“Inverse Compton gamma rays from a GRB reverse shock”

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Dec. 3rd, 2024,

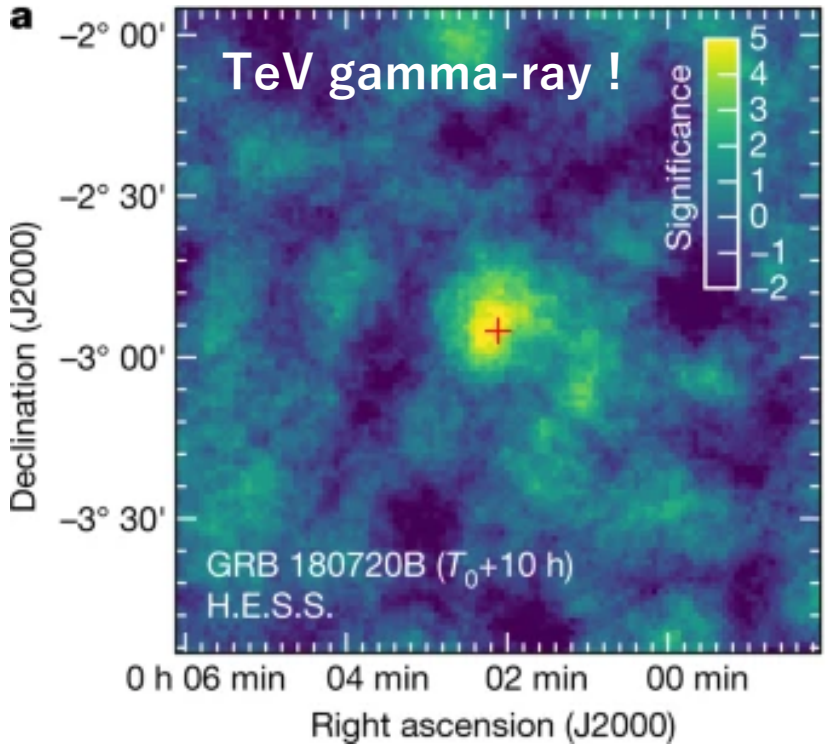
Workshop on GRB & CE

M. Arimoto et al., Nature Astronomy, 8, 134–144 (2024)

VHE emission from GRBs: *beyond synchrotron*

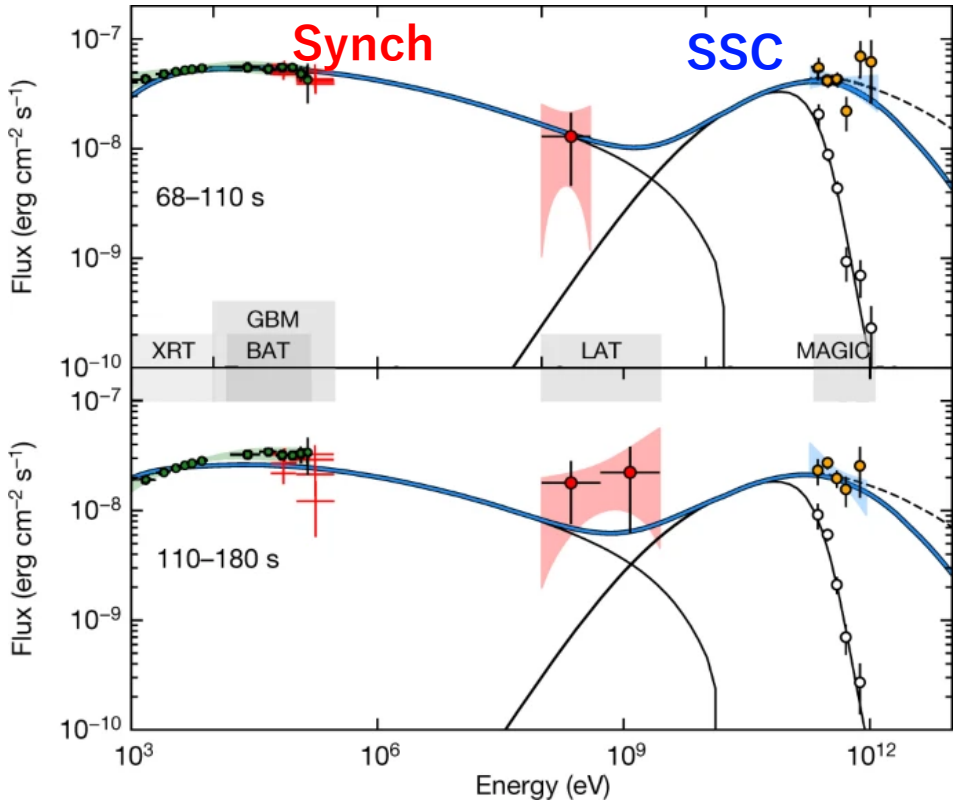
- ✓ VHE emissions in the TeV band detected for several GRBs
- ✓ Synchrotron process can **NOT** explain TeV photons → **S**ynchrotron **S**elf **C**ompton (SSC)

GRB 180720B



HESS Collaboration (2019)

GRB 190114C



MAGIC Collaboration et al (2019)

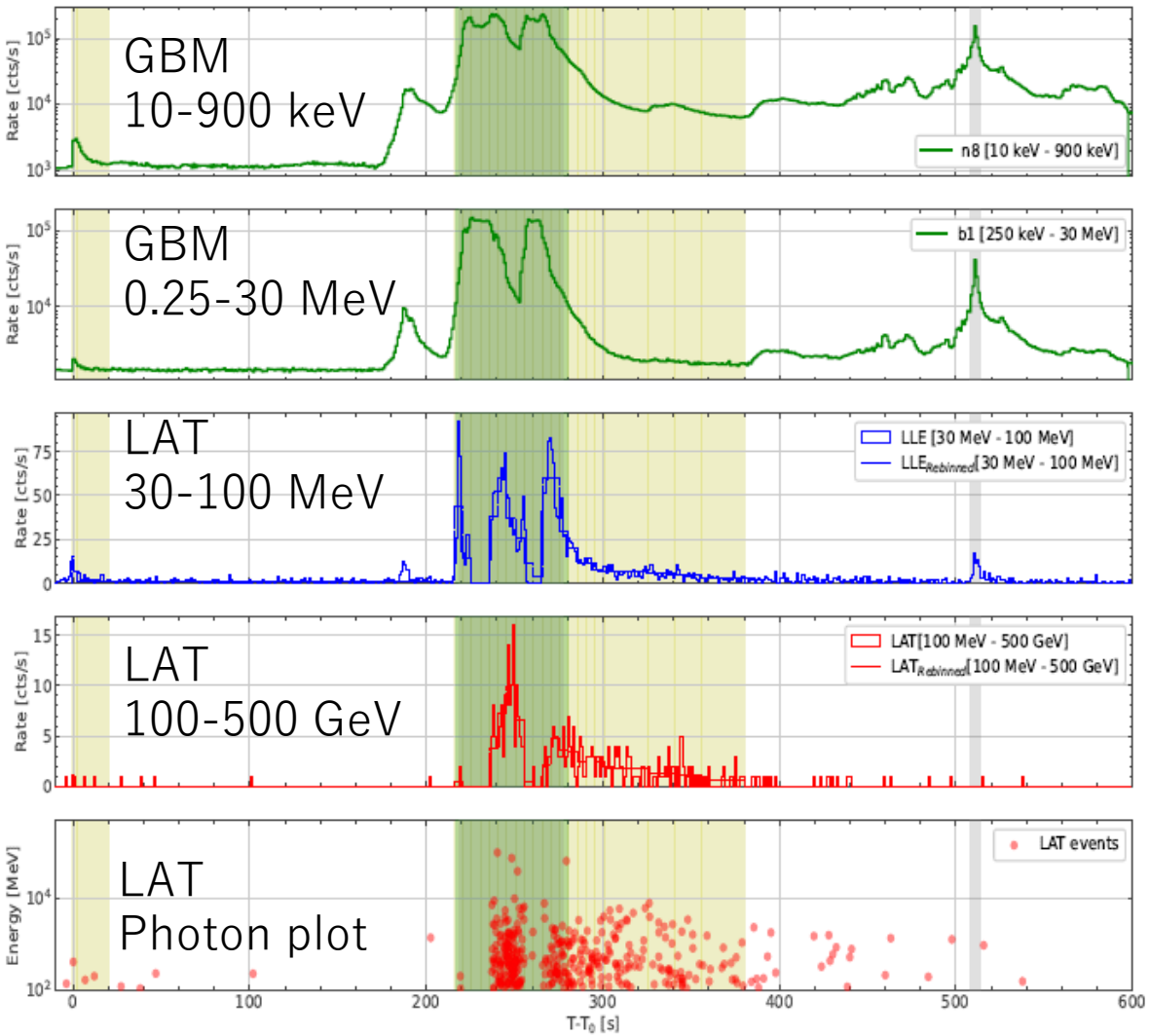
and more !

- 190829A
- 221009A

GRB221009A: BOAT

Axelsson+2024

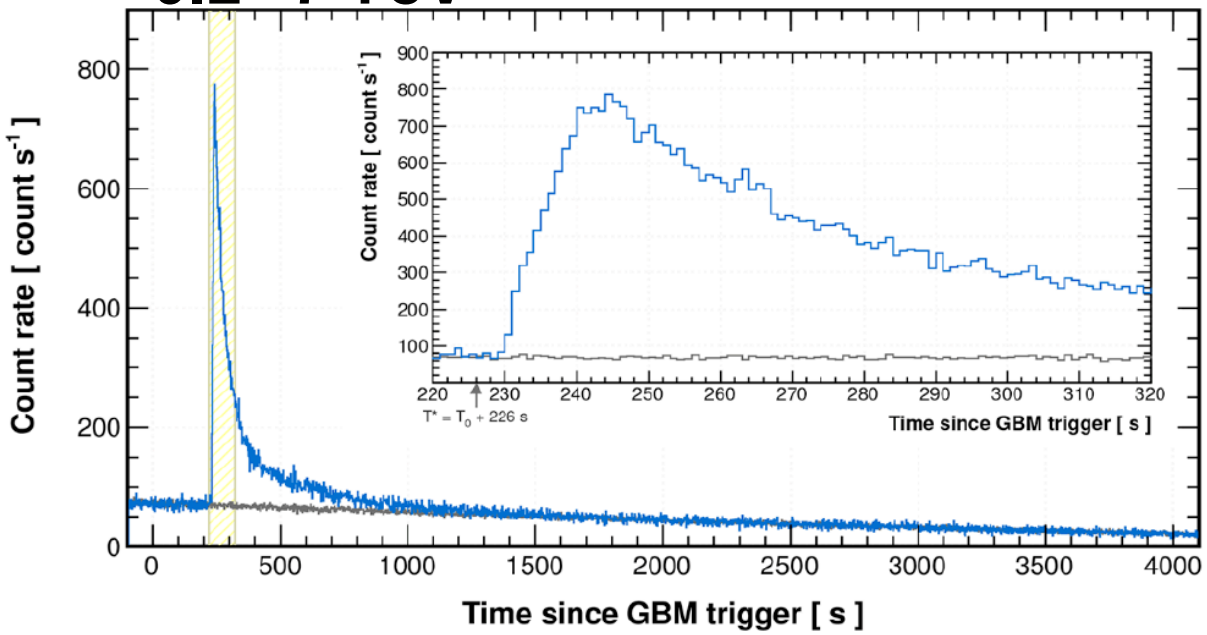
Saturated !



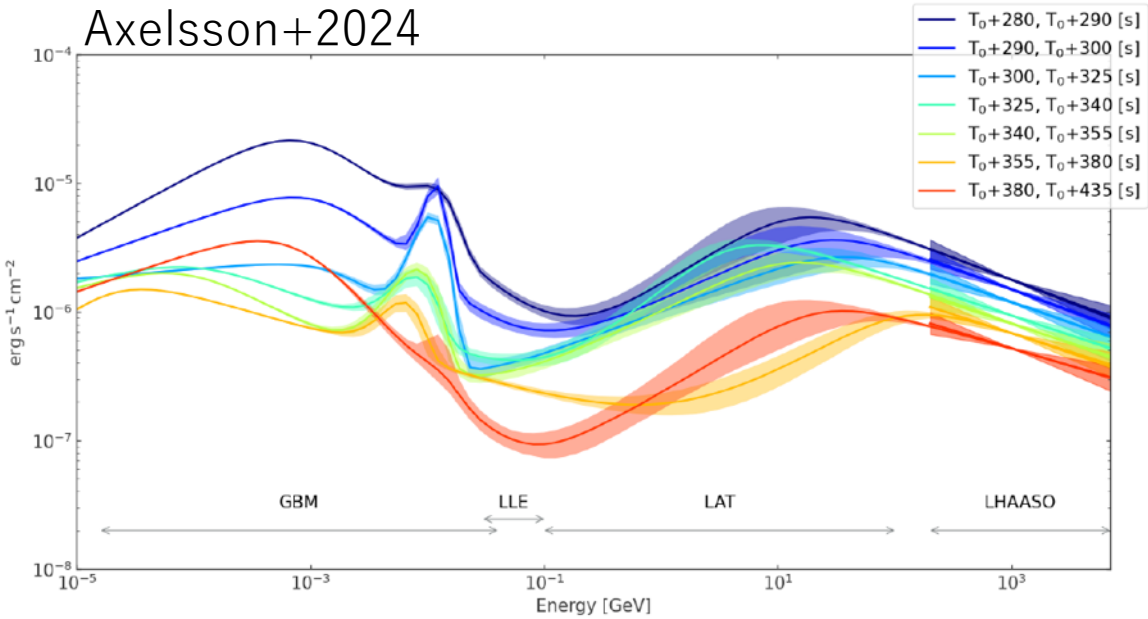
LHAASO 2023

~0.2 -7 TeV

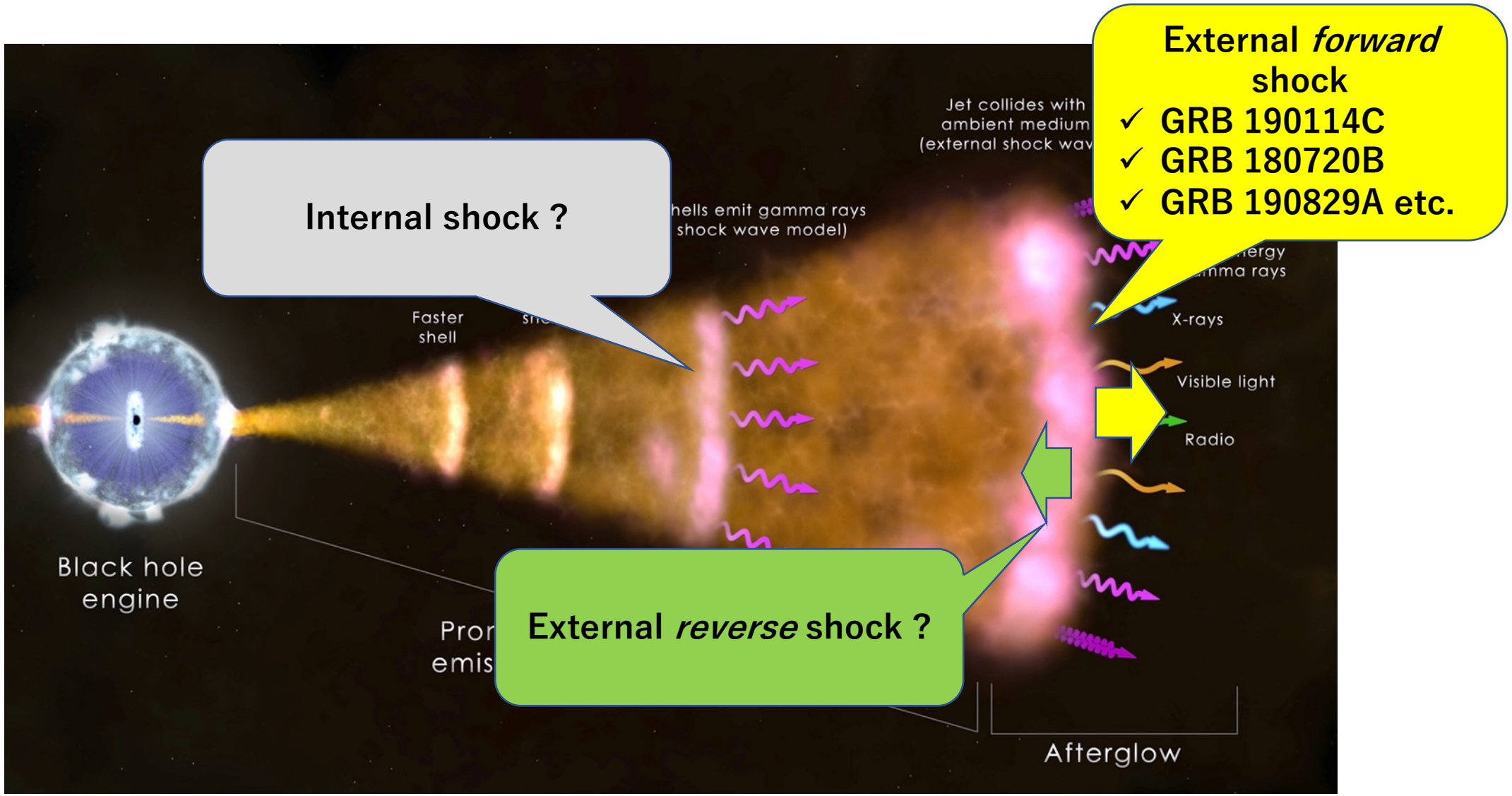
GRB 221009A



Axelsson+2024



Where is emission site of gamma-rays ?



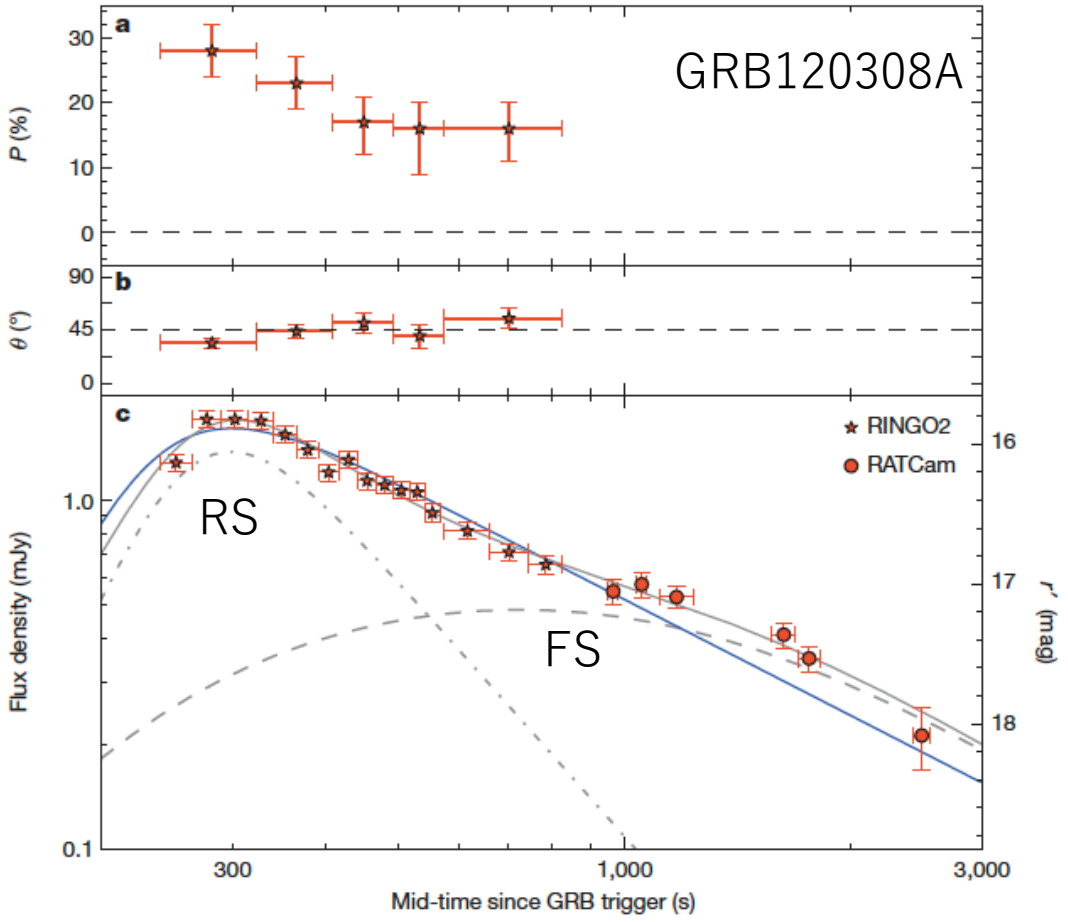
Objective

- Does the forward shock (FS) only contribute to HE/VHE gamma-ray IC emission ?
- What else ? e.g., **reverse shock (RS)**
  → **Early observation**

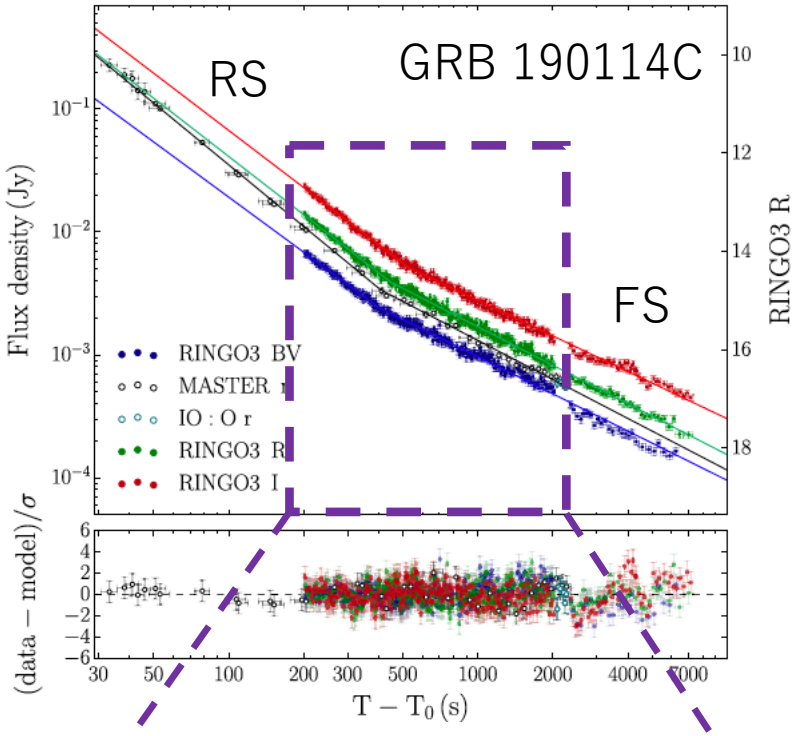
- What is the B field structure of IC emission ?
  → **Polarimetic observation**

Examples of the early optical polarimetric observations

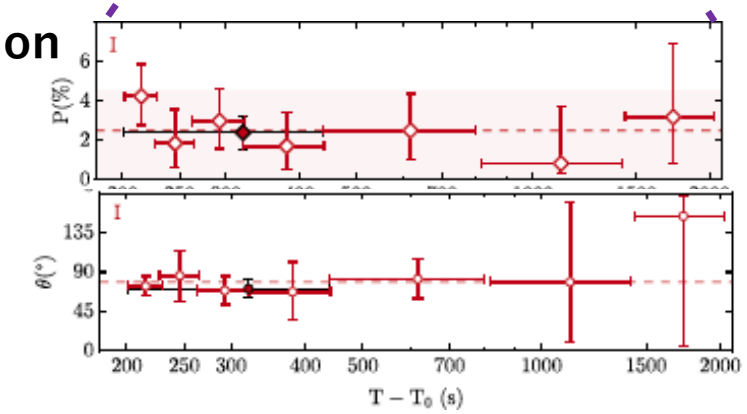
Mundell+ 2017



Jordana-Mitjans+ 2020

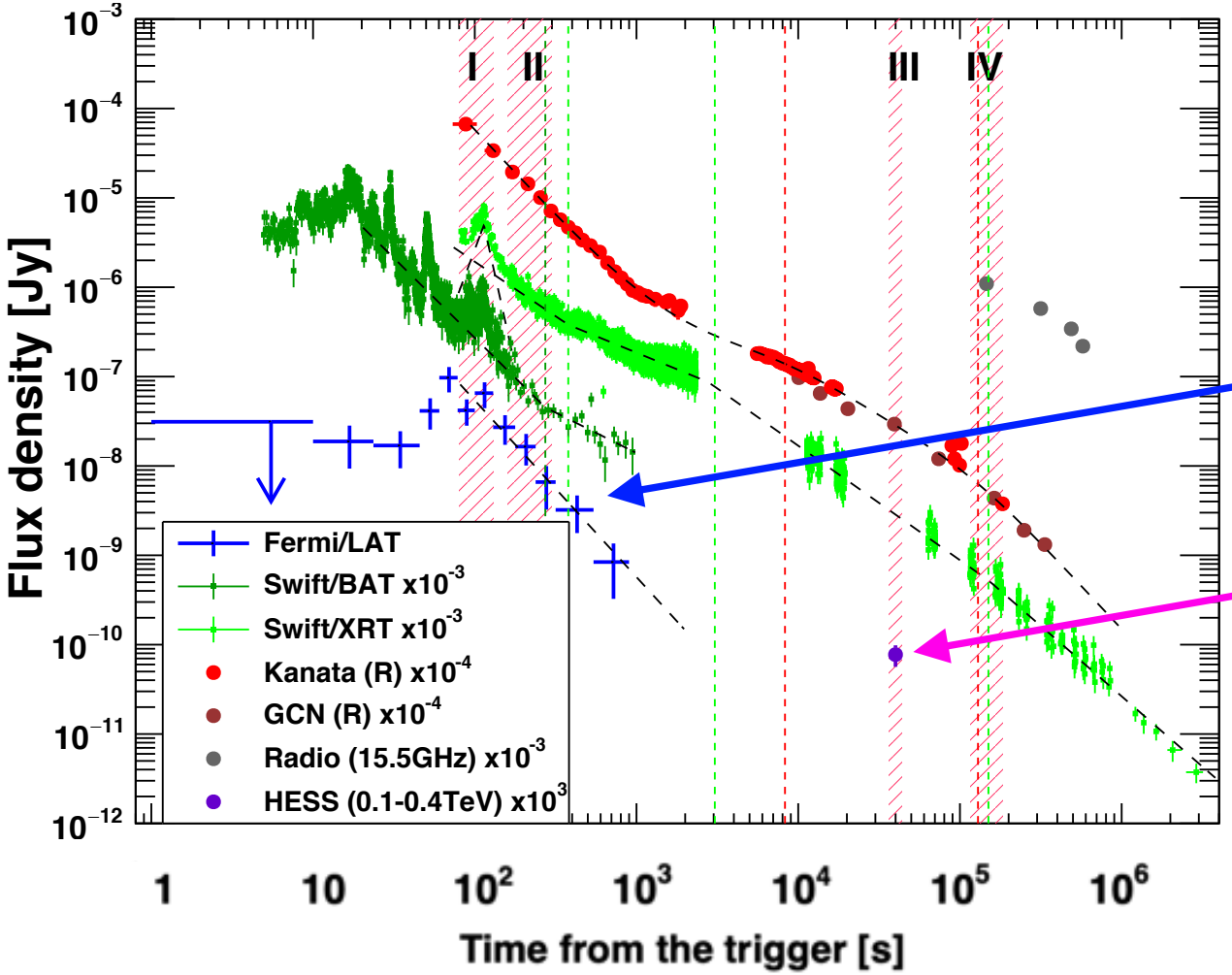


Polarization



GRB 180720B afterglow emission

Optical & GeV onset
(T_0 + ~100 s)



- z = 0.654 (Vreeswijk+ 18)
- E_{iso} ~ 5.5 x 10^{53} erg

✓ GeV: **Fermi-LAT**
✓ X-ray: Swift-BAT, XRT
✓ Radio: AMI-LA
✓ VHE: **HESS (Abdalla+19)**
✓ Optical: **Kanata**, others (GCNs)
Polarization

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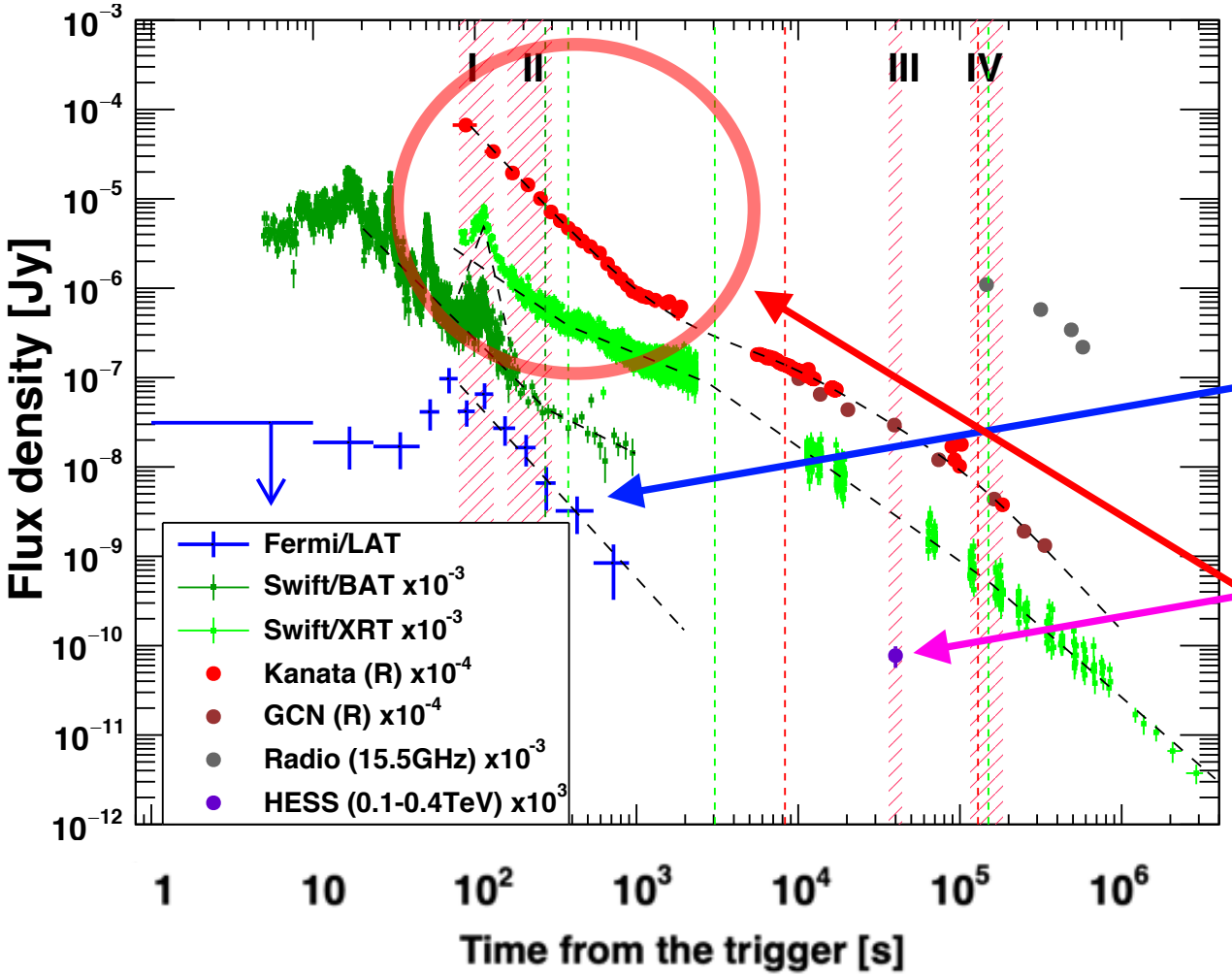

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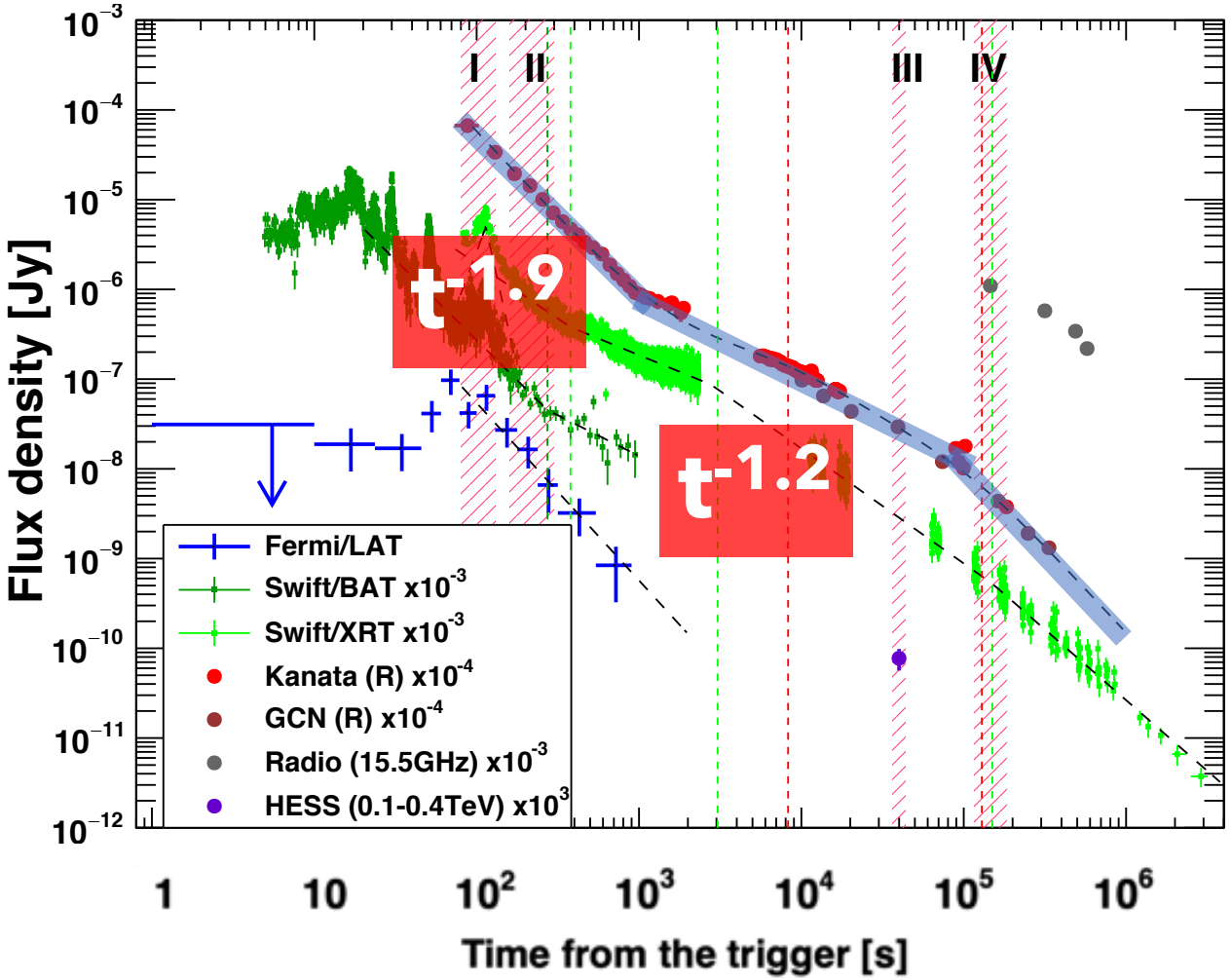
Polarization

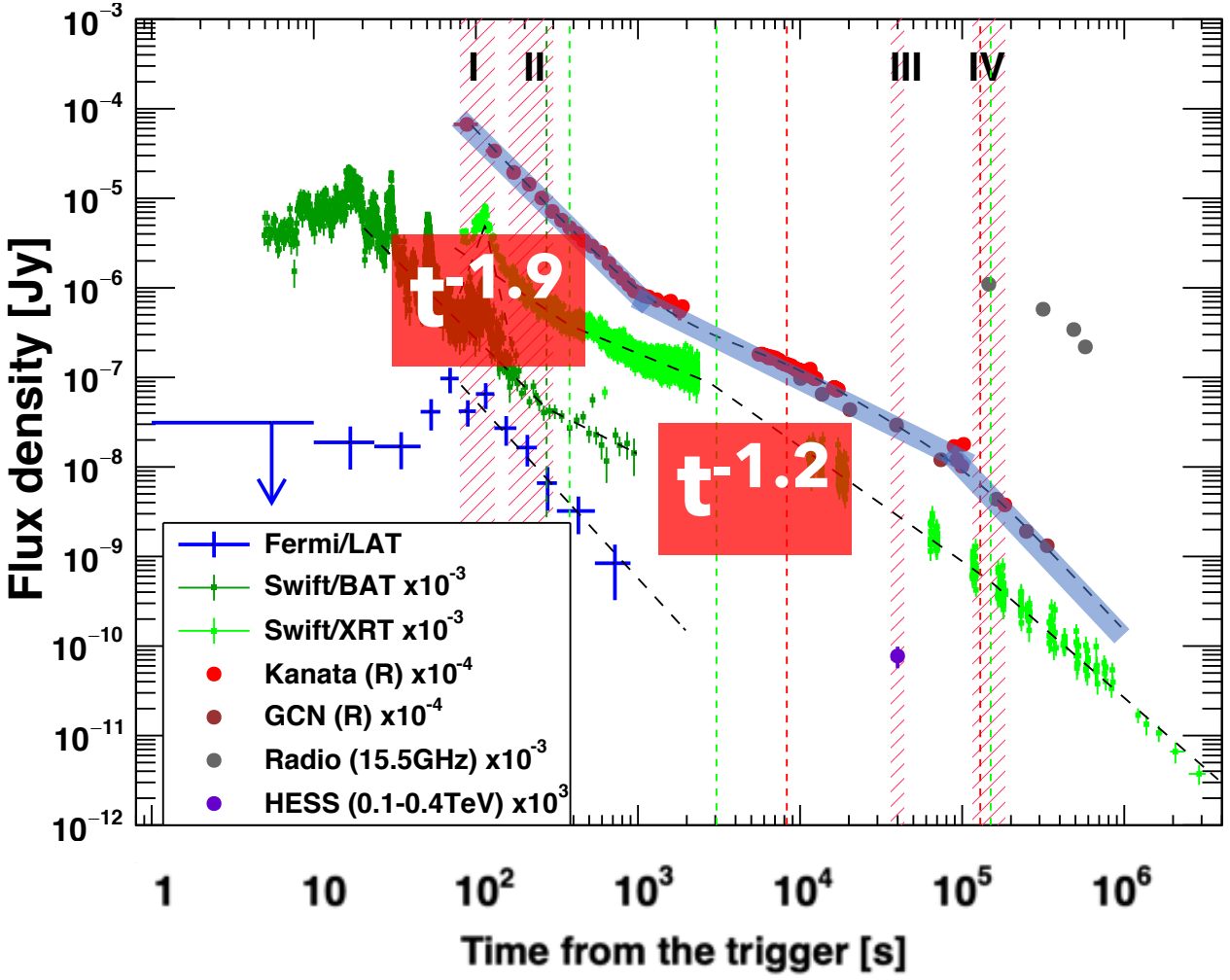
GRB 180720B **optical** emission

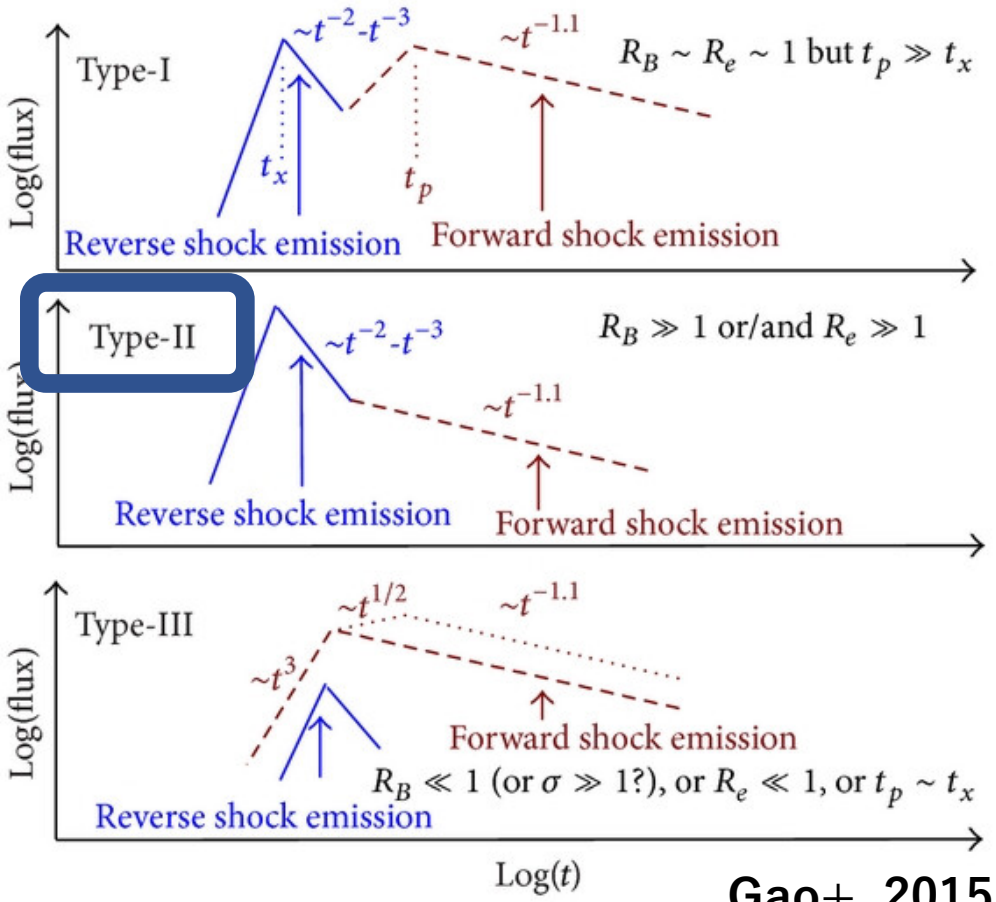


FS and RS lightcurves

$R_B = \varepsilon_{B,r}/\varepsilon_{B,f}$

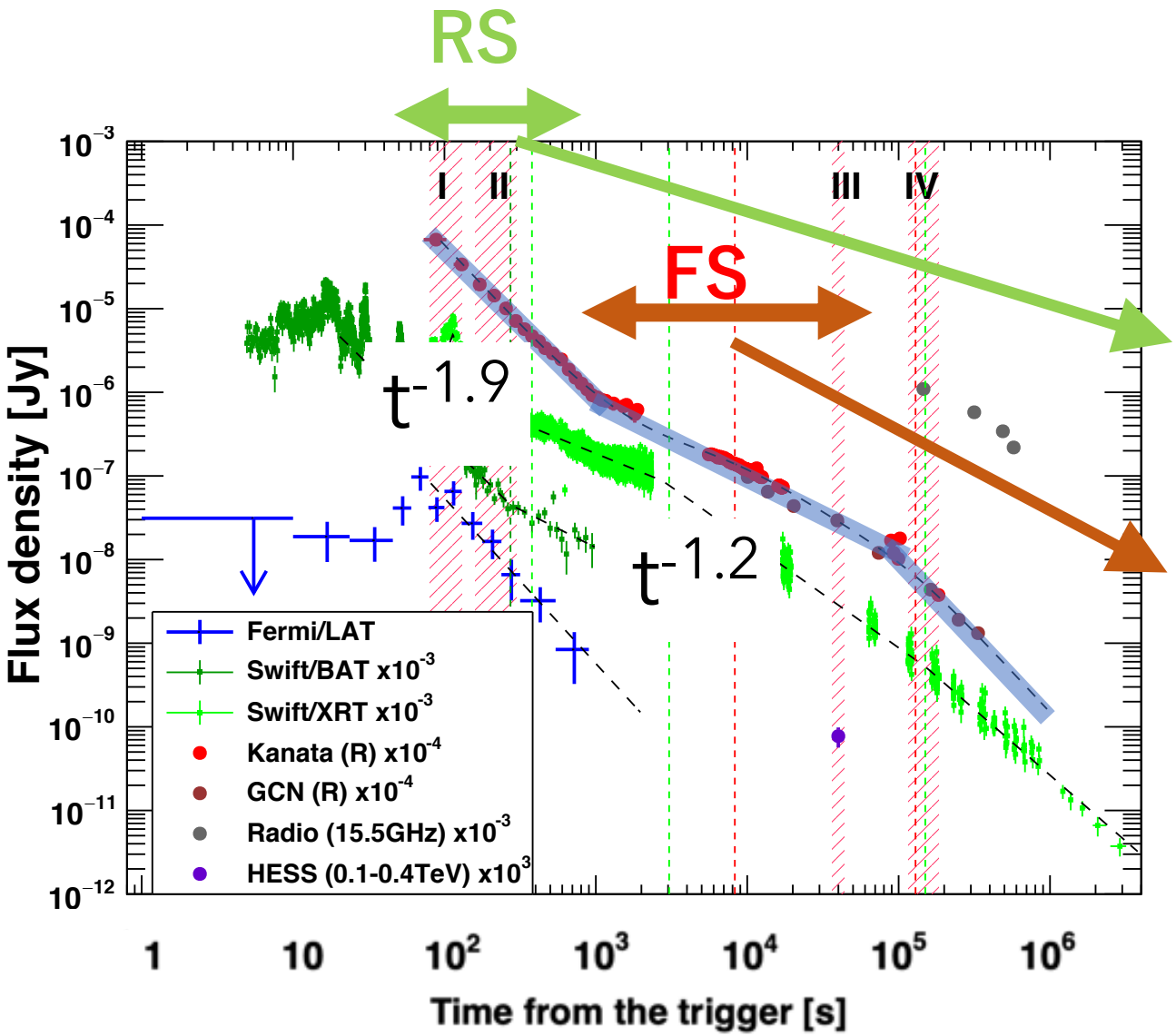
$R_e = \varepsilon_{e,r}/\varepsilon_{e,f}$





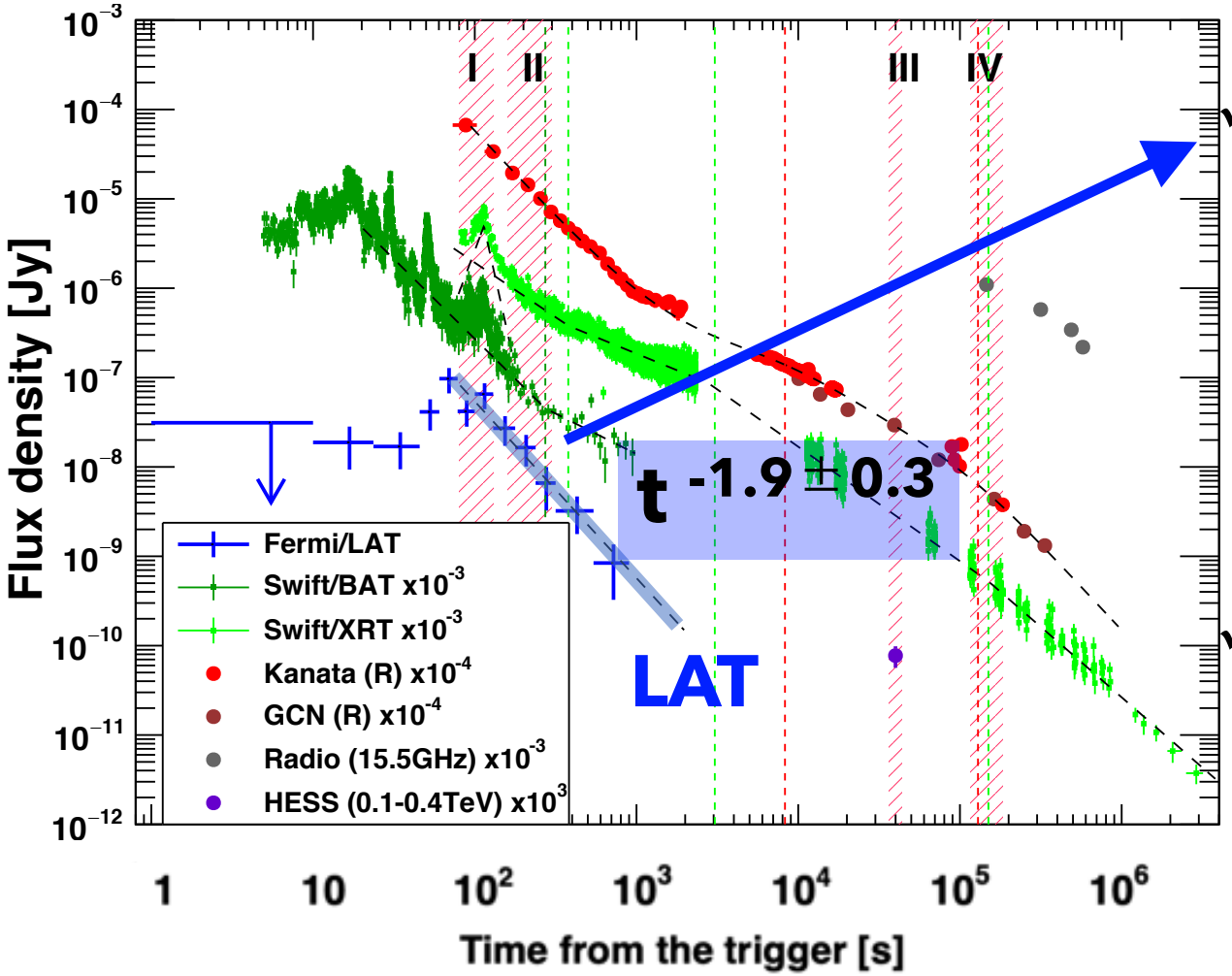
Gao+, 2015

GRB 180720B **optical** emission



- Steep decay ($t^{-1.9}$)
  →Reverse shock (Kobayashi+00)
- Moderate decay ($t^{-1.2}$)
  → Forward shock (e.g., Piran+04)

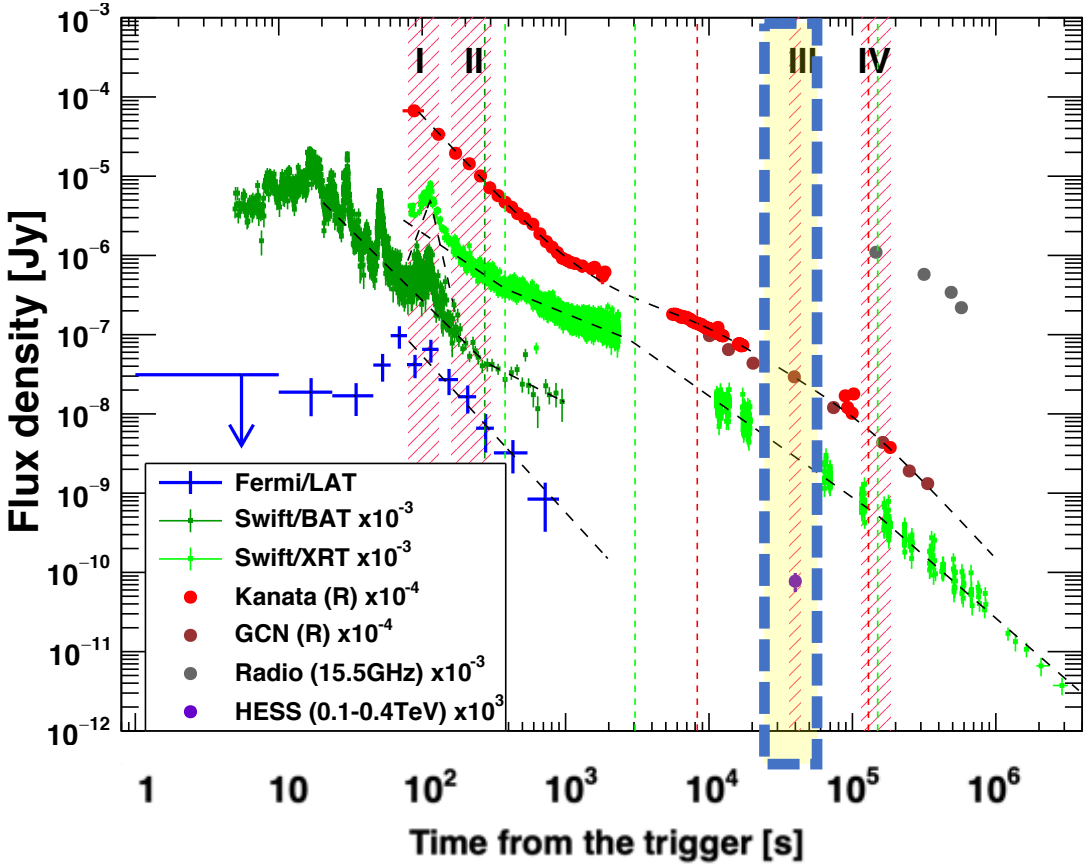
GeV band (LAT)



- ✓ The observed temporal index (~-1.9) is **steeper** than typical one.
  (α~-1.1; 2FLGC paper, Ackermann+19)
  - ✓ α ~ -1.1 → Forward shock
  - ✓ **α ~ -1.9** → Reverse shock ?
- ✓ <u>LAT emission comes from a **reverse shock** ?</u>

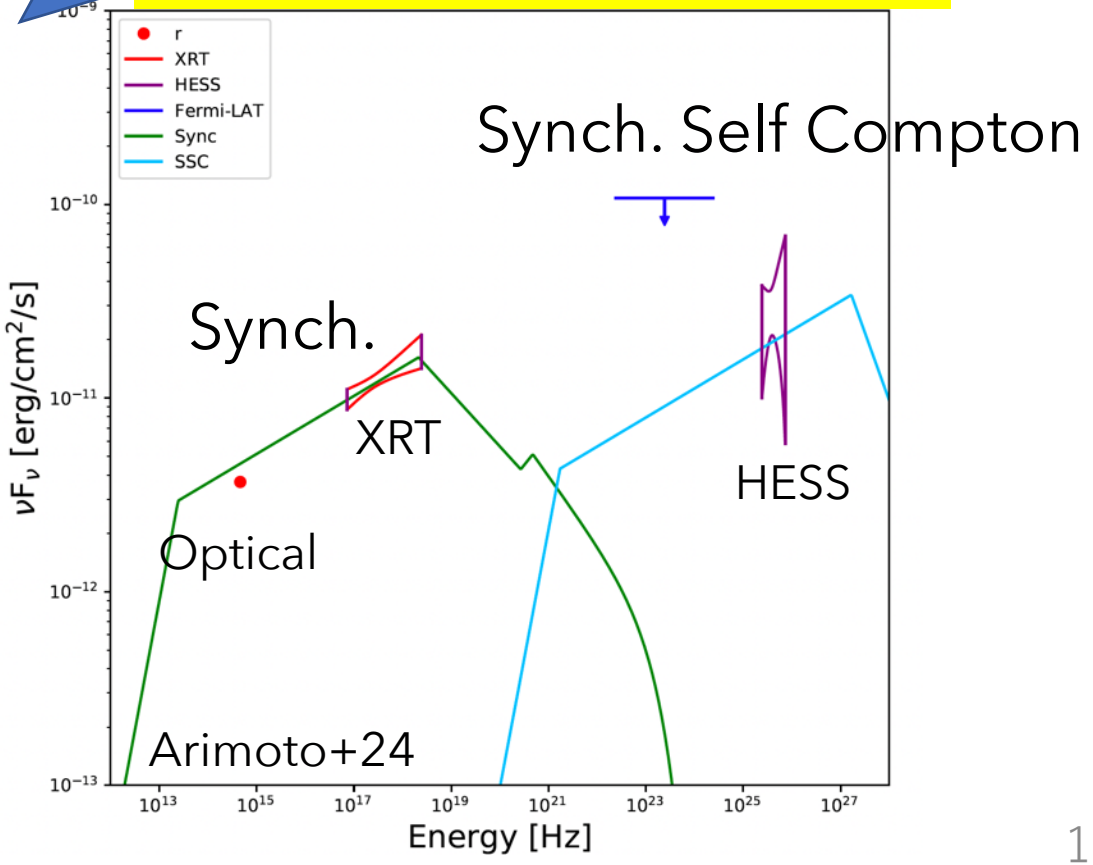
Emission in the **late** phase

RS FS

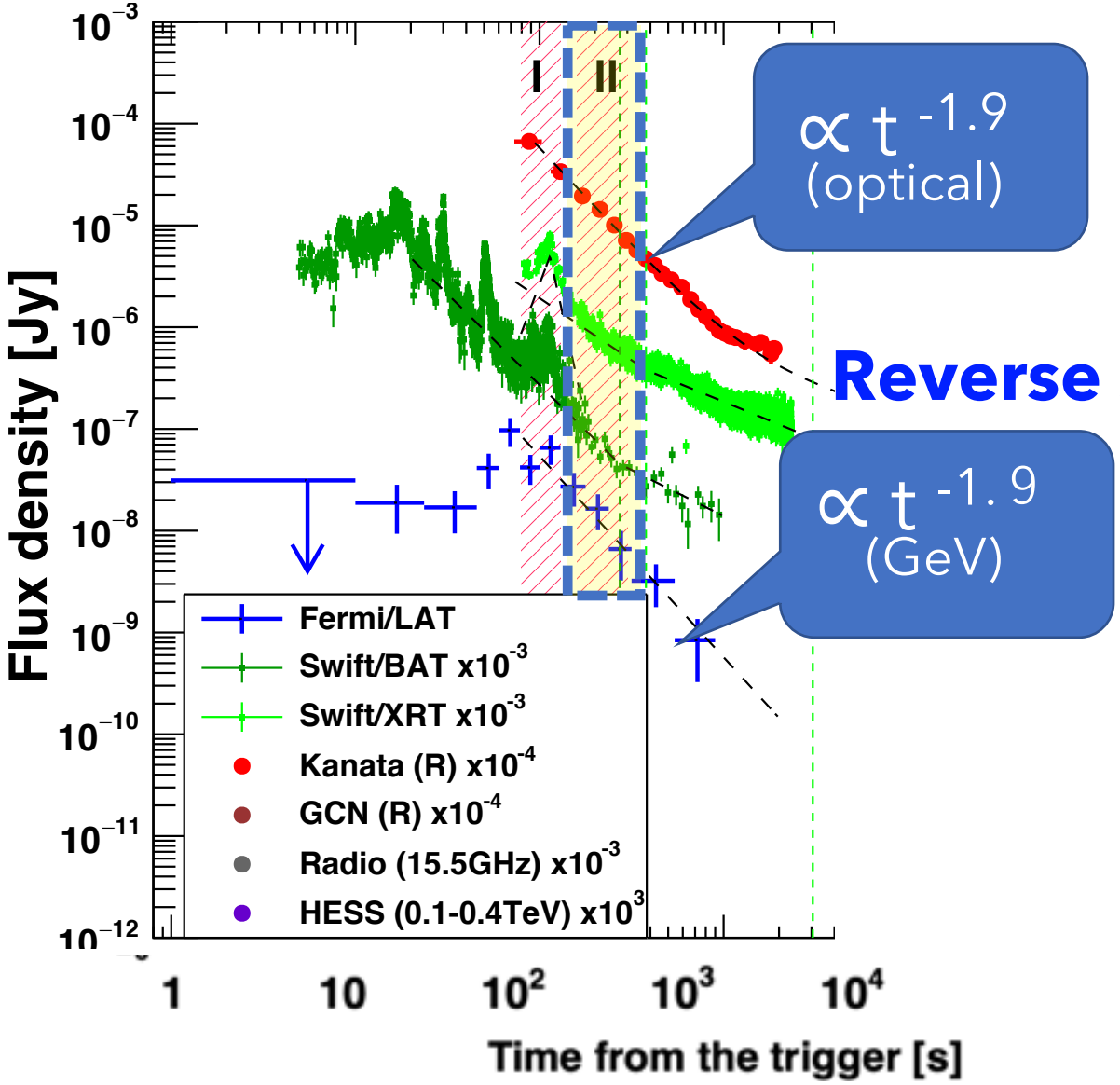


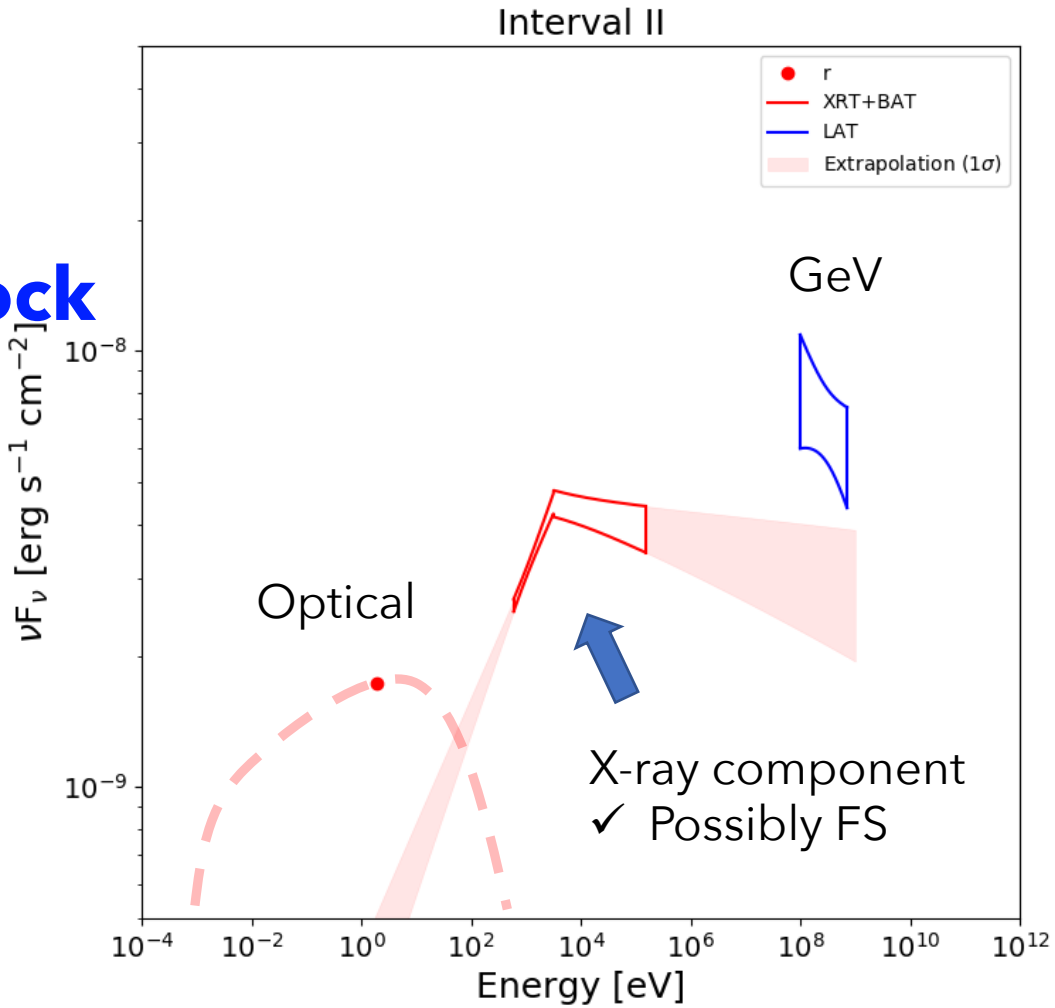
Forward shock model

- $\varepsilon_{e,f} = 0.2, \varepsilon_{B,f} = 1.5\times10^{-4}$
- $n_{ISM} = 5\times10^{-3}\ cm^{-3}$

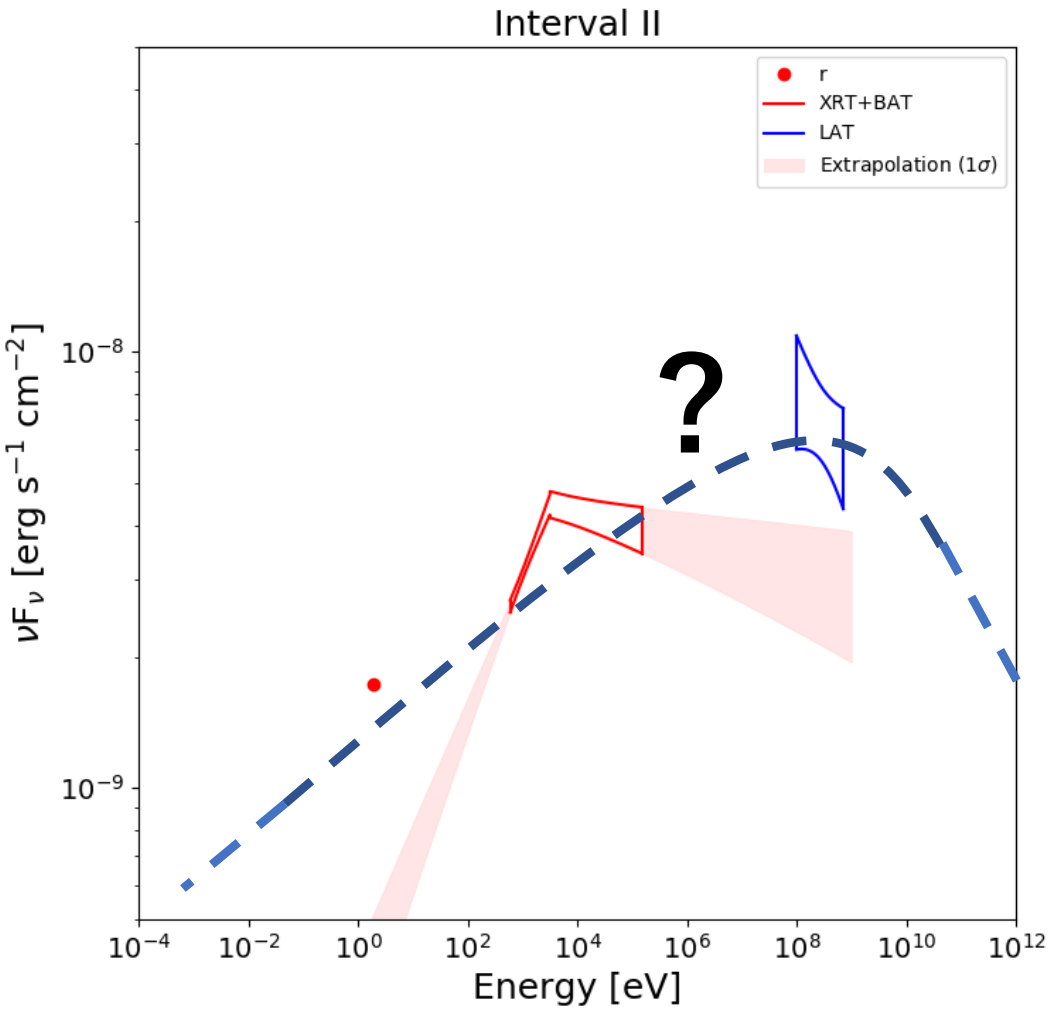


Emission in the **early** phase





Single component can explain the data ?

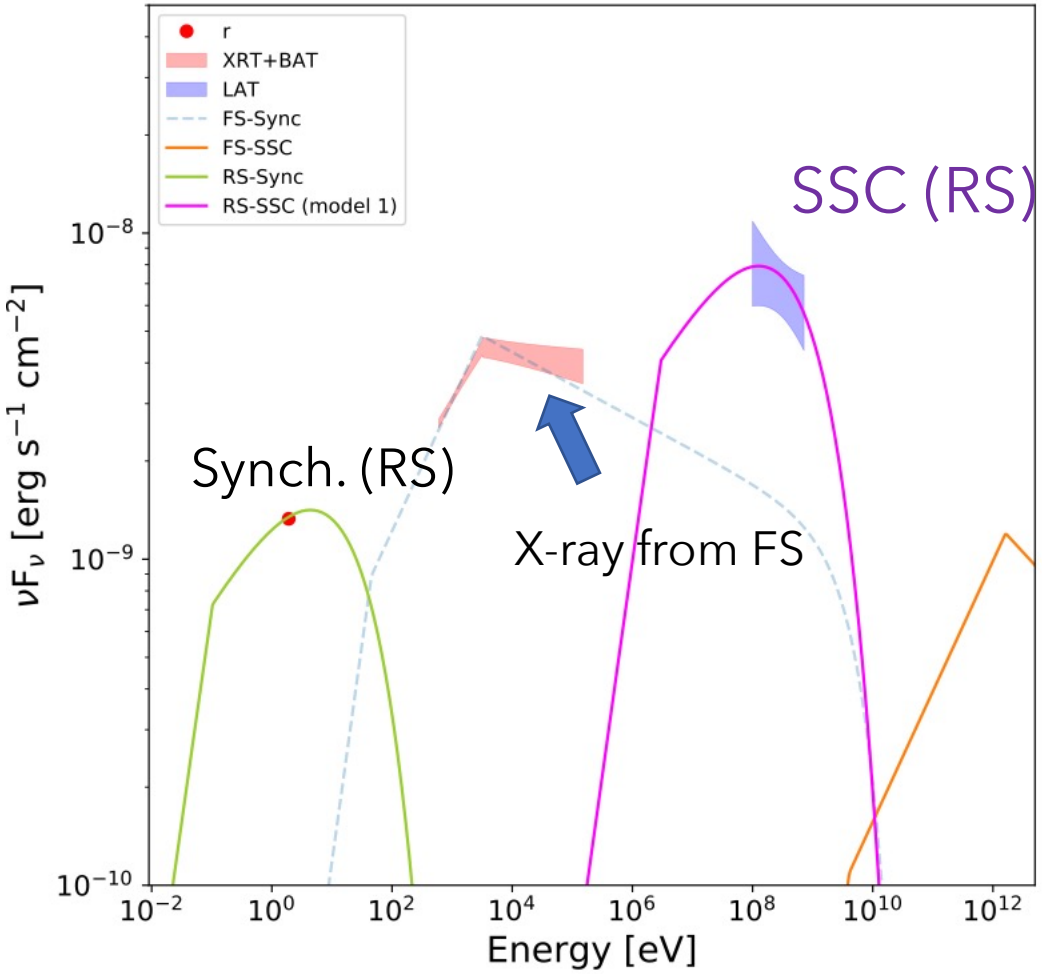


- Synch energy from RS cannot go up above $\nu_{c,r} \sim \mathrm{keV}$
  - No fresh particles injected after RS passes through the shell (Kobayashi+ 00 etc.)

- **Single** synch component is not feasible for RS

  → **Two components** are needed !

Emission in the **early** phase: Synch and SSC from a reverse shock



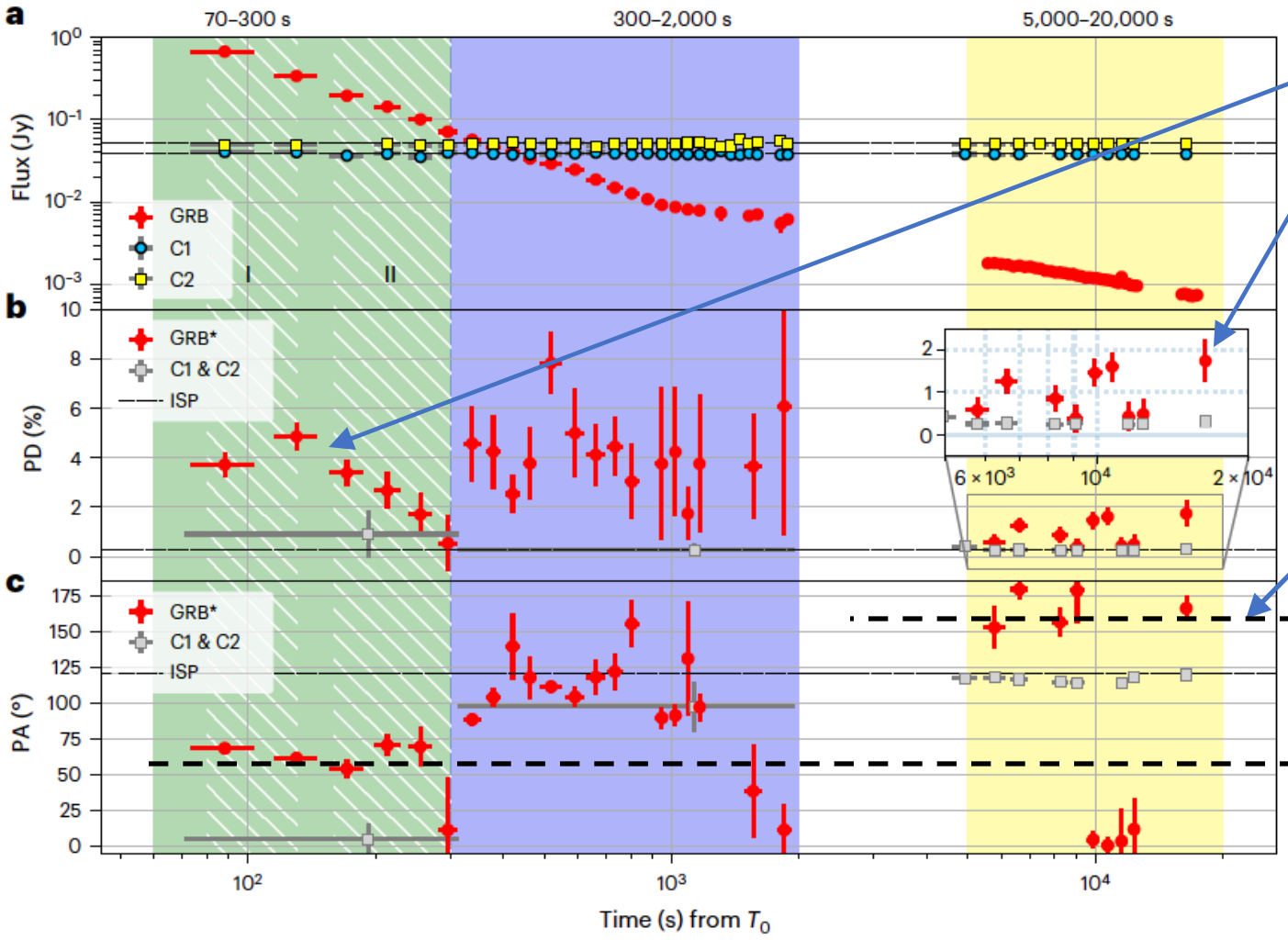
- High-energy gamma rays are well explained by inverse Compton scenario
  - SSC/Synch ratio: $\mathrm{Y} \sim 6$
  - $\varepsilon_{e,r} \sim 10^{-2}$
  - $\varepsilon_{B,r} \sim 7\times10^{-4}$
    - ✓ Ref: $\varepsilon_{B,f} = 1.5\times10^{-4}$
    - ✓ GRB ejecta relatively magnetized

✓ SSC from RS was predicted (Zhang+01)
✓ **Observational evidence** with optical and GeV (SSC) excesses

Optical polarization

✓ **First detection of polarization from RS and FS in a single GRB.**

RS dominant ⟷ **FS dominant**



✓ PD = 1-5% @ RS

✓ PD = 1-2% @ FS

Ref. 1-3 % (typ) Covino+03

✓ Relatively high PD @ RS

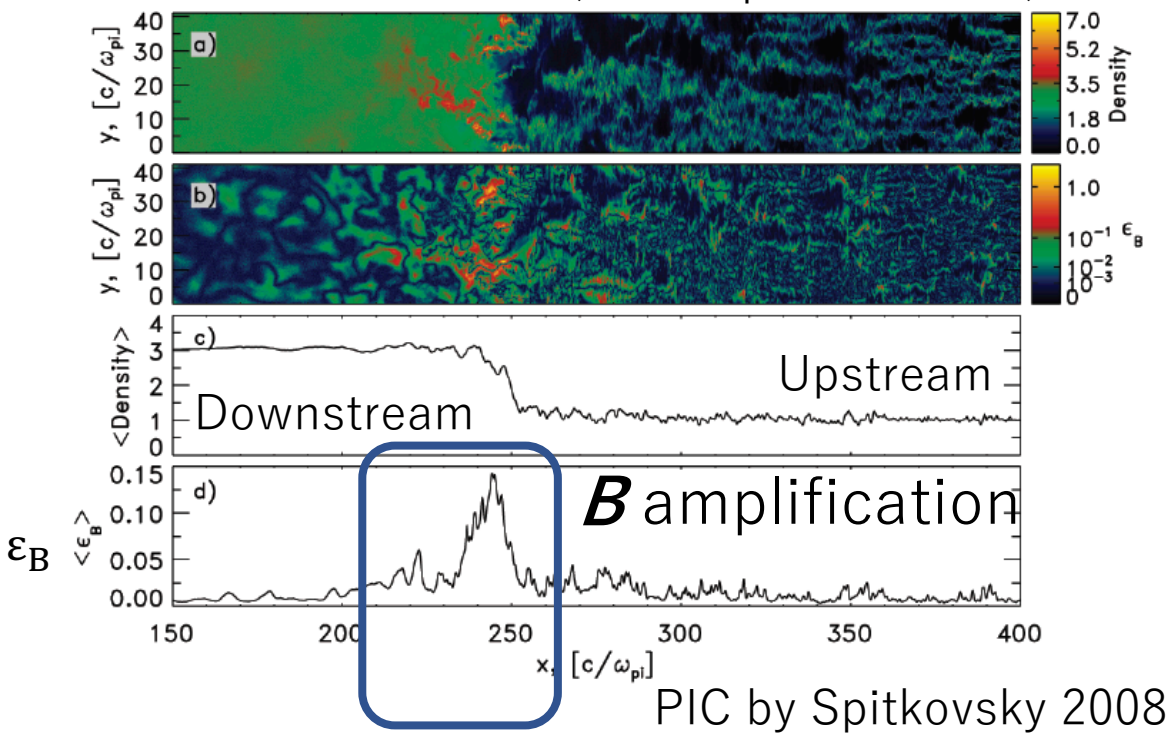
✓ PA change in the RS and FS phases

ΔPA = ~90°

Magnetic field in a collisionless shock

Weibel instability

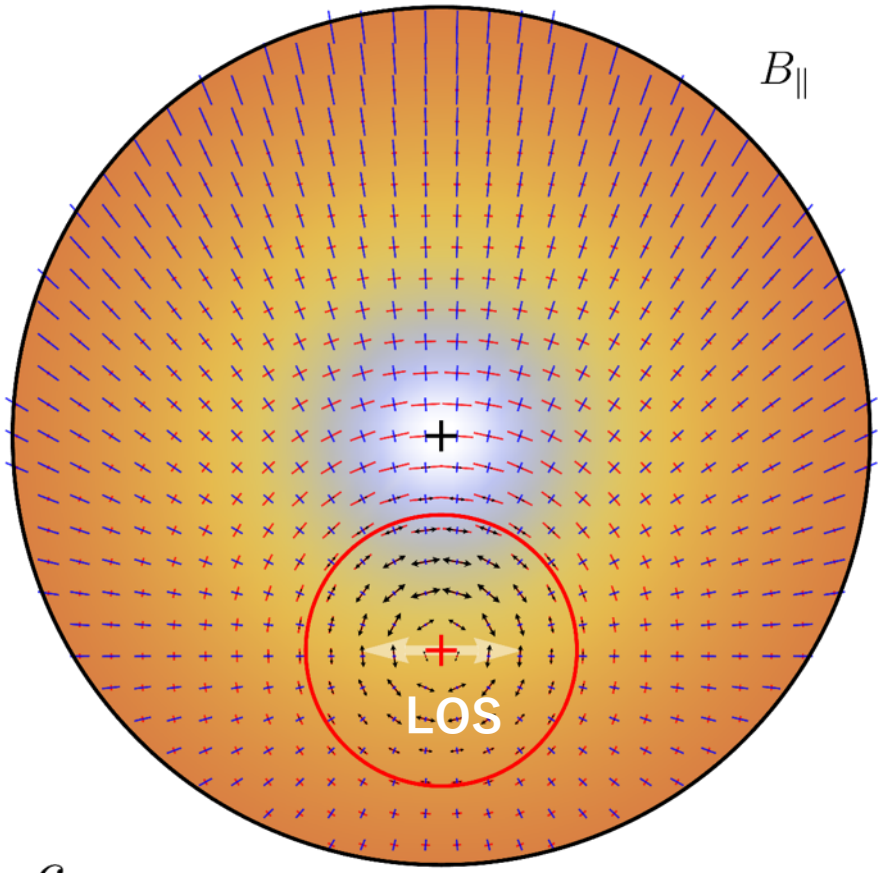
Weakly magnetized plasma
(e.g., Medvedv & Loeb 1999)
(skin depth ~ 10^5 cm)



PIC by Spitkovsky 2008

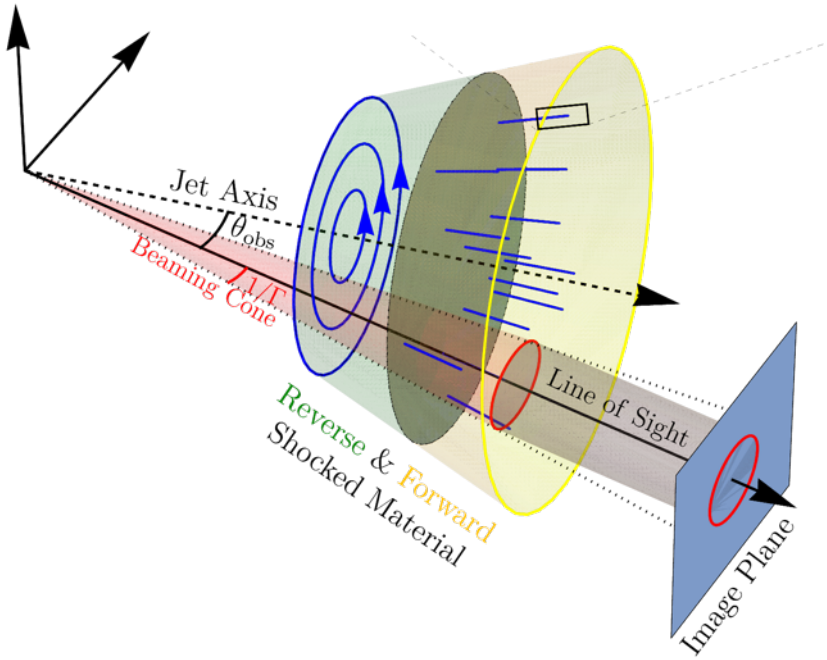
Amplified magnetic field decays immediately
→ **B-field size is very small** (≪ GRB shell size)

Magnetic field
Magnetic field
Polarization
Polarization



Gill & Granot 2020

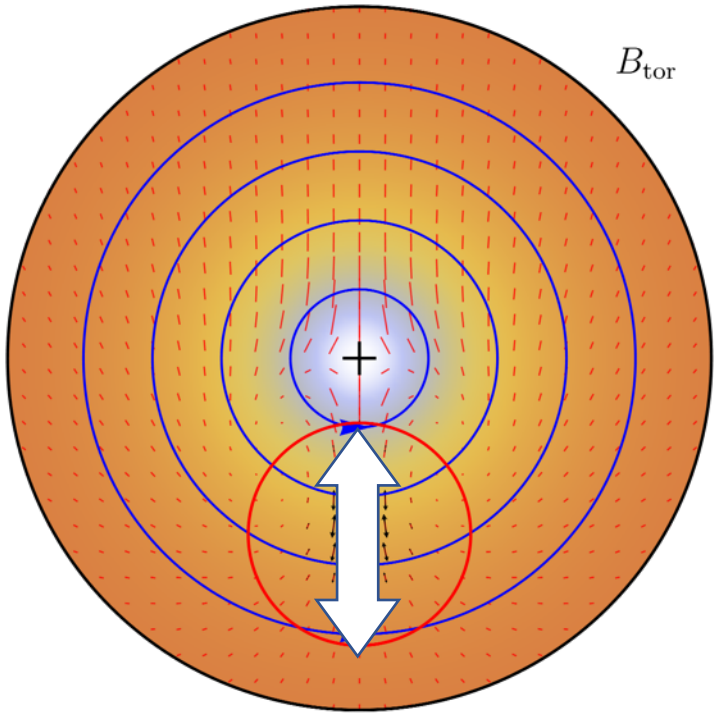
What causes Δ PA = 90deg ?



Special thanks go to R.G.

Early phase

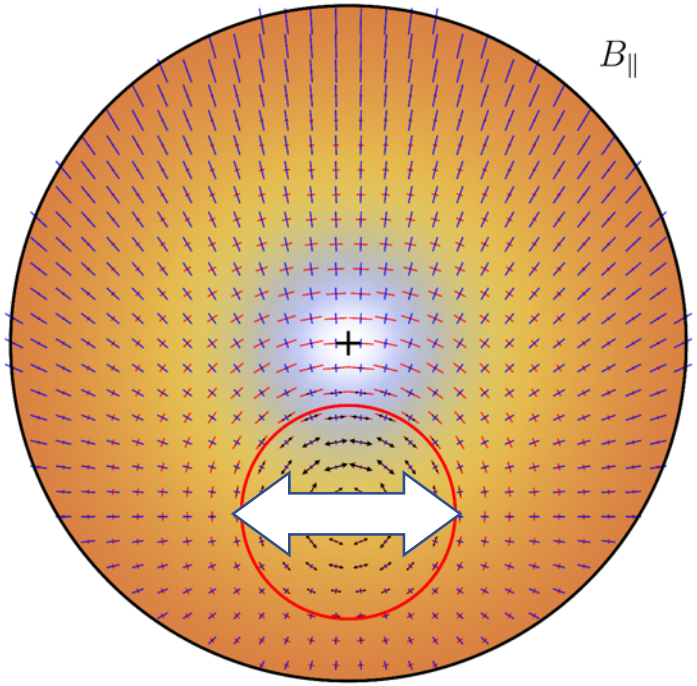
Toroidal B-field
@ RS



- ✓ **Ejecta** polarization
- ✓ **Origin**: **central engine, rotating blackhole** (e.g., Mészáros 98)

Late phase

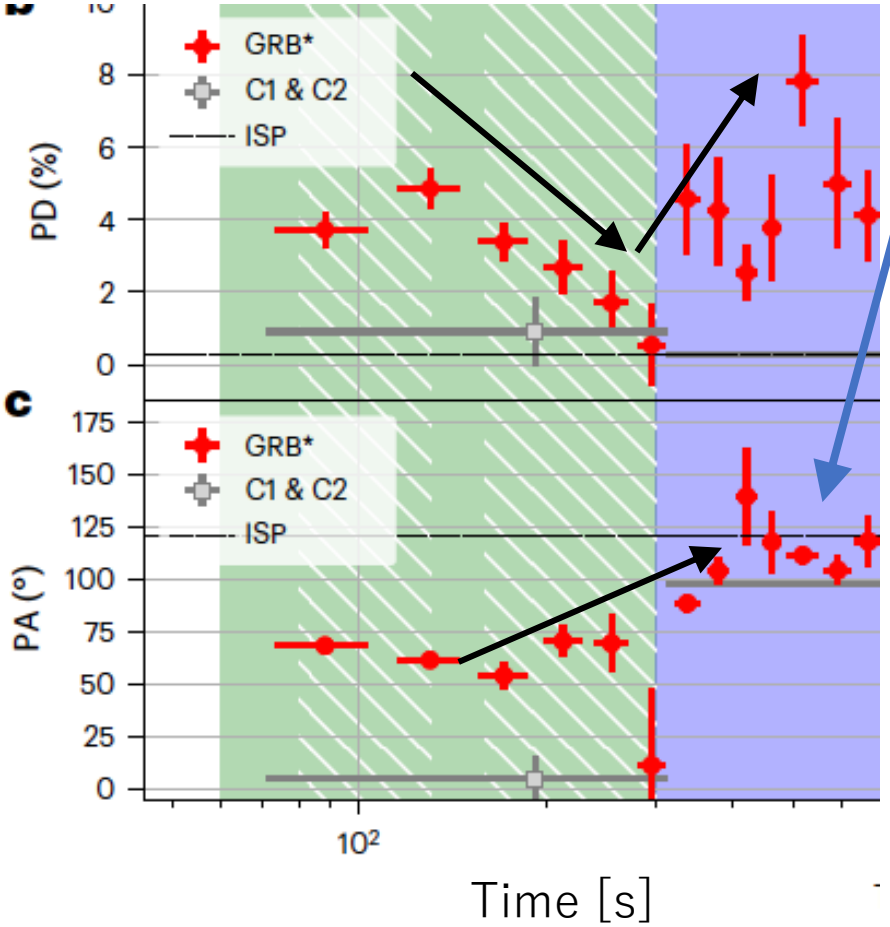
Radially stretched B-field
@ FS



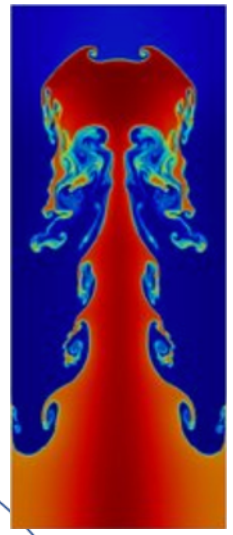
- ✓ **Shock-generated** polarization
- ✓ **Origin**: **plasma instability** in a shock (e.g., Medvedev 99)

SSC emission in a "turbulent B-field"

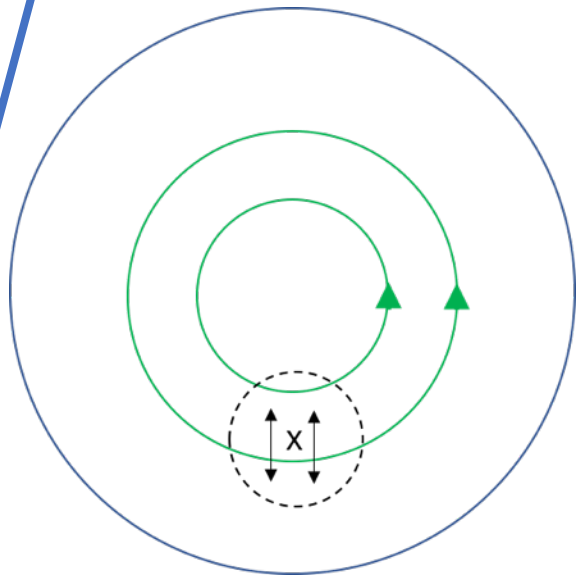
SSC from RS



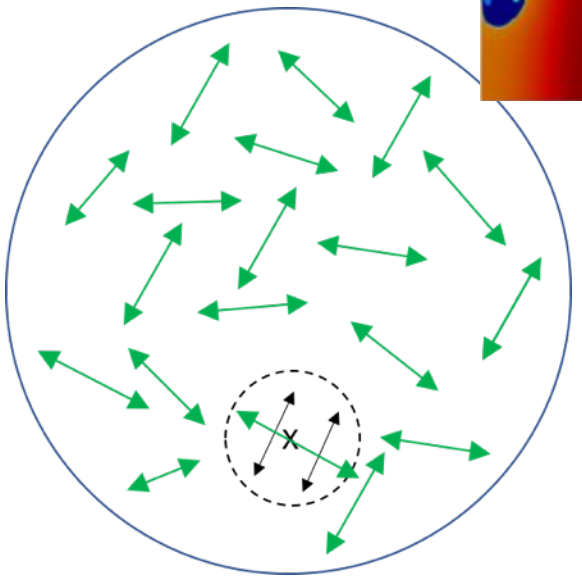
- ✓ **PD is fluctuating with high PDs**
- ✓ **PA is gradually changing**
- ✓ **Weibel inst. may not work**



Very Early phase



Toroidal



Randomly turbulent with **hydrodynamic** scale (e.g., Rayleigh Taylor instability)

Summary

- GRB 180720B shows
  - ✓Optical & GeV emission in the *early phase*
    → **Significant detection of SSC from external reverse shock**
  - ✓Optical polarization from RS and FS was detected
    - **First detection of polarization from RS and FS in a single GRB.**
    - Detection of ΔPD = ~90deg difference btw RS and FS
      → **Strong probe of B-field origin**
    - Fluctuating PD and PA during the SSC emission
      → **Existence of the turbulent B-field structure** when emitting gamma rays

Appendix

Theoretical lightcurves