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Research Council

Radiation Transport Simulations of Quasiperiodic Eruptions from Star–Disk Collisions

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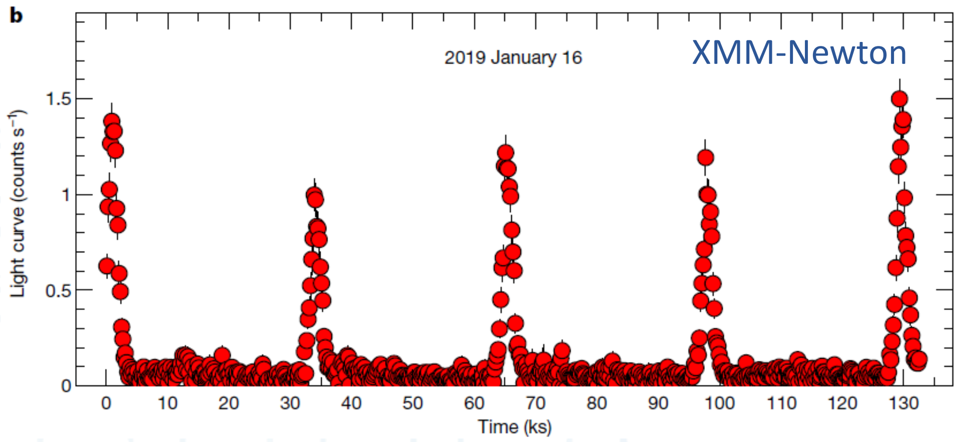
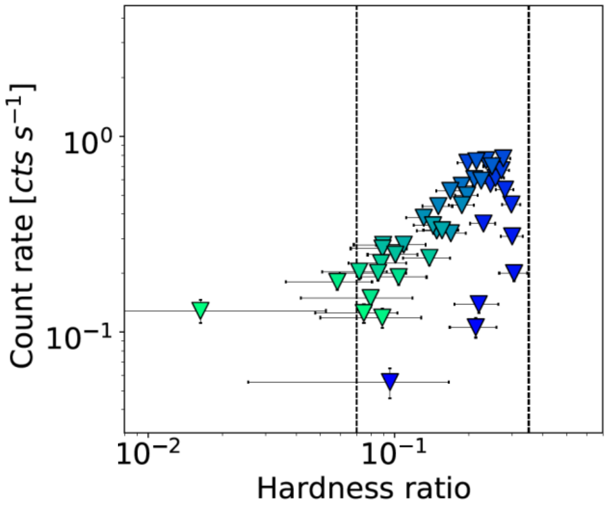
Quasi-periodic eruptions (QPE) from galactic centers

- Periodic flares from centers of low-mass galaxies lasting **tens of minutes to hours**
- Recurrence times from **hours to days** (duty cycle ~0.1)
- Peak **luminosities** $10^{41} – 10^{43}$ erg s^{-1}
- **Quasi-thermal spectra** with kT_{obs} ~ 100 – 200 eV
- **Asymmetric light curves**, broader and peaking later at lower energy bands
- **Hysteresis loops** on hardness-luminosity plane

1st observed QPE: GSN 069 (Miniutti et al. 2019)

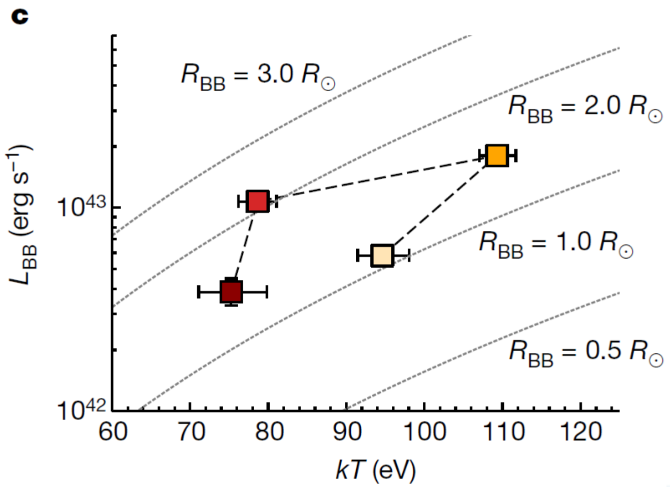


eRO-QPE1 (Obs2)

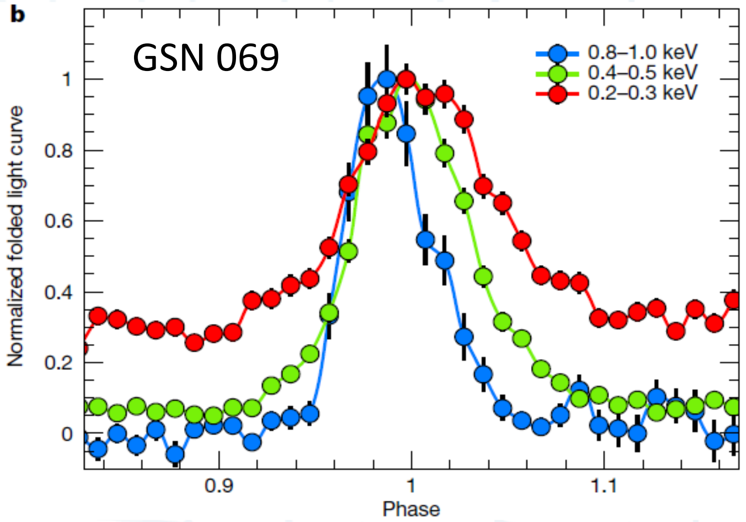


Arcodia et al. (2022)

AT2019qiz

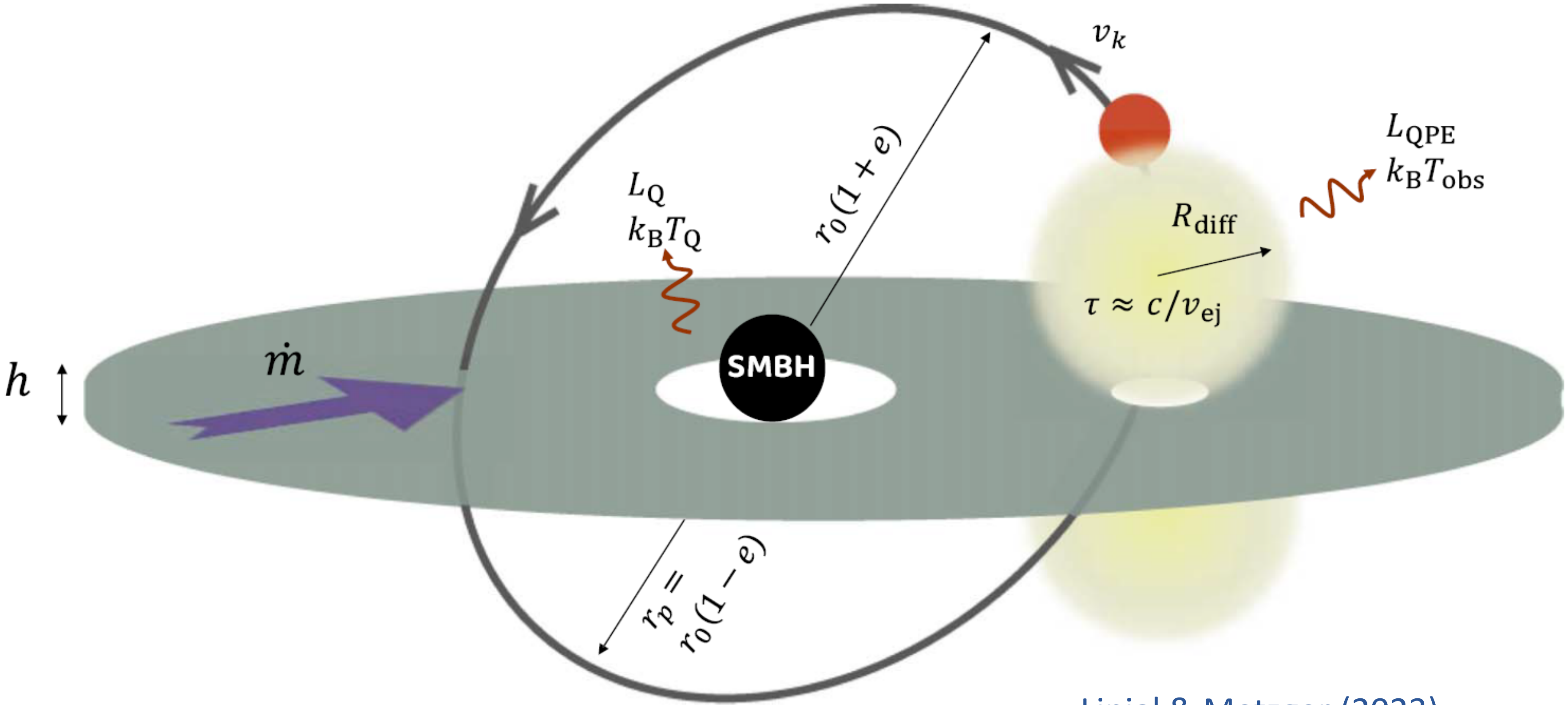


Nicholl et al. (2024)



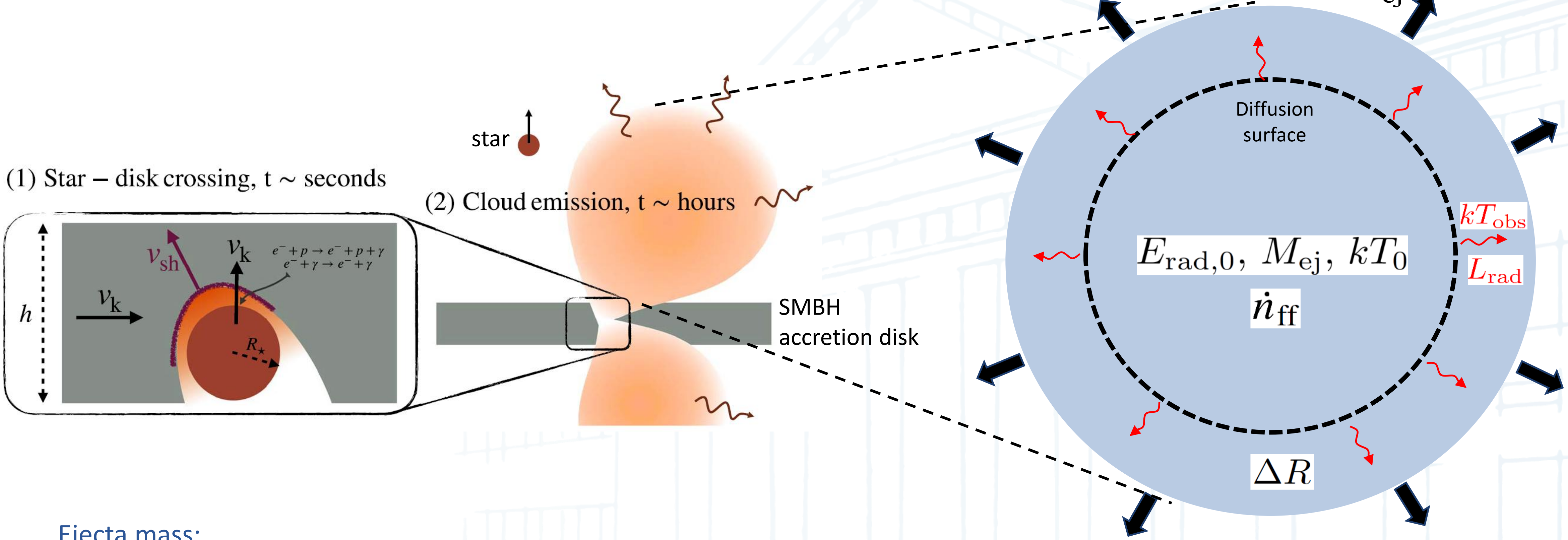
QPE = collisions between an orbiting body and the SMBH accretion disk

(e.g. Suková et al. 2021; Xian et al. 2021; Franchini et al. 2023; Linial & Metzger 2023)



Linial & Metzger (2023)

Disk-star interaction



Ejecta mass:

$$M_{ej} \simeq 2\pi R_\star^2 \Sigma \approx 3 \times 10^{-5} M_\odot R_{\star,12}^2 \left(\frac{\Sigma}{10^4 \text{ g cm}^{-2}} \right)$$

Collision velocity:

$$v_{coll} \approx \sqrt{2}\, v_K \approx 0.14\, c \left(\frac{r_0}{100\, R_g} \right)^{-1/2}$$

Flare duration ≈ radiative diffusion time:

$$t_{diff} \approx \left(\frac{\kappa_T M_{ej}}{4\pi c v_{ej}} \right)^{1/2} \approx 3.7 \times 10^3 \text{ s } R_{\star,12} \left(\frac{\Sigma}{10^4 \text{ g cm}^{-2}} \right)^{1/2} \left(\frac{r_0}{100 R_g} \right)^{1/4}$$

T_{rad} in hot ejecta cloud: thermalized or photon-starved?

- Observed radiation temperatures: $k_B T_{obs} \approx 100\text{–}200\,\mathrm{eV}$
- Theoretical predictions
  - With full thermalization: blackbody temperature at t_{diff}:

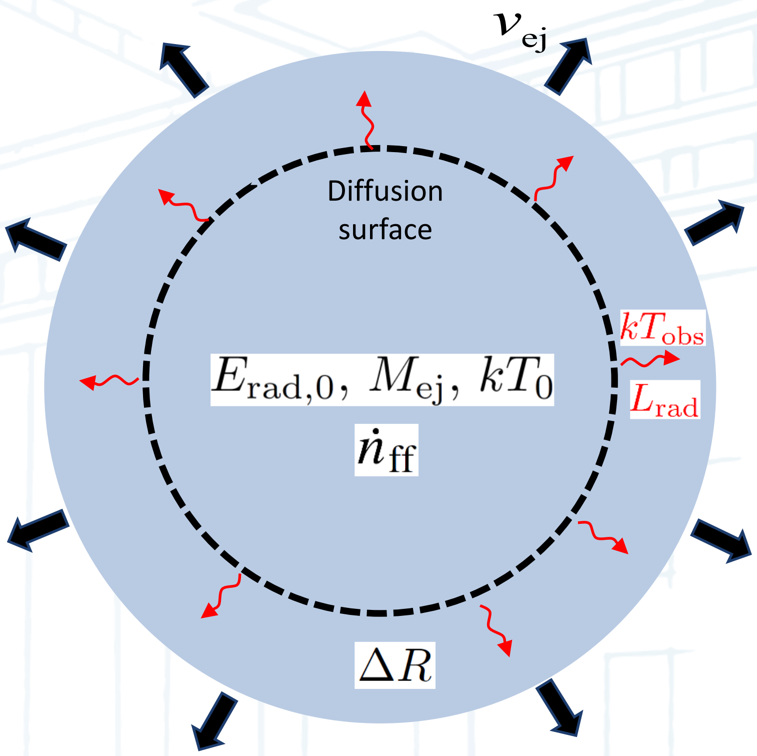
$$k_B T_{BB} \simeq k_B \left(\frac{u_\gamma}{a}\right)^{1/4} \approx 12.6\,\mathrm{eV} \frac{\alpha_{-1}^{1/4} \dot{m}_{-1}^{1/3} M_{\bullet,6}^{1/3}}{\mathcal{R}_\star^{1/3} \mathcal{P}_{QPE,4}^{1/4}}$$

  - With negligible photon production in the shocked disk material:

$$kT_{obs,starv} \sim \frac{m_p v_{ej}^2}{2} \frac{n_0}{n_{ph,0}} \frac{R_\star}{R_{diff}} \sim 1 - 10\,\mathrm{keV}$$

Source ...	$P_{QPE}^{(a)}$ (hr)	$L_{QPE}^{(b)}$ (erg s^{-1})	$t_{QPE}^{(c)}$ (hr)	$k_B T_{obs}^{(d)}$ (eV)
GSN-069	8.5–9.5	1.3×10^{42}	1.1	100–120
eRO-QPE2	2.36–2.75	1.5×10^{42}	0.18	190–240

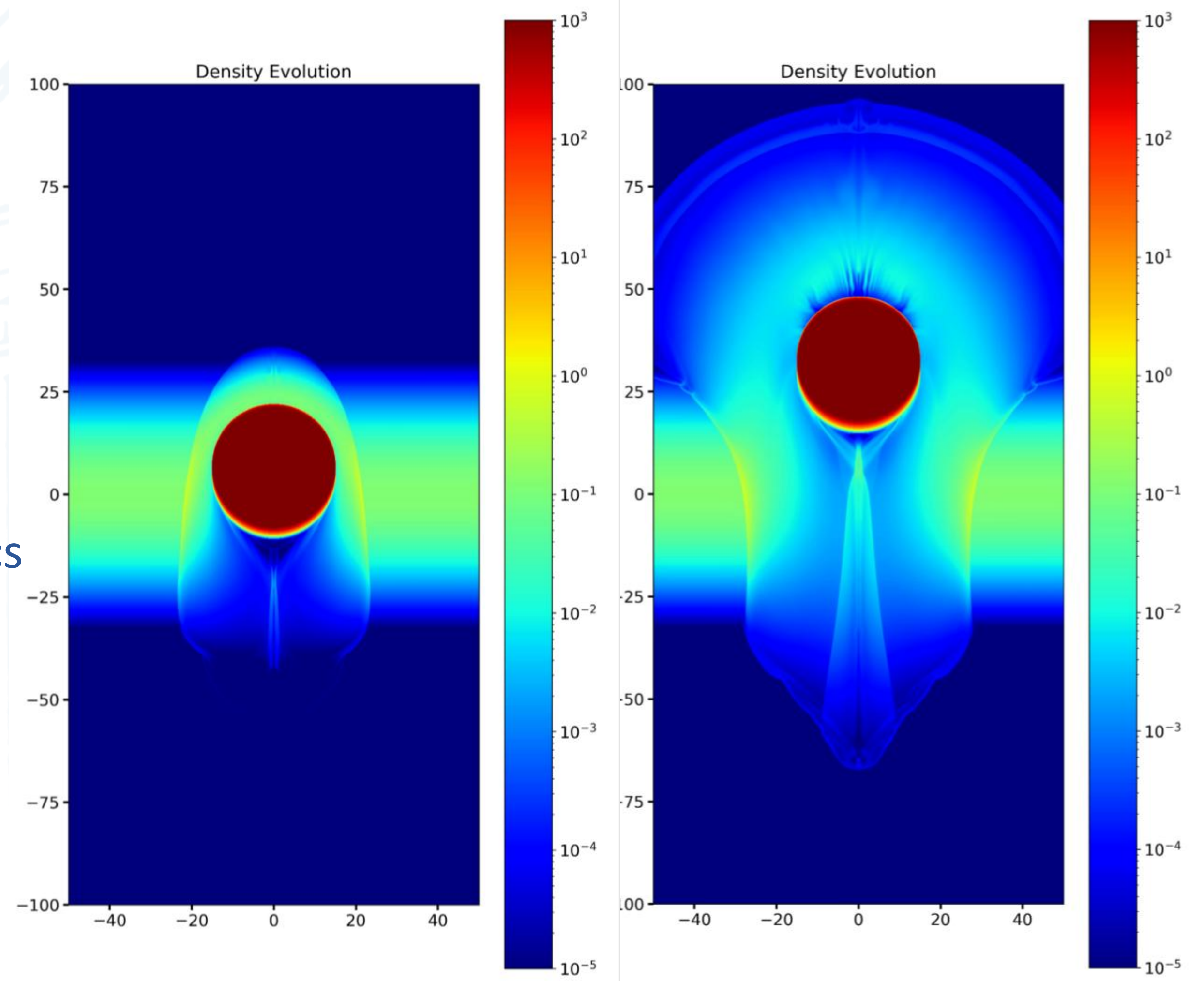
Linial & Metzger (2023)



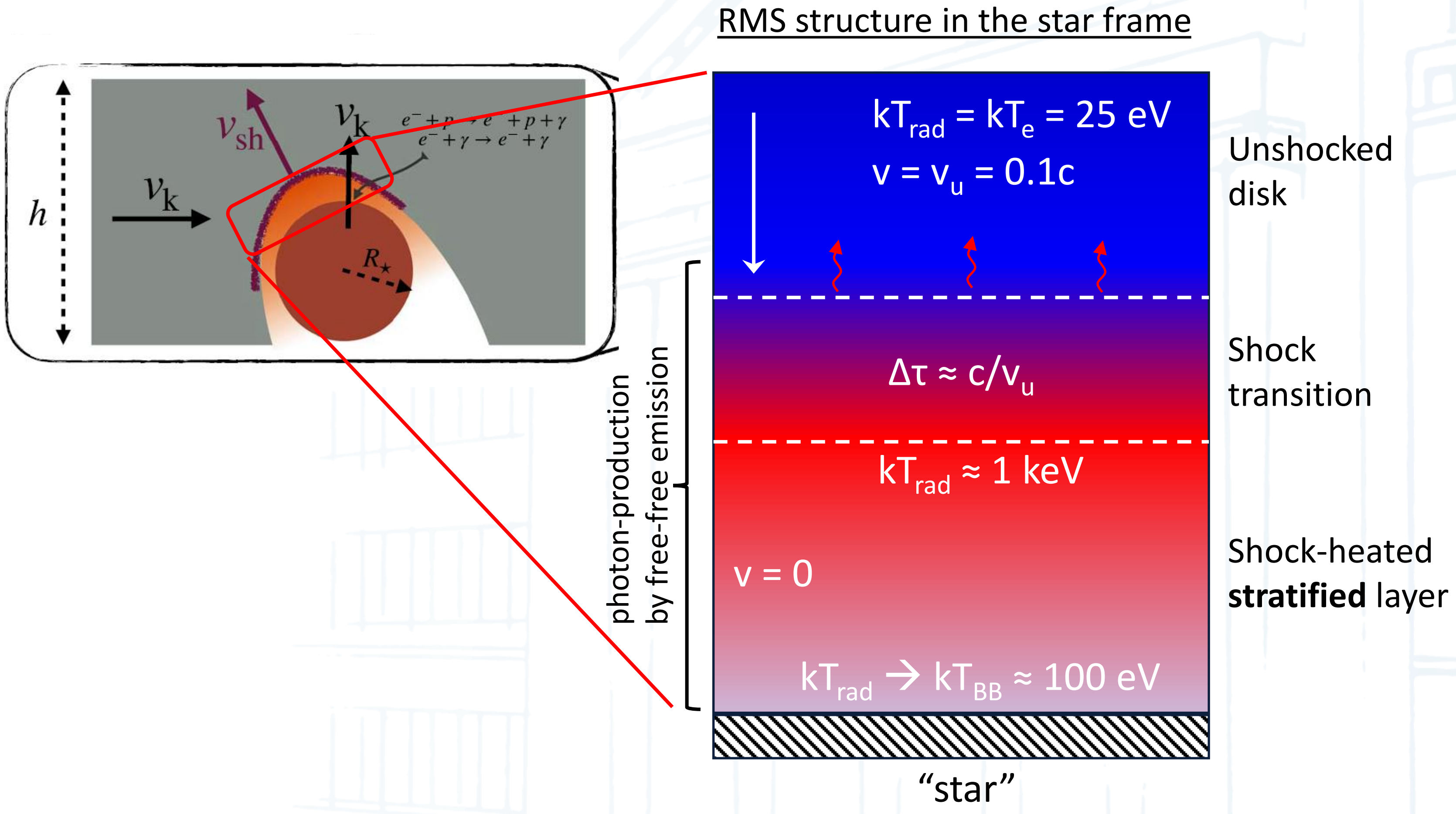
Star-disk interaction model

- Model
  - Spherical geometry centered on the star
  - Disk material impinging upon the stellar surface
  - Three main phases
    - **Accumulation** of shock-heated material on top of the stellar surface during disk passage
    - **Shock breakout** and transition to homologous expansion
    - **Passive expansion** to transparency

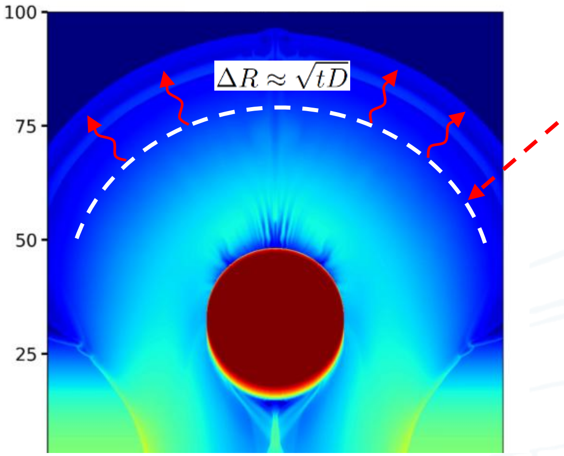
- Method: Monte Carlo radiative transfer + hydrodynamics
  - Radiation → matter coupling: **source terms** (energy/momentum) in hydro eq.-s from explicit MC interactions
  - Matter → radiation coupling: **emission/absorption/scattering coeffs**. in local rest frame, assuming thermal plasma
  - Processes: **Compton** scattering, **bremsstrahlung** (free-free) emission

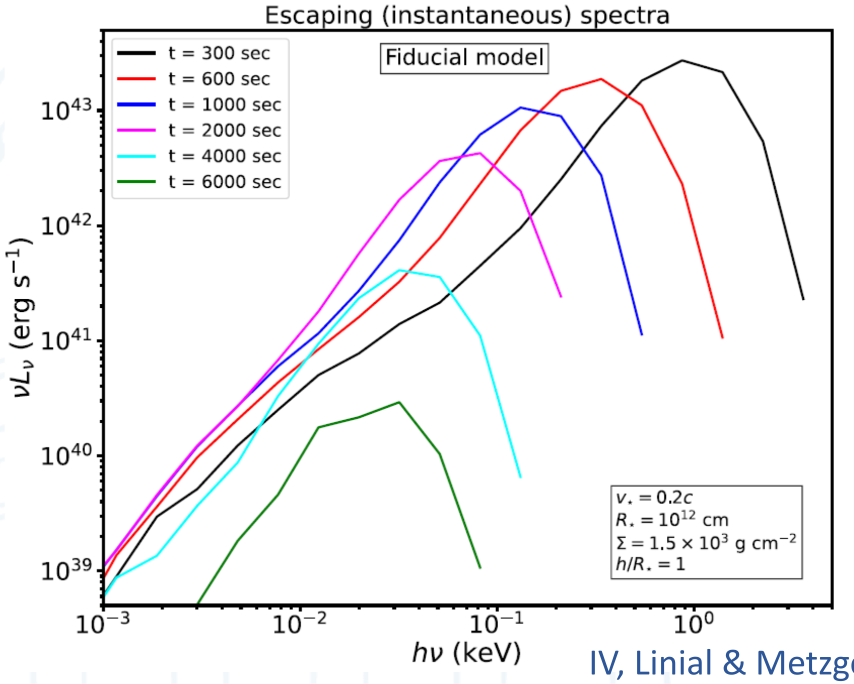


Passage through the disk: radiation-mediated shock (RMS)

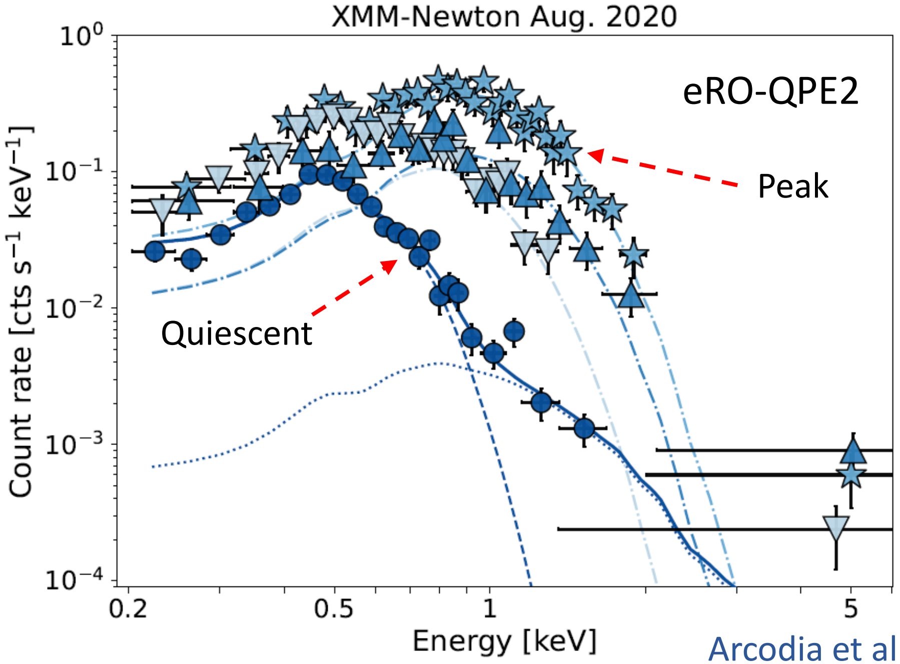


Breakout, free expansion, and emitted spectra





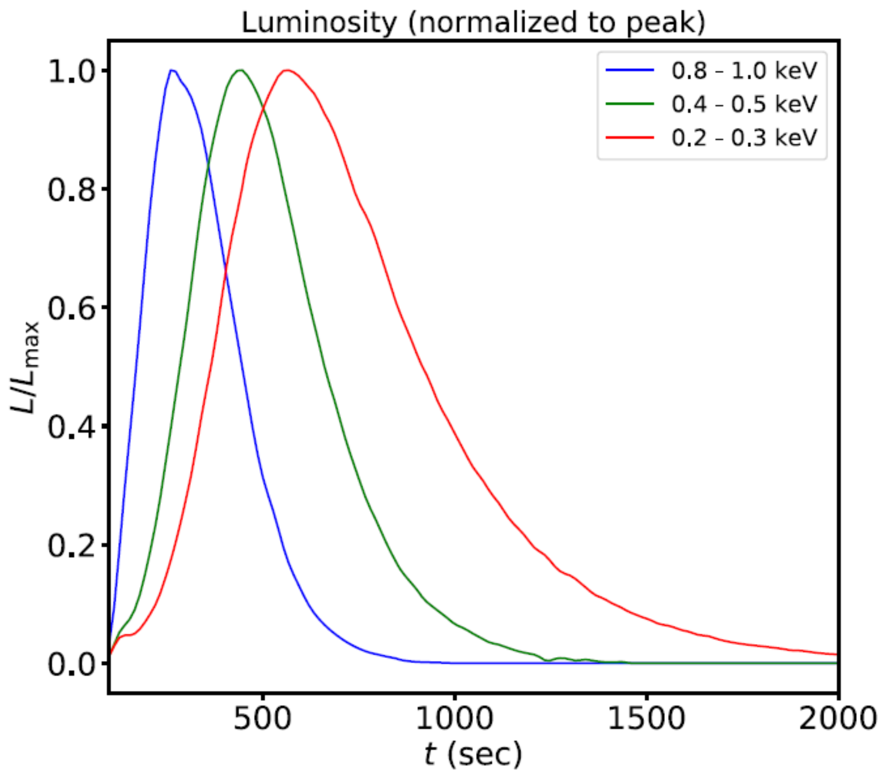
IV, Linial & Metzger (2025)



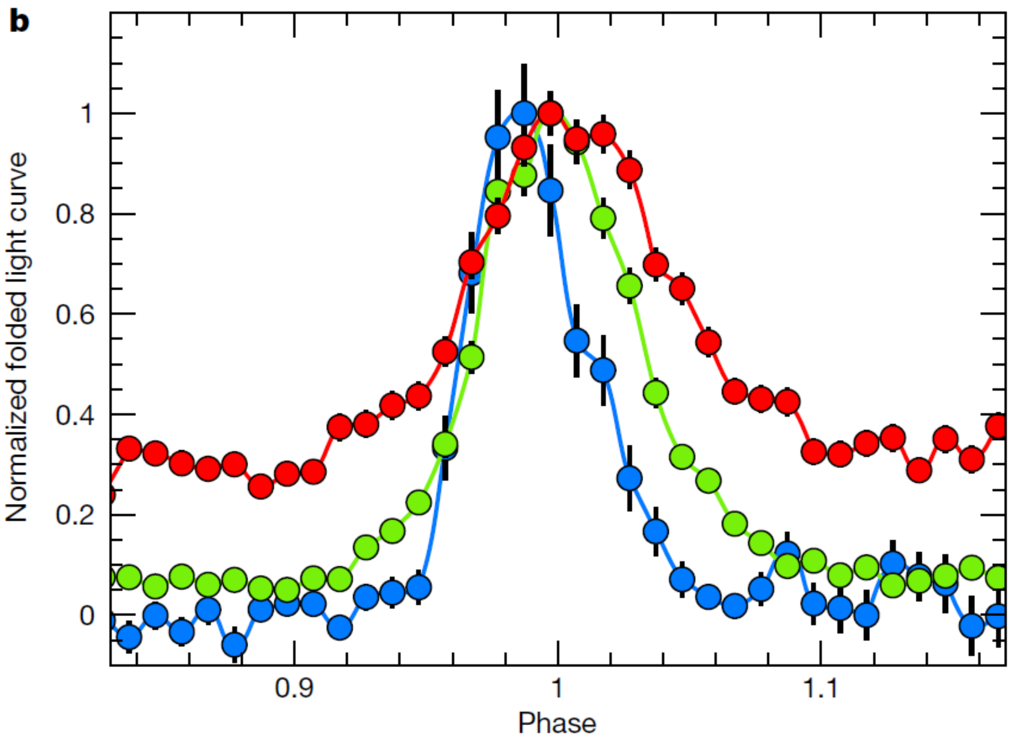
Arcodia et al (2024)

- Observed radiation originates from the **diffusion surface** that propagates inwards in mass coordinate, sampling the **stratified ejecta** set up by the RMS
- Spectrum: characteristic of (marginally) saturated **thermal Comptonization** of a soft (free-free) photon source
- kT_{rad}: **rapid rise** at shock breakout + **gradual decay**
- High L, kT_{rad} ~100 eV requires v > 0.15c, R > $10R_{Sun}$

Light curves



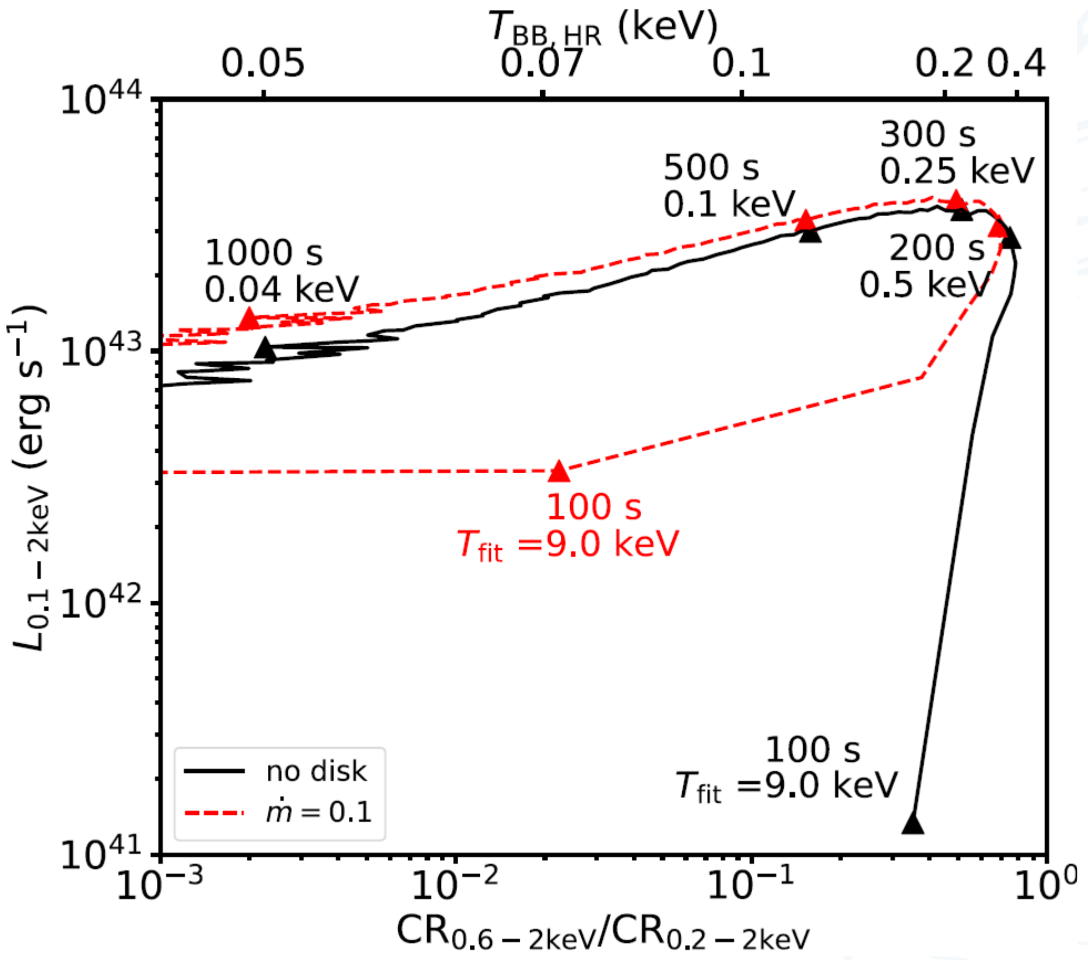
GSN 069

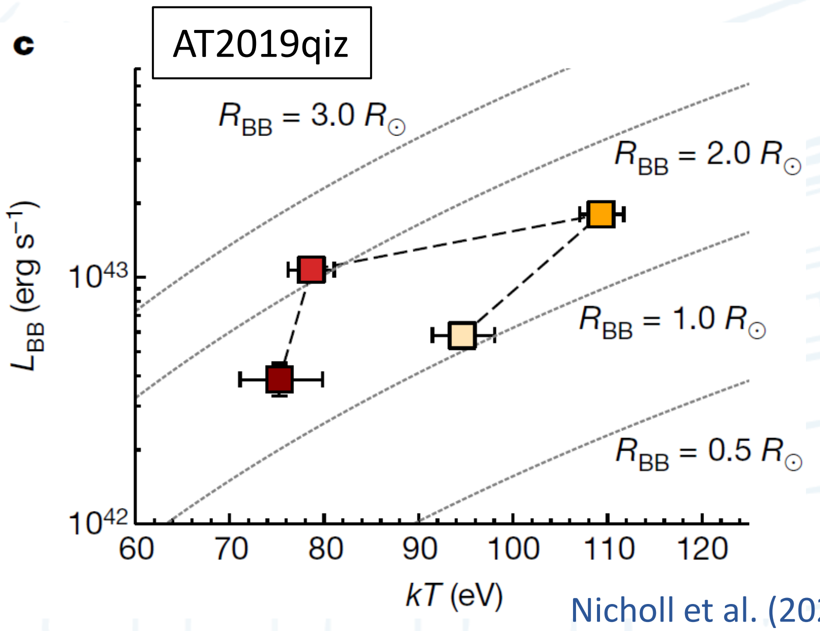


Miniutti et al. (2019)

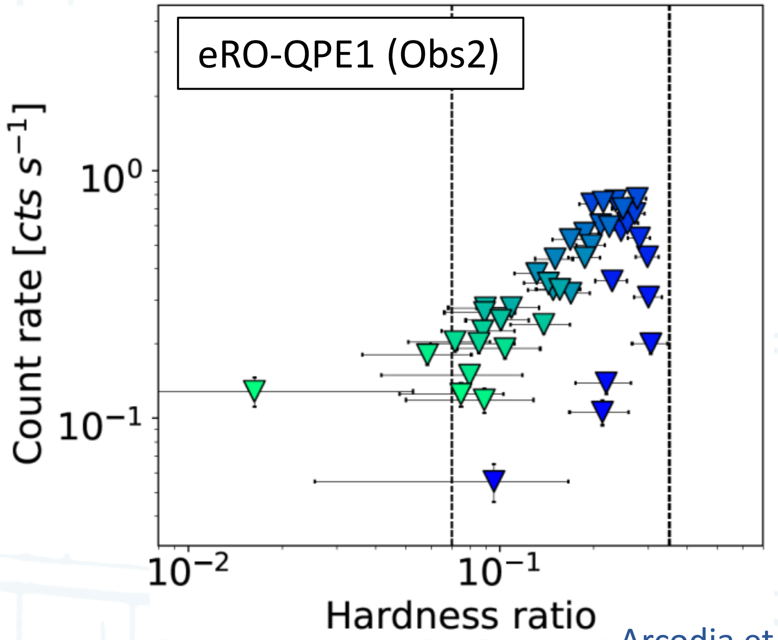
- Softer bands peak later and have broader light curves
- Ambiguity in rise phase due to simplified geometry

Hysteresis in hardness-luminosity evolution





Nicholl et al. (2024)



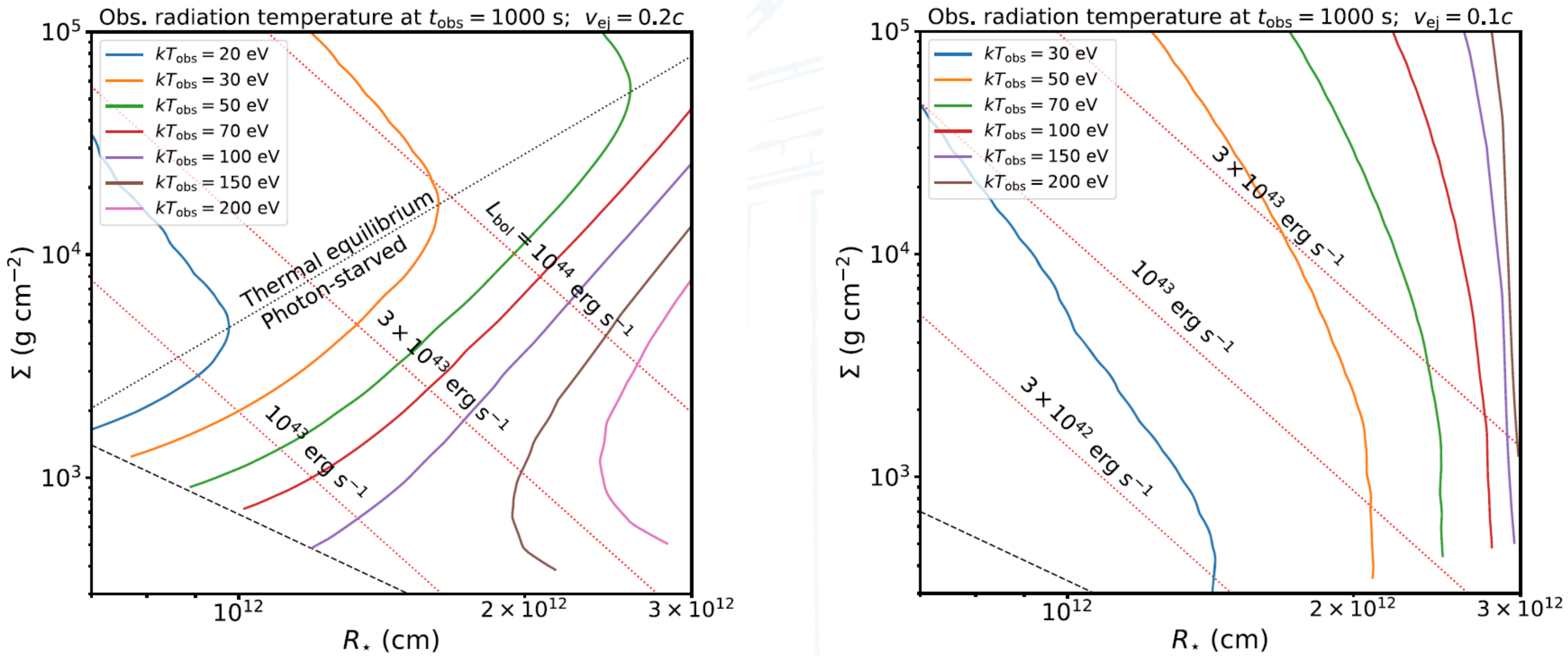
Arcodia et al. (2022)

Summary

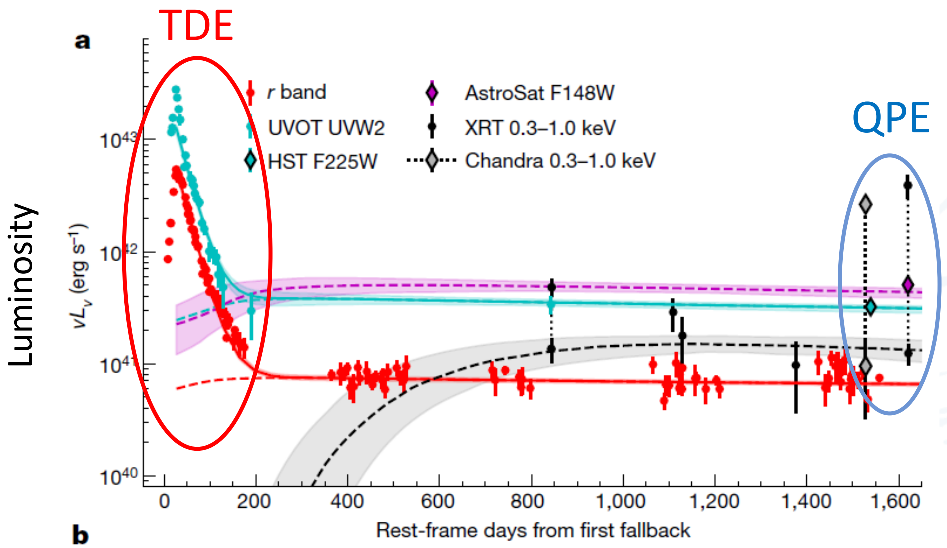
- Main phases of star-disk collision:
    1. passage of the star through the disk: dissipates kinetic energy via RMS and builds a hot stratified “cap” of material ahead of the star
    2. shock breakout from the disk and transition to free expansion
    3. free (homologous, mostly passive) expansion: a fraction of the shock-deposited energy is released, observable as an X-ray flare
- Gas and radiation not in equilibrium in general, necessitating explicit radiative transfer calculations for photon production and spectral formation
- Hard to soft evolution:
    - photons escaping at shock breakout are hardest and most luminous
    - softer emission from deeper layers emerges later; the bulk of radiated energy emerges over t_{diff}
    - light curves broader in softer bands
- Hysteresis loops in hardness-luminosity space, qualitatively similar to observations
- Observed flares with $kT \geq 100$ eV and $t_{obs} \geq 1000$ s limit parameter space to high $v_{coll} \geq 0.15c$, low $\Sigma \approx 10^3$ g cm^{-2}, and large $R_{star} \geq 10^{12}$ cm

Supplementary slides

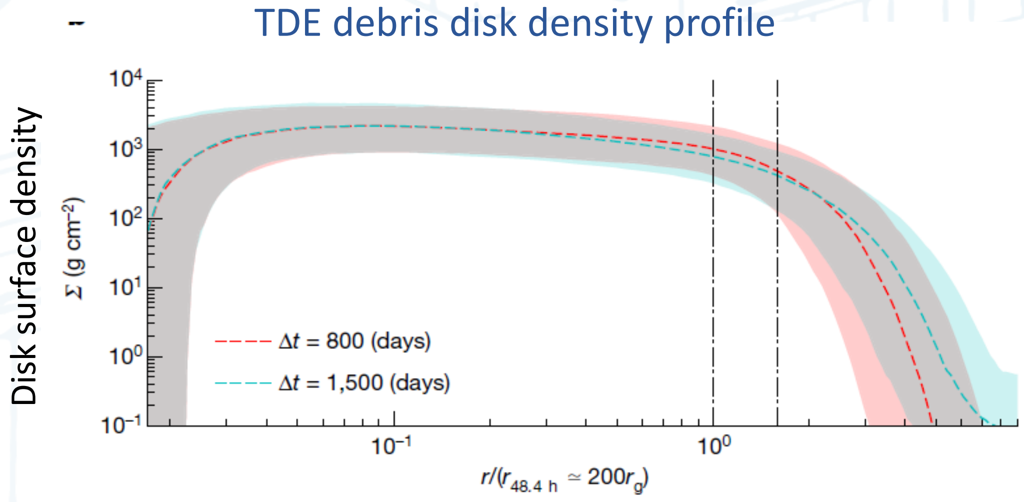
Observed radiation temperatures in R_* - Σ space

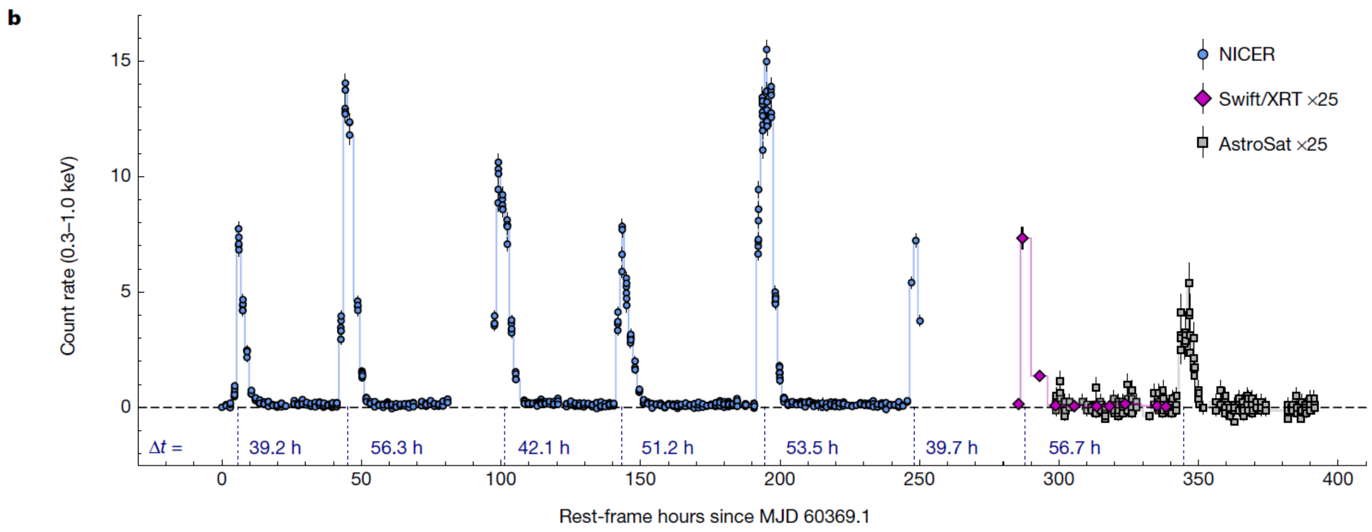


AT2019qiz: QPE following a TDE (Nicholl et al. 2024)



Nicholl et al. (2020); Short et al. (2023)





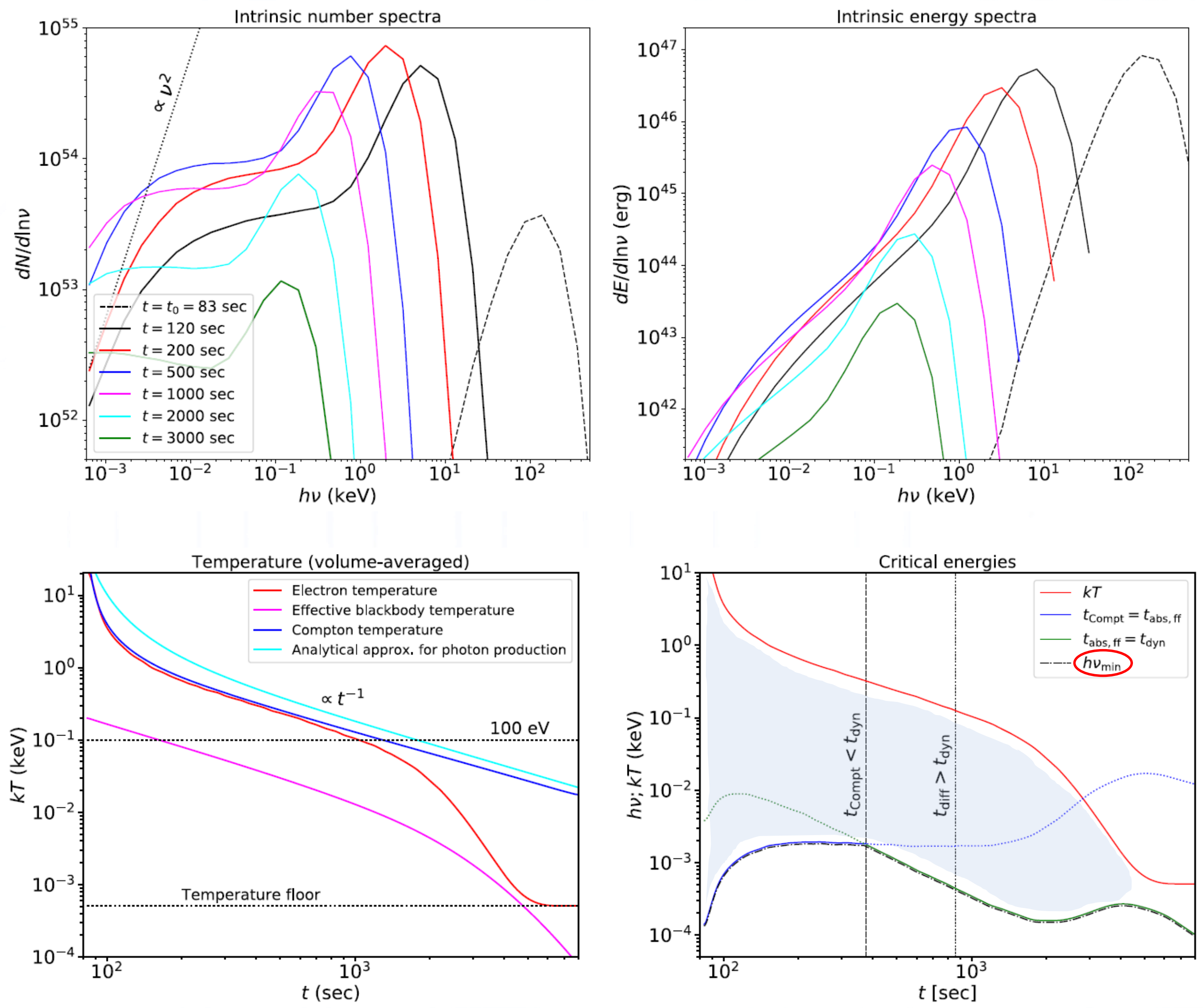
Photon production: mechanism and characteristic energies

Free-free emission/absorption
+ Comptonization

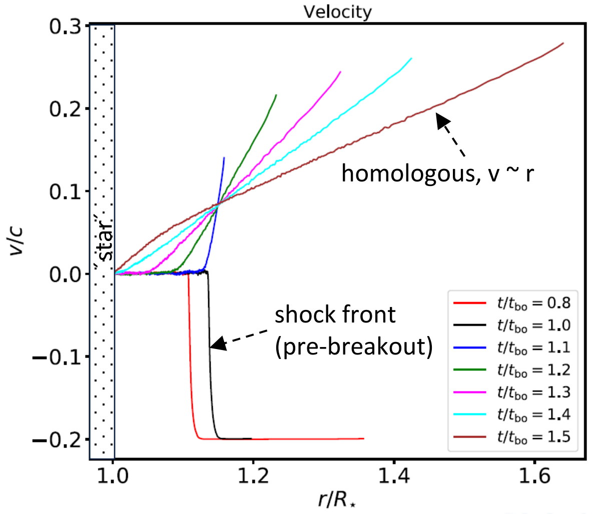
$$\begin{cases} \frac{1}{t^3}\frac{d}{dt}(t^3 n_{\rm ph}) = \dot{n}_{\rm ff} \\ \dot{n}_{\rm ff} \propto \rho^2\, T^{-1/2}\, E_1(h\nu_{\rm min}/kT) \end{cases}$$

$$\Rightarrow \left(\frac{n_{\rm ph}}{n_{\rm b}}\right)^{-1/2} \frac{d}{dt}\left(\frac{n_{\rm ph}}{n_{\rm b}}\right) \propto t^{-5/2}$$

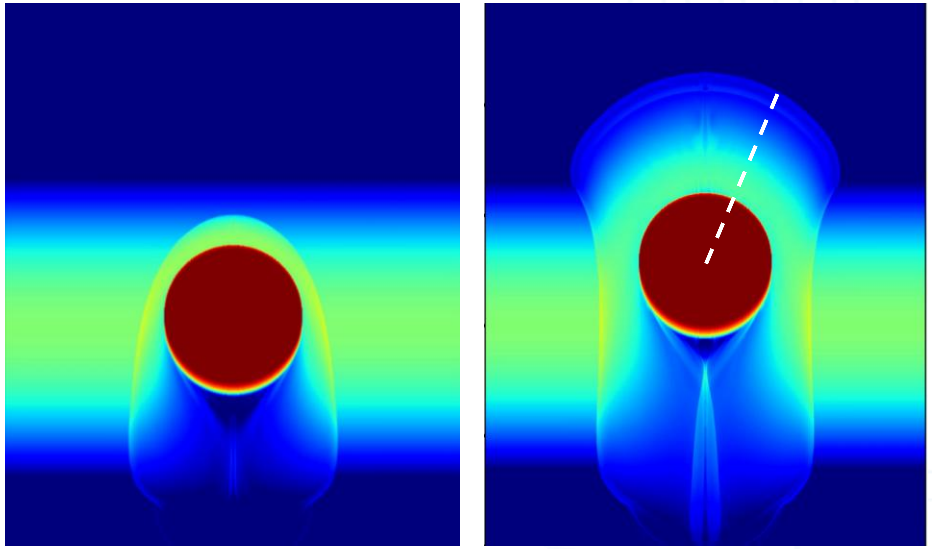
- The bulk of photon-production occurs at early stages of expansion

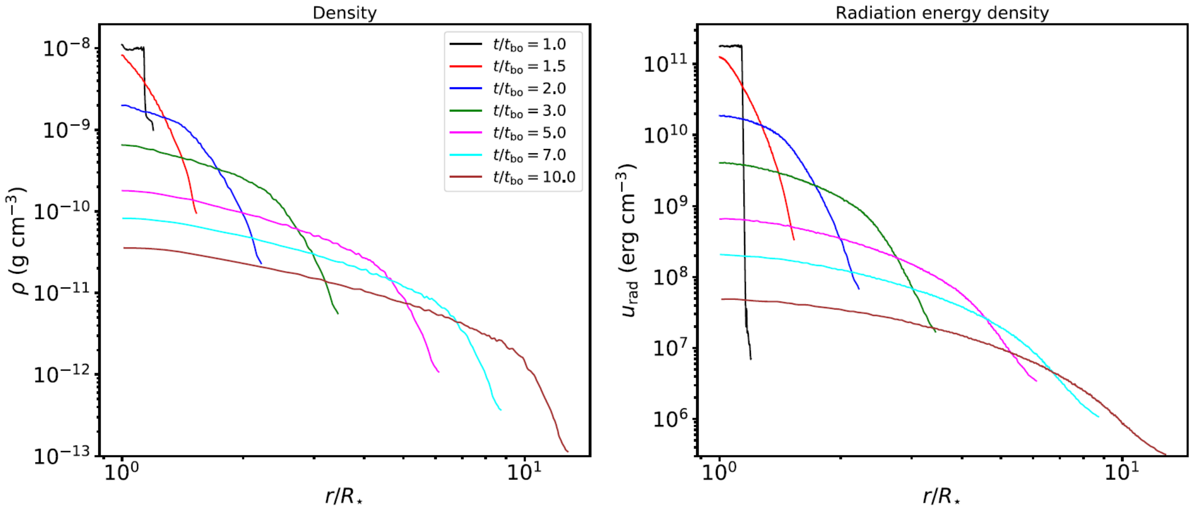


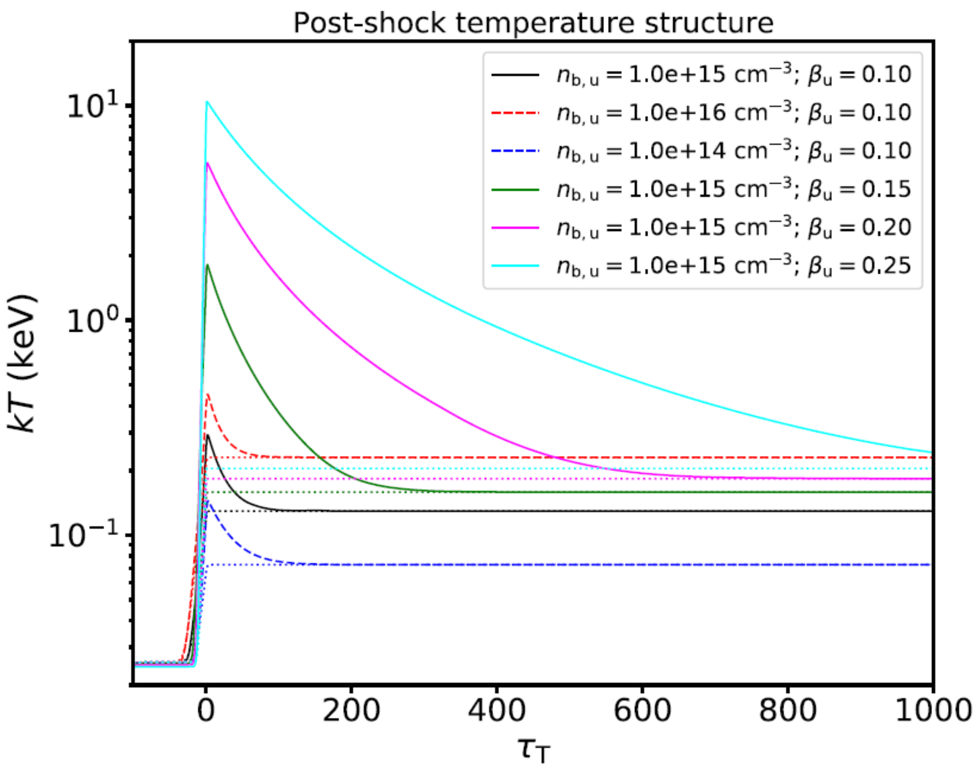
Shock breakout and transition to homologous expansion



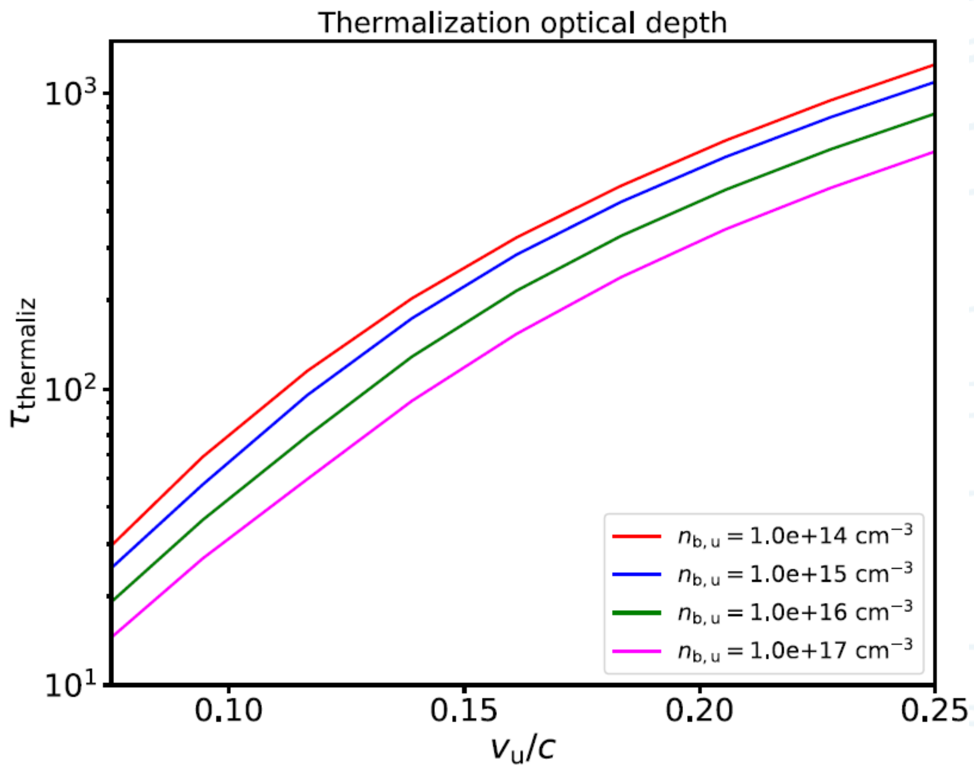
- Rapid transition to homologous expansion post-breakout
- Number of photons per baryon freezes in after approx. one expansion time, $(t - t_{bo}) \sim t_{bo}$







Post-shock temperature structure
$n_{b,u} = 1.0e+15\ cm^{-3}$; $\beta_u = 0.10$
$n_{b,u} = 1.0e+16\ cm^{-3}$; $\beta_u = 0.10$
$n_{b,u} = 1.0e+14\ cm^{-3}$; $\beta_u = 0.10$
$n_{b,u} = 1.0e+15\ cm^{-3}$; $\beta_u = 0.15$
$n_{b,u} = 1.0e+15\ cm^{-3}$; $\beta_u = 0.20$
$n_{b,u} = 1.0e+15\ cm^{-3}$; $\beta_u = 0.25$
kT (keV)
10^1
10^0
10^{-1}
0
200
400
600
800
1000
τ_T



Thermalization optical depth
$\tau_{thermaliz}$
10^3
10^2
10^1
$n_{b,u} = 1.0e+14\ cm^{-3}$
$n_{b,u} = 1.0e+15\ cm^{-3}$
$n_{b,u} = 1.0e+16\ cm^{-3}$
$n_{b,u} = 1.0e+17\ cm^{-3}$
0.10
0.15
0.20
0.25
v_u/c

Bound-bound/bound-free vs free-free emissivities