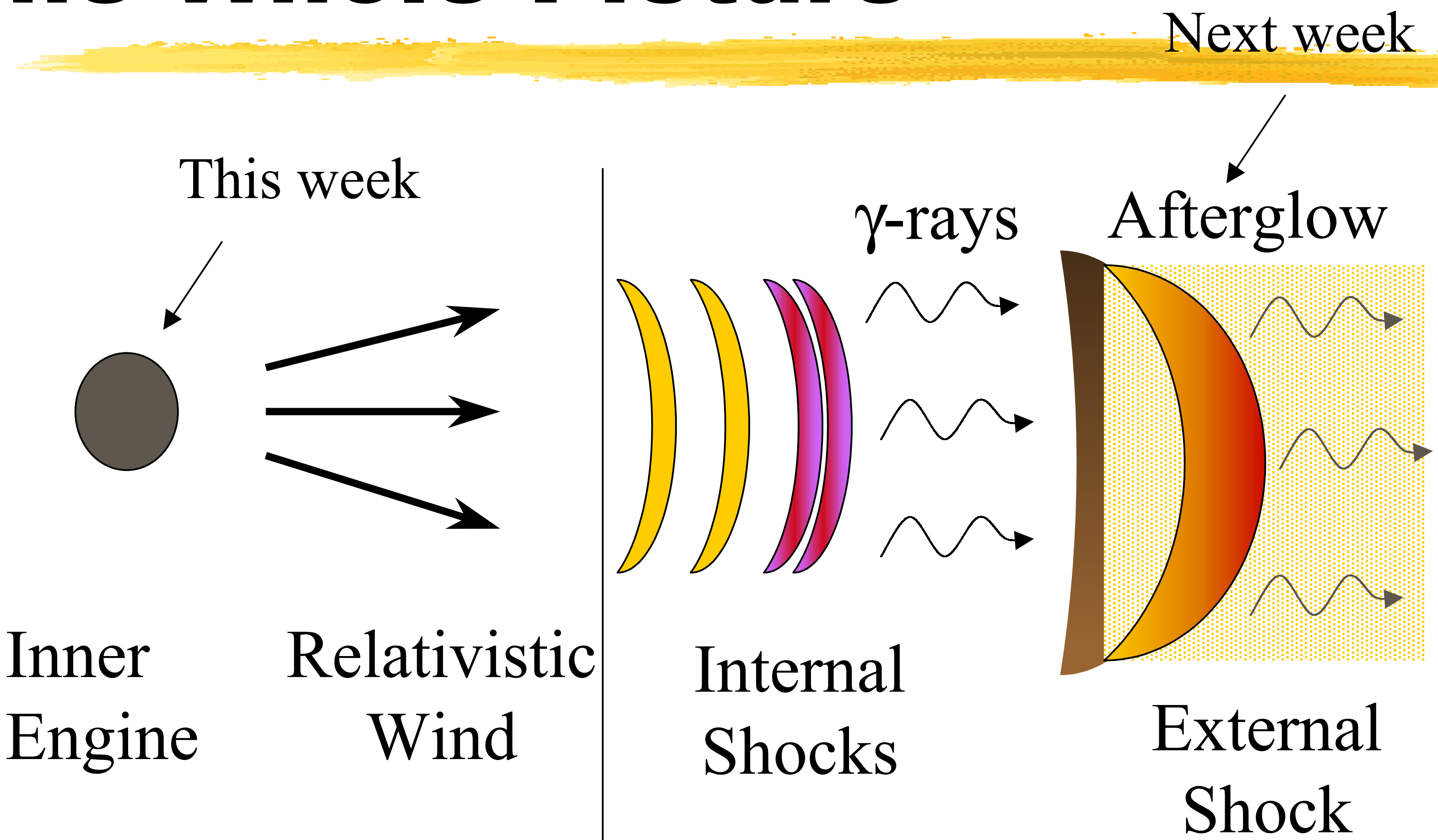
Understanding Cosmological GRBs

Central Engines!

The Whole Picture



We don't see this.

We see this.

Collapsars v. Binary Neutron Stars

- Collapsars are supernovae that produce black holes:
  - Associated with young stellar populations
  - Rate proportional to star-formation rate and fraction of really massive stars
- Binary neutron stars
  - Can be billions of years old
  - Rate proportional to star formation with a lag, plus binary fraction and evolution

Collapsars

- Stars that ultimately form black holes have initial masses greater than twenty times that of the sun.
- These stars live only a few million years so the GRB occurs in a star forming region.
- Only in galaxies with star formation (most likely spiral)

Binary Neutron Stars

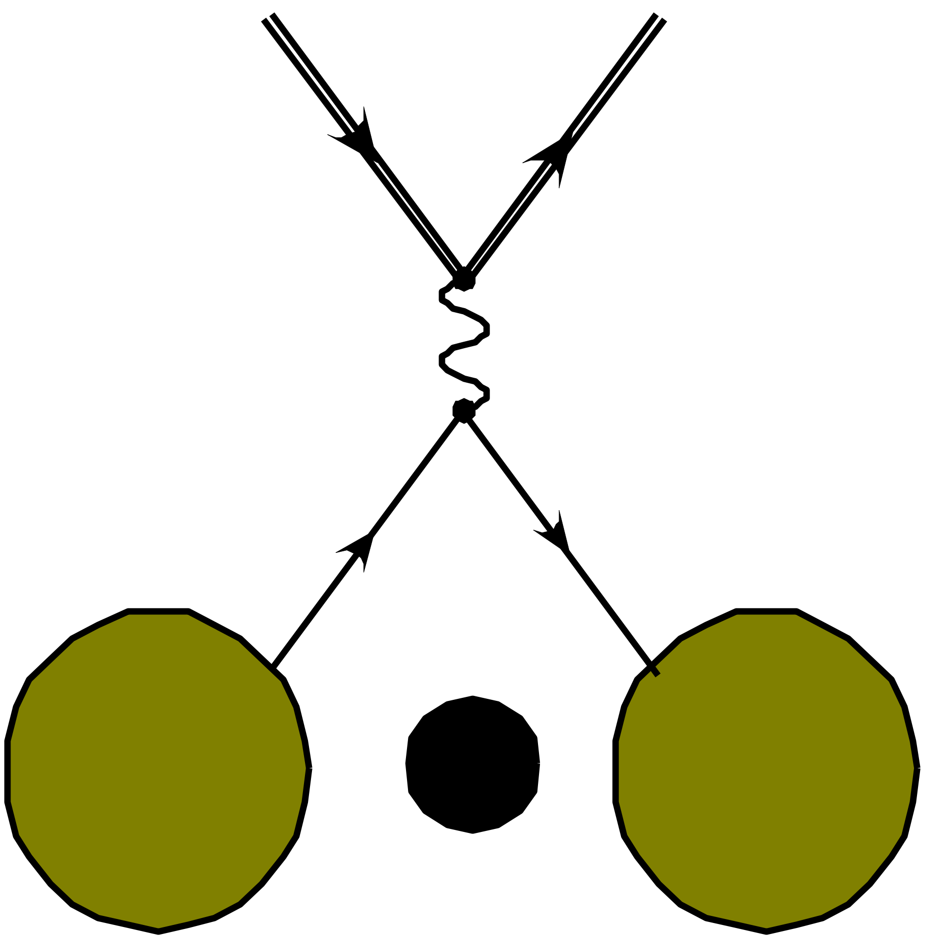
- Binary neutron stars may take billions of years to merge after the initial formation of the binary.
- The GRB itself may take place in a star-formation region or faraway from the disk of the galaxy.
- Could happen in any galaxy.

Basic Feature

- Either way you end up with a massive accretion disk (several tenths to several solar masses) at near nuclear density.
- The accretion exceeds the Eddington rate by many orders of magnitude so how do you get a baryon-free wind?
- What does baryon-free mean?
  - Remember we needed $\Gamma \sim 100$ and $E \sim 10^{51}$ erg
  - $E \sim \Gamma m c^2$ so $m \sim 10^{28}$ g $\approx 2 M_{\oplus}$

Neutrino Production/Annihilation (1)

- Carry the energy away with weakly interacting particles.
- For the double neutron star photons can do it.
- In the center of a star only neutrinos can drive a polar outflow.

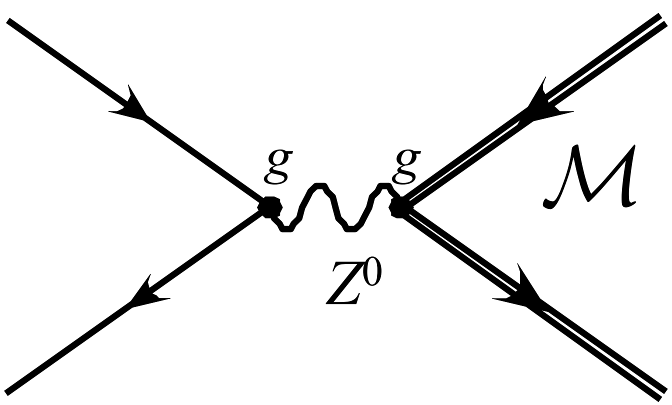


Neutrino Production/Annihilation (2)

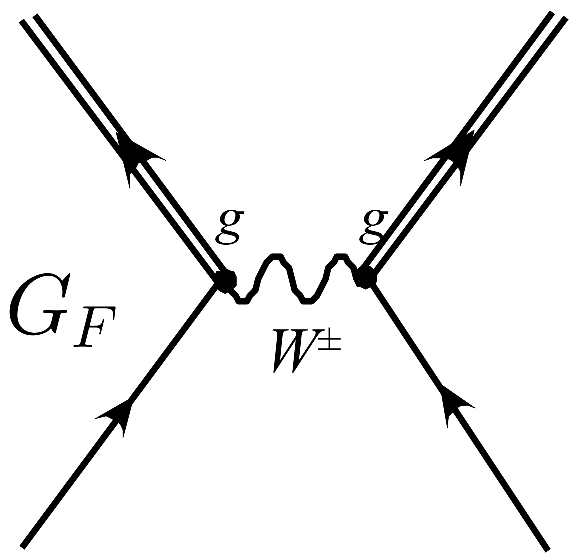
- Two neutrinos annihilate and form a high-energy electron-positron pair.
- The only place that this can occur is in the polar region where you get neutrinos with perpendicular momenta.
- The pairs shoot upward and produce the gamma-ray burst several hours later through internal shocks.

Neutrino Production/Annihilation (3)

- Does this hold water?
  - Is the neutrino cross-section large enough?
  - Is the jet powerful enough to rip through the rest of the star in the collapsar model?
- Cross-section: $\nu + \nu \Rightarrow e + e$



$$\mathcal{M} \sim \frac{g^2}{M_W^2} \sim G_F$$



Neutrino Production/Annihilation (4)

- We want the neutrinos to produce pairs in a few-kilometer region near the pole of the black hole.
- Cross-sections have dimensions of area (or mass^{-2}) and are proportional to M^2 so we have

$$\sigma \sim E^2|\mathcal{M}|^2 \approx G_F E^2 \approx 10^{-10} E^2 \mathrm{GeV}^{-4} = 4 \times 10^{-38} E^2 \mathrm{cm}^2 \mathrm{GeV}^{-2}$$

$$\tau = \sigma n l \approx \sigma \frac{E_{\mathrm{burst}}}{E_\nu l^3} l = 2 \times 10^4 E_{51} l_6^{-2} E_\nu \mathrm{GeV}^{-1} > 11 \Gamma E_{51} l_6^{-2}$$

$$\text{where } \Gamma \equiv E_\nu / m_e c^2$$

Neutrino Production/Annihilation (5)

- For this to work the effective temperature of the inner edge of the disk must exceed 511 keV (really 511 Γ keV) otherwise the photons or neutrinos will not produce hot enough pairs.
- Hmmm, if we only knew the effective temperature of an accretion disk, we could figure out the mass accretion rate.

Neutrino Production/Annihilation (6)

- Let's assume that the Stefan-Boltzman rule works for neutrinos.

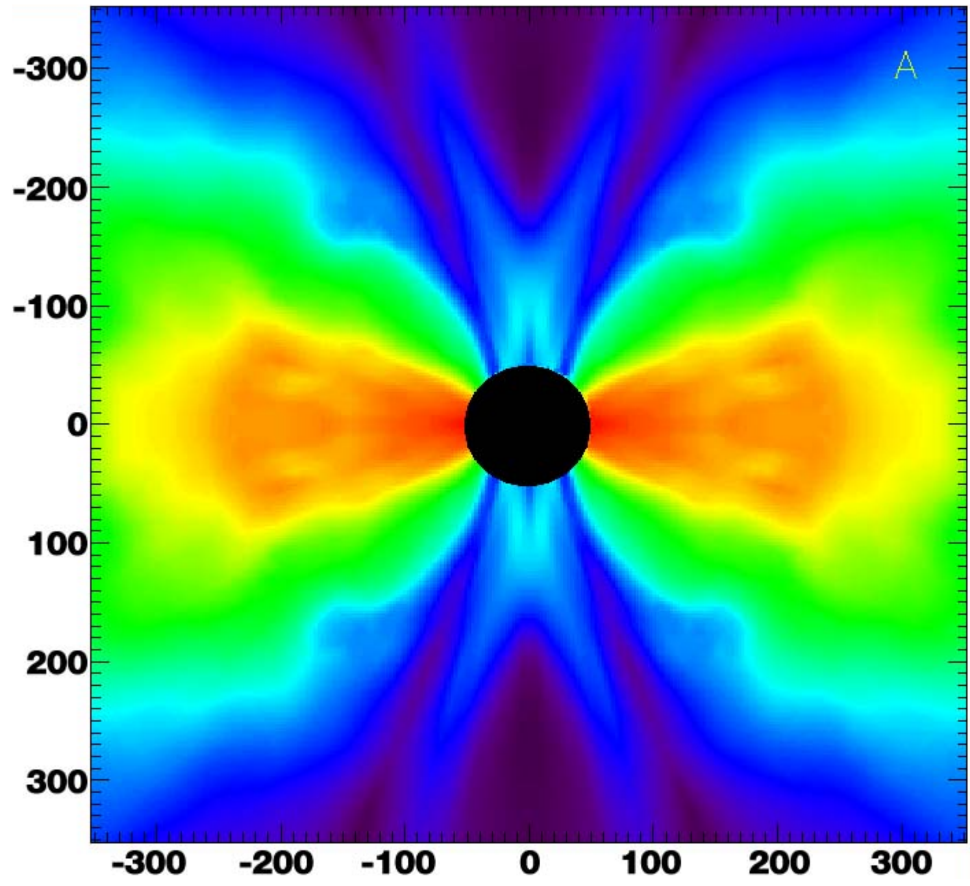
$$\sigma T^4 = F(r) = \frac{1}{2} \times 2h\dot{Q} = \frac{3\dot{M}}{8\pi r^2} \frac{GM}{r} \left[1 - \beta \left(\frac{r_I}{r} \right)^{1/2} \right]$$

$$\dot{M} \approx \sigma T^4 \frac{8\pi r^3}{3GM} \approx 576\pi \frac{\sigma T^4 G^2 M^2}{c^6} \sim 10^{-6} \Gamma^4 \left(\frac{M}{\mathrm{M}_\odot} \right)^2 \frac{\mathrm{M}_\odot}{\mathrm{s}}$$

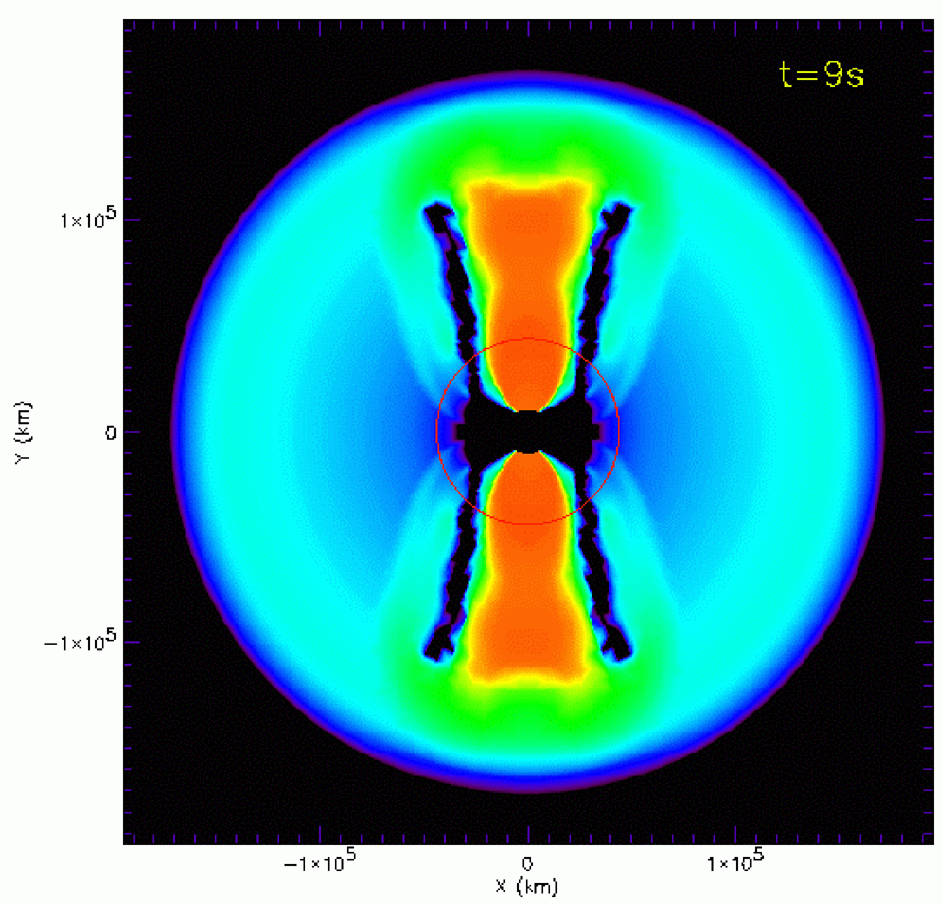
- There is also a neutrino Eddington limit for the luminosity.

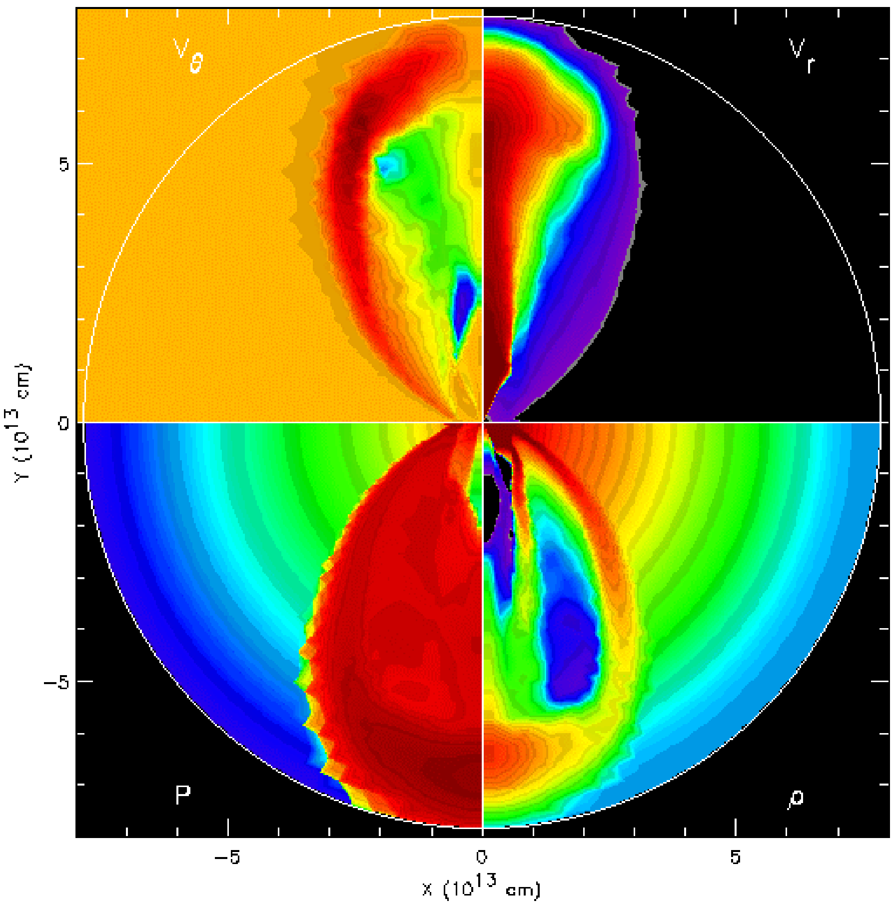
The Heart of a Collapsar

- Once this jet of material is launched from the accretion disk it has to pierce through the rest of the star.
- How the jet is launched is still not well understand but we almost always see jets in other accreting systems.



Piercing the star





Key Points

- Only a small fraction of the rest-mass energy of the material falling into the central black hole ends up in jet.
- The jet is relatively narrow so this energy is concentrated into a fraction of sky.
- A jet doesn't know it's a jet unless its opening angle is greater than $1/\Gamma$.

Relativistic Jets

- How fast does the head of the jet go?

$$\beta = 1 - 1/(2\Gamma^2)$$

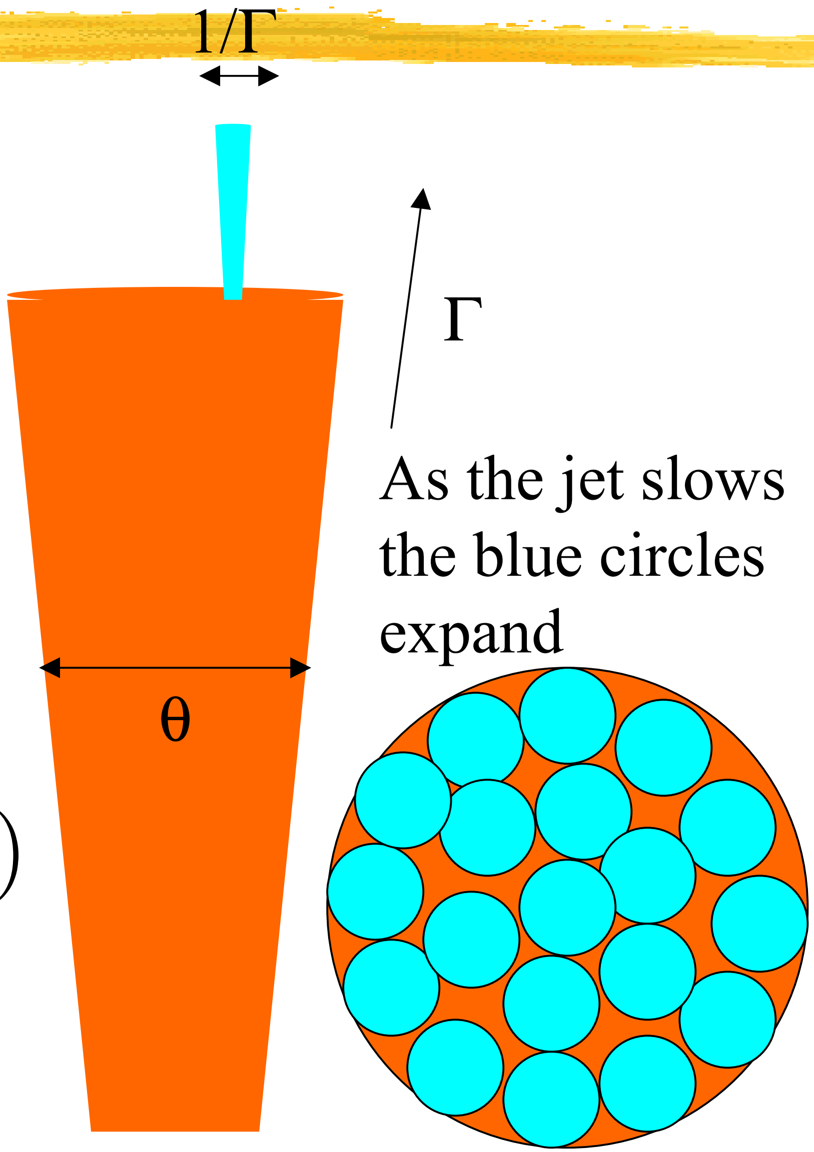
- How fast does the jet expand sideways?

$$\theta\beta = \theta(1 - 1/(2\Gamma^2))$$

- Switch to the frame of the head of the jet.

$$\Gamma\theta\beta = \Gamma\theta(1 - 1/(2\Gamma^2))$$

- If $\theta > \Gamma^{-1}$, light from the edge of the jet cannot reach the center.



Alternative: $n^* + n^* \Rightarrow$ GRB

- The collapsar model seems to work. Why another model?
- Axiom in astrophysics:
  - If it can happen, it will happen. You just don't know how often.
- Look in our own Galaxy.

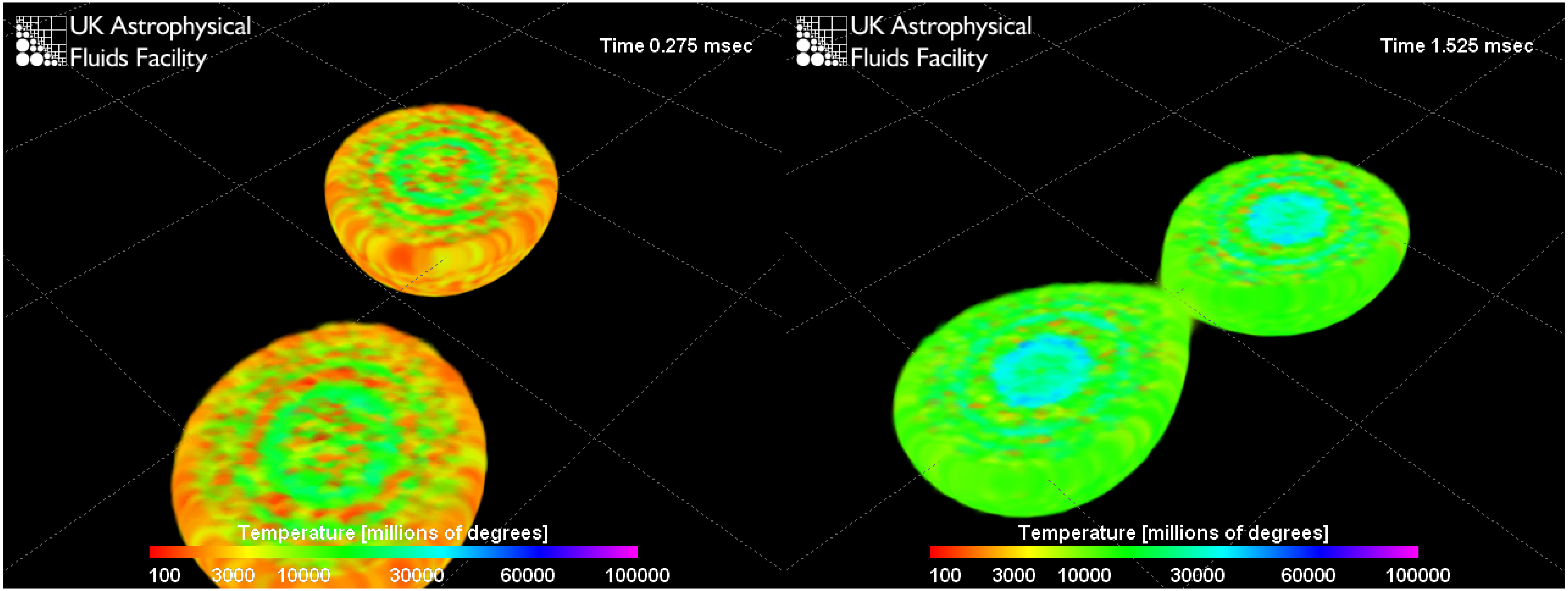
Some Binary Pulsars

Name	Orbital Period (hr)	Our t_f (Myr)	Careful t_f (Myr)
B1913+16	7.75	1600	320
B1534+12	10.1	3400	2900
J0757-3039	2.4	72	85

What might go wrong?

- In about 85 Myr two neutron stars will merge in our Galaxy. There are more than 85 x 10^6 x 365 galaxies in the universe so this may explain the GRB rate.
- But will it produce a gamma-ray burst?
  - The neutron stars could turn into black holes before they merge.
  - There might not be enough material in the accretion disk to fuel the burst

Merging Neutron Stars (1)



Merging Neutron Stars (2)