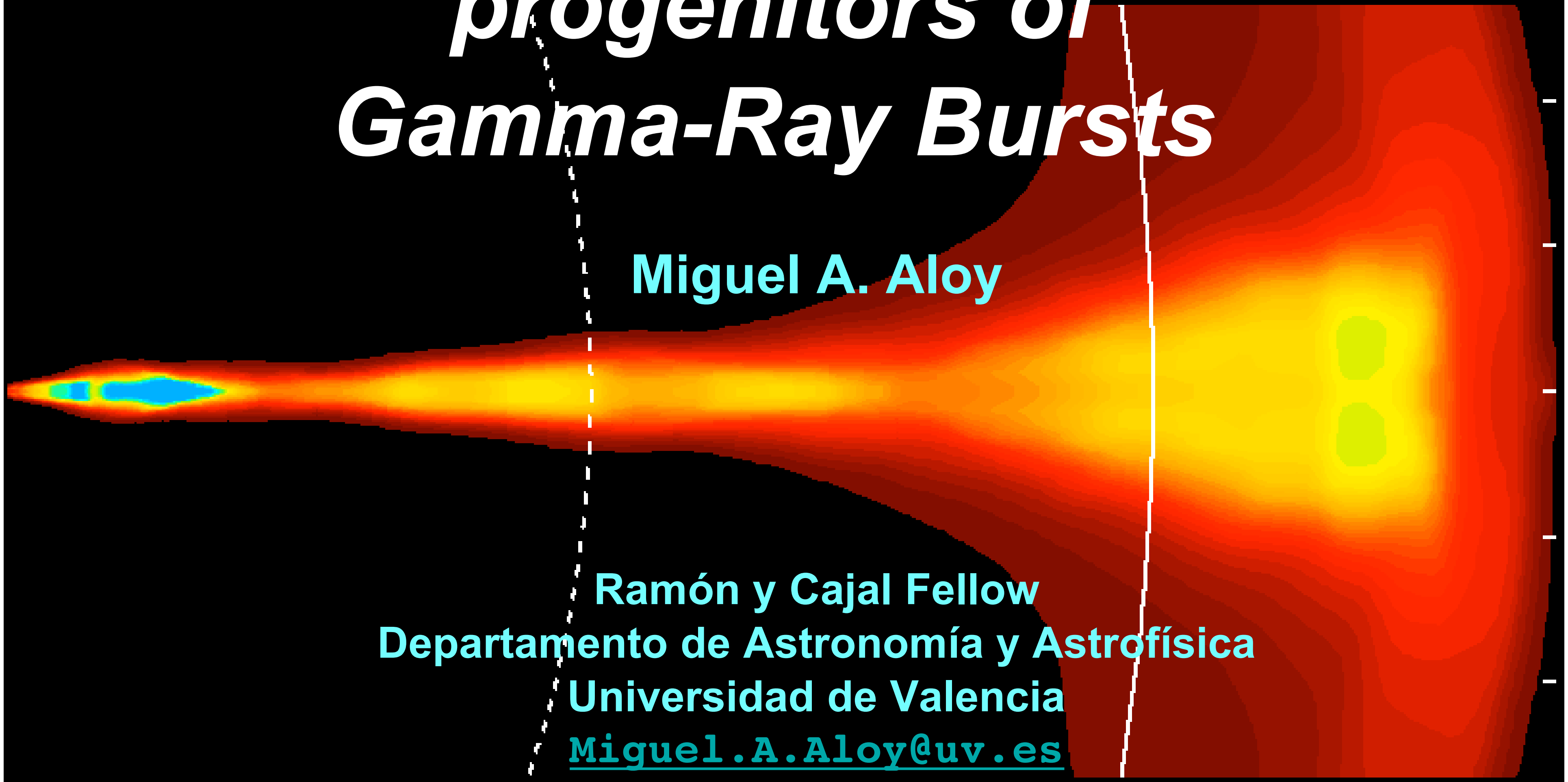
The elusive nature of progenitors of Gamma-Ray Bursts



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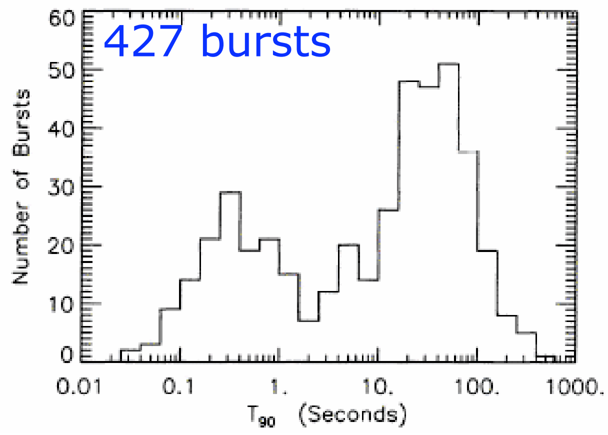
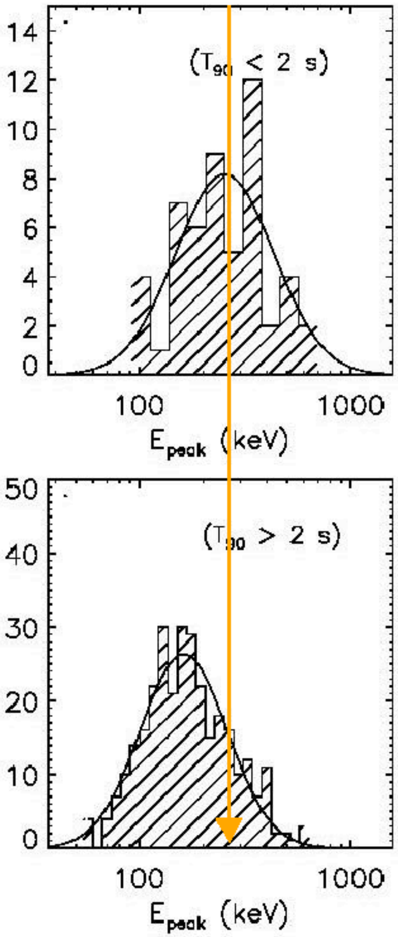
Introduction: definition and GRB types

- Definition: *GRBs are the most luminous events known in the universe since the Big Bang. They are flashes of γ-rays, coming from seemingly random places in the sky and at random times, that last from milliseconds to many minutes, and are often followed by "afterglow" emission at longer wavelengths (X-ray, UV, optical, IR, and radio).* [G.J. Fishmann, http://en.wikipedia.org/wiki/Gamma_ray_bursts#_ref-17]

- Types:
  - Short-hard GRBs (sGRBs): $T_{90} < 2$ s, harder, power law + exp cutoff
  - Long-soft GRBs (lGRBs): $T_{90} > 2$ s, softer, Band function





3rd BATSE GRB catalogue (Meegan et al. 1996)

General Properties of GRBs

Observed:

- Duration: 0.01-1000 s
- Fluence: $S \sim 10^{-7}$-10^{-3} erg/cm^2
- Spectrum: non-thermal,
  0.1-100 MeV
- Variability: high, 1-10 ms
- Rate: 1/day **(lGRBs)**
  0.3/day **(sGRBs)**
- Location:

  lGRBs: z=0.085 - 6.3, <z>~2.5,
  sGRBs: z=0.16 - 4.6(?), <z>~0.3

Associated events: afterglows in X-rays (~100%), optical (~70%), radio (~50%)

$F(t) \sim t^{-a}$ $a \sim 1 - 2$

Derived (lGRBs):

- Isotropic energy deposition

  $E_{iso} = 4\pi d_L{}^2 F/(1+z) \sim 10^{51}$ -10^{54} erg

  (but 980425 ~10^{48}erg)

  sGRBs: $E_{iso} \sim 10^{47}$ -10^{51} erg
- Evidences for jets due to the breaks in the afterglow-LC

  $\theta_j \sim 0.5^o$-10^o (lGRBs)
  $\theta_j \sim 5^o$- 20^o (sGRBs)
- Evidences for existence of ‘standard’ energy deposition

  $E_k \sim 5\text{x}10^{50}$erg
  $(E_k + E_\gamma) \sim 2\text{x}10^{51}$erg

  (Berger et al. 2003)
  (but 031203 < 10^{50}; Soderberg et al. 2004)
- Correlations (photon energy)

  $\nu F_\nu \sim E_{iso}$ (Amatti et al. 03, Ghirlanda et al. 04)

Relativistic outflows in GRBs?

- Our current understanding is that GRBs are the *birth cries* of stellar-mass BHs
- In other systems where (hyper-)accreting BHs fuel astrophysical jets (AGNs and BH X-ray binaries), there is a direct evidence of relativistic outflows and jet collimation (imaging)

  ⇒ Reasonable to believe that also GRBs are the result from *relativistic*, *collimated* outflows from accreting, stellar-mass BHs.
- We know that outflows yielding GRBs are *relativistic* because of
  - Observational constraints:
    - Radio scintillation of the interstellar medium (Frail et al. 1997)
    - Superluminal proper motions in imaged afterglows (Taylor et al. 2004)
  - Theoretical constrain: Compactness problem (Cavallo & Rees 1978)
- BUT, so far only *indirect evidence of collimation* based on:
  - Observational constraints:
    - Achromatic break in afterglow LCs (e.g., Harrison et al. 1999)
  - Theoretical constrains:
    - Reduced energy (Rhoads 1999; Sari et al. 1999): $E_\gamma = f_\Omega E_{\gamma,\mathrm{iso}}$, $f_\Omega \sim \theta_j^2/2$
    - **Simulations of progenitors yield collimated outflows** (e.g., Aloy et al. 2000)

GRBs, collimation: jets, winds

If GRBs are collimated jets they would radiate only in a fraction of the sky (Rhoads 1999; Sari et al. 1999) : $f_\Omega = (1\text{-cos }\theta_j) \sim \theta_j^2/2$

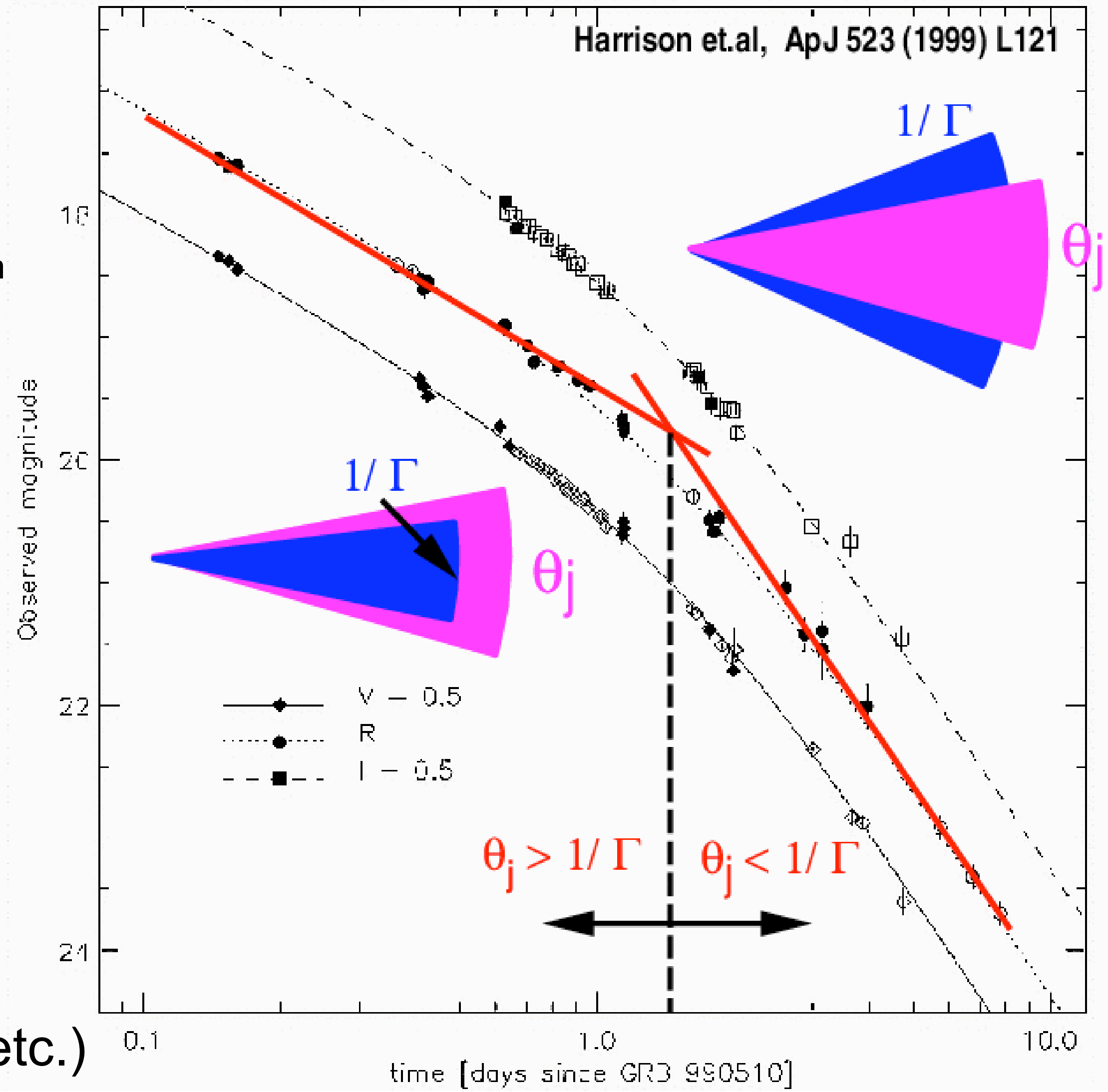
Relativistic beaming:

(at any time) ~ $1/\Gamma$

early: $\theta_j > 1/\Gamma \Rightarrow LC_{sphere} = LC_{beam}$

later: Γ drops $\Rightarrow \theta_j < 1/\Gamma$ for $t > t_b$

$\Rightarrow$ break in LC



GRB 990510:

$E_{\gamma,iso} = 3\text{x}10^{53}$ erg (observed)

$\Gamma_b \sim 12 \Rightarrow \theta_j \sim 4.8^o$

$\Rightarrow$ $E_\gamma = f_\Omega \, E_{\gamma,iso} = 1$ FOE (intrinsic)

Picture challenged by SWIFT!

(chromatic breaks, plateaus, etc.)

Fireballs: how are GRBs produced?

- Releasing ~ 10^{30} erg $cm^{-3}s^{-1}$ implies the formation of an e^+e^-, γ fireball (Cavallo & Rees 1978).

- Compactness problem: Since most of the energy detected is >0.5 MeV, the optical depth against $\gamma\gamma \Rightarrow e^+e^-$ is huge and photons cannot escape!

$$\tau_{\gamma\gamma} = 10^{13}\, f_p\, F_{-7} (D\,/\,3\mathrm{Gpc})^2\, (\Delta t\,/\,10\mathrm{ms})^{-2}$$

- Relativistic expansion reduces the effective threshold energy for pair production (Fenimore et al. 1993):

$$\Gamma \sim 100(\varepsilon_\gamma/10\ \mathrm{GeV})^{1/2}(\varepsilon_t/\mathrm{MeV})^{1/2}$$

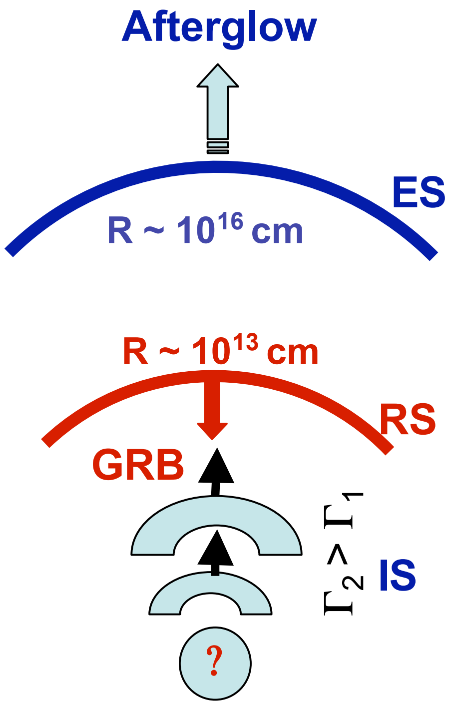
$$\tau_{\gamma\gamma} = 10^{13}\,/\,\Gamma^{4+2\alpha}\, f_p\, F_{-7} (D\,/\,3\mathrm{Gpc})^2\, (\Delta t\,/\,10\mathrm{ms})^{-2}$$

- Theoretically, a relativistic outflow results if an initial energy E_0 is imparted to a mass $M_0 \ll E_0/c^2$ (Relativistic Sedov solution; Blandford-McKee 1976).

- Expanding from r_l the gas converts its E_{int} into E_{kin} until $\Gamma \sim E_0/M_0c^2$ which happens at $r_s \leq r_l\Gamma$, beyond which the flow coasts with $\Gamma \sim 100$ (constant).

Fireballs: how are GRBs produced?

- γ-emission: produced either by internal shocks in the expanding shell, or by external shocks in an heterogeneous ISM.
  - – Internal shocks ⇒ *inside* the *GRB*
  - – External shocks (ES) ⇒ interaction GRB/ISM.
    - After the coasting phase: approx. self-similar deceleration of the ES $\Gamma_{BM} \sim r^{-3/2}$ (Blandford & McKee, 1976)
    - The ES produces the *afterglow* in X-rays, optical and radio
  - – Particle acceleration in shocks ⇒ *non-thermal spectra*



- Initial interaction of the GRB matter ⇒ Reverse shock (RS) propagating towards the fireball interior and decelerating the fluid.
  - – The RS *erases the memory* of the initial conditions, thus, it is hard to obtain information about the progenitor by looking at the afterglow

⇒ afterglow = smoking gun!

Progenitors: are GRBs the birth cries of black holes?

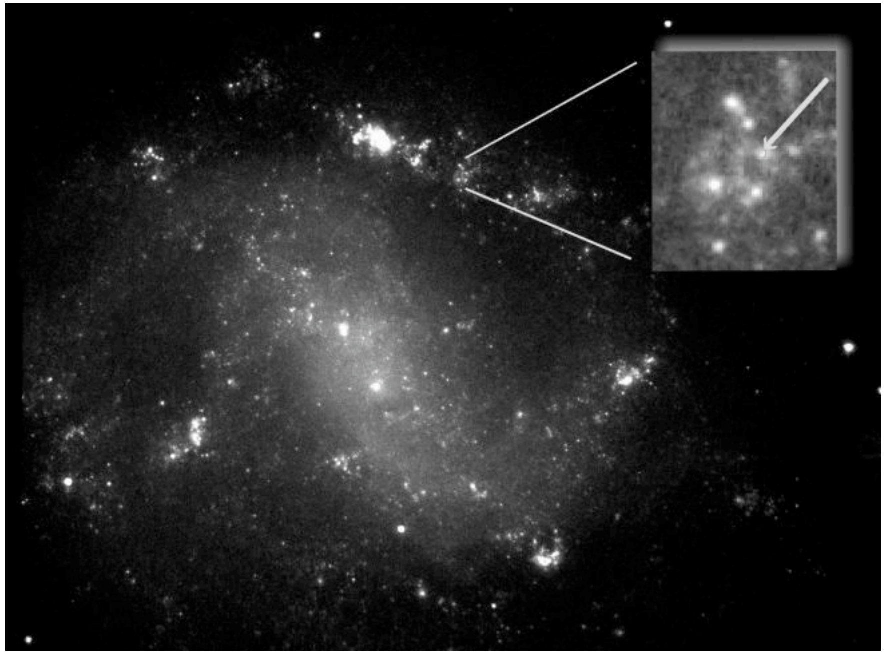
- Our knowledge about the astrophysical objects yielding GRBs is only indirect.
  - progenitors are 10^{-6}-10^{-7} times smaller than GRBs themselves and we can´t observe them!

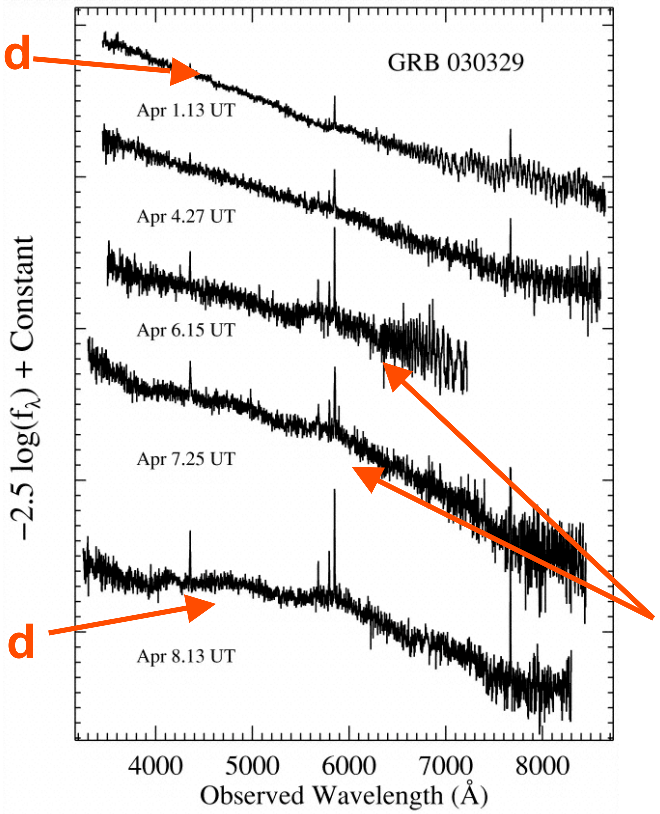
- But we have some hints:
  - Energy ~ rest mass energy of our Sun
  - Association with other high energy phenomena (SNe).
  - Host galaxies ⇒ environment where GRBs are produced.
  - Rates
  - Lack of repetitions ⇒ catastrophic events
  - Variability is high ⇒ produced in regions ~ 10^6-10^7 cm

Some evidences of lGRB/SN association

Two main indications:

1. **Photometry: GRB980425 / SN 1998bw in nearby galaxy ESO184-g8 (Galama et al. 1998; z=0.085)**





GRB+2.64 d

GRB+9.64 d

Broadening of the spectral peaks characteristic of SN

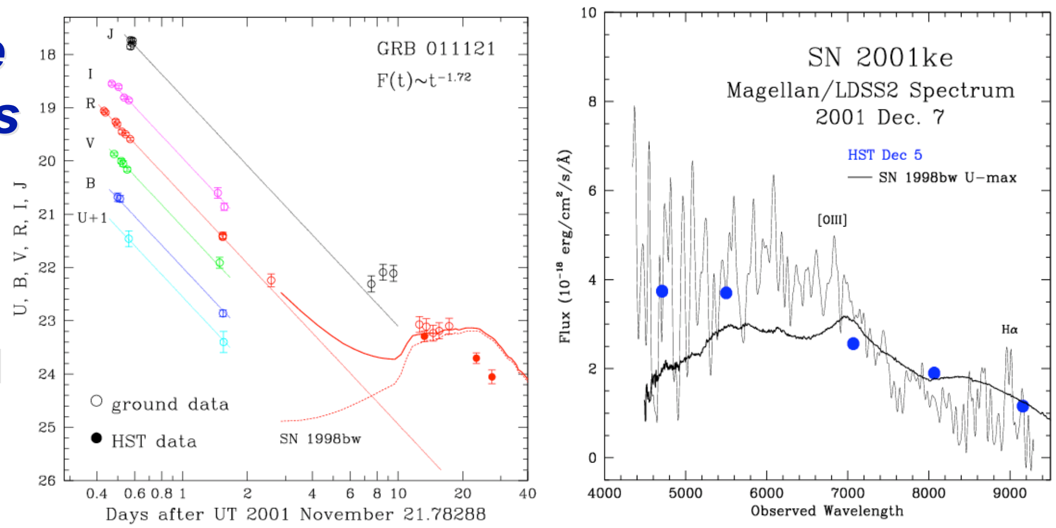
2. **Spectroscopy: GRB030329 / SN 2003dh (Stanek et al. 2003; z=0.168).**

⇒ Missing link lGRBs-SNIbc

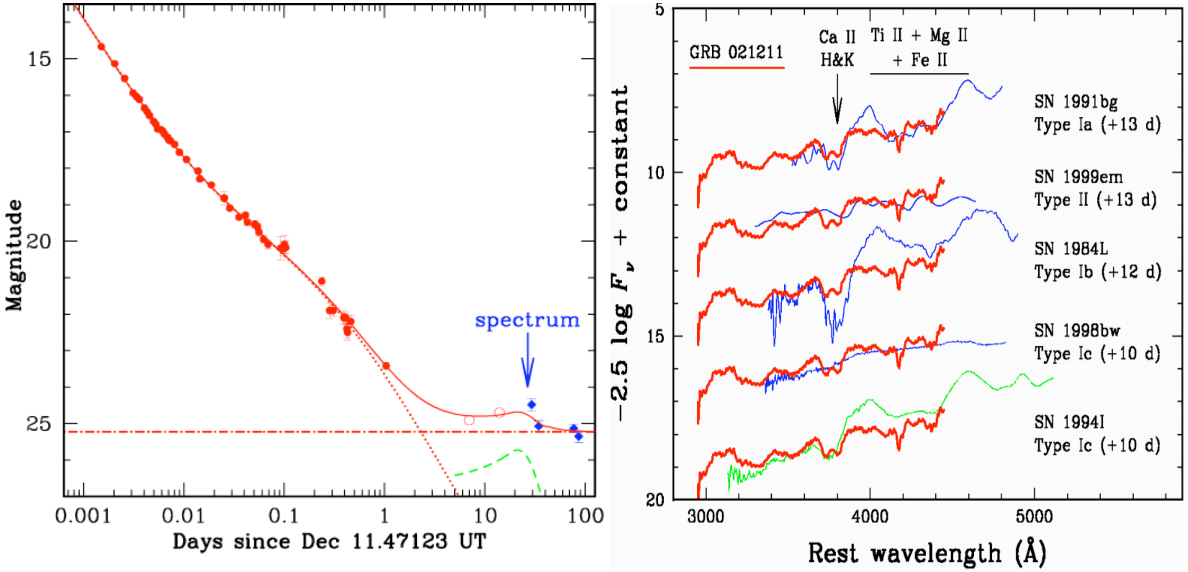
Some evidences of lGRB/SN association

Sometimes: *Bumps in the late (10-30 days) optical afterglows*

Red bumps are hard to explain with supranova models except if there is a variety of delays between the collapse to a NS and the subsequent collapse to a BH in a SN.



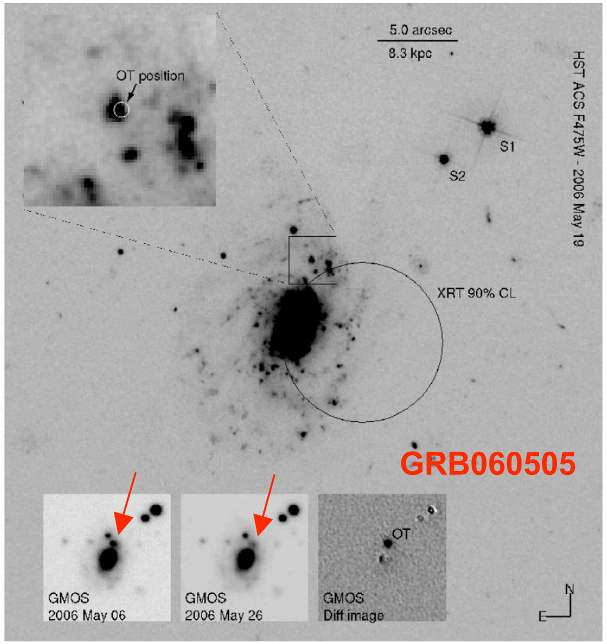
Garnavitch et al. (2003)



Della Valle et al. (2003)

Evidences of NO lGRB/SN association

But very recently: GRB 060505 (T_{90} ~ 4 s; z=0.09) & GRB 060614 (T_{90} ~ 100 s; z=0.125) **went off without any detectable SN!**

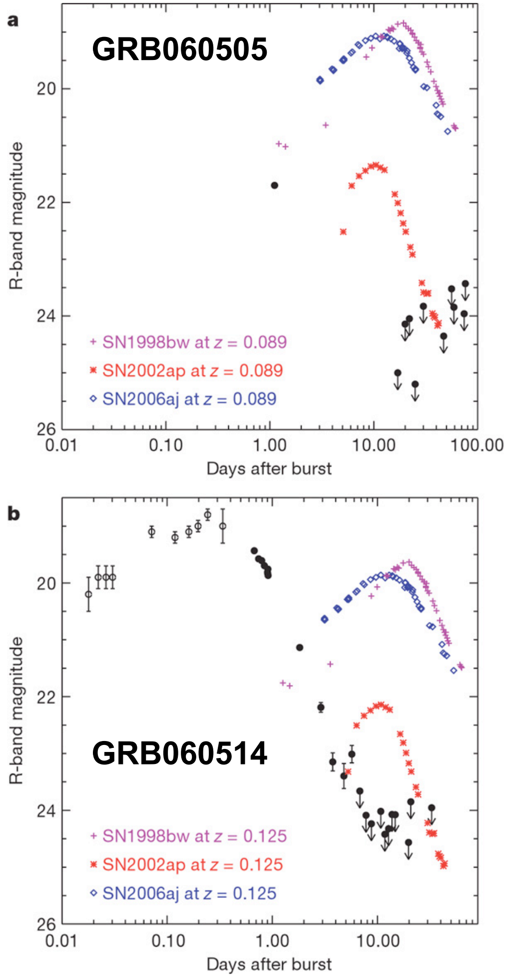


Ofek et al. (2007)

Implications:

⇒ New class of massive stellar death (Fynbo et al. 2006)?, this new class may be linked to the intermediate-group of GRBs proposed on the basis of an statistical analysis by e.g., Mukherjee et al. (1998) and Horváth (2002).

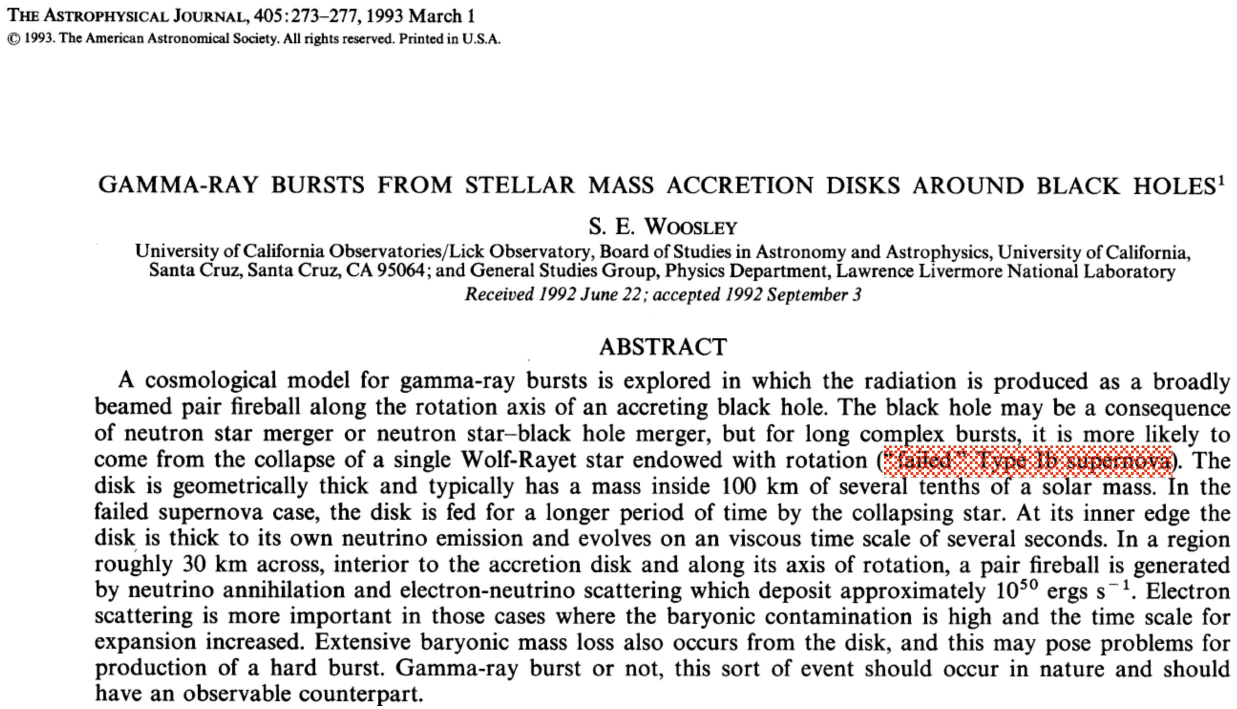
⇒ Mergers + AG blended with a macronova event (Li & Paczynski 1998; Kulkarni 2005)? [But hard to explain the duration of 060614]



Fynbo et al. (2006)

Is it really a problem if a lGRB is *not* associated to a SN?

⇒ NO!. Already in Woosley (1993), the most likely model to produce a GRB was a massive, rotating WR star ($M_{ZAMS}>25M_\odot$) which is not able to drive a SN explosion (*failed* SN!) but, instead forms a hyperaccreating ($\mathcal{M} \geq 1M_\odot s^{-1}$) BH ($M_{BH} \sim 3M_\odot$) girded by a thick accretion disk ($M_{disk} \sim 0.01M_\odot$- $0.1M_\odot$).



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GAMMA-RAY BURSTS FROM STELLAR MASS ACCRETION DISKS AROUND BLACK HOLES[1]

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ABSTRACT

A cosmological model for gamma-ray bursts is explored in which the radiation is produced as a broadly beamed pair fireball along the rotation axis of an accreting black hole. The black hole may be a consequence of neutron star merger or neutron star–black hole merger, but for long complex bursts, it is more likely to come from the collapse of a single Wolf-Rayet star endowed with rotation ("failed" Type Ib supernova). The disk is geometrically thick and typically has a mass inside 100 km of several tenths of a solar mass. In the failed supernova case, the disk is fed for a longer period of time by the collapsing star. At its inner edge the disk is thick to its own neutrino emission and evolves on an viscous time scale of several seconds. In a region roughly 30 km across, interior to the accretion disk and along its axis of rotation, a pair fireball is generated by neutrino annihilation and electron-neutrino scattering which deposit approximately 10^{50} ergs s^{-1}. Electron scattering is more important in those cases where the baryonic contamination is high and the time scale for expansion increased. Extensive baryonic mass loss also occurs from the disk, and this may pose problems for production of a hard burst. Gamma-ray burst or not, this sort of event should occur in nature and should have an observable counterpart.

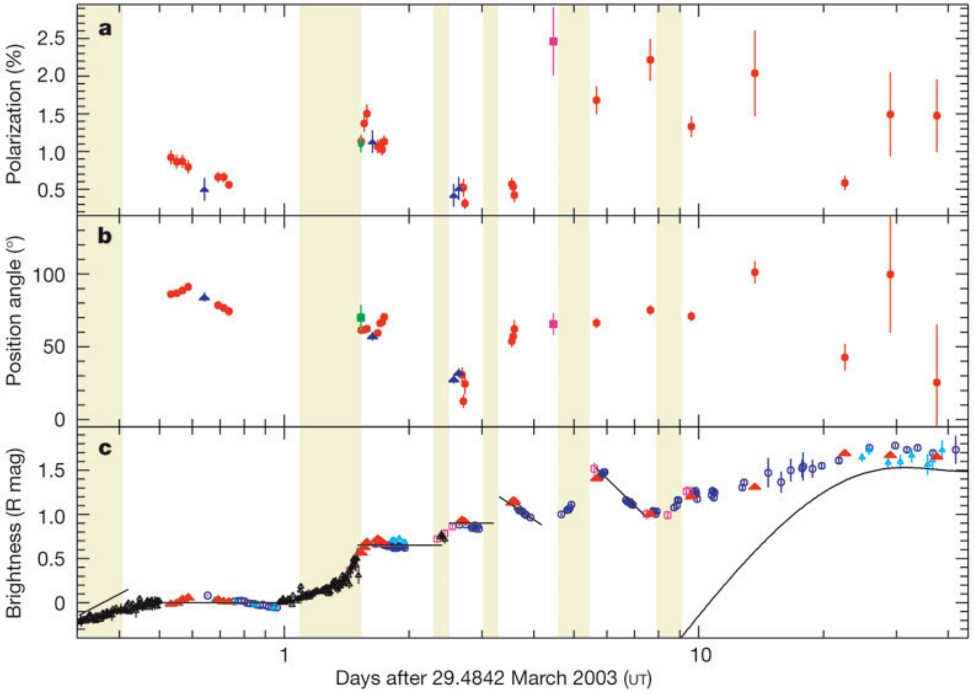
Environment of lGRB

Hosts:

1. star-forming, low metallicity galaxies (SFR~10^3 $M_{\odot} y^{-1}$, Berger et al. 2001, Frail et al. 2002) but bluer than typical starburst galaxies with little dust (Le Floc'h 2004) and lower masses than current ellipticals ⇒ *typical* environments of formation of massive stars

2. Offsets: within the host galaxies GRBs follow the light distribution ~ density of star formation (Bloom et al. 2002)

Optical variability and polarization suggests structured environment (Greiner et al. 2003)



SN/lGRB rates

SNIbc rate ~ 2 10^4 $Gpc^{-3}y^{-1}$ (Piran 2005)

Local lGRB rate: ρ_0 ~ 0.16 - 0.44 $Gpc^{-3}y^{-1}$ (Guetta, et al. 2005)

Uncertainties: SFR (~3)

Total lGRB rate ~ 33 ± 11 $Gpc^{-3}y^{-1}$ (Guetta, et al. 2005)

Uncertainties: Collimation (~10)

⬇

Only a few percent of SNIbc can be associated with lGRBs. Additional conditions (e.g., magnetic field, specific angular momentum, binarity, etc.) must be imposed on the progenitors

Progenitors of sGRBs: why different from those of lGRBs?

- Different duration and spectral properties.
- Different total intrinsic energy released although very similar luminosity.
- Lack of SN signature.
- Also detected in non-star-forming (old) galaxies, i.e., not associated to the death of massive stars.
- Some of them detected *outside* of the host galaxy

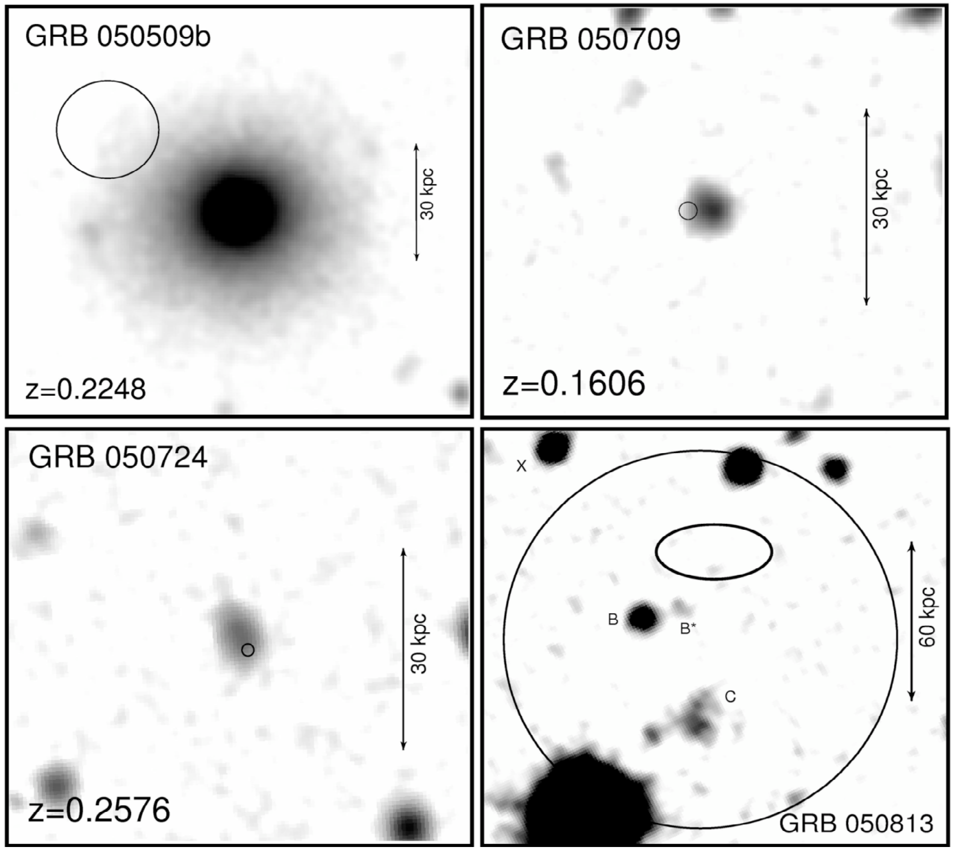
⇒ not (necessarily) associated to the death of massive stars, but still, firmly believed that they are produced in hyper-accreting BHs.

Environment of sGRB

Hosts:

1. **star-forming, and elliptical (old) galaxies (SFR~0.01 – 0.5 $M_{\odot}y^{-1}$, Fox et al. 2005, Prochaska et al. 2005)**
2. **The fact that sGRBs are associated with both star forming and old galaxies is *consistent* with NS+NS/BH mergers if one assumes that there are fast evolutionary tracks to form mergers (Tutukov & Yungelson, 1993, 1994; Belczynski et al. 2002).**
3. **Offsets: Typically found in the outer parts of their host galaxies (agrees with merger evolutionary tracks of ~ 1Gy).**

∴ So far, from the environment of sGRBs we obtain circumstantial evidence about the progenitor nature.



Prochaska et al. (2005)

NS+NS merger/sGRB rates

Mergers (NS+NS) rate ~ 800 Gpc^{-3}y^{-1} (Kalogera et al. 2005)

Local sGRB rate: $\rho_0 \sim 0.11 - 0.8$ Gpc^{-3}y^{-1} (Guetta & Piran 2005)

Uncertainties: SFR (~3)

Total sGRB rate:

Impossible to estimate lacking from clear detections of opening angles. Assuming every merger yields a sGRB $\Rightarrow \theta \sim 1.6^{o}$ (Guetta & Piran 2005)

Numerical simulations:

Aloy et al. (2005): $\theta \sim 15^{o}$- 25^{o}

Rosswog & Ramirez-Ruiz (2005): $\theta \sim 1^{o}$- 21^{o}

Only a few percent of NS+NS mergers need to produce sGRBs. Additional conditions (e.g., magnetic field, accretion disk mass, ratio of initial masses, etc.) must be imposed on the progenitors

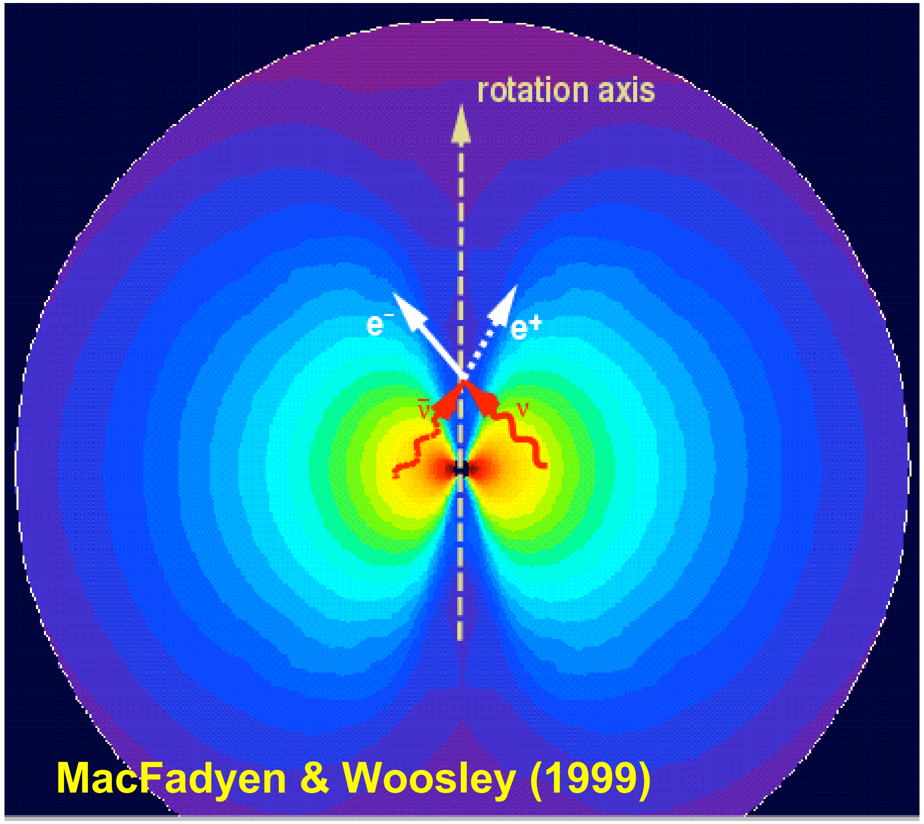
Progenitors lGRB: Collapsars

Woosley (1993)

- Collapse of a massive ($M_* \sim 30M_\odot$, WR) rotating star that does not form a successful SN but collapses to a BH ($M_{BH} \sim 3M_\odot$) surrounded by a thick accretion disk. The hydrogen envelope is lost by stellar winds, interaction with a companion, etc.

- The viscous accretion onto the BH ⇒ strong heating ⇒ thermal νν-annihilating preferentially around the axis ⇒ formation of a relativistic jet (Γ>10)?.

- Alternative generation: hydromagnetic (Blandford-Payne mechanism) or electromagnetic (Blandford Znajek mechanism).

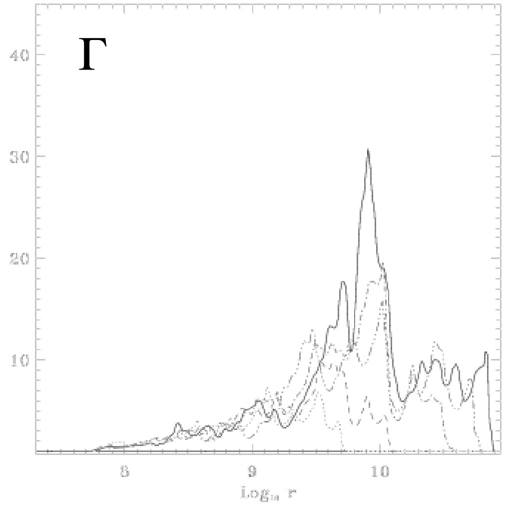


MacFadyen & Woosley (1999)

Generic features learned from numerical simulations of collapsars

VARIABILITY:

1. Outflows highly variable due to KH (Aloy et al. 2000; Gómez & Hardee 2004), SD (Aloy et al. 2002) or pinch MHD instabilities (McKinney 2006) ⇒ extrinsic variability which can be the source of internal shocks.
2. Extrinsic/intrinsic$^{(=\text{source})}$ variability might be indistinguishable.
3. Jets are also stable in 3D RHD (Zhang et al. 2004) but still unknown whether 3D RMHD collapsar-jets will be stable.

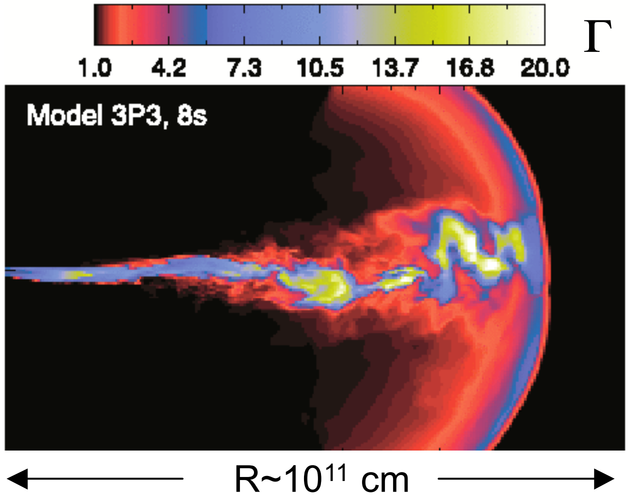


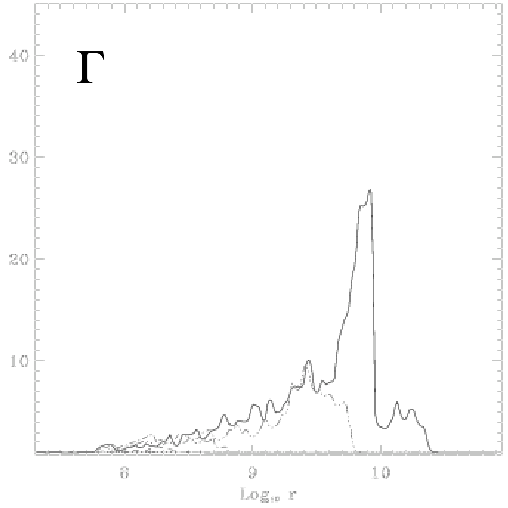
Model e50c100 of Aloy et al. (2000)

snapshot times:

0.00 s
1.44 s
2.39 s
3.87 s
4.65 s
5.24 s

Zhang et al. 2004





Model e50v100 of Aloy et al. (2000)

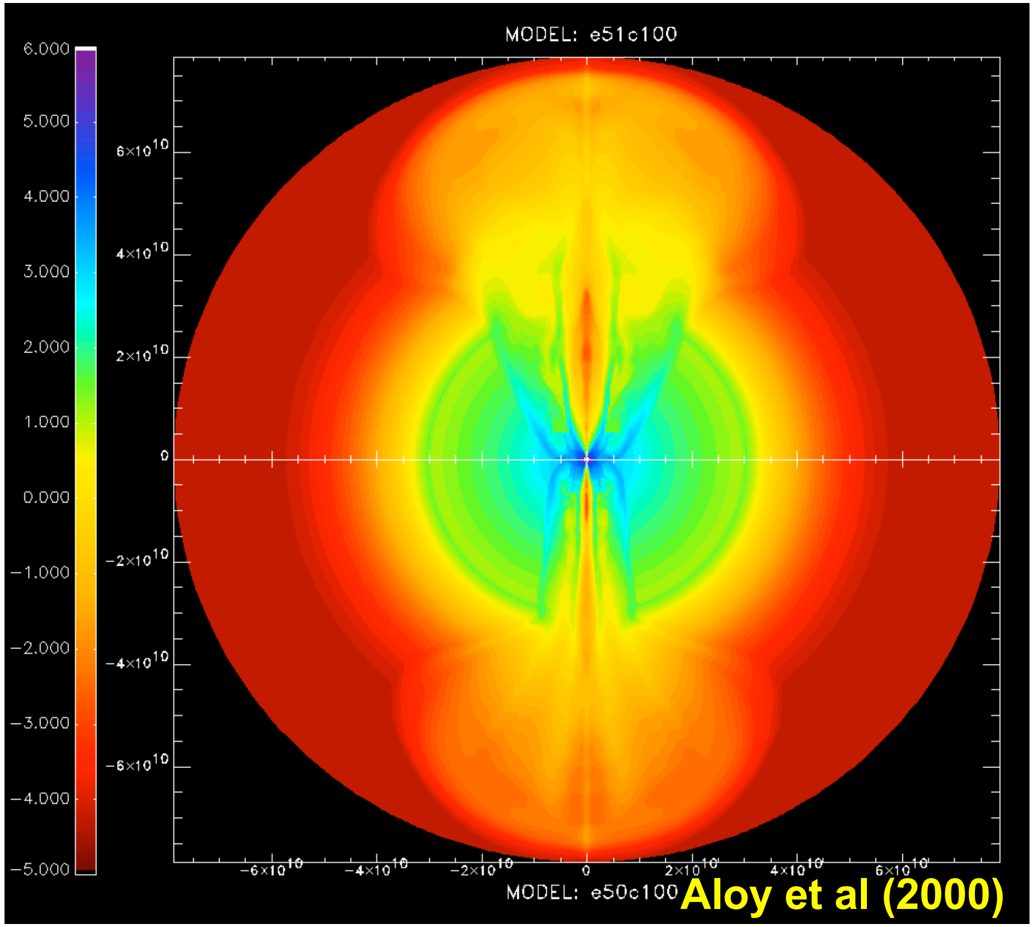
snapshot times:

0.00 s
0.03 s
0.13 s
0.50 s
1.50 s
3.31 s

Generic features learned from numerical simulations of collapsars

BREAKOUT:

- First studied in Aloy et al. (2000)
- ν-powered jets are very hot @ breakout ($E_{thermal}$ ~ 80% E_{tot})
  ⇒ on-going acceleration
- The jet breakout through the stellar surface and its interaction with the stellar wind could lead to some *precursor* activity (MacFadyen, Woosley & Heger 2001).
- The cocoon transports a sizeable fraction of the energy and could yield γ-ray/hard X-ray transients
  ⇒ unification GRBs/XRR-GRBs/XRF (Ramírez-Ruiz et al. 2002)



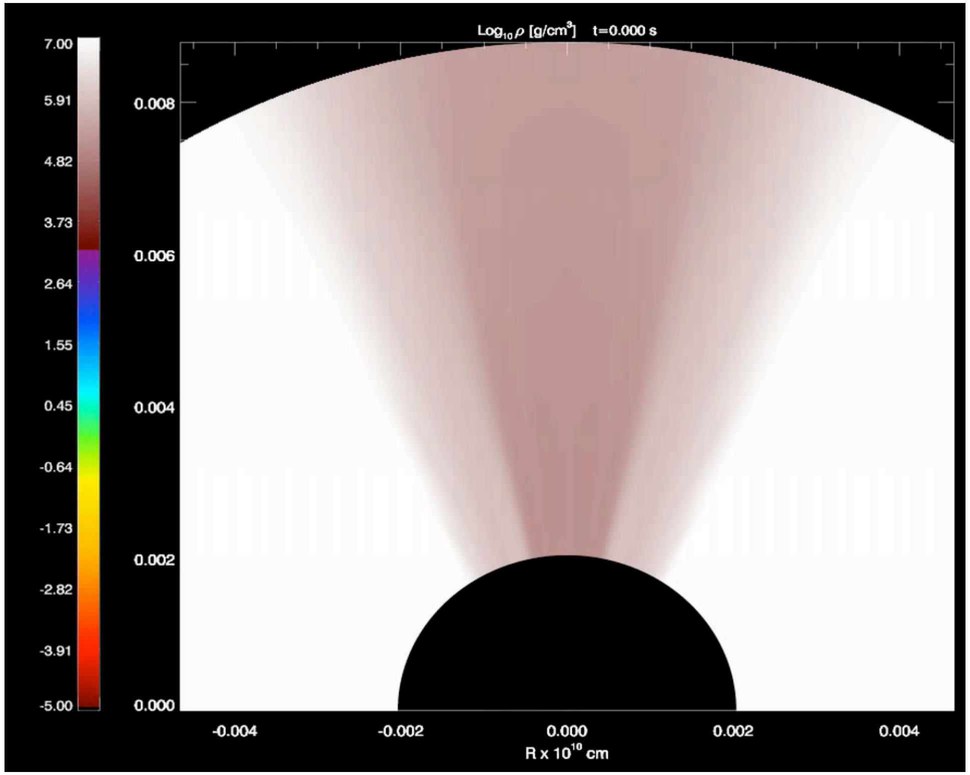
Aloy et al (2000)

Generic features learned from numerical simulations of collapsars

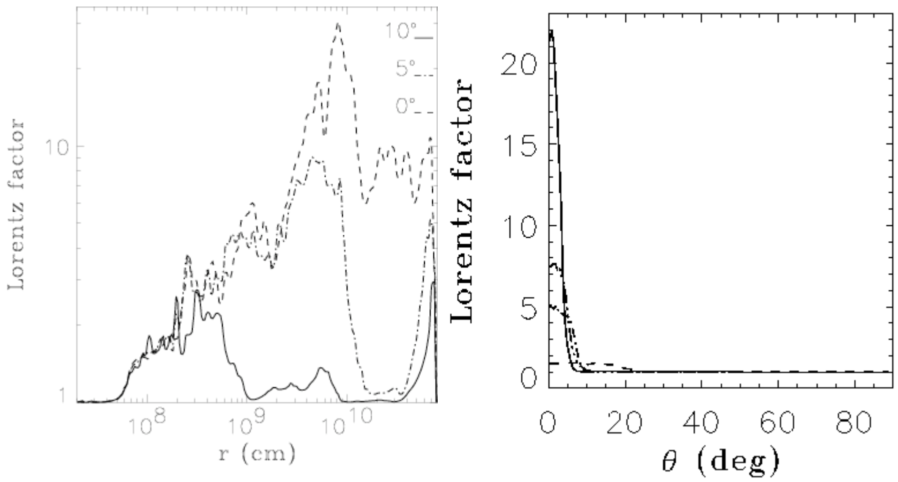
COLLIMATION:

- Jets are inertially (progenitor recollimation) or magnetically (self-collimation) confined with $\theta_{break}<5^o$ (even if $\theta_0=20^o$; Zhang et al 2003).

- Jets show transverse structure: ultrarelativistic spine ($\Gamma\sim50$) of $\theta_{core}<5^o$ + moderately relativistic, hot shear layer ($\Gamma\sim5$-10) extending up to $\theta_{shl}<30^o$.



Aloy et al (2000)



Aloy et al (2002)

Progenitors sGRB: NS+NS mergers

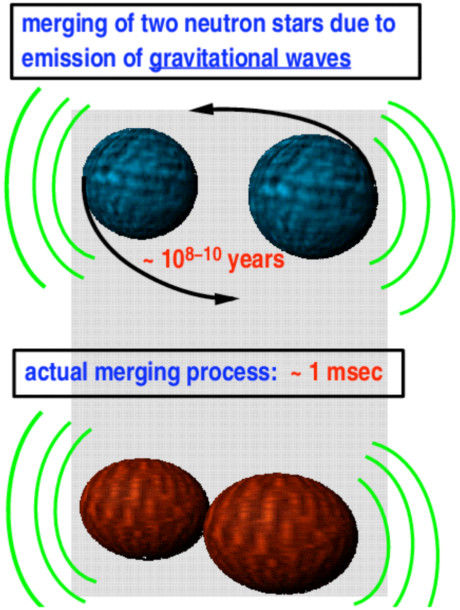
The numerical study of the merger of 2 NSs as they loose energy due to gravitational radiation is a formidable task that optimally involves

- 3D GRMHD
- detailed neutrino physics (and transport)
- nuclear reactions (good sites for *r-process*; Eichler et al. 1989)
- non ideal physics (viscosity, reconnection, resistivity).

A number of authors have addressed the merger problem with different degrees of sophistication and focusing on different physical aspects.

However, these simulations either did not followed the evolution of the system for sufficiently long time or with a consistent treatment of the neutrino transport to reach the generation of GRBs.

0-phase: pre-merger

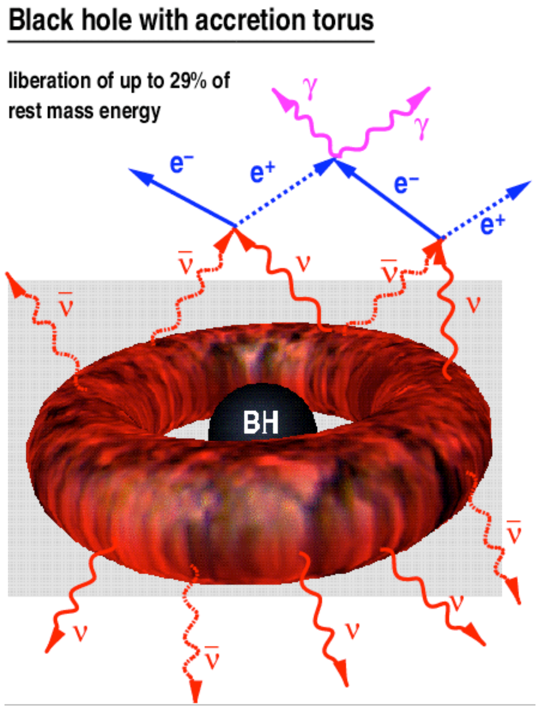

merging of two neutron stars due to emission of gravitational waves

actual merging process: ~ 1 msec

Progenitors sGRB: NS+NS mergers

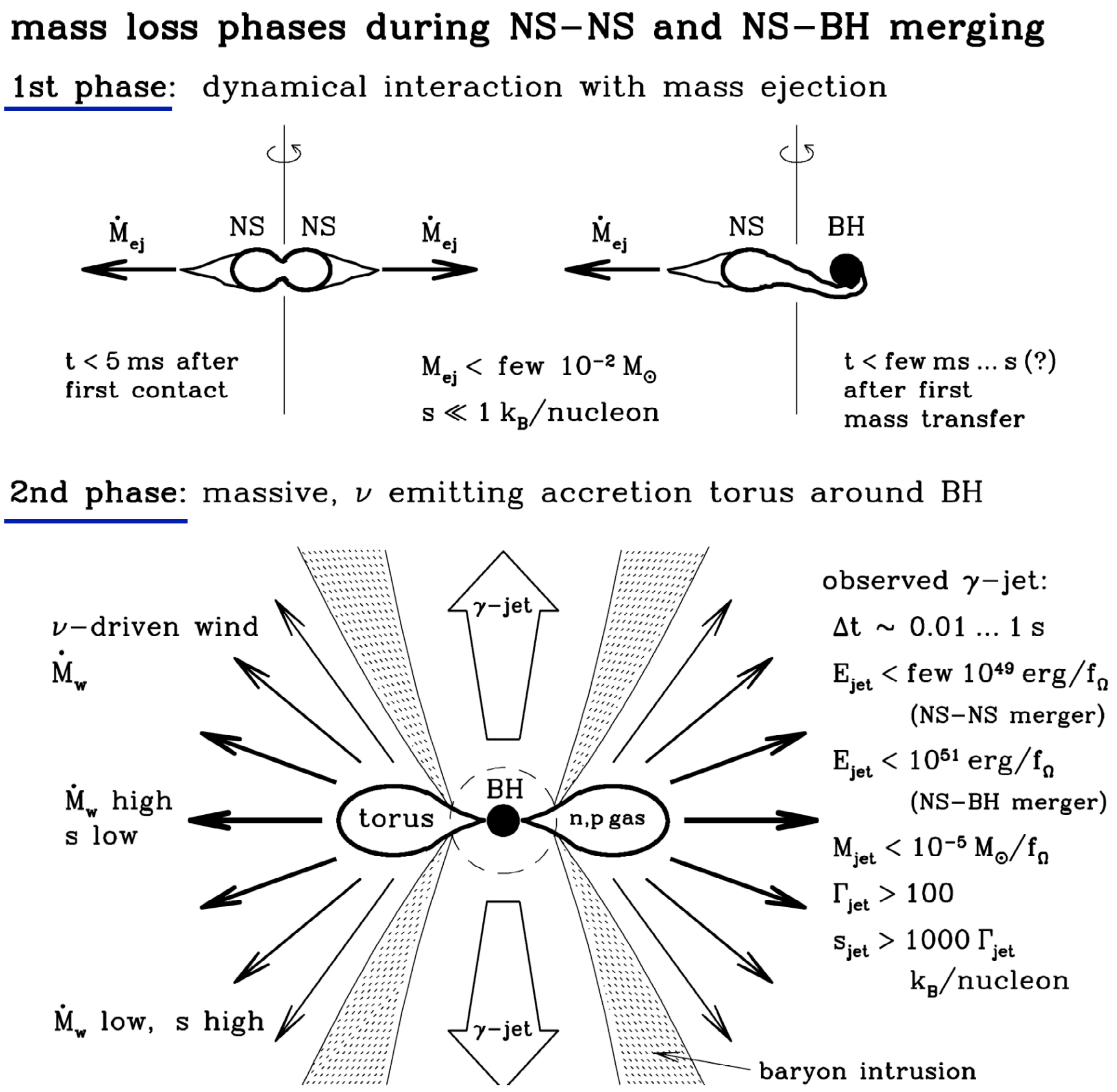
Our *idea* of the evolution inferred from previous simulations

(Oechslin & Janka 2005)



Black hole with accretion torus

liberation of up to 29% of rest mass energy



mass loss phases during NS−NS and NS−BH merging

1st phase: dynamical interaction with mass ejection

2nd phase: massive, ν emitting accretion torus around BH

observed γ−jet:

$\Delta t \sim 0.01 \ldots 1$ s

E_{jet} < few 10^{49} erg$/f_\Omega$ (NS−NS merger)

E_{jet} < 10^{51} erg$/f_\Omega$ (NS−BH merger)

$M_{jet} < 10^{-5}\,M_\odot/f_\Omega$

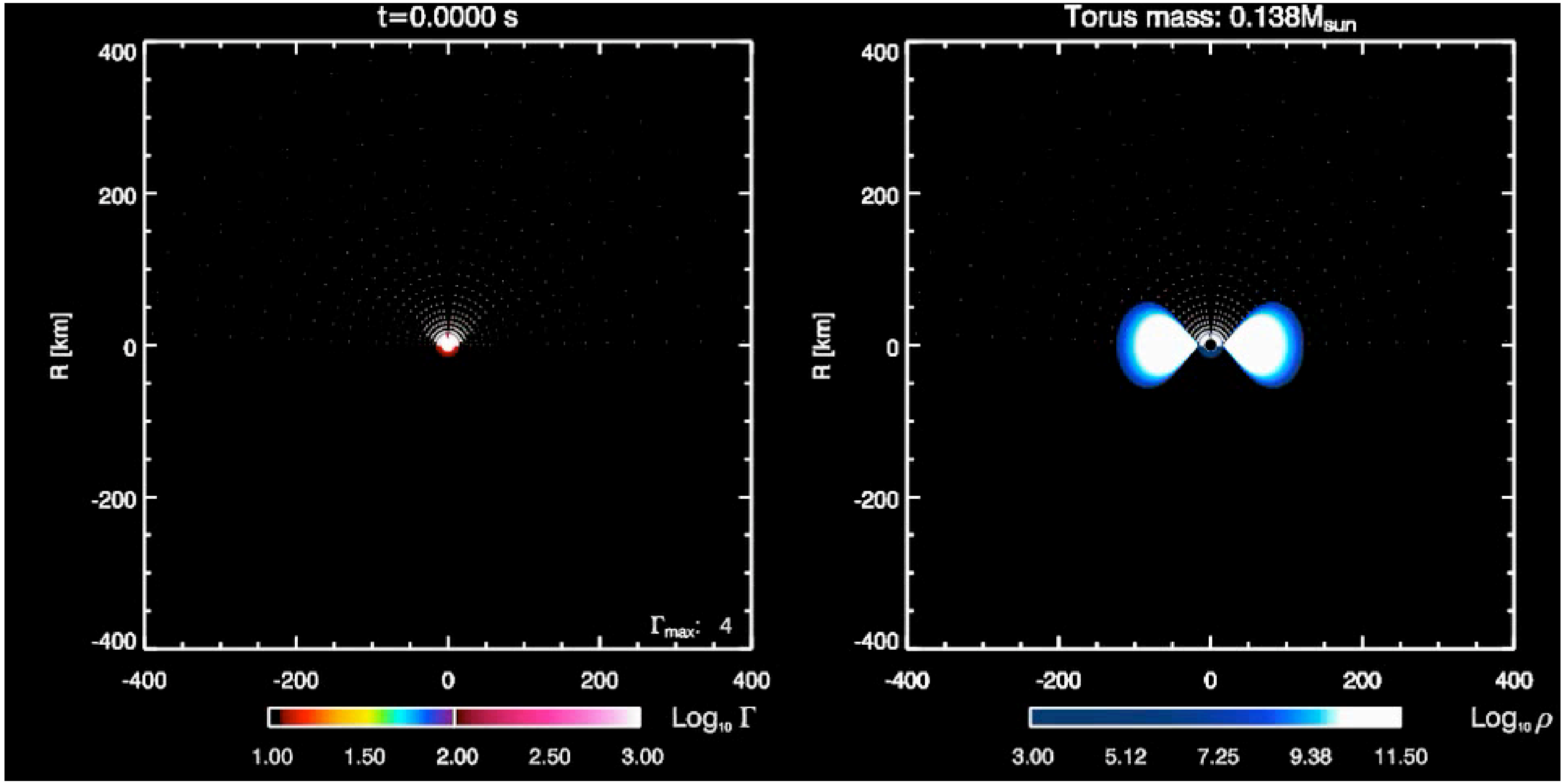
$\Gamma_{jet} > 100$

$s_{jet} > 1000\,\Gamma_{jet}$ k_B/nucleon

Things we learned from numerical simulations of post-NSs mergers

Releasing energy over the poles at rates above our P_{thr} and with a functional dependence suggested by Janka et al (1999) relativistic ($\Gamma_{max} \sim 1000$), collimated conical/jet-like, outflows are produced.

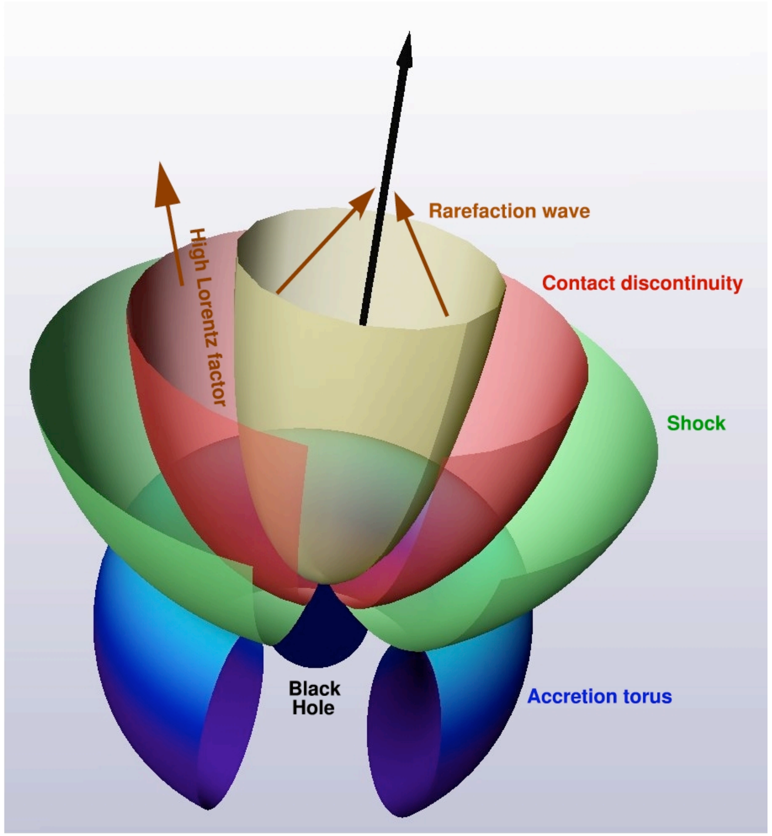
The fireball structure is heterogeneous both in radial and angular directions (KH-instab.) and has an ultrarelativistic core + relativistic, expanding layer.

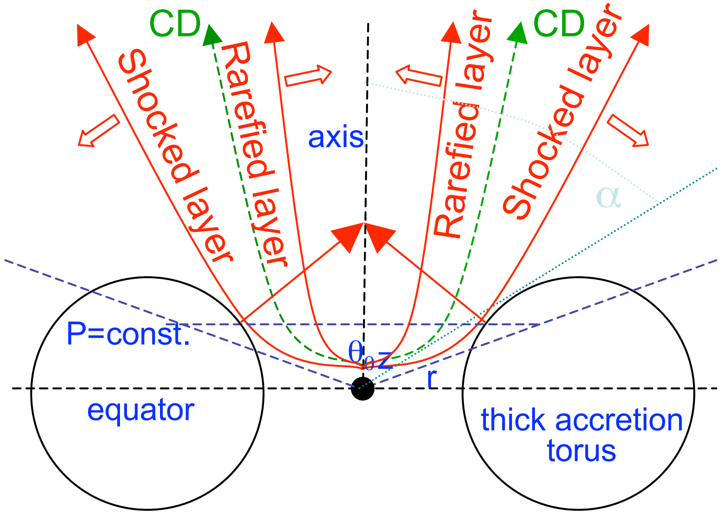


Things we learned from numerical simulations of post-NSs mergers

Collimation: via interaction with the external medium and/or the accretion torus. Application of the analytic Levinson & Eichler's collimation mechanism yields wrong results. Typical opening angles: $\theta_{\Gamma>100} \sim 5^o - 10^o$ ($\theta_{\Gamma>10} \sim 20^o - 30^o$).

∴ An observed rate of 100 y^{-1} short GRBs needs of 10^{-5} $galaxy^{-1}$ y^{-1} sGRB events, which is consistent with estimated NS+NS & NS+BH merger rates.



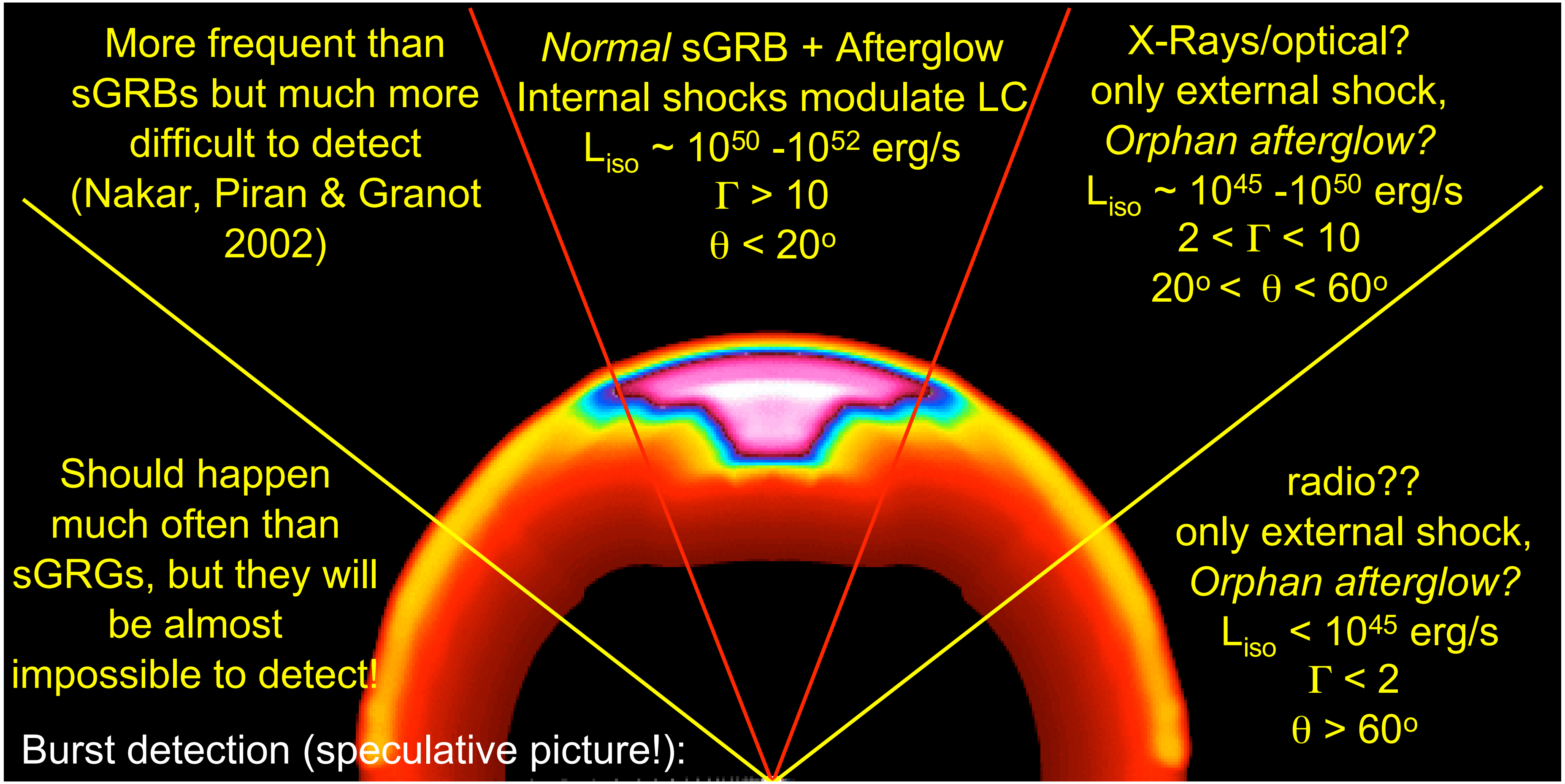


Aloy, Janka & Müller (2005)

1. The accretion torus (very heavy) collimates along its scale height an *almost* conical, BPJ.
2. Accretion disk = thick torus.
3. Interaction: thick shock.-raref. layer around the BPJ.

Lessons we learned from numerical simulations of post-NSs mergers

While mergers in low-density environments successful GRBs can be produced, in high-density media the observational signature may be a thermal UV-flash ($T \sim 5 \times 10^4$ K) with very low luminosity ($L \sim 10^{43}$ erg/s) and durations of ~1000 s.



More frequent than sGRBs but much more difficult to detect (Nakar, Piran & Granot 2002)

Normal sGRB + Afterglow
Internal shocks modulate LC
$L_{iso} \sim 10^{50} - 10^{52}$ erg/s
$\Gamma > 10$
$\theta < 20^o$

X-Rays/optical?
only external shock,
Orphan afterglow?
$L_{iso} \sim 10^{45} - 10^{50}$ erg/s
$2 < \Gamma < 10$
$20^o < \theta < 60^o$

Should happen much often than sGRGs, but they will be almost impossible to detect!

radio??
only external shock,
Orphan afterglow?
$L_{iso} < 10^{45}$ erg/s
$\Gamma < 2$
$\theta > 60^o$

Burst detection (speculative picture!):

Summary

- Both sGRBs and lGRBs seem to be powered by hyperaccreting BHs ⇒ GRBs are the *birth cries* of newly born BHs!

- There is an overwhelming amount of evidence that lGRBs are associated with the death of massive starts (SN associations, red bumps, Fe lines, host galaxies, but also there are some that take place without SNe!).

- Recently an appealing case is being made to demonstrate that sGRBs are not produced by the same progenitors as lGRBs (host galaxies, lack of SN signature, galactic offsets, redshift distribution).

- So far, associating sGRBs with NS+NS/BH mergers relies only on circumstantial evidence. Key for the future: detections of high energy neutrinos and GW!

- Numerical modeling of progenitor systems involving a new-born BH has allowed us to gain a refined understanding of the dynamics and global properties of relativistic outflows generated in these systems.