Radiative Hydrodynamics
&
Applications to Stellar Physics

CLAIRE MICHAUT

LUTH
OBSERVATOIRE DE PARIS

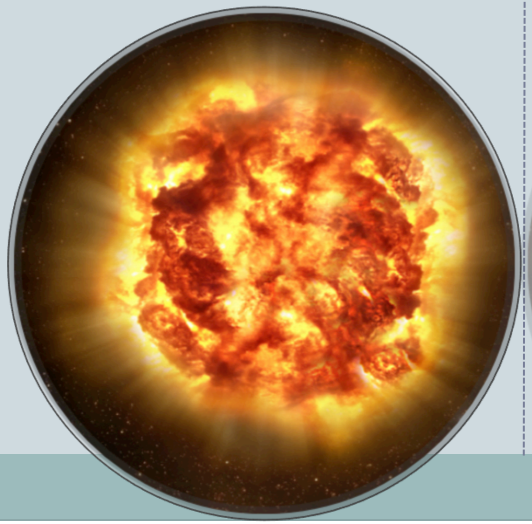
10/02/2018 SEMINAR

What is the subject?

- Radiative hydrodynamic modeling
- Application to stellar physics, including stellar disc formation
- Verification and Validation procedure (V&V)
- High energy density laboratory astrophysics
- Experimental analysis
  - give deep physics knowledge
  - are benchmark for numerical simulations
- New community
- HEDLA = theory, numerical simulations using high-power computers and experiments using high-power facilities

WHY?

- Radiation is a diagnostic
- from the Universe, all informations arrive transported by photons
- radiative transfer calculations are needed to understand sources



Artist illustration of a supernova © ESO

- Radiation is a dynamical actor
- in accretion/ejection systems
- fast matter flows => strong shocks
- emission, propagation, absorption of photons
- radiation effects modify the hydrodynamic behavior
- radiative transfer has to be coupled with hydrodynamics

How?

- Model requires
  - robust hydrodynamic schemes
  - sophisticated radiative transfer
  - at the same level of description
  - as moment method
  - HADES code
  - *Hydrodynamique Adaptée à la Description d'Ecoulements Supersoniques*

- Experiment requires
  - high-energy density
  - high-power facilities
  - very low volumes
  - nanosecond pulses
  - high Mach numbers

Dubroca & Feugeas, CRAS – Math 1999

Remington et al., POP 2000

Overview

- Theoretical considerations
- Radiative shocks
- Numerical model presentation
- Experiments of laboratory astrophysics
- Astrophysical applications

Radiative hydrodynamic model vs Mach number

$M >> M_{iso}$

pressure-dominated radiative regime

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) &= 0 \\ \frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho(\mathbf{u} \otimes \mathbf{u}) + p\mathbf{I}) + \frac{\partial}{\partial t}\left(c^{-2}\mathbf{F}_{rad}\right) + \nabla \cdot \mathbf{P}_{rad}) &= 0 \\ \frac{\partial E}{\partial t} + \nabla \cdot ((E + p)\mathbf{u}) + \frac{\partial}{\partial t}E_{rad} + \nabla \cdot \mathbf{F}_{rad} &= 0 \end{aligned}$$

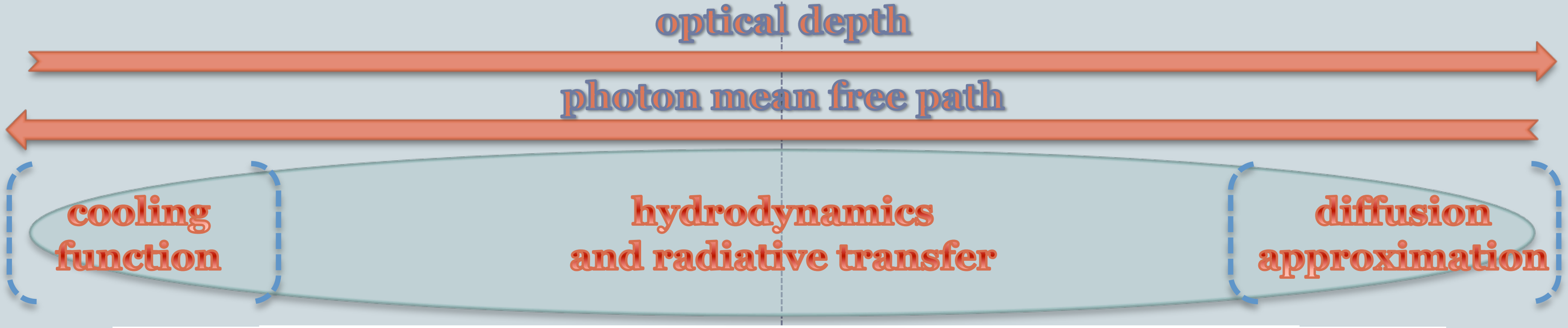
ρ density, $\mathbf{u}$ velocity, p pressure, E total energy

$\mathbf{F}_{rad}$ rad. flux, P_{rad} & E_{rad} radiative pressure & energy

- Radiative terms have to be calculated for all photon energies and are non-local terms
  - M_{iso}, M_{rad} are defined in Bouquet et al., ApJS, 2000
  - Shock classification in Michaut et al., ApSS, 2009
  - R.P. Drake's book, *HEDP: Fundamentals, Inertial Fusion and Exp. Astrophysics*, 2006
  - Mihalas & Mihalas, *Foundations of radiation hydrodynamics*, 1984

R H model vs medium optical properties

optically thin **optically very thick**



optical depth

photon mean free path

cooling function

hydrodynamics and radiative transfer

diffusion approximation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho(\mathbf{u} \otimes \mathbf{u}) + p\mathbf{I}) + \frac{1}{3}\nabla E_{rad}) = 0$$

$$\frac{\partial E}{\partial t} + \nabla \cdot ((E+p)\mathbf{u}) + \frac{\partial}{\partial t}E_{rad} + \nabla \cdot (\frac{4}{3}\mathbf{u}E_{rad}) - \frac{1}{3}\frac{c}{\kappa_R}\Delta E_{rad} = 0$$

ρ density, $\mathbf{u}$ velocity, p thermal pressure, E total energy, $\mathbf{F}_{rad}$ radiative flux,
$P_{rad} = \frac{1}{3}E_{rad}$, radiative pressure and energy

Hydro / RT coupling

- M1 multigroup

$$\begin{aligned} \partial_t E_g + \nabla_x \cdot \mathbf{F}_g &= S_{E_g}\,, \quad \forall g \\ \frac{1}{c^2}\partial_t \mathbf{F}_g + \nabla_x \cdot \mathbf{P}_g &= S_{\mathbf{F}_g}\,, \quad \forall g \end{aligned}$$

$$S_{E_g} = c\left(\sigma_g^e a_r \theta_g^4(T) - \sigma_g^a E_g\right),\ S_{\mathbf{F}_g} = -\frac{1}{c}\left(\sigma_g^f + \sigma^d(1-\delta_g)\right)\mathbf{F}_g$$

- Euler equations

$$\begin{aligned} \partial_t \rho + \nabla_x \cdot (\rho \mathbf{u}) &= 0 \\ \partial_t(\rho \mathbf{u}) + \nabla_x \cdot (\rho(\mathbf{u}\otimes\mathbf{u}) + p\mathbf{I}) &= -S_{\mathbf{F}} \\ \partial_t E + \nabla_x \cdot ((E+p)\mathbf{u}) &= -S_E \end{aligned}$$

Sum over all frequency groups

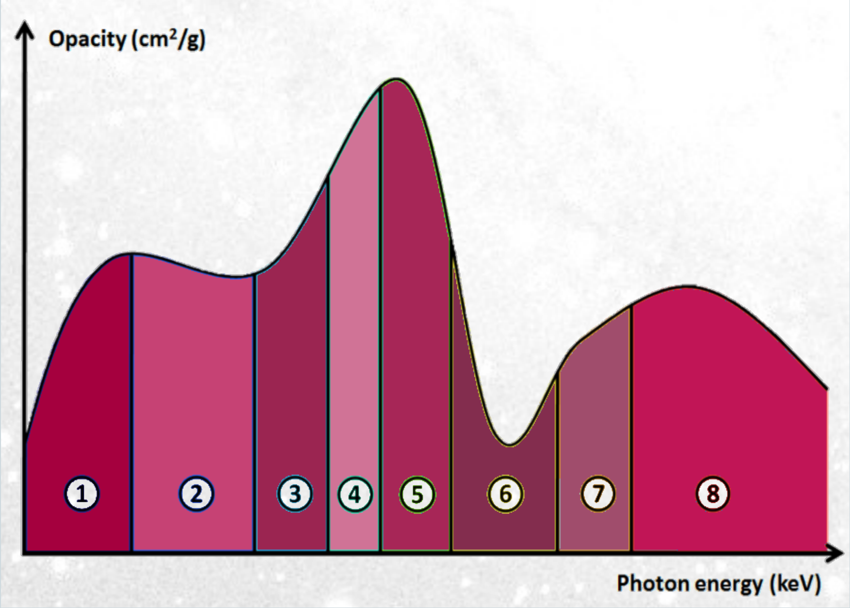
$$S_E = \sum_{g=1}^{N_g} S_{E_g}, \quad S_{\mathbf{F}} = \sum_{g=1}^{N_g} S_{\mathbf{F}_g}$$

frequency division

- Opacity gives mean free path of photons…
- but often uneven
- κ_R *Rosseland mean opacity*
- κ_P *Planck mean opacity*
- $B(\nu,T)$ *Planck function*

$$\kappa_R^{-1} = \frac{\int_\nu \chi^{-1}(\nu)\partial_T B(\nu,T)\ \mathrm{d}\nu}{\int_\nu \partial_T B(\nu,T)\ \mathrm{d}\nu}$$

$$\kappa_P = \frac{\int_\nu \kappa(\nu) B(\nu,T)\ \mathrm{d}\nu}{\int_\nu B(\nu,T)\ \mathrm{d}\nu}$$



multigroup

HADES

Hydrodynamics

Radiation

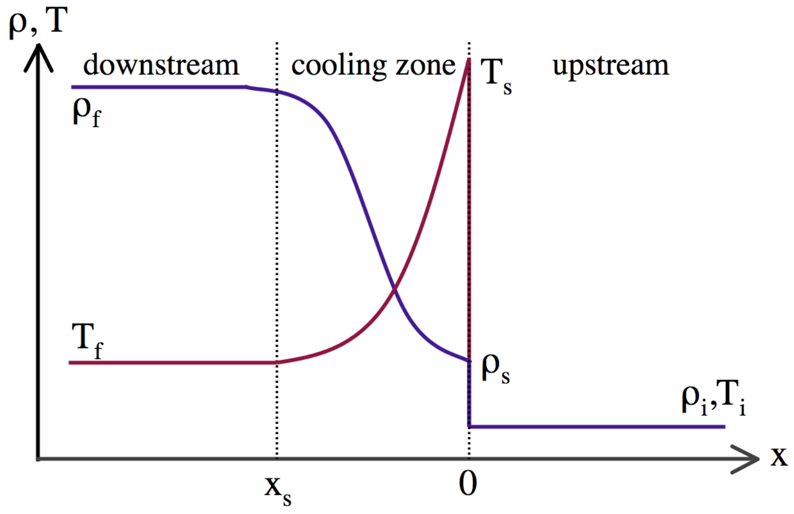
- 2D cartesian mesh
- MPI parallelization, spatial division
- Planar, cylindrical and spherical geometries
- Finite volume scheme
- MUSCL-Hancock method

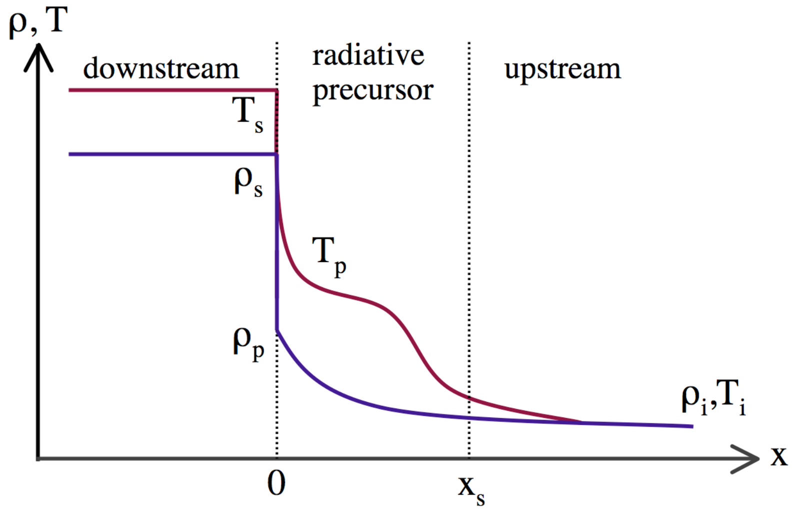
- Riemann solver:
  - HLLC (large M)
  - HLLE (stiff shock)

- Riemann solver:
  - HLL
  - as many times as frequency groups

Harten et al., SIAM Rev. 1983; Toro et al., Shock Waves 1994; Einfeldt, SIAM J. Num. An. 1988

RS morphology

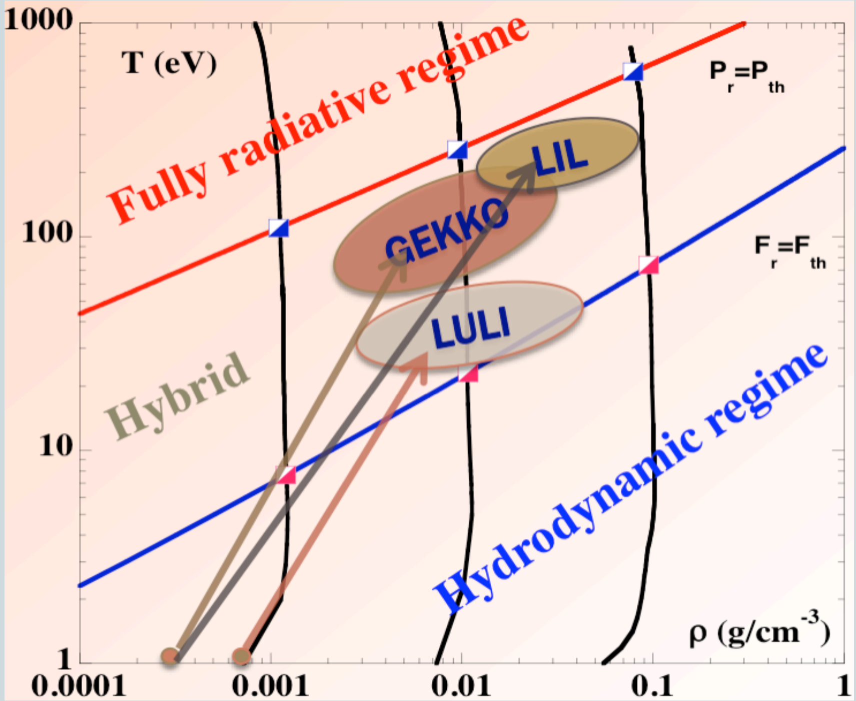




- Optically thin
- Photon mfp >> characteristic length
- Radiation escapes
- Compression in the downstream region

- Optically very thin
- Photon mfp << characteristic length
- Strong compression, emission of photons
- A part is absorbed in the upstream region
- RS propagates in medium with new physical properties
- Shock conditions are changed, which change the upstream region…
- A recursive system combining hydrodynamic conditions and radiative transport takes place

Typical experiment in terms of (ρ,T)



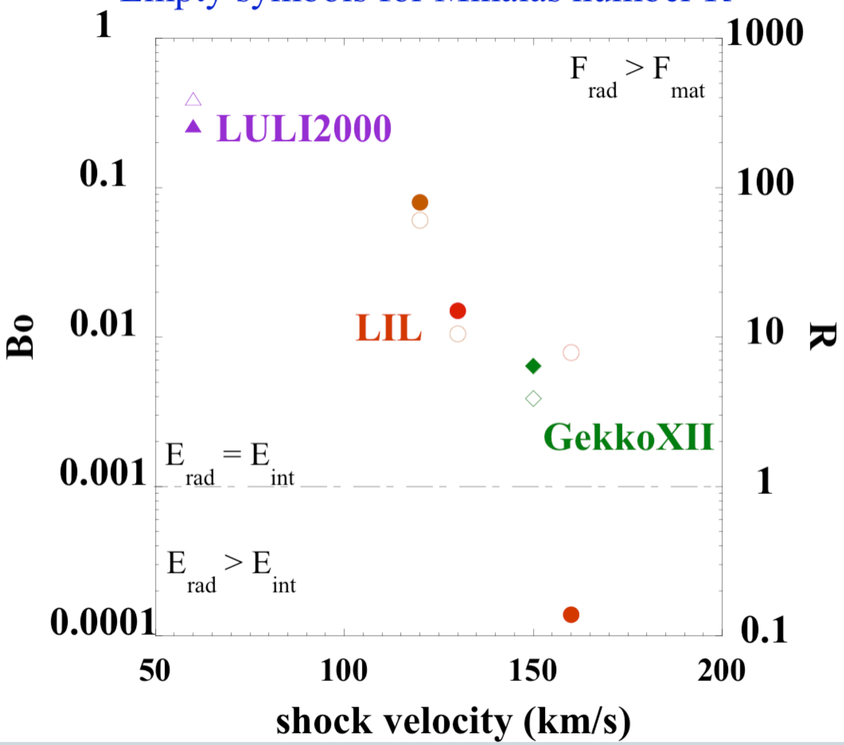
- LULI2000: I~10^{14} W/cm^2 - t~1 ns
  - ○ Xe, 100-200 mbar
  - ○ velocity [70-100] km/s
  - ○ only radiative effects due to F_{rad}

- GEKKO: I~10^{15} W/cm^2 - t~0,5 ns
  - ○ Xe, Kr, Ar, 50-100 mbar
  - ○ velocity [80-130] km/s
  - ○ radiative effects due to not only F_{rad} but also P_{rad} (E_{rad})
  - ○ P_{rad} ~ few % of P_{th}

- LIL: I~7.5 10^{14} W/cm^2 - t~2 ns
  - ○ Xe, Kr, 50 mbar
  - ○ velocity [120-165] km/s

In terms of dimensionless numbers

Plain symbols for Boltzmann number Bo
Empty symbols for Mihalas number R

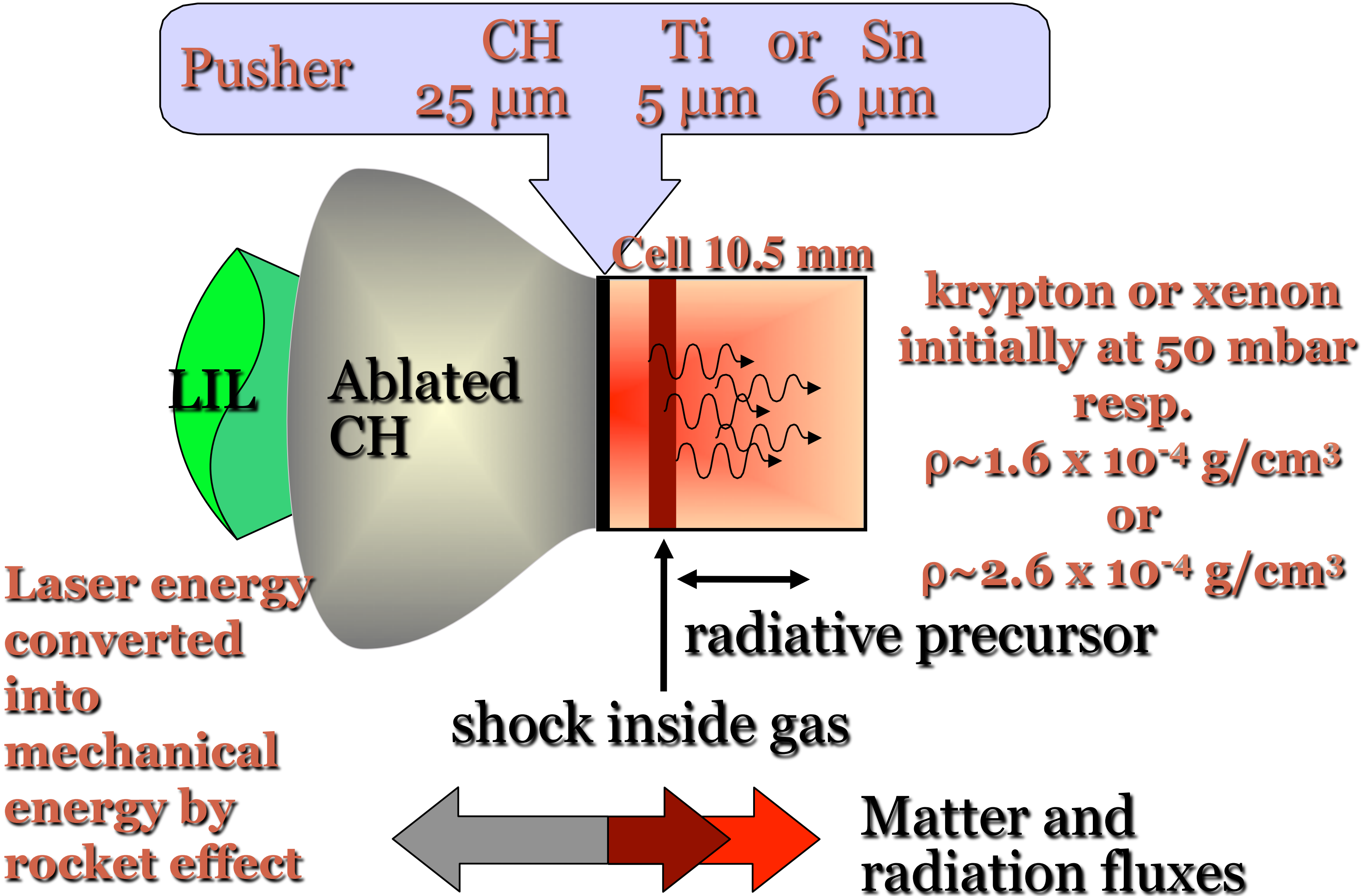


Bo compares fluxes
R compares energies
C. Michaut et al., ApSS 2009

- GekkoXII gives high radiative regimes, but does not maintain the shock until the complete formation

X. Fleury et al., LPB 2002
S. Bouquet et al., PRL 2004
M. Koenig et al., ApSS 2005
T. Vinci et al., ApSS 2005
T. Vinci et al., PoP 2006
M. Koenig et al., PoP 2006
S. Leygnac et al., PoP 2006
C. Michaut et al., ApSS 2007
A. Dizière et al., ApSS 2011
…

Radiative shock generation



Pusher CH 25 µm Ti 5 µm or Sn 6 µm

Cell 10.5 mm

LIL

Ablated CH

krypton or xenon initially at 50 mbar resp. $\rho \sim 1.6 \times 10^{-4}$ g/cm^3 or $\rho \sim 2.6 \times 10^{-4}$ g/cm^3

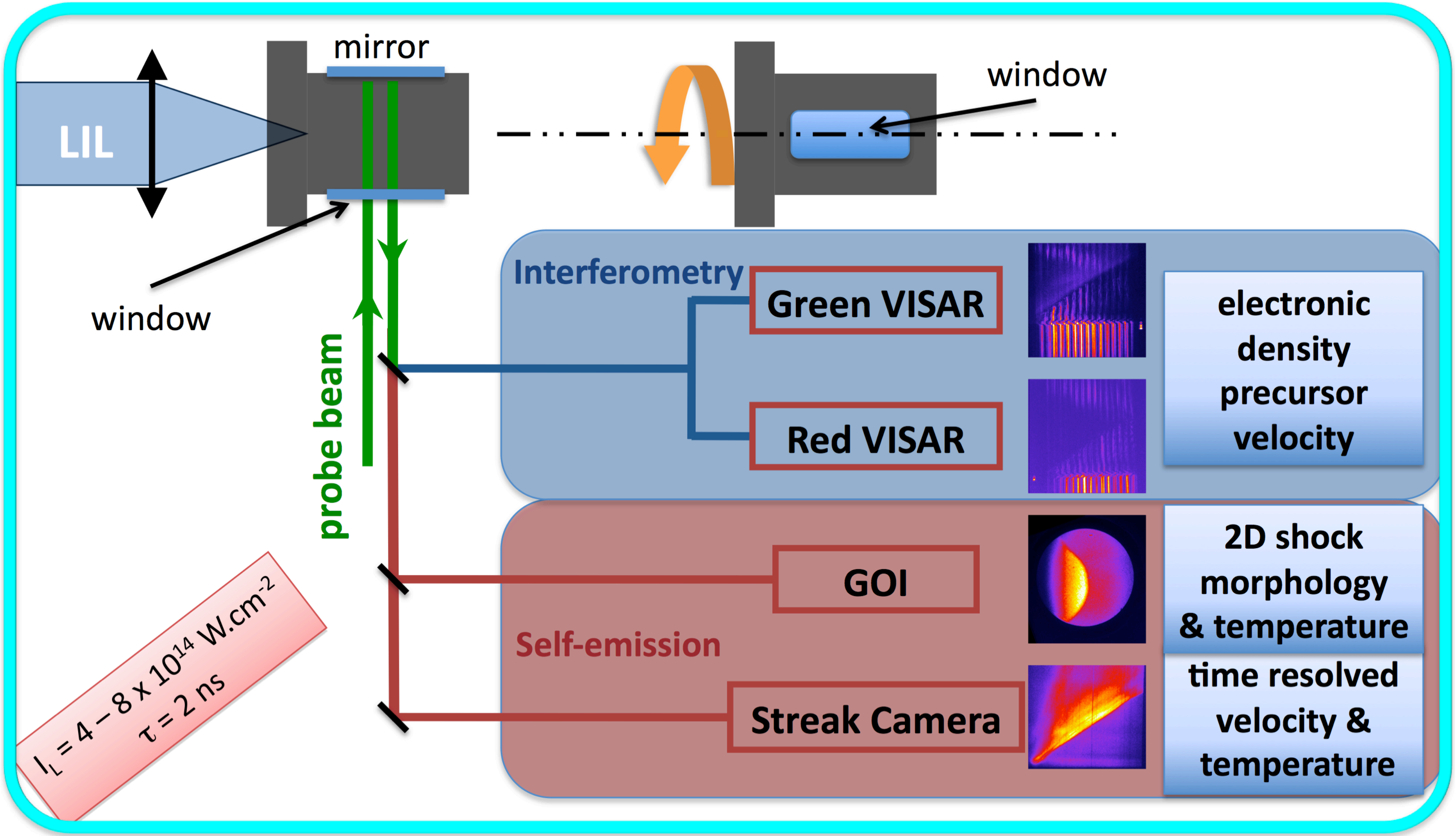
Laser energy converted into mechanical energy by rocket effect

radiative precursor

shock inside gas

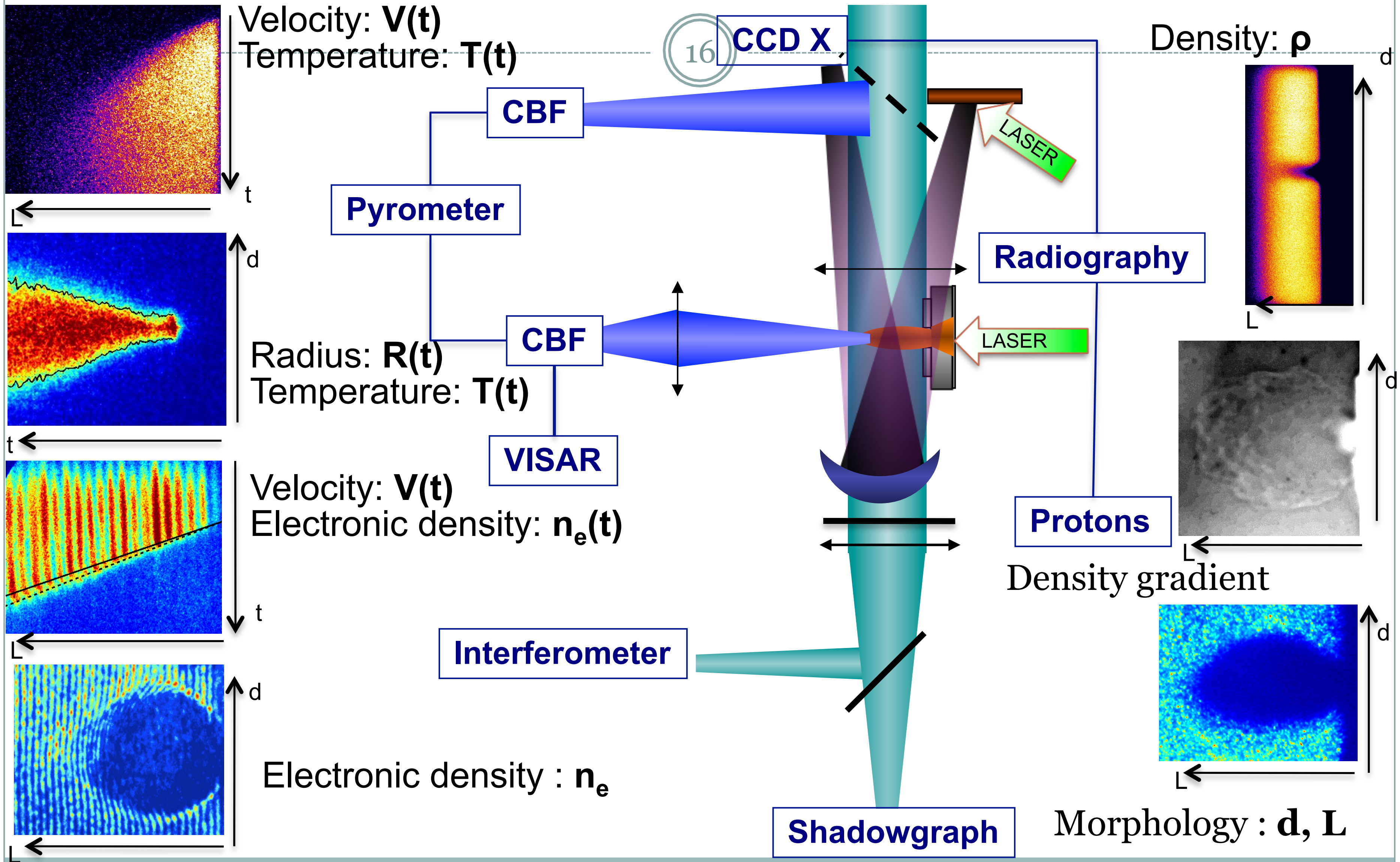
Matter and radiation fluxes

Typical experimental set-up



sometimes more complex with radiography, protongraphy…

More diagnostics



Velocity: **V(t)**
Temperature: **T(t)**

Radius: **R(t)**
Temperature: **T(t)**

Velocity: **V(t)**
Electronic density: $\mathbf{n_e(t)}$

Electronic density : $\mathbf{n_e}$

CCD X

CBF

Pyrometer

CBF

VISAR

Interferometer

Shadowgraph

Radiography

Protons

Density: **ρ**

Density gradient

Morphology : **d, L**

B. Loupias et al., PRL 2007

Astrophysical applications

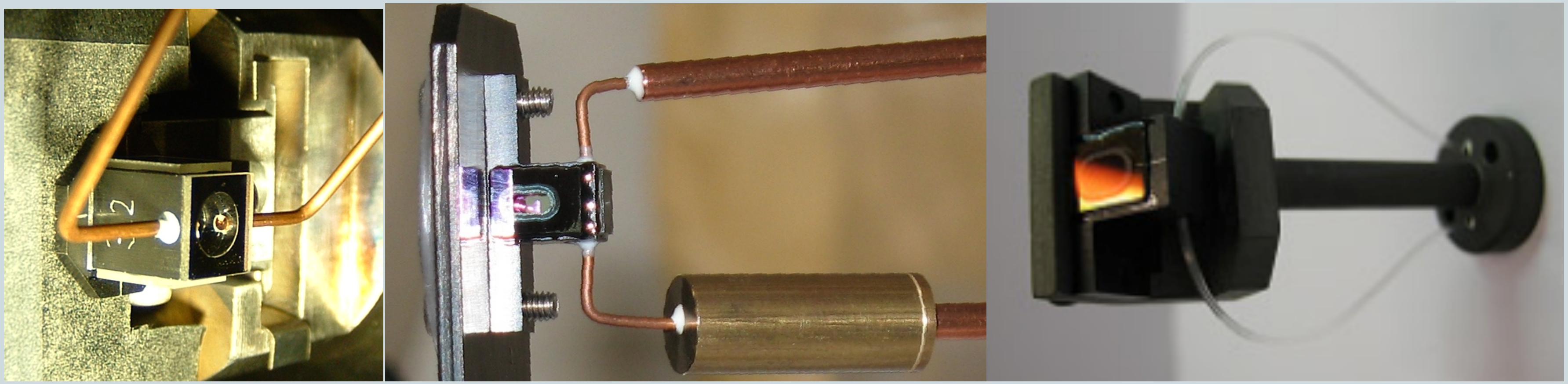
RADIATIVE SHOCKS
YOUNG STELLAR JETS
VISHNIAC INSTABILITY
ACCRETION COLUMNS
SHOCKS IN CEPHEID ENVELOPES

Radiative Shocks

- Radiative shocks are found in novae outbursts, supernovae, stellar atmospheres, accretion processes as star formation or cataclysmic variables, ejection processes as jets
- Supersonic (M>1) and hypersonic (M>>1) shock waves form frequently
- The three moments of radiation (flux, pressure, energy) are coupled to the three moments of matter (flux, pressure, energy)
- On the Earth we do not know naturally Prad and Erad
- Physics and numerical approaches need to be verified
- Experiments are performed in order to understand nonlinear physics and to validate numerical codes

Radiative Shocks in laboratory

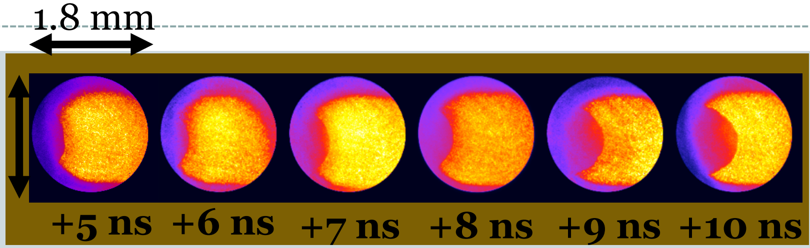
- gas-cell targets

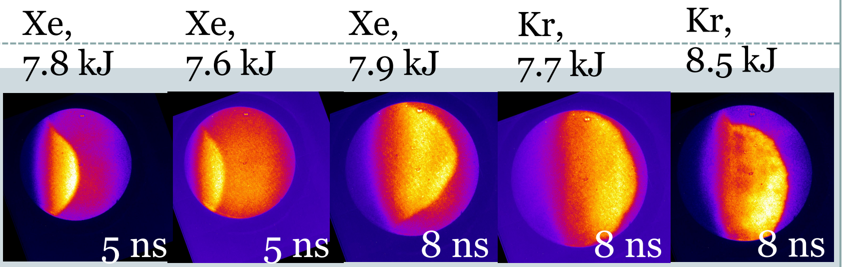


- achievable velocity depends on the laser (intensity)
- we want high-Mach numbers and strong ionization
- we need low initial **ρ**, high atomic weight **A**
- we put mainly xenon in gas-cell, sometimes krypton

S. Bouquet et al., APJS 2000

What we learn about RS?

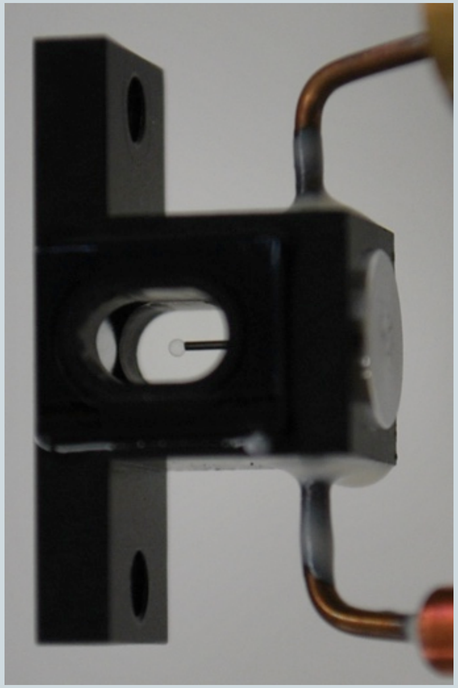


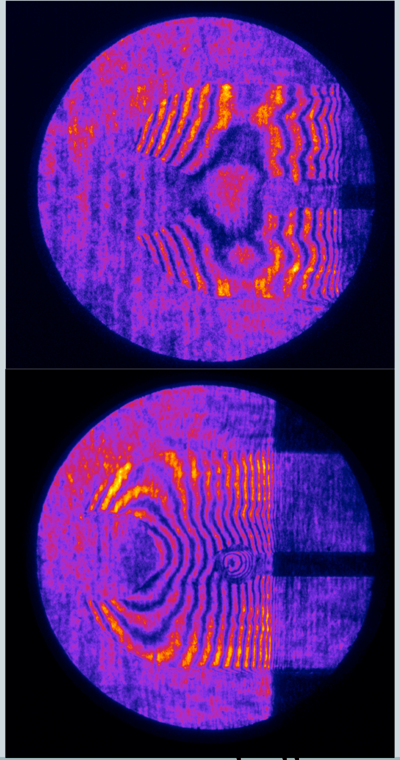


- Targets are designed according analytical model and 1D simulation
- Shock and precursor velocities up to 50 km/s and to 110 km/s
- Shock temperature [15 eV – 40 eV]
- Time-dependant shock curvature, radial expansion recorded
- 2D behavior of the radiative shock is clearly identified
- Good agreement of the shock velocity and temperature
- Good agreement of the curvature of the shock, and propagation
- Precursor length is difficult to predict (analytically)
- Laser intensity is fundamental to drive high speed shocks
- But shock formation takes few ns
- Long pulse duration sustains longer the shock wave and leads to more compressed material
- LIL experiments have demonstrated that the shock is faster the pusher after few ns
- A nonstationary shock is very different from a steady-state one
- Production of highly RS requires X-ray radiography to probe compressed material
- Production of radiative flux can be used to irradiate an obstacle

New design on GEKKO XII

- to understand the ablation front in molecular clouds
- radiative shock and obstacle
- radiation flux interacts with quartz ball



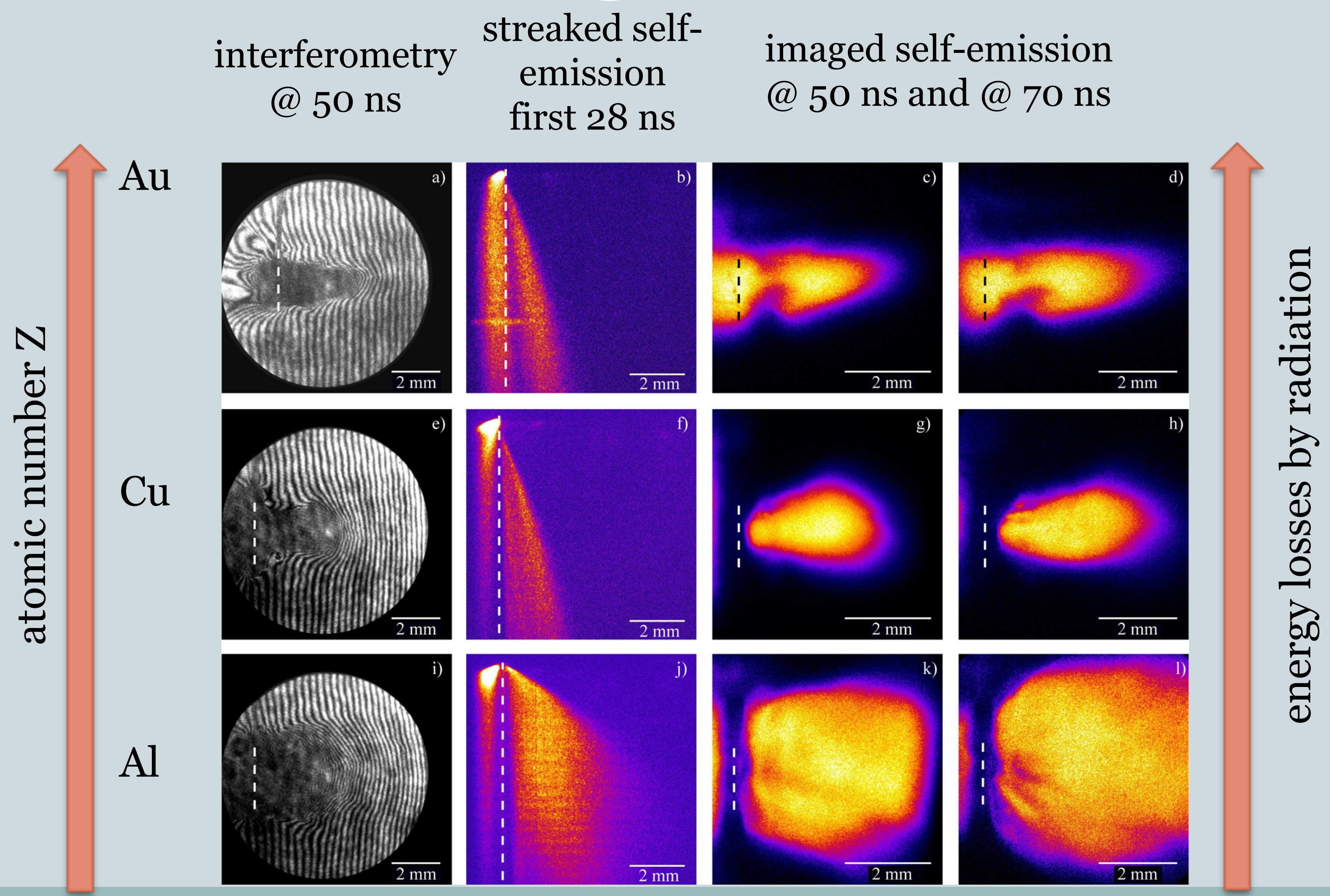


plain ball

empty ball

Young stellar jets

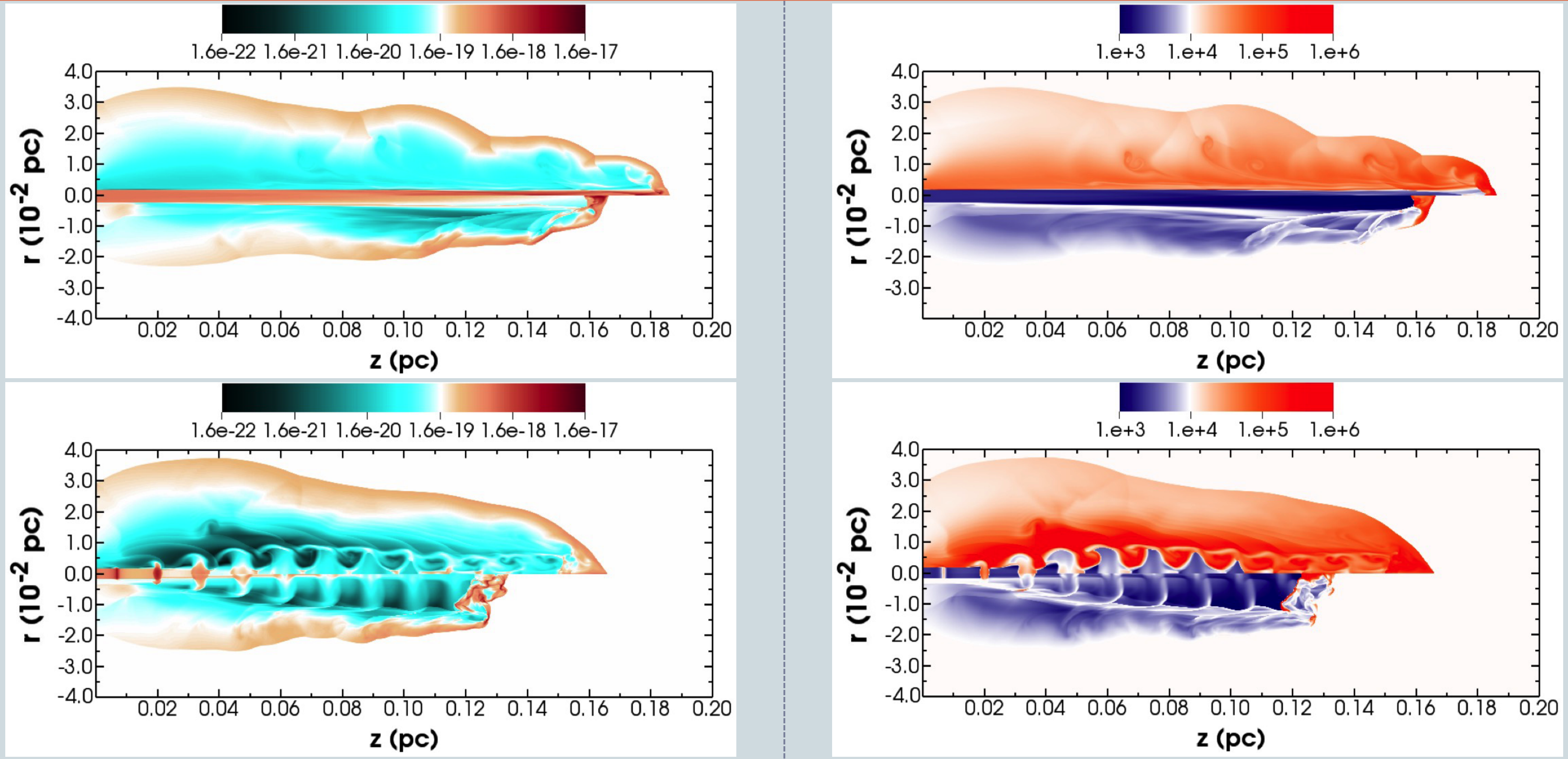
Radiation effect on flow morphology



C. Gregory et al., HEDP 2014

Jet morphology wo/with radiation

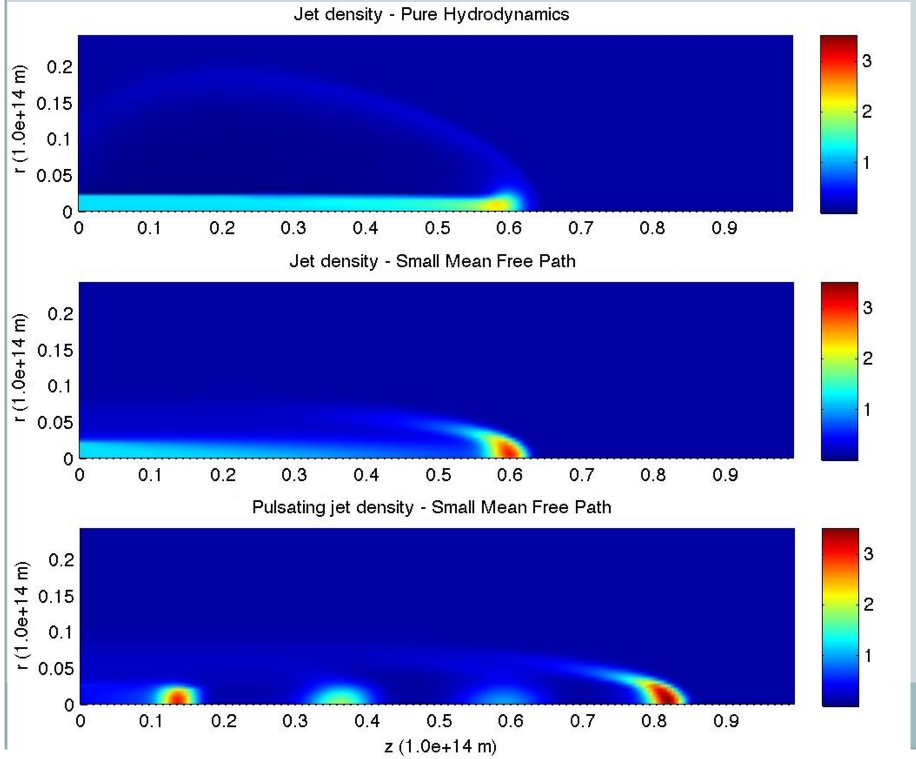
density **temperature**



C. Michaut et al., HEDP 2016

on long distance

- Jet morphology is due the collimation at the beginning depending on the star and on the magnetic field
- However, radiation must not be neglected
- Because energy losses by radiation pinch the flow


Jet density - Pure Hydrodynamics

Jet density - Small Mean Free Path

Pulsating jet density - Small Mean Free Path

Big cocoon

mfp of the order of the jet radius
gray opacity
thin jet

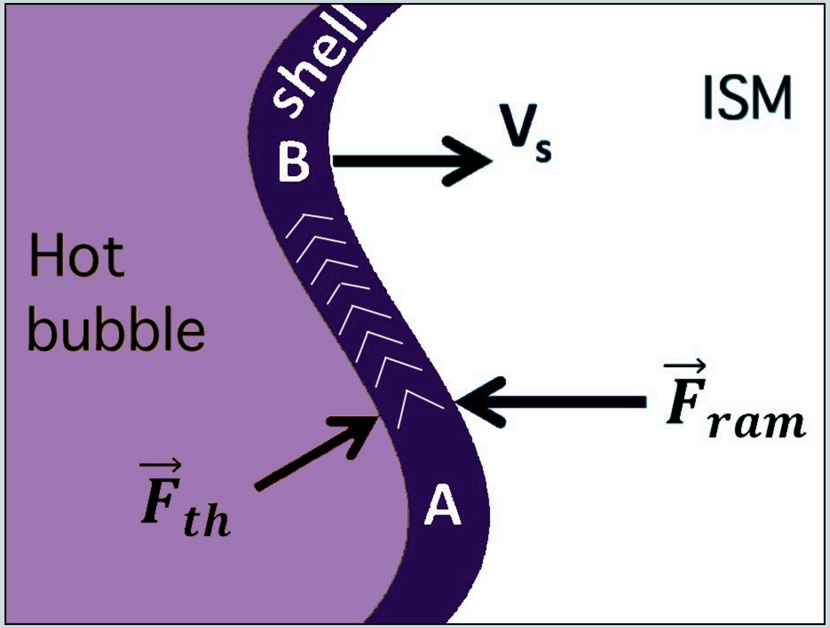
Jet velocity increased by pulsation
gray opacity
thin jet

C. Michaut et al., ApSS 2011

Vishniac Instability in SNR

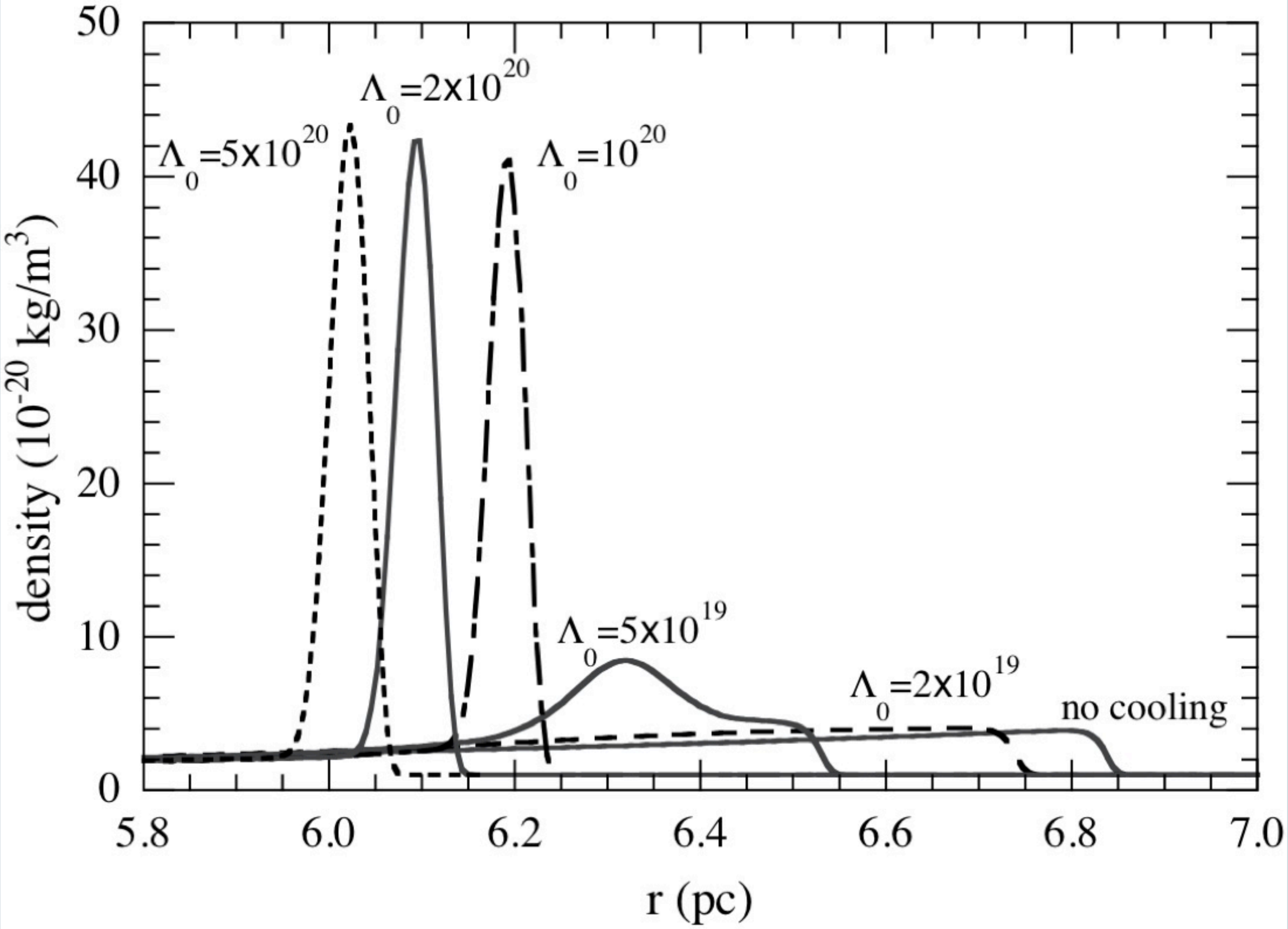
Simeis : 38 000 ans

© Digitized sky Survey, ESA/ESO/NASA FITS Liberator



- late stage = radiative stage
- VI is assumed to lead to complex structures as filamentation
- after 3 kyrs, a SNR is a blast wave that is modeled by a Sedov-Taylor explosion

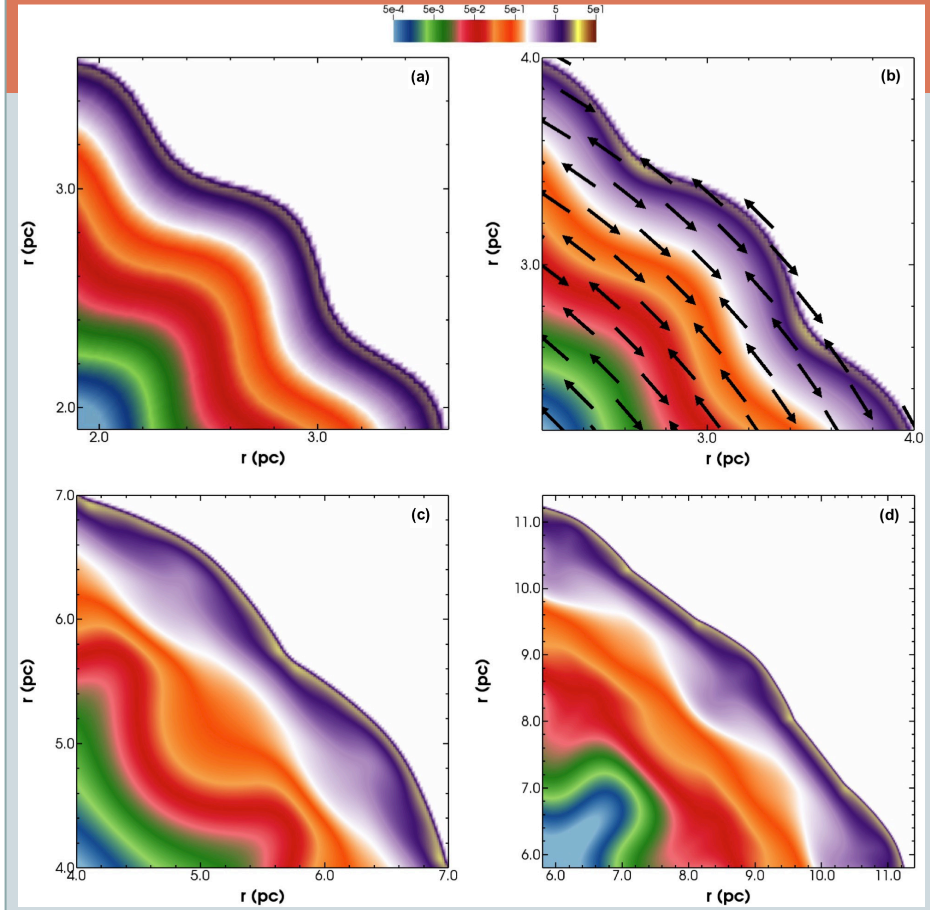
Blast wave expansion vs cooling amplitude



C. Michaut et al., HEDP 2016

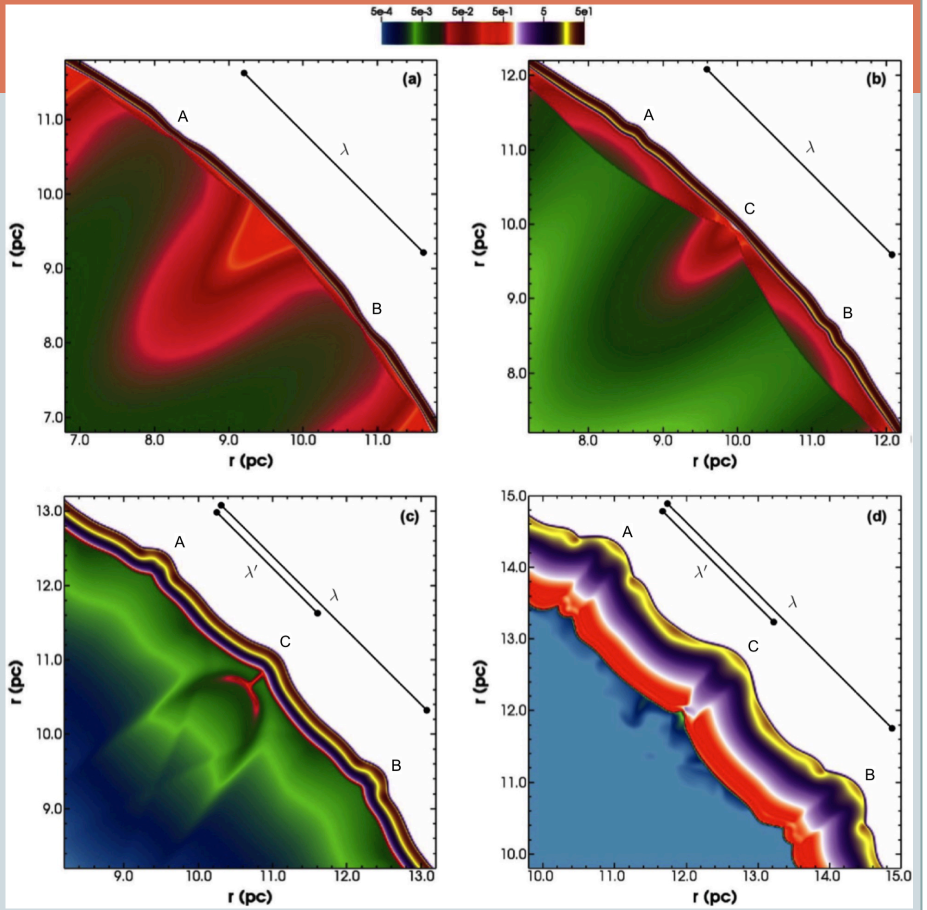
VI from 3 kyrs to 93kyrs

no cooling but γ=1.1



- 3; 4; 18; 53 kyrs

cooling with γ=5/3

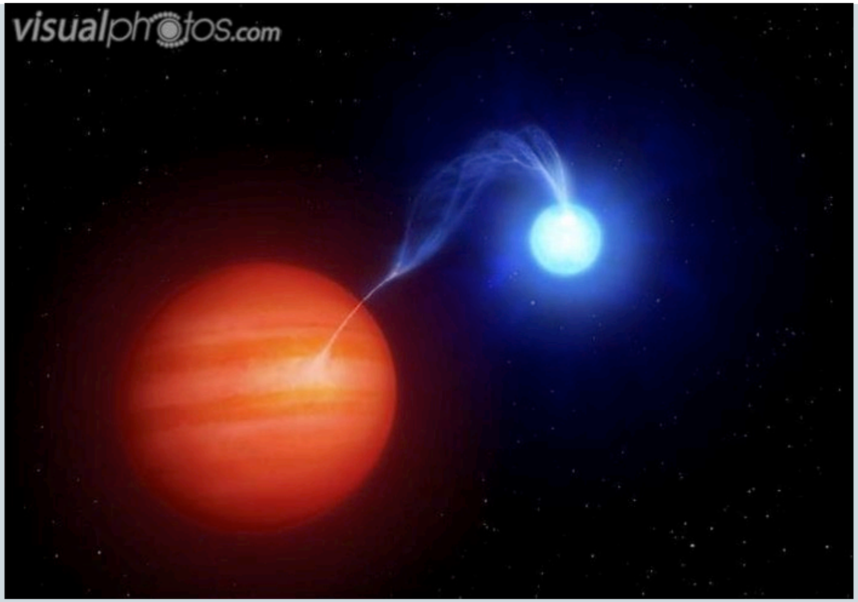


- 38; 43; 58; 93 kyrs

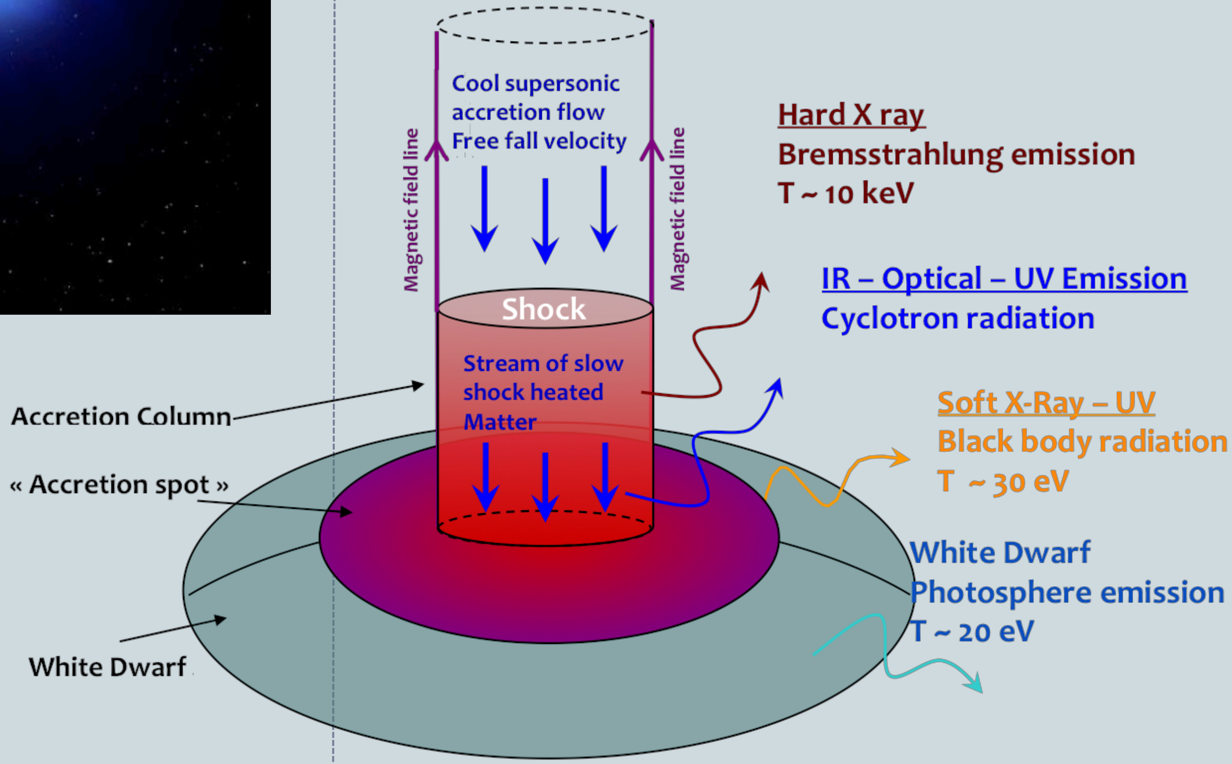
J. Minière et al., A&A 2018

new mode twice the first one

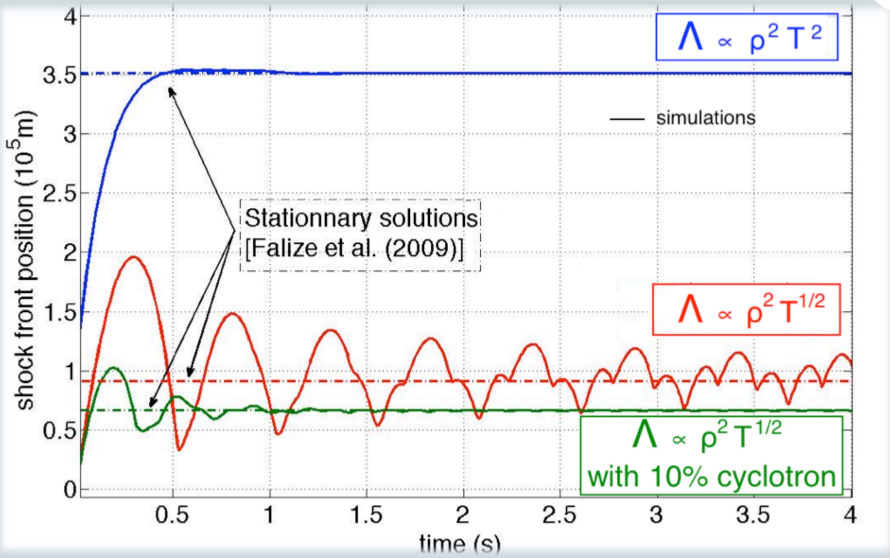
Accretion column in polar



main luminosity from the post-shock region

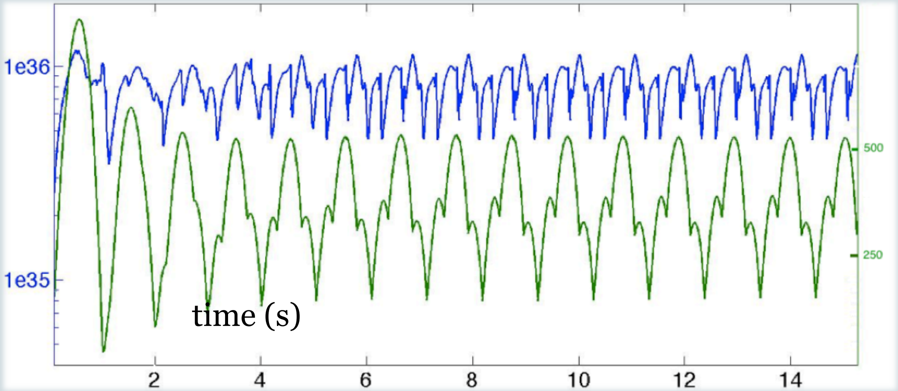


Shock position and observable

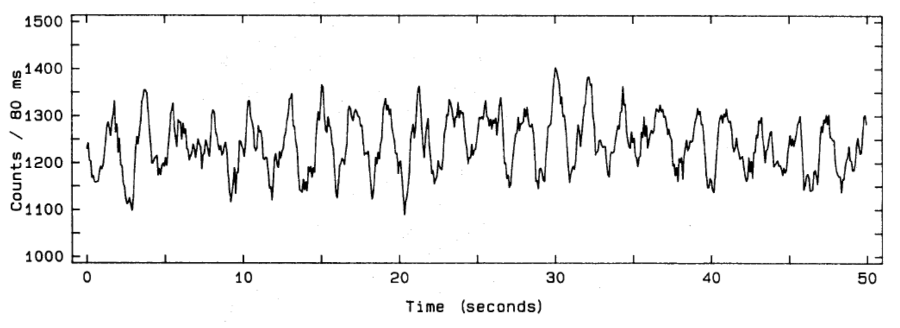


Chevalier & Immamura ApJ (1982), Wu et al. ApJ (1995)

- shock position depending on the type of cooling
- bremsstrahlung
- cyclotron



- shock position with bremsstrahlung, simulated polar luminosity

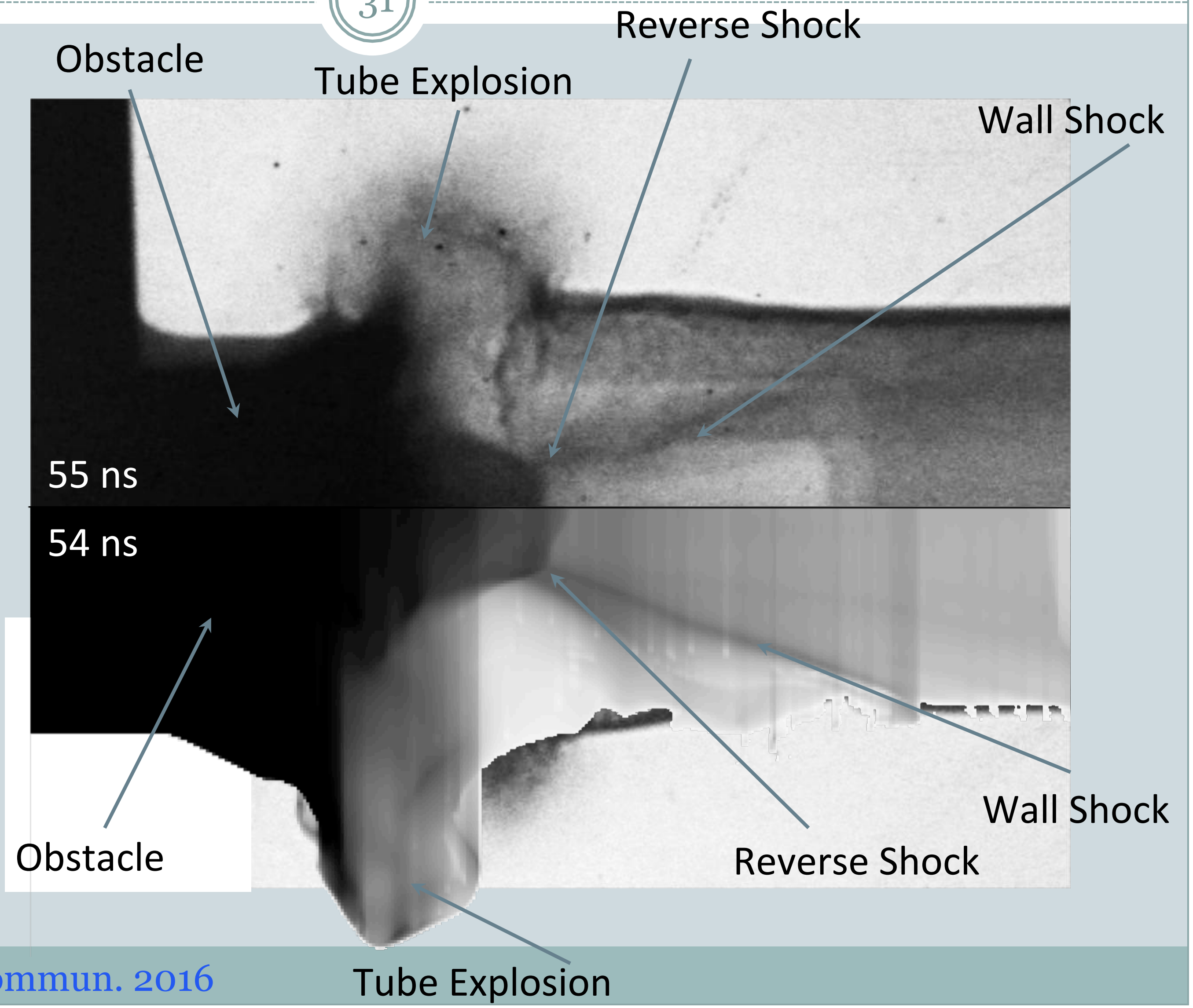


- observation of QPO's

E. Falize et al., ApSS 2009 ; C. Busschaert et al., and J.-M. Bonnet-Bidaud et al., A&A 2015

accretion column simulation in experiment

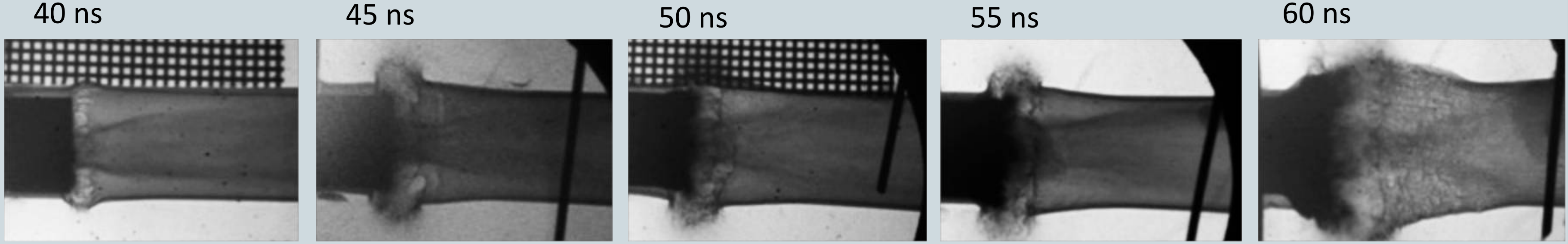
- Tube mimics B
- Obstacle mimics white dwarf
- Xray radiography
- numerical simulation with NYM Lagrangian code (laser-interaction phase), then linked to the PETRA code (propagation in the tube)



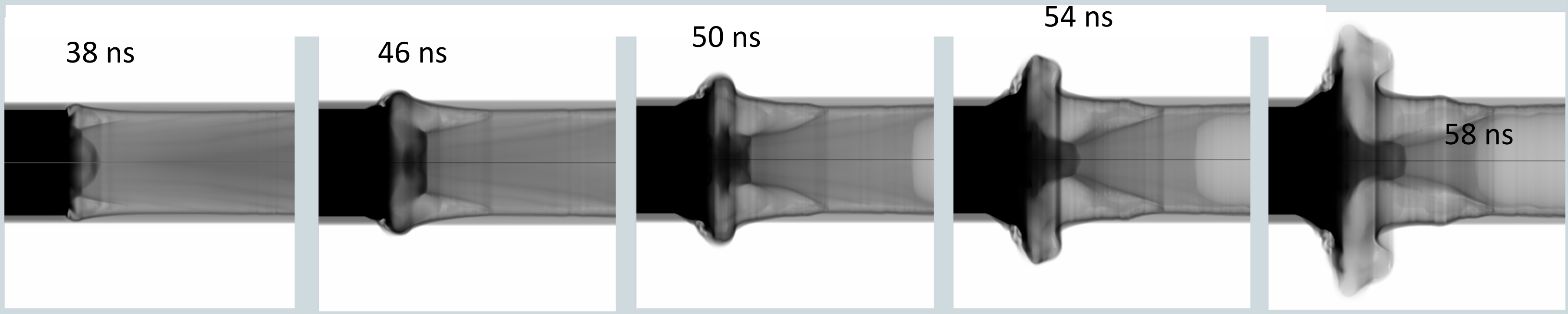
J. Cross et al., Nature Commun. 2016

Time sequence for accretion shock

Experimental radiography data



Numerical simulations



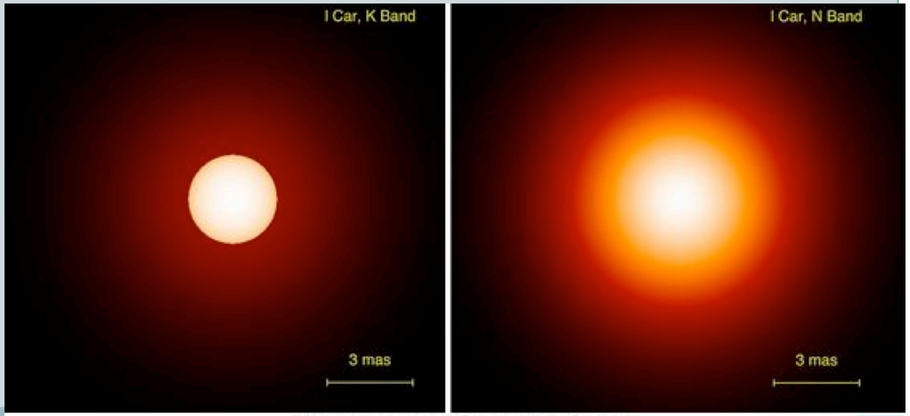
- Up to now, not enough energy to observe enough radiation escaping…

J. Cross et al., Nature Commun. 2016

Shock propagation in cepheids

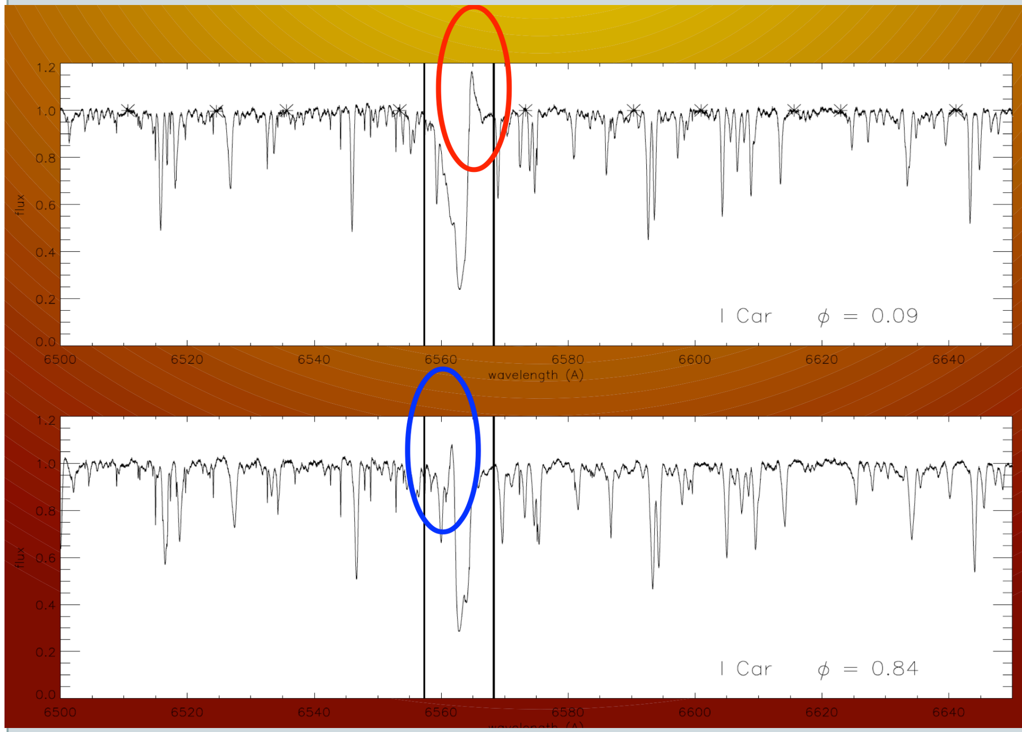
- 1784 : 1st Cepheid Cephei discovered by J. Goodricke
- Yellow or red supergiant stars
- Mass is 5 to 15 solar mass
- Luminosity is 100 to 30,000 times brighter than the sun.
- Stars with a regularly varying luminosity (P-L relationship discovered by H. Leavitt in 1912) $M = a(\log(P)\ 1) + b$
- Distance indicators for extragalactic astronomy
- Our model type is **l Carinae** which is a visible to the naked eye cepheid in the southern constellation of **Carina**

Period	Mass	Radius	Temperature	Radial velocity
35.560 d	8.4-13 $M_{\odot}$	180 $R_{\odot}$	5000 K	20 km/s



Model Image of Cepheid L Carinae
ESO PR Photo 09/06 (28 February 2006) (VINCI, MIDI/VLTI)

around the Halpha line

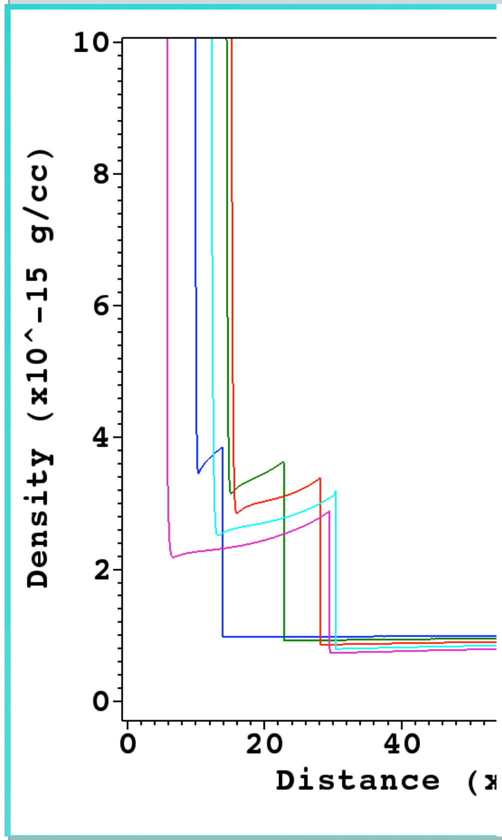


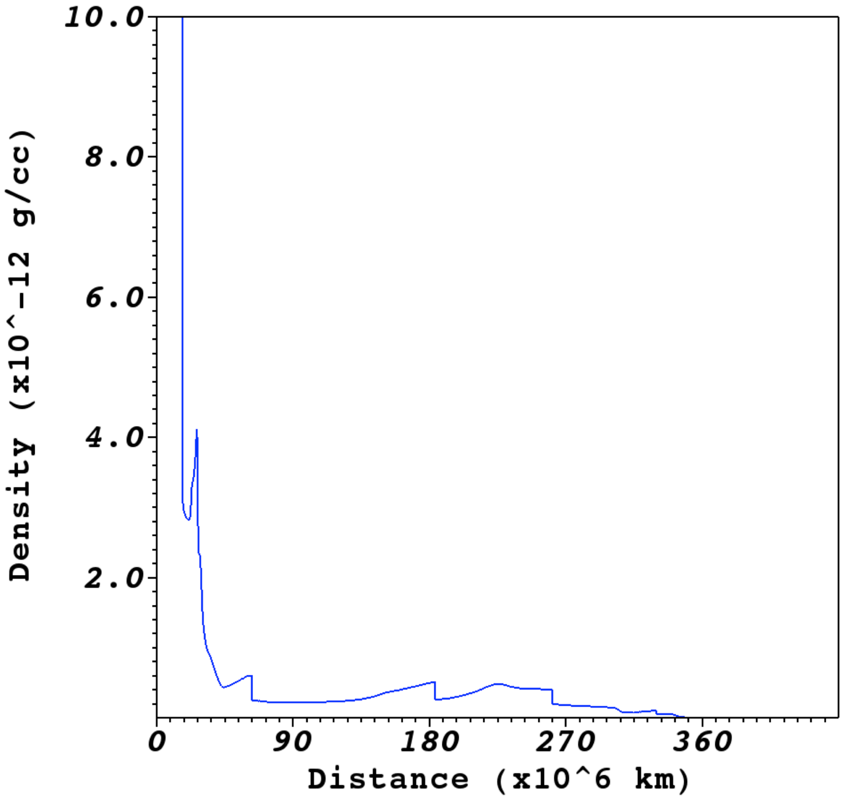
Cepheids with long-period exhibit asymmetries at the H alpha line :

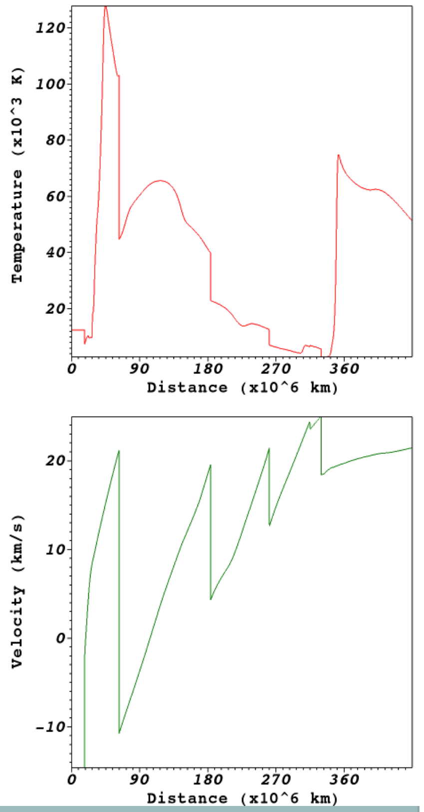
an absorption component with a redshifted or blueshifted emission component depending on the pulsation phase.

Propagation of shocks

- When the star pulses, shocks accumulate in the envelope.

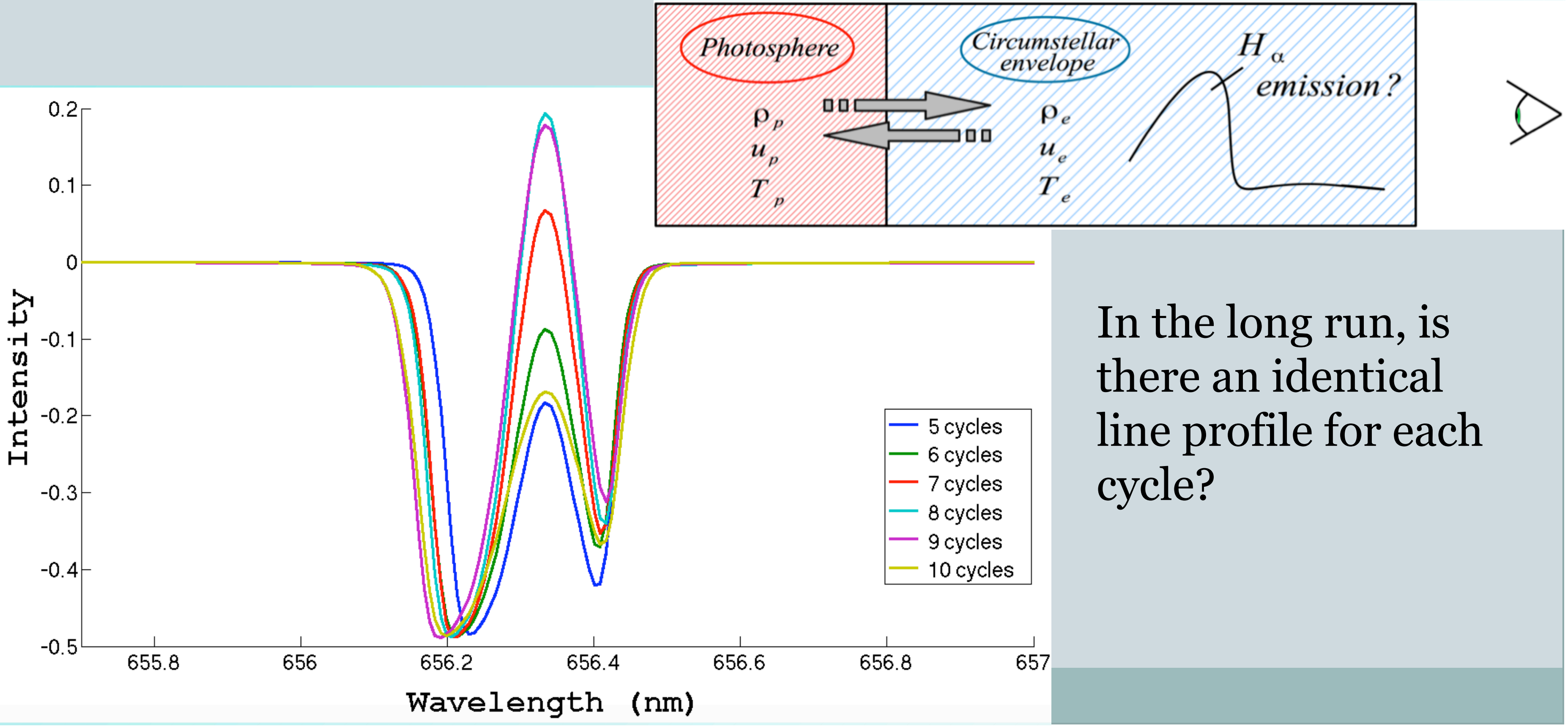






Need for observable

- numerical simulation results are in density, temperature, velocity
- observers have data in intensity vs wavelength



In the long run, is there an identical line profile for each cycle?

Perspectives

- LMJ radiative shock experiment (2020?)
  - collaboration with LULI and CEA
- Continue to apply radiative hydrodynamics to astrophysical situations
- Especially in the domain of cepheids
  - collaboration with N. Nardetto and F. Hocque
- Investigation of radiative hydrodynamic instability
  - collaboration S. Bouquet (CEA)
- Bring radiative aspects in code of protostellar disc formation
  - collaboration E. Méheut
- …

Summary

- Radiation is the better diagnostic in astronomy
- High-Mach plasma flows are ubiquitous in the Universe
- The coupling between radiation and hydrodynamics must be taken into account
- Models and numerical aspects are sufficiently hard to require long investigation
- However, this consideration gives new view points in stellar physics and even more

Collaborations

- Theory, mathematics, numerical simulations
  - H.C. Nguyen (LUTH, then Hanoï Univ.), C. Cavet (LUTH)
  - S. Bouquet, E. Falize, C. Busschaert, J. Minière, A. Gintrand (LUTH/CEA)
  - L. di Menza (Lab de mathématiques, Univ. de Reims)
  - (CEA/LUTH)
  - O. Saincir (Math, Univ. de Reims/LUTH)
- On LULI 6 beams and LULI2000 [2000-2006]
  - L. Boireau · C. Busschaert, S. Bouquet · E. Falize (LUTH/CEA)
  - M. Koenig, A. Benuzzi-Mounaix, T. Vinci, N. Osaki, A. Ravasio, B. Loupias, C. Gregory, T. Michel (LU
  - S. Atzeni (Università di Roma La Sapienza)
- On GEKKO XII [2009-2014]
  - A. Dizière · M. Koenig · C.D. Gregory · A. Ravasio· J.-M. Boudenne (LULI)
  - Y. Sakawa · Y. Kuramitsu · T. Morita · T. Ide · H. Tanji · H. Takabe (ILE)
  - P. Barroso (GEPI, Obs de Paris)
- On LIL [2012]
  - M. Koenig, A. Pelka, R. Yurchak, J.-M. Boudenne (LULI)
  - A. Casner, S. Laffite, S. Bouquet, D. Raffestin (CEA-DAM, France)
  - P. Barroso (GEPI, Obs de Paris)
  - R.P. Drake (Univ Michigan, USA), S. Le Pape (LLNL, USA)
- On ORION [2015]
  - J. Cross, G. Gregori (Oxford University, UK)
  - J. Foster, P. Graham (AWE, UK)
- Astronomical observations
  - M. Mouchet (LUTH), J.-M. Bonnet-Bidaud (CEA)
  - P. Kervella (LESIA, Obs de Paris) and now N. Nardetto, V. Hocque (Lagrange, OCA)

  - ..., sorry for forgetting, ...