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28 January 2007

Exploring Winds of Massive Stars

In honor of the birthday of Prof. J.C. Brown

University of Glasgow

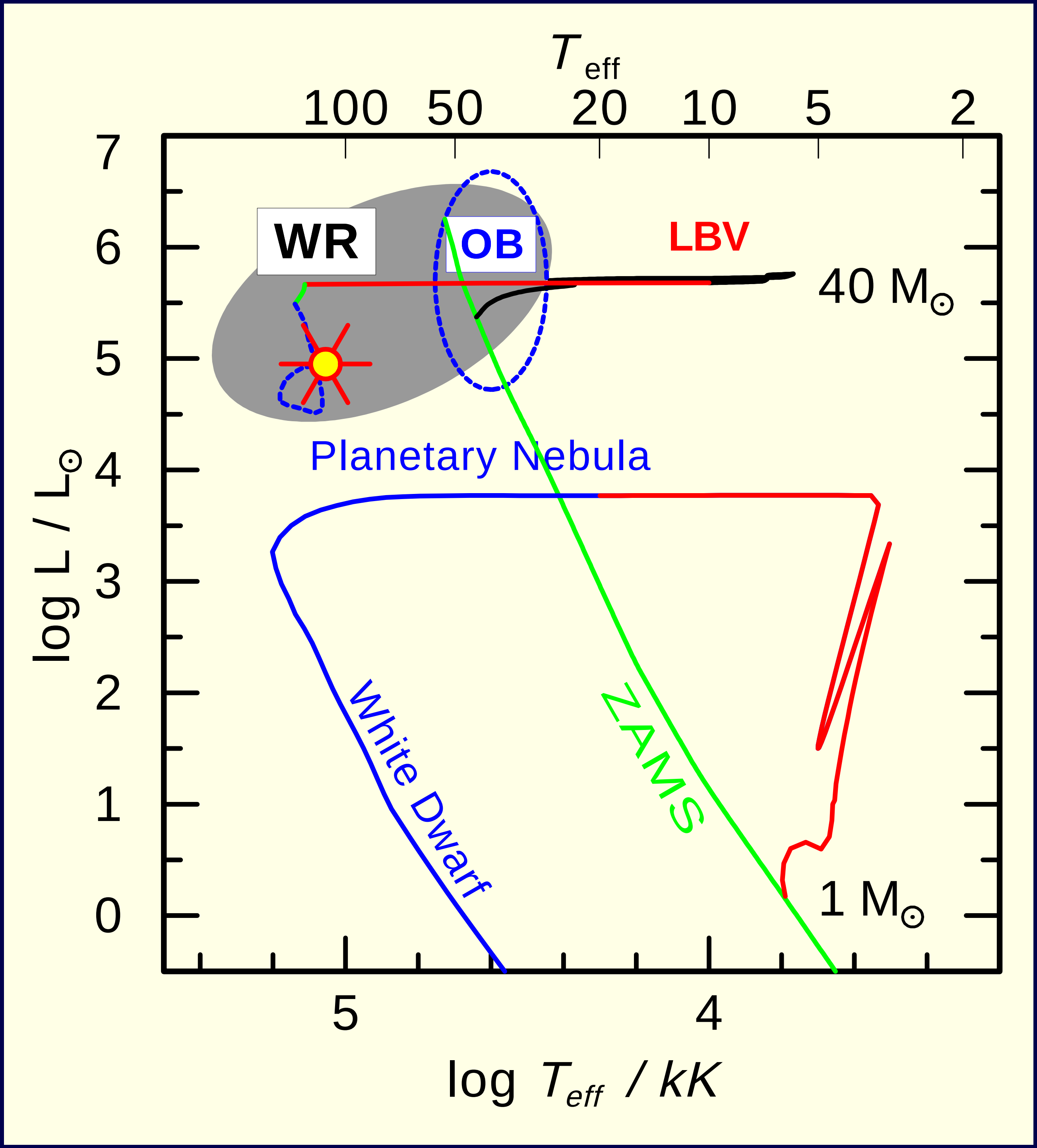
Massive Stars and Stellar Winds

$$M_* > 8M_\odot$$

Live Fast, Die Young (~ few Myr)

- $T_{\rm eff} > 10\,000$ K $\rightarrow$ high surface brightness
- Light: momentum (+ energy) $\rightarrow$ force to the scattering atoms
- Light force > gravitational force $\rightarrow$ **STELLAR WIND**
- Radiative driving is by line scattering
- Moving media: Doppler: line width $\Delta\nu \propto v$
- Feedback: radiative driving force depends on acceleration

The evolution of (very) massive stars



Evolution ← stellar wind (!)

- O and B type stars
- Luminous Blue Variables
- Wolf-Rayet (WR) stars

According to dominant spectral lines

WN (nitrogen) →

WC (carbon) →

WO (oxygen) →

The cosmic role of massive stars

Massive stars provide
- ionizing radiation
- kinetic energy (stellar winds, SN)
- chemical yields

Star formation in stellar clusters is
- triggered
- regulated
- terminated

by massive stars

NGC 602 in the SMC (HST)

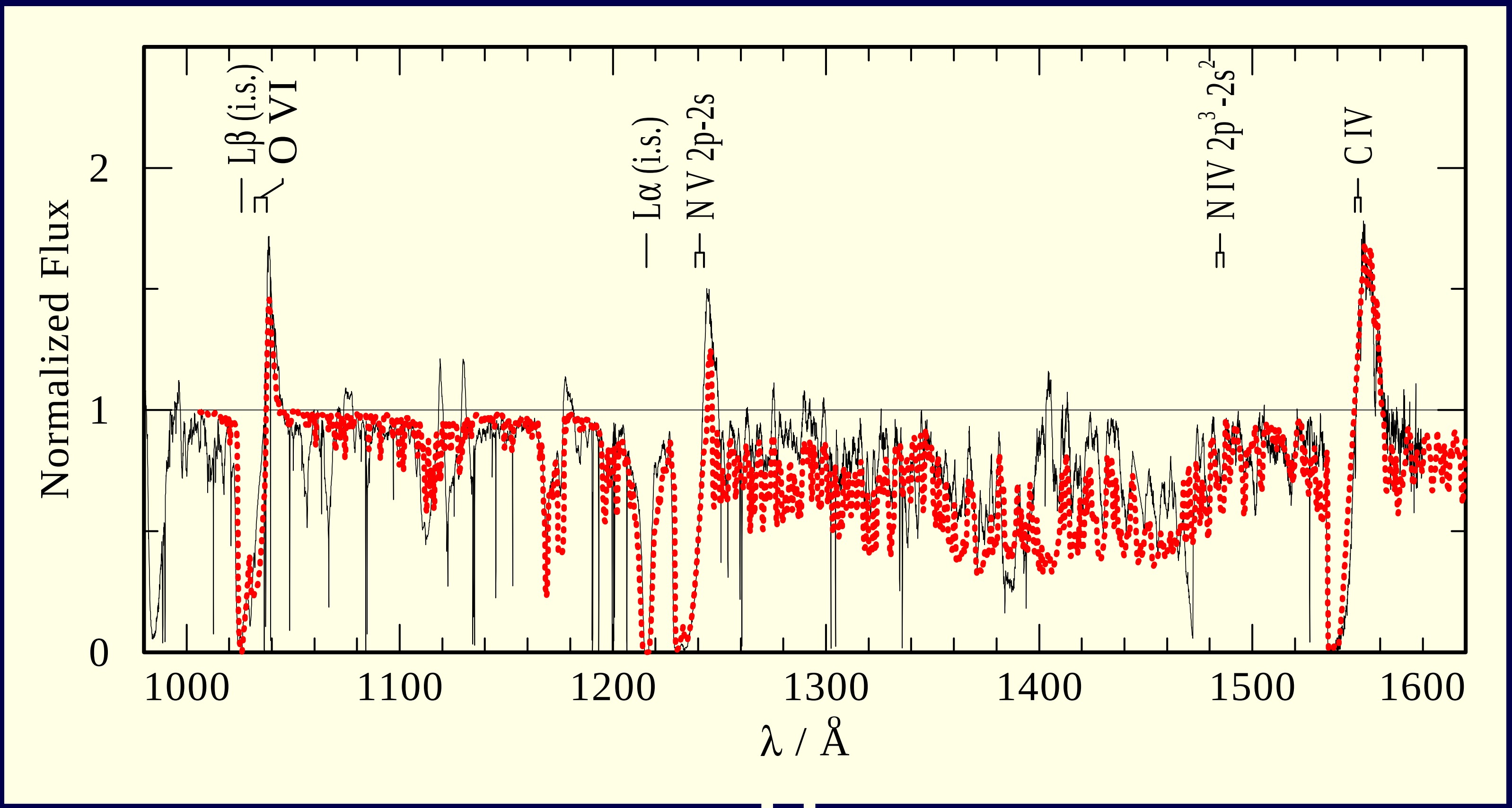
To understand visible Universe

we shall quantify the action of massive stars

Image: HST & JCB

Spectra of O-type stars (signatures of mass-loss)

- Hα in emission
- P Cygni profiles of UV resonance lines
- Thermal radio emission
- Superionization



IUE spectrum (black)

O-supergiant ζ Puppis

Model with X-rays (red)

Lamers & Cassinelli (1999)

"Introduction to STELLAR WINDS"

⇓

- Outflow of matter with speed $\upsilon \sim \mathrm{few} \times 10^3$ km/s or $\sim 1\%$ c
- Loss of mass $\dot{M} \sim 10^{-5..-7}\, M_\odot/\mathrm{yr} \approx$ 50 000 billion tonn per sec.

Line profile variability

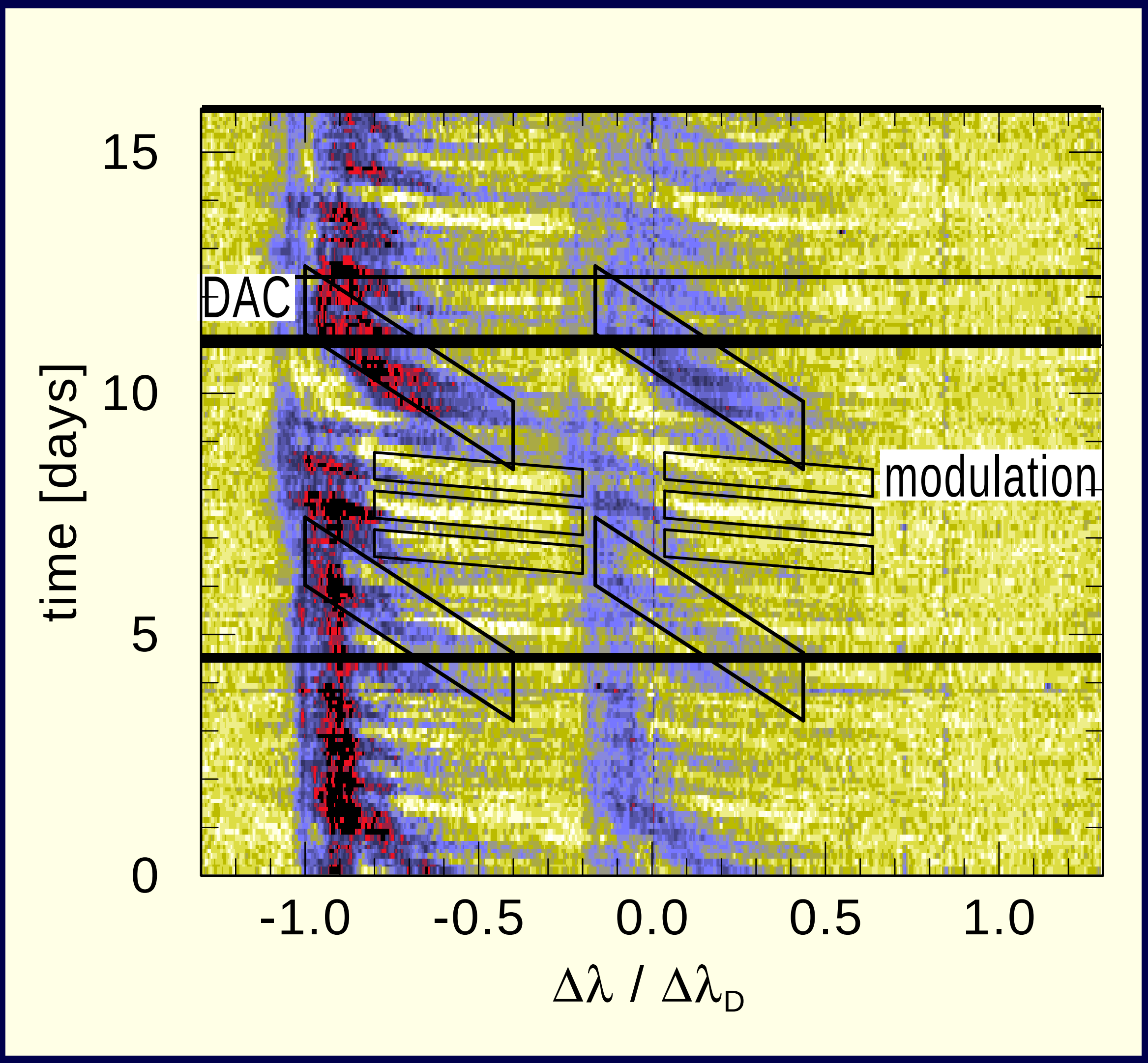
Theory of radiatively driven winds $\Rightarrow$ $v(r) \simeq v_\infty(1 - R_*/r)^\beta$, β=0.5..0.8

Continuity equation $\Rightarrow$ $\rho(r) = \dot{M}/4\pi r^2 v(r)$

Smooth monotonic accelerating radial outflow

Observations: IUE MEGA Campaign (Massa et al. 1995)

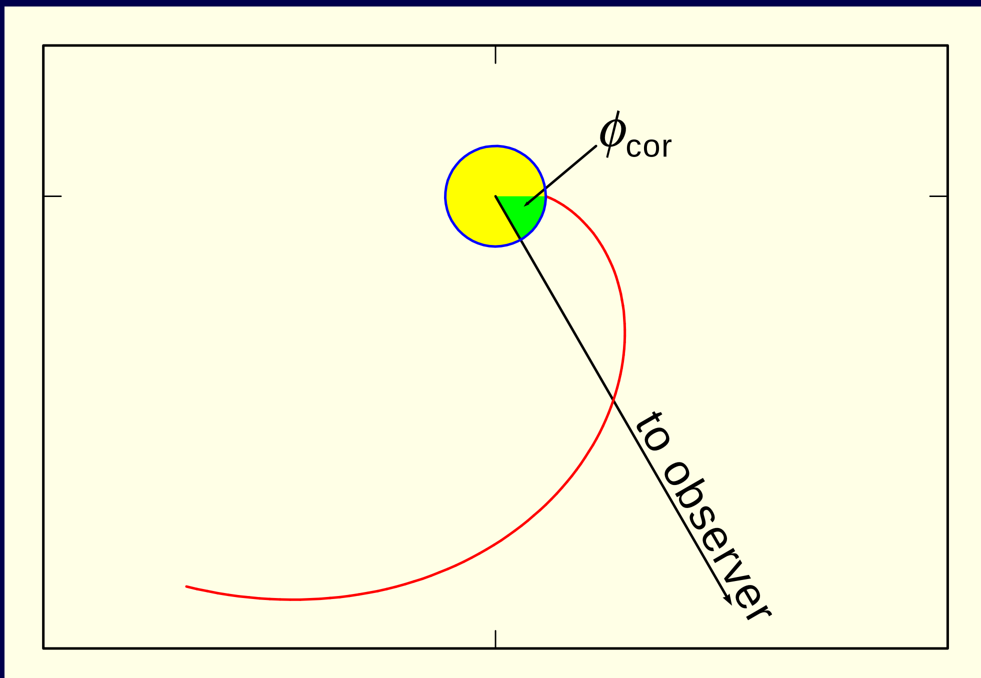
ζ Puppis Si IV resonance doublett: single observation minus mean template



Two types of *periodic* variations:

- Discrete Absorption Components
  DACs
  P(ζ Pup) = 5.21 days - Rotation (?)
  Observed in **ALL** O stars
- Modulations
  Lack of absorption (?)
  P(ζ Pup) = 19.2 hours
  no integer fraction of P (DAC)
  Obsevred sometimes

Rotationally-recurrent Line Profile Variations (LPV)



Structures with enhanced optical depth
Time-independent co-rotating pattern
Corotating Interaction Regions (CIRs)
(Mullan 1984, Cranmer & Owocki 1996, Hamann, Brown & Feldmeier 2001)

- Surface structures (spots?)
- Azimuthal variation of wind velocity
- Collision of fast / slow winds
- Spiral pattern in *Corotating frame*

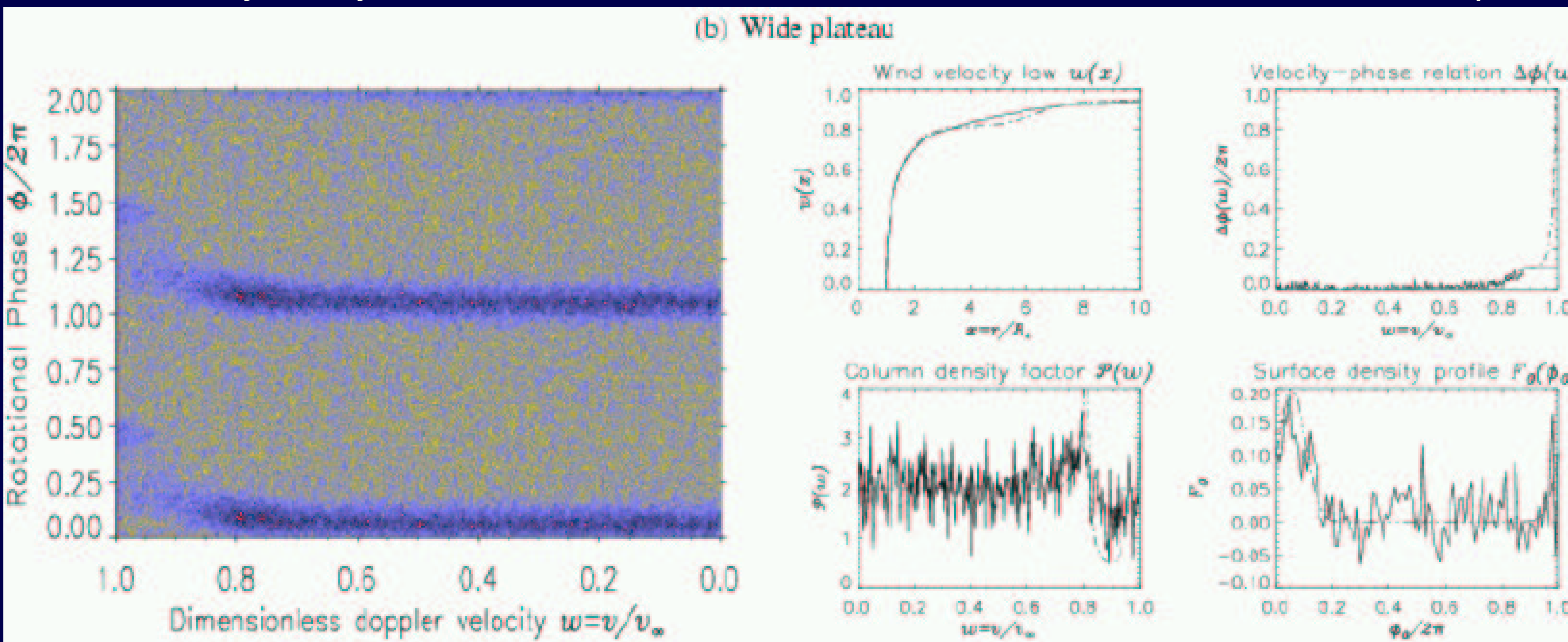
Model of rotationally-recurrent line profile variations (Brown et al. 2004)

- No specific dynamical assumptions
- Kinematical approach: any $v(r) + \dot{M}(\theta, \phi) \longrightarrow$ LPV
- Inverse problem (Craig & Brown 1986)
- Information content of data and verificaiton of the models

Inference of density stream properties from DACs

Brown et al. (2004):

- Optical depth $\tau(w, \varphi)$, where $w = \frac{\Delta\lambda}{\lambda}\frac{c}{v_\infty}$ and φ stellar rotation angle
- Bivariate relationship: $\tau(w, \varphi) \longleftrightarrow v(r),\ \Omega(r),\ \rho(r, \varphi)$
  $v(r)$ radial velocity, $\Omega(r)$ transverse rotation rate, $\rho(r, \varphi)$ density of the wide stream
- Inversion $\rightarrow$ complete information on all three distribution functions
- Data: different effects superimposed
- Check of hydrodynamic CIR models: Krticka, Barrett, Brown & Owocki (2004)



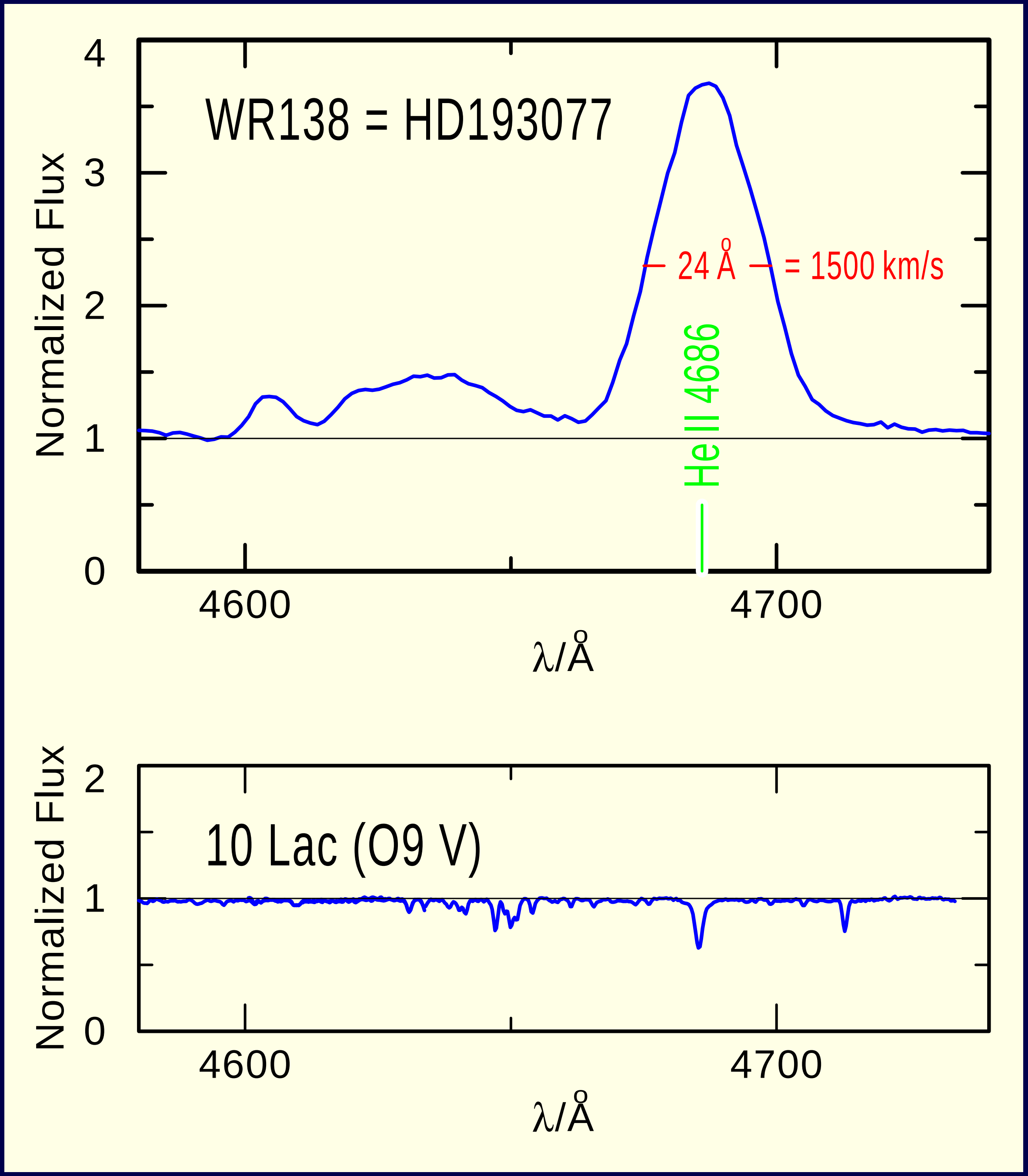
from Brown, Barrett, Oskinova, Owocki, Hamann, de Jong, Kaper, Henrichs (2004)

Wolf-Rayet (WR) stars: their unique spectral appearance

Discovery report: 1867,
letter to the *Academie Francaise*
by C. Wolf & G. Rayet:
“3 stars with bright emission lines
in Cygnus”

Spectrum of a Wolf-Rayet Star
dominated by emission lines

$$\dot{M}(\mathrm{WR}) \approx \mathrm{few} \times \dot{M}(\mathrm{O})$$

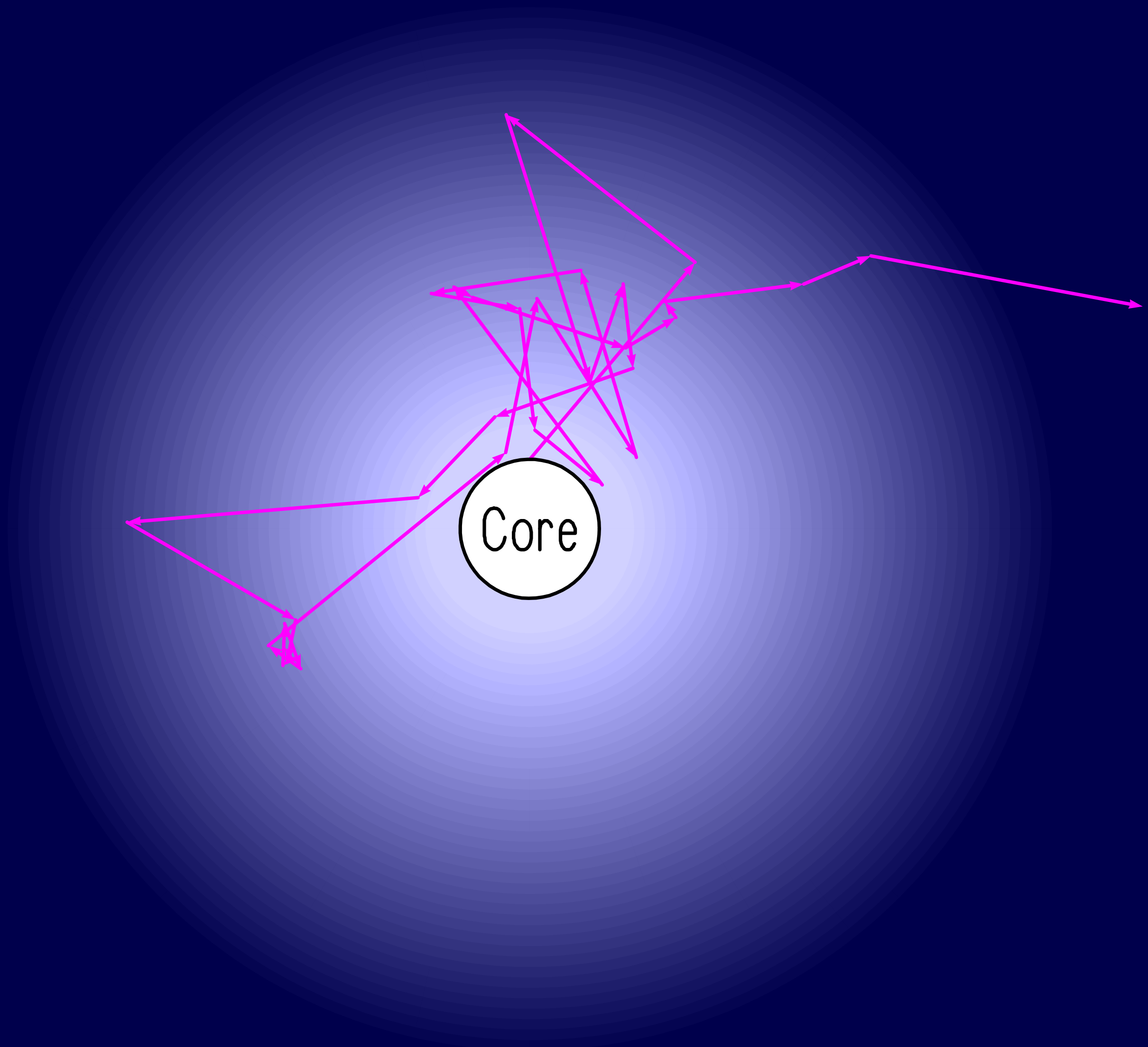


For comparison: Spectrum
of a main-sequence star with
similar effective temperature

How are the strong Wolf-Rayet winds driven ?

- CAK theory works fine (?) for OB stars
- ... but principally fails for WR stars: $L/c < \dot{M} v_\infty$

WR mass loss exceeds the *single-scattering limit*



! *full* radiative transfer + hydro !
(Graefner & Hamann 2004)

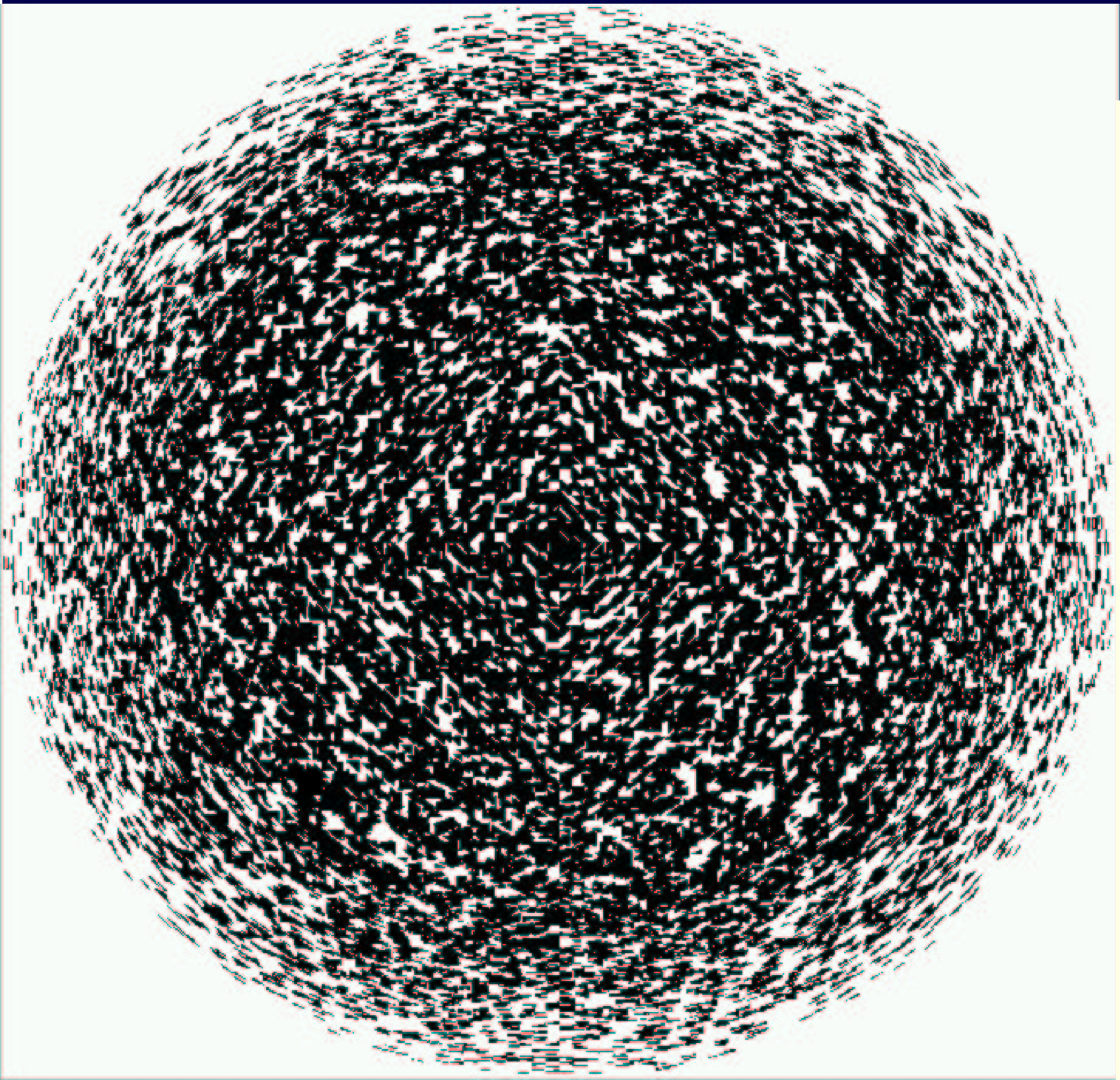
! Fitting the emission line spectra $\longrightarrow L, \dot{M}, v_\infty$

-> New sources of opacity are needed to increase driving force.

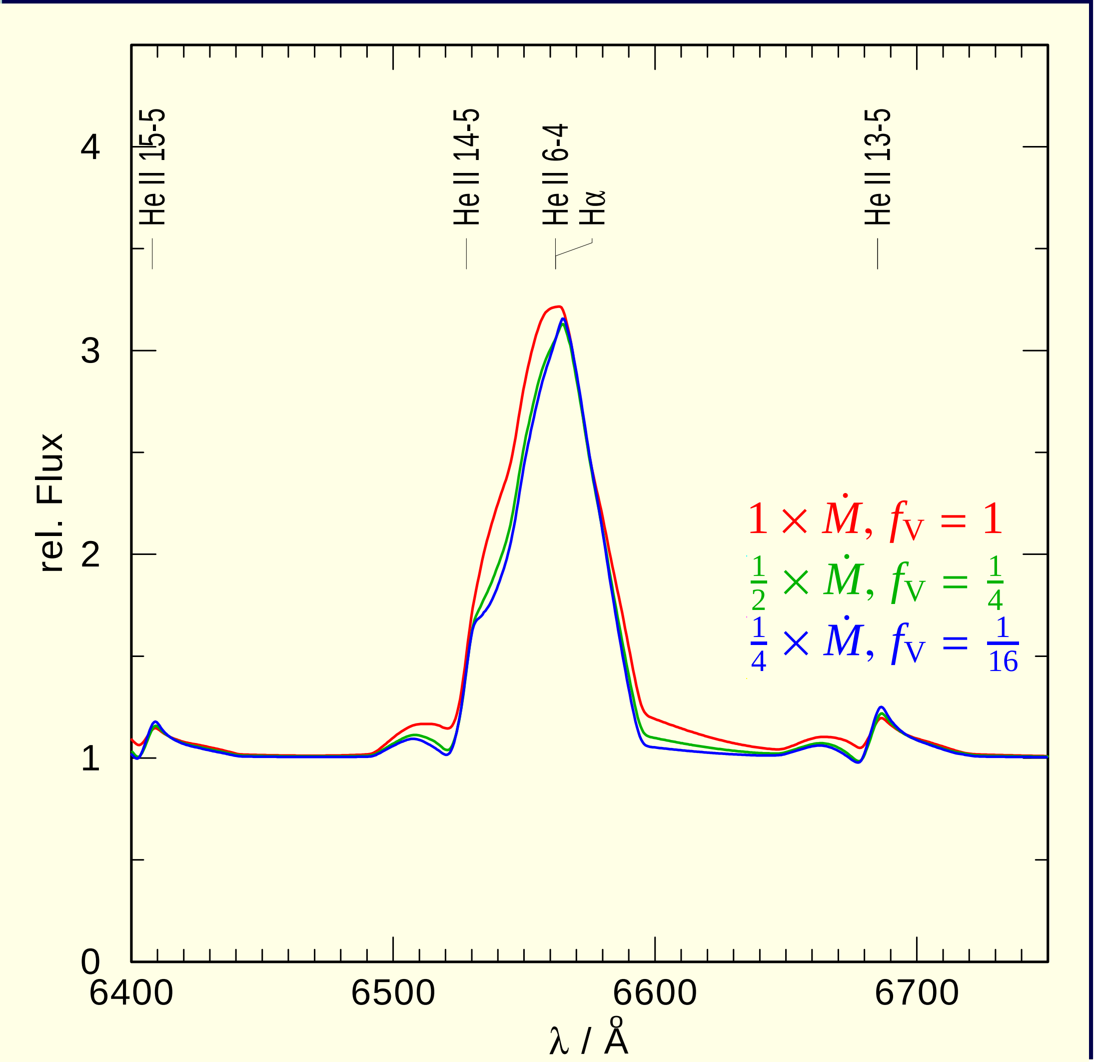
-> Empirically derived $\dot{M}$ shall be reduced

Empirical mass-loss estimates

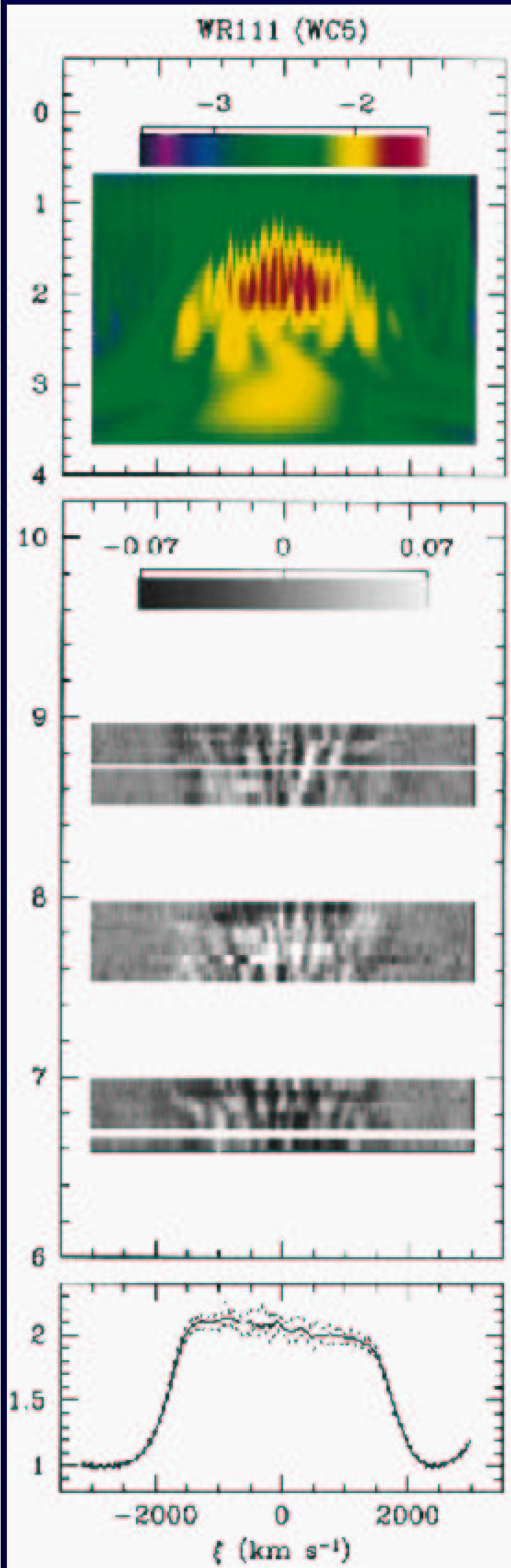
- Fitting emission recombination lines, i.e. Hα
- Two-body processes, $EM = \int \rho^2 dV$
- *Assume all matter is clumped* $\rightarrow$ *smaller mass-loss rate from line fit*



model fits with different density conrast



What data tell about the nature of WR-wind



Brown, Richardson, Cassinelli, Ignace (1997)

new technique

- **"Spherical de-projection" of the emission line:**
- Observed - line flux as function the line-of-sight velocity
- Derived - line flux as function of radial velocity
- Basis - optically thin emission line profile =
- Σ profiles from infinitesimally thin concentric wind shells.
- Brown et al. (1997): inverse problem $\longrightarrow$ velocity law

Further improved by Ignace, Brown, Richardson, Cassinelli (1998) and Ignace, Brown, Milne, Cassinelli (1998)

applyed to analyse spectra of 9 WR-stars

by Lepine & Moffat (1999).

WR winds made up of

- a large number
- randomly distributed
- radially propagating

BLOBS

(DWEEs)

(clumps)


INDESCRIBABLE...
INDESTRUCTIBLE!
NOTHING CAN STOP IT!
THE BLOB

Clumping Terminology

$$\dot{M} \propto \frac{1}{\sqrt{D}}$$

Optically thin clumps (Yes!)

Optically thick clumps (? ...wait!)

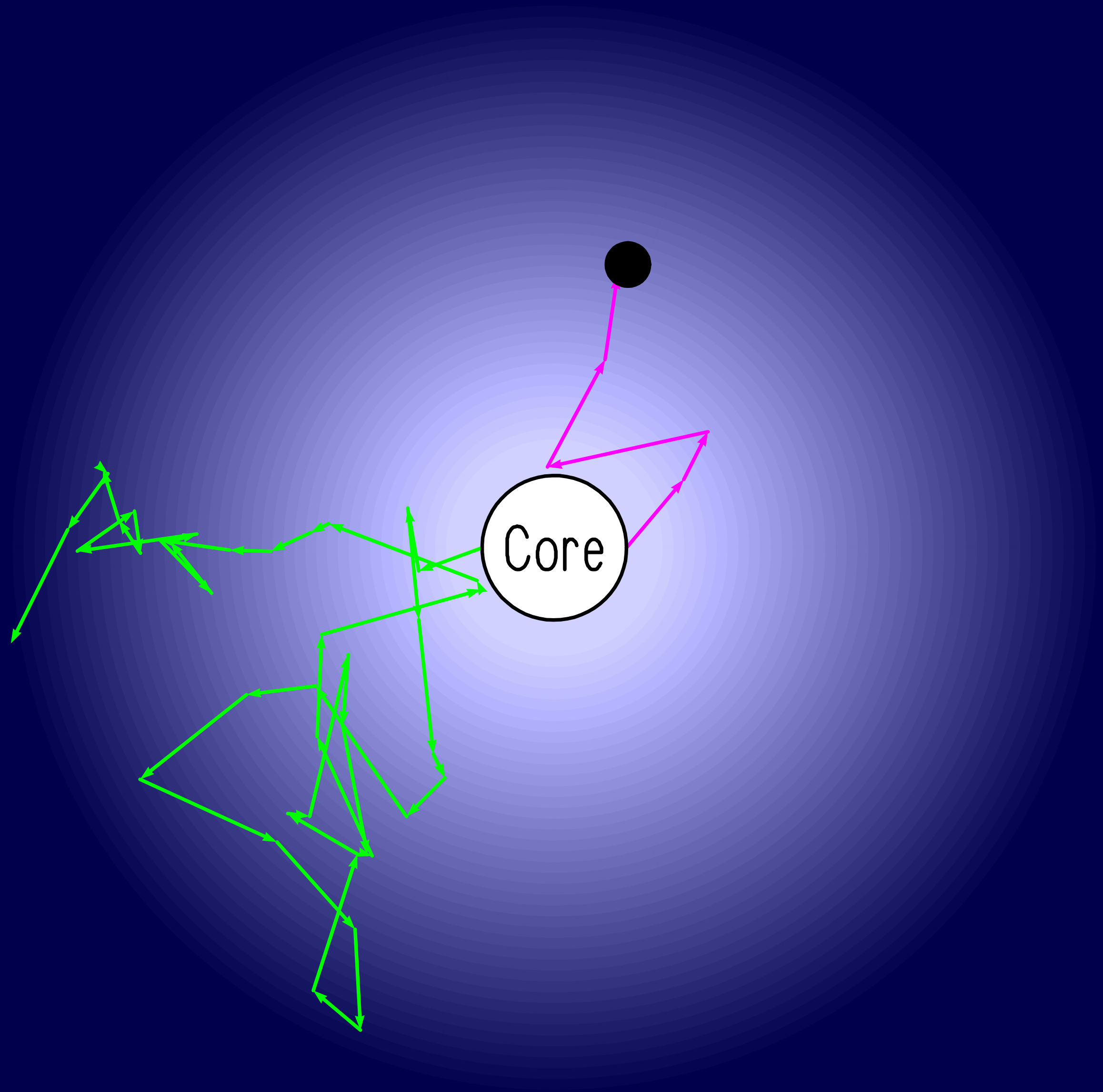
- Density within each clump is higher than average by factor D.
- All processes (e.g. scattering) which scale with density are affected.

- Optically thin Clumps $\tau_{\rm clump} \ll 1$: Photons do not "notice" these clumps **Used by ALL-1 published models**
- Optically thick Clumps $\tau_{\rm clump} \gg 1$: photons are absorbed in the clump **Brown et al. (2004)**

Optically thick clumps - not the solution to the WR wind momentum problem?

Brown, Cassinelli, Li, Kholtygin, Ignace (2004):

Optically thick clumping reduces multiple scattering and momentum delivery.



- **Smooth wind** $\longrightarrow$ large scattering optical depth $\tau \rightarrow$ enhanced momentum delivery $\longrightarrow$ $\tau L/c$

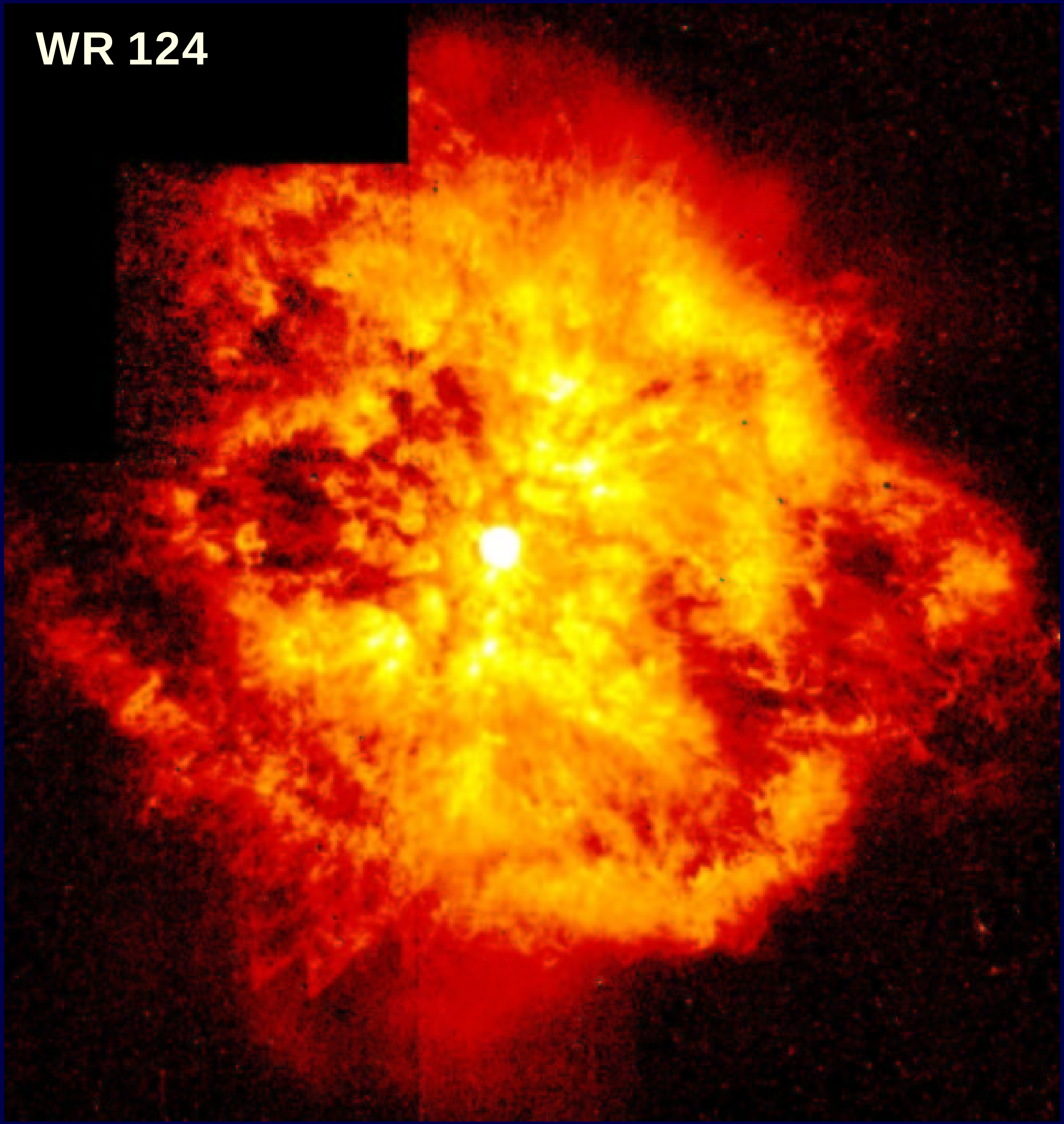
- **Clumped wind** $\longrightarrow$ atomic absorbers (ions) are effectively "hidden" $\longrightarrow$ optical depth is reduced

- **"Effective" optical depth** is largely determined by wind geometry

What is wrong with our picture of massive-star wind ?

Sensitive ingredients:

- **Mass loss rate $\dot{M}$ estimates**
- The effects of **rotation**
- The role of **magnetic fields**



Some WR stars surrounded by lost mass → "WR Ring Nebula"

A Magnetically Torqued Disk Model for Be Stars

Cassinelli, Brown, Maheswaran, Miller, Telfer (2002) and
Brown, Telfer, Li, Hanuschik, Cassinelli, Kholtygin (2004)

Key ingredients: Magnetic field + $\dot{M}$ + rotation

- Magnetic field exerts force
- matter flows along the flow tubes
- and is channeled into equatorial disk
- supported against infall by centrifugal forces

In: Stellar parameters + S_0 - fraction of critical velocity

Theory: Threshold surface field, B_0 to torque a Keplerian disk

- Disks are most common around B2 V stars! Positive.
- Requiered field strength 30-300 Gs. Plausible.
- Emission measures, IR exsess, polarisation. Positive.

Image: PPARC

Compact binaries as probes of stellar wind

- Massive star binaries
- Bound after SN $\longrightarrow$ HMXB
- $\sim$ 85% of HMXB: Be-star + NS
- Rest: OB/WR + NS/BH
- Powered by stellar wind accretion

Microquasar SS433: WR star + BH (?)

Brown et al. (1988), Brown et al. (1991), Brown & Fletcher (1992), Brown et al. (1995)

Transient "bullets": Hα, no X-ray

! Jet heating: collision with WR wind

! Radiative instability:
jet on a threshold

! Narrow parameter space:
rarity of microquasars!

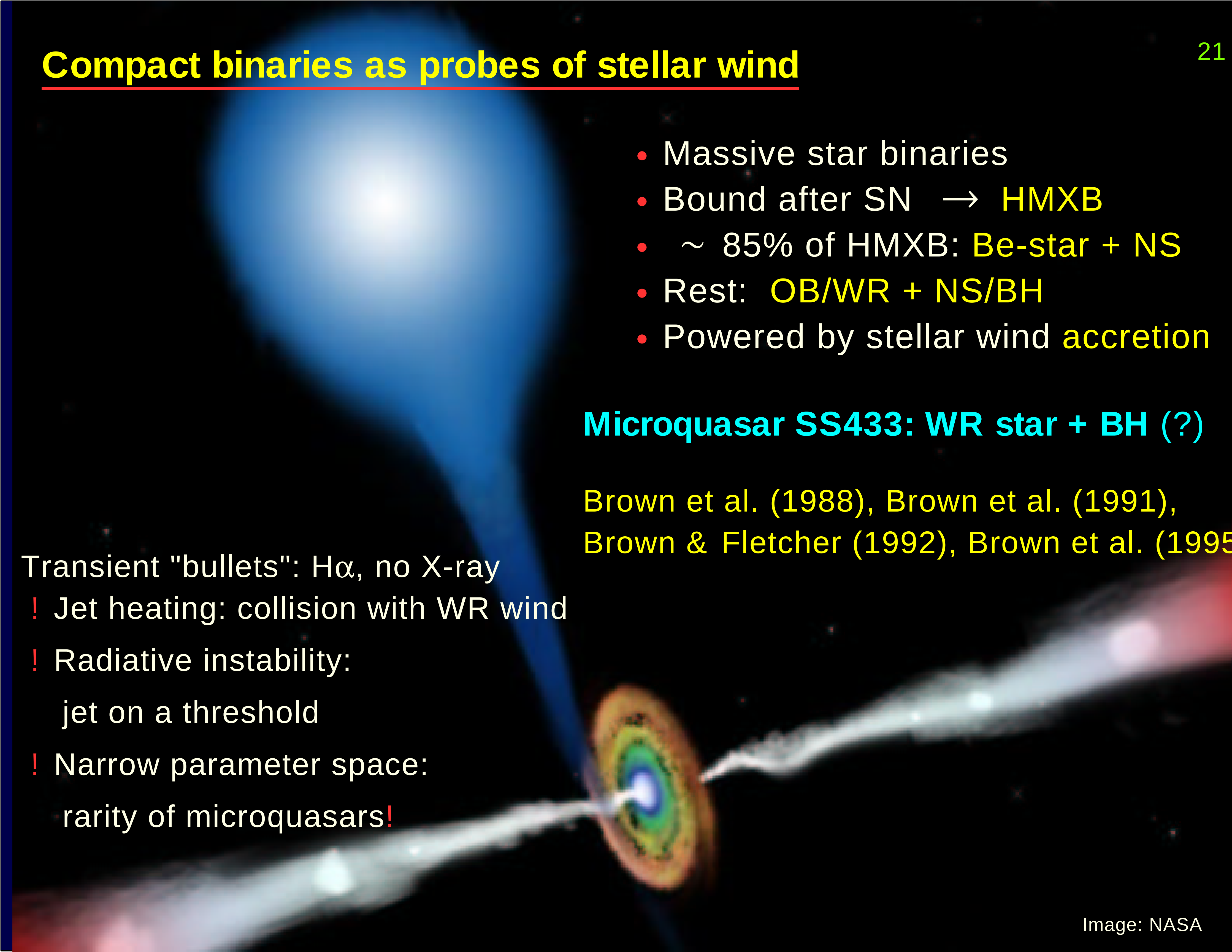


Image: NASA

Life and death in the inner solar system

Brown & Hughes (1977)

- LARGE fireball in the atmosphere $\Rightarrow$
- particle acceleration $\longrightarrow$ MeV neutrinos $\longrightarrow {}^{14}\mathrm{N}(n,p){}^{14}\mathrm{C} \longrightarrow {}^{14}\mathrm{C}$
- *Brown & Hughes mechanism:* carbon dating of cometary impacts

! Triggered by passage thru Orion spiral arm (Napier & Clube 1979)
! Tunguska - has interstellar origin (Clube & Napier 1984)
! Next shower expected 2000-2040 (Rampino & Stothers 1984)

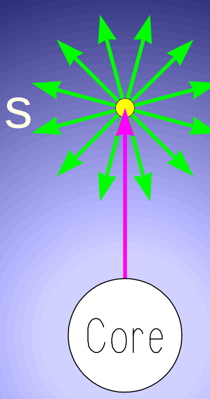
Image: Wikipedia


Happy
Birthday!

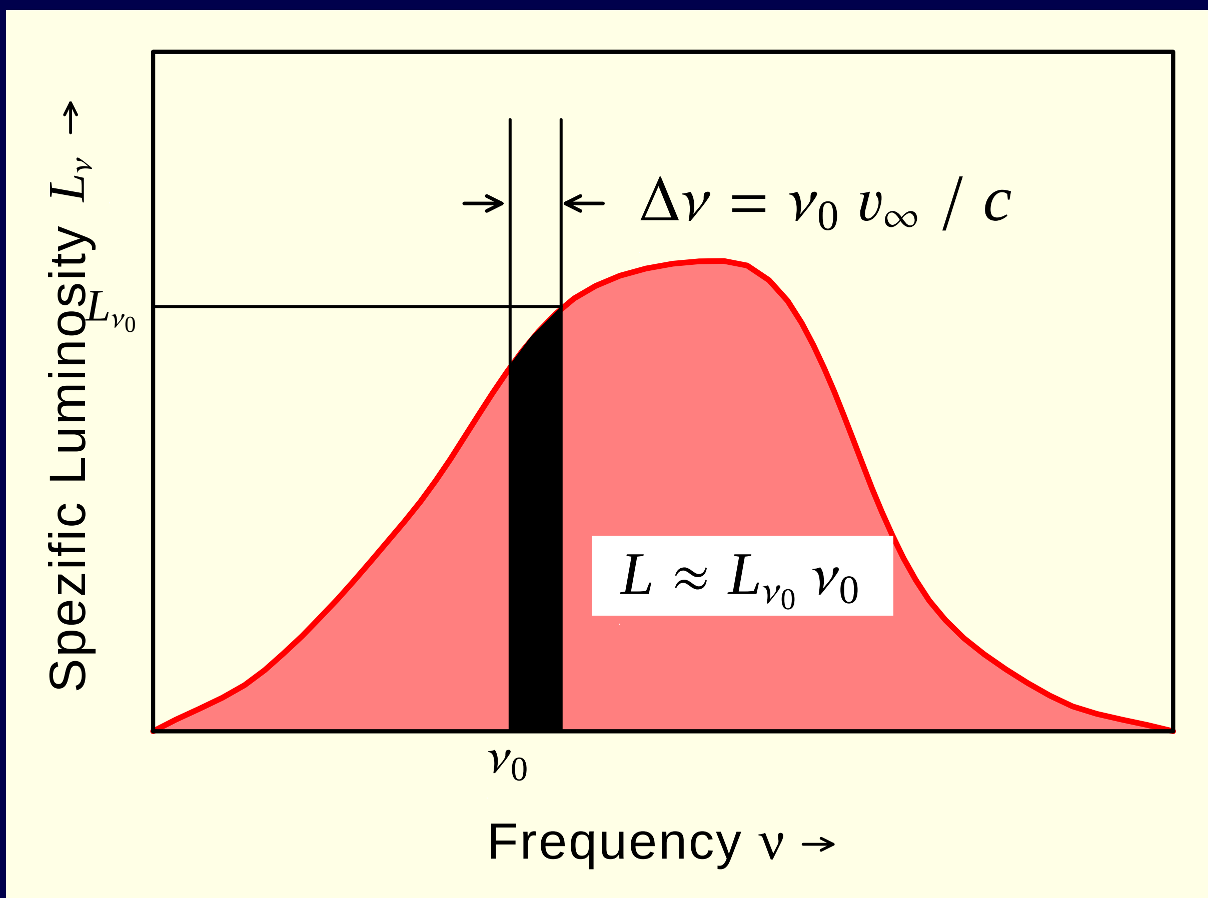
Line-driven stellar winds

(Castor, Abbott & Klein 1975)

- Stellar wind transparent in continuum, opaque in many lines
- Absorption from ~ radial direction; re-emission isotropic
- Acceleration → velocity → Doppler shift of the line
- Photons from a whole frequency band $\Delta\nu$ are swept up



In *one* line intercepted momentum per time: $L_{\nu_0}\,\Delta\nu/c = L\,v_\infty/c^2$



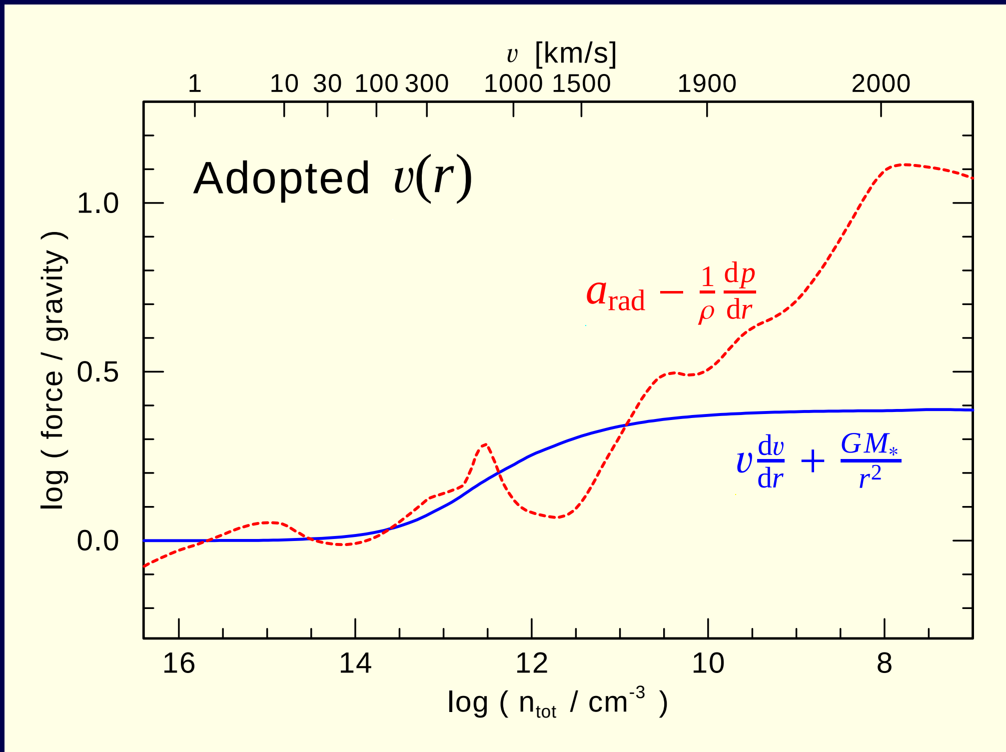
Wind momentum per time: $\dot{M}\, v_\infty$

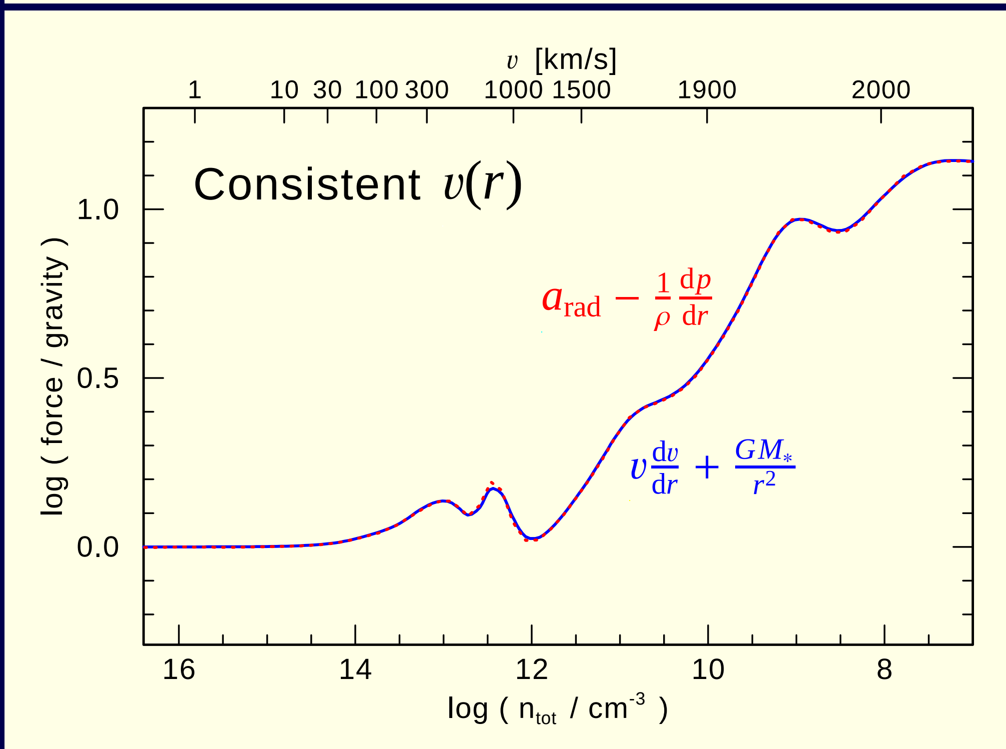
Mass loss driven by *one* line:

$$\dot{M} = \frac{L}{c^2}$$

= mass loss by nuclear burning

! $L = \frac{dE}{dt} = \frac{d}{dt}(Mc^2)$





A hydrodynamically consistent Wolf-Rayet wind model

Gräfener & Hamann (2005)

Equation of motion:

$$v\frac{dv}{dr} + \frac{GM_*}{r^2} = a_{rad} - \frac{1}{\rho}\frac{dp}{dr}$$

Optically thin clumping

Adopt mass-loss rate, velocity law

→ Eq. of motion not satisfied

iterate for $\dot{M}, v(r)$

→ consistent solution

Solution relays on models with

Large number of iron lines

+ CLUMPING

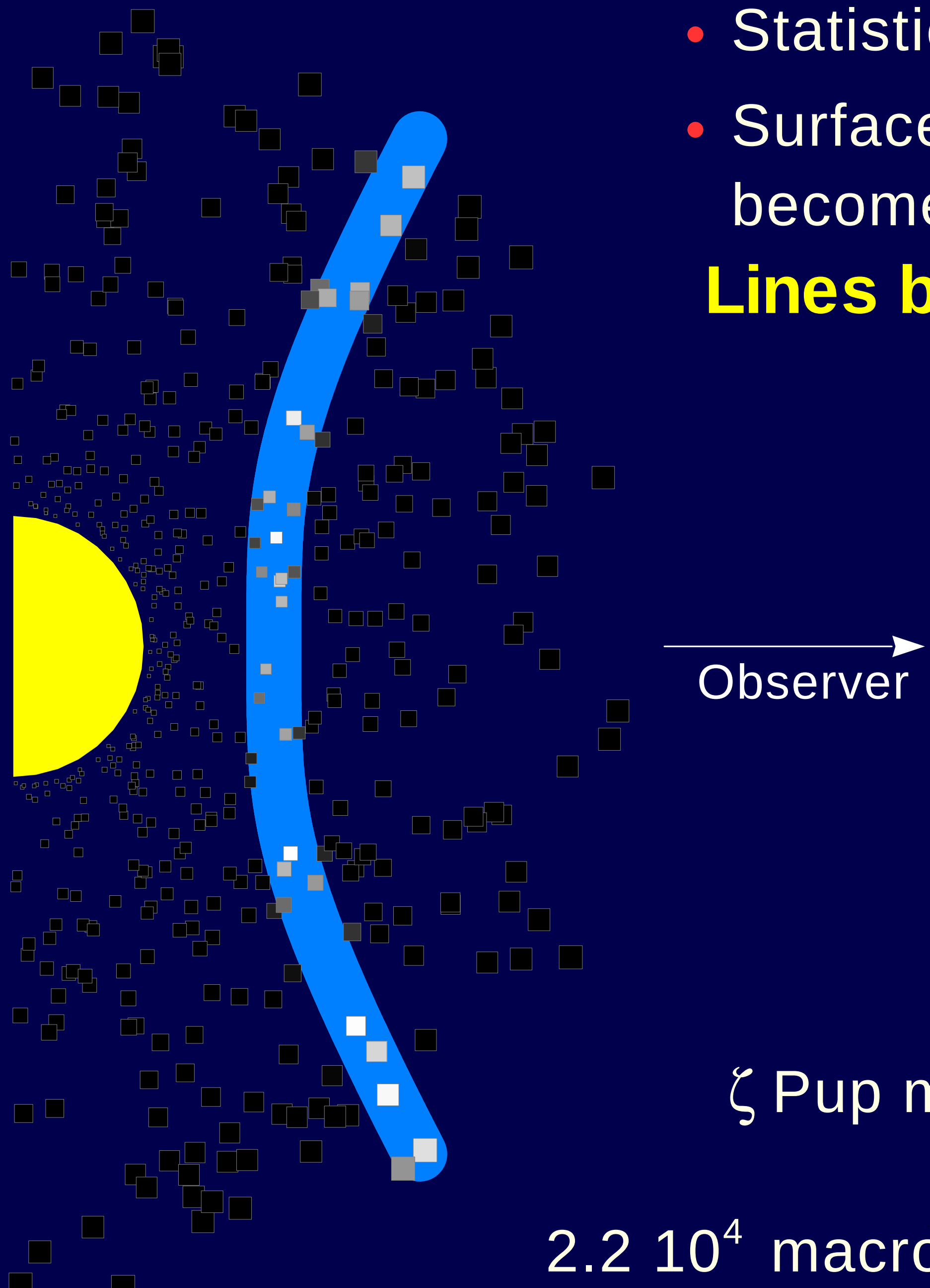
= higher opacity and smaller $\dot{M}$

Spectrum formation with optically thick clumps

Oskinova, Hamann & Feldmeier (submitted)

- Clumps may be optically thick (at lines!)
- Statistical treatment of *porosity effect*
- Surface of constant radial velocity (CRVS) becomes fragmented

Lines become weaker → $\dot{M}$ *under*estimated !



ζ Pup models →
$f_V = 0.1$
2.2 10^4 macro-clumps