MODELING HIGH ENERGY SYSTEMS WITH THE RAMSES CODE

Special relativity - non-thermal emission

Astrid Lamberts - Caltech

Guillaume Dubus (IPAG), Sébastien Fromang (CEA-Saclay),
Frédéric Daigne (IAP), Romain Teyssier (ETH)

Caltech

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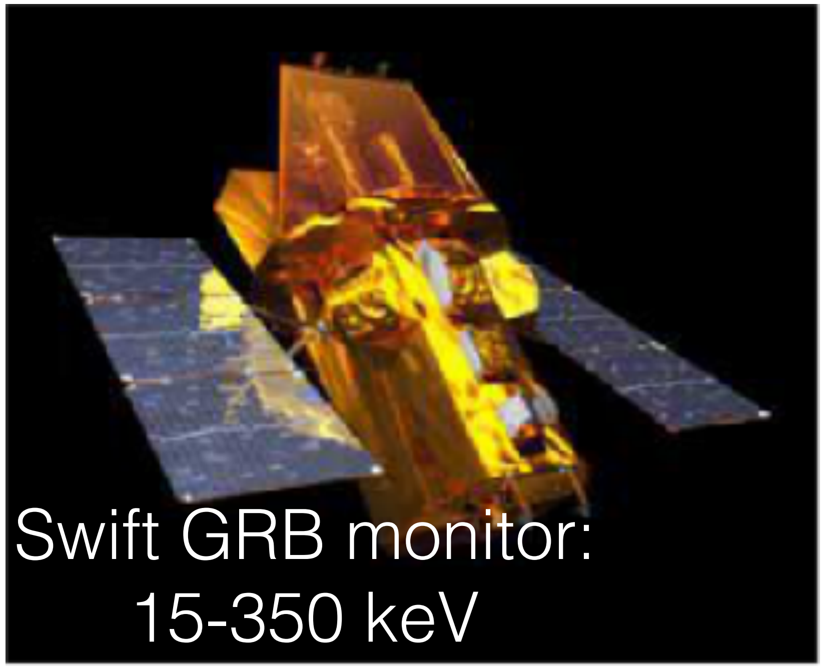
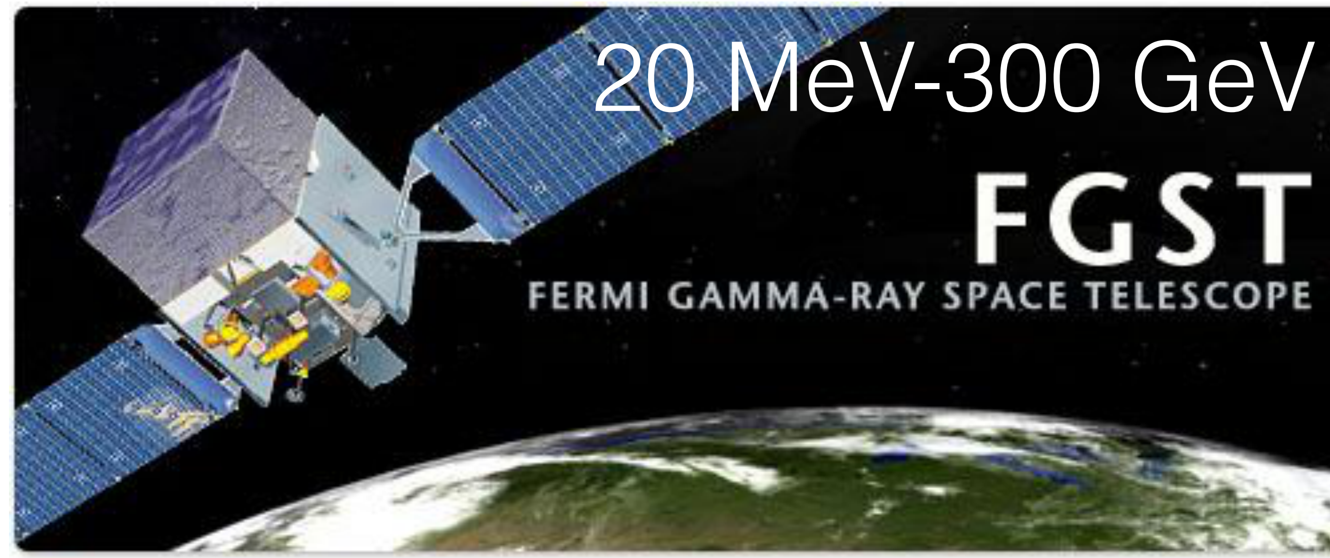
THE GOLDEN ERA OF HIGH-ENERGY ASTROPHYSICS





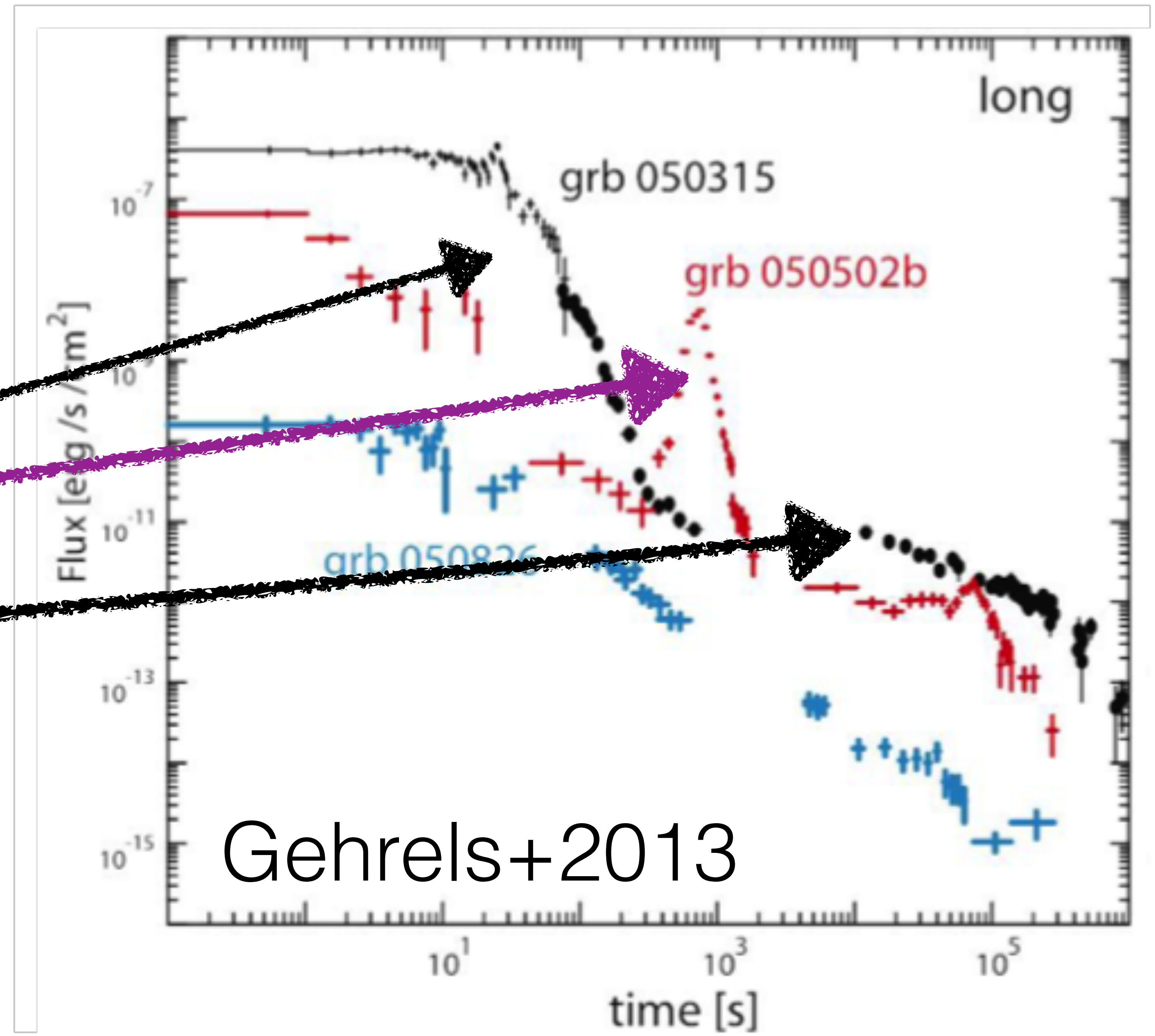
FUTURE

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

GRB AFTERGLOWS IN THE SWIFT ERA

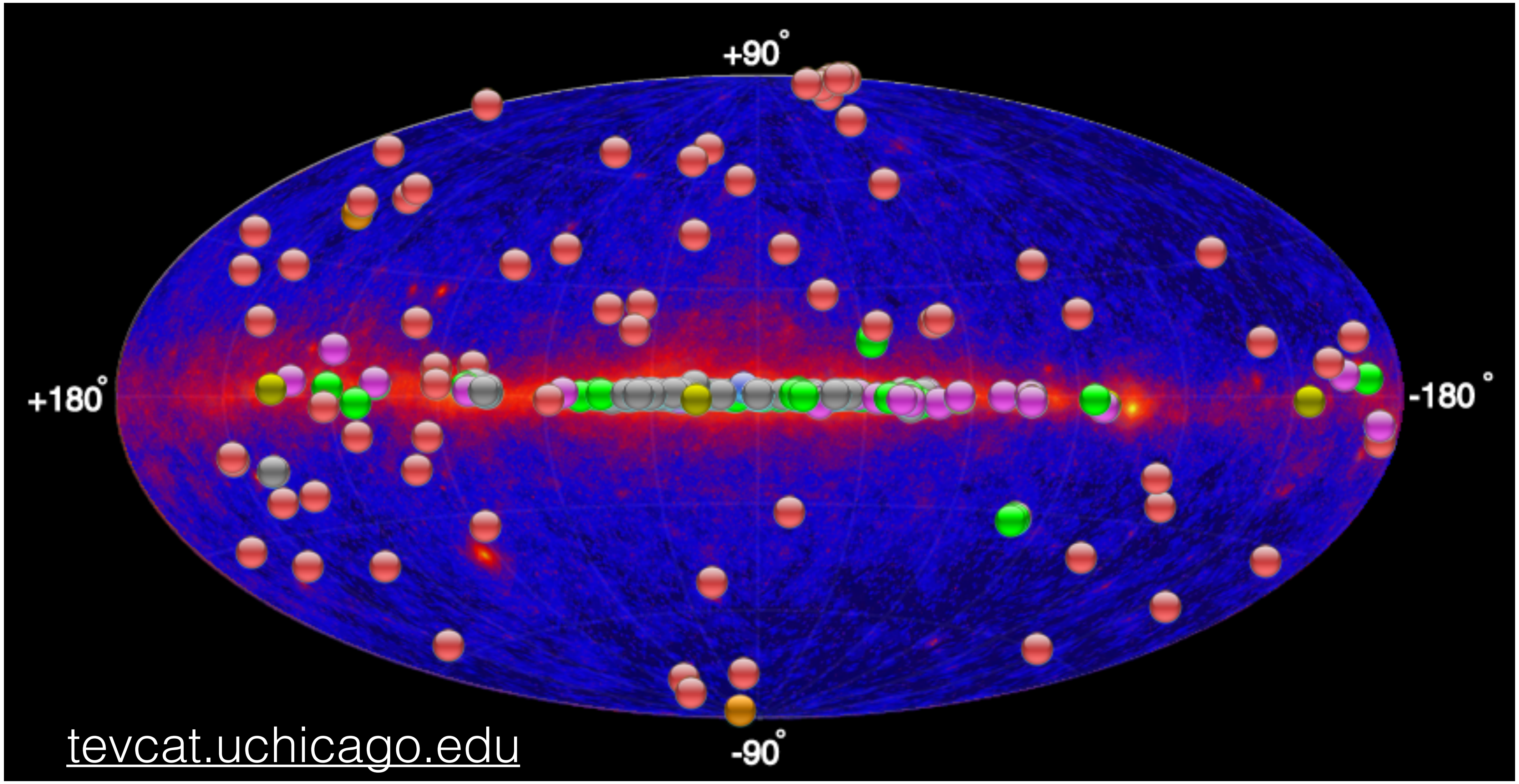
Unexpected diversity and variability in X-ray afterglow

- steep declines
- flares
- plateaus



How to explain it? Multi-wavelength picture?

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

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

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

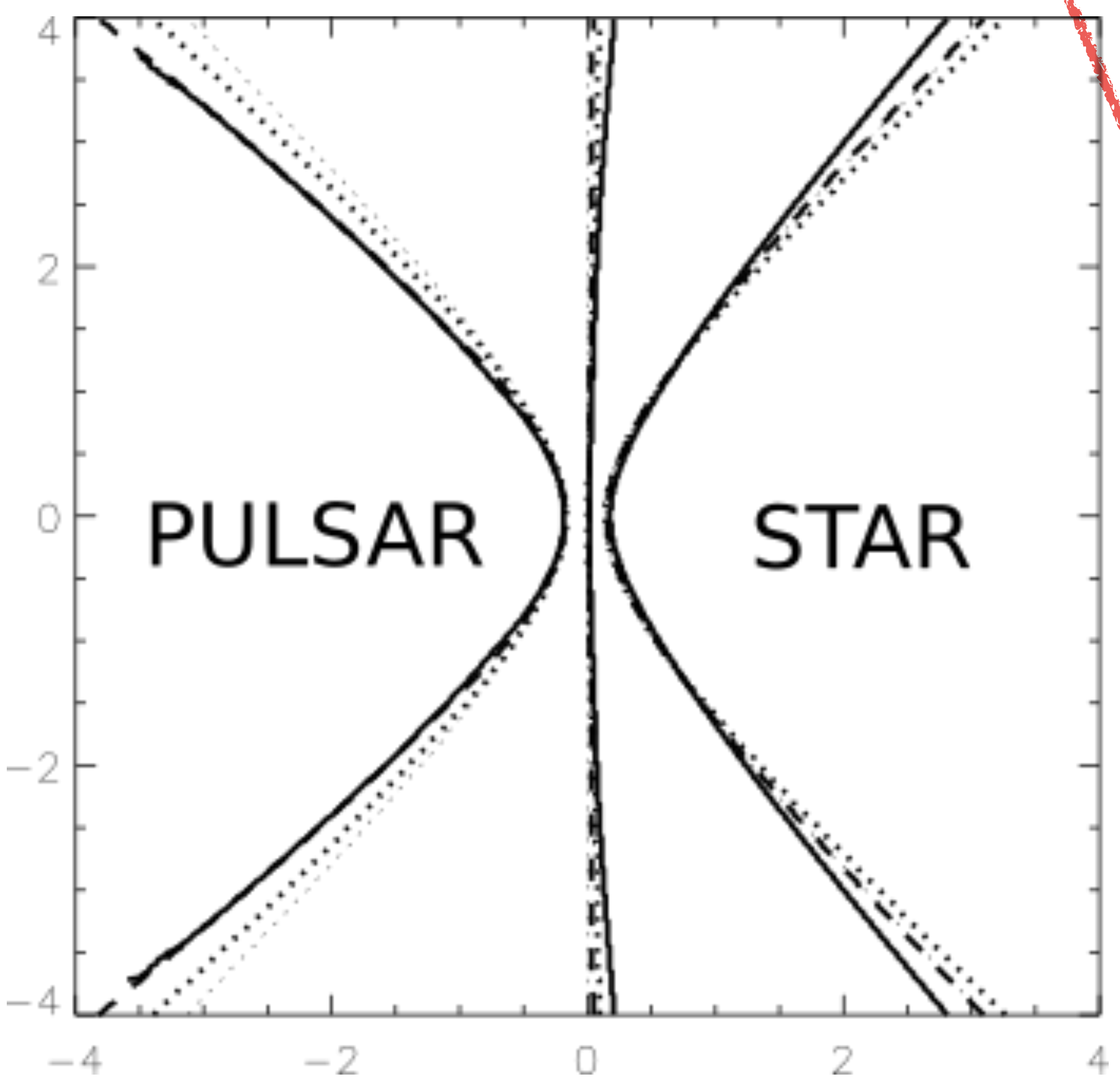
Directions are combined

RELATIVISTIC EFFECTS

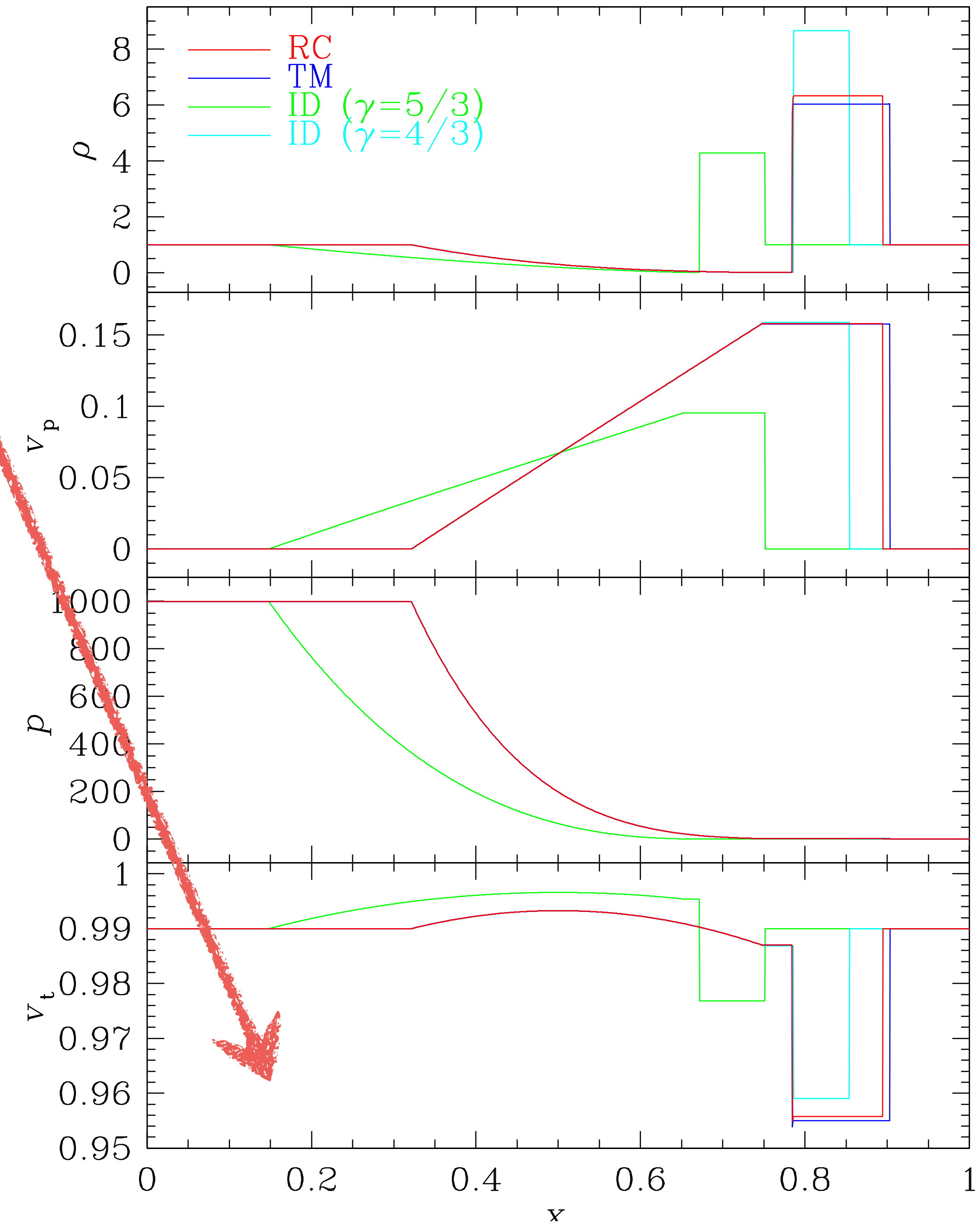
- Fluid relativistic because of bulk motion and/or thermal velocity
- Strong coupling of equations through Lorentz factor → effect of transverse velocities on motion
- $h = 1 + \varepsilon + P/\rho$, specific enthalpy, additional term due to rest mass energy
- "classical EOS" $P = (\gamma - 1)(\rho\varepsilon - \rho)$ → 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)

RELATIVISTIC SHOCKS

No analytic solution to jump conditions
Transverse velocities matter

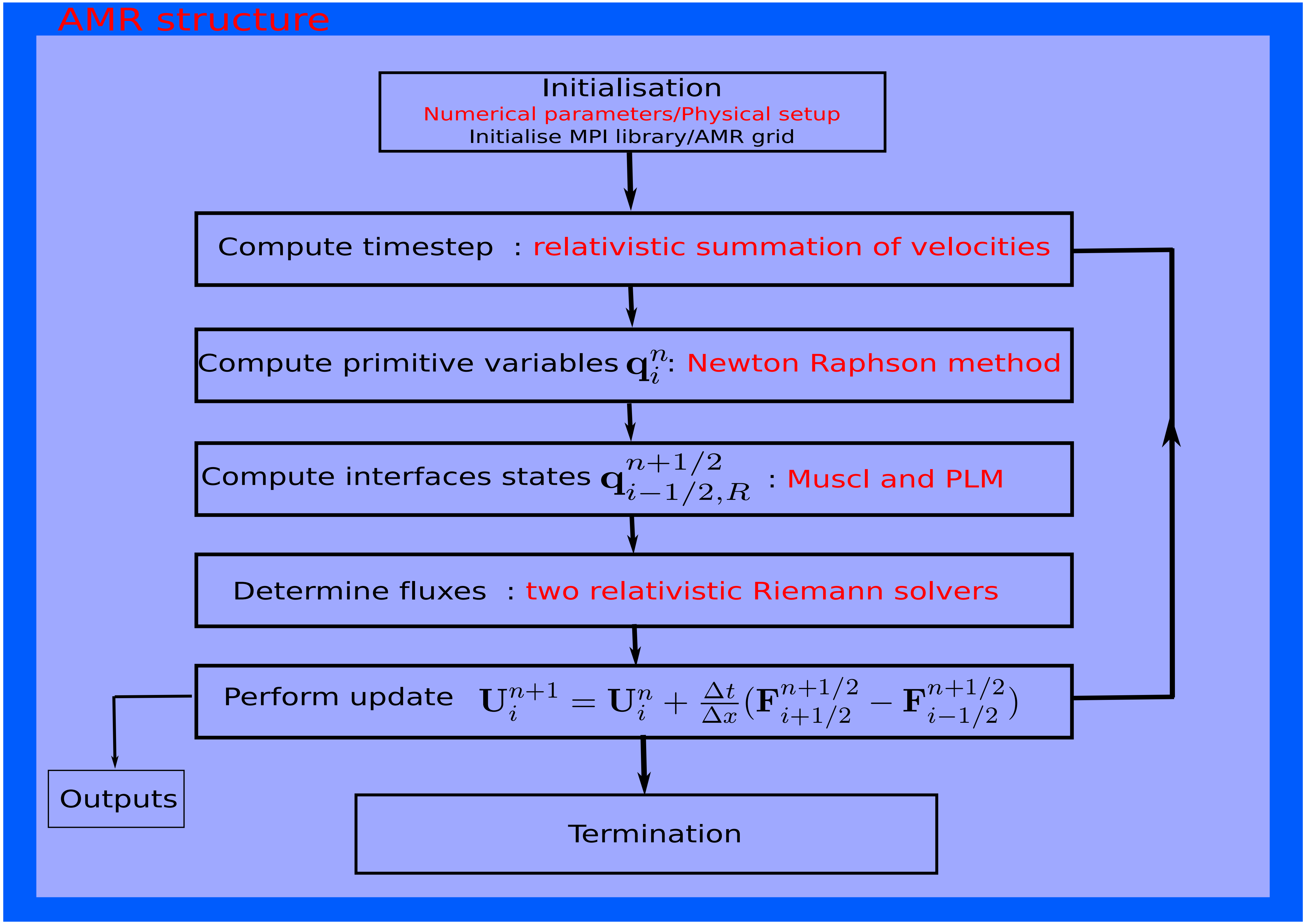


Lamberts+13

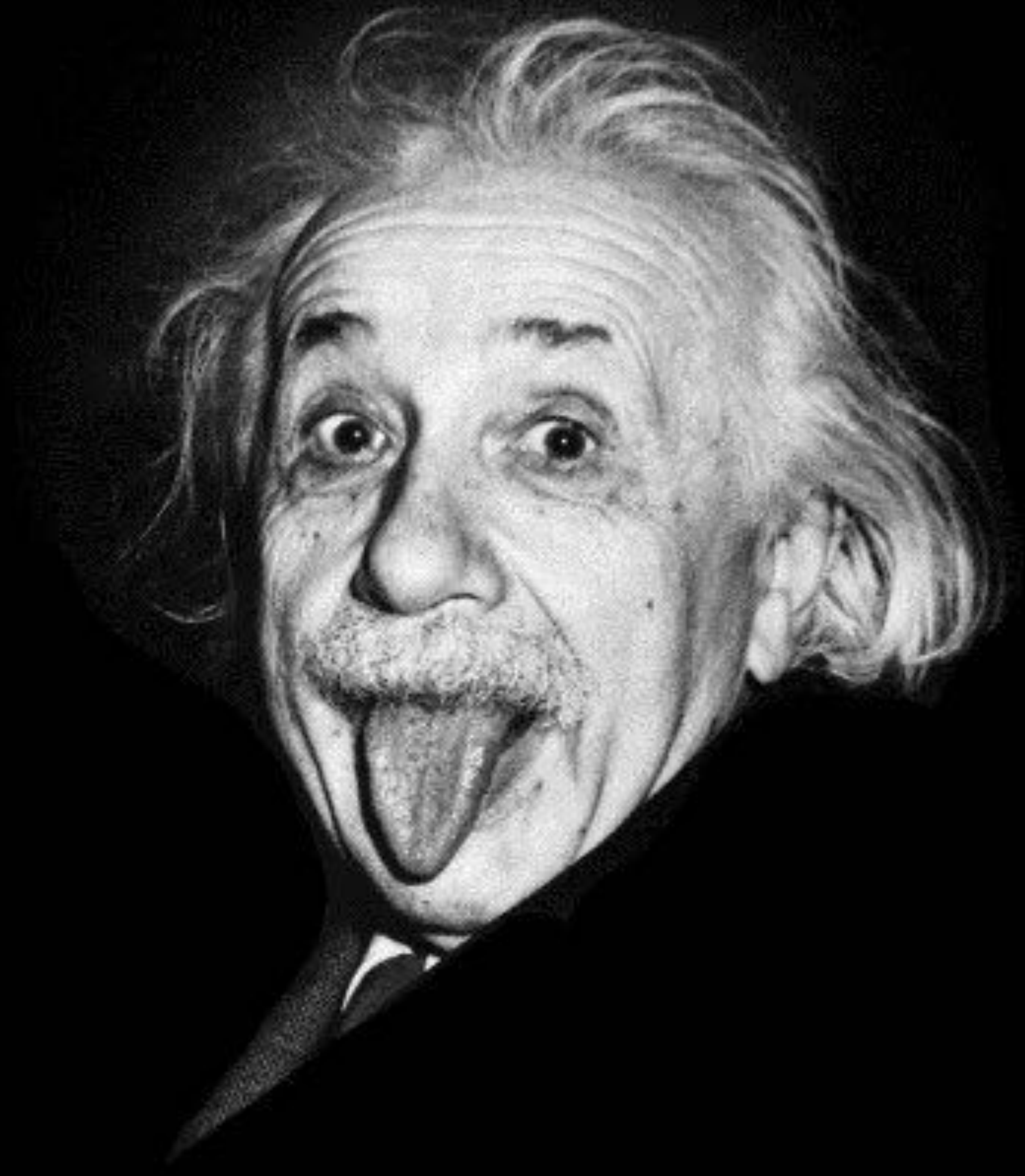


Ryu+2006

RELATIVISTIC RAMSES



(Lamberts+2013)



v < c NO CHEATING POSSIBLE !!!!!!!

FROM CONSERVATIVES TO PRIMITIVES

$$\mathbf{U} = \begin{pmatrix} D \\ M_i \\ E \end{pmatrix} = \begin{pmatrix} \Gamma\rho \\ \Gamma^2\rho h v_i \\ \Gamma^2\rho h - P \end{pmatrix} \quad \Rightarrow \quad \mathbf{q_i} = \begin{pmatrix} \rho \\ v_i \\ P \end{pmatrix}$$

Not straightforward, needs to be fast, accurate and stable

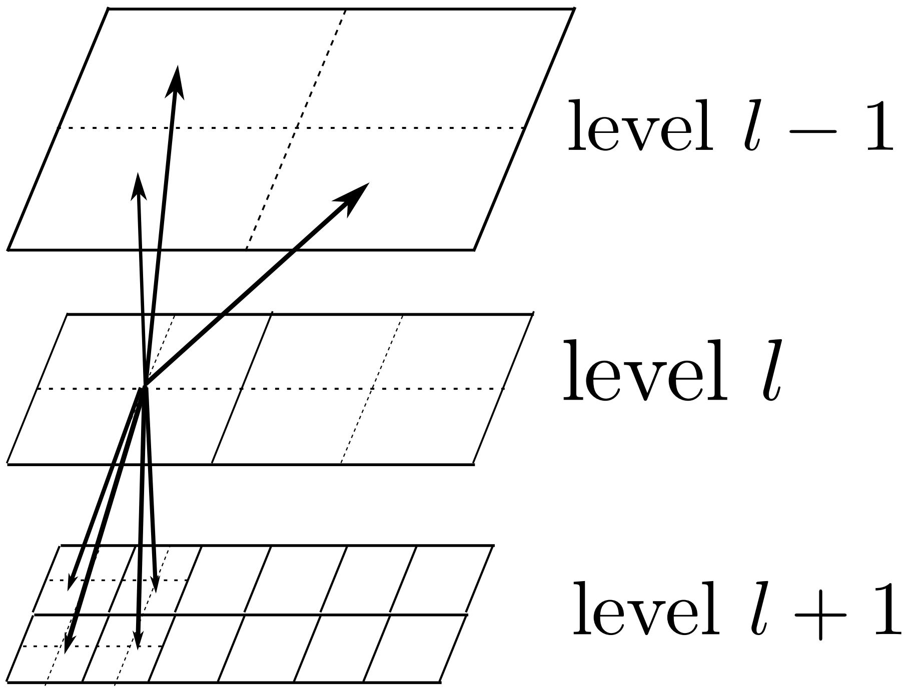
- Solve quartic equation (Ryu+2006), 2 solutions
- Rewrite energy E = W – P = ρhΓ2 – P, find W ⇒ numerical problems in UR and NR limit
- Solve same equation with W ′ = W – D and u = Γ2 v 2 (Mignone, McKinney, 2007) . Newton Raphson can be initialized with guess that guarantees P>0

(More complicated for other EOS)

ADAPTIVE MESH REFINEMENT

- Tree-based structure
  Interpolation l -1→ l : Consistent with second order reconstruction, switch to first order if non-physical state
- Restriction l +1→ l : RHD requires $E^2 > M^2 + D^2$ to have P,ρ > 0,v < 1. No guarantee for $E^2_{oct} > M^2_{oct} + D^2_{oct}$

⇒averaging performed on specific internal energy



(adapted from R. Teyssier)

Refinement on Lorentz factor

LIMITS AND POSSIBILITIES OF RHD SIMULATIONS

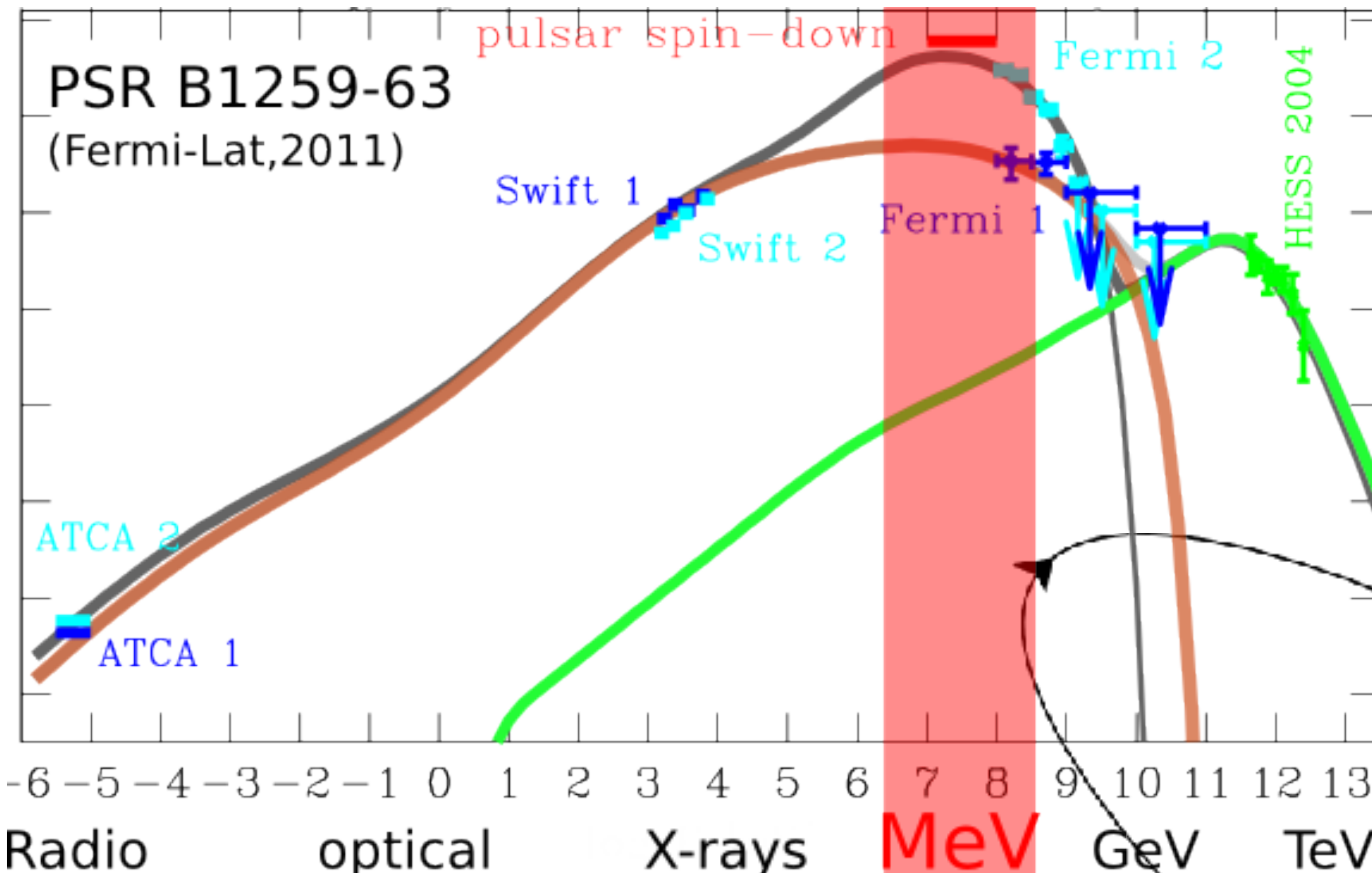
(some) Goals of RHD simulations : give Lorentz factor, determine geometry, model instabilities...

- The higher Γ, the higher the resolution needed
  State-of-the-art multiD simulations model $\Gamma \simeq 20$
- OK for AGN and microquasar jets, OK for internal GRB shocks
- Too low for external GRB shocks, way too low for pulsar winds

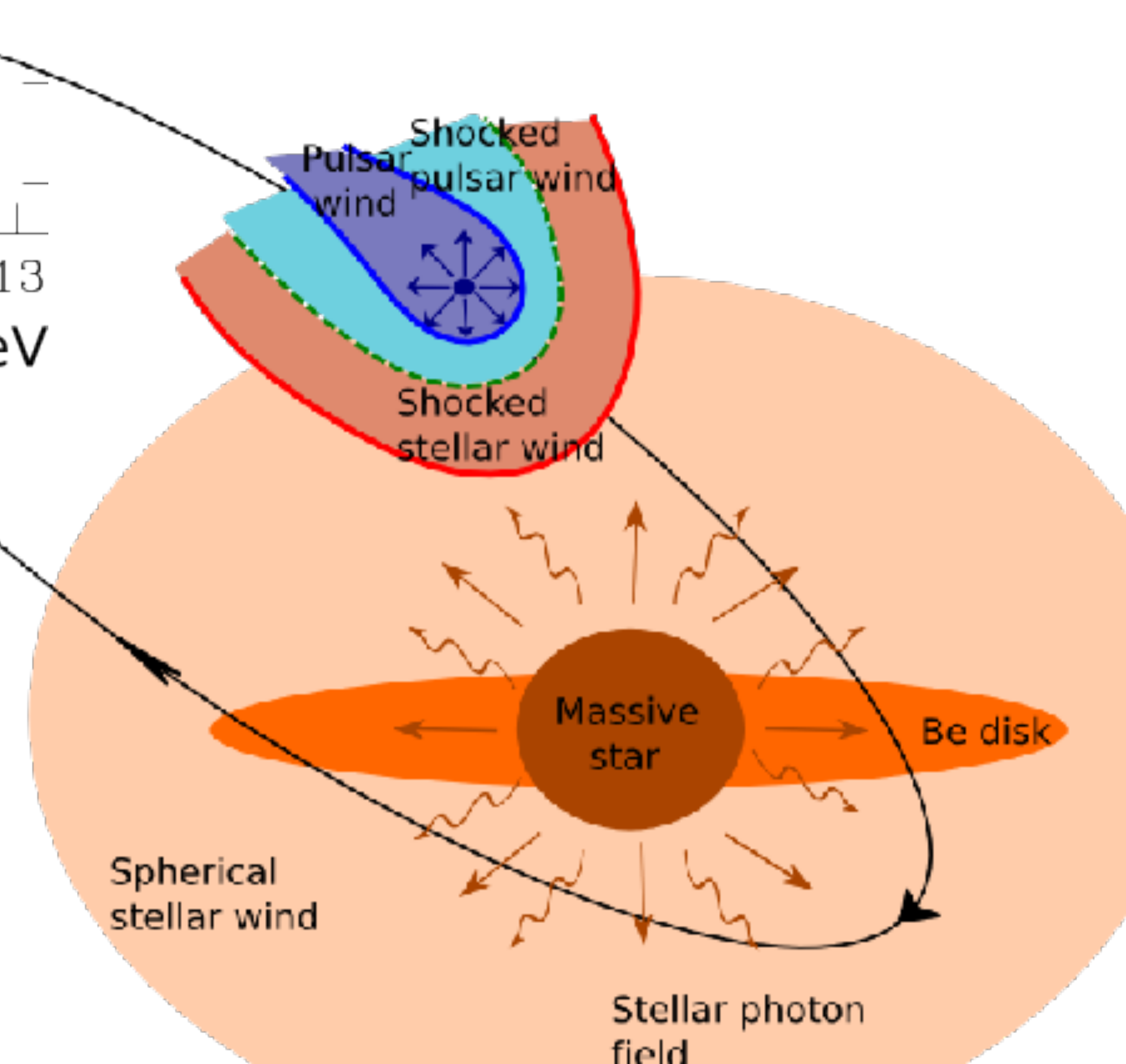
How to scale results from simulations to “real life” ?

How to model emission?

EX 1: GAMMA-RAY BINARIES



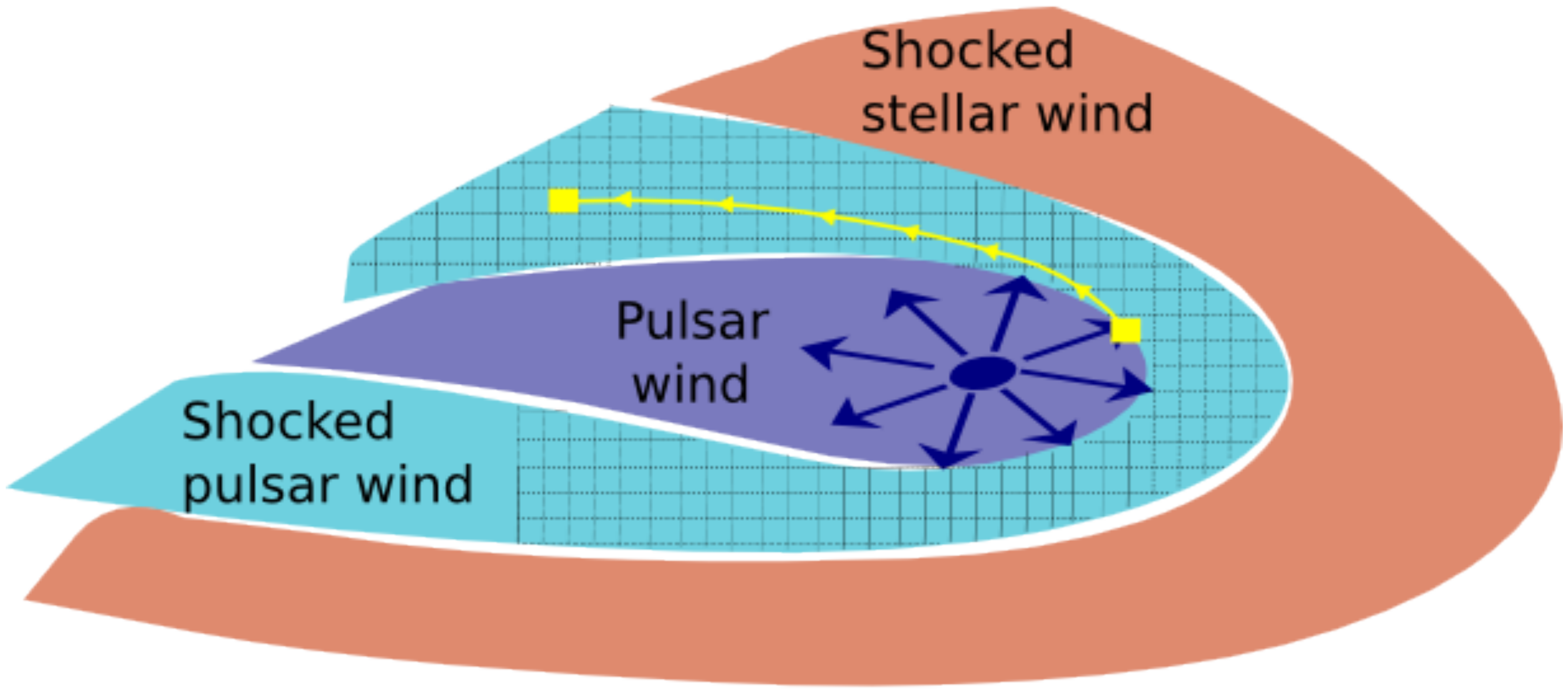
Pulsar wind + massive star wind => gamma rays at shocks



Emission from radio to TeV unexplained orbital modulations

Dubus, 2013

MODELING HIGH ENERGY EMISSION



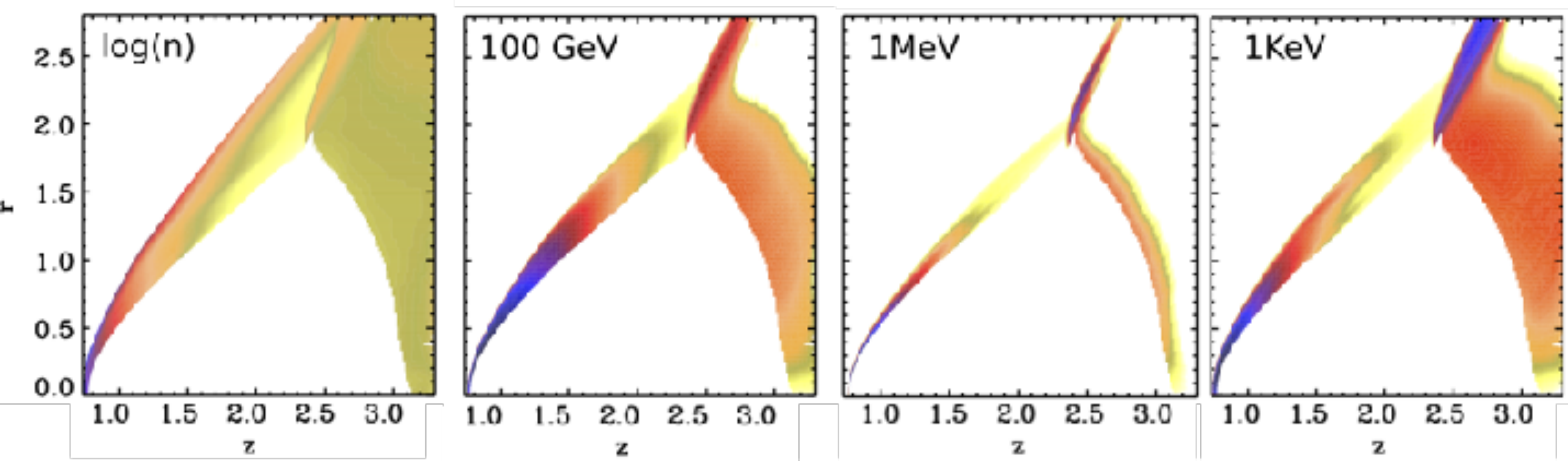
Post-processing :

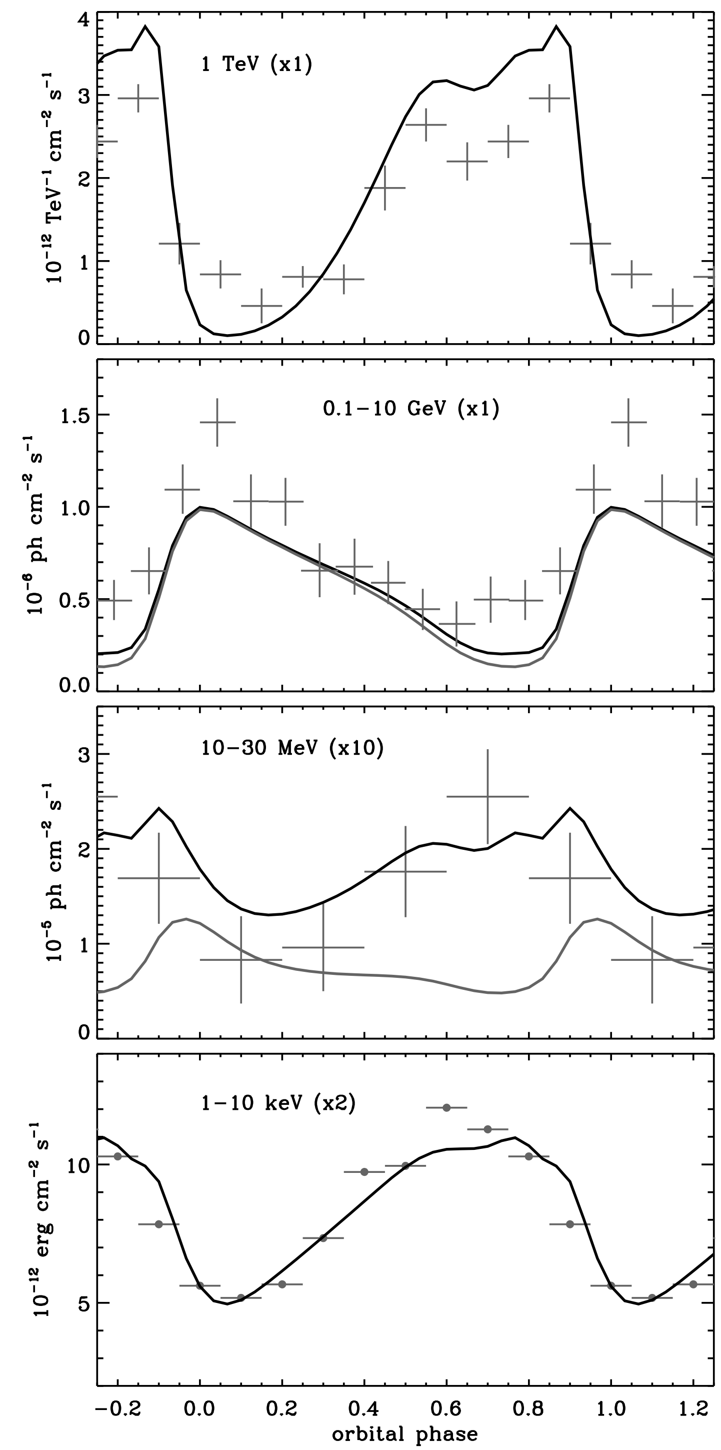
Particles injected at shock, with a powerlaw -> Follow streamlines in shocked pulsar wind

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

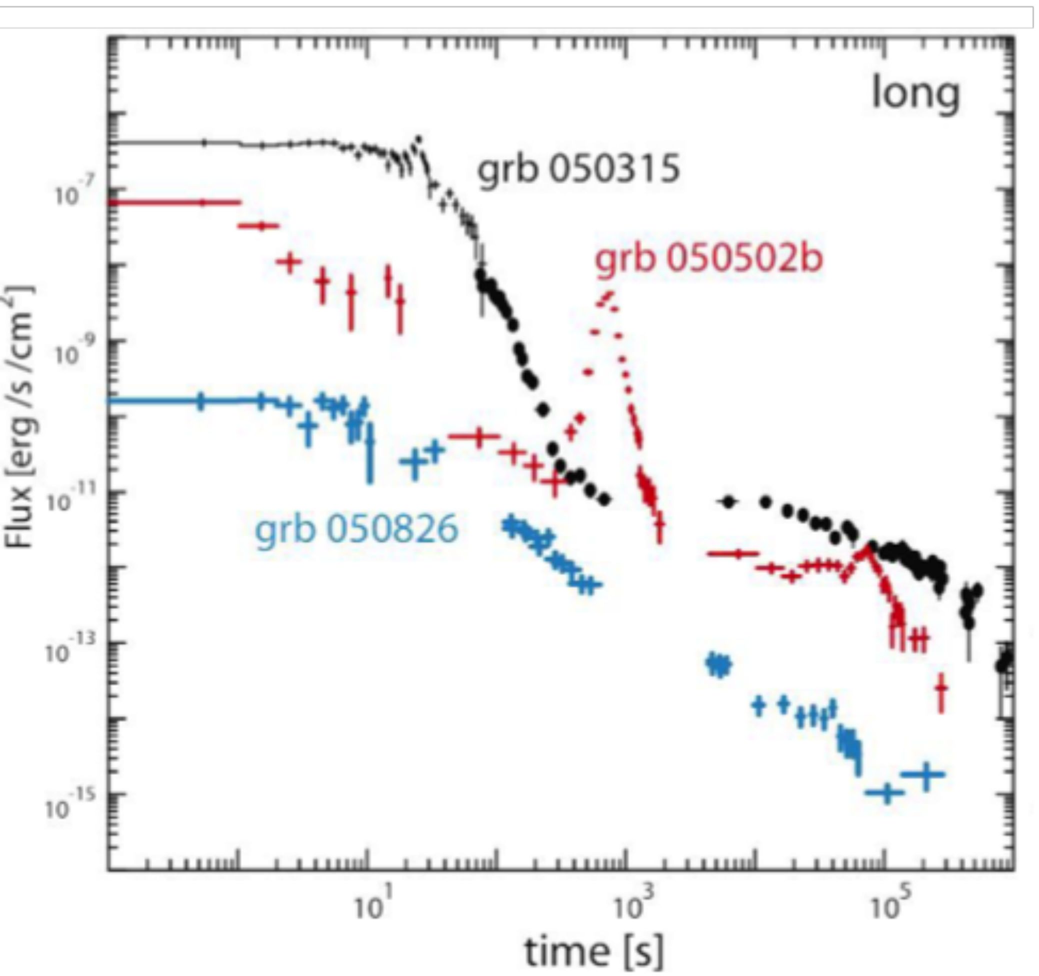


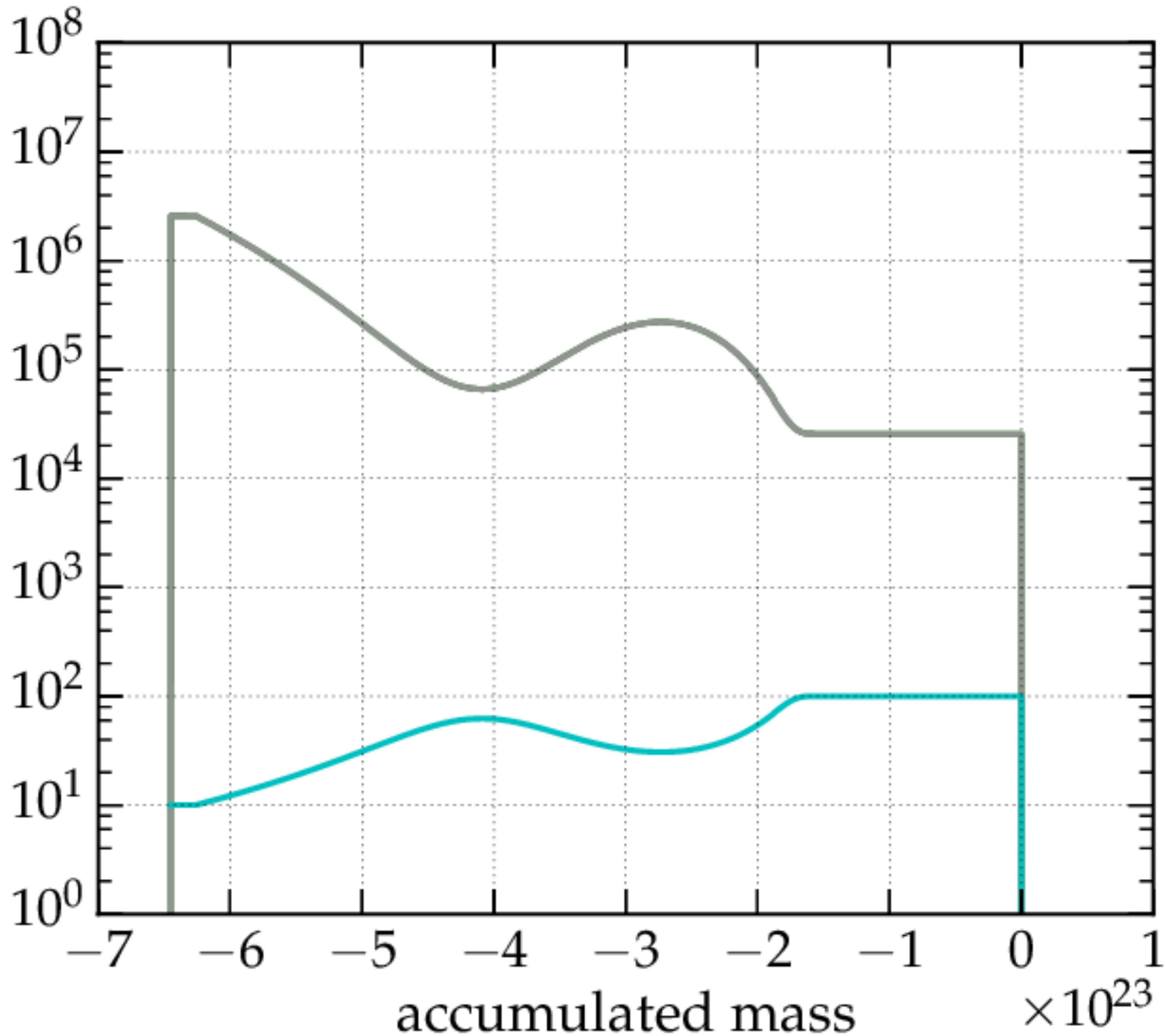


Spectra and lightcurves well reproduced
Radio would need RMHD

(Dubus, Lamberts, Fromang, 2015)

EX 2: GRB DYNAMICS





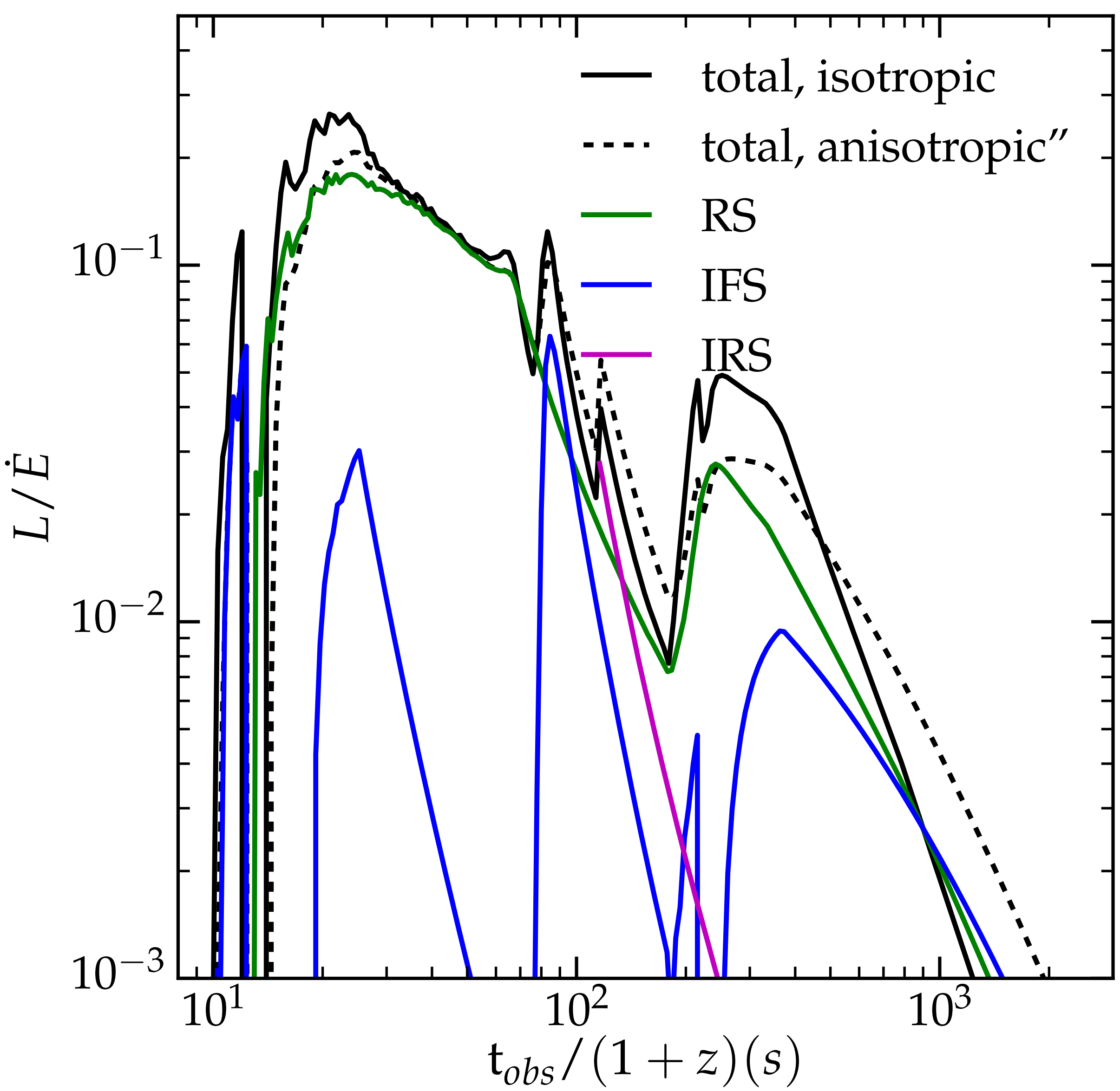
spherical 1D model,
sliding grid

(Lamberts, Daigne, 2017)

REPRODUCING GRB LIGHTCURVES

Post-processing

- Particles accelerate at shocks-> shock detection/ characterization needed
- fast cooling electrons synchrotron
- Anisotropy in the comoving frame
- Account for delayed photons off-axis



(Lamberts, Daigne, 2017, submitted)

Long-lived reverse shock + internal shocks

=

Flares

THINGS TO REMEMBER/THINK ABOUT

A wealth of different systems: pulsar winds, GRB, AGN jets…
Lots of observations coming!

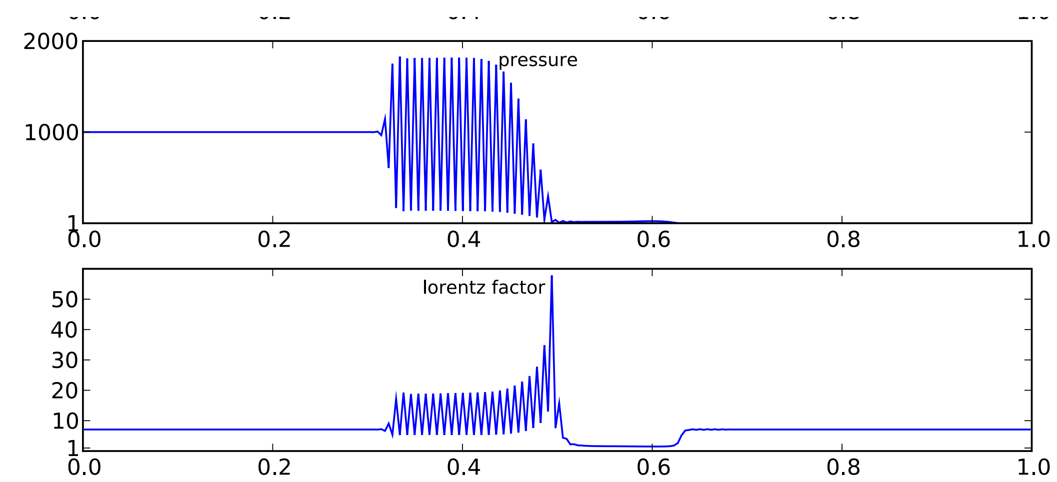
RHD sims work, but Lorentz factors are limited -> think about rescaling

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

RECONSTRUCTING INTERFACE STATES

$$\mathbf{q}_{i-1/2,R}^{n+1/2} = \mathbf{q}_i^n + \Delta\mathbf{q}_i^n + \frac{\partial q_i}{\partial t}\frac{\Delta t}{2}$$

Brute force fails



- MUSCL : $d\mathbf{q} = -\frac{\partial \mathbf{F}(\mathbf{q})}{\partial \mathbf{U}(\mathbf{q})}\frac{\partial \mathbf{q}}{\partial x}dt$

Need to reconstruct Lorentz factor separately, rescale v, can be inaccurate

- PLMDE $\frac{\partial \mathbf{q}}{\partial t} + \sum_j^N \mathbf{L}^\alpha \lambda^\alpha \mathbf{R}^\alpha \frac{\partial \mathbf{q}}{\partial x} = 0.$

Slopes projected on characteristics. Works well.

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

Pulsar wind nebula
Bucciantini+05