Short Gamma Ray Bursts: observations, physics, GW

(II)

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NewCompStar School 2017 - “Neutron stars: theory, observations and gravitational waves emission”
Outline of the lectures

I. The Gamma-Ray Bursts phenomenon
   - Basic Observations
   - Standard scenarions for progenitors and physics
   - Main open issues
   - GRB cosmology

II. Short Gamma-Ray Bursts
    - Short vs. long: classification issues
    - Short vs. long: physics
    - Short vs. long: progenitors
    - Associated X-ray and GW emission
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   - Short vs. long: classification issues
   - Short vs. long: physics
   - Short vs. long: progenitors
   - Associated X-ray and GW emission

HOT!!!
- energy budget up to $>10^{54}$ erg
- long duration GRBs
- metal rich (Fe, Ni, Co) circum-burst environment
- GRBs occur in star forming regions
- GRBs are associated with SNe
- likely collimated emission

- energy budget up to $10^{51} - 10^{52}$ erg
- short duration (< 5 s)
- clean circum-burst environment
- old stellar population
Long vs. short: classification issues

- Issues on the actual *duration* of “short” GRBs
GRB prompt emission physics: duration depends on energy band (e.g. BATSE 20-2000 keV, Swift/BAT 15-150 keV)

Bromberg et al. (2012) propose that the threshold duration for the Swift sample should be shorter than for the BATSE sample (0.6-0.7 s)

Swift GRBs with $1 \, \text{s} < T_{90} < 2 \, \text{s}$ can be (>50%) collapsars
Some short GRBs show an “extended emission” (weak/soft) following the short spike and lasting up to tens of seconds or more.
Some short GRBs show an “extended emission” (weak/soft) following the short spike and lasting up to tens of seconds or more.

![Graph showing time vs. count rate for different GRBs with different $S_{EE}/S_{spike}$ ratios.]

$T_{90} >> 2 \text{ s}$
Some short GRBs (as some long ones) show a “precursor”
Short / long additional discriminators: *time-lag*

- Short GRBs seem to have **zero lags**
- Long-duration GRBs
- Short-duration GRBs
- Supernova GRBs

*Ukwatta et al. 2011*

*Gehrels et al. 2006*
But…

Temporal lags

- High energy
- Low energy

LAG measured with CCF btw light curves in two separated energy bands

Spectral evolution
- Dermer 1998
- Kecevski+2003
- Ryde+2005
- Peng+2011

Short GRBs have null lags while long have positive lags
2. (in long) lags are anticorrelated with luminosity [Gehrels+2006; Norris+2006]

Swift BAT
[ Bernardini+2014 ]

Short GRBs have null lags … but also long GRBs do.
The case of GRB 060614

- Swift GRB 060614: a long GRB with a very high lower limit to the magnitude of an associated SN -> association with a bright GRB/SN is excluded
- high lower limit to SN also for GRB 060505 (and, less stringently, XRF 040701)
- In the spectral lag – peak luminosity plane, GRB060614 lies in the short GRBs region -> need for a new GRB classification scheme?
Short / long additional discriminators: spectral hardness

Hardness ratio: $HR = \frac{\text{countrate(hard)}}{\text{countrate(soft)}}$

Paradigm:
Long/soft
Short/hard
GRB 990123

Low-energy index
\[ \alpha = -0.6 \pm 0.07 \]

High-energy index
\[ \beta = -3.11 \pm 0.07 \]

\( vF_v \) Peak Energy
\[ E_p = 720 \pm 10 \text{KeV} \]

\[ \text{Flux (Photons/cm}^2 \times \text{s}^{-1} \times \text{MeV}^{-1}) \]

\[ \text{\( vF_v \) Flux (erg/cm}^2 \times \text{s}^{-1} \) \]

\( \text{Photon Energy (MeV)} \)
all SHORT Swift GRBs with known redshift and lower limits to Ep,i are inconsistent with the Ep,i-Eiso correlation

intriguingly, the soft tail of GRB050724 is consistent with the correlation

GRB 060614: no SN, first pulse inconsistent with correlation, soft/long tail consistent: evidence that two different emission mechanisms are at work in both short and long GRB, with different relative efficiency in the two classes (→ “intermediate” GRB)

Long vs. short: progenitors

**LONG**

- energy budget up to $>10^{54}$ erg
- long duration GRBs
- metal rich (Fe, Ni, Co) circum-burst environment
- GRBs occur in star forming regions
- GRBs are associated with SNe
- likely collimated emission

**SHORT**

- energy budget up to $10^{51} - 10^{52}$ erg
- short duration (< 5 s)
- clean circum-burst environment
- old stellar population
Current scenario: **short GRBs from NS-NS(BH) mergers**
Theoretical support: simulations

Evidence for possible formation of a jet [Rezzolla et al. 2011]
Observational support: no SNe associated to short GRBs

NO SN ASSOCIATION

SN peak magnitudes for Long GRBs

Limits for Short GRBs relative to SN1998bw

[Berger 2014]
Observational support: properties of host galaxies

- Host galaxies of long GRBs: blue, usually regular and high star forming, GRB located in star forming regions

- Host galaxies of short GRBs (more recent): no preferred type

Bloom et al. 2002, 2006
Early-type

Late-type

Host-less

GRB 050724
Barthelmy et al. 2005; Malesani et al. 2007

GRB 071227
D’Avanzo et al. 2009

- High-z?
- (very-)low luminosity HG?
- kicked progenitor?
Observational support: location w/r to host galaxy core

SGRBs have systematically larger offsets than LGRBs
SGB offsets broadly consistent with merger models

[Fong & Berger 2013]
Observational support: redshift distribution

[Image: Histogram showing the redshift distribution of Short GRBs (⟨z⟩ ≈ 0.5) and Long GRBs (⟨z⟩ ≈ 2.0).]

SGRBs have systematically lower redshifts than LGRBs.

[Berger 2014]
Redshift distribution & Progenitors

$<z> = 0.85$ and no evidence for a different environment for long and short GRBs can be derived from $N_H$

- Consistent with the "primordial binary" progenitors scenario with short coalescence time
- 10-25% of dynamically captured (or with large natal kicks) systems

D'Avanzo+ 2014
25% of the events of the sample have either a deep upper limit on the intrinsic $N_H$ or are “hostless” SGRBs. This can hint for bursts occurred in low-density environments, originated by progenitors kicked out from their HG (e.g. primordial binaries with long coalescing times) or sited in outlying globular clusters (e.g. binaries formed via dynamically capture)
Observational support: *burst variability time-scales*

Variability

[Morsony+2010; Zhang&Yan 2011; ...]

**T_{90} vs \tau_{\beta} (Observer Frame)**

- Long GRBs
- Short GRBs
- \( T_{90} = \tau_{\beta} \)

\( \delta t \gg \)

\( \delta t \ll \)

Ma, Lachlan+2013

**Internal Collision-induced Magnetic Reconnection Turbolence**

(ICMART - Zhang+2011)

(a) Initial collisions only distort magnetic fields

(b) Finally a collision results in an ICMART event

Variability reveals the central engine activity and/or the dissipation region
Standard scenario: engine of short GRBs is BH + torus from NS-NS merging
Variant: NS-NS produces supra-massive high-B fastly rotating NS ( -->BH?) which powers short GRB emission
Fireball nature: Poynting flux dominated
Observational support: extended emission and plateau

Magnetars as SGRBs progenitors:

- Extended emission

Source of energy: accretion

Source of energy: spin-down

Flux

Gompertz et al. 2014

Metzger et al. 2008
Bucciantini et al. 2012
Magnetars as SGRBs progenitors: plateau

Source of energy: spin-down

Rowlinson et al. 2013
Gompertz et al. 2014
Expected (but very difficult to detect): “kilonova” opt/IR
The merger of a pair of neutron stars is predicted to give rise to three major detectable phenomena: a short burst of -rays, a gravitational wave signature, and a transient electromagnetic signal powered by the synthesis of large amounts of very heavy elements via the r-process.

The latter transients, named “macronovae” or “kilonovae”, are believed to be signatures of the synthesis of most of these very heavy elements in the Universe.

Figure 11: The dark grey region shows the expected macronova r-band apparent magnitude for a source at 200 Mpc as a function of time from the burst onset. Solid curves show the expected GRB afterglow emission assuming different energetics and ISM densities. Red squares and blue triangles represent the afterglow detection (squares) and upper limits (triangles) for a sample of short GRBs (Metzger and Berger 2012). THESEUS/IRT can play crucial role in following-up GW source candidates found by survey telescopes as LSST or ZPTF, and identifying the GW-macronova counterpart.
Evidence for a Kilonova associated to short GRB 130603B

Tanvir et al. 2013
Berger et al. 2013
Alternative scenarios: e.g., Ruffini et al.
Long vs. short: physics

GRB prompt emission physics: still unresolved

- physics of prompt emission still not settled, various scenarios: SSM internal shocks, IC-dominated internal shocks, external shocks, photospheric emission dominated models, kinetic energy dominated fireball, Poynting flux dominated fireball
e.g., in synchrotron shock models (SSM) it may correspond to a characteristic frequency (possibly $\nu_m$ in fast cooling regime) or to the temperature of the Maxwellian distribution of the emitting electrons.
- e.g. in photospheric-dominated emission models it is linked to the temperature of BB photons (direct) or of scattering electrons (Comptonized).
Fireball nature: (baryon kinetic energy or Poynting flux dominated) and bulk Lorentz factor $\Gamma$ are still to be firmly established.
Prompt emission physics for short / long: same or different?

- Hardness-ratio: hints of different mechanism(s)?

Paradigm:
- Long/soft
- Short/hard
the extended emission of some short GRBs have HR typical of long bursts: two phases emission?
Beyond HR: spectral parameters

Low-energy index \( \alpha = -0.6 \pm 0.07 \)

\( vF_v \) Peak Energy \( E_p = 720 \pm 10 \text{MeV} \)

High-energy index \( \beta = -3.11 \pm 0.07 \)
Short GRBs tend to have higher values of $E_p$, but the most significant difference is in the low energy spectral index, much "flatter" (harder) than for long ones.

BUT…

Ghirlanda et al. 2009
… spectral parameters of the first 2s of emission of long GRBs have same spectral parameters distribution as short GRBs!

Ghirlanda et al. 2009
Ep – “intensity” correlations: similar or different ?!
- all SHORT Swift GRBs with known redshift and lower limits to $E_{p,i}$ are inconsistent with the $E_{p,i}$-$E_{iso}$ correlation.
- Intriguingly, the soft tail of GRB050724 is consistent with the correlation.
- GRB 060614: no SN, first pulse inconsistent with correlation, soft/long tail consistent: evidence that two different emission mechanisms are at work in both short and long GRB, with different relative efficiency in the two classes (-> “intermediate” GRB).

Afterglow emission: short GRBs are weaker, but similar phenomenology.
Early afterglow emission: short GRBs are weaker, but similar phenomenology.

About half of all Swift detected SGRBs appear to show a plateau phase [Rowlinson et al 2013]
Displayed by a number of short GRBs

GRB 100117A

[Margutti et al. 2011]
...Why similar afterglow behaviour if circum-burst environment expected to be different?
Afterglow and prompt-afterglow correlations: differences?

Berger et al. 2014

See also:
Nysewander et al. 2009
Margutti et al. 2013
Prompt-afterglow correlations: same behavior!

Bernardini et al. 2012; Margutti et al. 2013
A possible summary, but **still many open questions**

<table>
<thead>
<tr>
<th></th>
<th>SHORT</th>
<th>LONG</th>
</tr>
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<tbody>
<tr>
<td>Elementary pulse duration</td>
<td>smaller</td>
<td></td>
</tr>
<tr>
<td>Minimum variability</td>
<td></td>
<td>similar</td>
</tr>
<tr>
<td>Lags</td>
<td></td>
<td>similar</td>
</tr>
<tr>
<td>Precursors</td>
<td></td>
<td>similar</td>
</tr>
<tr>
<td>Spectra</td>
<td></td>
<td>Harder @ low E</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Similar Epeak</td>
</tr>
<tr>
<td>Spectral evolution</td>
<td></td>
<td>Similar</td>
</tr>
<tr>
<td>Thermal BB</td>
<td></td>
<td>Similar</td>
</tr>
<tr>
<td>GeV emission</td>
<td></td>
<td>Similar (temporal,spectral)</td>
</tr>
<tr>
<td>Short vs start of long</td>
<td></td>
<td>Similar (spectra, luminosity, energy)</td>
</tr>
<tr>
<td>Ep-Liso</td>
<td></td>
<td>similar</td>
</tr>
<tr>
<td>Bulk Lorentz factor</td>
<td></td>
<td>Larger (?)</td>
</tr>
<tr>
<td>Jet opening angle</td>
<td></td>
<td>similar</td>
</tr>
<tr>
<td>Luminosity function</td>
<td></td>
<td>Flatter at low L</td>
</tr>
</tbody>
</table>

**A short GRB is a long interrupted**

SIMILAR central engine, dissipation and emission mechanisms, outflow properties originating from DIFFERENT progenitors
Short GRBs: associated X-ray and GW emission

- The dawn of Gravitational-Wave astrophysics

LIGO Hanford (4km - USA)
LIGO Livingston (4km - USA)
Virgo (3km - Italy)

**Selected for a Viewpoint in Physics**

Physical Review Letters

PRL 116, 061102 (2016)

**Observation of Gravitational Waves from a Binary Black Hole Merger**

B. P. Abbott et al.∗
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of $1.0 \times 10^{-21}$. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203,000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of $410_{-110}^{+100}$ Mpc corresponding to a redshift $z = 0.09_{-0.03}^{+0.03}$. In the source frame, the initial black hole masses are $36.4_{-2.1}^{+2.5} M_\odot$ and $29.4_{-1.9}^{+3.1} M_\odot$, and the final black hole mass is $62.4_{-3.9}^{+4.9} M_\odot$, with $3.0_{-0.3}^{+0.4} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals.

These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.
First direct detection of GW: BH-BH merger
Sept 2015 – Jan 2016: LVC O1 science run

2 high-significance (FAR < 1/century) GW events during O1 (GW 150914, GW 151226) + 1 possible, low-significance event (LVT 151210). All BBH. (Abbott et al. 2016a,b)

LVC O2 run is ongoing (until August 2017)

Another BBH detected (GW 170104; Abbott et al. 2017). Improved strategies for EM follow-up at all wavelengths.

Sky localizations (90% credible area)
600 deg² GW 150914
1600 deg² LVT 151012
1000 deg² GW 151226

No EM counterpart found (despite huge observational effort)

No significant EM emission expected from BBH

EM emission expected for NSNS and/or NSBH

Image credit: LIGO/L. Singer/A. Mellinger
e.m. / GRB emission not expected from BH-BH, but…

Connaughton et al 2016

GBM detectors at 150914 09:50:45.797 +1.024s
GW radiation expected also from NS-BH and NS-NS mergers.
if short GRB progenitors are actually NS-NS or NS-BH mergers -> associated GW emission!!!
Independent diagnostics of SGRB binary progenitor

"low-energy" SGRBs ($\leq 1 \times 10^{51}$ erg) → "high-mass" BNSs

"high-energy" SGRBs ($>1 \times 10^{51}$ erg) → "low-mass" BNSs

[Andersson et al. 2010 with data from Rezzolla et al. 2010]
rate of short GRBs in coincidence with GW signals may be very low (GW emission isotropic, GRB emission highly collimated), but...

<table>
<thead>
<tr>
<th>$\theta_j$ (deg)</th>
<th>EM</th>
<th>EM and GW 2016-2017</th>
<th>EM and GW design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>yr$^{-1}$</td>
<td>yr$^{-1}$</td>
<td>yr$^{-1}$</td>
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<tr>
<td>0.3</td>
<td>$&lt; 10^{-3}$</td>
<td>$&lt; 10^{-3}$</td>
<td>$&lt; 10^{-3}$</td>
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<tr>
<td></td>
<td>$&lt; 10^{-3} - 0.002$</td>
<td>$&lt; 10^{-3} - &lt; 10^{-3}$</td>
<td>$&lt; 10^{-3} - &lt; 10^{-3}$</td>
</tr>
<tr>
<td>10</td>
<td>0.2</td>
<td>0.001</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>0.003 - 2.4</td>
<td>$&lt; 10^{-3} - 0.02$</td>
<td>$&lt; 10^{-3} - 0.5$</td>
</tr>
<tr>
<td>30</td>
<td>1.5</td>
<td>0.007</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>0.02 - 22</td>
<td>$&lt; 10^{-3} - 0.1$</td>
<td>0.003 - 2.6</td>
</tr>
</tbody>
</table>
rate of GRBs+GW increases substantially when considering off-axis viewing, isotropic X-ray emission, kilonova emission (isotropic)
off-axis viewing: low apparent luminosity but still detectable + later afterglow peak
additional signature of off-axis viewing: deviation from $E_p$-$L(E_{iso})$ correlations

$$\delta = \left[ \gamma (1 - \beta \cos(\theta_v - \Delta \theta)) \right]^{-1}, \Delta E_p \propto \delta, \Delta E_{iso} \propto \delta^{(1+\alpha)}$$

$$\alpha = 1 \div 2.3 \rightarrow \Delta E_{iso} \propto \delta^{(2 \div 3.3)}$$

isotropic X-ray emission: e.g., Ciolfi & Siegel (PWN-like)
isotropic X-ray emission: expectations from different models

Light curve peaks at 200 Mpc

Vinciguerra 2017
isotropic Opt/IR emission: Kilonova

Tanvir et al. 2013
Berger et al. 2013
Ingredients for computation of expected e.m. counterpart detection rates by LIGO/Virgo

Expected NSNS – NSBH EM counterparts

Short GRBs (γ-ray, X-ray, opt, NIR, radio)

Orphan afterglow (X-ray, opt, NIR, radio)

Macronova/Kilonova (optical, NIR)

How many within the LIGO-Virgo horizon?
e.m. counterpart detection rates by LIGO/Virgo (uncertainties of orders of magnitude due to models, assumptions, etc.)

important results should be announced by LVC by mid-October
WORKSHOP 2017
THESEUS mission design and science objectives
Probing the Early Universe with GRBs
Multi-messenger and time domain Astrophysics
The transient high energy sky
Synergy with next generation large facilities (E-ELT, SKA, CTA, ATHENA, GW and neutrino detectors)

INAF - Astronomical Observatory of Capodimonte
Naples, Italy
5-6 October 2017
GW observations

<table>
<thead>
<tr>
<th>Epoch</th>
<th>GW detectors</th>
<th>BNS horizon</th>
<th>BNS rate [yr⁻¹]</th>
<th>XGIS/sGRB rate [yr⁻¹]</th>
<th>SXI/X-ray isotropic counterpart rate [yr⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020+</td>
<td>Second-generation (advanced LIGO, Advanced Virgo, India-LIGO, KAGRA)</td>
<td>~400 Mpc</td>
<td>~40</td>
<td>~0.5-5</td>
<td>~1-3 (simultaneous)</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~6 18 (+follow-up)</td>
</tr>
<tr>
<td>2030+</td>
<td>Second + Third-generation (e.g. ET, Cosmic Explorer)</td>
<td>~15-20 Gpc</td>
<td>&gt;10000</td>
<td>~15-25</td>
<td>&gt;~300</td>
</tr>
</tbody>
</table>
Back-up slides
X-ray plateau and steep decay (XPSD)

Most popular explanation: Hypermassive NS collapsing to BH

Rowlinson+ 2013
Most common X-ray emission processes in astrophysical sources

I. Thermal
   - Black body emission
   - Thermal Bremsstrahlung

II. Non thermal
   - Synchrotron emission
   - Inverse Compton / Comptonization

In many classes of astrophysical sources, more than one of these processes is at work.
Thermal processes: black-body emission

- occurs in optically thick medium
- matter heated at **temperatures from \( \sim 10^6 \) to \( \sim 10^9 \) K emit black-body radiation in the X-ray energy band from \( \sim 0.1 \) to \( \sim 100 \) keV
- the continuum has the well-known Planckian shape

\[
I(v)dv = \frac{8\pi hv^3}{c^3} \cdot \frac{1}{\exp \left( \frac{hv}{kT} \right) - 1} dv
\]
physical information: temperature of the emitting medium \((kT)\)

examples: accretion disks in X-ray binaries and AGNs

the actual shape of the continuum may depend on the radial profile of the disk temperature, on the metrics (e.g, Schwarzchild or Kerr black hole), on the viewing angle
Thermal processes: thermalized bremsstrahlung

- occurs in optically thin plasma in thermal equilibrium

- Bremsstrahlung emission is due to the change in acceleration of a charged particle due to another particle. It is also sometimes referred to as ‘free-free’ emission

\[
\epsilon^f_{\nu} = 6.8 \times 10^{-38} Z^2 n_e n_i T^{-1/2} e^{-h \nu / kT} \frac{1}{g_{ff}}
\]
physical information: temperature \((kT)\) and properties of the emitting plasma

examples: stellar coronae, galaxy clusters, young SNR

e.g., by combining surface brightness mapping and spatial resolved X-ray spectroscopy, it is possible to map the density and temperature distribution and the “total” mass (galaxies + gas + DM) in clusters

Perseus cluster
Non thermal processes: synchrotron

- Synchrotron radiation is due to the movement of an electron charge in a magnetic field.

The frequency of synchrotron radiation is:

$$\omega_B = \frac{qB}{\gamma mc}$$

The total power emitted of each electron is:

$$\frac{dE}{dt} = \frac{4}{3} \sigma_T c \beta^2 \gamma^2 U_B$$

- of particular astrophysical interest is the synchrotron emission by a population of electrons with kinetic energies distributed as a power-law

$$I(\nu) = a(\rho) \frac{e^3}{m_e c^2} \left( \frac{3e}{4 \pi m_e^3 c^5} \right)^{(\rho - 1)/2} B^{(\rho + 1)/2} K L \nu^{-\frac{\rho - 1}{2}} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{Hz}^{-1}$$
Synchrotron self-absorption:

A photon interacts with a charged particle in a magnetic field and is absorbed (energy transferred to the charge particle).

This occurs below a cut-off.

For an input electron distribution given by:

\[ N(E) dE = CE^{-p} dE \]

It can be shown that the power will be related to the frequency by:

\[ P \propto \nu^{-(p-1)/2} \]

And so the spectral index \( s \) is related to the power law of the input electron index \( p \), by:

\[ s = \frac{p - 1}{2} \]
- physical information: distribution of the emitting electrons (p), properties of the magnetic field (B)
- examples: SNR, pulsars, GRB afterglows (and prompt ?)

**Crab nebula spectrum by BeppoSAX/PDS**

**Typical X-ray spectrum of a GRB (PL absorbed by Galactic**
Non thermal processes: inverse Compton and Comptonization

Inverse Compton Scattering (IC) is due to interaction between a low-energy photon and a relativistic electron.

From Blumenthal and Gould (1970), for a single frequency photon field, the change in the spectral will be given by:

$$I(\nu)d(\nu) = \frac{3\sigma_T c}{16 \gamma^4} \frac{N(\nu_o)}{\nu_o^2} [2\nu \ln \left(\frac{\nu}{4\gamma^2 \nu_o}\right) + \nu + 4\gamma^2 \nu_o - \frac{\nu^2}{2\gamma^2 \nu_o}] d\nu$$

The maximum and average frequency of the scattered photons are:

$$\nu_{max} \approx 4\gamma^2 \nu_o \quad \quad <\nu> = \frac{4}{3}\gamma^2 \nu$$
Comptonization in electron – photon plasma

\[ y = \text{average fractional energy changed per scattering} \]
\[ \text{[mean number of scatters]} \]

\[ y \approx \int \frac{4kT_e}{mc^2} \sigma_T n_e dx \]

\[ \alpha = \text{unsaturated} \]

\[ \alpha = \text{saturated} \]
物理信息：温度（$kT_e$）/电子分布，种子光子的谱，光学深度和源的几何。

例子：X射线双星，AGNs，blazars...

- Compton化$b b$种子光子（BHC，AGNs）
- Compton化同步辐射（Blazars）
Thus, the determination of the spectral continuum over a broad energy band (as often, in X-rays) is fundamental for discriminating the emission process.

\[
B_\nu(T) = \frac{2h}{c^2} \frac{\nu^3}{e^{h\nu/kT} - 1}
\]

\[
e_{\nu}^{\text{eff}} = 6.8 \times 10^{-38} \frac{\text{ergs}}{s \ cm^3 \ Hz} \ Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT} \gamma_{\text{eff}}
\]

\[
\frac{dE}{dt dV d\nu} = \frac{\sqrt{3}q^3}{mc^2(p+1)} \left( \frac{3q}{2\pi mc} \right)^{p-1} C_{\gamma} B_{\perp}^{p+1} \nu^{p-1} \Gamma_1 \Gamma_2
\]

\[
S_\nu \sim \nu^{5/2}
\]
in many classes of sources, more than one process is at work

Black-body from accretion disk

Comptonization by hot corona

Spectral states in BHC XTE1650-500
Possible KILONOVA signature in GRB130603b?

[Berger et al. 2013]
Short vs. Long: some questions

- Discriminators? (duration, time-lag, minimum variability time scale, hardness)
- Prompt emission physics: the same?
- Sub-classes? E.g. EE-SGRBs, long GRBs without SN (e.g., 060614), possible outliers of Ep-L correlation, paradigm by Ruffini et al., SGRs, …
- Jet angles, structure, $\Gamma$: similar or not?
- Why similar afterglow (e.g., Ex-Eiso-Ep) if circum-burst different?
- Engine: accreting BH vs. magnetar -> same?
- Different progenitors are adequately supported by observations ($E$, $\Delta T$, HGs, circum-burst, lum.fun, rates vs. $z$). Or not?
- Will we ever detect short GRBs in coincidence with GW signals? -> isotropic X-ray emission? Orphan afterglows?
Kilonova NIR excess

Fall-back Accretion or magnetar spin-down

Fong et al. 2014
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