The VHE afterglow emission of structured GRB jets: the case of GW 170817 and prospects for future detections

Clément Pellouin

Frédéric Daigne and **Irina Dvorkin**

HEPRO VIII – *26/10/2023*

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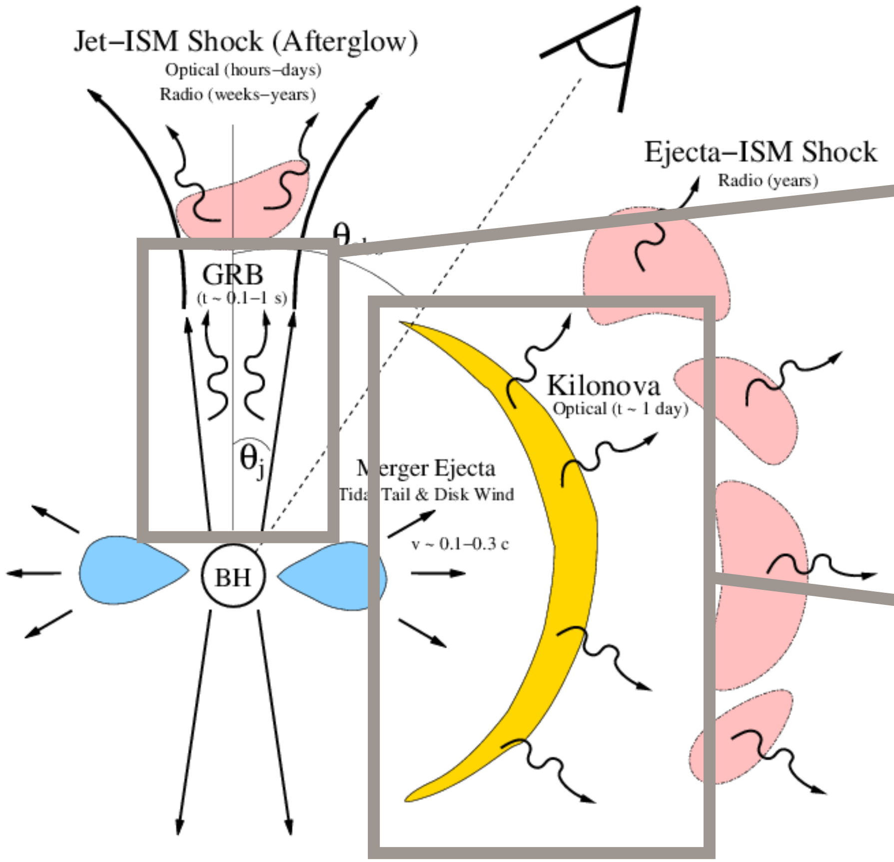
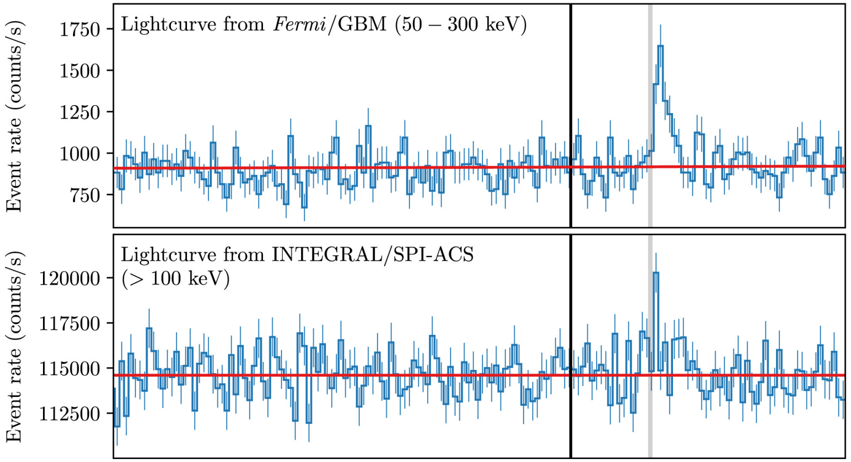
GW 170817: Electromagnetic counterparts



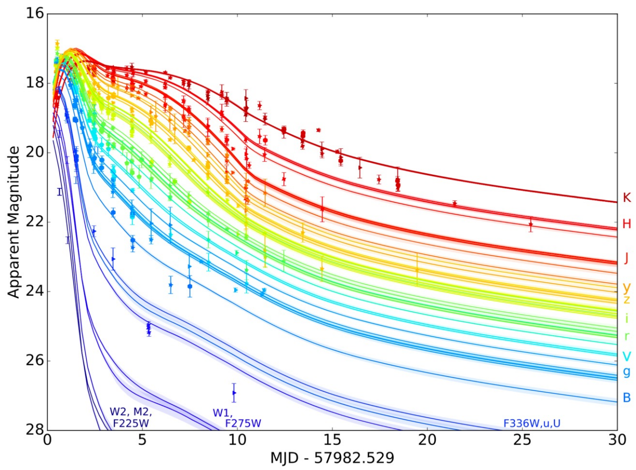
Metzger & Berger 2012, ApJ 746, 48

Post-merger outflows
(as predicted before GW 170817)



Abbott et al. 2017, ApJL 848, L13

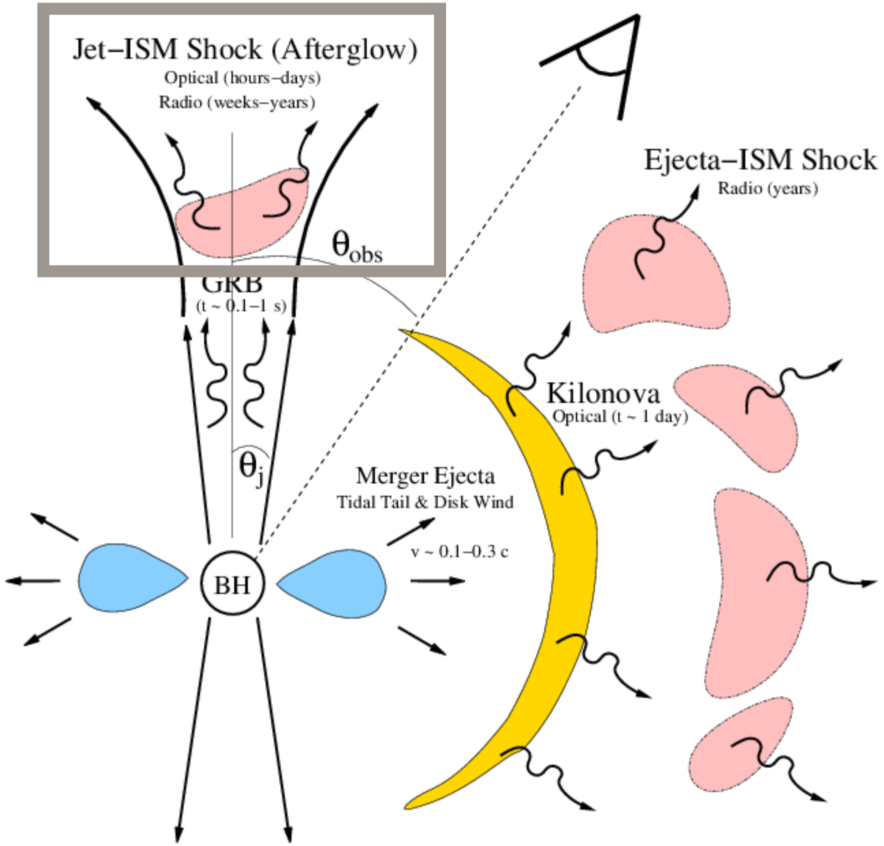
GRB 170817A
light curve



Villar et al. 2017, ApJ 851, L21

Kilonova emission from
GW 170817 (AT2017gfo)

GW 170817: Afterglow



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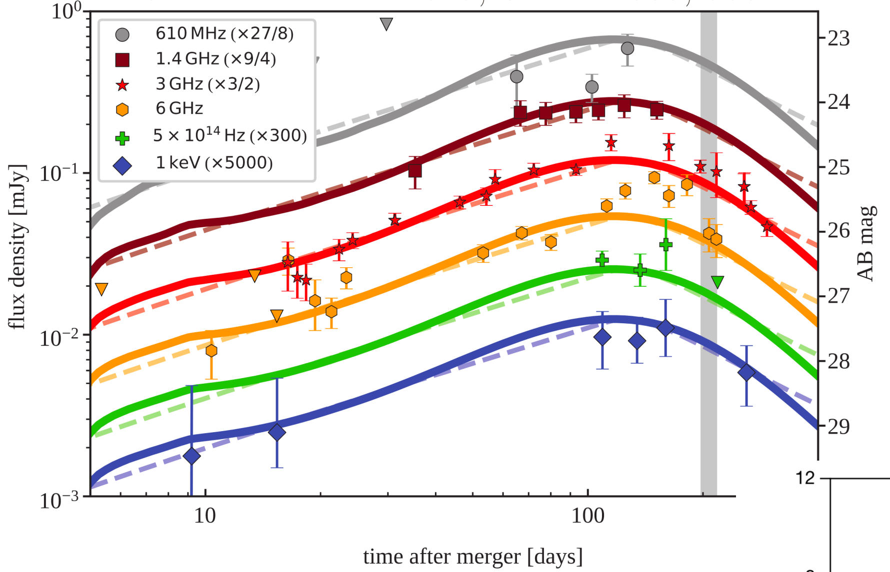
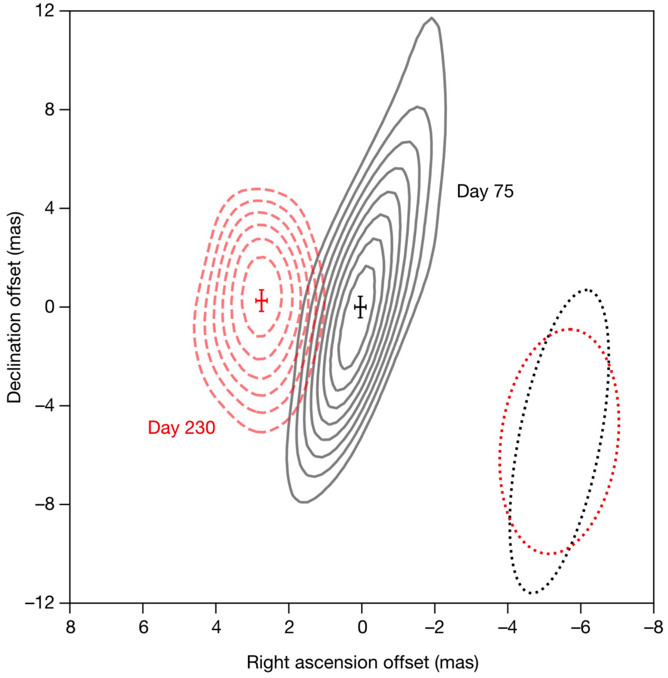


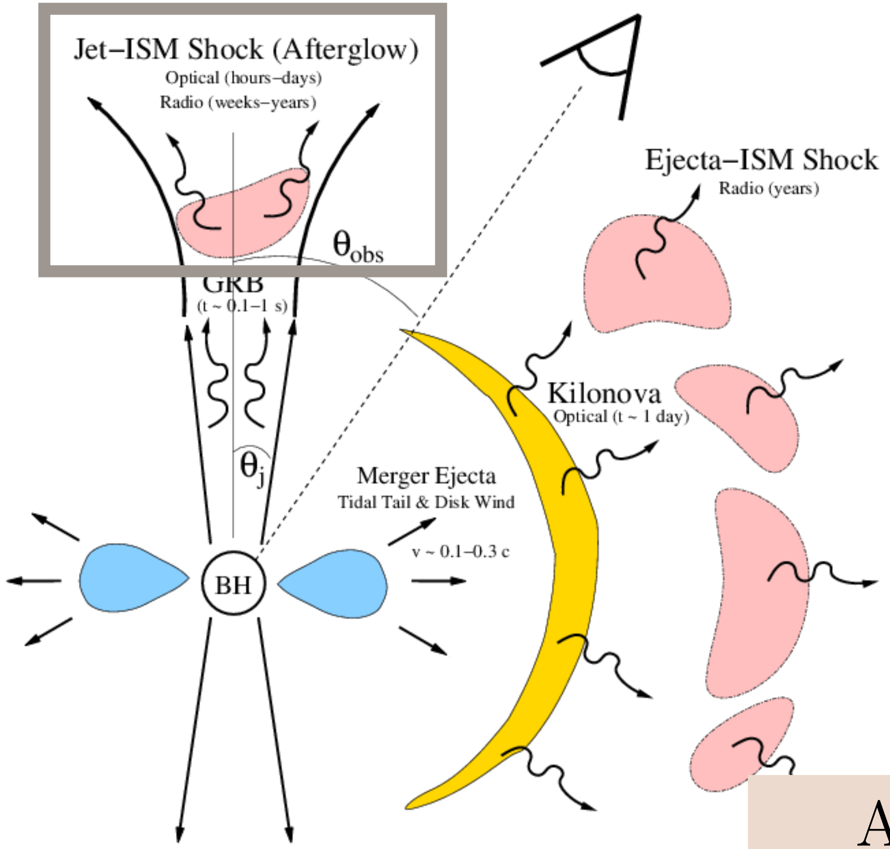
Afterglow light-curve
(radio to X-rays)

VLBI observations



Mooley et al. 2018, Nature 561, 355

GW 170817: Afterglow



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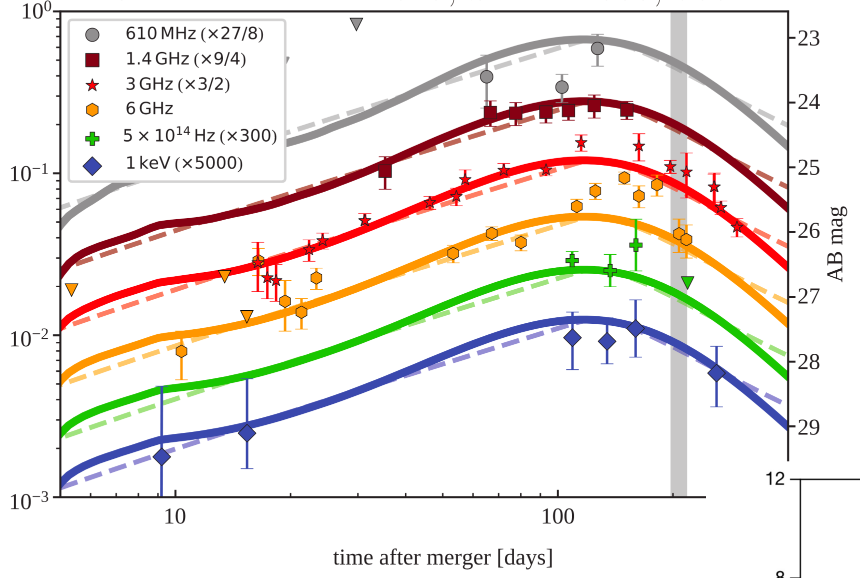

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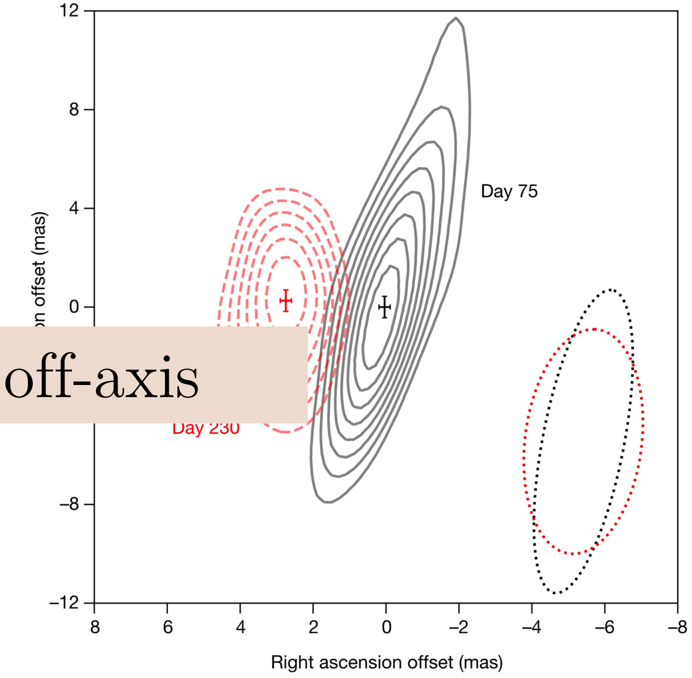

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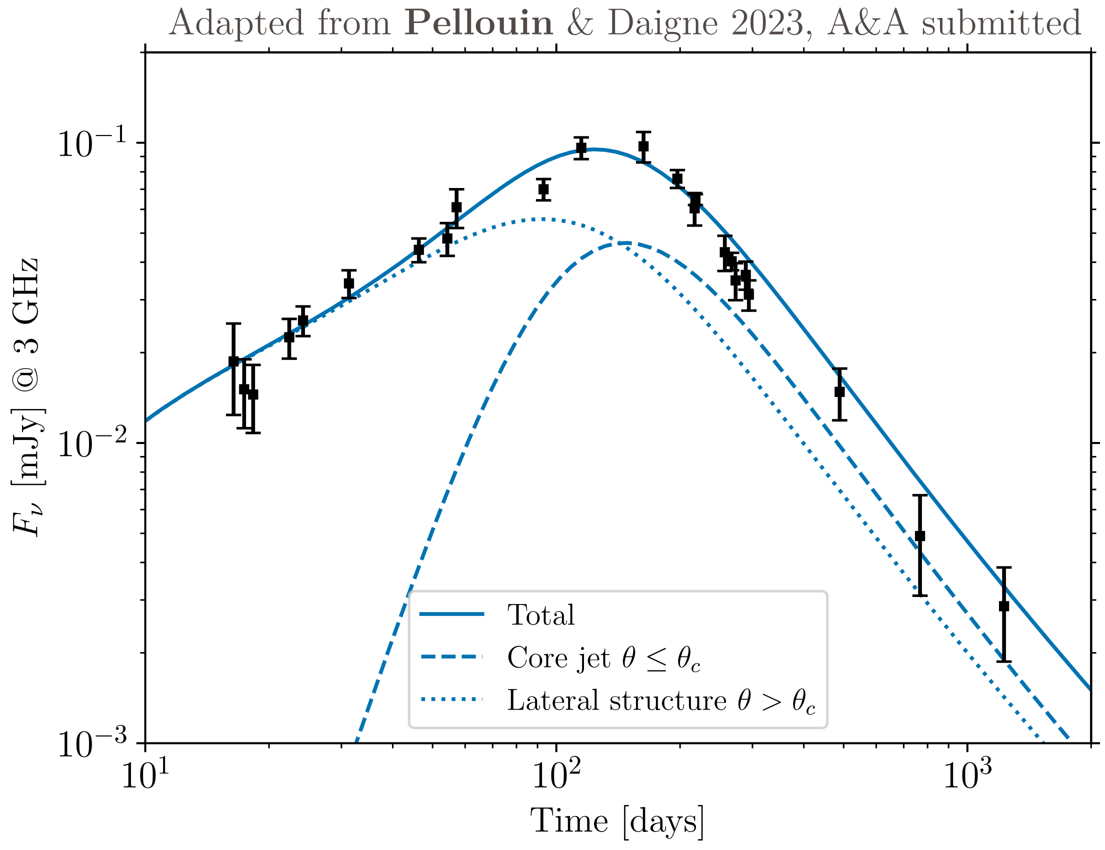
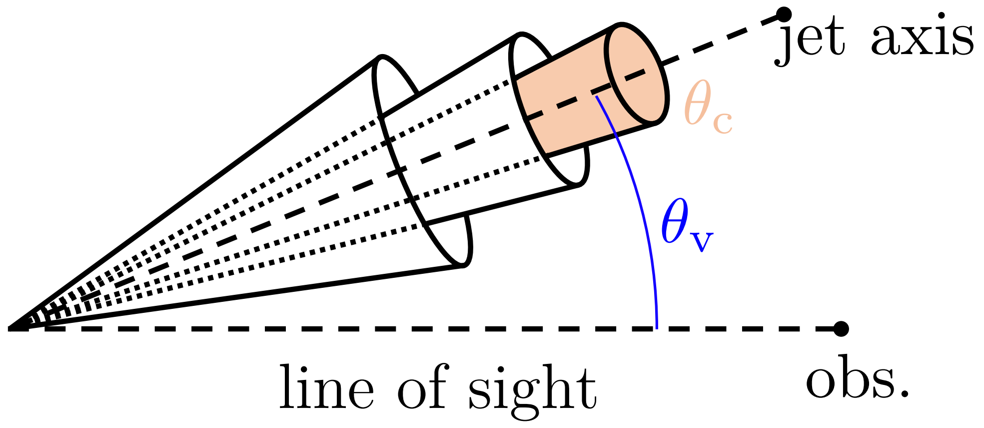
A structured relativistic jet seen off-axis

Recent advances: Structured jets



Radio afterglow light curve of
GW 170817



For GW 170817, see e.g. Abbott et al. 2017, Kasliwal et al. 2017, Ghirlanda et al. 2019, Fong et al. 2019, Troja et al. 2019, Mooley et al. 2018, 2022, Govreen-Segal & Nakar 2023, ...

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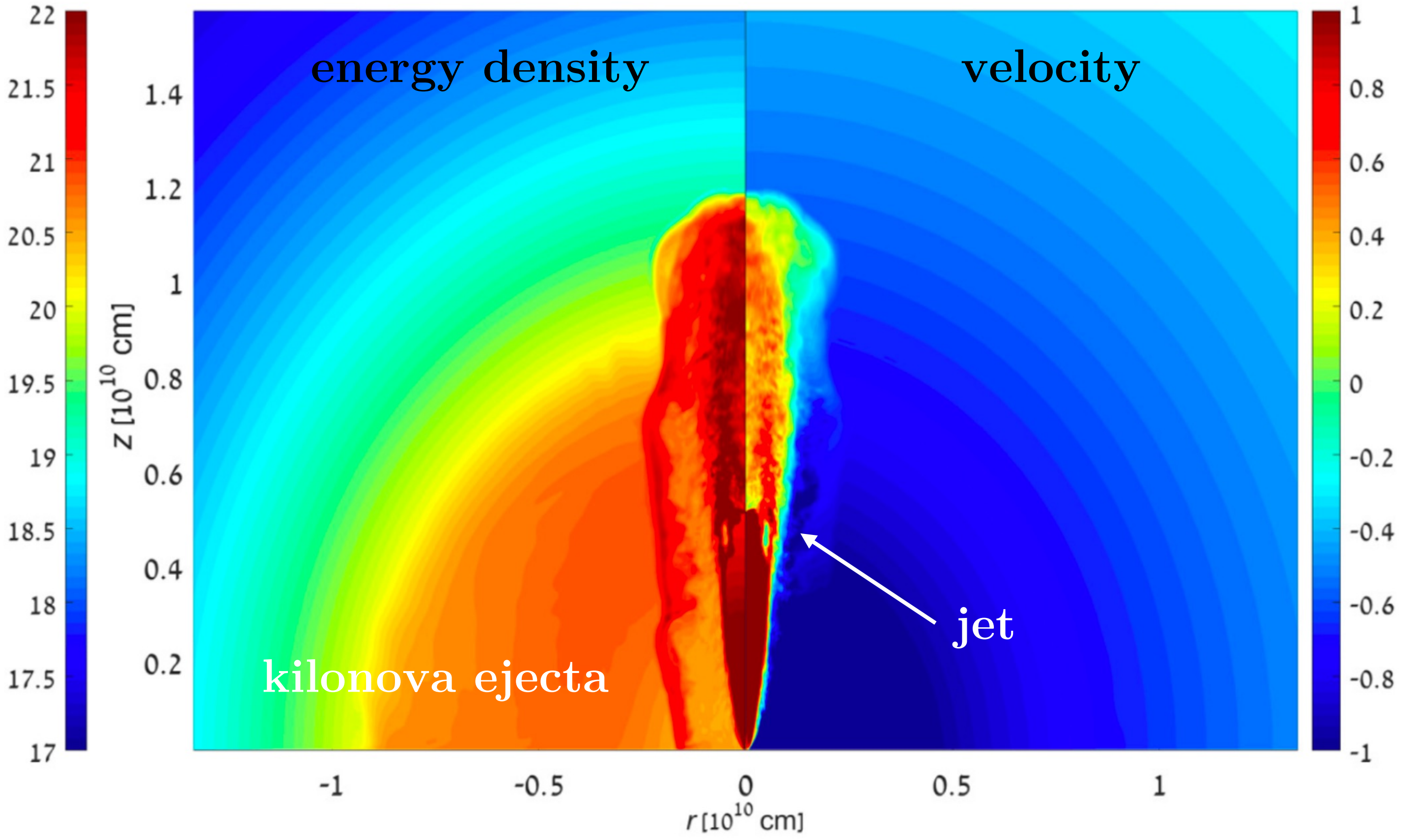

Gottlieb et al. 2018, MNRAS 479, 588

3D RMHD simulation of a successful relativistic jet

Recent advances: Very High Energy emission

Five recent detections of long GRB afterglows @ 0.1 – 10 TeV:

- GRB 180720B (H.E.S.S.)
- **GRB 190114C (MAGIC)**
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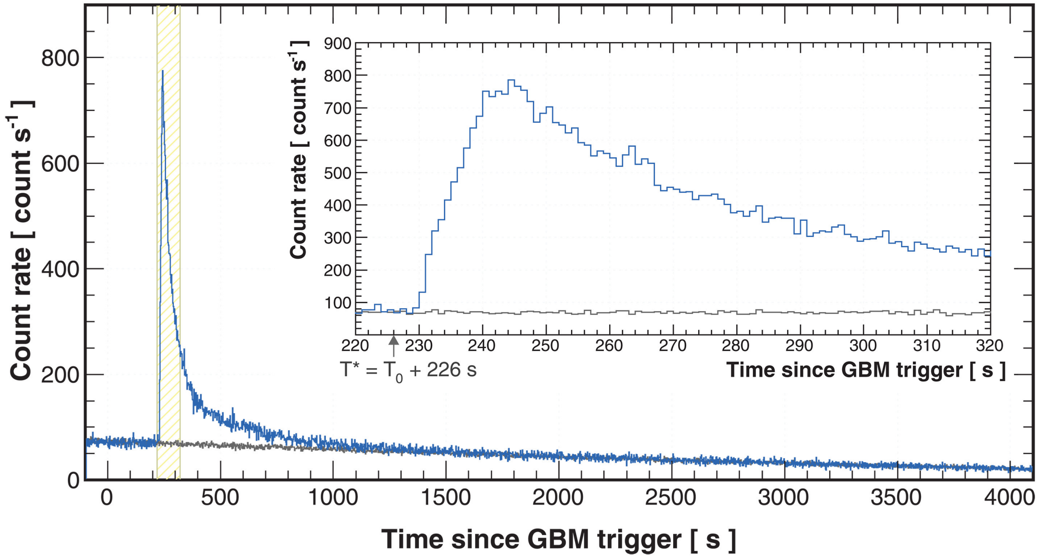
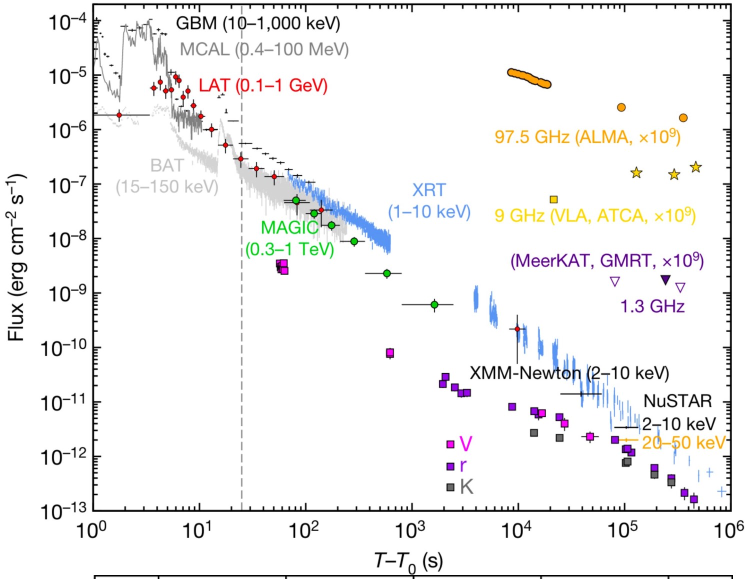
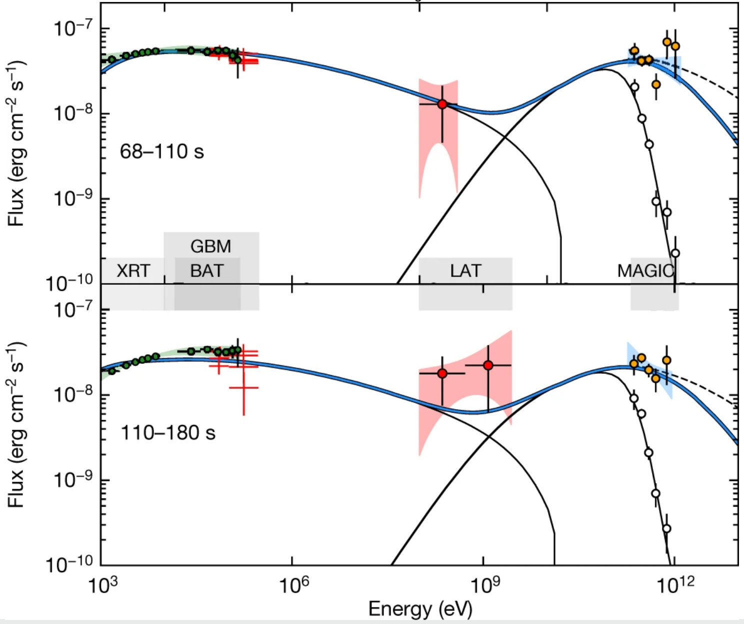
VHE light curve (0.2 – 7 TeV)



LHAASO Collaboration 2023, Science 380, 6652





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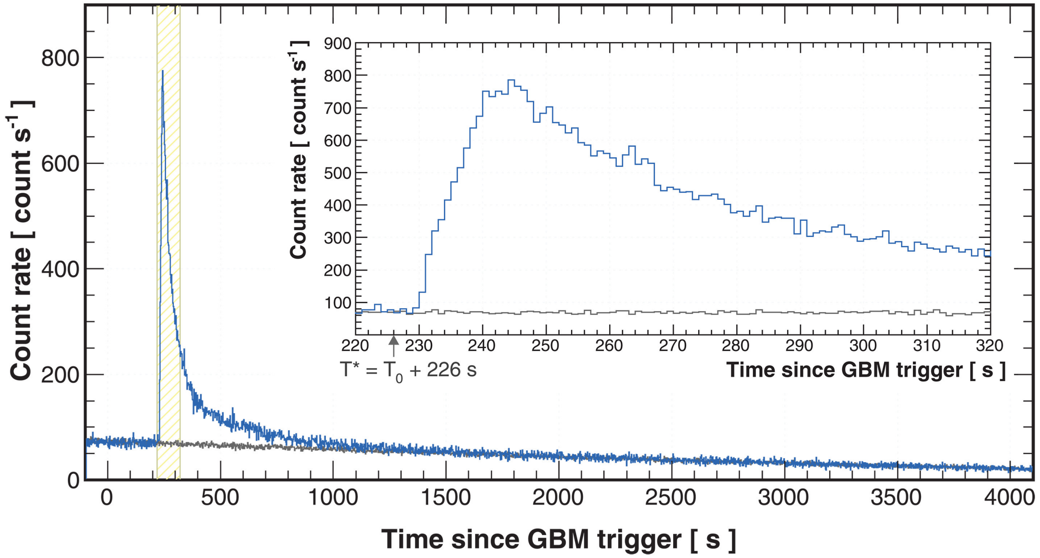

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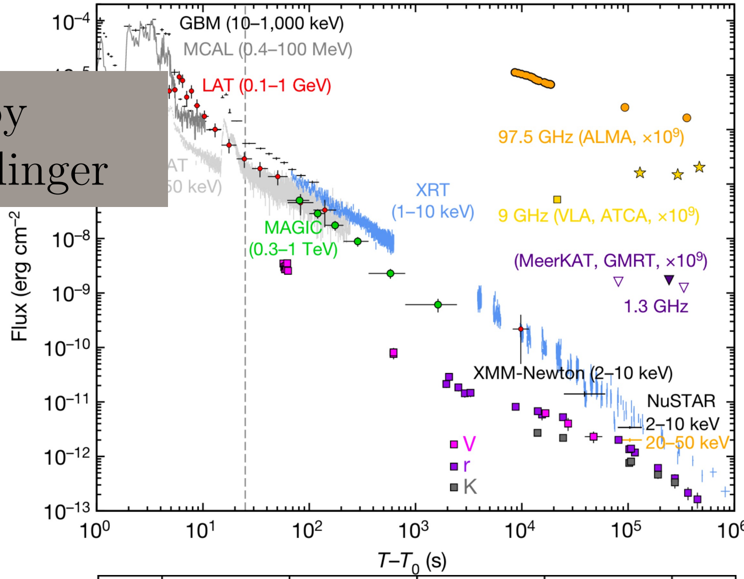

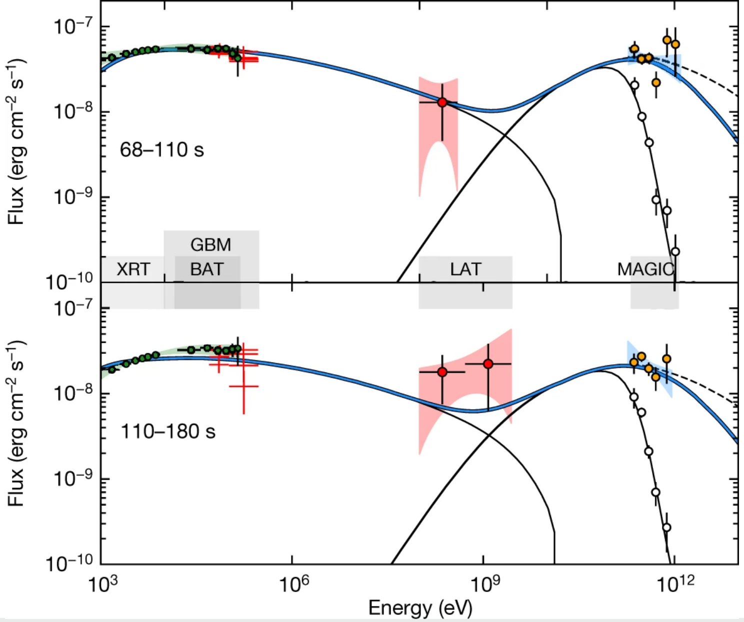

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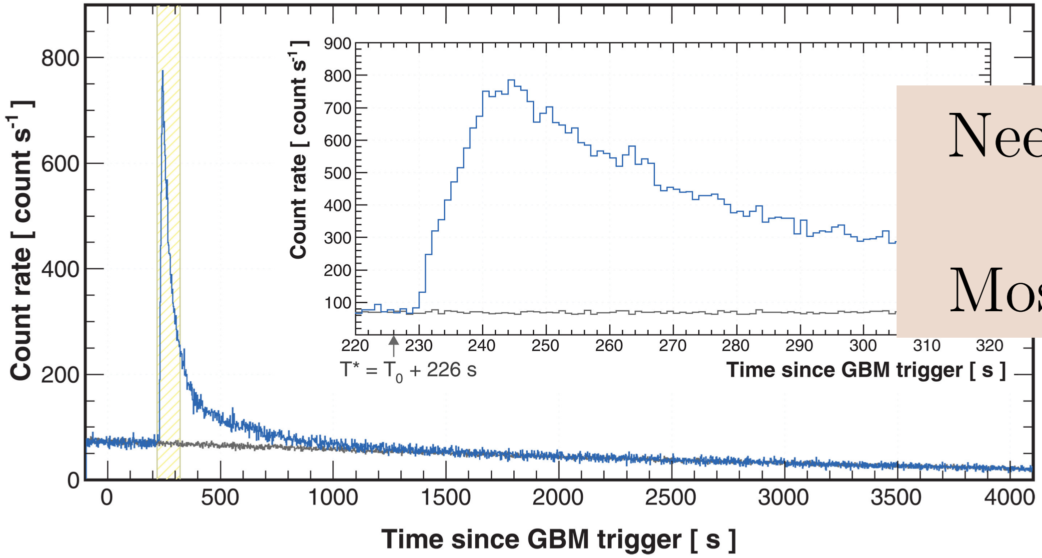

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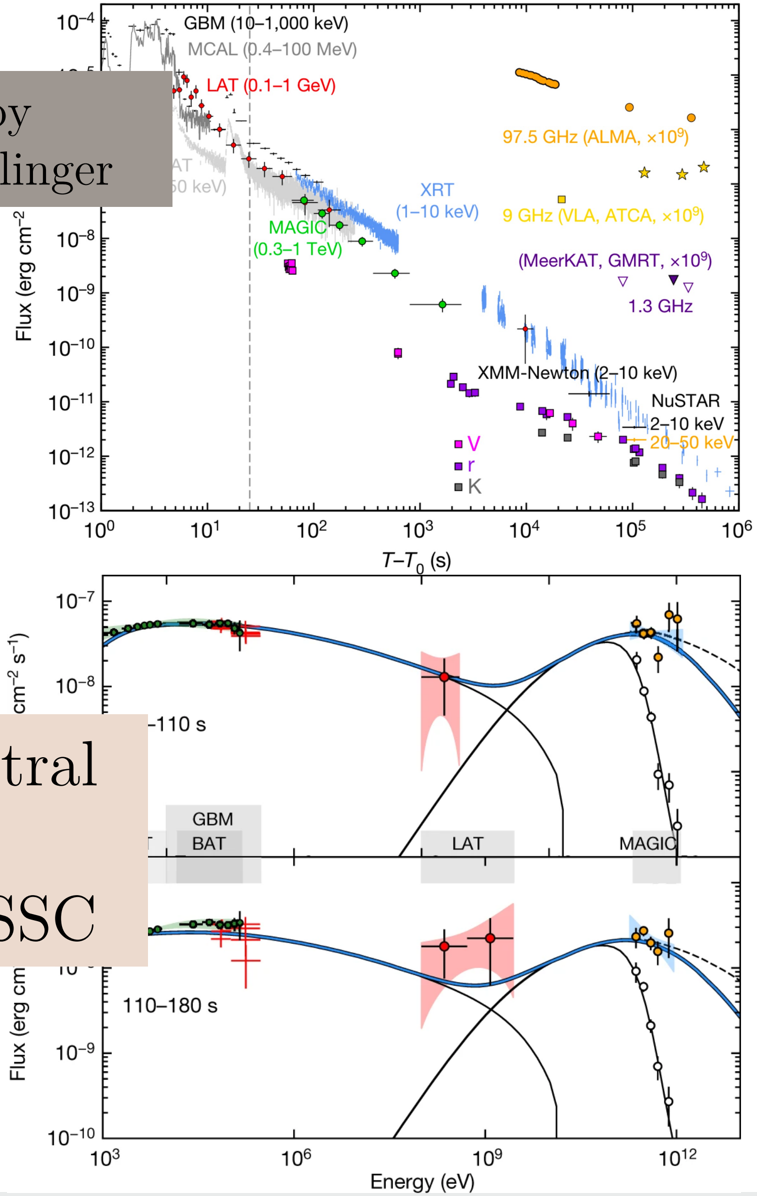
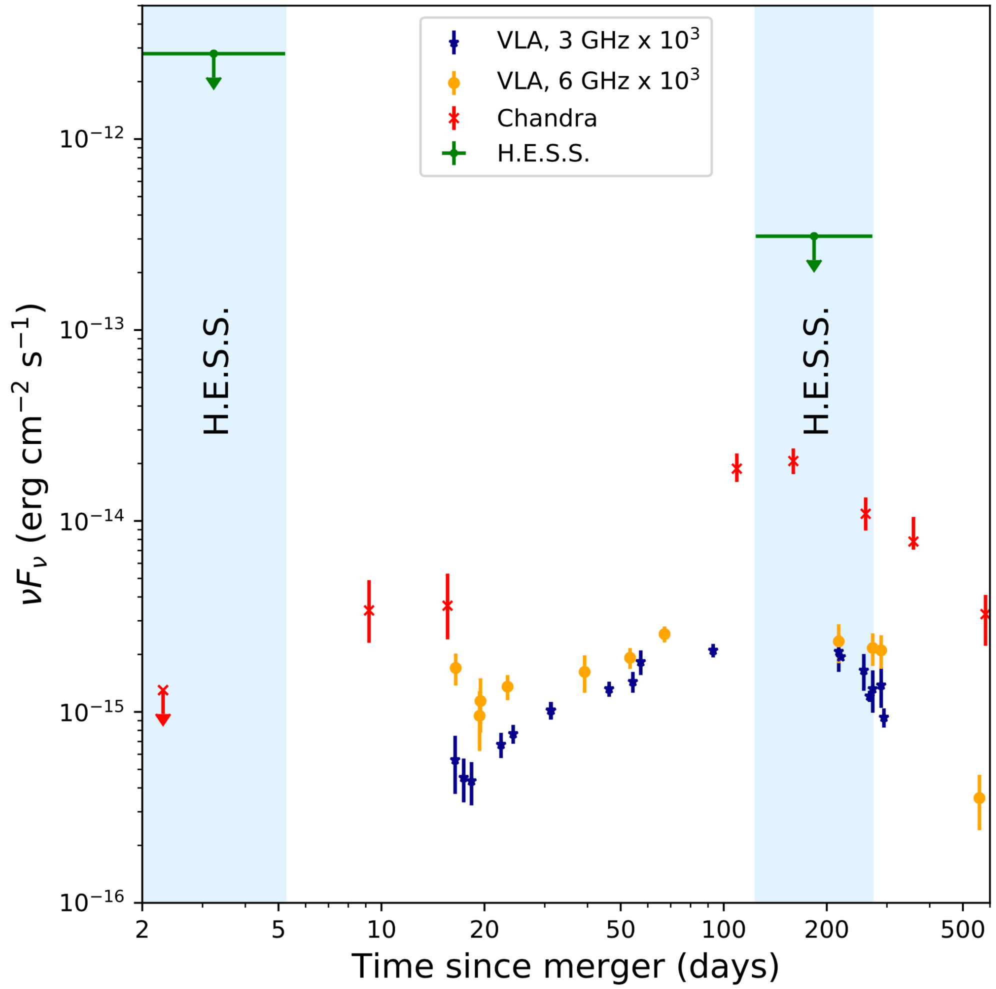


Need for an additional spectral component at VHE:
Most natural candidate = SSC

Veres et al. 2019, Nature 575, 459-463

Recent advances: Very High Energy emission



Abdalla et al. 2020, ApJ 894, L16

VHE observations of GW 170817 by H.E.S.S.

Afterglow modelling

Elements to model	**Parameters**
1. Lateral structure	$\theta_{\rm c}; \epsilon_0^{\rm c}; \Gamma_0^{\rm c}; a; b$
2. Jet dynamics (coasting phase, self-similar deceleration)	$n_{\rm ext}$
3. Microphysics at the shock	$\epsilon_{\rm B}; \epsilon_{\rm e}; \zeta; p$
4. Radiative processes in the shocked region	
5. From local emissivity to observed flux density	$\theta_{\rm v}; z \ (D_{\rm L})$

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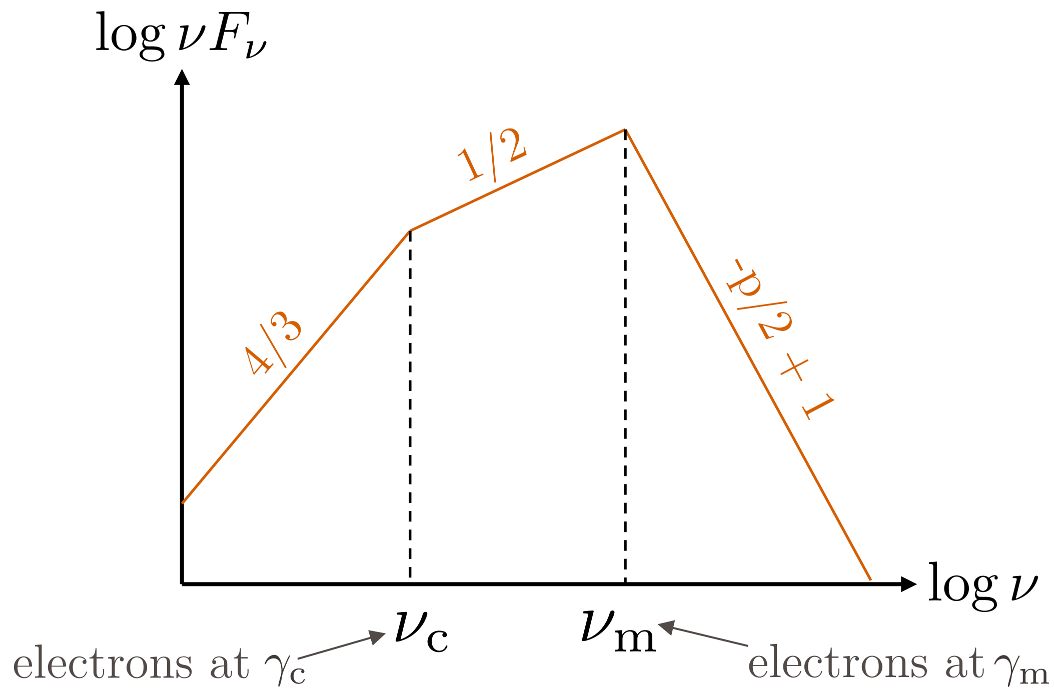
Radiative processes

See Sari et al. 1998, ApJ 497, L17



Synchrotron flux emitted by the population of radiating electrons (*fast cooling*, comoving frame)

γ_m minimal injection Lorentz factor

γ_c critical Lorentz factor

For each electron:

If $\gamma > \gamma_c$: radiatively efficient

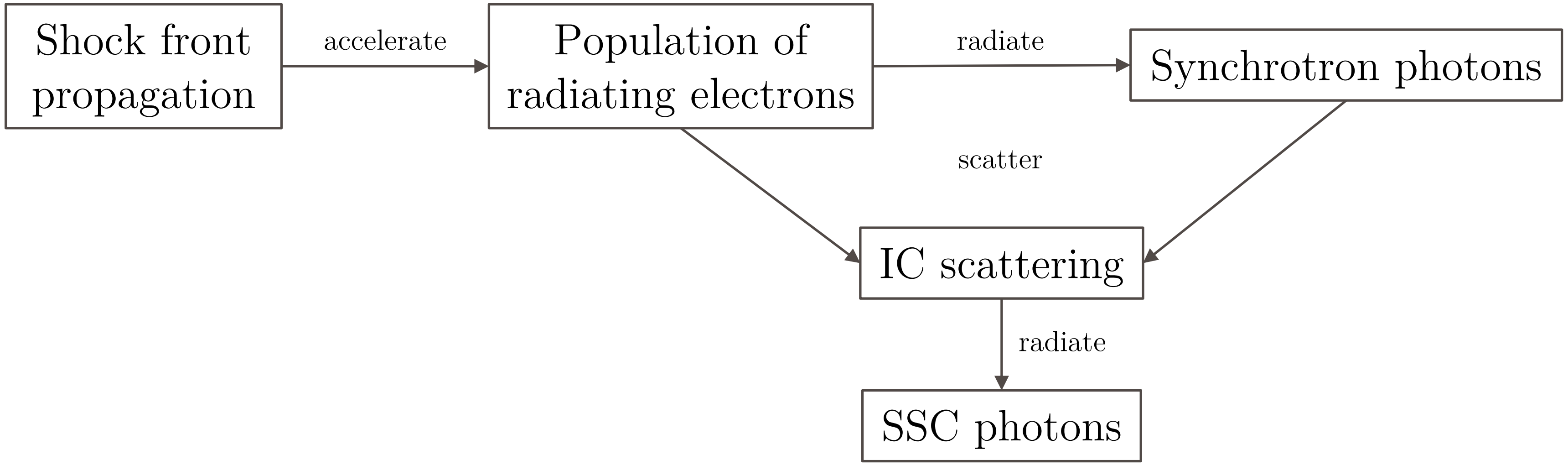
For the population:

2 emission regimes:

$\gamma_m > \gamma_c$: fast cooling

$\gamma_c > \gamma_m$: slow cooling

Radiative processes



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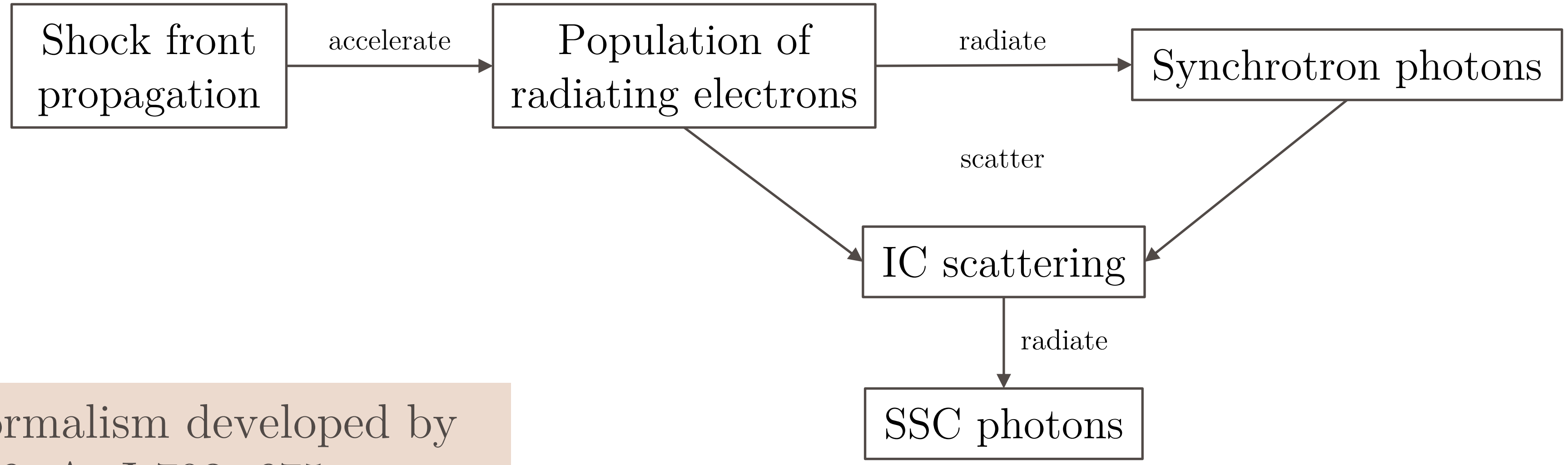
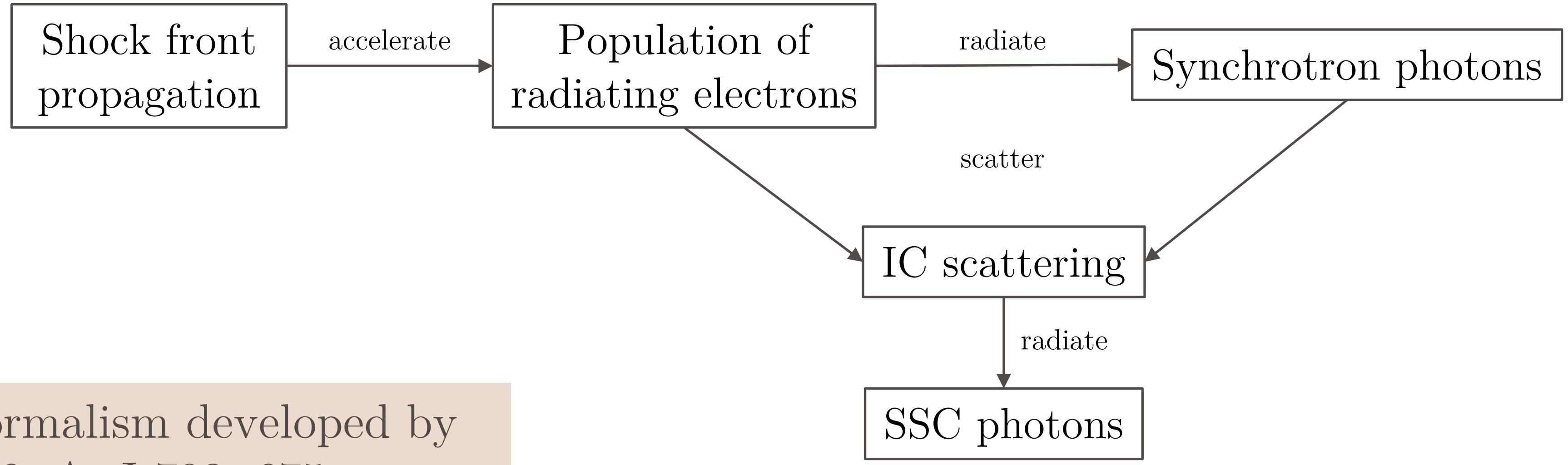


Following the formalism developed by Nakar et al. 2009, ApJ 703, 675

Determining the spectral shapes is not trivial, there are different regimes:
– synchrotron radiative efficiency
– SSC diffusions efficiency
– Thomson or KN regime

Radiative processes



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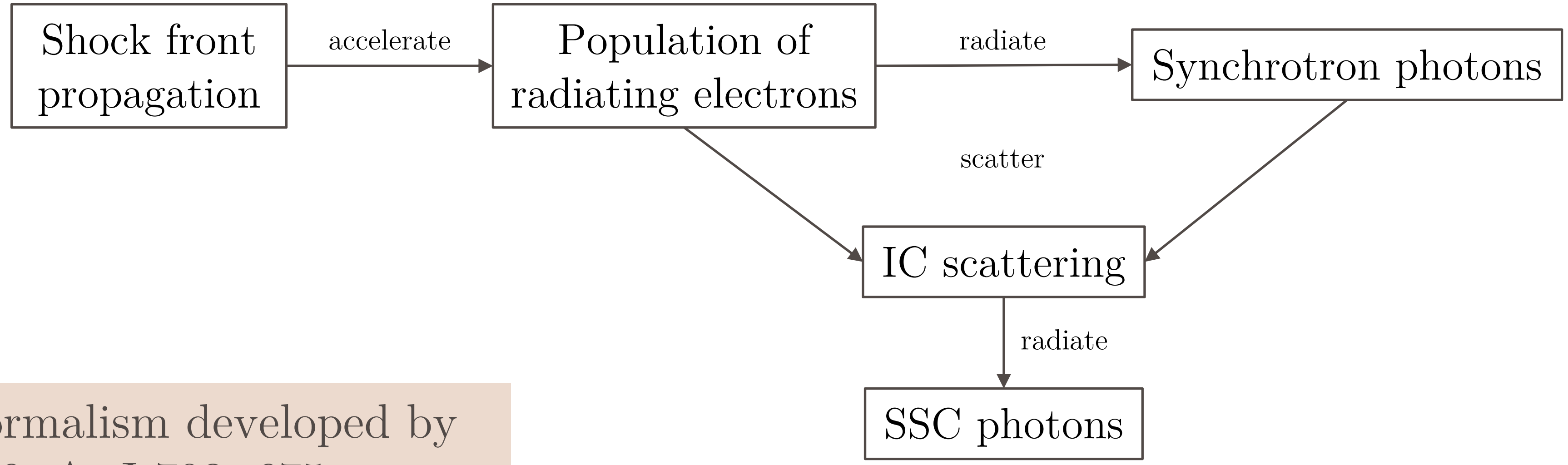

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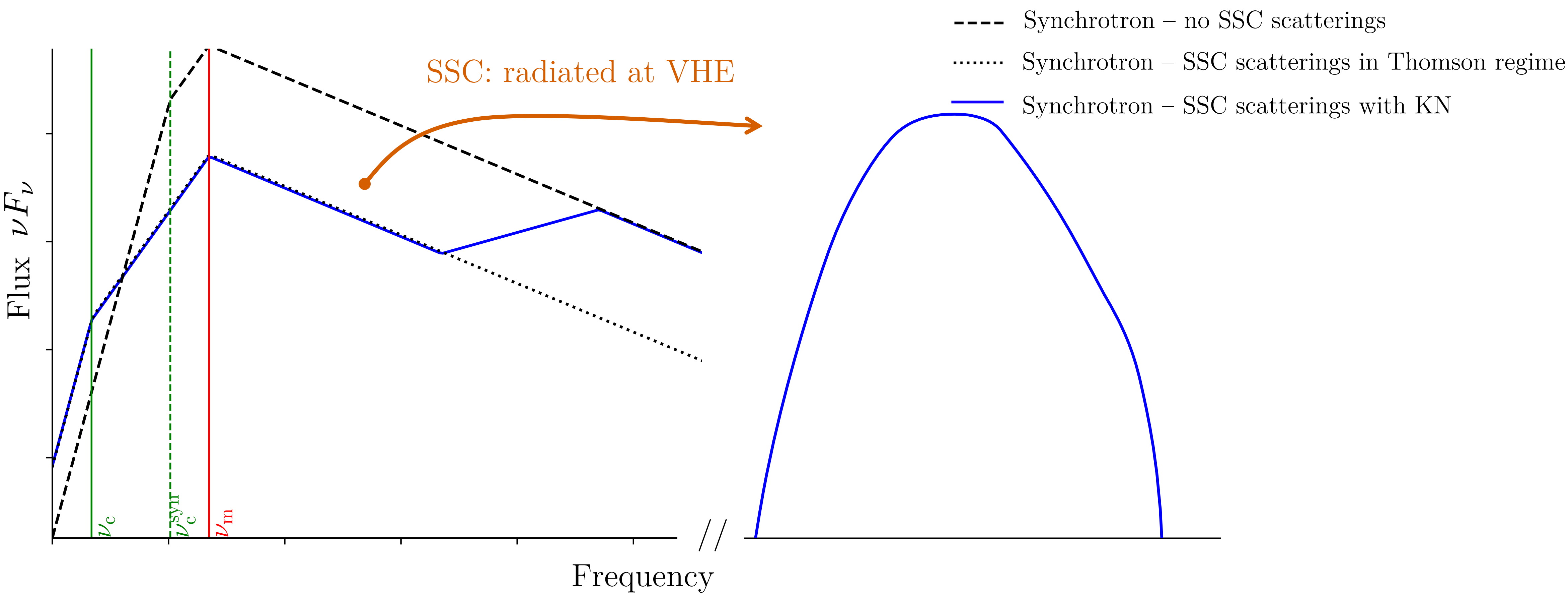
Numerically, iterative procedures to compute the radiative regime (synchrotron and SSC), the critical Lorentz factor γ_c and the maximum acceleration Lorentz factor γ_{max} + other effects:

– Pair production
– Synchrotron self-absorption

Radiative processes

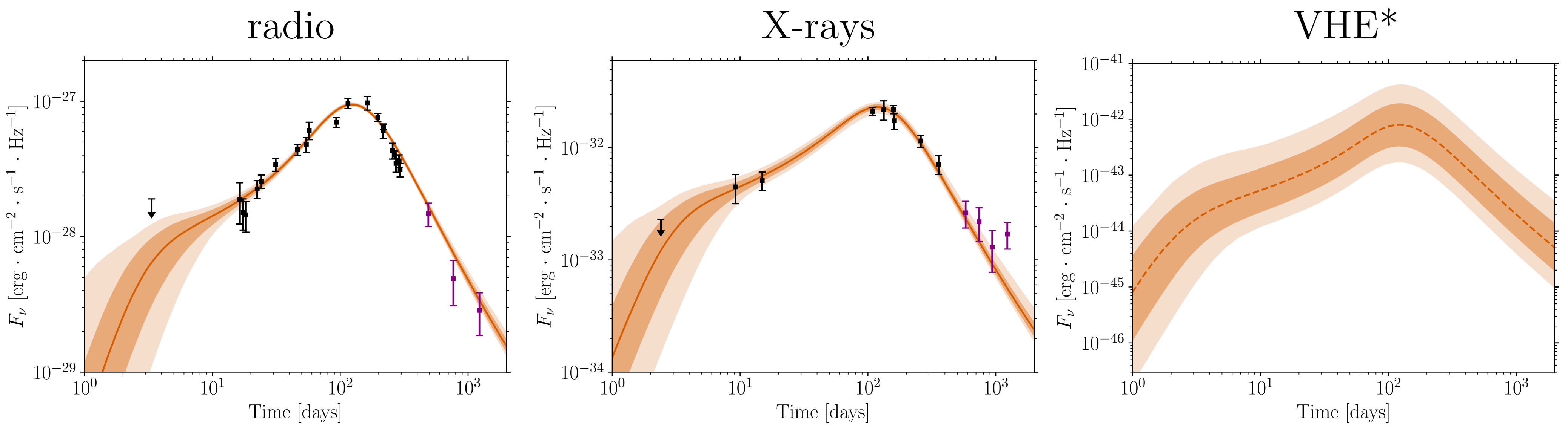
Based on the formalism developed by Nakar et al. 2009, ApJ 703, 675



Example: Fast cooling with strong SSC and high-energy KN suppression

Results: GW 170817

Pellouin & Daigne 2023, A&A submitted

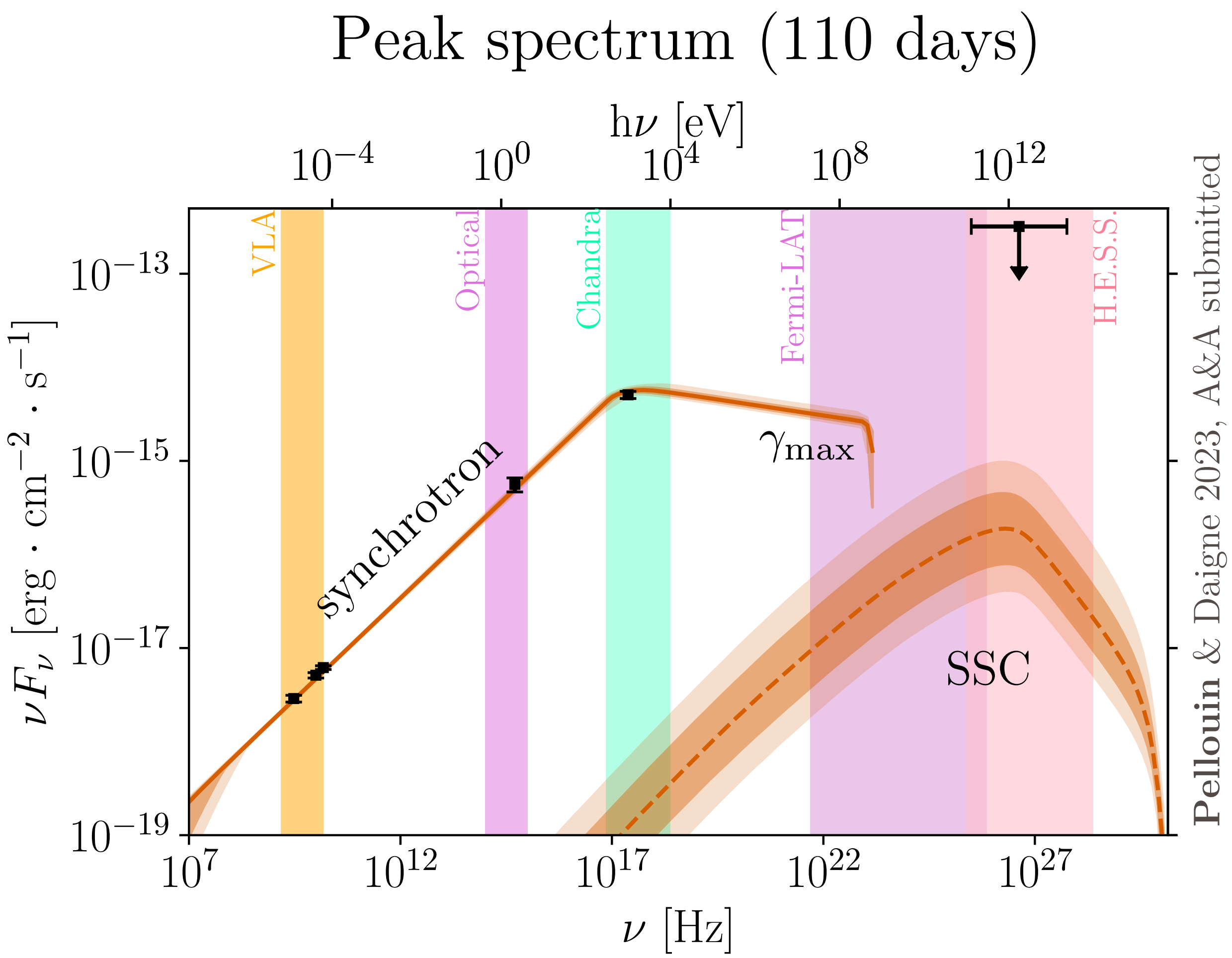


MCMC posterior afterglow light curves

Posterior parameters consistent with published literature, e.g.
Ryan et al. 2020, Lazzati et al. 2018, Hajela et al. 2020, Troja et al. 2019,
Lamb et al. 2019, Hotokezaka et al. 2019, Ghirlanda et al. 2019

*H.E.S.S. upper limit 2 orders of manitude higher

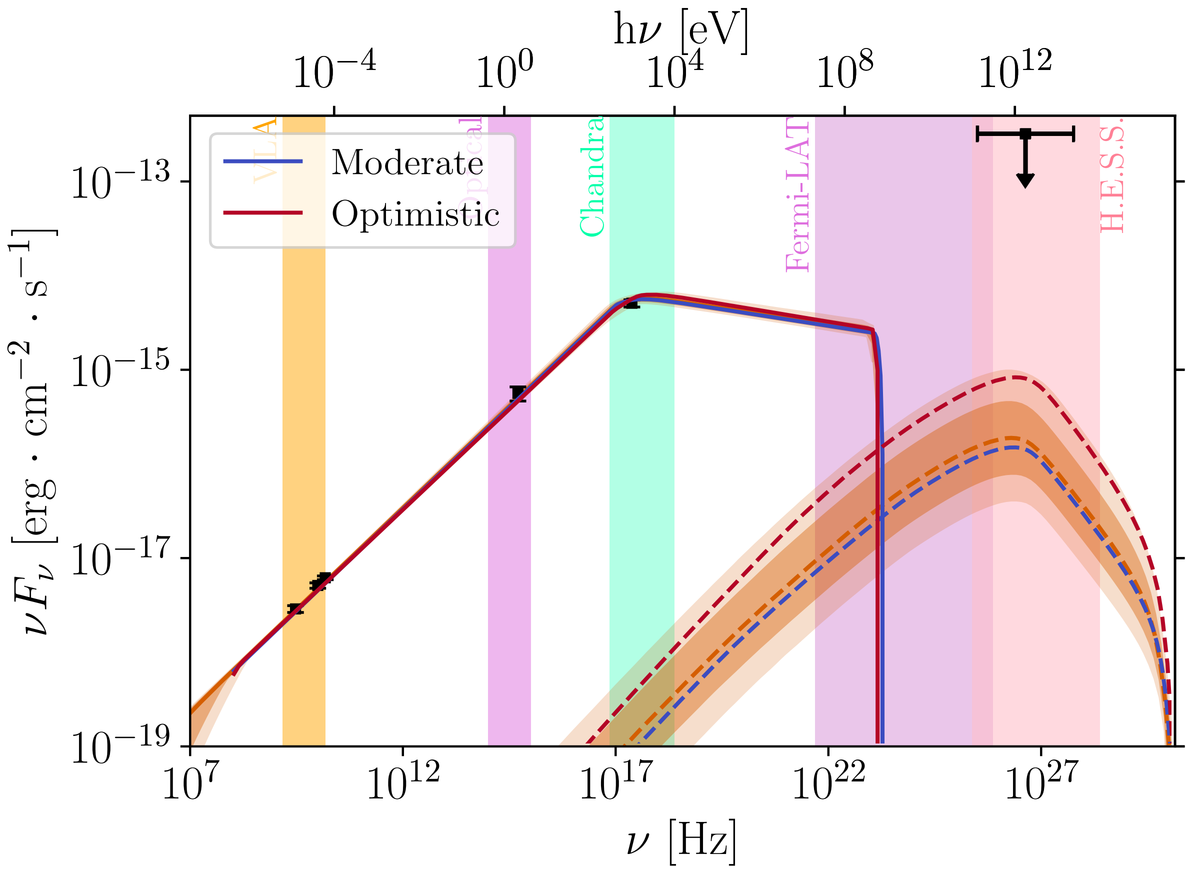
Results: GW 170817



VHE detection impossible with current sensitivities

Results: GW 170817

Peak spectrum (110 days)



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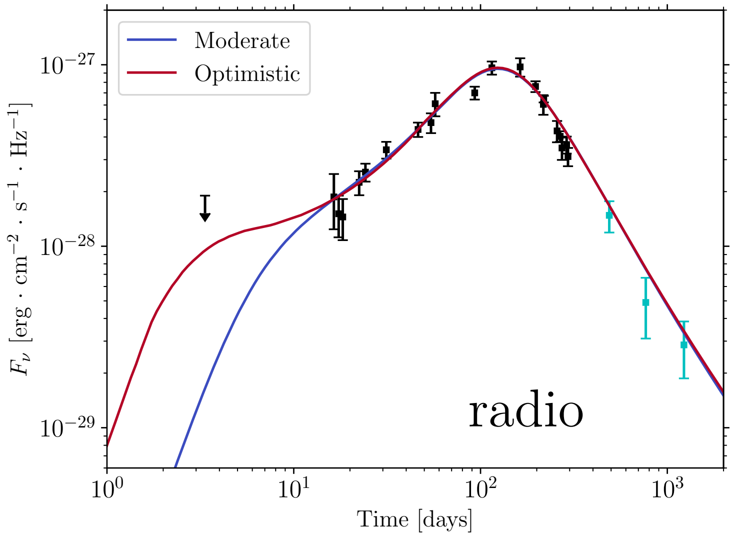

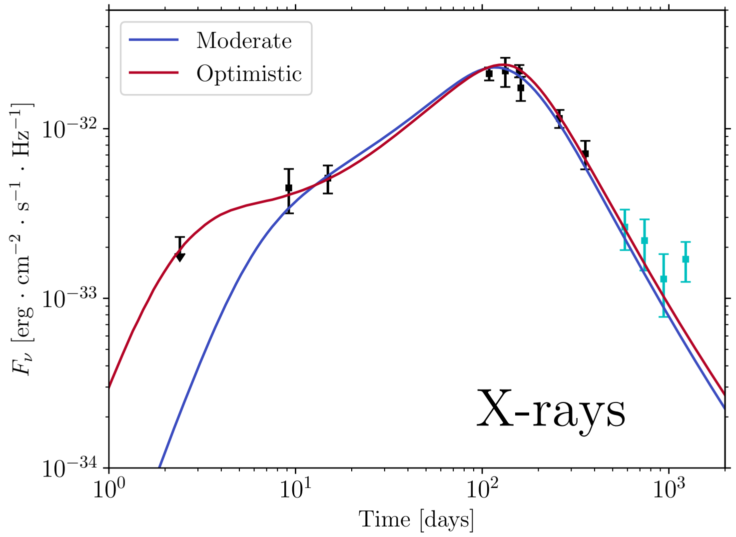

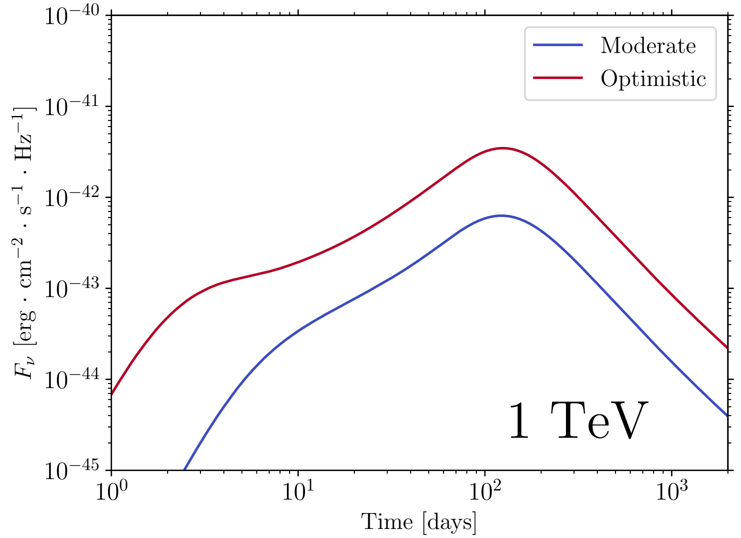

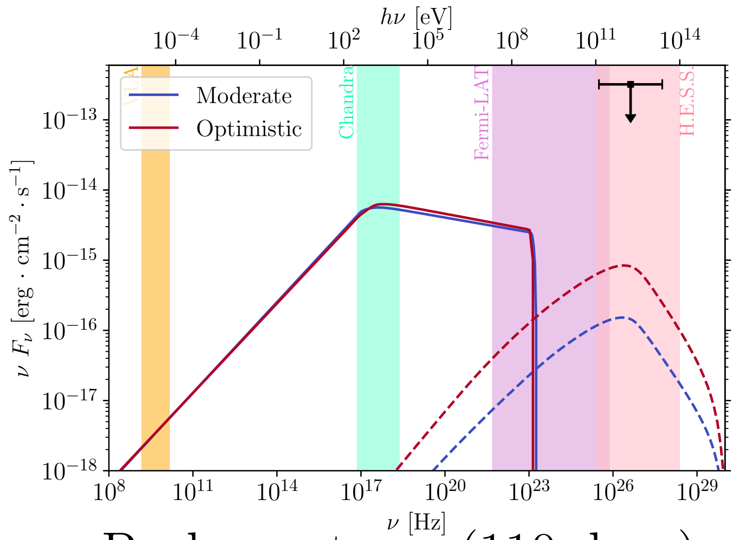

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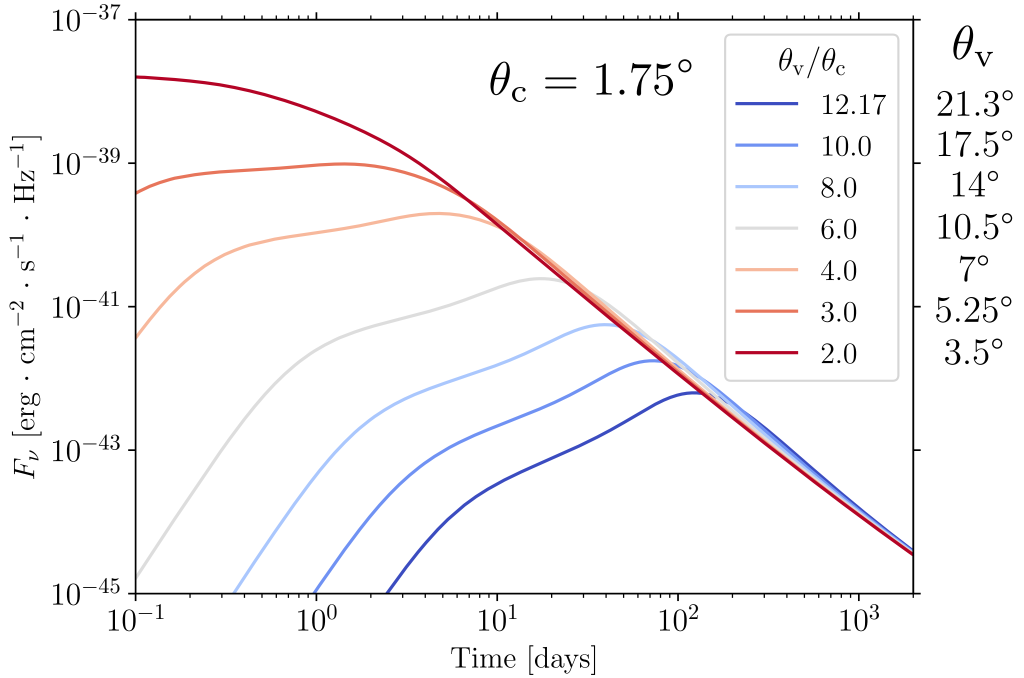
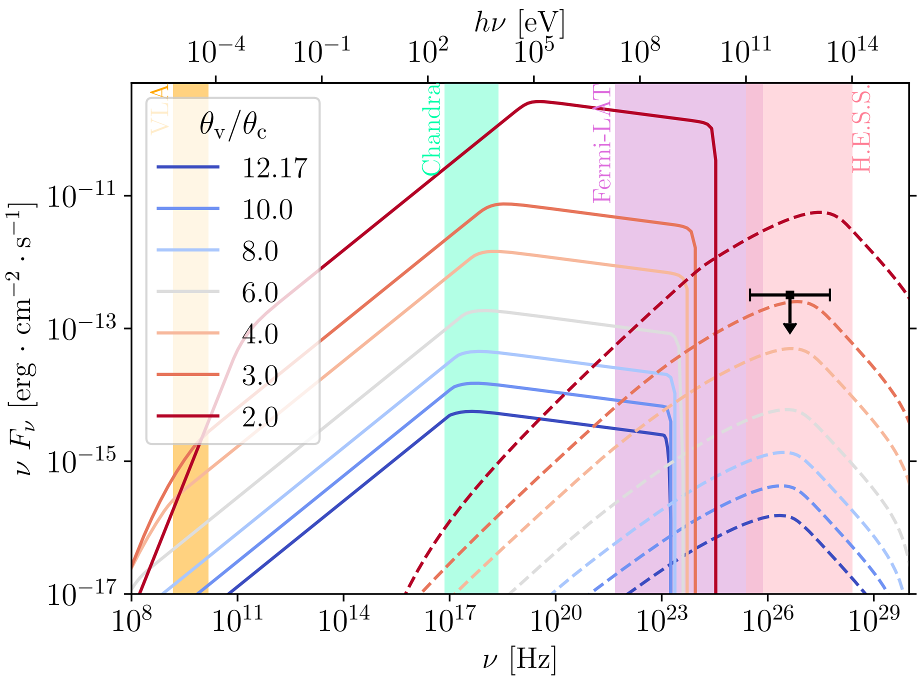
Predictions for GW 170817-like events

Lower viewing angles (moderate model)



light curves at 1 TeV



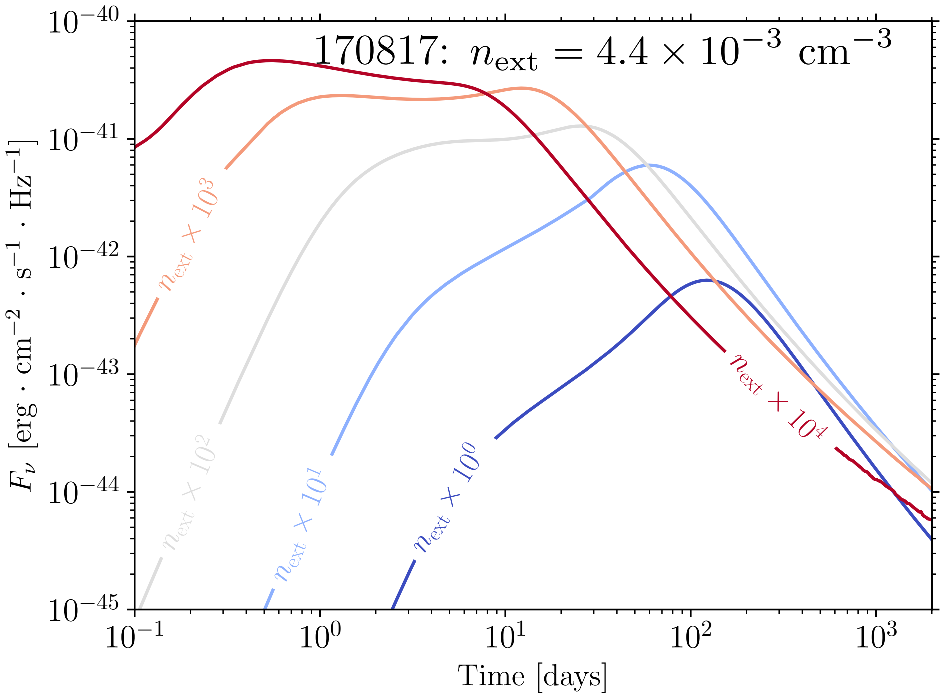
Peak spectra

Pellouin & Daigne 2023, A&A submitted

Moderate SSC emission detectable at 40 Mpc by CTAO
up to $\boldsymbol{\theta_v = 7°}$; Optimistic up to $\boldsymbol{\theta_v = 14°}$

Predictions for GW 170817-like events

Higher external densities (moderate model)



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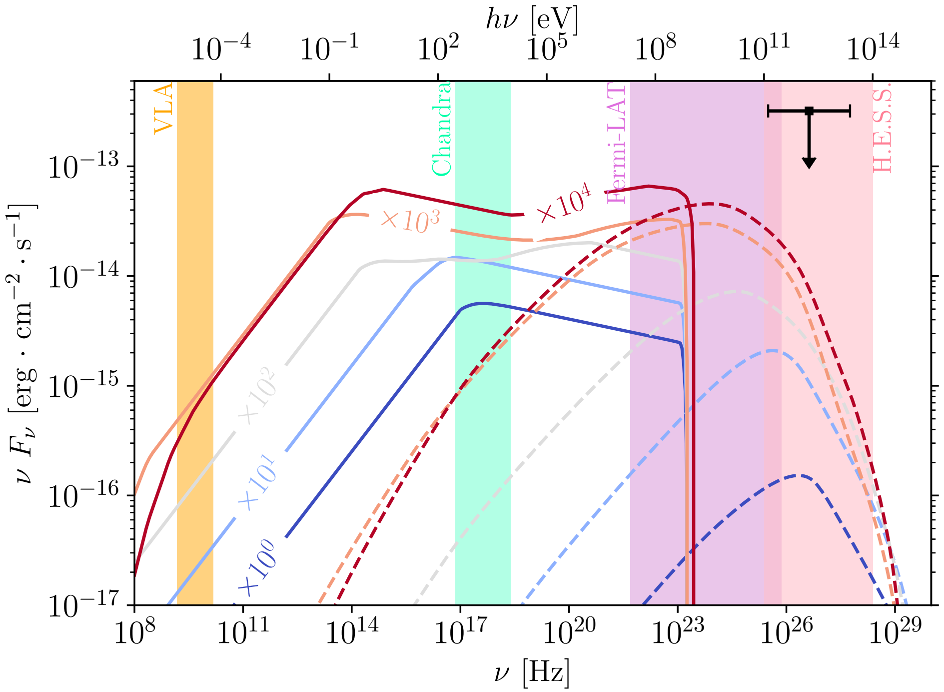


Peak spectra

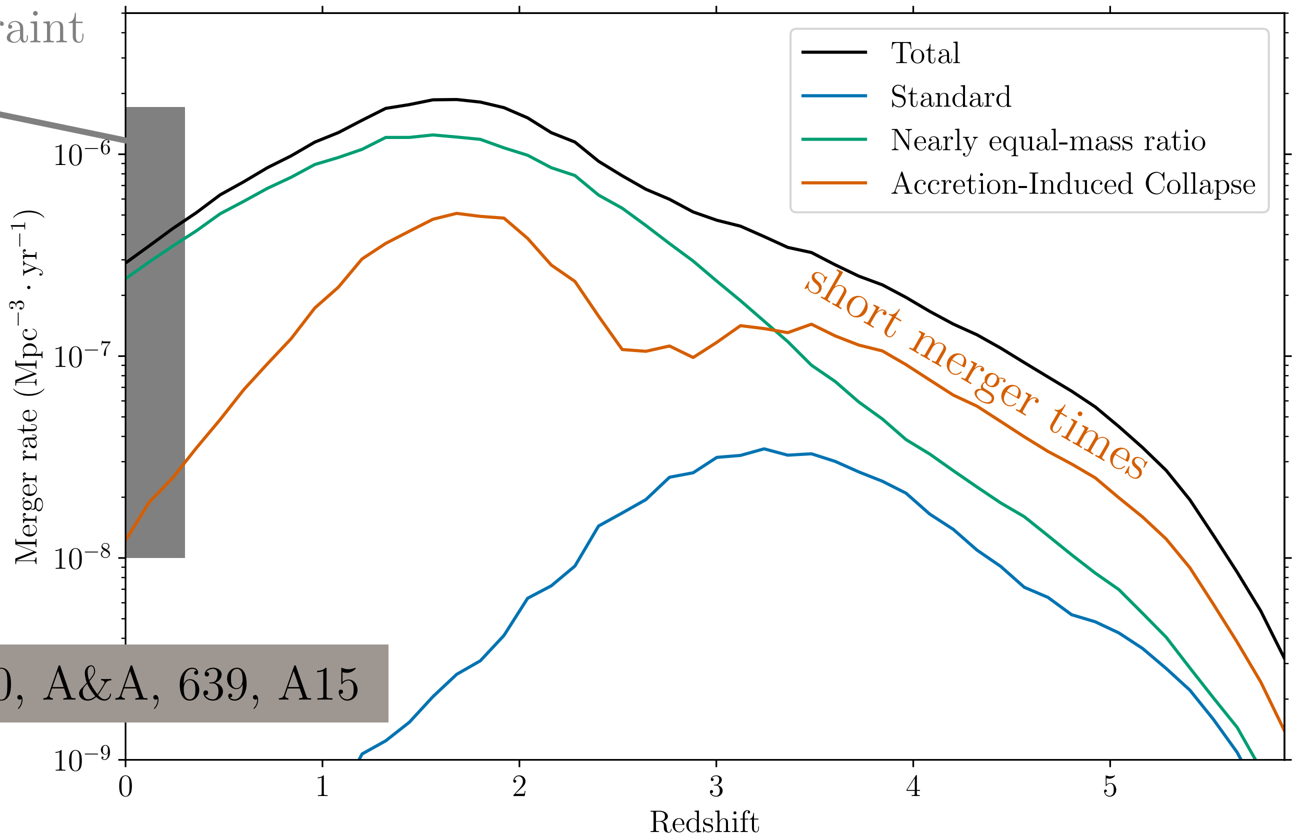
Pellouin & Daigne 2023, A&A submitted

Moderate model with $n_{ext} = 1\,\mathrm{cm}^{-3}$ and θ_v/θ_c=6 detectable by CTAO up to 90 Mpc; Optimistic up to 400 Mpc

Can we expect mergers with high external density?

Mergers in higher density environments: tracers of short merger times?

Current LIGO/Virgo constraint



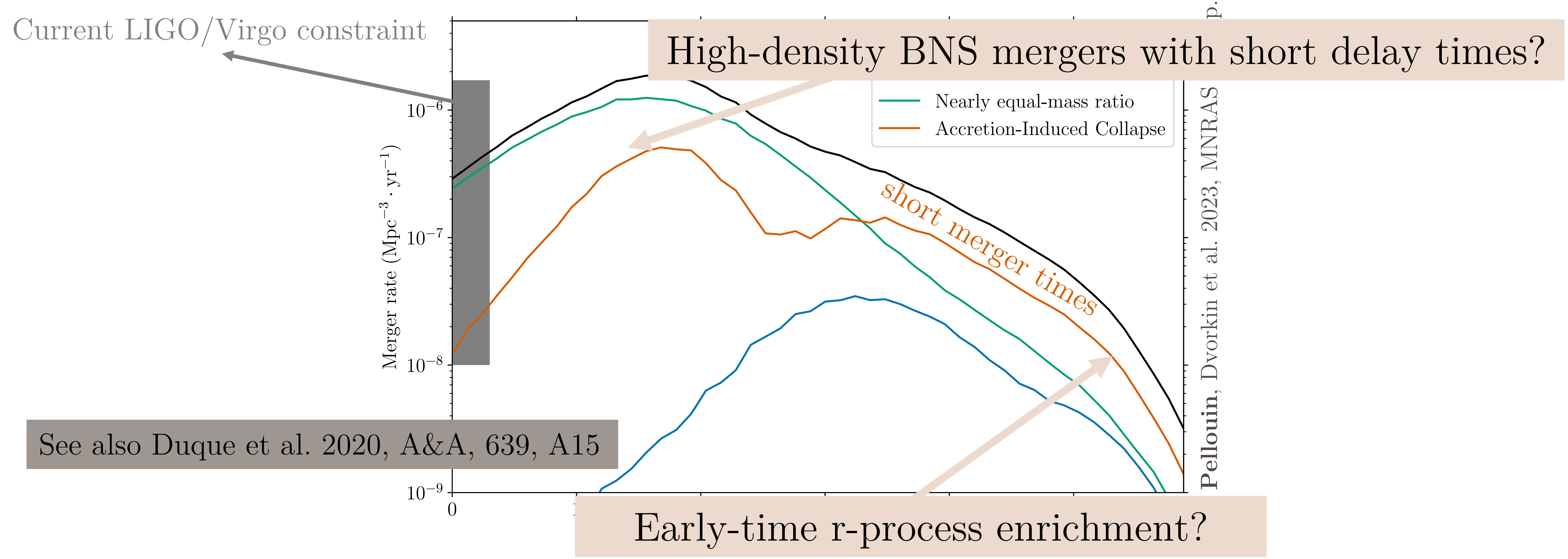
Pellouin, Dvorkin et al. 2023, MNRAS in prep.

See also Duque et al. 2020, A&A, 639, A15

Merger rate evolution with redshift

Can we expect mergers with high external density?

Mergers in higher density environments: tracers of short merger times?



See also Duque et al. 2020, A&A, 639, A15

Merger rate evolution with redshift

Conclusion

– A new code to model the afterglow emission of structured jets from radio to VHE, (computationally-efficient, for multi-wavelength data fitting)

– Application to GW 170817:

- Afterglow was not detectable at VHE with current sensitivity
- Lower viewing angles and/or higher external medium densities may allow for future detections of similar events

  (Moderate model with $n_{\mathrm{ext}} = 1\ \mathrm{cm}^{-3}$ and $\theta_{\mathrm{v}}/\theta_{\mathrm{c}}$=6 detectable by CTAO up to 90 Mpc)

– Mergers in high-density environments?

- Potential probes for fast mergers

– Work in progress: application of this model to long GRBs with VHE observations (GRB 221009A)

Thank you for your attention!