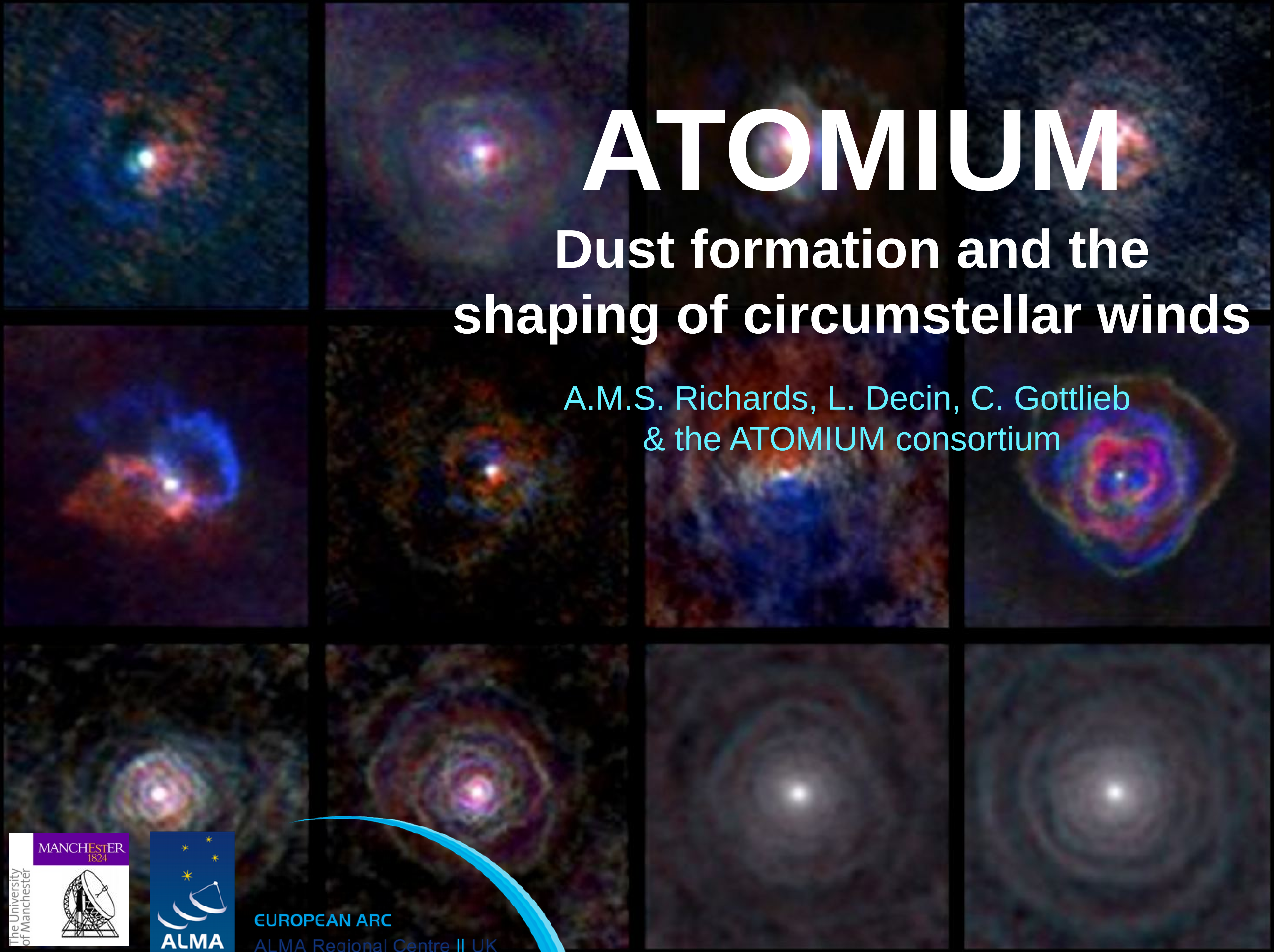

ATOMIUM

Dust formation and the shaping of circumstellar winds

A.M.S. Richards, L. Decin, C. Gottlieb
& the ATOMIUM consortium

ATOMIUM

The University of Manchester

MANCHESTER 1824

ALMA

EUROPEAN ARC

ALMA Regional Centre || UK

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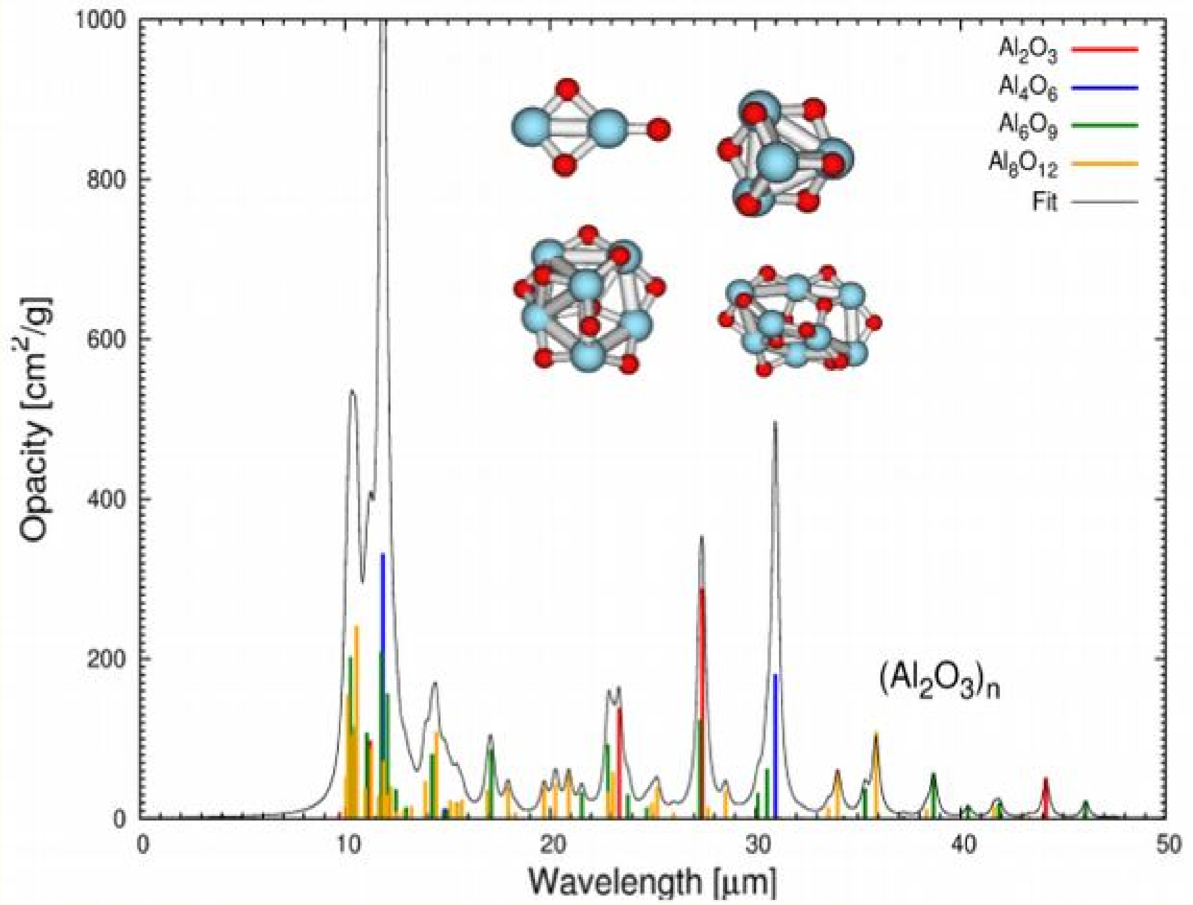
Based mostly in Europe and USA, originated from at least 5 continents

Many thanks to ALMA staff in Chile & ESO for help with observations and pipelining

ALMA Tracing the Origins of Molecules In dUst-forming oxygen-rich M-type stars

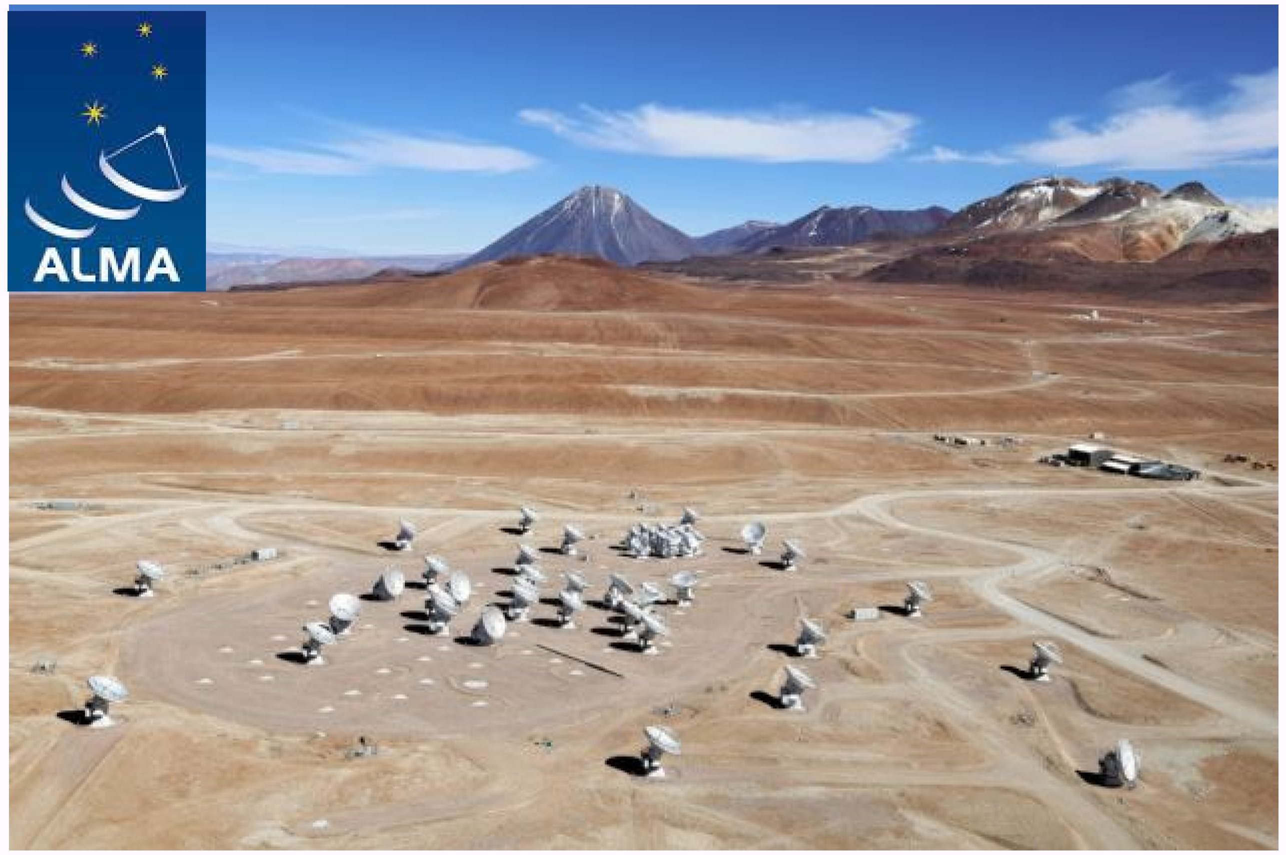
- Study phase transition: simple molecules > larger gas-phase clusters > dust grains
  - Formed in outflows from O-rich evolved stars
    - Rich chemistry and relatively simple dynamical structure
- Establish dominant wind physical & chemical processes
  - Sample a range of stellar masses, pulsation behaviours, mass-loss rates, evolutionary phases
    - unravel the phase transition from gas-phase to dust species
    - pinpoint the chemical pathways
    - map the morphology of the wind
    - study the *interplay* between dynamical and chemical phenomena
- Large Programme Legacy:
  - New results for evolved stars, astrochemistry, and the chemical life cycle of the ISM
  - Better understanding of astrochemical processes from proto-planetary disks to ULIRGS

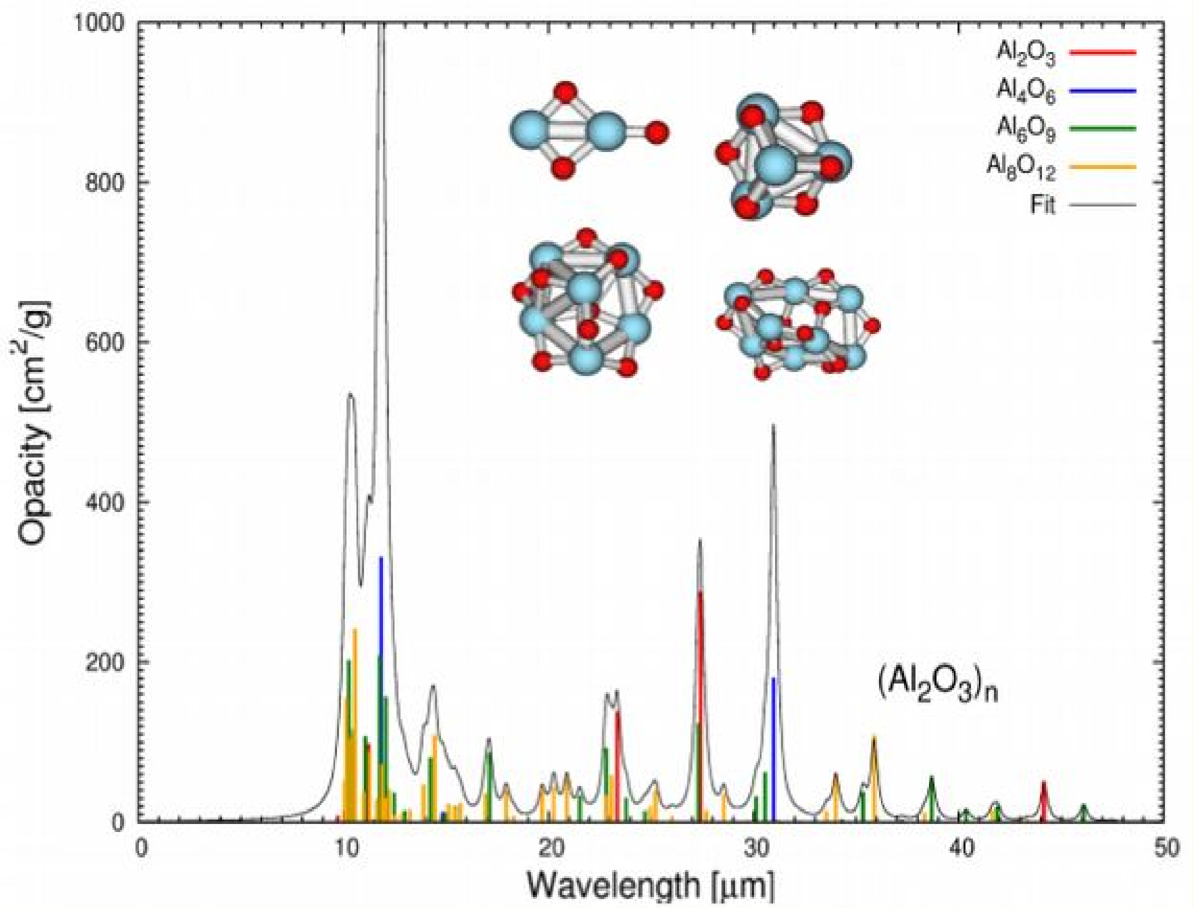


Analytic IR spectra: growth of $(Al_2O_3)_n$ clusters *Decin+17* (*Demyck+04* lab)

ALMA Tracing the Origins of Molecules In dUst-forming oxygen-rich M-type stars

- Study phase transition: simple molecules > larger gas-phase clusters > dust grains
- Dust precursor molecules at mm λ
  - FeO, MgO, MgOH, TiO, AlO
  - Other metal compounds, SiO

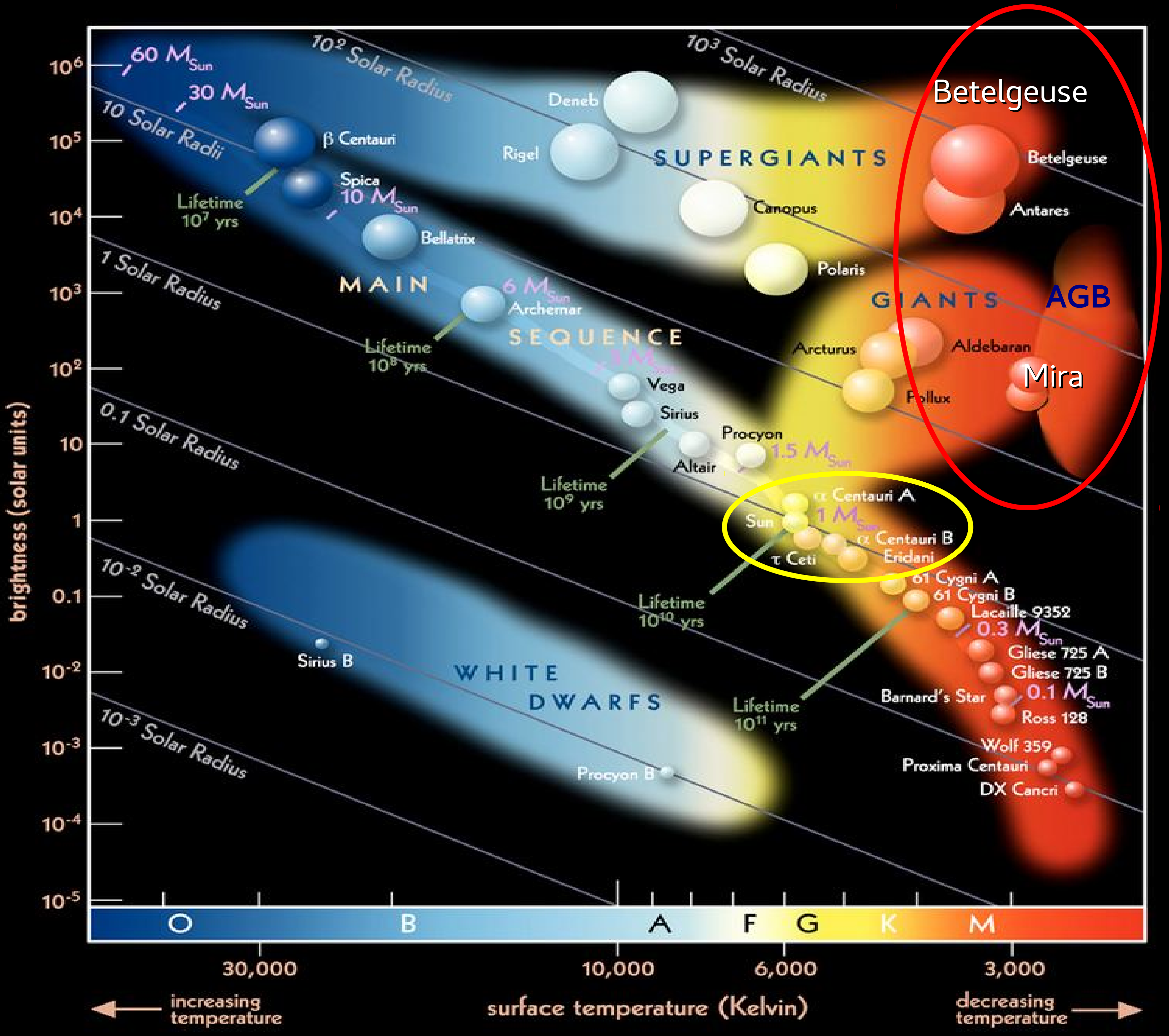




Analytic IR spectra: growth of $(Al_2O_3)_n$ clusters *Decin+17* (*Demyck+04* lab)

- Star, warm dust emission:
  - ALMA
  - SKA / ngVLA larger grains?
- Optical/IR
  - VLT/SPHERE
  - VLTI/MATISSE
  - MERCATOR/ HERMES

Red supergiants and AGB stars



Cool Red Supergiants & Miras

Sun-like stars

Herzsprung-Russell Diagram

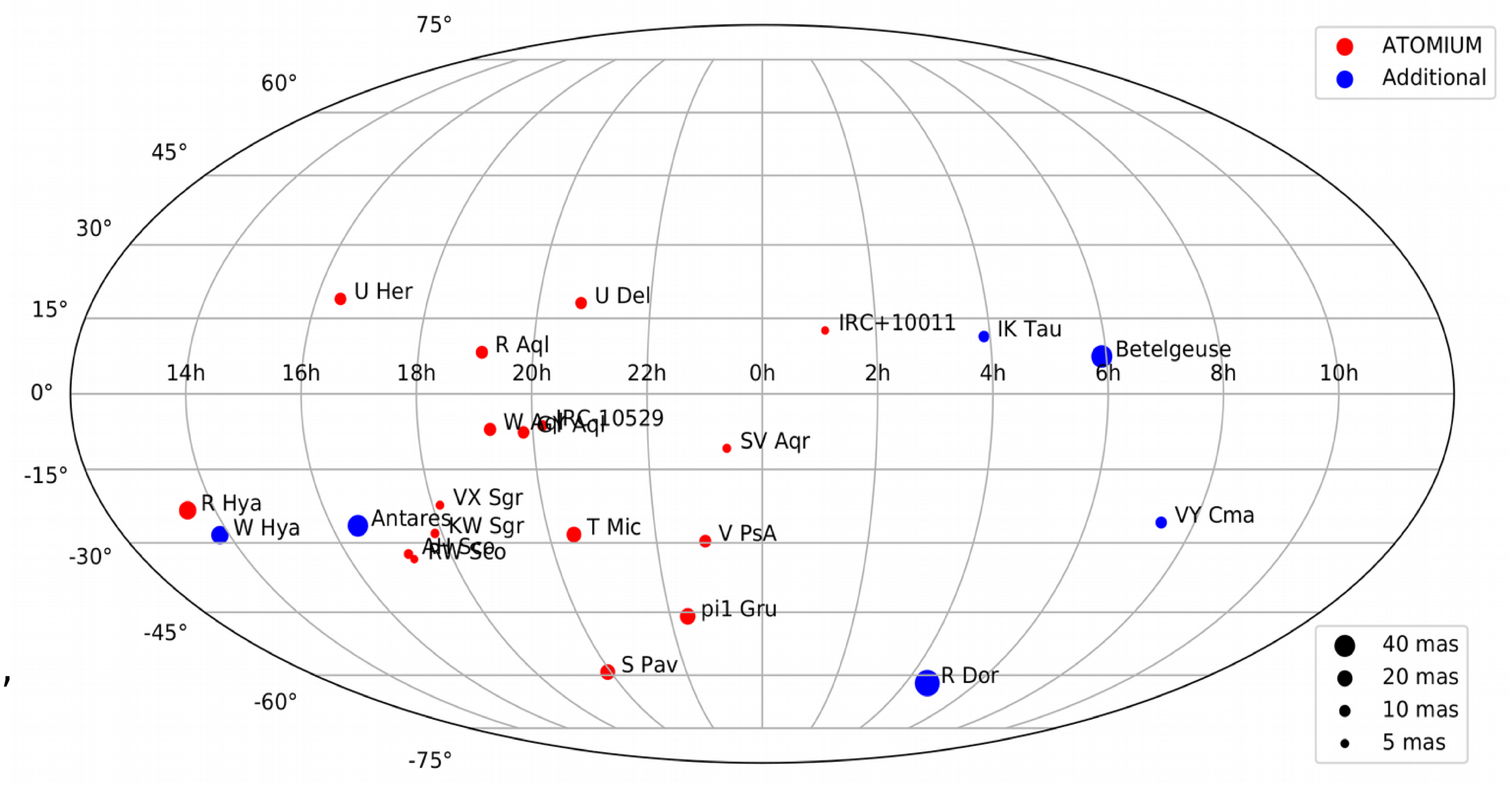
ATOMIUM sample

Star	Type	D✷ mas
S Pav	SRa	12
T Mic	SRb	9
U Del	SRb	8
RW Sco	OH/IR	5
V PsA	SRb	13
SV Aqr	LPV	4
R Hya	Mira	23
U Her	Mira	11
pi1 Gru	SRb	21
AH Sco	RSG	6
R Aql	Mira	12
W Aql	Mira	11
GY Aql	Mira	20
IRC-10529	OH/IR	6
KW Sgr	RSG	4
IRC+10011	OH/IR	7
VX Sgr	RSG	9

8e-8 Increasing mass loss rate 6e-5 M⊙/yr

Distribution of Atomium stars

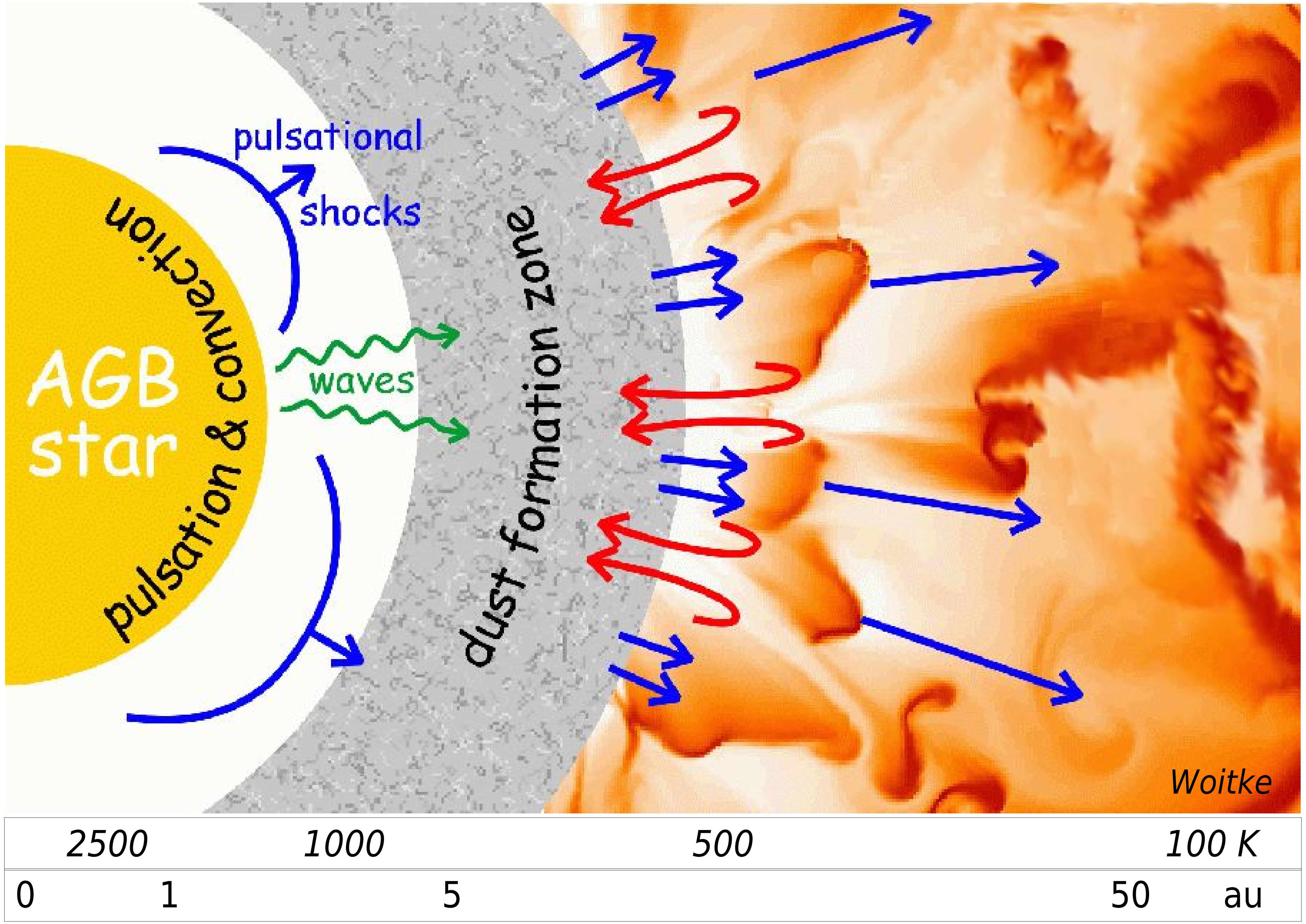
- Stars without previously known, dynamically significant companions
- Negligible surface rotation
- Mostly M-type, a few S-type



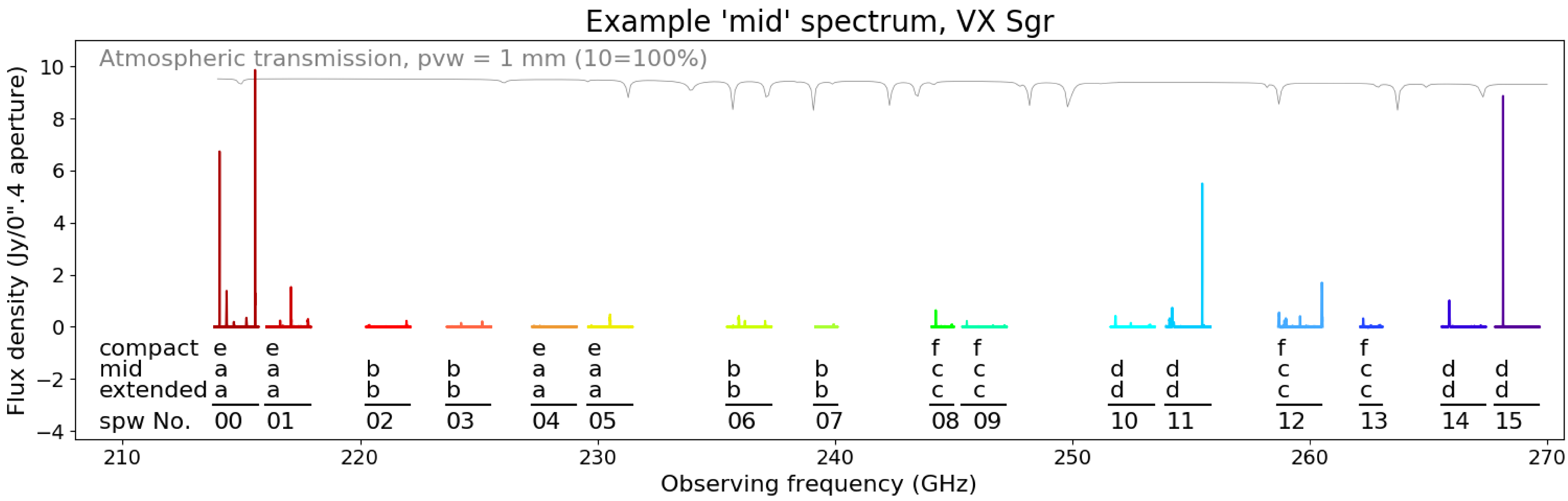
Miguel Montargès

Cool, red supergiants and AGB stars

- Contribute ~85% of gas and ~35% of dust to enrich the ISM
- Wind initiation:
  - Pulsations
    - Radiation pressure on lines
    - Scattering by nascent dust grains
- Dust driven wind once grains are formed
  - O-rich stars: metal oxides, silicates
- CO, SiO, HCN trace large-scale structure
- SiO, H_2O (OH) masers
  - e-MERLIN observations also

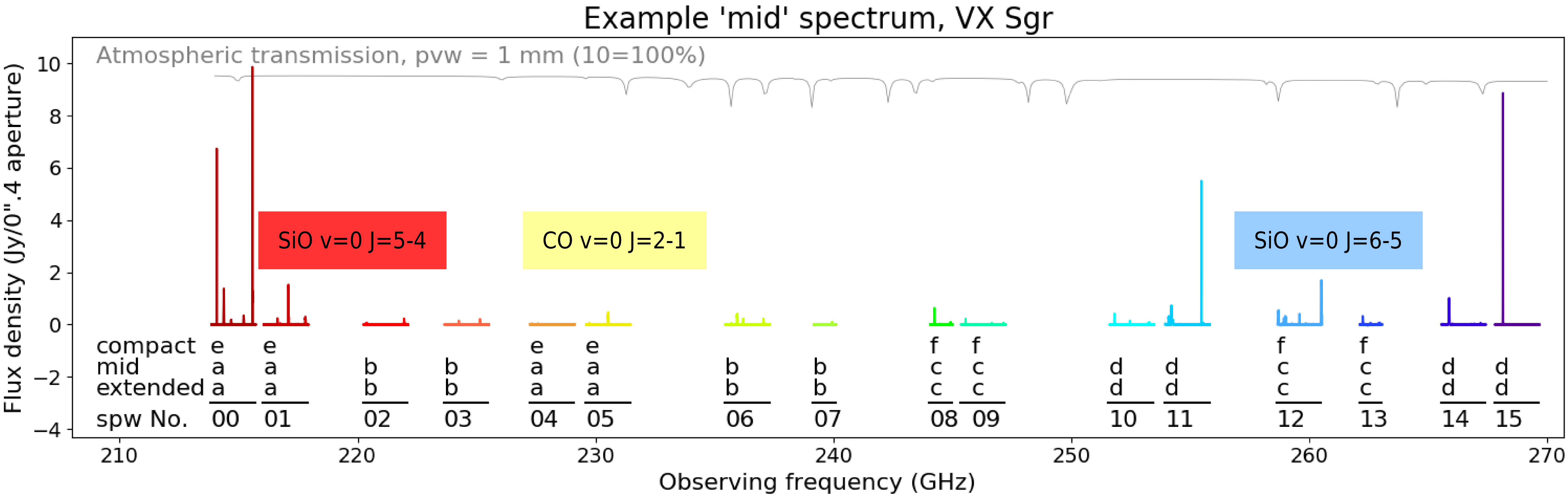


Design of Observations: tunings



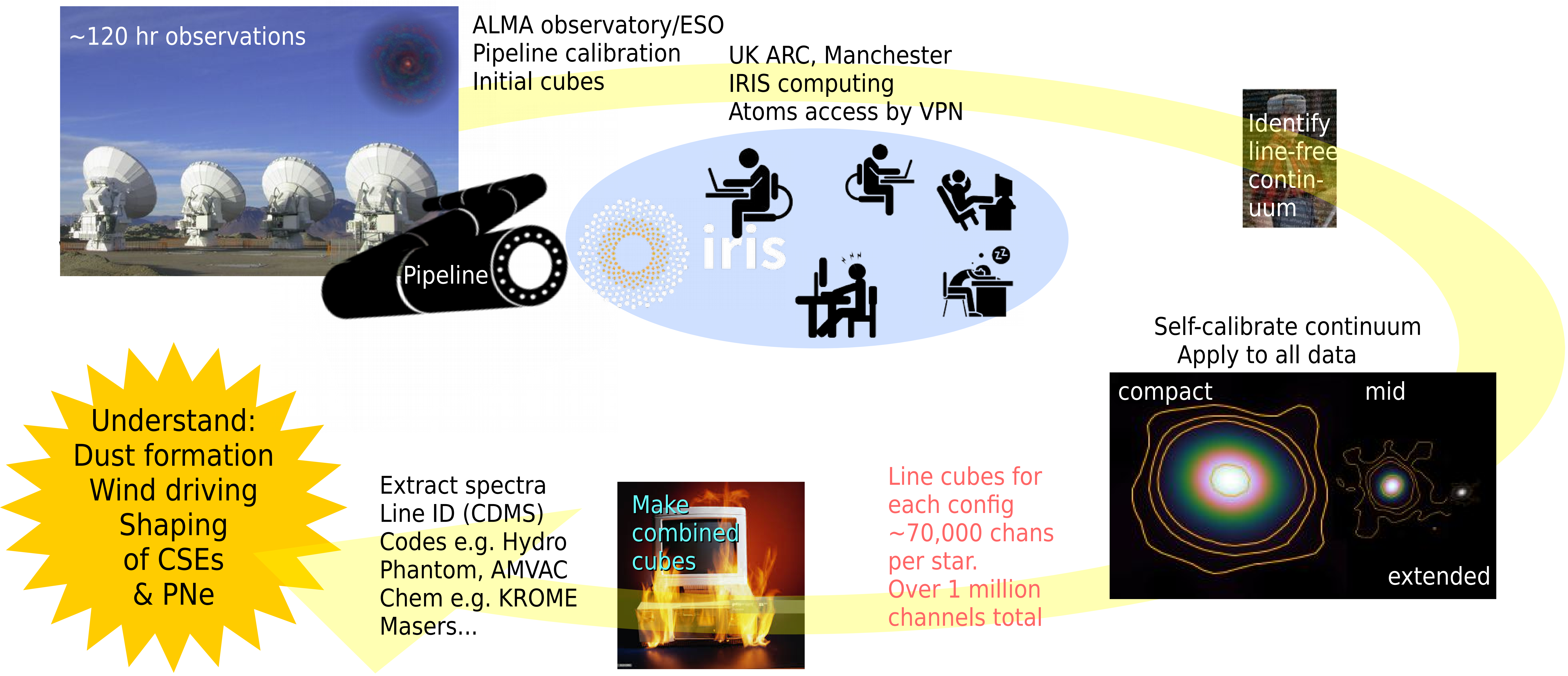
- Four tunings, each with 4 spw, between 214 to 270 GHz
  - Some half-width to fit priority lines on both edges of sideband limits
    - Velocity resolution 1.1 to 1.4 km/s

Design of Observations: resolution



- Extended config., 15 - 30 mas beam, locate AlO, TiO etc. relative to dust formation
- Compact config., ~0".9 beam, sensitive to SiO, CO etc. on up to ~10" scales
- Mid config., intermediate scales
- Combined images - weight to balance resolution : surface brightness sensitivity

Data Reduction



Combining configurations

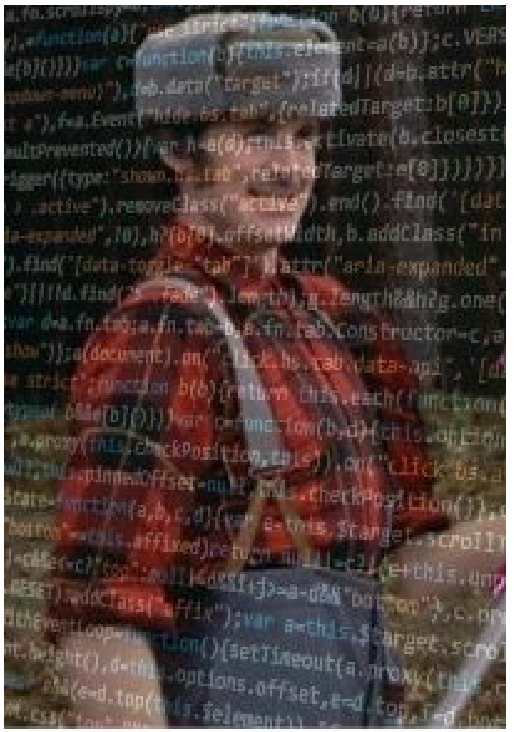
- POSITION
  - Different configurations/tunings months apart
    - Re-align spw if > 1 chan drift in Earth' motion
  - Proper motions few - few tens mas
    - Hipparcos positions only at proposal time
      - Prediction errors tens mas
  - Extended config astrometry ~5 mas
    - Align continuum peaks with Extended
- FREQUENCY
  - Earth's motion wrt LSR changes over months
    - Correct spw alignment if shift > 1 channel
- FLUX SCALE
  - Variability and uncertainty each 5~10%
      - Occasionally more
    - Compact knots far from star less variable
      - Masers near star can vary x10, x100...
    - Occasionally identified & corrected mis-scaling
      - Some compact maser variability artefacts remain
- CUBE SIZE AND RESOLUTION
  - Image all data in 8 arcsec cubes
  - Some lines e.g. CO >20 arcsec radius
    - Image to 0.2 Primary Beam sensitivity
      - 8192^2 x 5-mas pixels x all channels = years!
        - Image selected lines to size required
  - Adapt tapering to required balance
    - Resolution v. surface brightness sensitivity
- MASKING
  - Mid, Compact configs: automasking
    - Use Mid masks for Extended
  - Combined: 3-step process
    - Clean brightest, compact masers
    - Apply Mid masks (*multiscale clean*,
    - Clean whole image *more weight to large scales*)

Much advice and troubleshooting help from ARC Network

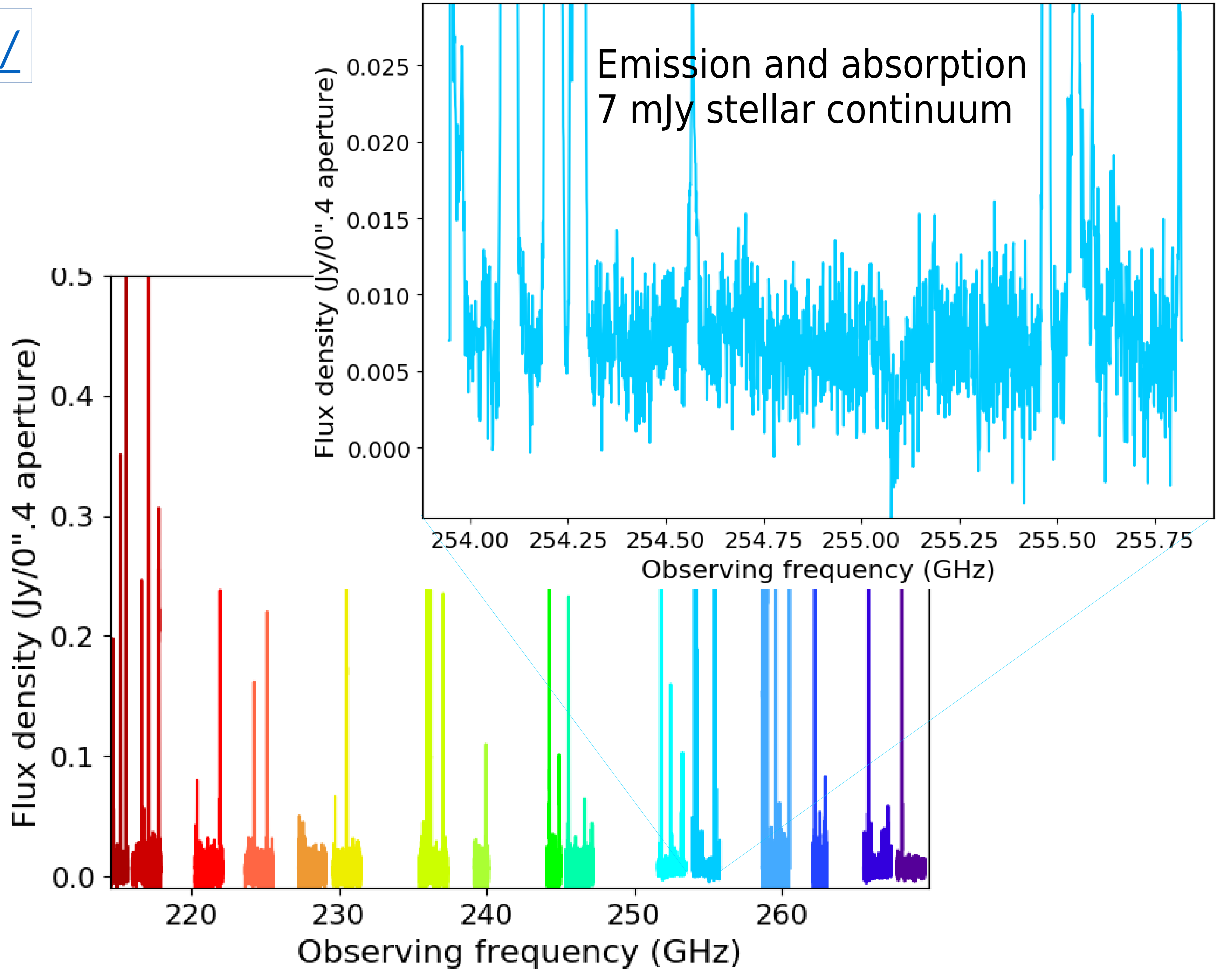
Lumberjack

https://github.com/adam-avison/LumberJack/

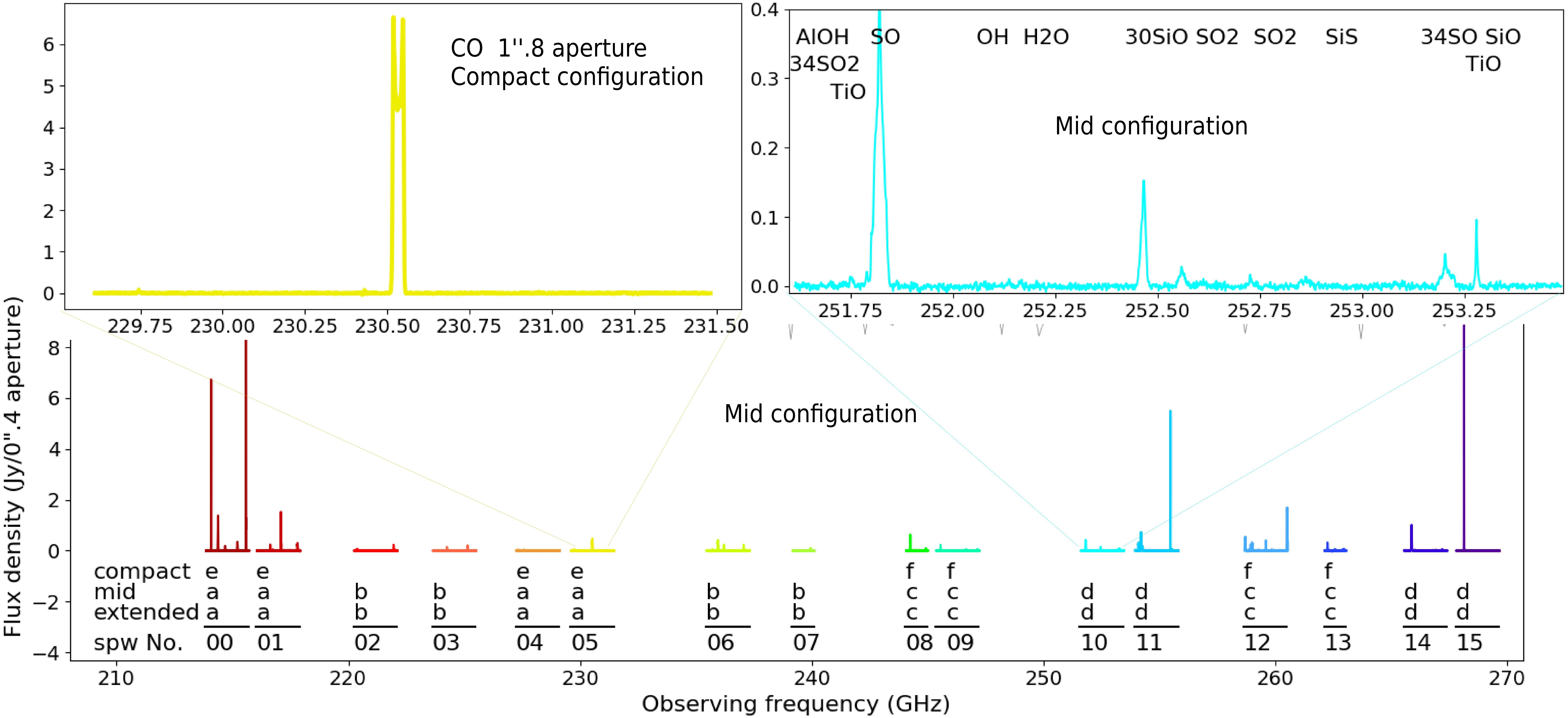
- 'Chops down' the line forest
  - Select channels without line emission
    - Looks for amplitudes spikes and gradients
- Take ALMA pipeline products
  - Use continuum to identify peak positions(s)
  - Get information required (resolution, predicted rms etc) from data
    - Produces list of line-free channels and diagnostic plots
      - User can tweak selection aperture
    - Currently script
      - Will be CASA task



Contact Adam Avison, UK ARC Node



~20 molecules identified, plus isotopologues, in >200 lines

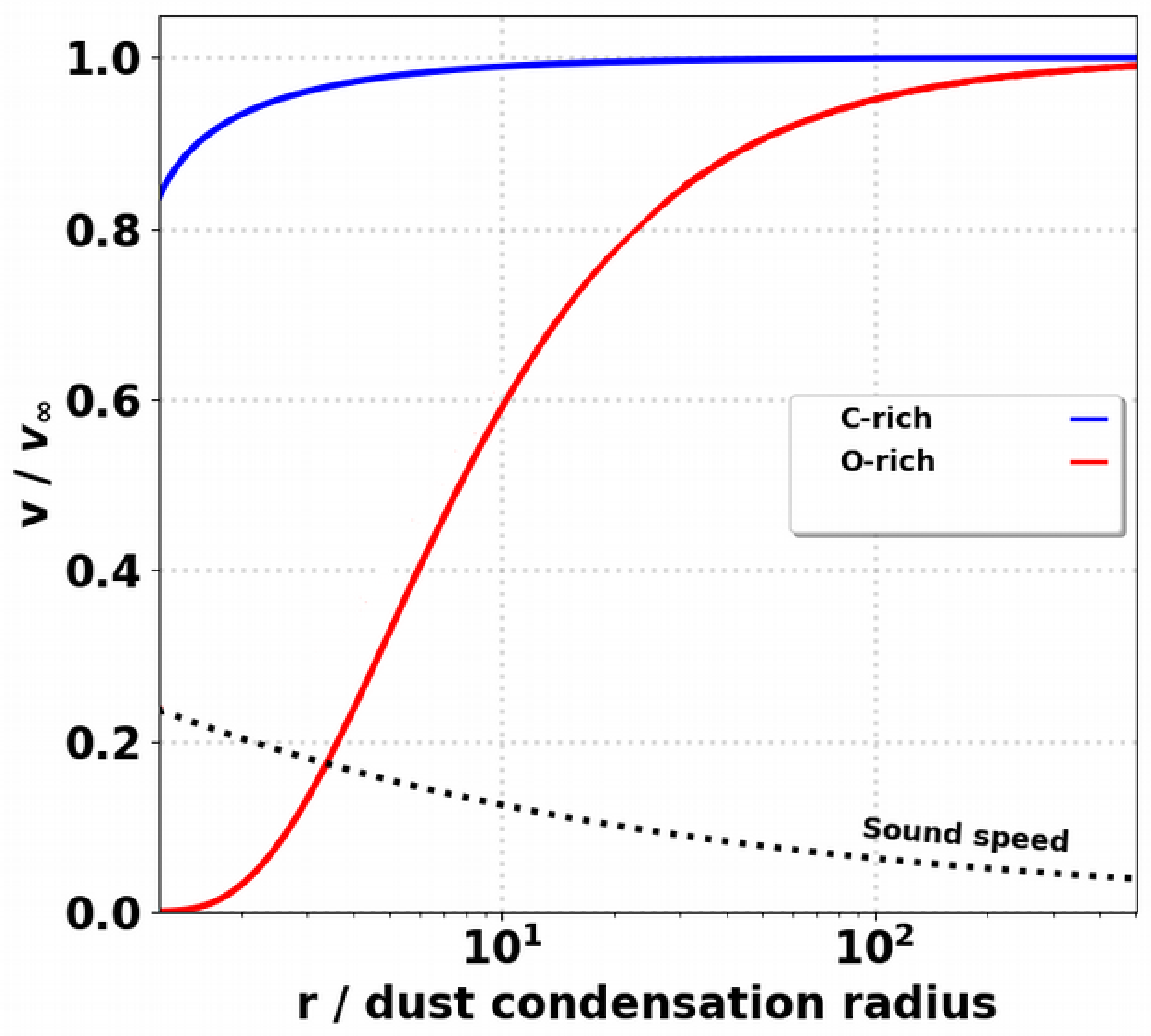


Dust formation

- Best candidate for nucleation TiO_2?
  - But does not form at high enough *T*
  - $(Al_2O_3)_n$ will form at high *T* but needs nuclei
- So far identified (lines including isotopes):
  - AlO (3); AlOH (2); Al halides (11)
  - FeO (1)
  - KCl (5); NaCl (7)
  - TiO (8); TiO2 (2)
  - SiO (14)
  - plus many H_2O, OH, SO, SO_2 etc. etc.
- Wind model
  - O-rich winds accelerated slowly
    - Less radial momentum near star
      - Companion can have more effect

Parametrized 1D radial wind model El Mellah

ß-velocity profile



$$v_\beta(r) = v_\infty(1 - R_0/r)^\beta$$

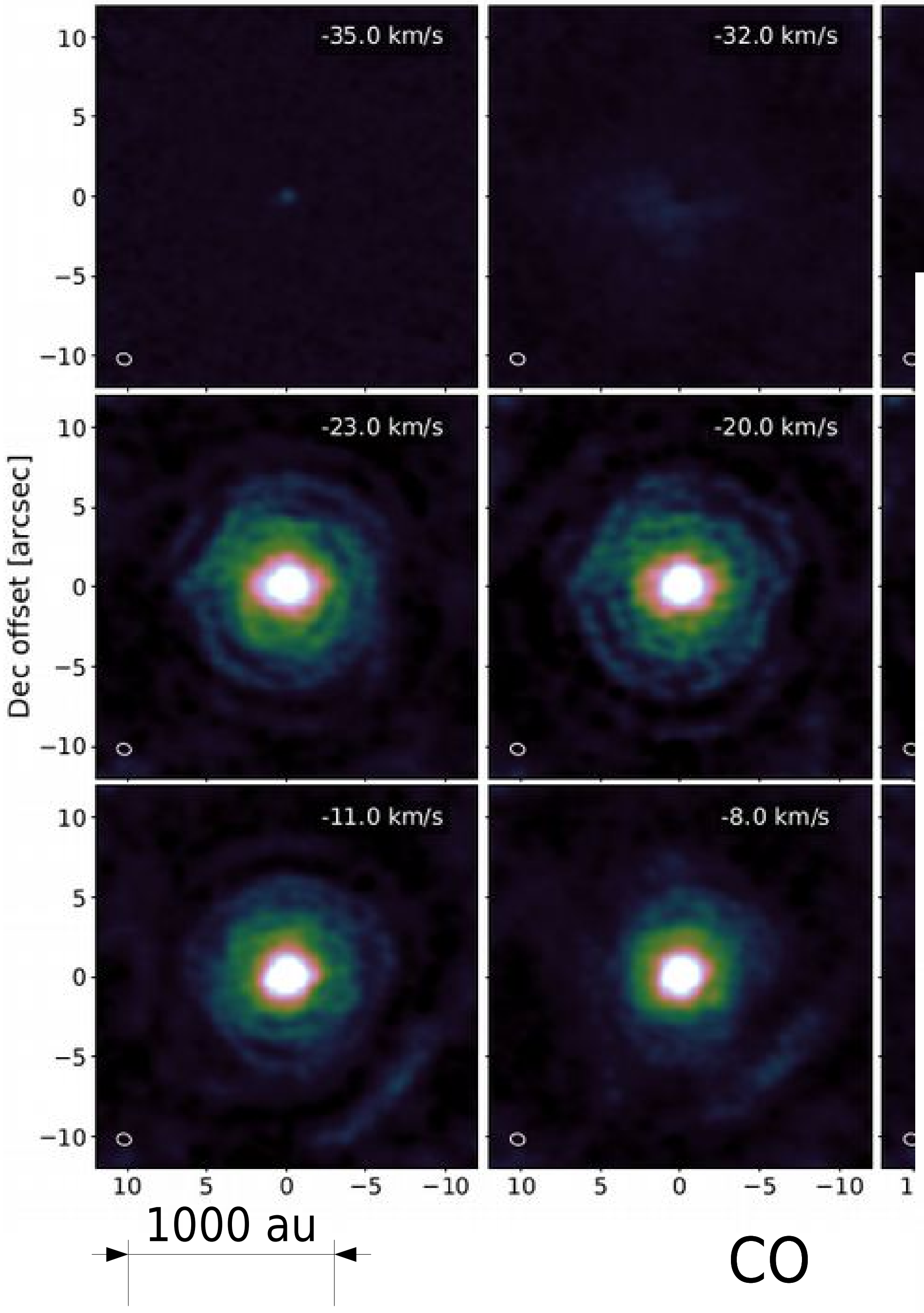
- dust condensation radius
- terminal velocity
- ß exponent

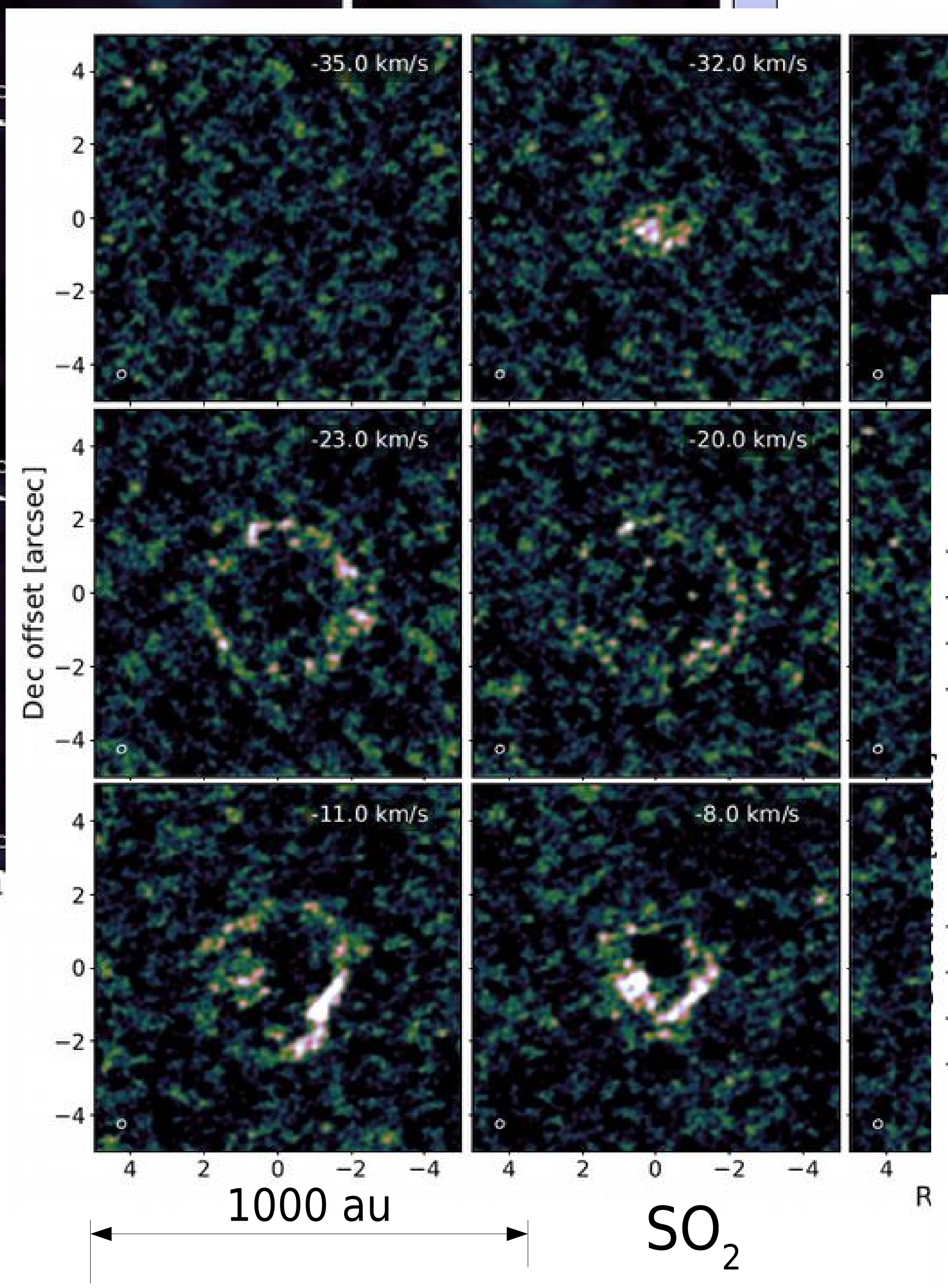
Sub or supersonic inflowing boundary?
- sonic point
- modified ß-wind

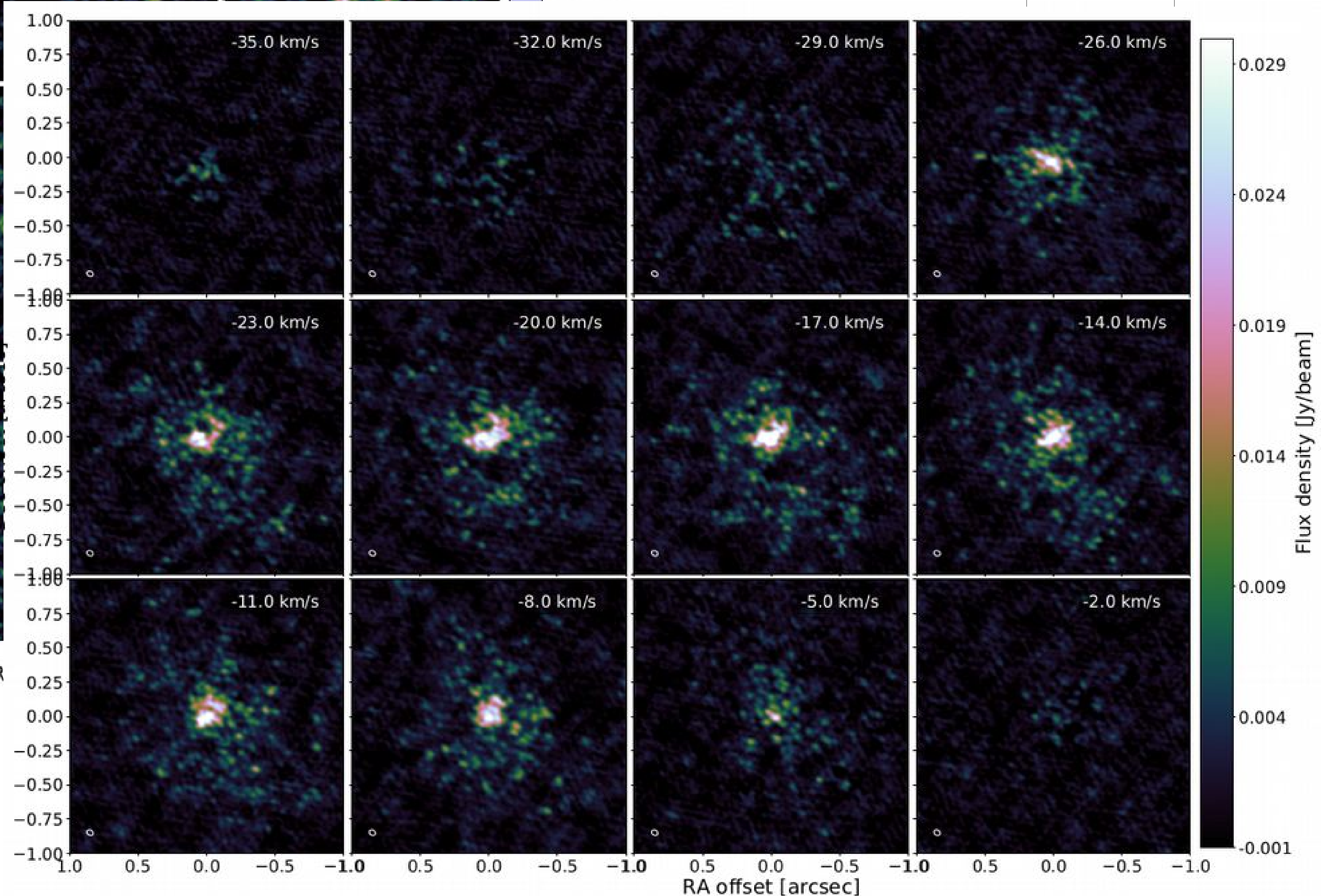
Effective acceleration
- stellar gravity
- radiative pressure

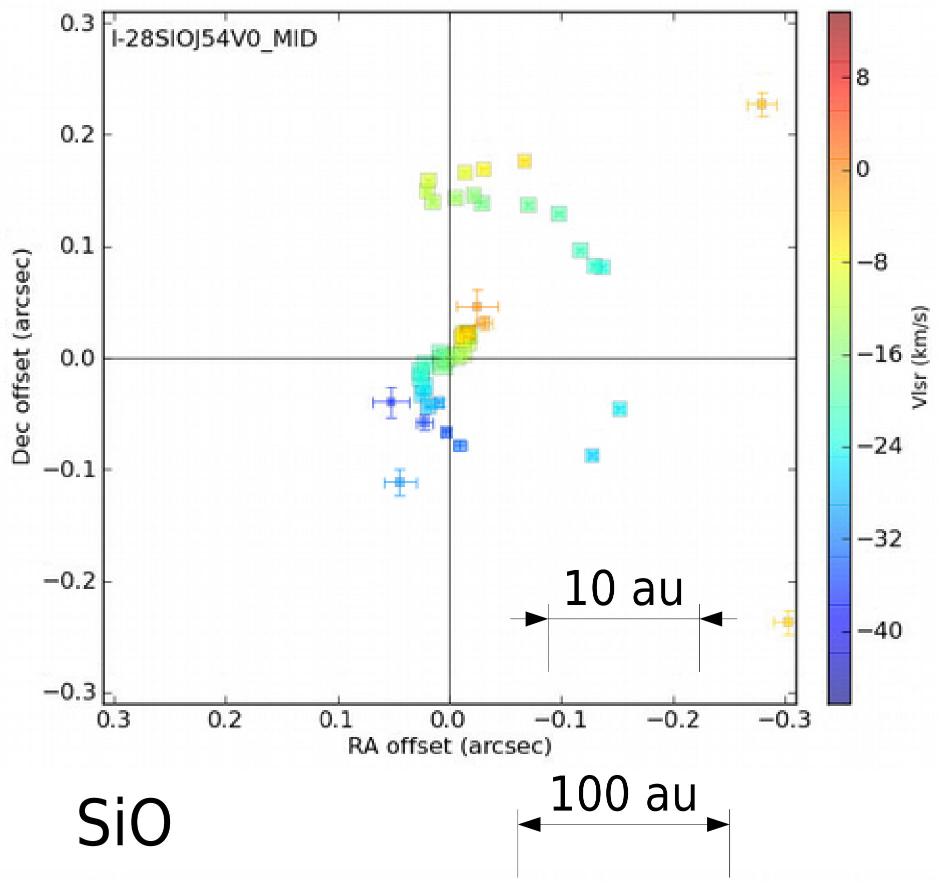
Co-rotating frame
- inertial forces
- non-spinning star

Circumstellar chemistry on multiple scales: IRC-10529

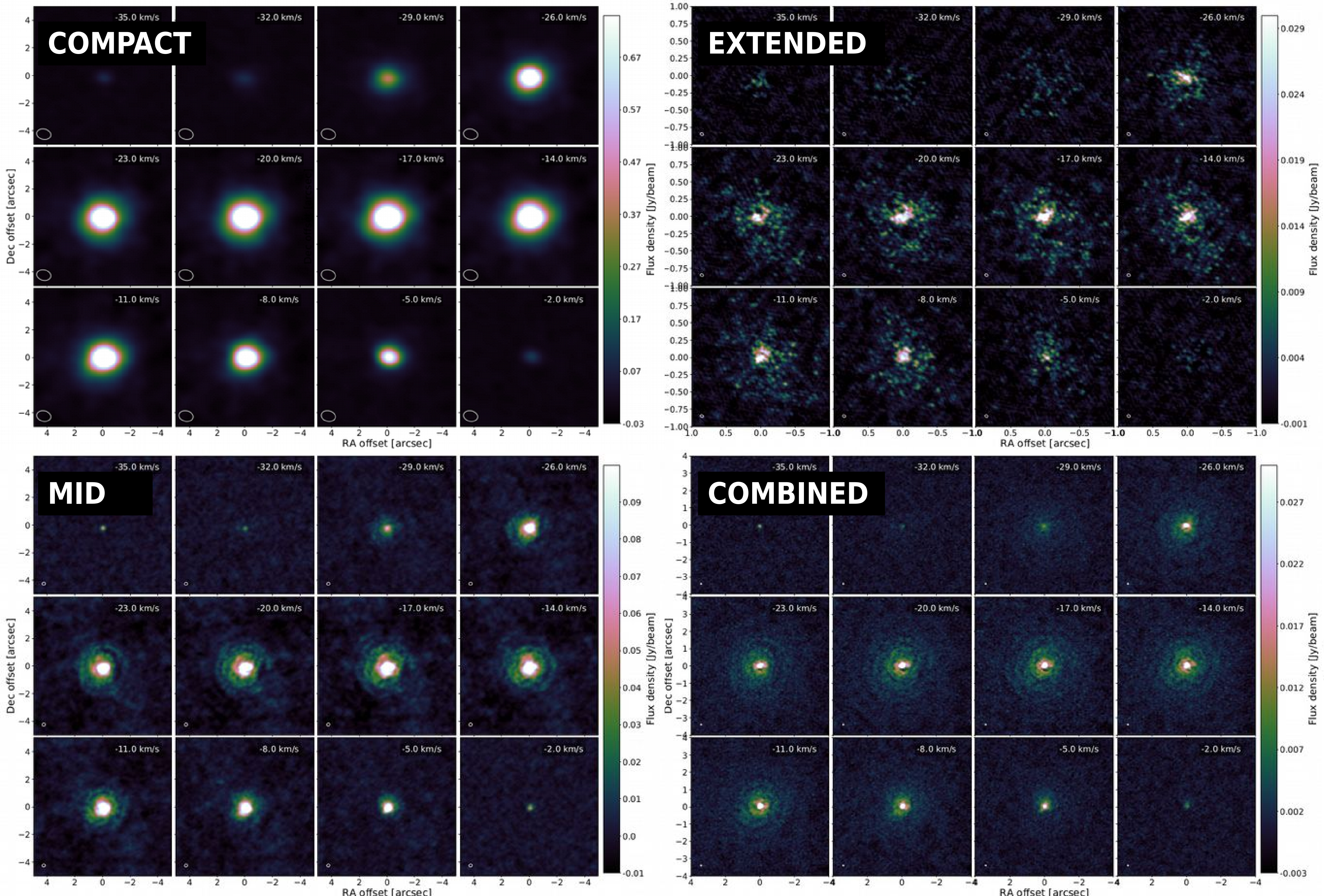




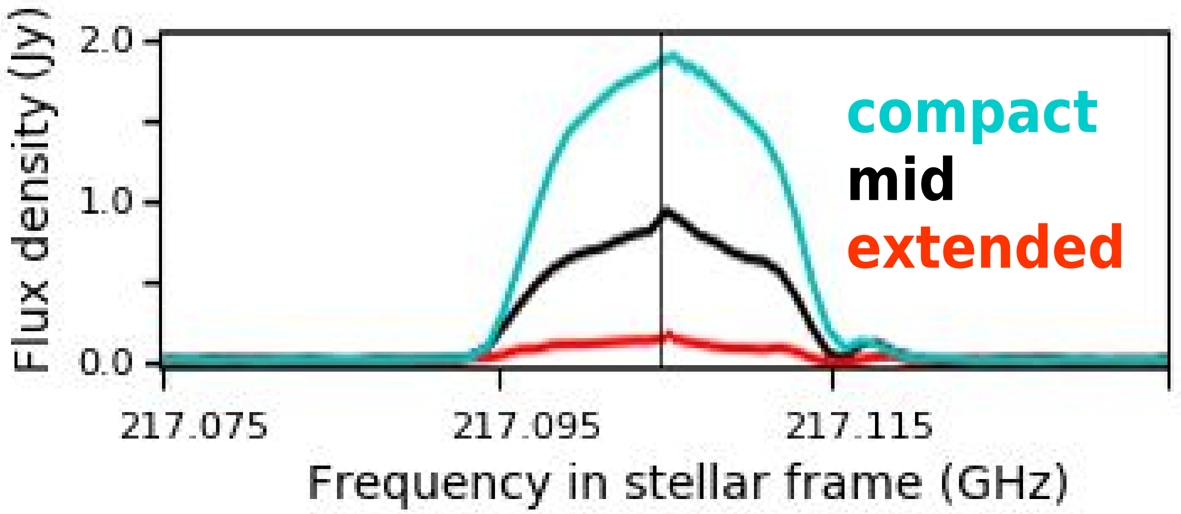




SiO v=0 J=5-4 OH/IR star



- Channel maps averaged to 3 km/s
  - Complex structure, arcs
    - Mid, Combined
- Spectra show mostly extended, thermal emission
  - Little maser spike
  - Compact central source in Extended config
    - Extended emission resolved-out



CO velocity distributions

- A to L AGB stars, increasing mass loss rate
  - Red/blue shifted with respect to V_*
- All asymmetric
  - Bipolar, spiral, rose-like, disc, equatorial density enhancement or irregular
- Onset of PNe asymmetries on AGB

Decin et al., Science, 2020

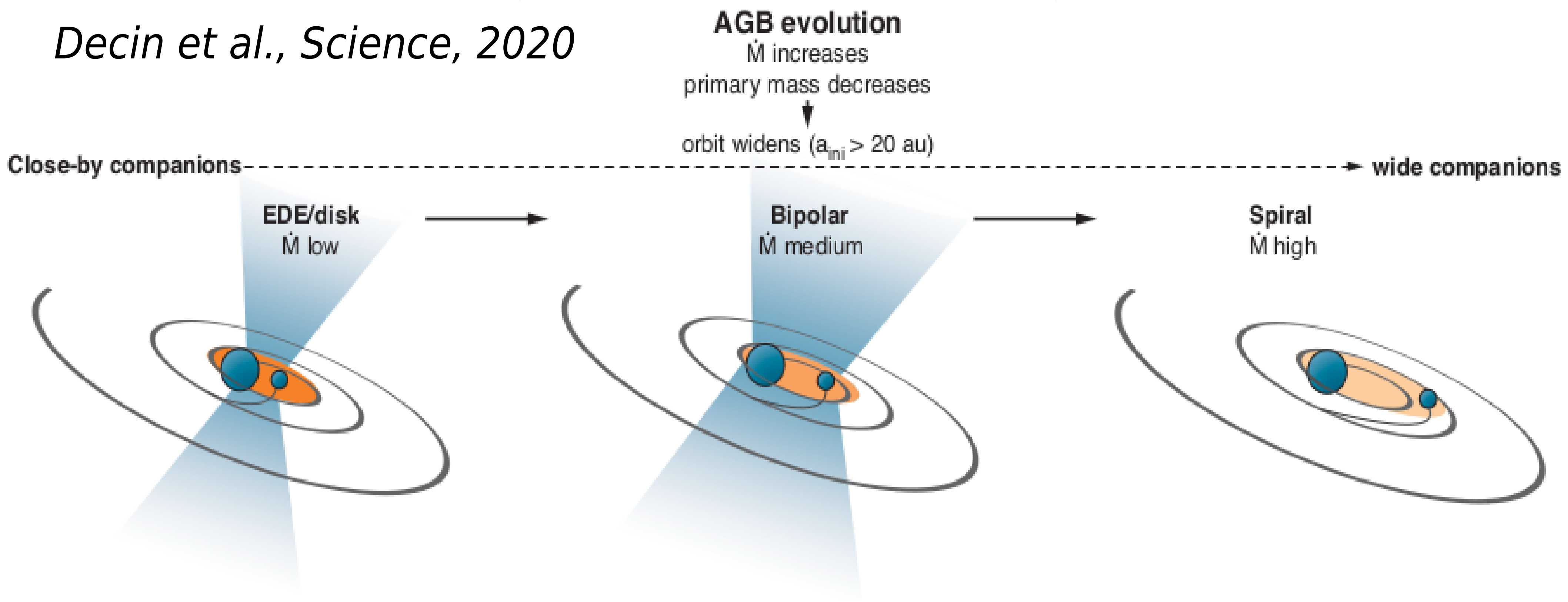
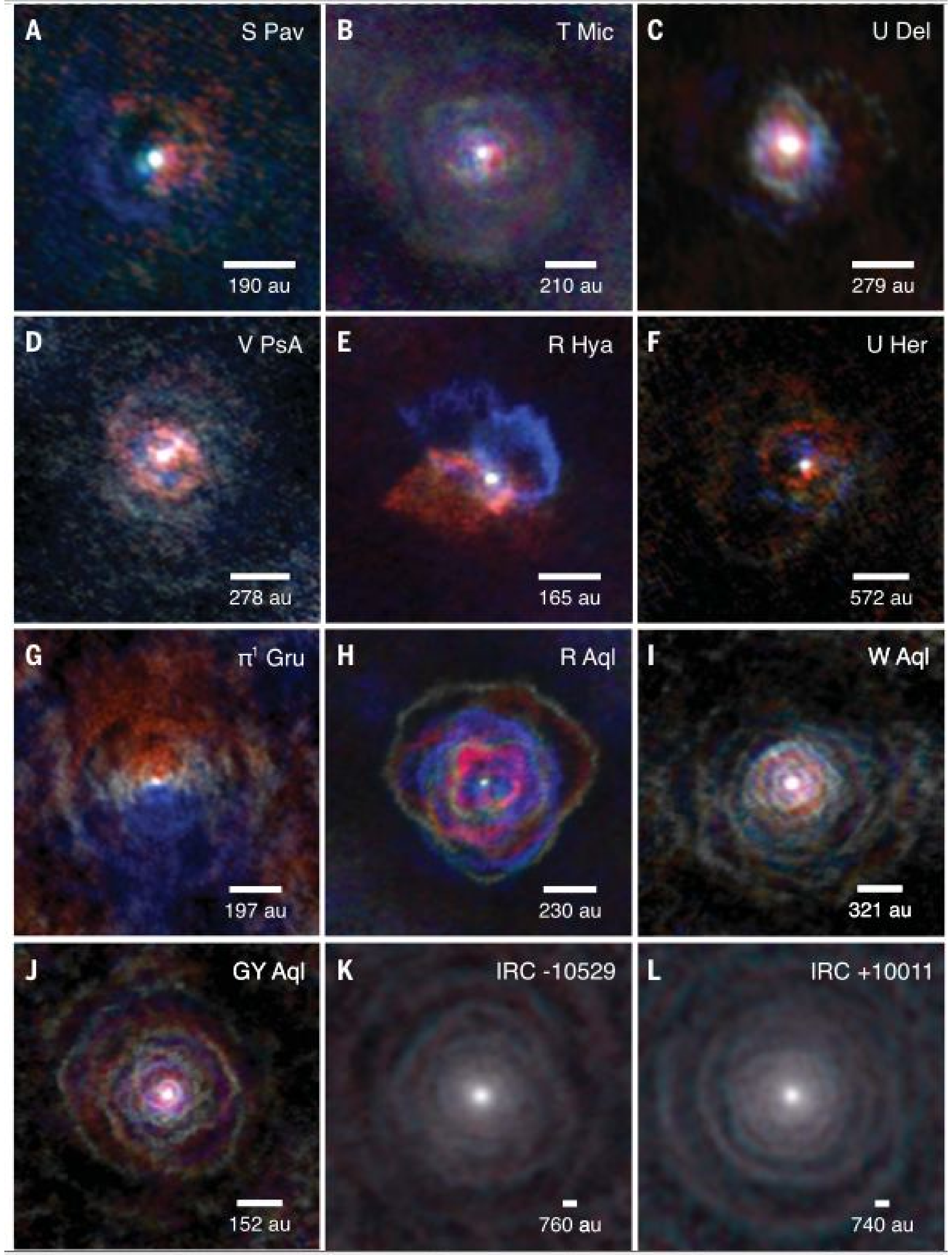
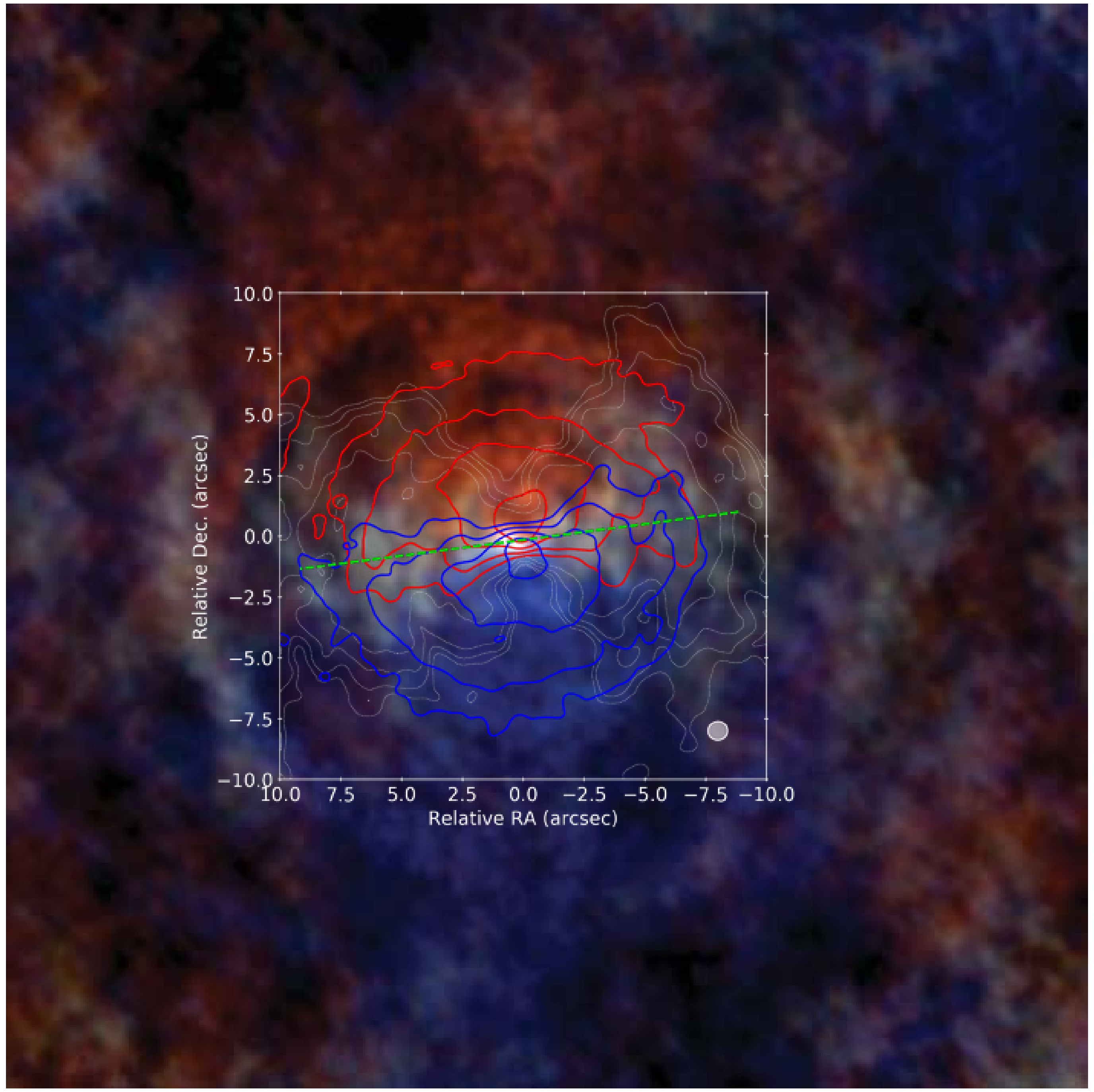
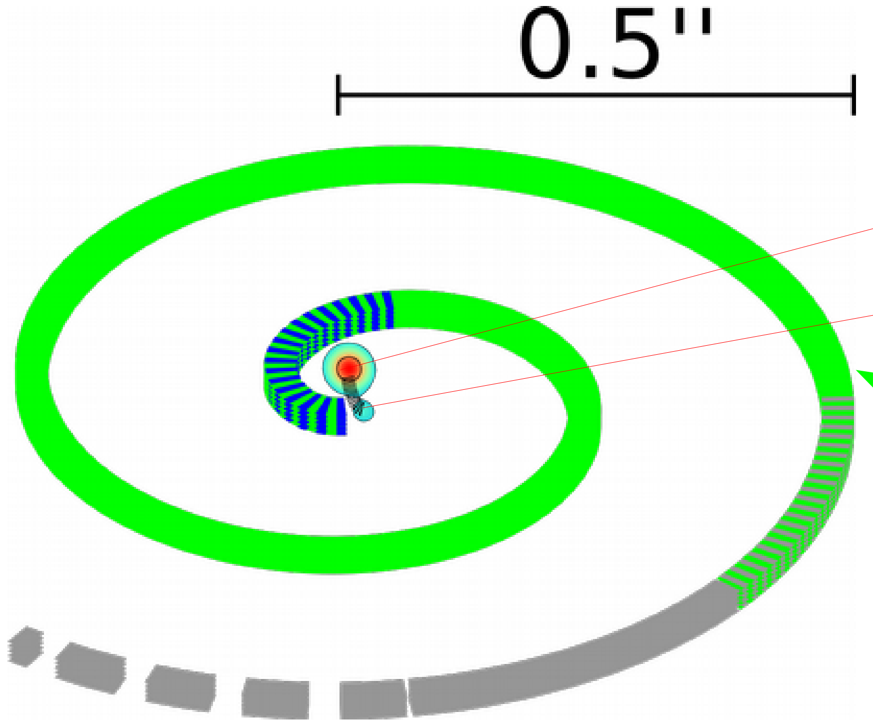


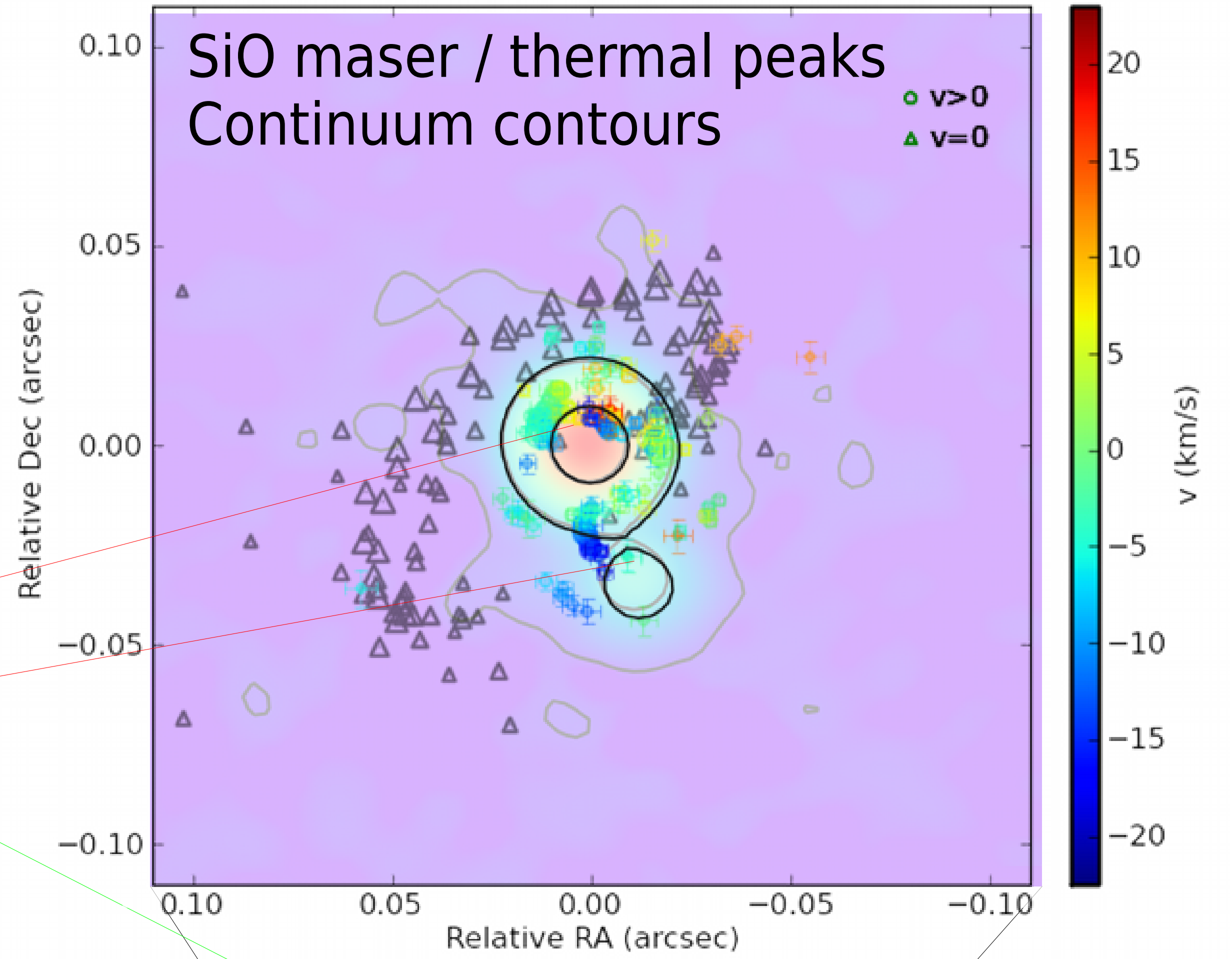
Fig. 2. Schematic illustration of our inferred evolution of wind morphology during the AGB phase. Most (sub)stellar companions have initial orbits (a_{ini}) greater than 20 au (*24*). These orbits widen during AGB evolution because the stellar mass decreases. Binary systems with close-orbiting companions often have a high-density EDE and accretion disk (orange) and complex inner wind dynamics. For increasingly wider orbits and higher mass-loss rates, the prevailing outflow morphology initially transitions to a bipolar structure (blue shading) and then to a regularly spaced spiral structure. EDEs or accretion disks can be present at these later stages, but at lower density.

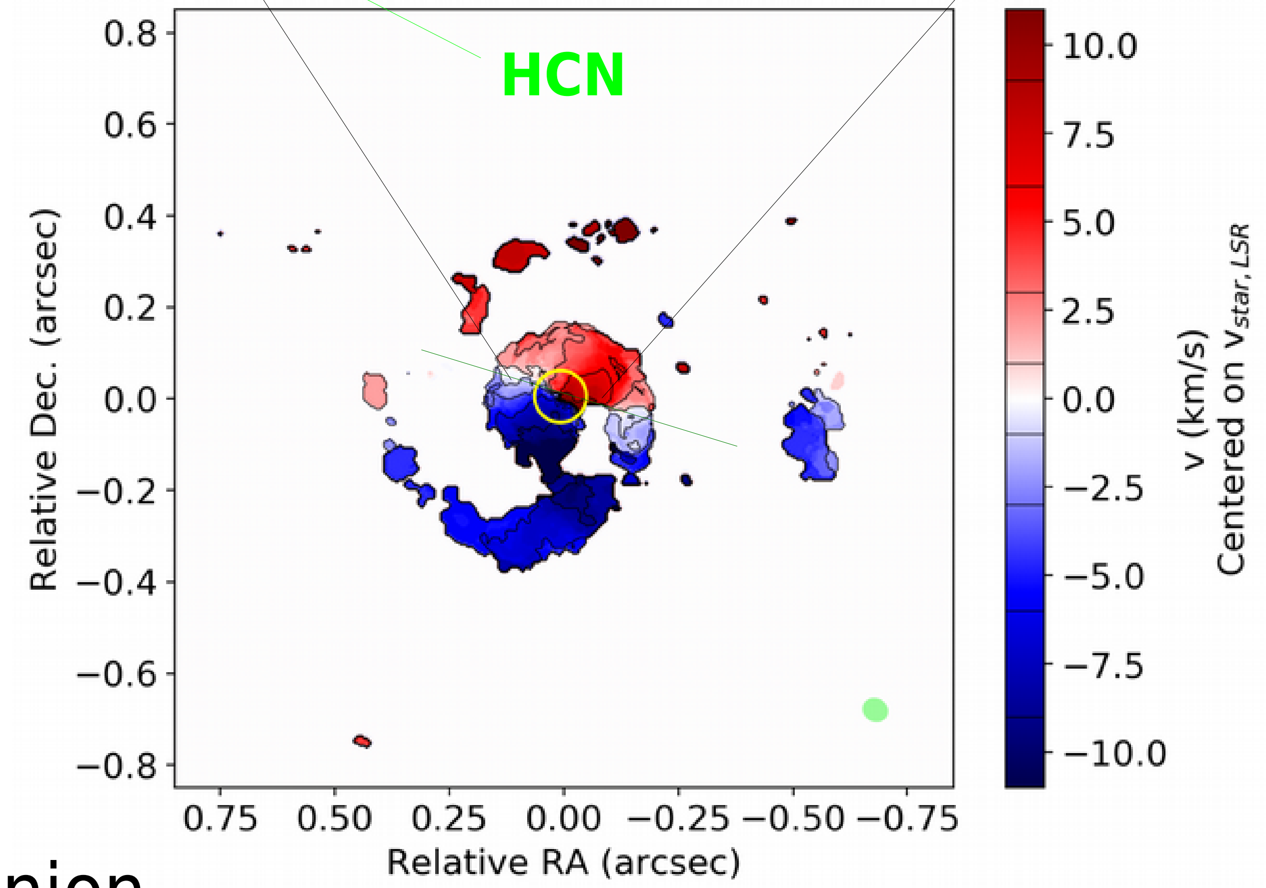


π1 Gru spiral





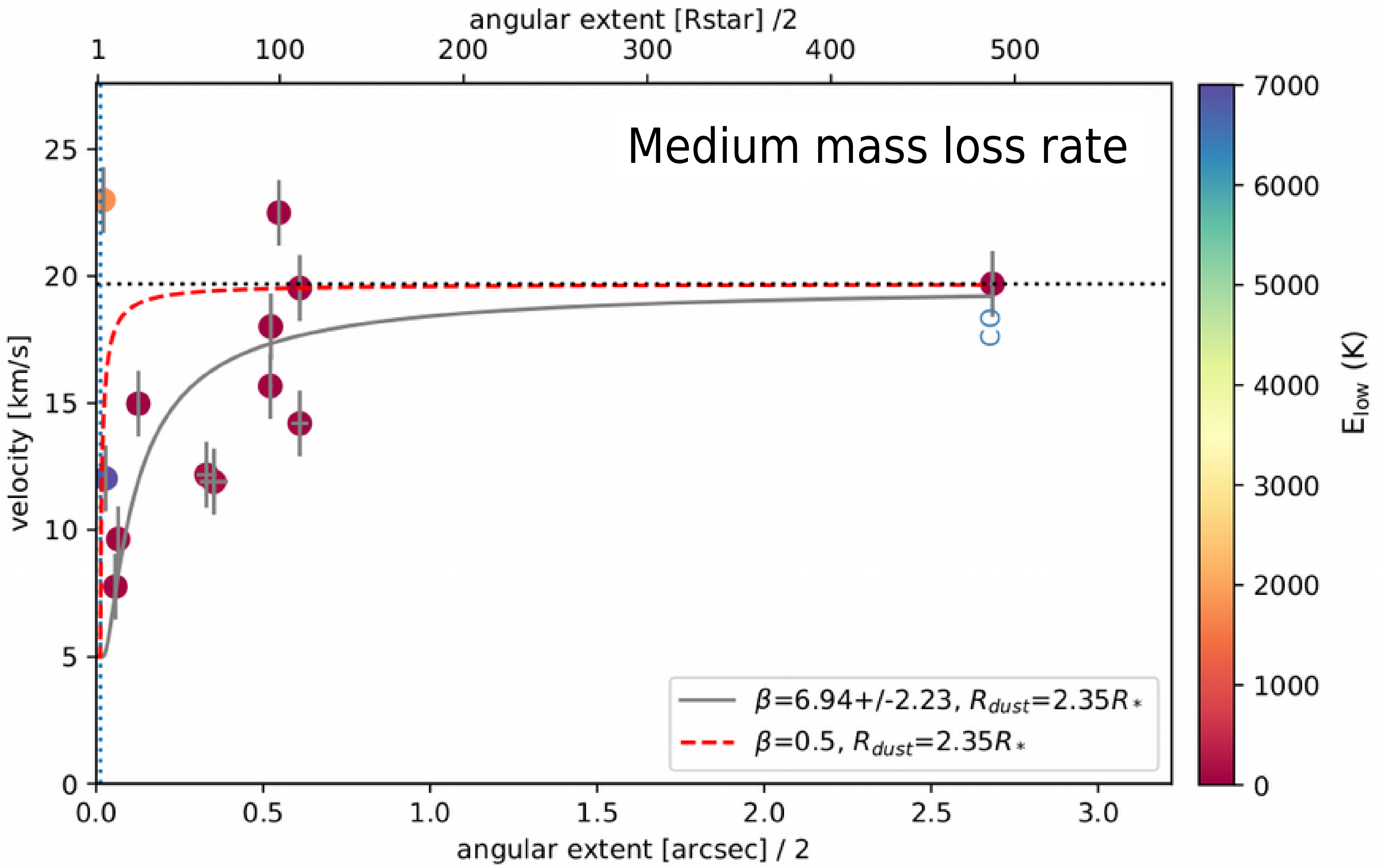


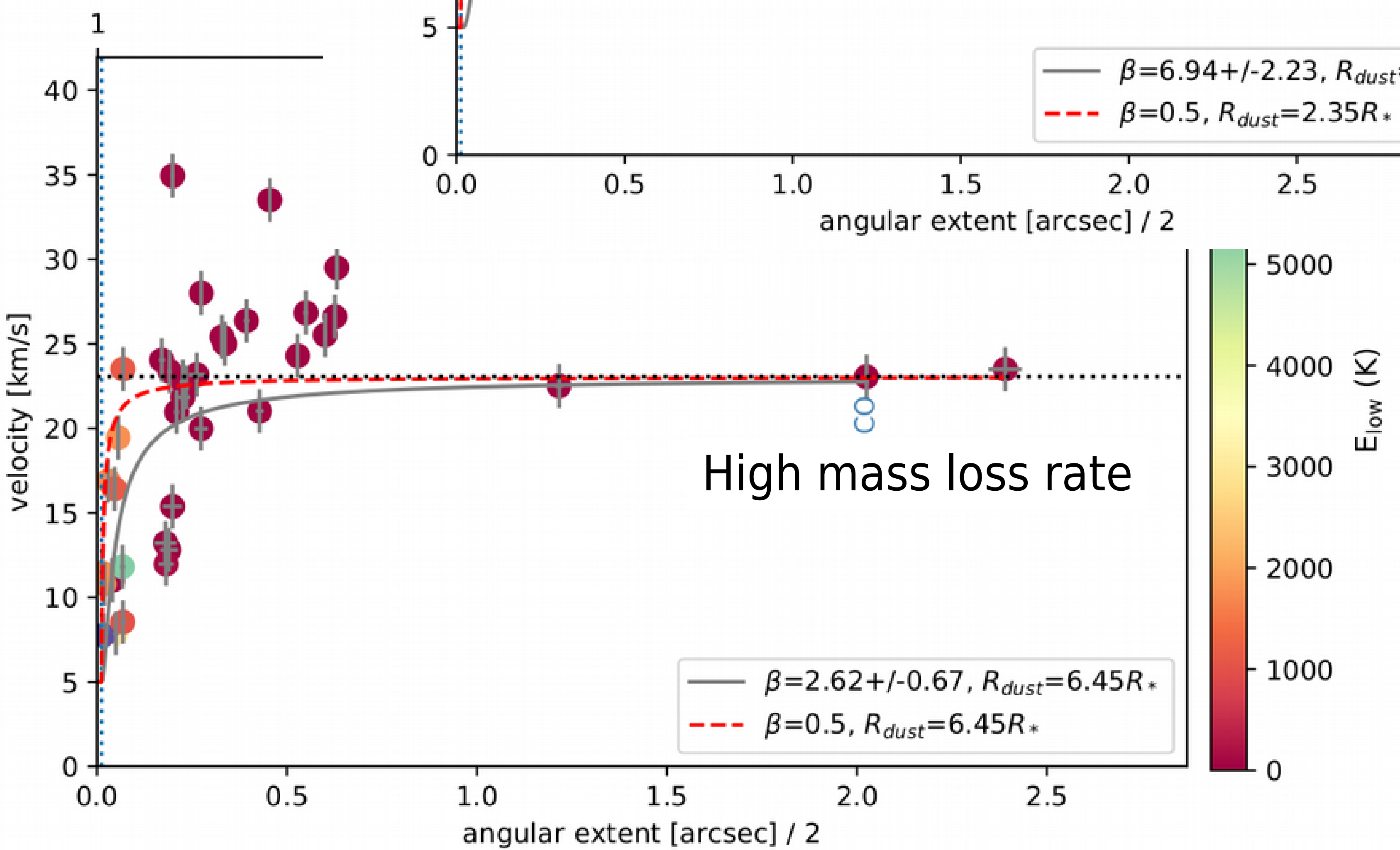


- CO traces >500-au radius tilted expanding spiral
- Angle of V_* plane precesses with decreasing radius
- ALMA resolves companion at ~7au
  - SiO masers show innermost spiral and flow from primary to companion

Homan et al. 2020

Wind dynamics: Max. outflow velocity v. angular size





- High-excitation lines can show high velocities close to star
  - Could be pulsation-related
- Lowest-excitation lines furthest from star
- Acceleration more gradual than simple momentum equation (β~1)
  - C-rich stars: β~0.5
  - O-rich: mostly much higher values of β

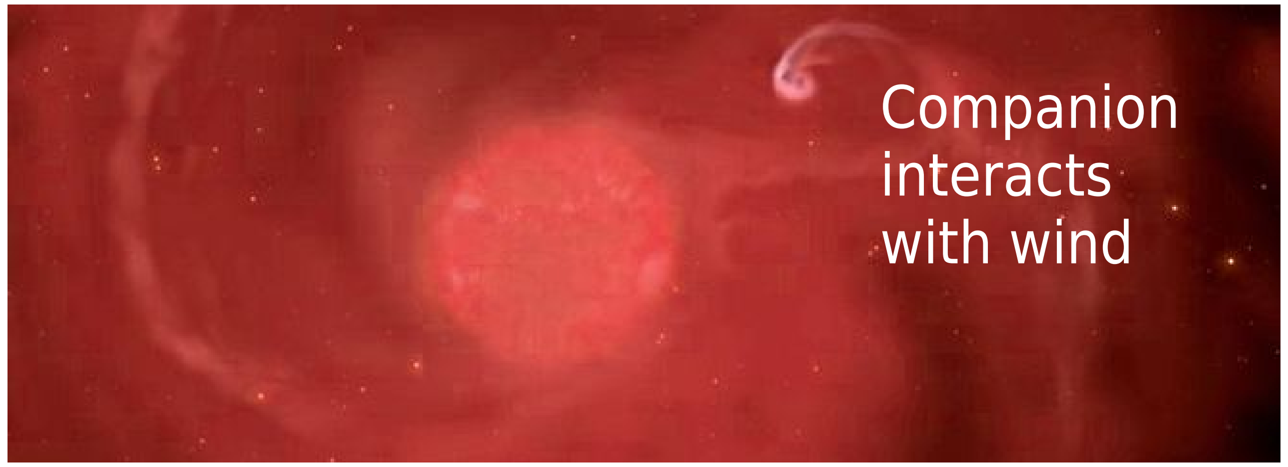
$$v(r) = v_0 + (v_\infty - v_0)\left(1 - \frac{R_{\rm dust}}{r}\right)^\beta$$

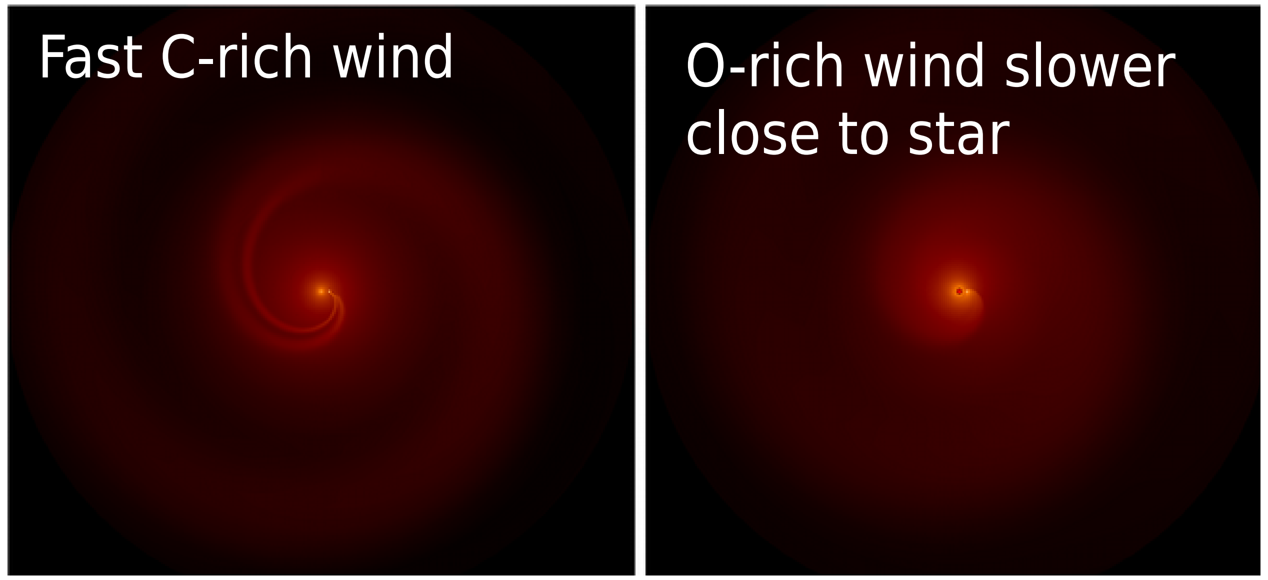
  - Grain surface properties evolve
    - Annealing? Fluffy/fractal?
- Some medium-excitation species at ≲100 R_* have higher terminal velocities than CO
  - Additional forces implied

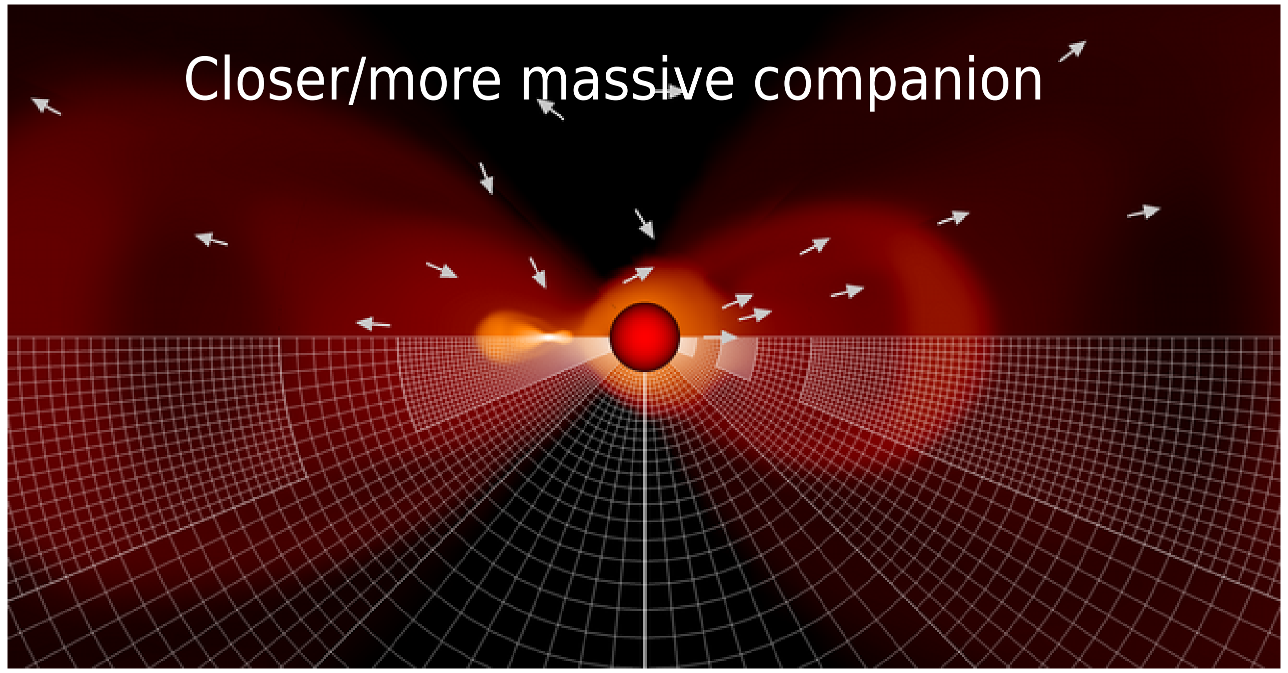
Gottlieb et al in prep

Modelling Asymmetric Circumstellar Envelopes

- Low mass loss rate stars: Equatorial density enhancement
- Medium mass loss rate: Bipolar/biconical outflow
- High mass loss rate: Spirals
- >50% stars $M < 1.5\ M_{\odot}$ have (a) companion(s)
  - Red, white or brown dwarfs, planets....
  - Even higher fraction of higher mass stars
- More complex effect on gradually-accelerating O-rich winds
  - Modelling: *el Mellah et al. 2020*
- Stars with strong H_2O masers: no wind rotation, irregular shapes
  - Selection effect due to velocity coherence needed?
- SiO masers very widespread
  - many shapes including spirals!







ATOMIUM next steps

- Last 2 science goals: observations still to be completed
  - 1 year after they are delivered, enhanced products available
- Papers published/in prep:
  - Companions Shape Stellar Winds *Decin et al. Science*
  - ATOMIUM I. Motivation, Sample, Calibration, and Initial Results *Gottlieb et al.*
  - Chemistry of dust ingredients *Danilovich et al.*
  - Modelling & theory, kinematic comparisons, chemistry (*Millar, El Mellah, Wahlstrom...*)
  - Individual stars (*Homan pi Gru, ...*),
  - Optical (*Montarges..*) & cm-wave (*Richards...*) observations,
  - Masers (*Pimpanuit, Etoka, Baudry, Gray, Richards...*)