Astrophysical Timescales

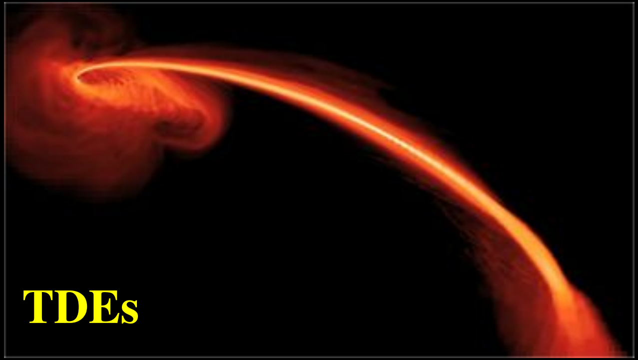
The Universe is Transient

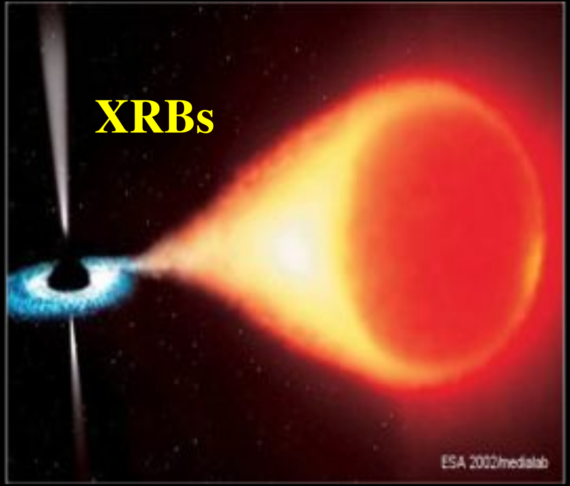
Credit: NASA; Gezari & Guillochon

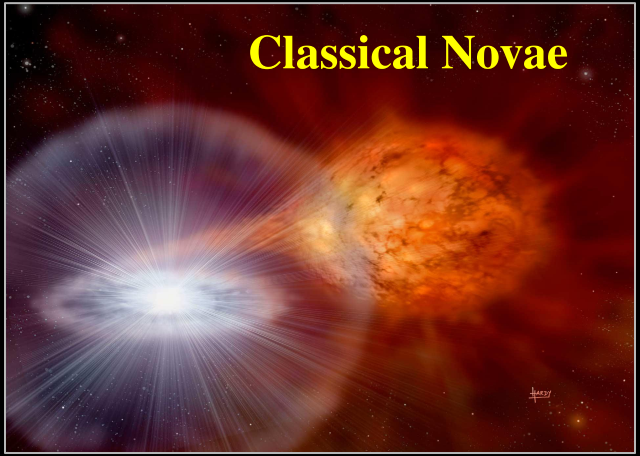

AGN

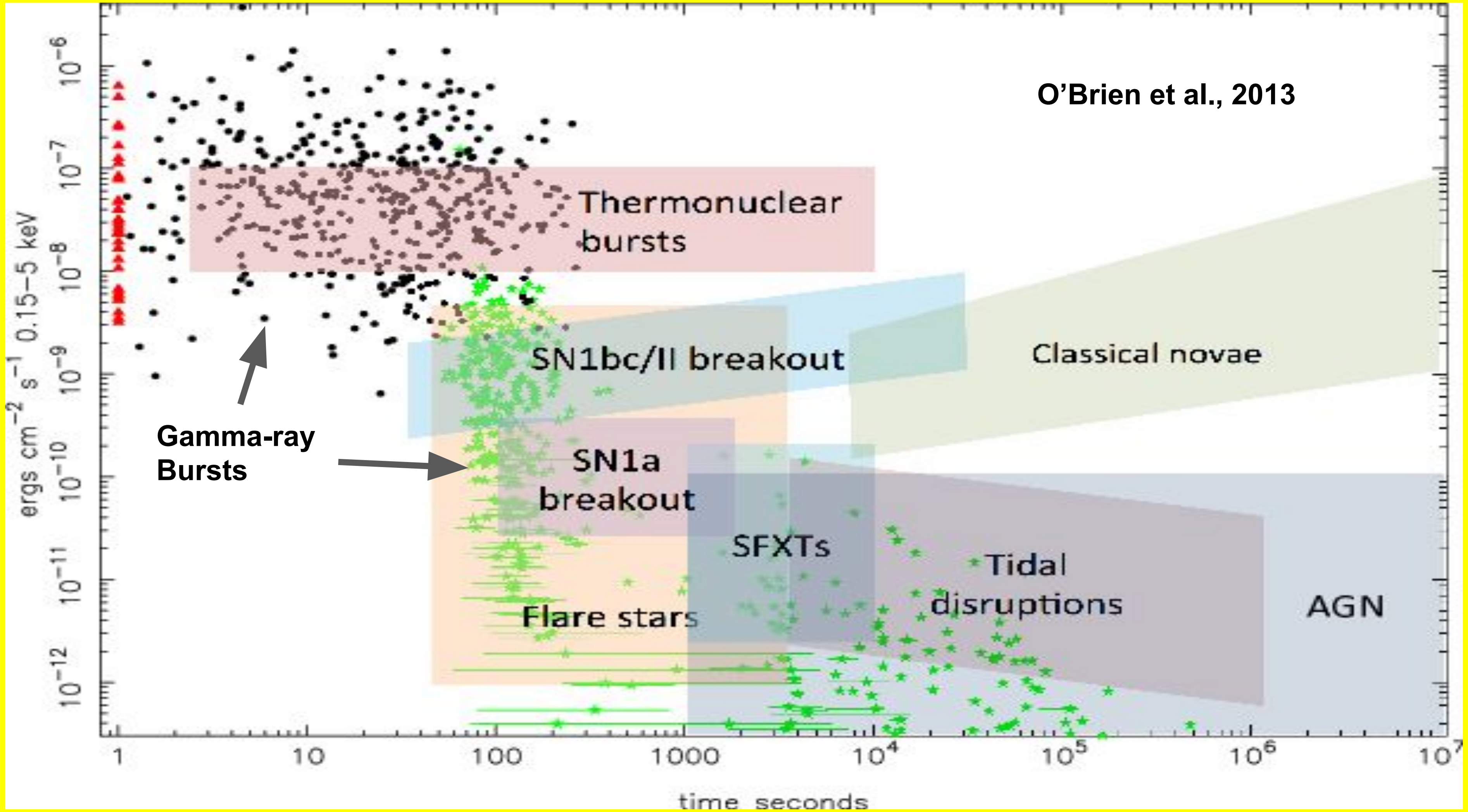

GRBs


Supernovae


TDEs


XRBs
ESA 2002/medialab


Classical Novae

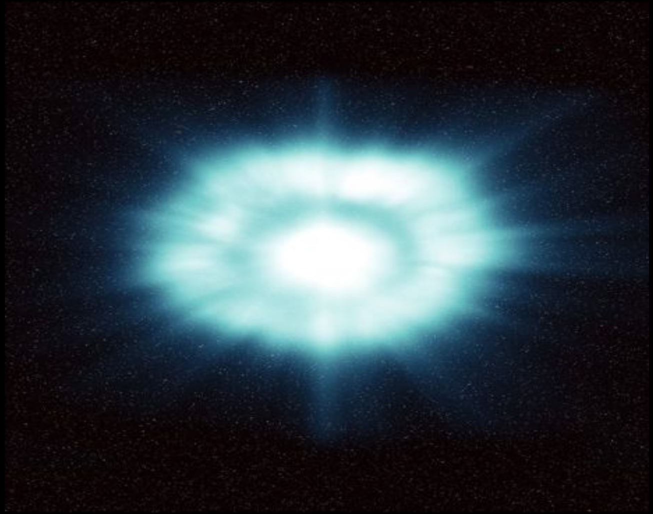


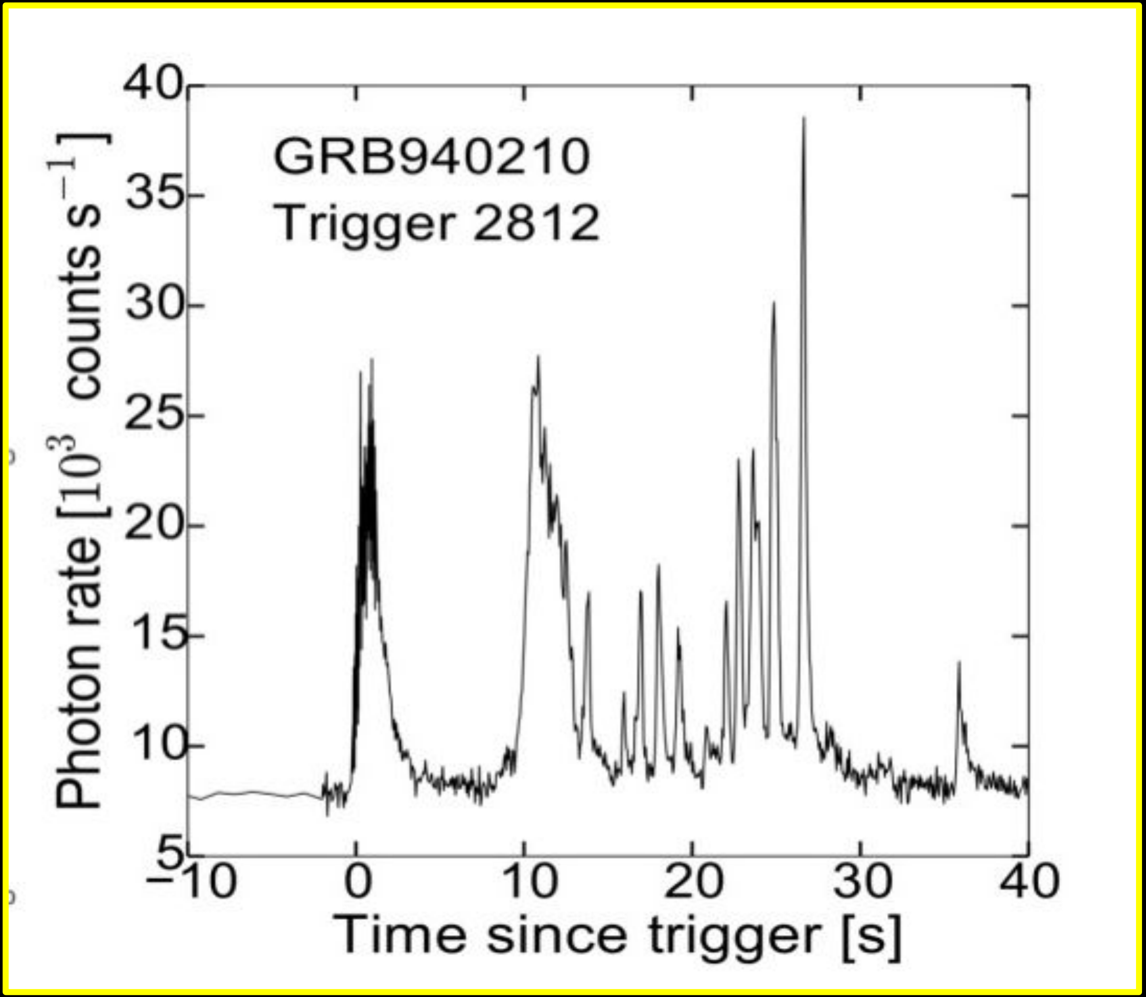
O'Brien et al., 2013
Thermonuclear bursts
SN1bc/II breakout
Classical novae
SN1a breakout
SFXTs
Tidal disruptions
AGN
Flare stars
Gamma-ray Bursts
ergs cm^{-2} s^{-1} 0.15–5 keV
time seconds
1
10
100
1000
10^4
10^5
10^6
10^7
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}

How do we use these timescales to learn what is going on with the physics of these objects?

How can we use their variability to learn what they are?

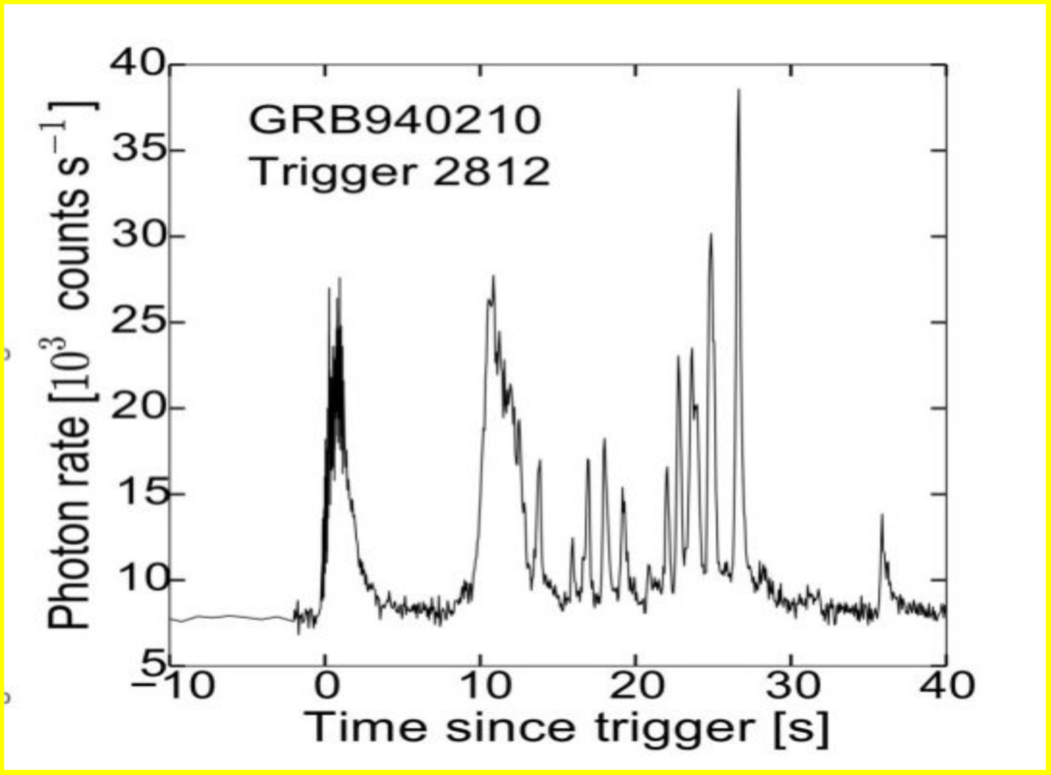
Gamma-ray Burst





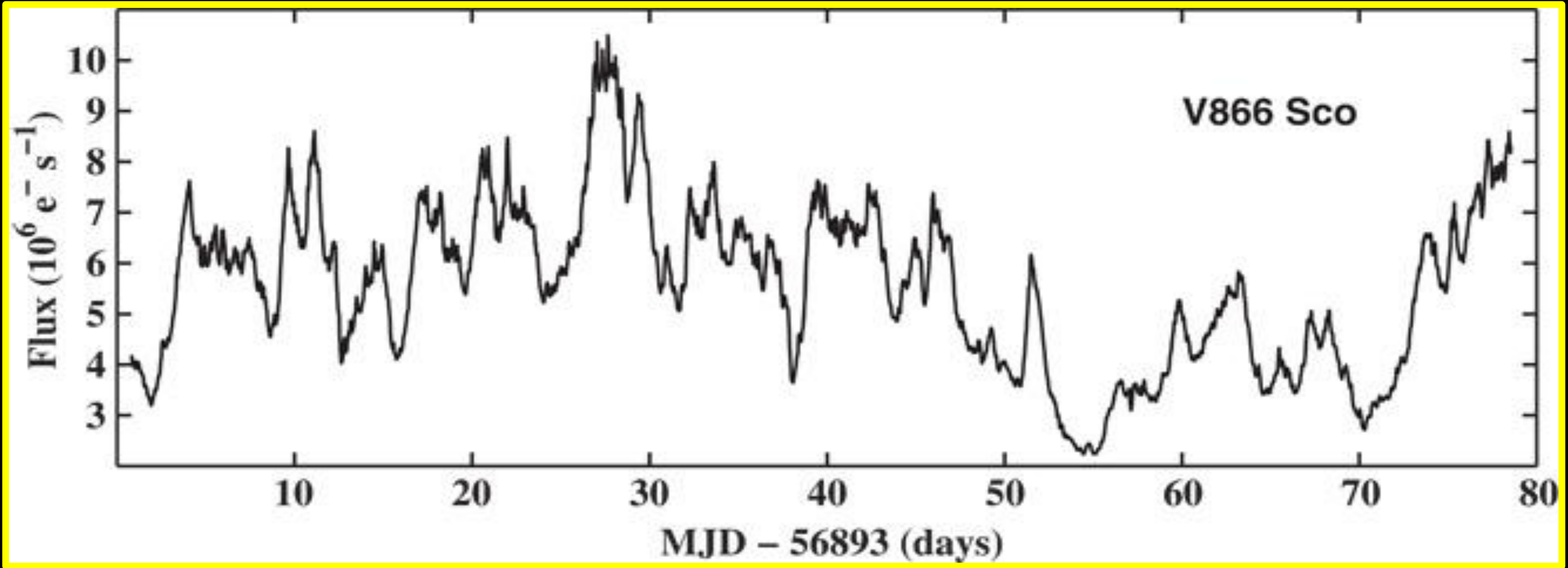
Light Crossing Timescale

$$t_{LC} \sim R/c$$



Relativistic corrections later.

Compare to AGN variability ~ days



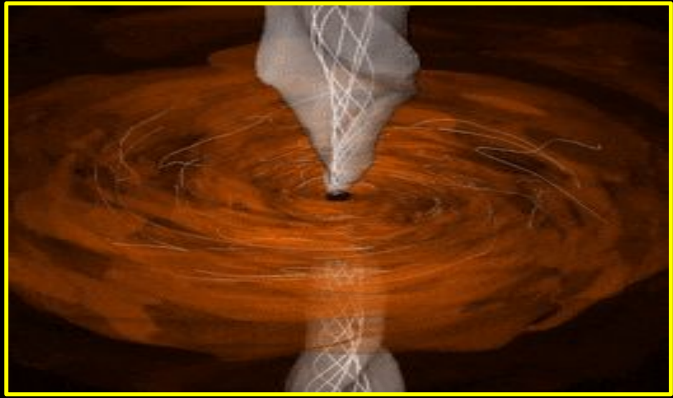
What is the mass of a Schwarzschild black hole ($R=2GM/c^2$) corresponding to $R = t_{var}c$?

Free Fall (dynamical) Time

$$t_{ff} \sim (2R^3/GM)^{½}$$

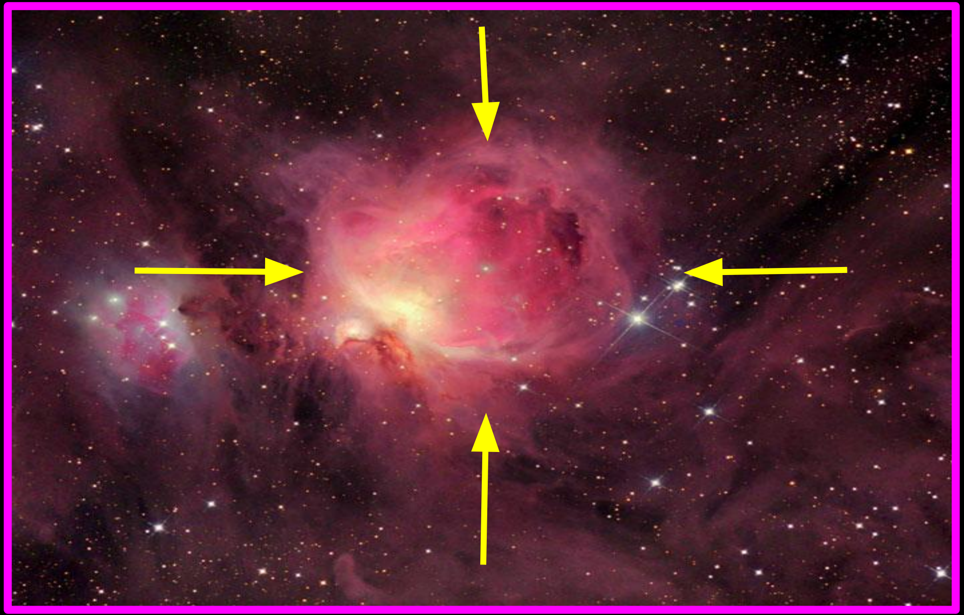
Keplerian Time

$$t_{circ} \sim (2\pi R^3/GM)^{½}$$



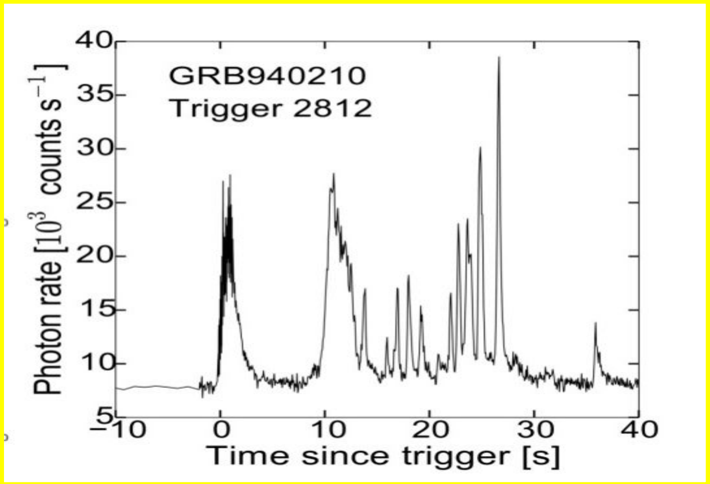
Exercise 1:

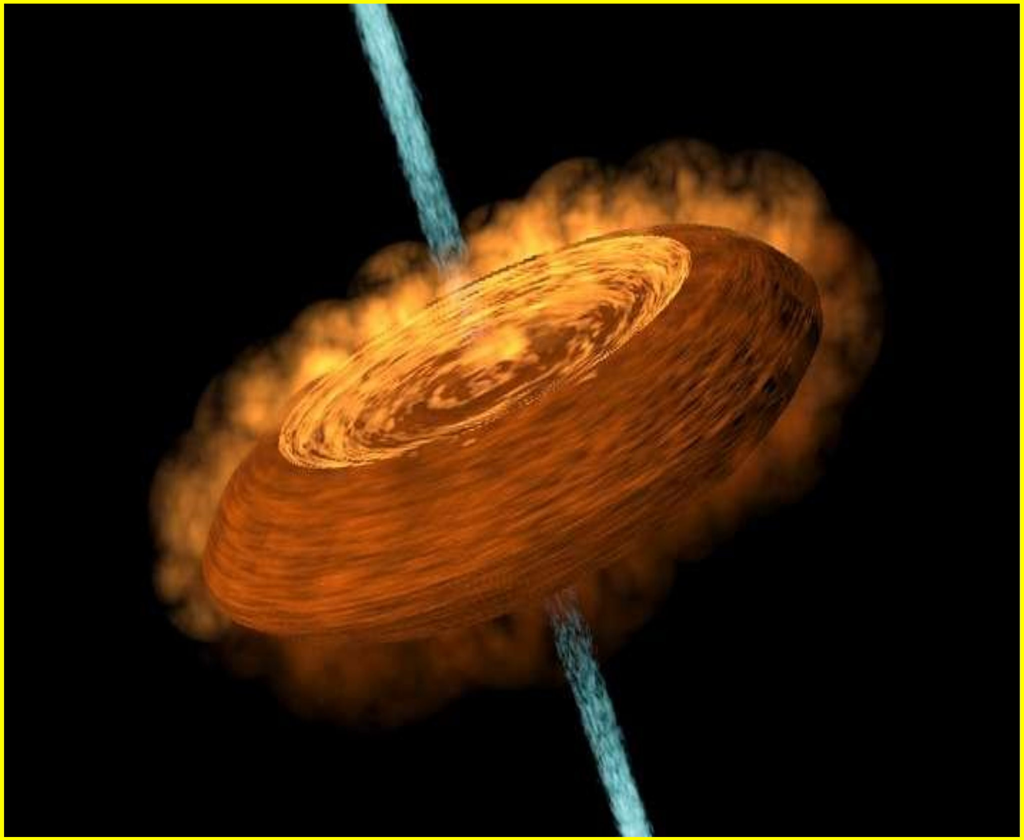
- What is the characteristic timescale for star formation if only gravity matters? Assume the density of a molecular cloud is ~ 10^{-19}g/cm^3 ? Is this consistent with observations?



Accretion Timescale - life of the inner engine

$$t_{acc} \sim (M/\dot{M})$$





Exercise 2:

- If a 20 solar mass star collapses and makes a 5 solar mass black hole, and we observe the central engine to be active for 20s, what is the accretion rate?

- How does this compare to the Eddington accretion rate?

Eddington Accretion:

- Radiation force balances gravity:

$$(\sigma_T/4\pi R^2)(L_{Edd}/c) = GMm_p/R^2$$

- $L_{Edd} = 4\pi GcMm_p/\sigma_T = \dot{M}_{Edd}c^2$

Exercise 3:

- What is the lifetime of a disk for a 10^9 solar mass black hole accreting at the Eddington rate (you'll need to make an assumption about the mass in the disk)?

Exercise 4:

- Compare the free fall time and light crossing time for a Schwarzschild black hole ($R = 2GM/c^2$) of mass M.

Radiative Timescale

$$t_{rad} = \text{Energy/Power}$$

$$\sim (\gamma m_e c^2)/(\sigma_T B^2 c \gamma^2) = m_e c/\sigma_T B^2 \gamma$$

Synchrotron
Radiation

Electron energy

Acceleration Timescale

$(\Delta p/\Delta t)\ r \sim E$ (work done on particle)

$t_{acc} \sim \Delta p\ r/\ E \sim cR/(v_A)^2$

(Alfven Turbulence, e.g.)

Exercise 5:

- Electrons are accelerated in the presence of a magnetic field B ~ 10 G, on a timescale 10^{-10}s. What is the maximum energy (or Lorentz factor) to which they can be accelerated?

But wait!

I want to simulate my astrophysical outflow. How do I describe my outflow? Is it a fluid? Is it a plasma?

Collision Timescale

$t_{coll} = \lambda/v = (1/n\sigma_T)/v$

Mean free path

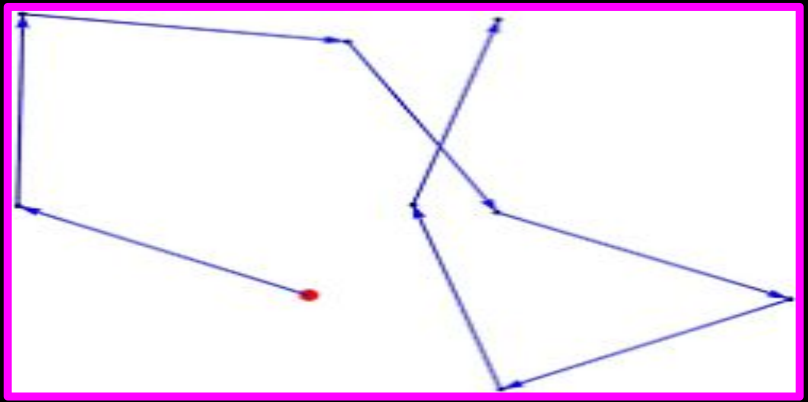
Diffusion Timescale

$$t_{diff} = Nt_{coll} = (L/\lambda)^2(\lambda/v) = L^2/\underline{\lambda v}$$

Random Walk

Size of system

Diffusion Coefficient (m^2/s)



Exercise 6:

- Compute the time for photons to diffuse out of the sun.

Viscous Timescale

$$t_{visc} = L^2/\nu$$

Viscosity (cm^2/s)

Timescale for evolution in a disk. What is the viscosity?

Exercise 7:

A typical (AGN) accretion disk has $R=10^{16}$cm, $T=10^4$K and $n \sim 10^{16}\text{cm}^{-3}$. The kinematic viscosity is $\nu = v_T\lambda$, where v_T is the thermal velocity $v_T \sim (kT/m)^{1/2}$ and λ is the mean free path ($\sim 10^{-3}$ cm for an ionized gas with this density and temperature - or you can make your own estimate!).

What is the viscous timescale for this accretion disk?

Is this a reasonable way to transport angular momentum and accrete?

Exercise 8:

Write down the viscous timescale for an alpha-disk:

- $\nu = \alpha c_s h$,
- $c_s = h\Omega$, $\Omega = (GM/R^3)^{½}$

Is this a better way to transport angular momentum? What is α?

Plasma Timescales

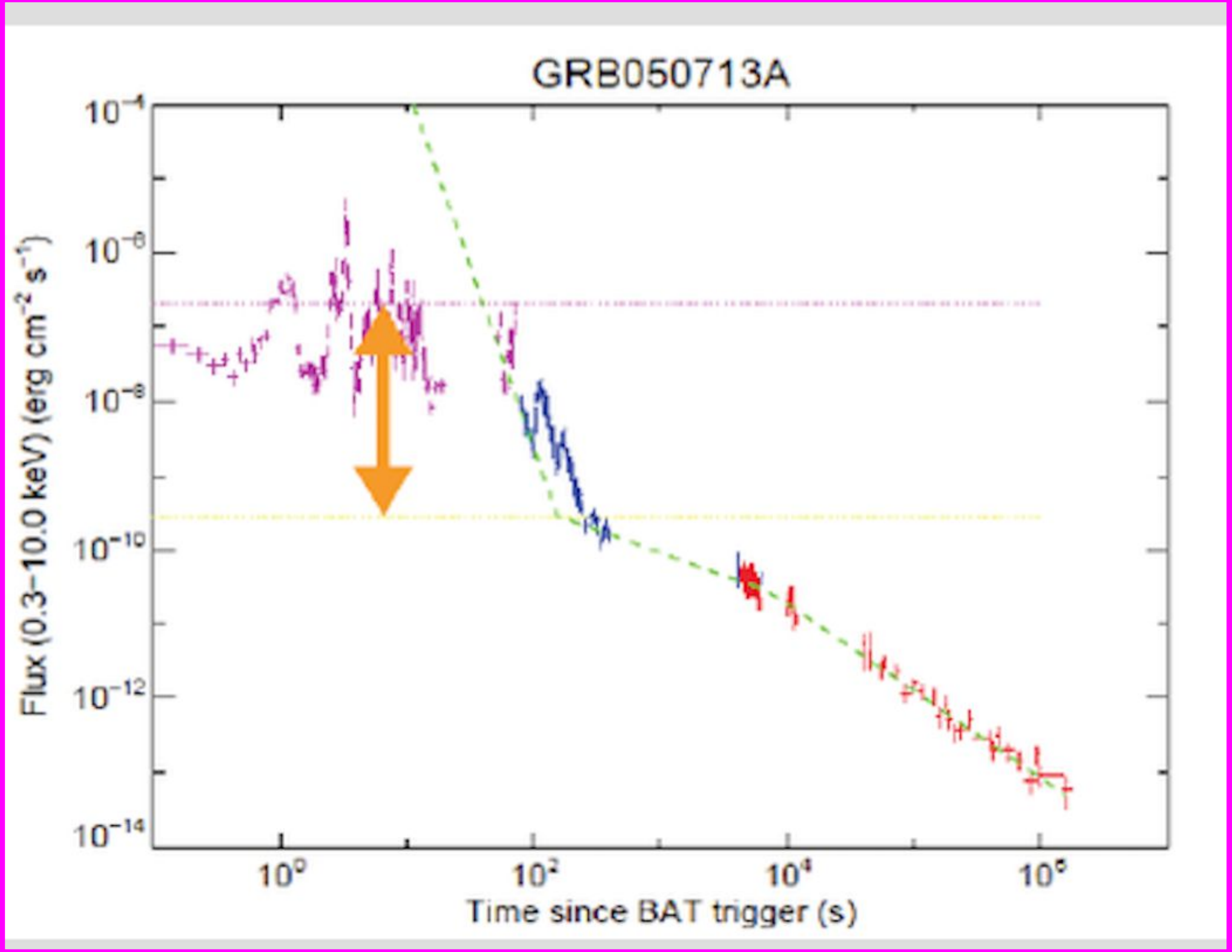
$$t_{plas} = \omega_p^{-1} = (m_*/4\pi n_* q^2)^{½}$$

$$t_{gyro} = \omega_g^{-1} = (m_* c/qB)$$

$$t_{Coulomb} = \omega_c^{-1} = (T^{3/2}\,10^6)/(n_* \ln\Lambda\ )$$

Onset of a GRB afterglow:

$$e=\Gamma^2 n m_p c^2$$



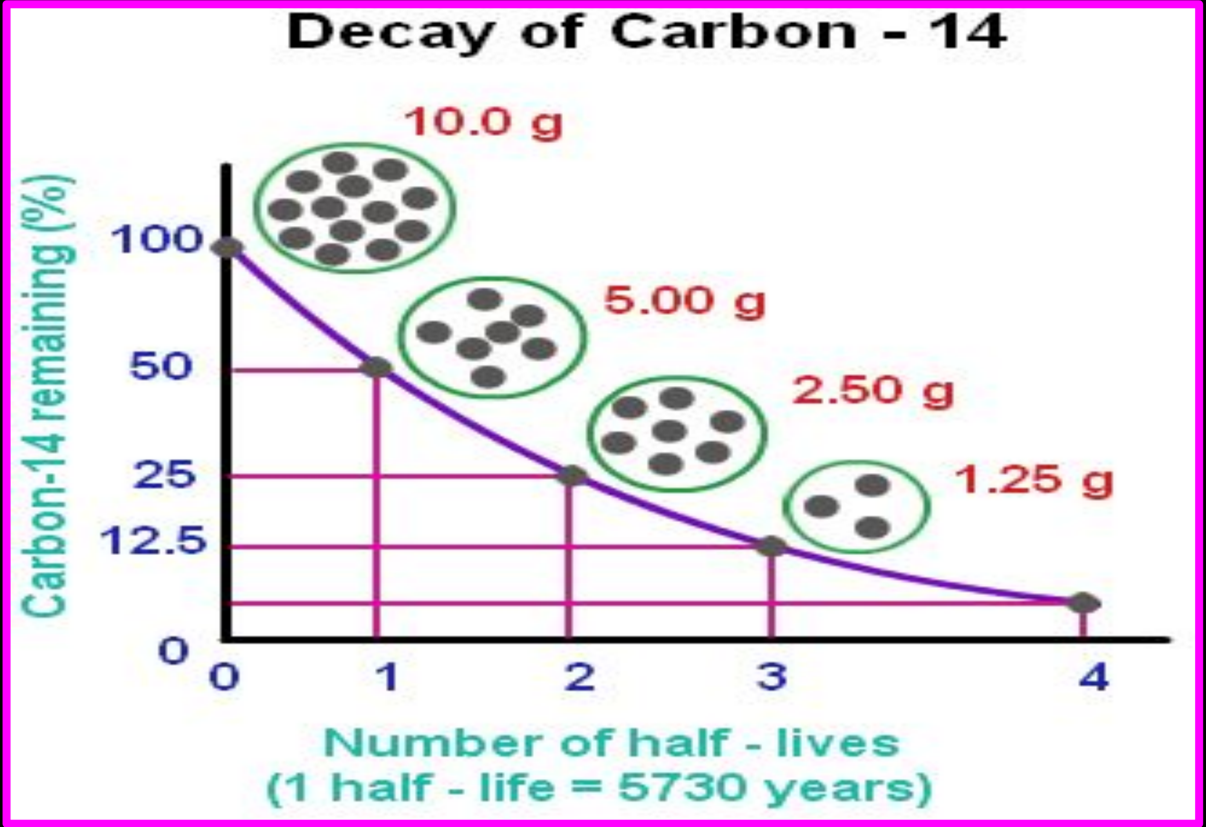
Deceleration Timescale

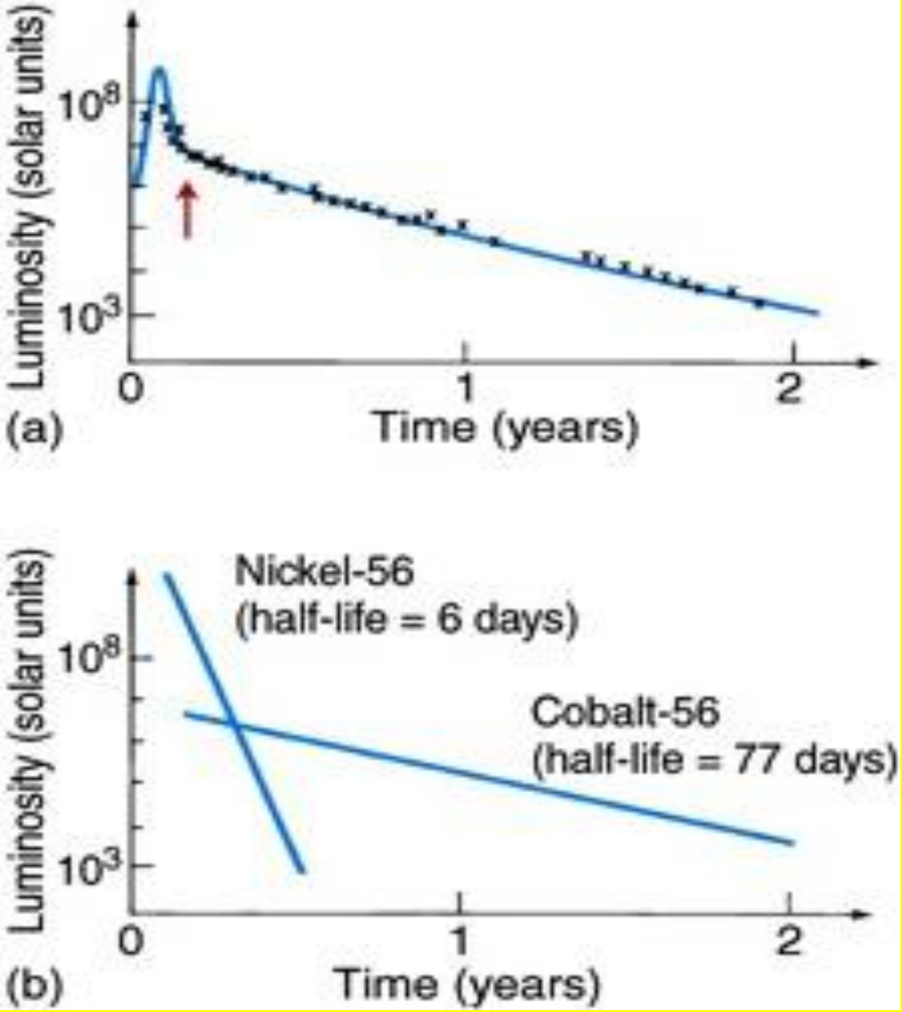
$$t_{dec} \sim (E/n)^{1/3} (\Gamma^8 c^5 m_p{}^2)^{-1/3}$$

Radial and Angular Timescales (relativistic corrections):

$t_r \sim R/(2c\Gamma^2)$

Radioactive Decay Time





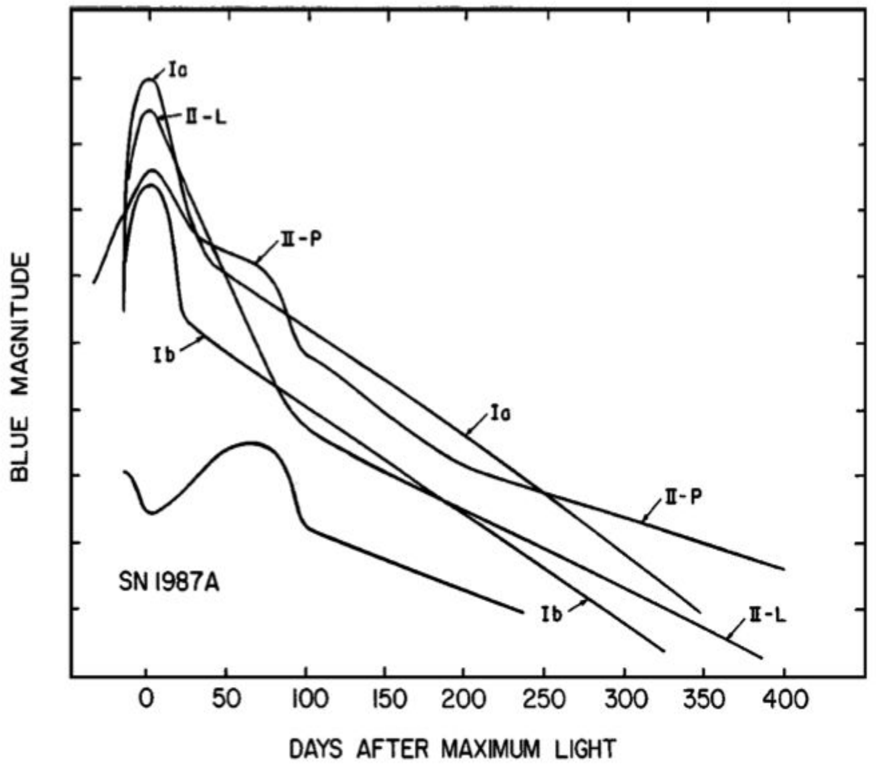
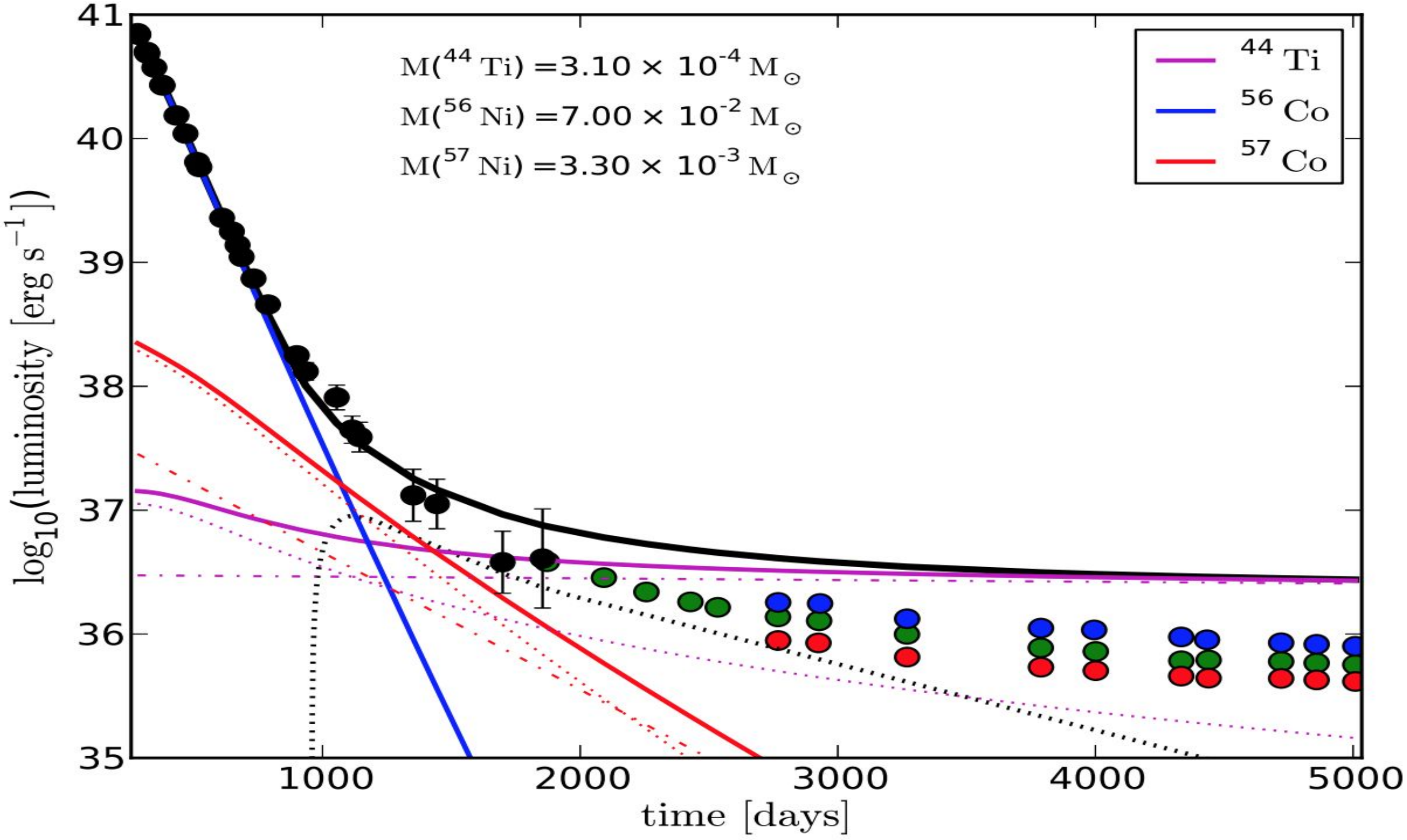


Figure 3 Schematic light curves for SNe of Types Ia, Ib, II-L, II-P, and SN 1987A. The curve for SNe Ib includes SNe Ic as well, and represents an average. For SNe II-L, SNe 1979C and 1980K are used, but these might be unusually luminous.

Figure Credit: Wheeler, J. C., & Harkness, R. P. 1990, RPPh, 53, 1467



M(^{44} Ti) =3.10 × 10^{-4} M$_\odot$
M(^{56} Ni) =7.00 × 10^{-2} M$_\odot$
M(^{57} Ni) =3.30 × 10^{-3} M$_\odot$
^{44} Ti
^{56} Co
^{57} Co
log$_{10}$(luminosity [erg s^{-1}])
time [days]
41
40
39
38
37
36
35
1000
2000
3000
4000
5000

Answers to Exercises:

Exercise 1:

- What is the characteristic timescale for star formation if only gravity matters? Assume the density of a molecular cloud is ~ 10^{-19}g/cm^3 ? Is this consistent with observations?

- Answer is free fall time ~ 2,700s/sqrt(ρ) = 10 Myr. But the peak of star formation is around 1 Gyr.
- => Star formation inefficient!

Exercise 2:

- If a 20 solar mass star collapses and makes a 5 solar mass black hole, and we observe the central engine to be active for 20s, what is the accretion rate?

  - 20s ~ mass of the disk/accretion rate => accretion rate ~ 0.5 solar masses/second

- How does this compare to the Eddington accretion rate?

  - Mdot_Eddington=$(4*\pi*G*M*m_p)/(\sigma T*c) = 10^{-17}(s^{-1})*(M)$. If M=5 solar masses, Mdot_Eddington=10^{-16} solar masses/second!

  - The accretion rate above (not unreasonable for gamma-ray bursts is very very highly super Eddington).

Exercise 3:

- What is the lifetime of a disk for a 10^9 solar mass black hole accreting at the Eddington rate (you'll need to make an assumption about the mass in the disk)?

  - Mdot_Eddington=$(4*\pi*G*M*m_p)/(\sigma T*c)$. I assumed the mass in the disk is roughly 10^8 solar masses. For a 10^9 solar mass black hole, the Eddington accretion rate is 10^{-8} solar masses/second. The lifetime of the disk is then Mdot/Mdisk $\sim 10^{16}$s $\sim 10^9$ yr!

Exercise 4:

- Compare the free fall time and light crossing time for a Schwarzschild black hole ($R = 2GM/c^2$) of mass M.

  - Remember the free fall time is $t_{ff} \sim (2R^3/GM)^{½}$ and the light crossing time is $t_{LC} \sim R/c$. If we plug in the relationship between mass and radius for a Schwarzschild black hole (given above), we find $t_{ff} \sim t_{LC} \sim 2GM/c^3$. That is, they are the same.

Exercise 5:

- Electrons are accelerated in the presence of a magnetic field B ~ 10 G, on a timescale 10^{-10}s. What is the maximum energy (or Lorentz factor) to which they can be accelerated?

    - To solve this, we want to consider the energy at which the radiative time is equal to the acceleration time - it is at this energy that particles lose their energy to radiation as fast as they can be accelerated, and so this sets the maximum energy scale to which they may be accelerated:
    - $t_{rad}=(m_e*c)/(B^2*\sigma*\gamma) = t_{acc}$. Plugging in the numbers given above and solving for γ, we find $\gamma \sim 10^5$!

    - Bonus: If the magnetic field went up by an order of magnitude (to 100 G), how does this energy/Lorentz factor change?

Exercise 6:

- Compute the time for photons to diffuse out of the sun.

  - $t_{diffusion} \sim L^2/\lambda v$, where λ is the mean free path $\sim 1/n\sigma_T$. The particle density $n \sim \rho_{sun}/m_H$ and σ_T is the Thomson cross section. Here, v=c and L=radius of the sun. Plugging in the numbers, we find the mean free path is roughly 1 cm, so $t_{diffusion} \sim 10^{11}$ s.

Exercise 7:

A typical (AGN) accretion disk has $R=10^{16}$cm, $T=10^4$K and $n \sim 10^{16}$cm^{-3}. The kinematic viscosity is $\nu = v_T\lambda$, where v_T is the thermal velocity $v_T \sim (kT/m)^{1/2}$ and λ is the mean free path ($\sim 10^{-3}$ cm for an ionized gas with this density and temperature - or you can make your own estimate!).

- What is the viscous timescale for this accretion disk?
  - The mean free path is given as 10^{-3} cm. Plugging in the temperature to compute the thermal velocity, we can compute the viscosity $v_T\lambda$.

  - The viscous timescale is then $R^2/\nu \sim 10^{29}$s $\sim 10^{22}$ year!! (so this simple kinematic viscosity cannot be responsible for the loss of angular momentum that allows material to accrete onto the central black hole - another mechanism must be at play to transport angular momentum, allowing material to accrete!

Exercise 8:

Write down the viscous timescale for an alpha-disk:

- $\nu = \alpha c_s h$,
- $c_s = h\Omega$, $\Omega = (GM/R^3)^{½}$

Is this a better way to transport angular momentum? What is α?

Bonus Exercise (only if time):

Relativistic electrons are scattered off Alfven turbulence. B-field is = 10G

Density ρ is = 10^{-18} g/cm^3

($v_A = B/(4\pi\rho)^{1/2}$)

To what energy can the particles be accelerated?

Extra Time? MADs. MAD definition, MAD timescales.