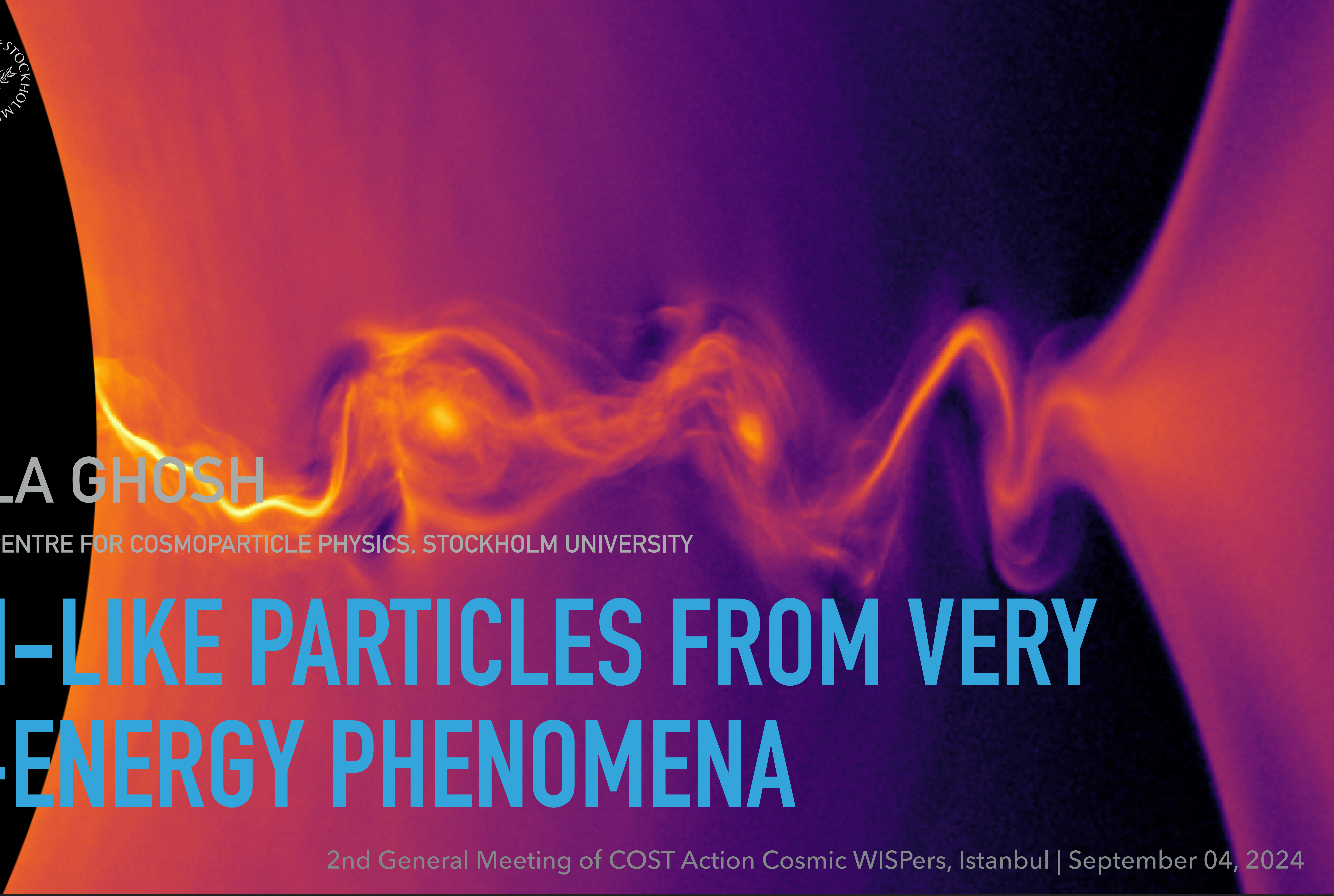


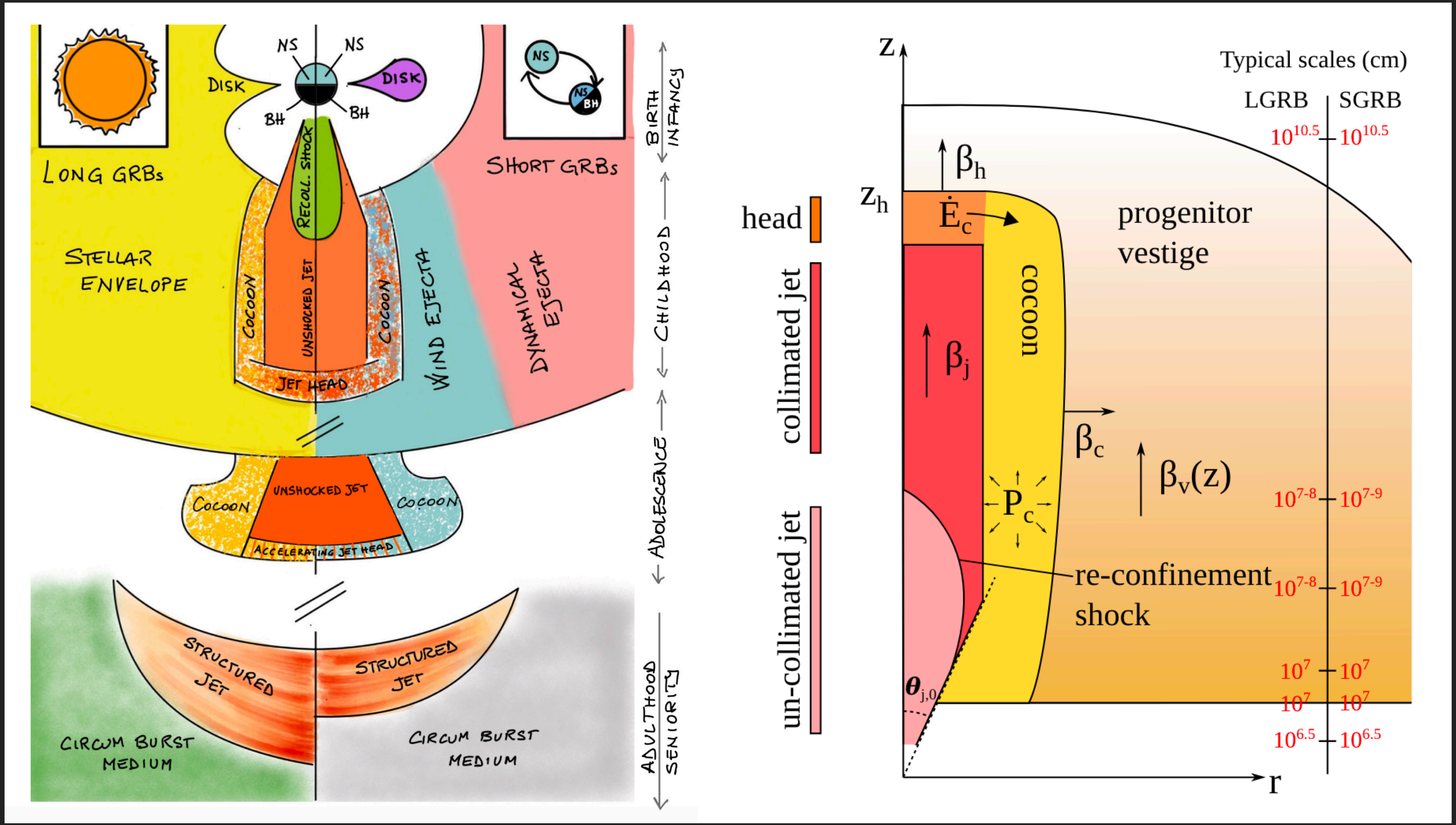
OINDRILA GHOSH

THE OSKAR KLEIN CENTRE FOR COSMOPARTICLE PHYSICS, STOCKHOLM UNIVERSITY

AXION-LIKE PARTICLES FROM VERY HIGH-ENERGY PHENOMENA

2nd General Meeting of COST Action Cosmic WISPers, Istanbul | September 04, 2024

ANATOMY OF A FAST TRANSIENT



Salafia & Ghirlanda, 2022

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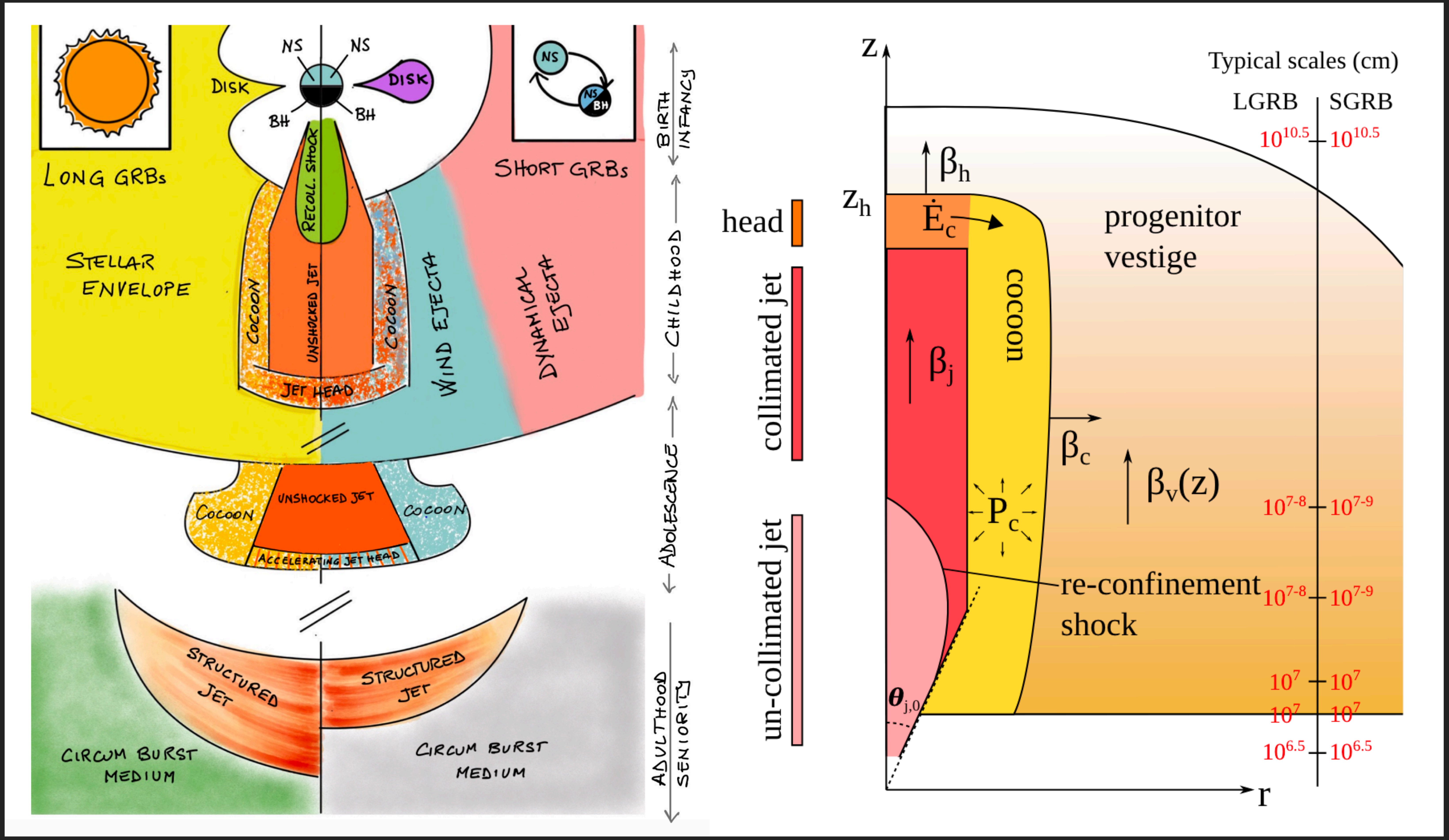

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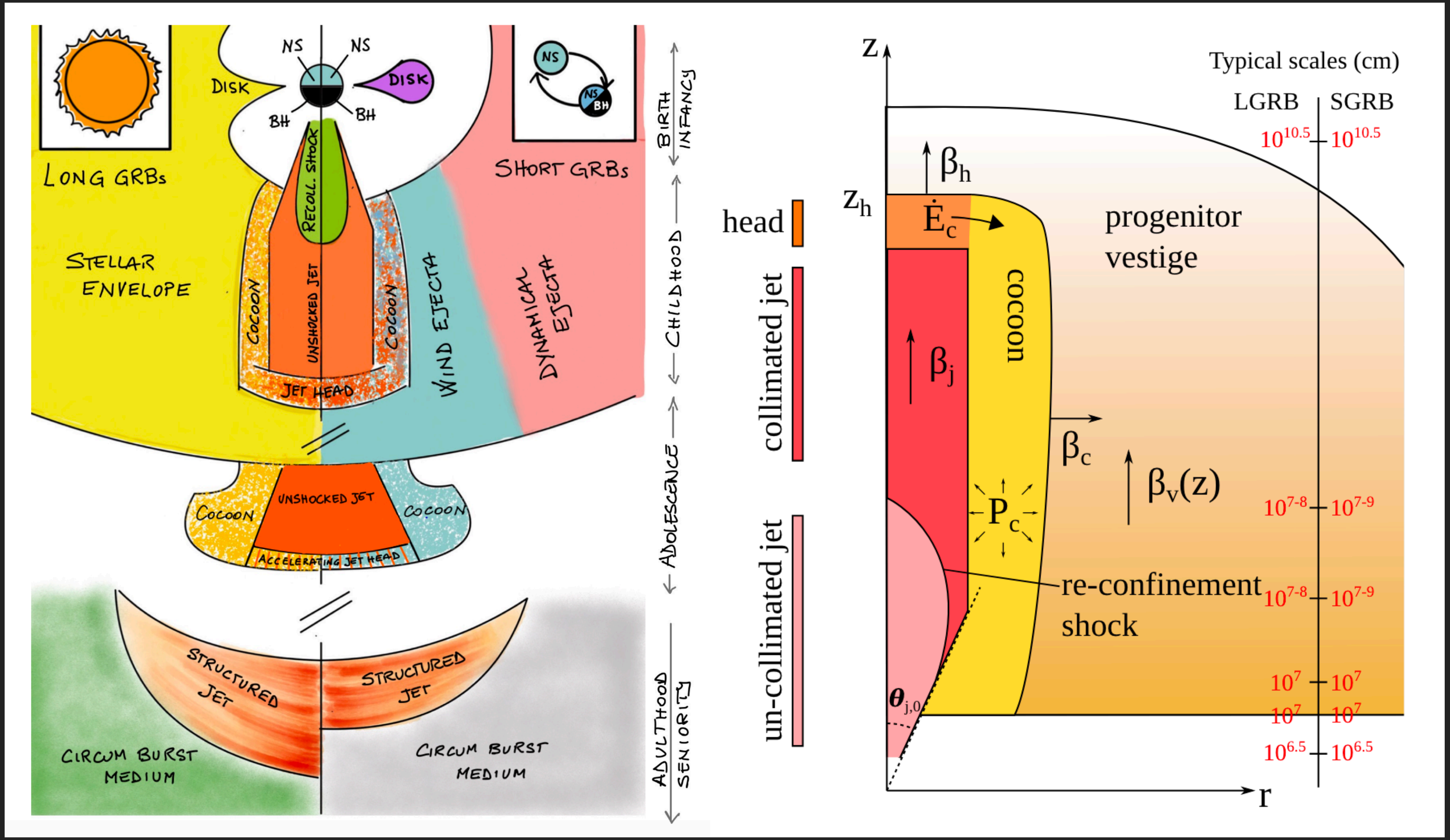

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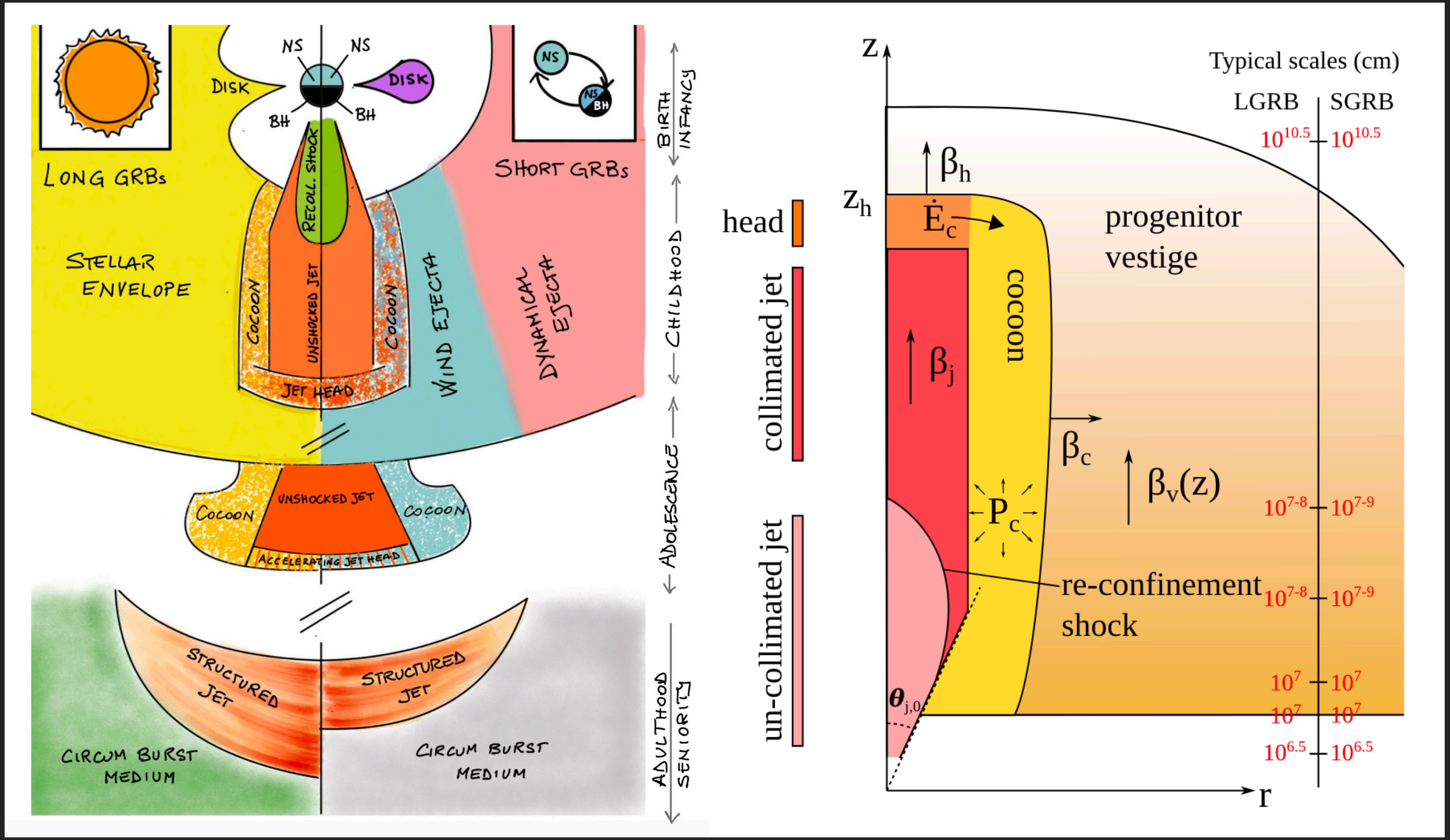

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ANATOMY OF A FAST TRANSIENT

- Central engine: compact object/merger remnant + accretion disk
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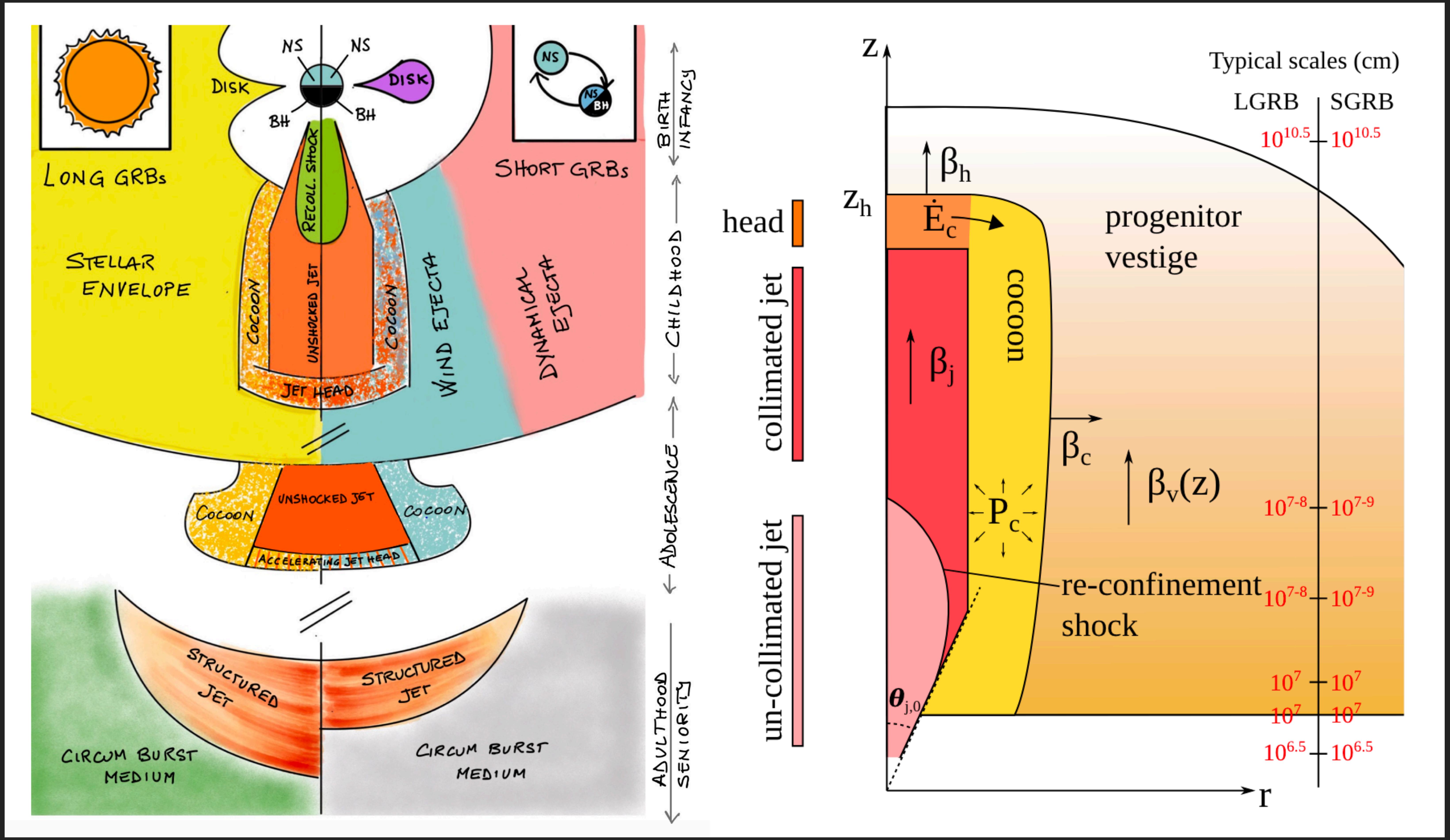
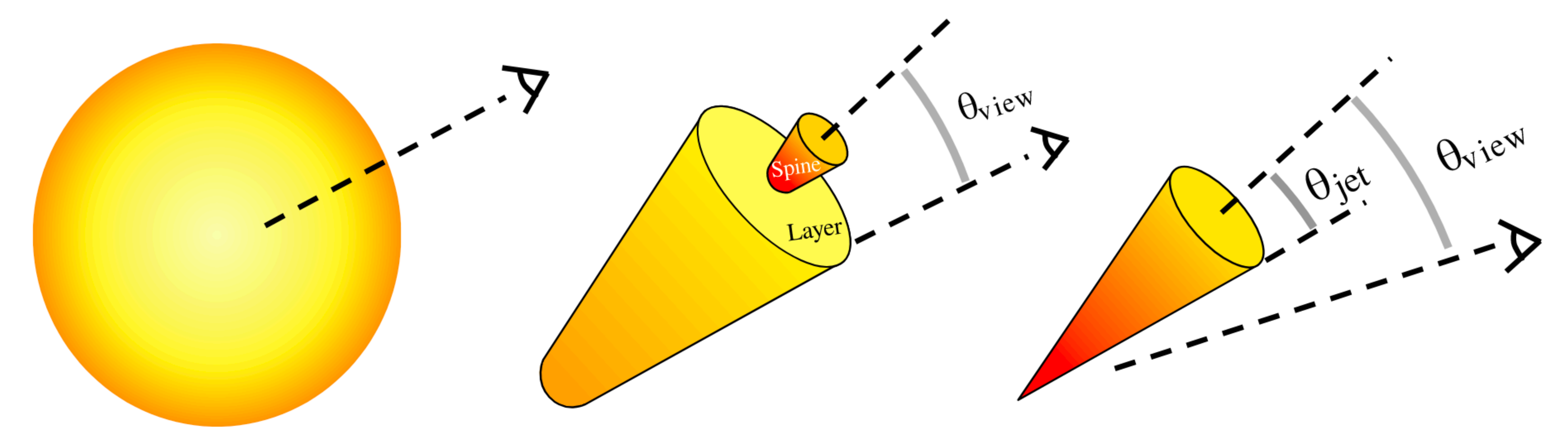
- The long-lasting multi-wavelength afterglow emission results from outflow interacting with the circumburst medium



Salafia & Ghirlanda, 2022

FIREBALL LAUNCH

- Several jetted and non-jetted models exist



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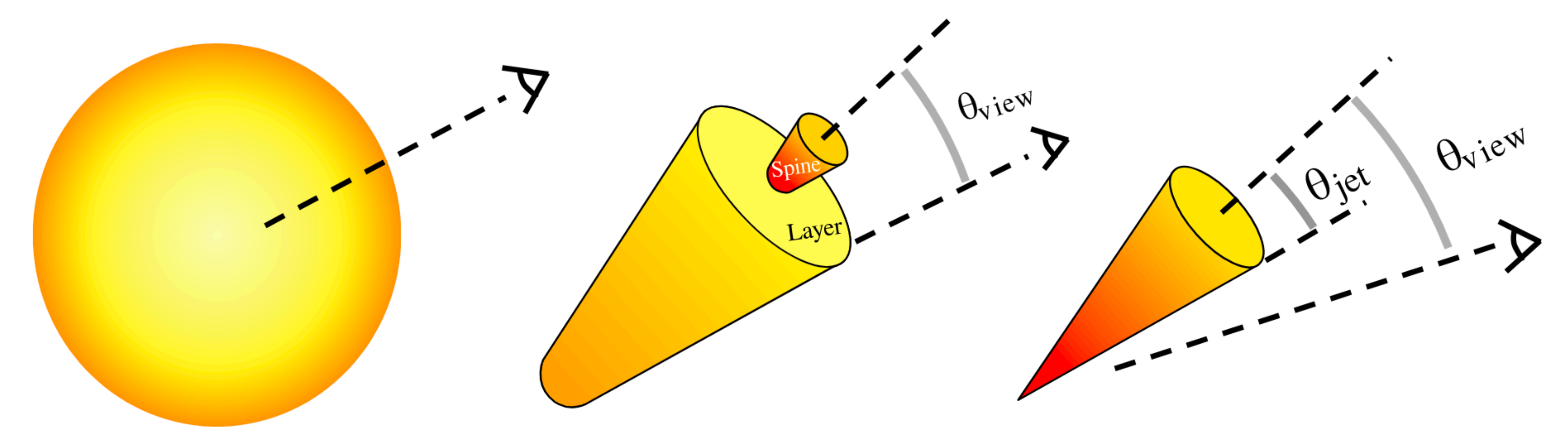

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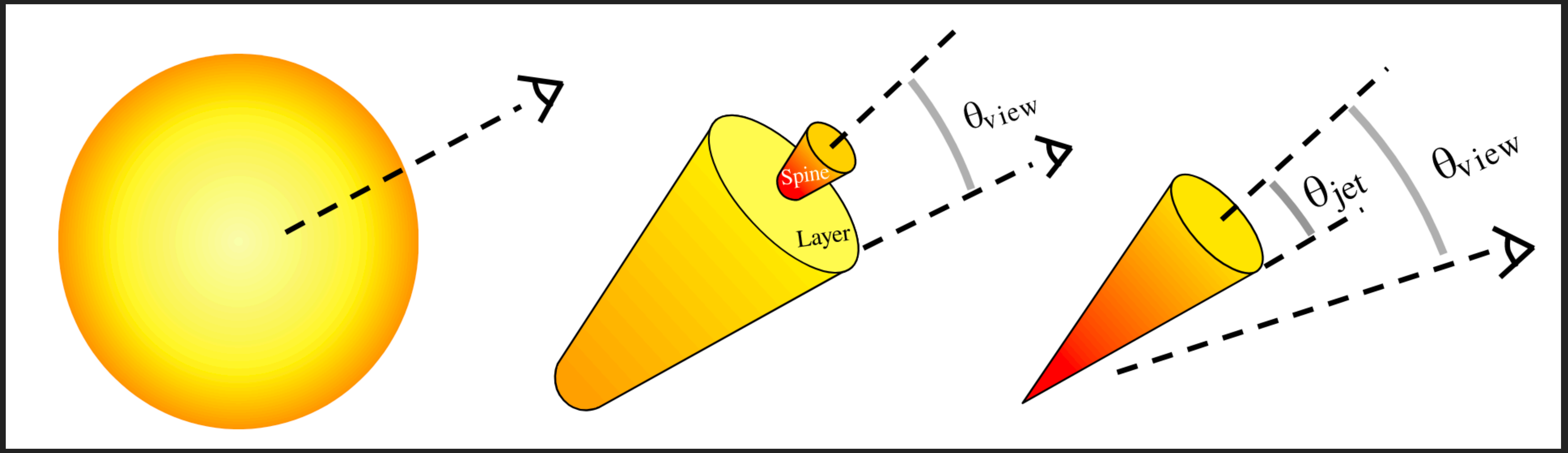

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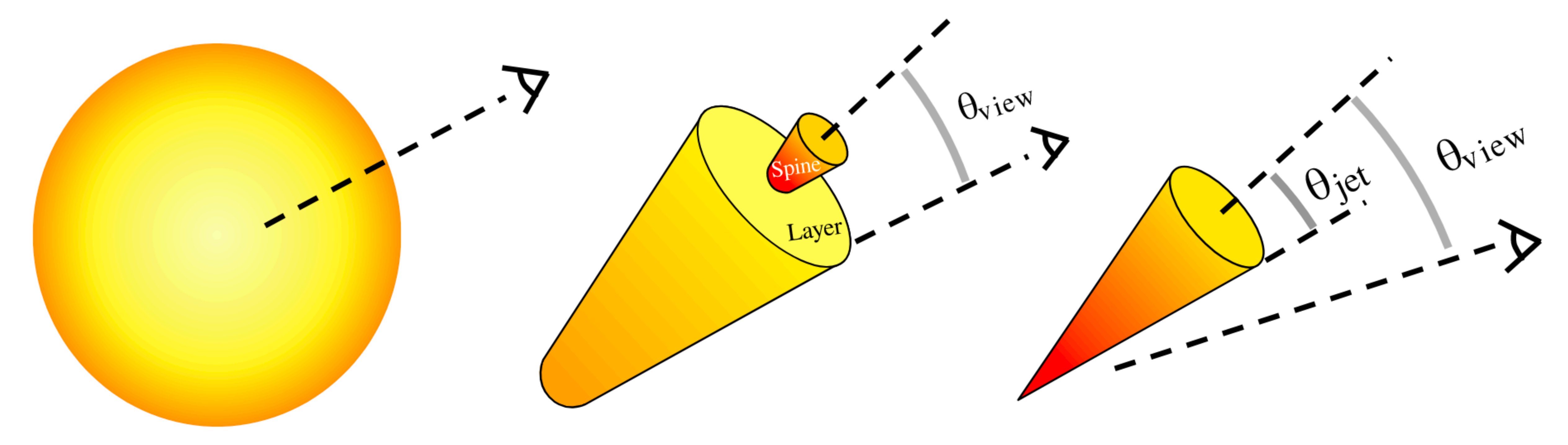

Salafia, Ghisellini & Ghirlanda, 2022

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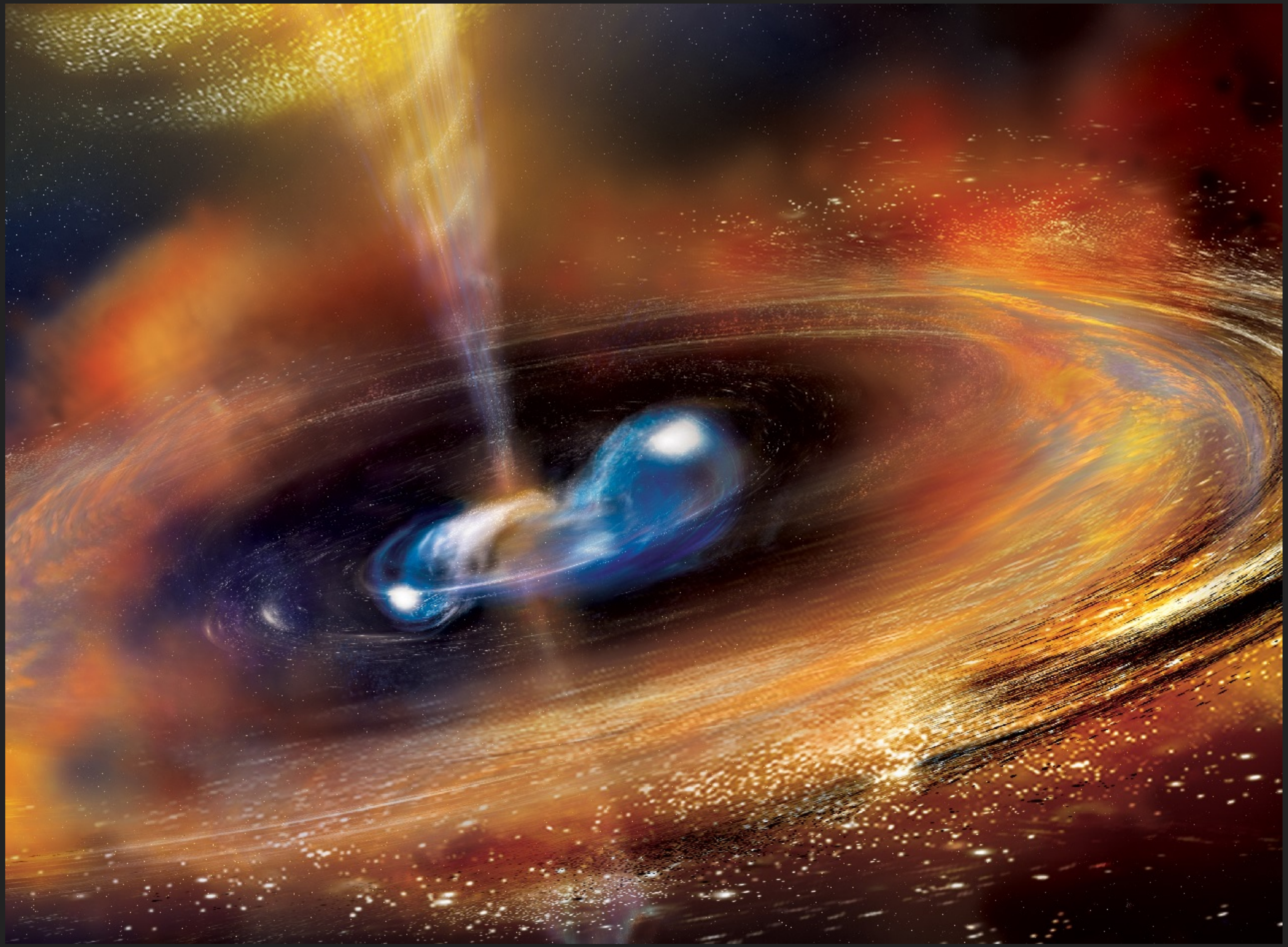
- Isotropic luminosity can reach $10^{54} - 10^{55}$ erg/s, with low-luminosity GRBs indicating a choked/cocooned jet

ENERGY DISSIPATION

- Central engine: kilonovae with gravitational wave counterparts



NASA

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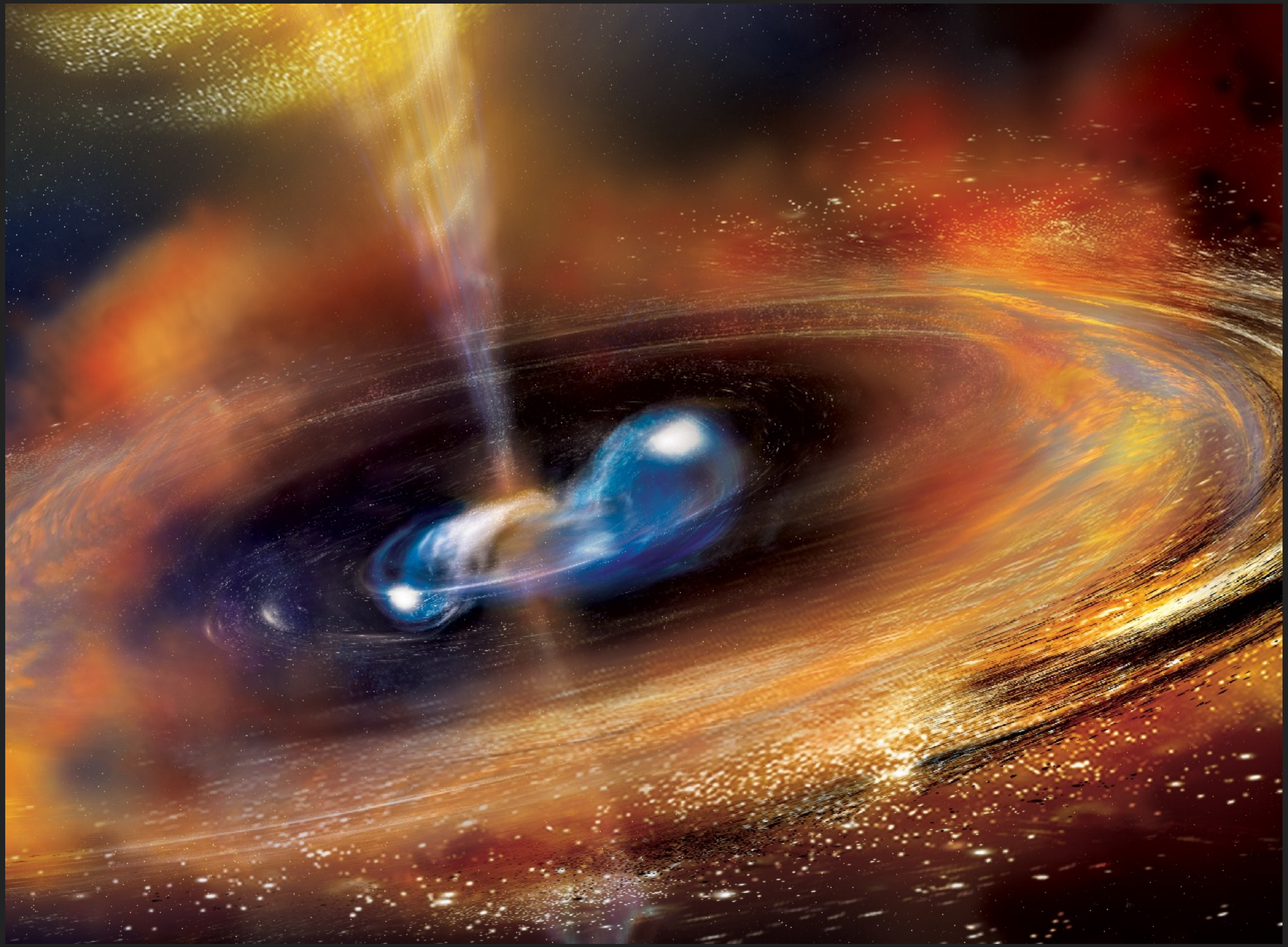

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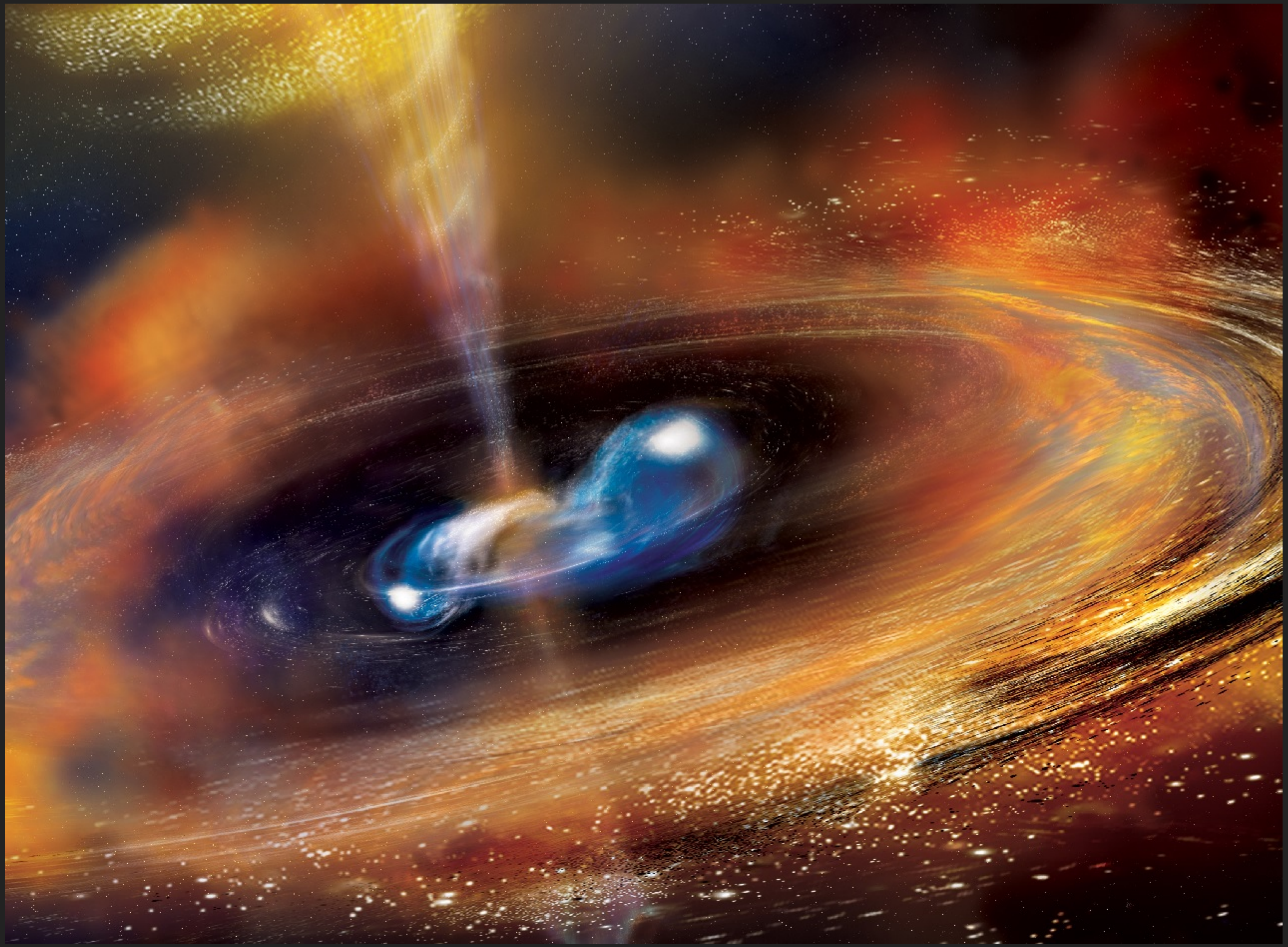

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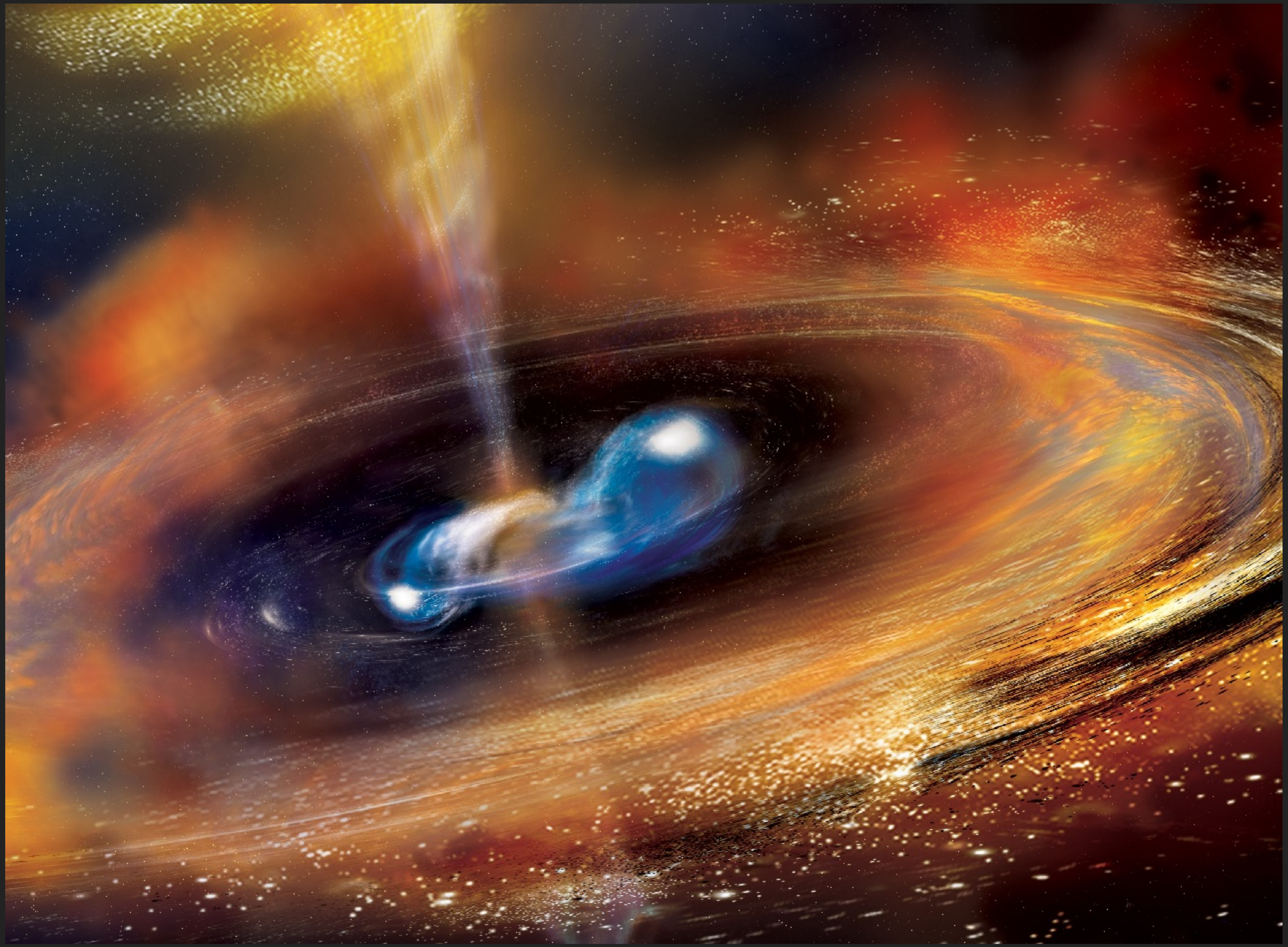
- Hadronic scenario: baryon loading



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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 $r_{ph} >> r_0 \sim R_s$

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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

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$2 \rightarrow 1$ PROCESSES

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

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

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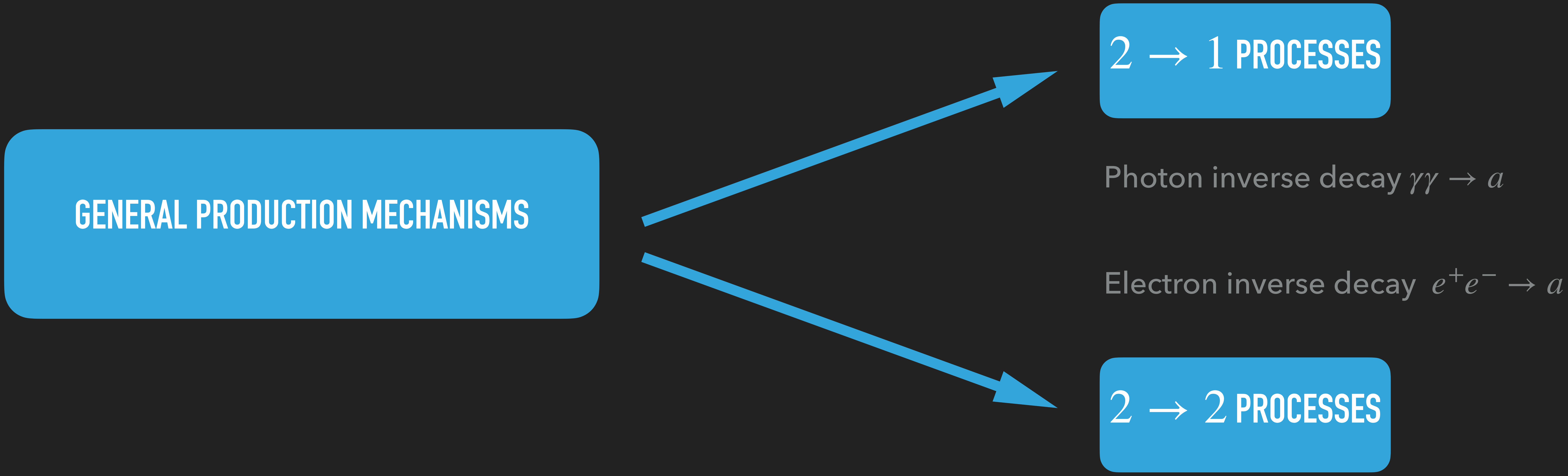

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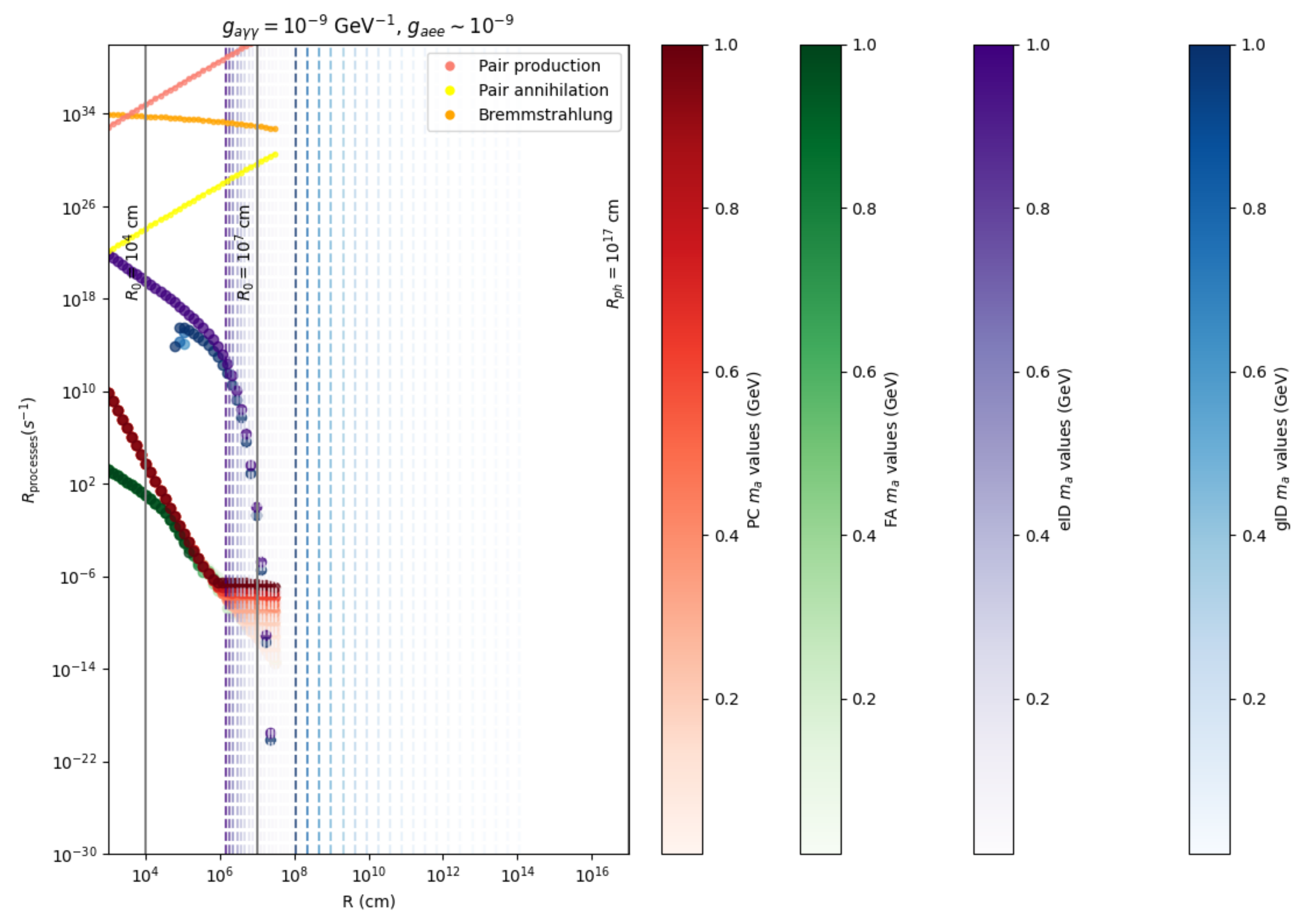
Fermion annihilation $e^+e^- \rightarrow a + \gamma$

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

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

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

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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

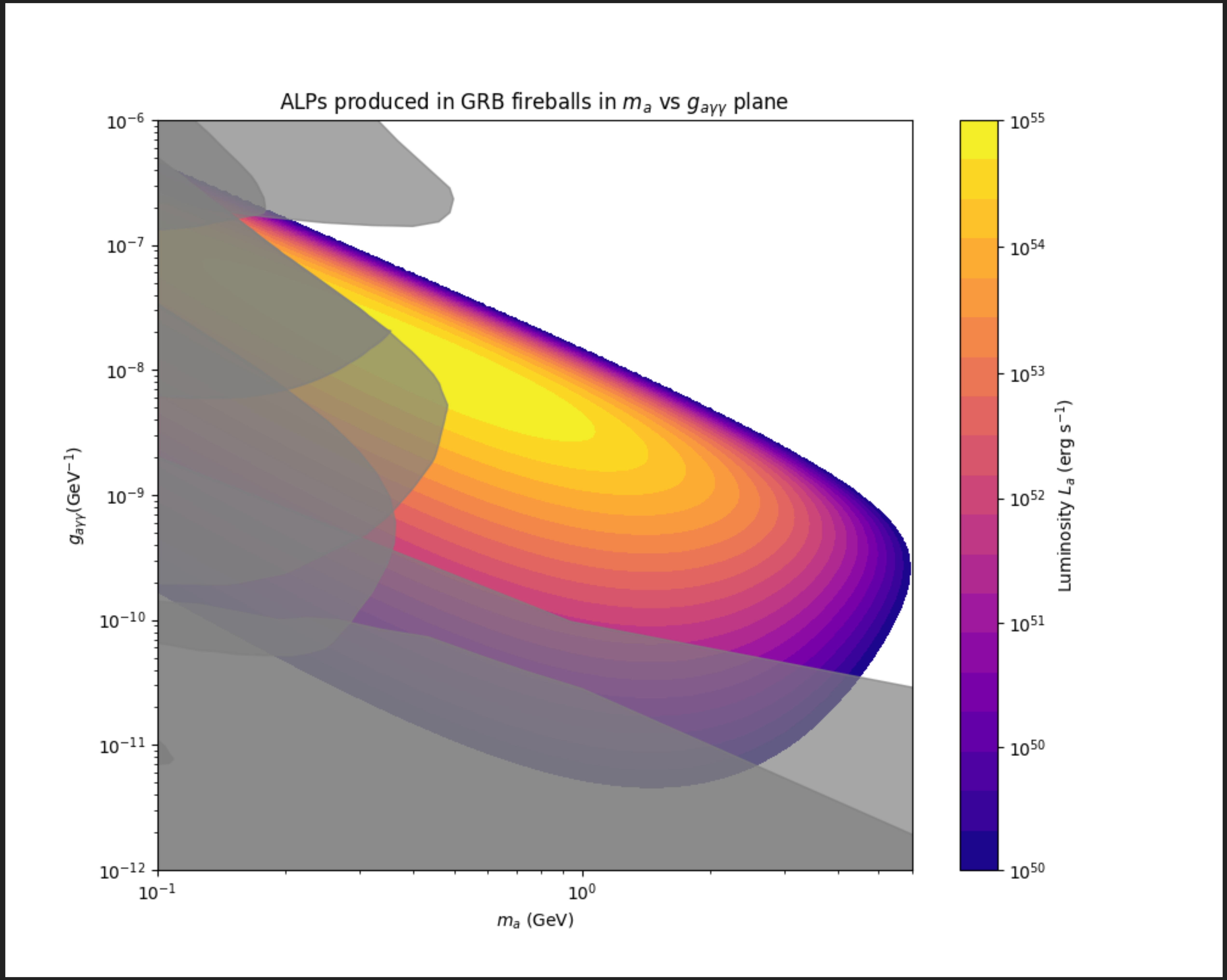
$$L_{a,prod} = \int \ldots \exp(-r/\lambda_{\gamma\gamma\to a})$$

- Average axion speed in the lab frame >> fireball expansion speed

HEAVY AXIONS DISRUPT GAMMA-RAY BURSTS

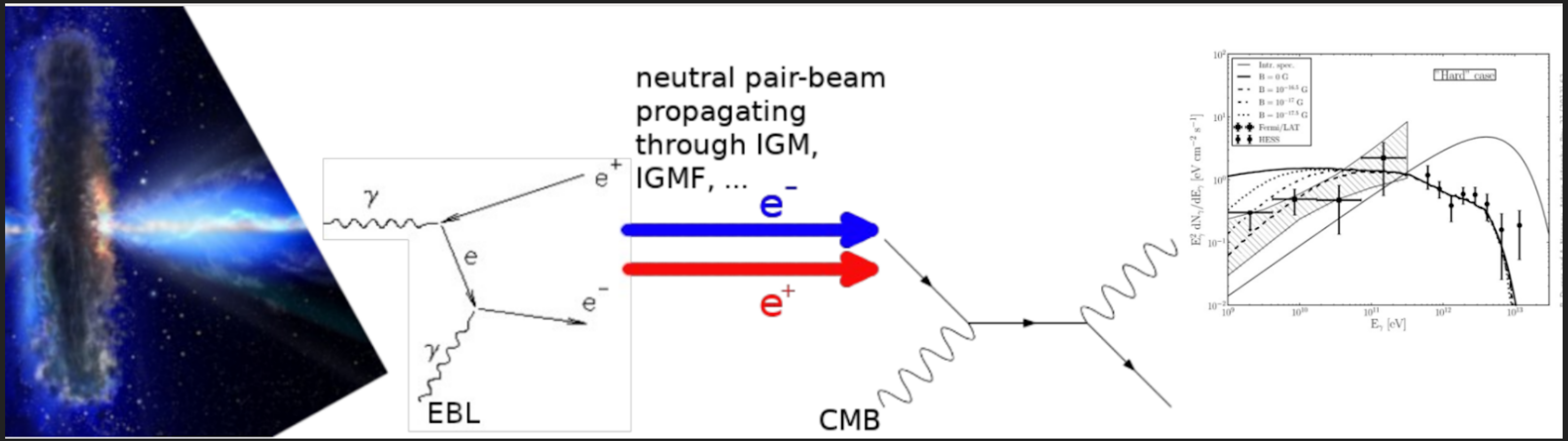
- We require $L_a \leq L_{intr} \sim 10^{50}$ erg/s for a complete disruption
- Calculated for a remnant mass of $3M_\odot$
- Assuming a conical geometry, less optimistic compared to an isotropically expanding fireball

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



MISSING CASCADES FROM TEV SOURCES

- TeV emissions from AGNs and GRBs reprocessed into the GeV band through inverse-Compton cooling
- Expected GeV cascade emission suppressed in the 100 GeV-1 TeV band
- Tension seems to be a universal trend for TeV sources observed with γ-ray telescopes



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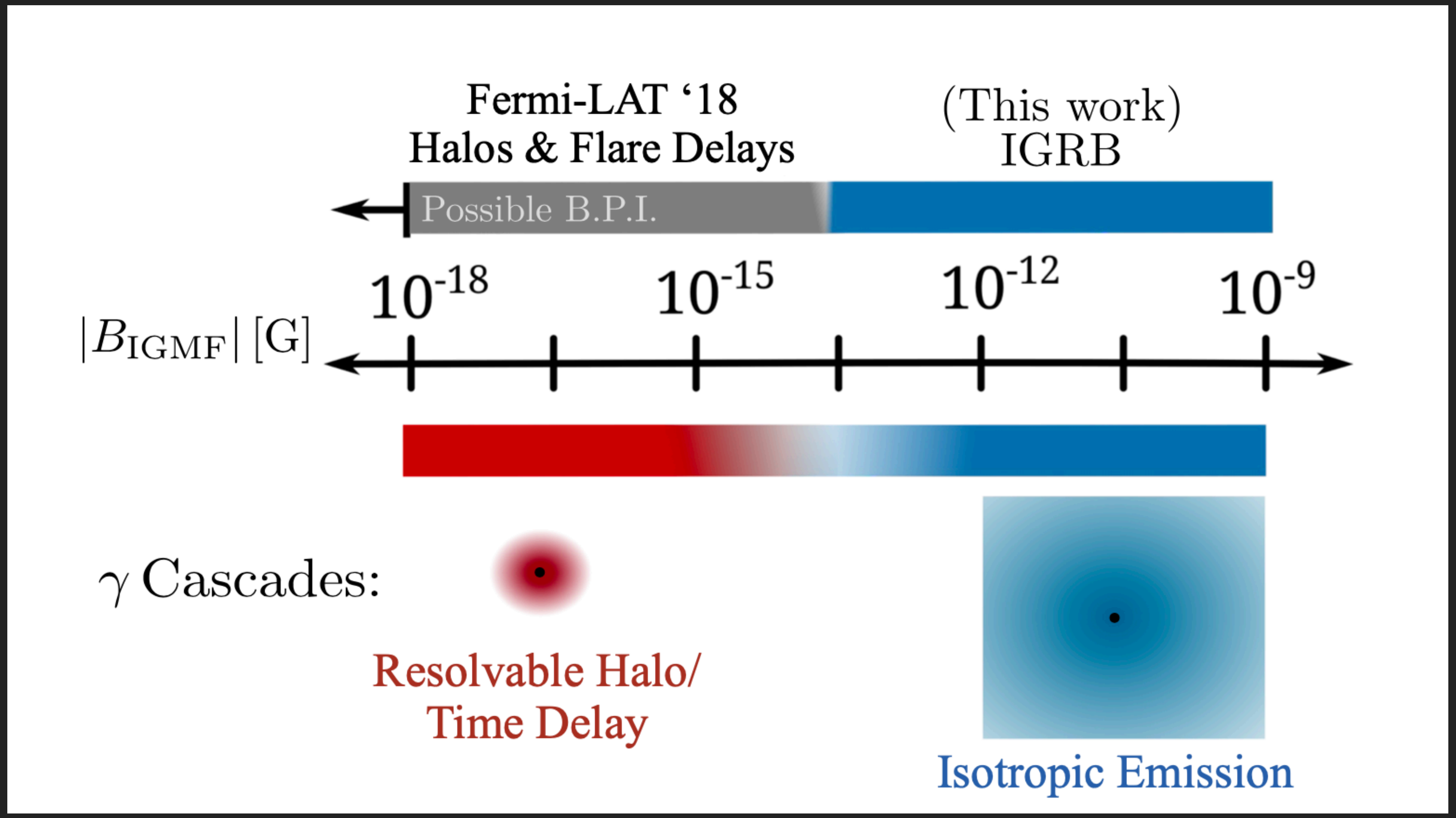
- Pair deflections off the intergalactic magnetic field (IGMF): *isotropisation* or creation of *pair halo*
- If weak and tangled, IGMF induces *magnetic diffusion* and beam broadening breaking down small-angle approximation

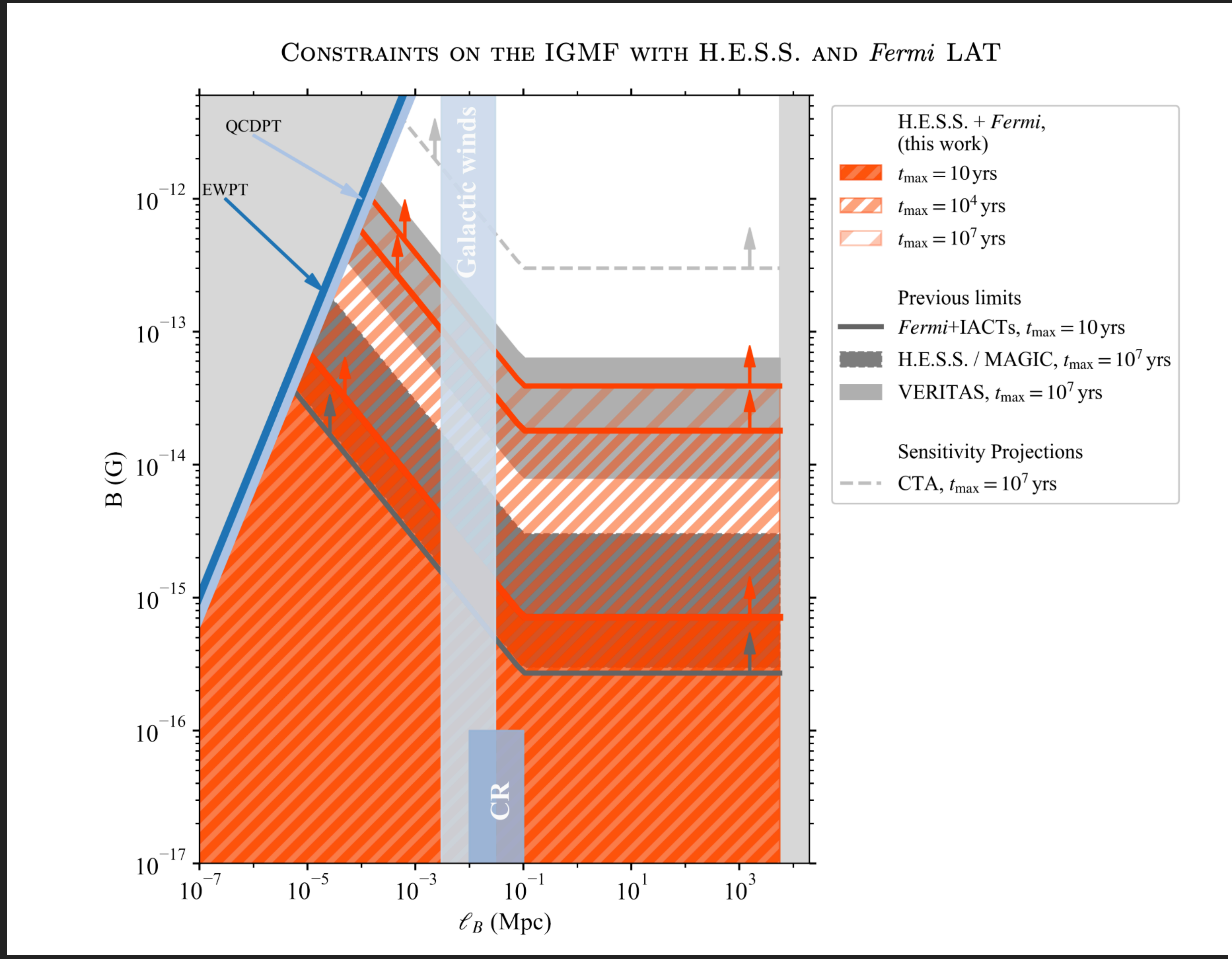
COMPETING EFFECTS OF INSTABILITY GROWTH AND IGMF STRENGTH

- When the IGMF strength ~ $10^{-18} - 10^{-14}$ G, the cascades should be detectable as degree-scale halos and as a time delay in flare
- When IGMF strength $> 10^{-14}$ G, cascades isotropise and contribute to the IGRB
- For realistic beam distributions participating in cascade, IGMF stronger than 10^{-14} G required to clearly outcompete plasma instabilities
- This introduces a sliding scale in critical IGMF strength ($\lambda_B \sim 1$ kpc) depending on the underlying instability mode for extreme TeV blazars

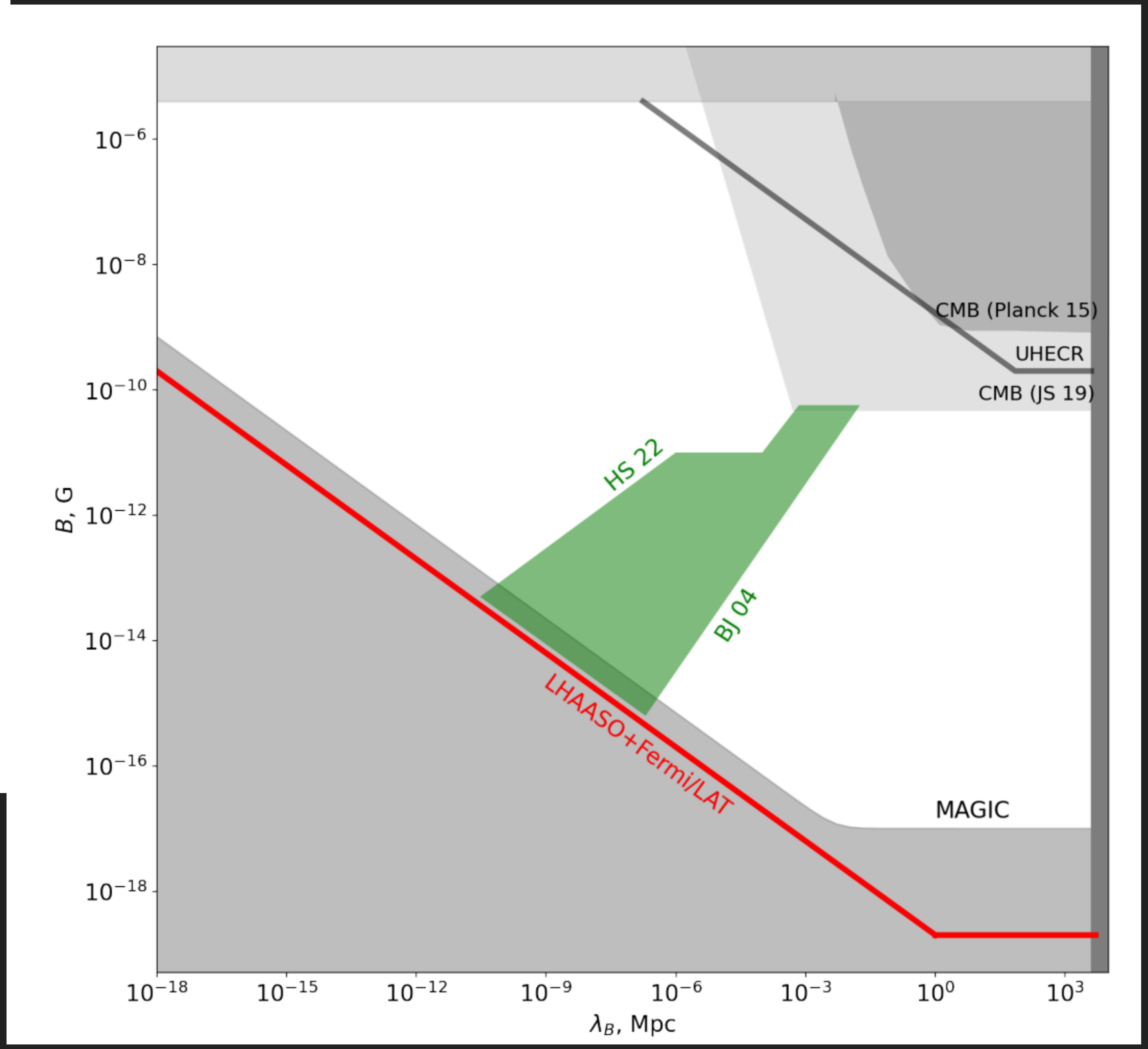


Blanco, **OG**, Jacobsen, Linden (2023) 2303.01524

OTHER CONSIDERATIONS



IGMF limit from blazars, joint H.E.S.S. & Fermi-LAT analysis, 2023



IGMF limit from 221009A: Vovk et al., 2023

- 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 $e, p/n$ couplings, secondary decay pairs participate in cascade

SUMMARY AND NEXT STEPS

- We derive leading limits down to $g_{a\gamma\gamma} \sim 10^{-11}\mathrm{GeV}^{-1}$ for ALP masses in the MeV-GeV scale
- Comprehensive treatment which also applies to hadronic sources
- Particularly interesting for sources associated with neutrino and GW events
- Axionic cascade contribute to various diffuse photon backgrounds: watch out for excesses (for a positive detection)
- Nonlinear feedback on IGMF limits due to ALP processes

Thank you!

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BACKUP: 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 $$\sigma_{\gamma\gamma\to e^+e^-} = \frac{\pi\alpha^2}{E_\gamma^2}\left[\left(2+\frac{2m_e^2}{E_\gamma^2}-\frac{m_e^4}{E_\gamma^4}\right)\right.$$ $$\left.\times\log\left|\frac{E_\gamma}{m_e}+\sqrt{\frac{E_\gamma^2}{m_e^2}-1}\right| - \sqrt{1-\frac{m_e^2}{E_\gamma^2}}\left(1+\frac{m_e^2}{E_\gamma^2}\right)\right]$$

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

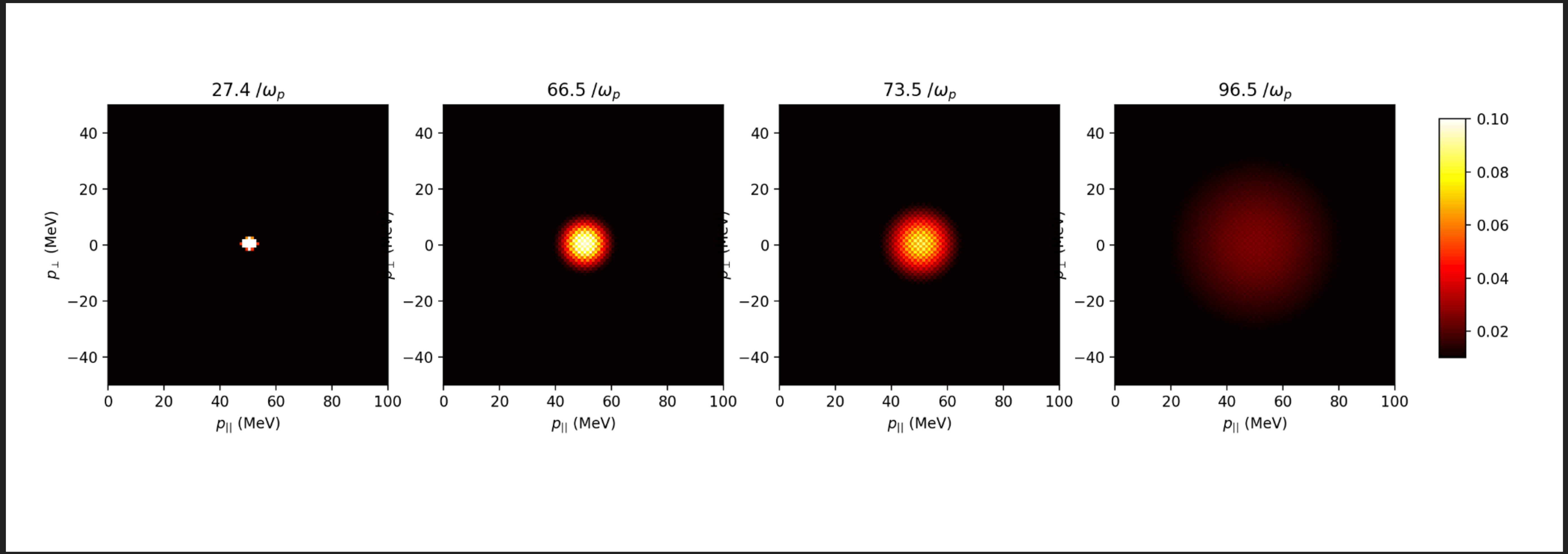
- Luminosity at production

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

BACKUP: COLLECTIVE PLASMA EFFECTS: GROWTH OF UNSTABLE MODES

- Instabilities occur when the Langmuir waves undergo Cherenkov resonance $\omega = \overrightarrow{k} \cdot \overrightarrow{v}$
- Such excitations in the beam transfer energy through the resonant window
- Spectral energy density in the background of intergalactic medium (IGM) grows as $W(k) = W_0 \int_0^\tau e^{2\ \mathrm{Im}(\tilde{\omega})\ t} dt$ through instability losses of the beam
- Dynamics and evolution of the beam-plasma interaction is set by characteristic length scales related to the background plasma frequency $\omega_p = \sqrt{4\pi n_p e^2/m_e}$

BACKUP: ENERGY LOSS (PLASMA HEATING) AND BEAM RELAXATION (SELF-HEATING)



- Evolution of beam-plasma system is diffusive-dissipative described best with a Fokker-Planck equation

$$\frac{\partial}{\partial t} f(\mathbf{p}, t) = -\frac{\partial}{\partial \mathbf{p}}[v(\mathbf{p}, t) f(\mathbf{p}, t)] + \frac{\partial}{\partial \mathbf{p}}\left[D(\mathbf{p}, k, t)\frac{\partial}{\partial \mathbf{p}} f(\mathbf{p}, t)\right]$$

- Consistent with results from particle-in-cell simulations for a laboratory astrophysics experiment

Beck, **OG**, Grüner, Pohl, Schroeder, Sigl, Stark, Zeitler 2023 2306.16839

BACKUP: ENERGY LOSS AND IGM HEATING

- Energy loss due to instabilities depend on growth rate
  $$W(k) = W_0 \int_0^\tau \exp[2\ \mathrm{Im}(\tilde{\omega})\ dt]$$
- Characteristic instability timescale $\tau \sim 1/\mathrm{Im}(\tilde{\omega})$
- Initial spectral energy density W_0 is determined by thermal fluctuations in the IGM plasma, $\sim \mathcal{O}(\mathrm{keV})$
- Maximum energy loss occurs for the oblique growth for near-monochromatic injection with the growth rate $\Gamma = \mathrm{Im}(\tilde{\omega}) \propto (\frac{\alpha}{\gamma_b})^{1/3}$