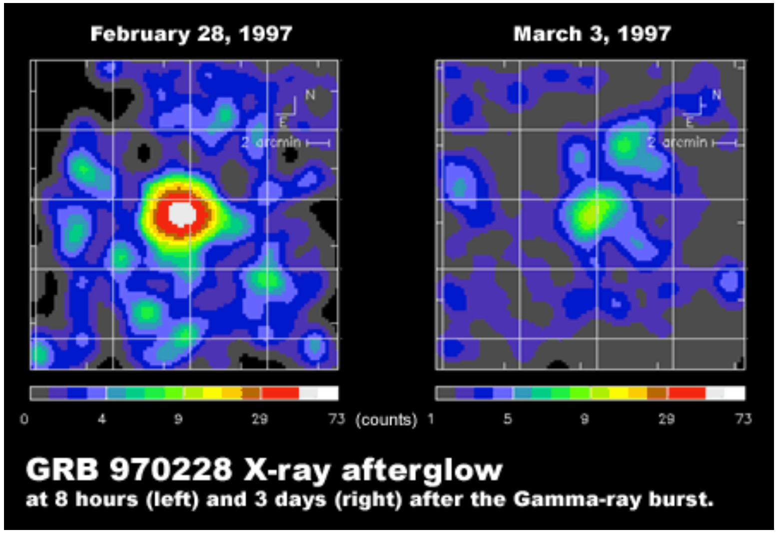
CGRO/BATSE

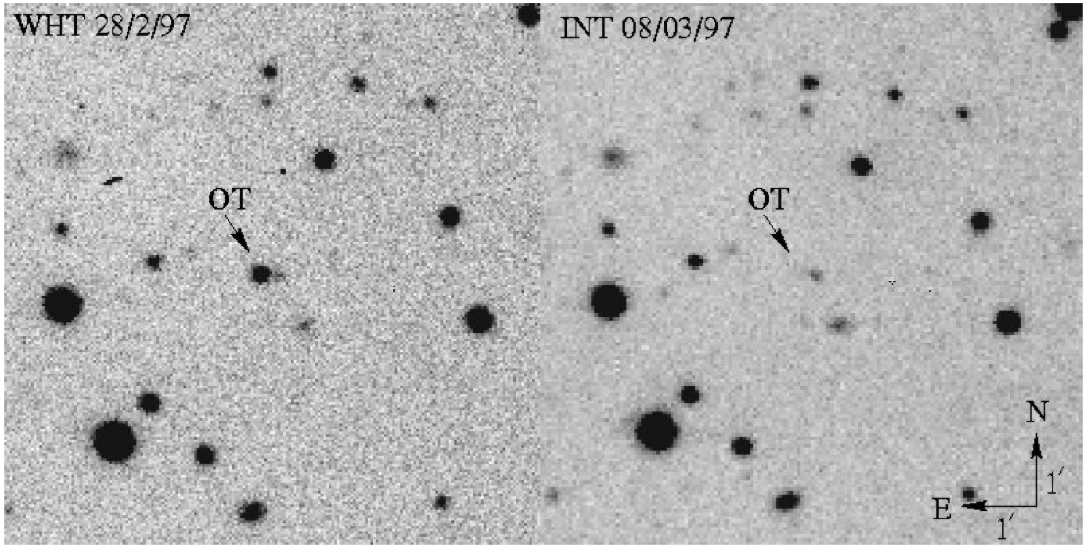
Gamma-ray bursts: afterglow

Beppo-SAX

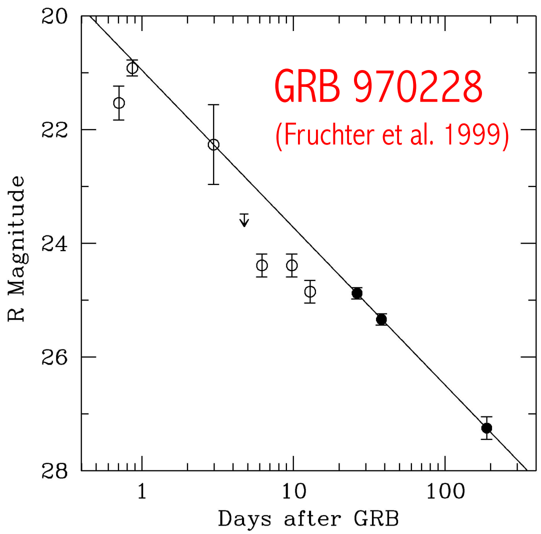


- Discovery: 1997 (X-rays: Beppo-SAX ; V: van Paradijs et al. 1997)





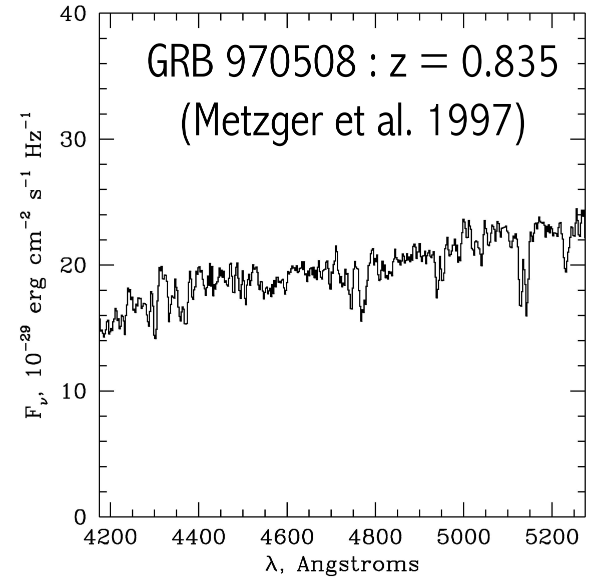
- Flux: power-law decay
- Non-thermal spectrum
- Spectral evolution: X-rays ⟶ V ⟶ radio

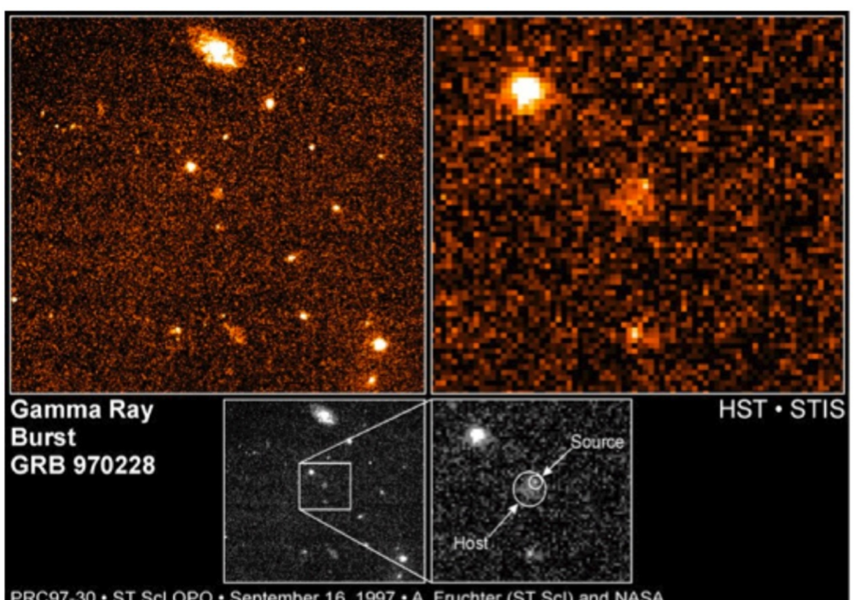


Gamma-ray bursts: afterglow

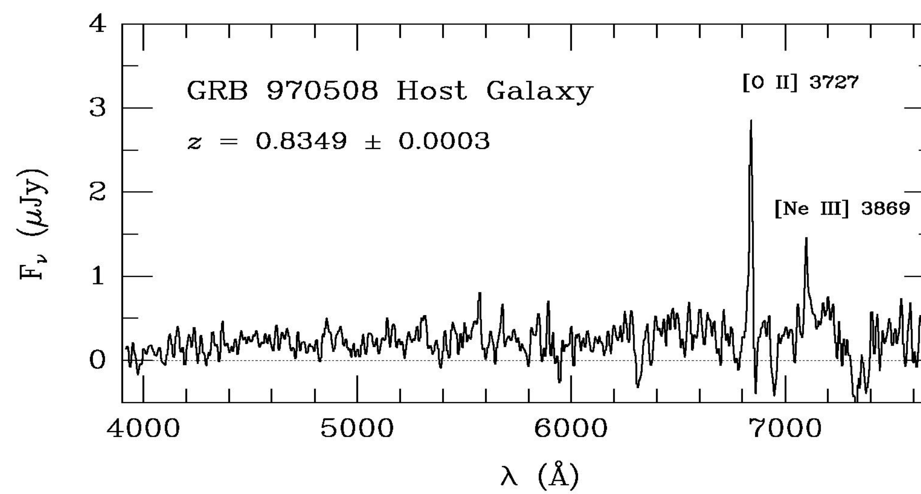
- Follow-up: redshift & host galaxy

- High redshift ($z_{max,obs} > 9$): huge luminosities!
  $E_{iso,\gamma} \sim 10^{51} - 10^{54}$ erg

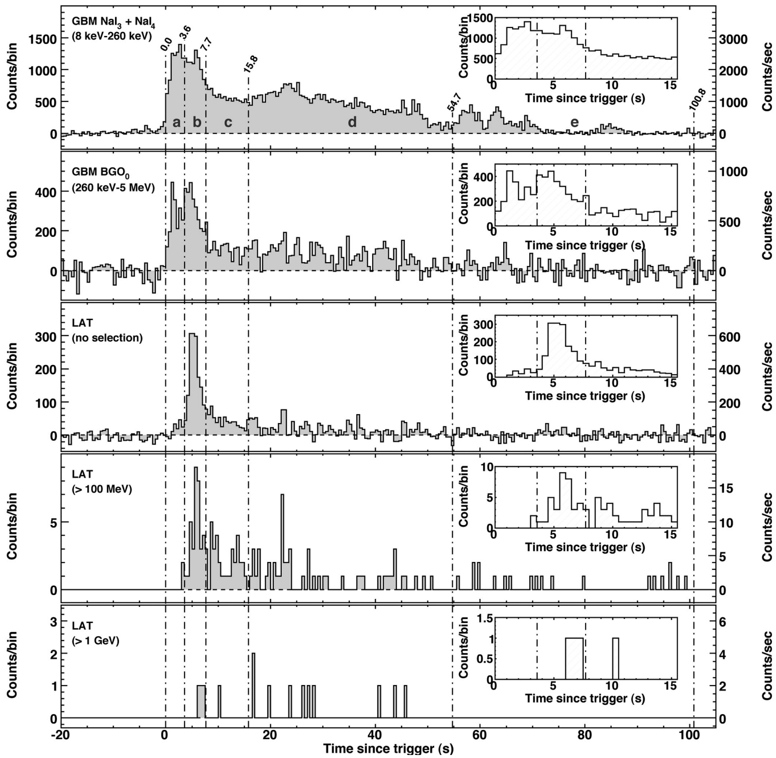




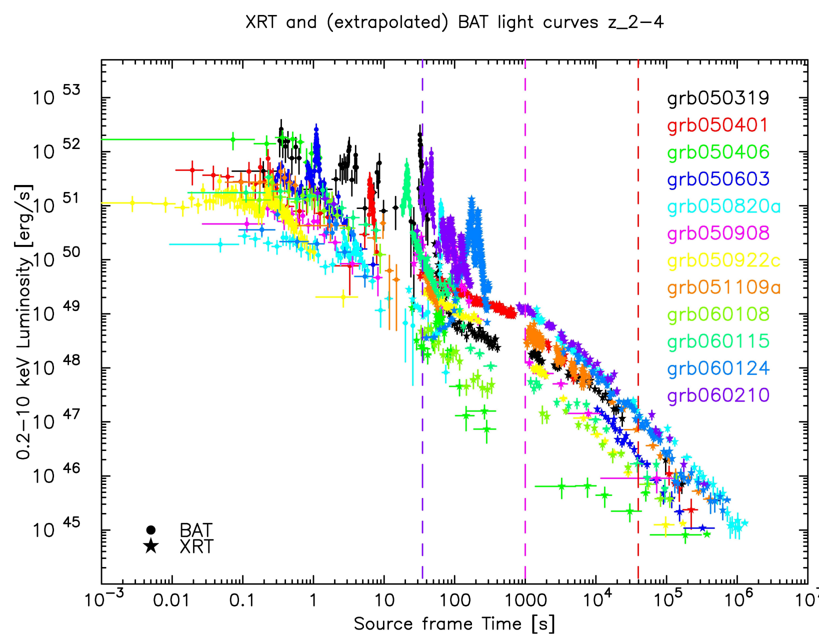
Fruchter et al. 1997



GRBs: Swift & Fermi observations

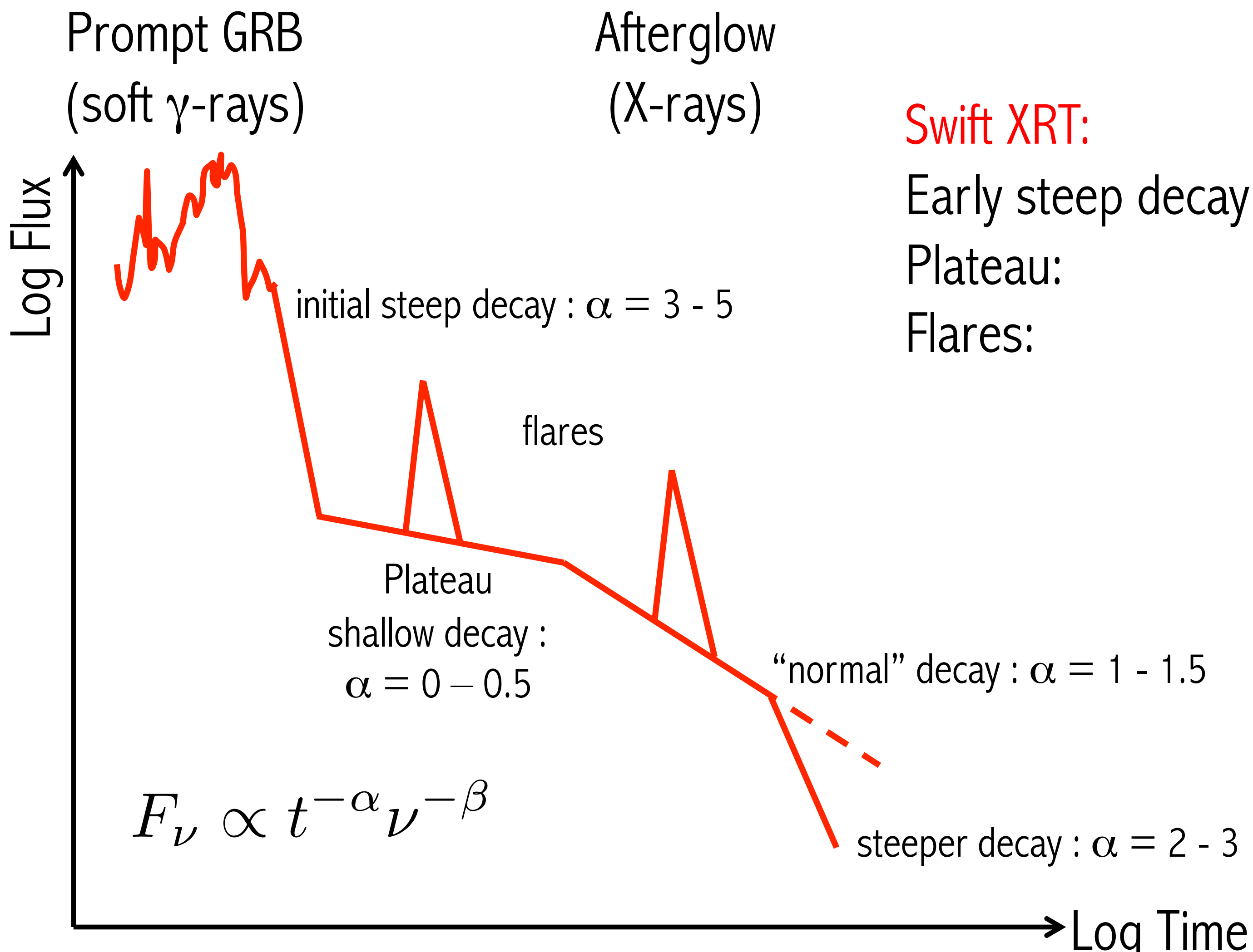


Prompt emission keV ➞ GeV (Fermi)



X-ray afterglow (Swift)

Observed emission: prompt $\longrightarrow$ afterglow



Swift XRT:

Early steep decay:	>90%
Plateau:	~60%
Flares:	~30%

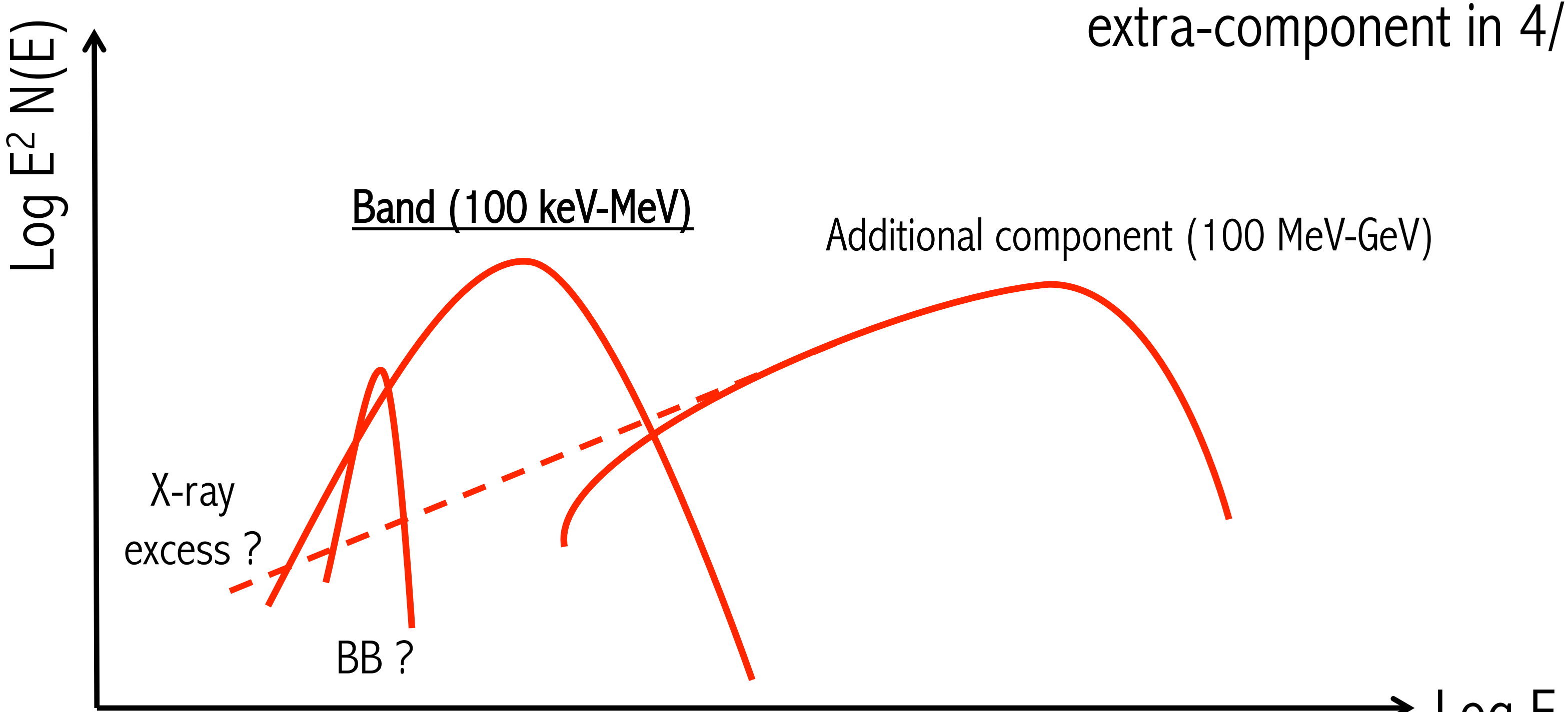
Also: prompt optical, GeV

Also: optical, radio afterglow long-lasting Fermi/LAT emission

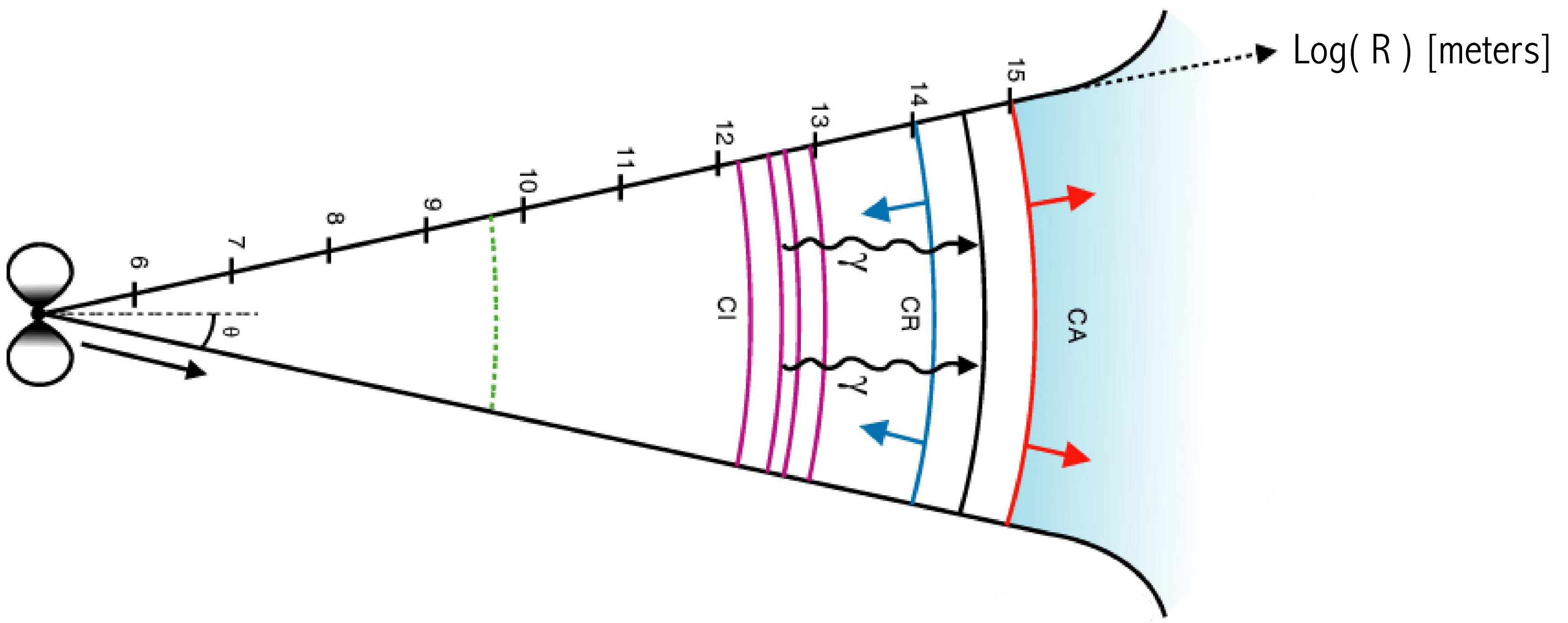
Observed prompt γ-ray spectrum

Fermi/GBM:
BB looked for in bright cases
& found in many cases

Fermi/LAT: 1st catalog
extra-component in 4/28



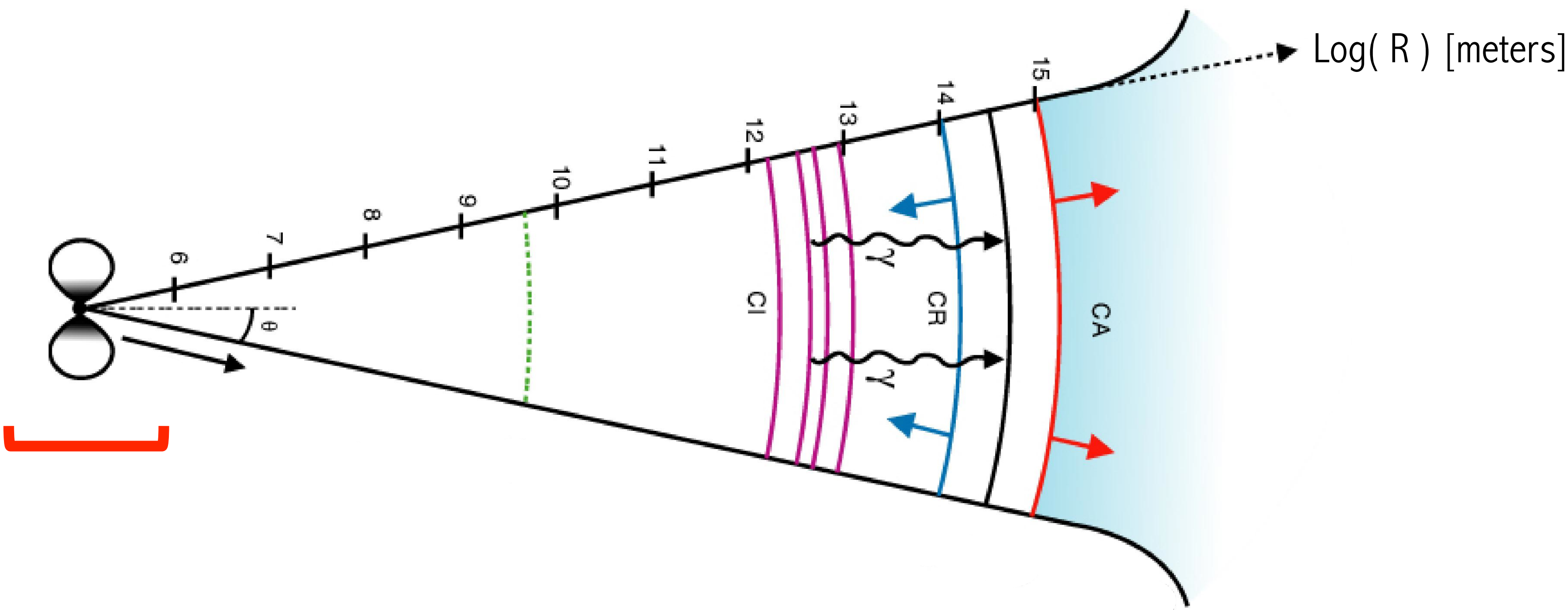
GRB physics



GRB physics

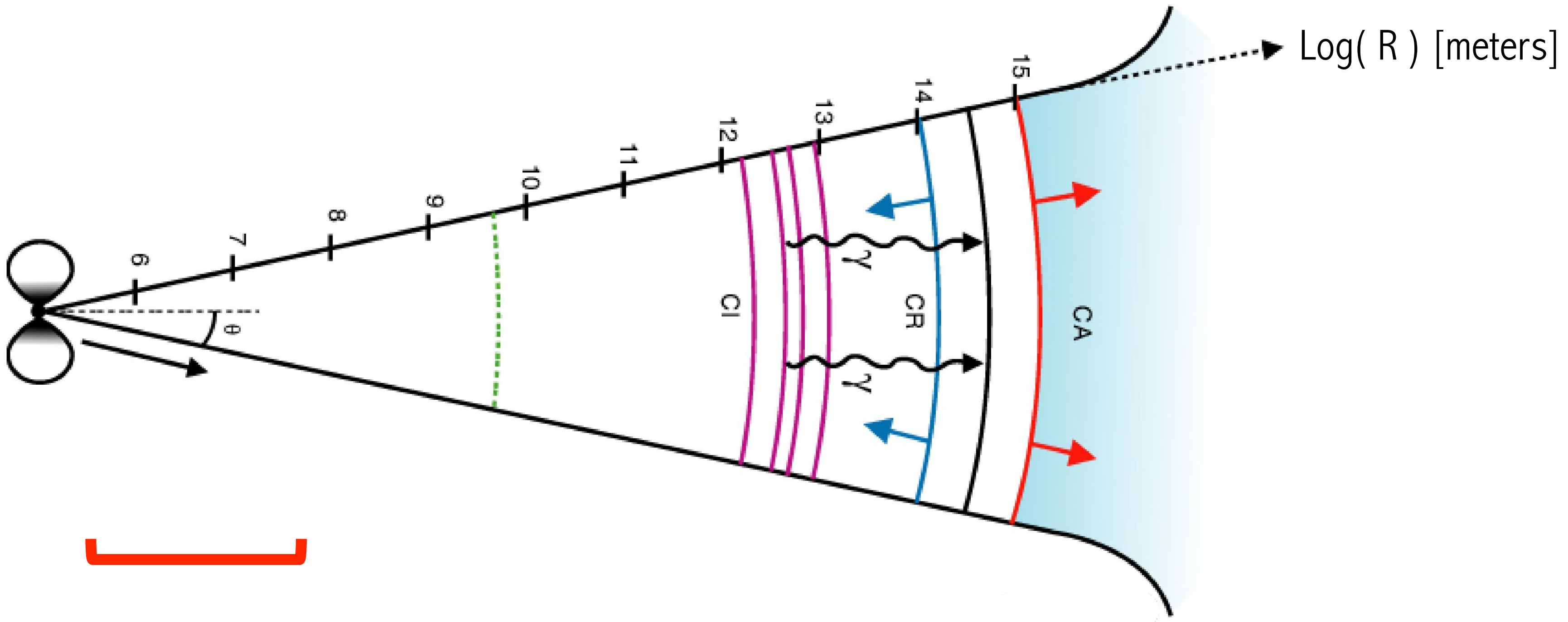
- Cosmological distance: huge radiated energy ($E_{iso,\gamma} \sim 10^{50}$-$10^{55}$ erg)
- Variability + energetics: violent formation of a stellar mass BH

Long GRBs: collapse of a massive star
Short GRBs: NS+NS/BH merger?



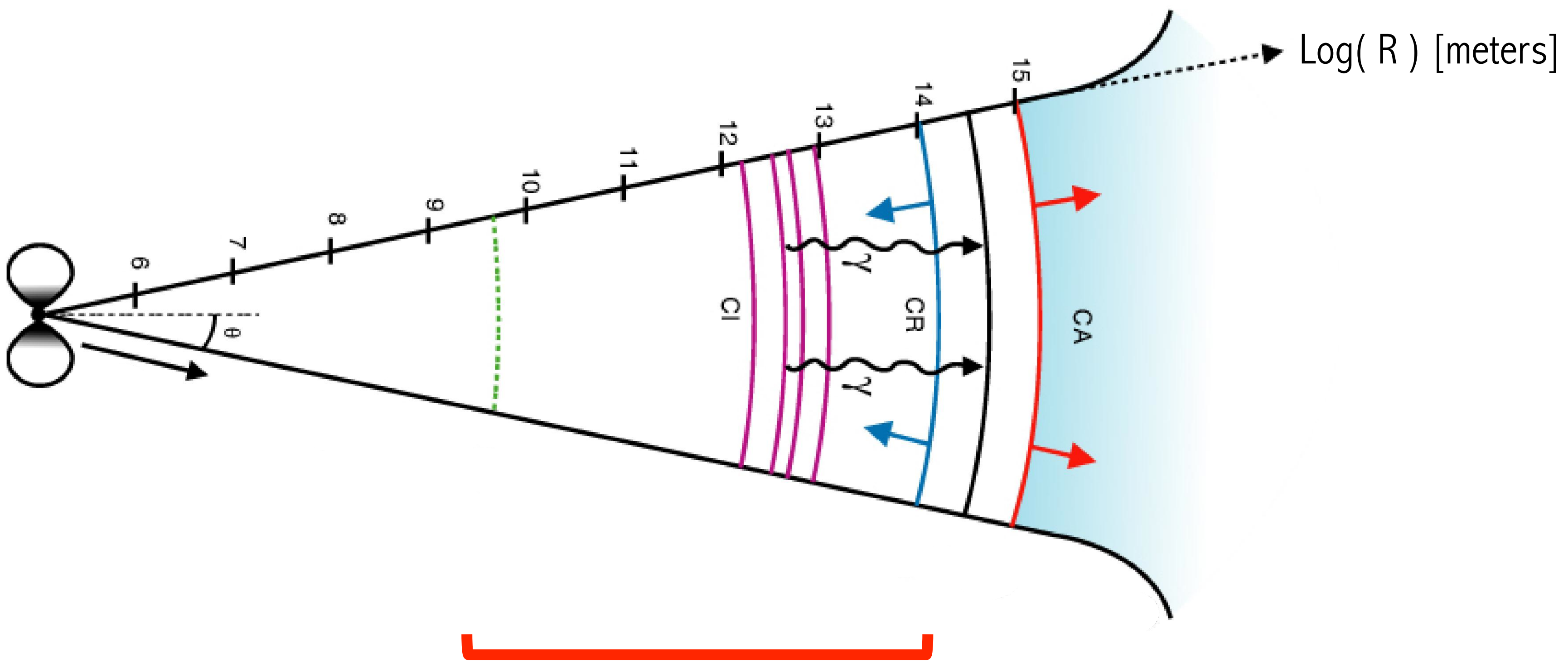
GRB physics

- Variability + energetics + gamma-ray spectrum: relativistic ejection



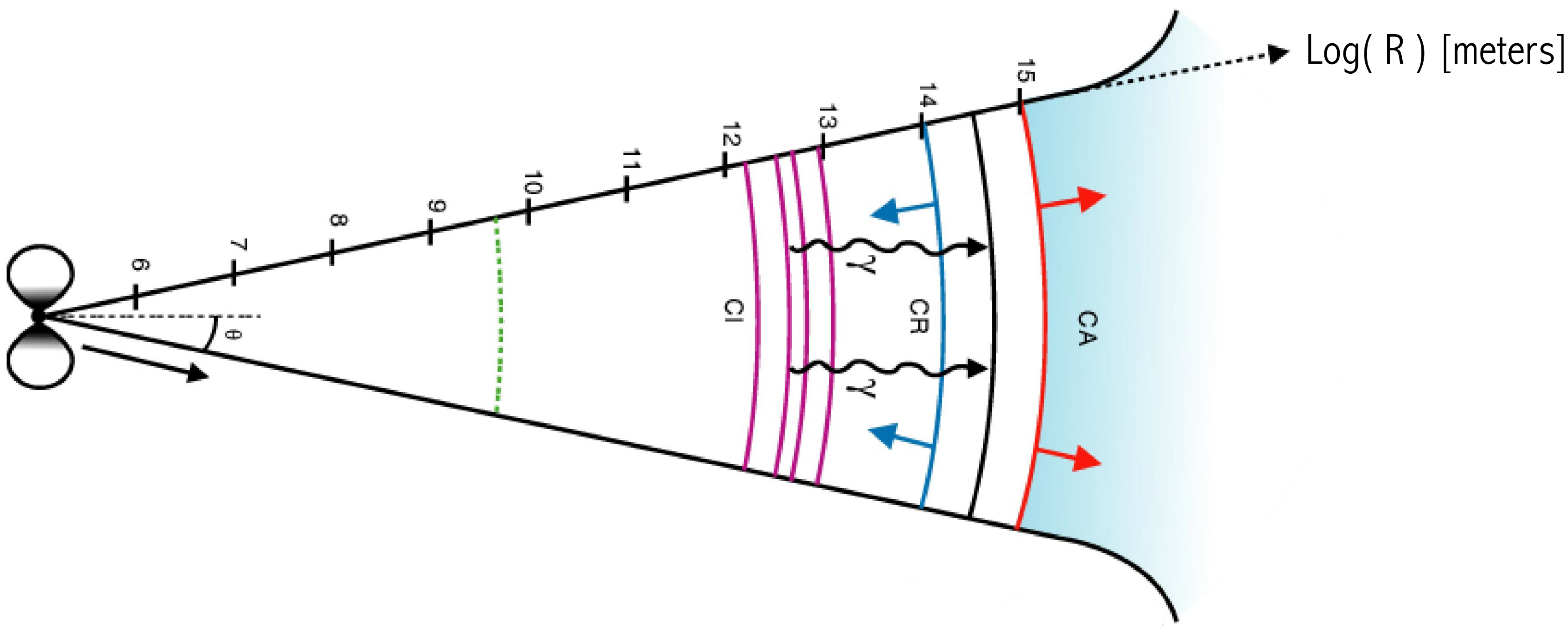
GRB physics

- Variability + energetics + gamma-ray spectrum: relativistic ejection
- Prompt emission: internal origin in the ejecta



GRB physics

- Variability + energetics + gamma-ray spectrum: relativistic ejection
- Prompt emission: internal origin in the ejecta
- Afterglow: deceleration by ambient medium



Relativistic outflows in GRBs

Indirect: necessary to avoid a strong $\gamma\gamma$ annihilation

Direct (in a few cases): apparent super-luminal motion

Apparent super-luminal motion in GRBs (radio afterglow)

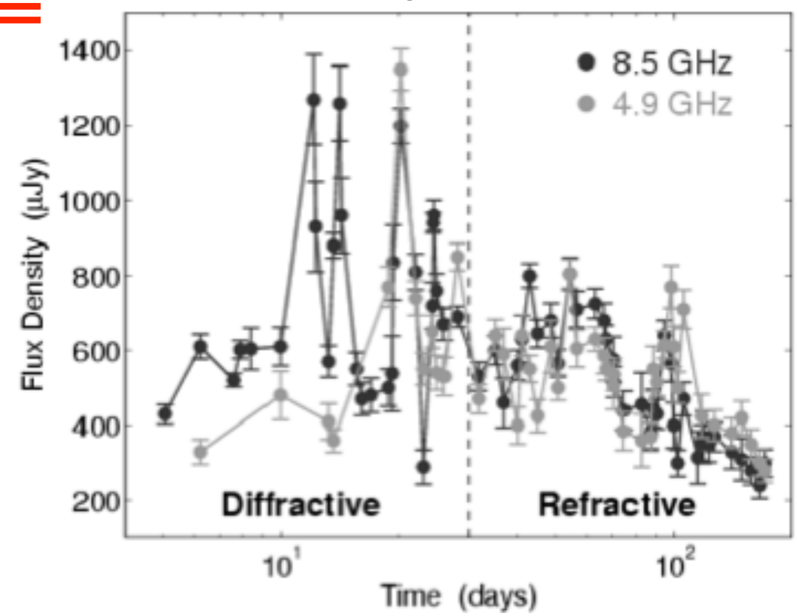
Method 1 :

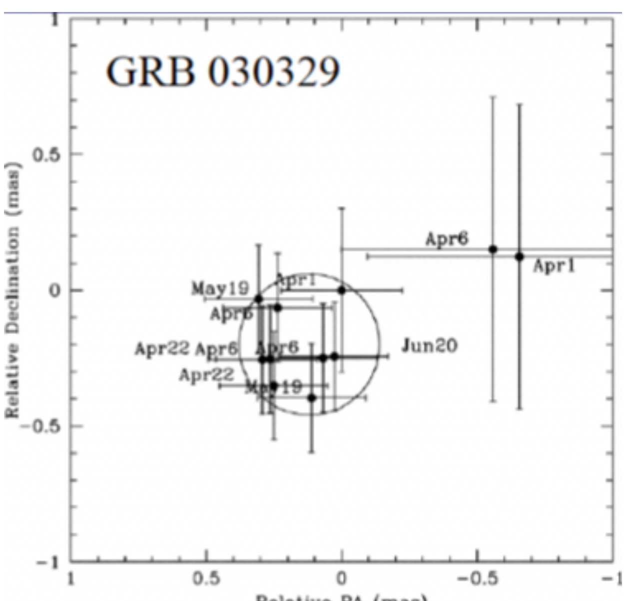
Radio scintillation quenches as the source increases
Transition diffractive / refractive : estimate of the angular size

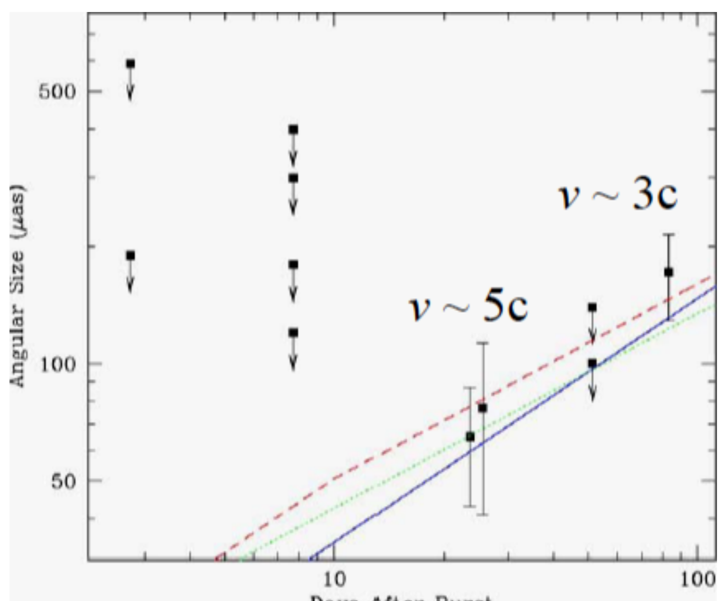
Method 2 :

VLBI allows to resolve the late afterglow for nearby GRBs

From the size, the apparent velocity is deduced:
superluminal apparent motion: relativistic motion







After 25 days:
65 μas (5.7 10^{17} cm)

Proper motion:
0.1 mas in 80 days

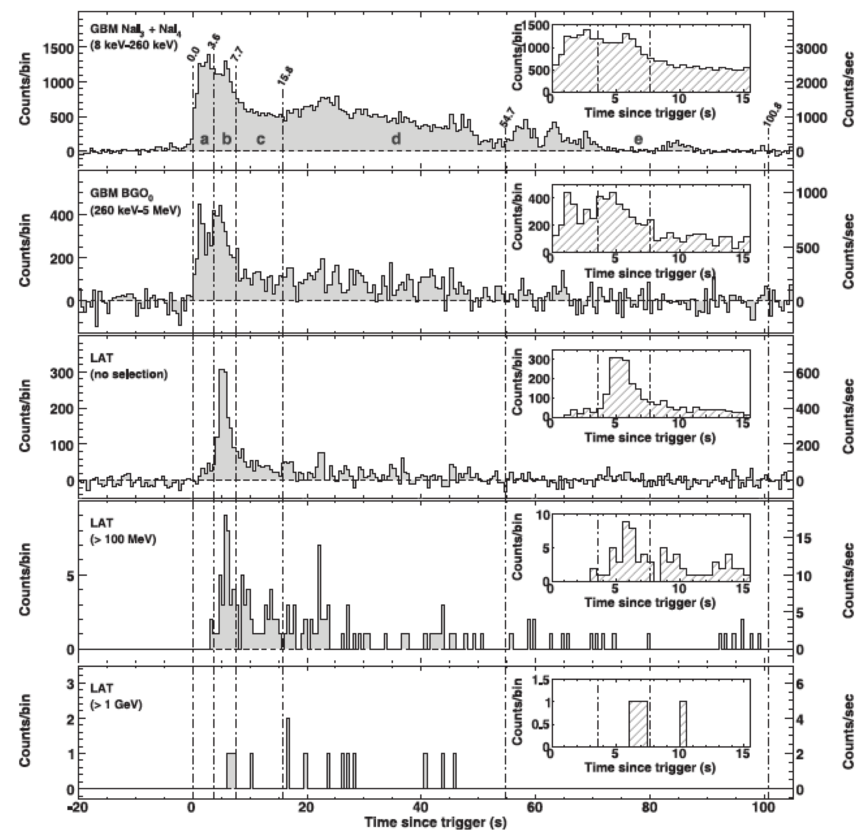
Taylor et al. 2004

How relativistic are GRB outflows?

Pre-Fermi (MeV range) : $\Gamma_{min} \sim 100\text{-}300$

GeV detection by Fermi: stricter Lorentz factor constraints

- GRB 080916C: $\Gamma_{min} \geq 887$ (Abdo et al. 09)
- GRB 090510: $\Gamma_{min} \geq 1200$ (Ackerman et al. 10)

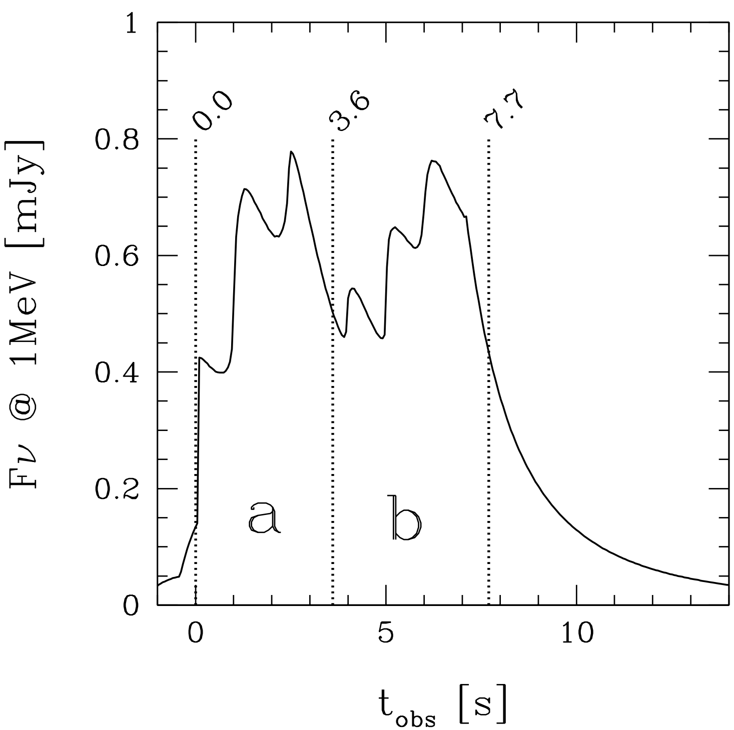


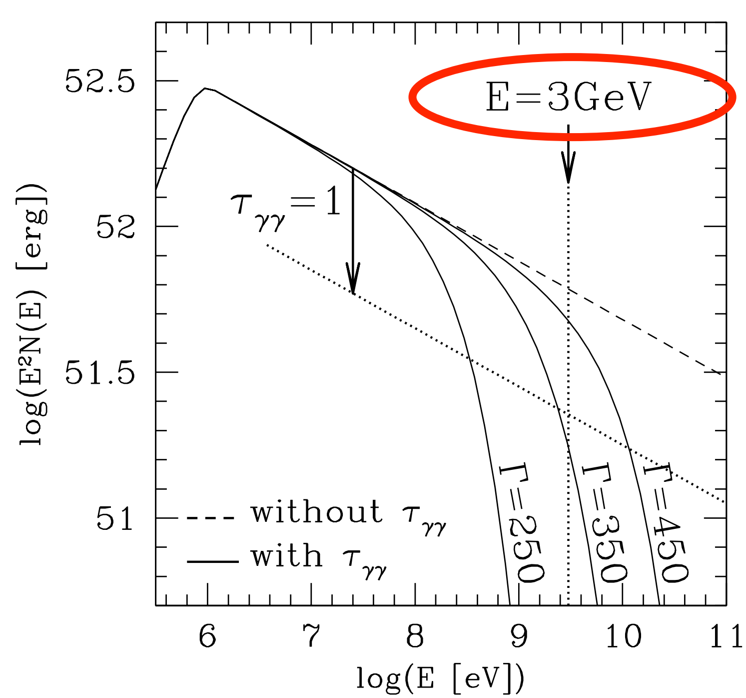
How relativistic are GRB outflows?

Detailed calculation: space/time/direction-dependent radiation field

the estimate of Γ_{min} is reduced by a factor ~ 2-3

(see Granot et al. 2008; Hascoët, Daigne, Mochkovitch & Vennin 2012)





GRB 080916C : Γ_{min} ~ 360 (Hascoët, Daigne, Mochkovitch & Vennin, 2012)

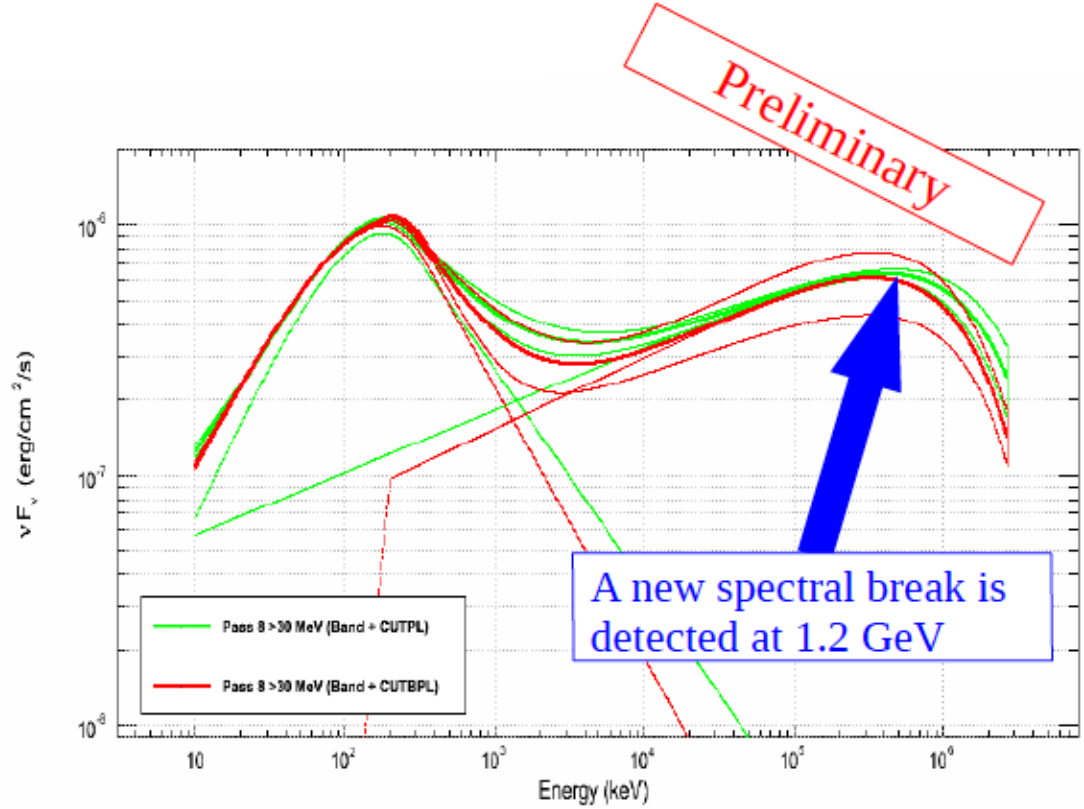
instead of ~900 (Abdo et al. 2009)

First observation of the γγ cutoff ?

- GRB 090926A (Fermi-LAT): first observed cutoff at high-energy (Ackermann et al. 2011)

- New analysis and interpretation:

  - Path 8: 447 ⟶ 1088 events in LAT
  - cutoff is *better* detected, in *several* time bins

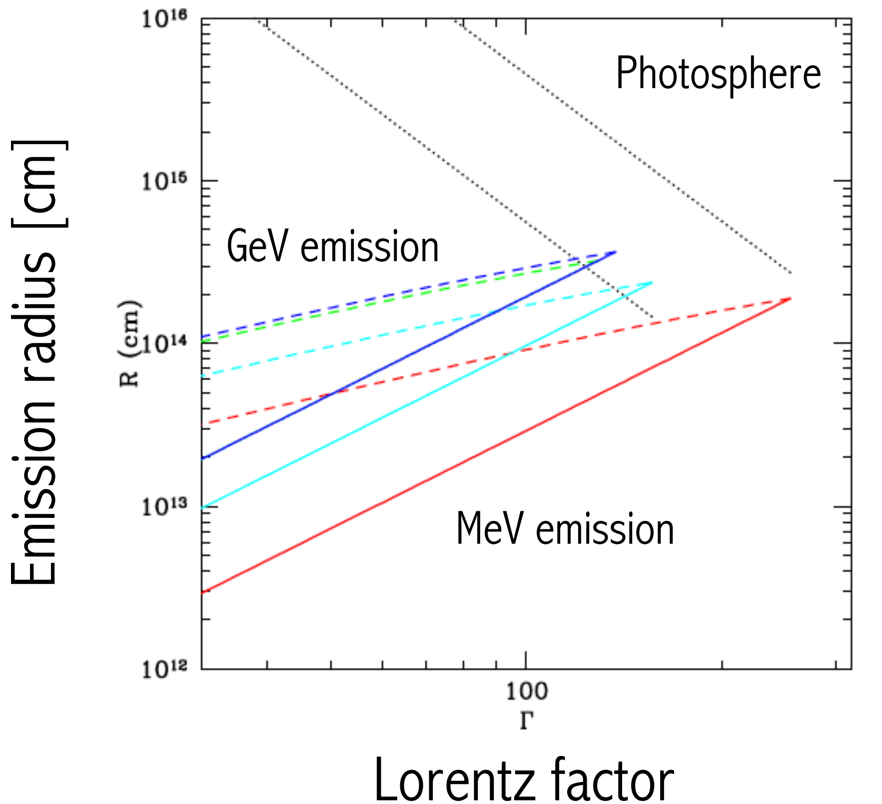


Yassine, Piron, Daigne & Mochkovitch, in preparation

First observation of the γγ cutoff ?

- GRB 090926A (Fermi-LAT): first observed cutoff at high-energy (Ackermann et al. 2011)
- New analysis and interpretation:

  - Time-evolution of cutoff is expected
  - Strong constraint on Lorentz factor and emission radius

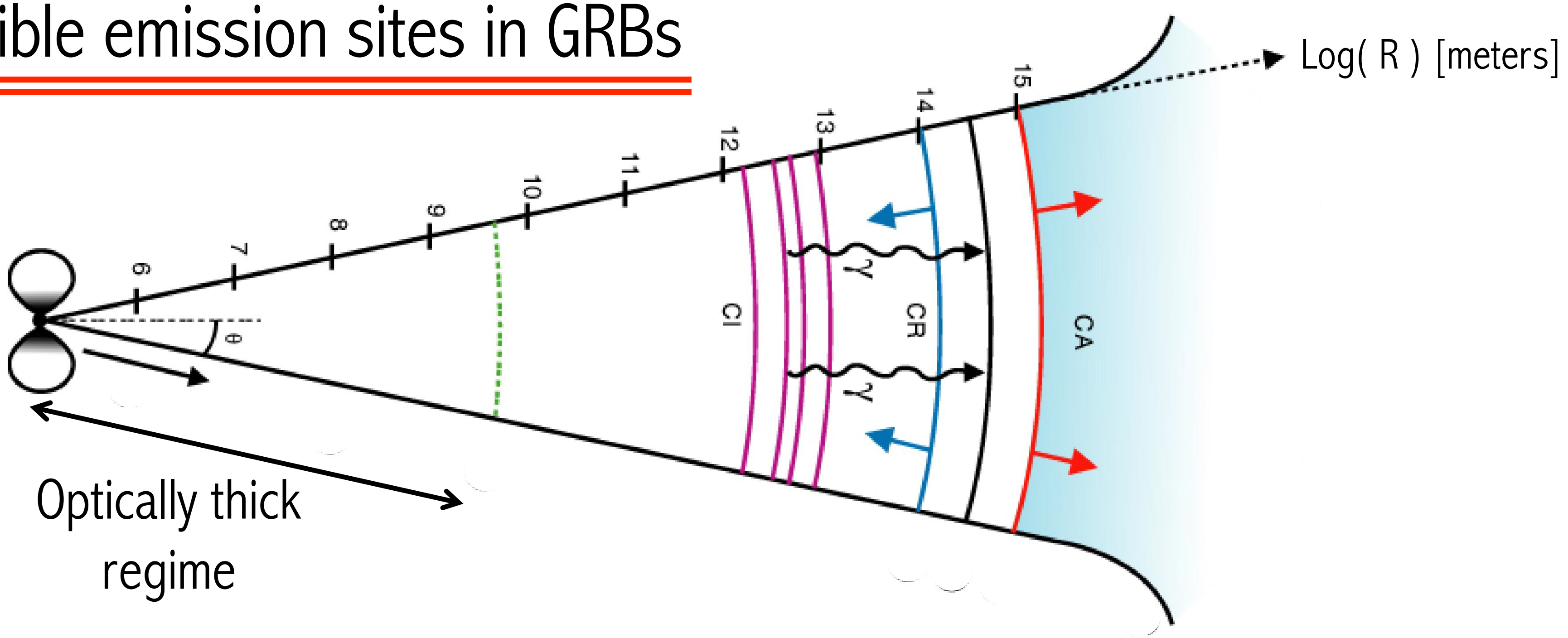


Alternative: no cutoff but intrinsic spectral shape (IC) ?

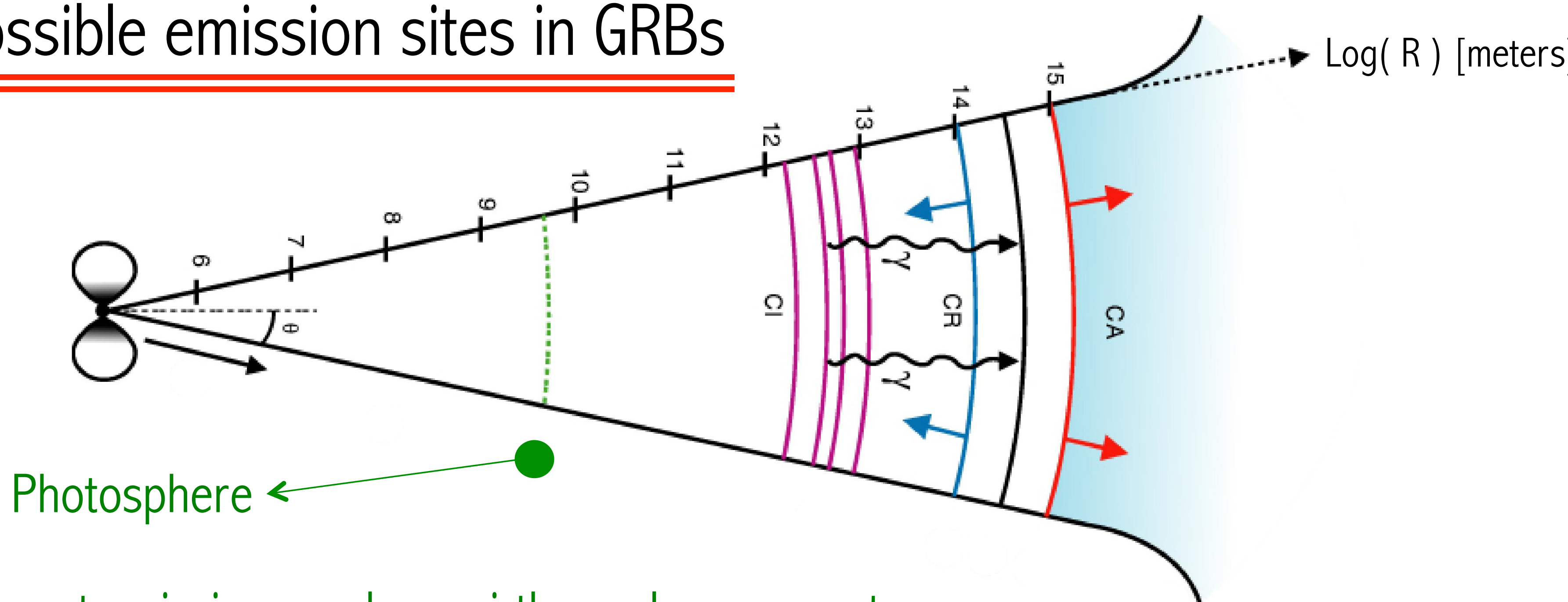
Yassine, Piron, Daigne & Mochkovitch, in preparation

GRBs: possible emission sites

Possible emission sites in GRBs

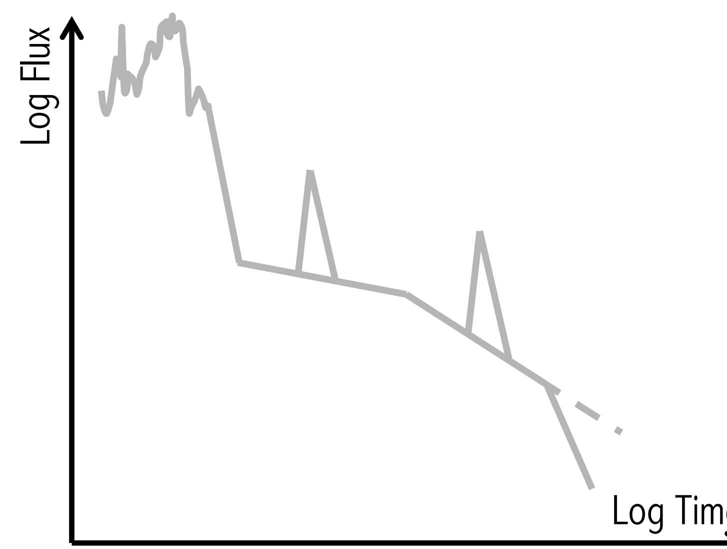


Possible emission sites in GRBs

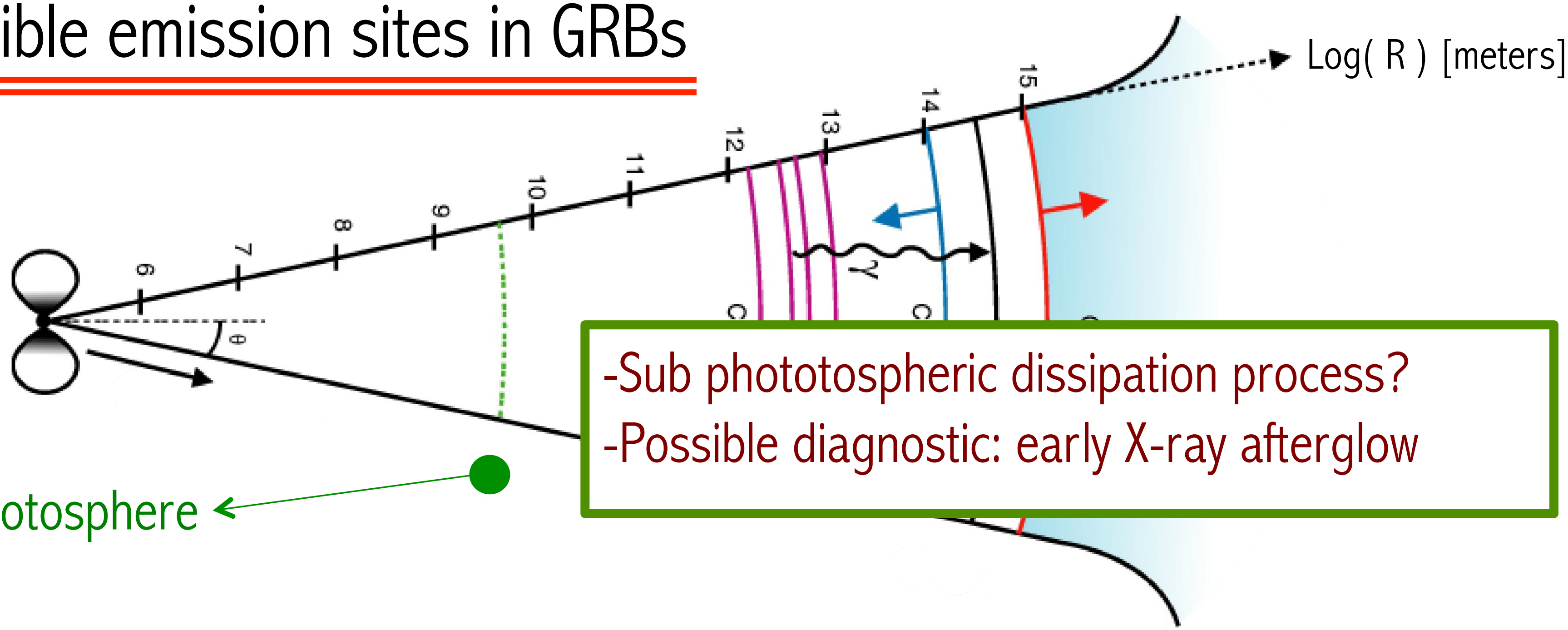


Prompt emission: weak quasi-thermal component

⟶ main spectral component produced at larger radius (shocks or reconnection)



Possible emission sites in GRBs

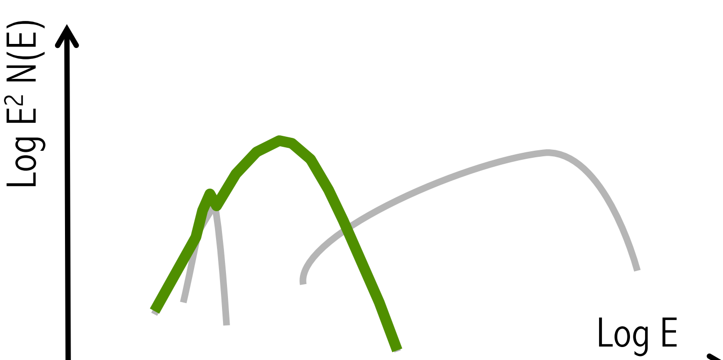


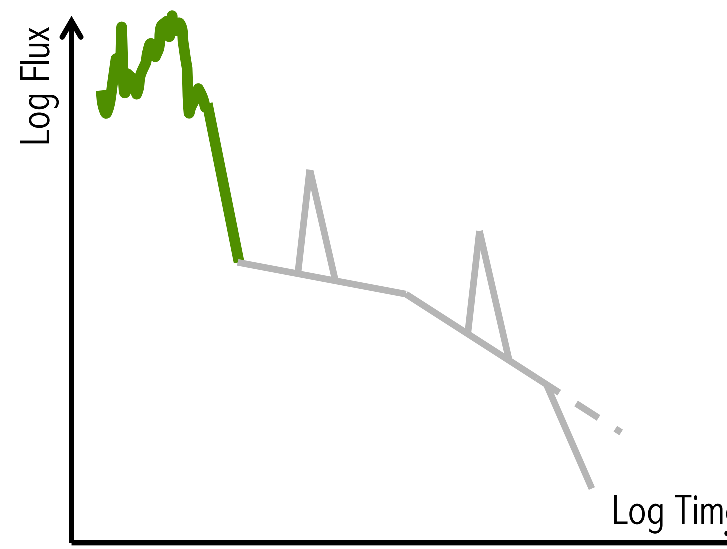
-Sub phototospheric dissipation process?

-Possible diagnostic: early X-ray afterglow

Prompt emission: weak quasi-thermal component

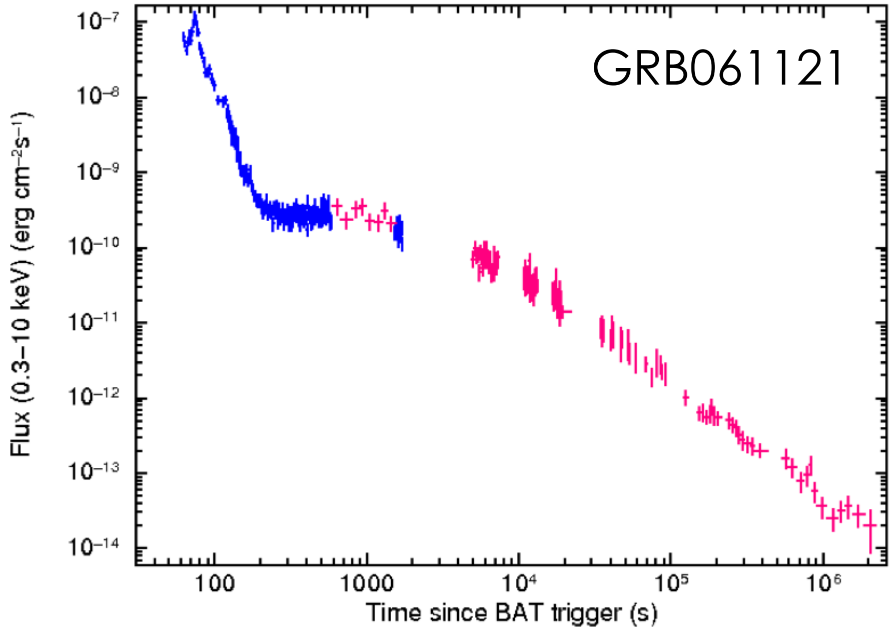
or dominant non-thermal component ?





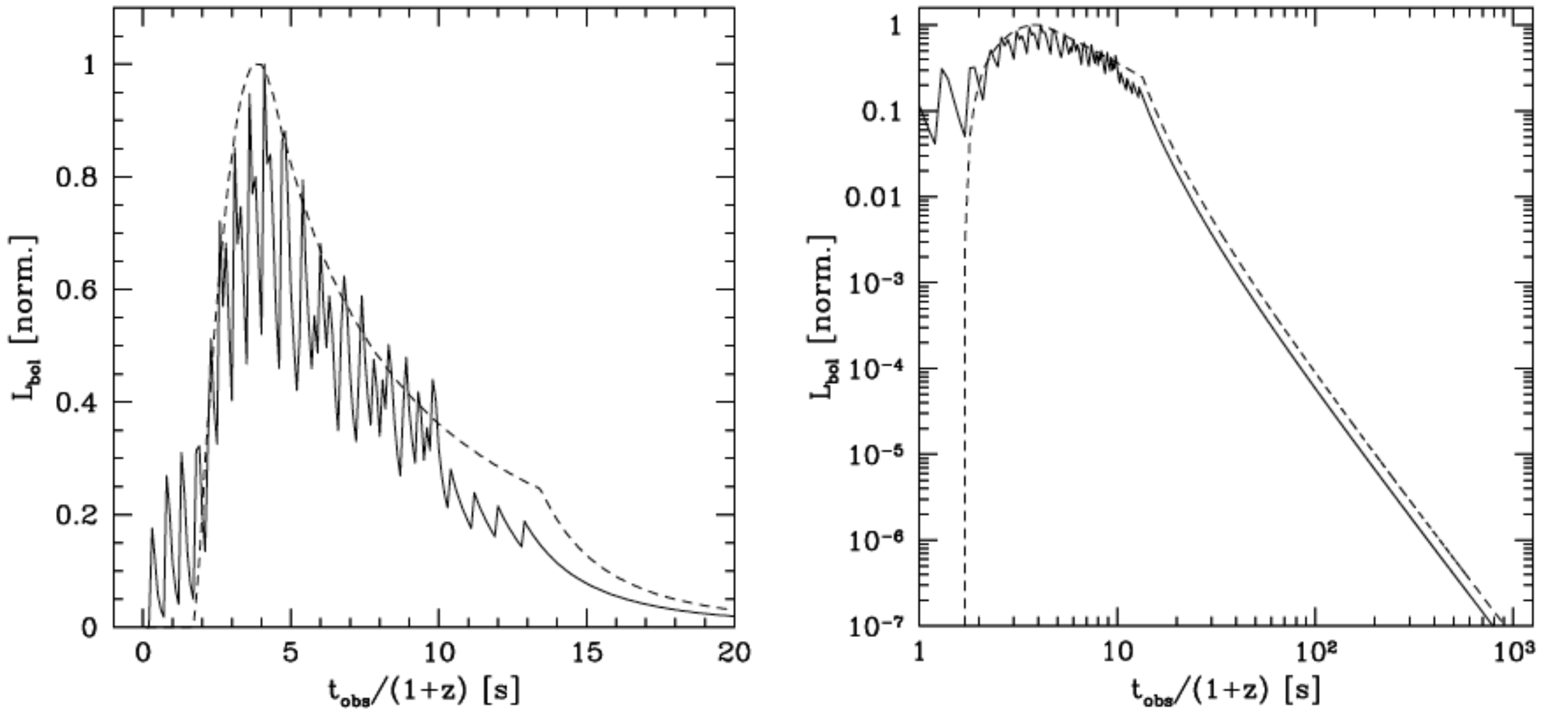
Early steep decay in the X-ray afterglow

Swift BAT+XRT



(Page et al. 2007)

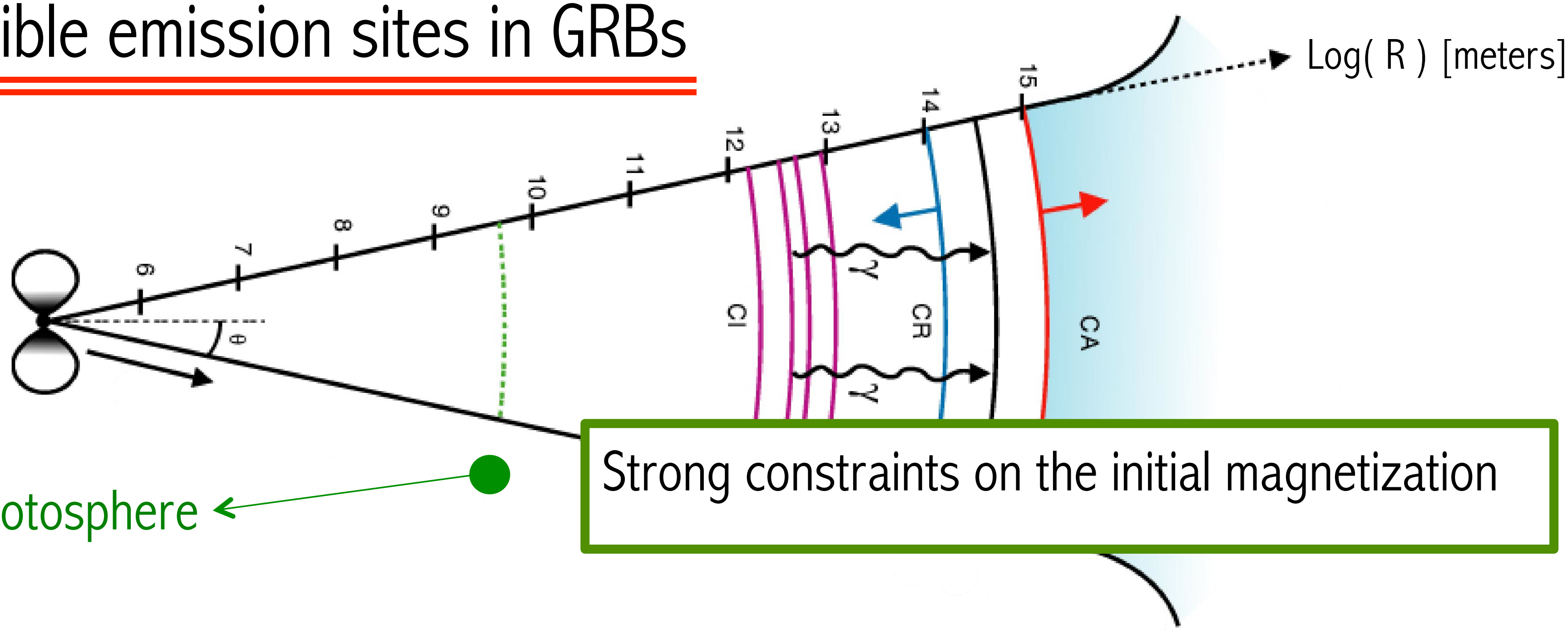
High latitude emission at the end of the prompt phase



Final radius of the order of Γ^2 c t_{burst}

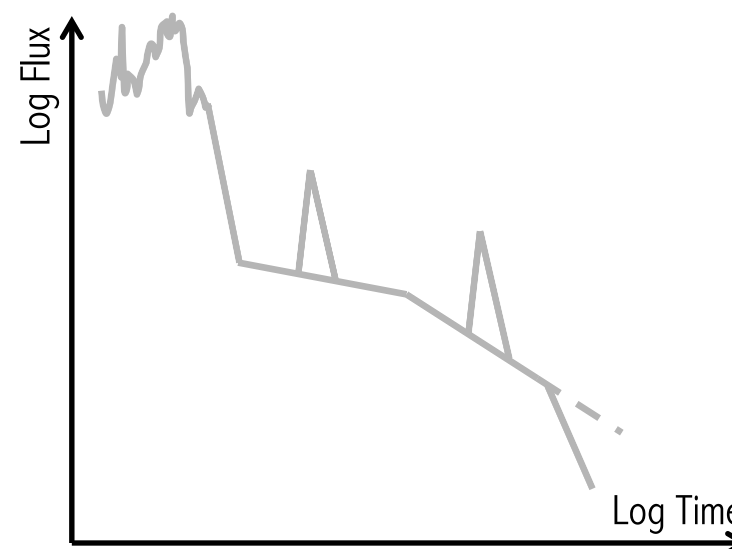
Hascoët, Daigne & Mochkovitch (2012)

Possible emission sites in GRBs



Strong constraints on the initial magnetization

Prompt emission: weak quasi-thermal component

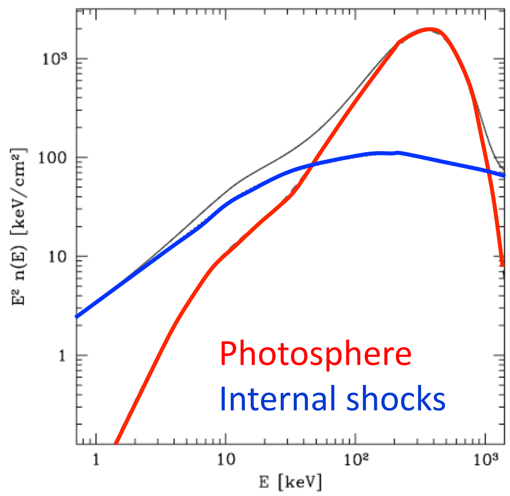


Weak quasi-thermal photospheric emission: constraints on the magnetization

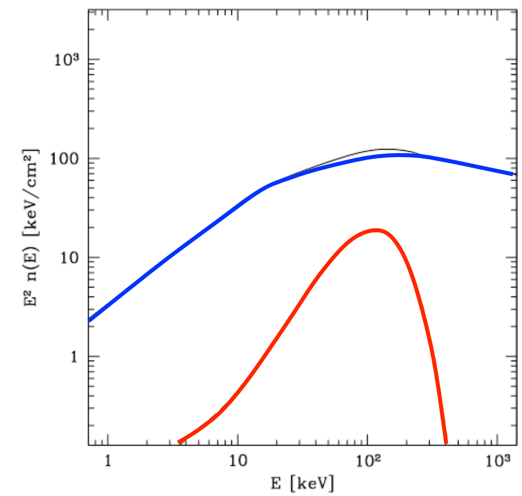
Weak quasi-thermal components in GRB spectra?

Daigne & Mohckovitch 2002

Low initial magnetization

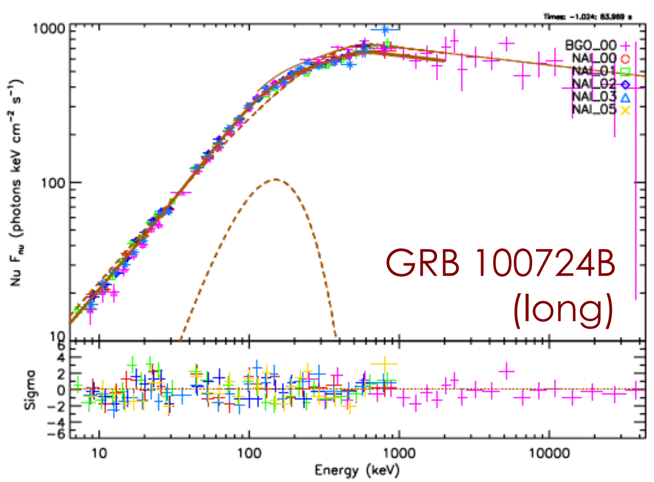


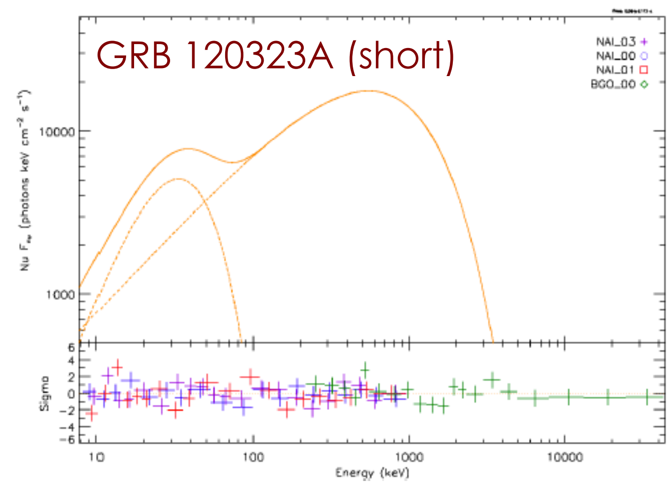
High initial magnetization



Expected case

Guiriec [FD] et al. 2011





Guiriec [FD] et al. 2013

Warning: spectral analysis based on forward folding technique

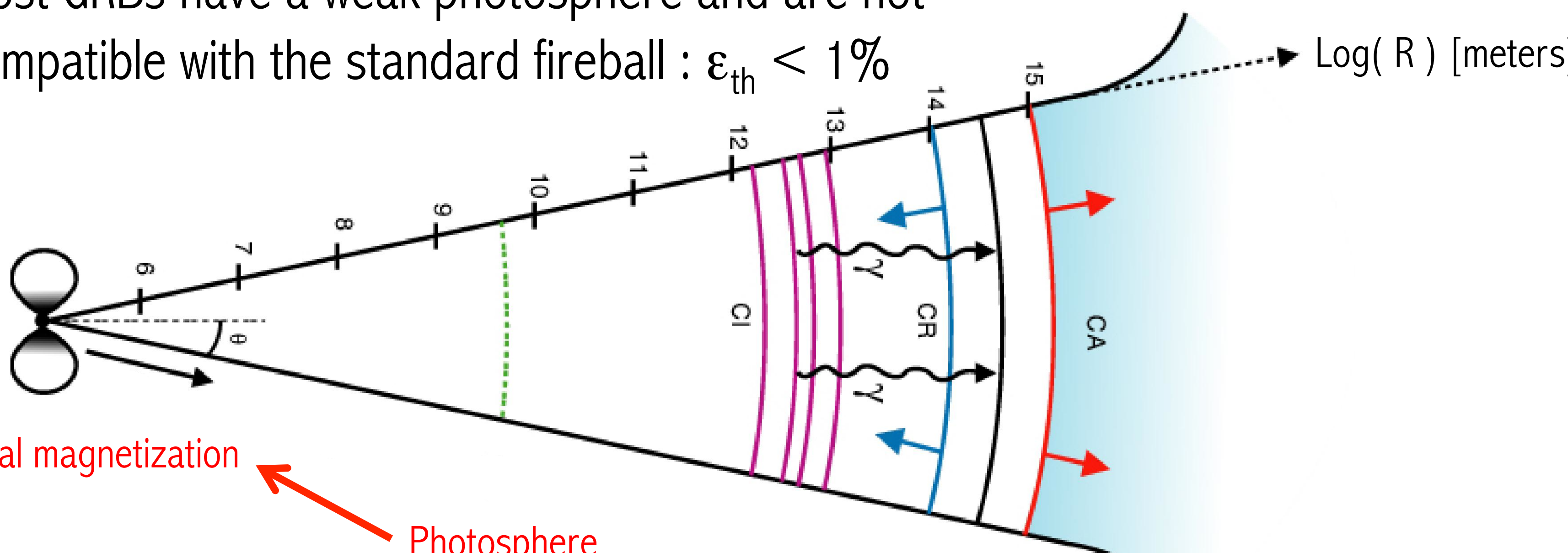
Other cases: Guiriec [Daigne] et al. 2015ab

Constraint on magnetization in GRB outflows

- Weak photospheric emission due to a high initial magnetization: predicted ! (Daigne & Mochkovitch 2002)

- Detection: thermal/non-thermal ratio puts a constraint on the initial magnetization.

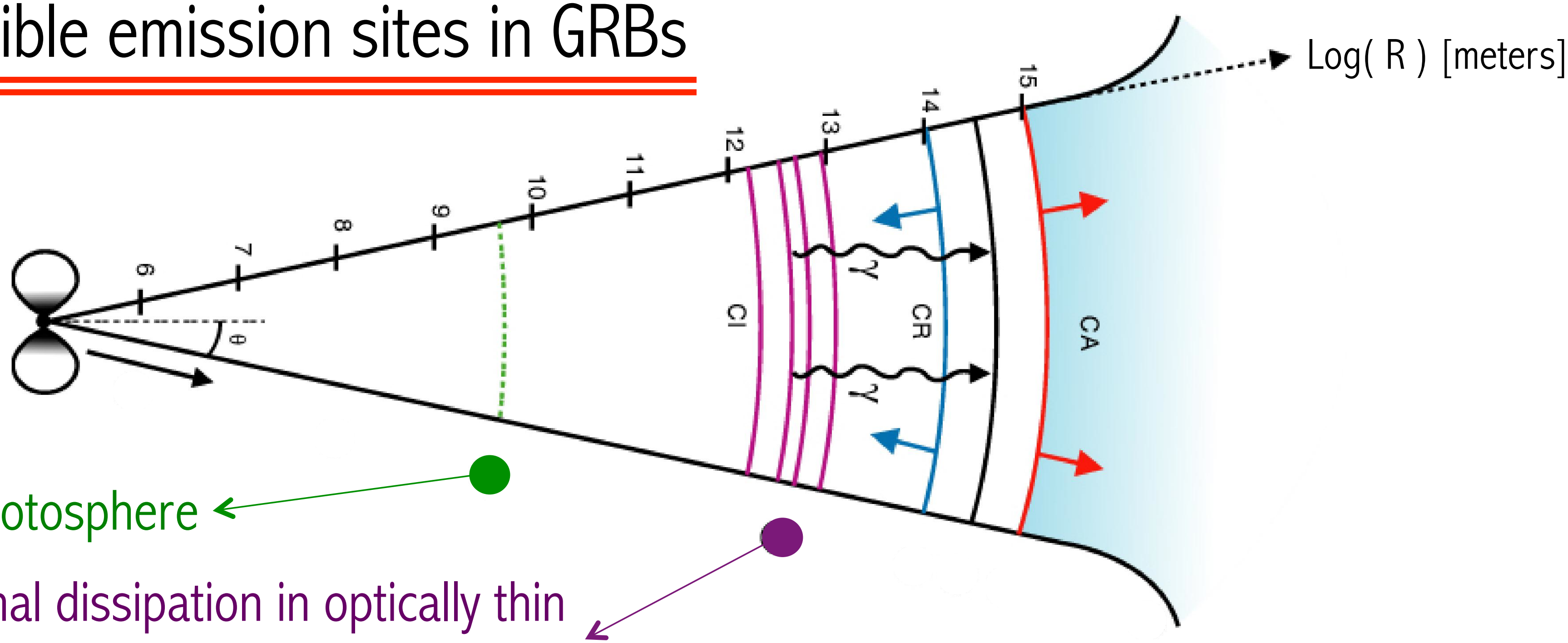
Most GRBs have a weak photosphere and are not compatible with the standard fireball : $\varepsilon_{th} < 1\%$



What is the magnetization σ at large distance?
Internal dissipation by shocks or reconnection?

Hascoët, Daigne & Mochkovitch (2013)

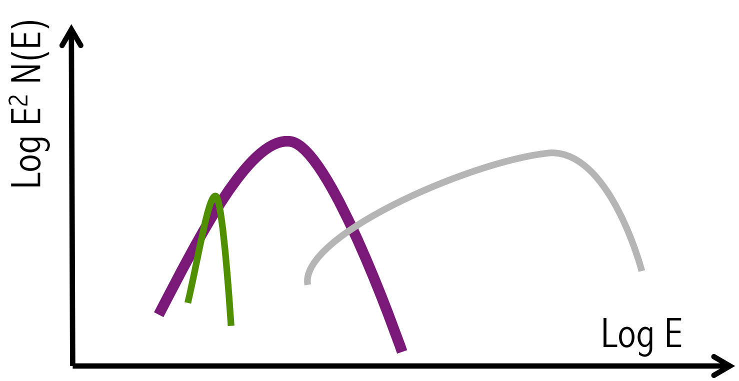
Possible emission sites in GRBs

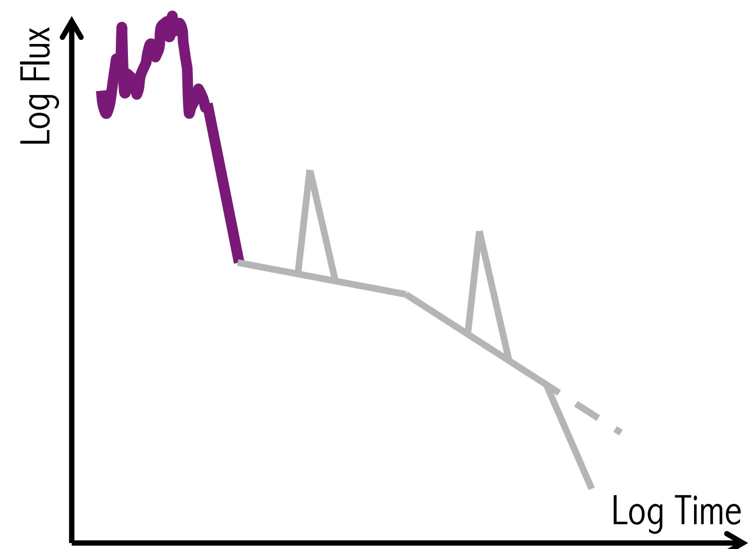


Photosphere

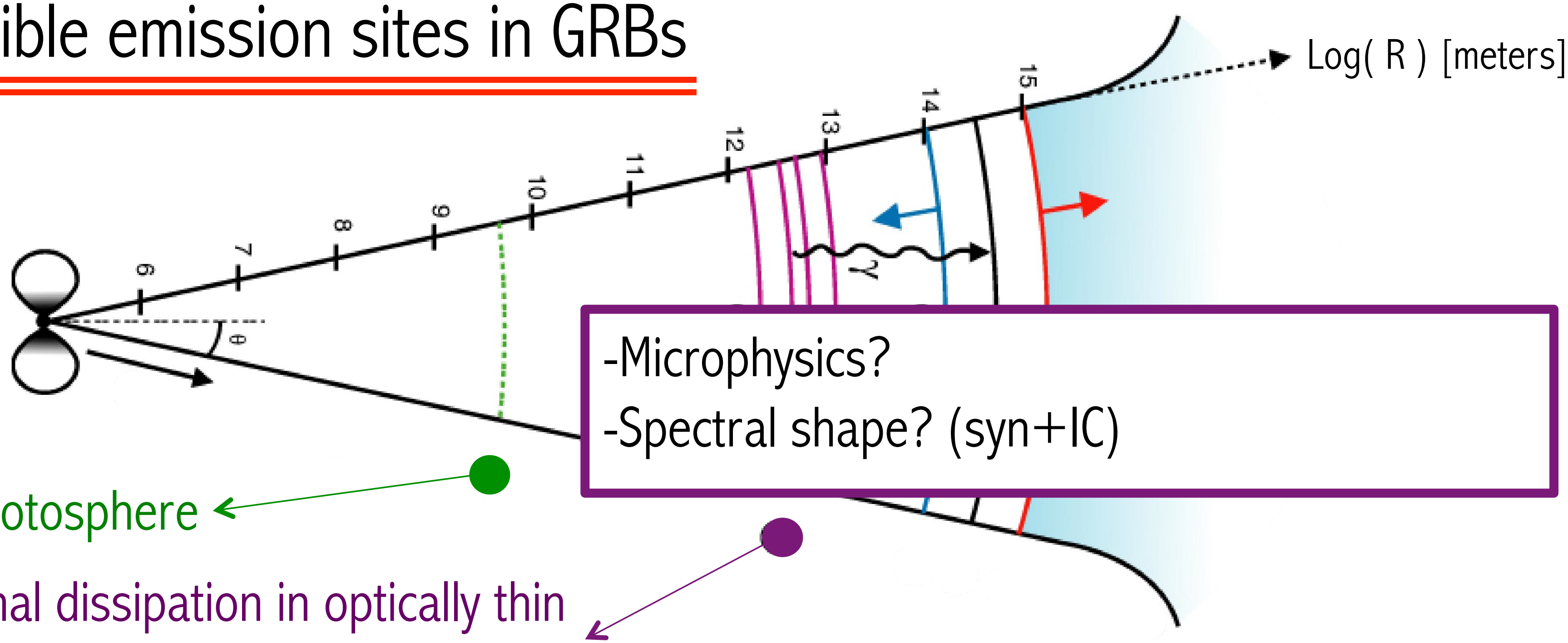
Internal dissipation in optically thin regime (shocks or reconnection)

Prompt emission: dominant non-thermal component?





Possible emission sites in GRBs



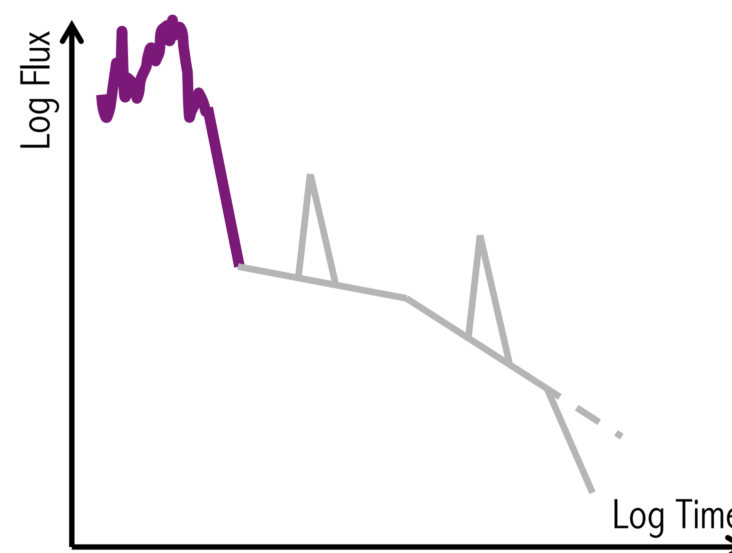
-Microphysics?

-Spectral shape? (syn+IC)

Photosphere

Internal dissipation in optically thin regime (shocks or reconnection)

Prompt emission: dominant non-thermal component?
+additional component ?



Prompt gamma-ray emission from internal shocks?

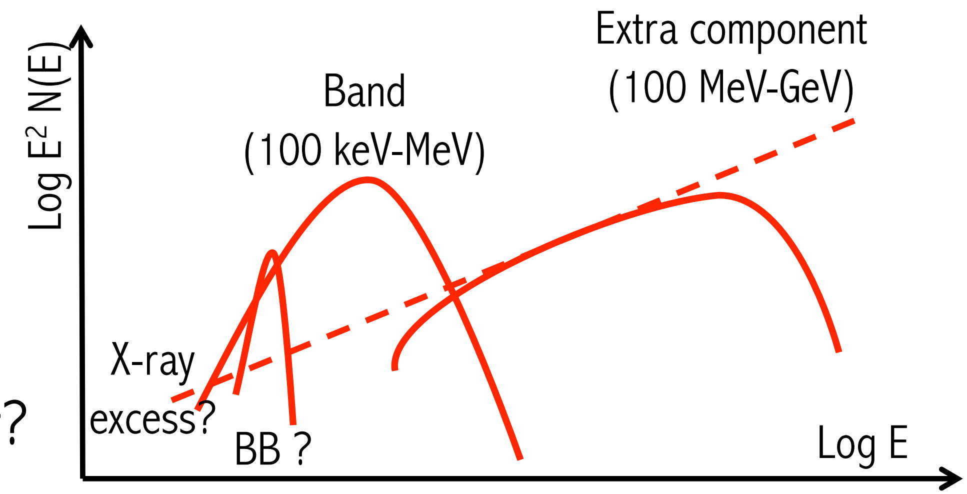
How to distinguish between the proposed mechanisms for the prompt emission?

-Lighcurves: OK for all scenarios

-Spectrum

-Spectral evolution

Spectrum



Main difficulty to model the prompt GRB with internal shocks: spectral shape

-depends on a complex microphysics

-observational constraints not always clear?

Low-energy photon index in fast cooling synchrotron spectrum?

-3/2 : pure fast cooling synchrotron

~ -1 : fast cooling synchrotron + inverse Compton in KN regime

(Derishev et al. 01 ; Bosnjak et al. 09 ; Wang et al. 09 ; Daigne et al. 11)

-2/3 : marginally fast cooling synchrotron (Daigne et al. 11 ; Beniamini & Piran 13)

-1 → -0.5 : fast cooling synchrotron + IC in decaying magnetic field

(Derishev 07 ; Lemoine 13 ; Uhm & Zhang 14 ; Zhao et al. 14)

X-ray excess?

Spectrum: new observations

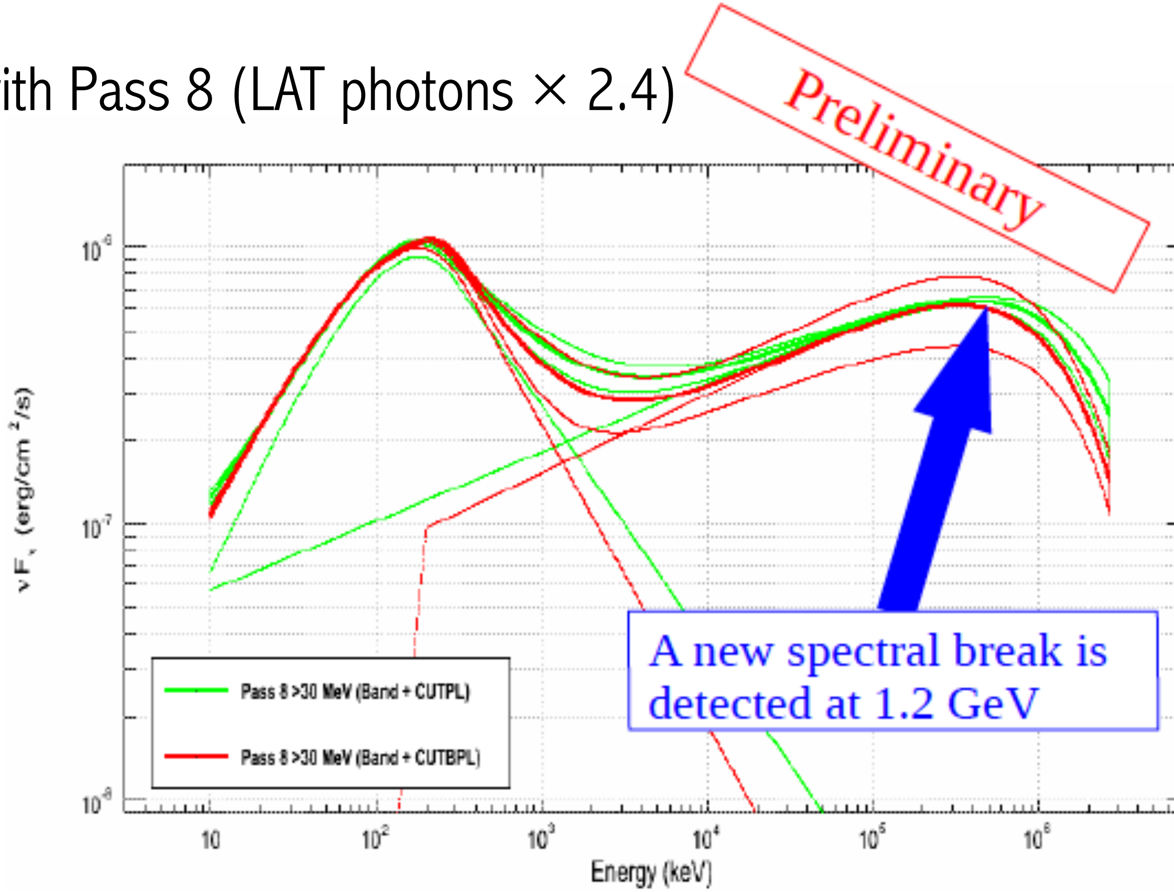
New analysis of GRB090926A with Pass 8 (LAT photons $\times$ 2.4)

Band + broken PL + cutoff
in bins c and d

-X-ray excess disappears

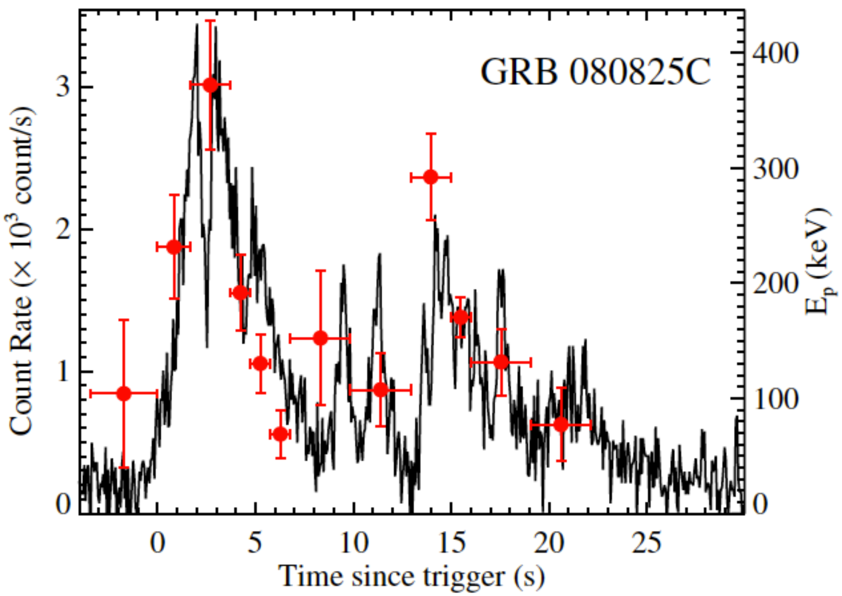
-Band ($\alpha \rightarrow$ -1)

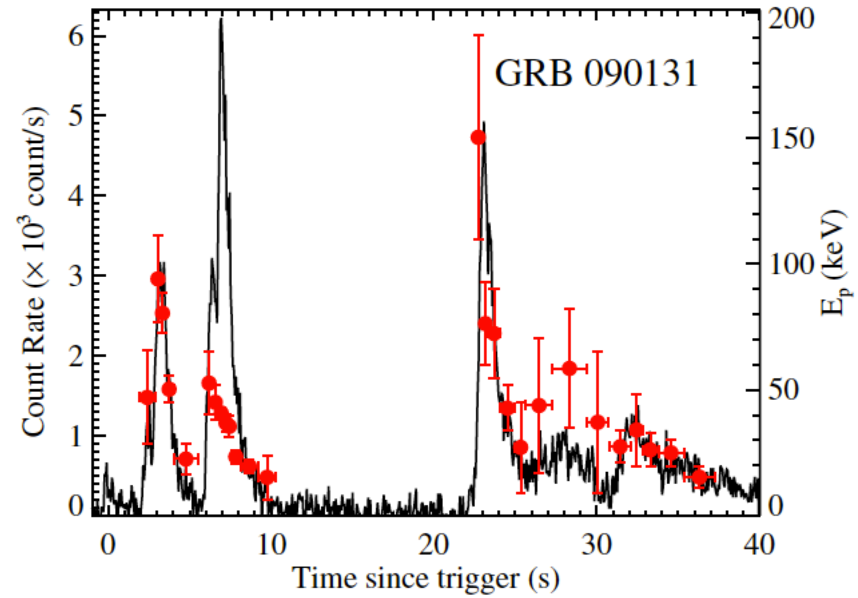
Syn+IC with KN/$\gamma\gamma$?

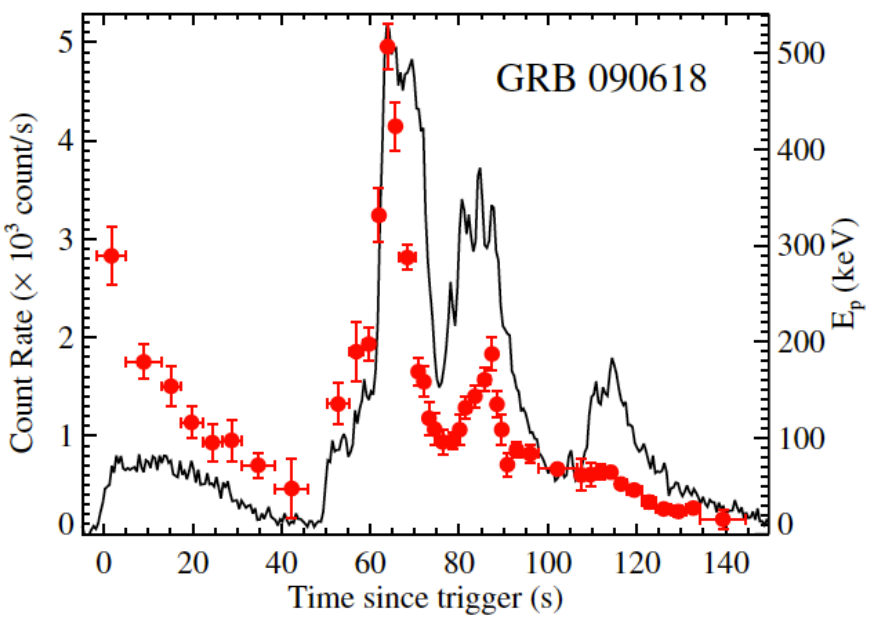


Yassine, Piron, <u>Daigne</u> & Mochkovitch, Fermi Symposium 2015, 2016 in preparation

Spectral evolution



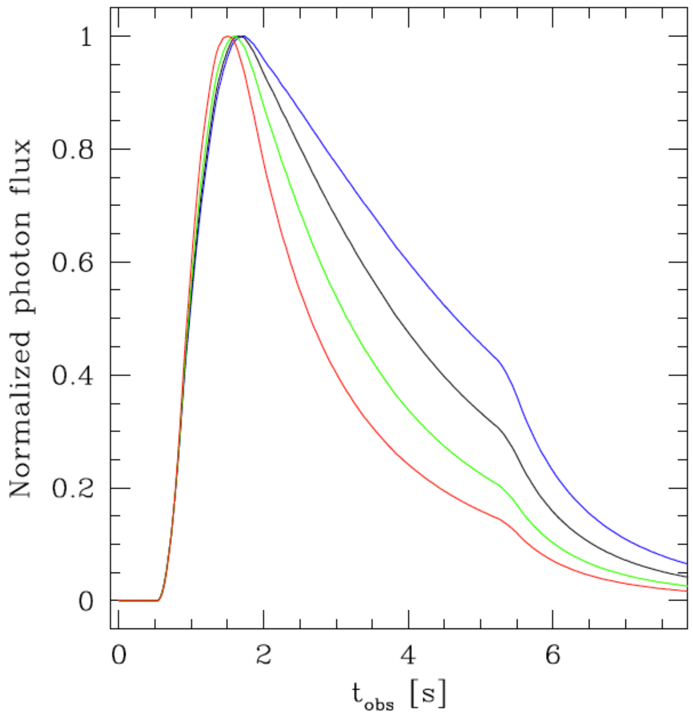




GBM bursts — Li et al. 2012

Spectral evolution

Example of a simulated GRB pulse produced by internal shocks
(full simulation: dynamics+radiation)

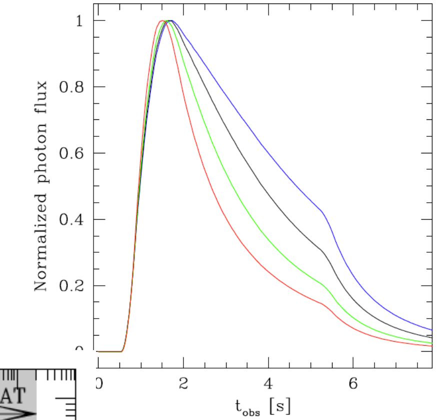


Light curve in BATSE range :
channels 1 (blue) to 4 (red)

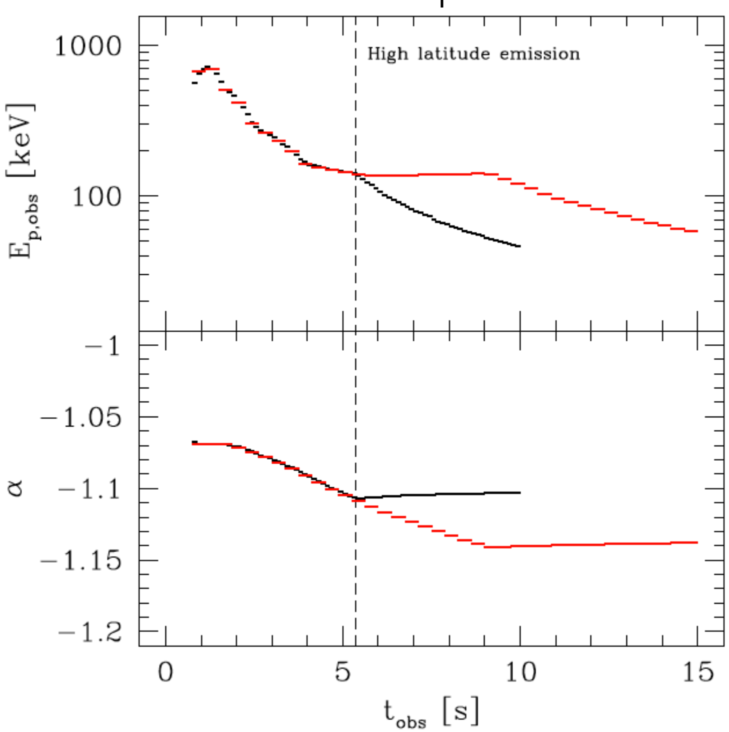
Bosnjak & Daigne 2014

Spectral evolution

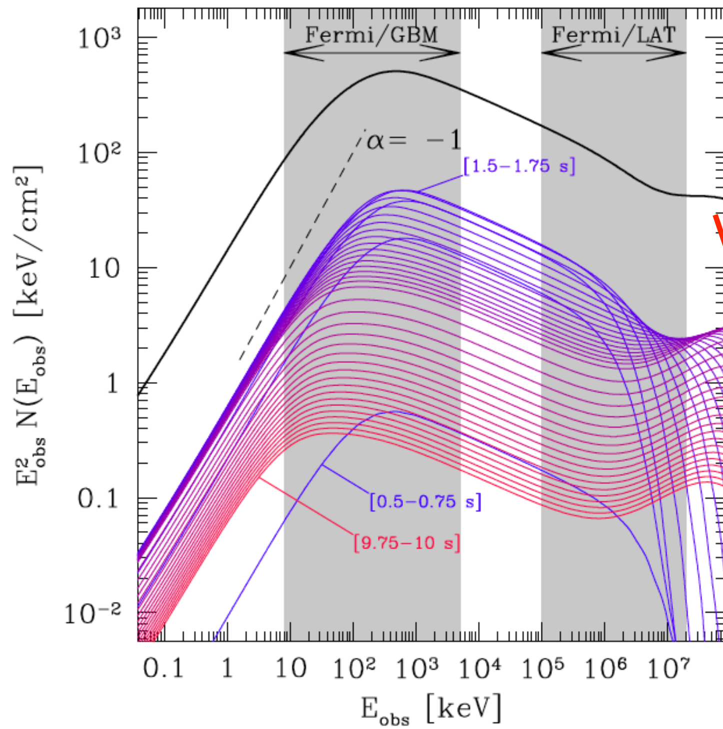
Example of a simulated GRB pulse produced by internal shocks
(full simulation: dynamics+radiation)



Evolution of E_{peak} and α



Time-evolving spectrum

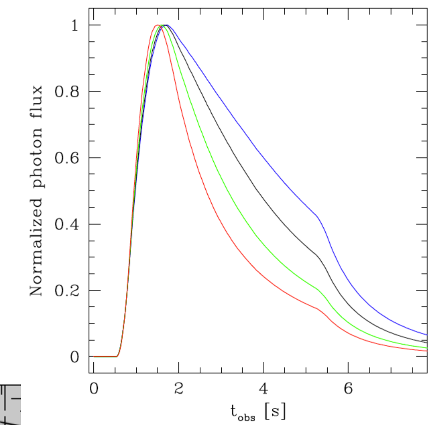


Extra component

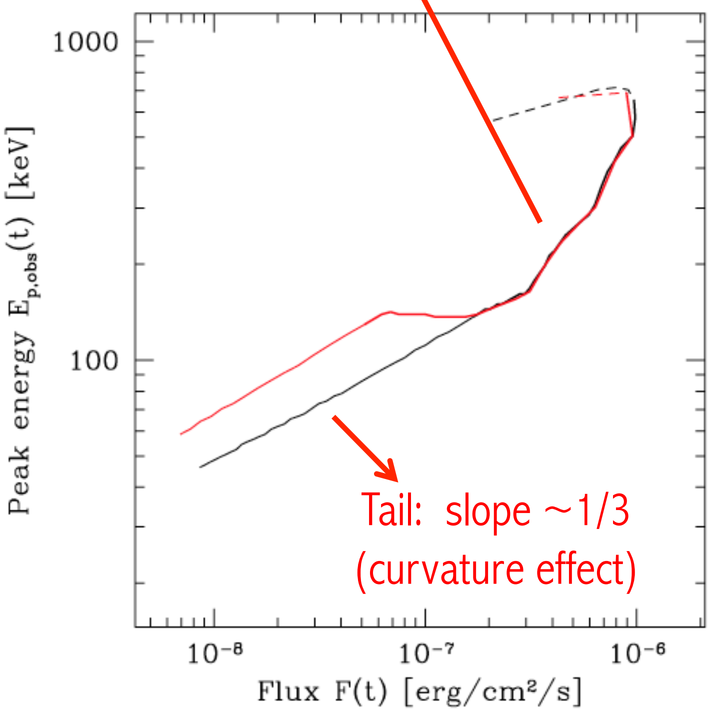
Bosnjak & Daigne 2014

Spectral evolution

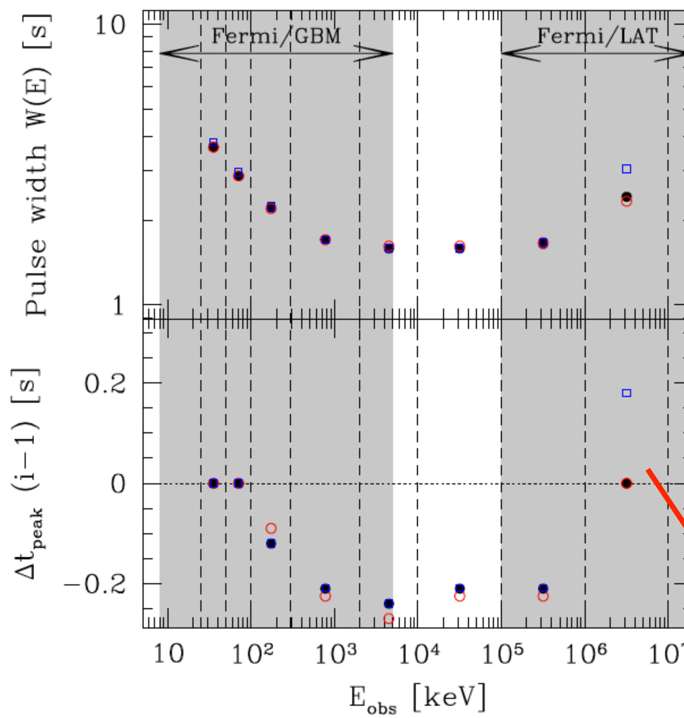
Example of a simulated GRB pulse produced by internal shocks (full simulation: dynamics+radiation)



Slope ~1-1.5 fixed by shock propagation



Tail: slope ~1/3
(curvature effect)



$$W(E) \propto E^{-a}$$

$$a \simeq 0.2 - 0.3$$

Hardness-Intensity Correlation

Pulse width and time lags

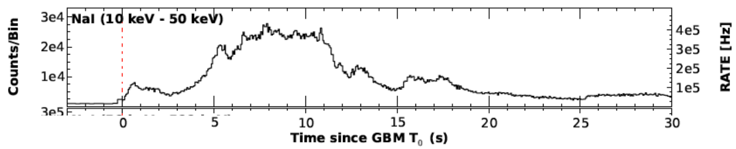
Delayed onset ? γγ ?

Bosnjak & Daigne 2014

(Hascoet [Daigne] et al. 2012)

Spectral evolution

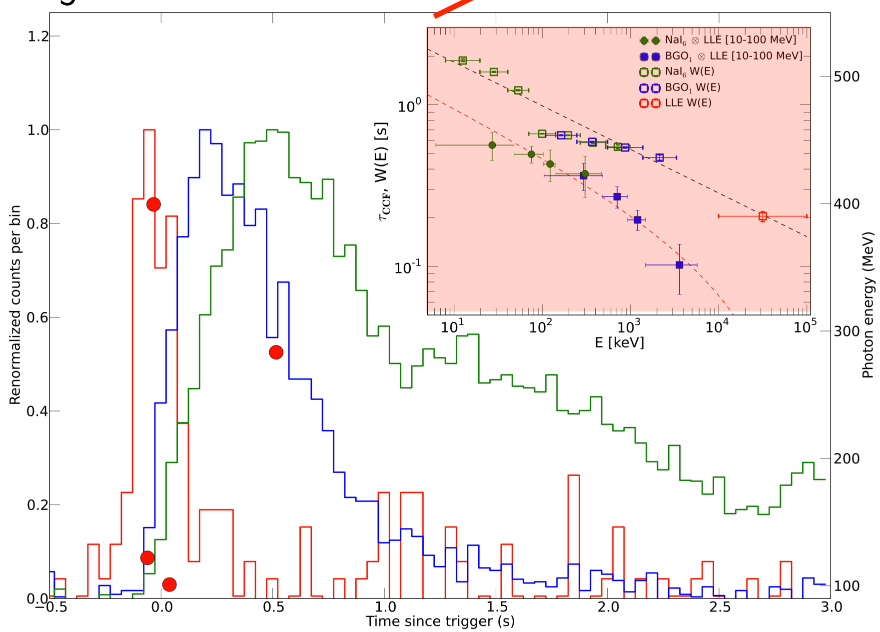
GRB 130427A

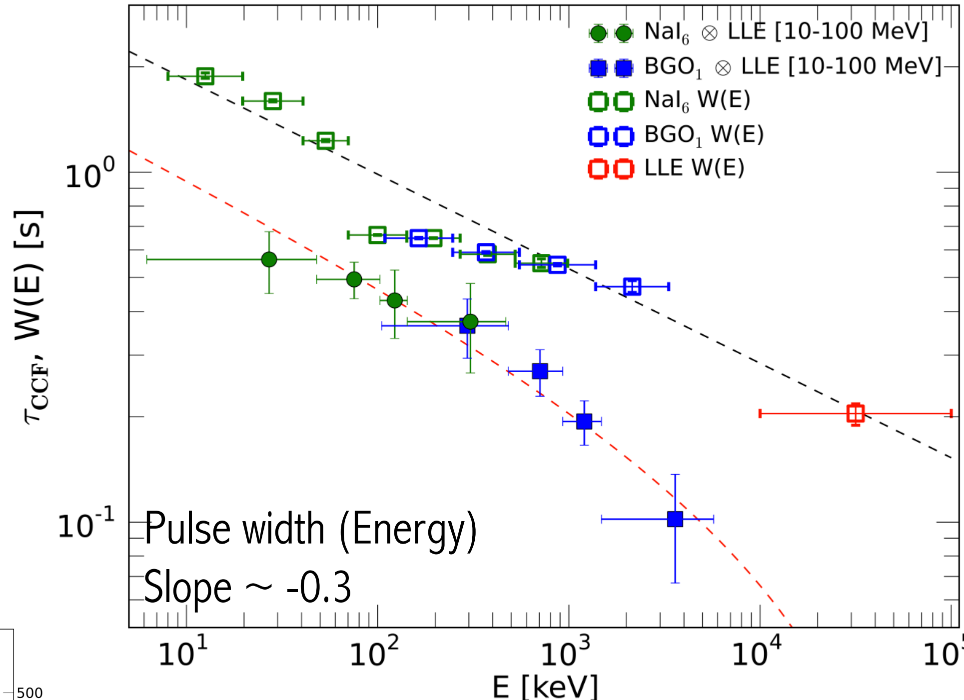


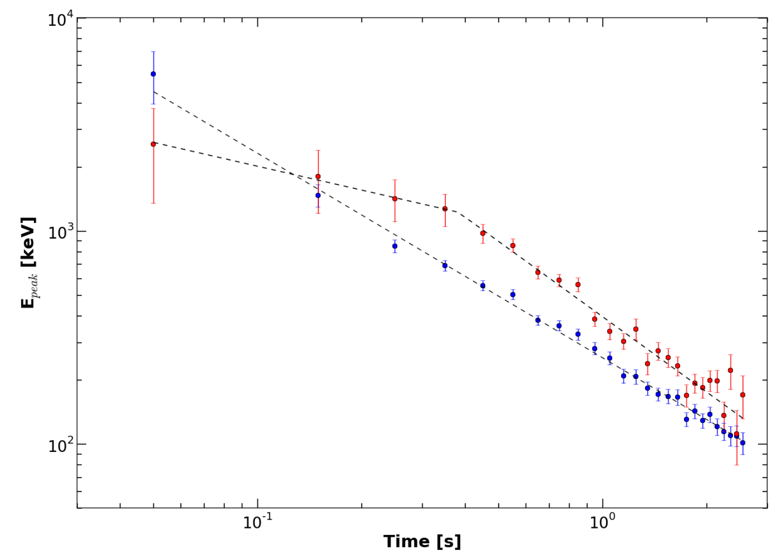
The first 3 s

zoom

Time lags



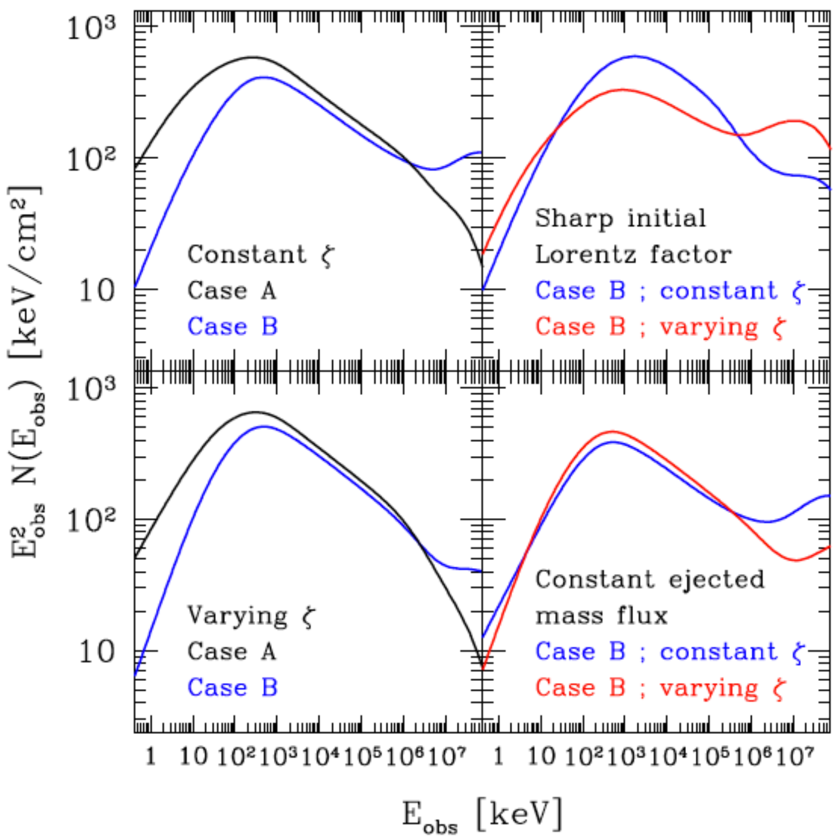


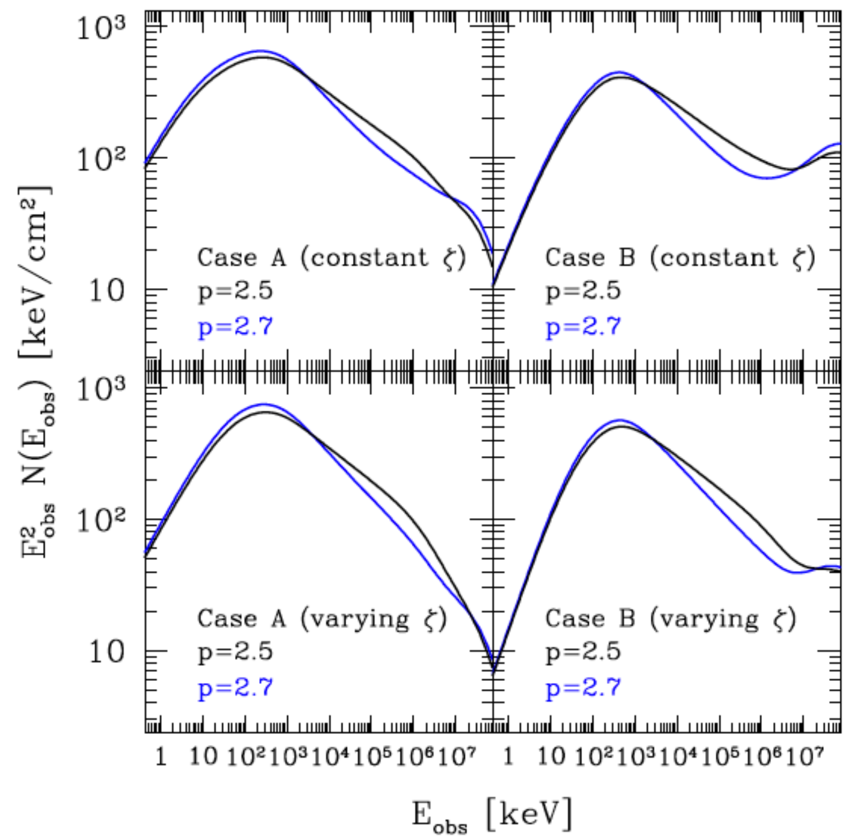


Preece et a.l. 2014

Not shown: hardness-intensity correlation slope 1.4

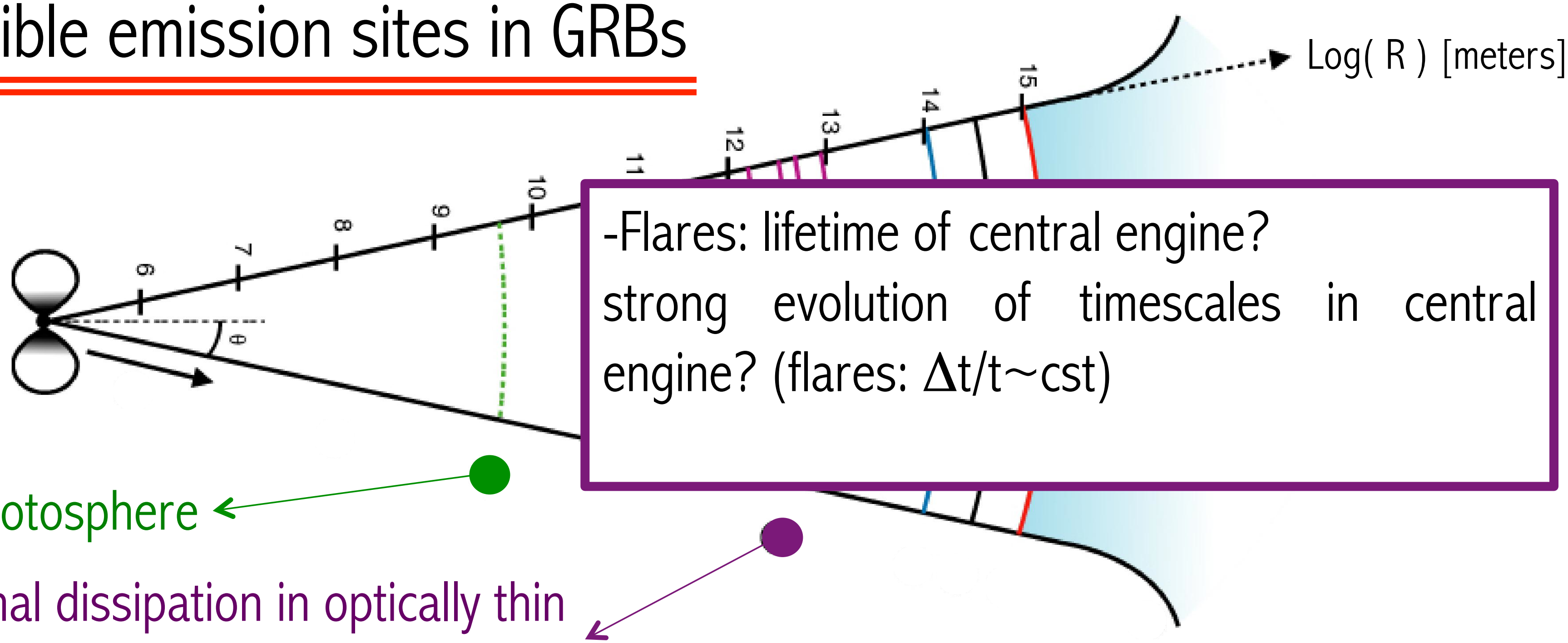
Prompt GeV emission from internal shocks





Bosnjak & Daigne 2014 ; see also Asano & Meszaros.

Possible emission sites in GRBs



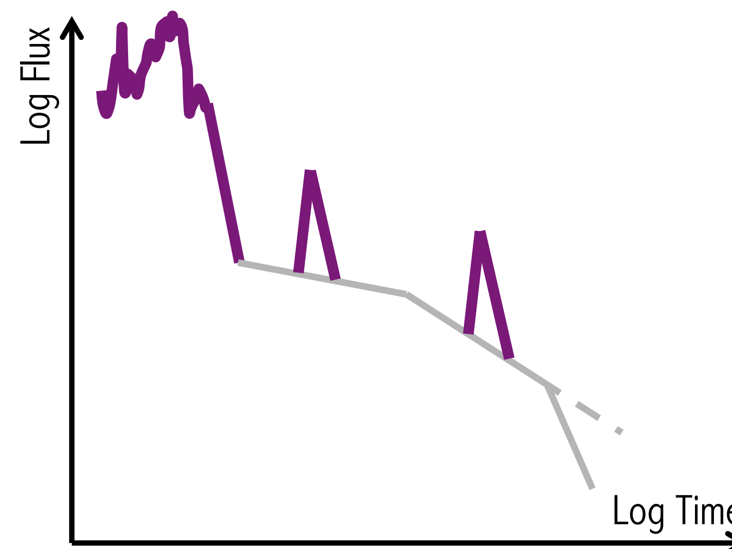
-Flares: lifetime of central engine?
strong evolution of timescales in central engine? (flares: Δt/t~cst)

Photosphere

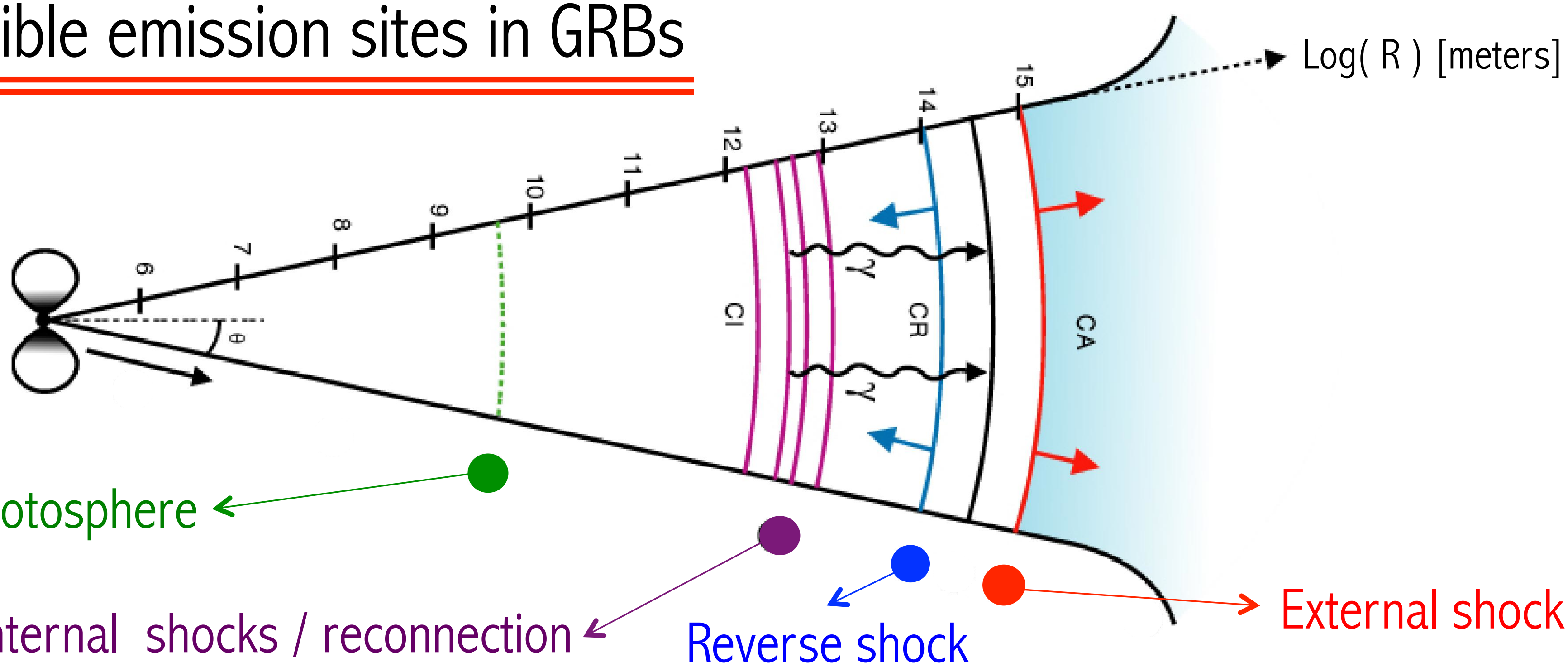
Internal dissipation in optically thin regime (shocks or reconnection)

Prompt emission: dominant non-thermal component?
+additional component ?

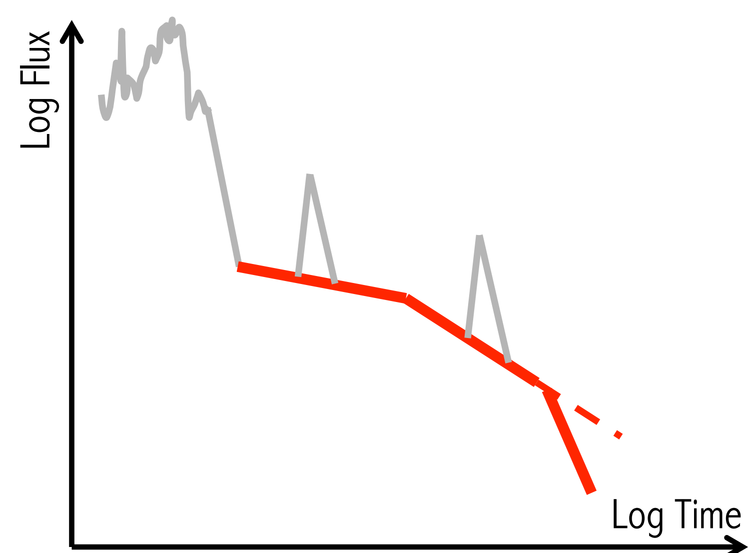
Afterglow: flares?



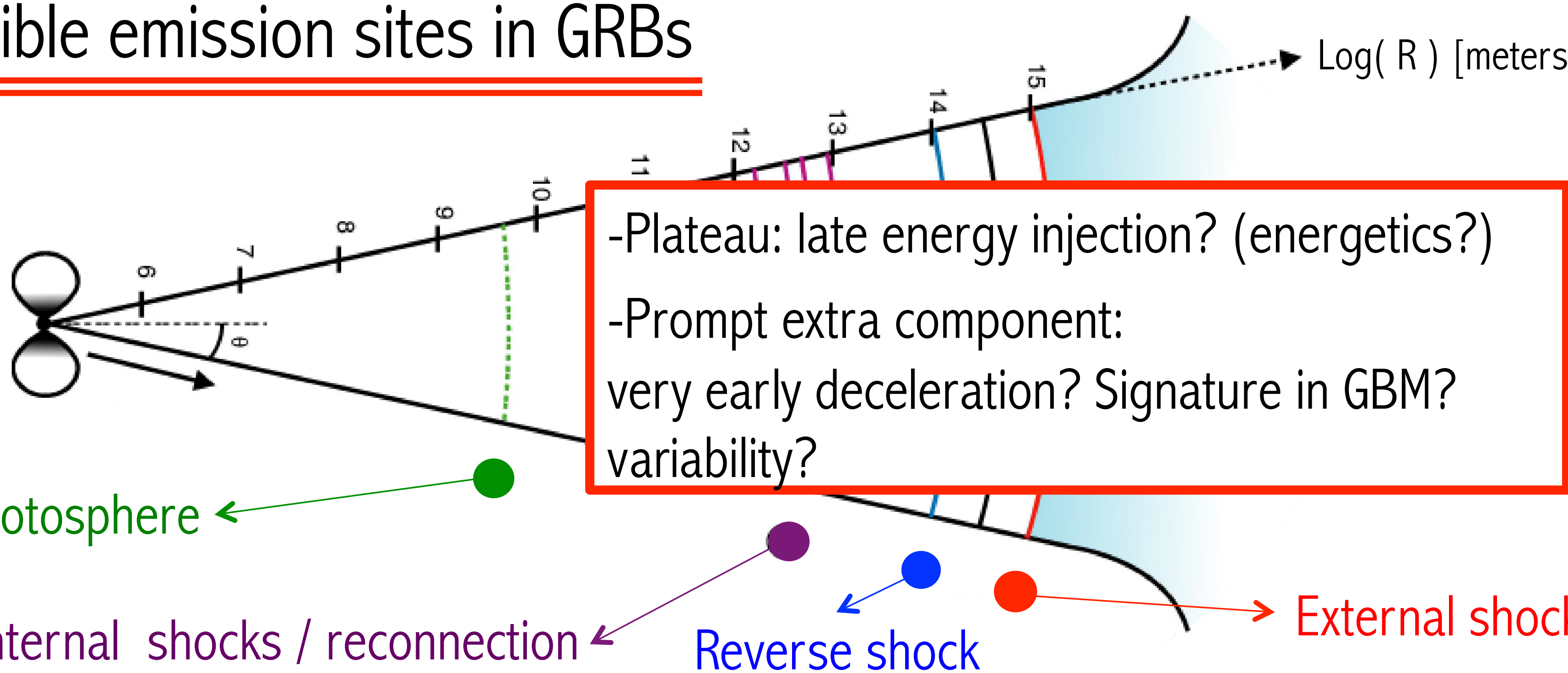
Possible emission sites in GRBs



RS:Prompt optical & FS: Afterglow



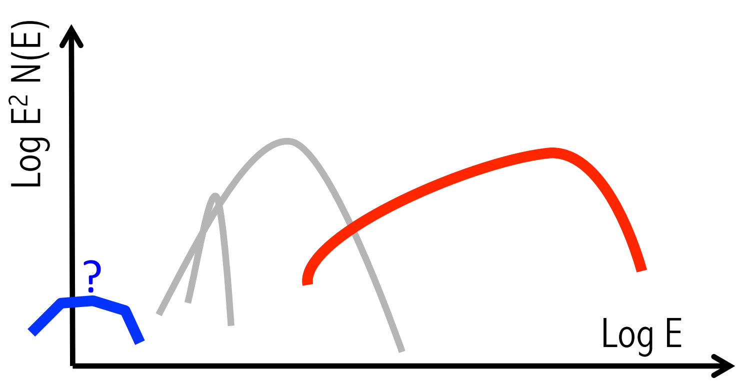
Possible emission sites in GRBs

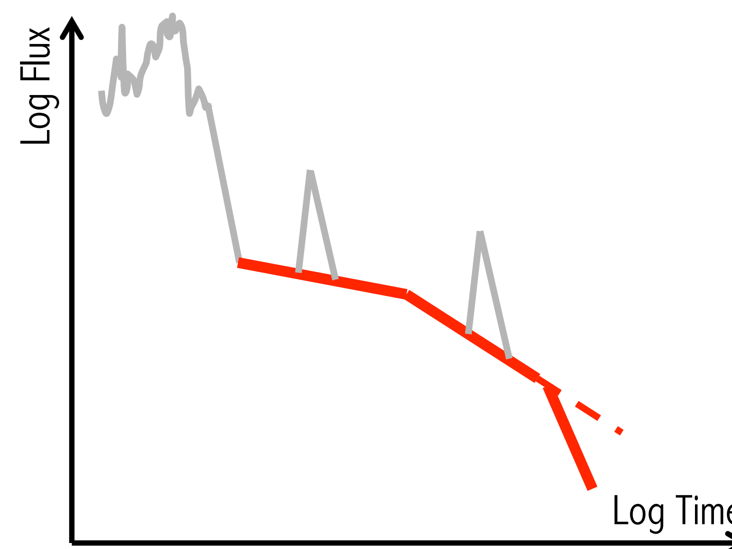


-Plateau: late energy injection? (energetics?)

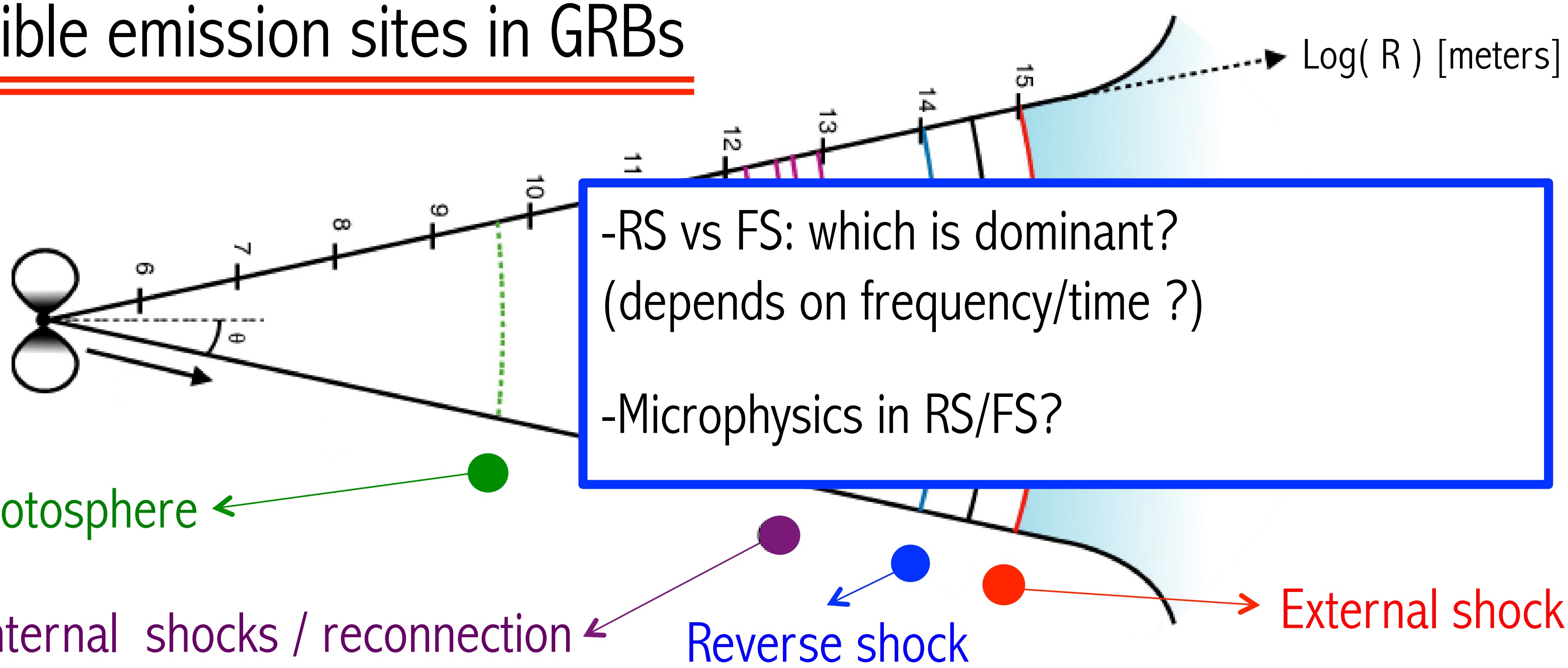
-Prompt extra component:
very early deceleration? Signature in GBM?
variability?

RS:Prompt optical & FS: Afterglow
+prompt additional component?





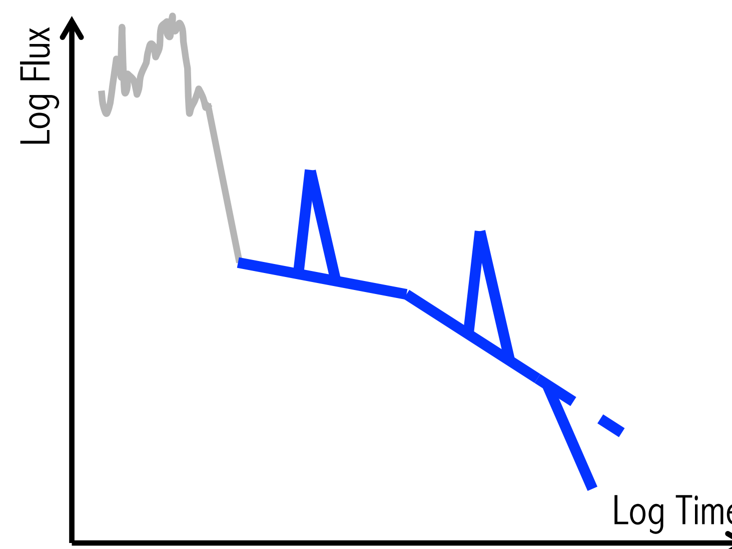
Possible emission sites in GRBs



-RS vs FS: which is dominant?
(depends on frequency/time ?)

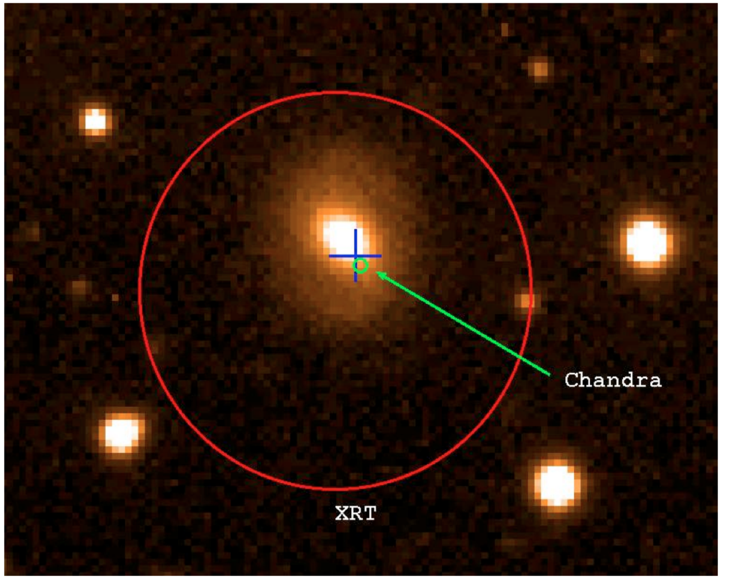
-Microphysics in RS/FS?

Long lived RS: (early ?) afterglow ?



Shorts GRBs

Merger scenario ? Indirect evidence = redshift & host galaxies



GRB 050724 @ VLT

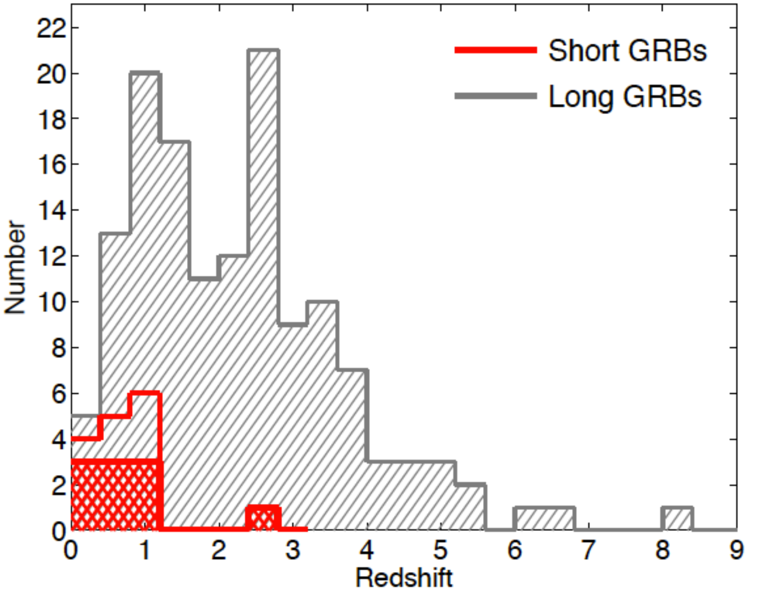
Barthelmy et al. 2005

Short GRBs: no correlation with star formation
offsets
(see recent review by Berger)

In good agreement with the merger scenario

Long GRBs: star forming galaxies

Berger et al. 2011

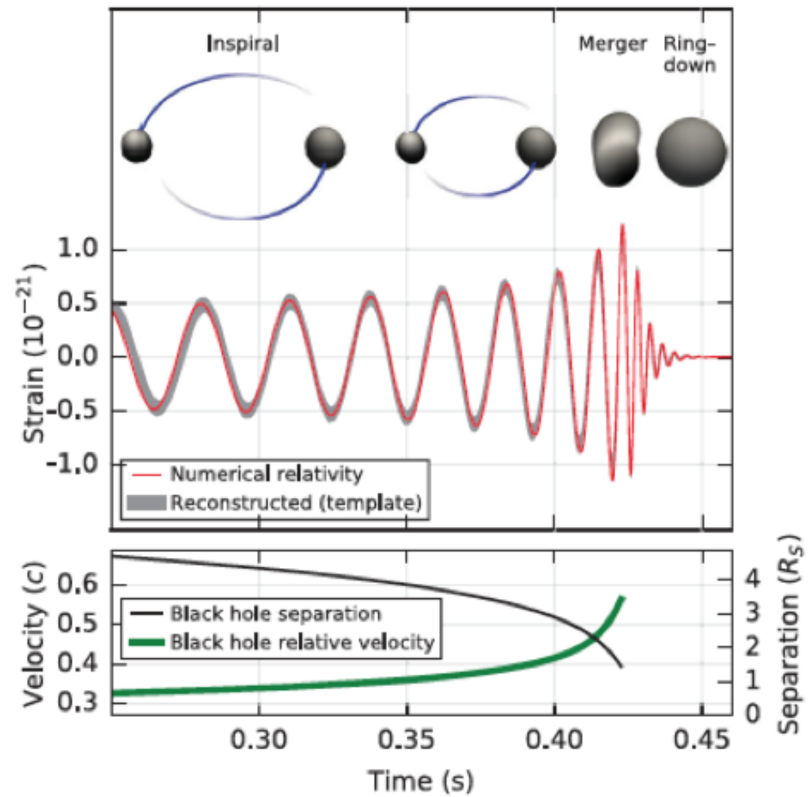


A new challenge: short GRBs in the GW era

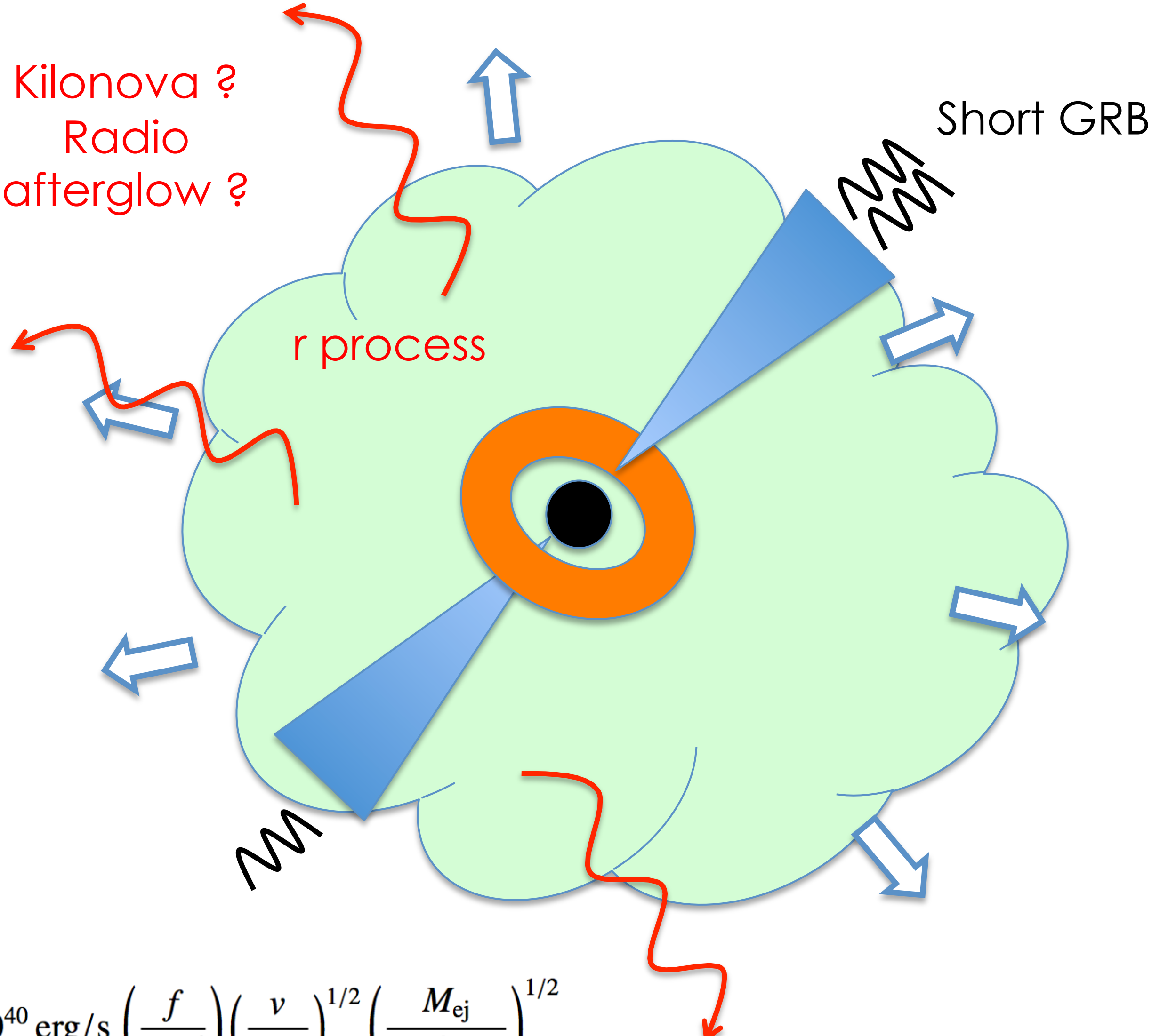
- First detection: GW150914 = BH+BH

- Advanced Ligo/Virgo:
  NS+NS NS+BH mergers are expected soon.

- **Next step: electromagnetic counterparts?**



Final state of a merger



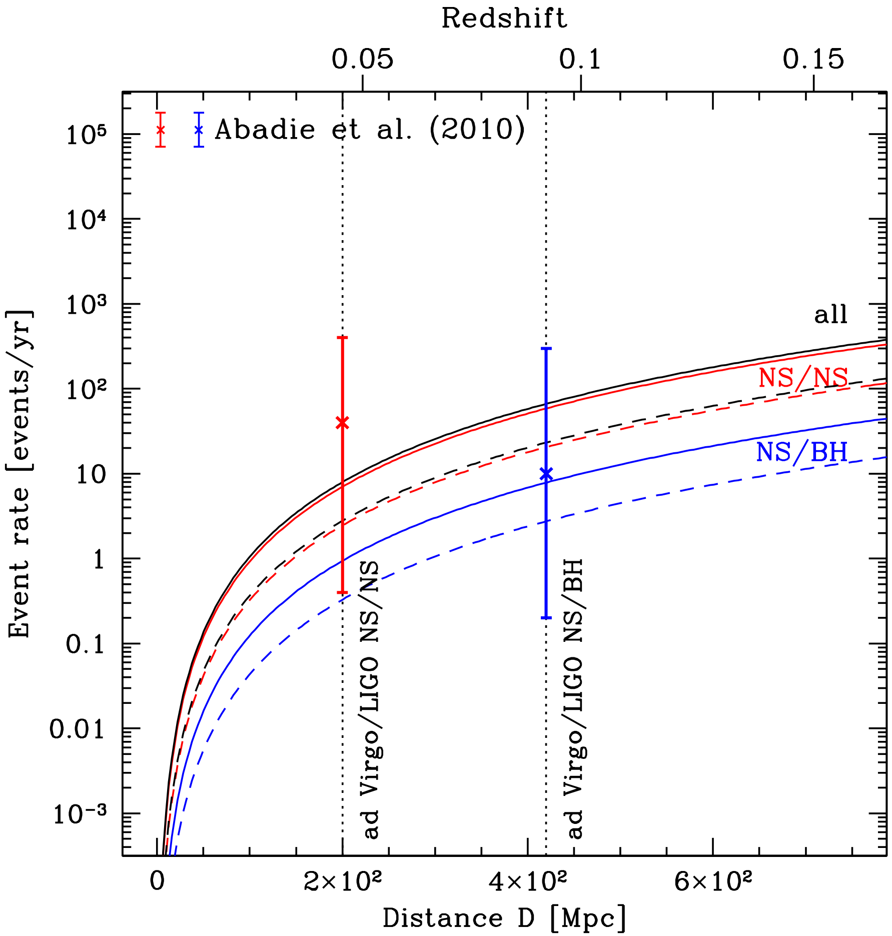
$$L_{\rm KN,peak} \simeq 5\times 10^{40}\,{\rm erg/s}\left(\frac{f}{10^{-6}}\right)\left(\frac{v}{0.1c}\right)^{1/2}\left(\frac{M_{\rm ej}}{10^{-2}\,M_\odot}\right)^{1/2}$$

(Metzger et al. 2010)

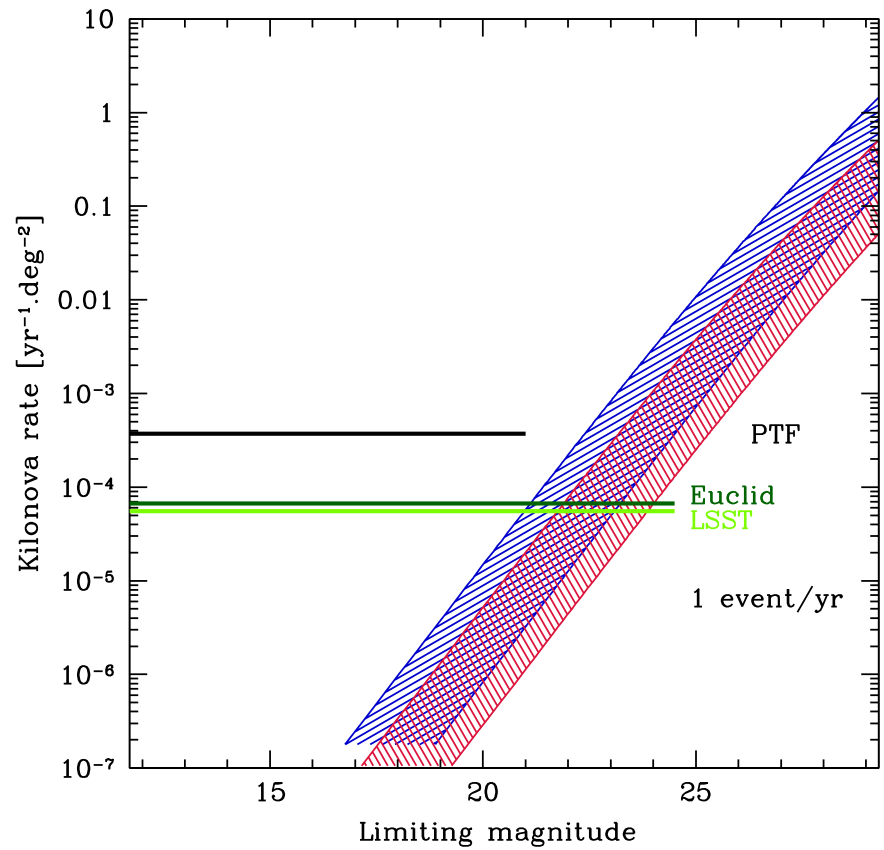
Original figure by B. Hotokezaka + M. Shibata

R process: constraints on the merger rate

Merger rate:

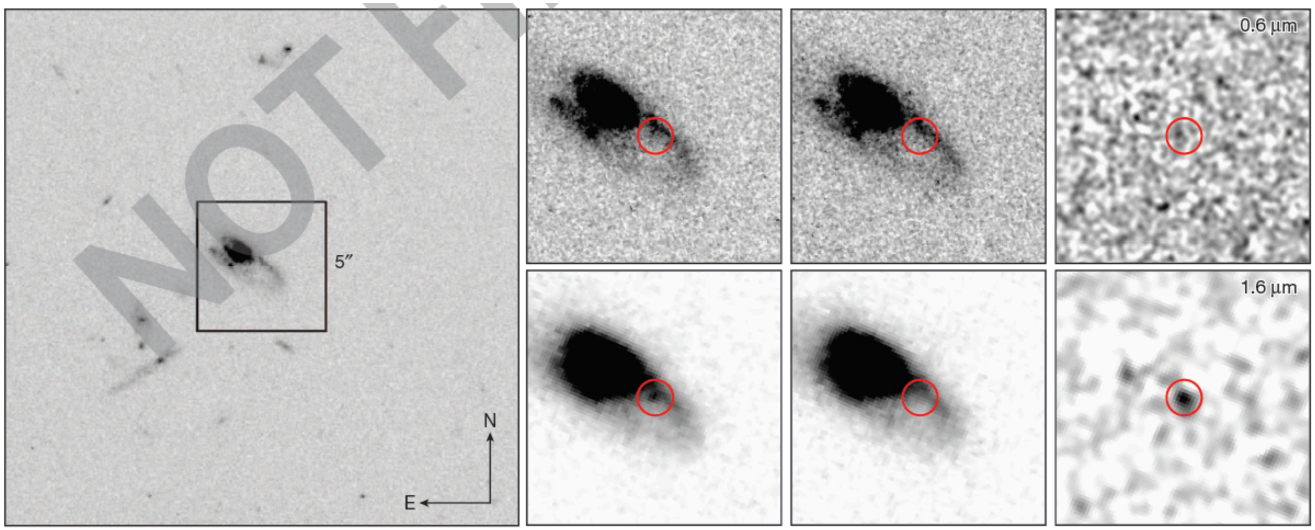


Kilonova rate:



Vangioni, Goriely, Daigne, François & Belczynski (2016)

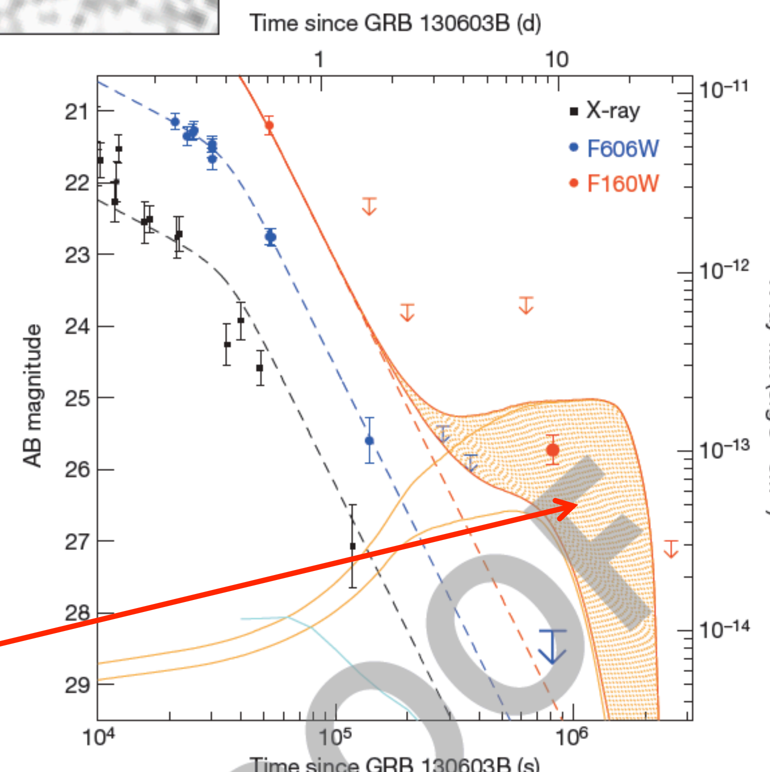
A first association short GRB + kilonova?



Tanvir et al. 2013

GRB 130603B (short GRB)

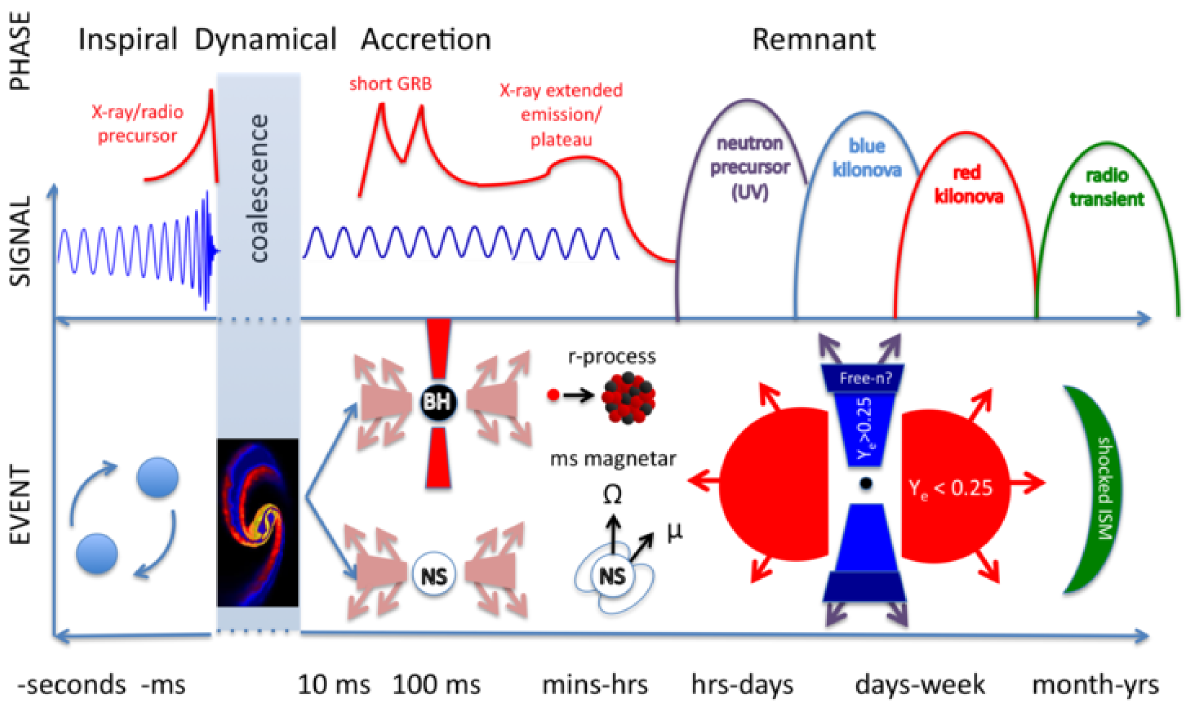
A few other candidates…



Kilonova ?

Expected counterparts

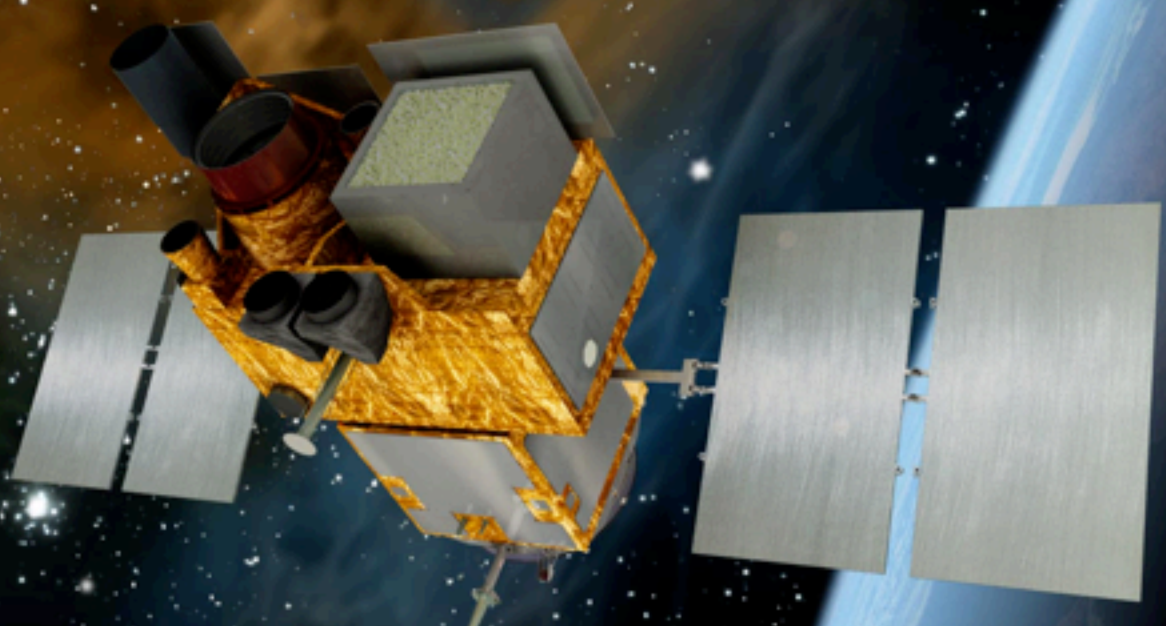
- **Gamma-rays:** Short GRB (+ soft tail ?)
- **X-rays:** X-ray afterglow
- **Visible:** Visible afterglow
  Kilonova
- **Radio** radio afterglow from the non-relativistic ejecta ?



Fernandez & Metzger (2015)

SVOM

SVOM



NAOC, Beijing
XIOPM, Xi'an
NSSC, Beijing
CEA-Irfu, Saclay
APC, Paris
LAM, Marseille
CPPM Marseille
GEPI Meudon
U. of Leicester
CNES, Toulouse

IHEP, Beijing
SECM, Shanghai
IRAP, Toulouse
IAP, Paris
LAL Orsay
LUPM Montpellier
Obs. Strasbourg
MPE, Garching

SVOM in context

- SVOM = Space-based multiband astronomical Variable Objects Monitor

- SVOM is a multi-wavelength Chinese-French mission dedicated to the transient sky.
- SVOM is a mission deployed on the ground and in space.
- The space segment of SVOM is planned to be launched early in the next decade (2021), for a 3 year nominal mission.

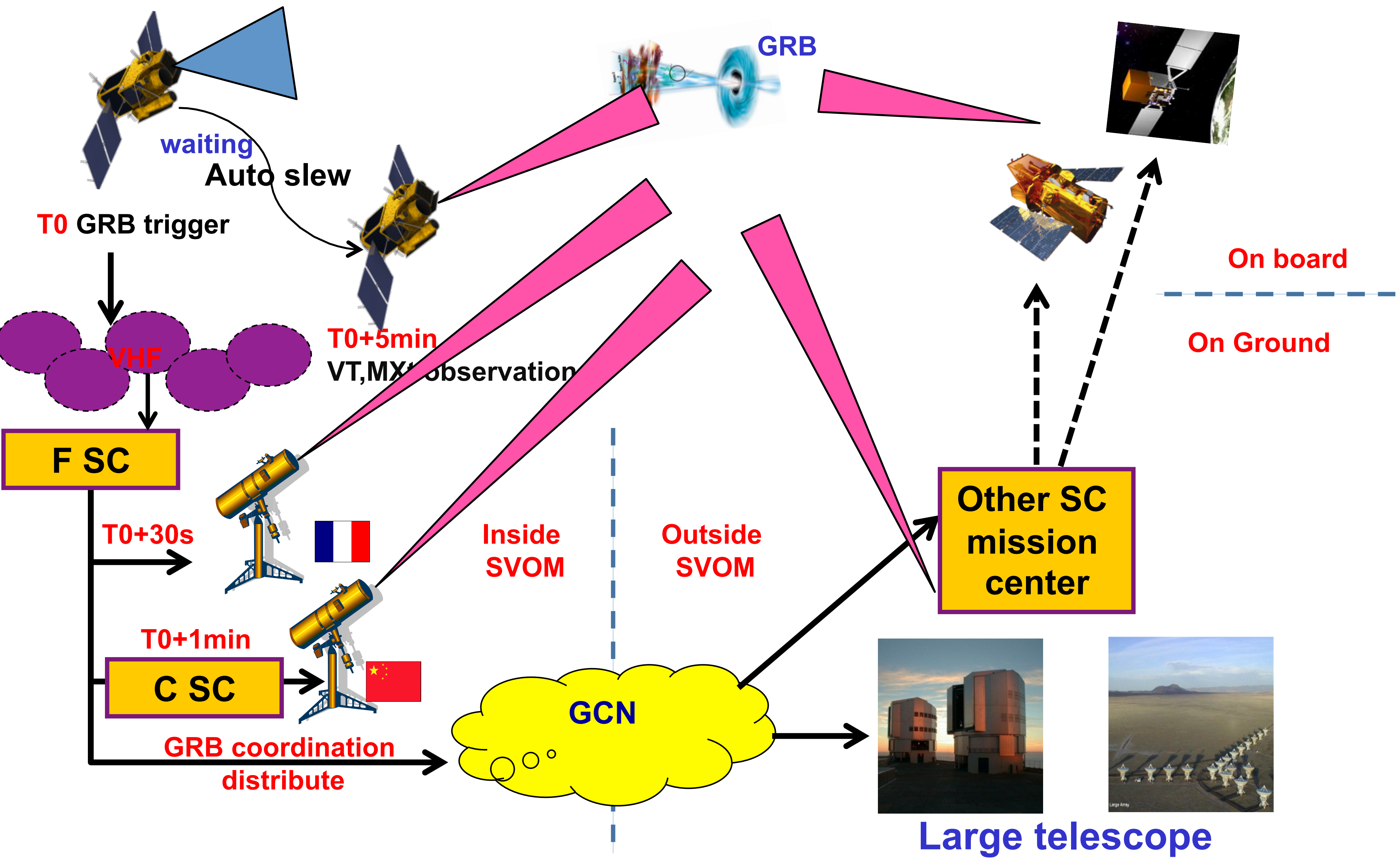
- SVOM is entering phase C soon (successful end of phase B PDR in Yantai last July)

SVOM science:

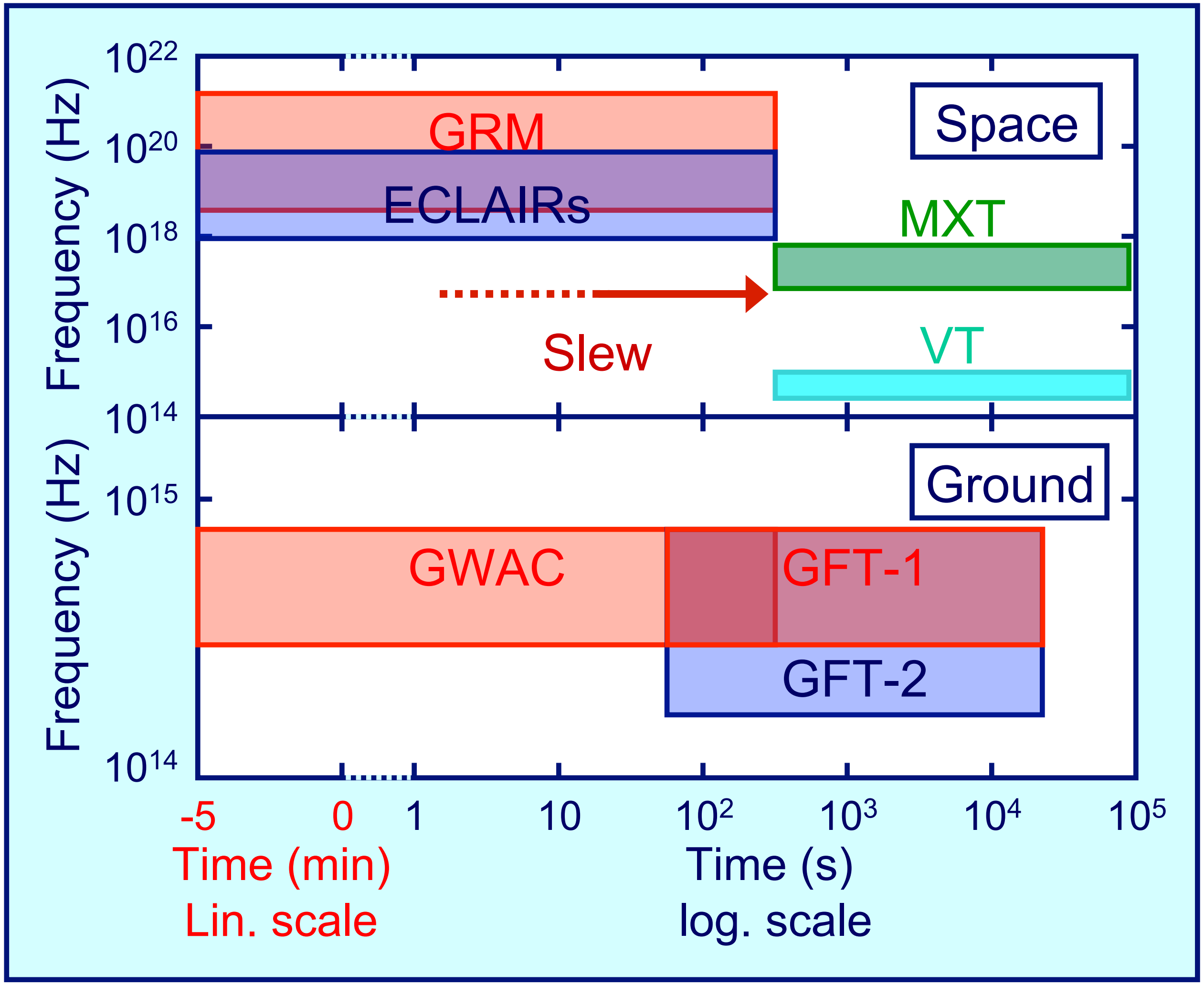
- Core program: GRB physics + GRB as a tool for cosmology
- Multi-wavelength observation of transient phenomena
- Follow-up: GW, HE neutrinos, but also: radio, V/IR, HE gamma-rays (CTA)
- Observatory program


SVOM
Satellite ~ 930 Kg
Payload ~ 450 kg
MXT
VT
ECLAIRs
GRM
GFT-2
GWAC
GFT-1

GRB observation scenario:



SVOM: spectral and temporal coverage



SVOM will be operational when time domain astronomy will truly come of age in terms of multi-wavelength, wide-field sky coverage plus multi-messenger information.

GRB Budget - B1 attitude law - 5°	1 year	3 years	5 years
Number of GRBs detected by ECLAIRs AlertThreshold **6,5 σ**	**44** **78**	132 234	220 391
Number of GRBs detected by GRM	90	270	450
Number of GRBs observable with GWACs	6 (12) 10 (21)	17 30	29 51
Number of Slew request Slew Treshold **8 σ**	**38** **71**	113 213	188 356
Number of GRBs immediatly observable by VT & MXT for at least 5 minutes	25 47	74 141	124 235
Number of GRBs immediatly detected by MXT	34 64	102 192	169 320
Number of GRB immediatly observable with GFTs	16 29	48 86	76 136
Number of GRBs immediatly observable by GFTs and LCOGT	33 59	99 176	159 282
Number of GRBs observable by at least one Ground Large Telescope	29 54	86 162	135 255

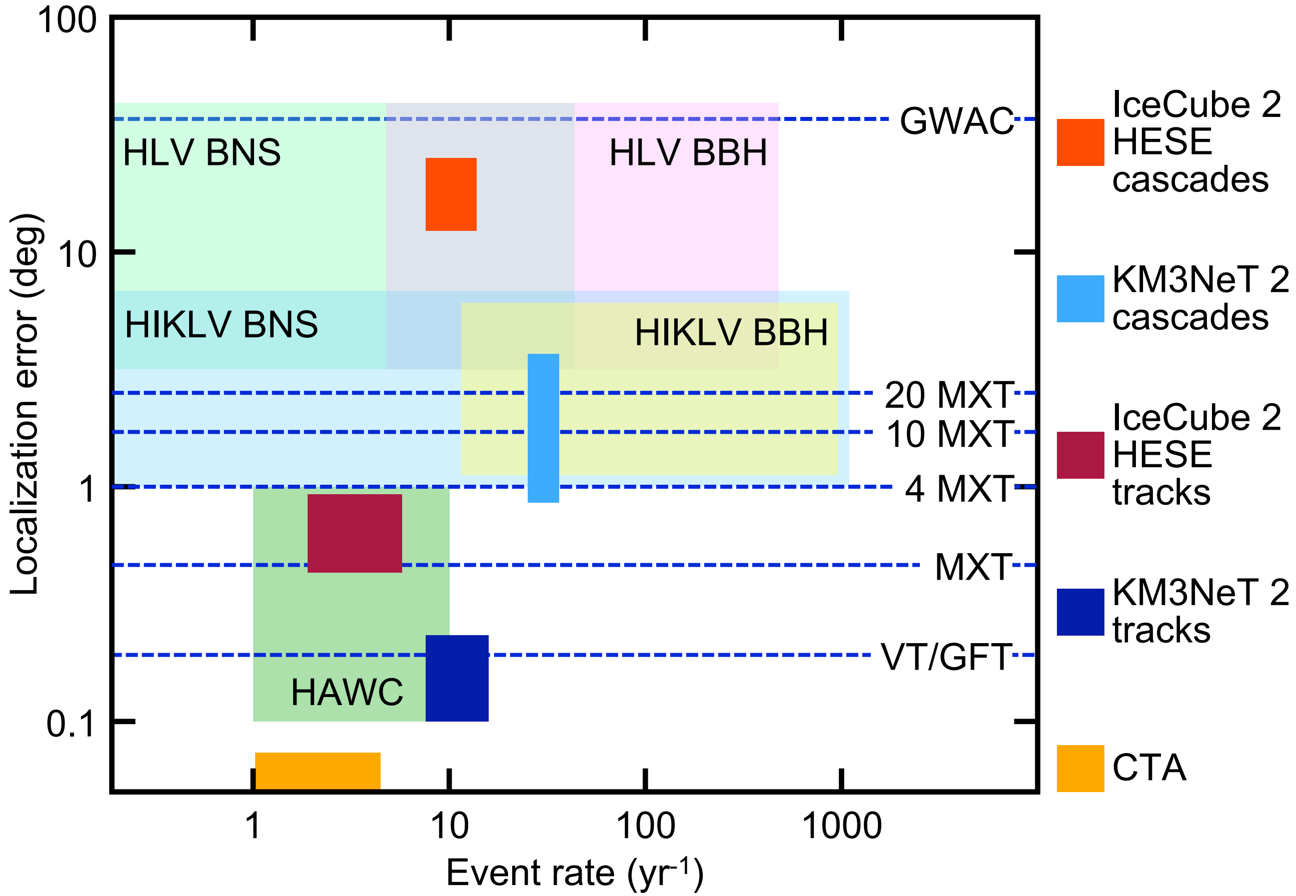
Prompt

Slew

Afterglow

Instrumental context:

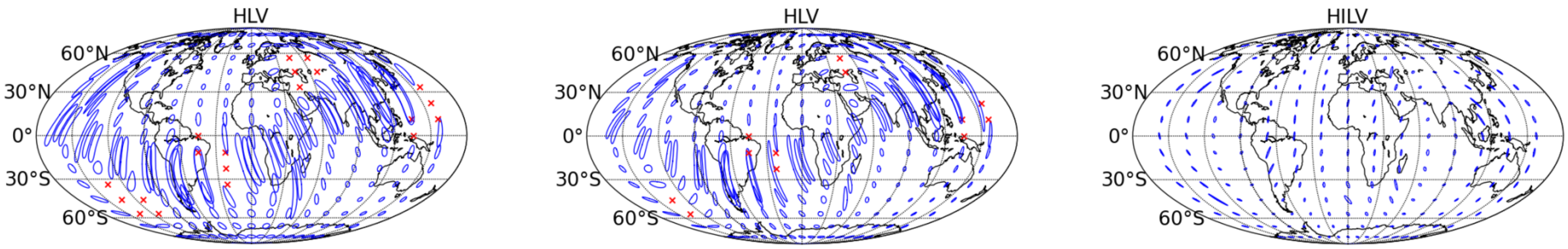
Search for SVOM counterparts to multi-messenger triggers



Perspective in terms of event rates and localization errors for multimessenger triggers

SVOM and the Gravitational Waves at the beginning of the next decade

GW observations in 2020+



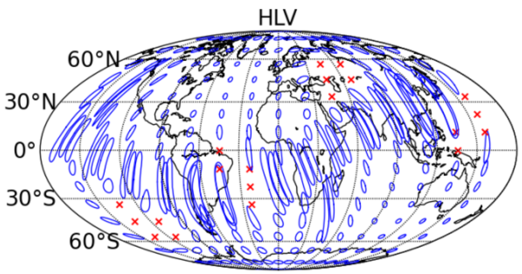
2015 2019 2022

- In 2020+ the network should be able to detect NS+NS/BH mergers within an error box of a few deg^2.

- Expected NS-NS mergers detection rate: about 40/year within 445 Mpc (z~0.1)
- Expected BH-NS mergers detection rate: about 10/year within 927 Mpc (z~0.2) (Abadie et al. 2010: large uncertainties)

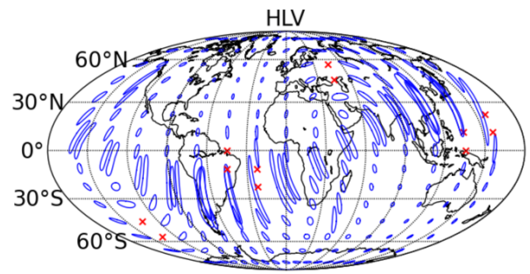
- SVOM launch: end of 2021

GW observations in 2020+: SVOM instruments

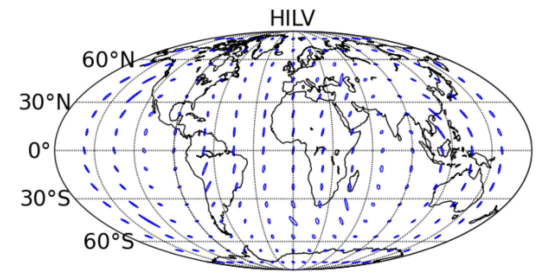


2015

Error box: ~>100 Sq.Deg

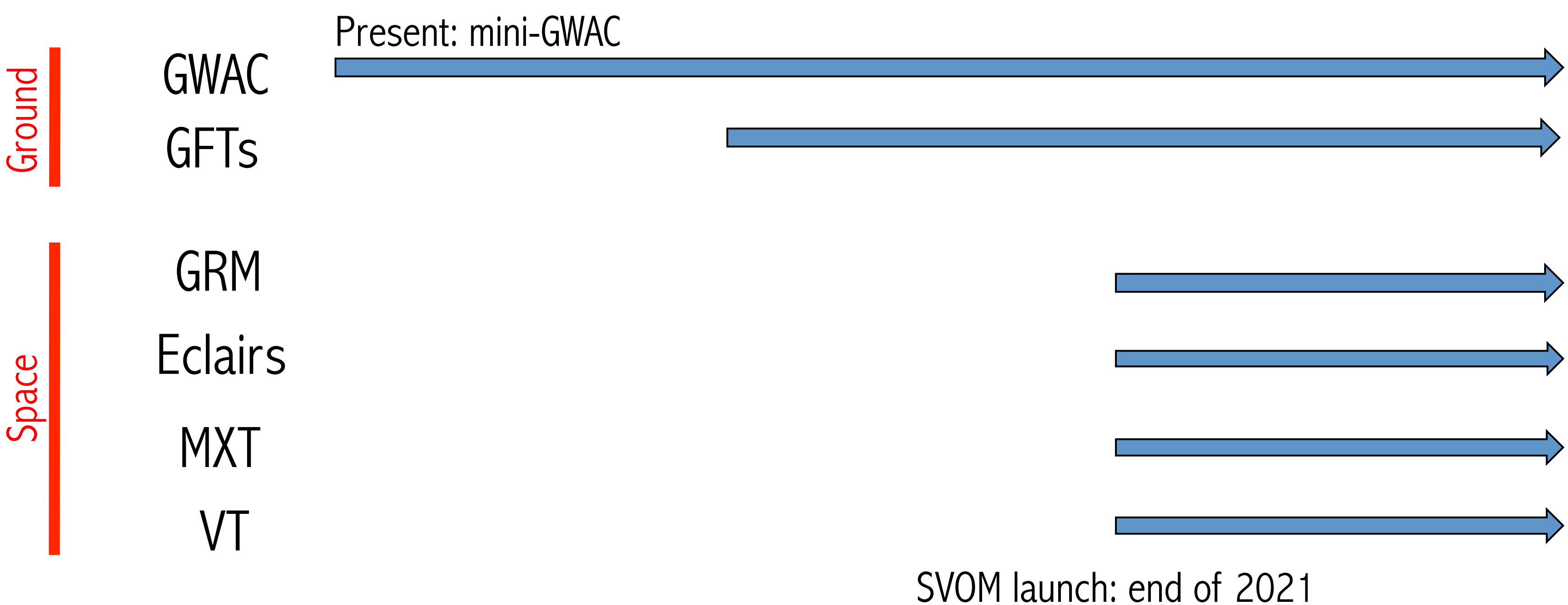


2019



2022

~<10 Sq.Deg.



Expected rates: SVOM lifetime = 5 years

- Large uncertainties in the intrinsic merger rates + GRB physics (jet opening angle)
  Usually assume:
  100% of NS-NS/NS-BH mergers lead to a GRB ; opening angle = 5-15°

  ~ 15 mergers+GRB/5 yr (4-34 with GRB uncertainties ; factor 10 for mergers…)

- SVOM large field of view instruments (ECLAIRs+GRM)
  Detection efficiency + f.o.v.: **0.3 to 4 mergers+GRB/5 yr for ECLAIRs or GRM3**
  1 to 8 mergers+GRB/5 yr for GRM1

- GW alert + afterglow: SVOM narrow-field instruments (MXT, VT)
  Detection efficiency + delay: **2 to 14** post-merger afterglows/5 yr for MXT
  [assumes GW error box of a few degrees in 2022+]

- Ground-based SVOM instruments: take into account weather…
  1 to 9 post-merger optical search/5 yr for GWAC2

- **Also VT, GFT, search for KN, …**

SVOM: summary

- SVOM science:
  - Core program: GRB physics + GRB as a tool for cosmology
  - Multi-wavelength observation of transient phenomena
    Follow-up: GW, HE neutrinos, but also: radio, V/IR, HE gamma-rays (CTA)
  - Observatory program

- Exemples:
  - Sample of GRBs with prompt+aferglow+redshift (cf. difficulty Swift <u>or</u> Fermi)
  - Explore the GRB diversity (soft, ultra-long GRBs, ...): the fate of massive stars
  - Synergy with CTA/HE neutrinos
  - Search for short GRBs / kilonovae in association with GW
  - High redshift galaxies

SVOM white paper to appear soon!

The Deep and Transient Universe: New Challenges and Opportunities

A White Paper in support of the CNSA/CNES SVOM Mission

J. Wei, B. Cordier, et al.
(For full list of contributors see overleaf)

Frontispiece : Artist view of the SVOM satellite

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