High energy neutrinos from charm in astrophysical sources

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Based on work with M.H. Reno and I. Sarcevic

Astrophysical sources → high energy neutrinos (?)

(Source = SN, SNR, pulsar, GRB, AGN, microquasar/microblazar)

Sources are cosmic beam dump experiments

- Accelerate protons and electrons
- These collide with protons and photons
- Produced mesons decay to γ and ν

Example: $pp \to \pi^+ + X$ and $\pi^+ \to \mu^+\nu_\mu \to e^+\nu_\mu\bar{\nu}_\mu\nu_e$

Idea for this talk:
Pions and kaons are long-lived and are cooled before decay — charmed mesons will persist to higher energies

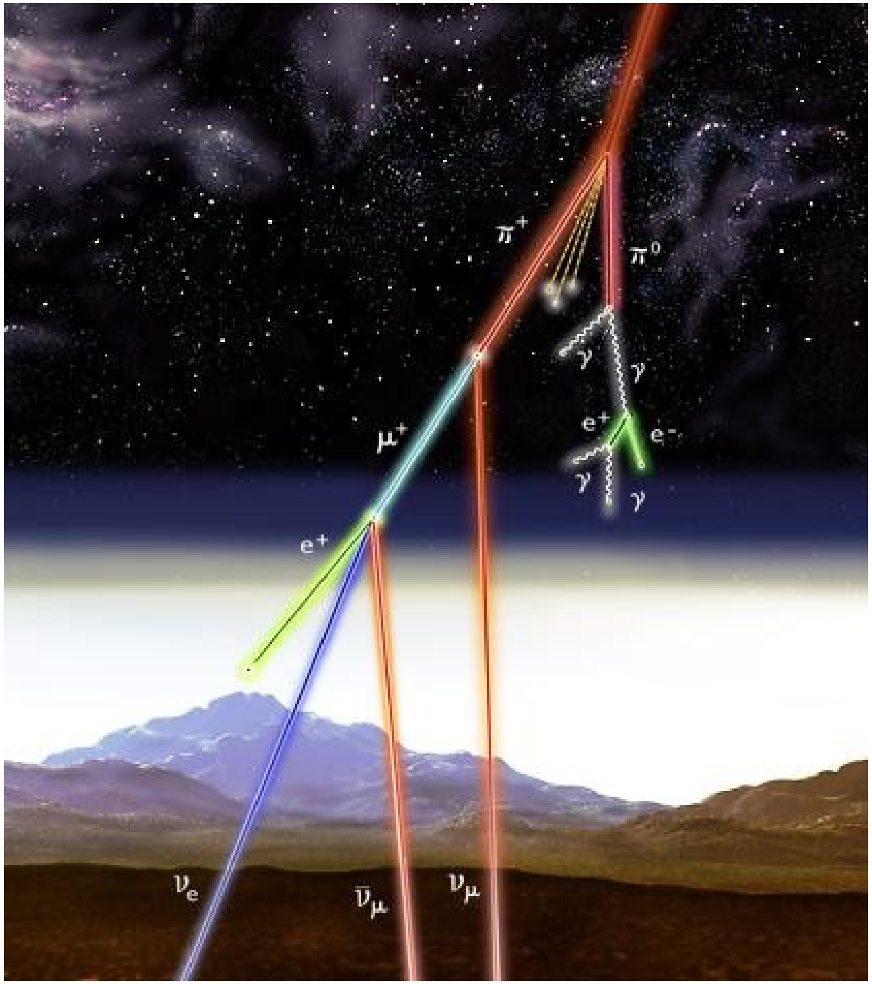
Just like for atmospheric neutrinos ...

Brief detour: Atmospheric neutrinos

- Cosmic rays bombard atmosphere and collide with air nuclei

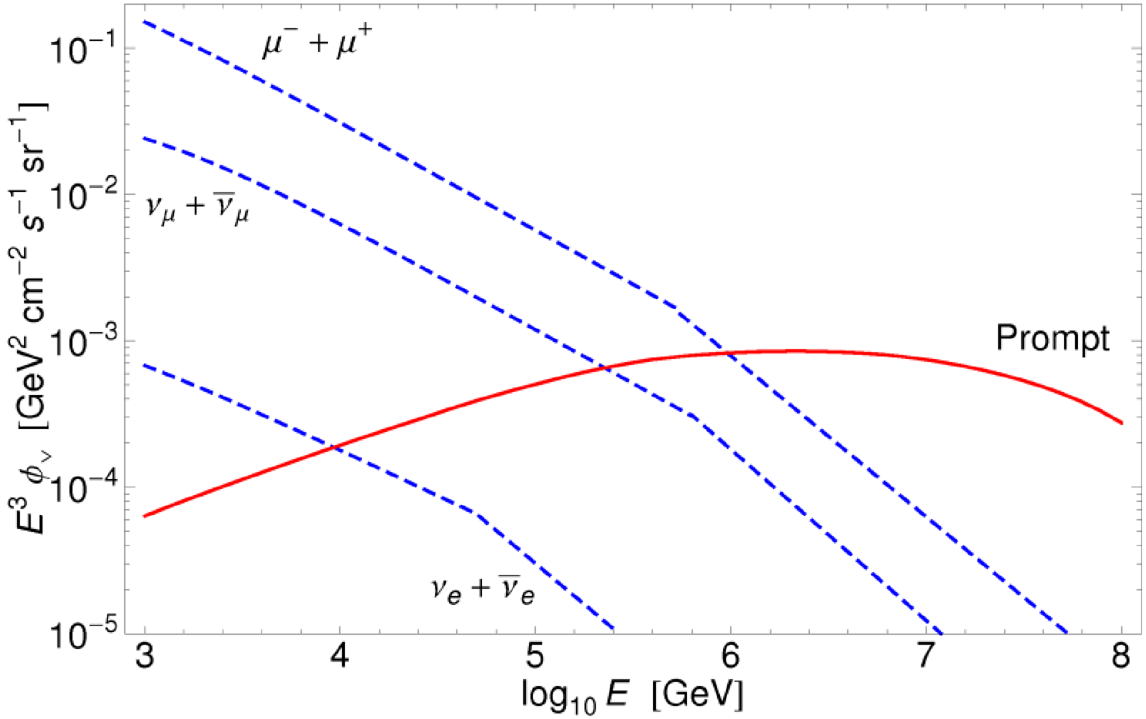
- CMS energy is large
  ⇒ secondary hadrons:
  pions, kaons, D-mesons ...

- Secondary particles interact and decay
  ⇒ cascade of particles



Credit: INFN-Notizie No.1 June 1999

Prompt vs conventional fluxes of atmospheric neutrinos

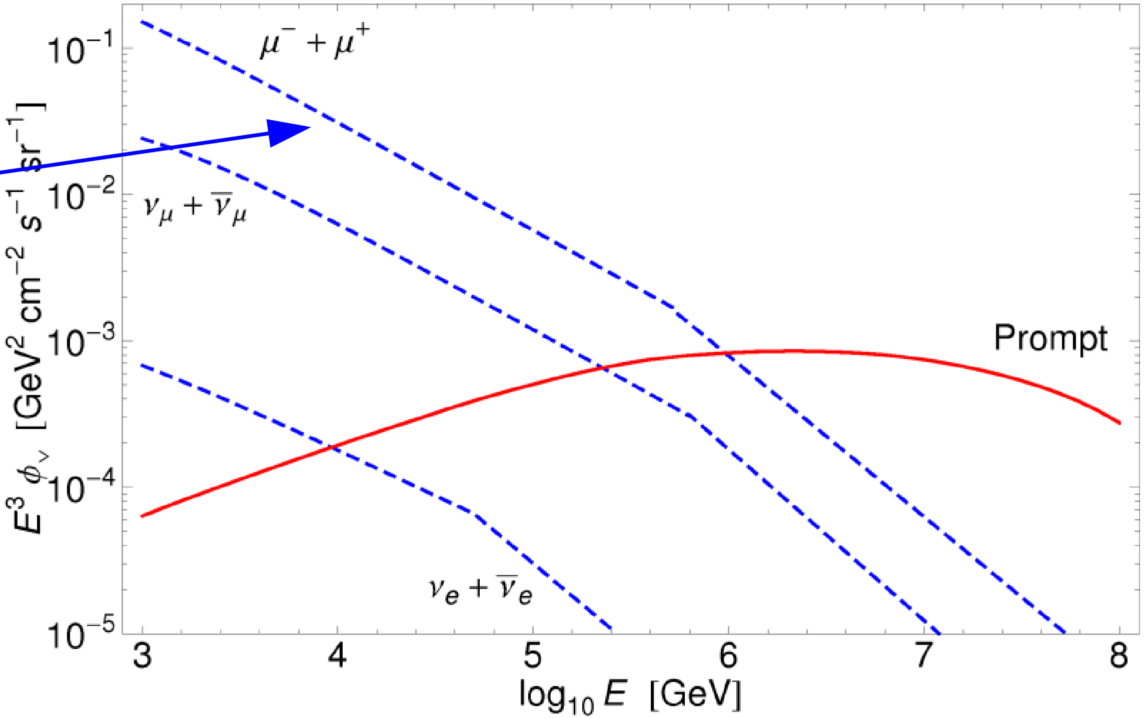


Prompt flux: RE, M.H. Reno, I. Sarcevic, arXiv:0806.0418 (in PRD)

Conventional: Gaisser & Honda, Ann. Rev. Nucl. Part. Sci. **52,** 153 (2002)

Prompt vs conventional fluxes of atmospheric neutrinos

Pions & kaons: long-lived ⇒ lose energy before decay



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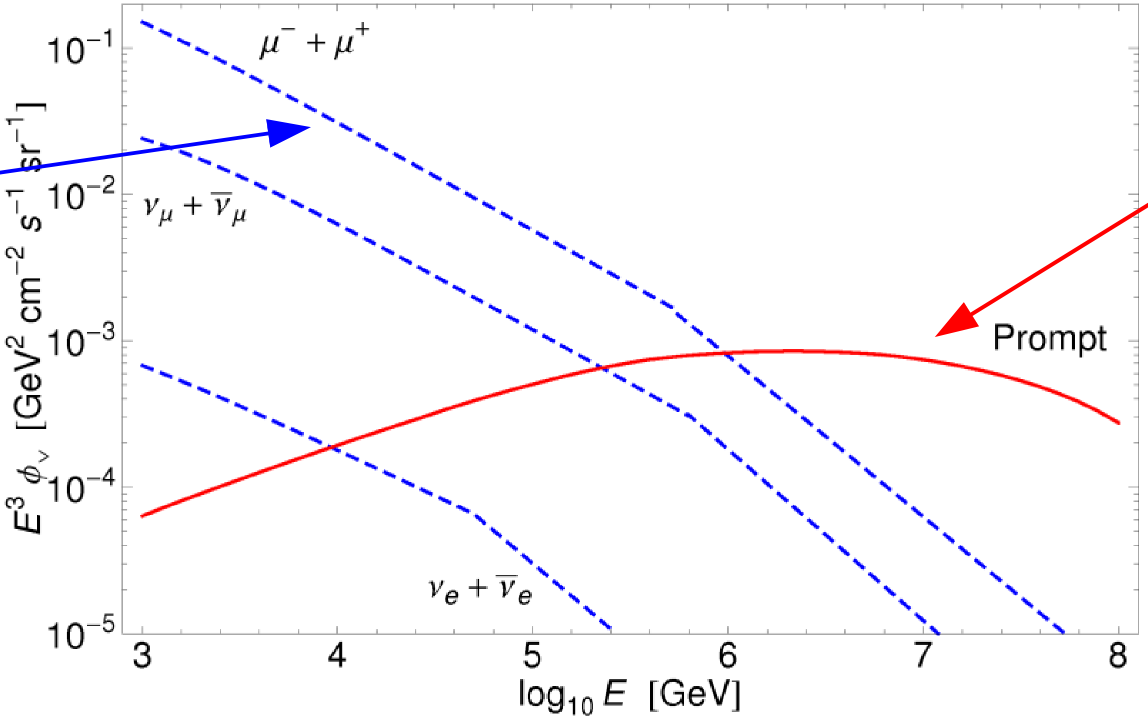

Charmed mesons: short-lived ⇒ don't lose energy ⇒ harder spectrum

Prompt flux: RE, M.H. Reno, I. Sarcevic, arXiv:0806.0418 (in PRD)

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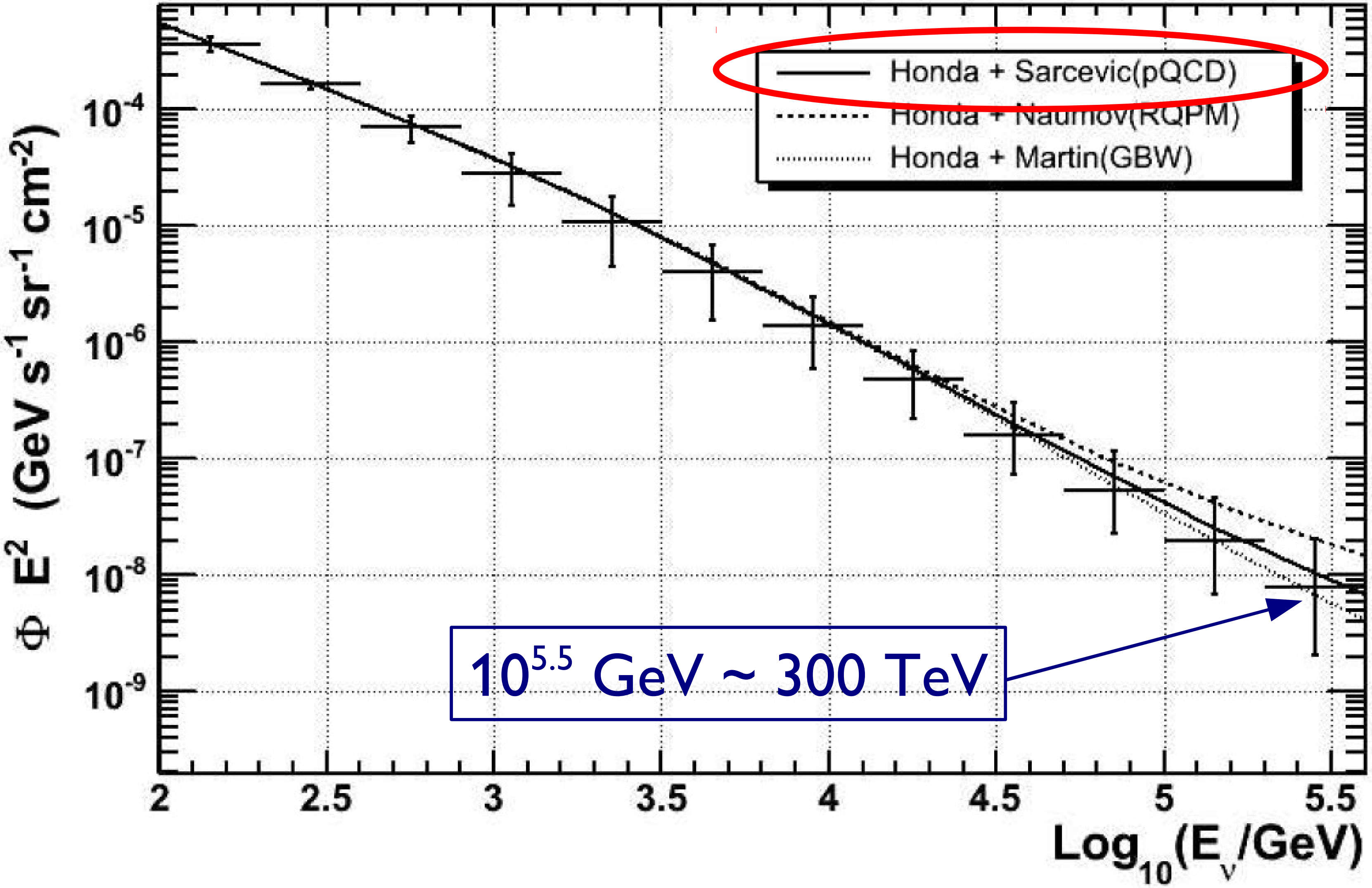
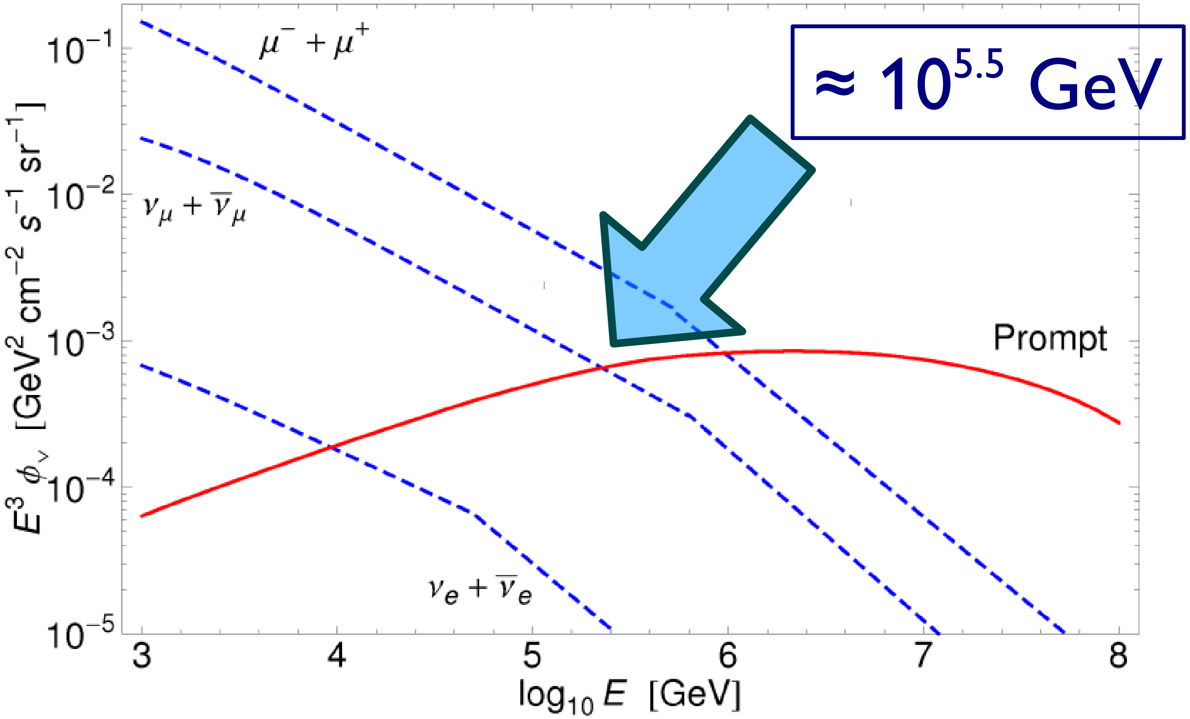
Predictions and IceCube 40 data



$10^{5.5}$ GeV ~ 300 TeV

Abbasi et al. (IceCube), arXiv:1010.3980

Cross-over of prompt and conventional fluxes



RE, M.H. Reno, I. Sarcevic, arXiv:0806.0418 (in PRD)

IceCube hasn't quite reached the cross-over energy!

Back to sources:
Highest energies – GRB and AGN

- Gamma Ray Bursts are enormously violent explosions with a burst of γ rays that lasts for **a few seconds or minutes**
  - Emit gamma rays, photons at other energies, and probably charged particles and neutrinos
  - Total energy output comparable to SN but emitted in much shorter time

- Active Galactic Nuclei: the **black hole at the galactic center** takes part in accelerating particles

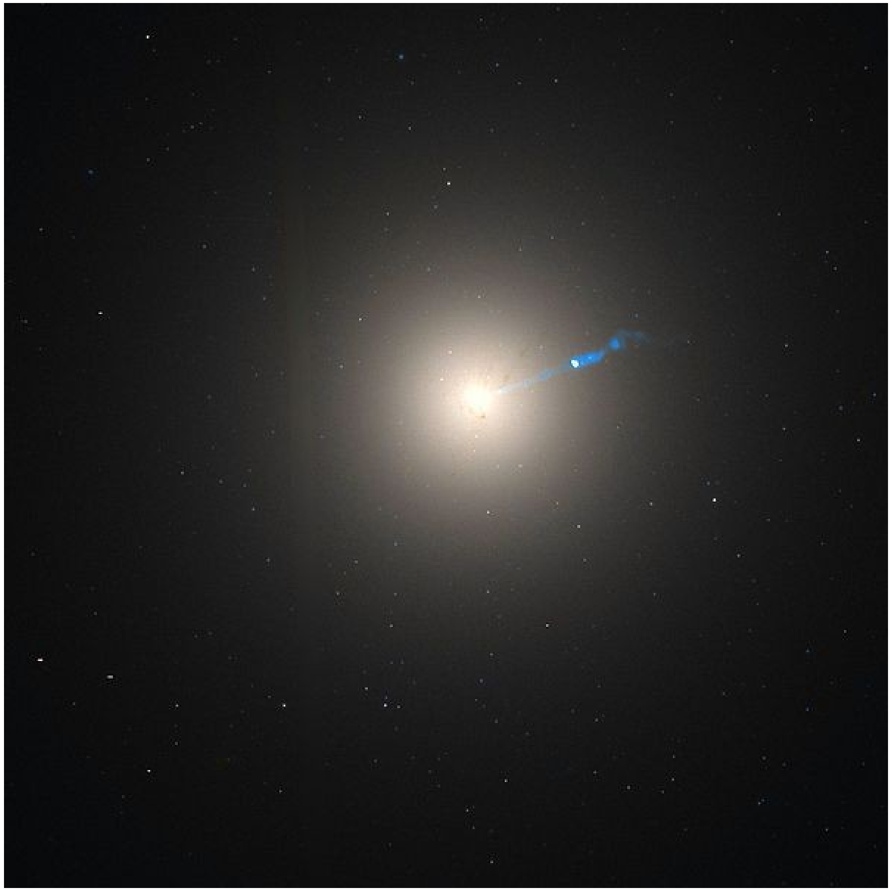
Example AGN: M87

M87: elliptic galaxy (Virgo cluster, 50 million lightyears away)

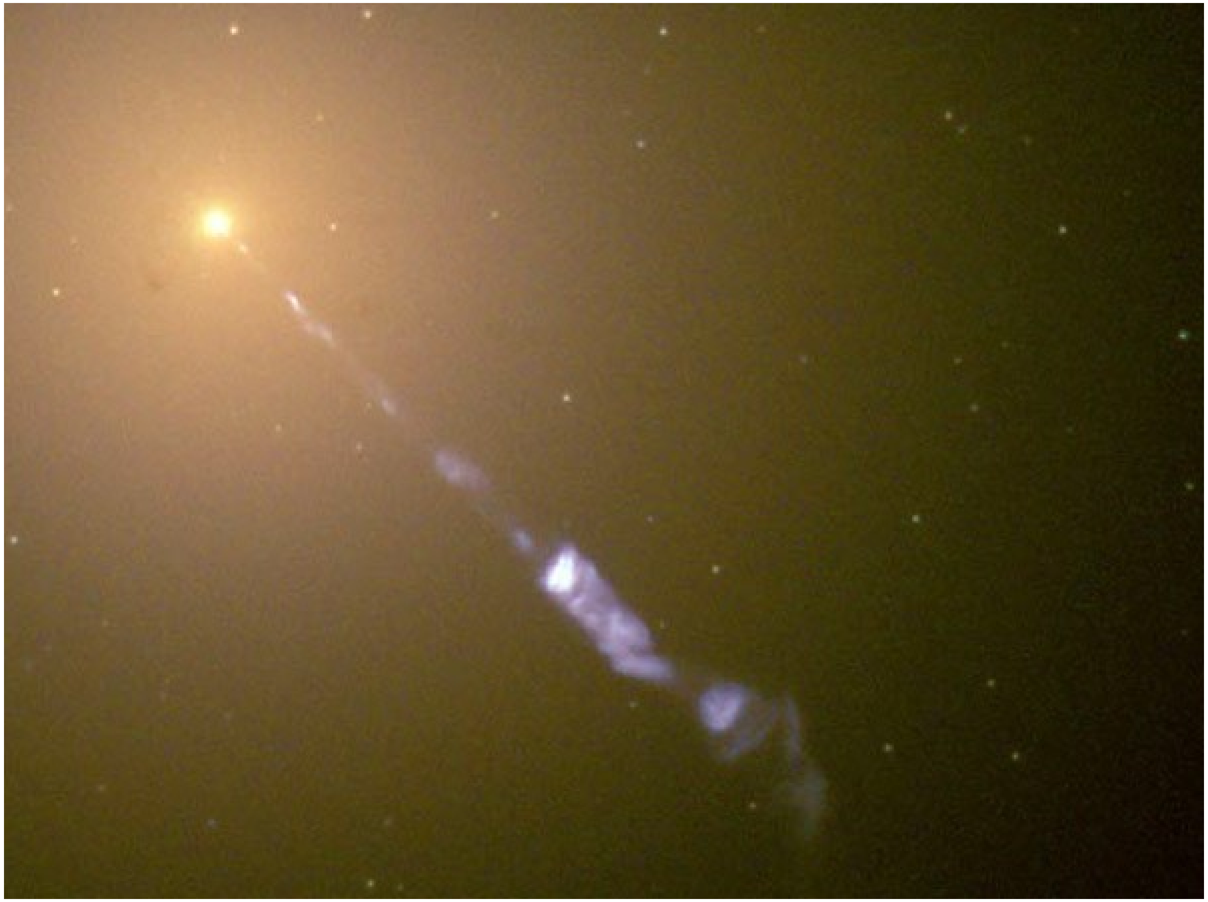
Supermassive black hole at the center with mass **6.4×10^9 $M_\odot$**

It has a **jet** protruding from the center

This jet is a collimated, relativistic outflow due to the black hole [gamma factor ~ O(10)]



Jet of M87



Hubble Space Telescope, 2000

The jet is 5,000 lightyears

Charged particles are shock accelerated there

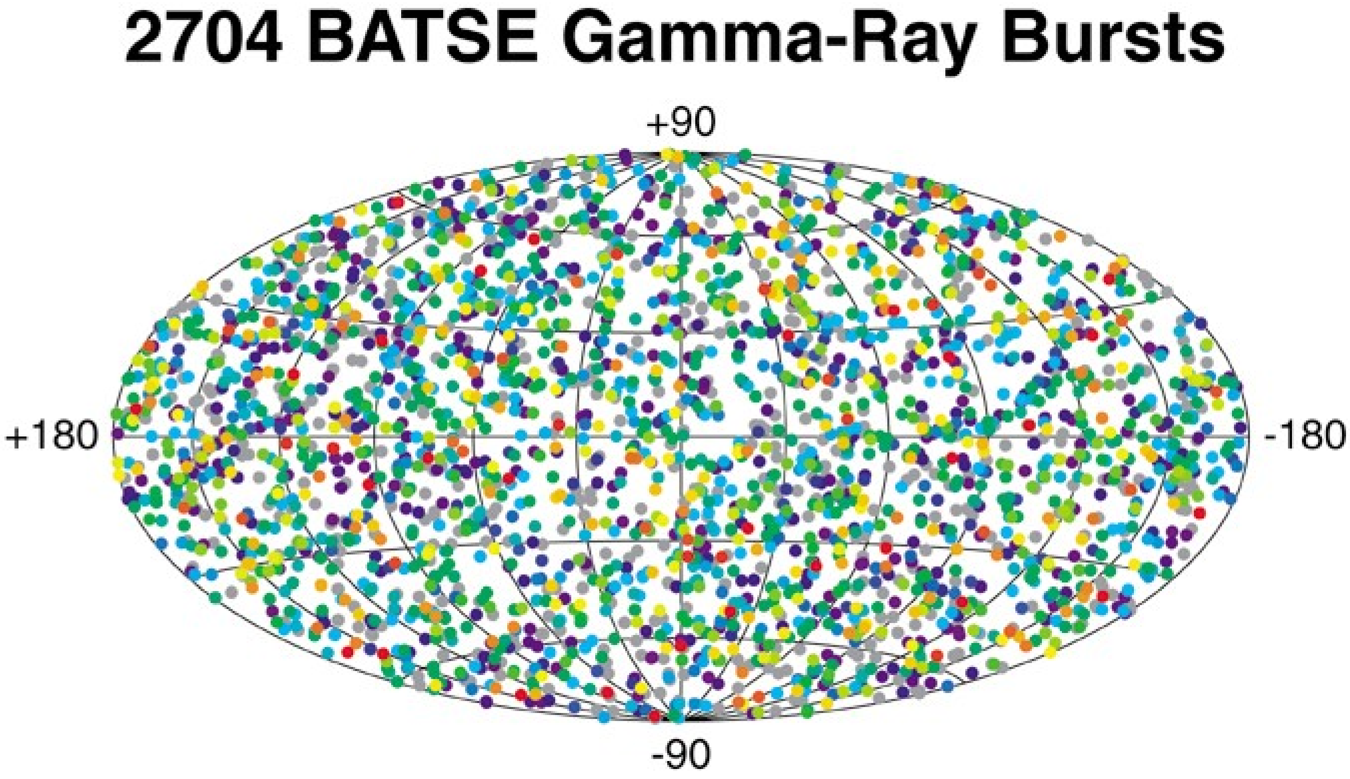
→ Synchrotron and inverse Compton photons emitted at large energies

Also emission of high energy cosmic rays? Hadronic production of gamma rays and **neutrinos**??

Gamma ray bursts (GRB)

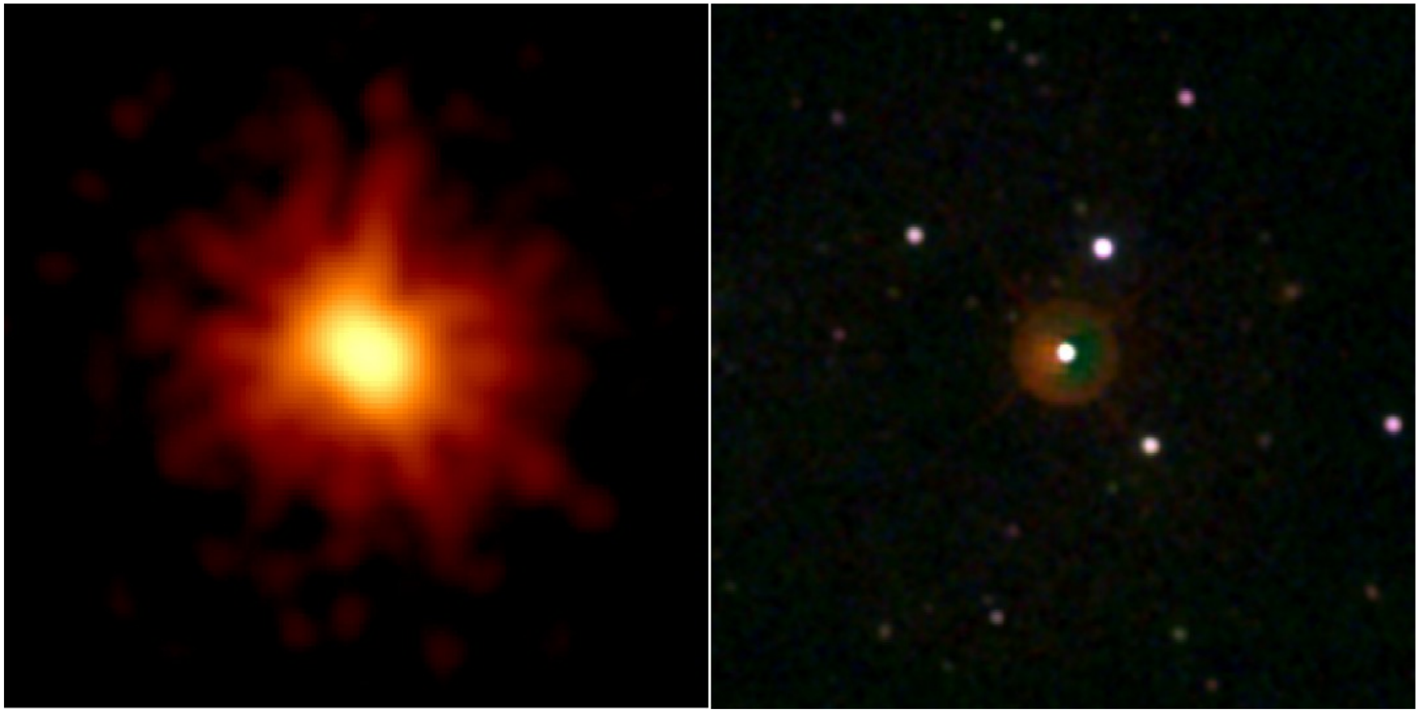
- GRBs: most violent phenomena observed in the universe
- Energy output in ~ seconds:
  ~ $10^{53} – 10^{54}$ ergs isotropic energy equivalent
  ~ $10^{51} – 10^{52}$ ergs if emission is *jetted* ($\theta \sim 5^\circ$)
- About 2–3 GRBs per day are observed
- Extragalactic

GRBs are extragalactic



Evenly distributed across sky → not in the Galaxy

Example GRB: GRB 080319B



NASA. Left: X-ray. Right: optical/UV

Was visible to the naked eye for 30 seconds and millions of times brighter than brightest SN

Brightest GRB ever seen, $z = 0.937$ → 7.5 billion years ago!!

GRBs also have jets

- Most GRBs are very far away and thus need to be **extremely energetic** (observed up to redshift $z = 6–7$)
- Again: black hole drives relativistic outflow in jets
- But more extreme: jets with gamma factors of 100 – 1000!

What catastrophe forms the GRB?

There are two broad classes of GRB:

- **Long:** *($t > 2$ s):*
  A special type of large supernova called ***hypernova*** or ***collapsar*** which forms a black hole instead of a neutron star (e.g. Wolf-Rayet stars, type Ib, Ic)

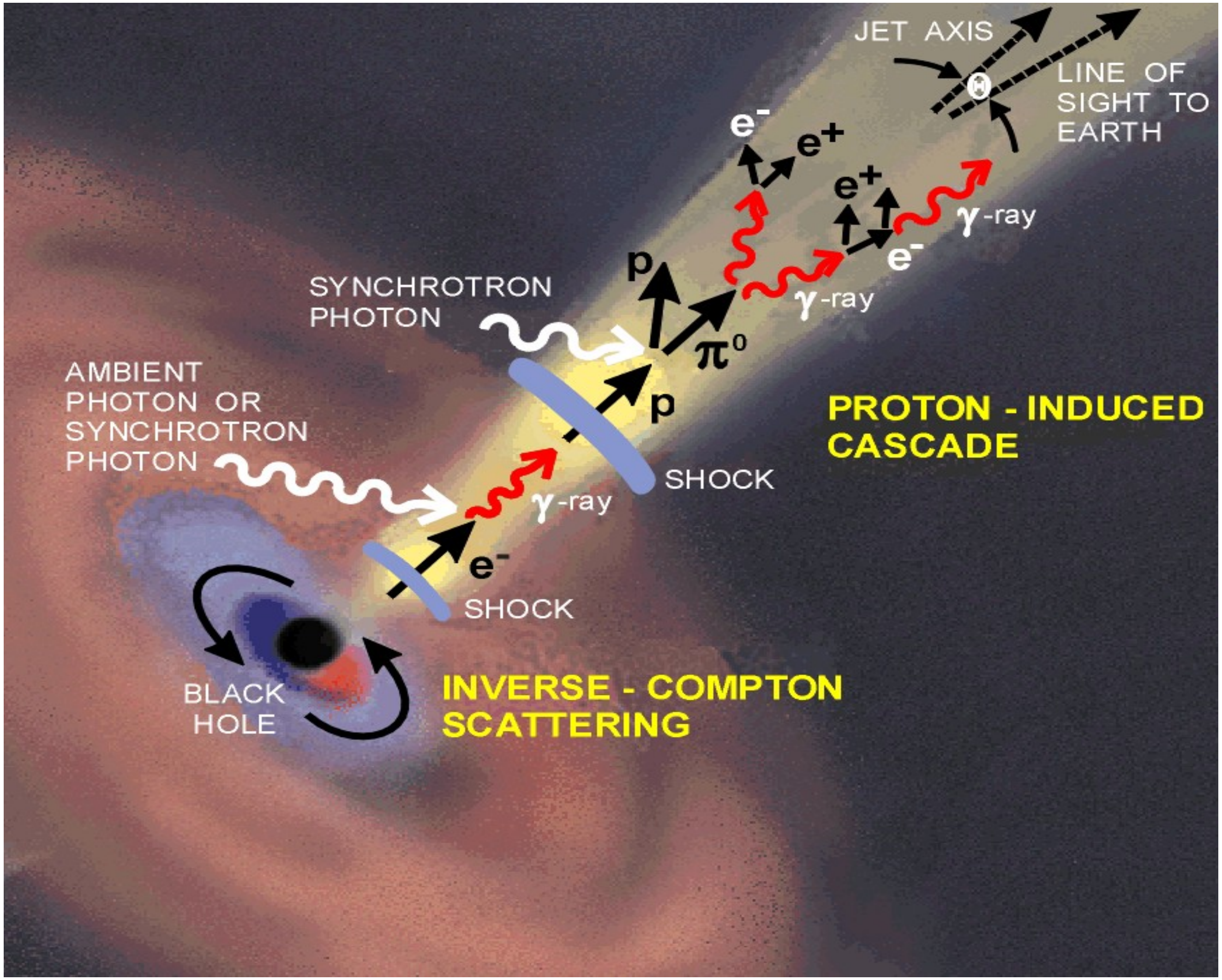
  First evidence: GRB 980425 and SN 1998bw

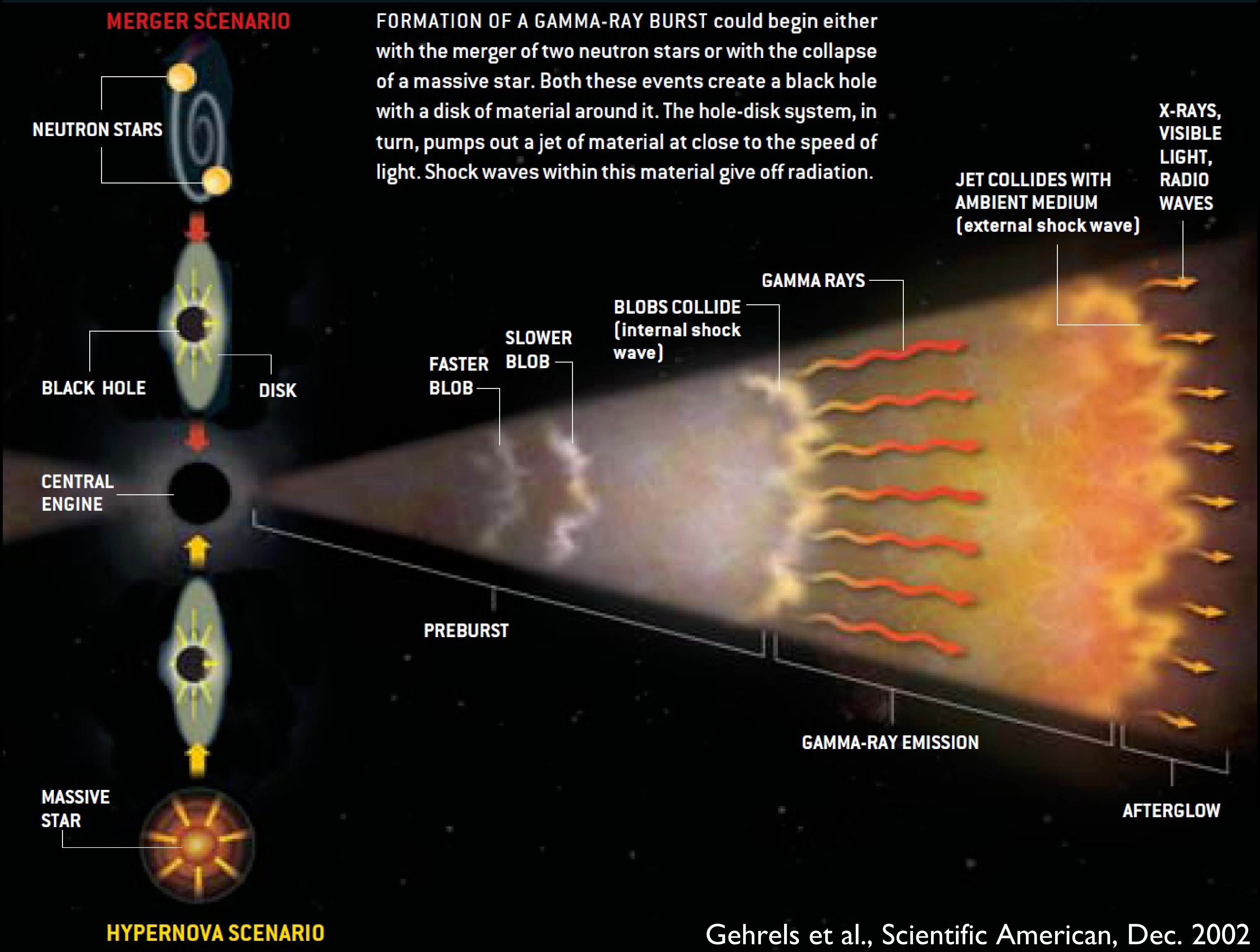
- **Short:** *($t < 2$ s):*
  Collision and ***merger of two neutron stars*** in a binary system (or two black holes, or one of each)

Acceleration and emission

- Electrons and protons: *shock accelerated* through *Fermi mechanism* → power law spectrum $\propto E^{-2}$
- Electrons cool down through synchrotron emission in magnetic field
- If optically thin: gamma rays escape → **burst**
- If optically thick: photons can thermalize
- Lorentz factor of jet must be **> 100** for thin system!

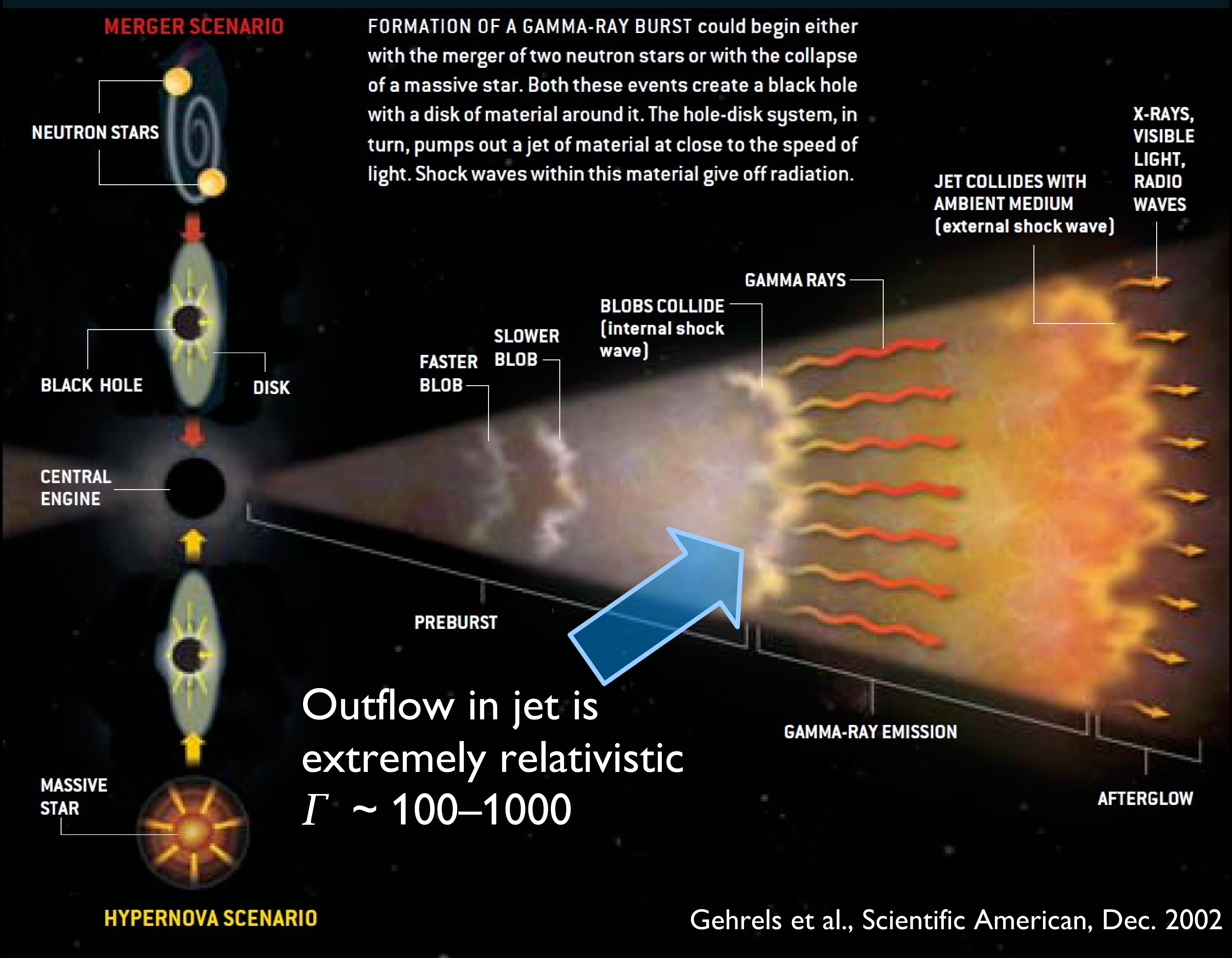
Relativistic jet





FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.

Gehrels et al., Scientific American, Dec. 2002



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Outflow in jet is extremely relativistic

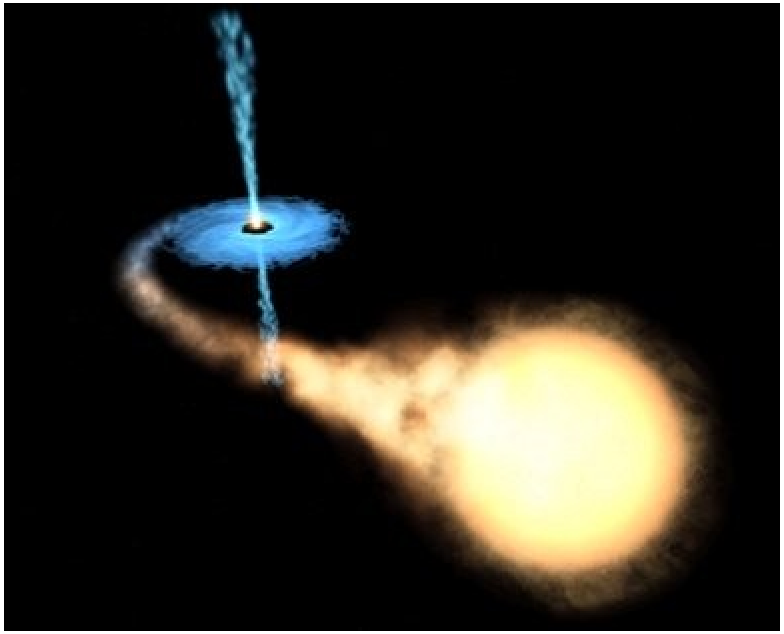
$\Gamma \sim 100\text{–}1000$

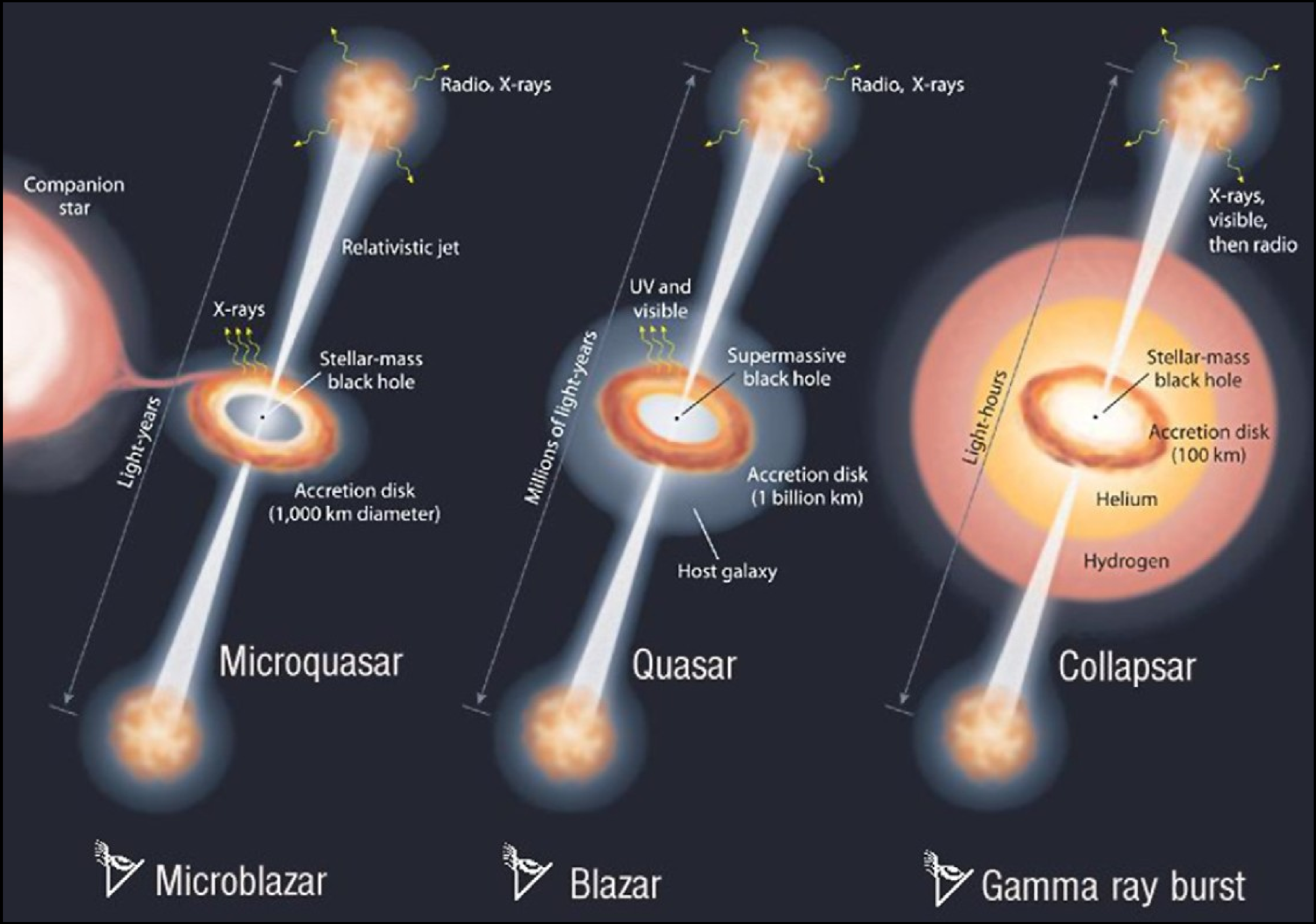
Gehrels et al., Scientific American, Dec. 2002

Microquasars – analogs to quasars

Quasars / blazars are AGN: supermassive black hole – millions or billions of $M_\odot$

Microquasar / microblazar: stellar mass black hole in binary





I. F. Mirabel, C. R. Physique 8 (2007) 7–15

Photons, neutrinos

- **Neutrinos**: Emitted in decay of charged pions $\pi^{\pm}$, which are copiously produced in collisions:

$$pp,\ p\gamma \to \pi^{+} + X \quad \text{or} \quad p\gamma \to n\pi^{+}$$

followed by

$$\pi^{+} \to \mu^{+}\nu_{\mu}$$
$$\mu^{+} \to \bar{\nu}_{\mu}\nu_{e}e^{+}$$

- **Photons**: "Hadronic" photons from e.g.

$$p\gamma \to p\pi^{0}$$
$$\pi^{0} \to \gamma\gamma$$

(ν, γ also from other decays)

Charm in astrophysical sources

- For atmospheric neutrinos, charm **dominates** at high energies as D-mesons **decay before they lose energy**
- Obvious question: what about **charm in astrophysical sources?** Not usually taken into account.

  (but see Kachelriess & Tomas, astro-ph/0606406)
- We'll see that electromagnetic energy loss can be more important, but the overall result is similar:

  $m_D >> m_\pi$ → D synchrotron losses much smaller (m^{-4})

Astrophysical sources

We consider two kinds of sources as examples:

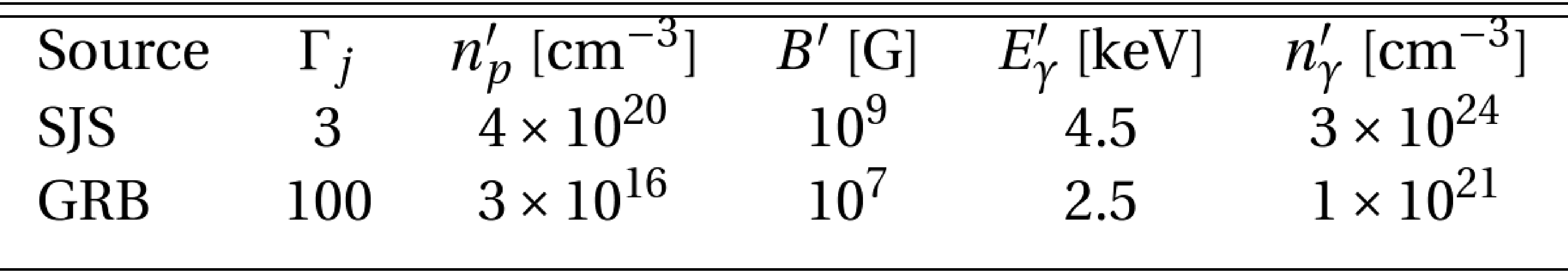
- **GRB:**
  - Non-thermal photons and highly relativistic jet

- **“Slow-jet supernova” (SJS):**
  - SN with mildly relativistic jets that don't punch through
  - Thermal photons
  - SNe with jets could be common (may help explosion?)

(Razzaque, Meszaros, Waxman; Ando and Beacom)

Parameters

Calculated or observed (comoving frame) with L_j=3×10^{50} erg/s :



Source	Γ_j	n'_p [cm^{-3}]	B' [G]	E'_γ [keV]	n'_γ [cm^{-3}]
SJS	3	4×10^{20}	10^9	4.5	3×10^{24}
GRB	100	3×10^{16}	10^7	2.5	1×10^{21}

We calculate the neutrino fluxes for these two model sources

To do this, we need to take proton and meson cooling into account

Cooling

- Time scales for cooling of protons and mesons are

$$t'_{\mathrm{cool}} = \frac{E'}{|dE'/dt'|}$$

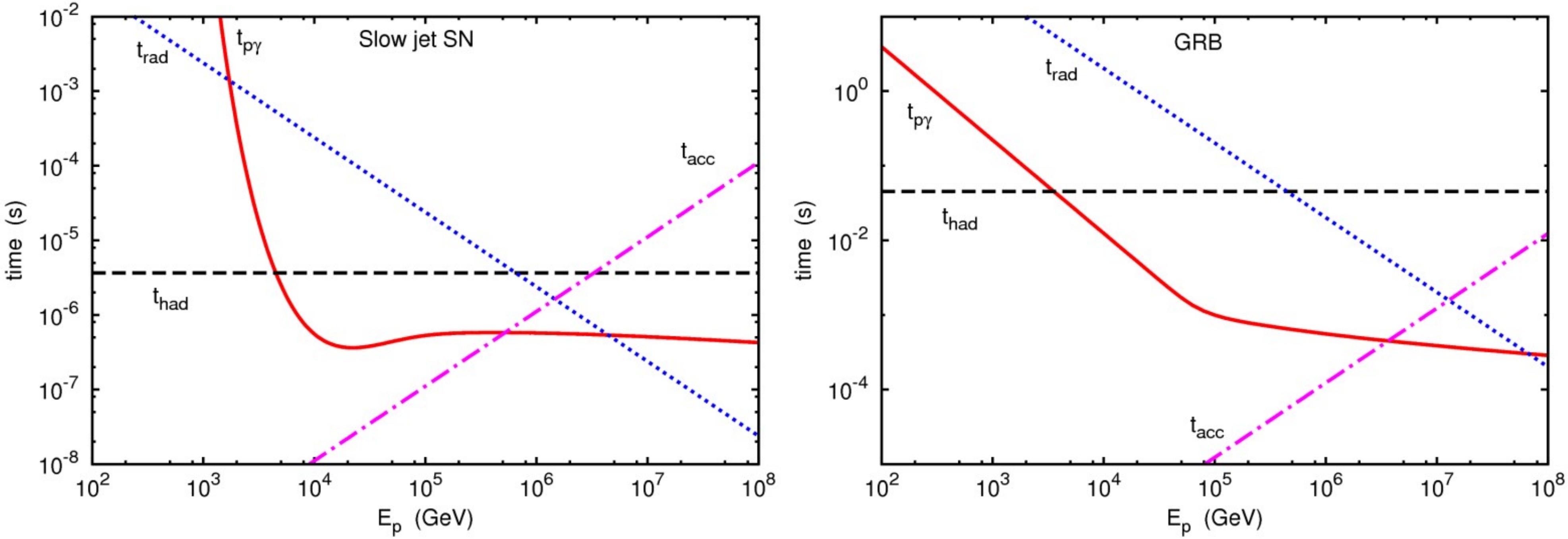
with

$$\left|dE'/dt'\right| \simeq n'\sigma v \Delta E$$

- For $p\gamma$, we use $\left|dE'/dt'\right| \simeq \langle n'\sigma v \rangle \Delta E$

averaged over the photon distribution

Time scales for protons

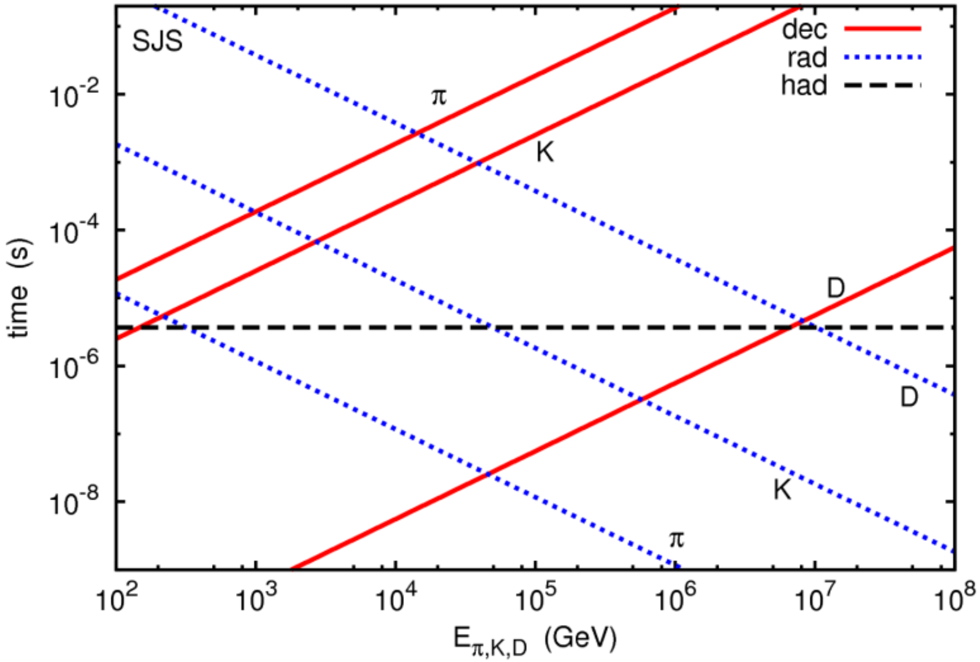


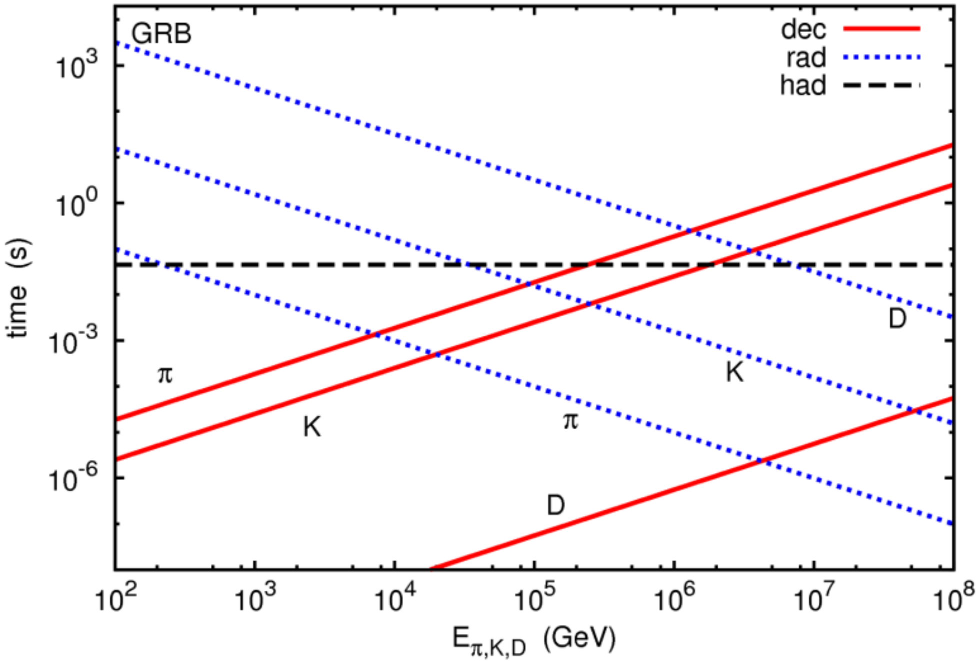
[RE, M.H. Reno, I. Sarcevic, arXiv:0808.2807]

Maximum proton energy estimated from where cooling times meet acceleration time

Above E_{max} : rather quick drop-off in proton flux

Time scales for mesons





Cooling time shorter than decay time → meson flux suppressed

- D-mesons decay before cooling below $E_D \sim 10^7$ GeV (SJS)
  $E_D \sim 10^9$ GeV (SJS)
- Pions, kaons are cooled much earlier

Computation of neutrino flux

- We generalize the method of Z-moments (spectrum-weighted moments) to apply to astrophysical sources
- Solve cascade equations for all species of particle *j* in the frame comoving with outflow, schematically

$$\frac{d\phi_j}{dx} = -\frac{\phi_j}{\ell_j^{\mathrm{tot}}} + S^{\mathrm{tot}}(jp \to jY)$$

- Use actual lengths *x* and *l* instead of column depth and assume constant density (small chock region)

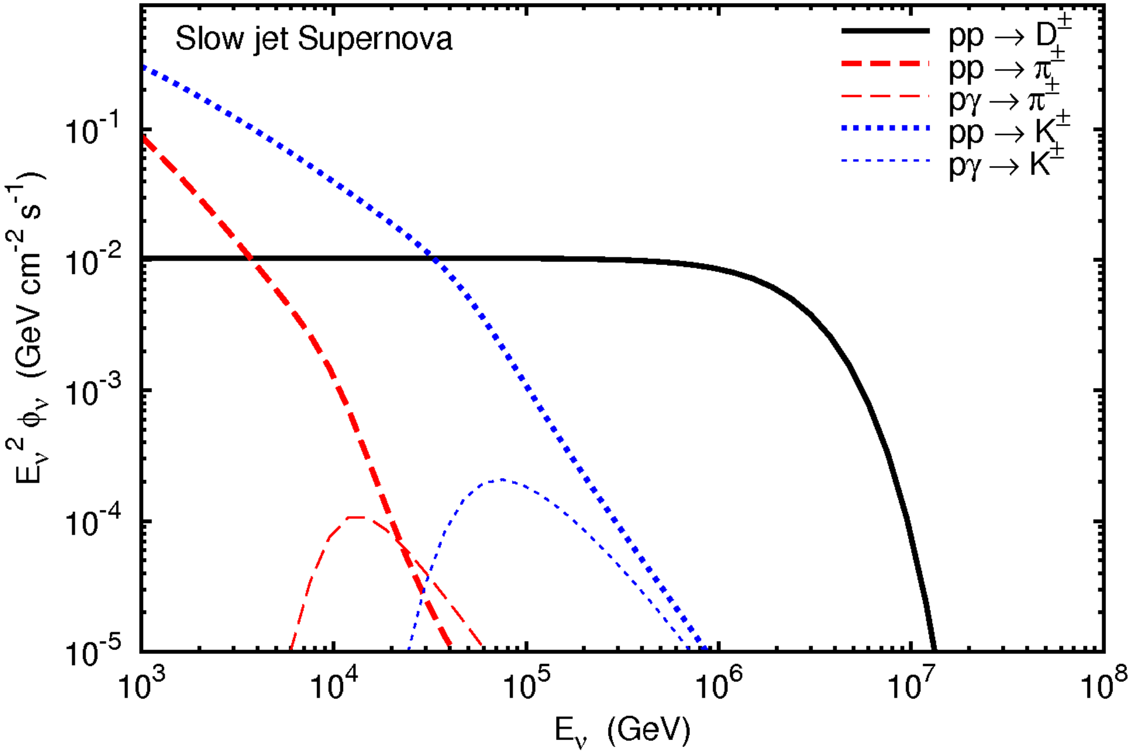
Observer frame neutrino flux

The normalization of the flux from a single source depends on the overall luminosity, jet opening angle, jet Lorentz factor, and the distance:

$$
\begin{aligned}
\phi_\nu(E) \quad &= \quad Z_{M\nu} \frac{L_M^{\mathrm{eff}}}{L_M^{\mathrm{dec}}(\ell_N^{\mathrm{had}} + \ell_N^{\gamma})} \\
&\times \quad (Z_{NM}\ell_N^{\gamma} + Z_{NM}^{\gamma}\ell_N^{\mathrm{had}}) \\
&\times \quad \frac{L_j\Gamma_j^2}{2\pi\theta_j^2 d_L^2 \ln(E'_{\mathrm{max}}/E'_{\mathrm{min}})} E^{-2}
\end{aligned}
$$

We choose $d_L = 20$ Mpc = 6×10^{25} cm (Virgo cluster)

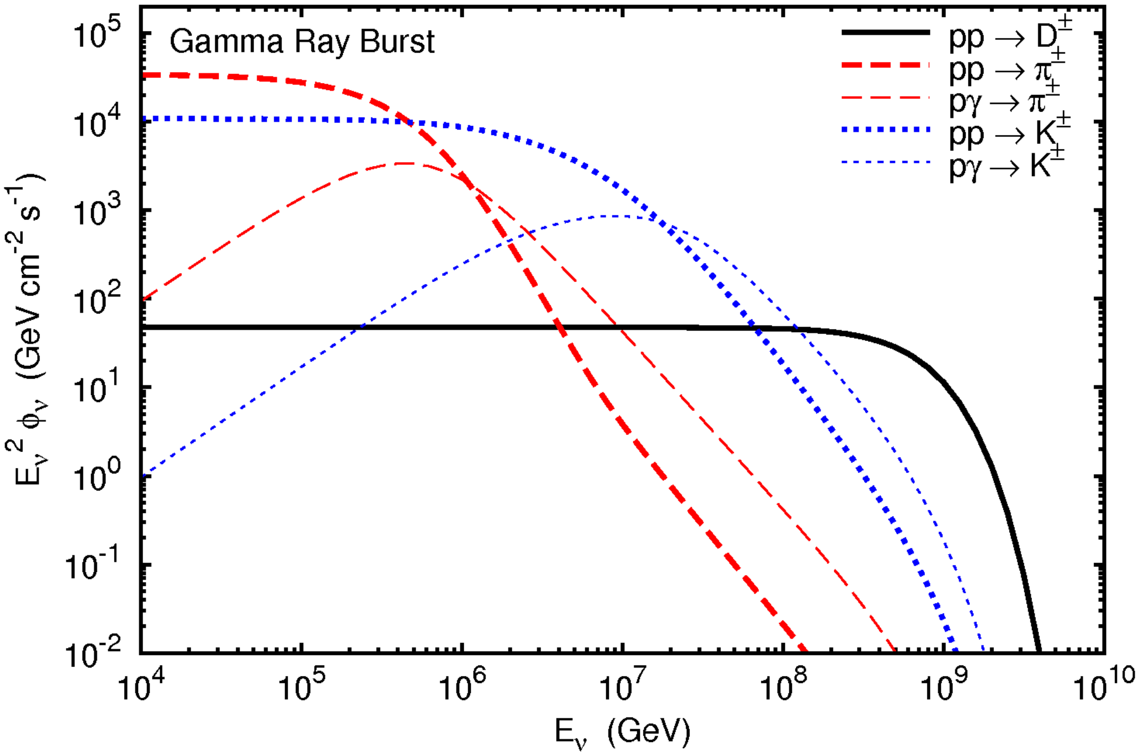
Neutrino flux from slow-jet SNe



[RE, M.H. Reno, I. Sarcevic, arXiv:0808.2807, in PRD]

- No cooling of D-mesons
- Fall-off is due to maximum proton energy
  (we use parameterization of Protheroe & Stanev, astro-ph/9808129)

Neutrino flux from GRB



[RE, M.H. Reno, I. Sarcevic, arXiv:0808.2807, in PRD]

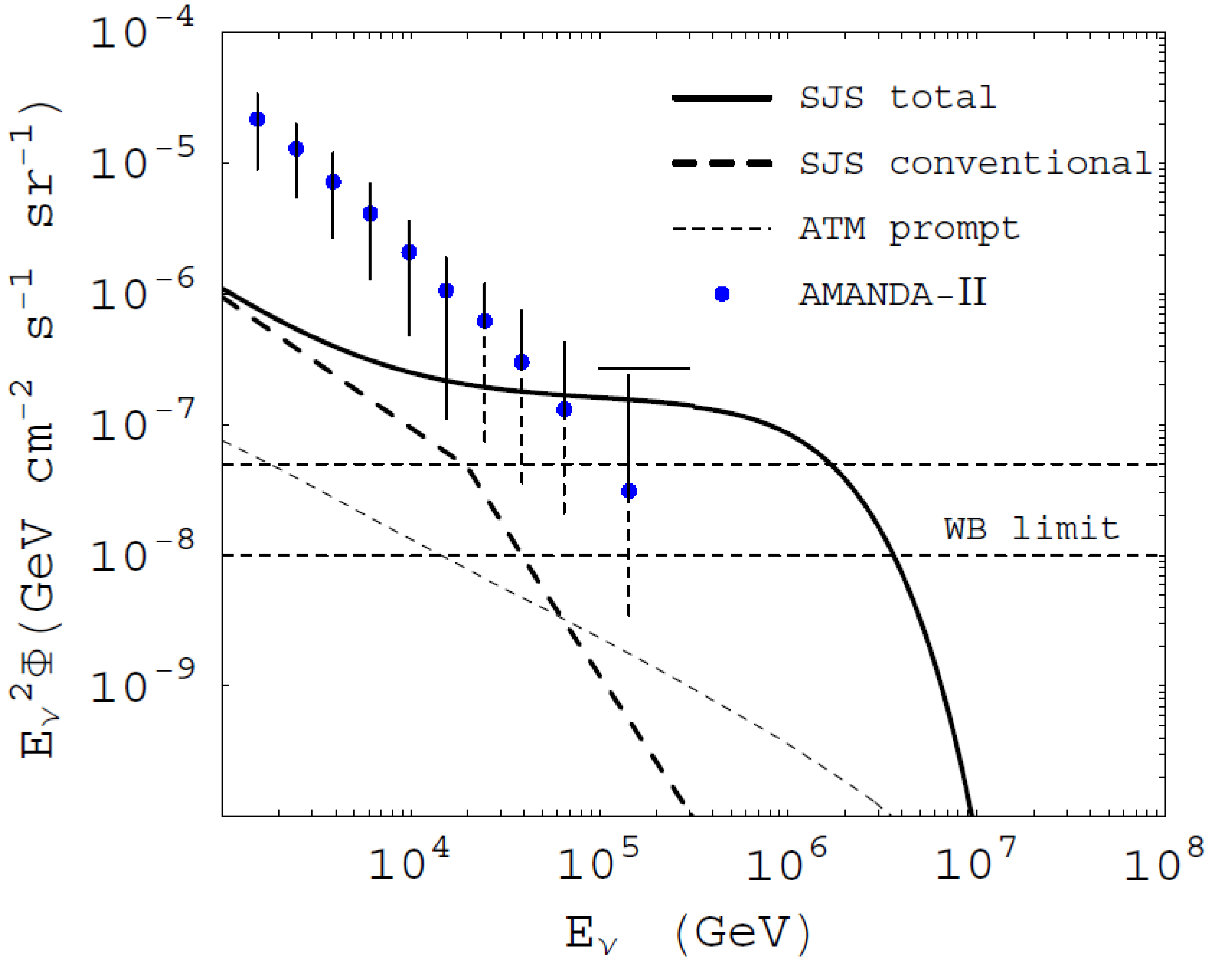
Next

- This was a simple model calculation to show feasibility

- Detection prospects. For SJS:
  Gandhi, Samanta & Watanabe, arXiv:0905.2483 (JCAP):
  Both diffuse flux and single source
  – IceCube are already looking for single GRBs

- More careful look at proton acceleration, cooling, source environment, different sources parameters, etc.

Diffuse flux ν_μ + anti-ν_μ



Gandhi, Samanta & Watanabe, arXiv:0905.2483 (JCAP)

Flavor ratios

- Pions lead to a 1:2:0 neutrino flavor ratio
- This is modified by oscillations to ~ 1:1:1
- D-mesons give an equal amount of ν_e and ν_μ
- Flavor ratios may be different at very high energy where charm dominates

[See also
Kachelriess & Tomas, astro-ph/0606406,
Gandhi, Samanta & Watanabe, arXiv:0905.2483]

What about microquasars?

- Microquasars are X-ray binaries with jets and mass transfer between the normal star and the compact object
- *Galactic* sources as opposed to GRBs:
  an estimated 100 of them in the Galaxy
- They may have the same processes for neutrino production as GRBs plus an additional process:

pp collisions between accelerated protons in the jet
and protons in the stellar wind from the companion star
– which may be very dense

Conclusions

- There can be a prompt neutrino flux of ultra-high energy neutrinos from astrophysical sources
- Harder energy dependence
- Details depend on properties of the source (baryon density, photon density, magnetic fields)
- If UHE neutrinos from astrophysical sources are seen, it tells us there are baryons in the jet

Backup slides

Protons and electrons

- The (comoving) density of protons and electrons in the jet is given by

$$n'_e = n'_p = \frac{L_j}{2\pi\theta_j^2 r_j^2 \Gamma_j^2 m_p c^3}$$

where L_j is the total jet power, Γ_j is the Lorentz factor and

$$r_j = 2\Gamma_j^2 c t_v$$

is the radius where the shock occurs

Photons and magnetic field

- The photon energy and number densities are

$$U'_\gamma = \frac{\epsilon_e L_j}{2\pi\theta_j^2 r_j^2 \Gamma_j^2 c} \qquad n'_\gamma = 2\zeta(3)\left(15^3/\pi^{14}\right)^{1/4}\left(\frac{U'_\gamma}{\hbar c}\right)^{3/4}$$

for thermal photons and $U'_\gamma = n'_\gamma E'_\gamma$ for non-thermal

- The magnetic field is

$$B' = \left[\frac{4\epsilon_B L_j}{\theta_j^2 r_j^2 \Gamma_j^2 c}\right]^{1/2}$$

Electromagnetic cooling & decay

- Synchrotron and Inverse Compton scattering are the two EM (radiative) cooling mechanisms:

$$t'_{\mathrm{syn},p} = \frac{6\pi m_p^4 c^3}{\sigma_T m_e^2 E'_p B'^2} \qquad t'_{IC,p} = \frac{3 m_p^4 c^3}{4\sigma_T m_e^2 E'_p U'_\gamma}$$

$$(t'_{\mathrm{rad},p})^{-1} = (t'_{\mathrm{syn},p})^{-1} + (t'_{IC,p})^{-1}$$

- Meson cooling times obtained by using meson mass
- Decay time scale is just $t'_{\mathrm{dec},M} = (E'_M / m_M c^2)\tau_M$
- Note that non-rel Thompson cross section is used for IC: this is OK because IC is irrelevant for higher energies when cooling time becomes very large

Hadronic cooling

- *pp* and *pγ* interactions as well as synchrotron and inverse Compton cool the accelerated protons
- Roughly, the cooling time scales are

$$t'_{p\gamma} = \frac{E'_p}{c\sigma_{p\gamma} n'_\gamma \Delta E'_p} \qquad t'_{pp} = \frac{E'_p}{c\sigma_{pp} n'_p \Delta E'_p}$$

- For photons,

$$\langle n'\sigma v\rangle = \frac{c}{8\beta'_p E'^2_p} \int dE'_\gamma \frac{\hat{n}_\gamma(E'_\gamma)}{E'^2_\gamma} \int ds(s - m_p^2)\sigma_{p\gamma}(s)$$

Z-moments

- Z-moments (spectrum-weighted moments) are defined as

$$Z_{kj} = \int_E^\infty dE' \, \frac{\phi_k(E')}{\phi_k(E)} \, \frac{\lambda_k^{\mathrm{had}}(E)}{\lambda_k^{\mathrm{had}}(E)} \, \frac{dn(k \to j; E', E)}{dE}$$

- Assume Feynman scaling, energy-independent cooling length, and power-law flux $\phi_N \sim E^{-\alpha}$:

$$Z_{NM} = \int_0^1 dx_E \, x_E^{\alpha-1} \frac{dn_{N \to M}}{dx_E}$$

where $x_E \equiv E_M / E_N$

Z-moments

- We calculate the Z-moments for charm production in the same way as we did for atmospheric charm

- For $pp \to \pi$ we use the parametrization (Costa et al)

$$\frac{dn_\pi}{dx_E} = 0.12 \frac{(1-x_E)^{2.6}}{x_E^2}$$

and for $p\gamma \to \pi$ we fit this form to HERA data. For kaons we rescale pions by 0.1.

The flux

The neutrino flux is proportional to the proton flux:

$$\phi_\nu(E') = Z_{M\nu} \frac{L_M^{\mathrm{eff}}}{L_M^{\mathrm{dec}}} \frac{Z_{NM}\ell_N^\gamma + Z_{NM}^\gamma \ell_N^{\mathrm{had}}}{\ell_N^{\mathrm{had}} + \ell_N^\gamma} \phi_N(E')$$

This is the flux in the frame comoving with the jet.

We are interested in the flux in the Earth frame.