HIGH ENERGY ASTROPHYSICS

Special relativity - non-thermal emission

Astrid Lamberts
Guillaume Dubus (IPAG), Sébastien Fromang (CEA-Saclay), Frédéric Daigne (IAP), Romain Teyssier (ETH), Zakaria Meliani (LUTh)

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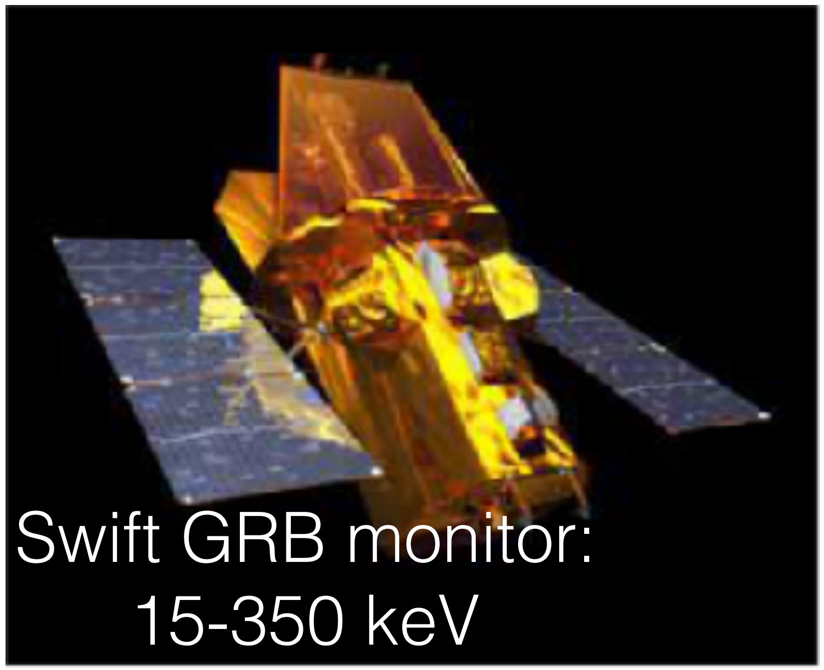
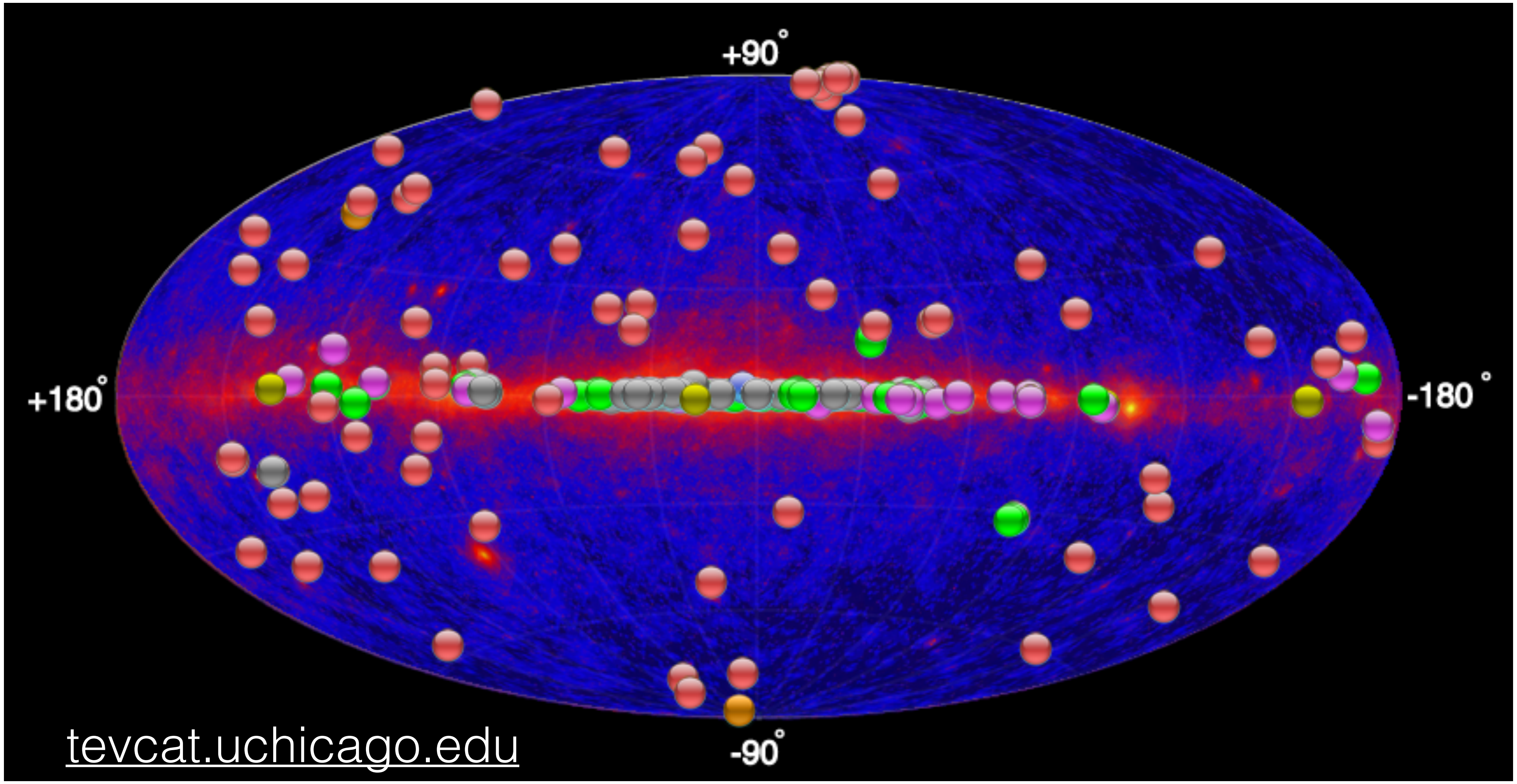
THE GOLDEN ERA OF HIGH-ENERGY ASTROPHYSICS



FUTURE

- CTA (2020): 20 GeV - 300 TeV
- SVOM (2022): GRB monitor
- Athena (2028): X-rays
- combined with gravitational wave / neutrino detections

HIGH ENERGY AND VERY HIGH ENERGY GAMMA RAYS



- Diffuse emission
- extragalactic: blazars + starburst galaxies
- galactic: pulsar wind nebulae, binaries, supernova remnants, star clusters

A WINDOW FOR EXTREME PHYSICS

- Overall very high energy budget
- (mostly) compact objects
- (mostly) relativistic outflows
- Particle acceleration at v~c, high B
- Feedback

LOTS OF PHYSICS

BUT

- Complex geometries
- High multi-wavelength variability
- Wide range of length scales
- (magneto)hydrodynamic instabilities

-> NEED FOR RELATIVISTIC HYDRO SIMULATIONS

Relativistic hydro (RHD) : only way to get Lorentz factor
BUT changes shocks, energetics, instabilities and emission

RELATIVISTIC SIMULATIONS

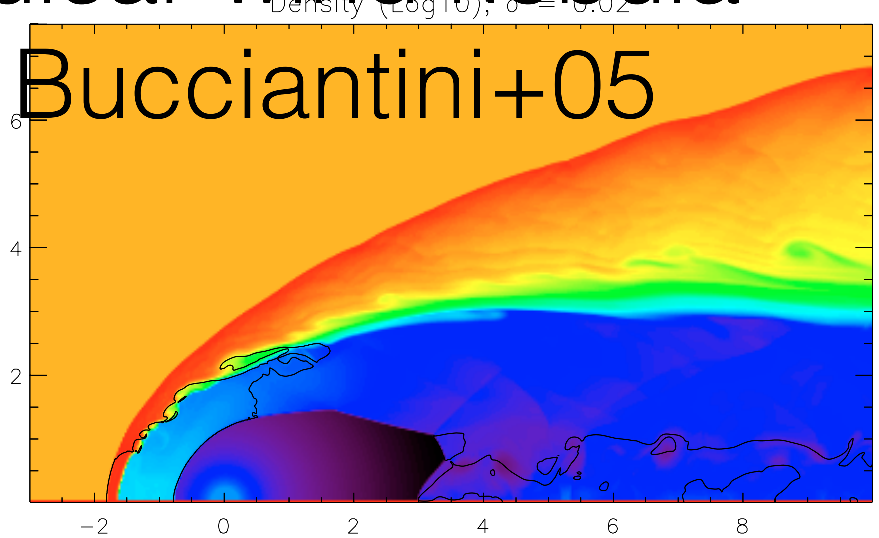
≃ 10 RHD codes : GENSESIS (Aloy+99), PLUTO (Mignone+07), r-ENZO (Wang+08), AMRVAC (Keppens+11), ATHENA (Beckwith+11), RAMSES (Lamberts+13)

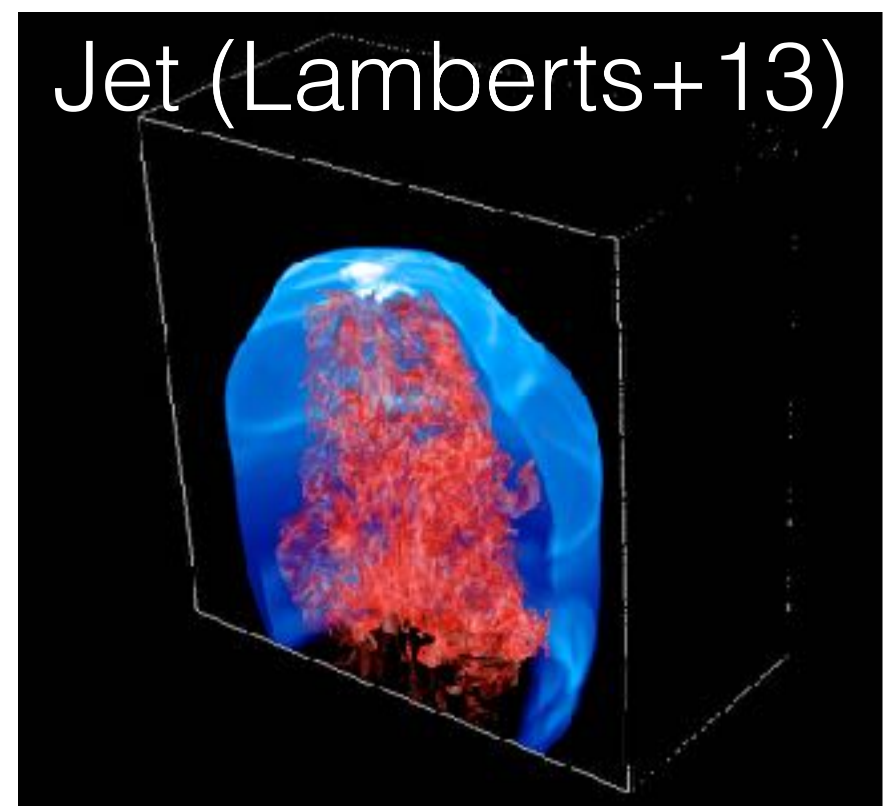
- Different degrees of adaptive mesh refinement
- Different physical features : magnetohydrodynamics, equations of state
  -> Methods still under development,

Especially for emission

Pulsar wind nebula

Bucciantini+05





Jet (Lamberts+13)

RELATIVISTIC HYDRO EQUATIONS

HD $$\frac{\partial \mathbf{U}}{\partial t} + \sum_{i=1}^{3} \frac{\partial \mathbf{F_i}}{\partial x_i} = 0 \quad \mathbf{U} = \begin{pmatrix} \rho \\ \rho v_i \\ \frac{1}{2}\rho v^2 + \frac{P}{\gamma - 1} \end{pmatrix} \quad \mathbf{F_i} = \begin{pmatrix} \rho v_i \\ \rho v_i v_j + P\delta^{ij} \\ v_i(E+P) \end{pmatrix}$$

RHD $$\mathbf{U} = \begin{pmatrix} D \\ M_i \\ E \end{pmatrix} = \begin{pmatrix} \Gamma \rho \\ \Gamma^2 \rho h v_i c^2 \\ \Gamma^2 \rho h - P \end{pmatrix} \quad , \quad \mathbf{F_i} = \begin{pmatrix} \rho \Gamma v_i \\ \rho h \Gamma^2 v_i v_j / c^2 + P\delta^{ij} \\ \rho h \Gamma^2 v_i \end{pmatrix}$$

$$\Gamma = (1 - v_x^2 - v_y^2 - v_z^2)^{-1/2}$$

Directions are combined

RELATIVISTIC EFFECTS

- Fluid relativistic because of bulk motion and/or thermal velocity
- Strong coupling of equations through Lorentz factor → effect of transverse velocities on motion
- additional energy term due to rest mass energy
- "classical equation of state" $P = (\gamma - 1)(\rho\varepsilon - \rho)$ → ok in non-relativistic ($\gamma = 5/3$) and ultrarelativistic limits ($\gamma = 4/3$).
  Relativistic kinetic theory → $\gamma = \gamma(h, p)$
- Sound speed $c_s = \sqrt{\frac{\gamma P}{\rho h}}$ < 1/3(UR),2/3(NR)

LIMITS AND POSSIBILITIES OF RHD SIMULATIONS

(some) Goals of RHD simulations : give Lorentz factor, determine geometry, model instabilities...

- The higher Γ, the higher the resolution needed State-of-the-art 3D simulations model $\Gamma \simeq 50$
- OK for AGN and microquasar jets, OK for internal GRB shocks
- Too low for external GRB shocks, way too low for pulsar winds

How to scale results from simulations to “real life” ?

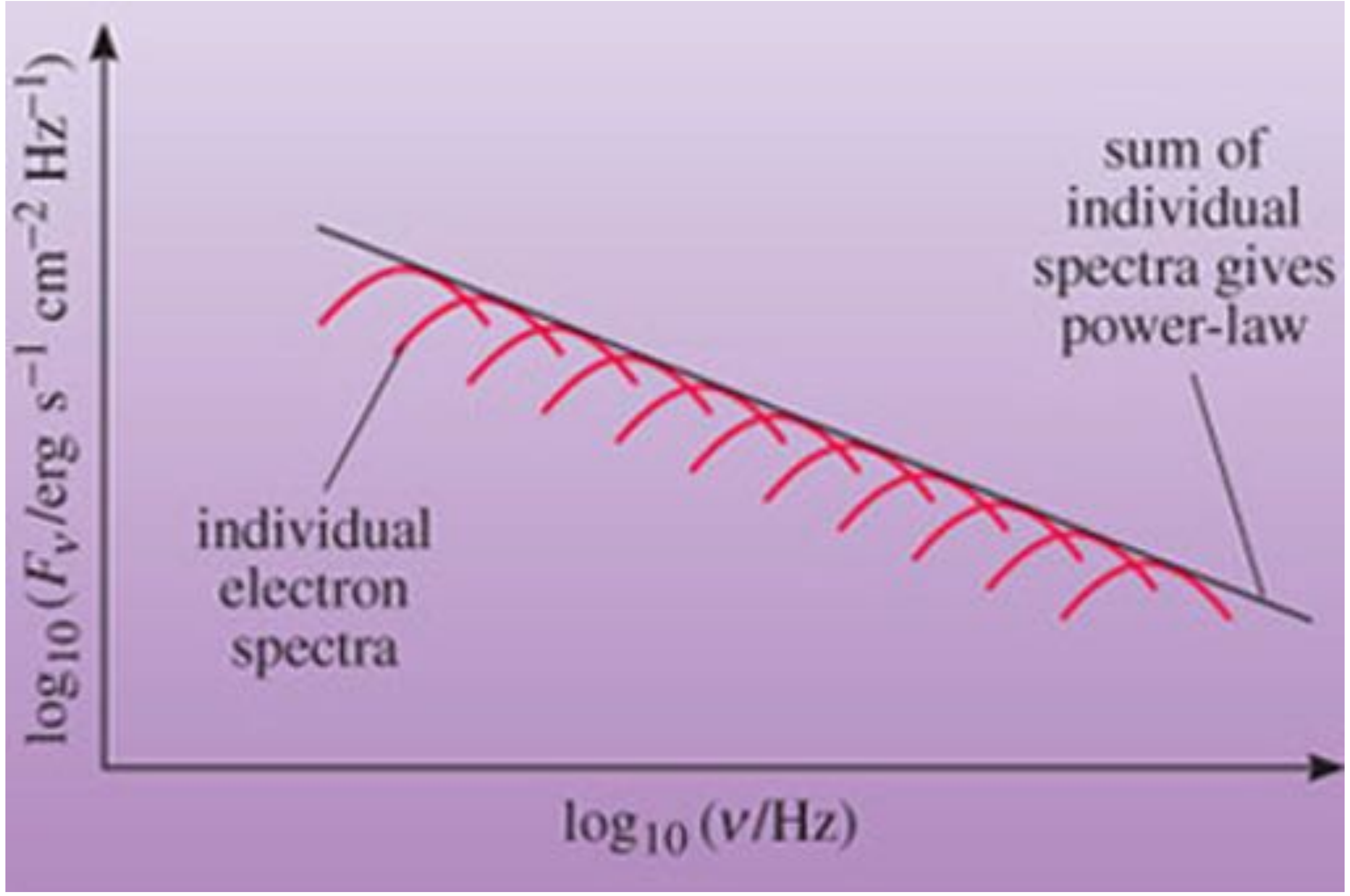
How to model emission? Post-processing ? Within hydro (PIC, particle-in-cell)

HIGH ENERGY EMISSION

Gamma-rays come from non-thermal particles accelerated somewhere (shocks, magnetic reconnection…)

Leptonic models (electrons/positrons) :

- Synchrotron emission : from electrons in B field
- Inverse Compton scattering of lower energy photons (background, companion star…)
- Absorption through pair creation

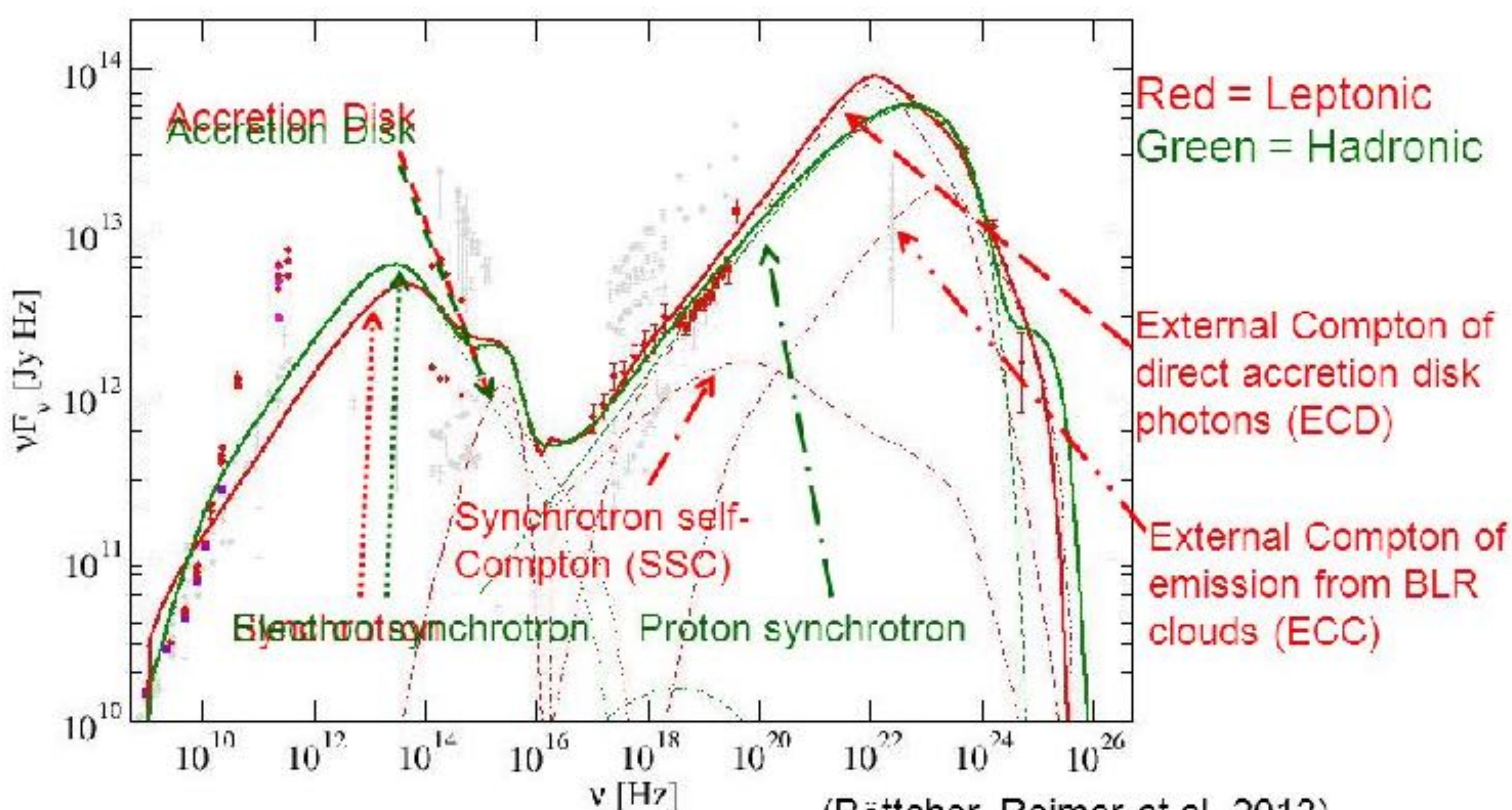


Also works for synchrotron radio

HIGH ENERGY EMISSION

Hadronic models (protons) :

- Accelerated proton -> Pion decay
- Proton Synchrotron radiation



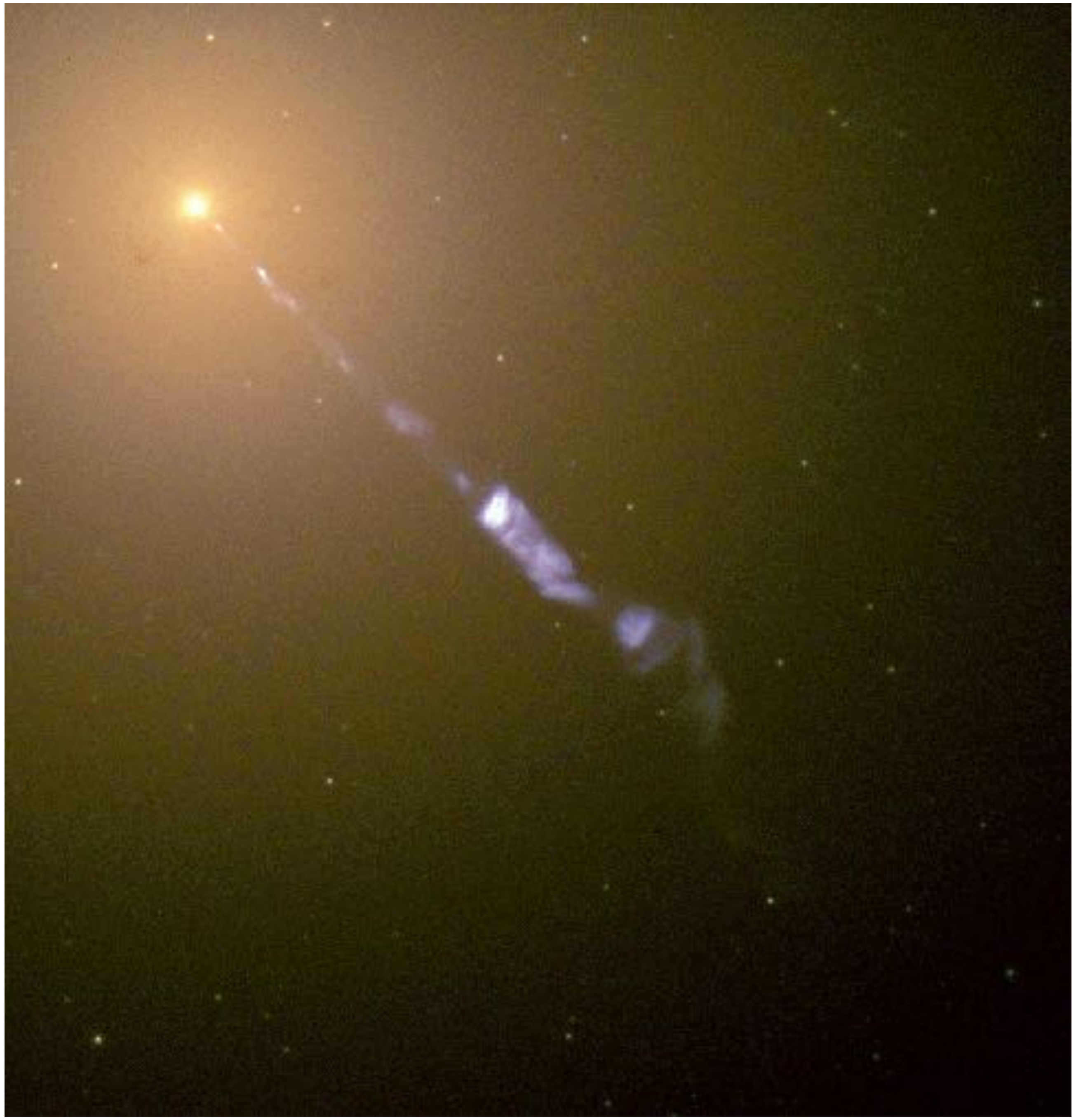
(Böttcher, Reimer et al. 2013)

Starting point : Spectrum of high energy particles

HIGH ENERGY EMISSION

Relativistic effects :

- Different timescales between flow and observer
- Increased flux if flow towards observed : Doppler boosting
- Increased Frequency
- Orbital effects
- Delayed arrival for off-axis photons



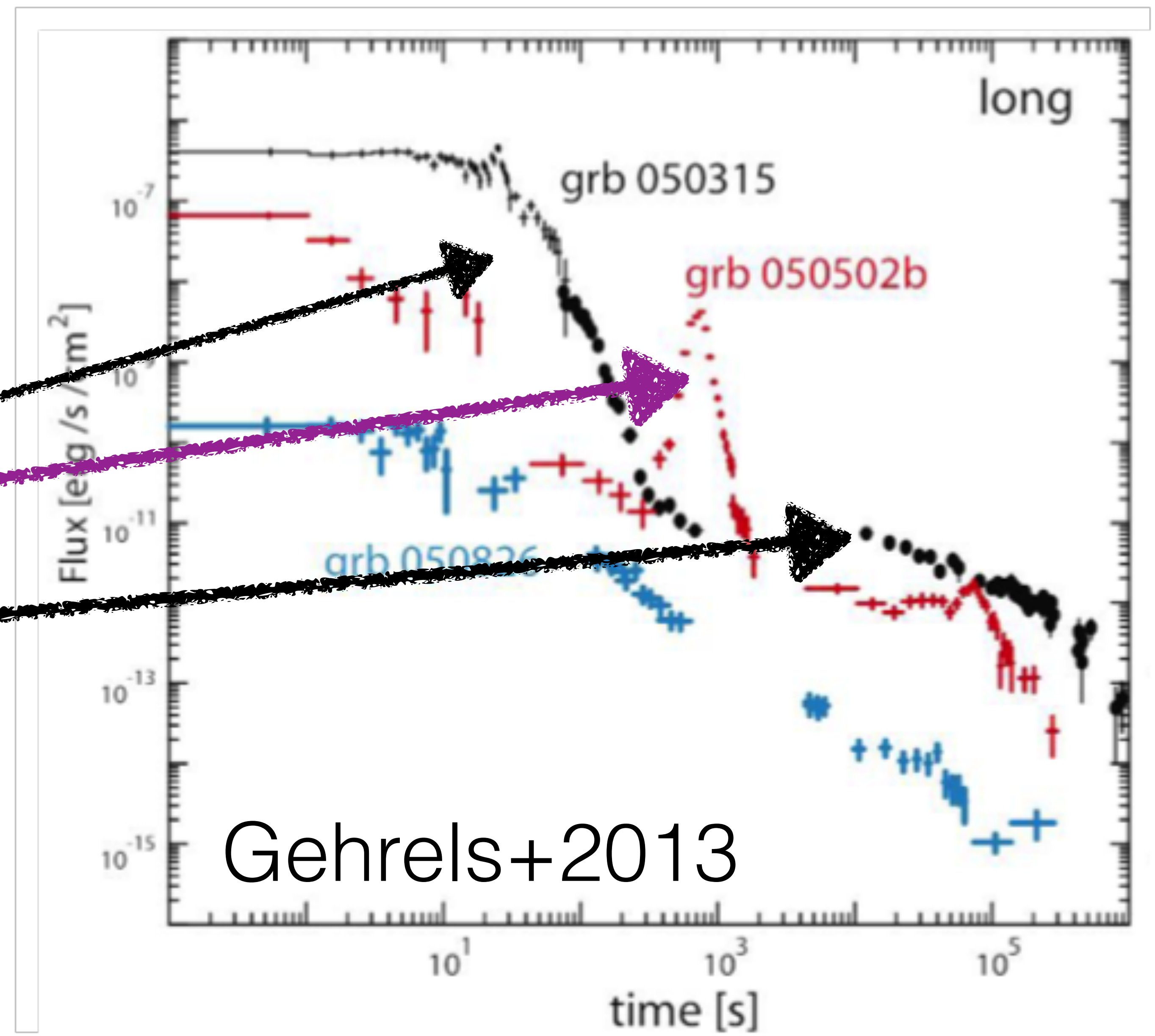
Different particle models (e.g. PLUTO)

No “standard/open source” codes for RT : mostly “homemade” routines.

EX 1: GAMMA-RAY BURST AFTERGLOWS

Unexpected diversity
and variability
in X-ray afterglow

- steep declines
- flares
- plateaus



How to explain it? Multi-wavelength picture?

RELATIVISTIC SIMULATION

Relativistic RAMSES (Lamberts+13)

- Γ_{max} =100: ultra relativistic
- GRB scales: 6 orders of magnitude in space

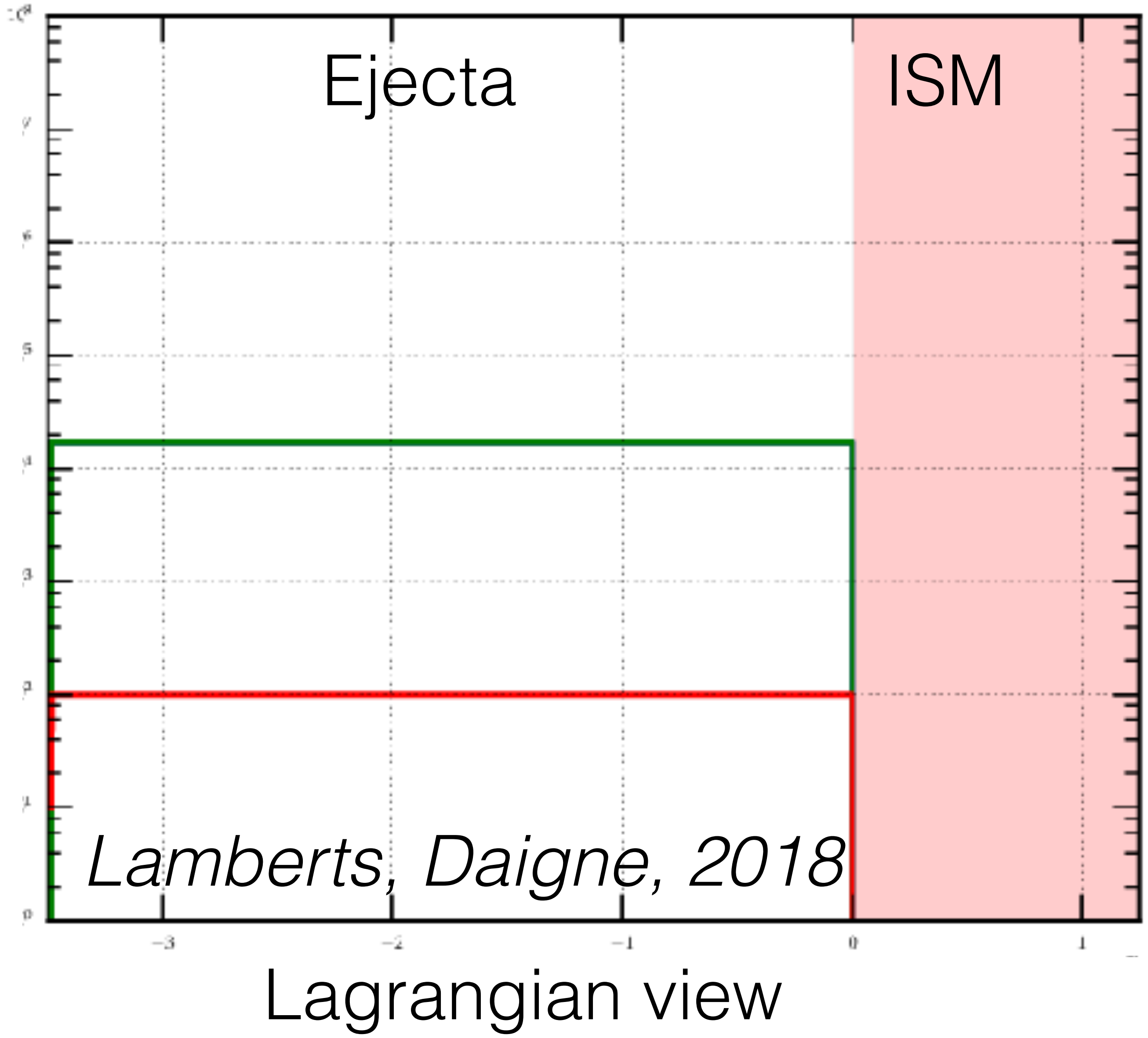
->1D spherical grid + moving boundaries

Uniform setup

pressure

density

Lorentz factor



BOLOMETRIC EMISSION

shocks -> particle acceleration
synchrotron fast cooling

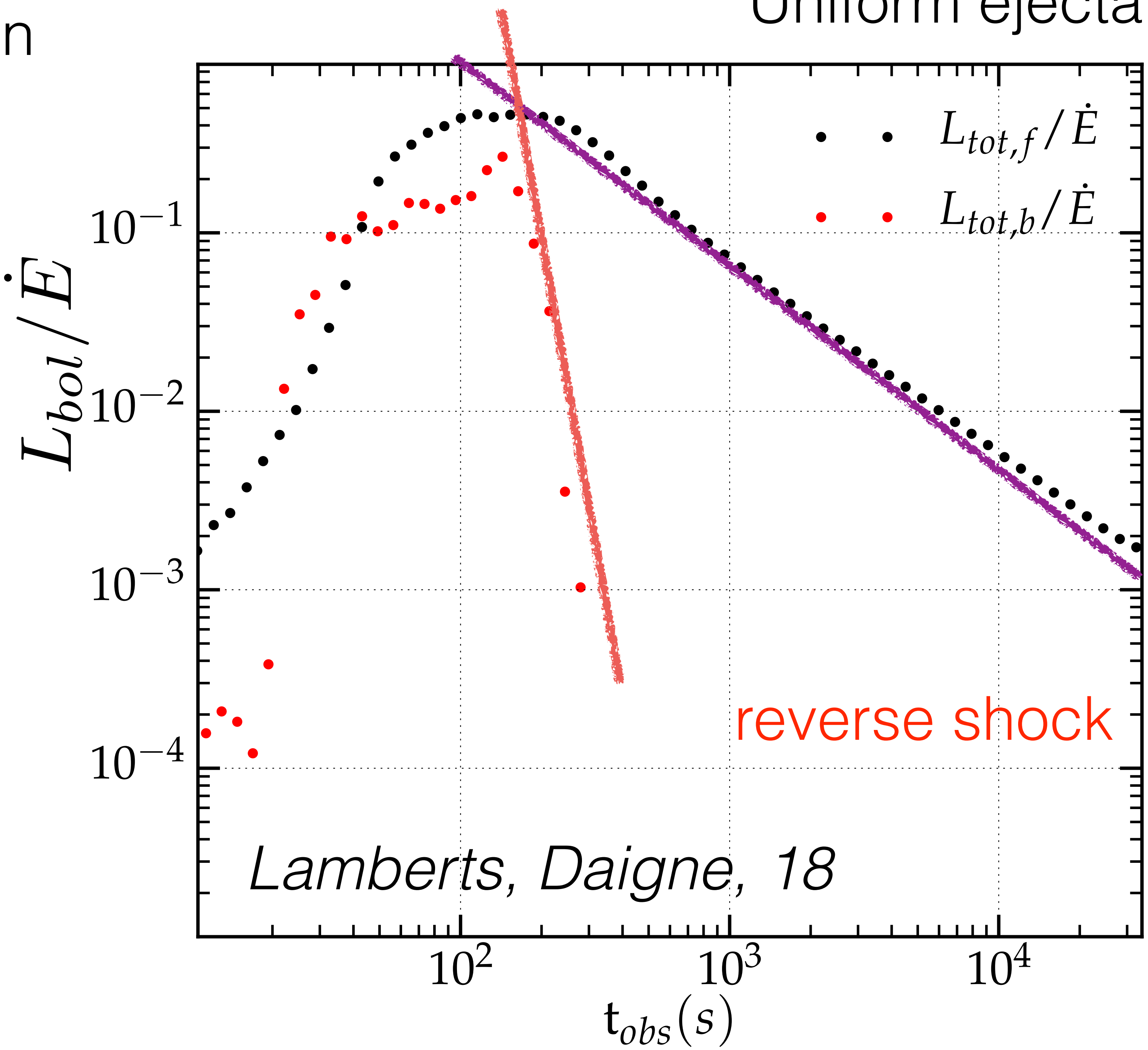
- Find shocks
- compute energy release
- Find maximal emission freq. over time

Relativistic outflow

- delays to observer's frame
- account for curvature of emitting shells

forward shock F~t^{-1}

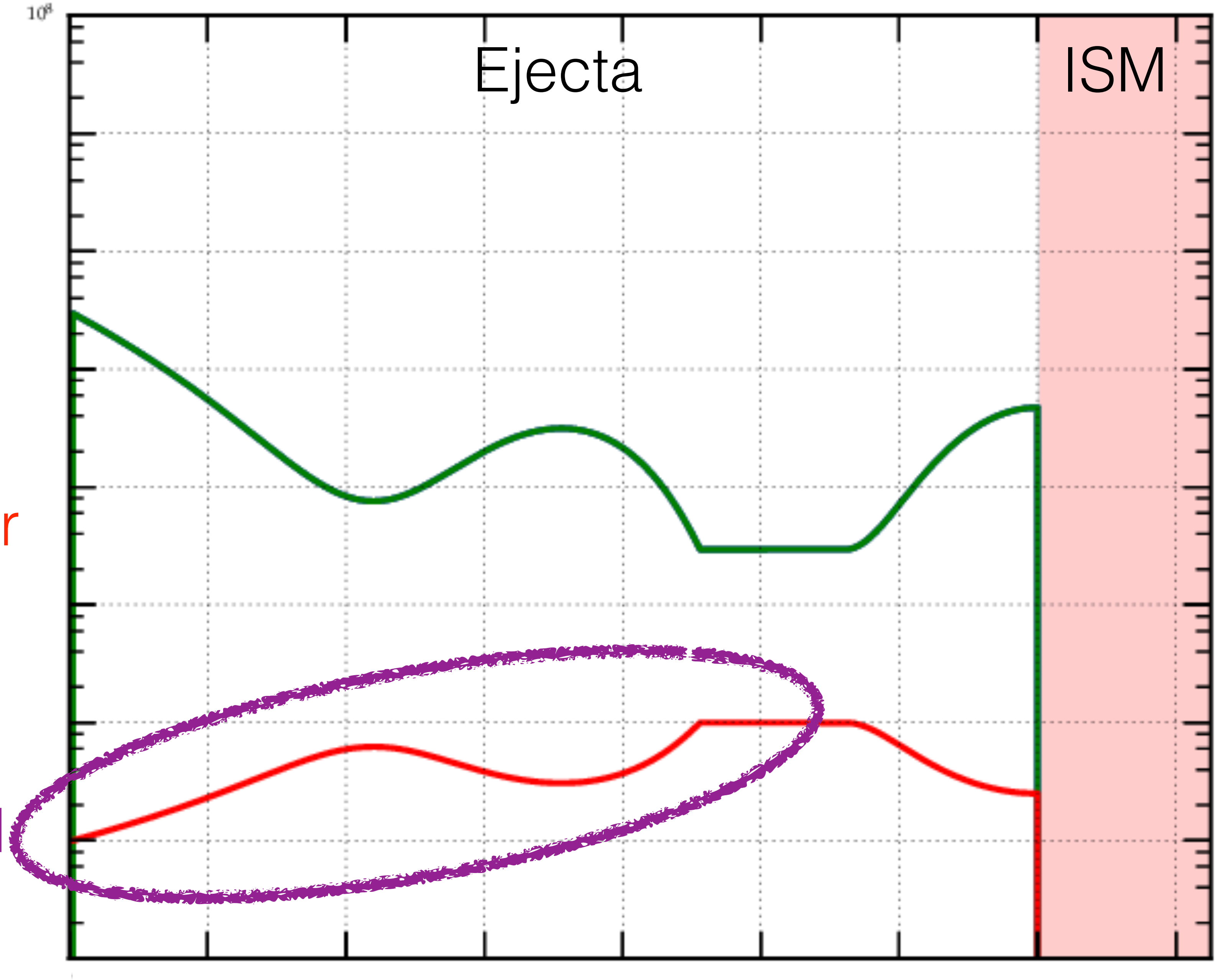
Uniform ejecta



STRATIFIED EJECTA CREATE SHOCKS

pressure
density
Lorentz factor

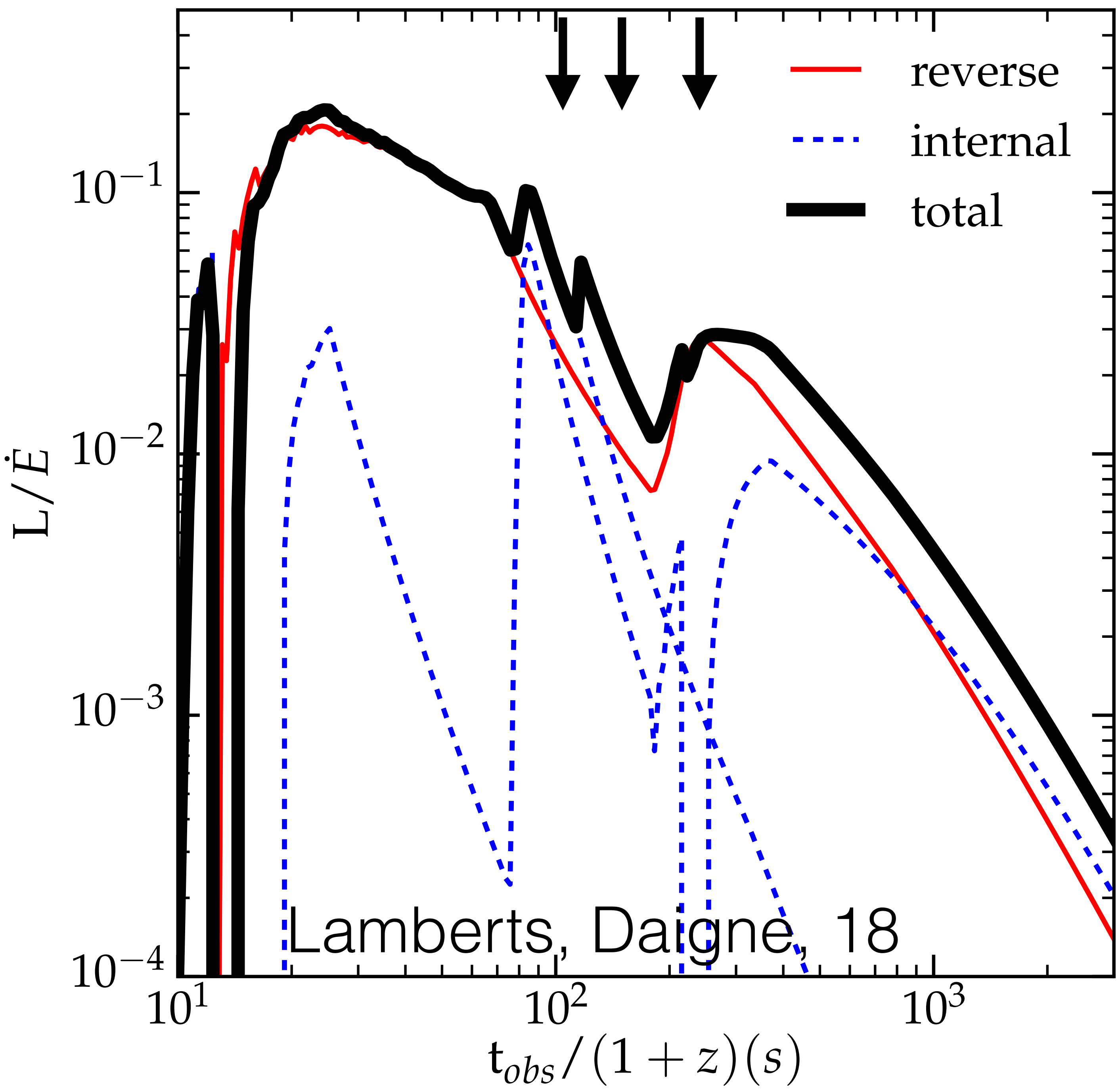
Fast material
behind slow
flares expected



Lagrangian view

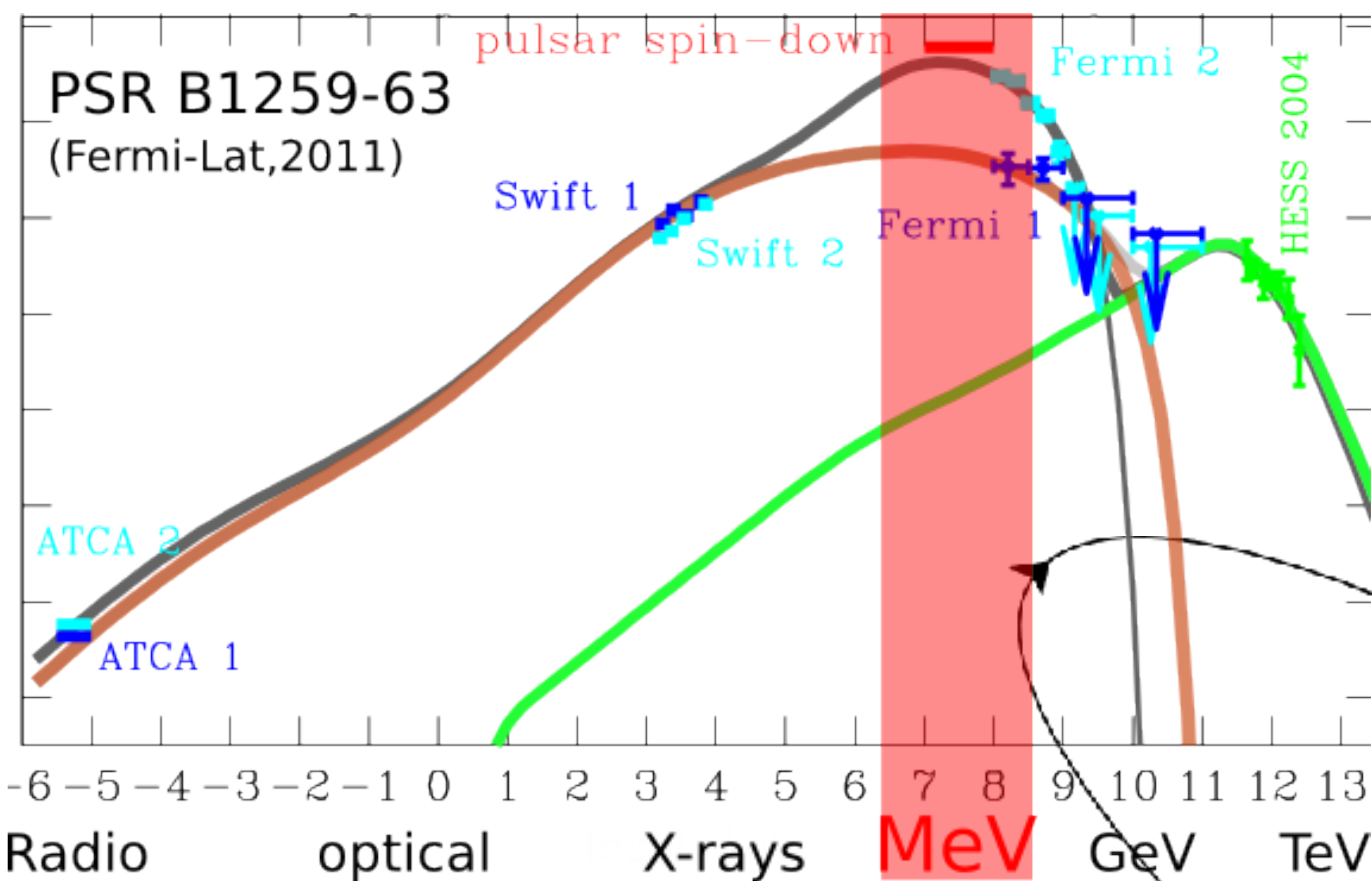
Lorentz factor profile-> complex dynamics with multiple shocks

X-RAY FLARES FROM SHOCK INTERACTIONS

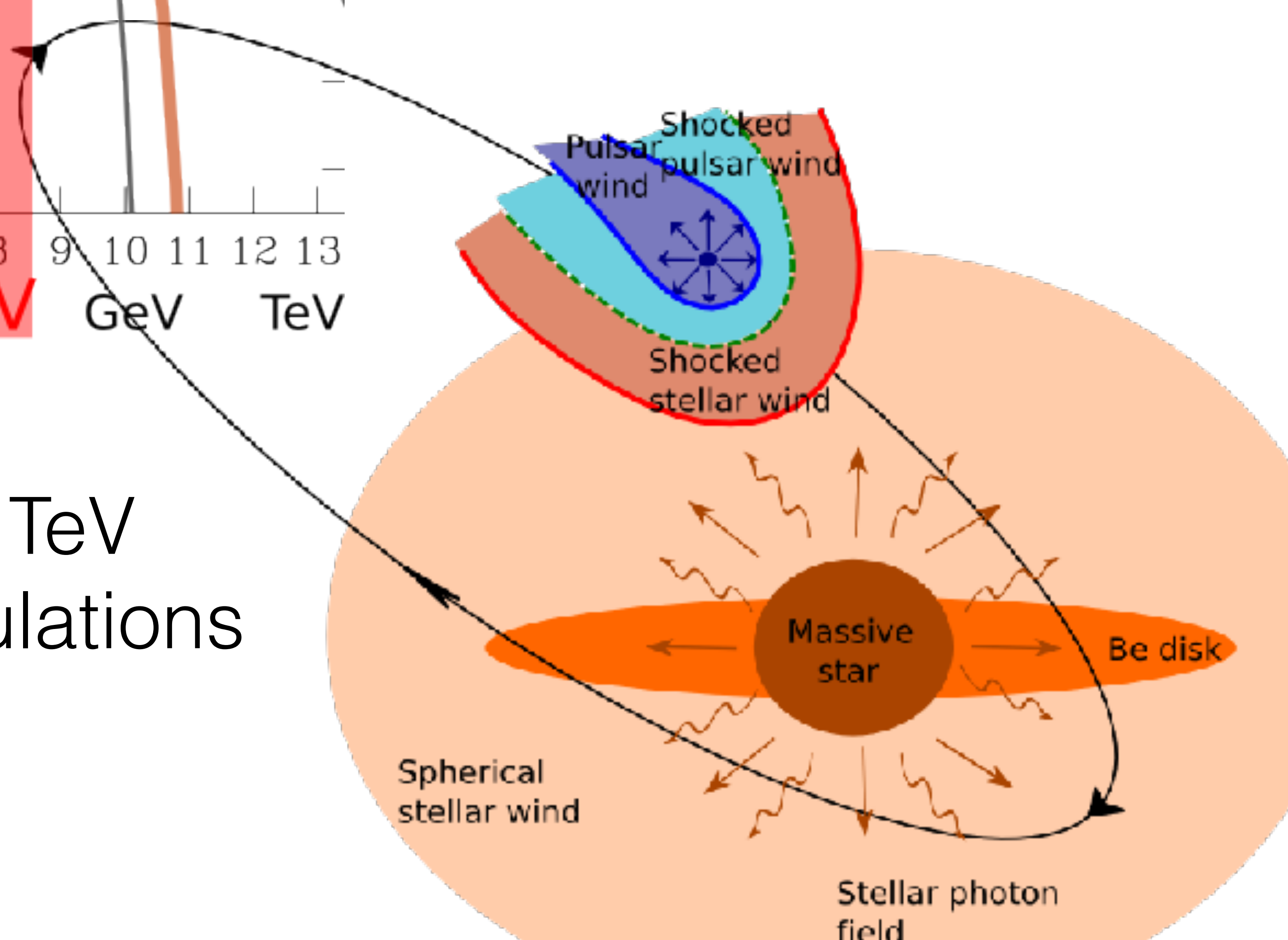


Result: Shock interactions produce X-ray flares in afterglow
- > constraints on microphysics

EX 2: GAMMA-RAY BINARIES



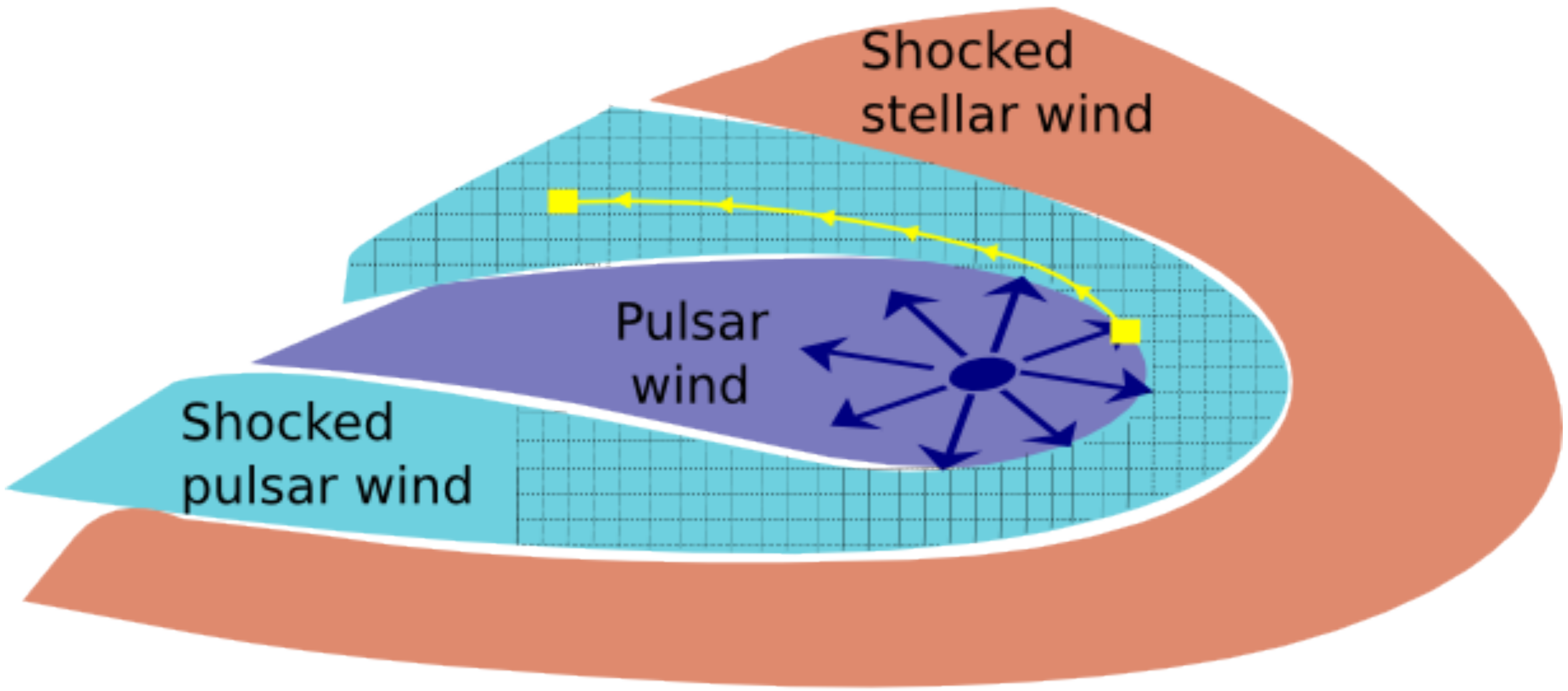
Pulsar wind + massive star wind => gamma rays at shocks



Emission from radio to TeV
unexplained orbital modulations

Dubus, 2013

MODELING HIGH ENERGY EMISSION



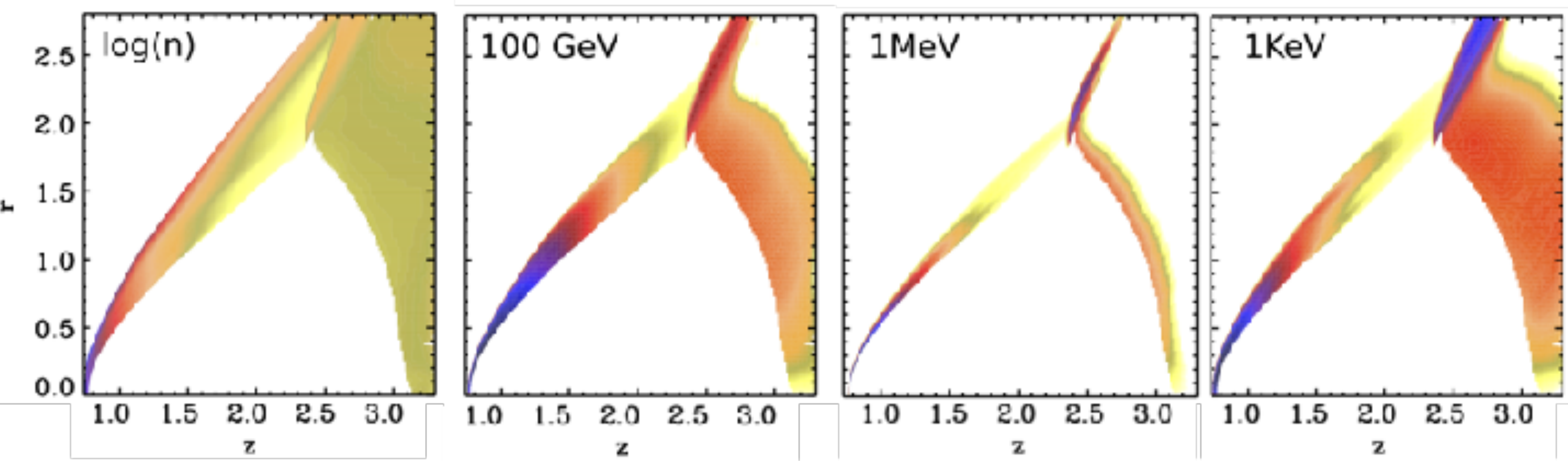
Post-processing :

Particles injected at shock, with a powerlaw -> Follow streamlines in shocked pulsar wind

Energy losses : adiabatic (from hydro), inverse-Compton emission, synchrotron emission

For each cell in pulsar wind → energy distribution of particles

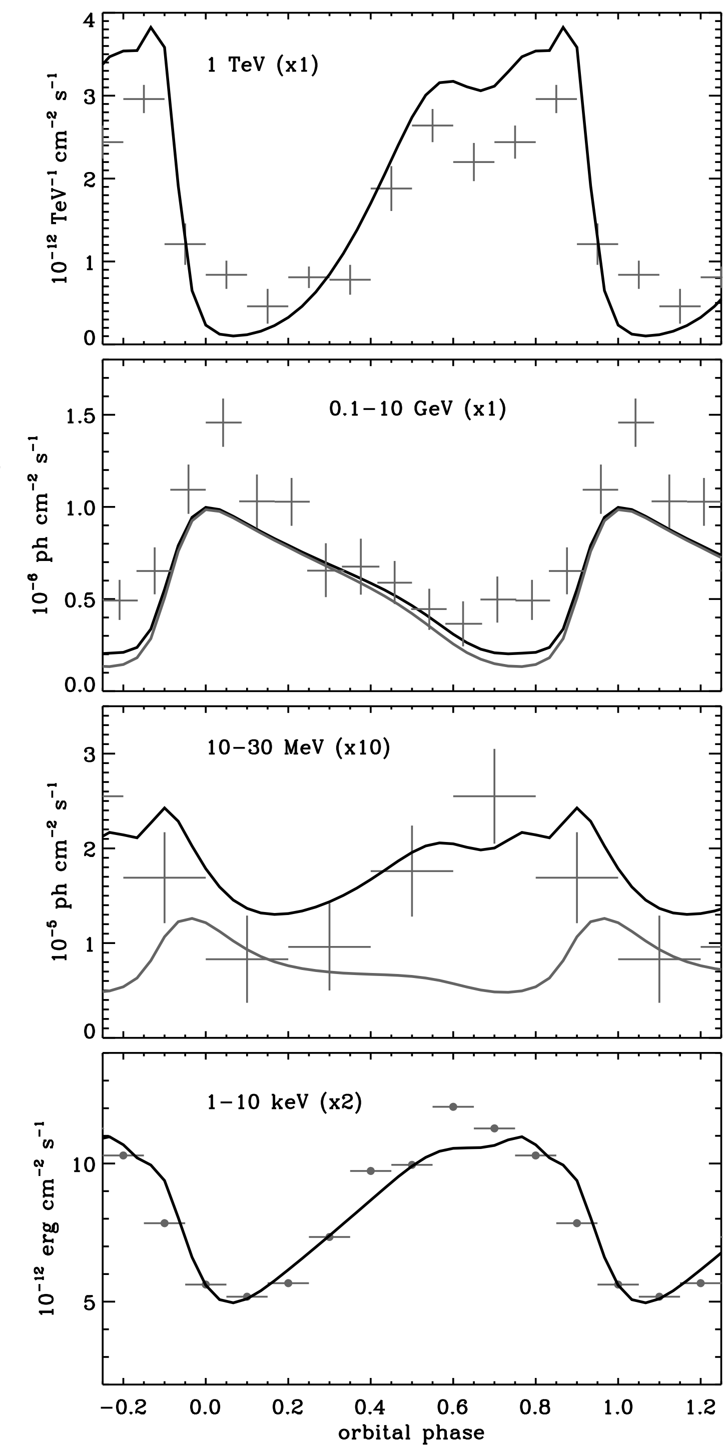
HIGH ENERGY EMISSION IN GAMMA-RAY BINARIES



In each cell : compute emission from particles

Spectra and lightcurves well reproduced
Radio would need relativistic magnetohydrodynamics

(Dubus, Lamberts, Fromang, 2015)



THINGS TO REMEMBER/THINK ABOUT

Non-thermal emission : 1) Determine particle acceleration
Determine radiation

A wealth of different systems: pulsar winds, GRB, AGN jets…

RHD sims work, but Lorentz factors are limited

Modeling emission is harder:
- acceleration : how to characterize shocks?
-transport : how to follow them ?
-cooling: how to trace spectral bins?
-need for B fields for synchrotron

GW170817 : work in progress