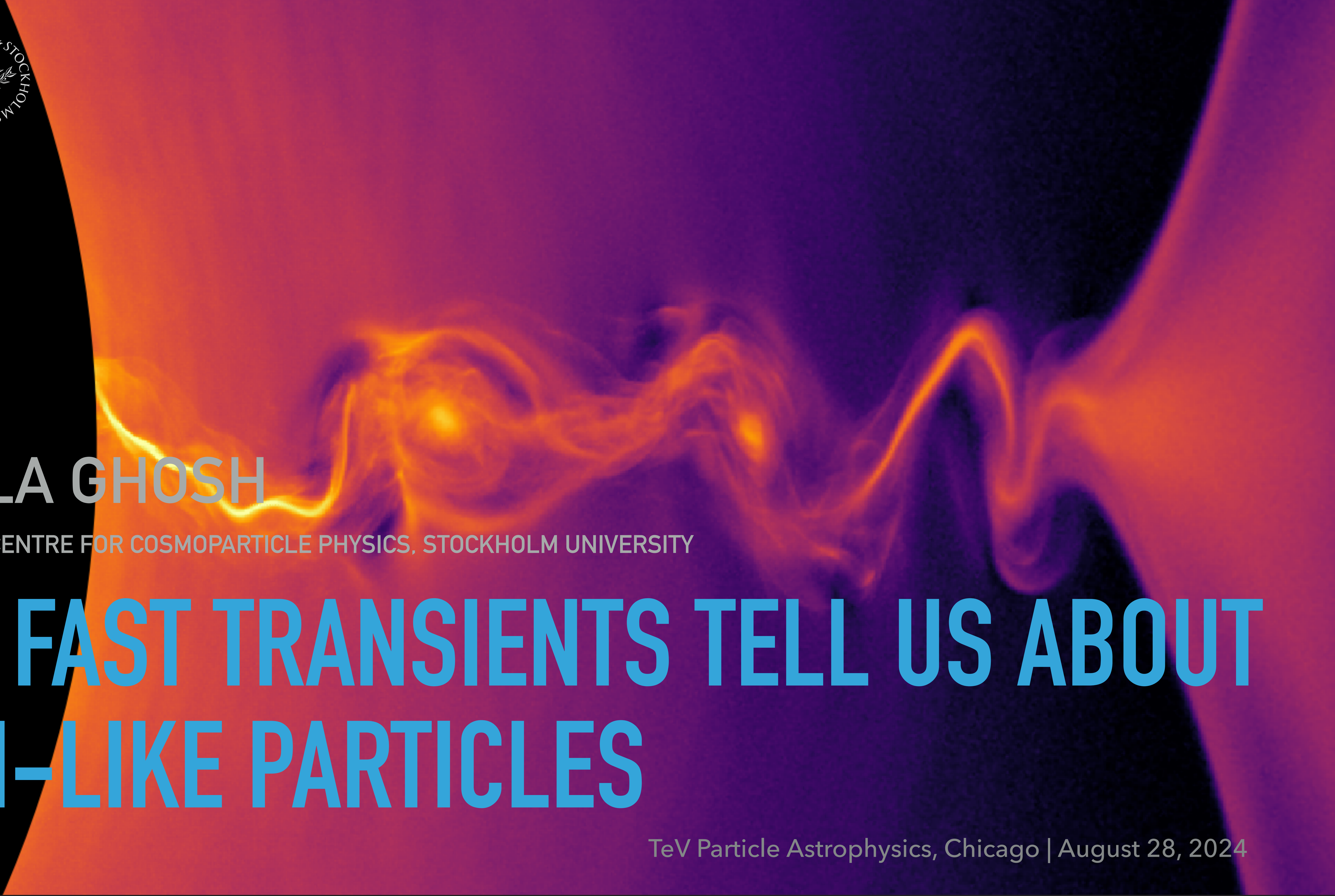


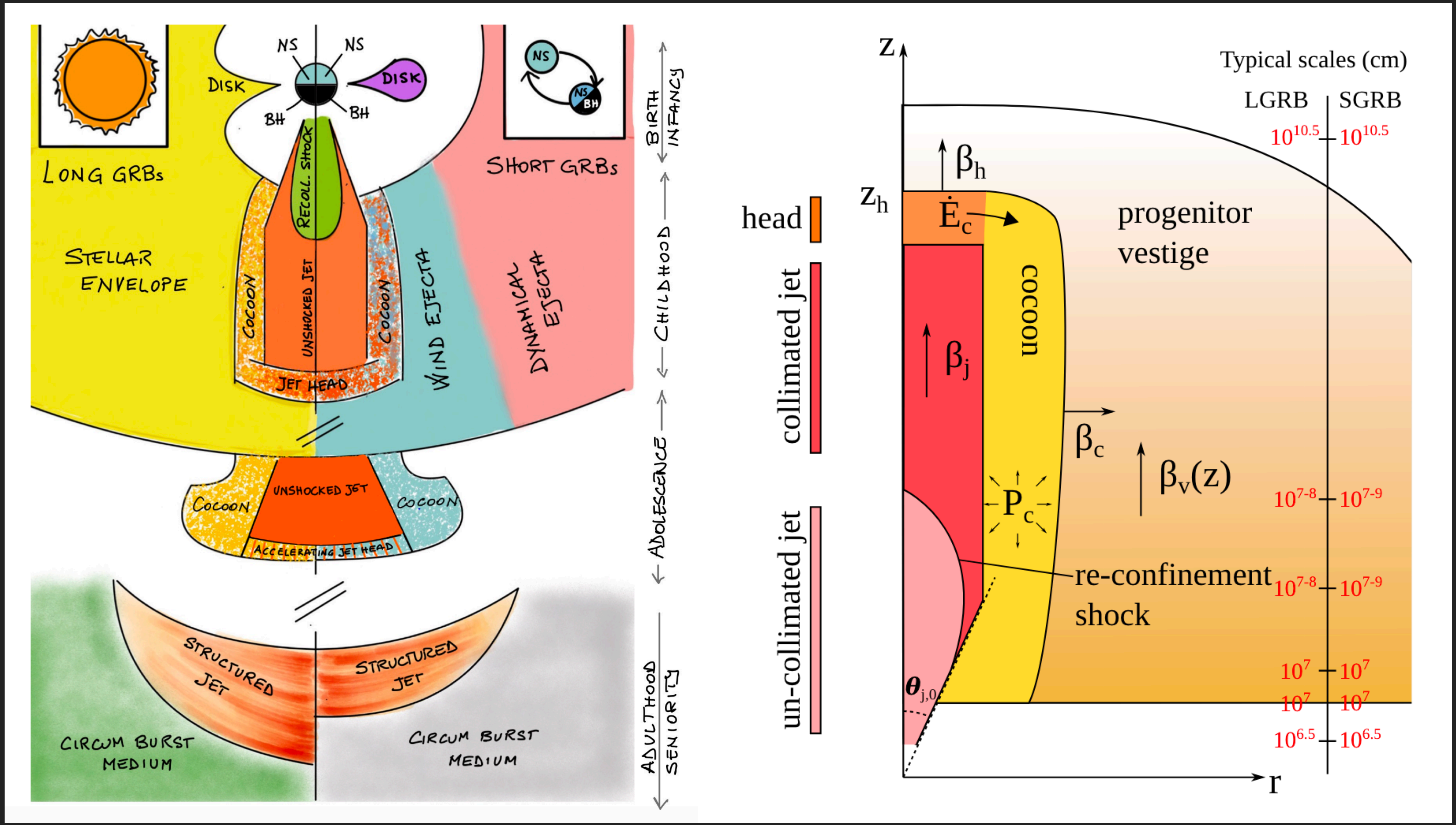
OINDRILA GHOSH

THE OSKAR KLEIN CENTRE FOR COSMOPARTICLE PHYSICS, STOCKHOLM UNIVERSITY

WHAT FAST TRANSIENTS TELL US ABOUT AXION-LIKE PARTICLES

TeV Particle Astrophysics, Chicago | August 28, 2024

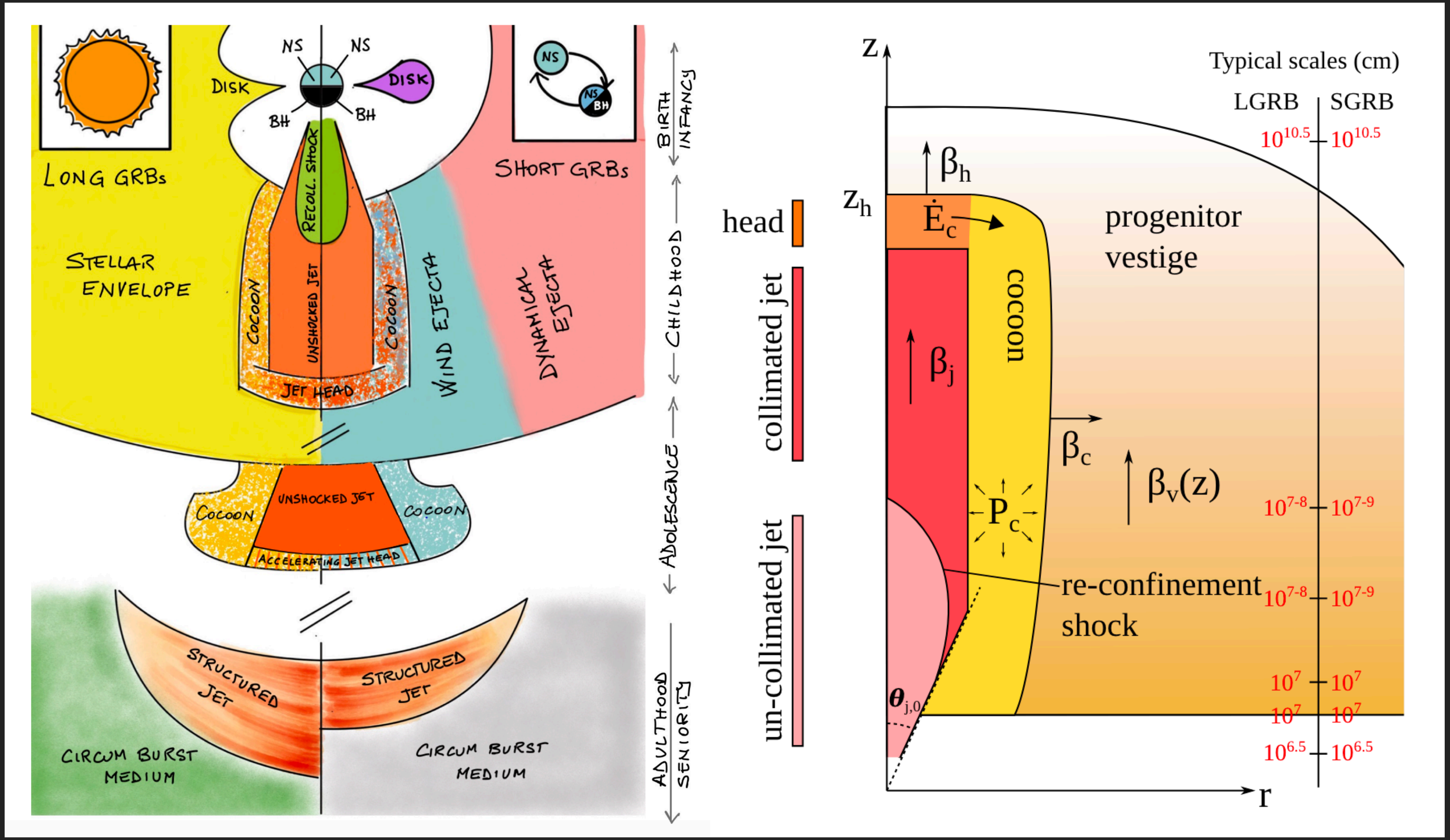
ANATOMY OF A FAST TRANSIENT



Salafia & Ghirlanda, 2022

ANATOMY OF A FAST TRANSIENT

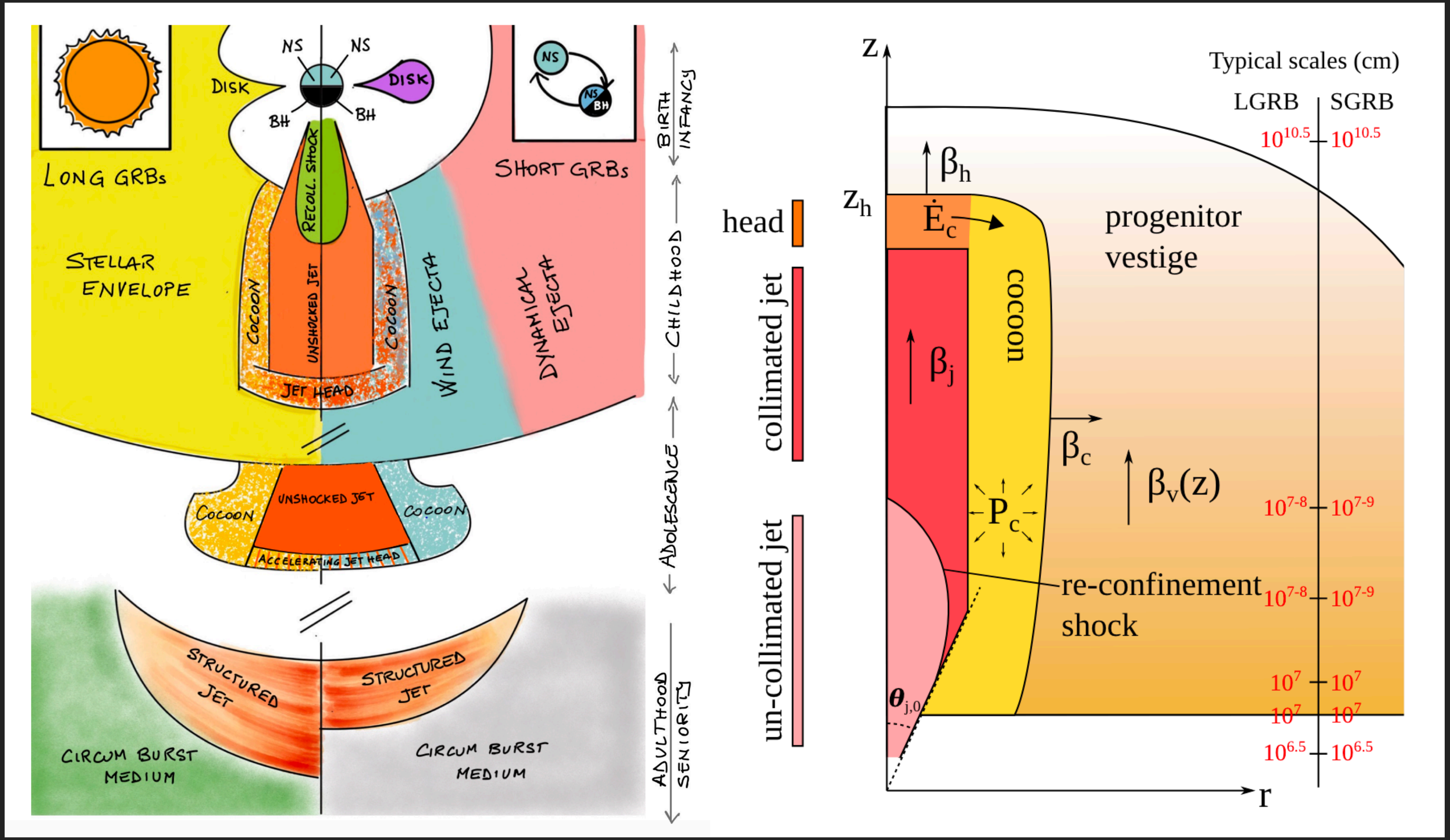
- Central engine: compact object/ merger remnant + accretion disk



Salafia & Ghirlanda, 2022

ANATOMY OF A FAST TRANSIENT

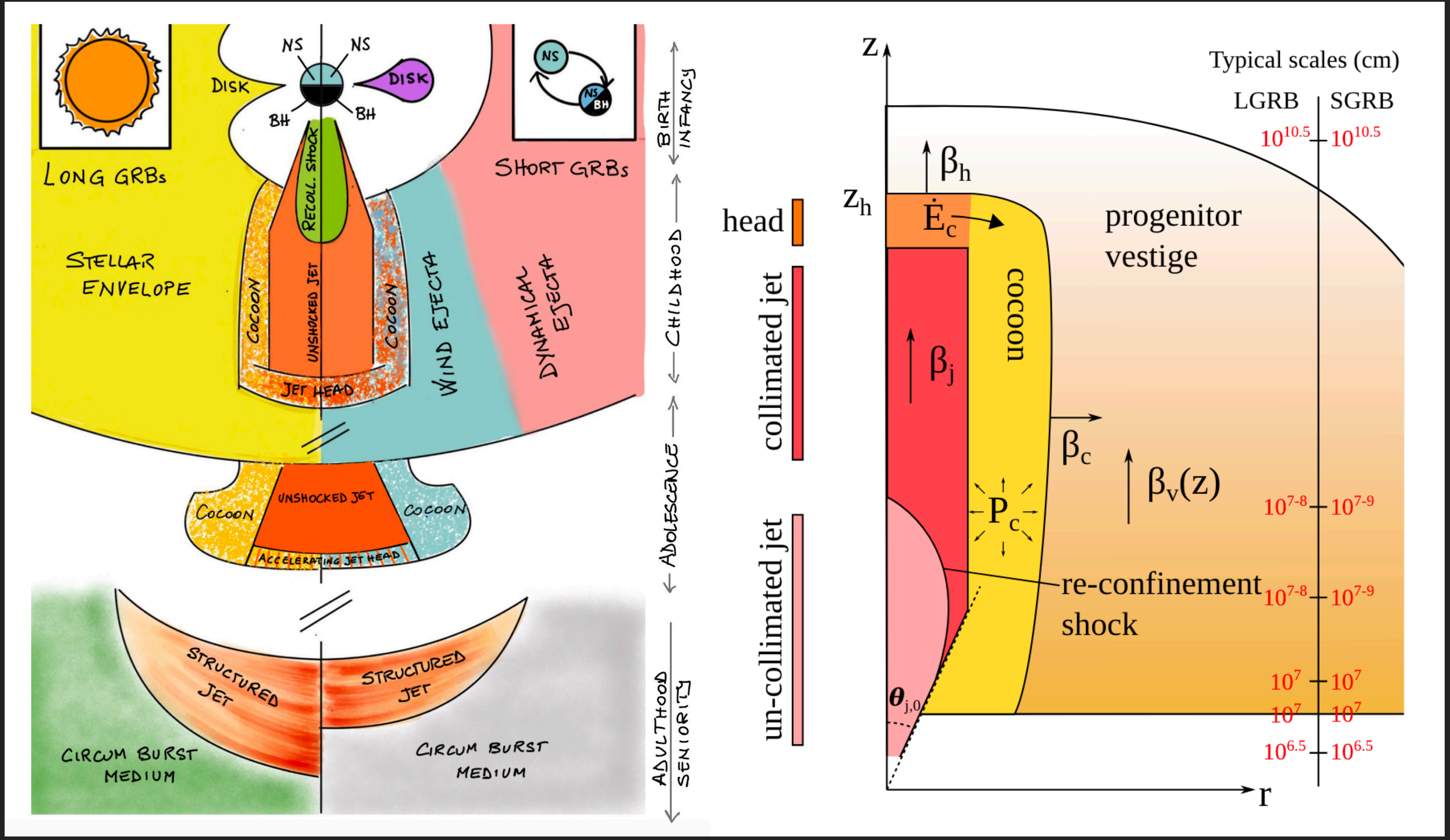
- Central engine: compact object/ merger remnant + accretion disk
- A bipolar relativistic collimated ejecta is launched



Salafia & Ghirlanda, 2022

ANATOMY OF A FAST TRANSIENT

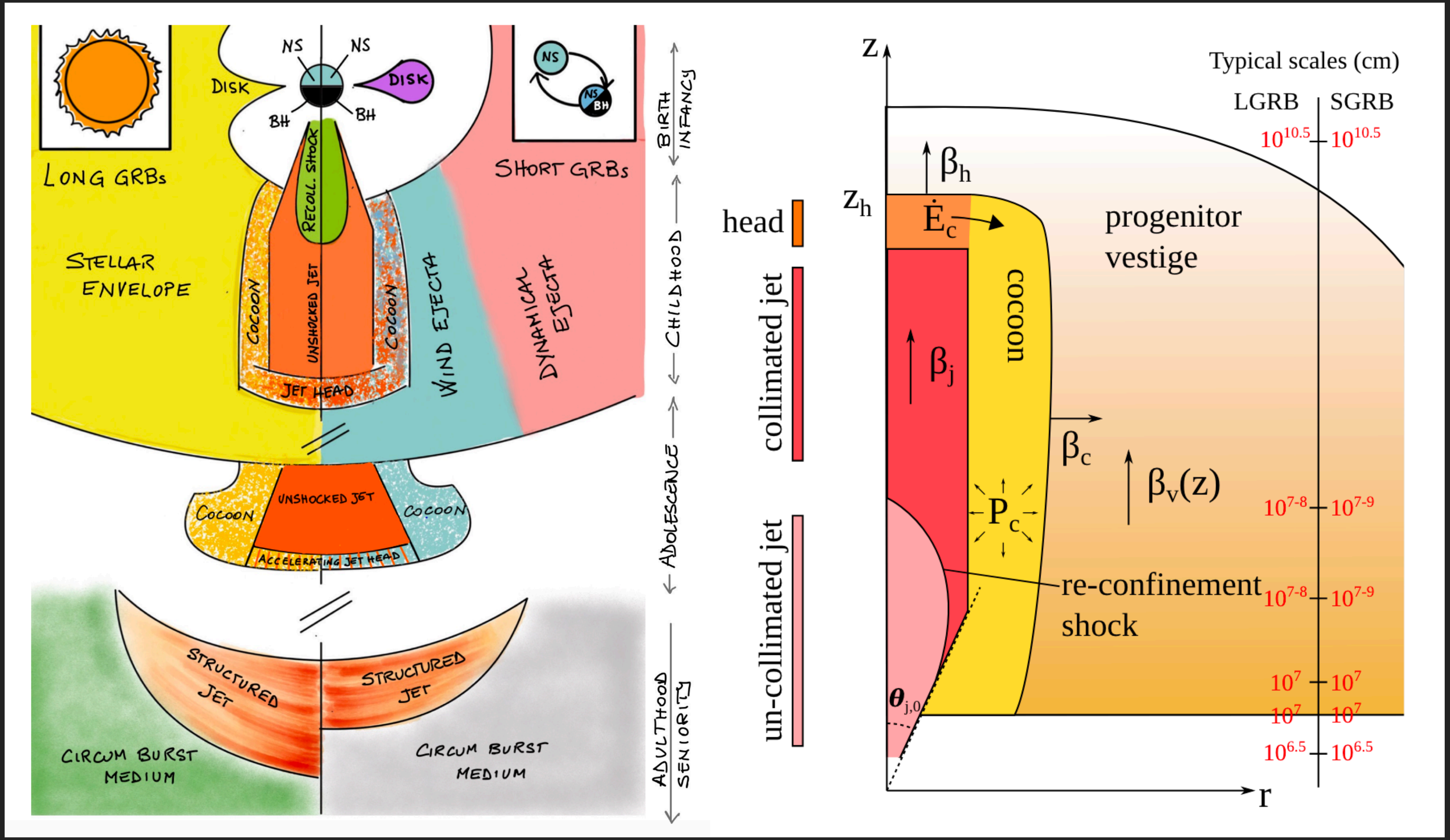
- Central engine: compact object/ merger remnant + accretion disk
- A bipolar relativistic collimated ejecta is launched
- Bulk energy dissipation leads to bright, highly variable, non-thermal prompt emission



Salafia & Ghirlanda, 2022

ANATOMY OF A FAST TRANSIENT

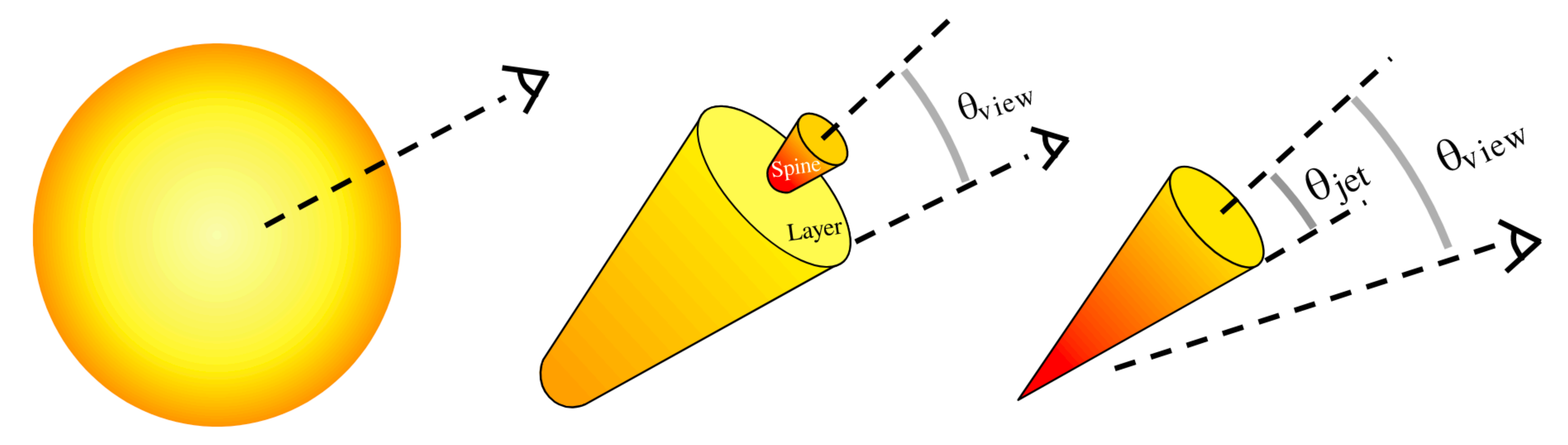
- Central engine: compact object/merger remnant + accretion disk
- A bipolar relativistic collimated ejecta is launched
- Bulk energy dissipation leads to bright, highly variable, non-thermal prompt emission
- The long-lasting multi-wavelength afterglow emission results from outflow interacting with the circumburst medium



Salafia & Ghirlanda, 2022

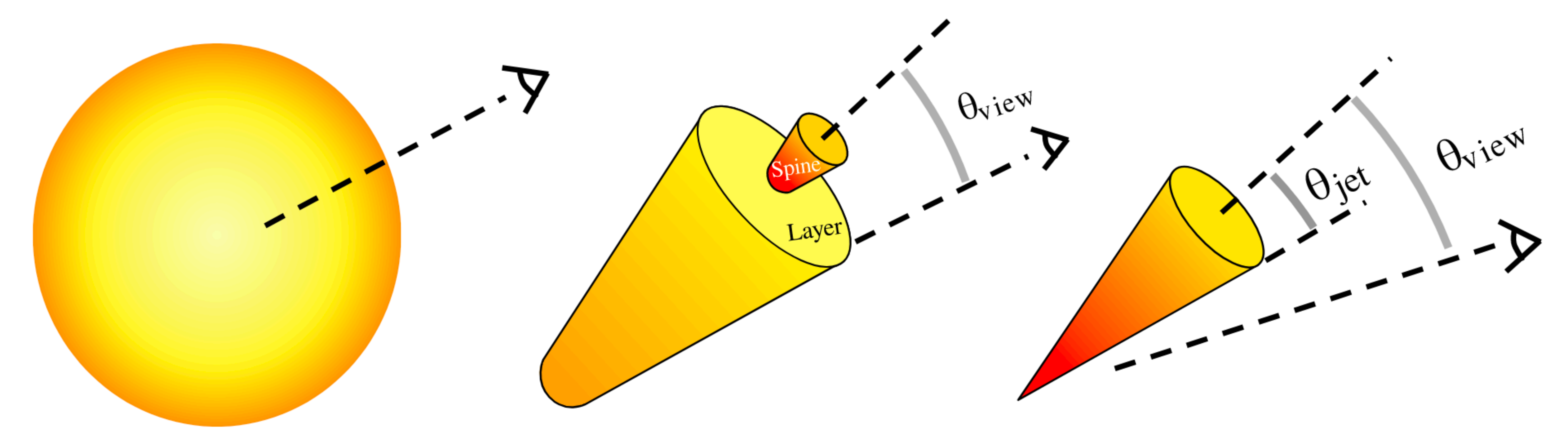
FIREBALL LAUNCH

- Several jetted and non-jetted models exist



Salafia, Ghisellini & Ghirlanda, 2022

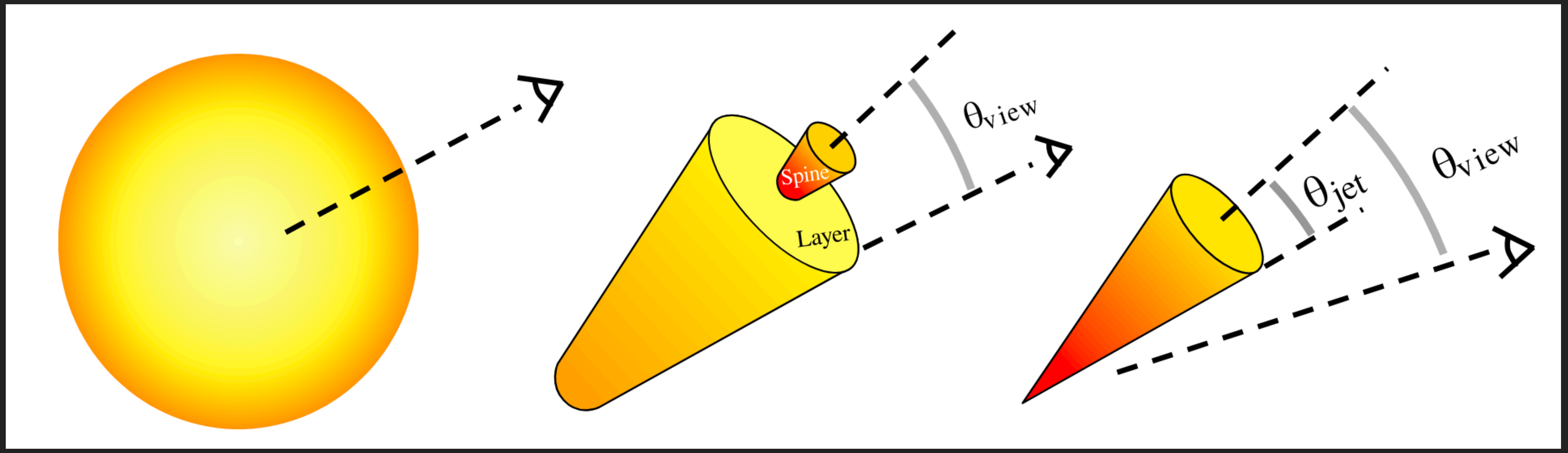
FIREBALL LAUNCH



Salafia, Ghisellini & Ghirlanda, 2022

- Several jetted and non-jetted models exist
- For structured jets, viewing angles play an important role in brightness estimation

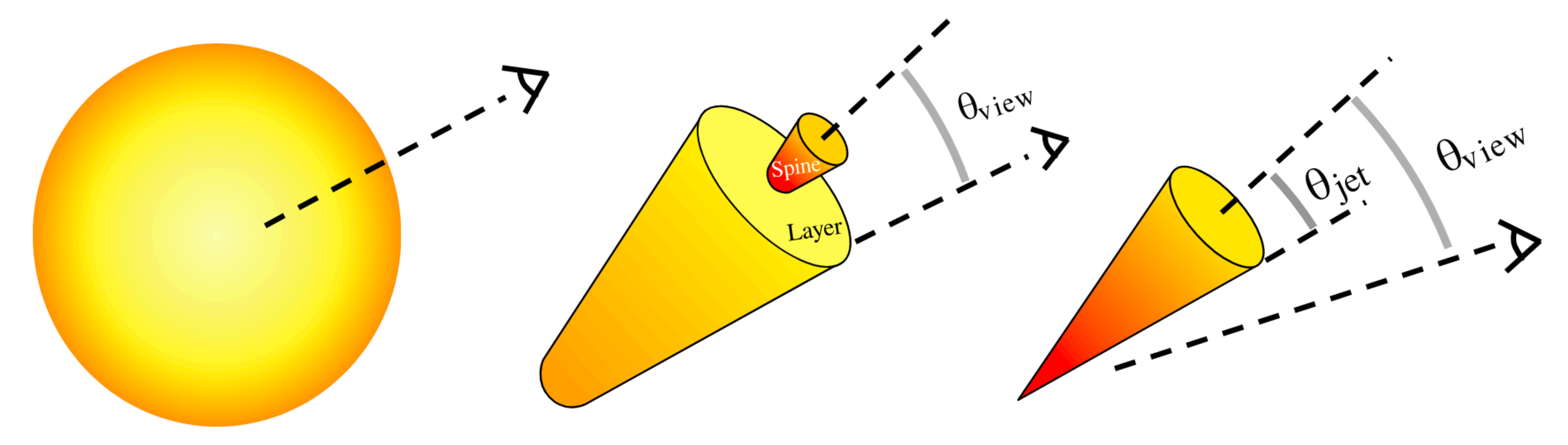
FIREBALL LAUNCH



Salafia, Ghisellini & Ghirlanda, 2022

- Several jetted and non-jetted models exist
- For structured jets, viewing angles play an important role in brightness estimation
- When outflow is collimated within an angle θ, adjusting for the beaming factor $\theta^2/2$

FIREBALL LAUNCH

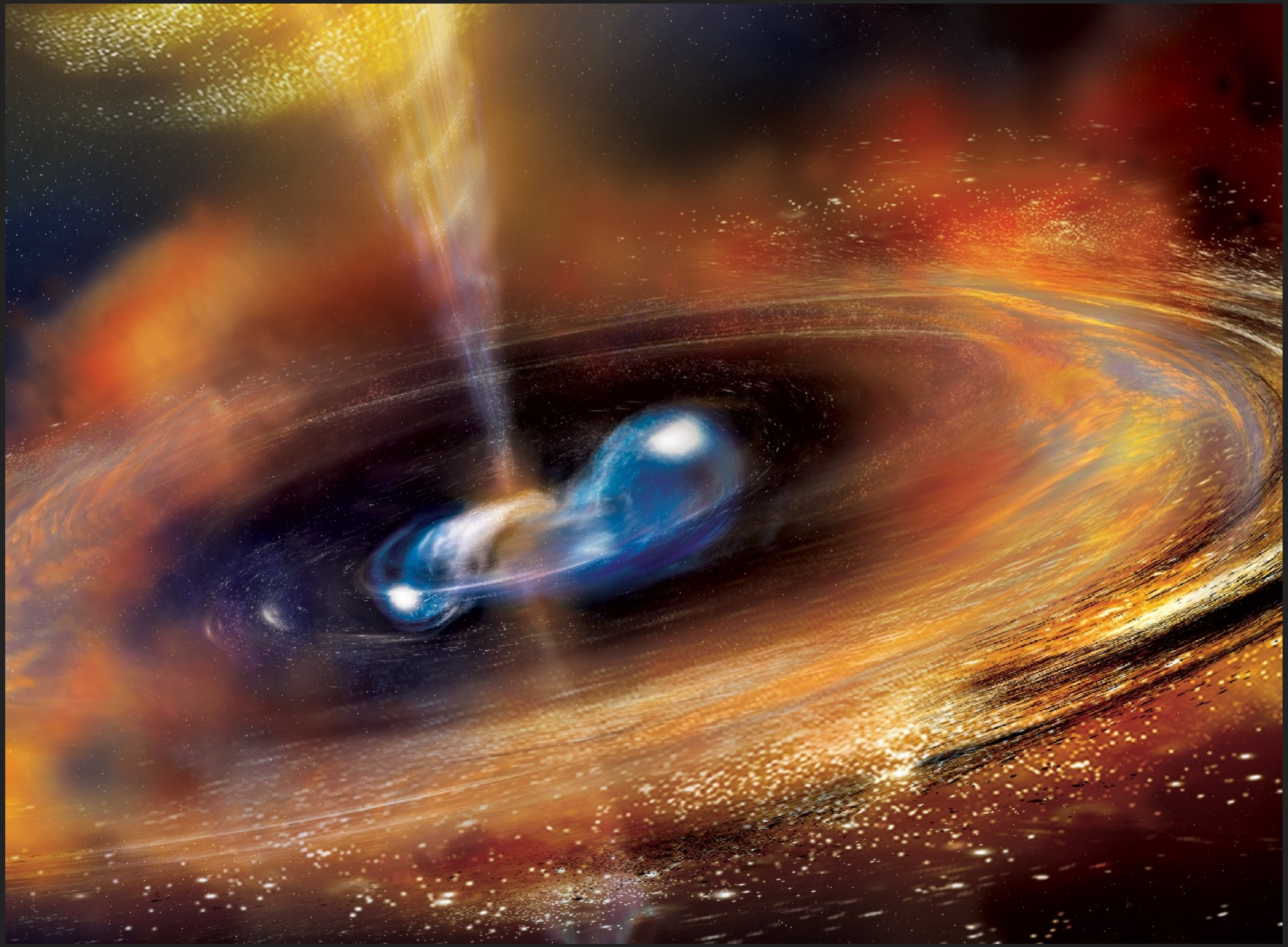


Salafia, Ghisellini & Ghirlanda, 2022

- Several jetted and non-jetted models exist
- For structured jets, viewing angles play an important role in brightness estimation
- When outflow is collimated within an angle θ, adjusting for the beaming factor $\theta^2/2$
- Isotropic luminosity can reach $10^{54} - 10^{55}$ erg/s, with low-luminosity GRBs indicating a choked/cocooned jet

ENERGY DISSIPATION

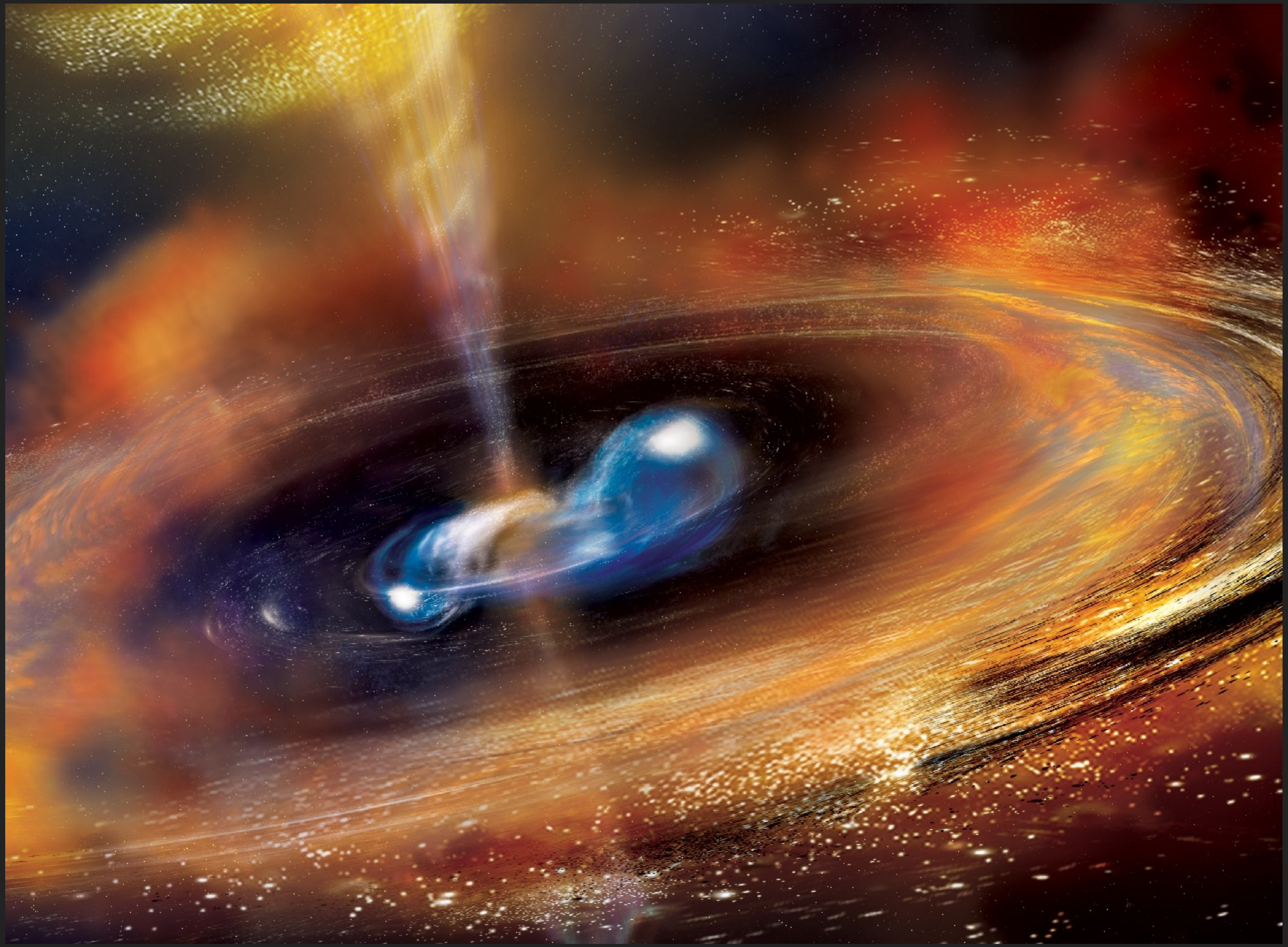
- Central engine: kilonovae with gravitational wave counterparts



NASA

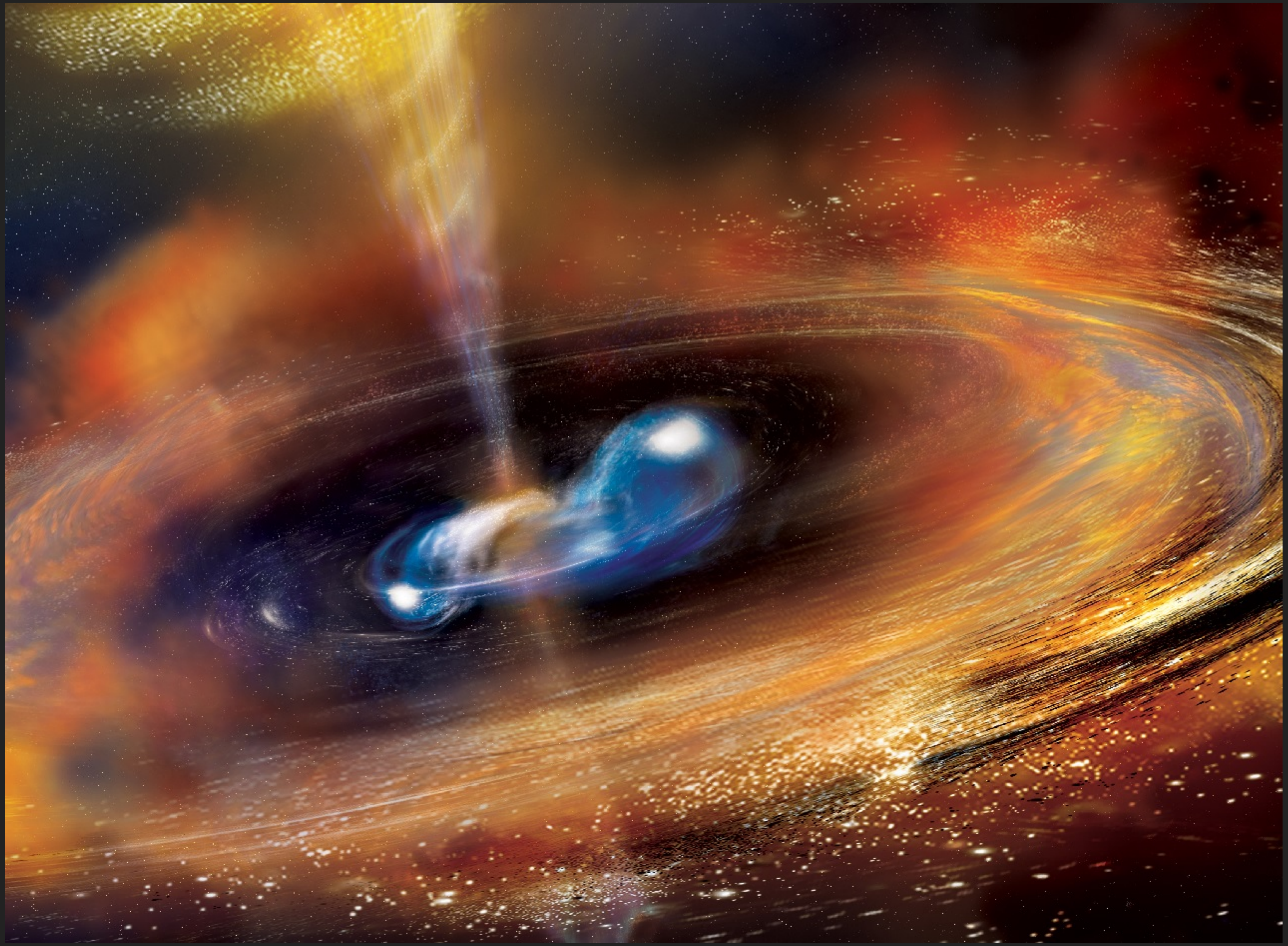
ENERGY DISSIPATION

- Central engine: kilonovae with gravitational wave counterparts
- Average intrinsic luminosity for sGRBs ~ 10^{50} erg/s


NASA

ENERGY DISSIPATION

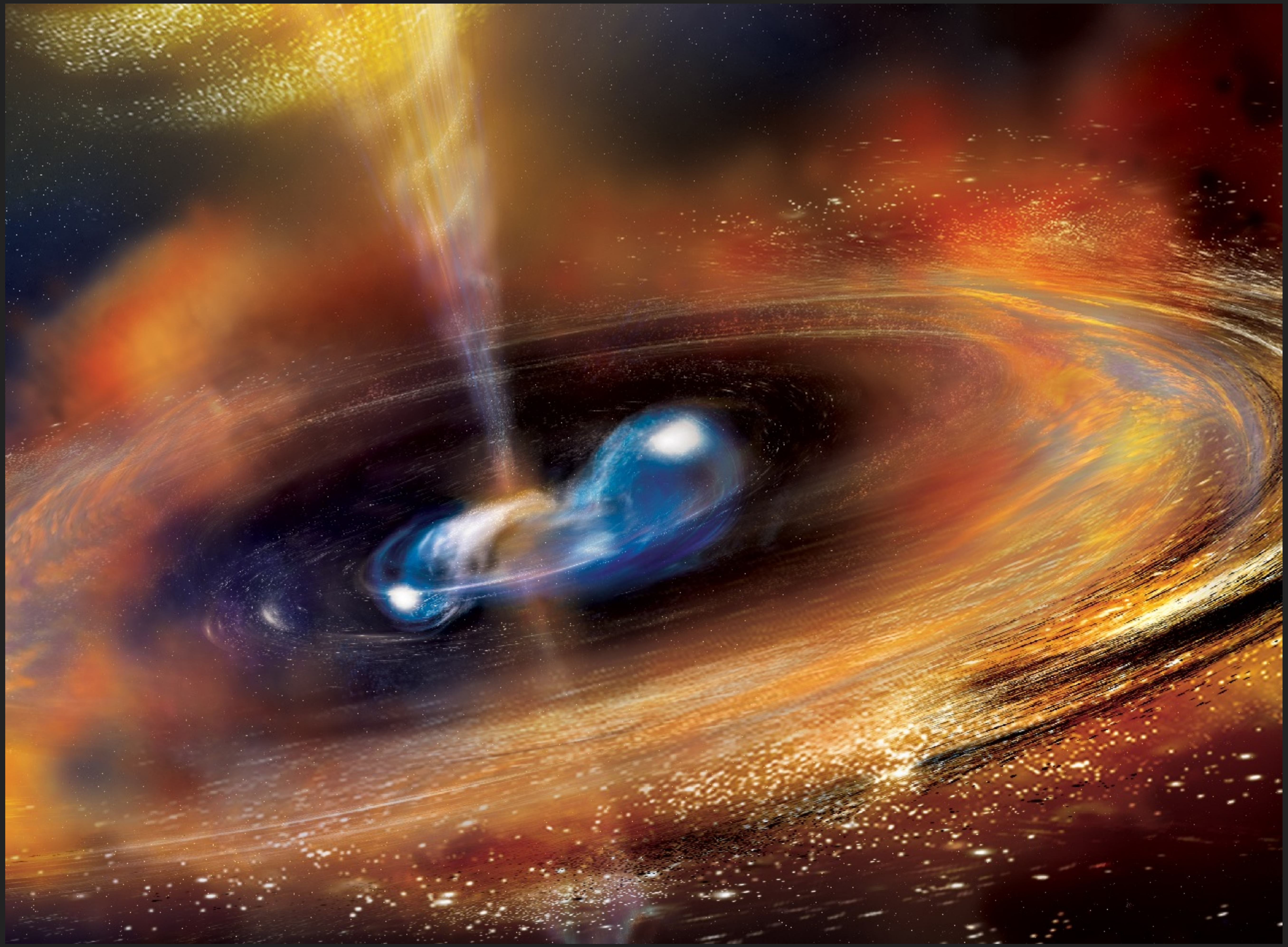
- Central engine: kilonovae with gravitational wave counterparts
- Average intrinsic luminosity for sGRBs ~ 10^{50} erg/s
- Leptonic scenario: pure radiative photon-lepton fireball, Poynting-dominated, launched through Blandford-Znajek mechanism



NASA

ENERGY DISSIPATION

- Central engine: kilonovae with gravitational wave counterparts
- Average intrinsic luminosity for sGRBs ~ 10^{50} erg/s
- Leptonic scenario: pure radiative photon-lepton fireball, Poynting-dominated, launched through Blandford-Znajek mechanism
- Hadronic scenario: created by neutrino-antineutrino annihilation



NASA

THE PURELY RADIATIVE PHOTON-LEPTON FIREBALL

- A sphere with a characteristic injection radius r_0 and with a surface temperature T_0 would emit blackbody radiation at rate $\dot{E}$ till the photosphere is reached $r_{ph} > > r_0 \sim R_s$

THE PURELY RADIATIVE PHOTON-LEPTON FIREBALL

- A sphere with a characteristic injection radius r_0 and with a surface temperature T_0 would emit blackbody radiation at rate $\dot{E}$ till the photosphere is reached $r_{ph} > > r_0 \sim R_s$

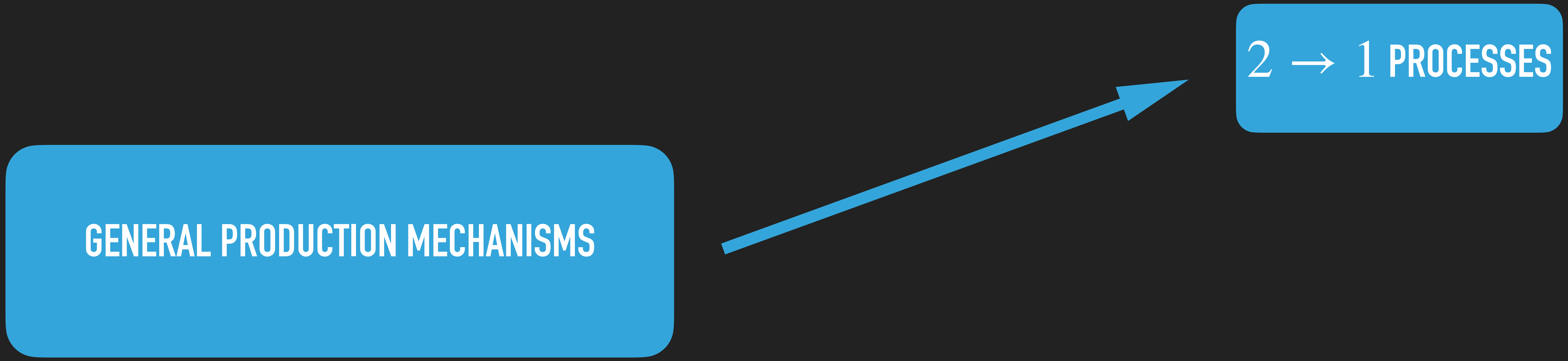
Solving Flammang's equation for a steady-state relativistic outflow

- Temperature scaling $T = T_0 r_0 / r$
- Lorentz factor scaling $\gamma = r / r_0$
- Luminosity $\dot{E} = \frac{16}{3} 4\pi r_0^2 \sigma T_0^4$

HEAVY ALP PRODUCTION IN A LEPTONIC FIREBALL

GENERAL PRODUCTION MECHANISMS

HEAVY ALP PRODUCTION IN A LEPTONIC FIREBALL



GENERAL PRODUCTION MECHANISMS

$2 \rightarrow 1$ PROCESSES

HEAVY ALP PRODUCTION IN A LEPTONIC FIREBALL

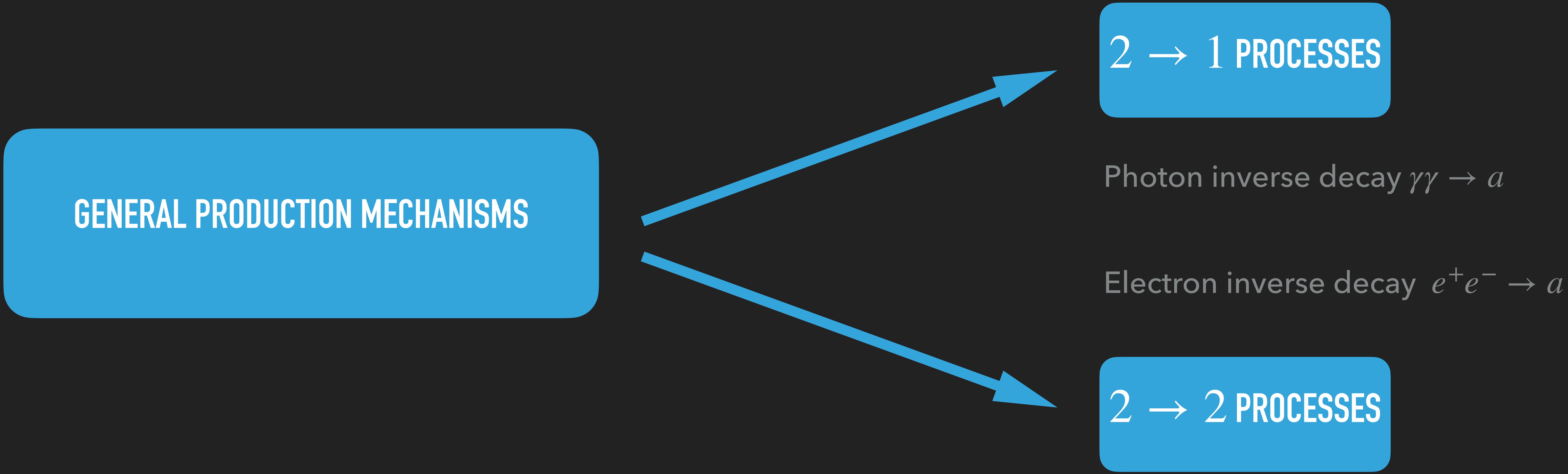
GENERAL PRODUCTION MECHANISMS

$2 \rightarrow 1$ PROCESSES

Photon inverse decay $\gamma\gamma \rightarrow a$

Electron inverse decay $e^+e^- \rightarrow a$

HEAVY ALP PRODUCTION IN A LEPTONIC FIREBALL



GENERAL PRODUCTION MECHANISMS

$2 \rightarrow 1$ PROCESSES

Photon inverse decay $\gamma\gamma \rightarrow a$

Electron inverse decay $e^+e^- \rightarrow a$

$2 \rightarrow 2$ PROCESSES

HEAVY ALP PRODUCTION IN A LEPTONIC FIREBALL

GENERAL PRODUCTION MECHANISMS

$2 \rightarrow 1$ PROCESSES

Photon inverse decay $\gamma\gamma \rightarrow a$

Electron inverse decay $e^+e^- \rightarrow a$

$2 \rightarrow 2$ PROCESSES

Fermion annihilation $e^+e^- \rightarrow a + \gamma$

Photon conversion $e^\pm + \gamma \rightarrow e^\pm + a$

SM PROCESS RATES

- Bremsstrahlung rate

$$\Gamma_{\text{brem}} \approx \frac{2n_e\alpha^3 \log\left(e^{\gamma_E}m_e^2/T(r)^2\right)}{9m_e^2}\left[12\log\left(e^{\gamma_E}m_e^2/T(r)^2\right) - 84 + 48\log\left(e^{\gamma_E}m_e/T(r)\right)\right]$$

SM PROCESS RATES

- Bremsstrahlung rate $$\Gamma_{\text{brem}} \approx \frac{2n_e\alpha^3\log\left(e^{\gamma_E}m_e^2/T(r)^2\right)}{9m_e^2}\left[12\log\left(e^{\gamma_E}m_e^2/T(r)^2\right) - 84 + 48\log\left(e^{\gamma_E}m_e/T(r)\right)\right]$$
- Annihilation rate $$\Gamma_{\text{annih}} \approx \frac{\pi n_e\alpha^2}{m_e^2}\left(1 + \frac{2\left(T(r)/m_e\right)^2}{1+\log\left(\frac{2T(r)}{m_e e^{\gamma E}} + 1.3\right)}\right)^{-1}$$

SM PROCESS RATES

- Bremsstrahlung rate $$\Gamma_{\text{brem}} \approx \frac{2n_e\alpha^3 \log\left(e^{\gamma_E}m_e^2/T(r)^2\right)}{9m_e^2}\left[12\log\left(e^{\gamma_E}m_e^2/T(r)^2\right) - 84 + 48\log\left(e^{\gamma_E}m_e/T(r)\right)\right]$$

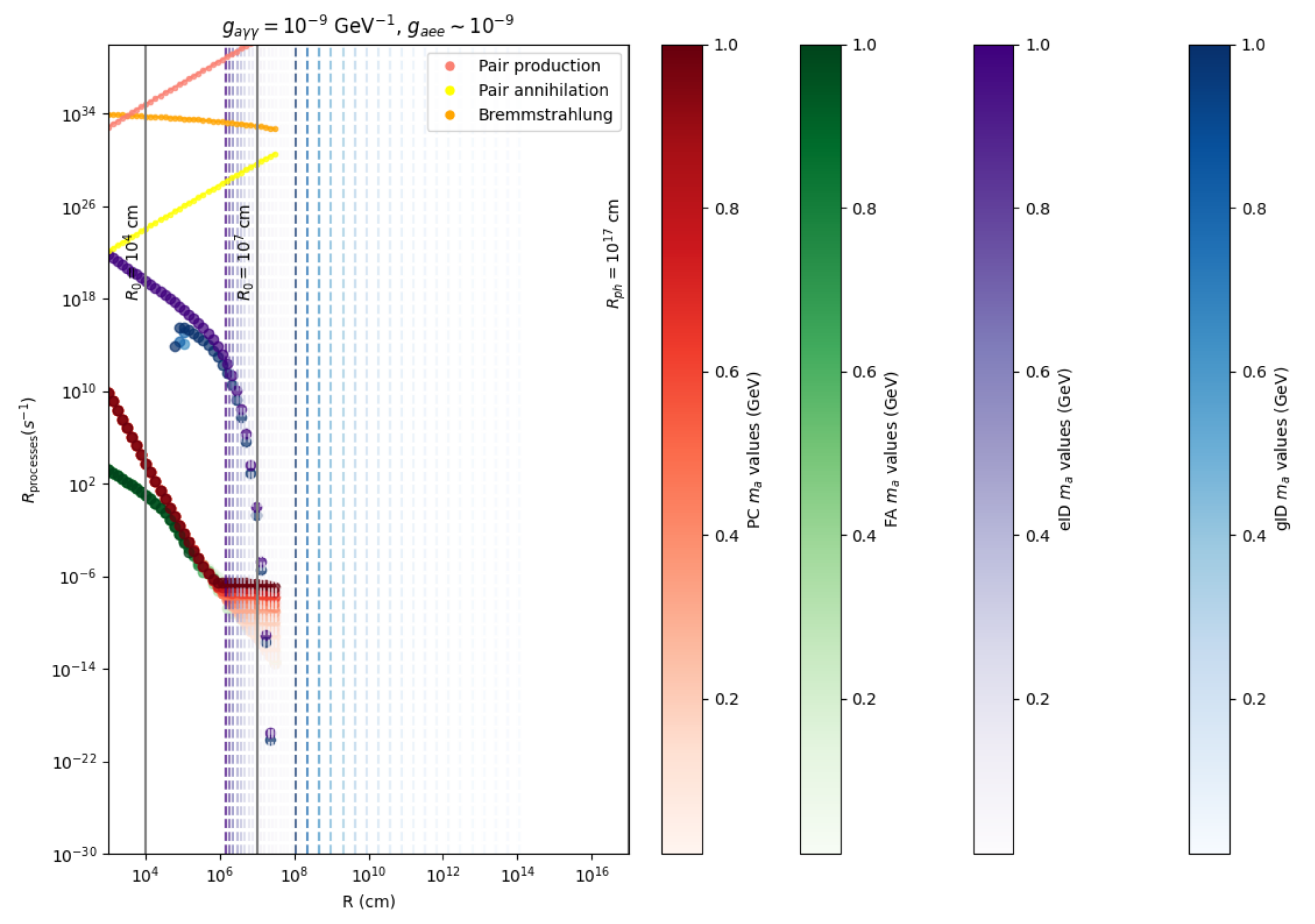
- Annihilation rate $$\Gamma_{\text{annih}} \approx \frac{\pi n_e\alpha^2}{m_e^2}\left(1 + \frac{2\left(T(r)/m_e\right)^2}{1+\log\left(\frac{2T(r)}{m_e e^{\gamma_E}} + 1.3\right)}\right)^{-1}$$

We assume $E_\gamma = T$

The mean photon energy taking on the thermal energy in the blackbody

- Pair production rate $$\Gamma_{\text{prod}} = \begin{cases} 0, & T < 10m_e \\ n_\gamma \cdot \sigma_{\gamma\gamma\to e^+e^-} \cdot c, & T \geq 10m_e \end{cases}$$ with $$\sigma_{\gamma\gamma\to e^+e^-} = \frac{\pi\alpha^2}{E_\gamma^2}\left[\left(2 + \frac{2m_e^2}{E_\gamma^2} - \frac{m_e^4}{E_\gamma^4}\right) \times \log\left|\frac{E_\gamma}{m_e} + \sqrt{\frac{E_\gamma^2}{m_e^2} - 1}\right| - \sqrt{1 - \frac{m_e^2}{E_\gamma^2}}\left(1 + \frac{m_e^2}{E_\gamma^2}\right)\right]$$

ALPS BORN IN LEPTONIC FIREBALLS



- Fireball is launched at a distance scale from the central engine of the order of the Schwarzschild radius

$$R_s = \sqrt{\frac{2G}{c^2}\left(\frac{M}{3M_\odot}\right)} = 8.86 \times 10^5 \text{ cm}$$

- Most of the ALP production takes place before the fireball expands to its photospheric radius
- ALPs perform energy transport out of the fireball and decay outside

OG, Jacobsen, Linden (this work) 2409.XXXXX

LUMINOSITY CALCULATION FOR A PHOTOPHILIC ALP

- Produced ALP spectra

$$\frac{d\dot{n}_a}{dE_a}(r) = \frac{g_{a\gamma}^2}{128\pi^3} m_a^4 p \left(1 - \frac{4\omega_{\rm pl}^2}{m_a^2}\right)^{3/2} e^{-E_a/T(r)}$$

LUMINOSITY CALCULATION FOR A PHOTOPHILIC ALP

- Produced ALP spectra

$$\frac{d\dot{n}_a}{dE_a}(r) = \frac{g_{a\gamma}^2}{128\pi^3} m_a^4 p \left(1 - \frac{4\omega_{\rm pl}^2}{m_a^2}\right)^{3/2} e^{-E_a/T(r)}$$

We set $R_c = 10^7$ cm

- Luminosity at production

$$L_{a,prod} = \pi \Delta\theta^2 \int_{r_s}^{R_c} dr r^2 \int_{m_a}^{\infty} dE E \frac{d\dot{n}_a(r)}{dE_a}$$

GRAVITATIONAL TRAPPING

- Accounting for gravitational trapping does not significantly alter our estimates

$$L_{a,prod} = \int \dots \Theta\left(E_a - m_a - \frac{2GMm_a}{rc^2}\right)$$

- Ejecta/ fireball expansion speed ~ 0.3c - 0.6c
- Boosted further by the fireball Lorentz factor in the observer frame $\Gamma_0 \sim 4/3$ at birth

GRAVITATIONAL TRAPPING

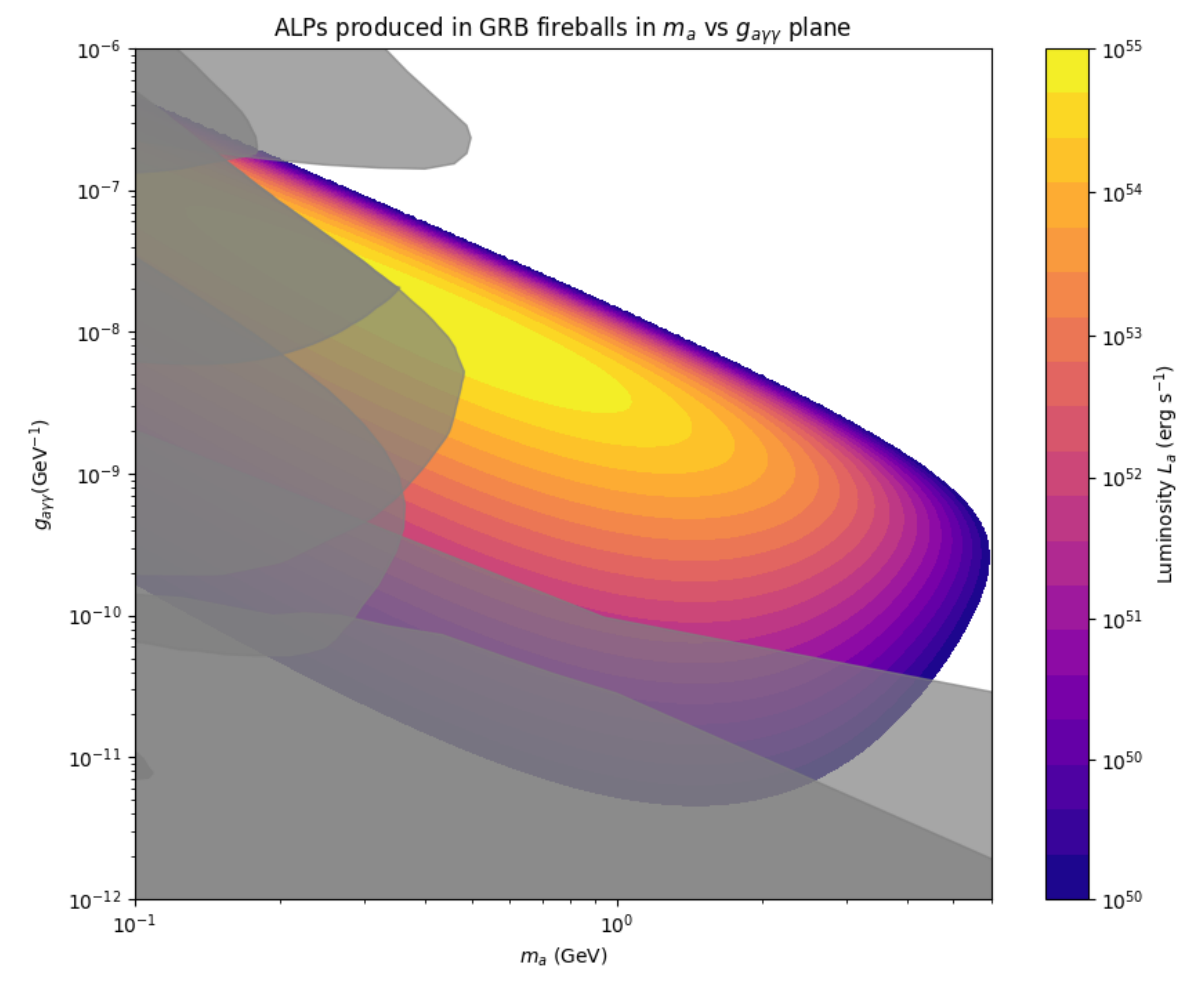
- Accounting for gravitational trapping does not significantly alter our estimates
$$L_{a,prod} = \int \ldots \Theta\left(E_a - m_a - \frac{2GMm_a}{rc^2}\right)$$
- Ejecta/ fireball expansion speed ~ 0.3c - 0.6c
- Boosted further by the fireball Lorentz factor in the observer frame $\Gamma_0 \sim 4/3$ at birth

TRAPPING BY DECAY

- Decay length
$$\lambda_{\gamma\gamma\to a} = \frac{64\pi}{g_{a\gamma}^2 m_a^4}\sqrt{E_a^2 - m_a^2}$$
- Decay-adjusted luminosity
$$L_{a,prod} = \int \ldots \exp(-r/\lambda_{\gamma\gamma\to a})$$
- Average axion speed in the lab frame >> fireball expansion speed

HEAVY AXIONS DISRUPT GAMMA-RAY BURSTS: LEADING BOUNDS

- We require $L_a \leq L_{intr} \sim 10^{50}$ erg/s for a complete disruption
- Calculated for a remnant mass of $3M_{\odot}$
- Assuming a conical geometry, less optimistic compared to an isotropically expanding fireball



OG, Jacobsen, Linden (this work) 2409.XXXXX

OTHER CONSIDERATIONS

- Also applicable to AGNs, in particular flaring sources, with specific accretion flow solutions consistent with observations
- For parameter space leading to $L_a < \mathcal{O}(10^{50}\ \mathrm{erg/s})$, even if a fraction of the energy goes into axions, regular electromagnetic cascades can still take place
- Intergalactic magnetic field constraints are significantly weakened
- For ALPs with nonzero electron and nucleon couplings, secondary decay e+e- pairs also participate in cascade

SUMMARY AND FUTURE

- We derive leading limits down to $g_{a\gamma\gamma} \sim 10^{-11}\mathrm{GeV}^{-1}$ for ALP masses in the MeV-GeV scale
- Nonlinear feedback on IGMF limits due to ALP processes
- Comprehensive treatment which also applies to fireballs with baryon loading
- Particularly interesting for sources associated with neutrino and GW events
- Primary and secondary decay products contribute to various diffuse photon backgrounds → watch out for excesses!

Thank you!

oindrila.ghosh@fysik.su.se

oindrilaghosh.com