OINDRILA GHOSH

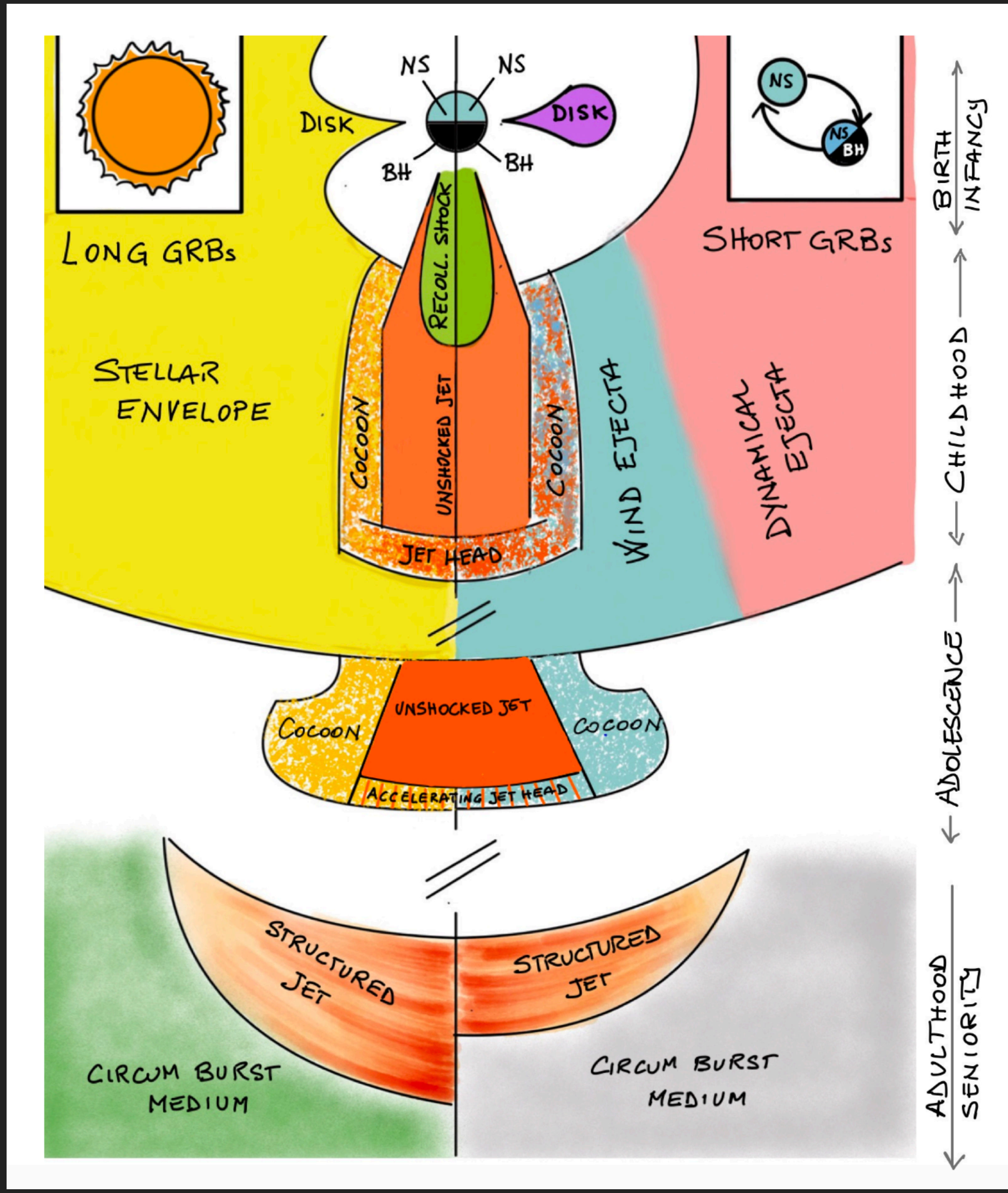
THE OSKAR KLEIN CENTRE FOR COSMOPARTICLE PHYSICS, STOCKHOLM UNIVERSITY

DO AXIONS PUT OUT GAMMA-RAY BURSTS?

TeVPA, Valencia | November 6, 2025

ANATOMY OF A FAST TRANSIENT

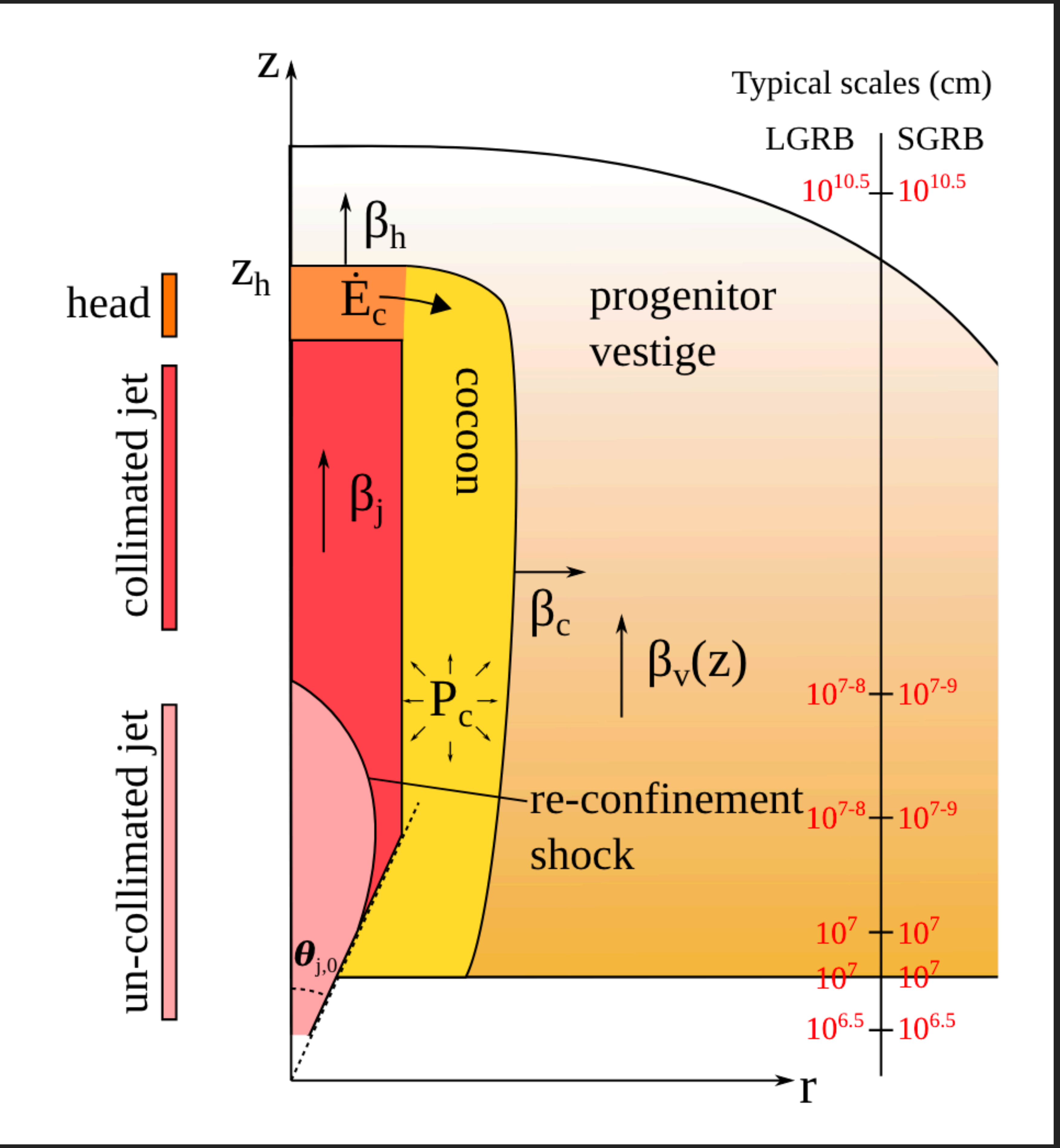
- Central engine: compact object/merger remnant + accretion disk
- A bipolar relativistic collimated ejecta is launched
- Bulk energy dissipation leads to bright, highly variable, non-thermal prompt emission
- The long-lasting multi-wavelength afterglow emission results from outflow interacting with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



Salafia & Ghirlanda, 2022

FIREBALL EVOLUTION

- A pure radiation fireball ($r \leq 10^8$ cm): Baryons negligible, fireball is radiation dominated: photon-lepton fireball



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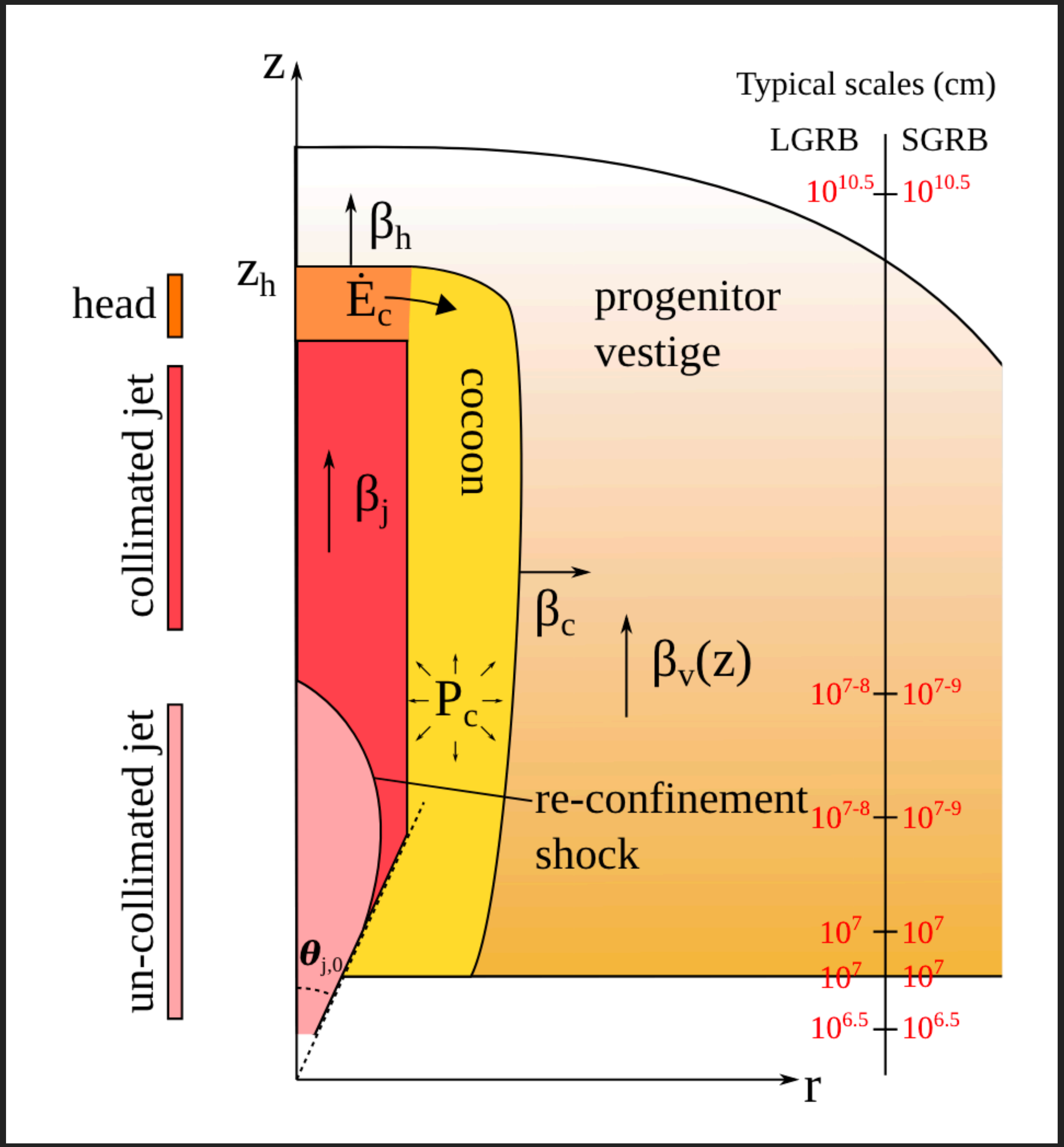

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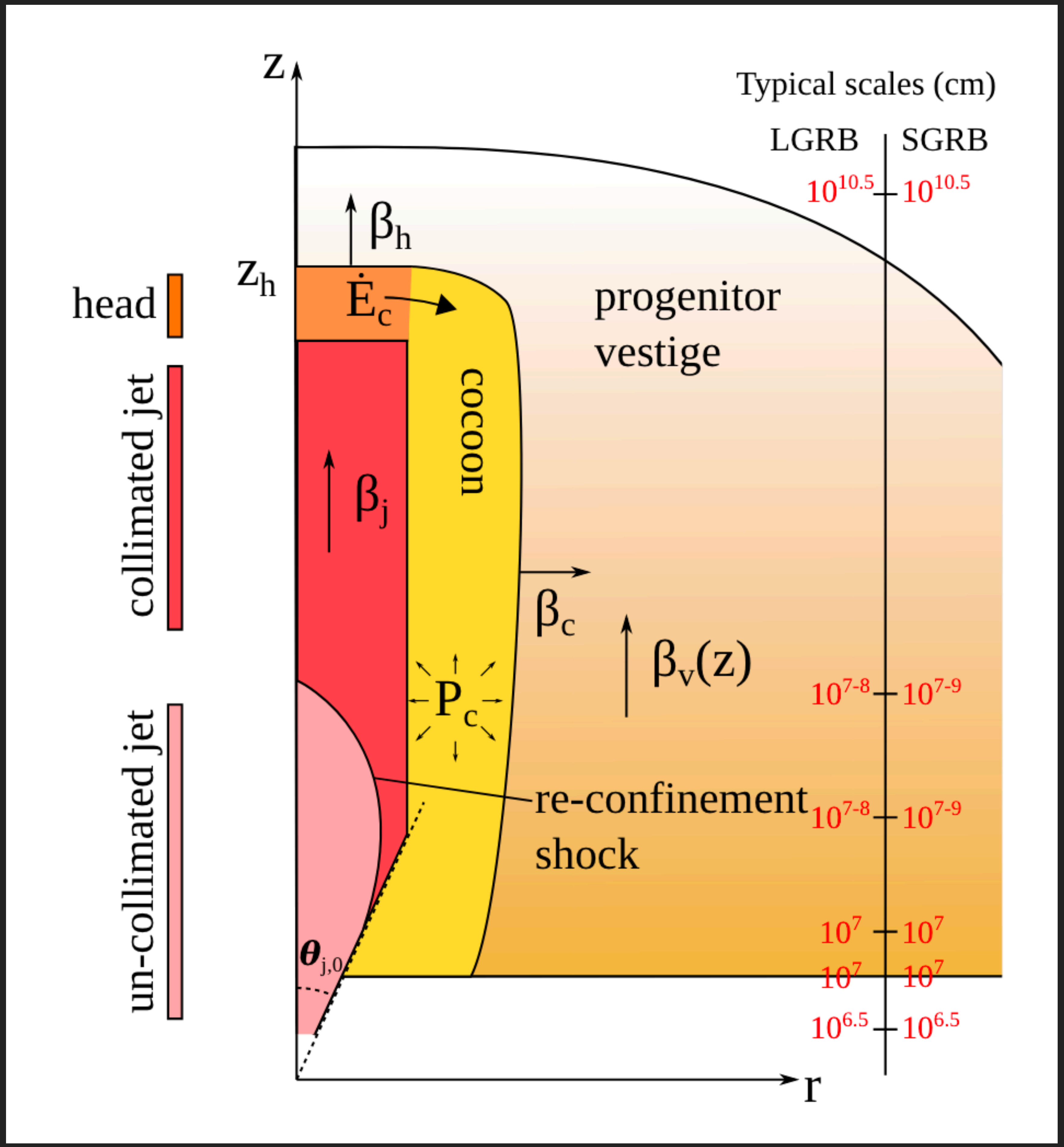
- Relativistic baryonic fireball ($r \sim 10^9$ cm): Fireball is matter-dominated, as it re-thermalises swept-up mass. Internal energy converted into bulk kinetic energy of baryons, fireball decelerates



Salafia & Ghirlanda, 2022

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 $\dot{E} = \frac{16}{3} 4\pi r_0^2 \sigma T_0^4$

STANDARD MODEL PROCESSES IN THE FIREBALL

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

  $ee \to ee\gamma$

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

  $e^+e^- \to \gamma\gamma$

- 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

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

  $\gamma\gamma \to e^+e^-$

We assume $E_\gamma = T$

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

HEAVY ALP PRODUCTION IN A LEPTONIC FIREBALL

GENERAL PRODUCTION MECHANISMS

HEAVY ALP PRODUCTION IN A LEPTONIC FIREBALL

GENERAL PRODUCTION MECHANISMS → $2 \rightarrow 1$ PROCESSES

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GENERAL PRODUCTION MECHANISMS

→ $2 \to 1$ PROCESSES

Photon inverse decay $\gamma\gamma \to a$

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

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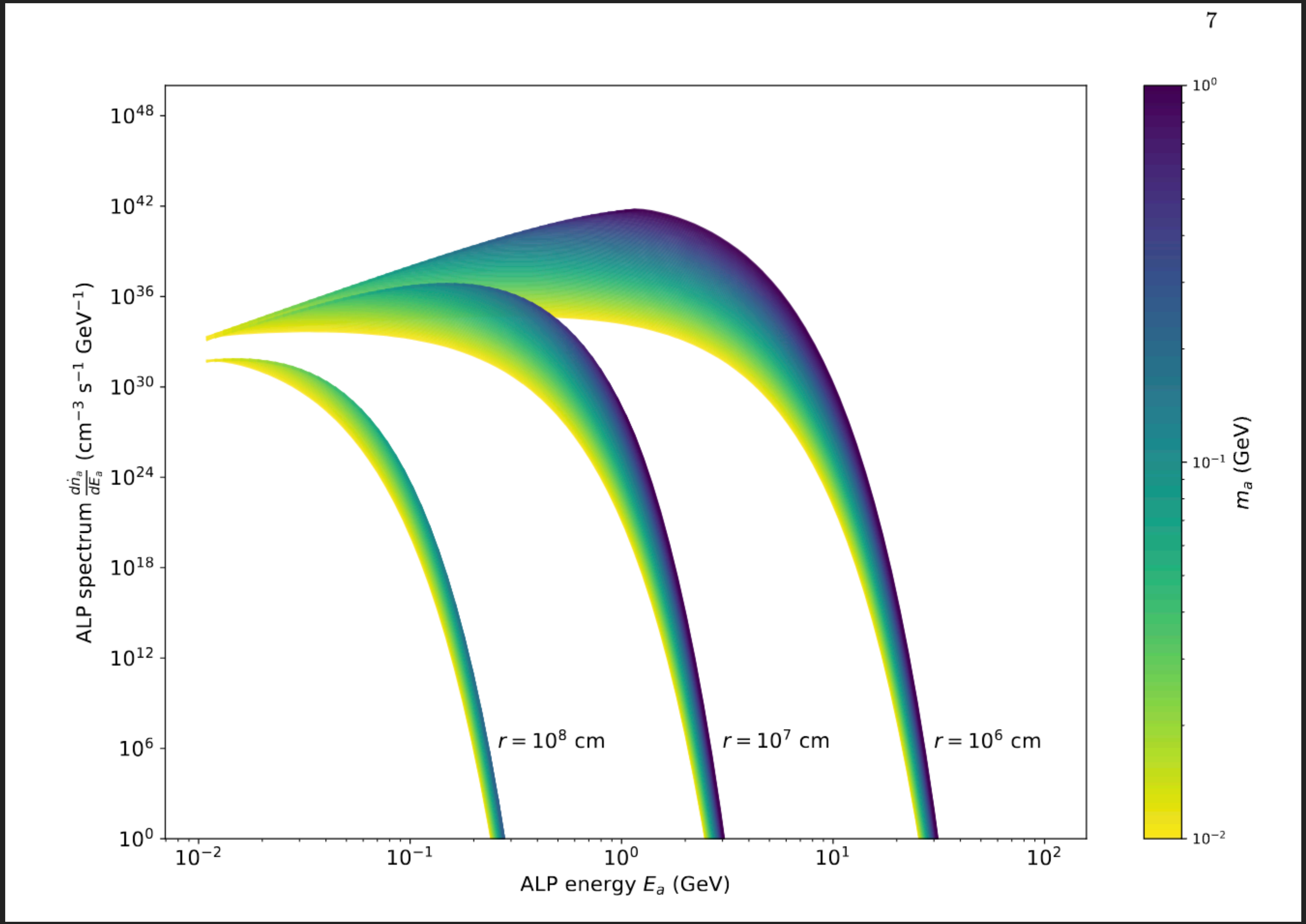
$2 \to 2$ PROCESSES

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

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

ALP SPECTRA IN LEPTONIC FIREBALLS

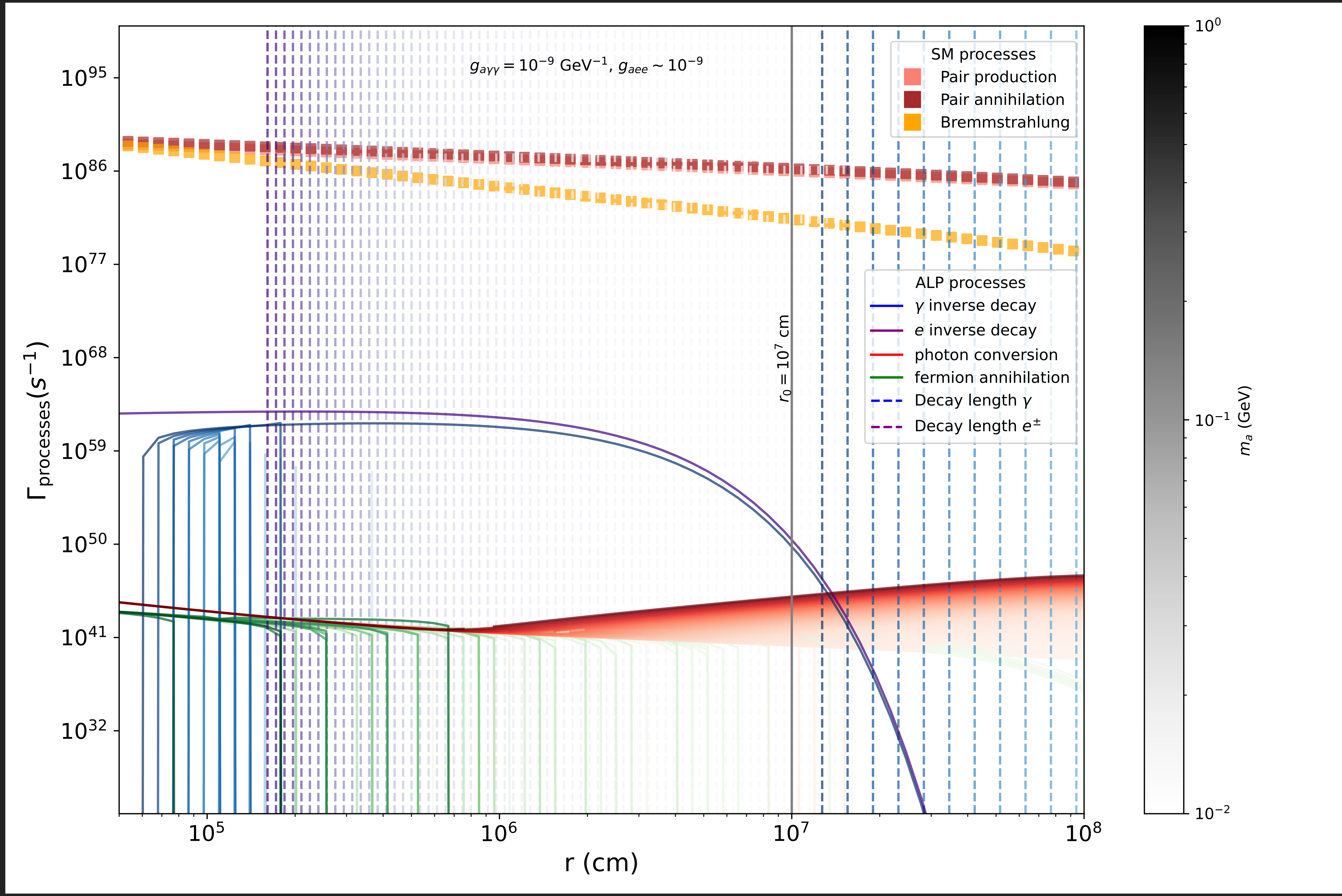


- Production depends on the radius (temperature) of the fireball
- Produced ALP spectra

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

OG, Jacobsen, Linden. *Phys Rev D* (arXiv: 2501.08978)

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. *Phys Rev D* (arXiv: 2501.08978)

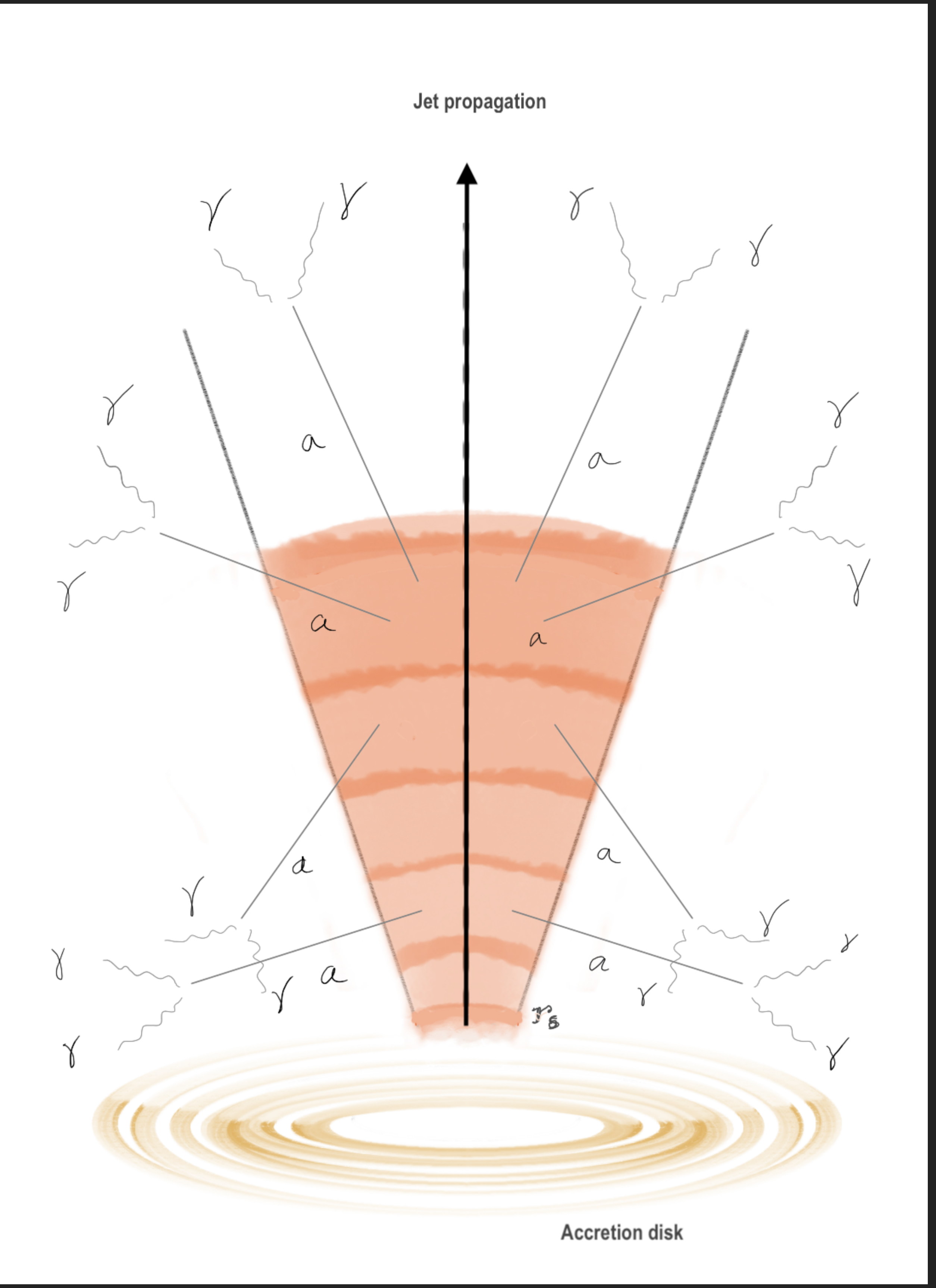
LUMINOSITY CALCULATION FOR A PHOTOPHILIC ALP

- Luminosity at production

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

- Baryon-loading starts becoming effective at critical radius

$$r_c \approx 3 \times 10^7 \text{ cm} \left(\frac{v_{\text{ejecta}}}{0.1c}\right)\left(\frac{\delta t}{10 \text{ ms}}\right)$$



GRAVITATIONAL TRAPPING

- Accounting for gravitational trapping requires introducing lapse factor $\alpha(r)$:
  $L_a = \int \ldots \Theta\left(E_a - \alpha(r)\ m_a\right)$
- For $r \gg r_s$ the weak gravity formula applies $\alpha_{\text{weak}}(r) \approx 1 + \frac{r_s}{r} = 1 + \frac{GM}{rc^2}$
- In the strong regime closer to the remnant,
  $\alpha(r) = \alpha_{\text{strong}}(r) = \sqrt{1 - \frac{r_s}{r}} = \sqrt{1 - \frac{2GM}{rc^2}}$
- Relative error: $16\,\%$ at $1.5r_s$, $5.6\,\%$ at $2r_s$, $2.5\,\%$ at $3r_s$

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
  $$L_a = \int \ldots \exp(-r/\lambda_{\gamma\gamma\to a})$$
- Ejecta/ fireball expansion speed ~ $0.3c - 0.6c$
- $\langle \gamma_a \rangle \gg \gamma_{a,\mathrm{cr}} \sim 1.05$ set by the fireball expansion speed

r	T (GeV)	m_a (GeV)	$\langle \gamma_a \rangle$
$r_s(2M_\odot) = 5.93 \times 10^5$cm	0.506	0.01	100.984308
		0.08	12.935285
		0.2	5.551709
		0.5	2.713063
		1	1.817522
$r_s(3M_\odot) = 8.90 \times 10^5$cm	0.337	0.01	67.377468
		0.08	8.808573
		0.2	3.956192
		0.5	2.111106
		1	1.529511
$r_s(4M_\odot) = 1.19 \times 10^6$cm	0.253	0.01	50.584786
		0.08	6.765675
		0.2	3.174323
		0.5	1.817522
		1	1.385863
$r_c = 3.00 \times 10^7$cm	0.01	0.01	2.692544
		0.08	1.115430

Energies of ALPs produced at various radii(temperatures) and remnant masses

CAN THE FIREBALL EMERGE AGAIN?

Inside the source

- Mean free path of thermal photons

$\lambda_{mfp,\,\text{decay}} = hc/E_{\gamma,\,\text{decay}} = 1/(100\text{MeV}) \sim 10^{-13}$ cm

- Critical density needed for thermalisation

$n_{\text{cr}} \sim 1/\left(\lambda_{mfp,\text{th}}\sigma_T\right) \sim 10^{37}\ \text{cm}^{-3}$

- Inside fireball, thermal photons have density

$n_\gamma = (16\pi\zeta(3))/\left(c^3h^3\right)\left(k_BT\right)^3 \approx 20.3(100\text{MeV})^3 \sim 10^{37}\ \text{cm}^{-3}$

Outside the source

- Mean free path of VHE photon in the circum-burst medium

$\lambda_{mfp,\,\text{decay}} = hc/E_{\gamma,\,\text{decay}} = 1/(1\ \text{GeV}) \sim 10^{-14}$ cm

- Critical number density required for decay photons from GeV-scale ALPs to thermalise via pair production outside

$n_{cr} \sim 1/\left(\lambda_{mfp,\,\text{decay}}\,\sigma_T\right) \sim 10^{38}\ \text{cm}^{-3}$

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- For a burst duration of 10 ms, total number of ALP produced ~ 10^{52}
- For a GeV-scale ALP with decay length ~ 10^{7} cm, number density of decay photons $N_{\gamma,\,\mathrm{decay}} / \left(\frac{4}{3}\pi\lambda^3_{\mathrm{decay}}\right) \sim 10^{27}\ \mathrm{cm}^{-3}$

UPON DECAY, THE PHOTOPHILIC ALPS PRODUCE A PHOTON FIELD TOO RAREFIED FOR THERMALISATION!

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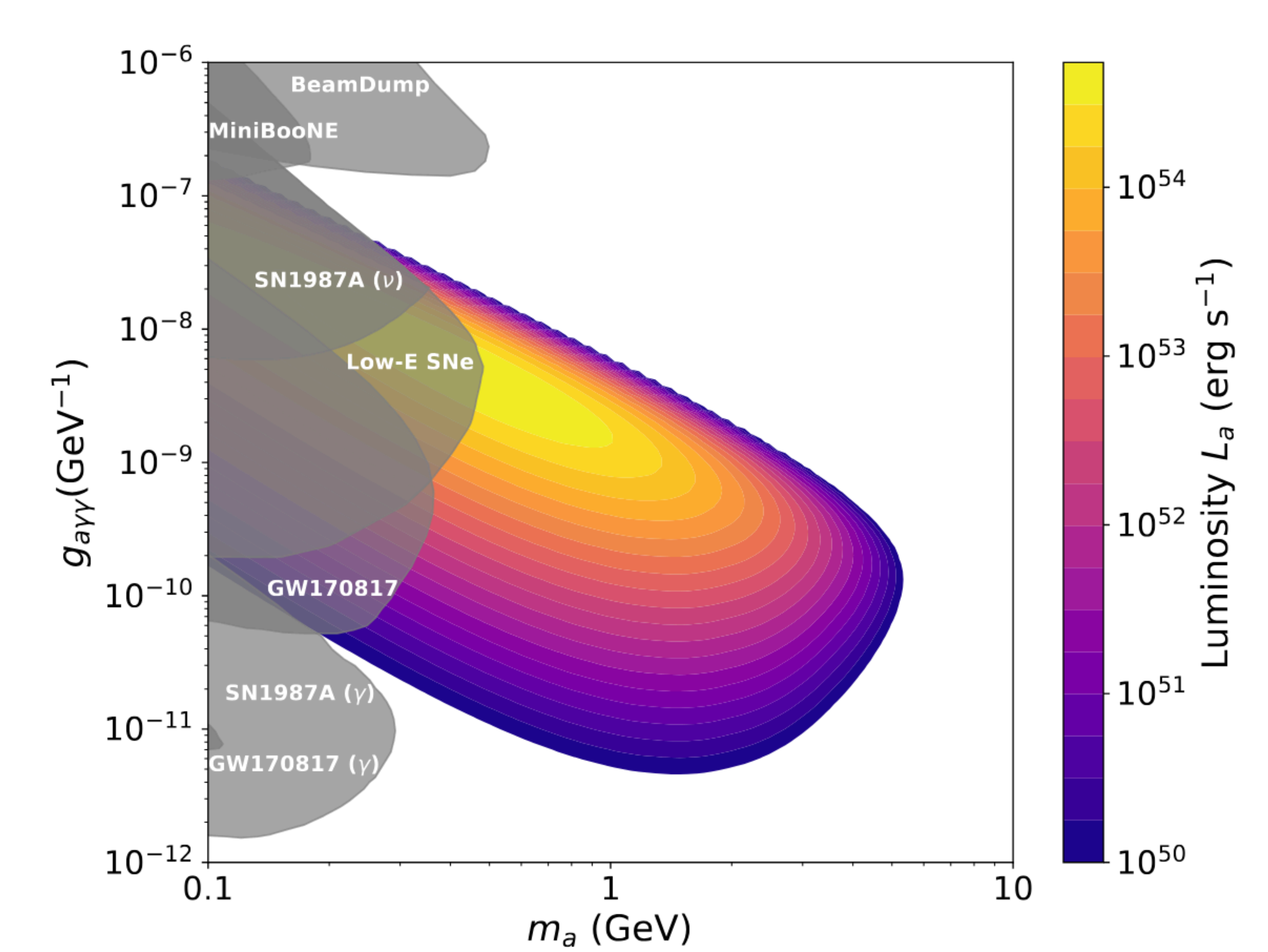
NO NEW FIREBALLS CAN FORM ONCE RADIATIVE TRANSFER OCCURS!

HEAVY AXIONS DISRUPT GAMMA-RAY BURSTS: STATE-OF-THE-ART 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



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BARYON LOADING IN GRB FIREBALLS

- Wall accretion: Neutrons drift into the jet sideways at a rate $\dot{M}_{\rm n} = 2\pi\theta_{\rm BZ} r_z^2 J_{\rm D}(r)$ where incoming neutron flux is determined by mfp of $n - p$ collisions and wind parameters

- Floor accretion: Goldreich-Julian baryon-loading rate through the base of the central engine magnetosphere
$\dot{M}_{\rm GJ} = 7 \times 10^{-2} \left(m_p + \varsigma m_e \right) 4\pi r_\bullet^2 B_\bullet \Omega_{\rm F} c / 2\pi$

Lei, Zhang, Liang (2019)

BARYON LOADING IN GRB FIREBALLS

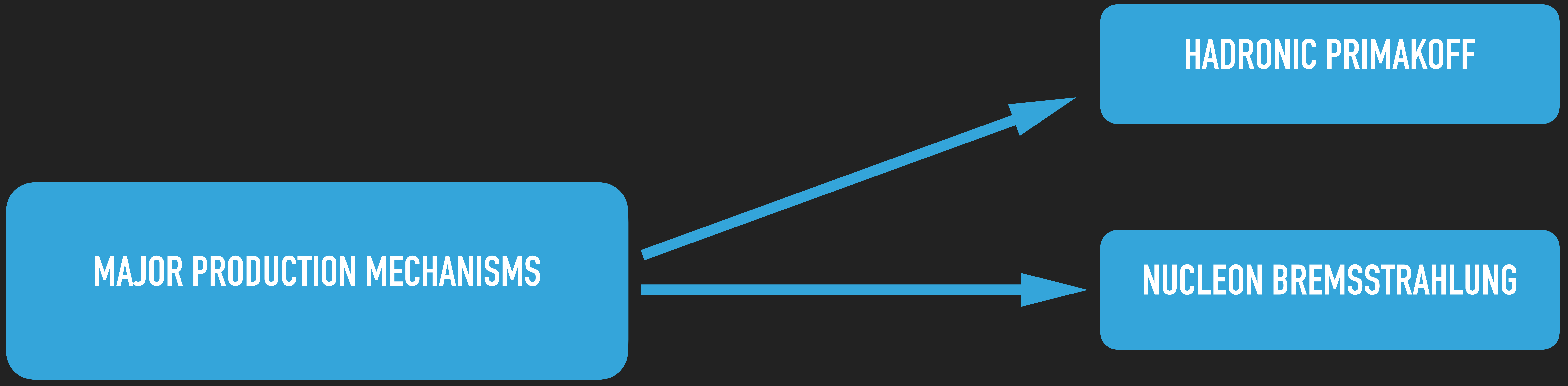
- Comoving baryon density derived from baryon loading rate as $n_B = \dot{N}_{\rm B}/\pi\theta_j^2 r_c^2 c$ with $\dot{N}_B = \dot{N}_{B,0} + \dot{N}_n$ where $\dot{N}_n = \dot{M}_{\rm GJ}/m_n$
- Jet arises beyond the critical radius $r_c \approx 3 \times 10^7 \text{ cm} \left(\frac{v_{\text{ejecta}}}{0.1c}\right)\left(\frac{\delta t}{10 \text{ ms}}\right)$
- The fireball temperature falls from $\mathcal{O}(10 \text{ MeV})$ as $T(r) = T_0(r_0/r)^{3/2}$

ALP PRODUCTION IN A HADRONIC FIREBALL

MAJOR PRODUCTION MECHANISMS → HADRONIC PRIMAKOFF

$$\gamma + Ze \to a + Ze$$

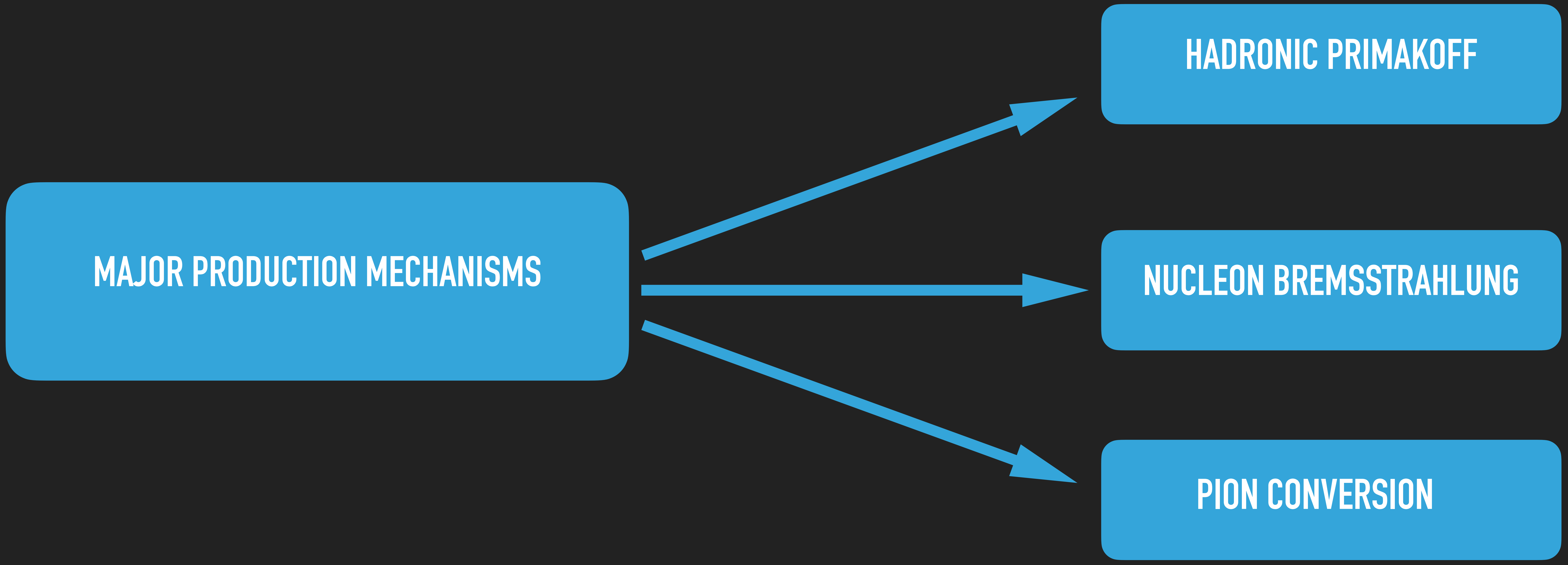
ALP PRODUCTION IN A HADRONIC FIREBALL



$\gamma + Ze \to a + Ze$

$N + N \to N + N + a$

ALP PRODUCTION IN A HADRONIC FIREBALL

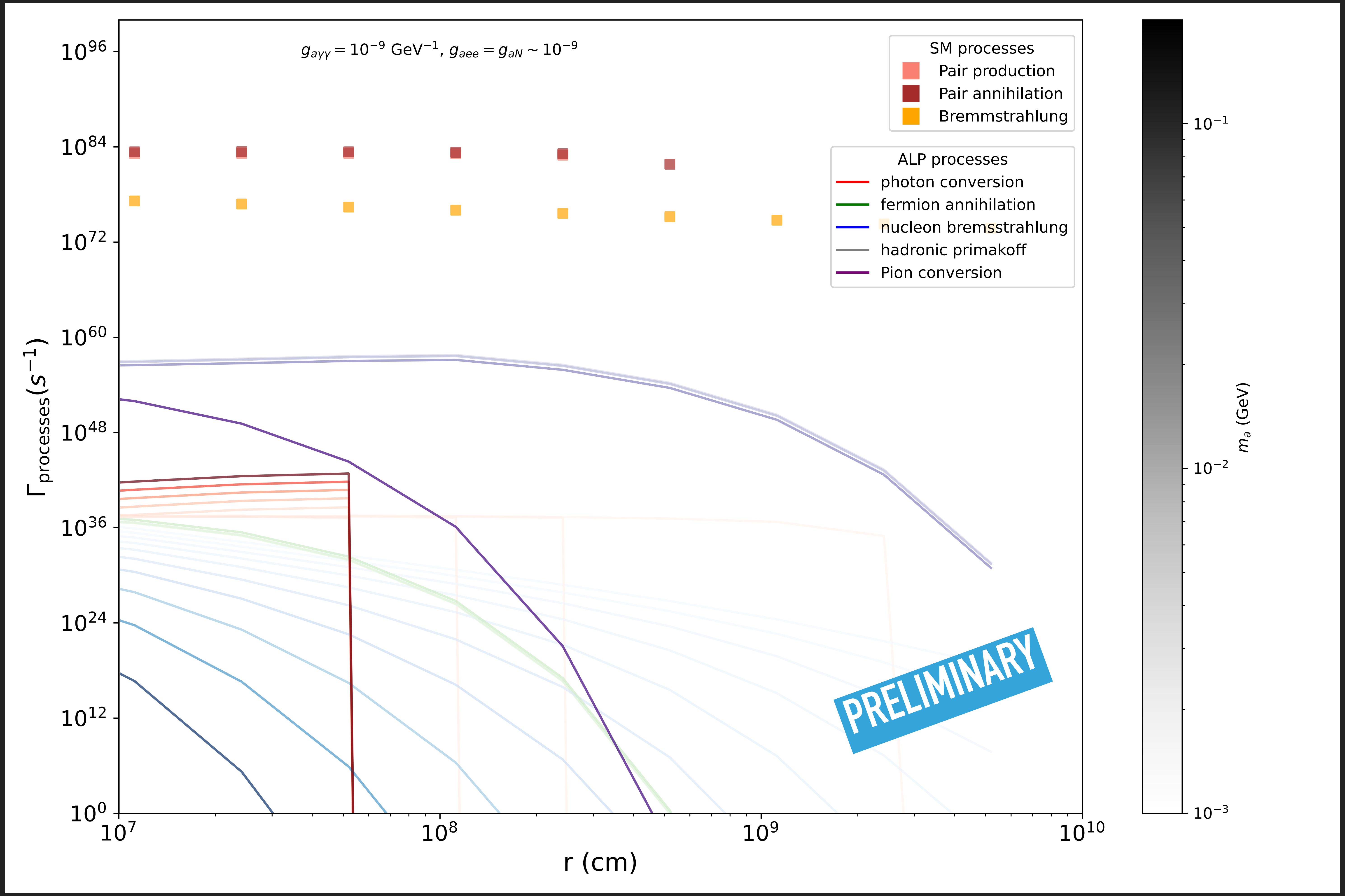


$\gamma + Ze \rightarrow a + Ze$

$N + N \rightarrow N + N + a$

$\pi + N \rightarrow N + a$

ALPS PRODUCED IN HADRONIC FIREBALLS

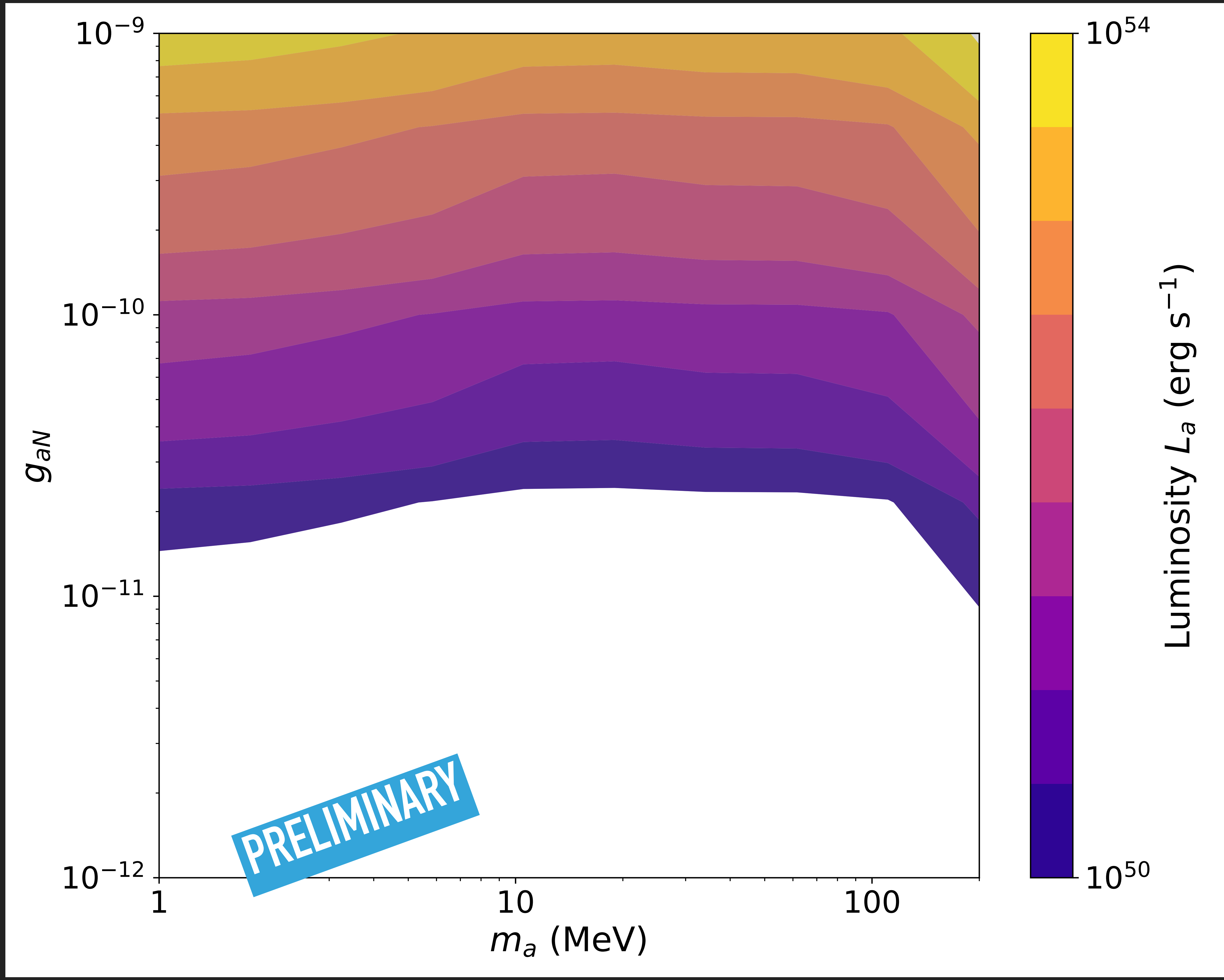


- Rates depend on nuclear structure functions
- Mean-free path of backreactions are too large owing to low density of hadronic matter
- Fireball is essentially transparent to hadronically produced ALPs

Upcoming work **OG**, T Linden [to appear soon]

STATE-OF-THE-ART BOUNDS FROM HADRONIC GRB JETS

- ALP luminosity cannot exceed observed GRB luminosity $L_a \leq L_\gamma$
- Beyond $r \sim 10^{10}\text{cm}$, GRB jet enters the coasting phase
- In addition to $L_a \leq L_\gamma$, future projected limits from potential neutrino observations can lead to additional bounds $L_a \leq L_\nu^{(p\gamma)} \propto \xi_p L_\gamma^2 / \Gamma^4 t_v \varepsilon_b$ for photomeson $p\gamma$ processes (shock dissipation and $L_a \leq L_\nu^{(pp)} \propto \xi_p L_\gamma^2 / \eta_\gamma r \Gamma^3$ for inelastic nucleon collisions pp/pn (denser sub-photospheric region, pionosphere)



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SUMMARY

- We derive state-of-the-art limits down to $g_{a\gamma\gamma} \sim 4 \times 10^{-12} \mathrm{GeV}^{-1}$ for ALP masses in the 200 MeV-1 GeV range from initial photon-lepton fireball
- Gravitational trapping marginally affects ALPs produced in leptonic fireballs
- Decay γ field outside source too rarefied → fireball cannot reemerge
- Lighter ALPs w/ masses in the 1-200 MeV range can be hadronically produced in the later stages, to which the jet is transparent pushing sensitivity below ALP-nucleon coupling $g_{ap} \sim 10^{-11}$ (constraint independent from $g_{a\gamma\gamma}$ or g_{ae} couplings)

Thank you!

oindrila.ghosh@fysik.su.se

oindrilaghosh.com

BACKUP: ALP SPECTRA IN HADRONIC FIREBALLS

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