Nucleosynthesis of heavy elements in gamma ray bursts

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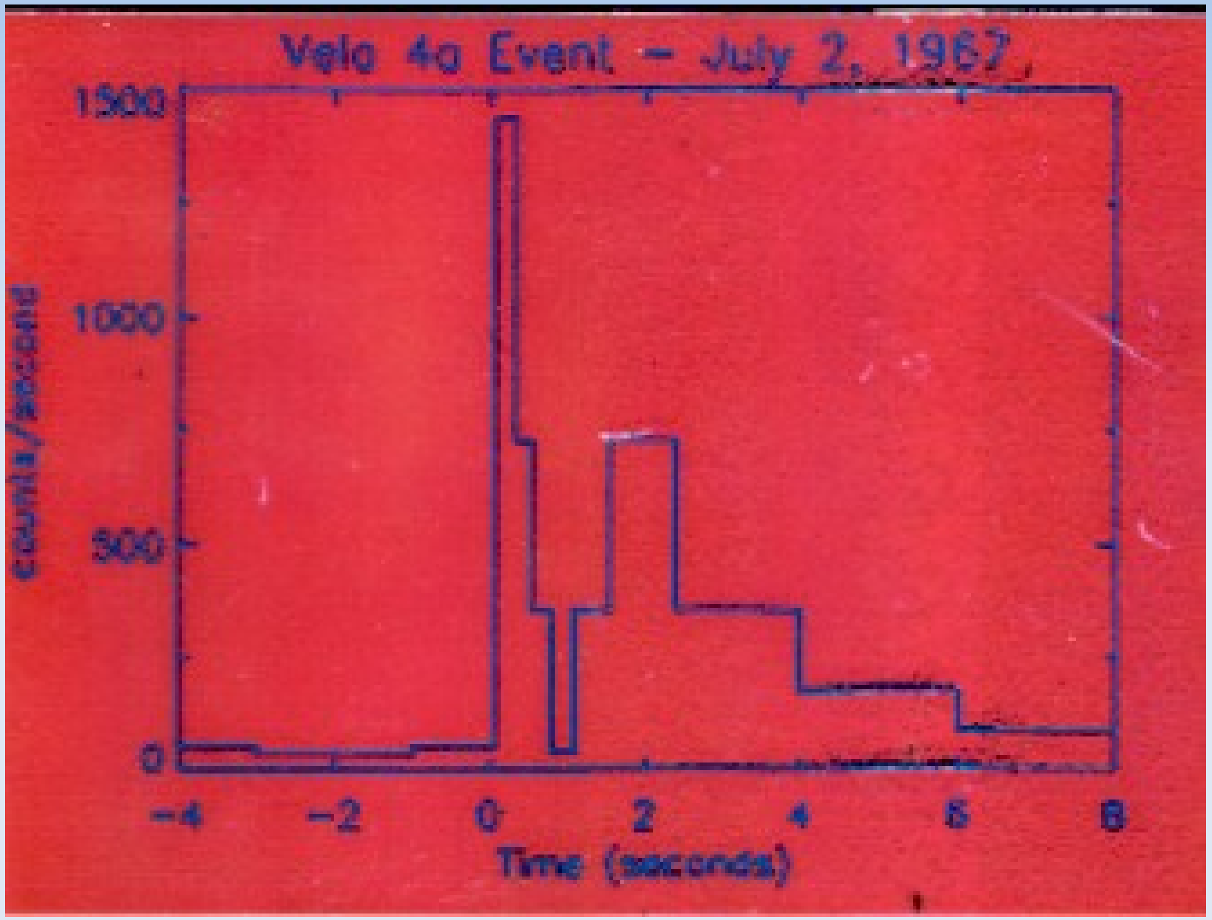
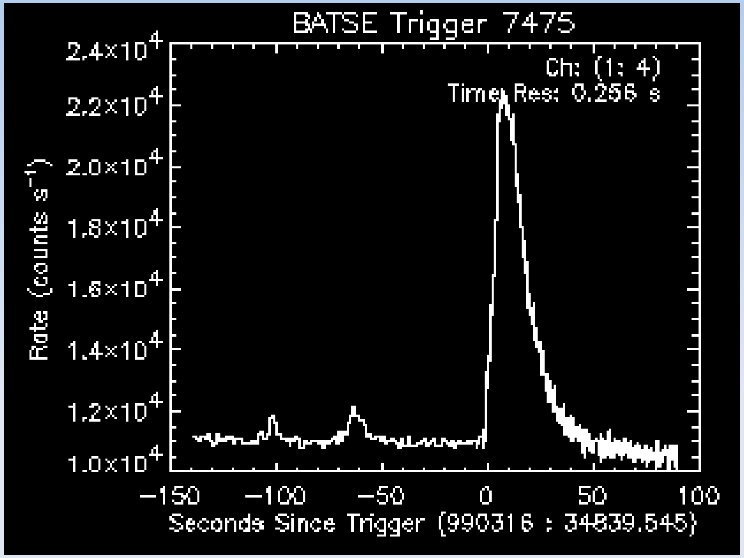
Historical GRB

- Firs gamma ray burst: detected by Vela satellite
- X-rays, 3-12 keV
- Gamma-rays CsI detector, 150-750 keV

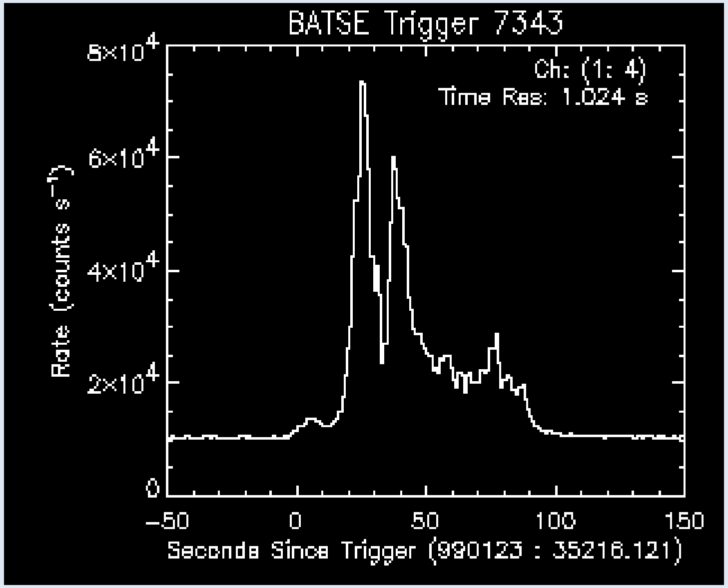


Lightcurves

GRB990316



- Time Profile FRED (*fast rise, exponential decay*)
- Substructure, multiple peaks
- Time duration from 0.001 to >1000 s.

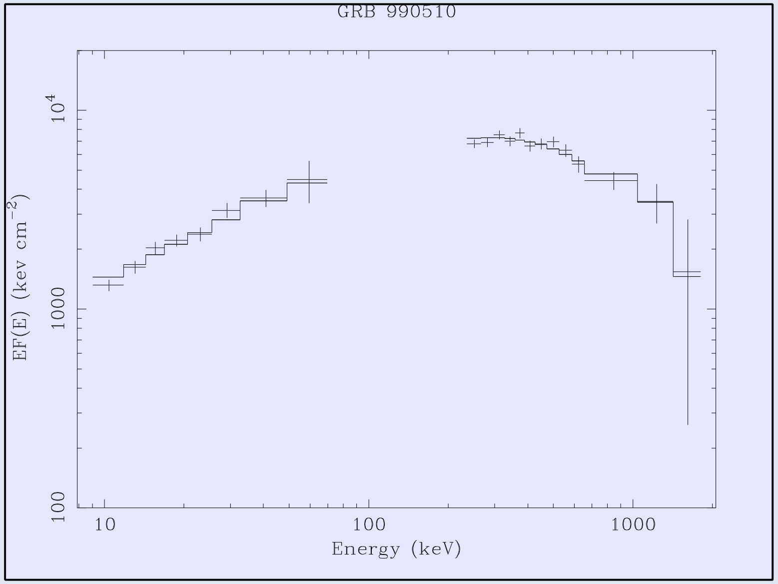


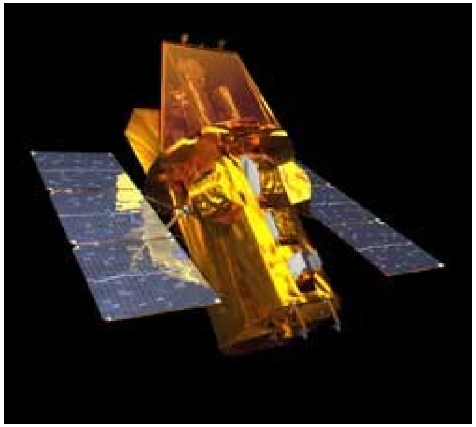
GRB990123

Energy spectrum

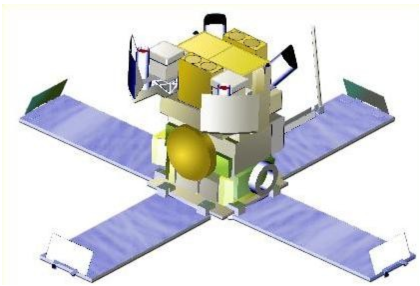
- Typically, broken power-law (Band et al. 1993)

$$N(\nu) = N_0\,(h\nu)^{\alpha}\exp(-h\nu/E_0) \qquad h\nu<(\alpha-\beta)E_0$$
$$= N_0\,[(\alpha-\beta)E_0]^{(\alpha-\beta)}(h\nu)^{\beta}\exp(\beta-\alpha) \qquad h\nu>(\alpha-\beta)E_0$$





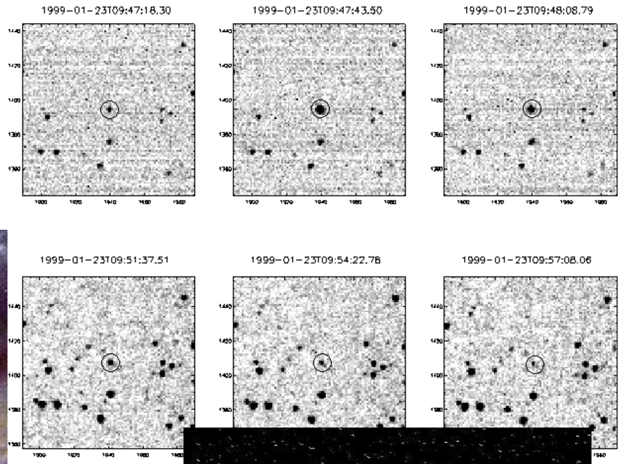
Swift, 2004- ;
detected first afterglow of a short GRB



HETE-II, 2000- ; first mission dedicated for GRB; discovered about 100 of them

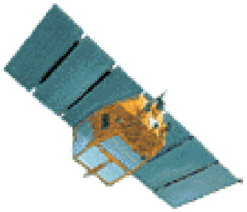
Chandra, 1999-
GRB991216 first emission lines in X

XMM-Newton, 1999-
GRB011211 lines of S, Mg, Ca, Ar

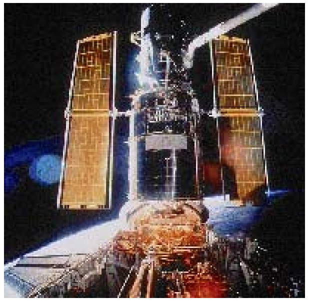


ROTSE, 1998-
GRB990123 first optical counterpart of a GRB

BATSE, 1991-2000;
proved GRBs to be extragalactic

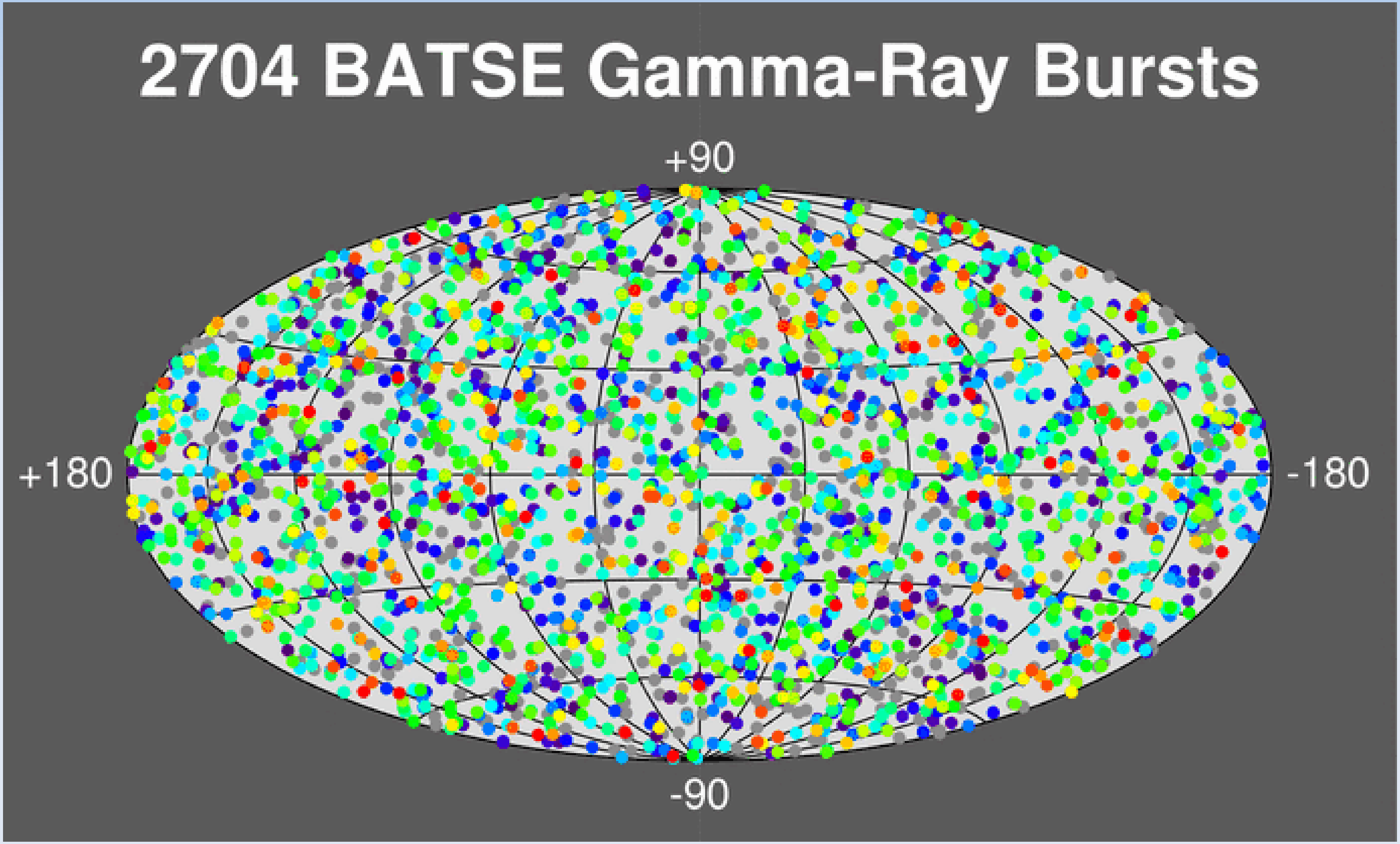


BeppoSAX, 1996-2002;
GRB970228 first optical afterglow



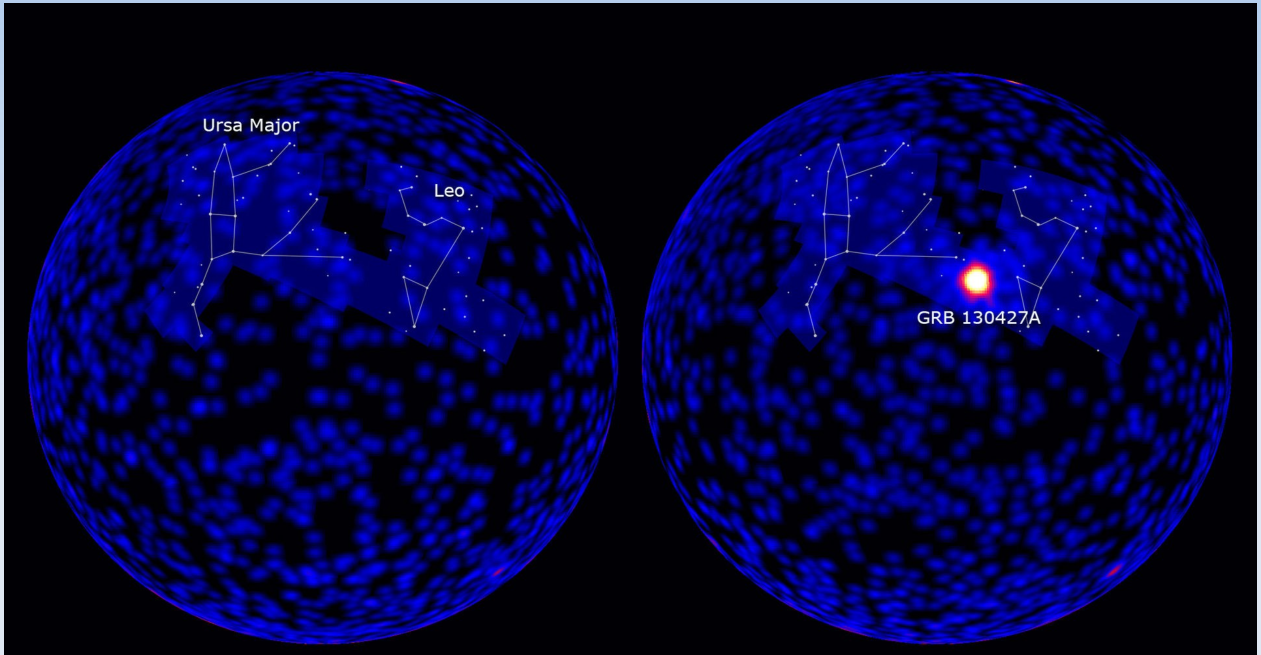
HST, 1990-
GRB970228 host galaxy identifiedj

BATSE GRBs sample



GRB 130427A

- Detected by Swift and FermiLAT (photons with energies of 2.7 GeV)
- Associated with z Supernova, registered on 2 May, 2013
- Very close, d~3.6 Mlyrs



Before and after Fermi LAT views of GRB 130427A, centered on the north galactic pole

GRB 980425

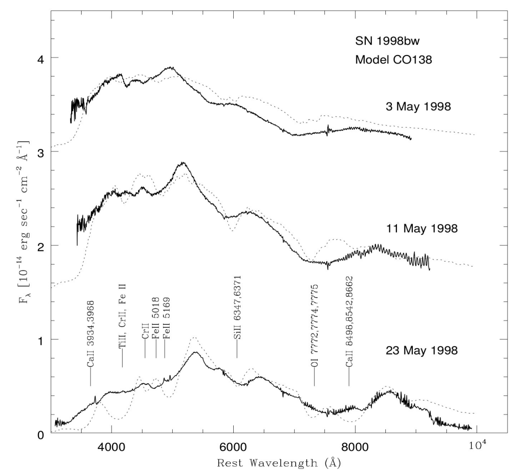


Figure 2: Three observed spectra (full lines, Patat *et al.*, in preparation), where the galaxy background has been subtracted, are compared with the synthetic spectra (dashed lines) computed with the Monte Carlo code[14], improved with the inclusion of photon branching (Mazzali & Lucy, in preparation), using model CO138. The synthetic spectra were computed using the luminosity derived from the light curve and a distance of 39 Mpc, and assuming no reddening. The observed featureless spectra are the result of the blending of many metal lines reaching large velocity and with a large velocity spread. The apparent emission peaks are actually low opacity regions of the spectrum where photons can escape. The 3 May and the 11 May spectra have been shifted upwards by 3.0 and 1.5×10^{-14} erg s^{-1} cm^{-2} $Å^{-1}$, respectively. The most important lines are marked on the 23 May spectrum, but they also contribute to the 3 May and 11 May spectra, although with somewhat different ratios. Line blending in the case of SN 1998bw is even more severe than it was in the massive type Ic supernova 1997ef[8], indicating an even larger mass. The massive progenitor model is the only one that gives the correct extent of line blending. Differences in the blue band between the observed spectrum and the synthetic one are probably due to uncertainties in the determination of the abundance and distribution of Fe-group elements in high velocity parts of the ejecta. The possible presence of O I line absorption in the early spectra complicates any derivation of velocities in the high velocity wings of the feature conceivably ascribed to Ca II absorption.

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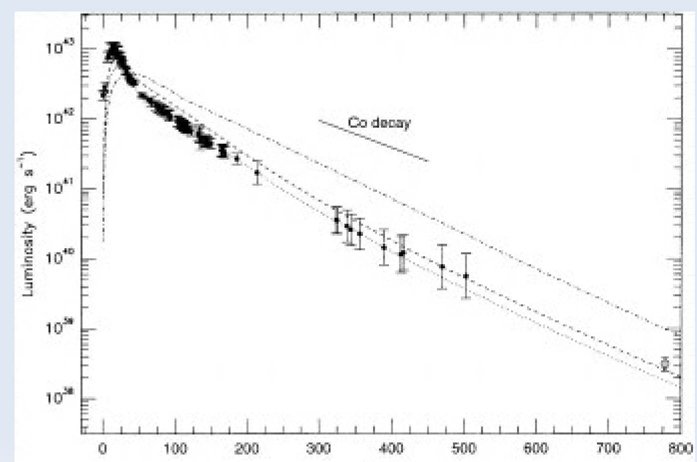
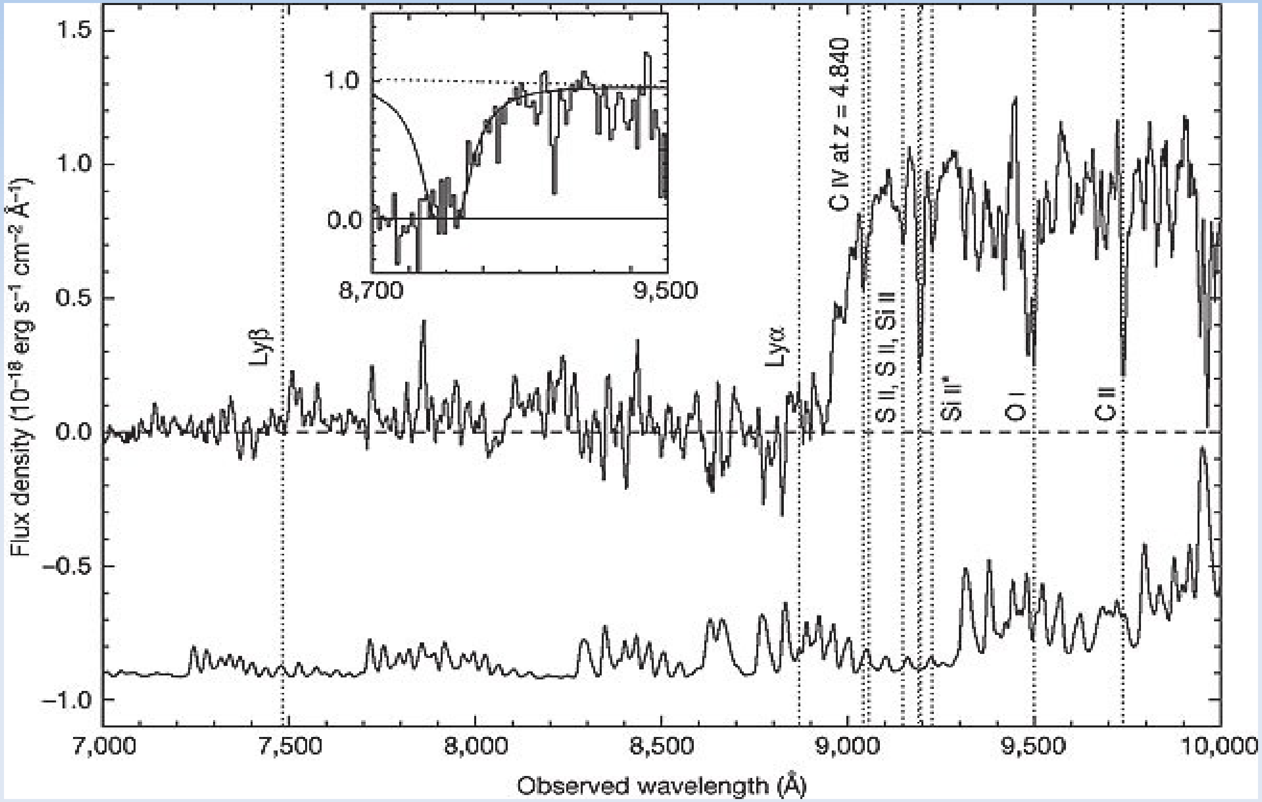
- Optical spectrum of SN 1998bw, observed by ESO
- Explosion of massive C-O star, E >2×10^{52} erg
- Nickel 56 produced



Iwamoto et al. (Nature, 1998)

Nakamura et al. (ApJ, 2001)

GRB 050904

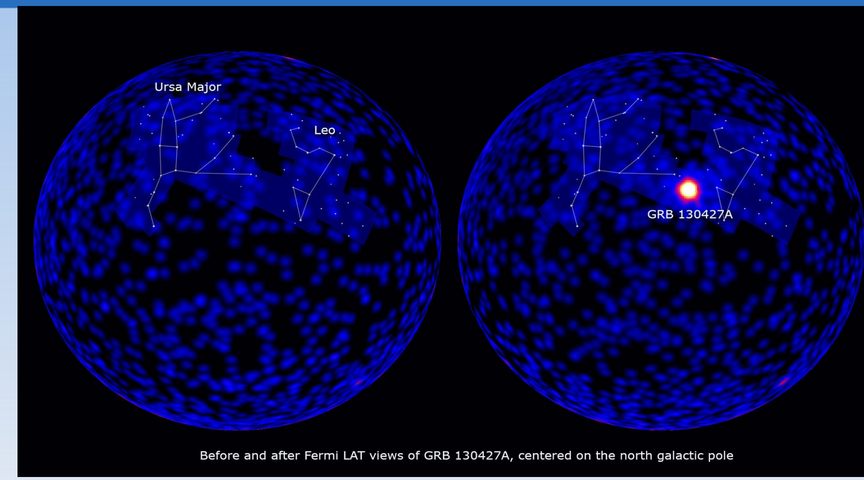


Kawai et al. (Nature, 2006)

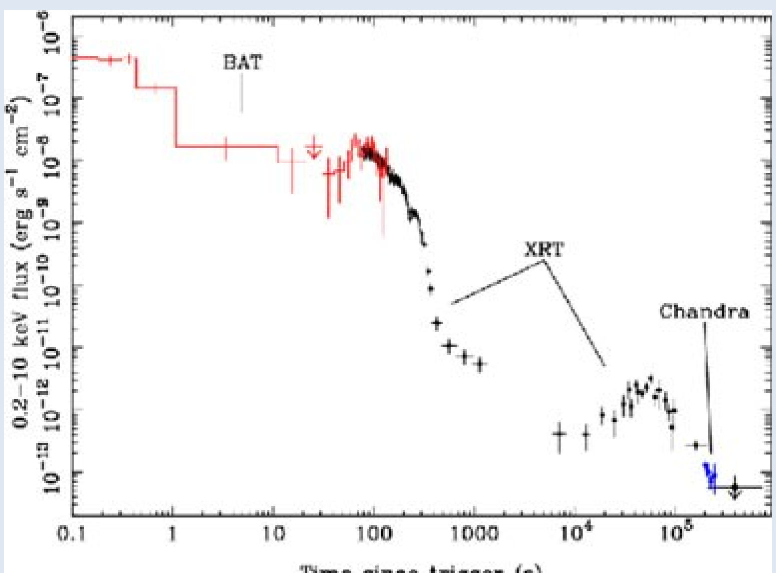
- Optical afterglow, observed by Subaru
- z=6.295
- Metallicity [x/H]=-2.4, -2.3 -2.6 i -1.0 for C,O,Si i S

Swift GRBs

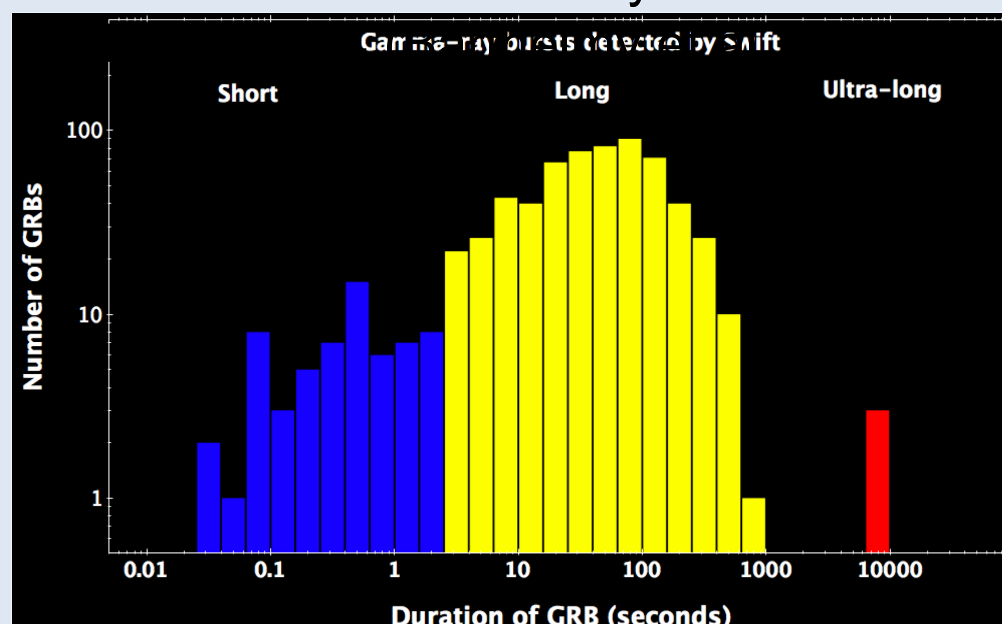
- X-ray afterglows
- GRBs at large z (e.g., GRB 090423, z=8.3)



GRB 130427A, associated with SN outburst on 02 May 2013



GRB 050724 afterglow (Barthelmy et al. 2005)

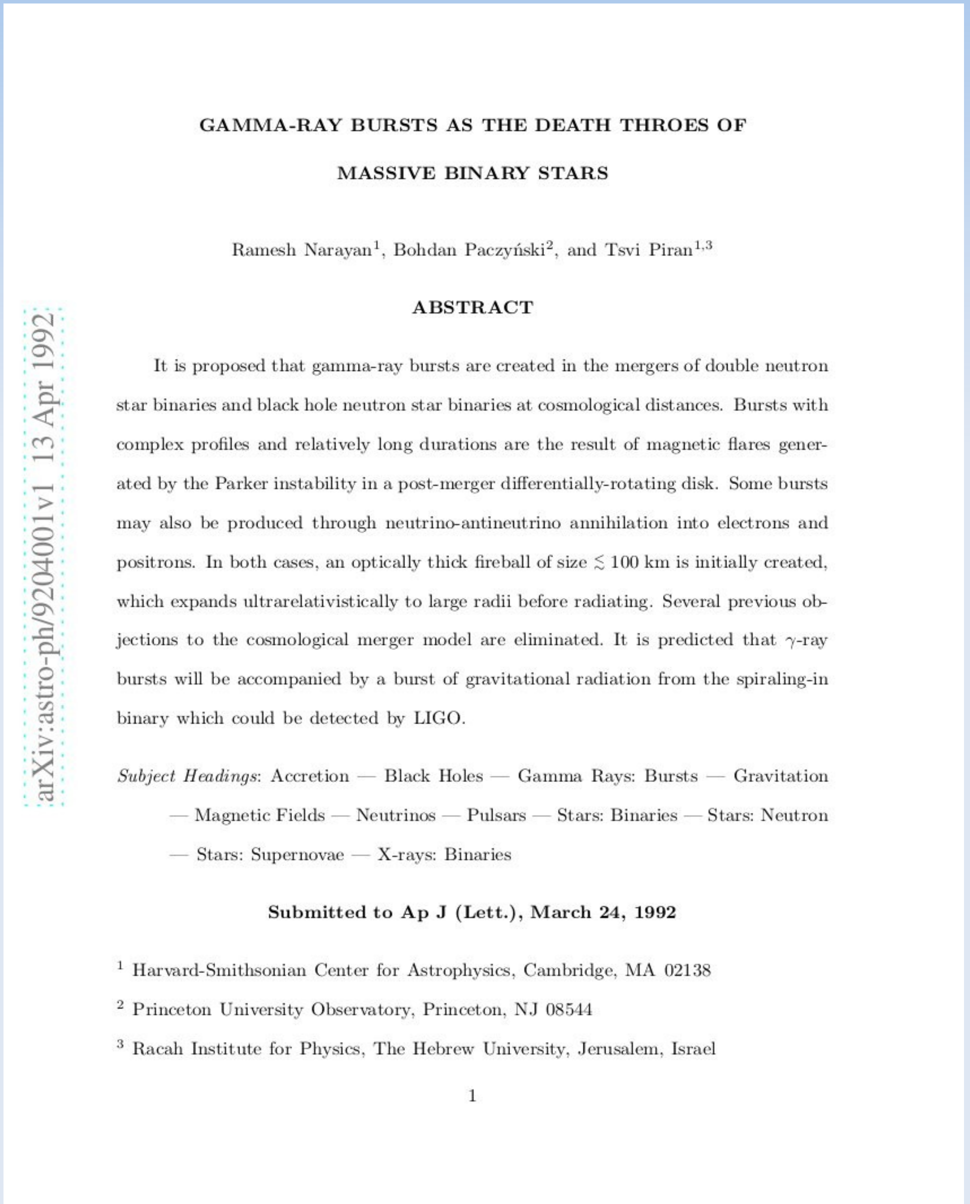


Some history of models

- Until 1992, about 100 theoretical models for GRBs were proposed
- They differed in localisations by orders of magnitude: from Solar System to extragalactic
- Energy requirements, flux x distance^2, differed by 20 orders of magnitude
- Examples: atmospheric lightning, magnetic reconnections in Heliopause, accretion onto a comet, starquake of a neutron star, white holes, cosmic strings...

First preprint on arXiV

- Astro-ph/9204001
- Ramesh Narayan, Bohdan Paczyński, Tsvi Piran
- ”Gamma Ray Bursts as the death throes of massive stars”



GAMMA-RAY BURSTS AS THE DEATH THROES OF

MASSIVE BINARY STARS

Ramesh Narayan[1], Bohdan Paczyński[2], and Tsvi Piran[1,3]

ABSTRACT

It is proposed that gamma-ray bursts are created in the mergers of double neutron star binaries and black hole neutron star binaries at cosmological distances. Bursts with complex profiles and relatively long durations are the result of magnetic flares generated by the Parker instability in a post-merger differentially-rotating disk. Some bursts may also be produced through neutrino-antineutrino annihilation into electrons and positrons. In both cases, an optically thick fireball of size $\lesssim$ 100 km is initially created, which expands ultrarelativistically to large radii before radiating. Several previous objections to the cosmological merger model are eliminated. It is predicted that γ-ray bursts will be accompanied by a burst of gravitational radiation from the spiraling-in binary which could be detected by LIGO.

Subject Headings: Accretion — Black Holes — Gamma Rays: Bursts — Gravitation — Magnetic Fields — Neutrinos — Pulsars — Stars: Binaries — Stars: Neutron — Stars: Supernovae — X-rays: Binaries

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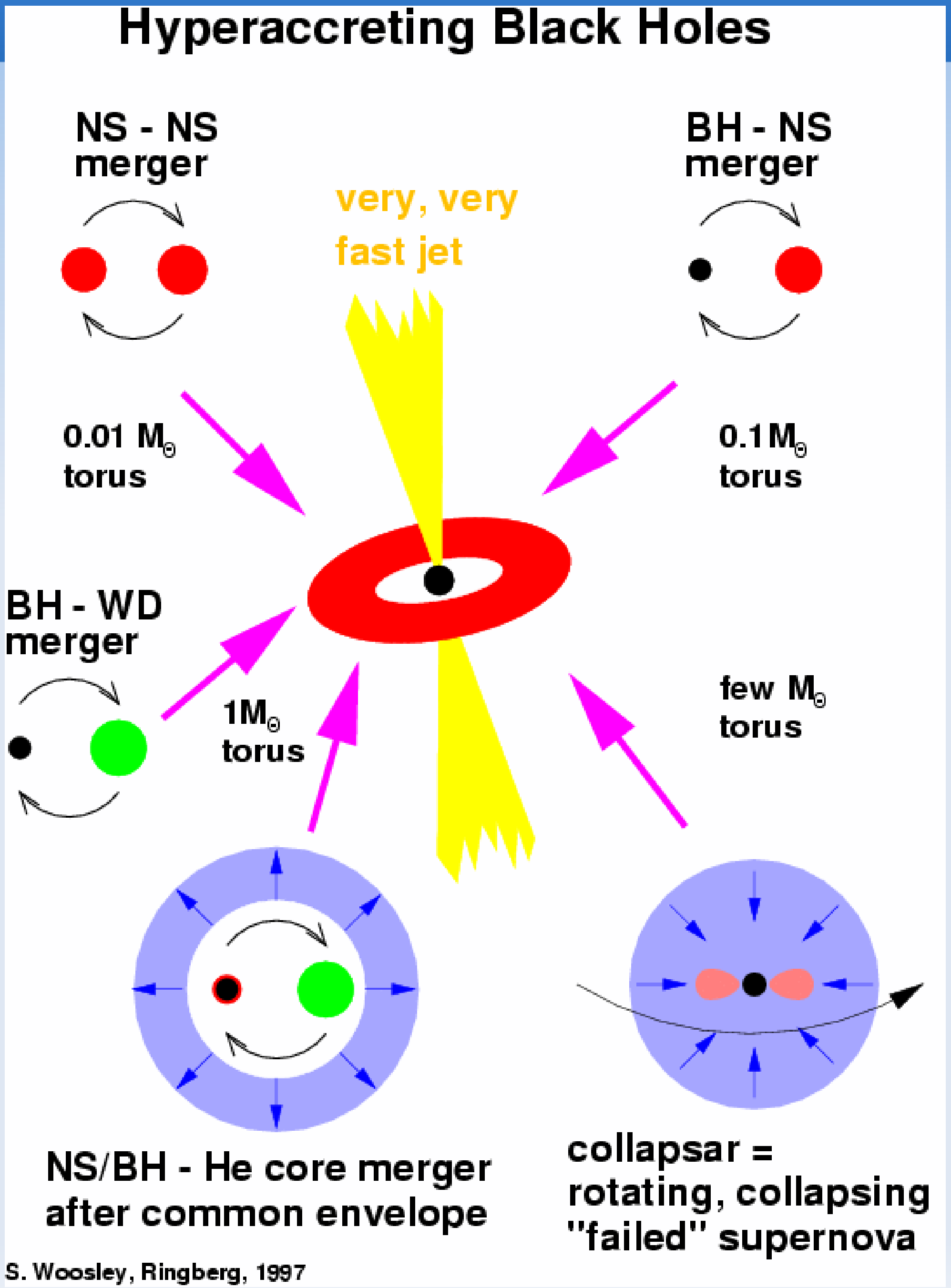
BH accretion

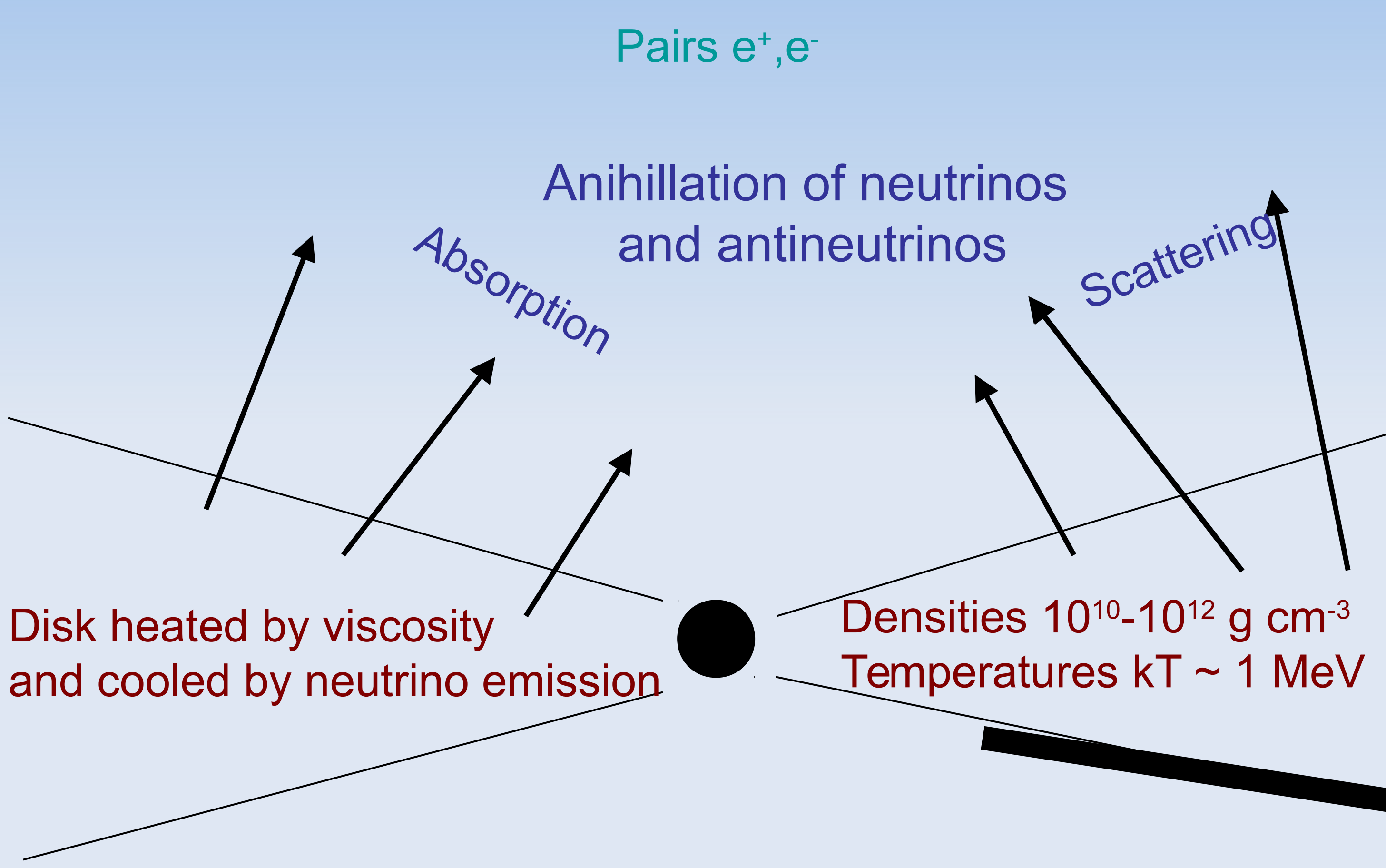
- Cosmological GRBs require powerful energy source
- Hyperaccretion helps produce an ultra-fast jet, in which the gamma rays are ultimately emitted

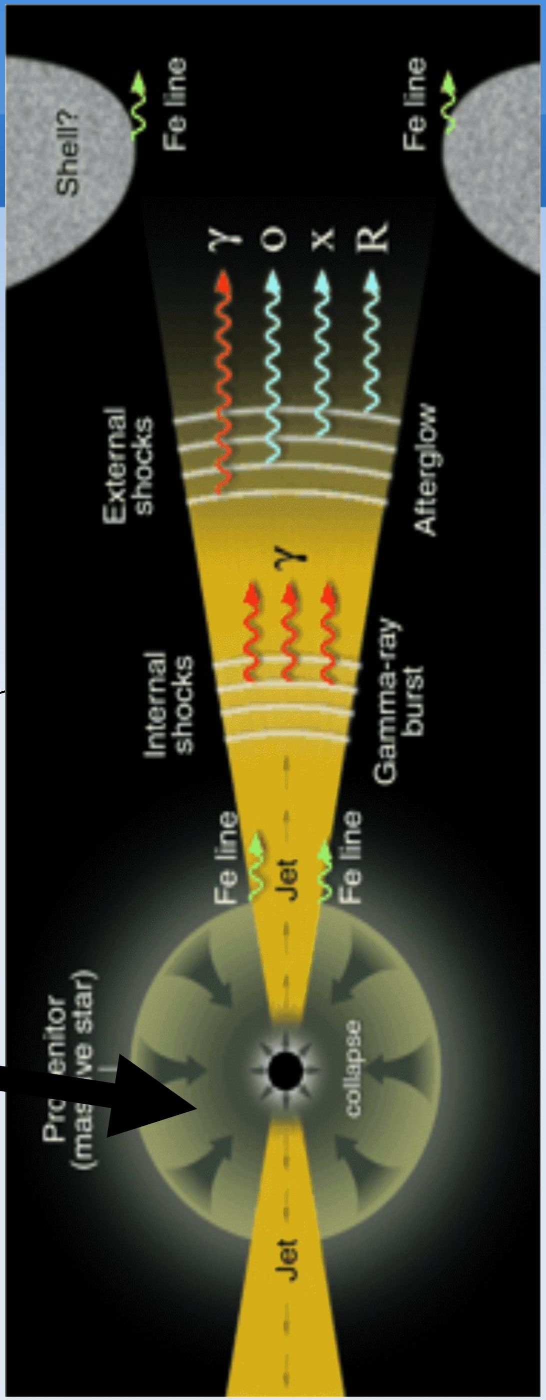


Progenitors

- Progenitors range from mergers of compact stars to collapse of massive stars
- Massive star must form a black hole: 10% of all collapsing stars; moreover the star must have enough rotation in its envelopee to form a disk: another 10%. GRBs (due to collapsars) may therefore occur in about 1% of all core-collapse supernovae (Type I b/c)
- Models must account for the energy of explosion, collimation, rapid variability, range of durations, statistics

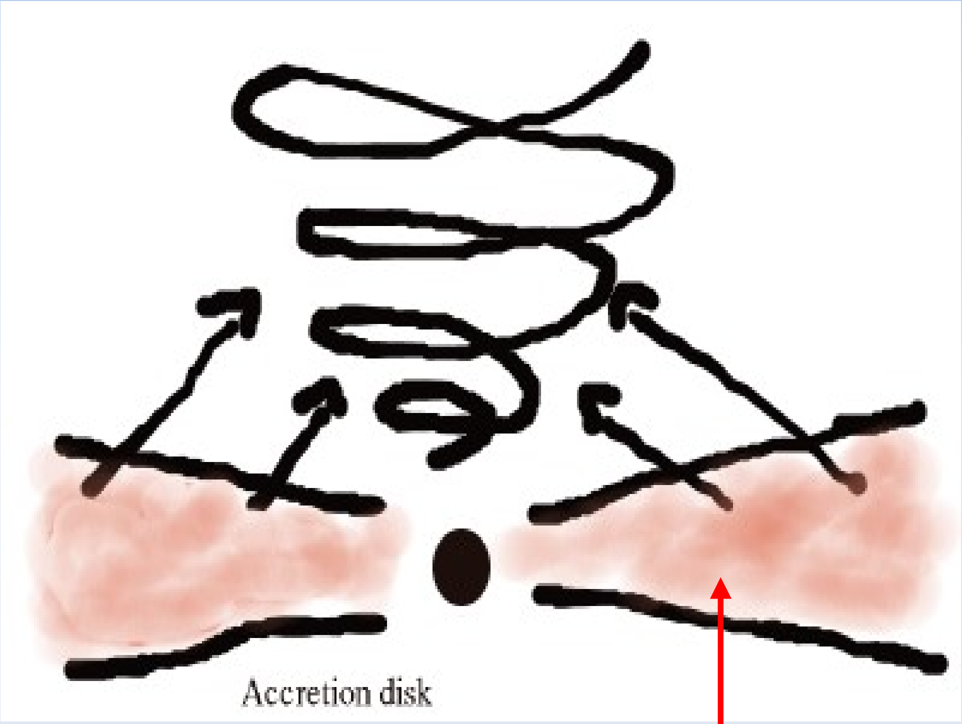
GRB Progenitor





Conditions in Hiperaccretion disk

- Hiperaccretion: rates of 0.01-10 M_{Sun}/s
- Chemical and pressure balance required by nuclear reaction rates
- These are given under degeneracy of species
- Charge neutrality condition; neutrino opacities

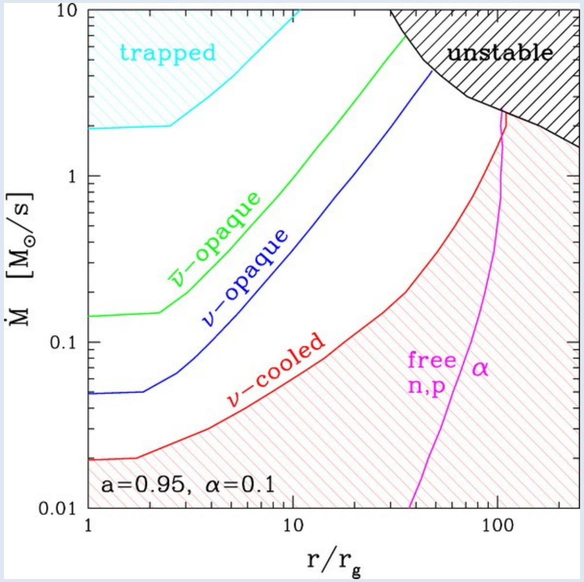


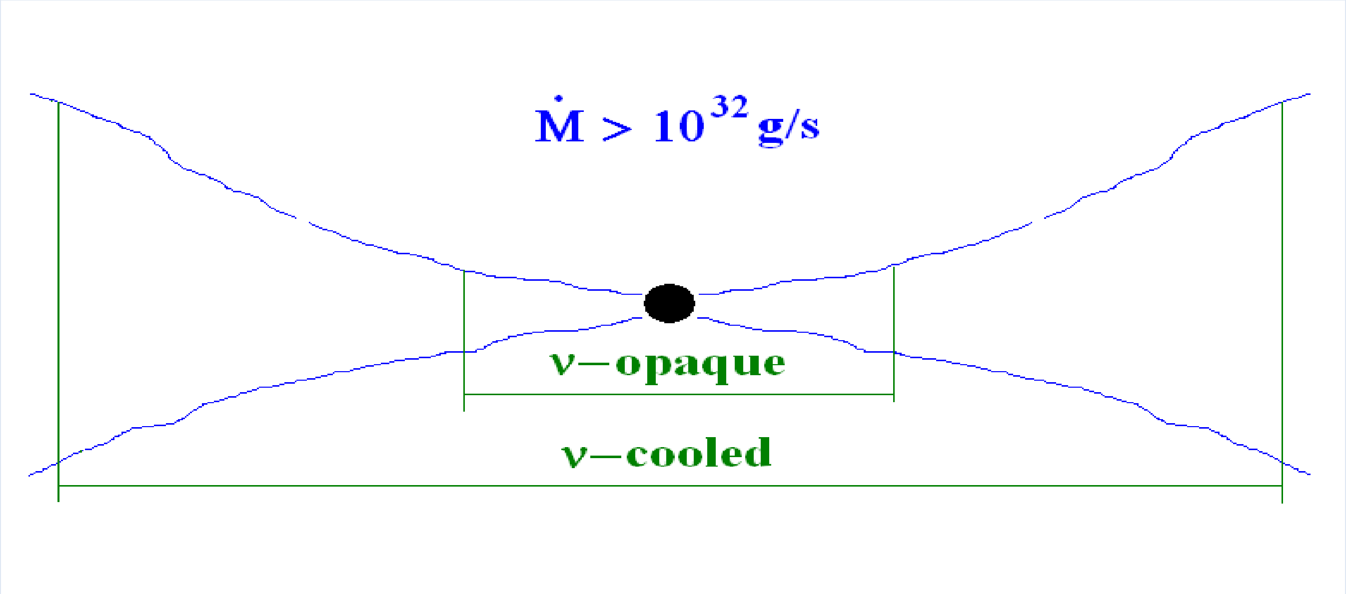
Popham et al. 1999; Di Matteo et al. 2002; Kohri et al. 2002, 2005; Chen & Beloborodov 2007; Reynoso et al. 2006; Janiuk et al. 2004; 2007; 2010; 2013

p, n, e^+, e^-
He,
ν_μ, ν_e, ν_τ
γ

Hiperaccretion disk

- Model must account for coupling between degeneracy of matter and neutrino cooling. Cooling → lower temperature →degeneracy → low density of positrons → lower cooling → higher temperature





Chen & Beloborodov (2007)

Equation of state

- The total pressure must include the contributions from gas, radiation, and degenerate electrons:

$$P = P_{gas} + P_{rad} + P_{deg} = \frac{k}{m_p} \rho T \left(\frac{1}{4} + \frac{3}{4} X_{nuc}\right) + \frac{11}{12} a T^4 + 2\pi h \frac{c}{3} \left(\frac{3}{8} \pi m_p\right)^{4/3} \left(\frac{\rho}{\mu_e}\right)^{4/3}$$

where mass fraction of free nucleons depends non-linearly on density and temperature (Popham et al. 1999; Di Matteo et al. 2002; Janiuk et al. 2004)

- In more advanced modeling, the equation of state must be computed numerically by solving the balance of nuclear reactions (Yuan 2005; Janiuk et al. 2007; EOS by Lattimer & Swesty 1991; Setiawan et al. 2004)

Model of hyperaccretion disk

Chemical composition of the disk: e+, e-, p and n

- we assume the gas to be in beta equilibrium, so that the ratio of proton to neutron satisfies the balance between forward and backward nuclear reactions

- we assume neutrino cooling via electron, muon and tau neutrinos in the plasma opaque to their absorption and scattering

Neutrinos are formed in the URCA process (electron-positron capture on nucleons), e+e- pair annihilation, nucleon-nucleon bremsstrahlung and plasmon decay.

- leptons and baryons are relativistic and may have arbitrary degeneracy level. We compute the gas pressure using the appropriate Fermi-Dirac integrals

Equation of state

$$P = P_{\mathrm{nucl}} + P_{\mathrm{He}} + P_{\mathrm{rad}} + P_{\nu} \, .$$

where

$$P_{\mathrm{nucl}} = P_{\mathrm{e-}} + P_{\mathrm{e+}} + P_{\mathrm{n}} + P_{\mathrm{p}}$$

with

$$P_{\mathrm{i}} = \frac{2\sqrt{2}}{3\pi^2}\frac{(m_i c^2)^4}{(\hbar c)^3}\beta_i^{5/2}\left[F_{3/2}(\eta_{\mathrm{i}},\beta_{\mathrm{i}}) + \frac{1}{2}\beta_{\mathrm{i}}F_{5/2}(\eta_{\mathrm{i}},\beta_{\mathrm{i}})\right] .$$

Now the total pressure is contributed by nuclei, pairs, helium radiation, and partially trapped neutrinos.

$$\begin{aligned} P_\nu &= \frac{7}{8}\frac{\pi^2}{15}\frac{(kT)^4}{3(\hbar c)^3}\sum_{i=e,\mu,\tau}\frac{\frac{1}{2}(\tau_{a,\nu_i}+\tau_s)+\frac{1}{\sqrt{3}}}{\frac{1}{2}(\tau_{a,\nu_i}+\tau_s)+\frac{1}{\sqrt{3}}+\frac{1}{3\tau_{a,\nu_i}}} \\ &\equiv \frac{7}{8}\frac{\pi^2}{15}\frac{(kT)^4}{3(\hbar c)^3}b, \end{aligned}$$

Neutrino cooling

- The photons are totally trapped in the very opaque disk. The main cooling mechanism is the emission of neutrinos, via the following reactions:
  - Electron and positron capture on nucleons (URCA reactions) → electron neutrinos
  - Electron-positron pair anihillation (electron, muon and tau neutrinos)
  - Bremsstrahlung (all neutrino flavours)
- Emissivities in first two cases must be computed numerically (Itoh et al. 1996; Yakovlev 2005)

Neutrino production reactions

The reactions of electron and positron capture and neutron deacy must establish an equilibrium

$p + e^- \rightarrow n + \nu_e$

$p + \sim\nu_e \rightarrow n + e^+$

$p + e^- + \sim\nu_e \rightarrow n$

$n + e^+ \rightarrow p + \sim\nu_e$

$n \rightarrow p + e^- + \sim\nu_e$

$n + \nu_e \rightarrow p + e^-$

The rates of these reactions are given by appropriate integrals (Reddy, Prakash & Lattimer 1998) and at temperature 10^{11} K and densities of > 10^{10} g/cm^3, neutrinos are efficiently produced.

Reaction rates

$$\Gamma_{p+e^- \to n+\nu_e} = \frac{1}{2\pi^3}|M|^2 \int_Q^\infty dE_e E_e p_e (E_e - Q)^2 f_e (1 - b_e f_{\nu_e}),$$

$$\Gamma_{p+e^- \leftarrow n+\nu_e} = \frac{1}{2\pi^3}|M|^2 \int_Q^\infty dE_e E_e p_e (E_e - Q)^2 (1 - f_e) b_e f_{\nu_e},$$

$$\Gamma_{n+e^+ \to p+\bar{\nu}_e} = \frac{1}{2\pi^3}|M|^2 \int_{m_e}^\infty dE_e E_e p_e (E_e + Q)^2 f_{e^+} (1 - b_e f_{\bar{\nu}_e}),$$

$$\Gamma_{n+e^+ \leftarrow p+\bar{\nu}_e} = \frac{1}{2\pi^3}|M|^2 \int_{m_e}^\infty dE_e E_e p_e (E_e + Q)^2 (1 - f_{e^+}) b_e f_{\bar{\nu}_e},$$

$$\Gamma_{n \to p+e^- +\bar{\nu}_e} = \frac{1}{2\pi^3}|M|^2 \int_{m_e}^Q dE_e E_e p_e (Q - E_e)^2 (1 - f_e)(1 - b_e f_{\bar{\nu}_e}$$

$$\Gamma_{n \leftarrow p+e^- +\bar{\nu}_e} = \frac{1}{2\pi^3}|M|^2 \int_{m_e}^Q dE_e E_e p_e (Q - E_e)^2 f_e b_e f_{\bar{\nu}_e}.$$

Here Q is neutron-proton mass difference, $|M|^2$ is averaged transition rate, and b_e reflects percentage of partially trapped neutrinos (”grey body” model).

Neutrino cooling

- Other neutrino emission processes are: electron-positron pair annihillation, bremsstrahlung, plasmon decay. Rates have to be calculated numerically, with proper integrals over the distribution function of relativistic, partially degenerate species.
- $e- + e+ \longrightarrow \nu_\iota + \sim\nu_\iota$
- $\gamma \longrightarrow \nu_e + \sim\nu_e$
- $n + n \longrightarrow n + n + \nu_i + \sim\nu_i$

Neutrino cooling rate

The neutrino cooling rate, in [erg s^{-1} cm^{-3}] is finally given by the two-stream appoximation

$$Q_\nu = \frac{7/8\,\sigma T^4}{3/4} \sum_i \frac{1}{\frac{\tau_{a,\nu_i}+\tau_s}{2} + \frac{1}{\sqrt{3}} + \frac{1}{3\tau_{a,\nu_i}}} \frac{1}{H}$$

We compute the total luminosity in neutrinos by integration over the simulation volume

Chemical balance in the disk

The ratio of protons to nucleons must satisfy the balance between number densities and reaction rates

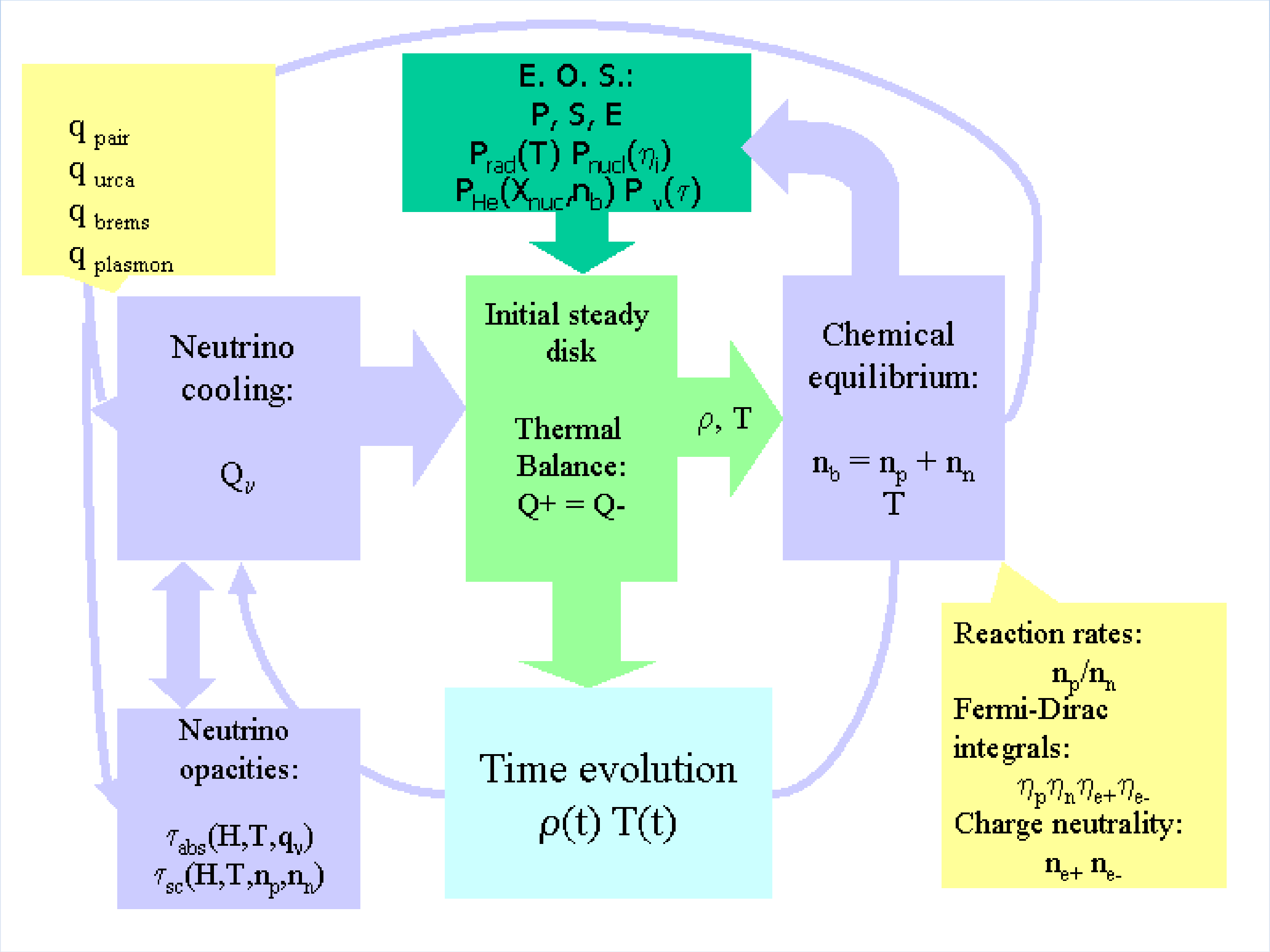
$$n_p\,(\Gamma_{p+e^- \to n+\nu e} + \Gamma_{p+\sim\nu e \to n+e+} + \Gamma_{p+e-+\sim\nu e \to n}) =$$

$$n_n\,(\Gamma_{n+e+ \to p+\sim\nu e} + \Gamma_{n \to p+e-+\nu e} + \Gamma_{n+\nu e \to p+e-})$$

Matter must also satisfy conservation of baryon number, $n_n + n_p = n_b\ X_{nuc}$

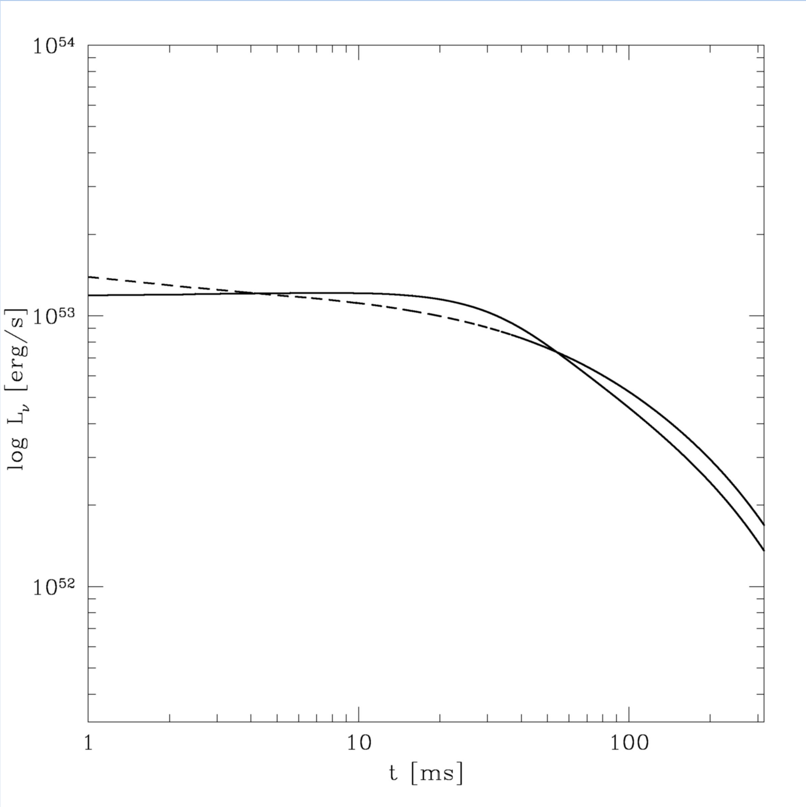
Charge neutrality $n_e = n_{e-} - n_{e+} = n_p + n_e^0$, where number of electrns in Helium: $n_e^0 = 2\,n_{He} = (1-X_{nuc})n_b/2$

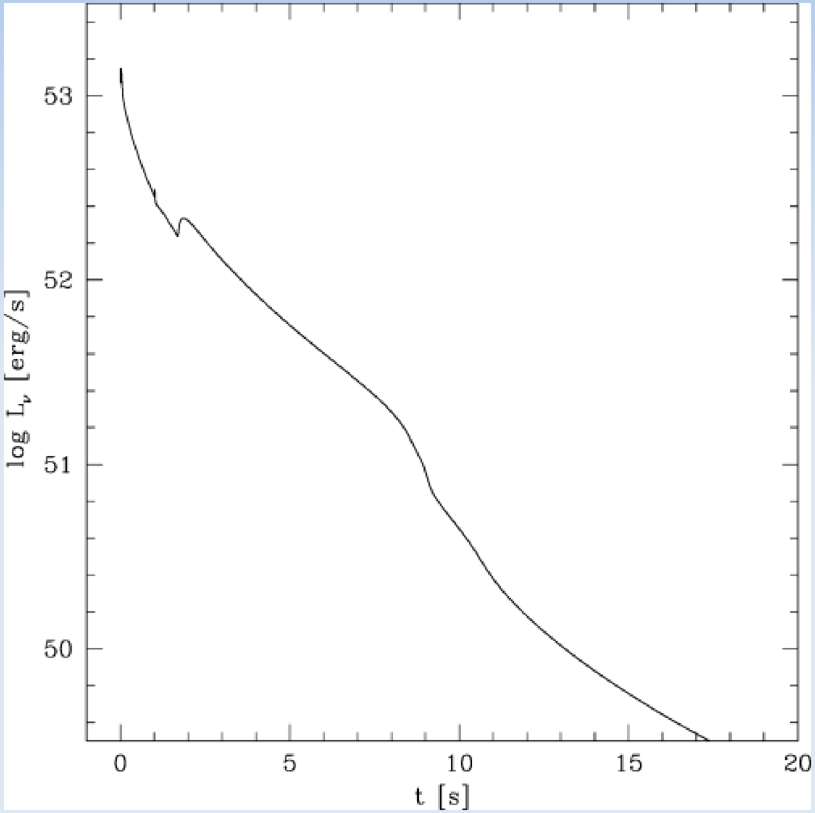
Stucture of the disk



Janiuk, Yuan, Perna & Di Matteo (2007)

Luminosity

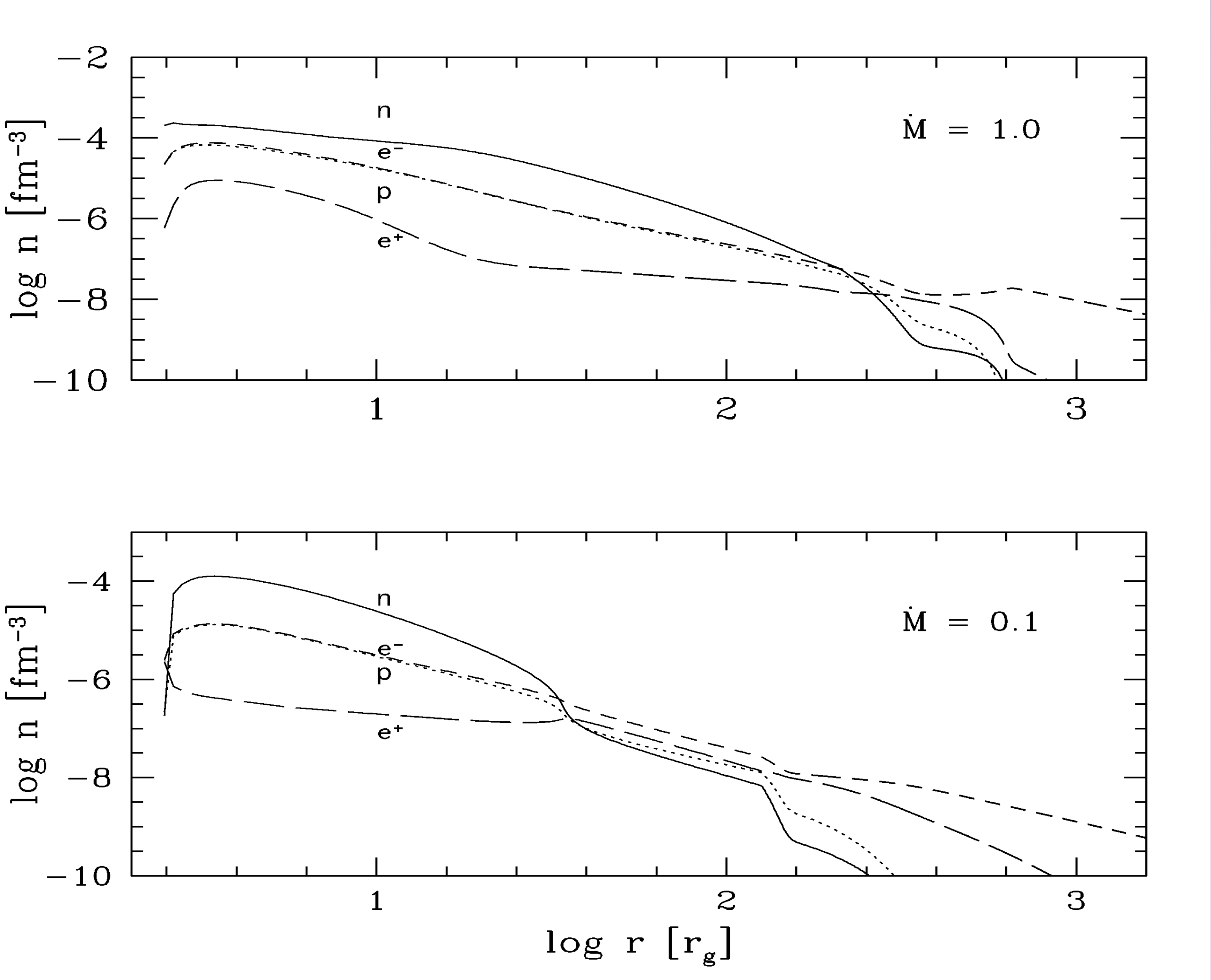




Janiuk i in. (2004)

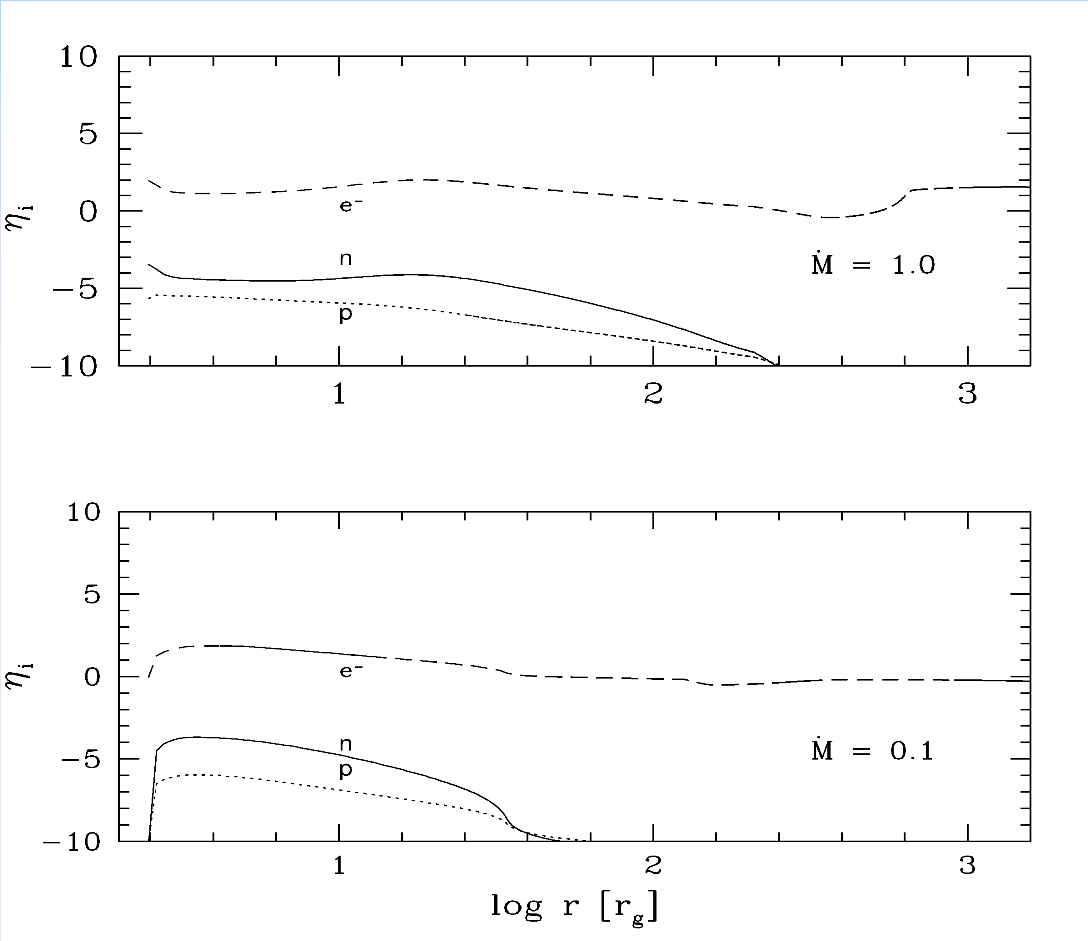
Two scenarios: merger (short GRB) and collapsar (long GRB)

Equilibrium in the disk



Distribution of free protons, neutrons, electrons and positrons in the equatorial plane of the hyperaccreting disk in GRB

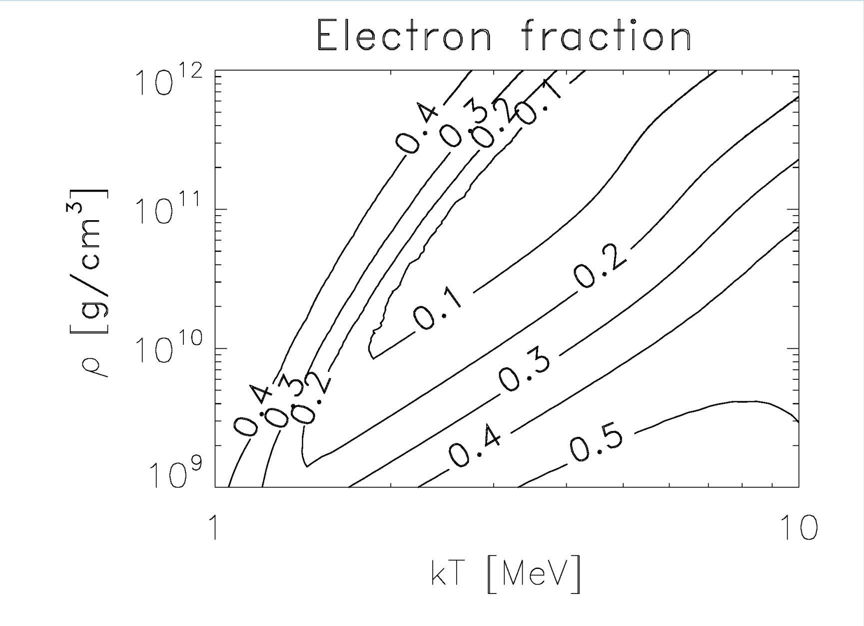
Degeneracy of species

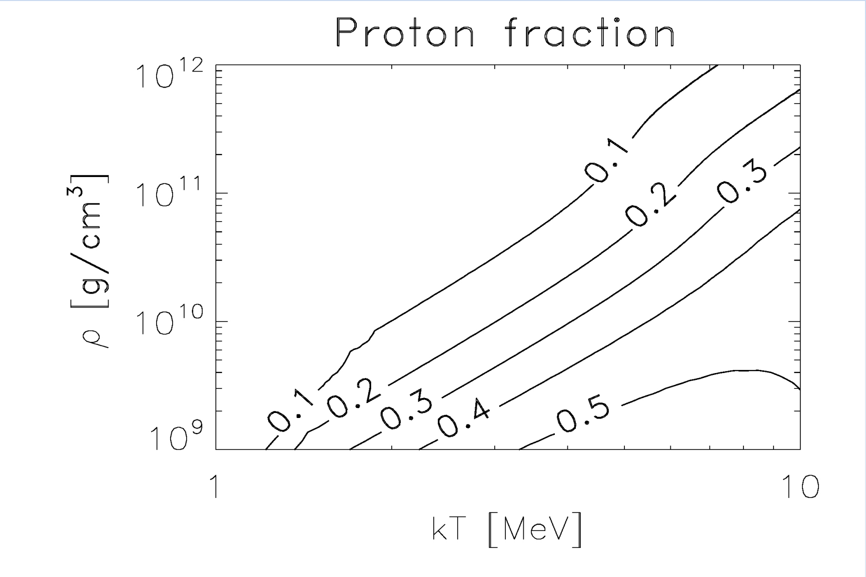


Chemical potentials of protons, neutrons, electrons and positrons in the equatorial plane of the hyperaccreting disk in GRB

Electron and proton fraction

Differ due to presence of electron-positron pairs and helium in the disk

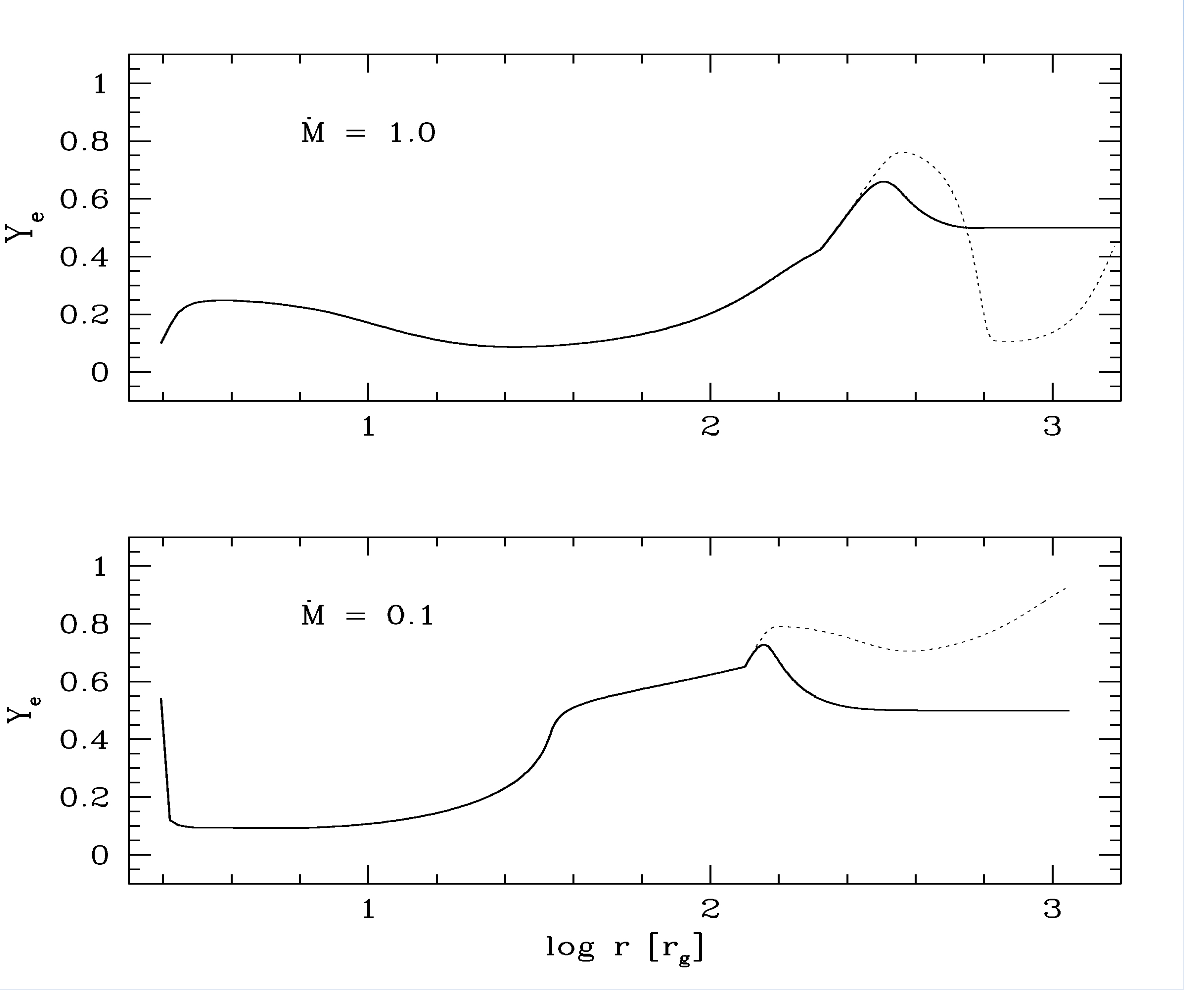




$Y_e = (n_{e-} - n_{e+})/n_b$

$Y_p = 1/(1+ n_n/n_p)$

Electron fraction distribution



Distribution of electron fraction in the equatorial plane of the hyperaccreting disk in GRB

Statistical reaction network

- Thermonuclear fusion due to capture/release of n, p, α, γ.
- Reaction sequence produces subsequent isotopes
- Set of non-linear differential equations solved by Euler method (*Wallerstein et al. 1997 Rev.Mod.Phys*.)
- Abundances calculated under assumption of nucleon number and charge conservation for a given density, temperature and electron fraction ($T \leq 1$ MeV)

Reaction network

Nuclear reactions may proceed with 1 (decays, electron-positron capture, photodissociacion), 2 (encounters) or 3 nuclei (3-alpha reactions)

$$\dot{Y}_i = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{j,k} \rho N_A < j,k > Y_j Y_k + \sum_{j,k,l} N^i_{j,k,l} \rho^2 N_A^2 < j,k,l > Y_j Y_k Y_l$$

where $Y_i = n_i/\rho\ N_A$ is the abundance of i^{th} isotope,

Abundances $\Sigma A_i Y_i = 1$, electron fraction $Y_e = \Sigma Z_i Y_i$

Integrated cross-sections depending on kT are determined with Maxwell-Boltzmann or Planck statisctics. Background screening and degeneracy are accounted for.

Our Recipe

Nucleosynthesis of heavier elements in the disk surface

- we use the thermonuclear reaction network code (http://webnucleo.org) and compute the nuclear statistical equlibria established for fusion reactions.

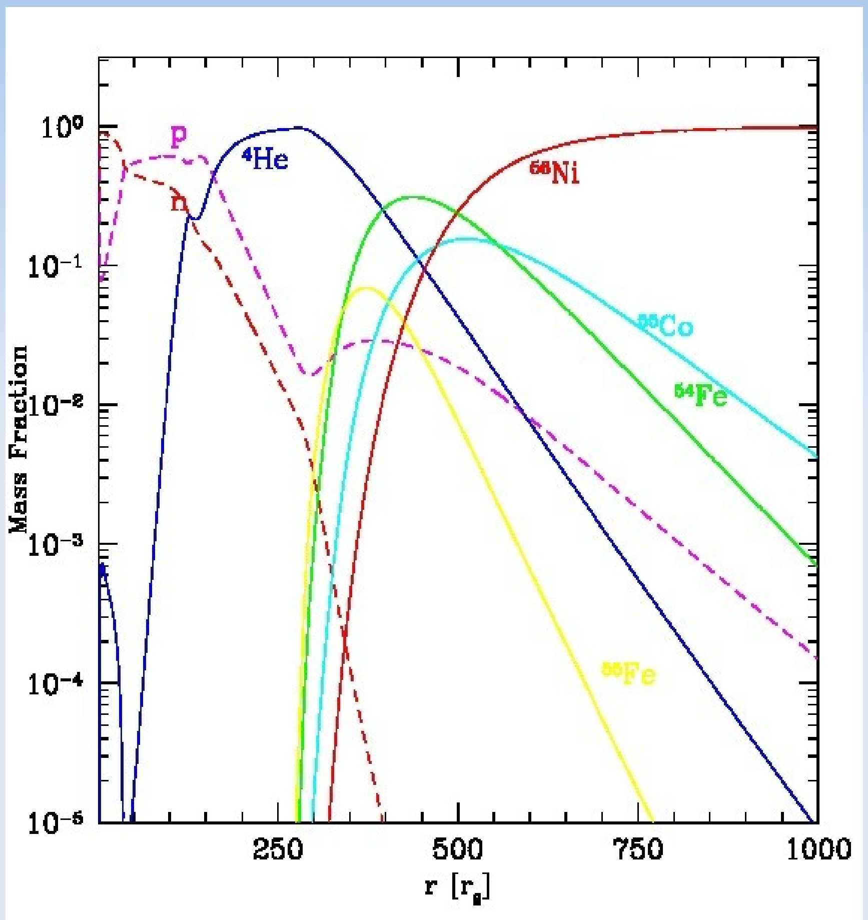
- the reaction data are taken from the JINA reaclib online database (http://www.jinaweb.org)

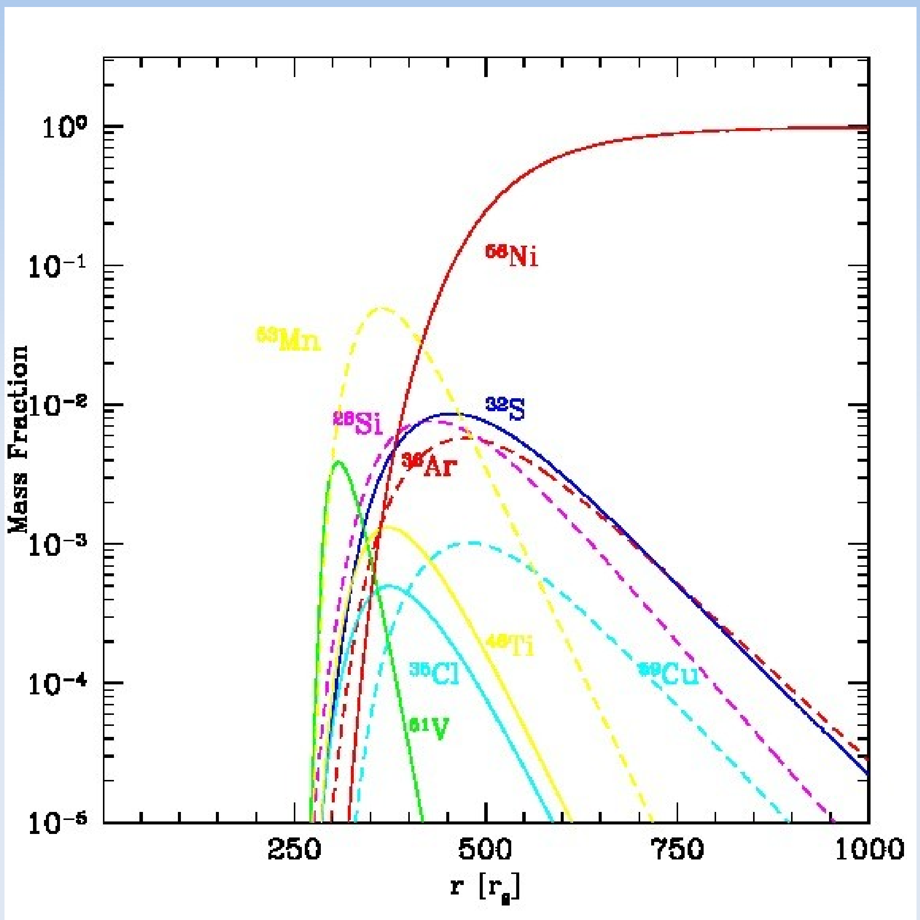
- the network is appropropriate for temperature ranges below 1 MeV, appropriate to the outer radii of accretion disk in GRB engine

- the mass fraction of all elements is solved for converged profiles of density, temperature and electron fraction in the disk

- parameters of the model are accretion rate, BH mass, spin, and viscosity in the disk

Heavy elements in disk

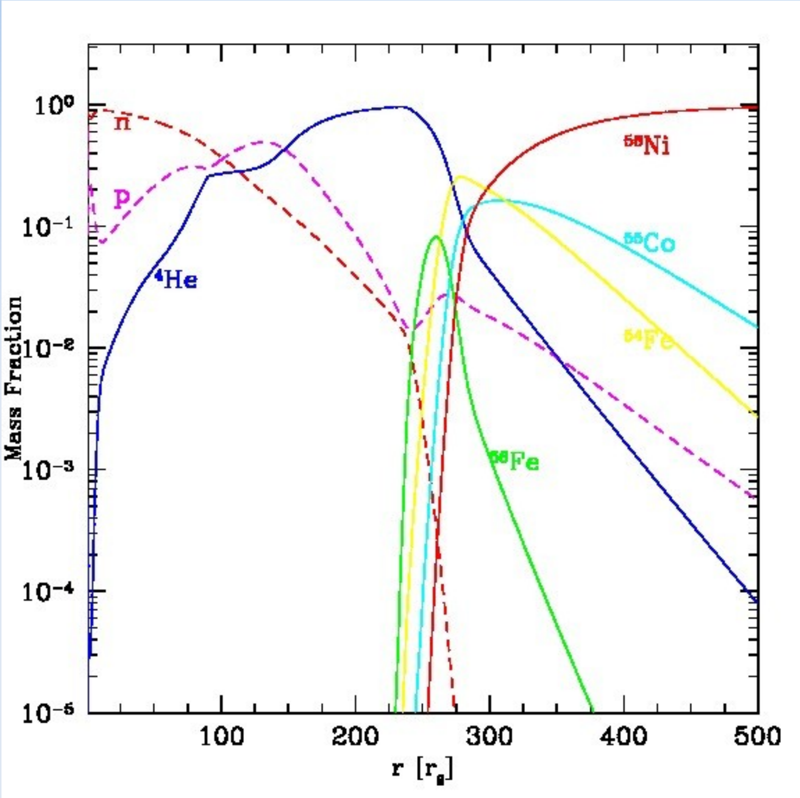


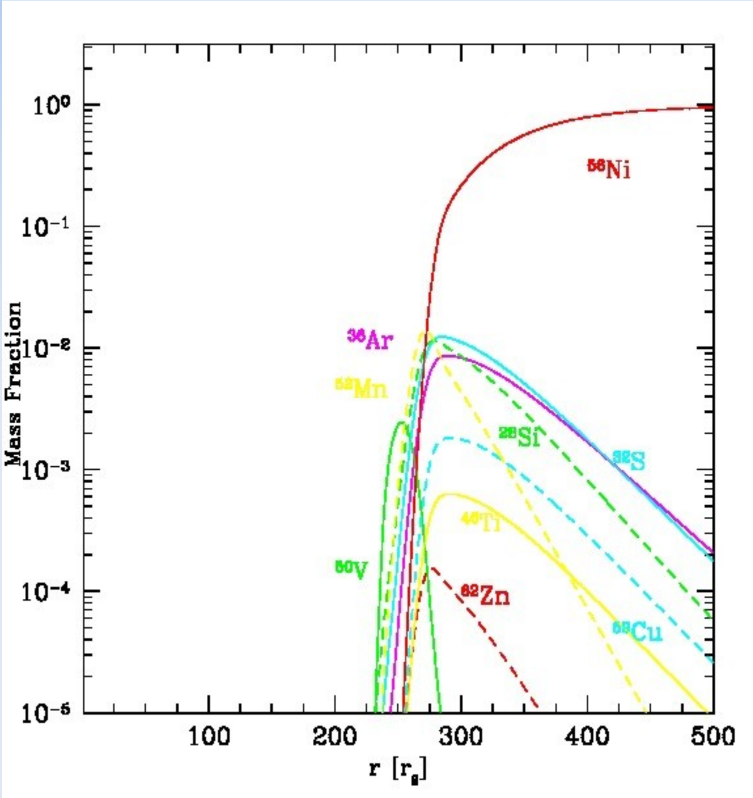


- Most abundant isotopes synthesized in the disk. Disk model parameters:
- M=3 M_{sun}, Mdot=0.1 M_{sun}/s, a= 0.9

Janiuk A., 2014, A&A, 568, 105

Heavy elements in disk



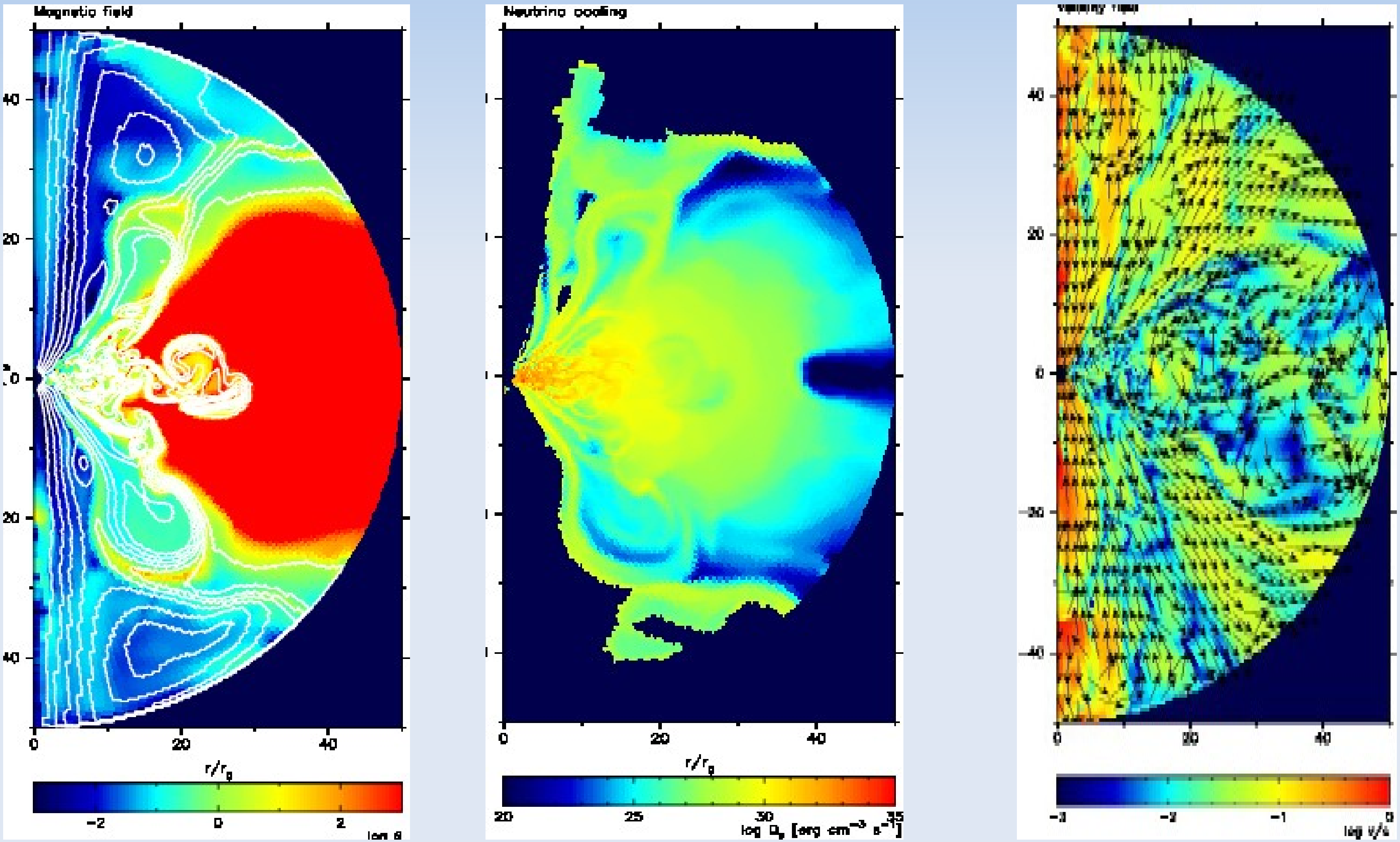


- Most abundant isotopes synthesized in the disk. Model parameters:
- $M=3\ M_{sun}$, $Mdot=1.0\ M_{sun}/s$, $a=\ 0.9$

Main results

- We synthesized the elements up to Nickel, Cuprum and Zinc, with mass fractions above 1.e-5, or Gallium above 1.e-6, in the higher accretion rate disks.
- Free neutrons disappear above 300 rg, and heavy elements dominatee above 500 rg. Below 10 rg, we have a bit more neutron rich disk than eg. Banerjee & Mukhopadhyay (2013)
- Up to 1000 rg, further layers of dominant Oxygen, Silicon and Calcium are present (Fujimoto et al. 2004). There is a trend of shifting those layers outwards, with increasing accretion rate
- Above the Iron peak, elements up to ^{84}Rb and ^{90}Zr, are found with yields of 1.e-12 and 1.e-14, similarly to other works (e.g. Surman et al. 2006).
- Surman & McLaughlin (2004; 2006) described the disk outflows with spherical geometry and simple velocity profile.

2-D torus modeling



Janiuk, Mioduszewski, Mościbrodzka, 2013, ApJ, 776, 105

2D GR MHD

Simulation made with code HARM (High Accuracy Relativistic Magnetohydrodynamics; Gammie et al. 2003). The code provides solver for continuity and energy-momentum conservation equations.

$(\rho u)_{;\mu} = 0 \qquad T^{\mu}{}_{\nu;\mu} = 0 \qquad p = K\rho^{\gamma} = (\gamma - 1)u$

where:

$T^{\mu\nu} = T^{\mu\nu}{}_{gas} + T^{\mu\nu}{}_{EM}$

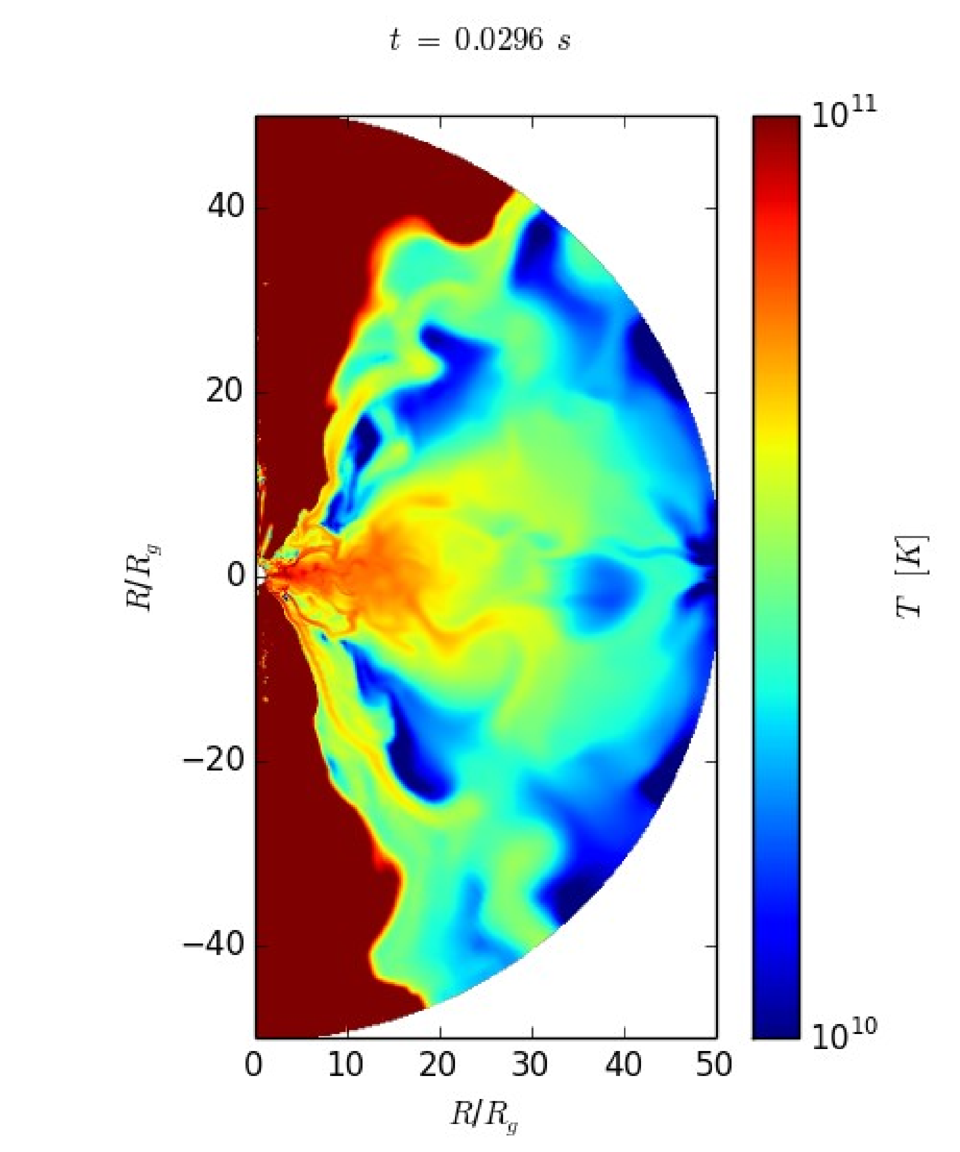
$T^{\mu\nu}{}_{gas} = (\rho + u + p)u^{\mu}u^{\nu} + pg^{\mu\nu}$

$T^{\mu\nu}{}_{EM} = b^2 u^{\mu}u^{\nu} + 1/2\, b^2 g^{\mu\nu} - b^{\mu}b^{\nu}$

assuming force-free approximation.

Original code was modified to account for EOS and neutrino cooling (via internal energy update)

2-D model of GRB engine

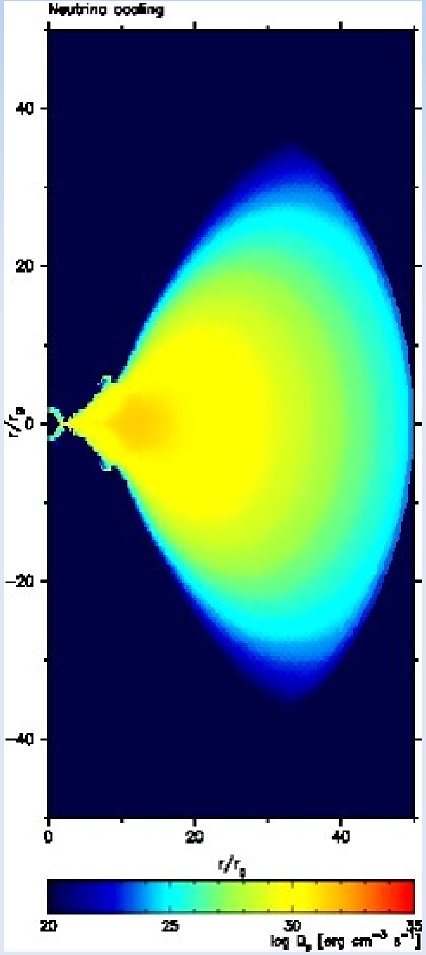


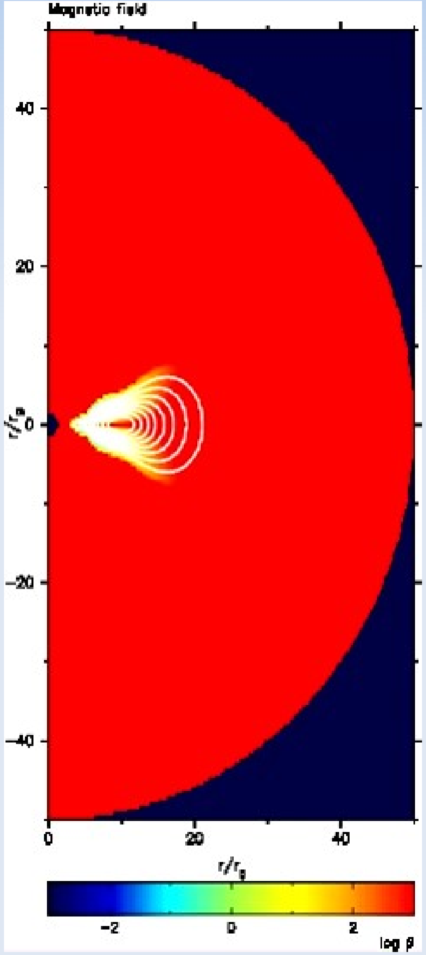
Temperature in the innermost 50 R_g of the GRB central engine. Snapshot is taken at the end of an axisymmetric GR MHD simulation (time=2000M).

Physical parameters: black hole mass: M=10 M_{sun}, its spin a=0.9, disk mass 1.0 M_{sun}.

AJ & B. Kaminski; arXiV:1504.00145

2-D simulation: GRB engine





Outflows from the disk

- The outflow from accretion disk may be driven by centrifugal force and magnetic fields. Neutrino cooled disks in GRBs have faster outflows.
- The slowly accelerated outflows will allow for production of heavier elements via triple-alpha reactions up to Nickel 56 or above the Iron peak nuclei.
- The radioactive decay of certain isotopes should be detectable via the emission lines observed by X-ray satellites, such as NuSTAR. In XMM-Newton, the instrument EPIC may also be able to detect lines below 15 keV, e.g. for ^{45}Ti, ^{57}Mn, ^{57}Co.

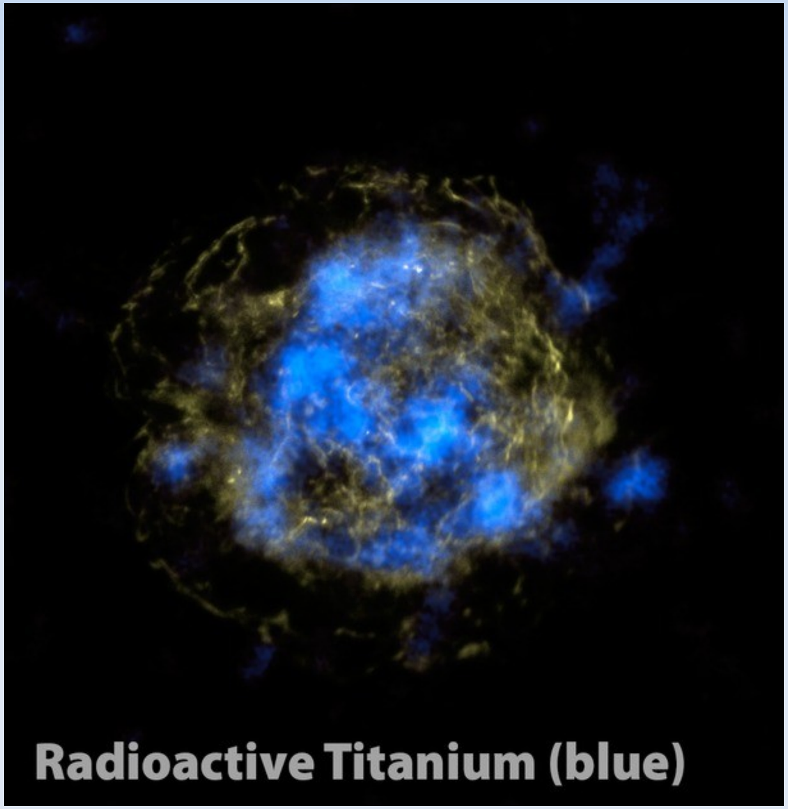
Possible detection

The radioactive decay of certain isotopes should be detectable via the emission lines observed by X-ray satellites. Such lines, e.g. the decay of ^{44}Ti to ^{40}Ca with emission of hard X-ray photons at 68 and 78 keV have been detected by NuSTAR in case of supernova remnants.

The energy band of this instrument (3-80 keV) should allow in principle for finding the X-ray signatures of other elements synthesized in the accretion disks in GRB central engines, like the radioactive isotopes of Cuprum, Zinc, Gallium, Cromium and Cobalt.

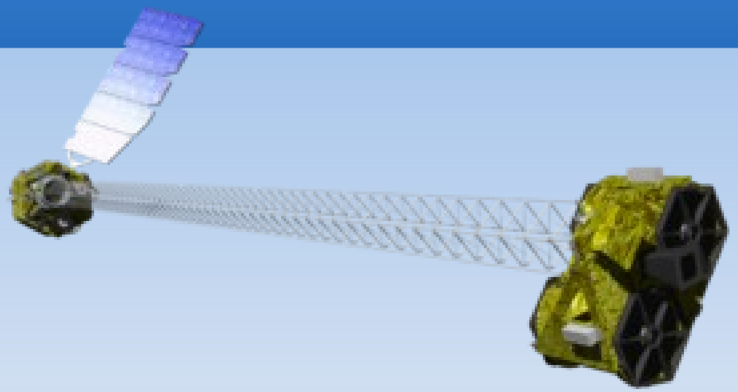
NuSTAR

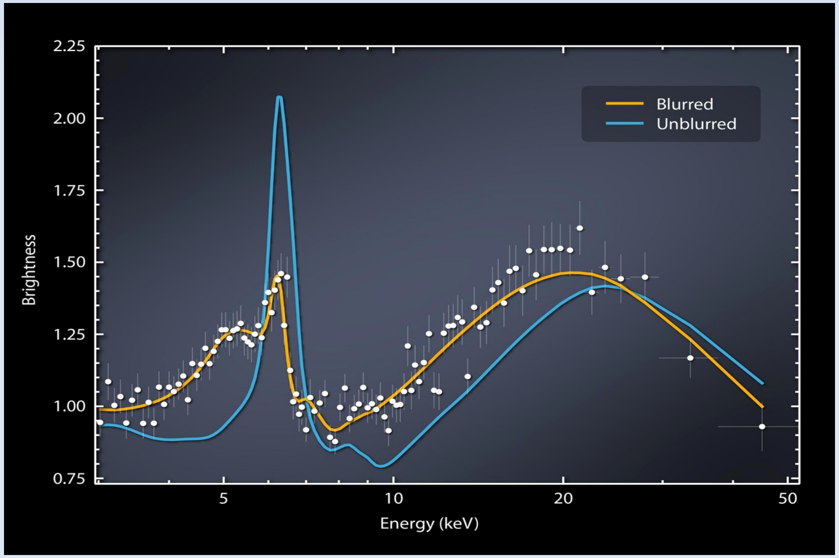
- NASA's Nuclear Spectroscope Telescope Array, or NuSTAR, has, for the first time, imaged the radioactive "guts" of a supernova remnant. The NuSTAR data are blue, and show high-energy X-rays. Yellow shows non-radioactive material detected previously by NASA's Chandra X-ray Observatory in low-energy X-rays.



Possible detection in X-rays

- NuSTAR. Launched by NASA, in 2012
- Energy 5-80 keV
- Good energy resolution
- Possible detection of X-ray photons from radioactive decay of isotopes: Ti, Co, Mn, Cu, Zn, Ga, Cr...

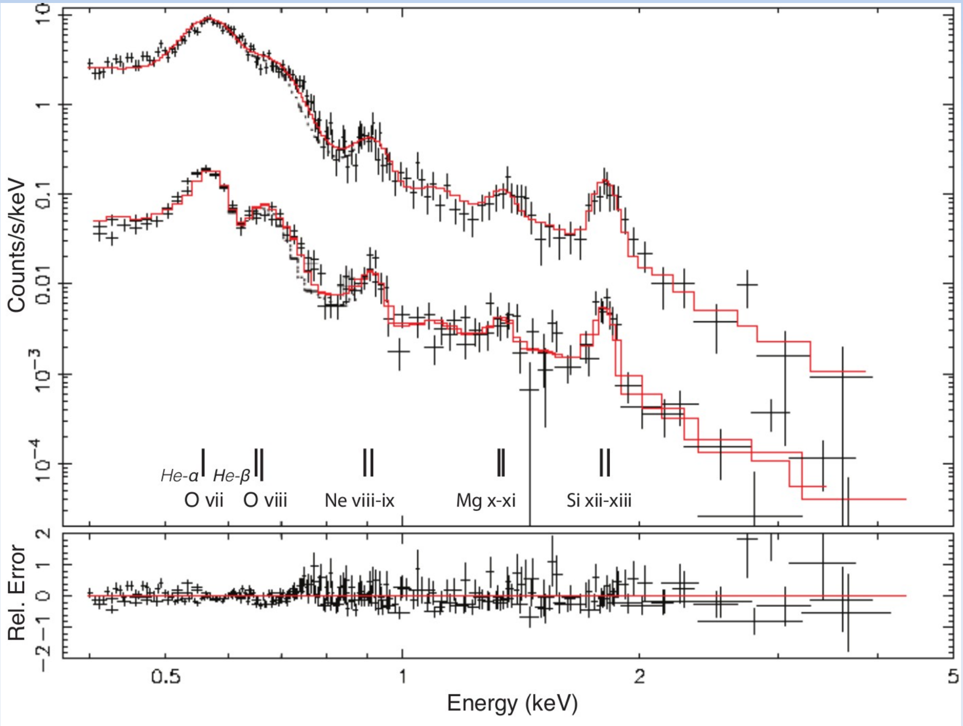




Iron line, detection by NuSTAR
Clavin et al. (2014)

Possible detection in X-rays?

- XMM/Newton
- EPIC detector, sensitive to 15 keV, possible to find isotopes of Ti, Mn, Co



SN 1006 (Broersen et al. 2013)

Radioactive astronomy

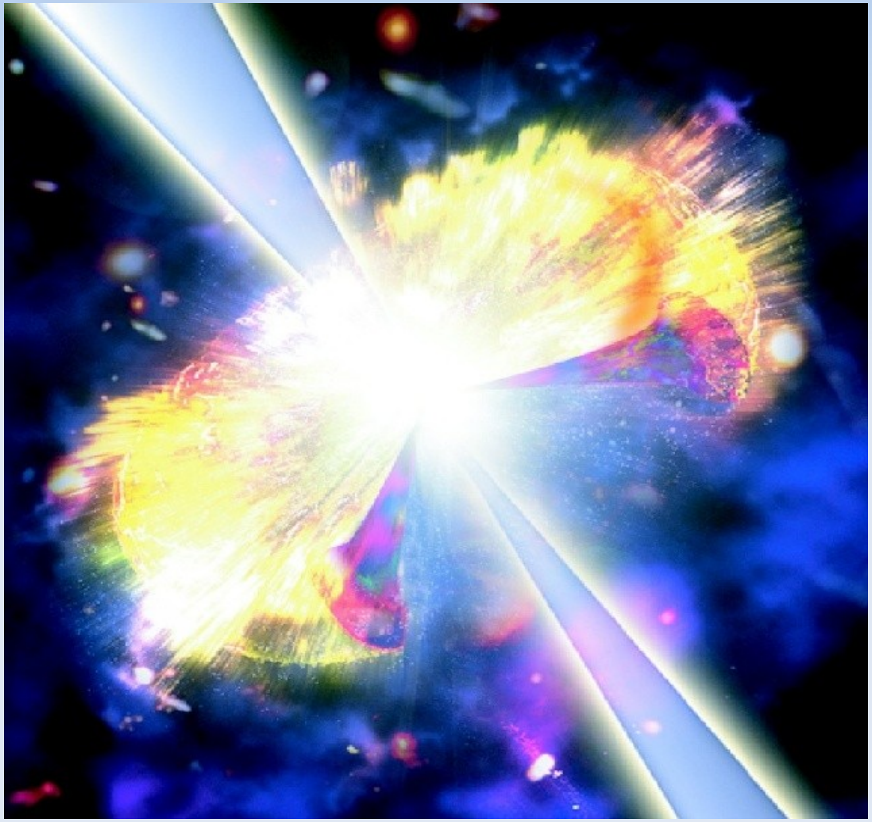
- Studying radioactive elements offers astronomers a more direct method for probing supernova blasts than observing non-radioactive elements. This is because this radioactive material glows with X-rays no matter what, while the X-rays detected by Chandra and other telescopes are generated only after heating with shock waves from the explosion. Because the non-radioactive material only lights up after the explosion, it does not offer a direct look at the blast itself.

Summary

Gamma Ray Bursts (GRB) are the extremely energetic transient events, visible from the most distant parts of the Universe. They are most likely powered by accretion on the hyper-Eddington rates that proceeds onto a stellar mass black hole newly formed in the center of a rotating collapsing star or via a merger of two compact stars. This central engine gives rise to the powerful, ultra-relativistic jets that are responsible for energetic gamma ray emission, as well as to the winds launched with smaller velocities from the accretion disk.

We consider the hyperaccreting disks and outflows from Gamma Ray Bursts. The torus is composed of free nucleons, Helium, electron-positron pairs, and is cooled by neutrino emission. The significant number density of neutrons in the disk and outflowing material will lead to subsequent formation of heavier nuclei. We study the process of nucleosynthesis and its possible observational consequences.

Thank you



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