Effects of Goldstone Bosons on Gamma-Ray Bursts

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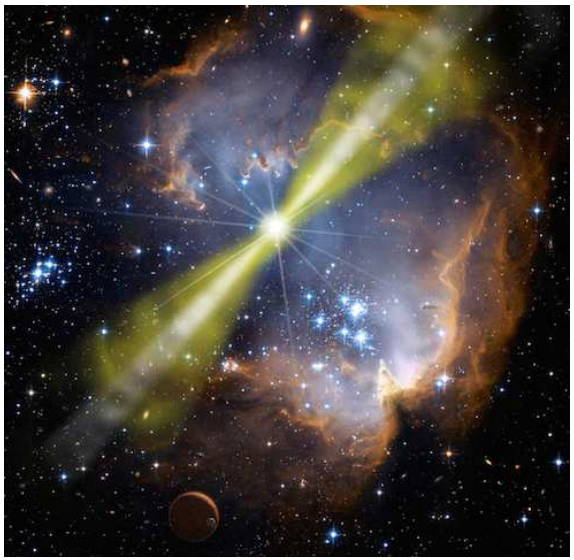
[HT and Ng, JCAP 03 (2016) 037]

Motivation

- Gamma-ray bursts (GRBs): most energetic explosion events in the universe
- Potential for being laboratory for testing particle physics
- Effects of neutrino on initial fireballs of GRBs
- Weinberg's Higgs portal model

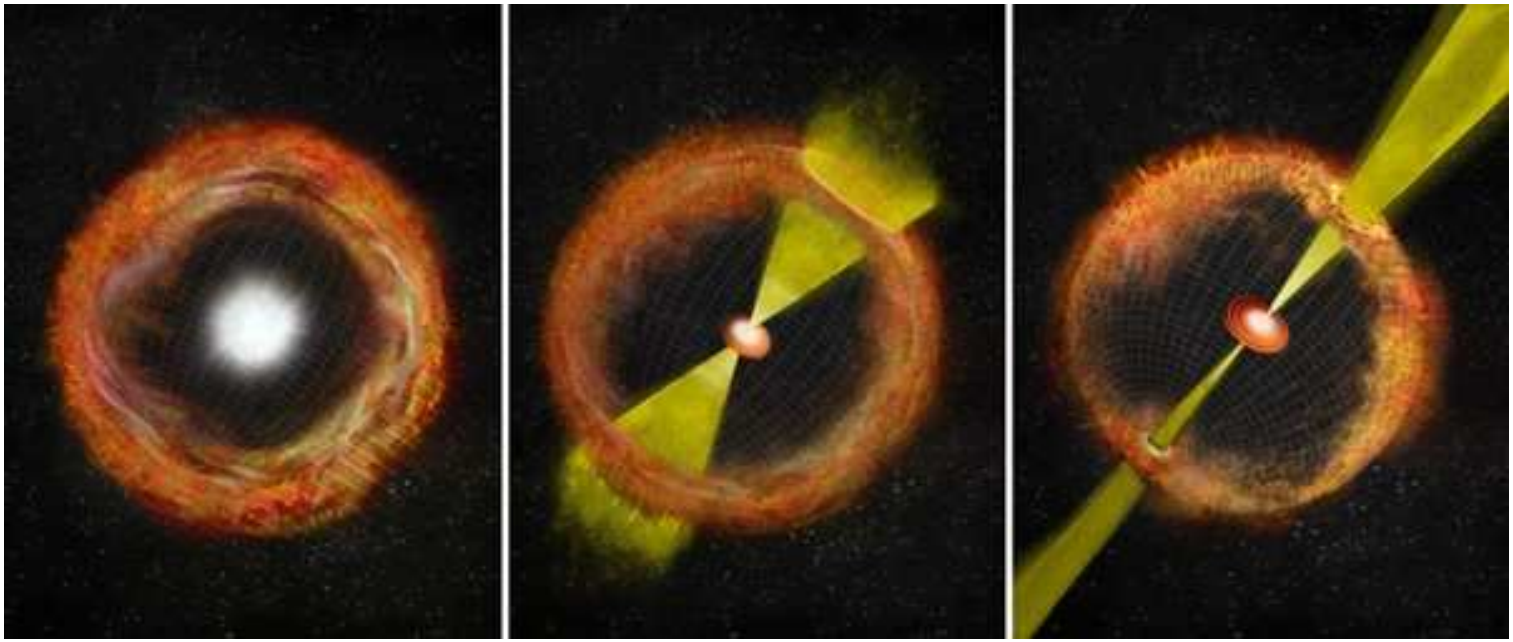


[http://imagine.gsfc.nasa.gov/news/10sep08.html]

Gamma-Ray Bursts

- Emit energy amount $\gtrsim 10^{52}$ erg
- Initial burst followed by afterglow
- Observed by Vela satellites, BASTE, BeppoSAX, Konus/Wind, HETE-2, Swift, INTEGRAL, AGILE, and Fermi
- Cosmological origin ($z > 1$, record $z = 9.4$)
- Long ($T_{90} > 2$ s) and short bursts

Supernovae and Gamma-Ray Bursts

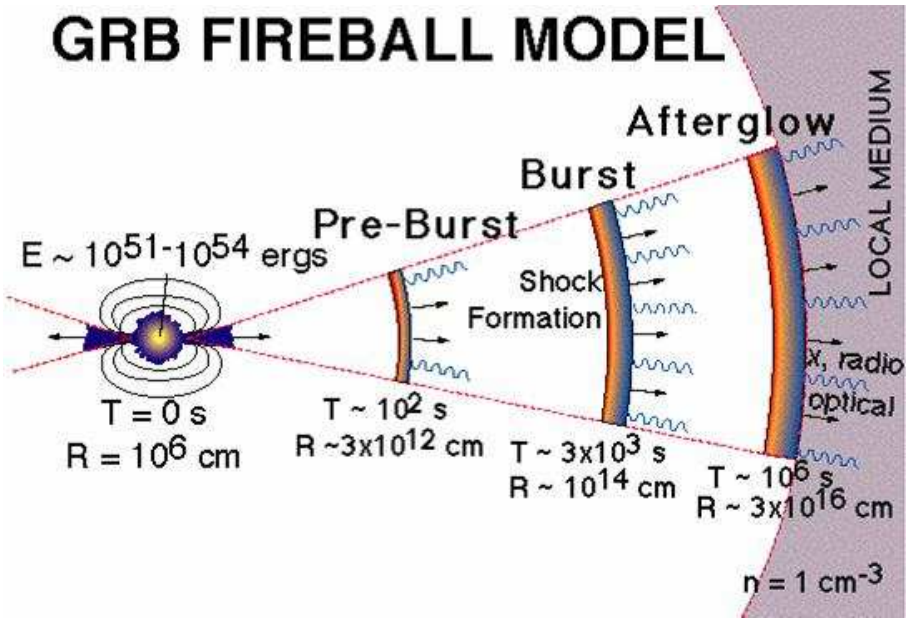


[http://www.astronomy.com]

GRB Fireball Model

- Central engine: black hole or neutron star
- Jets: magnetic fields or neutrino pair annihilation
- Neutrinos and gravitational waves
- Fireball: γ, $e^{\pm}$ plasma
- Baryons: radiation energy converted to bulk kinetic energy
- Shocks: internal and external

[Cavallo, Rees 1978; Paczyinski 1986; Goodman 1986; Shemi, Piran 1990; ...]



[http://www.swift.ac.uk/about/grb.php]

Effects of Neutrinos on GRB Intial Fireballs

- Production: $e^- e^+ \rightarrow \nu\bar{\nu}$
- Scattering: $\nu e^{\pm} \rightarrow \nu e^{\pm}$
- Stage I: neutrinos produced rapidly compared to expansion rate; fireball opaque to all 3 neutrino flavours.
- Stage II: ν_μ and ν_τ decouple from the plasma; neutrino production rate low.
- Stage III: ν_e decouple; neutrino production rate too low.

[Koers and Wijers, MNRAS 364 (2005) 934]

Weinberg's Higgs Portal Model

Lagrangian

$$\mathcal{L} = \left(\partial_\mu S^\dagger\right)\left(\partial^\mu S\right) + \mu^2 S^\dagger S - \lambda (S^\dagger S)^2 - g(S^\dagger S)(\Phi^\dagger \Phi) + \mathcal{L}_{\mathrm{SM}}$$

where Φ is the SM Higgs doublet.
Define

$$S(x) = \frac{1}{\sqrt{2}}\left(\langle r \rangle + r(x)\right) e^{2i\alpha(x)}$$

Mixing angle between the radial field and the SM Higgs field

$$\tan 2\theta = \frac{2g \langle \varphi \rangle \langle r \rangle}{m_\varphi^2 - m_r^2}$$

Model parameters: g, m_r and $\langle r \rangle$

Lab Constraints On Weinberg's Higgs Portal Model (I)

- SM Higgs decay widths in Weinberg's model

$$\Gamma_{\varphi\to\alpha\alpha} = \frac{1}{32\pi}\frac{g^2\langle\varphi\rangle^2 m_\varphi^3}{(m_\varphi^2-m_r^2)^2}$$

$$\Gamma_{\varphi\to rr} = \frac{1}{32\pi} g^2\langle\varphi\rangle^2 \frac{\sqrt{m_\varphi^2-4m_r^2}}{m_\varphi^2}$$

- LHC: $\Gamma_{h\to\text{inv.}} < 1.2\ \text{MeV}$ (branching ratio $< 19\%$)

[Cheung, Lee, Tseng, PRD90 (2014) 095009]

$$\Rightarrow \boxed{|g| < 0.011}$$

[Cheung, Keung, Yuan, PRD 89 (2014) 015007]

- ILC: branching ratio $< 0.4 - 0.9\%$
  $\Rightarrow$ bound improved by factor $5 \sim 7$

[Bechtle, Heinemeyer, Stål, Stefaniak, Weiglein, arXiv:1403.1582]

Lab Constraints on Weinberg's Higgs Portal Model (II)

- Muon anomalous magnetic moment

$$\Delta a_\mu = 288(63)(49) \cdot 10^{-11} \Rightarrow \theta \lesssim \mathcal{O}(1)$$

- Radiatie Upsilon decays

$$\mathcal{B}\left(\Upsilon(nS) \to \gamma + r\right) < 3 \cdot 10^{-6} \Rightarrow \theta < 0.2$$

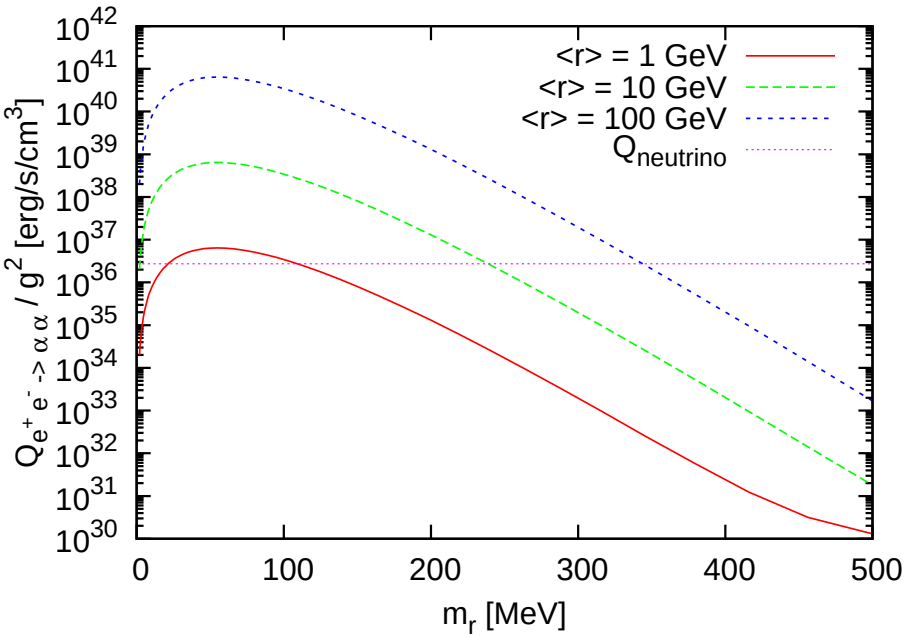
- B and K meson decay

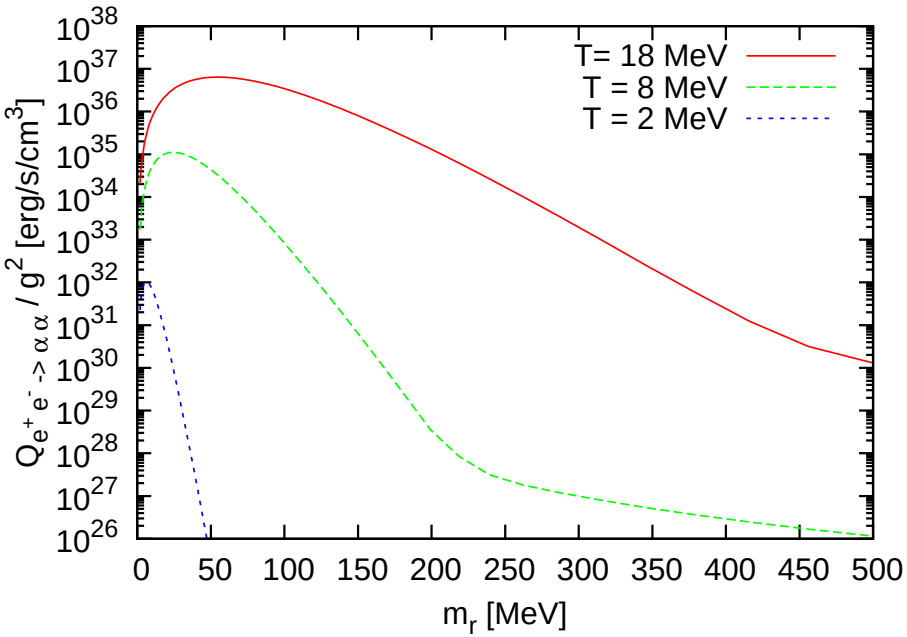
$$\mathcal{B}(B^+ \to K^+ + r) < 10^{-5} \Rightarrow \theta < 0.0016$$
$$\mathcal{B}(K^+ \to \pi^+ + r) < 10^{-10} \Rightarrow \theta < 8.7 \cdot 10^{-5} \quad (m_r < 354\ \mathrm{MeV})$$

[Huang, Li, Shao, Wang 2014; Anchordoqui, Denton, Goldberg, Paul, Silva, Vlcek et al. 2014]

Goldstone Boson Production in GRB Fireball

- Fiducial GRB parameters:
  $\mathcal{E} = 10^{52}$ erg, $R_0 = 10^{6.5}$ cm, $T_0 = 18$ MeV
- $e^+e^- \to \alpha\alpha$
- $NN \to NN\alpha\alpha$

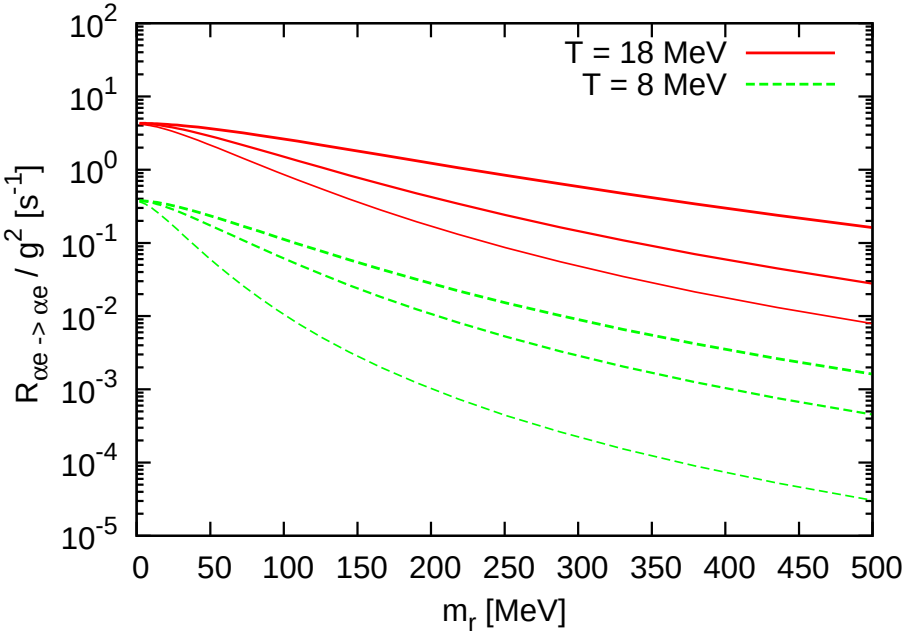


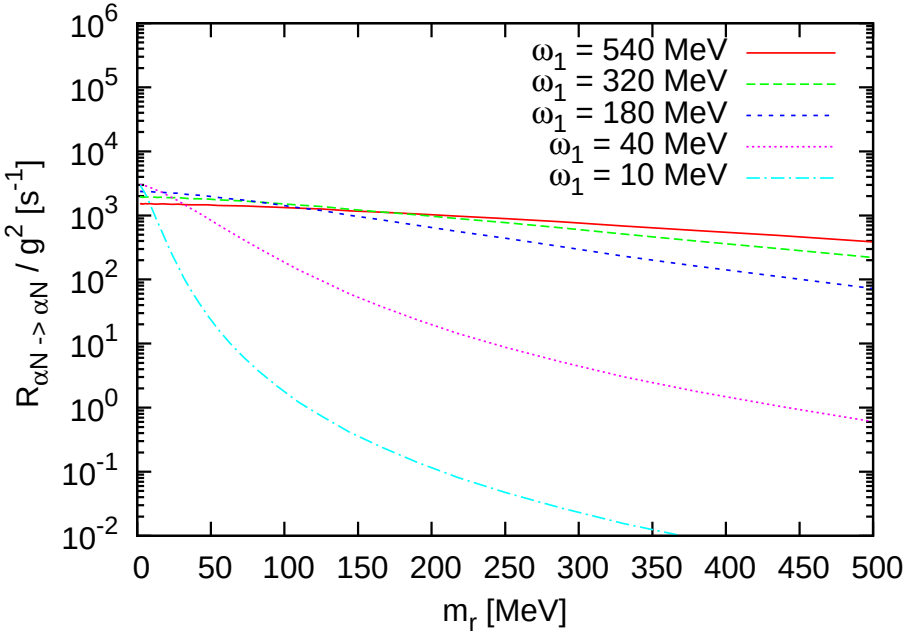


[HT, Ng 2016]

Goldstone Boson Mean Free Path in GRB Fireball

- $\alpha e^{\pm} \to \alpha e^{\pm}$
- $\alpha N \to \alpha N$





[HT, Ng 2016]

$$\Rightarrow \lambda_\alpha \gtrsim 7 \cdot 10^{10}\ \text{cm} \gg R_0 \sim 10^{6.5}\ \text{cm}$$

Hydrodynamics of GRB Fireball in the Presence of Goldstone Boson Production

- Conservation of baryon number and of energy and momentum

$$\partial_\mu N^\mu = 0\,, \quad \partial_\mu T^{\mu\nu} = j^\nu$$

- Stress-energy tensor with shear and bulk viscosity

$$T^{\mu\nu} = (\epsilon_0 + \delta\epsilon)\, u^\mu u^\nu + (p_0 + \pi_b)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

- Shear viscosity coefficient from kinetic theory

$$\eta \approx \frac{1}{3} \sum_j n_j \langle p \rangle_j \lambda_j$$

GRB Energy Loss Criterion

- In the GRB fireball comoving frame ($t' = t/\Gamma$, $R' = \Gamma R$)

$$\frac{\partial n_B}{\partial t'} = 0\,, \qquad \frac{\partial \epsilon}{\partial t'} = j^0 = Q\,, \qquad \frac{\partial p}{\partial R'} = 0$$

- Constraints on the Goldstone boson emissivity in the GRB initial fireball

$$|\Delta\epsilon| = |-Q_{e^+e^-\to\alpha\alpha}\,\Delta t'| \approx Q_{e^+e^-\to\alpha\alpha}\,\frac{1}{\Gamma_0}\frac{\Delta R_0}{\beta_0} \gtrsim \frac{\mathcal{E}}{\Gamma_0 V_0}$$

- Comparison of cooling timescale t_c with fireball expansion timescale t_e

$$\chi \equiv \frac{t_c}{t_e} \approx \frac{\mathcal{E}/\left(Q_{e^+e^-\to\alpha\alpha}V_0\right)}{R_0/\beta_0} \lesssim 1$$

[Koers, Wijers 2005]

Uncertainties in GRB Fireball Bounds

- Total energy $\mathcal{E}$: $\sim$ factor 2

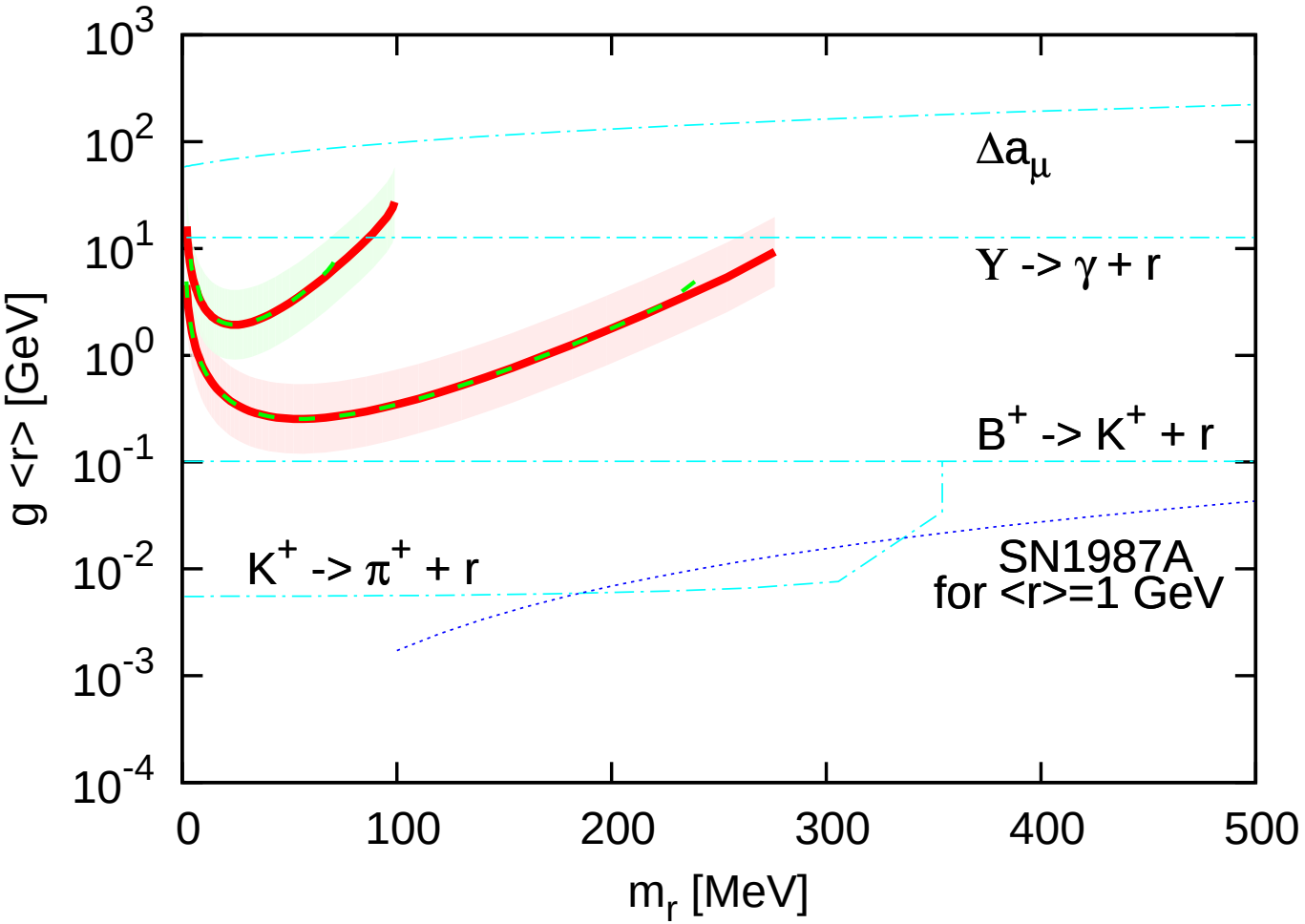
  [Wygoda, Getta, Mandich and Waxman 2015]

- Initial (acceleration) radius R_0: $\sim$ 20–100%

  [Pe'er, Barlow, O'Mahony, Margutti, Ryde, Larsson et al. 2015]

- Initial temperature T_0: $\sim$ 30–80%

GRB Constraints on Weinberg's Higgs Portal Model



[HT and Ng, JCAP 2016]