The impact of pair production on Gamma-Ray Burst prompt emission spectra

Journées SF2A - June 2026

M. Gnaoui, F. Daigne, C. Guépin

INSTITUT D'ASTROPHYSIQUE DE PARIS
Unité mixte de recherche 7095 Observatoire des sciences de l'Univers

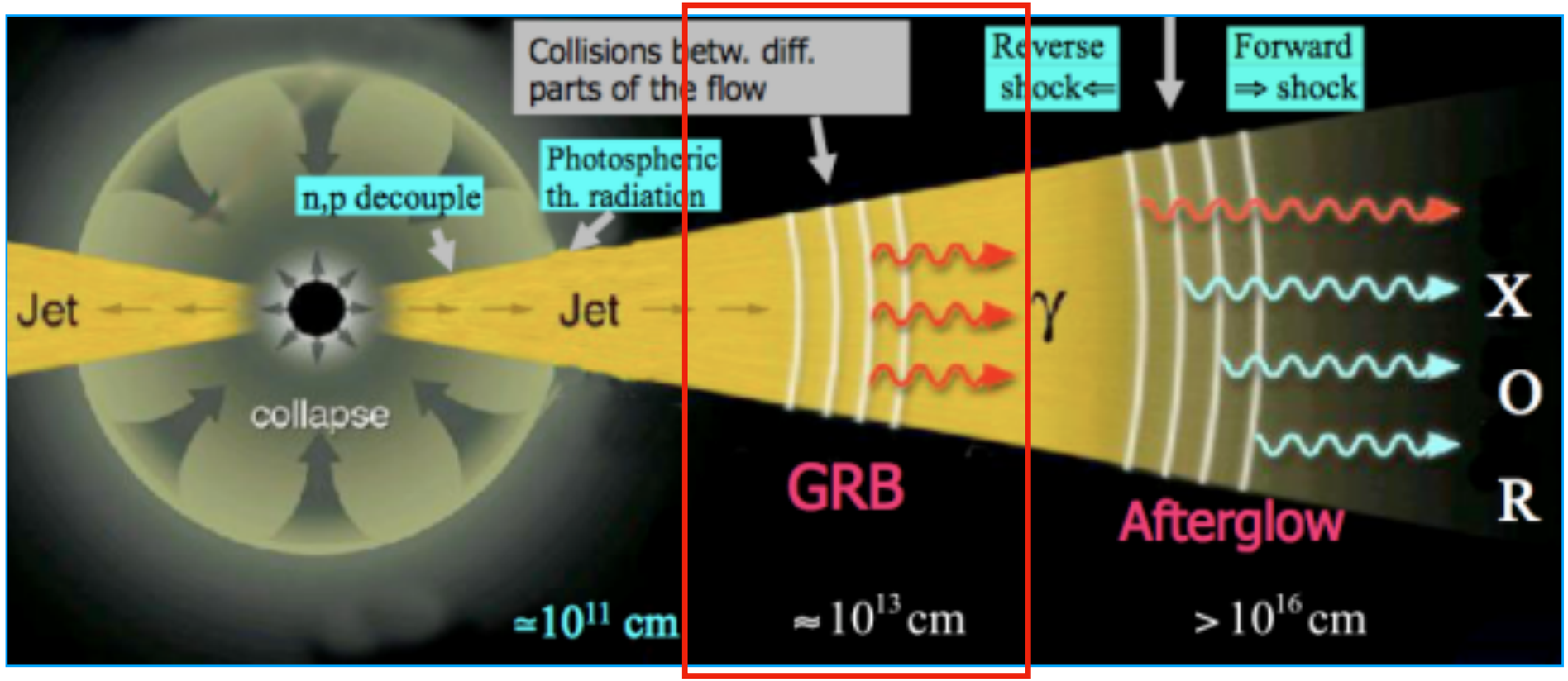
1. Pair production in internal shocks
2. Coupled photons–leptons evolution
3. Identifying spectral components associated to pair production
4. The MeV line in GRB 221009A

Pair production in internal shocks

Is it important ?

Prompt emission model :

- Internal shocks dissipate energy **above** the photosphere
- Accelerate electrons + magnetic field
- Radiation : Synchrotron, Inverse Compton scattering
- Pair production



Rees & Mészáros 1994
Mészáros 2019

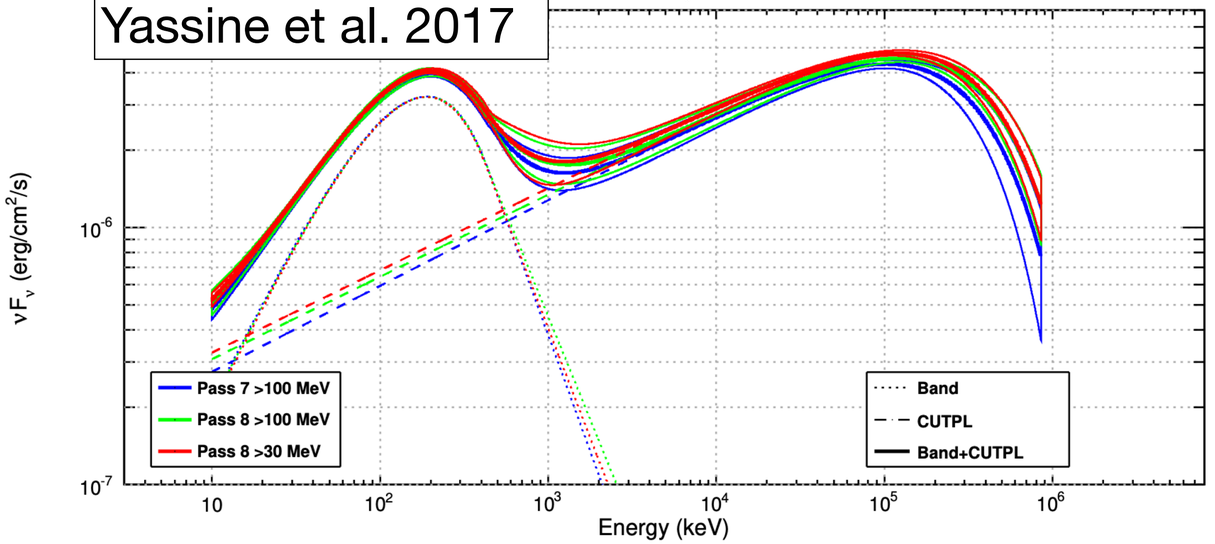
Pair production in internal shocks Is it important ?

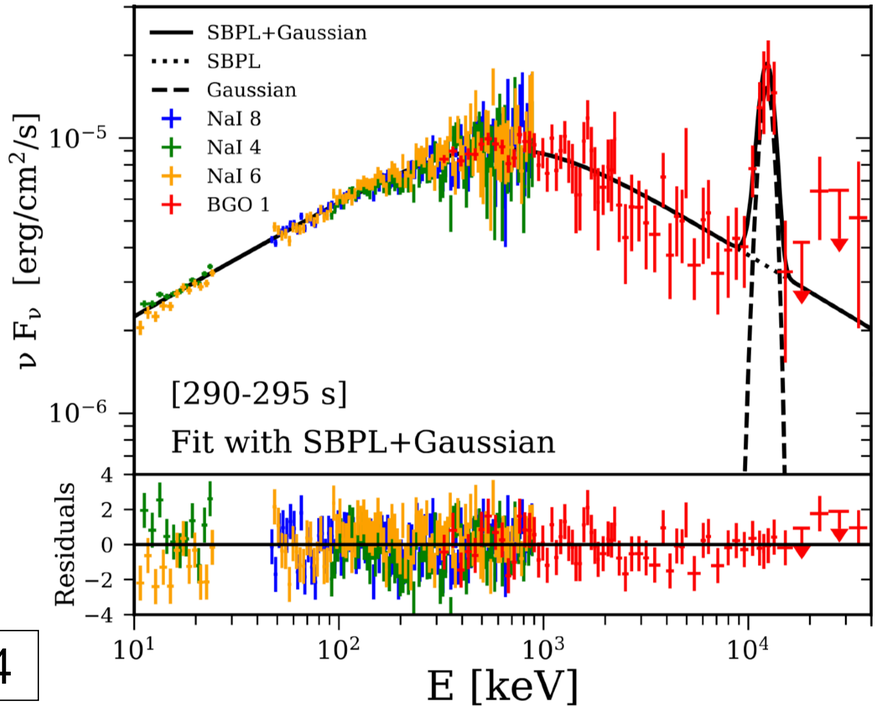
- GRB spectra = Band/BPL peaking at ~1 MeV, + High energy components ?
- Tail or second component prone to pair production : $\gamma + \gamma = e^- + e^+$
- Cutoff energy : constraint on γ or lower limit.

What is the effect of the pairs beyond this ?

- Pairs carry energy ~ $\frac{\epsilon_{\rm cut}}{2} \Rightarrow$ relativistic
- Secondary emission ? Additional components ?
- Pair annihilation line (BOAT GRB221009A) ?

Yassine et al. 2017





Ravasio et al. 2024

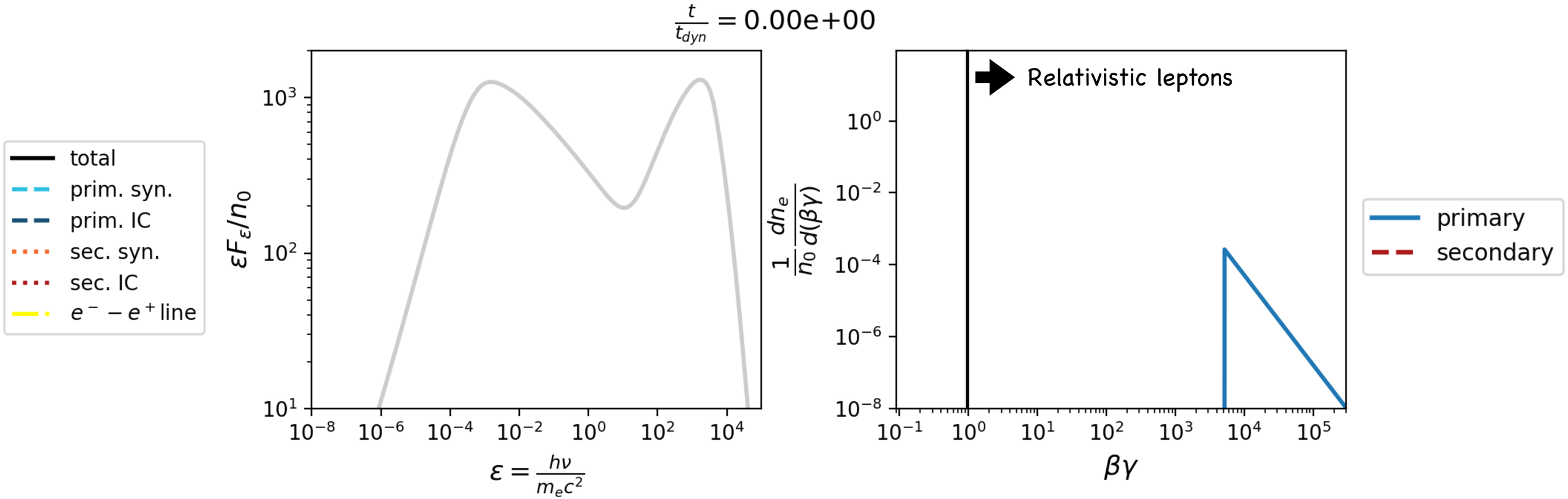
1. Pair production in internal shocks
2. Coupled photons–leptons evolution
3. Identifying spectral components associated to pair production
4. The MeV line in GRB 221009A

Coupled photons-leptons evolution

Modelling the emission region

- One zone : uniform + isotropic
- Parameters (comoving frame) :
  - Injected electrons : $n_0, \gamma_{\rm min}, p$
  - Magnetic field : B
  - Dynamical timescale : $t_{\rm dyn}$
- Processes :
  - Radiation (syn. & IC), adiabatic cooling
  - Pair production : $\gamma + \gamma \rightarrow e^- + e^+$
  - Pair annihilation : $e^- + e^+ \rightarrow \gamma + \gamma$

Parameters:
$t_{\rm dyn} = 1000{\rm s}$
$B = 500{\rm G}$
$n_0 = 10^8{\rm cm}^{-3}$
$\gamma_{\rm min} = 5000$
$p = 2.5$

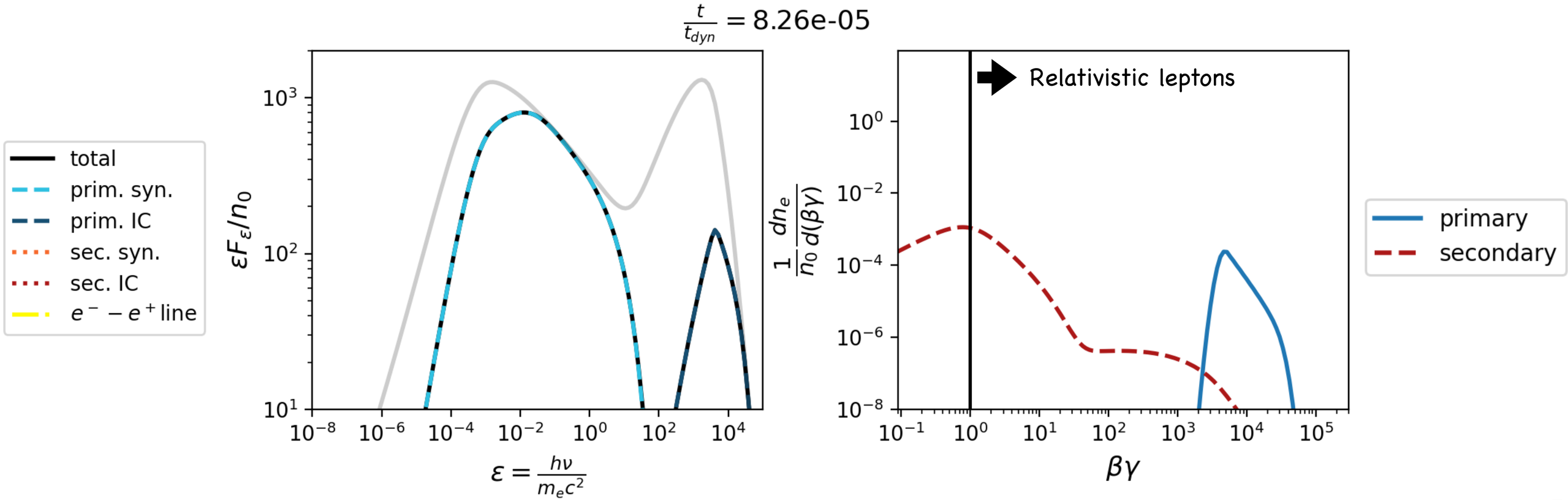


Coupled photons-leptons evolution

Modelling the emission region

- One zone : uniform + isotropic
- Parameters (comoving frame) :
  - Injected electrons : $n_0, \gamma_{\rm min}, p$
  - Magnetic field : B
  - Dynamical timescale : $t_{\rm dyn}$
- Processes :
  - Radiation (syn. & IC), adiabatic cooling
  - Pair production : $\gamma + \gamma \rightarrow e^- + e^+$
  - Pair annihilation : $e^- + e^+ \rightarrow \gamma + \gamma$

Parameters:
$t_{\rm dyn} = 1000{\rm s}$
$B = 500{\rm G}$
$n_0 = 10^8{\rm cm}^{-3}$
$\gamma_{\rm min} = 5000$
$p = 2.5$

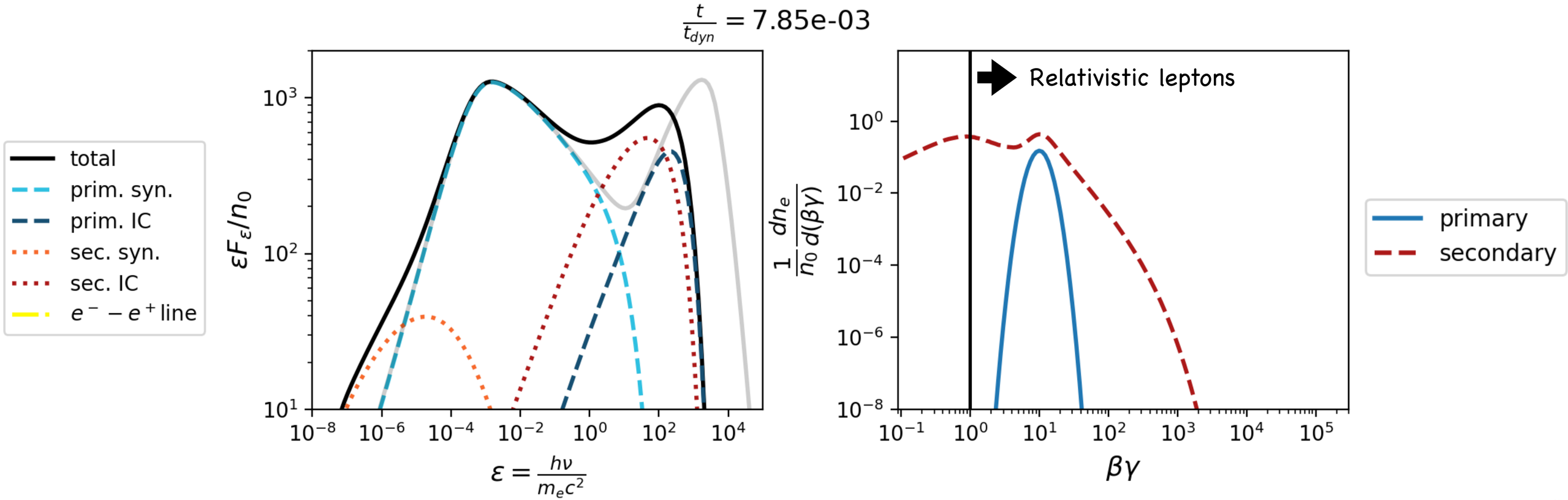


Coupled photons-leptons evolution

Modelling the emission region

- One zone : uniform + isotropic
- Parameters (comoving frame) :
  - Injected electrons : $n_0, \gamma_{\rm min}, p$
  - Magnetic field : B
  - Dynamical timescale : $t_{\rm dyn}$
- Processes :
  - Radiation (syn. & IC), adiabatic cooling
  - Pair production : $\gamma + \gamma \rightarrow e^- + e^+$
  - Pair annihilation : $e^- + e^+ \rightarrow \gamma + \gamma$

Parameters:
$t_{\rm dyn} = 1000{\rm s}$
$B = 500{\rm G}$
$n_0 = 10^8{\rm cm}^{-3}$
$\gamma_{\rm min} = 5000$
$p = 2.5$

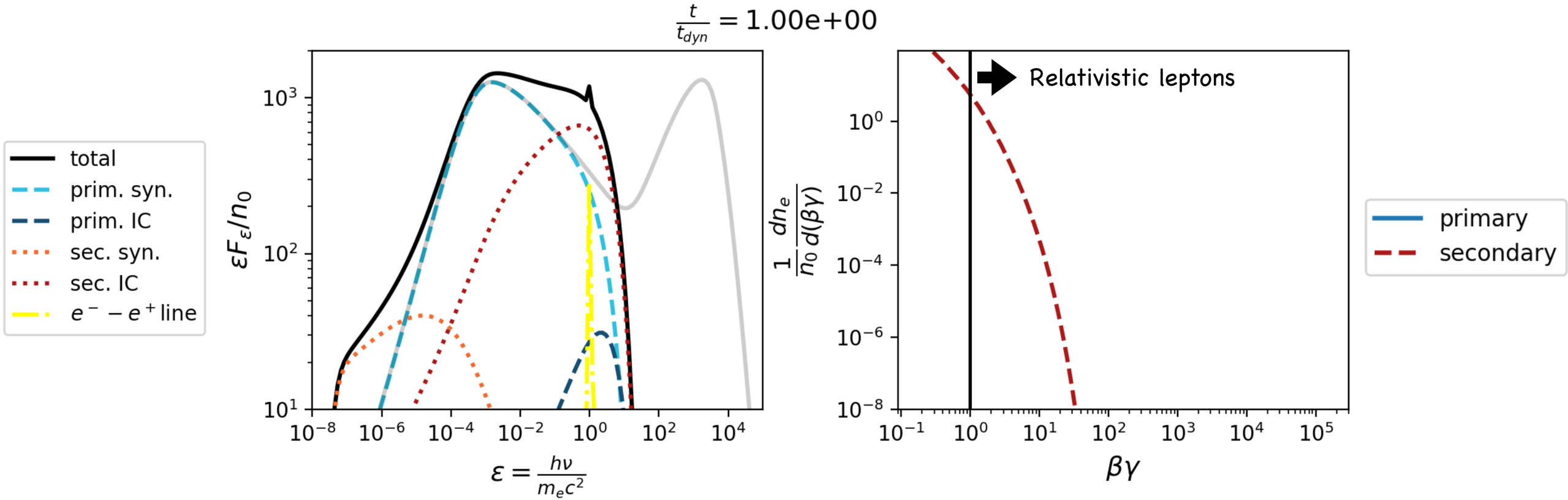


Coupled photons-leptons evolution

Modelling the emission region

- One zone : uniform + isotropic
- Parameters (comoving frame) :
  - Injected electrons : $n_0, \gamma_{\rm min}, p$
  - Magnetic field : B
  - Dynamical timescale : $t_{\rm dyn}$
- Processes :
  - Radiation (syn. & IC), adiabatic cooling
  - Pair production : $\gamma + \gamma \rightarrow e^- + e^+$
  - Pair annihilation : $e^- + e^+ \rightarrow \gamma + \gamma$

Parameters:
$t_{\rm dyn} = 1000{\rm s}$
$B = 500{\rm G}$
$n_0 = 10^8{\rm cm}^{-3}$
$\gamma_{\rm min} = 5000$
$p = 2.5$



Coupled photons-leptons evolution Modelling the emission region

Parameter space :

- Well model the GRB population
- Optically thin for primary leptons : $\tau_T \leq 0.1$

Parameter	Min	Max	Steps
$t_{\rm dyn}$ (s)	10^{-2}	10^{3}	10
B (G)	1	10^{4}	10
n_e ($\rm cm^{-3}$)	10^{4}	10^{10}	10
γ_m	10	10^{4}	10
p	2.0	3.0	5

Question : What are the spectral components associated to pair production ?

1. Pair production in internal shocks
2. Coupled photons–leptons evolution
3. Identifying spectral components associated to pair production
4. The MeV line in GRB 221009A

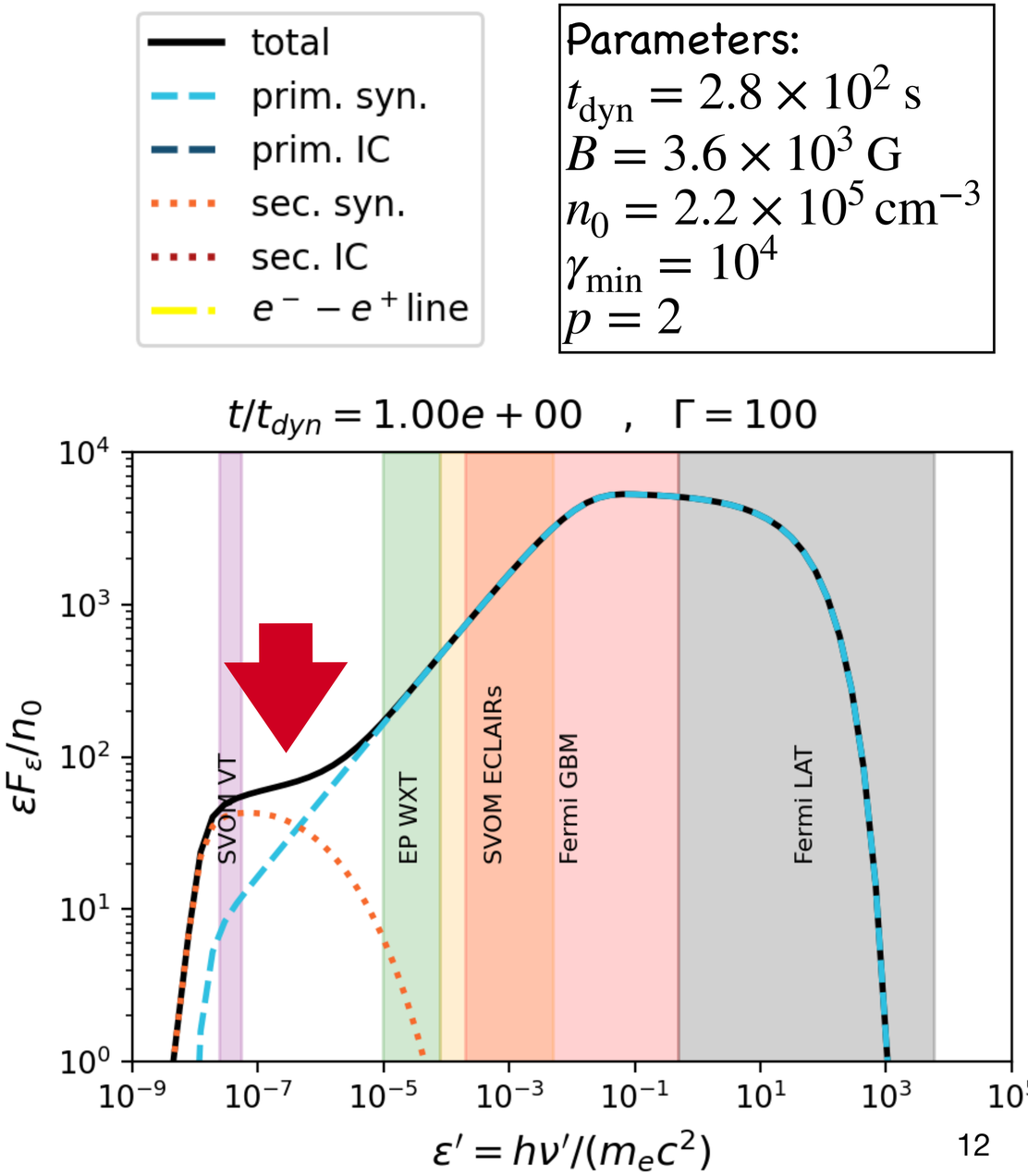
Identifying the spectral components associated to pair production

Synchrotron dominated cases ($u_B \geq u_\gamma$) :

- Primary synchrotron dominates + Abundant pair production

  ⇒ Secondary synchrotron dominates at lower energy (pairs $\gamma < \gamma_m$)

  ⇒ Break and softening of the low energy photon index
- Is a unique signature of abundant pair production
- Not observed => constraints on pair production
- Observable ? Could explain some optically bright GRBs ?



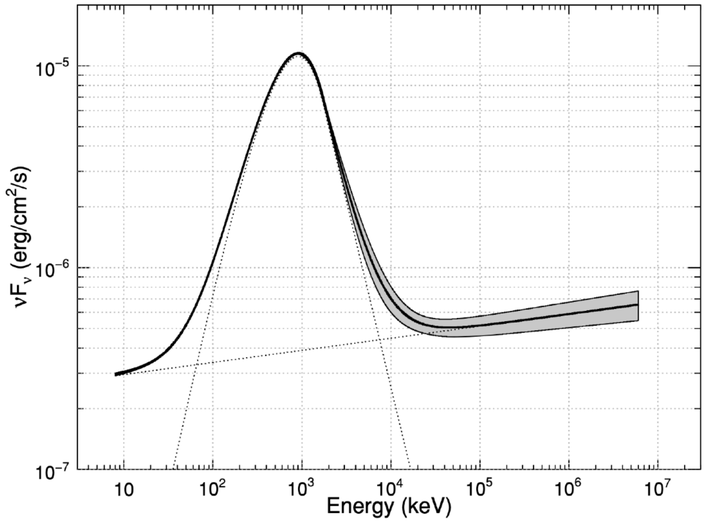
Identifying the spectral components associated to pair production

IC dominated cases ($u_B < u_\gamma$) :

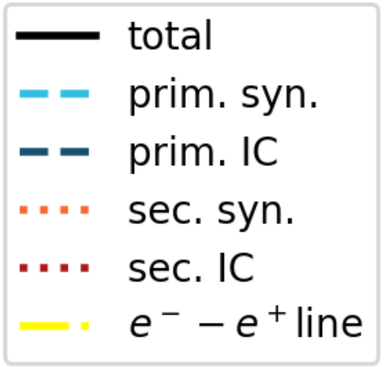
If primary Inverse Compton is important at High Energy and is strongly absorbed :

- Secondary IC dominates at high energy
- Synchrotron may still dominate at lower energy

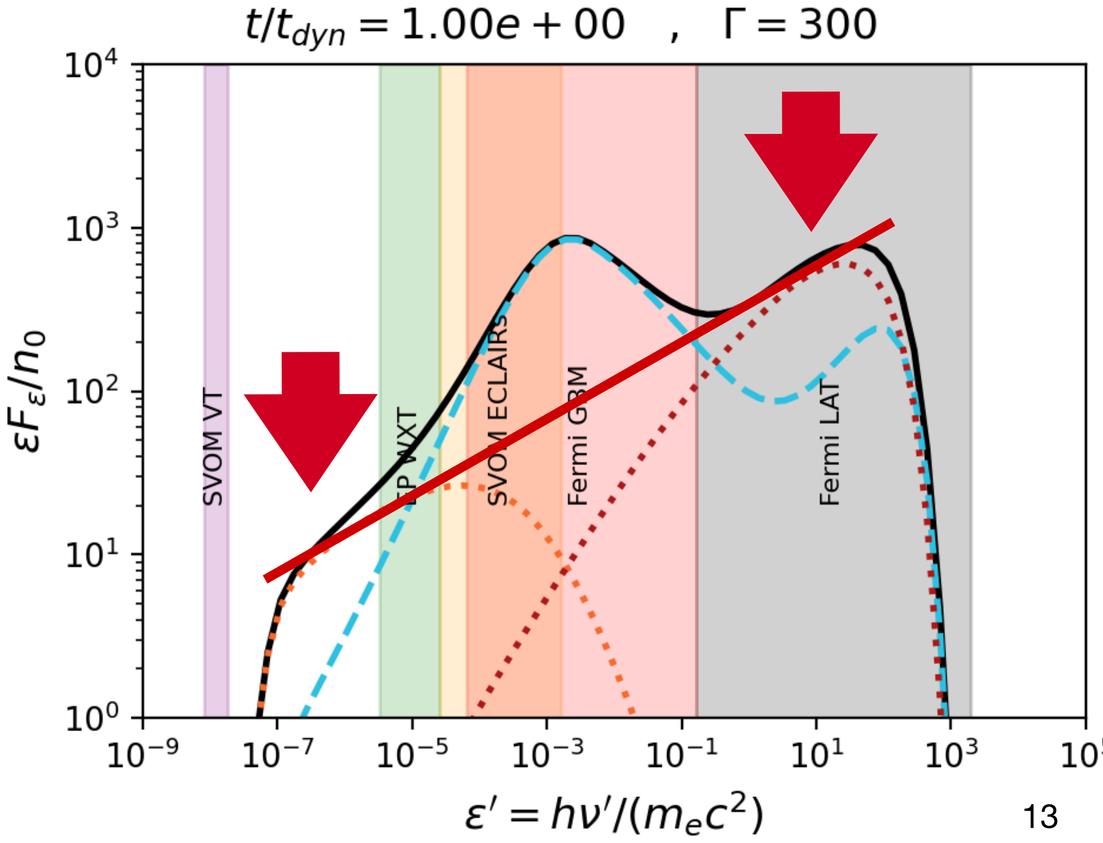
⇒ coupled low and high energy components (BPL + PWL fit ? GRB 090902B,...)



Abdo et al. 2009



Parameters:
$t_{dyn} = 1.6$ s
$B = 1.3 \times 10^3$ G
$n_0 = 2.2 \times 10^9$ cm^{-3}
$\gamma_{min} = 4.6 \times 10^3$
$p = 3$



Identifying the spectral components associated to pair production

Pair annihilation line :

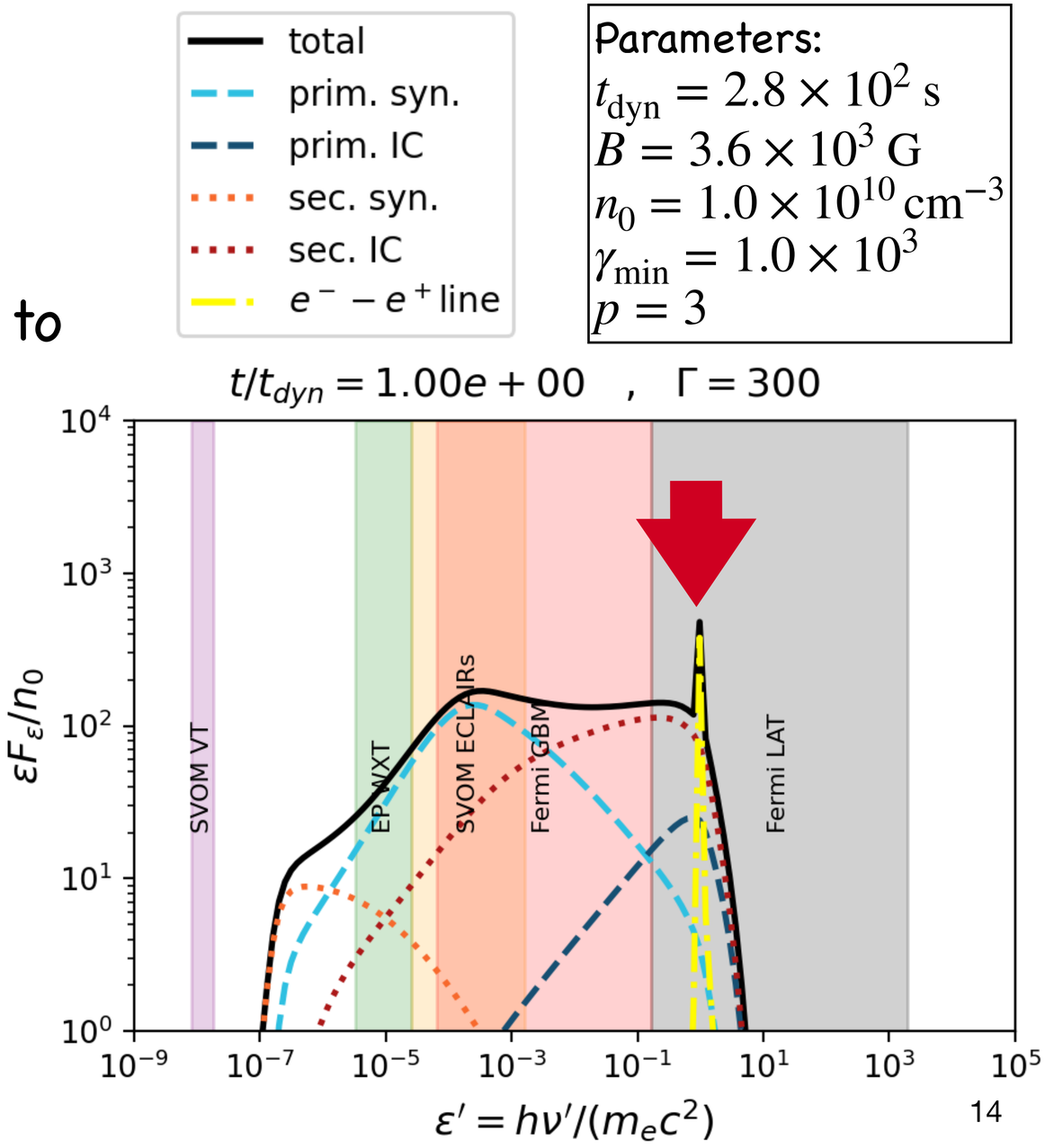
In sufficiently compact cases :

- Very abundant pair production
- Annihilation of positrons and electrons close to threshold

⇒ Narrow emission line at 0.511 MeV

Pairs must cool down before annihilating

⇒ Line always accompanied by secondary emission

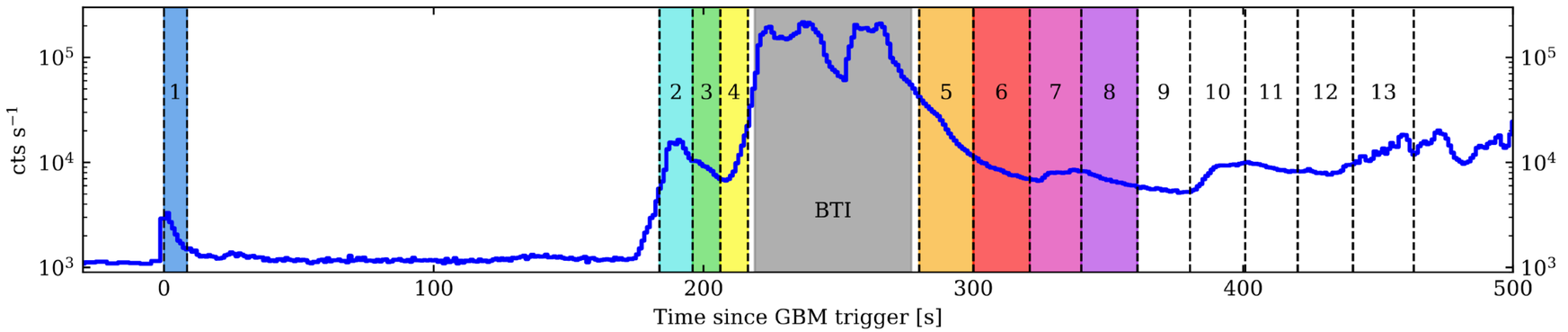


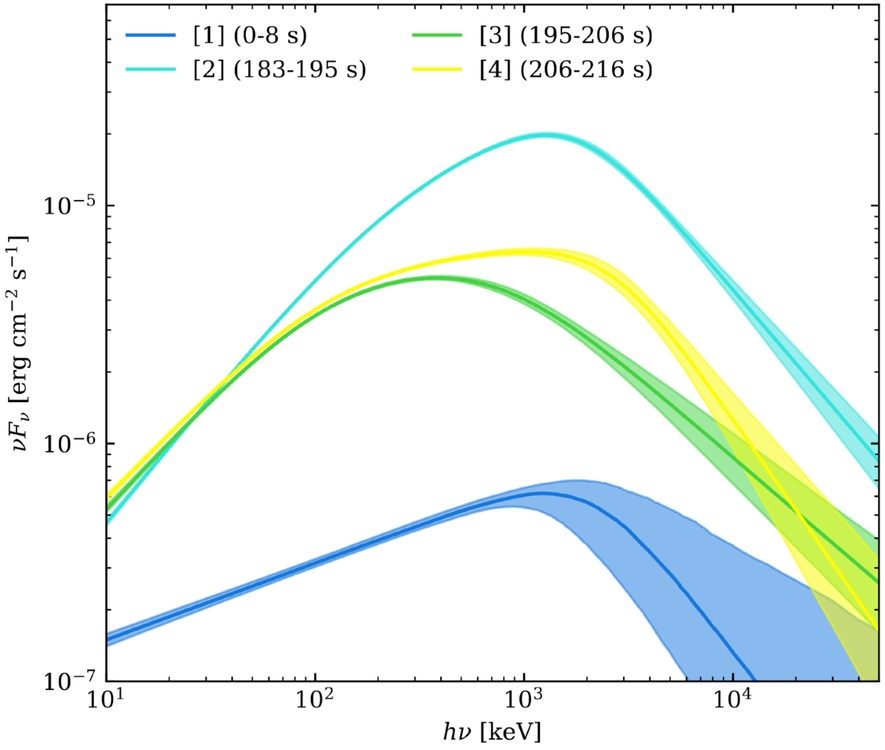
1. Pair production in internal shocks
2. Coupled photons–leptons evolution
3. Identifying spectral components associated to pair production
4. The MeV line in GRB 221009A

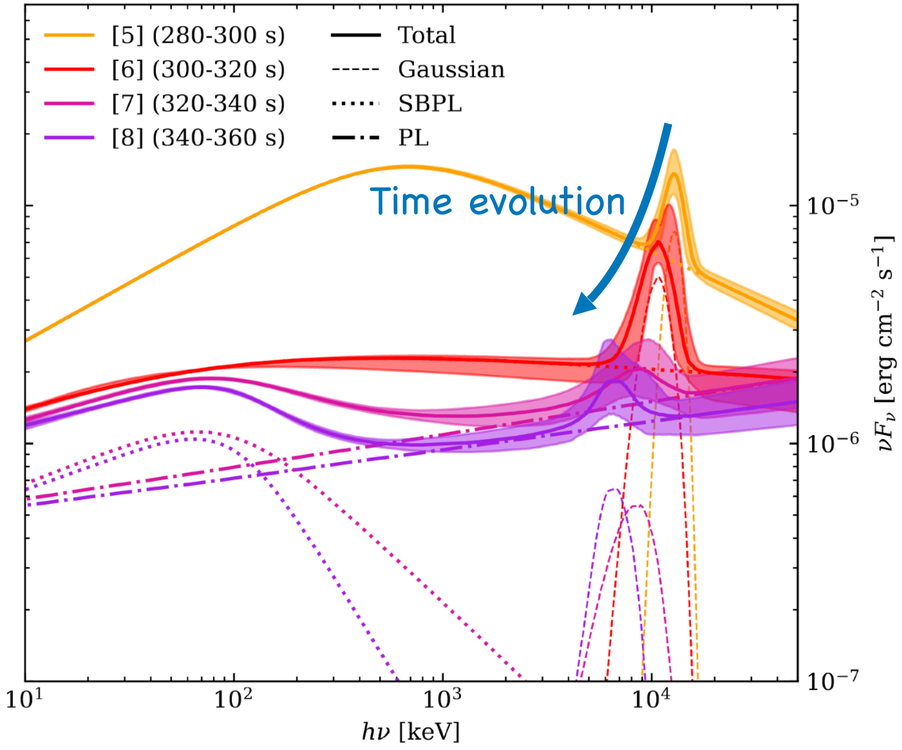
The MeV line in GRB221009A A.K.A. the brightest of all time

3 time intervals :

- No line
- Bad Time Interval
- ~10 MeV residuals







Ravasio et al. 2024

The MeV line in GRB221009A A.K.A. the brightest of all time

3 time intervals :

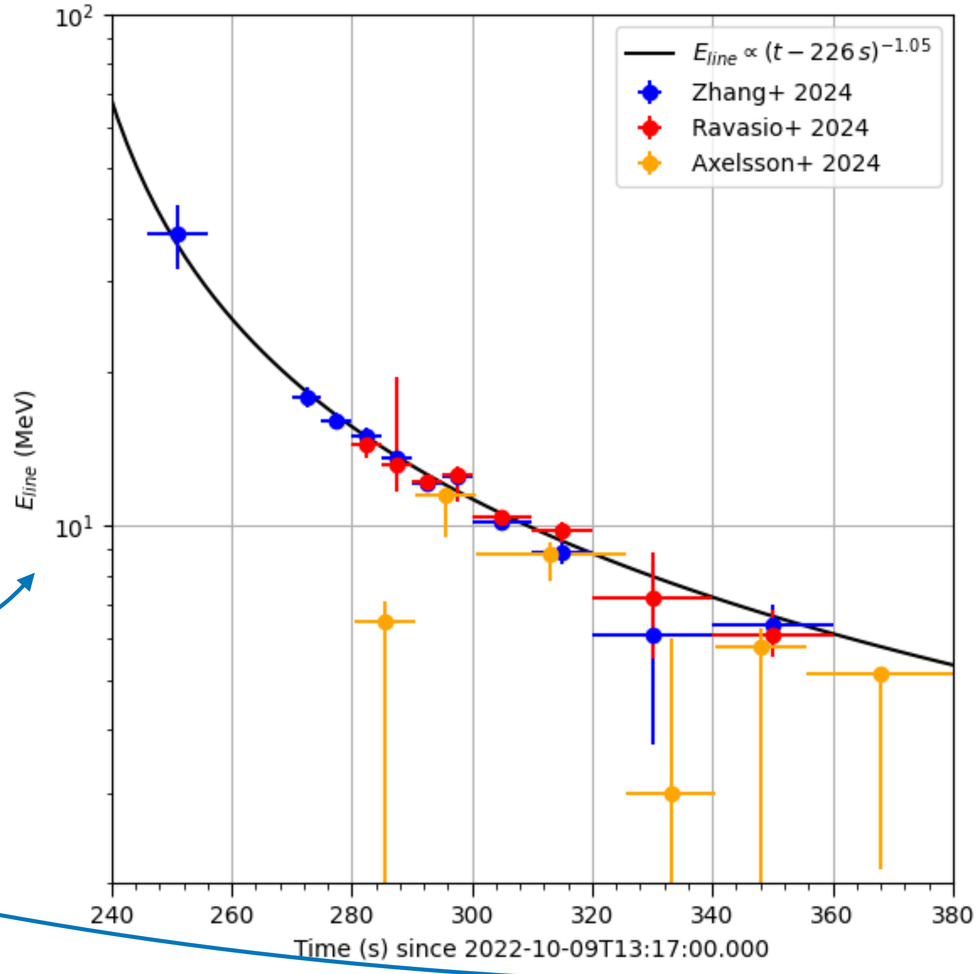
- No line
- Bad Time Interval
- ~10 MeV residuals

Line properties :

- Evolve with time
- $E_{line} \propto (t - t_0)^{-1}$
- $L_{line}^{bolometric} \propto (t - t_0)^{-3}$

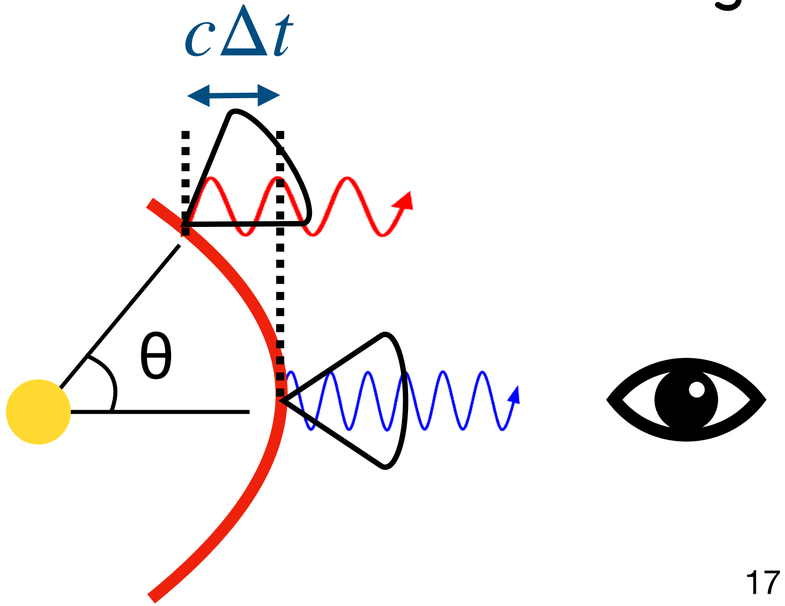
⇒ High Latitude Emission ?

⇒ $e^- + e^+ \rightarrow \gamma + \gamma$?



(All use Fermi GBM data, Zhang+2024 also use GECAM)

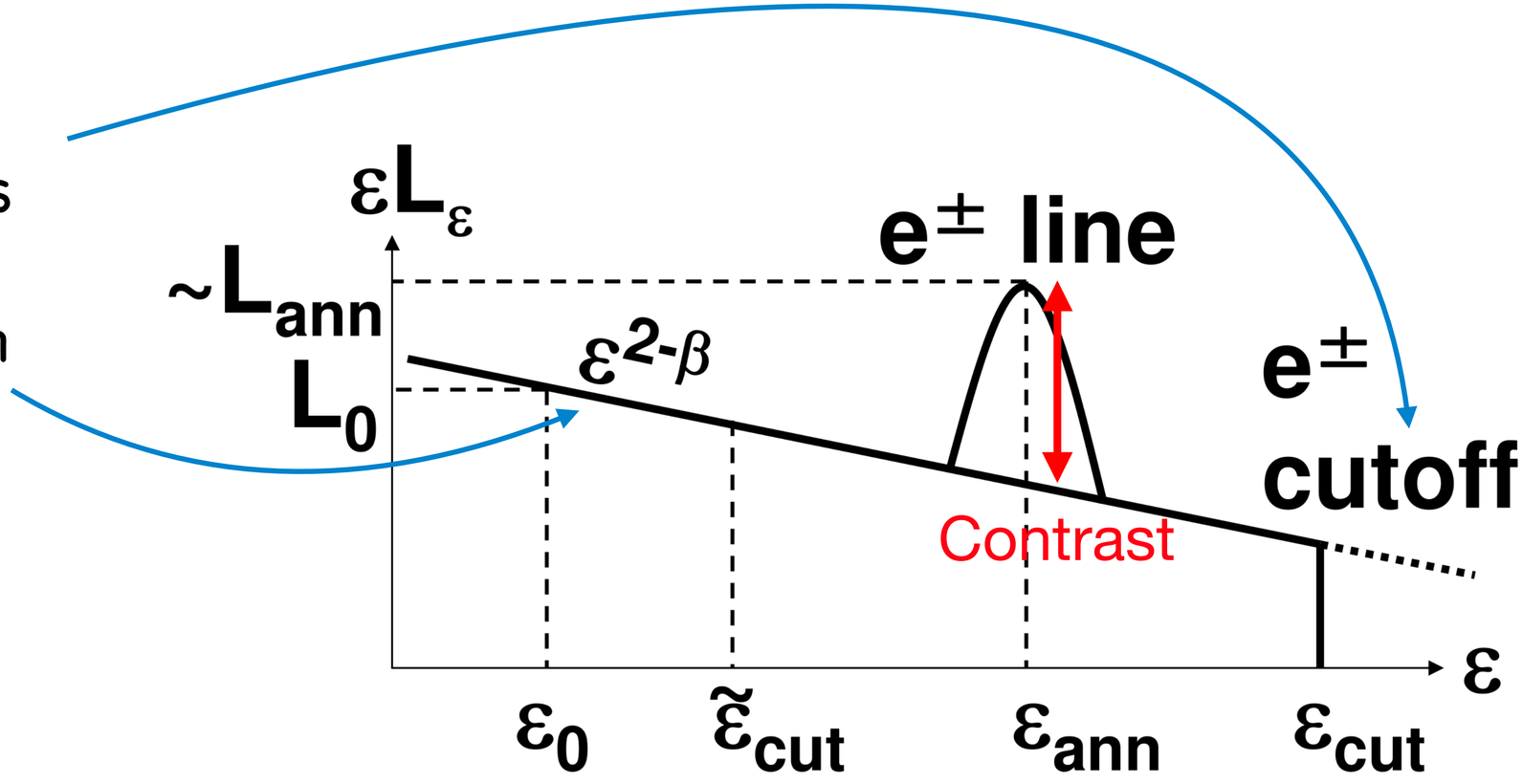
HLE schematic drawing



The MeV line in GRB221009A A.K.A. the brightest of all time

But producing a visible line is not easy :

- Pair production & annihilation reprocess high energy photons into the **line**
- There's often less energy than the **continuum**



We define the **Contrast** :

- $\nu F_\nu(line)/\nu F_\nu(continuum)$
- > few from data

Can we reproduce the high contrast with our **one zone** emission model ?

Murase & Ioka 2008

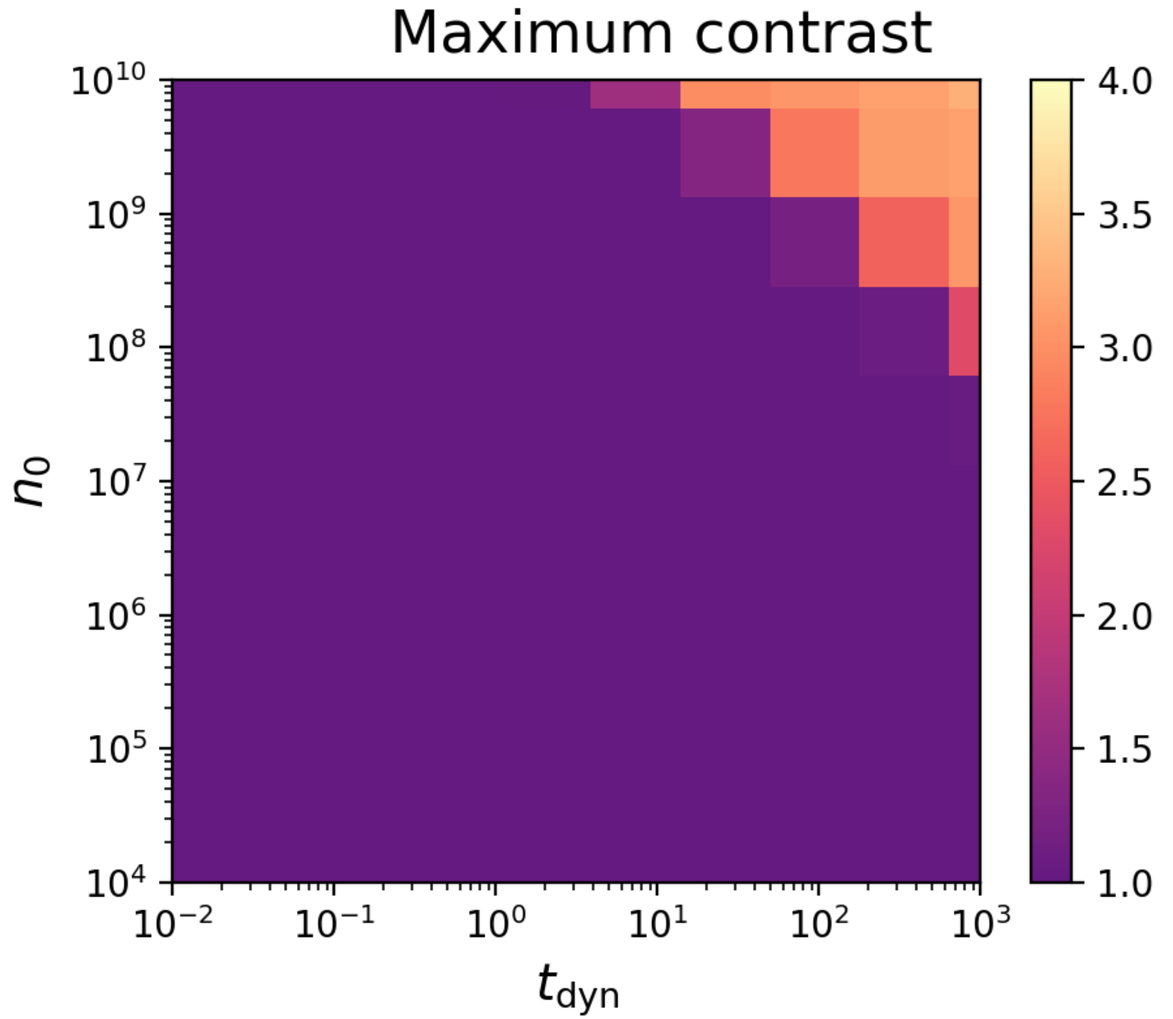
The MeV line in GRB221009A

Looking for high contrast

- No pairs in most cases : Expected

BOAT = Unique ⇒ Extreme conditions ?

- Diagonals : $\tau_t = c\sigma_T t_{\rm dyn} n_0$ constant (Without pairs)
- High contrast when opacity with pairs > 1



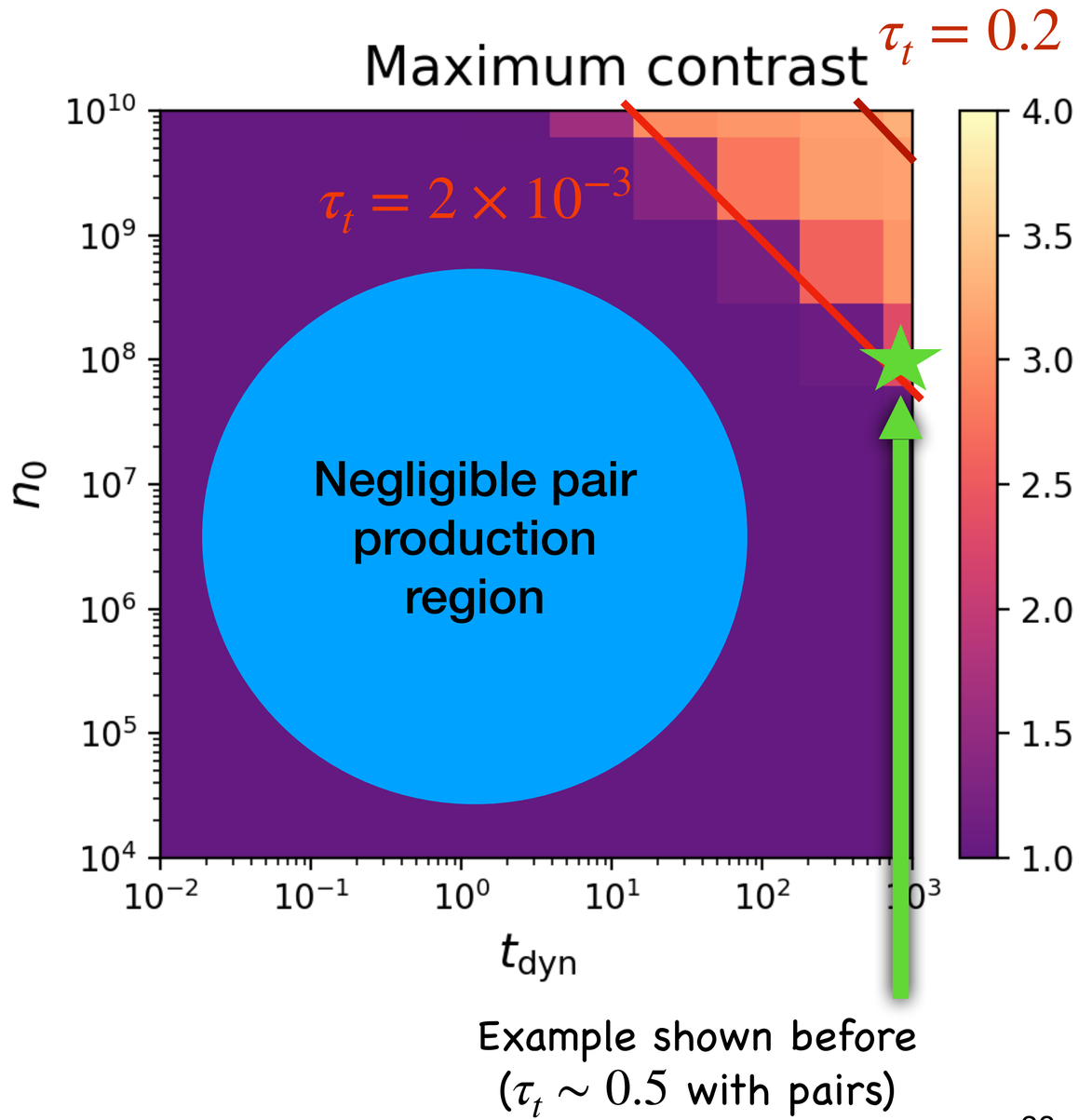
The MeV line in GRB221009A

Looking for high contrast

- No pairs in most cases : Expected

BOAT = Unique ⇒ Extreme conditions ?

- Diagonals : $\tau_t = c\sigma_T t_{\rm dyn} n_0$ constant (Without pairs)
- High contrast when opacity with pairs > 1



Example shown before
($\tau_t \sim 0.5$ with pairs)

The MeV line in GRB221009A

Looking for high contrast

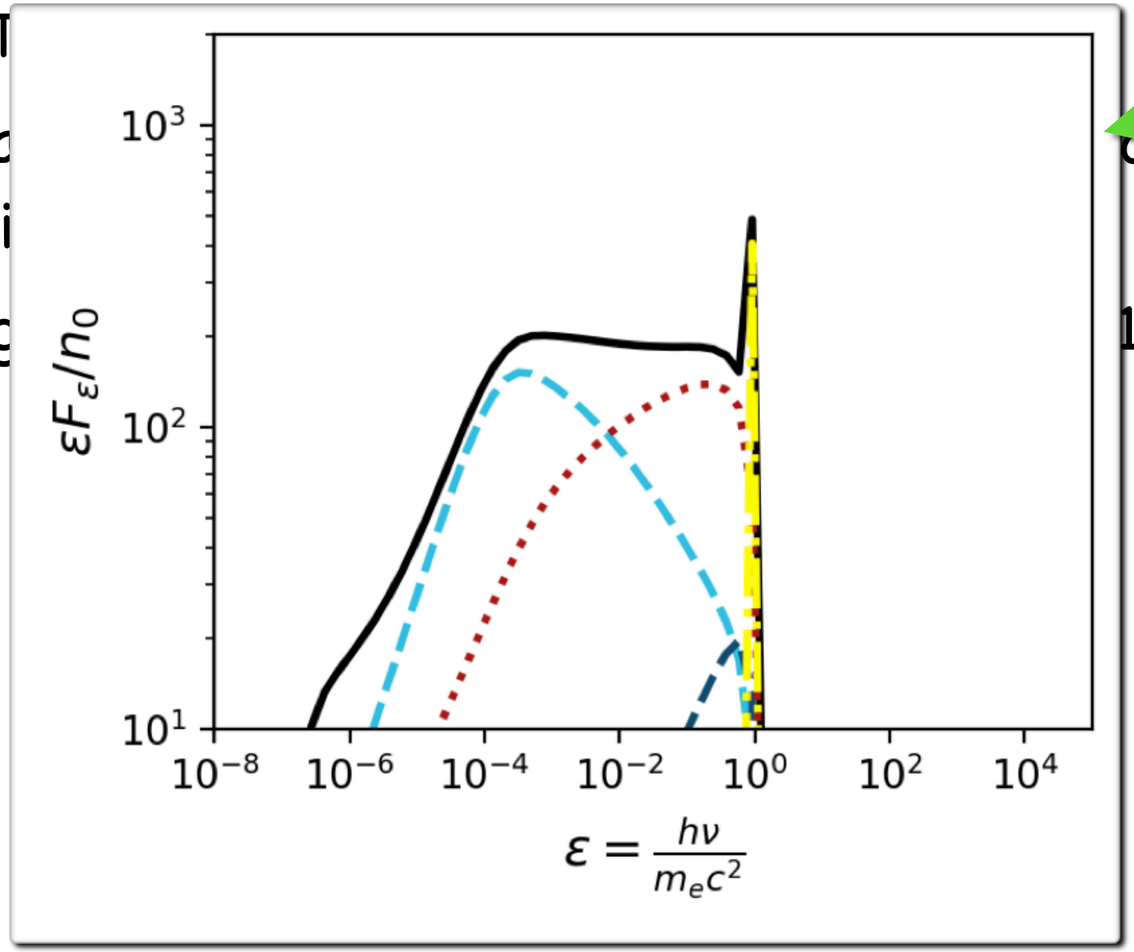
- No pairs in most cases : Expected

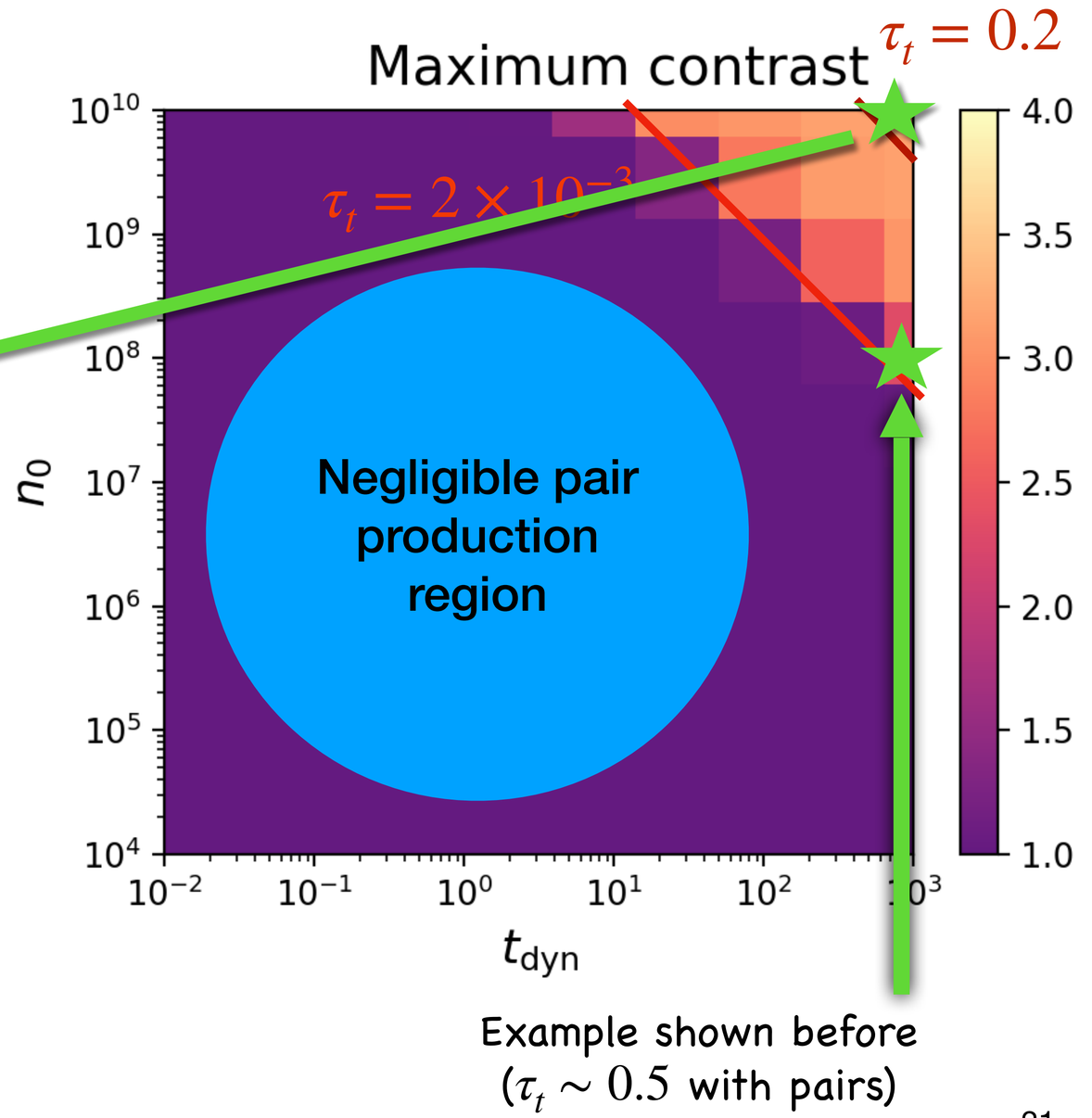
BOAT

- Dic
  pai
- Hig

out

1





Example shown before
($\tau_t \sim 0.5$ with pairs)

Summary

- Pair production is not expected to happen in all GRBs but can be a clue for the emission processes that drive prompt emission
- Abundant pair production could be detected as :
  - a low energy break (softening). It could explain some optically bright bursts
  - An excess below and above the main peak, not unlike GRB 090902B, GRB090926A
  - A narrow emission line in the most extreme cases (GRB221009A ?)
- The emission line in GRB221009A could be associated to pair annihilation, but the observed spectrum (line+continuum) is unlikely to be produced in a single region.
  - Solution (?) : Temporal decoupling of pair radiation and annihilation (photon escape ? Pair production region different from annihilation region ? See scenario by Salafia+ 2026)

Perspectives

- Further analysis to check model compatibility for specific bursts/population, parametrised in X, optical, and high energy ⇒ need for a well characterised sample !
- Parametrise emission region using dynamics to identify most realistic scenarii.