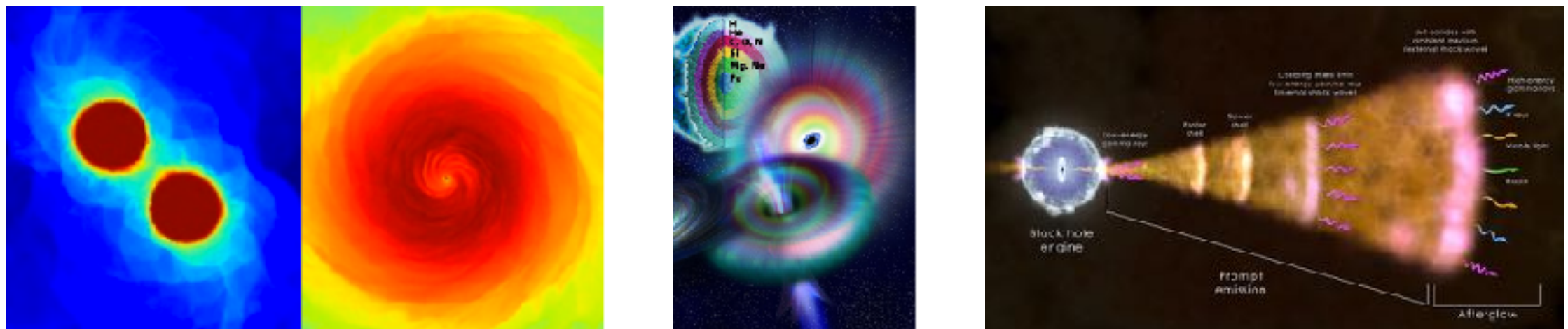# ICTP school: GRB afterglows slides
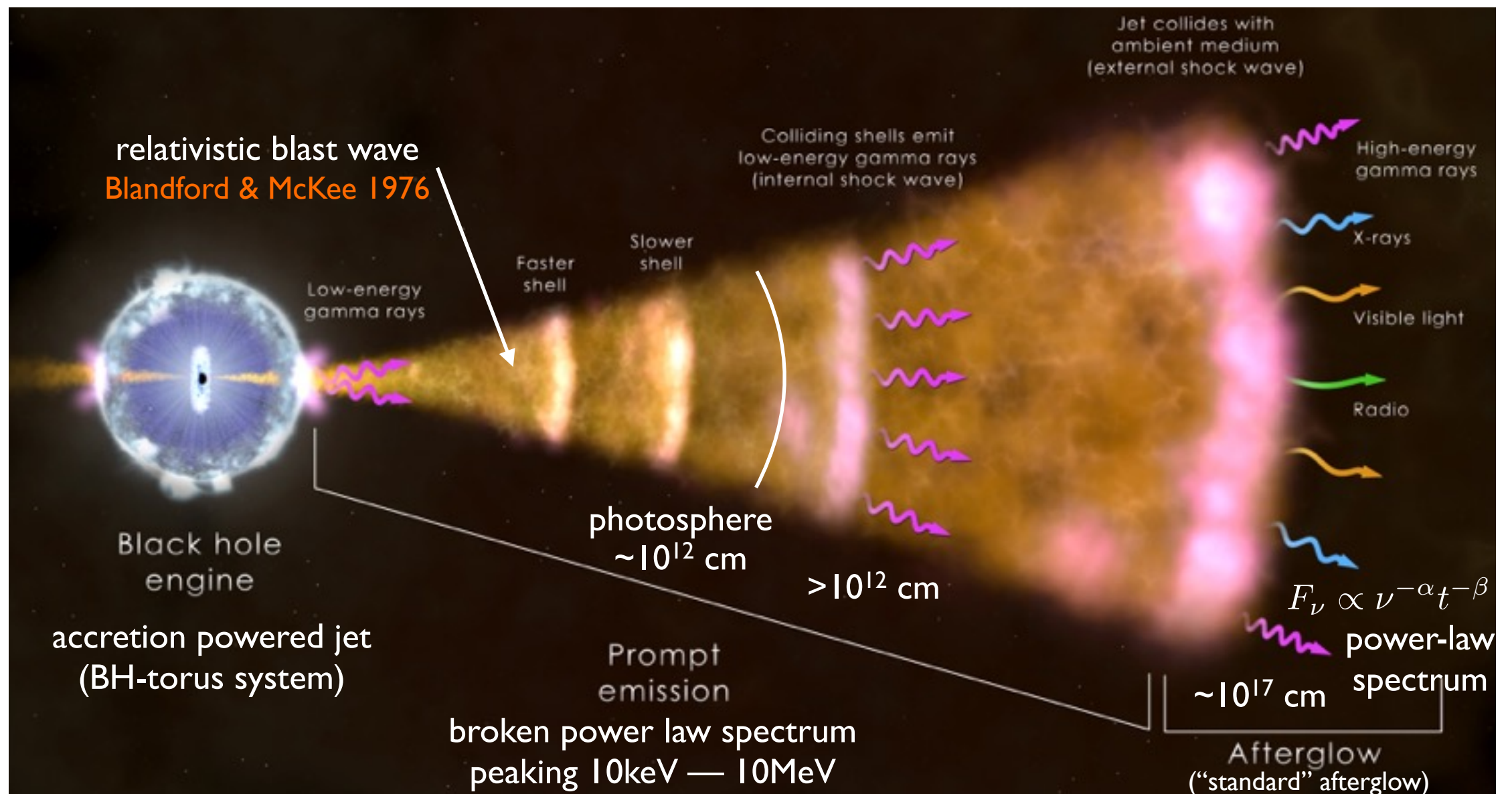
Daniel M. Siegel

Center for Theoretical Physics & Columbia Astrophysics Laboratory

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ICTP school *The Sound of Space-time: The Dawn of Gravitational Wave Science*, Sao Paulo, Dec 10-14, 2018
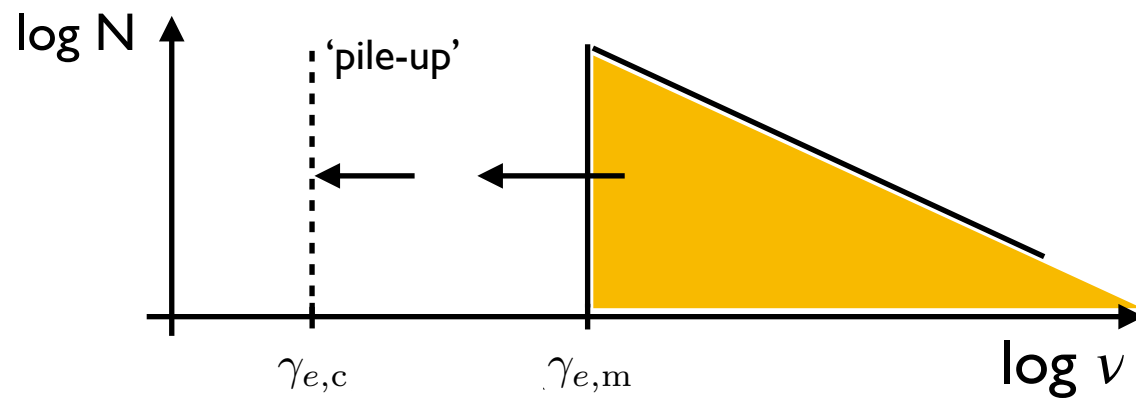
The canonical GRB picture

- What is the nature of the central engine, how is its energy tapped? Association to BNS?
- Composition of the outflow (e⁺e⁻, photons, baryons)? Collimation?
- How is the energy stored (thermal, kinetic or magnetic)? How does the relativistic blast wave give rise to observable emission?
- What are the dominant emission mechanisms (synchrotron, inverse Compton, thermal)?

Synchrotron afterglow spectrum

Two regimes:

fast cooling $(\gamma_{e,\mathrm{m}} > \gamma_{e,\mathrm{c}})$

$$F_{\nu,\mathrm{tot}} = \begin{cases} (\nu/\nu_{\mathrm{c}})^{1/3} F_{\nu,\mathrm{max}}, & \nu < \nu_{\mathrm{c}} \\ (\nu/\nu_{\mathrm{c}})^{-1/2} F_{\nu,\mathrm{max}}, & \nu_{\mathrm{c}} < \nu < \nu_{\mathrm{m}} \\ (\nu/\nu_{\mathrm{m}})^{-p/2}(\nu_{\mathrm{m}}/\nu_{\mathrm{c}})^{-1/2} F_{\nu,\mathrm{max}}, & \nu > \nu_{\mathrm{m}} \end{cases}$$

log N

'pile-up'

$\gamma_{e,\mathrm{c}}$ $\gamma_{e,\mathrm{m}}$ log ν

slow cooling $(\gamma_{e,\mathrm{m}} < \gamma_{e,\mathrm{c}})$

$$F_{\nu,\mathrm{tot}} = \begin{cases} (\nu/\nu_{\mathrm{m}})^{1/3} F_{\nu,\mathrm{max}}, & \nu < \nu_{\mathrm{m}} \\ (\nu/\nu_{\mathrm{m}})^{-(p-1)/2} F_{\nu,\mathrm{max}}, & \nu_{\mathrm{m}} < \nu < \nu_{\mathrm{c}} \\ (\nu/\nu_{\mathrm{c}})^{-p/2}(\nu_{\mathrm{c}}/\nu_{\mathrm{m}})^{-(p-1)/2} F_{\nu,\mathrm{max}}, & \nu > \nu_{\mathrm{c}} \end{cases}$$

log N

$\gamma_{e,\mathrm{m}}$ $\gamma_{e,\mathrm{c}}$ log ν
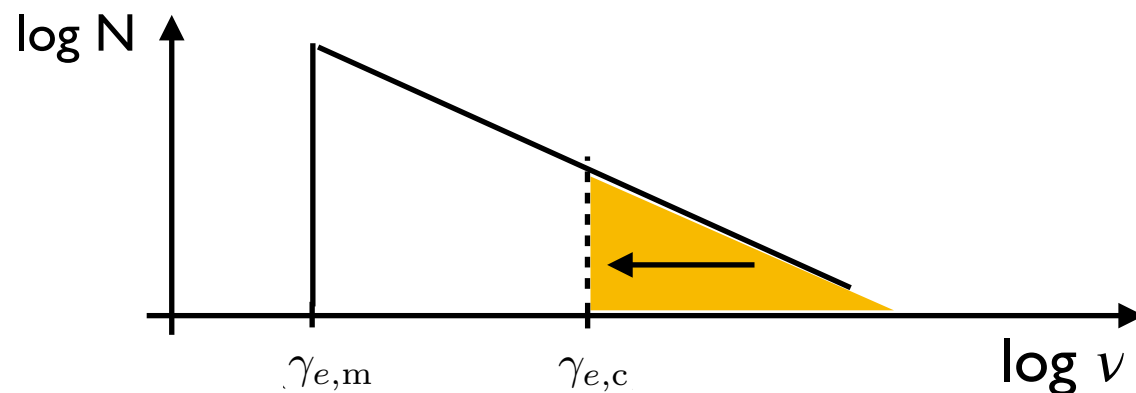
Synchrotron self-absorption
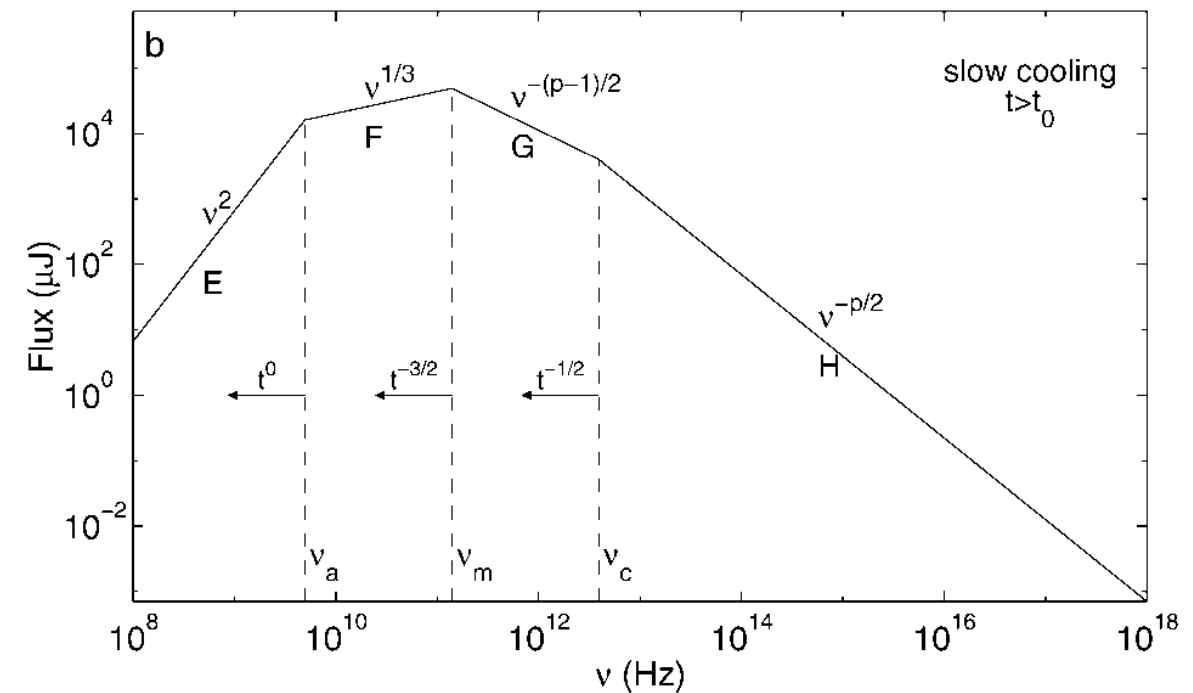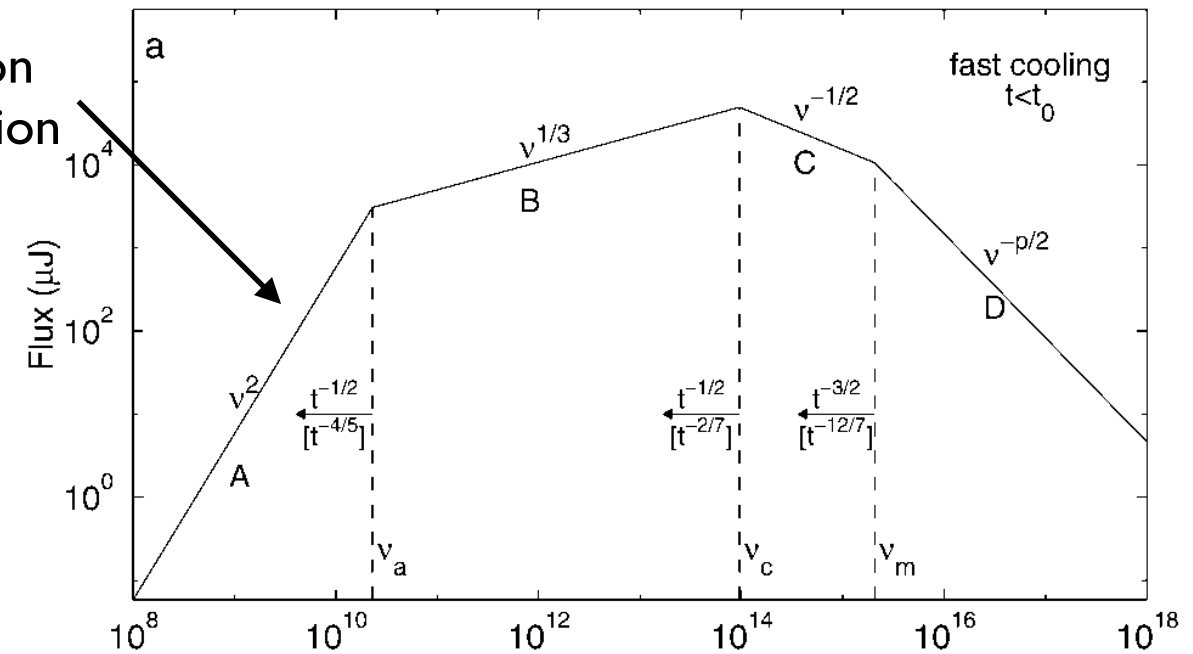
Sari+ 1998

$$F_{\nu,\mathrm{max}} = \frac{1}{4\pi D^2} N_e P_{\nu,\mathrm{max}} = \frac{m_e c^3 \sigma_{\mathrm{T}}}{9e}(32\pi m_{\mathrm{p}})^{1/2} \epsilon_B^{1/2} n^{3/2} \gamma^2 R^3 D^{-2}$$

Synchrotron afterglow lightcurves
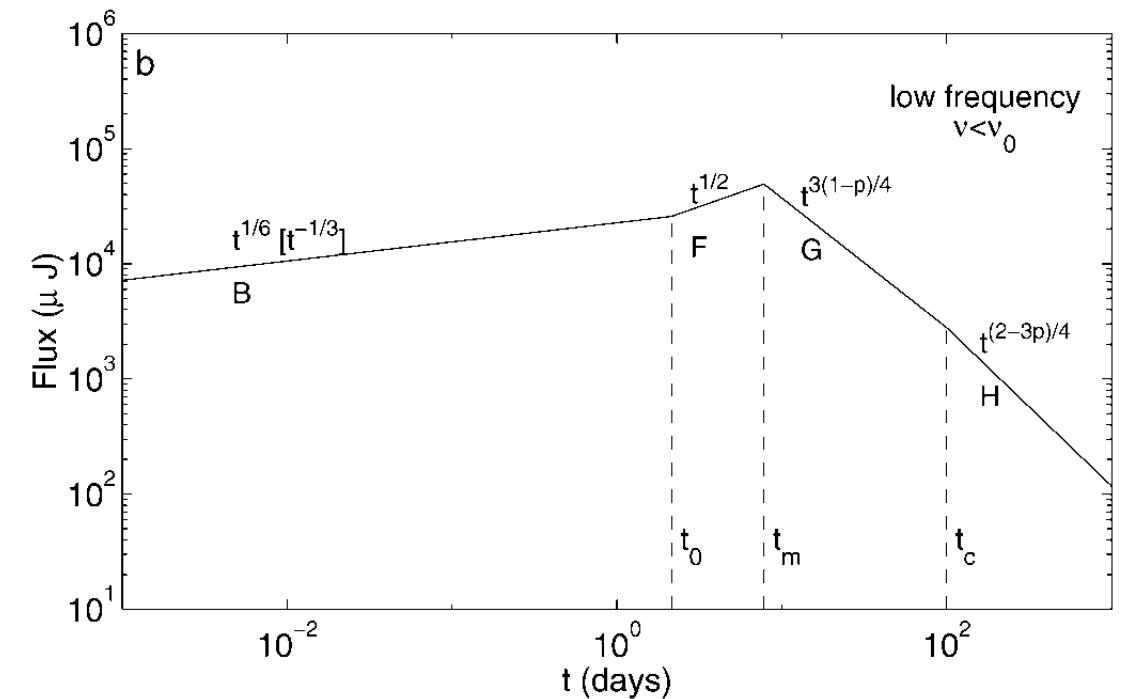
Two scenarios:

High-frequency lightcurve: $\nu_{\mathrm{obs}} > \nu_0$

$$L \simeq \nu_{\mathrm{obs}} F_{\nu,\mathrm{tot}}(\nu_{\mathrm{obs}}) \propto \begin{cases} \nu_c^{-1/3}, & \propto t^{1/6}, & t < t_c \\ \nu_c^{1/2}, & \propto t^{-1/4}, & t_c < t < t_m \\ \nu_c^{1/2}\nu_m^{(p-1)/2}, & \propto t^{-(3p-2)/4}, & t > t_m \end{cases}$$
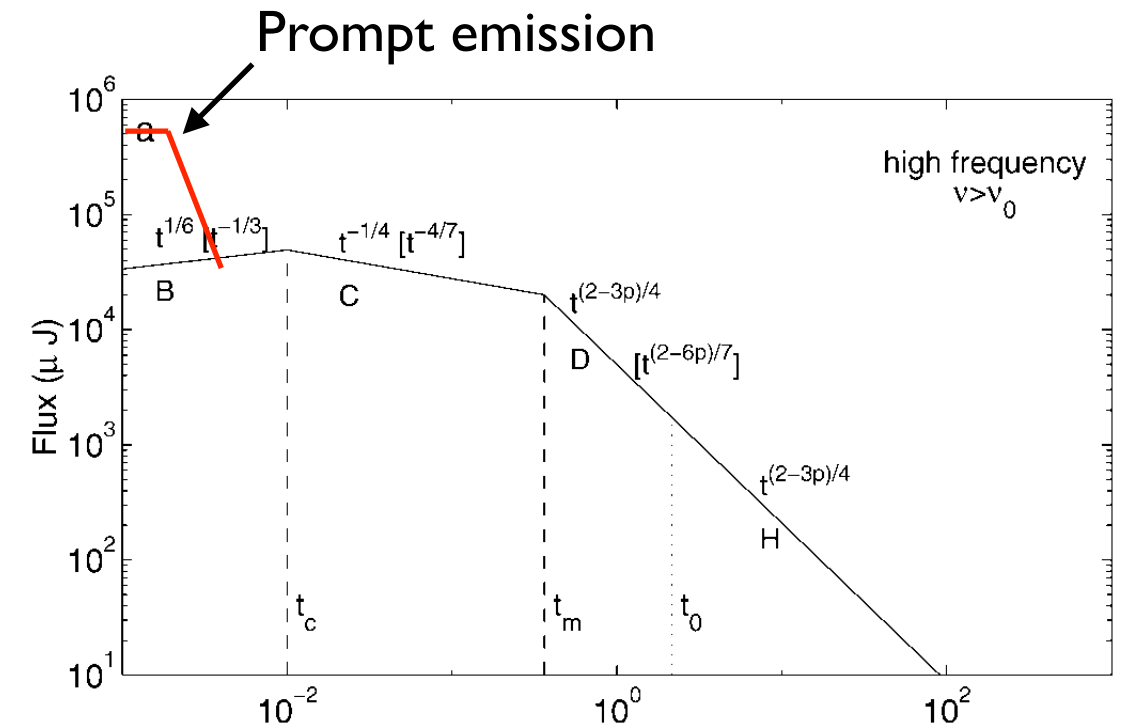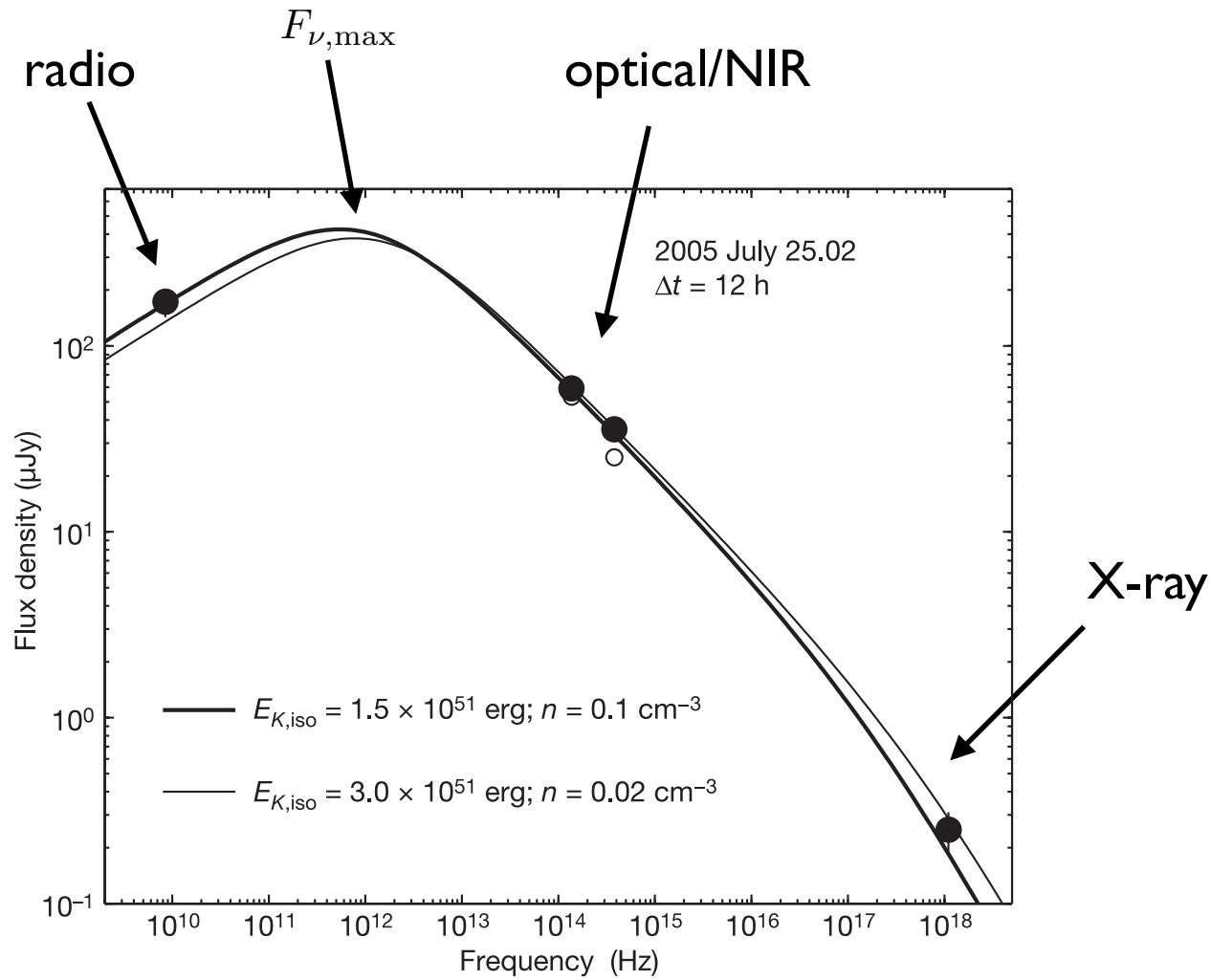
Low-frequency lightcurve: $\nu_{\mathrm{obs}} < \nu_0$

$$L \simeq \nu_{\mathrm{obs}} F_{\nu,\mathrm{tot}}(\nu_{\mathrm{obs}}) \propto \begin{cases} \nu_c^{-1/3}, & \propto t^{1/6}, & t < t_0 \\ \nu_m^{-1/3}, & \propto t^{1/2}, & t_0 < t < t_m \\ \nu_m^{(p-1)/2}, & \propto t^{-3(p-1)/4}, & t_m < t < t_c \\ \nu_m^{(p-1)/2}\nu_c^{1/2}, & \propto t^{-(3p-2)/4}, & t > t_c \end{cases}$$
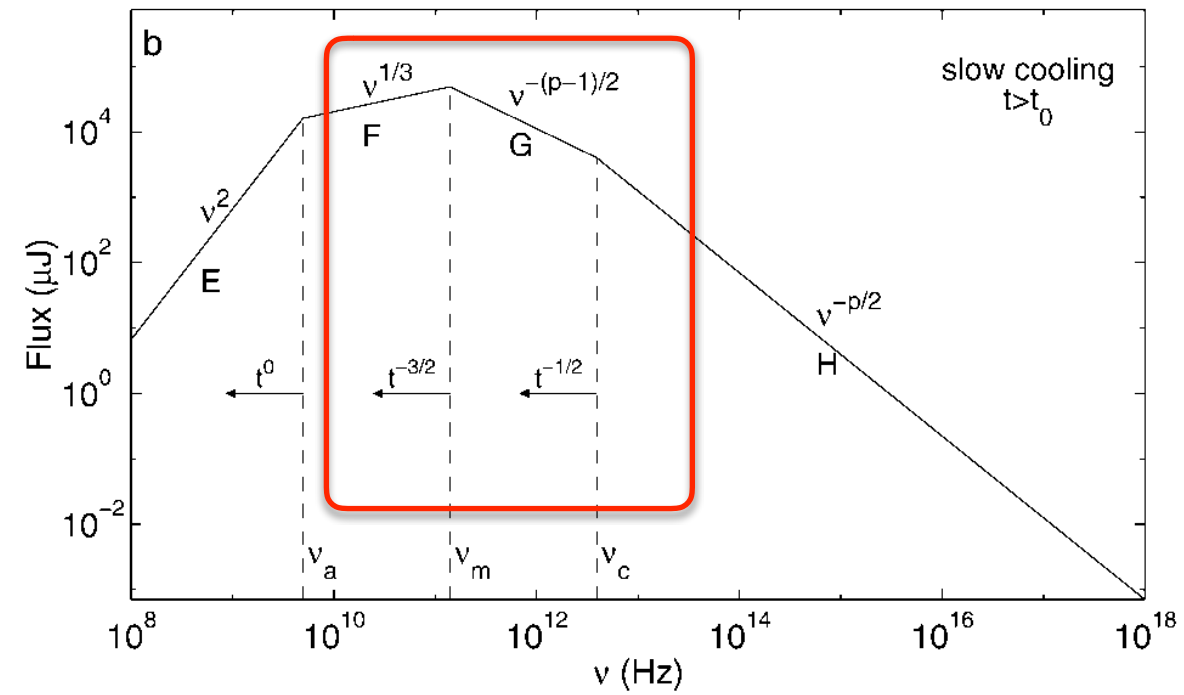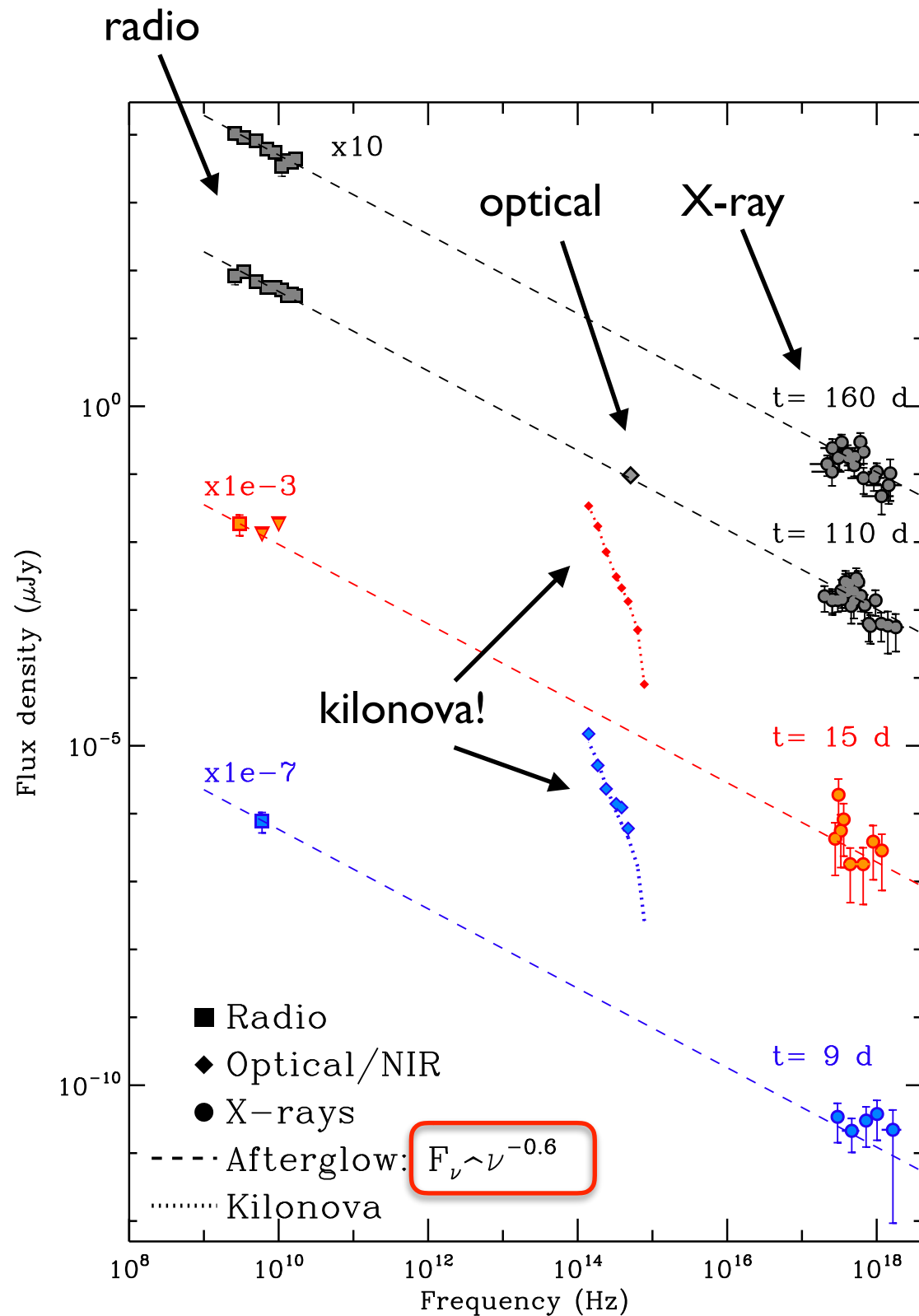

Sari+ 1998

Afterglow spectrum of GRB 050724

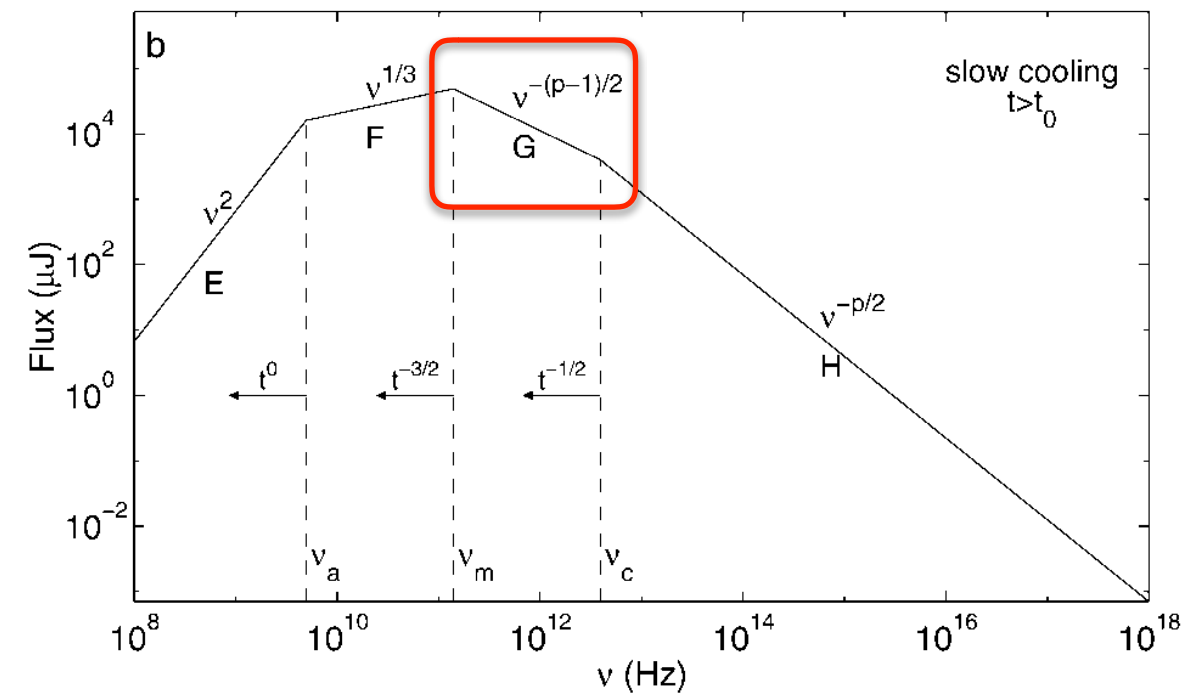First observed short GRB with detected radio+optical/NIR+X-ray afterglow

Berger+ 2005, Nature

Afterglow spectrum of GW170817

radio

optical   X-ray

x10

$t=$ 160 d

$t=$ 110 d

x1e−3

kilonova!

$t=$ 15 d

x1e−7

$t=$ 9 d

- ■ Radio
- ◆ Optical/NIR
- ● X−rays
- --- Afterglow: $F_\nu \sim \nu^{-0.6}$
- ········ Kilonova

Flux density (μJy)

Frequency (Hz)

Margutti+ 2018

b

slow cooling
$t > t_0$

$\nu^{1/3}$

$\nu^{-(p-1)/2}$

ν^2

F   G

E

t^0 $t^{-3/2}$ $t^{-1/2}$

$\nu^{-p/2}$

H

ν_a ν_m ν_c

Flux (μJ)

ν (Hz)

- perfect power-law over 9 orders of magnitude in frequency!

  ν_c above X-rays

  ν_m below radio

  → slow-cooling regime

  $$(p-1)/2 = 0.6 \;\; \Rightarrow \;\; p = 2.2$$

- other inferred parameters:

  $E \sim 5 \times 10^{50}$ erg, $\;\; n \sim 10^{-4}$ cm^{-3}, $\;\; \epsilon_e = 0.02$, $\;\; \epsilon_B = 0.001$