Nagyenergiás fotoni, kozmikus sugárzási, neutrínó sugárzási és gravitációs hullámbeli fényességük és a kozmológiai szerepük

Mészáros Péter
ELTE, 2004 Május 19
GRB: → Hyperaccreting Black Holes (current paradigm)

Short
\( t_\gamma \lesssim 2 \text{ s} \)

Long
\( t_\gamma \gtrsim 2 \text{ s} \)

NS - NS merger

\( 0.01 \, M_\odot \) torus

very, very fast jet

BH - NS merger

\( 0.1 \, M_\odot \) torus

BH - WD merger

\( 1 \, M_\odot \) torus

NS/BH - He core merger after common envelope

collapsar = rotating, collapsing "failed" supernova


Mészáros, gb2_ELTE 04
Jet (outside the star) → shocks

- **Shocks** expected in any unsteady supersonic outflow (esp. in a non-vacuum environment)

- **Internal** shocks: fast shells catch up slower shells (unsteady flow)

- **External** Shock: flow slows down as it plows into external medium

- **NOTE**: “external” and “internal” shocks might be expected also while jet is **inside** star, as well as after it is **outside** the star.
  
  If inside: γs do **not** escape (but ν can)
  
  If outside: γs do **escape** (and ν too)
Observed Log N – Log P
(BATSE experiment)

- Slope is $-3/2$ (Euclid) for bright bursts
- Roll-off at faint fluxes implies that we are running out of sources
  $\Rightarrow$ we are seeing the edge of the source distribution, or seeing cosmological effects.
- Combined with isotropic distribution on sky
  $\Rightarrow$ cosmological distances
Cosmology with GRBs?

High-z GRB distance measures

• Positive K-correction:
  → flux ~ constant at z ≥ 5
• Optical/UV: Ly α cutoff → redshift out to z ≤ 5 for Swift
• Forward shock exp. fluxes↓

• XR cont: detect with Swift for z ≤ 20 @ t ≤ 1 dy
• Fe Kα XR line unabsorbed by gal. for z ≤ 20
• Swift det. Fe Kα to z ≤ 3 @ t ≤ 3 hrs, 3σ level
• XMM det. Fe Kα to z ≤ 15 @ t ≤ 1 day, 3σ level

Meszaros, Rees 03 ApJ 591, L91

Lamb, Reichart 00

O/IR

0.1 1 10 keV

XR

Gal.H abs

z = 20 5 3 0

Meszáros, gb2_ELTE 04
Reverse Shock light-curve

- Brief reverse O/IR light curve is *brighter* (while it lasts) than forward l.c.
- At high-z, reverse l.c. *lasts longer* (in obs. frame)

---

Fig. 1.— Typical light curves, for a redshift $z = 1$. Reverse shock emission (dashed), forward shock emission (solid), total flux (symbols). Parameters: $\delta_B = 0.001$, $R_S = B_0 / B_f = 5$, $\rho_0 = 0.1$, $E_{10} = 10$, $p = 2.5$, $\gamma = 120$, $n_0 = 1 \text{ cm}^{-3}$. a): V band ($\nu = 5.45 \times 10^{14} \text{ Hz}$); b): K band ($\nu = 1.36 \times 10^{14} \text{ Hz}$).
IR & XR
hi-z detectability

XR detectability ↓

O/IR → ↓
detectability

Chandra

V-band

K-band

Swift

JWST

Meszaros, gb2_ELTE 04
The Time Gap

![Graph showing X-ray flux vs. time for GRB970228 and GRB970111. The graph includes a line with a slope of -1.3 and a brightness factor of 10,000. There is a highlighted time gap of 8 hours between Swift and Beppo SAX data.]
Swift: The Gamma-Ray burst Explorer Mission

- Objectives
  - Determine origin of GRBs
  - Use GRBs to probe Universe
  - Perform hard X-ray survey
- Rapidly re-pointing spacecraft
  - ~ 1 minute response
- Data distributed immediately (seconds) to astronomical community world-wide
The **Swift MIDEX**

- **Prime Institution:** NASA-GSFC (Neil Gehrels, PI)
- **Lead University Partner:** Penn State (PSU)
- **Countries Involved:** USA, Italy, UK
- **Spacecraft Partner:** Spectrum Astro
Swift Instruments

- **Burst Alert Telescope (BAT)**
  - CZT detectors
  - Most sensitive gamma-ray imager ever
- **X-Ray Telescope (XRT)**
  - Arcsecond GRB positions
  - CCD spectroscopy
  - Jet-X mirrors, XMM Detectors
- **UV/Optical Telescope (UVOT)**
  - Sub-arcsecond imaging
  - Grism spectroscopy
  - 24\textsuperscript{th} mag sensitivity (1000 sec)
  - Finding chart for other observers
  - Copy of XMM OM
Swift: new multiwavelength rapid-response observatory in space

- GRB database with good statistics:
  100-150 GRB/year with good localization,
  plus another 100-150/year unlocalized
- Observations immediately follow GRB when emission is brightest
- Rapid identification of counterparts
  - Arcsec position immediately to ground for spectroscopy
  - Sub-arcsec relative positions for hundreds of bursts for host galaxy ID and GRB origin determination
- Measure distances (redshifts) for hundreds of bursts
- Multiwavelength afterglow observations on all timescales
- Low Earth orbit: 600 km altitude, 20 degree inclination
- Rapid dissemination of data
- **Launch in Sept. 2004**
Observing Scenario

1. Burst Alert Telescope triggers on GRB, calculates position on sky to < 4 arcmin
2. Spacecraft autonomously slews to GRB position in 20-70 s
3. X-Ray Telescope determines position to ~3 arcseconds
4. UV/Optical Telescope images field, transmits finding chart to ground
Why a Burst Alert Telescope?

To rapidly locate a wide range of Gamma Ray Bursts

BAT burst detection abilities:
- Sensitive to energy range containing GRB peak energy fluxes (15-150 keV)
- Accurately positions GRB of short and long durations (milliseconds to minutes)
- Large field of view (2 Steradian)
- Large effective area (5200 cm²: 5x more sensitive than BATSE)
- Sufficient angular resolution to rapidly localize within XRT, UVOT fields of view (17’ full width, 1-4’ centroid)

<table>
<thead>
<tr>
<th>BAT Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope</td>
</tr>
<tr>
<td>Timing Resolution</td>
</tr>
<tr>
<td>Detector</td>
</tr>
<tr>
<td>Detector Format</td>
</tr>
<tr>
<td>Detector Readout Modes</td>
</tr>
<tr>
<td>Field of View</td>
</tr>
<tr>
<td>Pixel Scale</td>
</tr>
<tr>
<td>Position Knowledge</td>
</tr>
<tr>
<td>Energy Range</td>
</tr>
<tr>
<td>Effective Area</td>
</tr>
<tr>
<td>Sensitivity</td>
</tr>
<tr>
<td>Operation</td>
</tr>
</tbody>
</table>

Mészáros, gb2_ELTE 04
BAT Instrument

CZT Detectors

Detector Module
The Burst Alert Telescope (BAT)
Image Taken during Calibration

17 arcmin PSF
Why an X-ray Telescope?

A: because > 80% of GRBs have X-ray afterglows

GRB Afterglow Detections

<table>
<thead>
<tr>
<th>GRB</th>
<th>Trigger Mission</th>
<th>X-ray</th>
<th>Optical</th>
<th>Radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>970111</td>
<td>Beppo SAX</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>970228</td>
<td>Beppo SAX</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>970402</td>
<td>Beppo SAX</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>970508</td>
<td>Beppo SAX</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>970616</td>
<td>BATSE/RXTE</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>970828</td>
<td>BATSE/RXTE</td>
<td>X</td>
<td></td>
<td>?</td>
</tr>
<tr>
<td>971214</td>
<td>Beppo SAX</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>971227</td>
<td>Beppo SAX</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>980326</td>
<td>Beppo SAX</td>
<td>?</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>980329</td>
<td>Beppo SAX</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>980425</td>
<td>Beppo SAX</td>
<td>?</td>
<td>SN</td>
<td>X</td>
</tr>
<tr>
<td>980515</td>
<td>Beppo SAX</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>980519</td>
<td>Beppo SAX</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>980613</td>
<td>Beppo SAX</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>980703</td>
<td>BATSE/RXTE</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>981226</td>
<td>Beppo SAX</td>
<td>?</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>990123</td>
<td>Beppo SAX</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

XRT Characteristics

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope</td>
<td>3.5 m Wolter I</td>
</tr>
<tr>
<td>Telescope PSF</td>
<td>15 arcsec HPD @ 1.5 keV</td>
</tr>
<tr>
<td>Detector</td>
<td>EEV CCD-22</td>
</tr>
<tr>
<td>Detector Format</td>
<td>600 x 600 pixels</td>
</tr>
<tr>
<td>Detector Readout Modes</td>
<td>Photon counting, Imaging, &amp; Timing</td>
</tr>
<tr>
<td>Field of View</td>
<td>23.6 x 23.6 arcmin</td>
</tr>
<tr>
<td>Pixel Scale</td>
<td>2.36 arcsec / pixel</td>
</tr>
<tr>
<td>Energy Range</td>
<td>0.2 - 10 keV</td>
</tr>
<tr>
<td>Effective Area</td>
<td>110 cm²@ 1.5 keV</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$2 \times 10^{-14}$ erg cm⁻²s⁻¹ in 10⁴ s</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>1 cps per milliCrab</td>
</tr>
<tr>
<td>Position Accuracy</td>
<td>2.5 arcseconds (2 sigma)</td>
</tr>
<tr>
<td>Operation</td>
<td>Autonomous</td>
</tr>
</tbody>
</table>
1) Brilliant Flash

GRB X-ray counterparts and afterglows

X-ray burst intensities (SAX/WFC, RXTE)

Swift XRT

Use Imaging Mode: 0.1 s exposure time integrated image provides accurate centroids for $F_x < 26 \text{ Crabs}$
Source Centroids

2.5 arcsec centroids
Redshift Measurement

100 s Observation of 150 mCrab Afterglow with Narrow Fe line

Spectral Parameters:
- $I(E) = A E^{-2.0}$
- $N_H = 2.5 \times 10^{22}$
- $E_{\text{line}} = 6.4 \text{ keV}$
- $R = 150 \text{ cps}$
- $t = 100 \text{ s}$

(150 milliCrab source)
**XRT Sensitivity**

**Use Timing Mode and/or Photon-Counting Mode:**

- **Timing Mode:** Accurate Light Curves and Spectroscopy for $20 \text{ mCrabs} < I < 8.5 \text{ Crabs}$
- **Photon-Counting Mode:** Accurate Position, Lightcurve, and Spectroscopy for $I < 20 \text{ mCrabs}$

*GRB X-ray counterparts and afterglows*

- **X-ray burst intensities** (SAX/WFC, RXTE)
- **X-ray afterglows**

*XRT Sensitivity Limit*

- Flux (ergs/cm$^2$/s)
- Time since burst (s)
- milliCrabs
XRT Integration to Spacecraft
Why a UV/Optical Telescope?

A: subarcsecond positions, redshifts

<table>
<thead>
<tr>
<th><strong>Telescope</strong></th>
<th>30 cm modified Ritchy-Cretien</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>F-number</strong></td>
<td>12.7</td>
</tr>
<tr>
<td><strong>Telescope PSF</strong></td>
<td>Diffraction-limited</td>
</tr>
<tr>
<td><strong>Detector</strong></td>
<td>Photon-counting intensified CCD</td>
</tr>
<tr>
<td><strong>Detector Format</strong></td>
<td>2048 x 2048 virtual pixels</td>
</tr>
<tr>
<td><strong>Field of View</strong></td>
<td>17 x 17 arcmin</td>
</tr>
<tr>
<td><strong>Pixel Scale</strong></td>
<td>0.50 arcsec / pixel</td>
</tr>
<tr>
<td><strong>Bandpass</strong></td>
<td>170 – 650 nm</td>
</tr>
<tr>
<td><strong>Spectroscopy</strong></td>
<td>2 grisms + 6 broad band colors</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>B=24th magnitude in $10^3$ s (white light)</td>
</tr>
<tr>
<td><strong>Position Accuracy</strong></td>
<td>0.3 arcseconds @ 350 nm</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>Autonomous</td>
</tr>
</tbody>
</table>
UVOT: Heritage Hardware
Wavelength response of UVOT

Grisms

Broadband filters
UVOT Improved UV Response

Before Launch Throughput
(Both Channels)

![Graph showing effective area vs. wavelength for different channels.](image)

- Green: Swift-UVOT (A)
- Blue: Swift-UVOT (B)
- Red: XMM-OM
UVOT Integration to Spacecraft
Swift Ground System

Spacecraft
Spectrum Astro
Rapid Autonomous Slewing

Payload
BAT
XRT
UVOT

TDRSS

Malindi

Mission Operations Center (MOC)

PSU

Science Center
GSFC

User Community
Swift is scheduled to launch on a Delta II rocket in September.
The Swift Explorer in Orbit
GeV \gamma

emission from

GRB, PSR, SNR,
other galactic, extragalactic & un-id sources

- GeV: space obs. (SAS-2, HEAO-A4, Kvant….)
- EGRET spark chamber: 5 GRB, 6 PSR & 60 blazars @ \approx 10 GeV
- + ~25 other Unidentified EGRET \gamma-ray sources
Two EGRET spark chamber GeV Bursts

- >10 GeV photon flux can last for $\gtrsim 1$ hr, start with MeV trigger
- Energy Fluence $F_{0.1-10 \text{ GeV}} \sim F_{0.1-10 \text{ MeV}}$
Simplest “delayed” GeV $\gamma$ mech.

- GeV emission seen, start $\sim$ same time as MeV trigger, but lasting $\gg 1$ hr:
  - could be
    a) **internal** shock synchrotron
      → normal duration **MeV** to $\lesssim$**GeV**
    b) **external** shock (moder. $\Gamma$, low $n_{ext}$)
      IC → $\gtrsim$ **GeV** to TeV, lasts $\sim$mins-hr

(Meszaros & Rees 1994 MNRAS 269, L41)

- Other possib (Katz 94) : proton impact on bin. comp.* pp → $\gamma$
GeV-TeV photons from GRB

- Internal shocks: $\gamma\gamma \rightarrow e^\pm$, $\tau_{\gamma\gamma} \geq 1$ @ $E_\gamma \gtrsim \Gamma^2_{300} \text{GeV}$
  - pair cutoff in spectrum
  - get info about $r_{sh}$ (compactness, $\tau_{\gamma\gamma}$)
- In ext. shock, $\tau_{\gamma\gamma} \leq 1$ on GRB target $\gamma$;
- test if shock is int. or ext;
  - test bulk Lorentz factor, shock accel efficiency, magnetic field in shock
  - max. $e^\pm$ energy? $\rightarrow$ size of accel region

Mészáros, gb2_ELTE 04
GRB 941017: $p\gamma$ signature?

- Hard (10-200 MeV) comp. in EGRET TASC calorimeter not compatible w. BATSE MeV fit (but in 26 other bursts a single BATSE/TASC fit works well)
- Hard comp. more prominent in time $\rightarrow p\gamma$ signature? might explain delay, hardness
- Alternative: could be IC, in regime where IC sp is harder than sync PL; e.g. scatt. of lower energy synch. asymptote; or observe IC region where electrons with a range of energies scatter off a range of photon energies (Granot, Guetta, astroph/0309231)

Gonzalez, Dingus et al, 03, Nature 424, 749
GLAST: LAT (Stanford +)

- LAT: launch exp ’06, Delta II, 2-300 GRB/2yr
- Pair-conv.mod+calor.
- 20 MeV-300 GeV, $\Delta E/E \lesssim 10\% @ 1$ GeV
- fov=2.5 sr (2xEgret), $\theta \sim 30''-5'$ (10 GeV)
- Sens $\gtrsim 2.10^{-9}$ ph/cm$^2$/s (2 yr; $\approx 50$x Egret)
- 2.5 ton, 518 W

Also on GLAST: GBM (next slide)
Hadronic processes – $\gtrsim$TeV?

basic $p, \gamma \rightarrow$ UHE $\nu, \gamma$

- If protons present in jet $\rightarrow$ they are also Fermi accelerated (as are $e^-$)
- $p, \gamma \rightarrow \pi^\pm \rightarrow \mu^\pm, \nu_\mu \rightarrow e^\pm, \nu_e, \nu_\mu$ (\(\Delta\)-res.: $E_p E_\gamma \sim 0.3 \text{ GeV}^2\))
- $\rightarrow E_{\nu,\text{br}} \sim 10^{14} \text{ eV}$ for MeV $\gamma$s (int. shock)
  $\rightarrow E_{\nu,\text{br}} \sim 10^{18} \text{ eV}$ for 100 eV $\gamma$s (ext. rev. sh.) $\implies$ ICECUBE
- $\rightarrow \pi^0 \rightarrow 2\gamma \rightarrow \gamma\gamma$ cascade $\implies$ GLAST, ACTs..
  (Waxman-Bahcall 1997; 99; Boettcher-Dermer 1998; 00; )
- Test hadronic content of jets (are they pure MHD/$e^\pm$ ...?)
- Test acceleration physics (injection effic., $\epsilon_e, \epsilon_B$..)
- Shock radius: $\gamma\gamma$ cascade cut-off: $\epsilon_\gamma \lesssim \text{GeV}$ (internal shock)
  $\epsilon_\gamma \lesssim \text{TeV}$ (ext shock/IGM)
  Different $\gamma\gamma$ cut-off due to \(\neq\) compactness param. ($\tau_{\gamma\gamma}, R_{\text{sh}}$)

$\rightarrow$ photon cut-off: diagnostic for int. vs. ext-rev shock
GeV-TeV $\gamma$ experiments underway
Point Source Sensitivities

- **MAGIC**: La Palma (Munich)  
  Monoc. 1x17m, >30 GeV, ‘01
- **HESS**: Namibia (Heidelberg)  
  Stereo 4x12m, > 50 GeV, ’02
- **CANGAROO-III**: Austral(Tokyo)  
  Stereo 4x10m, >50 GeV, ’03
- **VERITAS**: Arizona (SAO)  
  Stereo 7x10m, >50 GeV, ’05
- **STACEE**: Sandia (UCLA/Chic)  
  solar tower, 20-300GeV, ’01
- **MILAGRO** (ITO), LANL, NM  
  water, > 20 GeV, A~5.10^7 cm^2
- **GLAST** (LAT): space (Stanford)  
  Silicon, 20 MeV-300 GeV, ‘06
TeV $\gamma$ Detection Status

- **Milagrito**: Tentative
  $\Phi_{\text{TeV}} \sim 10 \Phi_{\text{MeV}}$; but, no $z$ (abs? $d < 100$ Mpc?)

- **Tibet** array: superpose
  50-60 $\neq$ bursts in time-coincid. w. MeV: joint TeV det. significance $6\sigma$?
  (Amenomori et al AA '96)

- **GRAND**: GRB 971110
  $\leftarrow$ TeV reported at $2.7\sigma$
  (Poirier et al PRD 03, aph/0004379)
\(\gamma\gamma\) Opacity of the Universe

- In all but the densest (veiled) AGN sources (e.g. gal.nuc?), \(\tau_{\gamma\gamma} \leq 1\) for >TeV on “local” target photons, but..
- In IGM, \(\tau_{\gamma\gamma} \geq 1\) for >TeV on IR bkg \(\gamma\) \((D \leq 100\text{Mpc}) \rightarrow\) test IR bkg spectral density,
- constrain early star formation rate & z-distr of SFR, LSS, cosmology

Coppi & Aharonian ‘97

Mészáros, gb2_ELTE 04
UHE $\nu$ ($\& \gamma$) in GRB

4 possible collapsar-jet sites

1. At collapse, make GW + thermal $\nu$s

2. If jet outflow is baryonic, have $p,n \rightarrow p,n$ relative drift, $pp/pn$ collisions
   $\rightarrow$ inelastic nuclear collisions
   $\rightarrow$ VHE$\nu$ (GeV)

3. Shocks while jet is inside $\star$ can accel. protons $\rightarrow p\gamma, pp/pn$ collisions
   $\rightarrow$ UHE$\nu$ (TeV)

4. Shocks outside $\star$ accel. protons
   $\rightarrow p\gamma$ collisions (+pp/pn - if supranova)
   $\rightarrow$ UHECR, UHE$\nu$, UHE$\gamma$
   ($<10^{20}, 10^{14}-10^{18}, >10^9$ eV)

5. If supranova (SN >2 days before GRB)
   $\rightarrow p\gamma, pp$ of jet protons on shell targets
   $\rightarrow$ UHE$\nu$ (> TeV)
(2) Jet inside star: GRB $\gamma,\nu$ Precursor

- Jet propagating through progenitor, \textit{BEFORE} emerging from stellar envelope, can have int. shocks which accel. $p^+ \rightarrow p\gamma$ on unobserved X-rays, $\rightarrow \pi^\pm, \nu$
- \text{pp, pn on stellar envelope $\rightarrow \pi^\pm, \nu$
- $\longrightarrow \sim$ few TeV neutrino precursor

- If progenitor has $R_\star \sim 10^{12}$ cm (BSG) $\rightarrow$
  \text{Rate}(\nu_\mu, \text{TeV})_{\text{prec}} > \text{Rate}(\nu_\mu, 100 \text{TeV})_{\text{int.shock}}$
  \text{(easier to detect in ICECUBE)}
- But, if WR, $R_\star \sim 10^{11}$ cm $\rightarrow$
  \text{Rate}(\nu_\mu, \text{TeV})_{\text{prec}} < \text{Rate}(\nu_\mu, 100 \text{TeV})_{\text{int.shock}}$
  \text{→ test progen. size (e.g. @ high $z$: popIII?)}
- At jet break-out: $\longrightarrow$ photon flashes
  \text{(Ramirez-Ruiz, McFadyen, Lazzati 02; Waxman, Mészáros 02)}
  \text{i) thermal keV $\gamma$ flash}
  \text{ii) non-therm. 10-100 MeV $\gamma$ (IC upscatt of XR)}
  $\rightarrow$ precursors ($\approx$ few sec.) of “usual” MeV $\gamma$

- (3) $\longrightarrow$ Blue $\nu$- spectrum: $\gtrsim 100$ TeV $p, \gamma \rightarrow \nu$ from shocks outside star
GRB 030329: SN shell & precursor with ICECUBE

Burst of $L_\gamma \sim 10^{51}$ erg/s, $E_{SN} \sim 10^{52.5}$ erg, $@ z \sim 0.17$, $\theta \sim 68^\circ$

Razzaque, Mészáros, Waxman 03 PRD 69, 23001
Diffuse UHE $\nu$ from pop.III collapse

- At $z \sim 5-30(?)$ pop.III, $M \sim 30-300 \, M_\odot$, $E_{\text{iso}} \sim 10^{54}-10^{56}(?)$ erg
- Buried jets $\rightarrow p \gamma \rightarrow \nu_\mu$, $\rightarrow \nu$-bursts, AMANDA/ICECUBE
- “low-z” GRB, AGN etc too
- Detect highest $z$ form’n, get primordial IMF,

Schneider, Guetta, Ferrara aph/0201342
ICECUBE: \( \text{km}^3 \)

- Extension of Amanda
  \( 0.15 \text{ km}^3 \rightarrow \text{km}^3=1\text{Gton} \)
- Initial funding approved \( \sqrt{\text{}} \)
- 80 strings \( , \) 4800 PMTs (ice) \( + \) air shower surface array
- Design for det.all flavor \( \nu' \)s , from \( 10^7 \text{ eV (SN)} \) to \( 10^{20} \text{ eV} \)
• French/Italian/UK… collaboration
• Site off Toulon
• Also: NESTOR

Greek/German/Russian…

• Km³ water Cherenkov detector
• Deployment approx. 2010
• Complement ICECUBE: \( \lambda_{sc,abs} \sim (100,10) \) H₂O, \( \lambda_{sc,abs} \sim (20,100) \) Ice
• Northern site: at lower E complementary sky coverage
Diffuse UHE $\nu$: CR bound and sensitivity, bckg

FIG. 8: The neutrino flux from compact astrophysical accelerators. Shown is the range of possible neutrino fluxes associated with the the highest energy cosmic rays. The lower line, labeled “transparent”, represents a source where each cosmic ray interacts only once before escaping the object. The upper line, labeled “obscured”, represents an ideal neutrino source where all cosmic rays escape in the form of neutrons. Also shown is the ability of AMANDA and IceCube to test these models.
CR Protons from GRB

- Internal & extern. (rev) shocks NR Fermi acc. → spectrum \( N(E) \propto E^{-2} \)
- Can reach \( E \sim 10^{20} \text{ eV} \) (for \( \xi_B \xi_e \approx 0.02, \Gamma \approx 130 \))
- CR energy input at \( 10^{20} \text{ eV} \)
  \[ \frac{dE}{dt dV} \sim 10^{44} \text{ erg/Mpc}^3/\text{yr} \]
  where \( \zeta \sim 0.5-3 \) (z-evol.)
- Entire \( > 10^{20} \text{ eV} \) CR flux from GRB? yes/no/possib

(Waxman, Neutrino 2000, hep-ph/0009152)

(Waxman NucPhS 87:345’00; Stecker APPh 14:207 ’00)
UHECR total power in GRB?

- Previous (1995-00): \( E_\gamma \sim 10^{51} \) erg, \( R(z=0) \sim 30 / \text{Gpc}^3/\text{yr} \),
  \( dE/dtdV \sim 0.3 \times 10^{44} \) erg/\text{Mpc}^3/\text{yr}
- New (>2000): \( E_\gamma \sim 2.5 \times 10^{53} \) erg (isot.equiv);
  \( R(z=0) \sim 5 \times 10^{-10} / \text{Mpc}^3/\text{yr} \),
  \( dE/dtdV \sim 1.3 \times 10^{44} \) \( \zeta \) erg/\text{Mpc}^3/\text{yr} . (\zeta \sim 3-8 \text{ to } z \sim 1, \text{ evol})

  Jets: \( \frac{4\pi}{500} (E_\gamma \downarrow, R\uparrow, \sqrt{\zeta}) \)
- \( \rightarrow E_e^2 \, d\nu_e^{\text{GRB}}/dE_e \, dt \sim 10^{44} \) \( \zeta \) erg/\text{Mpc}^3/\text{yr}

- UHECR exg obs: \( dE_p^{\text{CR}}/dt \sim 3 \times 10^{44} \) erg/\text{Mpc}^3/\text{yr}
  \( \rightarrow E_p^2 \, d\nu_p^{\text{CR}}/dE_p \, dt \sim 0.7 \times 10^{44} \) erg/\text{Mpc}^3/\text{yr}, \sqrt{\zeta}, \text{OK.}

(Waxman, astro-ph/0210638)
UHE Cosmic Rays

• \( \approx (\gtrsim?) \ 10^{20} \text{ eV (GZK)} \) energy (\(\sim 4 \text{ cal} \sim 17 \text{ J} \), \(\sim\) fast base/cricketball)

• Slam into upper Earth atmosphere \(\rightarrow\) electromagn. shower of secondary particles

• Detect fluoresc. light, Cherenkov light, ioniz/excit/charge

• Origin: GRB, AGN, SN..?
Pierre Auger
Ultra-high energy cosmic ray observatory

- NSF & international, South station: (Argentina) partly complete – North: planned
- Planned area 3,000 km$^2$, sensitive to CR energies >$10^{20}$ eV (GZK lim)
- GRB: expect $E_{p,\text{max}} \sim 10^{20}$ eV from Fermi accel. in same shocks where $e,B \rightarrow \gamma$
- 1600 ground detectors, 11 kiliters ea., 1.5 km apart + 24 air fluoresc. telescope
- current: 400 ground det. (350 sq. km) & 8 air fluoresc. tel. installed, July O4
- Also: tau-nu (horiz.l shower capability: Earth-skimming & through Andes)
**LIGO**

- Hanford (WA) site, + Livingstone (LA)
- 4 km Michelson interf., vacuum laser refl.
- Sci. runs ≳7/02 (6 wks); Valentine’s Day 03 (>mo)

**VIRGO**

- Italian/French: @ Cascina, Pisa →
- 2x3 km arms laser interf.
- Completed June 03, comissioning

- Science goals: test GR +
- Compact bin. inspiral (dns,dbh,nsbh)
- GRB, core-coll. SN, NS r-mode osc.
- Stochastic GW backgr (inflation)
- Also: Geo-600, TAMA
**GRB-GW**: Progenitor Rates & Min. Distances for 1 event/year

<table>
<thead>
<tr>
<th>Progenitor</th>
<th>Rate (avg)</th>
<th>Rate-rge</th>
<th>Dist (avg)</th>
<th>Dist-range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Myr(^{-1})gal(^{-1})</td>
<td>Myr(^{-1})gal(^{-1})</td>
<td>Mpc</td>
<td>Mpc</td>
</tr>
<tr>
<td>DNS</td>
<td>1.2</td>
<td>0.01-80.</td>
<td>220</td>
<td>53-1100</td>
</tr>
<tr>
<td>BH-NS a</td>
<td>2.6</td>
<td>0.001-50</td>
<td>170</td>
<td>62-2300</td>
</tr>
<tr>
<td>BH-NS b</td>
<td>0.55</td>
<td>0.001-50</td>
<td>280</td>
<td>62-2300</td>
</tr>
<tr>
<td>BH-WD</td>
<td>0.15</td>
<td>0.0001-1</td>
<td>430</td>
<td>230-4900</td>
</tr>
<tr>
<td>BH-He</td>
<td>14</td>
<td>0.1-50</td>
<td>95</td>
<td>62-490</td>
</tr>
<tr>
<td>Collapsar</td>
<td>630</td>
<td>10-1000</td>
<td>27</td>
<td>23-110</td>
</tr>
</tbody>
</table>

Simple parametrized astrophysical GRB GW model: Shiho Kobayashi & P.M.

**In-spiral phase**

- **Inspiral of** \( m_1, m_2 \) (binaries):
  \[
  h_c(f) = f \left| \hat{h}(f) \right| : \text{characteristic strain}
  \]

\[
\langle (S/N)^2 \rangle = 4 \int \left( | \hat{h} |^2 / S_h \right) df = (2/5 \pi^2 d^2) \int df \left( 1/ f^2 S_h \right) (dE/df)
\]

\[
dE/df = [(\pi G)^{2/3} /3] \mathcal{M}^{5/3} f^{-1/3} : \text{energy sp.} \quad \text{[Flanagan, Hughes 99]}
\]

\[
\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5} : \text{chirp mass}
\]

- \( \rightarrow \)

\[
h_c(f) \sim (1/\pi d) [(G/10c^3)(dE/df)]^{1/2}
\]

\[
\sim 1.4 \times 10^{-21} (d/10\text{Mpc})^{-1} (\mathcal{M}/M_\odot)^{5/6} (f/100\text{Hz})^{-1/6}
\]
Merger

• binary (or coll. blob) in-spiral ends (DNS/BH-WD-He) at 
  \[ f_i \sim 10^3 \left( \frac{M}{2.8M_\odot} \right)^{-1} \text{Hz} / 0.1\left( \frac{M}{M_\odot} \right)^{1/2} \left( \frac{I}{10^9 \text{cm}} \right)^{-3/2} \text{Hz} \]

• Merger ends (quasi-normal ring \( l=m=2 \) starts) at 
  \[ f_q \sim F(a) \frac{c^3}{2\pi} GM \sim 32 F(a) \left( \frac{M}{M_\odot} \right)^{-1} \text{kHz} \]
  \[ ; \left[ F(a)=1-0.63(1-a)^{3/10} \right] \]

• En. Radiated: \( E_m = \epsilon_m \left( \frac{4\mu}{M} \right)^2 M c^2 \); \[ \epsilon_m \sim 5\% , \mu=m_1m_2/M \]

• \( \frac{dE}{df} \sim E_m/(f_q - f_i) \sim E_m/f_q \) (asume simple flat spectrum)

• \( h_c(f) \sim (1/\pi d) [(G/10 \ c^3)(dE/df)]^{1/2} \)
  \[ \sim 2.7 \cdot 10^{-22} F(a)^{-1/2} \left( \frac{\epsilon_m}{0.05} \right)^{1/2} \left( \frac{4\mu}{M} \right) \left( \frac{M}{M_\odot} \right) (d/10\text{Mpc})^{-1} \]

(e.g. Lai & Wiseman 96; Khanna etal 99; Flanagan & Hughes 98)
Bar / Dynamical Instabilities

- Bar mass m, length 2r, around BH mass m’,
  rot. freq. $\omega = (Gm’/r^3)^{1/2}$
- Disk: dynamical instab. $\rightarrow$ blob, mass m $\sim \alpha M_\odot$
  around BH mass $\sim 3-10 M_\odot$
- Both $\rightarrow$ similar expression,
  $h = (32/45)^{1/2} (G/c^4)(mr^2 \omega^2/d)$
  $h_c \sim N^{1/2} h$  
    [N : # of cycles of approx. coherence $\sim 10$]
  $\sim 2.10^{-21} (N/10)^{1/2} (mm’/M_\odot^2)(d/10\text{Mpc})^{-1} (r/10^6 \text{cm})^{-1}$

(e.g. Fryer, Holz & Hughes 02)
Ring-down

- Deformed BH $\rightarrow$ damped oscillations, slowest mode: $l=m=2$ (also pref. excited)
- Spectrum peaks at $f_q \sim 32 \, F(a)(M/M_\odot)^{-1}$ kHz,
  width $\Delta f \sim \tau^{-1} \sim \pi \, f_q / Q(a)$; [ $Q(a)=2(1-a)^{-9/20}$ ]
- $dE/df \sim (E_r \, f^2 / 4 \pi^4 \, f_q^2 \, \tau^3)$.
- $h_c \sim 2 \times 10^{-21} \left( \frac{\epsilon_r}{0.01} \right)^2 \left( \frac{Q}{14F} \right)^{1/2} (\mu/M_\odot) (d/10\text{Mpc})^{-1}$
GRB Progenitor GW Signals: DNS


Double neutron star
Charact. Strain $h_c$
D (avg) = 220 Mpc,
$m_1 = m_2 = 1.4 M_\odot$,
a = 0.98, $\epsilon_m = 0.05$,
m = $m' = 2.8 M_\odot$, N = 10,
$\epsilon_r = 0.01$

Dashed: LIGO II sensitivity
Solid: inspiral; Dot-dash: merger;
circle (bar inst); spike: ring-down);
shaded region: rate/distance uncertainty
GRB Progenitor GW Signals: Collapsar


Collapsar w. core breakup, bar inst.
(optimistic numbers!)

d=270 Mpc,
m_1=m_2=1 M_☉, a=0.98,
ε_m =0.05,
merge at r=10^7 cm;
m=1 M_☉, m'= 3 M_☉ ,
N=10, ε_r =0.01

Solid: inspiral; dot-dash: merger;
circle :bar inst; spike: ring-down);
shaded : rate/dist uncertainty

Dashed: LIGO II noise [f Sh(f)]^{1/2}
Detectability:

- **Binary progenitors:** upper limits, in one year LIGO II
  
  **BH-NS, NS-NS:** waveform templates
  
  $S/N_{\text{bin}} = \left[ 4 \int \left\{ \hat{h}(f) \right\}^2 / S_h(f) \, df \right]^{1/2} \gtrsim 5$
  
  (where $S_h(f)$: noise power of detector)

- **Collapsars:** upper limits, in one year LIGO II:
  
  No templates (e.g. merger, ring-down):
  
  $S/N_{\text{Coll,merg}} \sim 3 \left( \epsilon_m/0.05 \right) \left( F[a]/0.8 \right) \left( T/10 \text{ s} \right)^{-1/2}$
  
  $\cdot \left( \mu/0.5 \, M_\odot \right)^2 \left( R/630 \, \text{Myr}^{-1} \, \text{gal}^{-1} \right)^{2/3}$

Summary & Prospects

- GRB, XXR, XRF may form a continuum; jet geometry unknown, but unlikely to be very narrow
- Polarization (O, γ?) will provide important clues
- X-ray lines may serve as very high z (≲15) distance gauge
- GRB continuum (if present) detectable to z ≲30
- UHE γ,ν will test proton/MHD content of jets, shock accel.physics, magnetic field generation, turbulence
- Probe hadron/EM interactions at ≳ TeV-PeV energies
- Investigate stellar evolution & death, star formation rates and large scale structure at redshifts of first objects
- Test strong field gravity, ultrahigh mass/energy densities