Contemporary physical challenges for Heliospheric and AstRophysical Models

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IAP Phase VII

- **CHARM**: one of 47 selected IAP phase VII networks
  - $\Rightarrow$ Phase VII selected networks at

http://www.belspo.be/iap

  - $\Rightarrow$ **Interuniversity Attraction Pole** spans years 2012-2017
  - $\Rightarrow$ our (new) IAP network officially started 1 October 2012
- CHARM status and achievements

CHARM - IAP P7/08

- our network: 7 teams, each partner team with spokesman
  ⇒ **P1** http://wis.kuleuven.be/CmPA Centre for mathematical Plasma Astrophysics, KU Leuven [Rony Keppens]
  ⇒ **P2** http://www.astro.ugent.be Sterrenkundig Observatorium UGent [Maarten Baes]
  ⇒ **P3** http://aqua.ulb.ac.be Fluid and plasma dynamics Research Unit ULB [Bernard Knaepen]
  ⇒ **P4** http://www.sidc.be Solar physics research department of ROB [David Berghmans]
  ⇒ **P5** http://www.aeronomie.be Solar Wind research unit of BISA [Viviane Pierrard]
  ⇒ **INT1** http://www.strw.leidenuniv.nl Computational Astrophysics at Leiden University [Simon Portegies Zwart]
  ⇒ **INT2** http://icc.dur.ac.uk Institute for Computational Cosmology at University of Durham [Tom Theuns]

CHARM research themes

- **high performance computing** approaches, to **confront models with observations**
- **research theme on turbulence and particle acceleration**,
- **treatments of the radiative-dynamical feedback loop**.
- **interplay between global magnetohydrodynamic and phase-space based kinetic physics**.
- *breakthroughs in our understanding of reconnection events*,
- **unravel galaxy evolution questions, thanks to simulation and software engineering efforts like the EAGLE cosmological hydro challenge or the AMUSE framework**.

CHARM objectives

- **couple existing tools and models towards more realistic multi-physics descriptions**
  - $\Rightarrow$ work package 1, leader Giovanni Lapenta, KU Leuven
- **confront model predictions with measurements**
  - $\Rightarrow$ work package 2, leader David Berghmans, ROB
- **gas and plasma dynamics with turbulent fluctuations**
  - $\Rightarrow$ work package 3, leader Bernard Knaepen, ULB
- **MHD to kinetic treatments in the heliosphere**
  - $\Rightarrow$ work package 4, leader Viviane Pierrard, BISA
- **dynamics with radiatively controlled phenomena**
  - $\Rightarrow$ work package 5, leader Maarten Baes, UGent

CHARM Meetings

- kickoff: held on 8-9 October 2012, Leuven
- website `http://wis.kuleuven.be/CHARM`
  - $\Rightarrow$ mailing list **charm@ls.kuleuven.be**
- Reporting
  - $\Rightarrow$ **yearly activity report**: 2013 & 2014 report online
  - $\Rightarrow$ **newsletter: each summer**: online 2013/2014/2015
  - $\Rightarrow$ **final report by 31 december 2017**

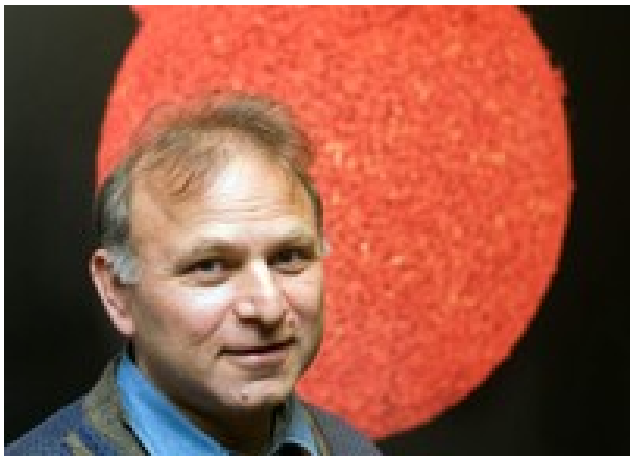
- annual meetings held at:
  - $\Rightarrow$ 18-19 april 2013, ROB (Brussels)
  - $\Rightarrow$ 30-31 January 2014, UGent (Gent)
  - $\Rightarrow$ 18-19 September 2014, ULB (Brussels)
  - $\Rightarrow$ 4-5 June 2015, BIRA (Brussels)

Major activities

- schools:

  $\Rightarrow$ Leiden, 27-31 May 2013, on **Radiative transfer treatments for astrophysical applications**

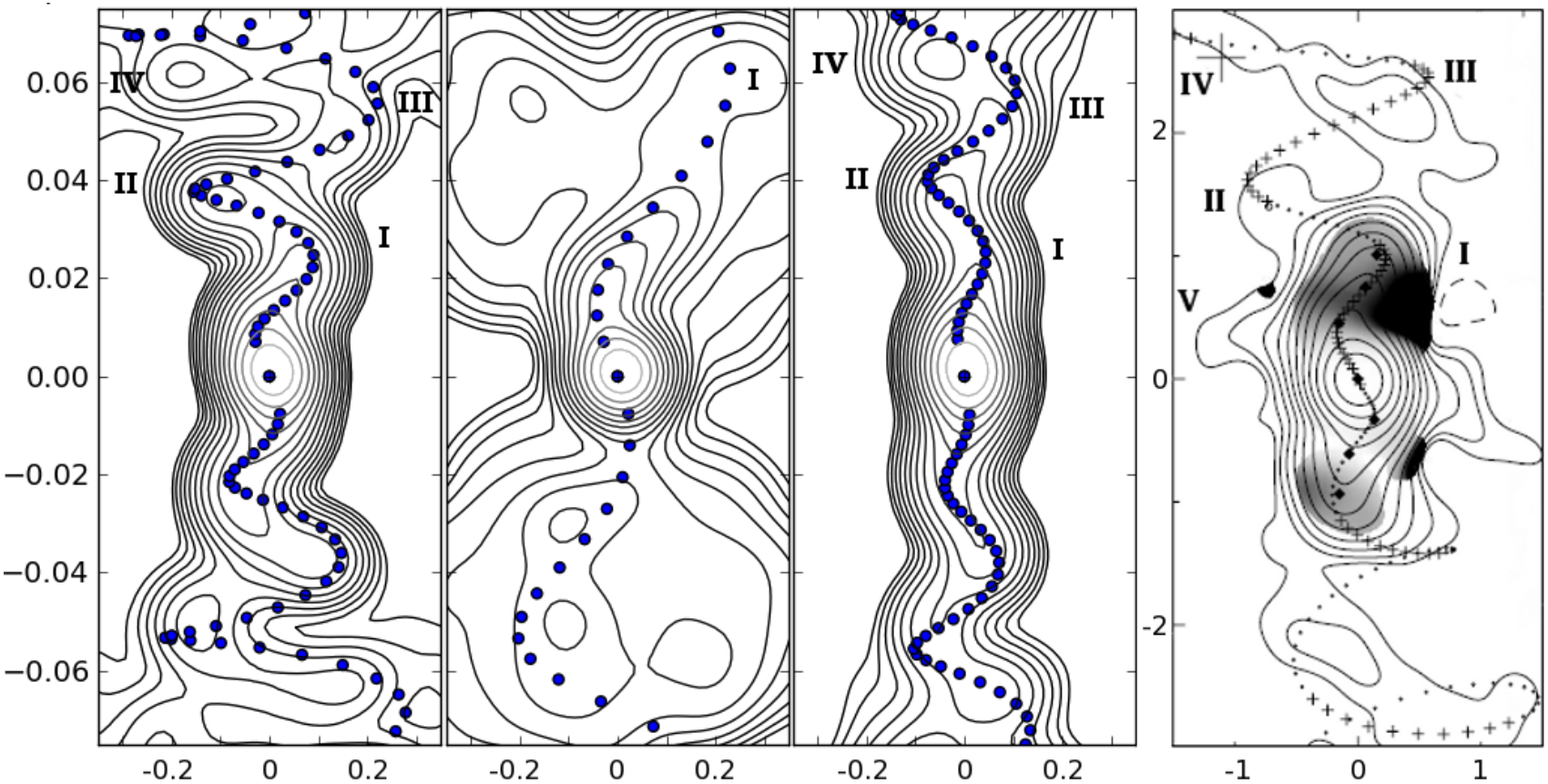
  $\Rightarrow$ Leuven, 16-19 September 2013, on **Space science traning week**, with public evening lecture by Sami Solanki (MPI-director)



  $\Rightarrow$ CSAM2015: **14-18 september 2015: FZ Julich Computational solar and astrophysical modeling**; `http://www.fz-juelich.de/ias/jsc/csam-2015`

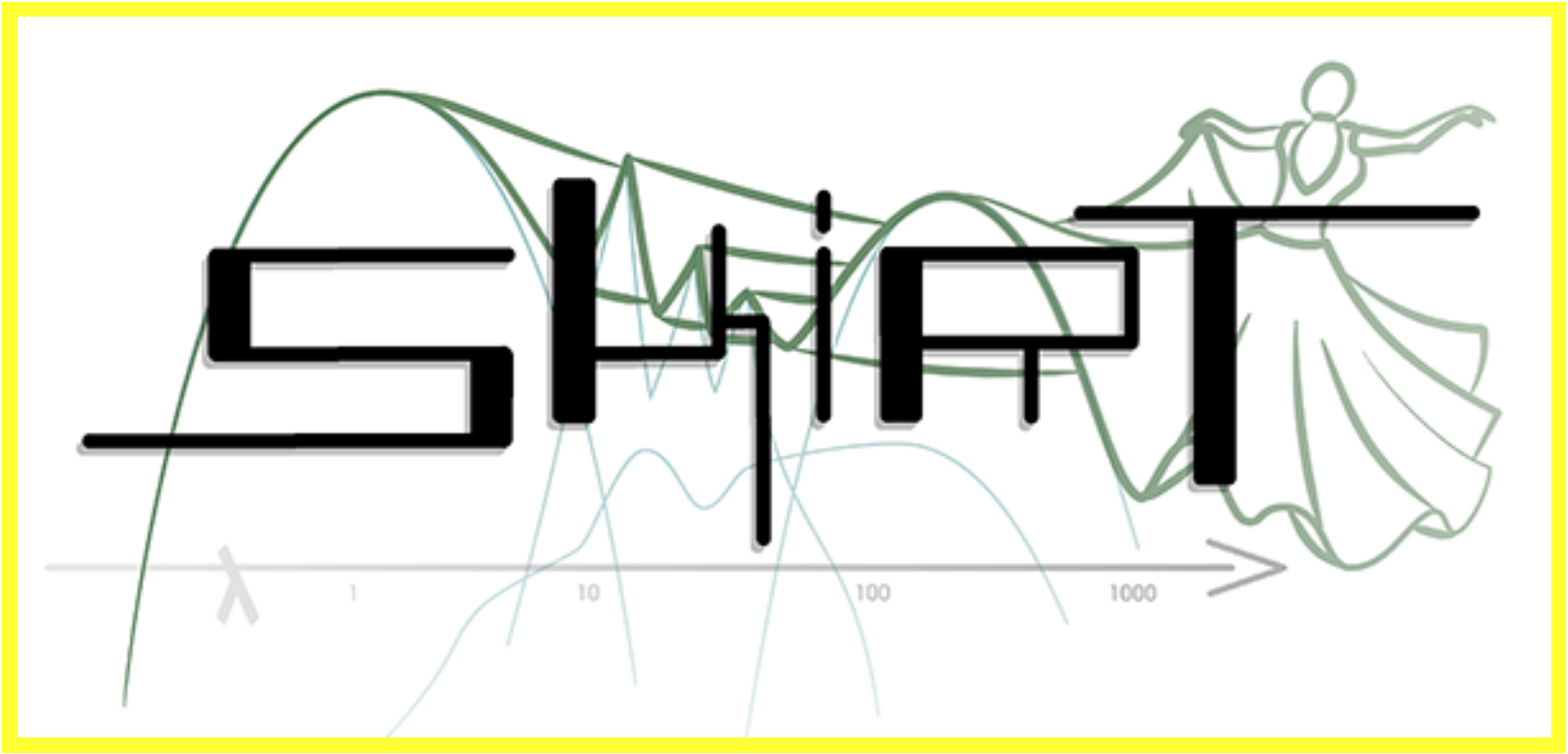
- annual reports show many highlights:
  - ⇒ space weather tool: Eufhoria (European WSA-ENLIL)
  - ⇒ coupling fluid and PIC approaches (BATS-R-US & iPIC3D)
  - ⇒ relativistic 3D hydro for **SS433 helical [precessing] jet**,

virtual radio maps (Monceau-Baroux et al) versus reality



- Selected Highlights of CHARM research:

  $\Rightarrow$ MPI-AMRVAC (KU Leuven) coupling with Monte Carlo SKIRT code (UGent) & typical applications

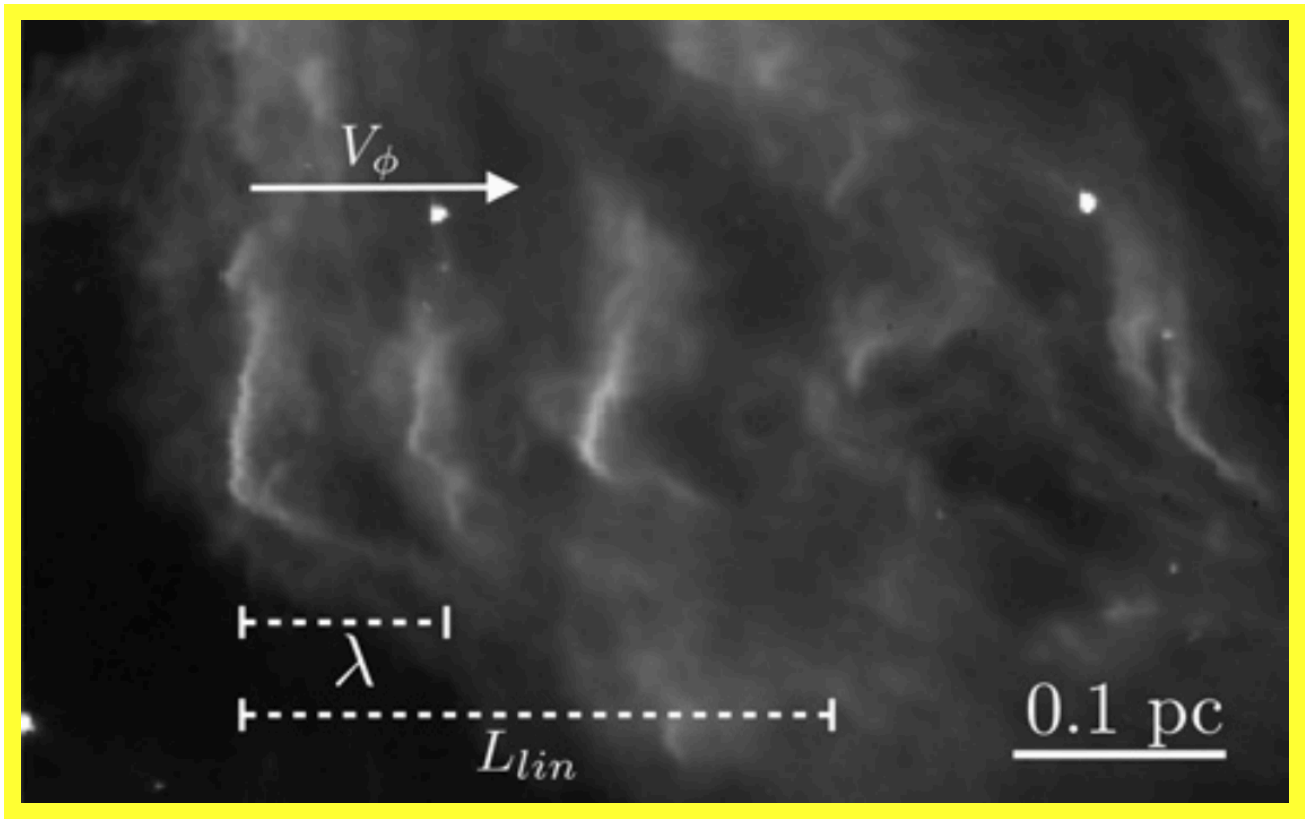


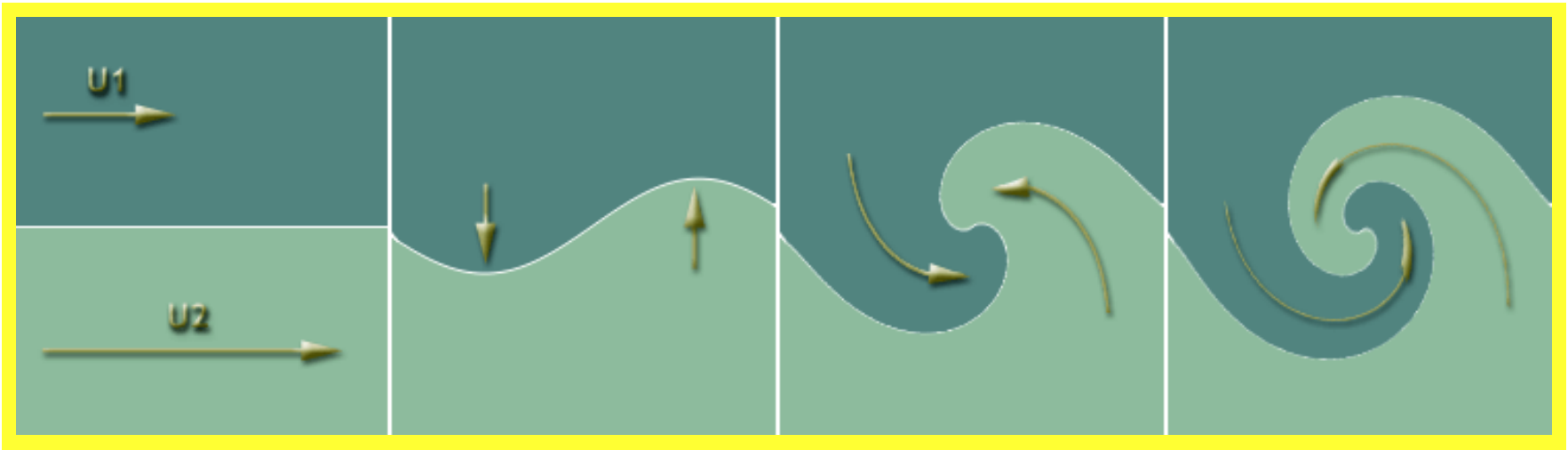
  $\Rightarrow$ EAGLE cosmological simulation (& SKIRT analysis of virtual galaxy morphologies) [Tom Theuns]

- MPI-AMRVAC can e.g. solve gas+dust dynamics (see dustyRM)
  - $\Rightarrow$ dust drag-coupled to gas, each dust bin pressureless fluid
  - $\Rightarrow$ specify number of dust bins in size range $a \in [a_{min}, a_{max}]$
  - $\Rightarrow$ grain-specific density and distribution $n(a) \propto a^{-3.5}$
  - $\Rightarrow$ result: **time evolution of gas and dust densities in space, on block-AMR grid**
- SKIRT: can read in native $*.dat$ format files from MPI-AMRVAC
  - $\Rightarrow$ will typically regenerate grid using dust distribution info, use similar 'bins' and grain size distribution
  - $\Rightarrow$ specify light source (launch photon packages)
  - $\Rightarrow$ MC treatment scattering/absorption/re-emission on dust
  - $\Rightarrow$ output: virtual (infrared) observations, convolved with instrument PSF, also computes temperature for dust particles

Ripples in Orion

- Berné & Matsumoto: Spitzer views on Orion nebula
  - $\Rightarrow$ at 8 μm, clear ripples detected: periodicity, wavelength
  - $\Rightarrow$ hot, low density H_{II} region neighbours cold, dense molecular cloud (only dust present in cloud)
  - $\Rightarrow$ H_{II} region shear flows past cloud flank at 10 km/s

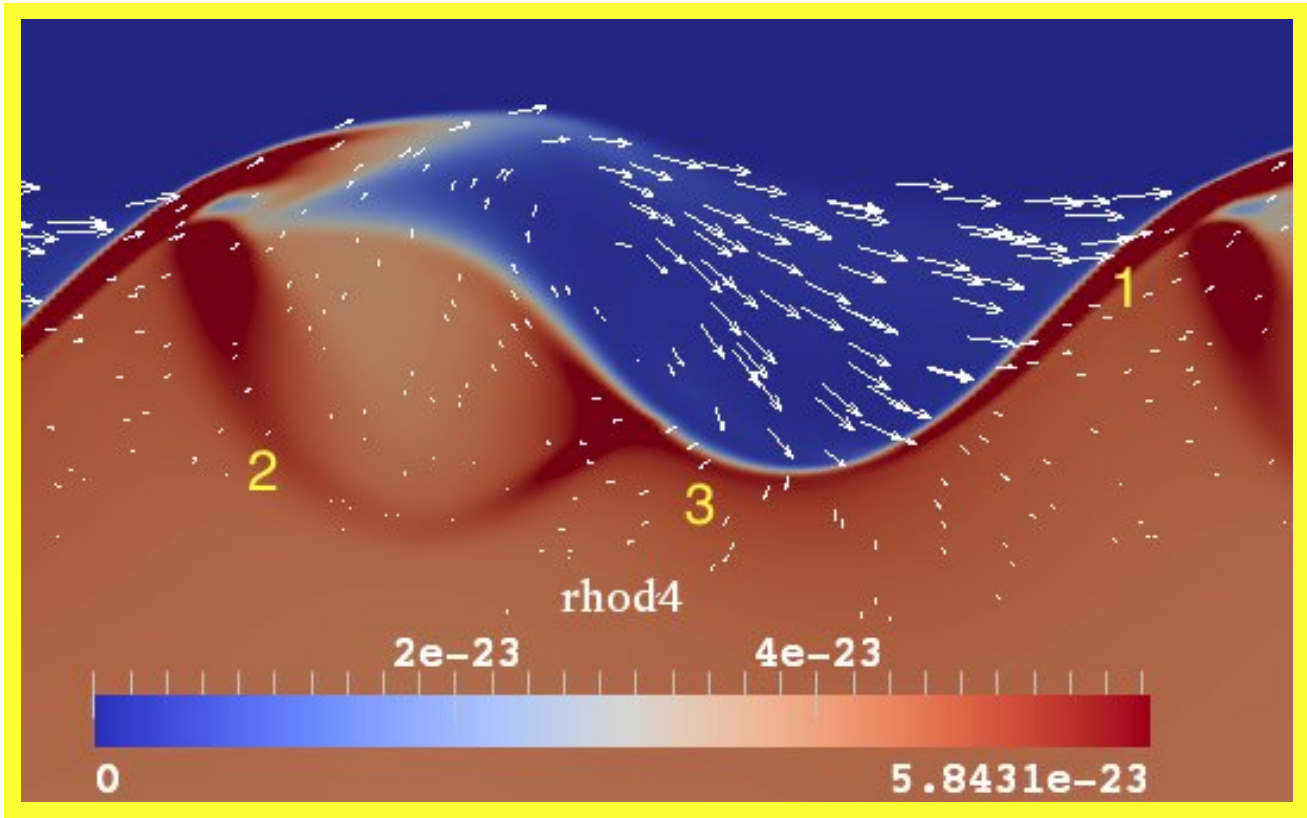



U1
U2

Hendrix et al, 2015: MPI-AMRVAC simulations

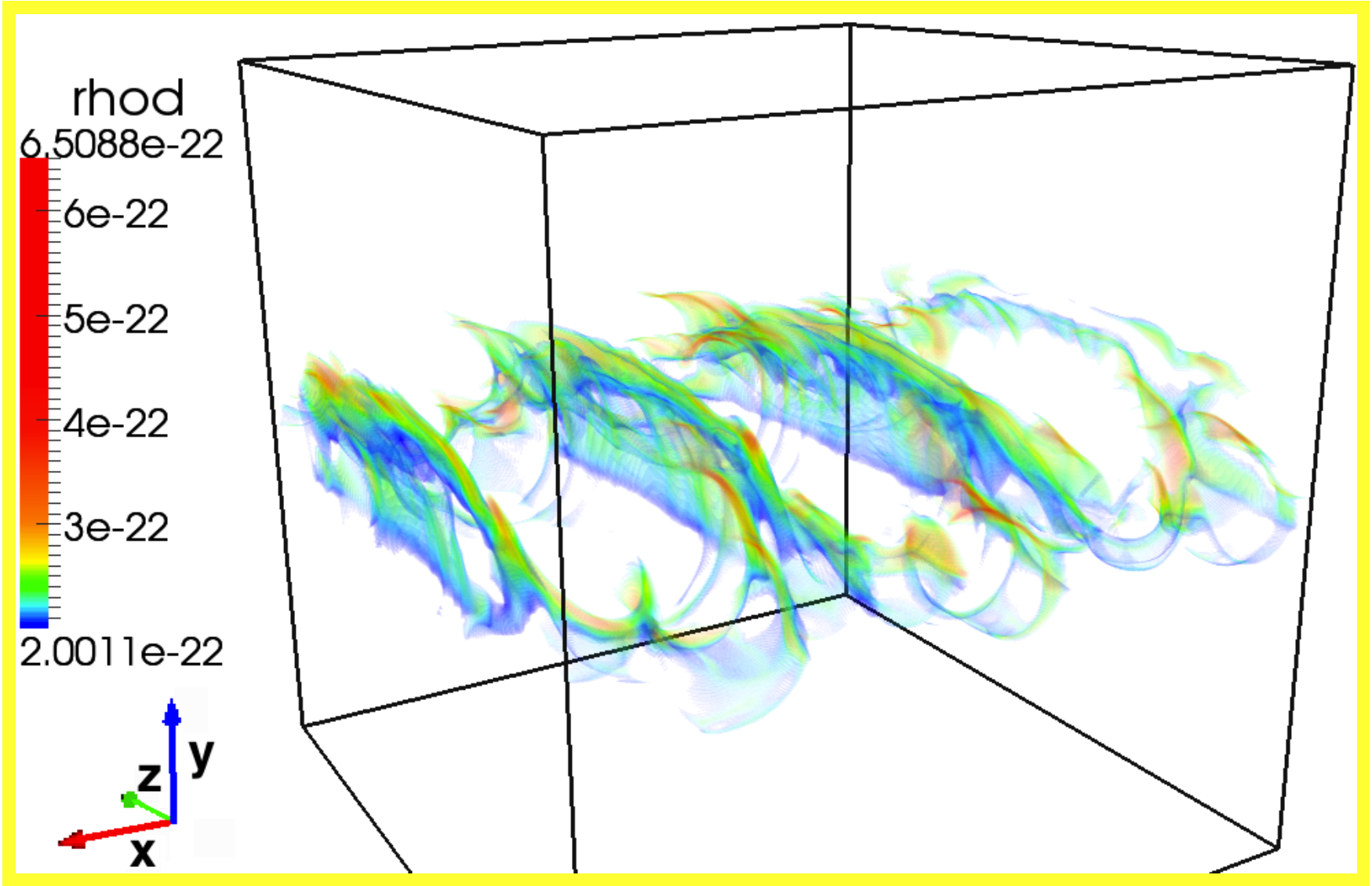
- 3D setup shows (as inferred from observations) Kelvin-Helmholtz development

  $\Rightarrow$ density of largest dust (size 189 nm) with its velocity field

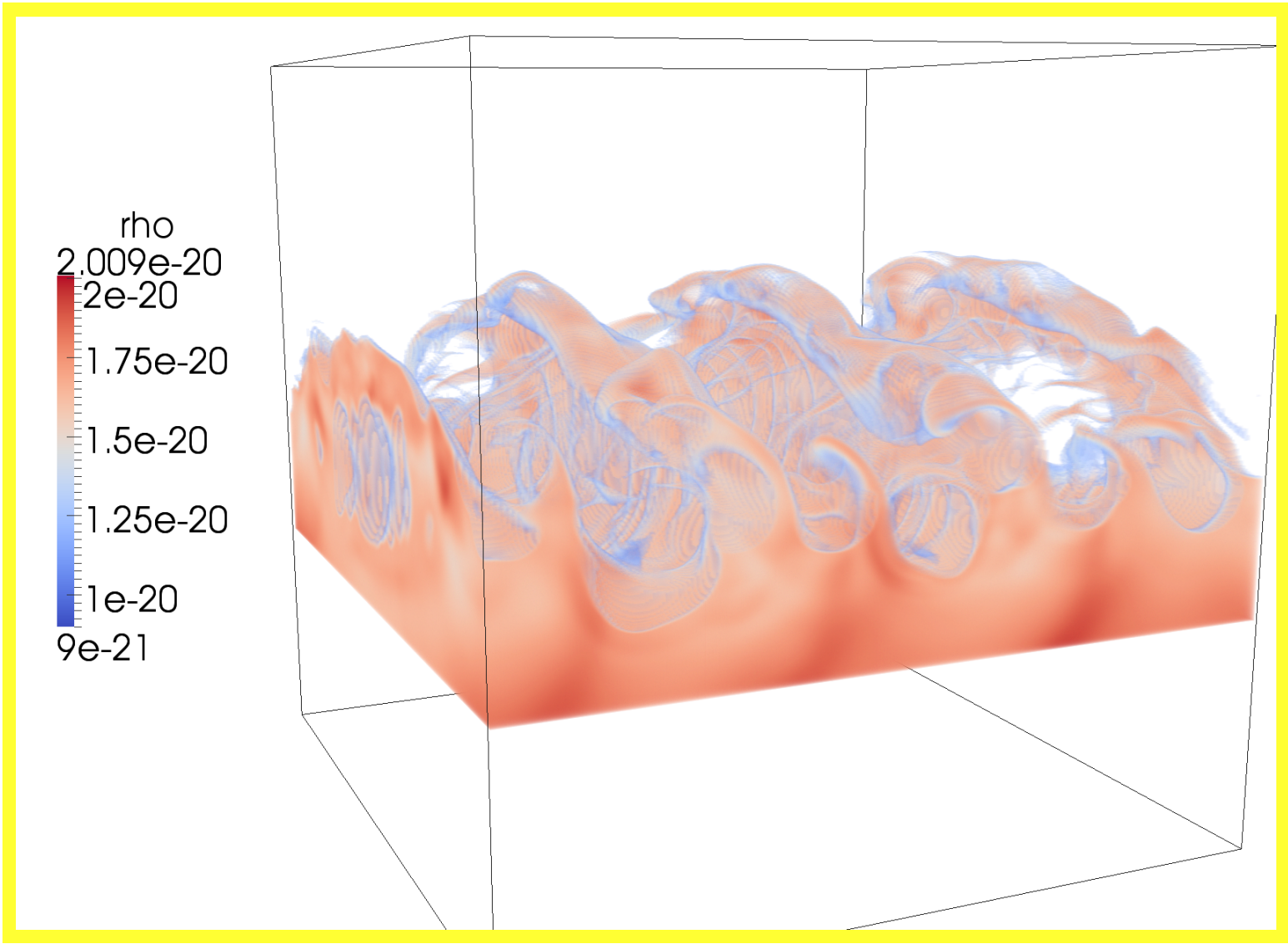


- preferred regions for dust concentrations (flanks KH billows)

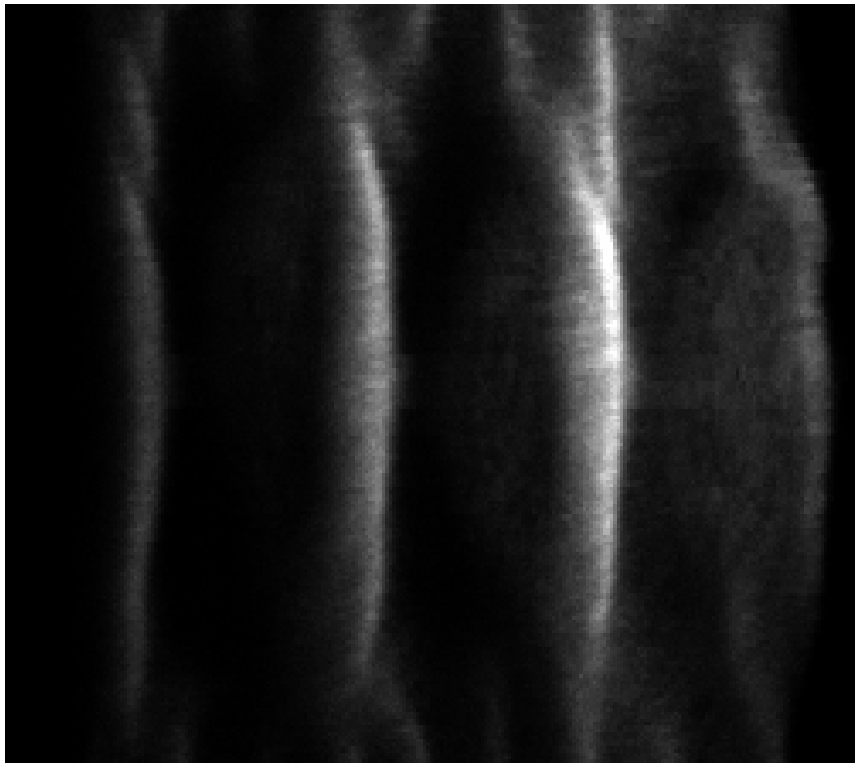
- **3D view on dust concentration** (higher than initial density)

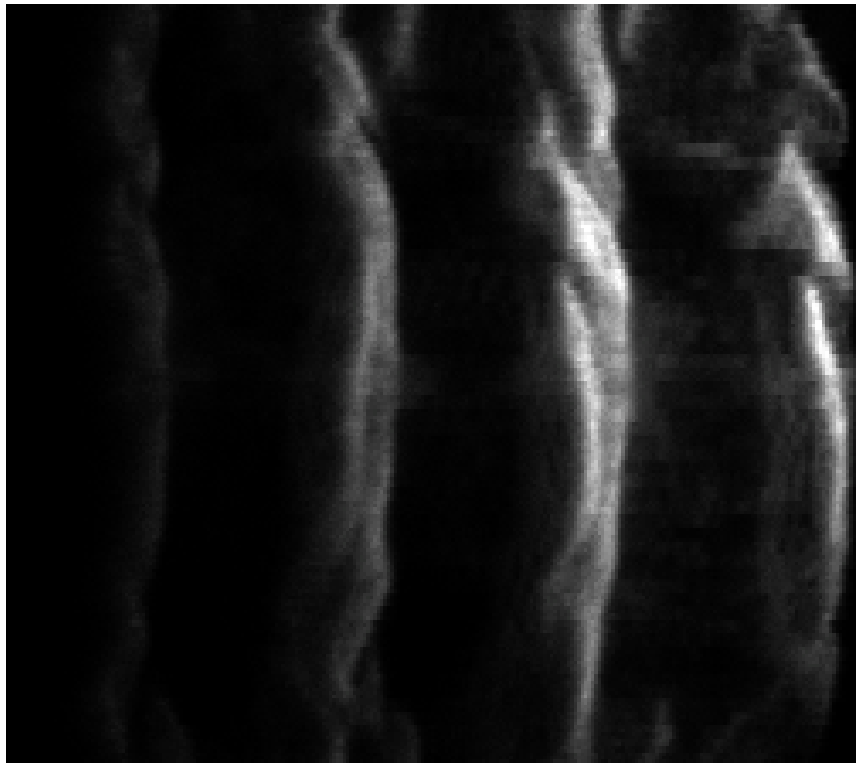


- dust versus gas distribution: markedly different



- SKIRT virtual view at 8.25μm: role of precise relative orientations (source/observer/billows)

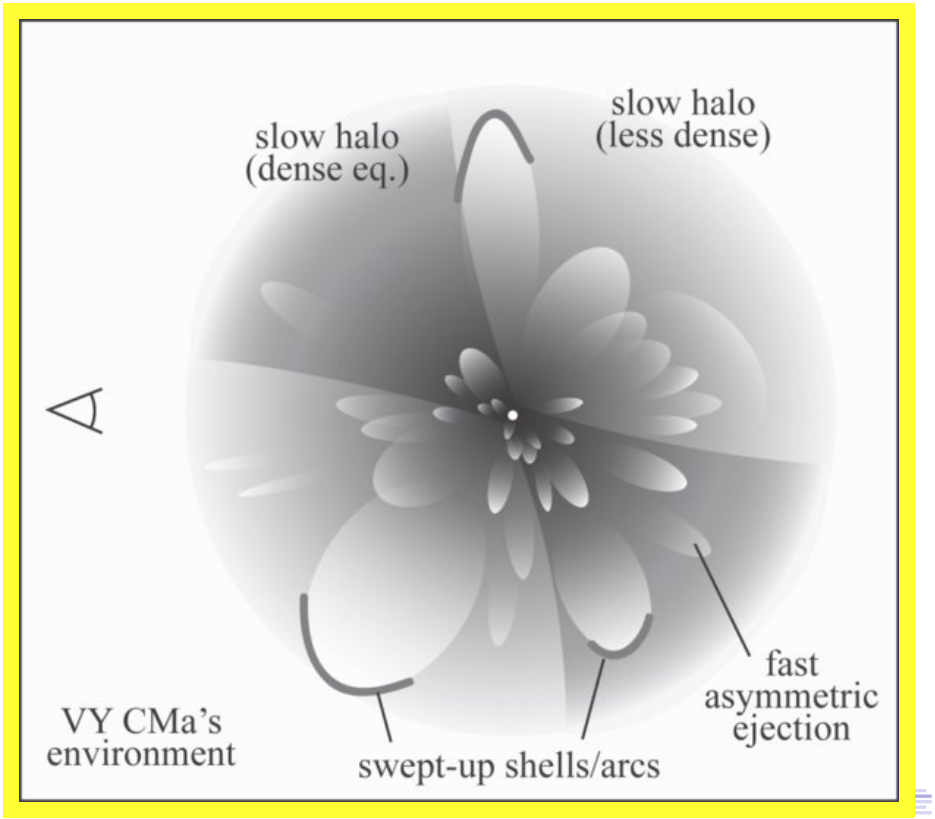




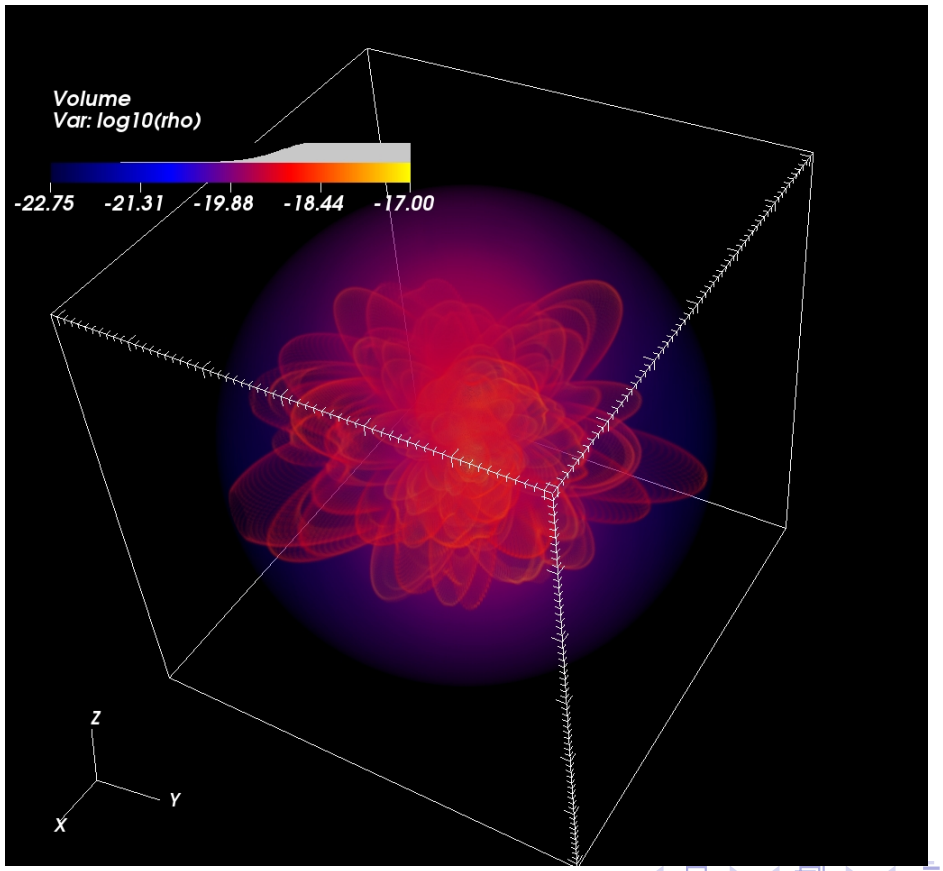
$\Rightarrow$ two consecutive times, KH nonlinear development

Circumstellar environments

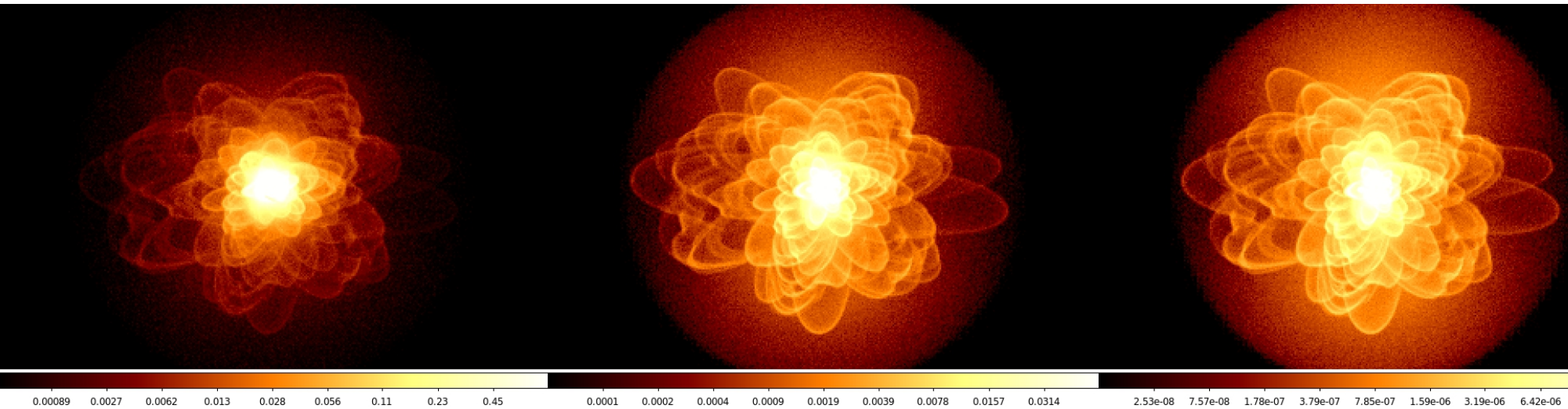
- 3D modeling of stellar wind environments now possible!
  - $\Rightarrow$ 3D effects key for e.g. red supergiants (Betelgeuse or VY Canis Majoris) [*Smith et al, Astron. J. 137, 3558, 2009*]
  - $\Rightarrow$ episodic mass ejections in steady wind
  - $\Rightarrow$ Cartoon pre-supernova environment for VY CMa



- **van Marle et al**: assume 3D bipolar steady outflow (25 km/s, typical mass loss rate for RSG), superpose randomized bursts (once every 10 years): **VY CMa modeling**
  - $\Rightarrow$ 3D gas + dust evolution, cover $\mathcal{O}(2000)$ yr timescale
  - $\Rightarrow$ grid-adaptive spherical grid (3 levels, $\mathcal{O}(100^3)$ base)
  - $\Rightarrow$ volume rendering gas density, full resolution



- MPI-AMRVAC simulation and SKIRT analysis: emission at wavelengths probable by James Webb [MIRI 5μm], Herschel (112μm, no longer available), ALMA [500μm] [ideal resolution]



$\Rightarrow$ 2 dust species, drag-coupled to the gas

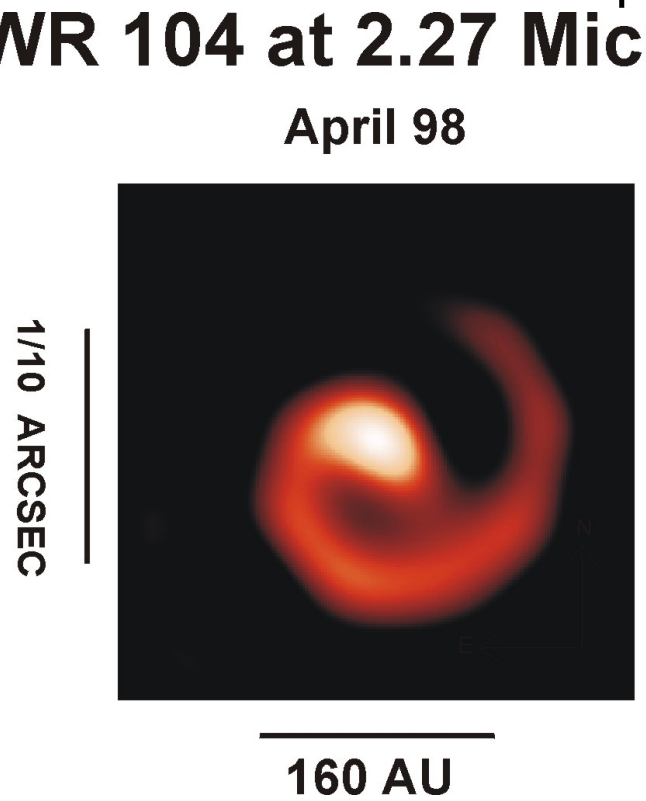
$\Rightarrow$ representing 10^{-8} to 10^{-5} m sized dust grains ($a^{-3.5}$)

3D simulations meet 3D printing!

van Marle et al. (3D HD simulations for a red supergiant circumstellar environment)

Need for dust inclusion

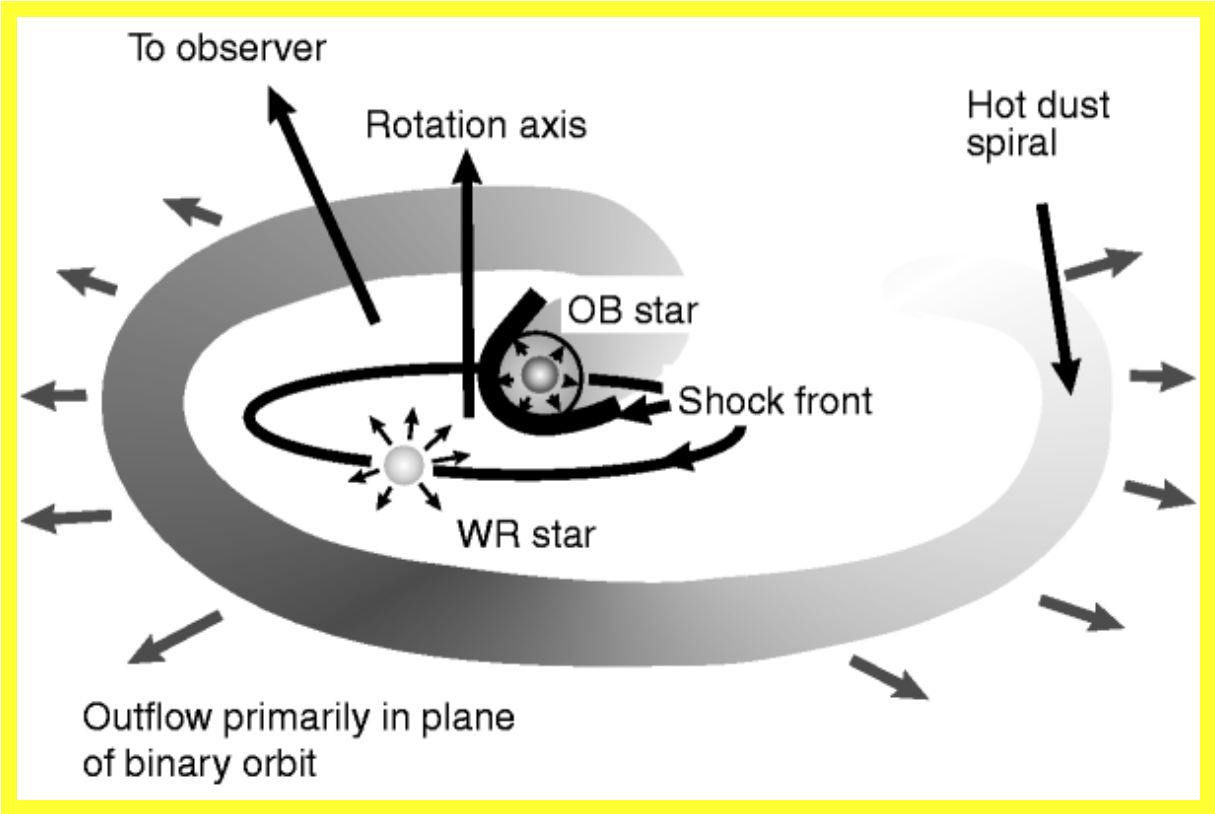
- larger scale models needed for systems like Wolf-Rayet 104
  - $\Rightarrow$ known binary with Wolf-Rayet and luminous blue OB star
  - $\Rightarrow$ bow shock about OB star: hot dust spiral, **seen in infrared**



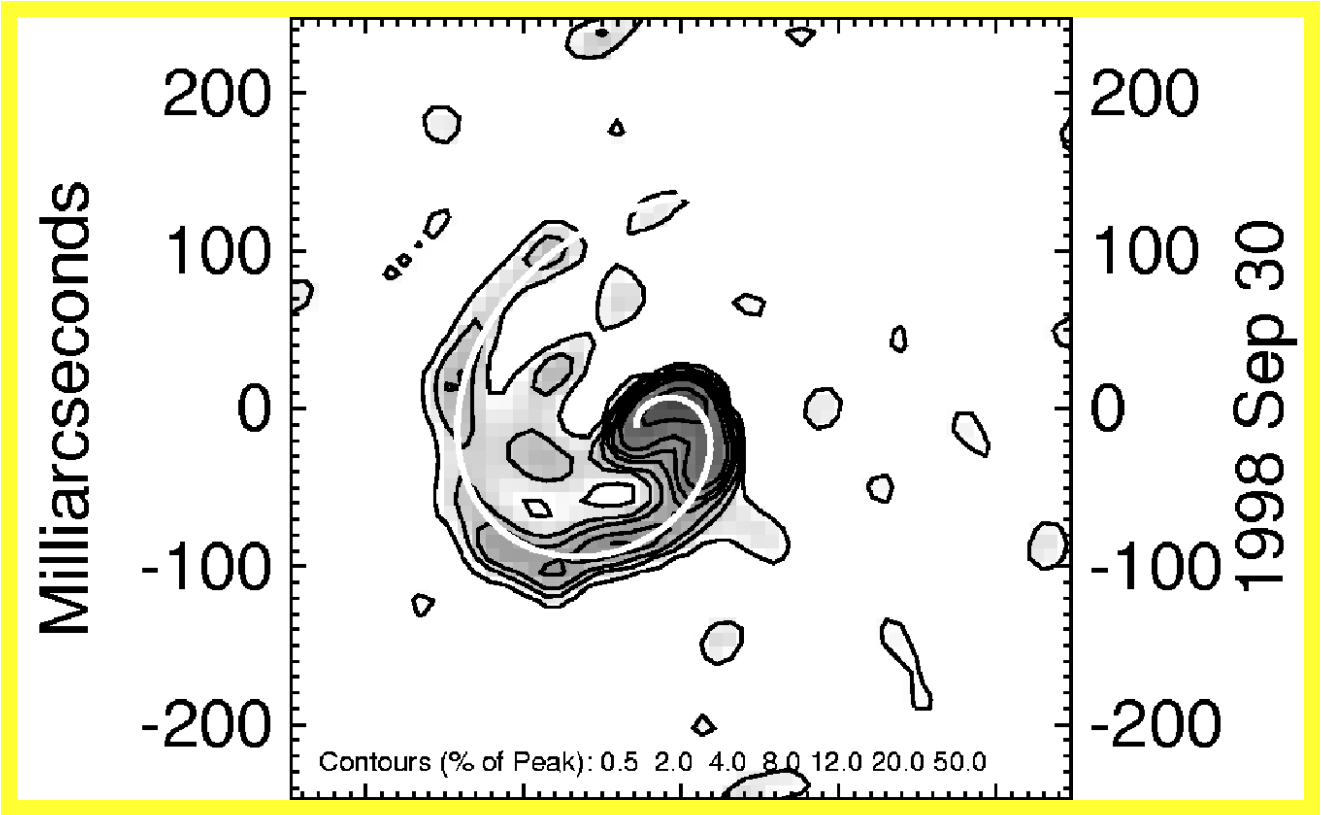
  - $\Rightarrow$ *cfr. Nature 398, 487, 1999*
- puzzling to find dust in WR circumstellar environment!

- 3D gas + dust hydro simulations: Tom Hendrix et al. (dr. since 10 september 2015)

  $\Rightarrow$ binary WR98a: $10M_{\odot}$ WR star and $18M_{\odot}$ OB companion



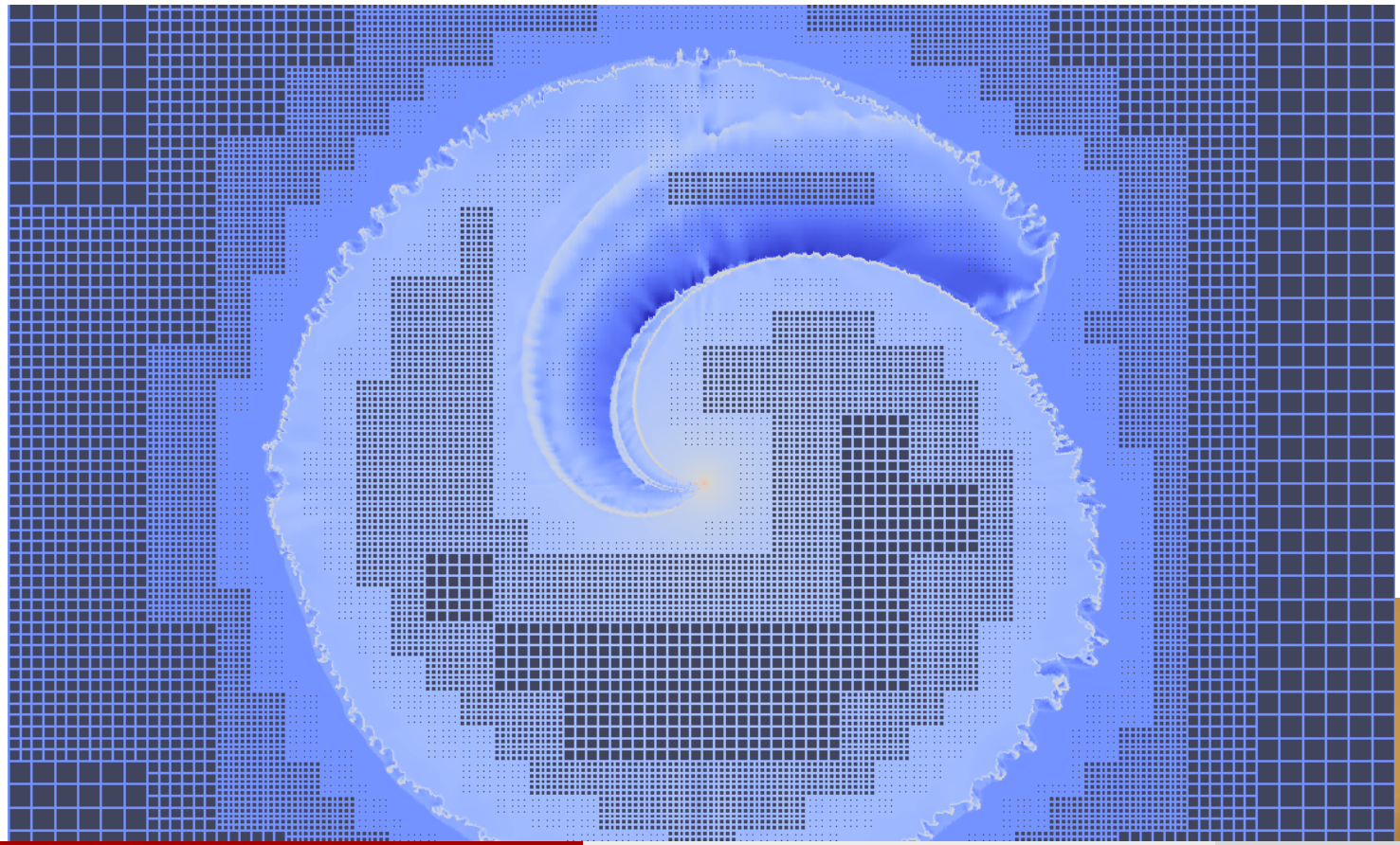
- historic observations at 2.2 μm [Monnier et al, 1999]

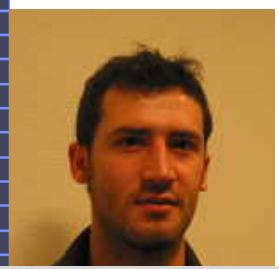


$\Rightarrow$ important parameter: momentum flux ratio of stellar winds

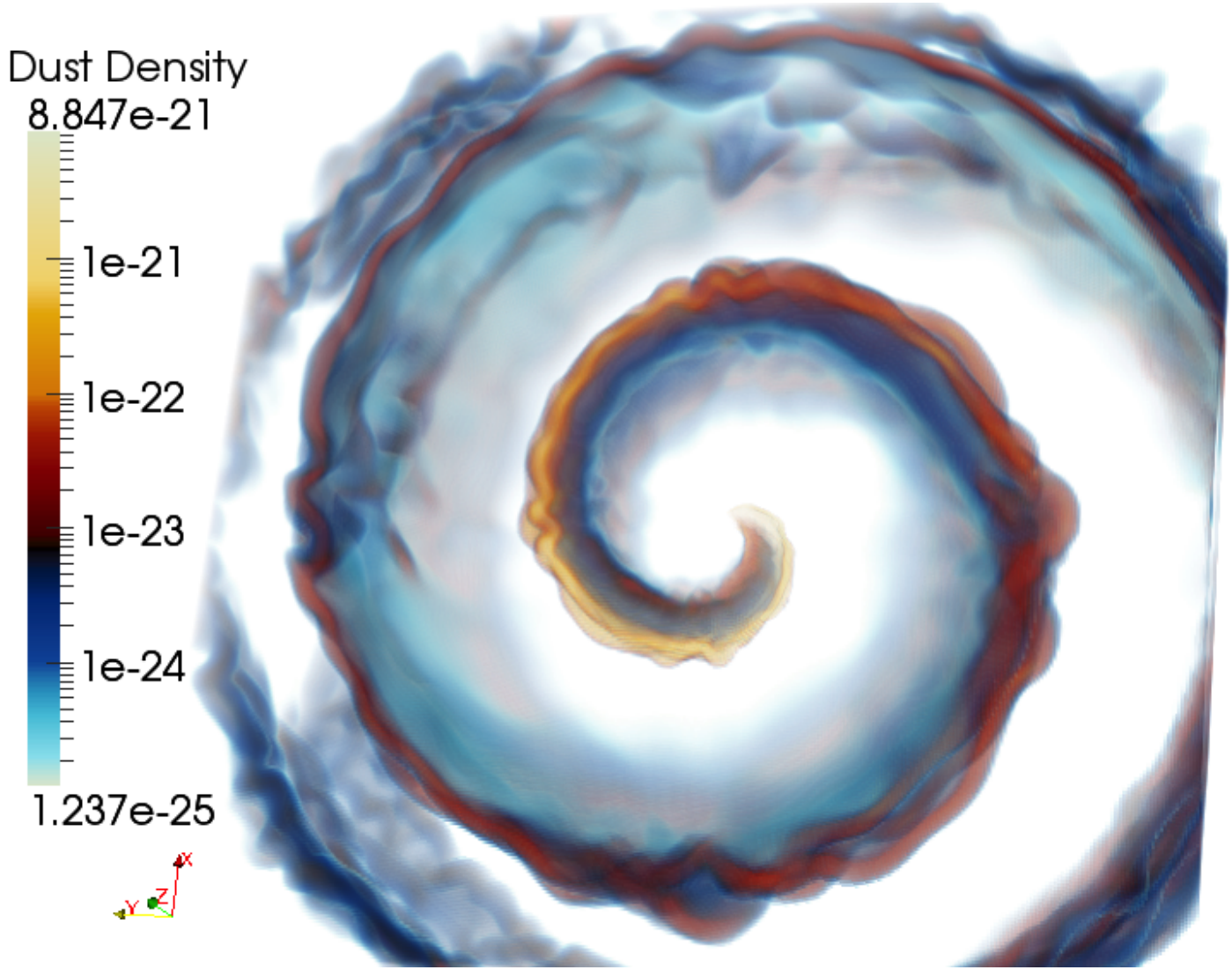
$\eta \approx 0.022$ (WR dominant), separation is 4 AU (period 565 days)

- domain of size 320, 320, 140 in separation units, 11 AMR levels, effective resolution $81920 \times 81920 \times 24576$
  - $\Rightarrow$ internal boundaries for wind zones on Keplerian orbit
  - $\Rightarrow$ tracers for identifying mixing zone between both winds
  - $\Rightarrow$ mixing used in heuristic model for dust insertion/creation
- **Wolf-Rayet binaries: even 13 AMR levels in 2D variants**





Wolf-Rayet binaries:2D cases with eccentric systems



Wolf-Rayet binaries:3D mixing zone evolution

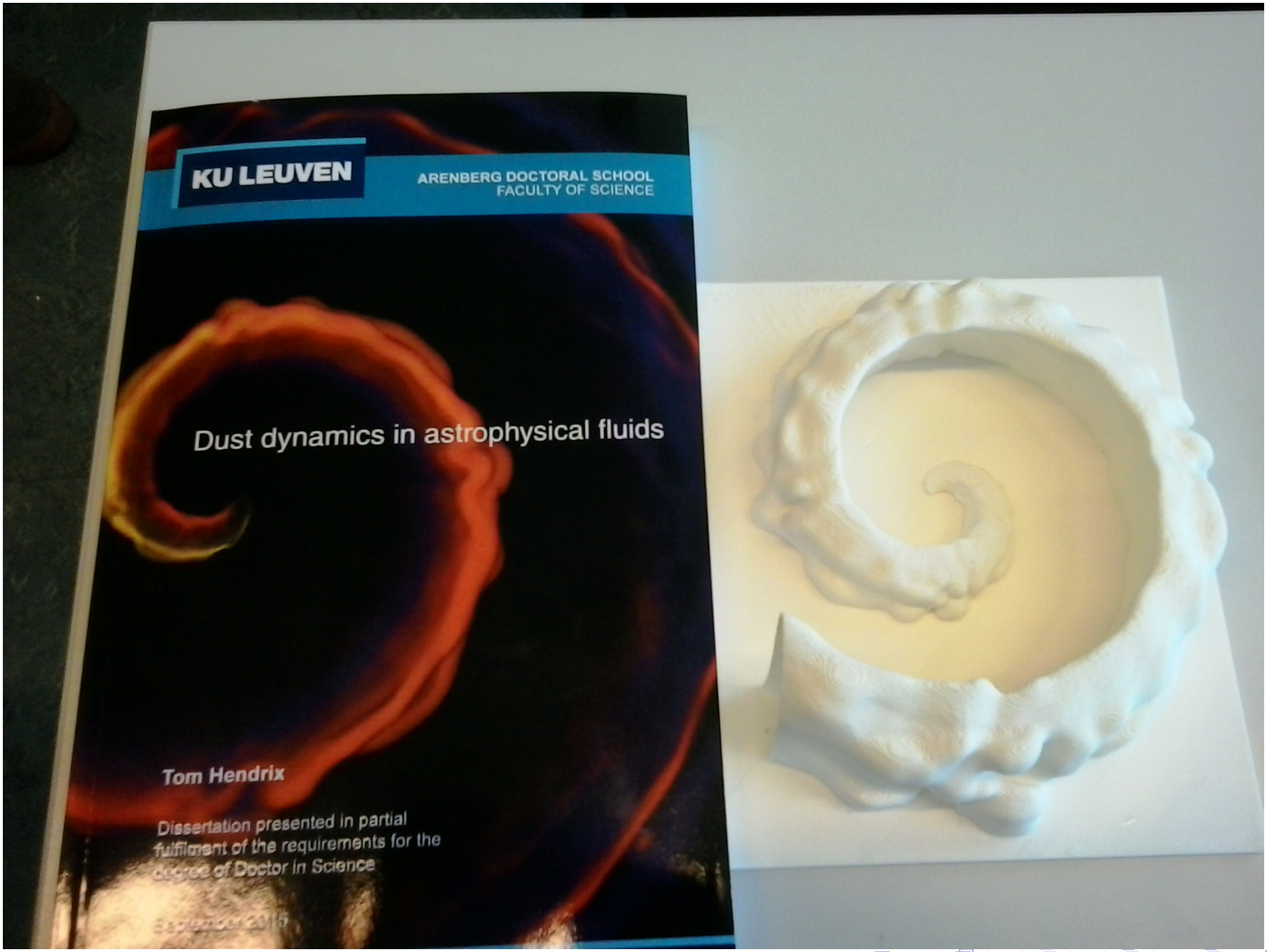
- Keck or ALMA resolutions (virtual views with SKIRT postprocessing of dust distribution, using realistic stellar SEDs for illumination) [20 vs 2 pixel convolutions]

  $\Rightarrow$ **WR98a@Keck [2.4μm]** vs **WR98a@ALMA [400μm]**

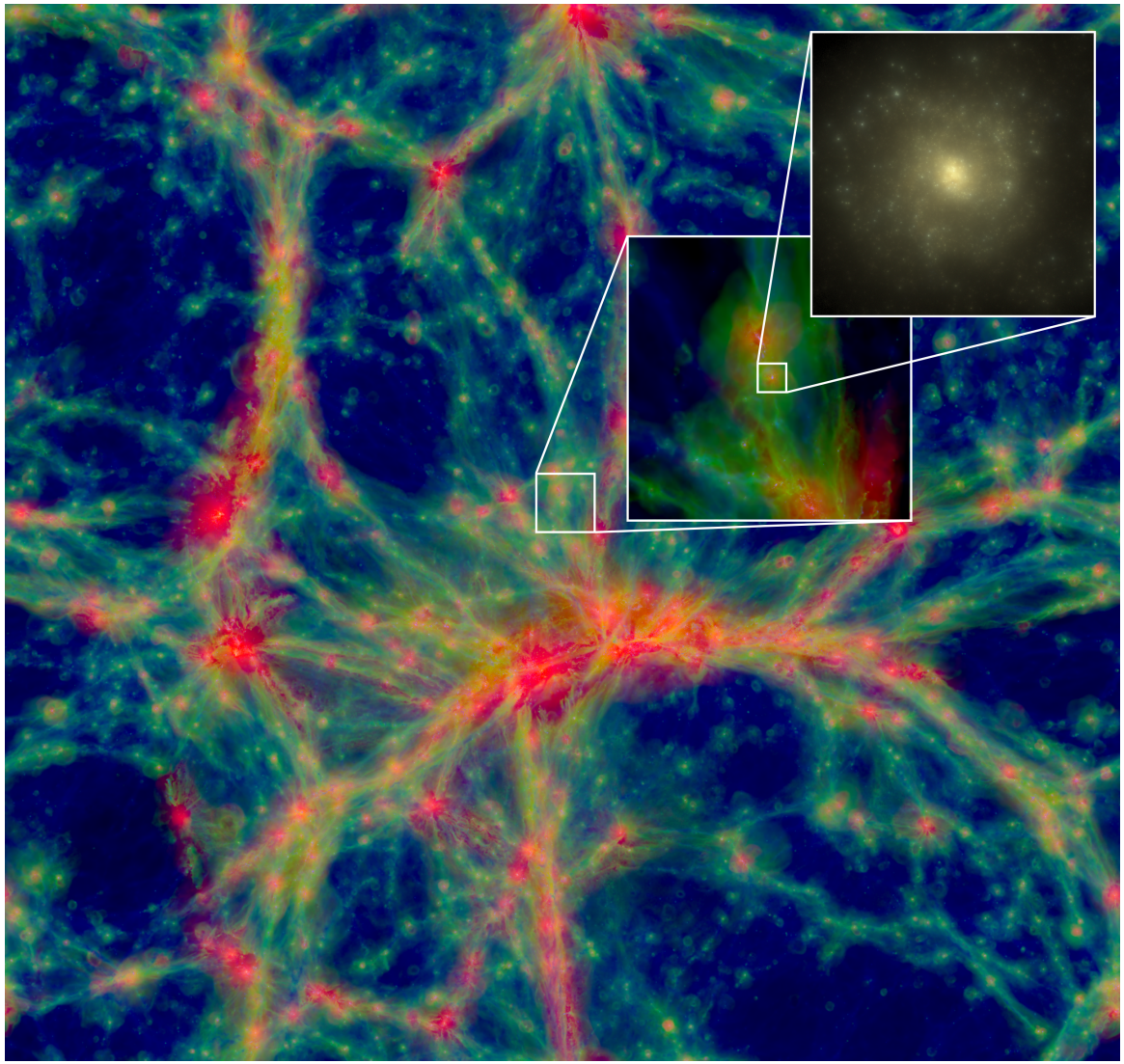
- effects studied:

  $\Rightarrow$ 2D parametric survey of radiative cooling efficiency **(clumpiness in winds)**

  $\Rightarrow$ 3D dust redistribution: trailing-leading spiral arm asymmetries (dust view not same as high density zone view)


KU LEUVEN
ARENBERG DOCTORAL SCHOOL
FACULTY OF SCIENCE
Dust dynamics in astrophysical fluids
Tom Hendrix
Dissertation presented in partial
fulfilment of the requirements for the
degree of Doctor in Science

- The Eagle has landed ! [Tom Theuns] 10000 galaxies in a (expanding, cosmological) box.... `icc.dur.ac.uk/Eagle/`



- largest SPH simulation for box with sides 100 Megaparsec
  $\Rightarrow$ SKIRT views on individual galaxies (Hubble sequence)