Supernova Explosions in AGN discs

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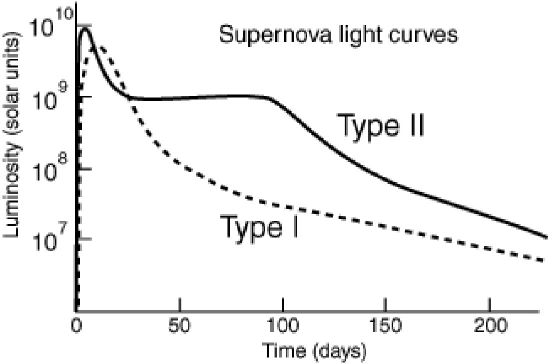
Type Ia Supernovae are used as standard candles

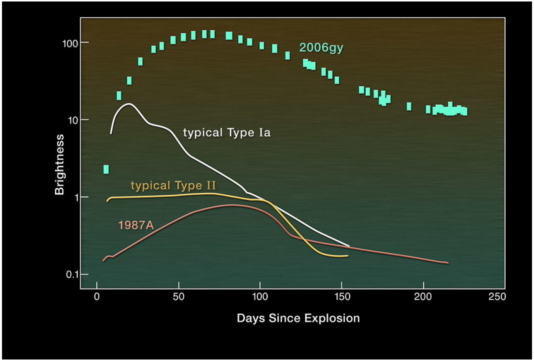
- Ejected mass $\sim M_\odot$, energy $E_0 \sim 10^{51}\mathrm{erg}$, velocity $v_0 \sim \sqrt{E_0/M_\odot} \sim 10^9 \mathrm{cm\ s}^{-1}$
- Peaks at $\sim L_{\mathrm{peak}} \sim 10^{43} \mathrm{erg\ s}^{-1}$
- Duration at peak ~ 30 days



Adapted from Chaisson & McMillan

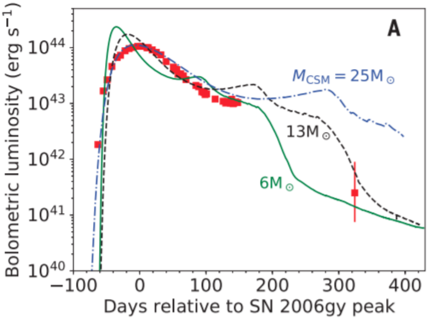
Interaction with a medium leads to sulerluminous events

- Interaction with pre-existing circumstellar medium (CSM):
  - more efficient conversion of kinetic outflow to radiation (Woosley+2007, Nature; Jerkstrand+2020, Science)



Different CSM mass changes the peak and duraction of the lightcurve

- Less CSM mass - shorter and brighter events
- More CSM mass - longer duration and less bright

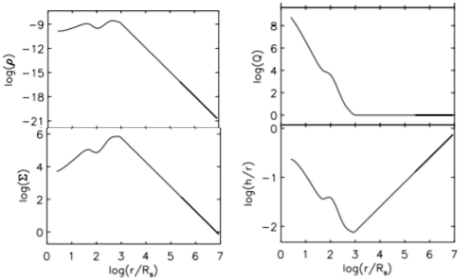


(Woosley+2007)

- Origin of the CSM is usually its wind itself.
- What about SNe in different environments?

AGN discs are modelled as accretion discs

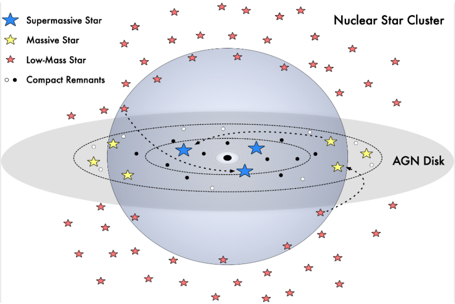
- Geometrically thin $H \ll r$, optically thick $\tau \gg 1$ accretion discs
- Marginally stable for $r > 10^5 r_s,\ r_s = 2GM_\bullet/c^2$
- Potential migration traps around maximal density @$r \sim 10^3 r_s$
  (Bellovary+2016)



(Sirko and Goodman 2003)

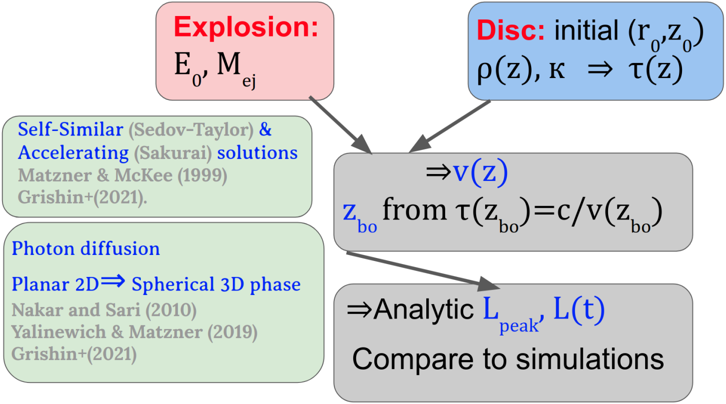
AGN accretion discs host many stellar populations

- Many stars and stellar remnants (Miranda+2000, Bartko+2010)
- Star formation: instability (Paczynski 1987, Dittmann+2020) or disc capture (Artymowicz 1993)
- Accretion and migration, changing mass and orbits (Ostriker+1983, Cantiello+2021)



(Cantiello+2021)

Lightcurve is detremined from explosion and AGN disc initial conditions



Explosion: E_0, M_{ej}

Disc: initial (r_0, z_0)
$\rho(z), \kappa \Rightarrow \tau(z)$

Self-Similar (Sedov-Taylor) & Accelerating (Sakurai) solutions
Matzner & McKee (1999)
Grishin+(2021).

$\Rightarrow v(z)$
z_{bo} from $\tau(z_{bo}) = c/v(z_{bo})$

Photon diffusion

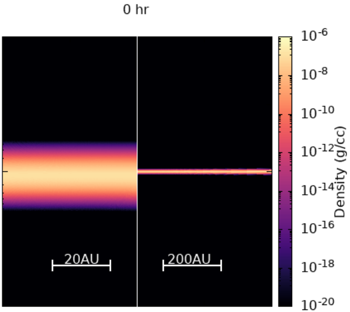
Planar 2D $\Longrightarrow$ Spherical 3D phase
Nakar and Sari (2010)
Yalinewich & Matzner (2019)
Grishin+(2021)

$\Rightarrow$Analytic L_{peak}, $L(t)$

Compare to simulations

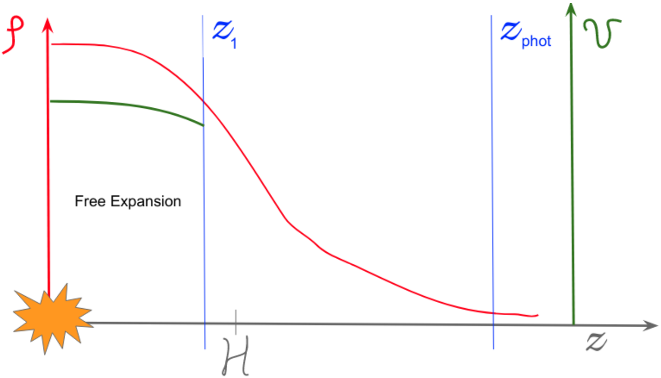
We compare the analytics with two different codes

- SuperNova Explosion Code (SNEC): spherically symmetric Lagrangian radiation hydrodynamicals (Morozova+2016)
  - Ideal for obtaining lightcurves, radiative transfer, opacity tables
- HORMONE: Eulerian grid-based Godunov type scheme hydrodynamics code (Hirai+2016) - study disc morphology



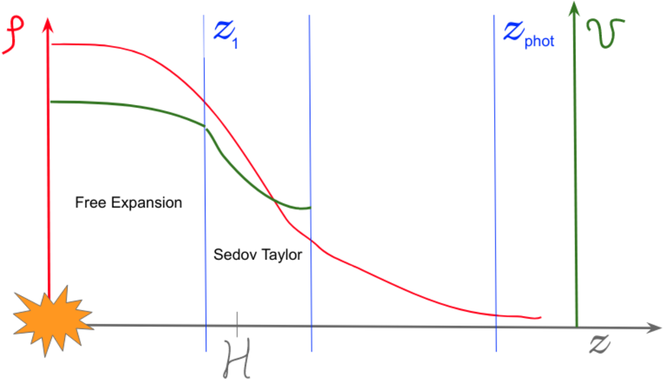
The shock wave propagates in three phases

- Free expansion: The shock sweeps mass $M_{\rm sw} \sim \rho_0 z^3 \gg M_{\rm ej}$, and the density is uniform, the velocity is roughly constant



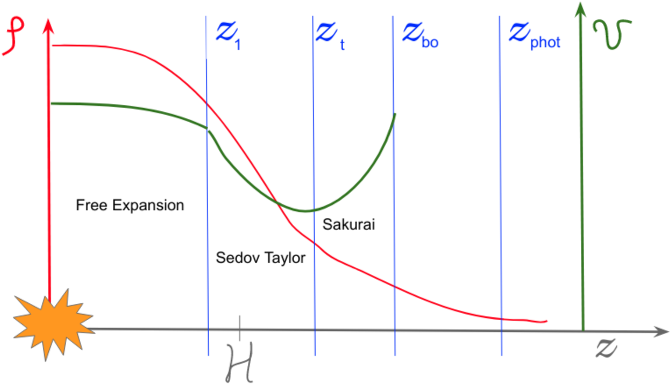
The shock decelerates

- When $M_{\rm sw} \gtrsim M_{\rm ej}$, the shock decelerates via the Sedov-Taylor solution $R \propto (E/\rho_0)^{1/5} t^{2/5}$, $v(t) \propto (E/\rho_0)^{1/5} t^{-3/5}$

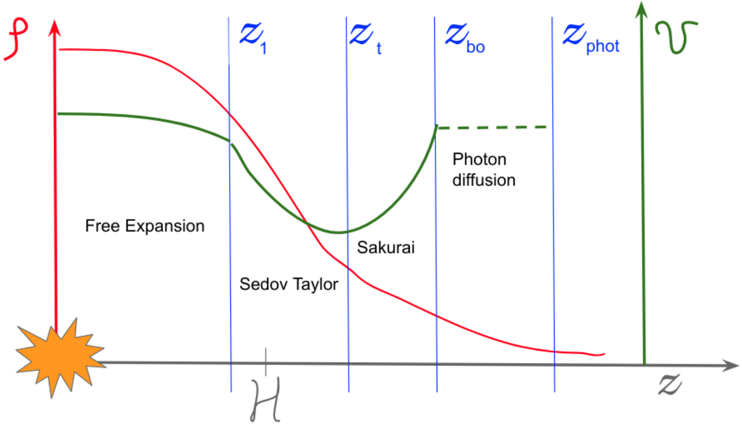


Finaly the shock accelerates and breaks out

- When $\rho(z) \ll \rho_0$ in the upper layers, the Shock accelerates as a Sakurai Law $v \propto \rho^{-\mu}$ ($\mu \approx 0.19$), (Sakurai 1960) and breaks out
- z_{bo} is where $\tau(z_{\text{bo}}) = c/v(z_{\text{bo}})$ (Nakar and Sari 2010)



The photons then diffuse to the photosphere (Grishin+2021)

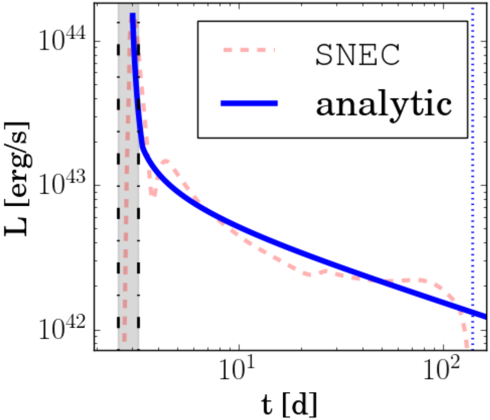


Once $v(z)$, $\tau(z)$ is known, analytical lightcurve estimation $L(t)$ is possible (Grishin+2021)

- $v(z)$ from an extrapolation: $v(z) = \left(\frac{E_0}{M_{\rm ej}+M_{\rm sw}(z)}\right)^{1/2}\left(\frac{\rho(z)}{\rho_0}\right)^{-\mu}$ (Matzner & McKee 1999),
  - For ST: $v^2 \sim E/M \sim E/(\rho v^3 t^3) \rightarrow v^5 \sim (E/\rho t^3)$
- $\rho, \tau, z_{\rm bo}$-> $L(t)$ via analytical means (Yalinewich & Matzner 2019, Grishin+2021)
- Photosphere expansion: $d = d_0 + v_{\rm bo} t$
  - planar phase: $v_{\rm bo} t \ll z_{\rm phot} - z_{\rm bo}$ constant τ.
  - Spherical phase, $v_{\rm bo} t \gtrsim z_{\rm phot} - z_{\rm bo}$, τ decreases
- We later vary the explosion and disc properties.

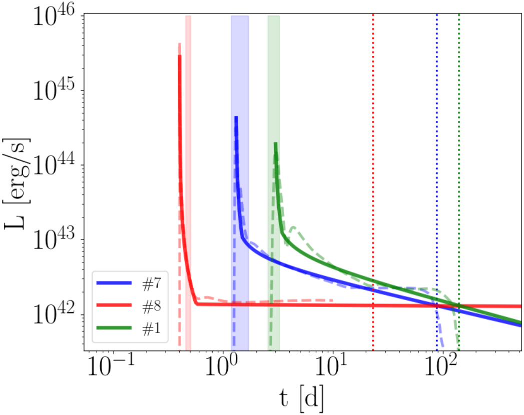
The analytic lightcurve reproduces the simulation (Grishin et al. 2021)

- Gray area - range of times to breakout $t_{\rm bo} = \int_0^{z_{\rm bo}} dz/v(z)$
- Blue line - end of the spherical phase (Yalinewich and Matzner 2019)

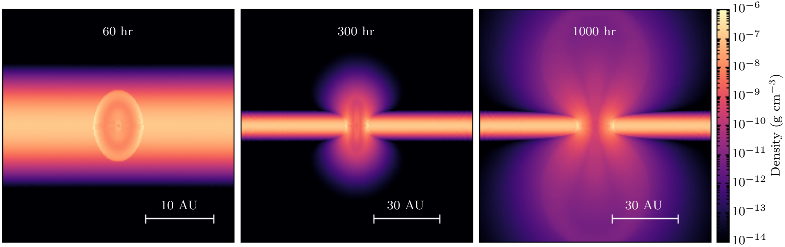


Lightcurve depends on the different vertical Structure (Grishin et al. 2021)

- (#1: Gaussian) (#7: Radiation dominated profile) (#8 - Uniform)

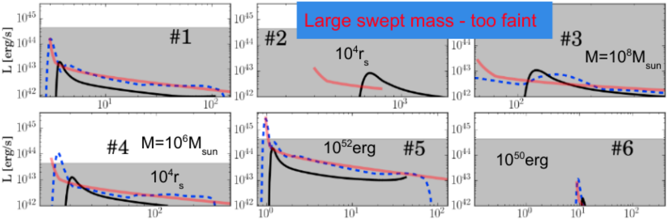


2D Hydrodynamical simulations uncover the disc morphology(Grishin et al. 2021)



Low density and/or high explosion energy events may be observable (Grishin et al. 2021)

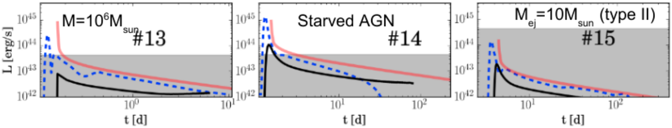
- Gray area - expected to be obscured by the AGN luminosity $L_{\rm AGN} = 0.3 L_{\rm Edd} \sim 4 \cdot 10^{44} (M_\bullet / 10^7 M_\odot)$erg/s (Hubeny+2001)
- Some AGNs could be much less luminous $L_{\rm AGN} = 0.01 L_{\rm Edd}$ (Fabian+2009)


Large swept mass - too faint

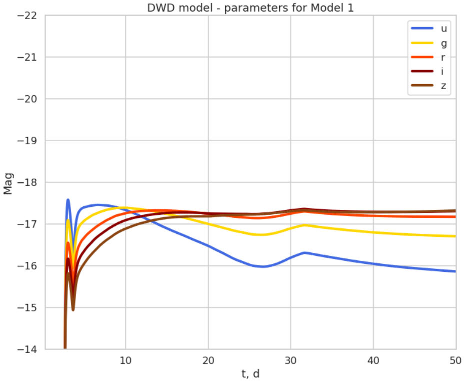
Lower density environments are more likely to be observable

(Grishin et al. 2021)

- More massive ejecta as in core collapse SN behave similarly



Early breakout could be blue optical/UV or hour-long X-ray flare (Grishin et al. 2021)



Upper rate limit comparable to AGN BBH marger rates

(Grishin et al. 2021)

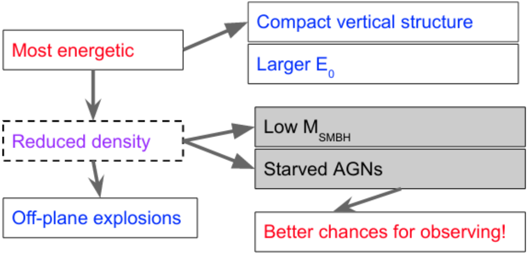
- Mass doubling time ˜ AGN lifetime $\sim 10^8$yr
- $100 M_\odot$ form a SNe $\implies$ 10^{-3} SNe per yr per AGN
- 1% of galaxies have AGN disc, typical number density of $n_{\rm AGN} = 10^{-4} {\rm Mpc}^{-3} \implies \mathscr{R} = 100$ AGN SNe ${\rm yr}^{-1}$ ${\rm Gpc}^{-3}$
- BBH merger rate in AGN discs $0.002 - 18$ ${\rm yr}^{-1}$ ${\rm Gpc}^{-3}$ $({\rm Groebner} + 2020)$

Rate has very large uncertaities (Grishin et al. 2021)

- Proper mass function of AGN discs? Fraction of starved AGNs?
- Most of them could be observable **if** occur near migration traps $\sim 10^3 r_s$(Bellovary+2016)
  - Direction of migration could reverse (Gruzinov+2016)
- Accretion could render most stars into supermassive ones (Cantiello+2021)
  - Rotation / radiative feedback can limit accretion, especially in denser regions near $10^3 r_s$ (Jermyn+2021)
  - Extreme $\tau \sim 10^6$, energy release is blocked, accretion rate reduced: "Bondi explosions" (Wang+2021)
  - Accretion onto WD $\implies$ Chandrasekhar WD and type Ia SNe (Ostriker 1983), increasing $\mathscr{R}$, but accretion efficiency is also uncretain

Environments of reduced $\rho_{\rm AGN}$ have more chances to be observed (Grishin et al. 2021)

- Reduced $\rho_{\rm AGN}$ is better for observations
- Compactness, such that $\rho_{\rm AGN} H^3 \lesssim M_{\rm ej}$, otherwise the explosion could be choked



Most energetic

Compact vertical structure

Larger E_0

Reduced density

Low $M_{\rm SMBH}$

Starved AGNs

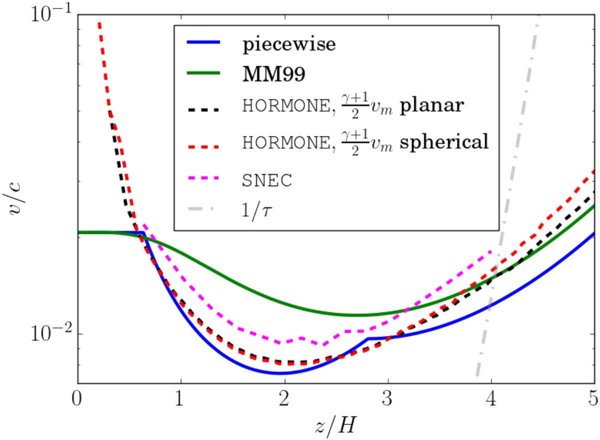
Off-plane explosions

Better chances for observing!

Summary

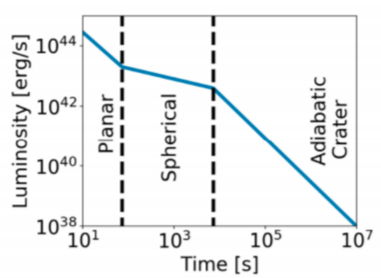
- Understanding AGN explosions opens a window to AGN disc physics and their interactions with the supernova progenitors.
- Typical peak luminosity is around $10^{44} - 10^{46}$ erg s^{-1}.
  - The most energetic events are also the quickest to break out, $t\sim$hours to days and occur in low ρ regions
- The upper limit for the event rate is $\mathscr{R} \lesssim 100$ yr Gpc^{-3}, with large uncertaities
- AGN variability observed on larger tiemscales
  - Future high-cadence transient surveys may be able to identify AGN SNe.

The simulated velocity is somewhere in between (Grishin+2021)



Off-center explosion also experience a 'crater' phase

- If the explosion is at the origin, energy production stops (without nuclear sources)
  - If the explosion is close to the surface, the shells inner to the original explosion will be removed (Yalinewich and Matzner 2019)
- Initial slab geometry, additional crater/gap phase: somewhat similar to AGN disc

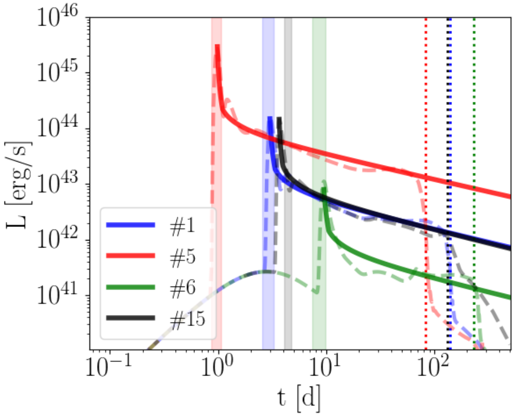


Caveat: We use local approximation of a power law for an extended material!

(Yalinewich and Matzner 2019)

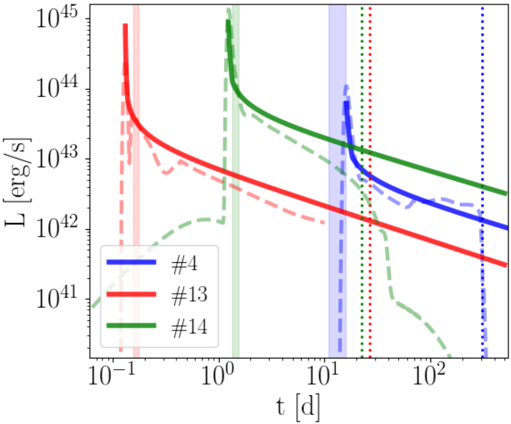
Different energies and masses fit well(Grishin et al. 2021)

- (#1,canon); (#5,10^{52}erg,) (#6,10^{50}erg); (#15, $M_{\rm ej} = 10 M_\odot$)



Different radial AGN locations not always fit (Grishin et al. 2021)

- (#4: $M_\bullet = 10^6 M_\odot, r = 10^4 r_s$); (#13: $M_\bullet = 10^6 M_\odot$); (#14 - starved: $\rho \to \rho/10$)
- Reduced densities, less mass in the CSM



Different vertical Structure (Grishin et al. 2021)

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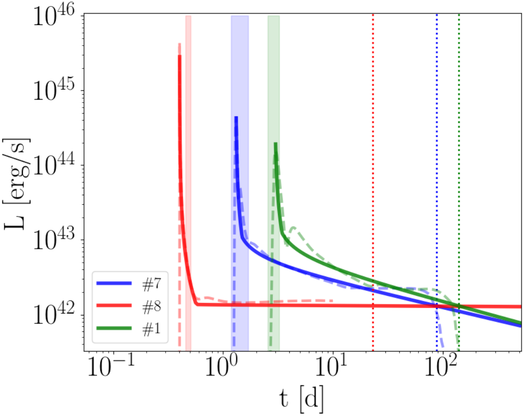
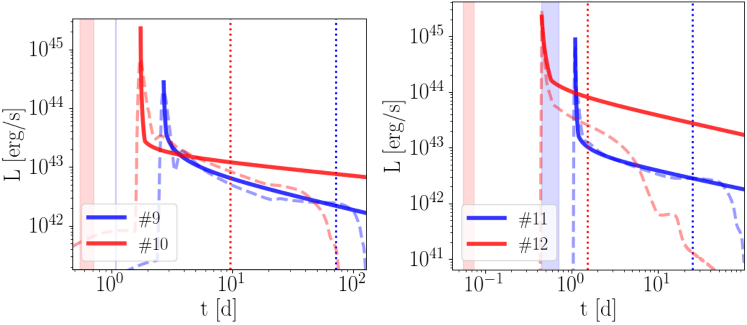


Off plane AGN locations not always fit (Grishin et al. 2021)

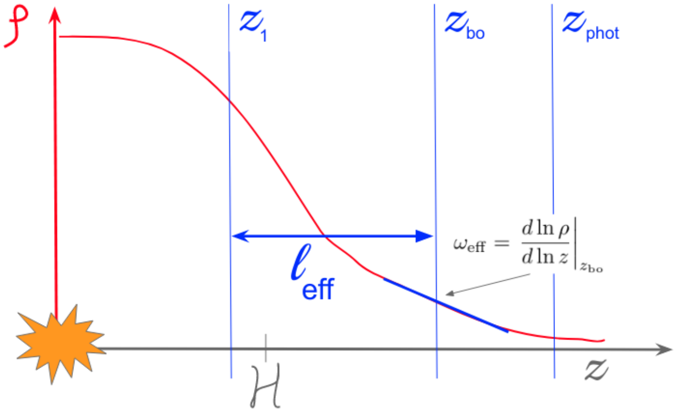
	$z = H$	$z = 2H$
Gaussian	9	10
Radiation	11	12



- very low swept mass

Back up - YM19 model

- We take $\tau_0 = \kappa\rho_0 H$ and $\Gamma = E_0/(M_{\rm ej} + \rho_0 l_{\rm eff}^3)$, $l_{\rm eff} = z_{\rm bo} - z_1$ and ω evaluated at $z_{\rm bo}$
- This uniquely detremines the lightcurve



Back up - YM19 model

- We take
  $\Gamma = E_0/(M_\mathrm{ej} + \rho_0 l_\mathrm{eff}^3)$, $l_\mathrm{eff} = z_\mathrm{bo} - z_1$ and ω evaluated at z_bo

$$L_i(t) = \frac{E_0 c}{H} \times \begin{cases} \Gamma^{(\omega\mu - 2\omega/3 - 5/6)\delta_-} \tau_0^{(5\omega\mu/3 - \omega - 4/3)\delta_-} \left(\frac{ct}{H}\right)^{-4/3} & pl \\ \Gamma^{(-\omega\mu + 1/6)\delta_+} \tau_0^{(\omega\mu - \omega - 4/3)\delta_+} \left(\frac{ct}{H}\right)^{(-4\omega\mu + 2/3)\delta_+} & sph \end{cases}$$

where $\delta_\pm = 1/(1 + \omega \pm \omega\mu)$

Vertical structure

- Hydrostatic Eq. $\frac{dP}{dz} = -\rho g_z = K\gamma\rho^{\gamma-1}\frac{d\rho}{dz}$ where $P = K\rho^\gamma$ is the EOS
- Isothermal (gas pressure)
  $P = c_s^2\rho \implies \rho(z) = \rho_0 \exp(-z^2/2H^2)$
- General polytope: Vertical gravity in a disc: $g_z \approx \Omega^2 z$, we have $\rho^{\gamma-2}d\rho = -\frac{\Omega^2}{\gamma K}. \implies \gamma = 4/3$ is
  $\rho(z) = \rho_0\left[1-(\gamma-1)\frac{z^2}{2H^2}\right]^{1/(\gamma-1)}$
- $H^2 = \frac{\Omega^2}{c_s^2} = \frac{\Omega^2}{\gamma K\rho_0^{\gamma-1}}$ is the scale height.