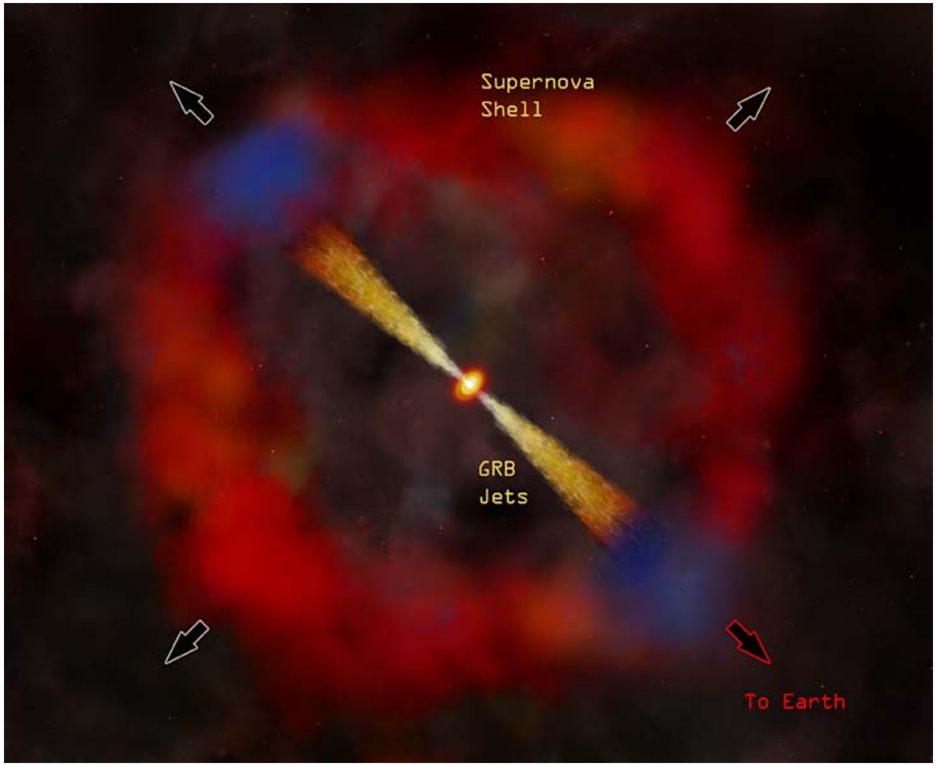
Stochastic Wake Field particle acceleration in GRB



(image credits to CXO/NASA)

G. Barbiellini(1), F. Longo(1), N.Omodei(2), P.Tommasini(3), D.Giulietti(3), A.Celotti(4), M.Tavani (5)

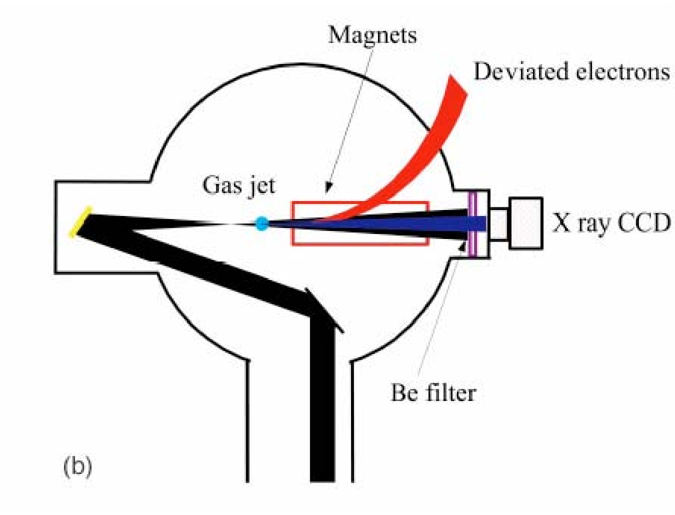
(1) University and INFN Trieste (2) INFN Pisa, (3) University of Pisa

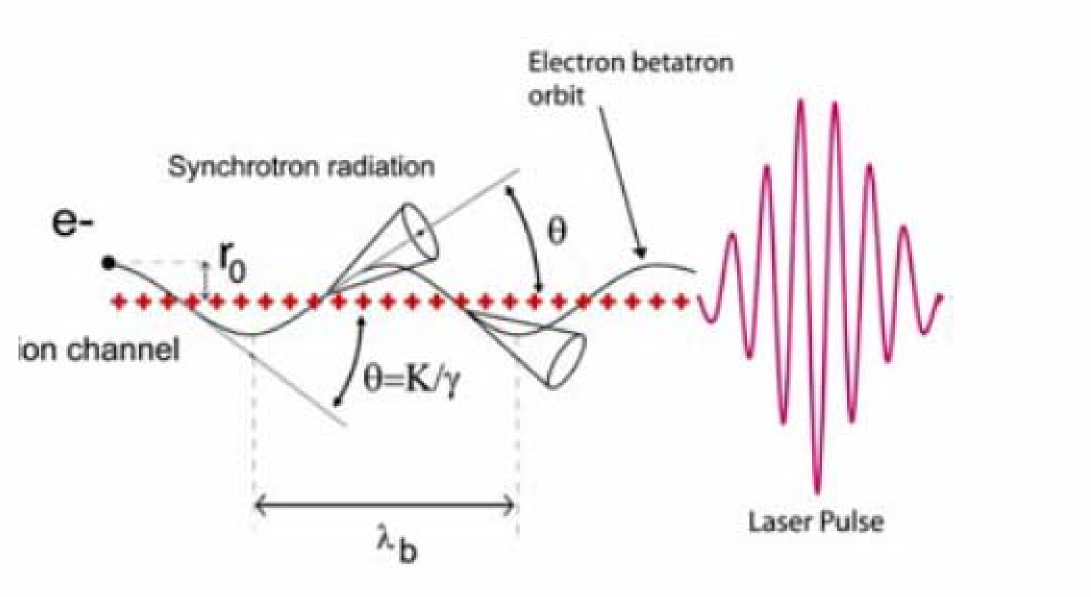
(4) SISSA Trieste (5) INAF Roma & Roma2 University

Gamma-Ray Bursts in laboratory

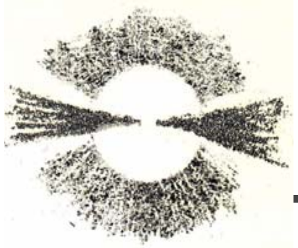
WakeField Acceleration

(Ta Phuoc et al. 2005)





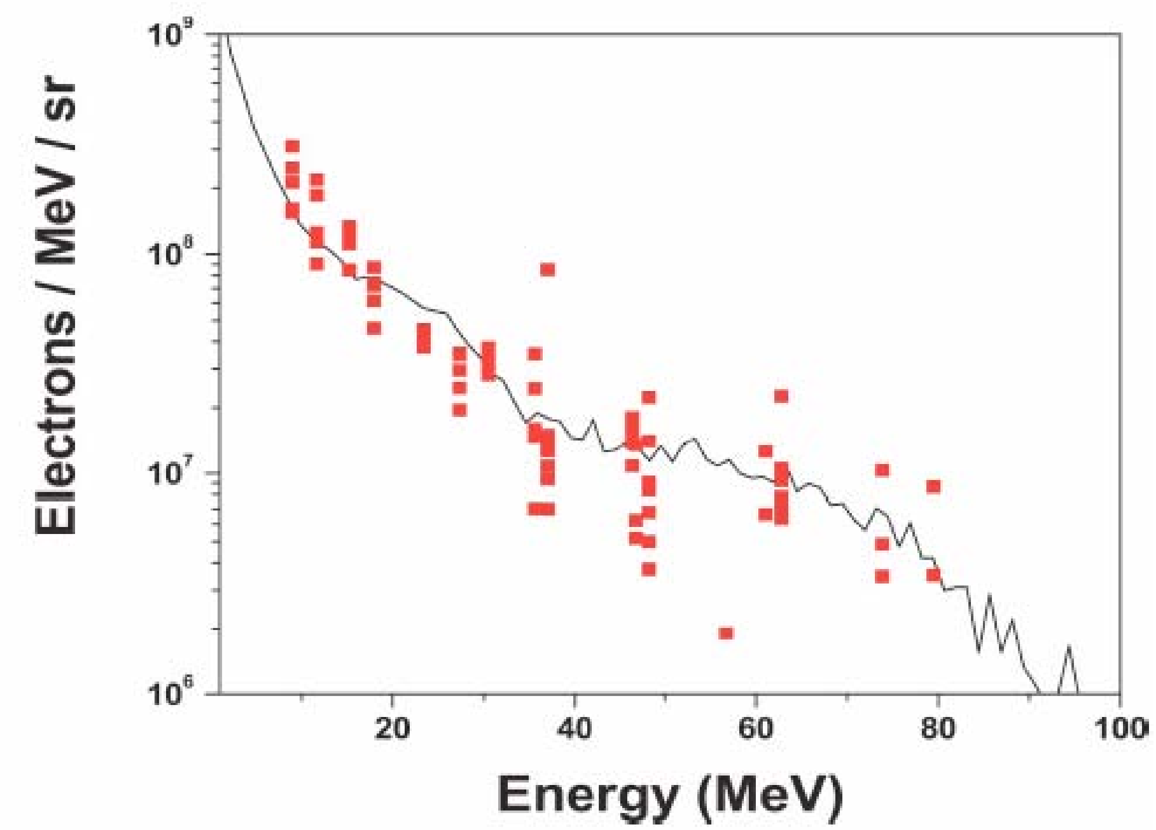
Laser Pulse $t_{laser} = 3\ 10^{-14}$ s
Laser Energy = 1 Joule
Gas Surface = 0.01 mm^2
Gas Volume Density = 10^{19} cm^{-3}
Power Surface Density $\sigma_W = 3\ 10^{18}$ W cm^{-2}



Gamma-Ray Bursts in laboratory

WakeField Acceleration

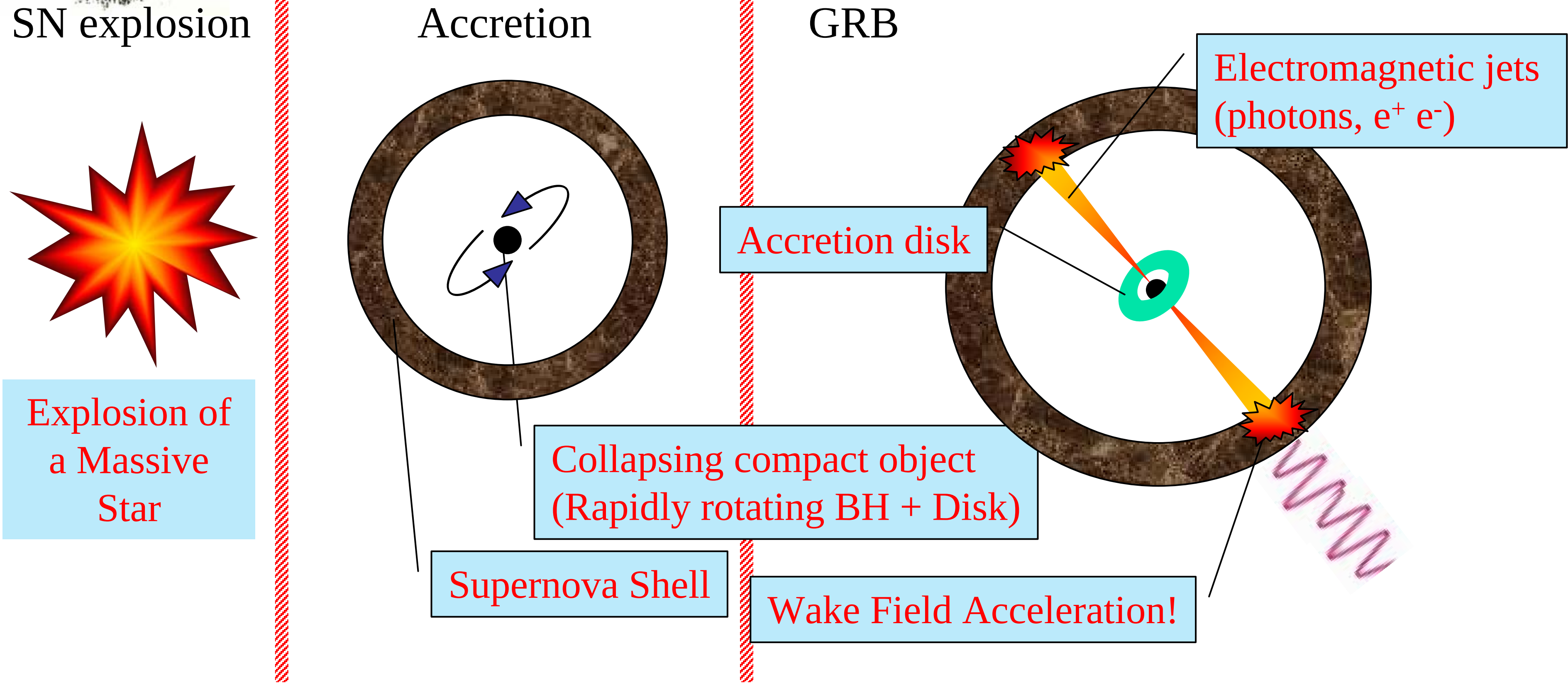
(Ta Phuoc et al. 2005)



Electron Spectrum ~ Energy^{-2}

Typical astrophysical accelerated electron distribution!

Gamma-Ray Bursts in Space



SN explosion

Accretion

GRB

Electromagnetic jets (photons, e^+ e^-)

Accretion disk

Explosion of a Massive Star

Collapsing compact object (Rapidly rotating BH + Disk)

Supernova Shell

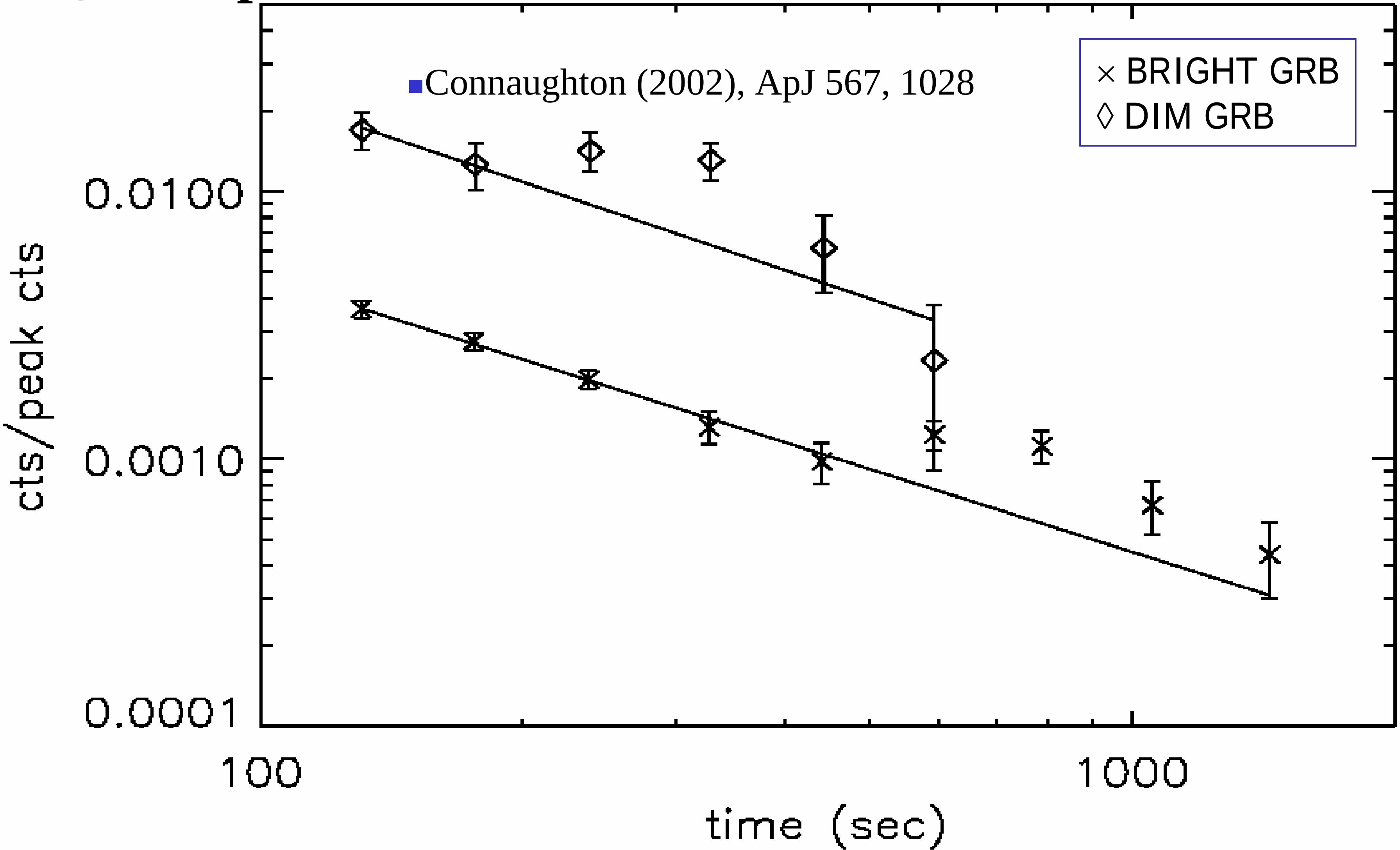
Wake Field Acceleration!

- An electromagnetic jet (I.e. photons) plays the role of the lab laser
- The Supernova Shell is the target plasma (at $R \sim 10^{15}$ cm, with $n \sim 10^{9}$ cm^{-3})
- Stochasticity has to be taken into account (laser->not coherent radiation) !
- Available Energy (order of magnitude): 10^{53} ergs !!!!

Bright and Dim GRB

BATSE data
(every point contains statistics of 100 bursts)

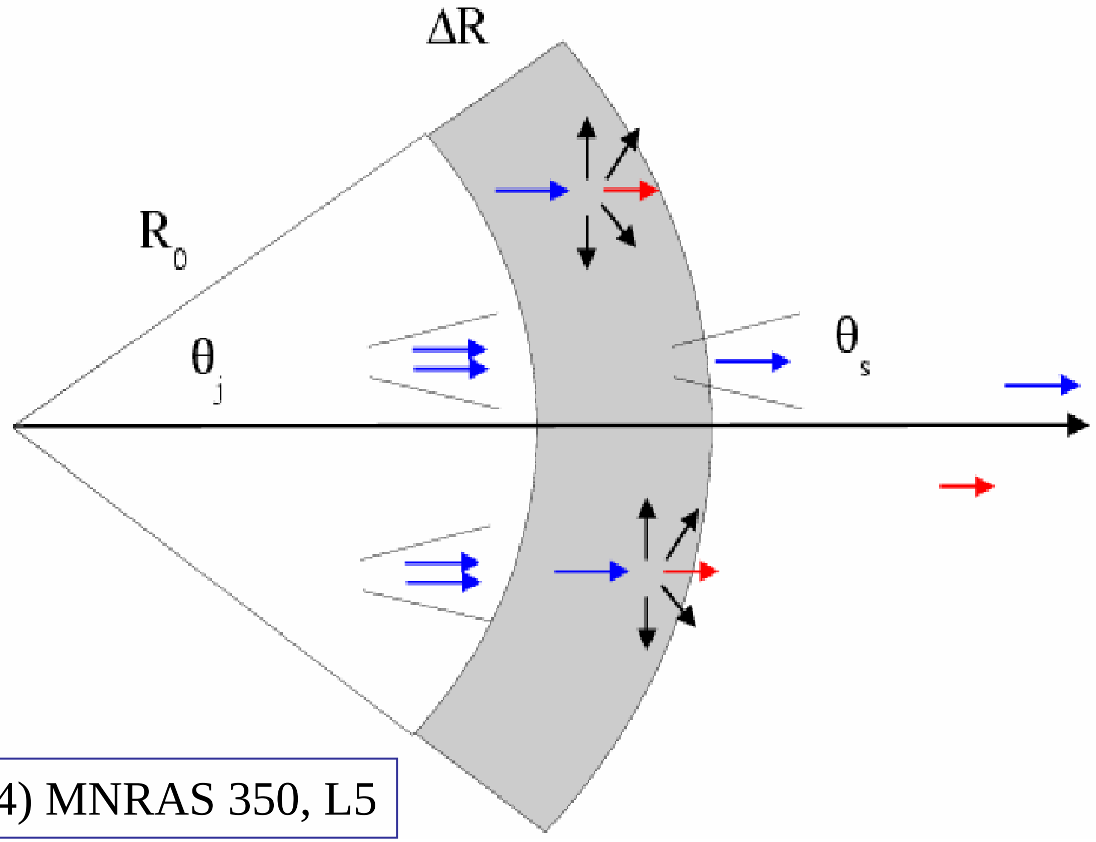
Q = cts/peak cts



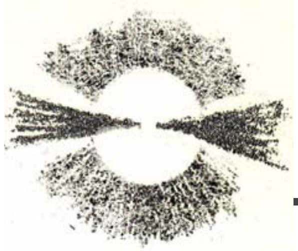
- Connaughton (2002), ApJ 567, 1028

Interpretation: the Compton Tail

Dim bursts are dim because they are absorbed (do not see them) via Compton scattering!
Scattered light should arrive after the prompt (unabsorbed) emission.
Dense material is needed !
Dim bursts come earlier



Barbiellini et al. (2004) MNRAS 350, L5



The Compton tail

- “Prompt” luminosity

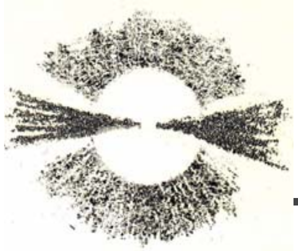
$$\langle L_{\rm s}\rangle = \langle \frac{dn_{\rm s}}{d\Omega\ dt}\rangle \simeq \frac{n_{\rm p}\ e^{-\tau}}{\pi\theta_{\rm s}^2\ t_{\rm grb}} \cdot \frac{\theta_{\rm s}^2}{\theta_{\rm j}^2}$$

- Compton “Reprocessed” luminosity (arrive later)

$$\langle L_{\rm c}\rangle = \frac{n_{\rm p}\ (1-e^{-\tau})}{2\pi\ t_{\rm geom}} \qquad t_{\rm geom} \sim \frac{(R_0+\Delta R)\theta_{\rm j}^2}{c}$$

- “Q” ratio

$$\boxed{Q = \frac{\langle L_{\rm c}\rangle}{\langle L_{\rm s}\rangle} = (e^{\tau}-1)\cdot\frac{c\ t_{\rm grb}}{(R_0+\Delta R)}}$$



Bright and Dim Bursts

- Bright bursts (tail at 800 s)
  - Peak counts >1.5 cm^{-2} s^{-1}
  - Mean Fluence 1.5 × 10^{-5} erg cm^{-2}
  - Q = 4.0 ± 0.8 10^{-4} (5 σ) fit over PL
  - $\tau = 1.3$
- Dim bursts (tail at 300s)
  - peak counts < 0.75 cm^{-2} s^{-1}
  - Mean fluence 1.3 × 10^{-6} erg cm^{-2}
  - Q = 5.6 ± 1.4 10^{-3} (4 σ) fit over PL
  - $\tau = 2.8$
- "Compton" correction

$R = 10^{15}$ cm

$n \sim 10^{8}$-10^{9} cm^{-3}

$\Delta R \sim R$

$\theta \sim 0.1$

$$E = e^{\tau} E_{\rm obs}$$

Wake field in GRB: scaling relations

1) The “required” power density:

From the experiment:

$$w_t = 3 \times 10^{18} \left(\frac{n}{10^{19}\ cm^{-3}} \right)\ \mathrm{W\ cm^{-2}}$$

$$w_t(laser) = 3 \times 10^{18}\ \mathrm{W\ cm^{-2}}$$

$$w_t(grb) = 3 \times 10^{8}\ \mathrm{W\ cm^{-2}}$$

create coherently the same phenomenon in GRB needs less power density

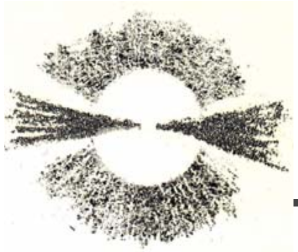
1) The “available” power density:

$$R^2\theta^2 = 10^{27}\ \mathbf{cm}^2 \qquad t_p \sim t_{grb} \sim 30/(1+z)\ \mathbf{s}$$

$$w_{grb} = \frac{E_p}{t_{grb} R^2 \theta^2} \sim 2 \times 10^{16}\ \mathrm{W\ cm^{-2}}$$

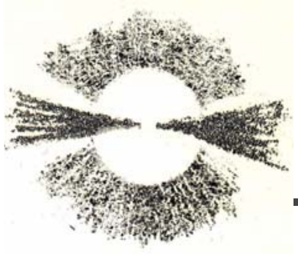
- GRB have 10^8 more power than the required (experiment) one
- Stochastic resonance and formation of plasma wave

GRB is not coherent but have more power than needed.
Can the extra power supply coherence?



New GRB Model

- This model explains GRB in analogy with laser accelerated plasma X-ray emission
  - It makes predictions for the prompt and X-Opt-Radio afterglow energy bands
    - Currently working on the expectations for GLAST.
- Assume prompt emission is not only powerful BUT also short-pulsed
  - The key point is the power available in each frequency band
- Knowledge of environment around GRB is important
  - assumes the Compton tail results to derive the amount of material in front of the GRB



SABER proposal

- Proposal for SABER
  - Create a pulsed beam to very scaling relations of density
    - not focused on a particular model
  - Measure the X-ray spectrum vs the density of the plasma.
- Experimental Set-up (beam parameters)
  - Laser Pulse tlaser
    - 3 $^{10-14}$ s
  - Laser Energy
    - 1 Joule
  - Gas Surface
    - 0.01 mm^2
  - Gas Volume Density
    - 10^{19} cm^3
  - Power Surface Density (σW)
    - 3 10^{18} W cm^{-2}

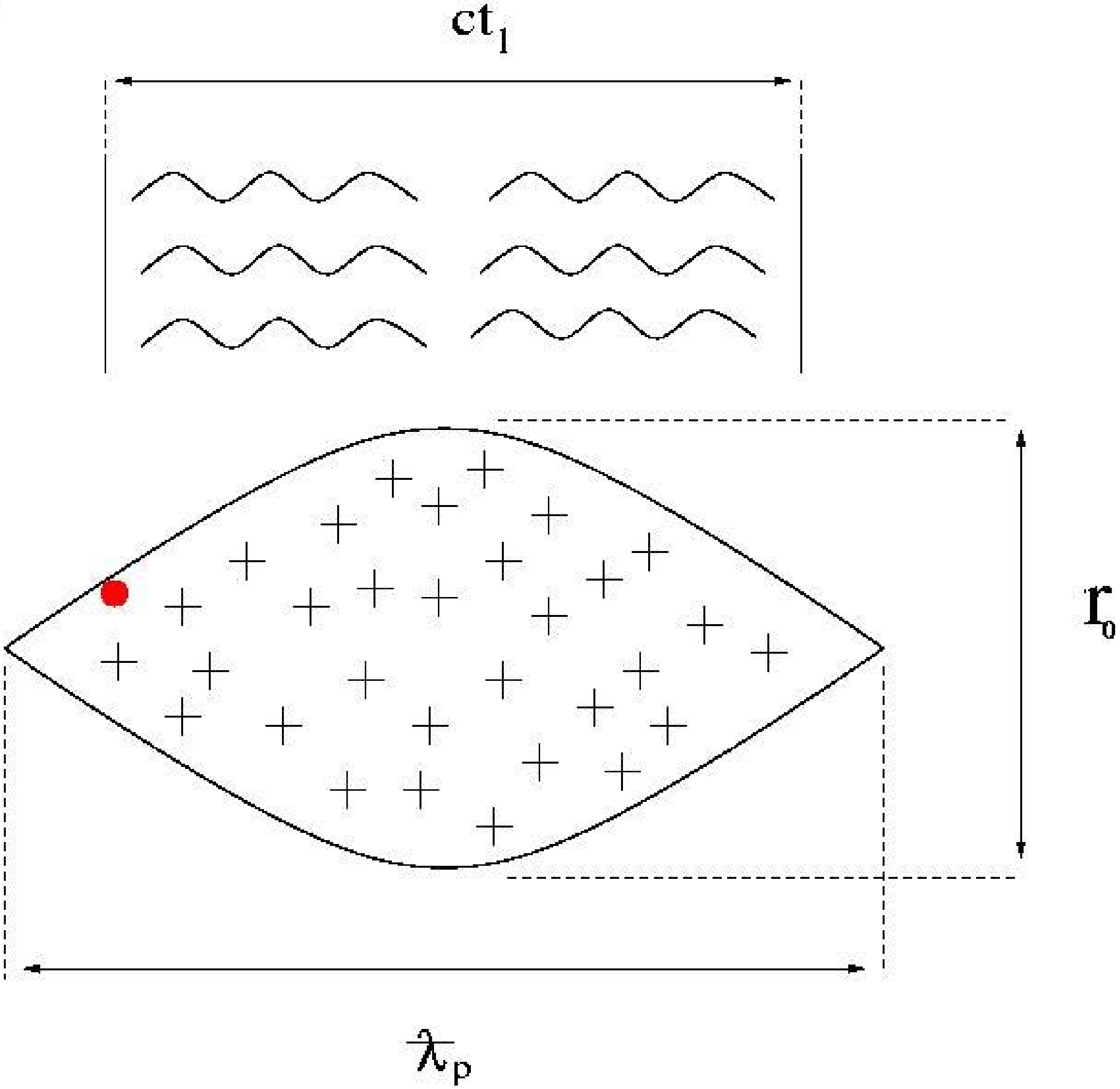
References

- Compton Tail
  - G. Barbiellini et al., MNRAS, 350 L5 (2004)

- Laser WF acceleration
  - K. Ta Phuoc, et al., Physics of Plasmas, 12, 023101 (2005)

back up slides

Scaling relations



$$r_0 = 6 \times 10^2\, n^{-1/3}$$

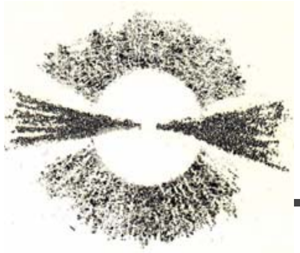
$$\gamma_e = 2 \times 10^8\, n^{-1/3}$$

$$\lambda_p = 5 \times 10^5\, n^{1/2}$$

$$\gamma(10^{19}) \sim 10^2$$

$$\gamma(10^{9}) \sim 2x10^5$$

$$\gamma(10^{2}) \sim 2x10^8$$



GRB and wake fields

$$E_p(\gamma) = \frac{3}{4}\hbar c \gamma^2 \frac{r_0}{\lambda_b} \qquad < E_p(\gamma) >= \frac{3}{4}\hbar c \frac{r_0}{\lambda_b}\gamma_{min}\gamma_{max}$$

- In case of coherent radiation (single electron):

$$E_{peak} \propto n^{-2/3} n^{-1/3} n \sim const$$

- Assuming stocasticity on theta (ensamble of electrons):

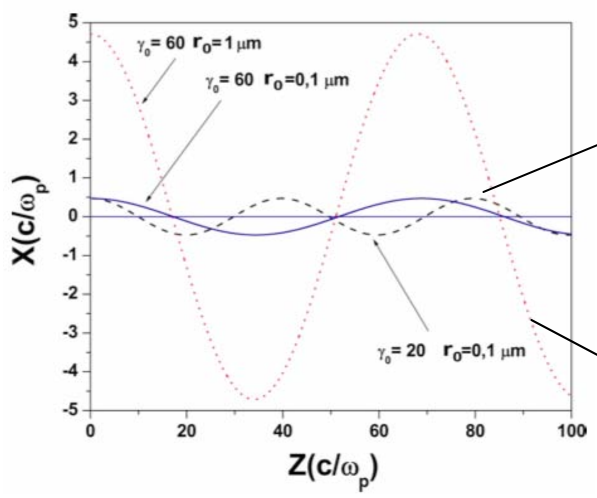
$$\theta_i = \frac{r_0}{\lambda_b} \rightarrow \frac{r_0}{\lambda_b}\sqrt{\frac{R}{\lambda_b}} \qquad \boxed{E_{peak} \propto n^{5/9} R^{2/3} \theta^{-4/3} \gamma_{max}}$$

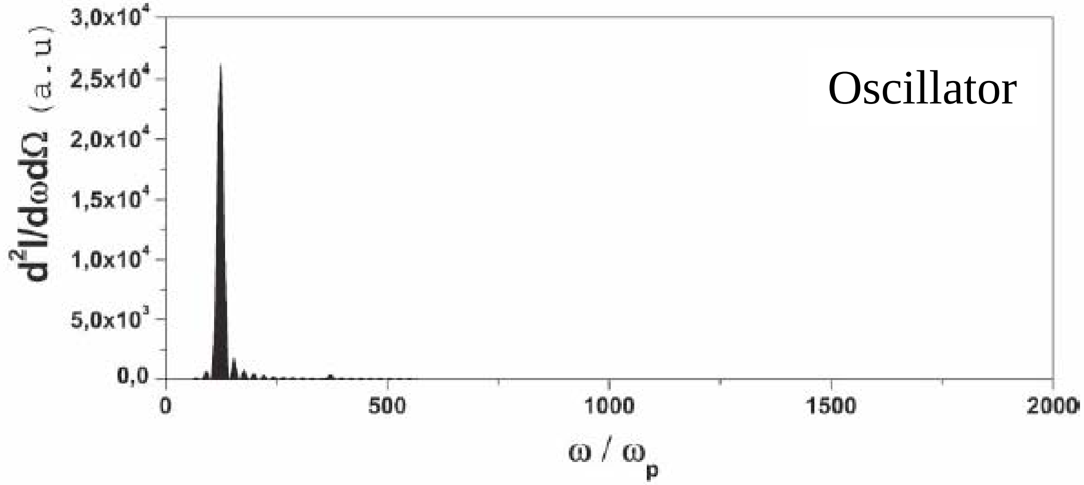
- Wake field particle acceleration relates a geometric info (theta) with a spectral info (Ep)

Gamma-Ray Bursts in laboratory

WakeField Acceleration

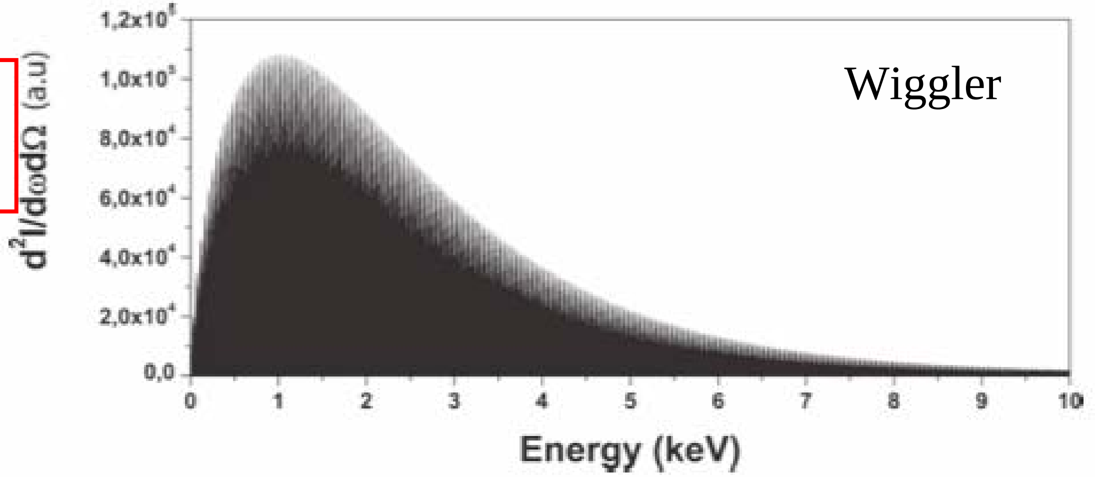
(Ta Phuoc et al. 2005)



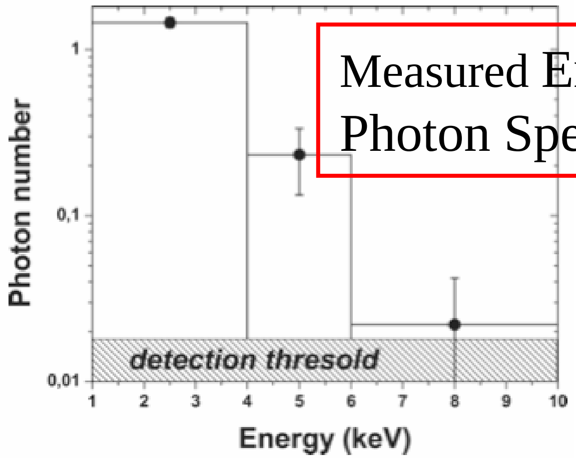


Oscillator

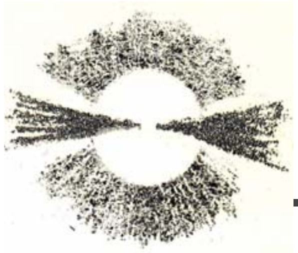
Simulated Emitted Photon Spectrum



Wiggler



Measured Emitted Photon Spectrum



The observational evidence

- Connaughton (2002), ApJ 567, 1028
  - Search for Post Burst emission in prompt GRB energy band
  - Looking for high energy afterglow (overlapping with prompt emission) for constraining Internal/External Shock Model
  - Sum of Background Subtracted Burst Light Curves
  - Tails out to hundreds of seconds decaying as temporal power law $\delta = 0.6 \pm 0.1$
  - <u>Common feature for long GRB</u>
  - Not related to presence of low energy afterglow
- Bright and Dim bursts have different “tails”:
  - Bright bursts (Peak counts >1.5 cm^{-2} s^{-1} ,Mean Fluence 1.5×10^{-5} erg cm^{-2})
  - Dim bursts (Peak counts < 0.75 cm^{-2} s^{-1}, Mean fluence 1.3×10^{-6} erg cm^{-2})