Title: Leveraging Intensity Interferometry Towards Understanding Massive Stars and Supernovae

Speakers: Jared Goldberg

Collection/Series: Future Prospects of Intensity Interferometry

Subject: Cosmology

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LEVERAGING INTENSITY INTERFEROMETRY TO UNDERSTAND MASSIVE STARS AND SUPERNOVAE

(A THEORIST'S WISHLIST)

Jared A. Goldberg* – Future Prospects of Intensity Interferometry – 1 November 2024

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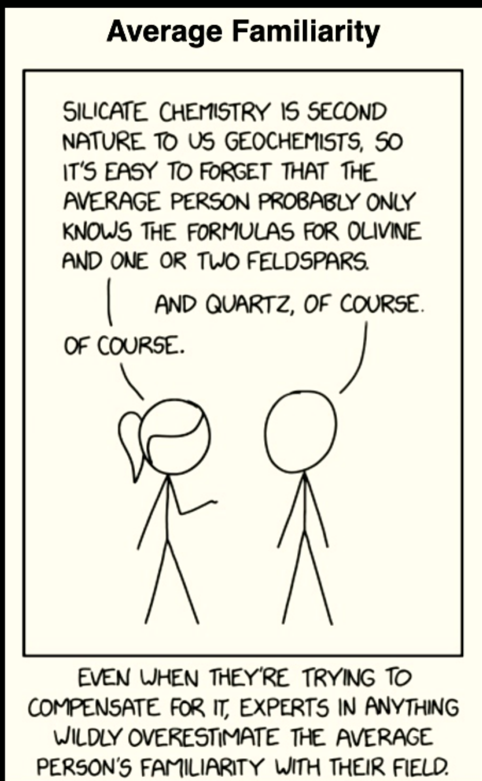
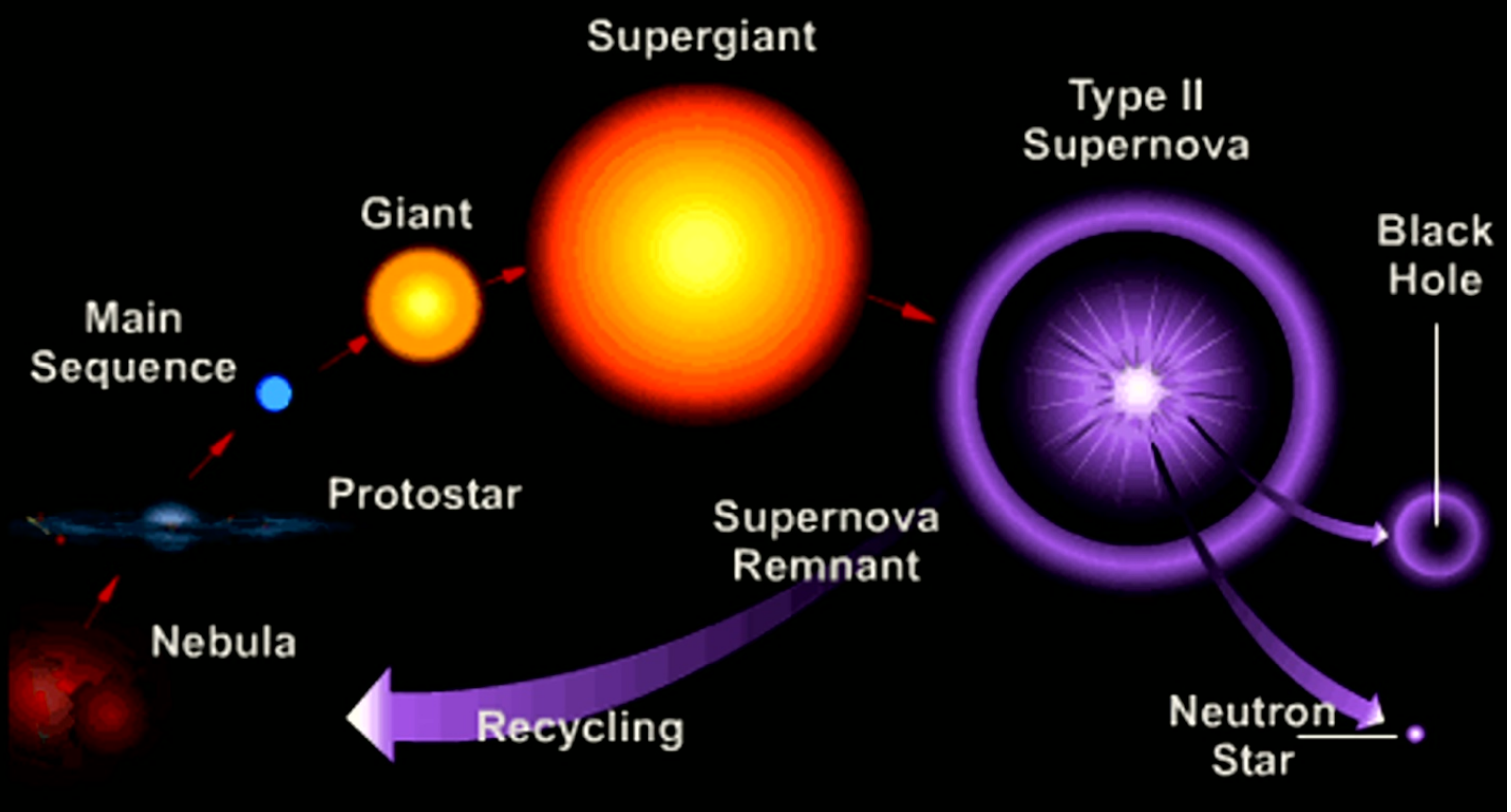
+ Work with Iman Behbehani (CUNY Masters) & Thavisha Dharmawardena (NYU) & Meridith Joyce (University of Wyoming) & László Molnár (Konkoly Observatory) & Yan-fei Jiang (Flatiron CCA) & Lars Bildsten (KITP/UCSB) & others

MASSIVE STAR LIFE CYCLE

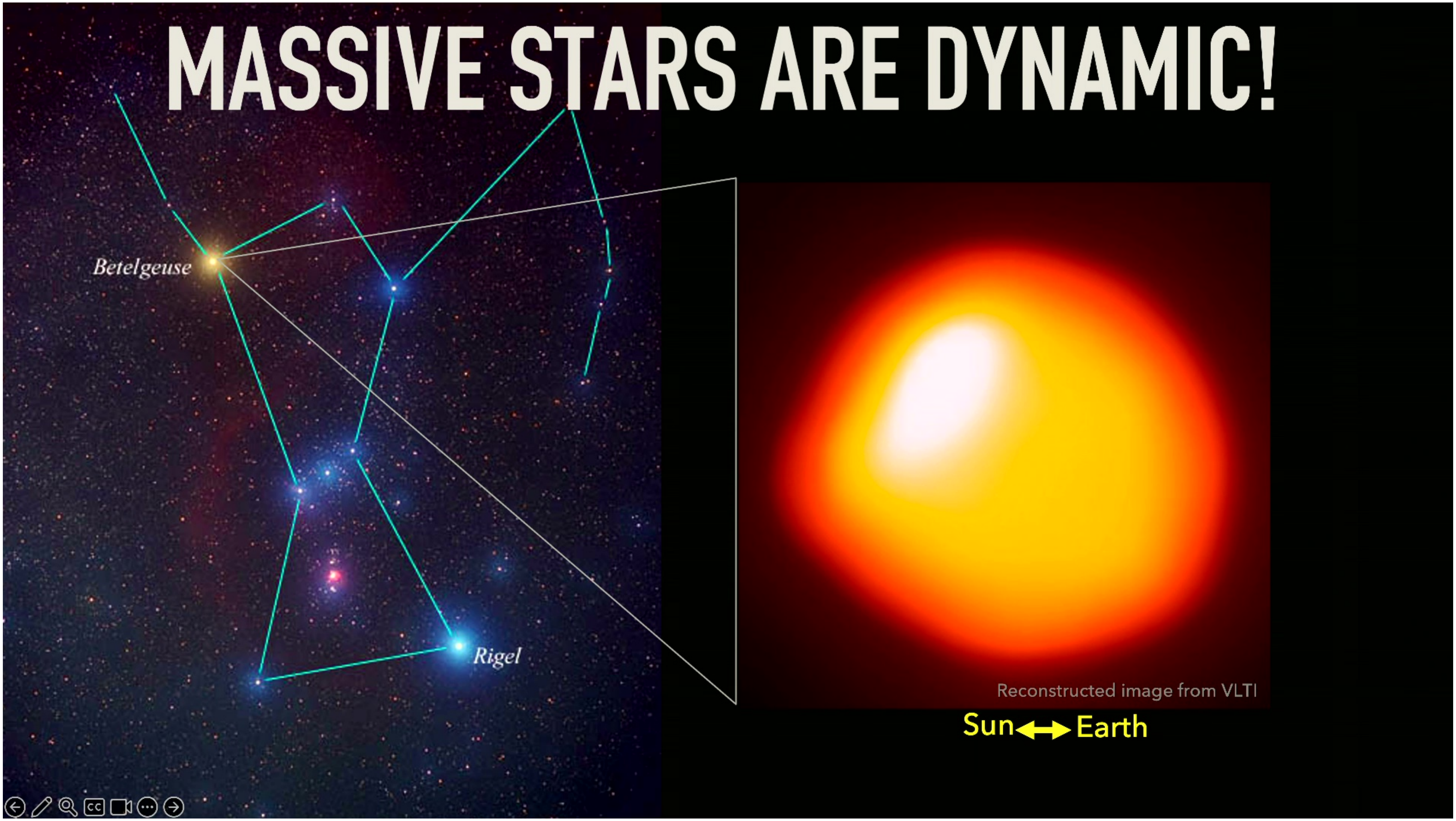
1

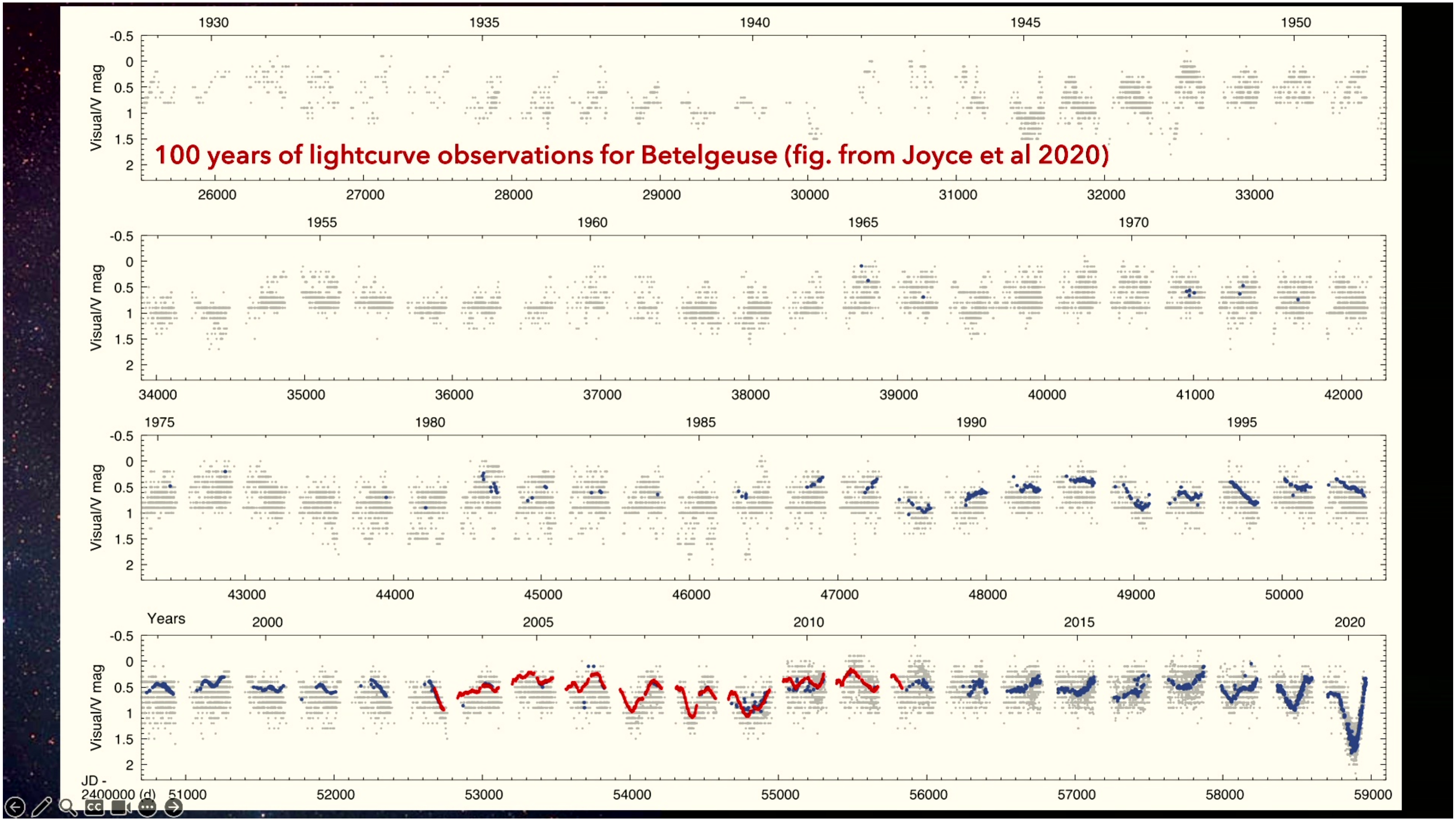




(Image credit: Brooks/Cole Thomson Learning)

MASSIVE STARS ARE DYNAMIC!




100 years of lightcurve observations for Betelgeuse (fig. from Joyce et al 2020)
Visual/V mag
Years
JD - 2400000 (d)
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
-0.5
0
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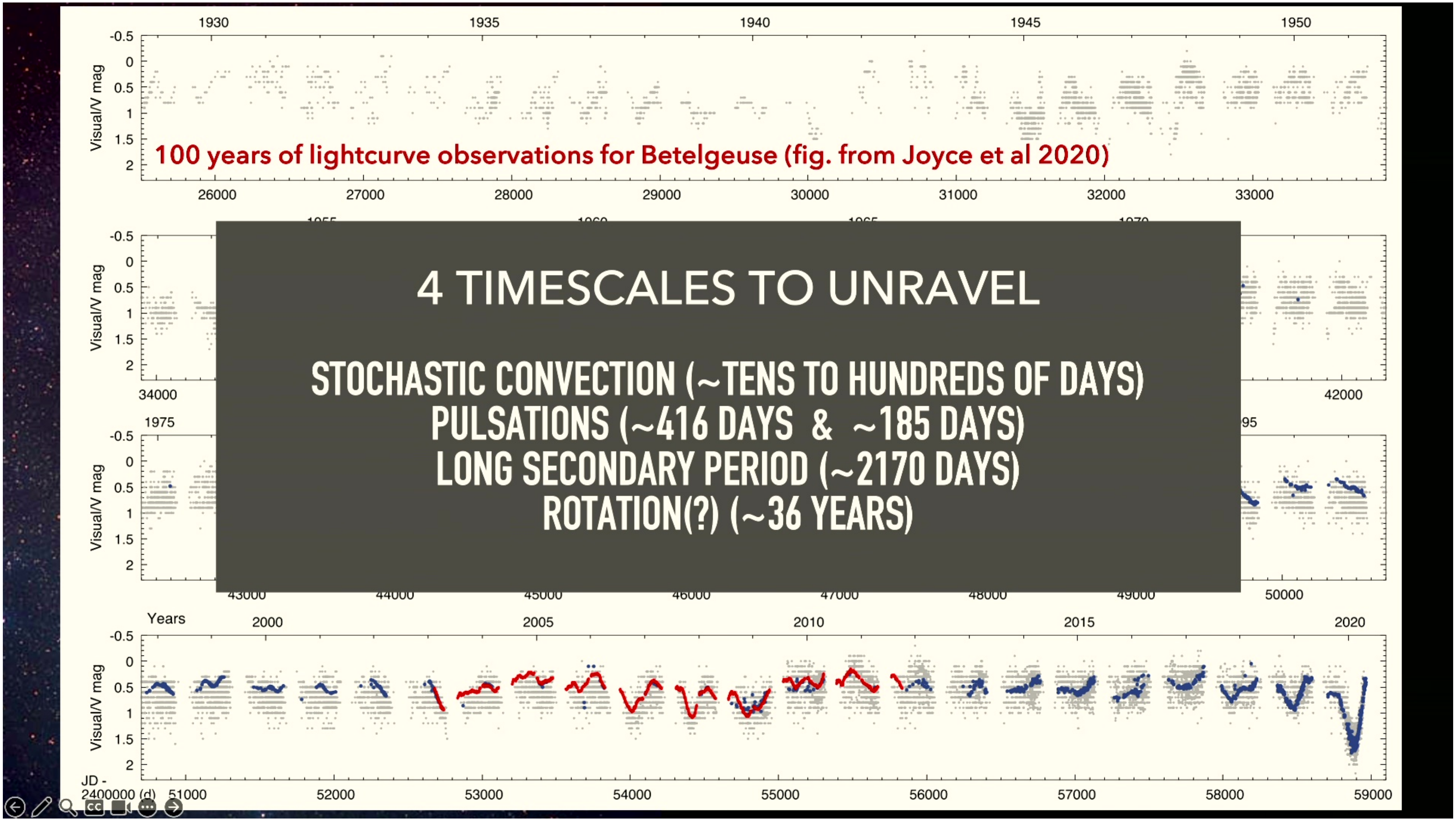
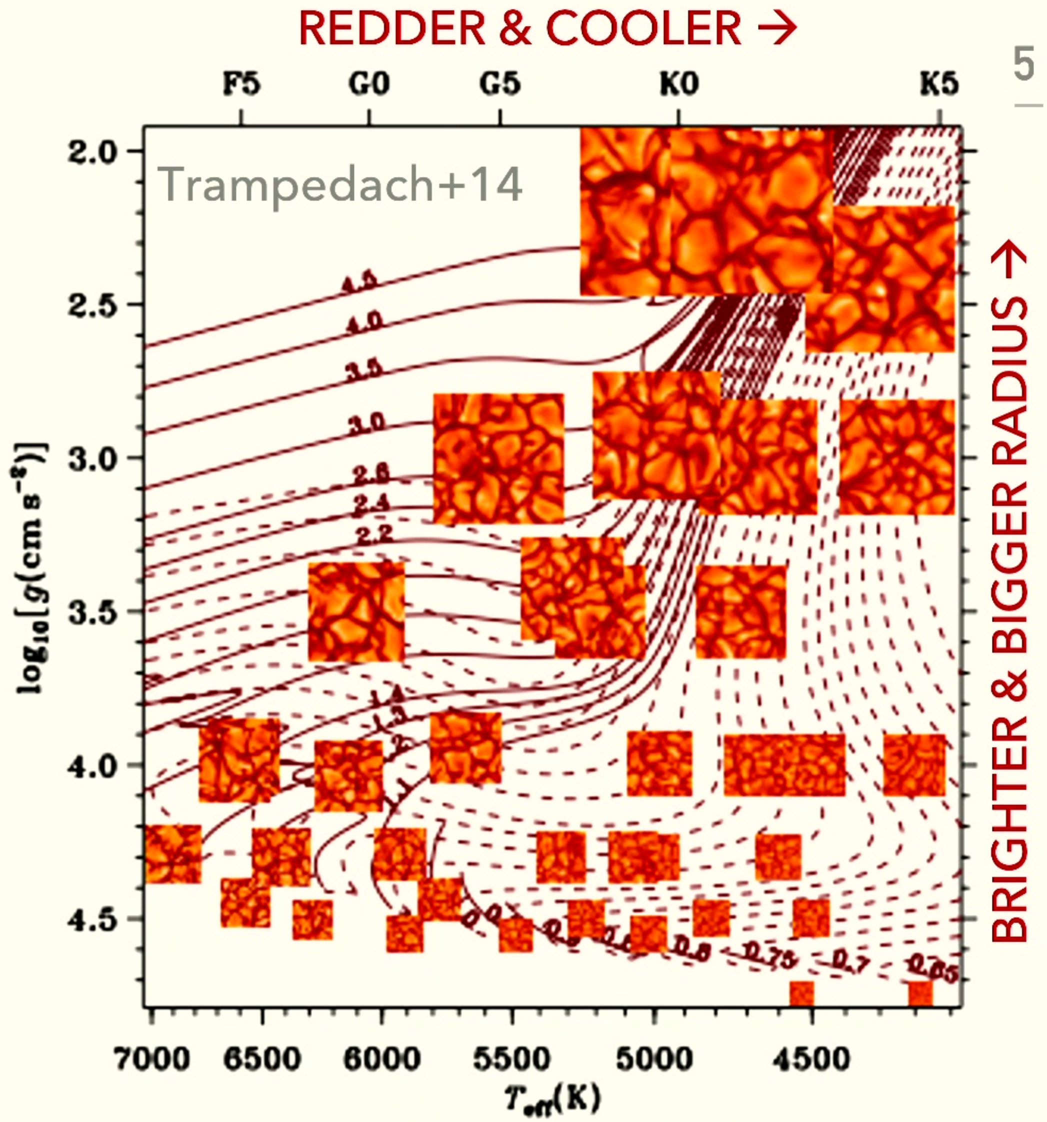

100 years of lightcurve observations for Betelgeuse (fig. from Joyce et al 2020)
4 TIMESCALES TO UNRAVEL
STOCHASTIC CONVECTION (~TENS TO HUNDREDS OF DAYS)
PULSATIONS (~416 DAYS & ~185 DAYS)
LONG SECONDARY PERIOD (~2170 DAYS)
ROTATION(?) (~36 YEARS)
Visual/V mag
Years
JD - 2400000 (d)

CONVECTION, PULSATIONS, COMPANIONS, EXPLOSIONS!

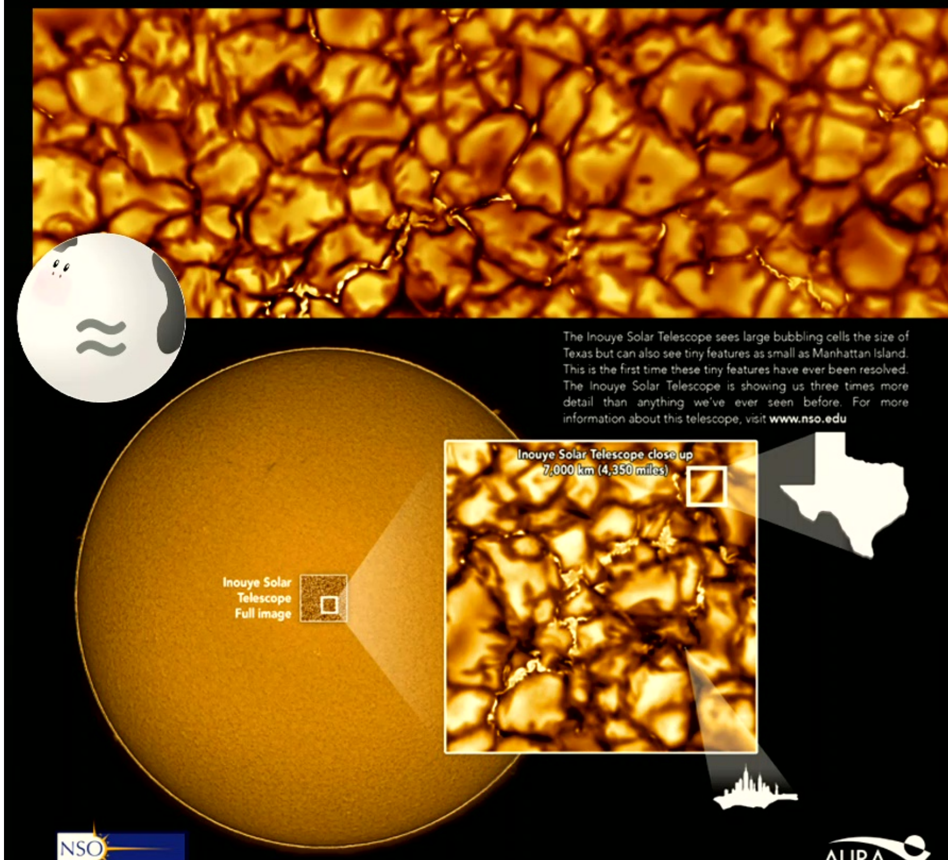
+ Rotation, Winds, Interaction, Eruptions, Mergers, Dynamics, & more....

WHY DO WE CARE?

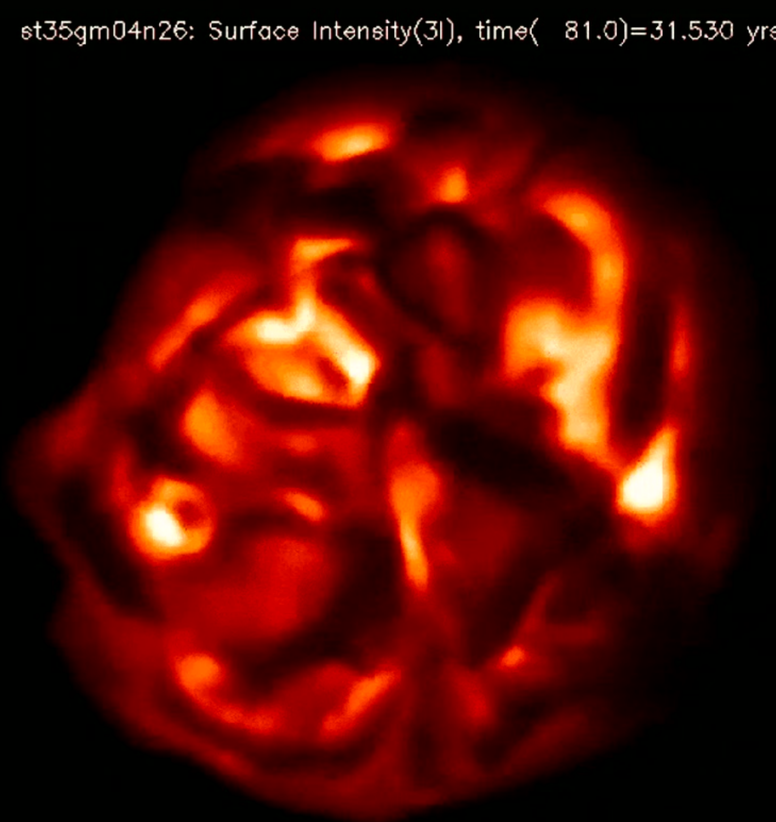
- Observations: Both Micro- and macro-turbulence imprint on L, RV's, etc
- Theory: Energy transport (convective efficiency) determines stellar envelope structure (which is in turn what we observe)
- Simulations + theory show that bigger stars = bigger convective cells, but observations are necessary to ground & calibrate this theory!



CONVECTION: THE SUN VS RSGS

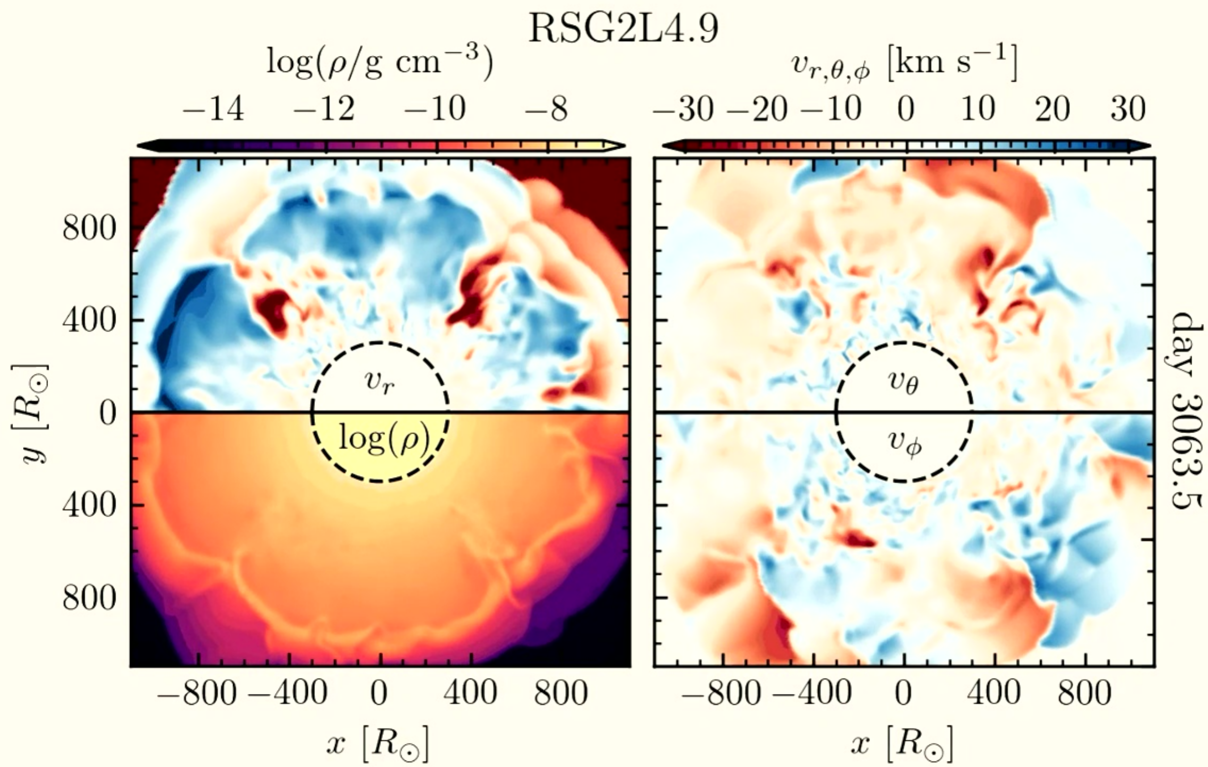


Data courtesy of DKIST

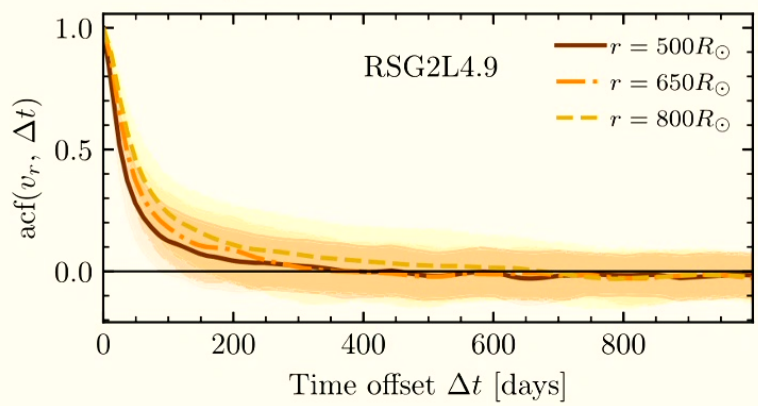


3D RHD Sim. from website of Bernd Freytag; see also Chiavassa+ 2009, 2010a,b, 2011, 2012; JAG, Jiang, & Bildsten 2022a; Chiavassa, Kravchenko, & JAG 2023

RSG CONVECTIVE VELOCITIES COHERENT FOR A FEW HUNDRED DAYS 7



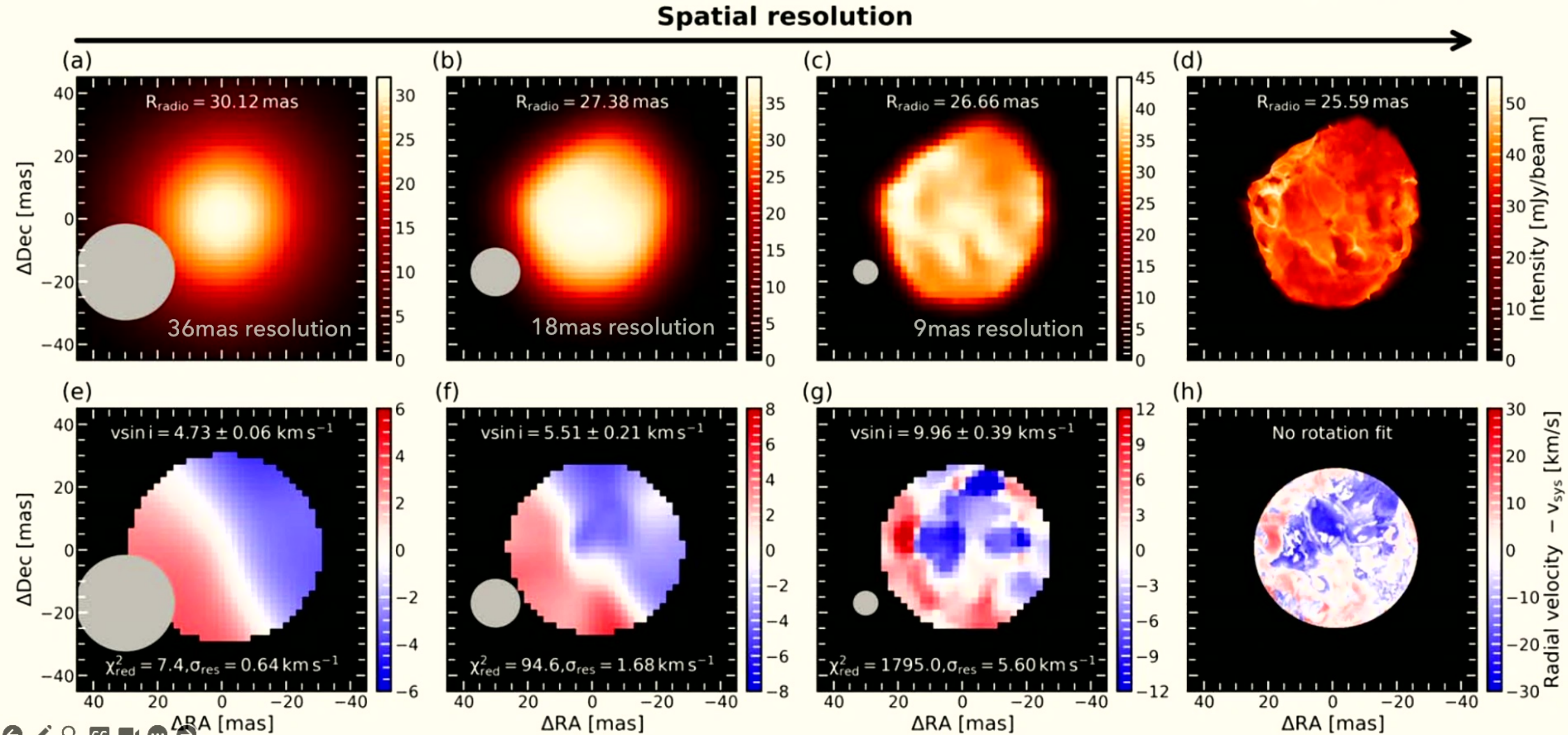
Coherence time tells you about the sound speed, convective mach number, typical plume size relative to stellar radius, etc. Can we measure this directly?



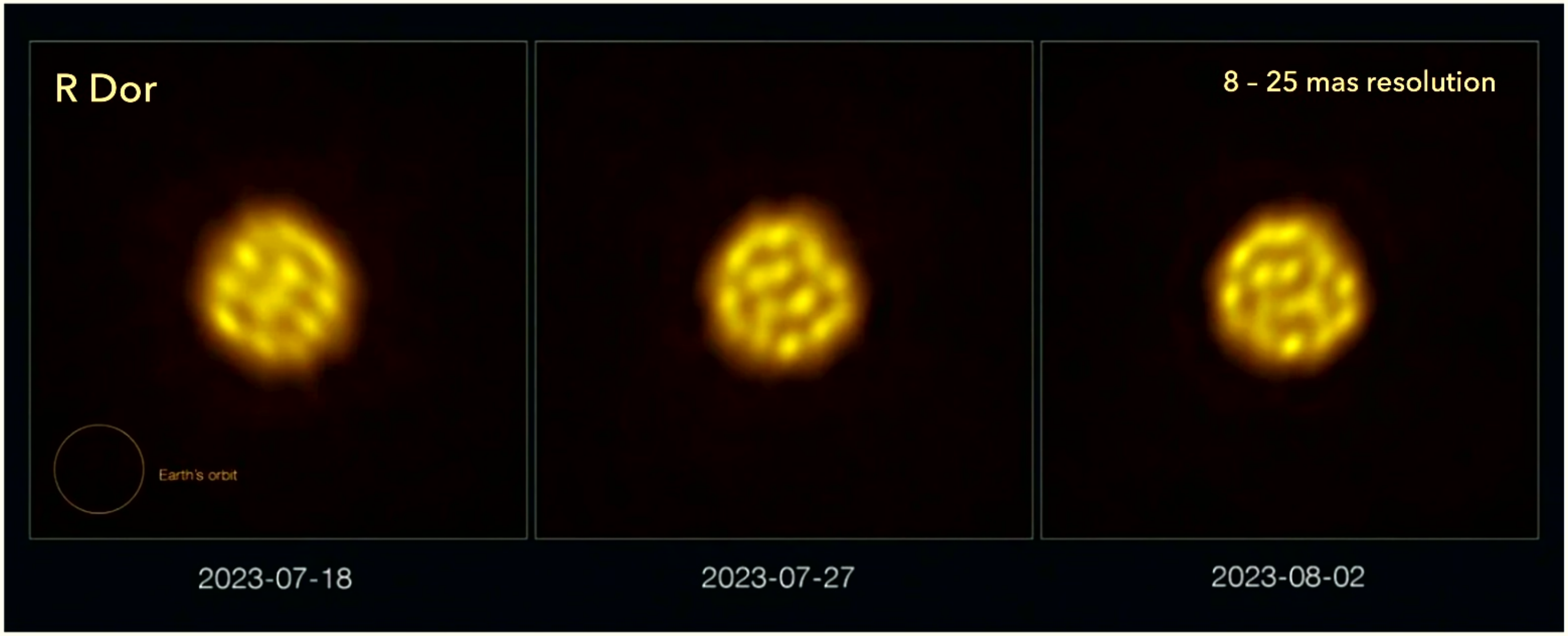
Simulations from Goldberg, Jiang, Bildsten (2022a, ApJ)

SPATIAL RESOLUTION DISENTANGLES CONVECTION FROM ROTATION

Fig. from Ma et al 2024



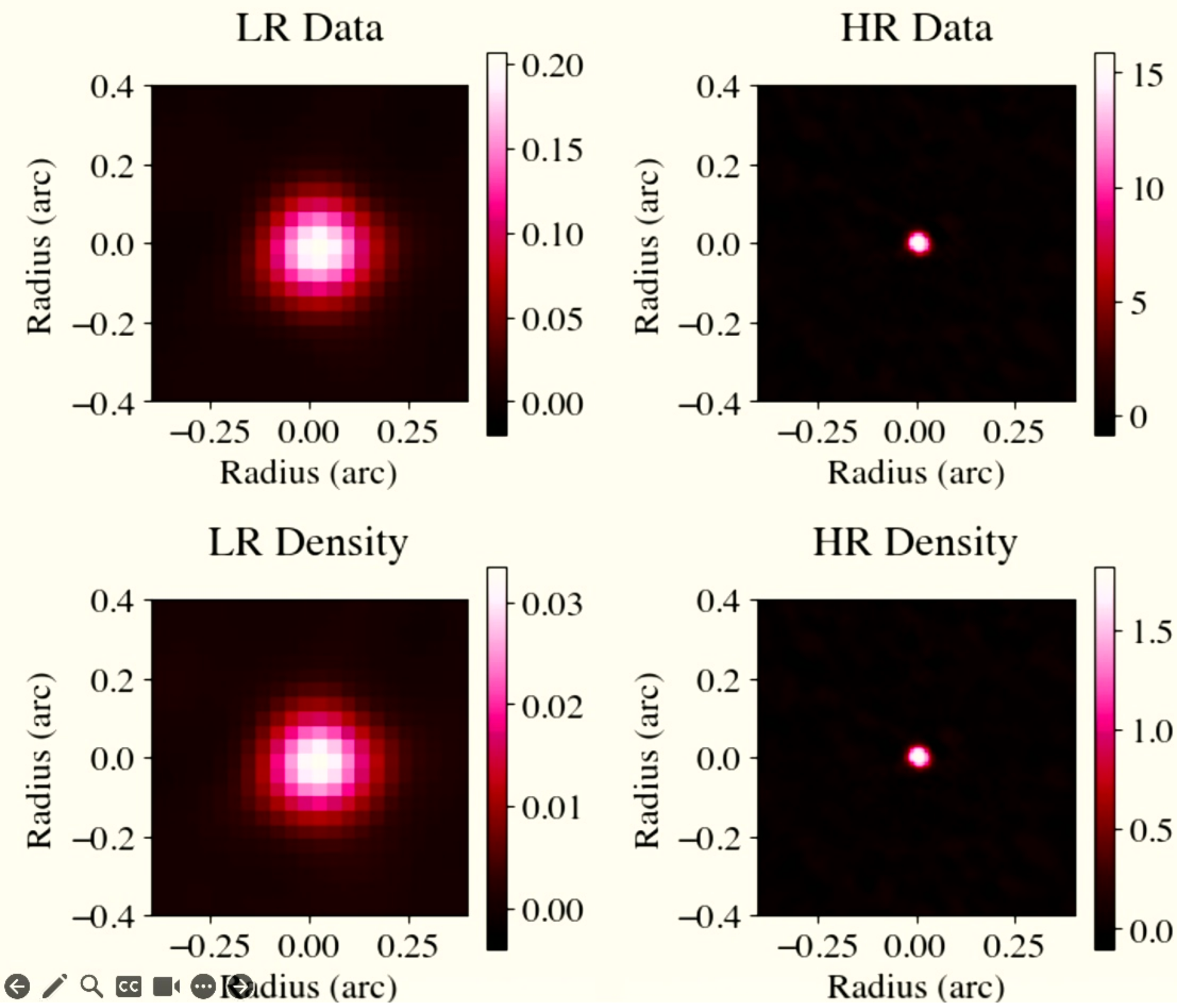
ALMA CAN "RESOLVE" COOL GIANT STAR CONVECTION!



This series of images of the star R Doradus, captured by ALMA, show bubbles forming on the star's surface in incredible detail. Credit: ALMA (ESO/NAOJ/NRAO)/W. Vlemmings et al.

Vlemmings et al 2024 (Nature)

CAN WE RESOLVE THE OPTICAL PHOTOSPHERE?

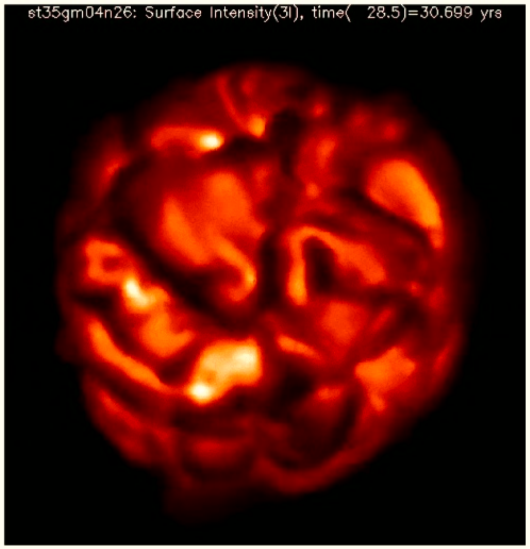


- Different resolutions probe different regions near the star
- HR probes close to star (~15 mas resolution), LR probes Circumstellar Material (~150 mas resolution)
- T_{eff} = 3600 K ~ 800nm = lots of photons not in radio or NIR
- Optical Intensity interferometry can do what traditional IR & Radio can't!

Iman Behbehani (CUNY Masters), Dharmawardena, & Goldberg, in prep.

LARGE-SCALE CONVECTION = ASTROMETRIC JITTER

Chiavassa+2022: Few plumes → variable photocenter



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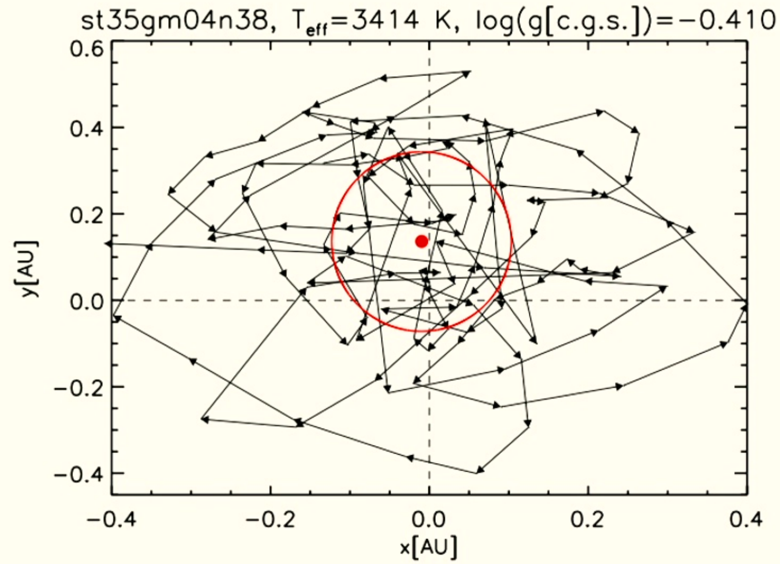


However, GAIA error increases for bright sources (Kochanek 22), ruling out GAIA's ability to detect this.

Motion of a RSG photocenter in GAIA band

Figure from Chiavassa+2022

>>> An astrometric tool for bright sources would be revolutionary!

43 mas = 7ish AU for Betelgeuse

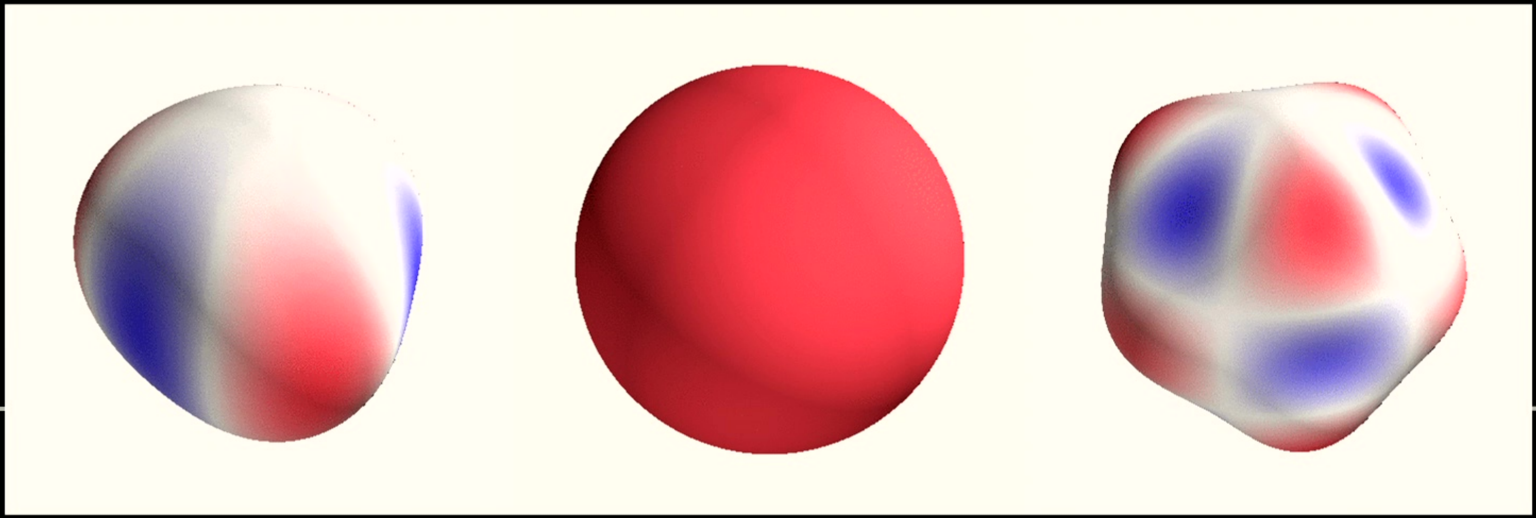
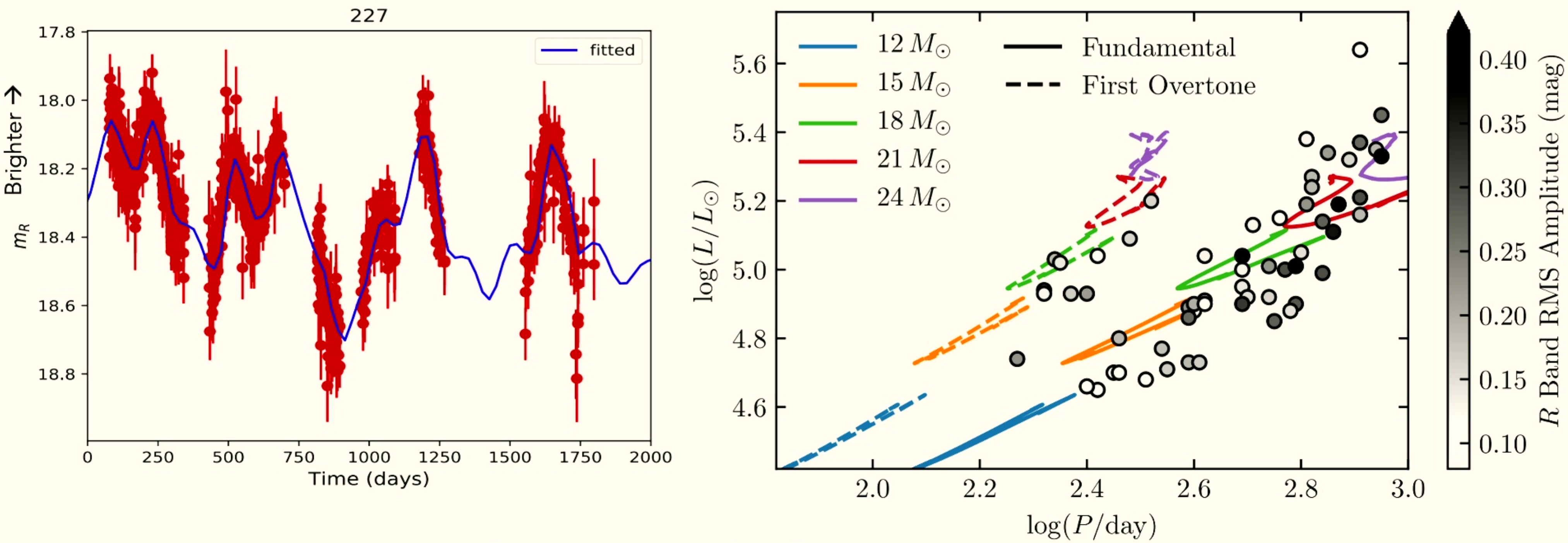


Figure courtesy of Evan Bauer

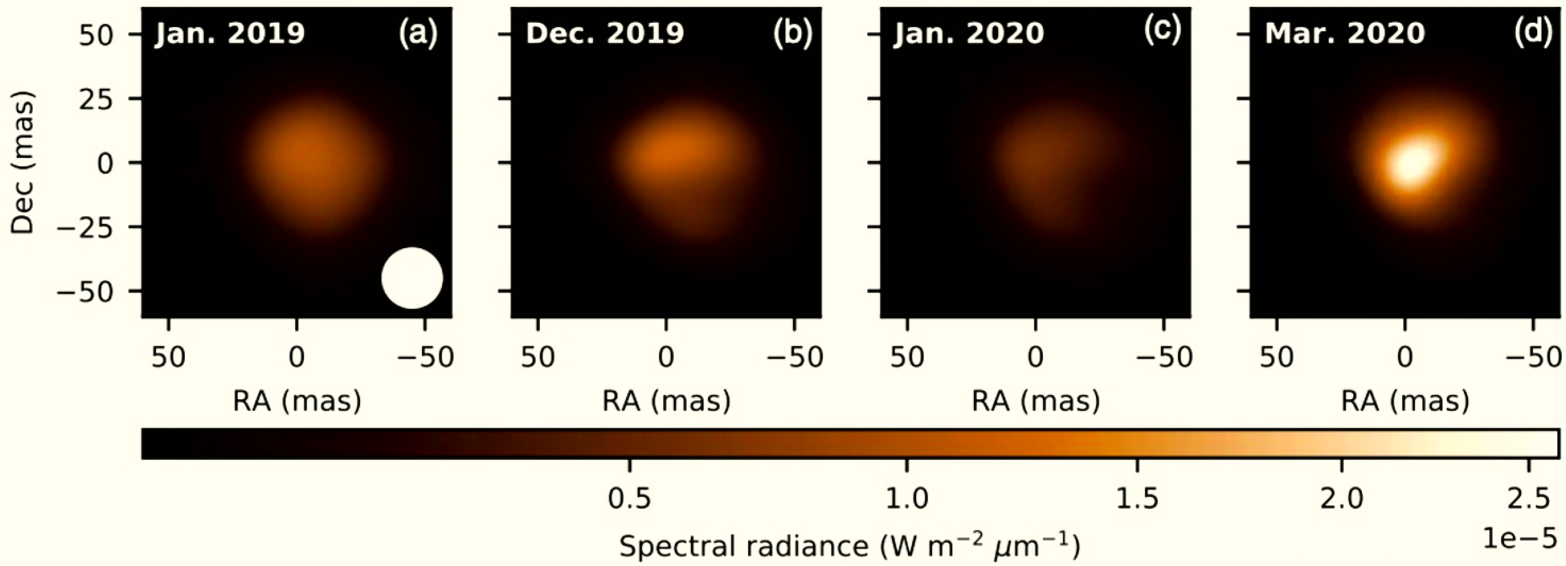
THE BRIGHTER THE STAR, THE STRONGER THE PULSATION

- Many red (super)giants pulsate, including Betelgeuse, Antares, and others. Q: On a pulsation cycle, does the angular diameter change by 10% (a few mas)? 1% (a fraction of a mas)?

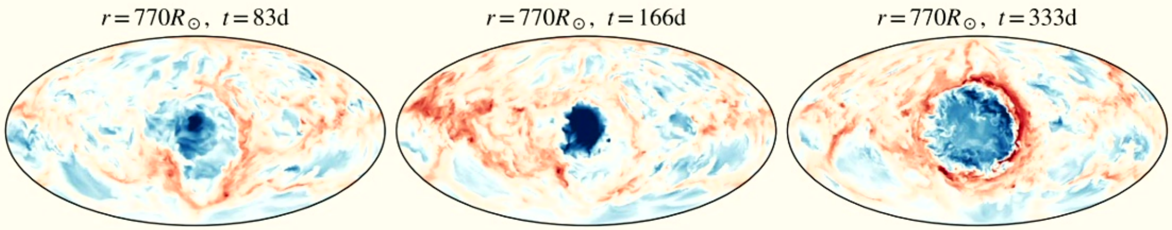


Pulsations in M31 from Soraisam et al 2018

DUST OBSCURATION: BETELGEUSE'S GREAT DIMMING (2020)



VLTI observations, Figure from Montarges et al 2022

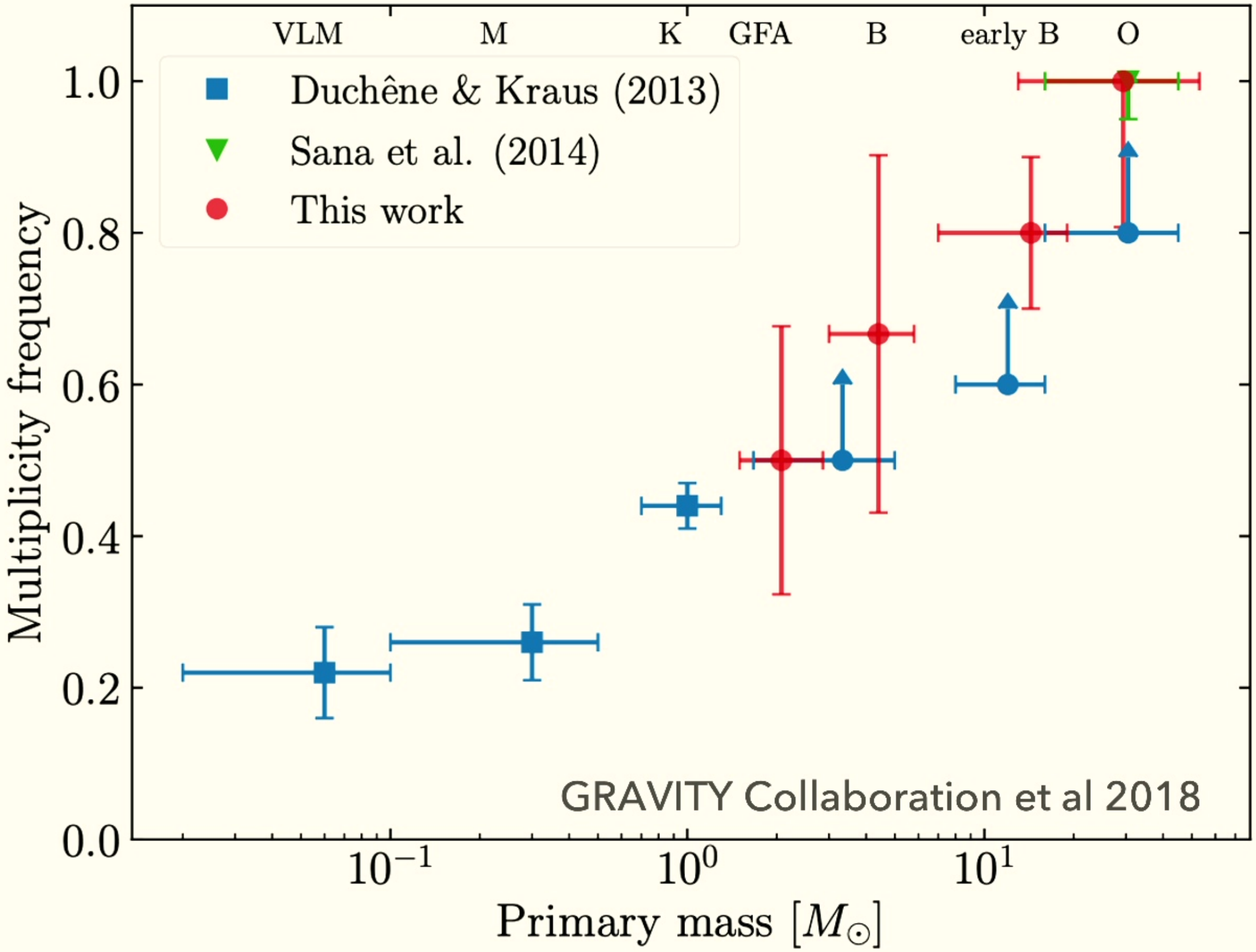


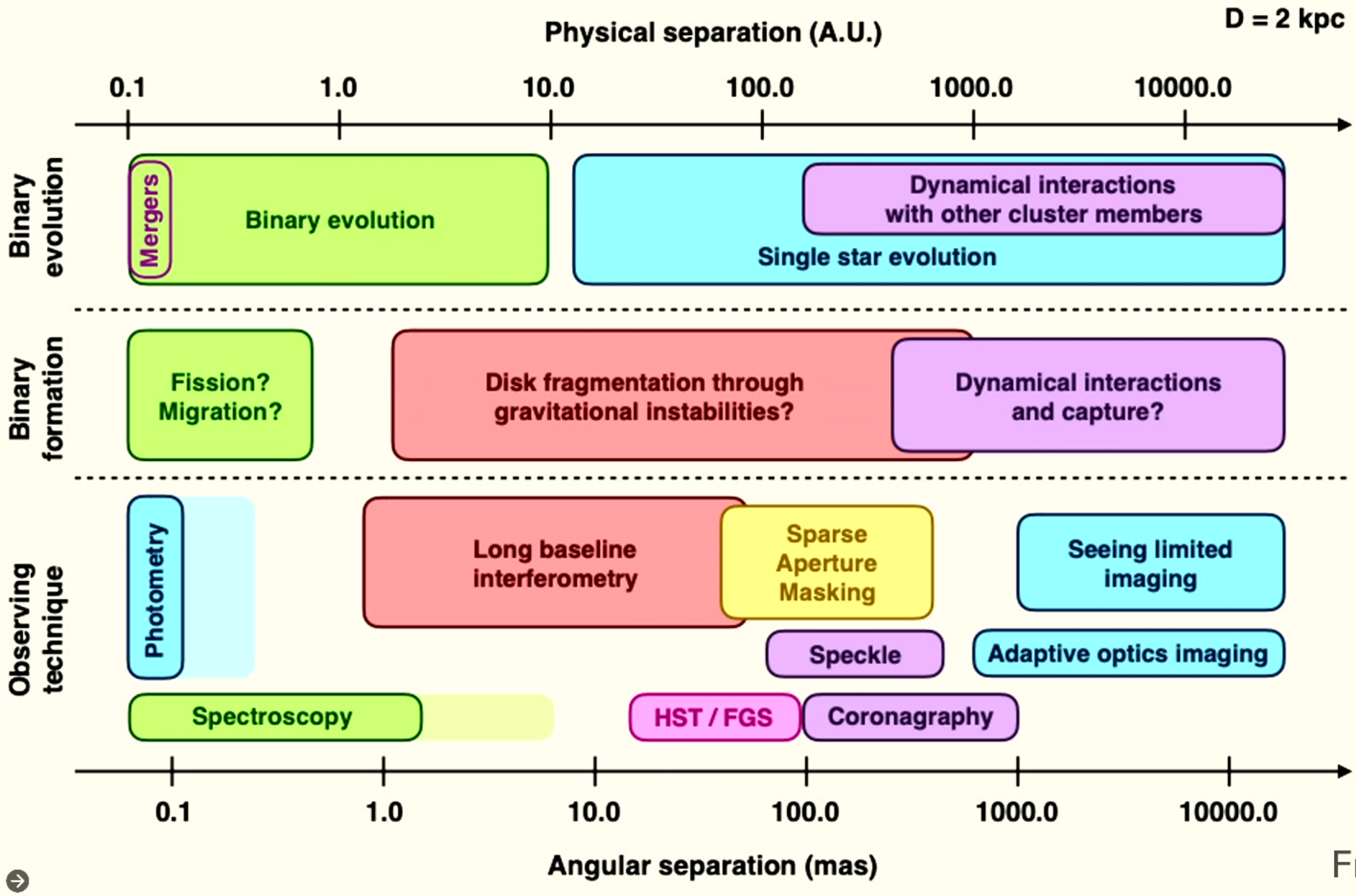
Simulations by MacLeod, Antoni et al 2023

COMPANIONS

MOST MASSIVE STARS ARE BORN IN BINARIES!

- Massive stars born in binaries!
- And these are just the binaries where you can see the companion!





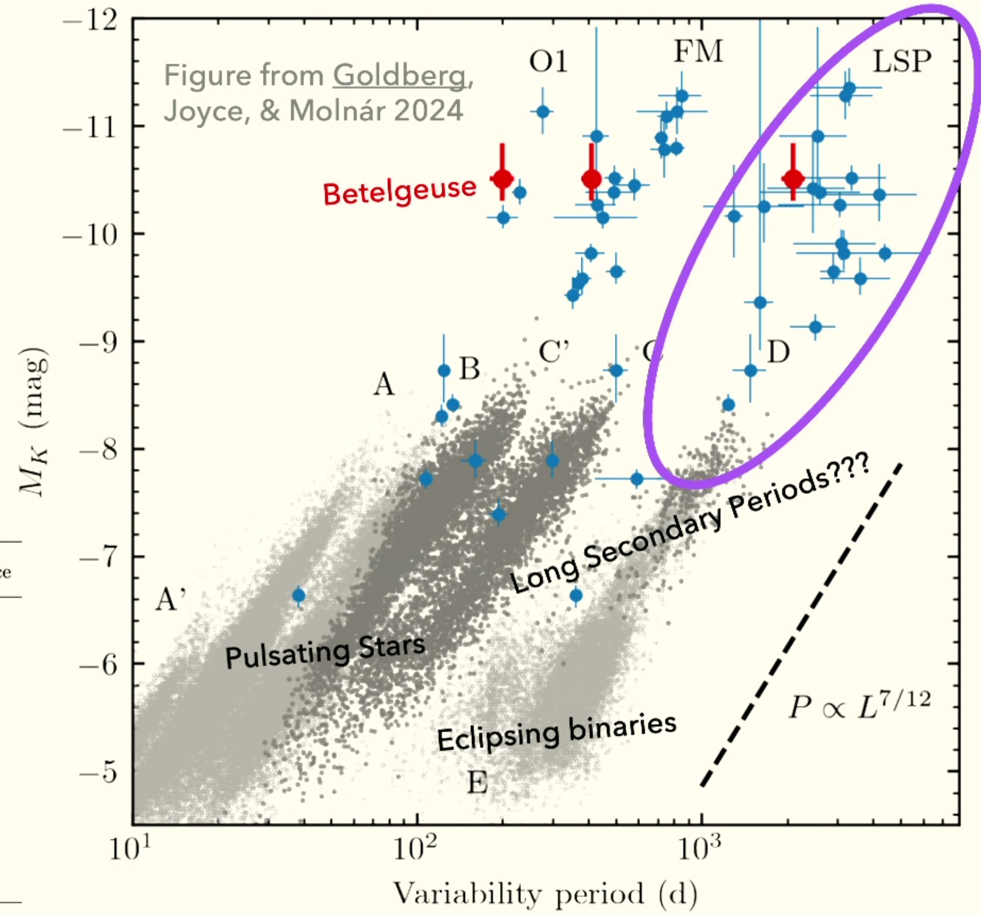
From Sana+2017

LONG SECONDARY PERIODS = BINARITY?

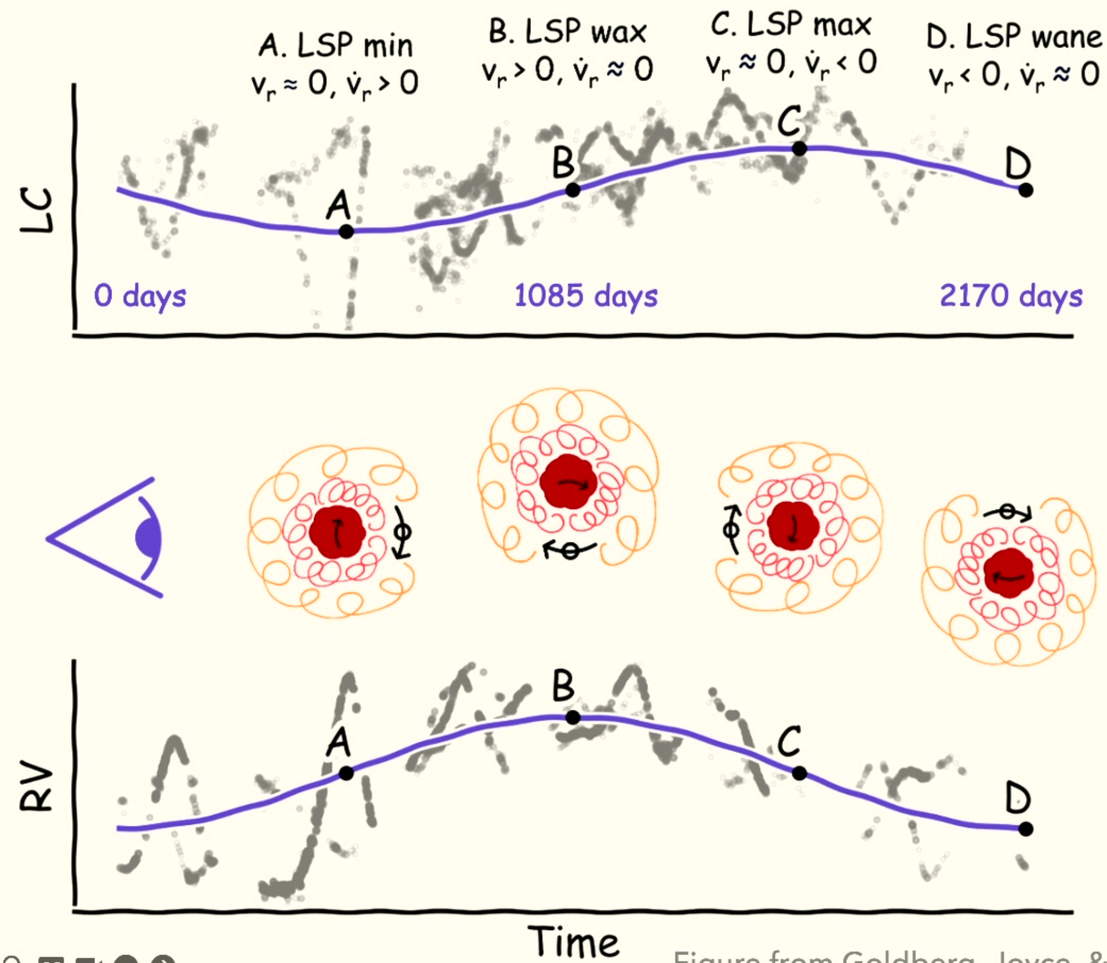
- 30% of pulsating red giants, AGBs, and Red Supergiants have a "Long Secondary Period"!
- The best explanation for the Long Secondary Period (LSP) is the presence of a low-mass companion!

Hypothesis	Section	Timescale	Properties of RV	Low variation in $T_{\rm eff}$	Dust-like chromaticity	LC-RV offset	Persistence
Misidentified FM	4.1	✓	X	?	-	?	✓
Giant convective cells	4.2	✓?	?	✓?	-	-	X
Mode interactions	4.3	X	X	-	-	-	X
Rotation	4.4	X	✓?	?	?	✓?	✓
Magnetism	4.5	X	-	X	X	?	?
Non-radial pulsation	4.6	✓	✓?	?	?	?	X
Dust-κ	4.7	✓	✓	X	✓	✓	✓?
Binarity: tidal	4.8.1	X	✓	?	?	?	✓
Binarity: occultation	4.8.2	✓	✓	✓	✓	X	✓
Binarity: dust modulation	4.8.3	✓	✓	✓	✓	✓	✓

Table from Goldberg, Joyce, and Molnar 2024



WHERE IS THE COMPANION? HOW CAN IT CAUSE THE LSP?



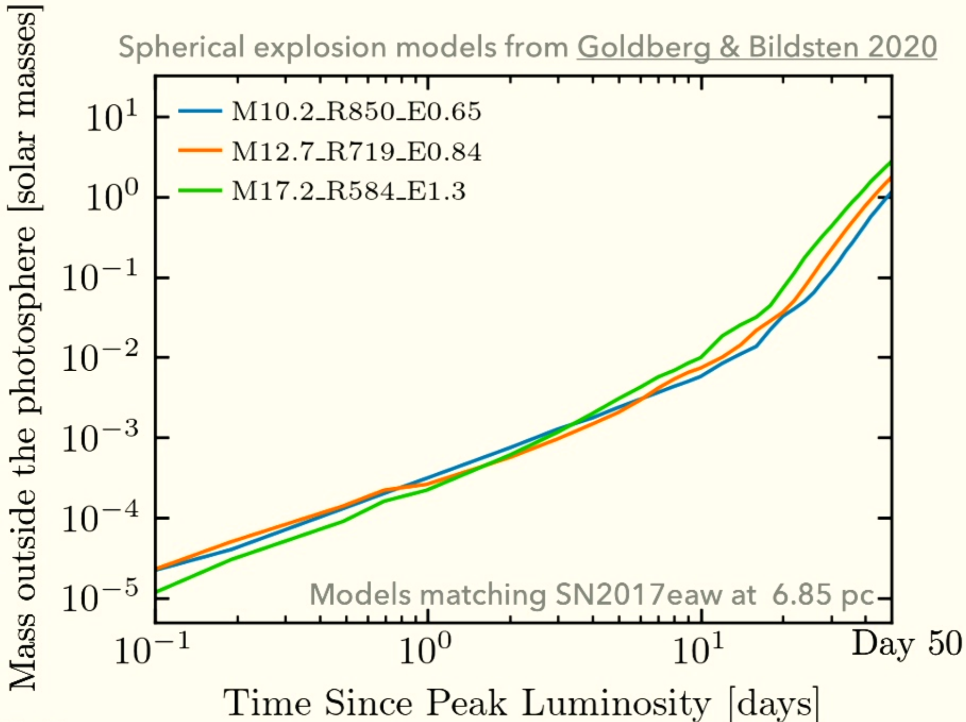
- The LSP is an open problem, but there's good reason to think binarity is responsible.
- ALMA can probe the changing dust shell, but the dust is messy. Directly observing periodic photocenter displacement can resolve this!
- Current best for astrometry = Hipparcos measurements which find some periodic variaions only at the ~1-sigma level (MacLeod+2024)
- Yet another use case for an astrometric tool which is *better* rather than *worse* for bright stars!

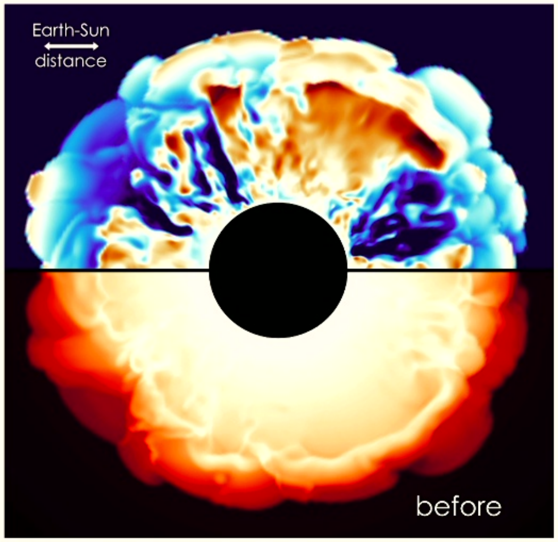
Figure from Goldberg, Joyce, & Molnár 2024

EARLY-TIME SUPERNOVA EMISSION FROM "SURFACE"

- Early supernova emission is sensitive to the shock-cooling of the outermost ~**0.01-0.1$M_\odot$** which either lives in the asymmetric surface or any circumstellar material.

Spherical explosion models from Goldberg & Bildsten 2020





Adapted from Goldberg et al 2022b

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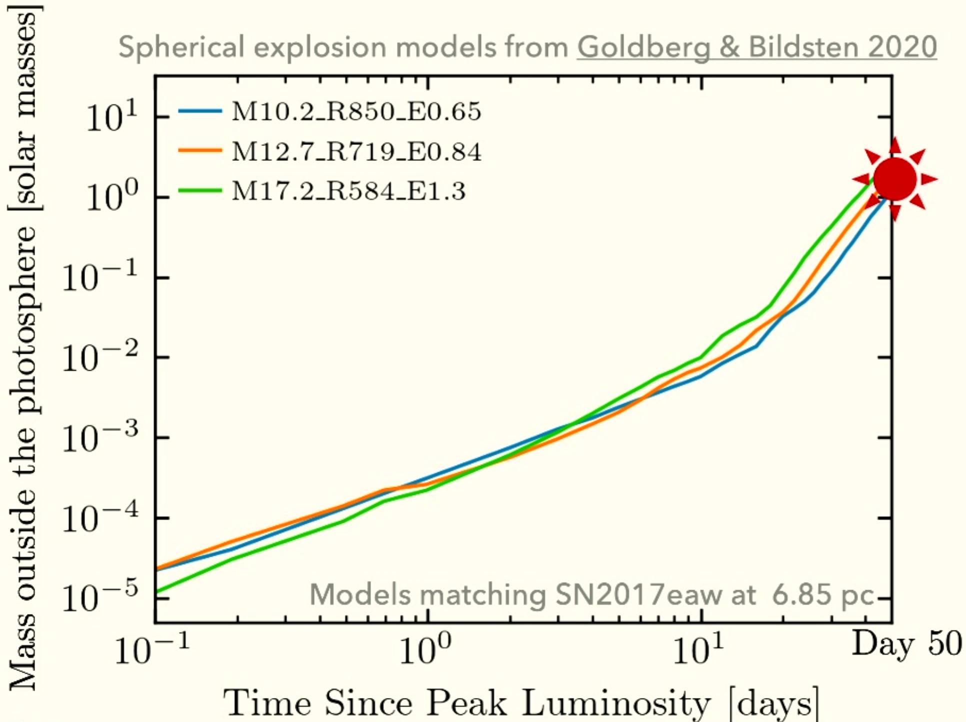
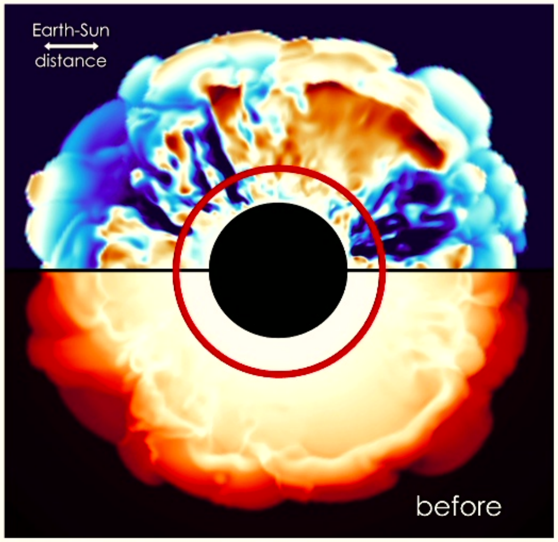




Adapted from Goldberg et al 2022b

TYPE IIP "STANDARD CANDLE" RELATIONSHIP

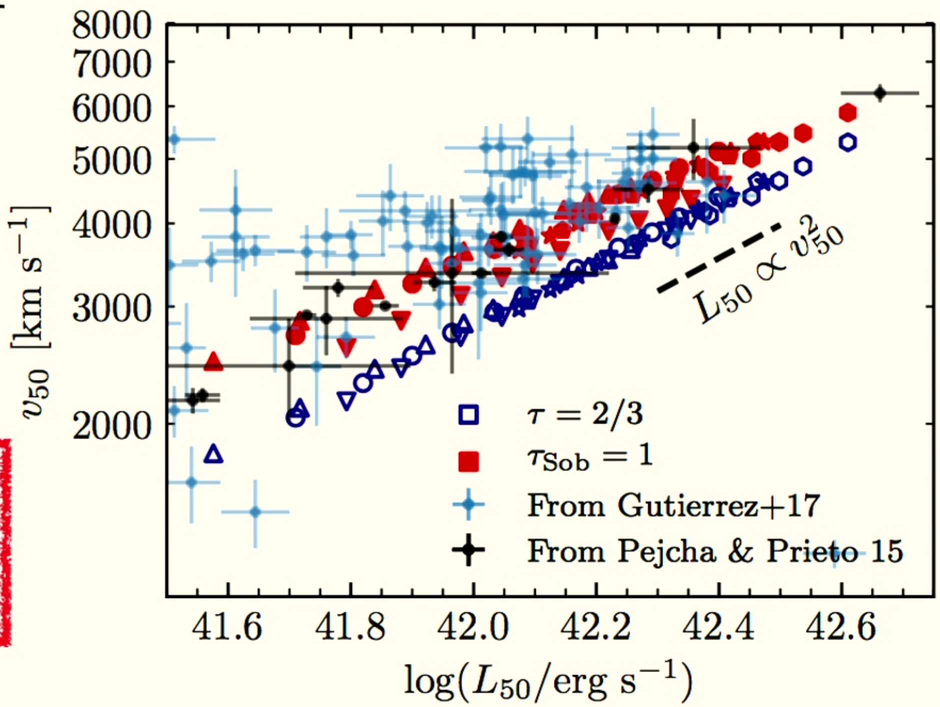
- Observed: Hamuy 2003; Theory: Kasen & Woosley 2009
- Luminosity and velocity are tightly correlated – this is also the basis of the "Expanding Photosphere Method" (Kirshner & Kwan 1974)

$$L \sim 4\pi R^2 \sigma (T_{ph})^4$$

$$R \sim vt$$

$$T_{ph} \sim 6000\,\mathrm{K}$$

$$L_{50} \propto v_{50}^2$$



THE EXPANDING PHOTOSPHERE METHOD FOR DISTANCES

$$\theta = R/D$$

$$\theta = [f_\nu/\pi B_\nu(T)]^{1/2}$$

$$R = v(t - t_0) + R_0$$

$$D = \frac{v_2(t_2 - t_1) + R_0(1 - v_2/v_1)}{\theta_2 - (\theta_1 v_2/v_1)}$$

- We could get a GREAT constraint on θ!
- Having v, f_ν and θ directly overconstrains the system – but that's good to calibrate the method!

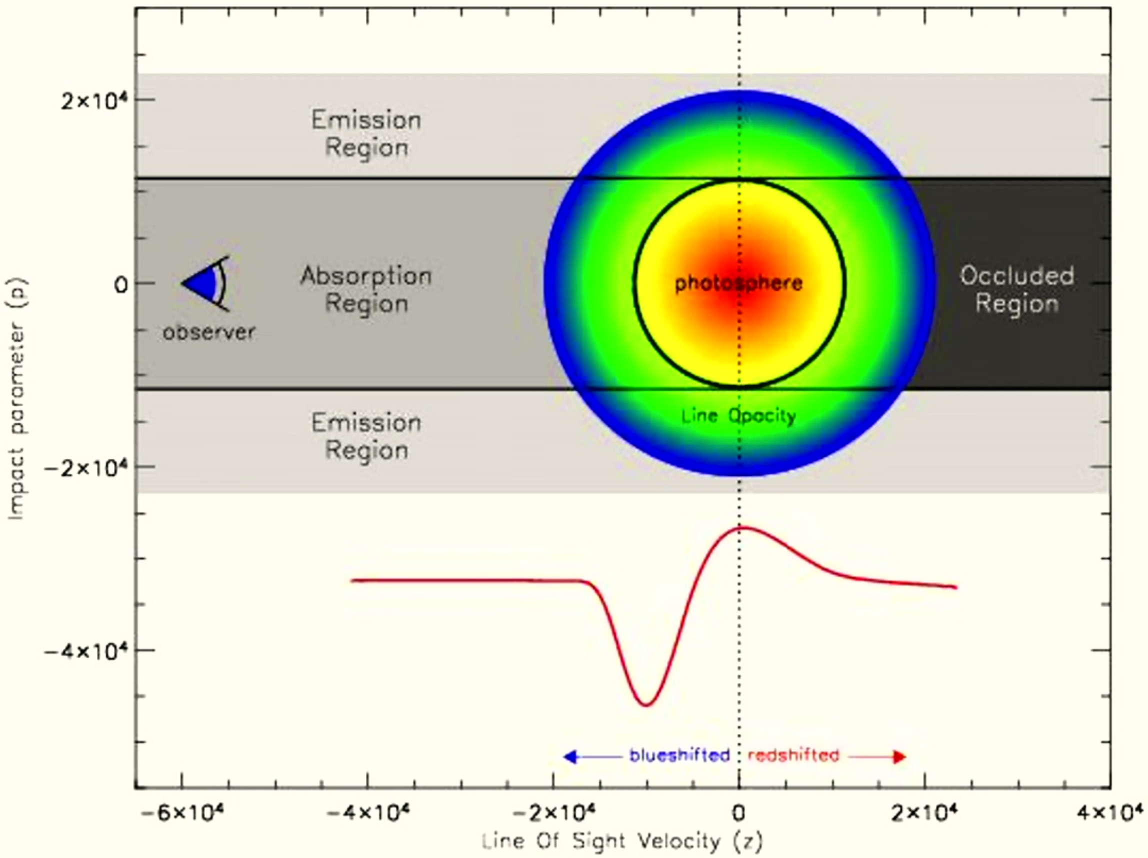
$$L \sim 4\pi R^2 \sigma (T_{ph})^4$$

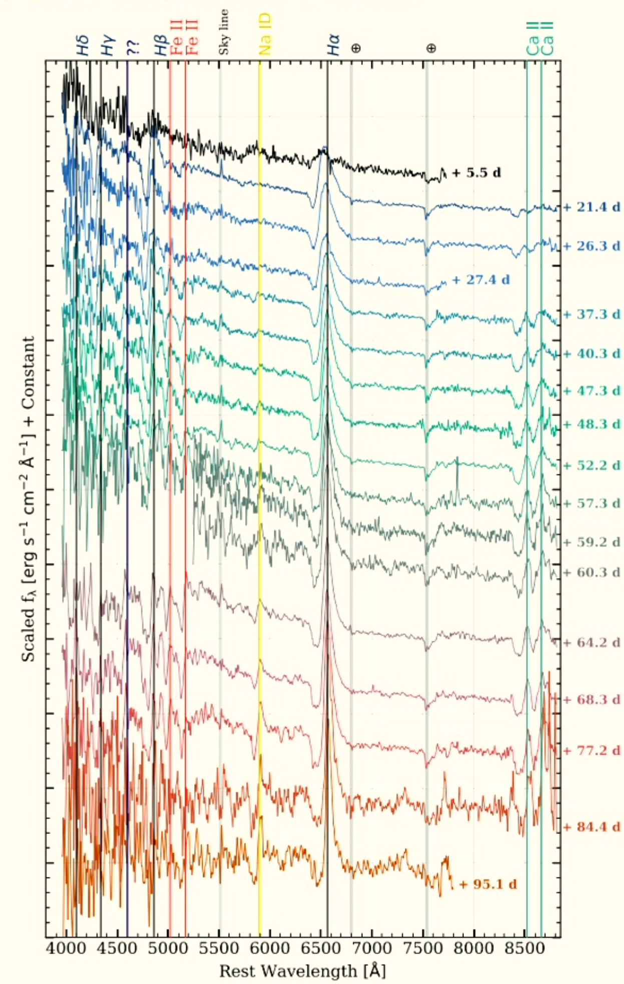
SO… THERE'S LOTS OF SCIENCE TO BE DONE!

- Convection
  - Size and coherence times of large-scale plumes at the stellar surface
  - Photocenter jitter from convection in bright resolved sources
- Pulsations
  - Direct measurement of radial pulsation amplitude
  - How does the optical "surface" change across pulsation cycles
- Companions
  - Direct measurement of astrometric periods especially for **bright** sources where GAIA fails
  - Resolved binaries? Other applications?
- Explosions
  - Learn about the stellar surface and circumstellar environment
  - Directly measure expansion rate in terms of angular size on the sky – can probe accelerations (interaction with CSM), AND can be used to measure the Hubble Constant (see Calvin's talk!)

MEASURING VELOCITIES IN TYPE IIP SUPERNOVAE

Figure from Dan Kasen's website: Theory





Observed spectra from Teja, Goldberg et al 2024

BETELGEUSE'S RV AND BRIGHTNESS VARIATIONS ARE OUT OF PHASE

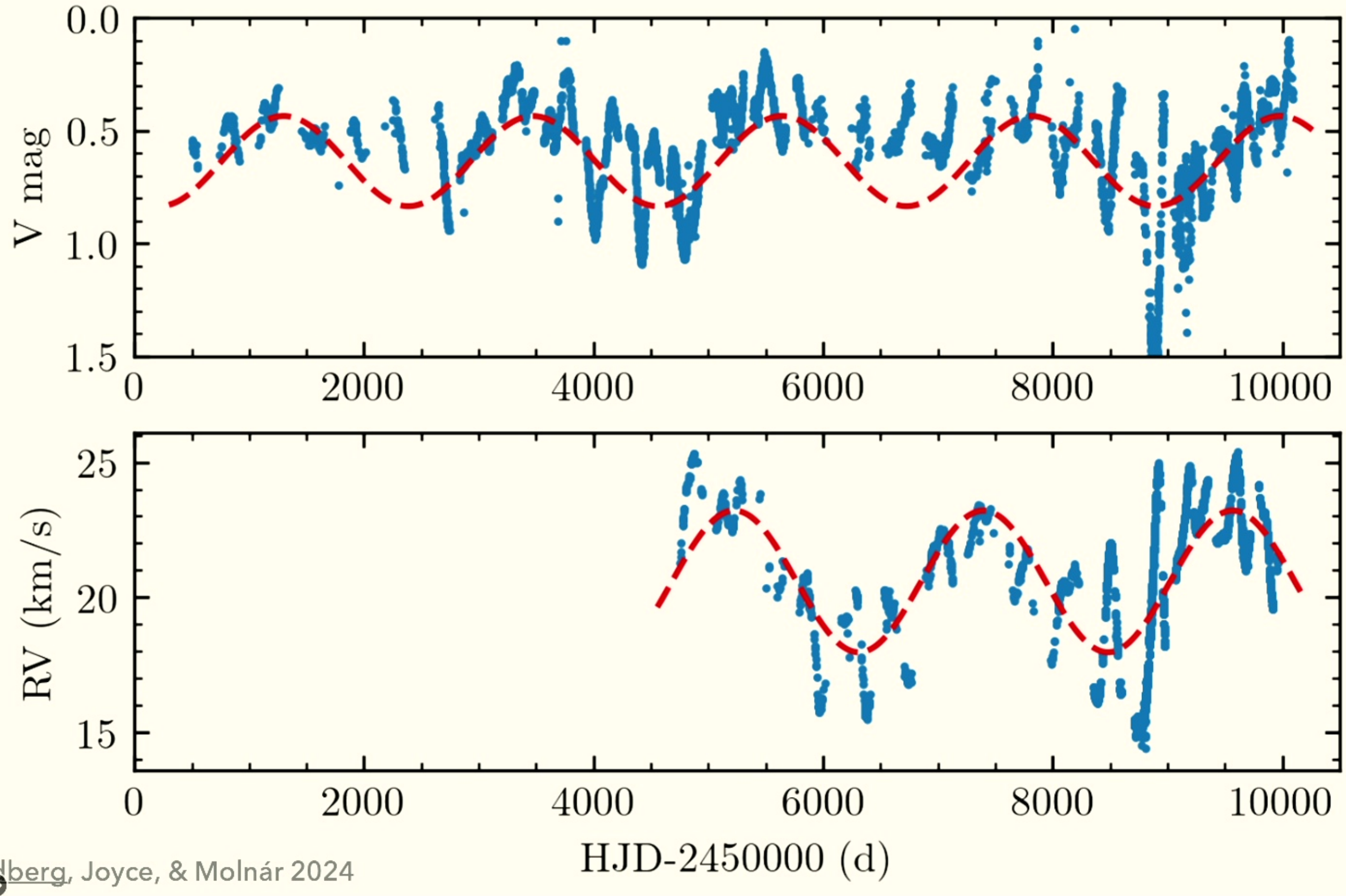


Figure from Goldberg, Joyce, & Molnár 2024