Magnetic fields around evolved stars:
theory & radio/submm (line) observations

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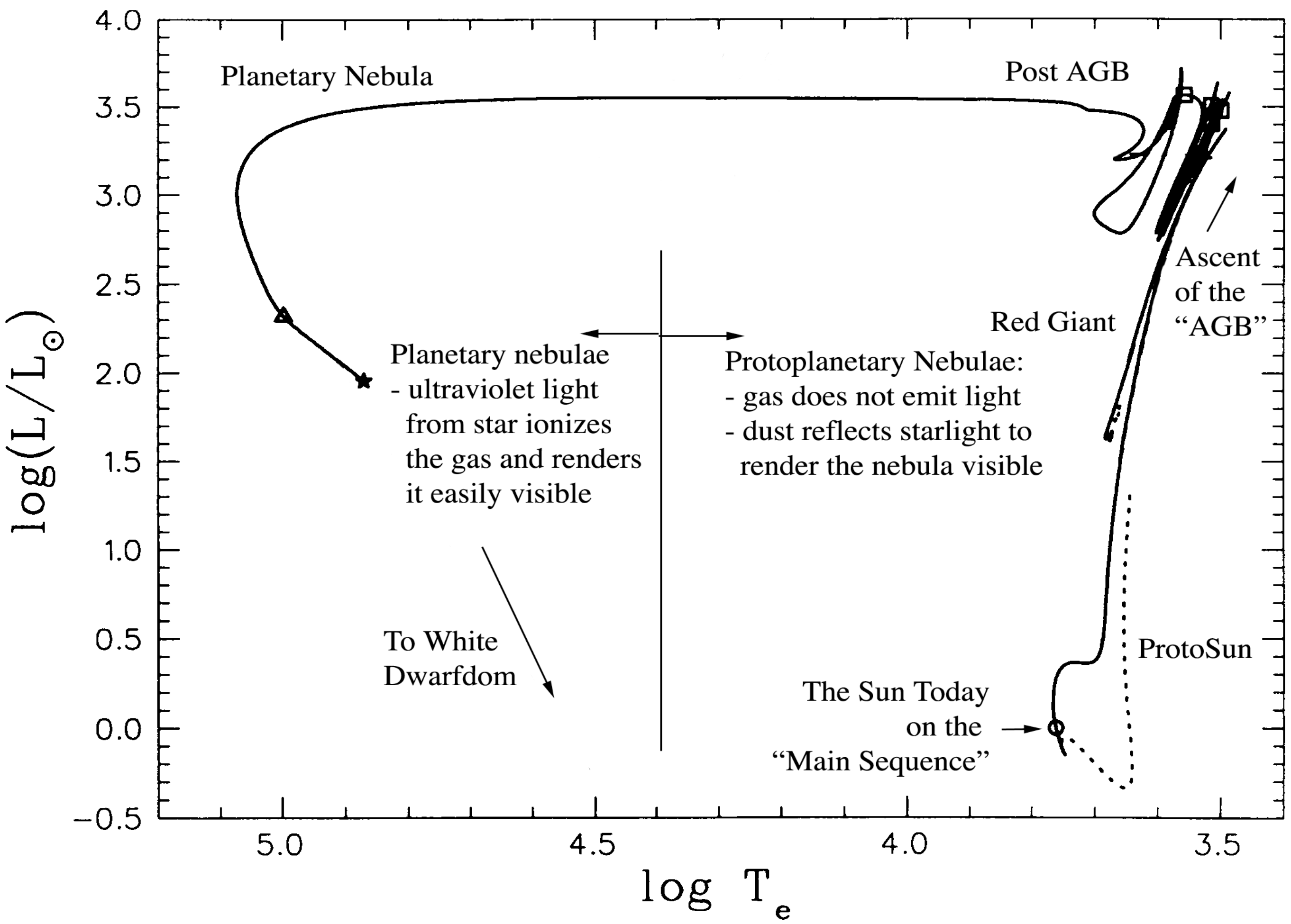
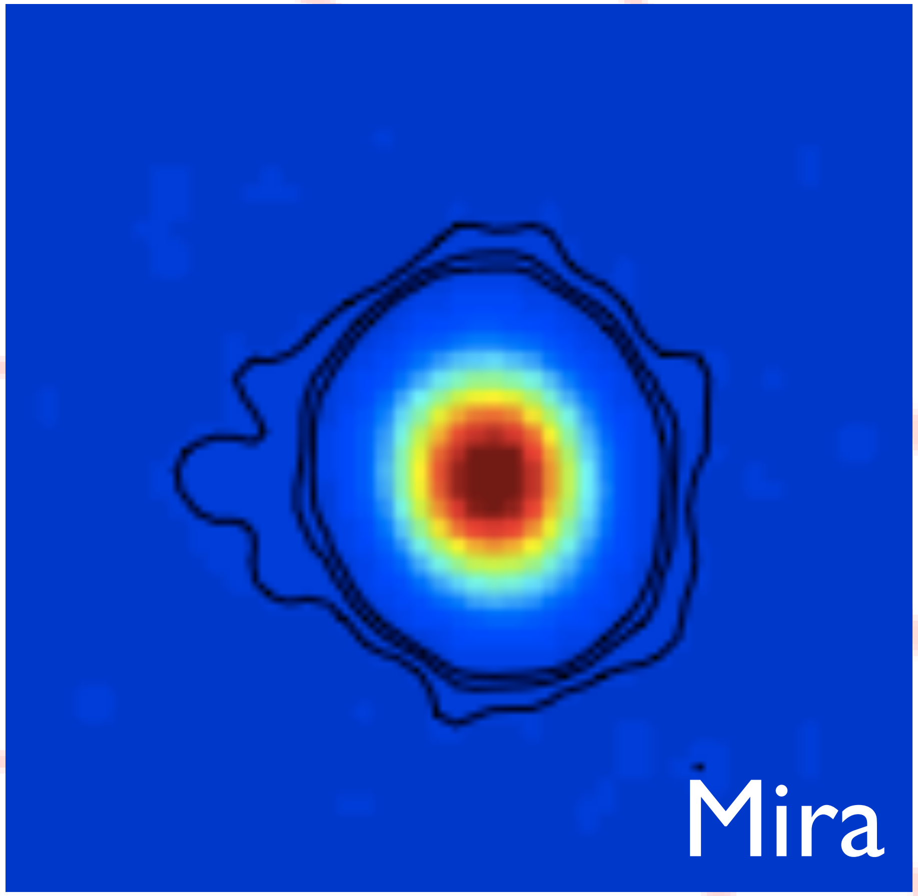
Outline

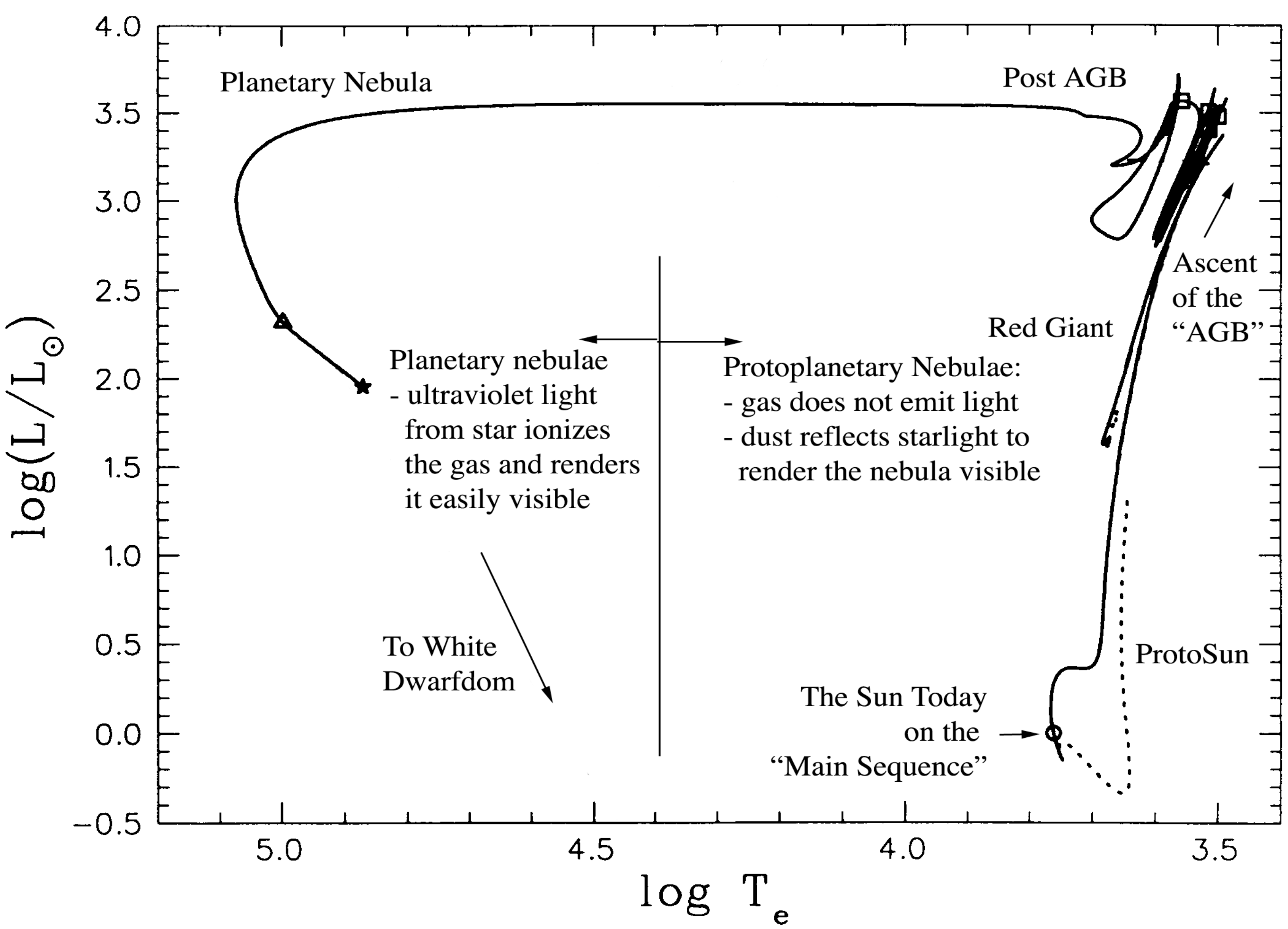
- Introduction
- B-fields and binaries
    - possible Effects of B-fields
    - Observations of B-fields
    - Origin of the magnetic field
- ALMA observations of the stellar activity of Mira A
    - Indications of surface B-field activity?
- Conclusions

from AGB to PNe





from AGB to PNe



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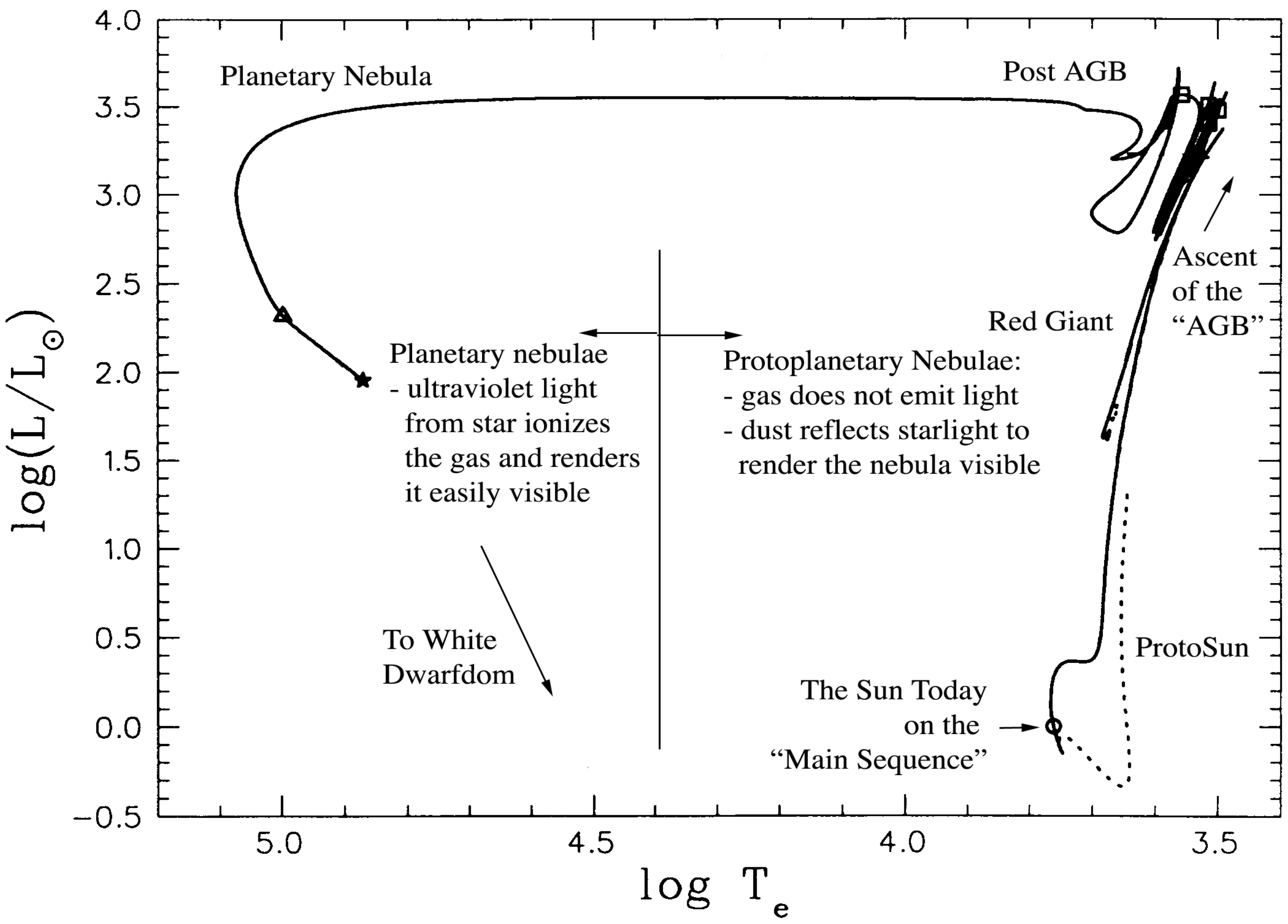

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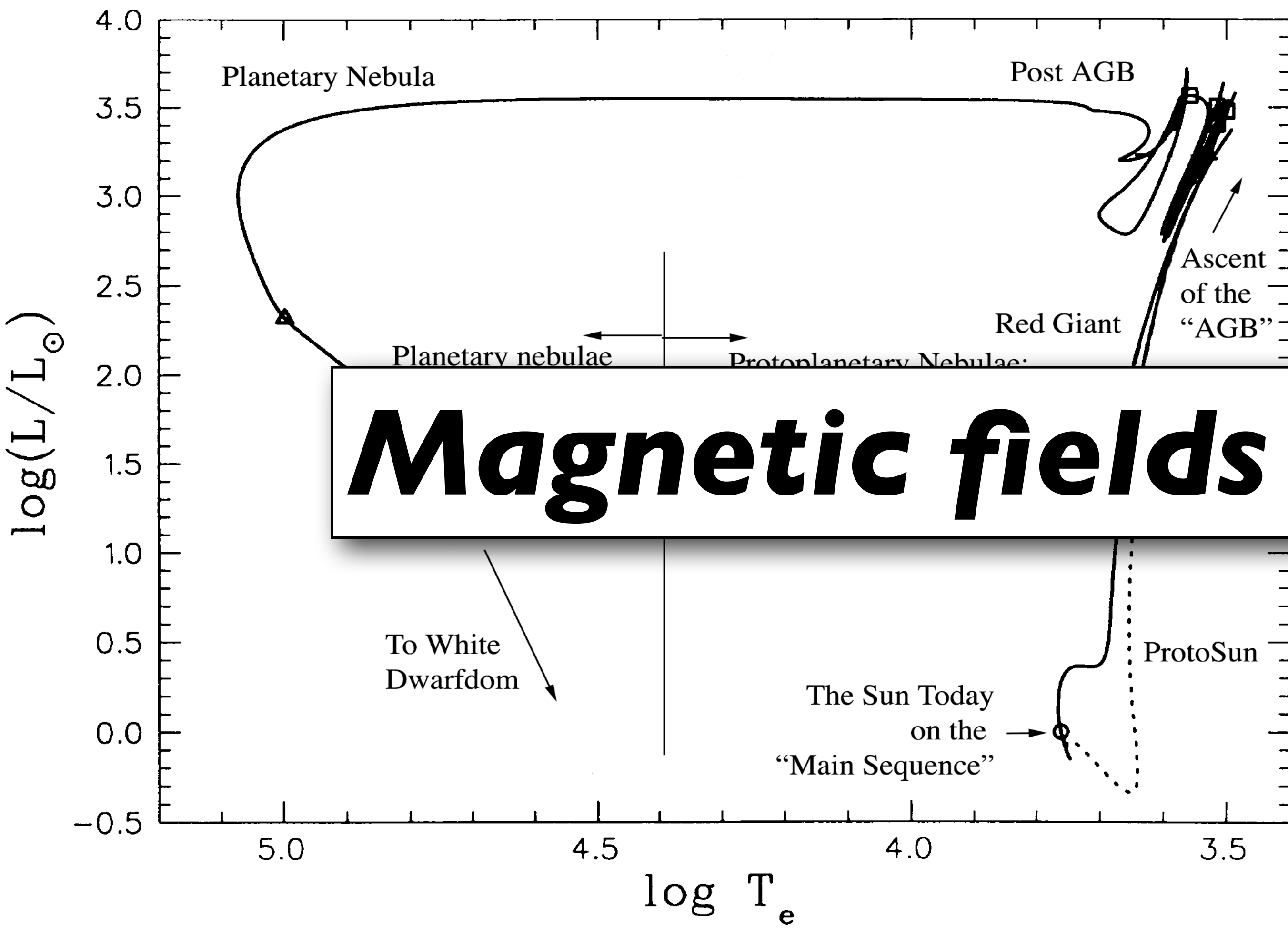
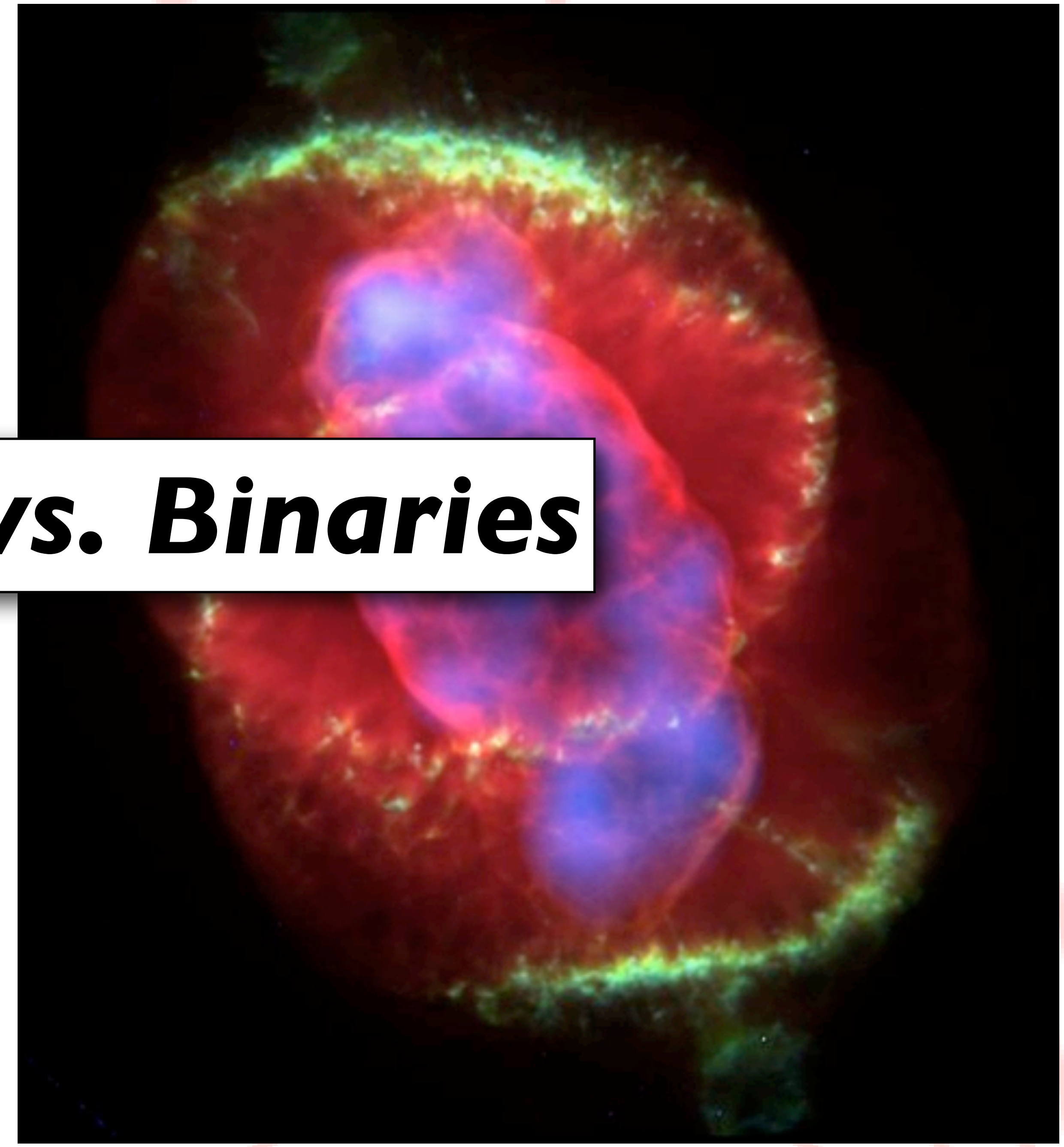
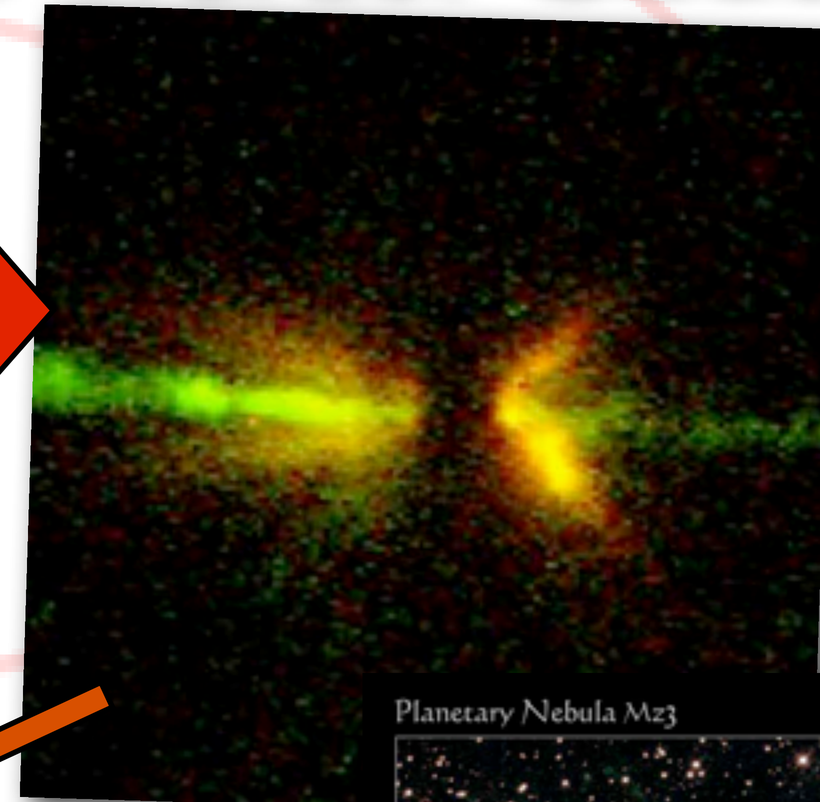
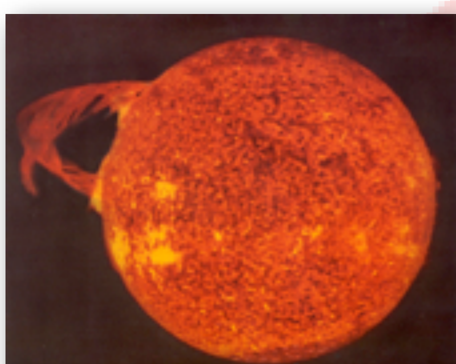


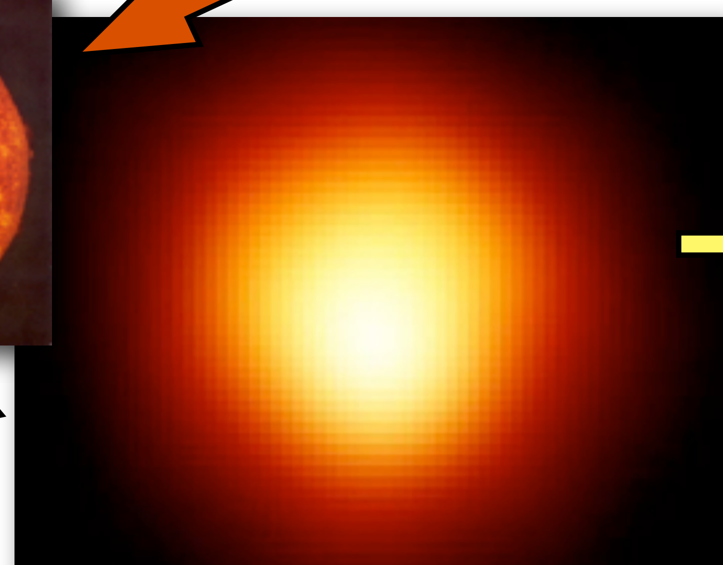


Magnetic fields vs. Binaries

B-fields: Cause......

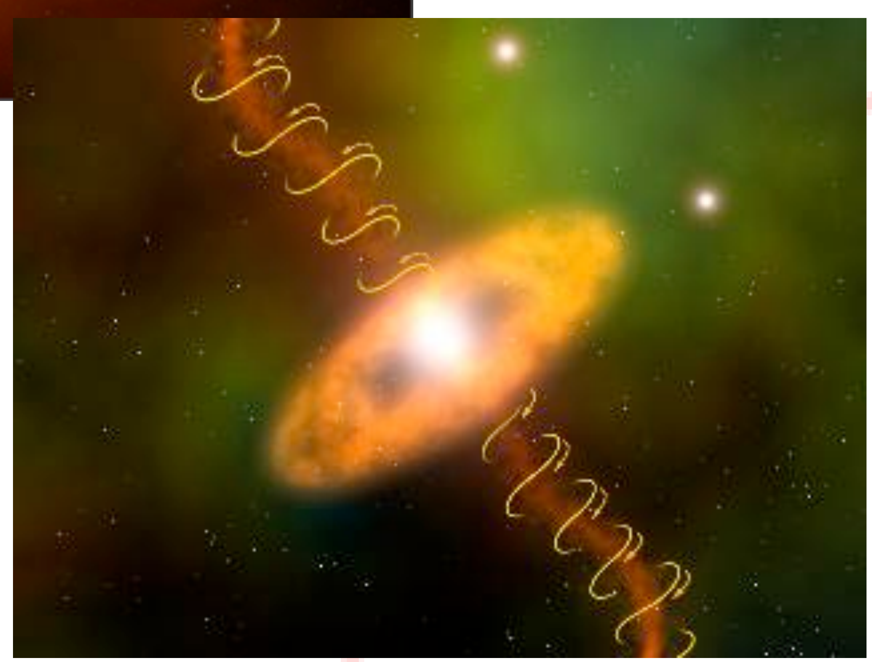






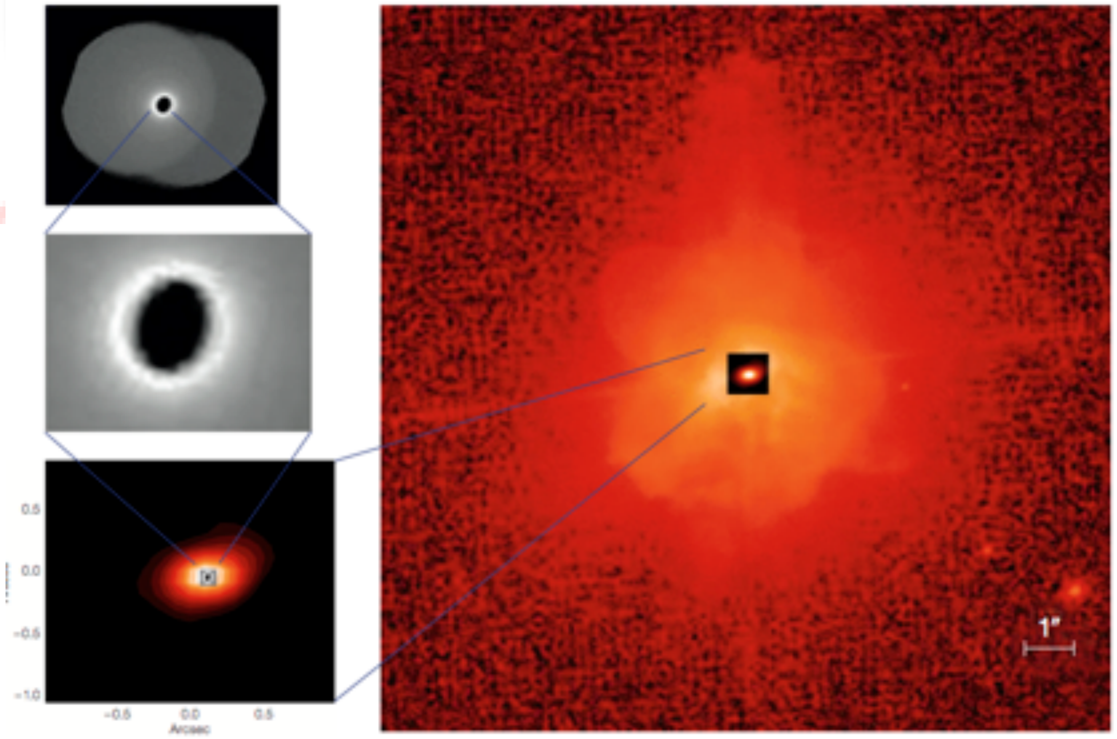
B-fields: or (secondary) effect?

- Magnetic fields arising -
  - locally from stellar activity?
  - from disk interaction?
  - from binary interaction?
  - all of the above?



The case for Binaries

- Several PNe central stars are known binaries
  - >10-15% are close binaries
- Single star dynamo action needs source of energy
  - unless convective energy (e.g. Sun)
- AGB superwind from common-envelope ejection?
  - difficult to launch for <2.5 $M_\odot$
- Post-AGB disks could be naturally explained by binaries
- Binaries are *primary* agents
  - e.g. Collimated jets arise from binary (planet?) induced magnetic field



De Marco et al.; Soker et al., Nordhaus et al., van Winckel et al.

CPD-56 (Zijlstra et al. 2006)

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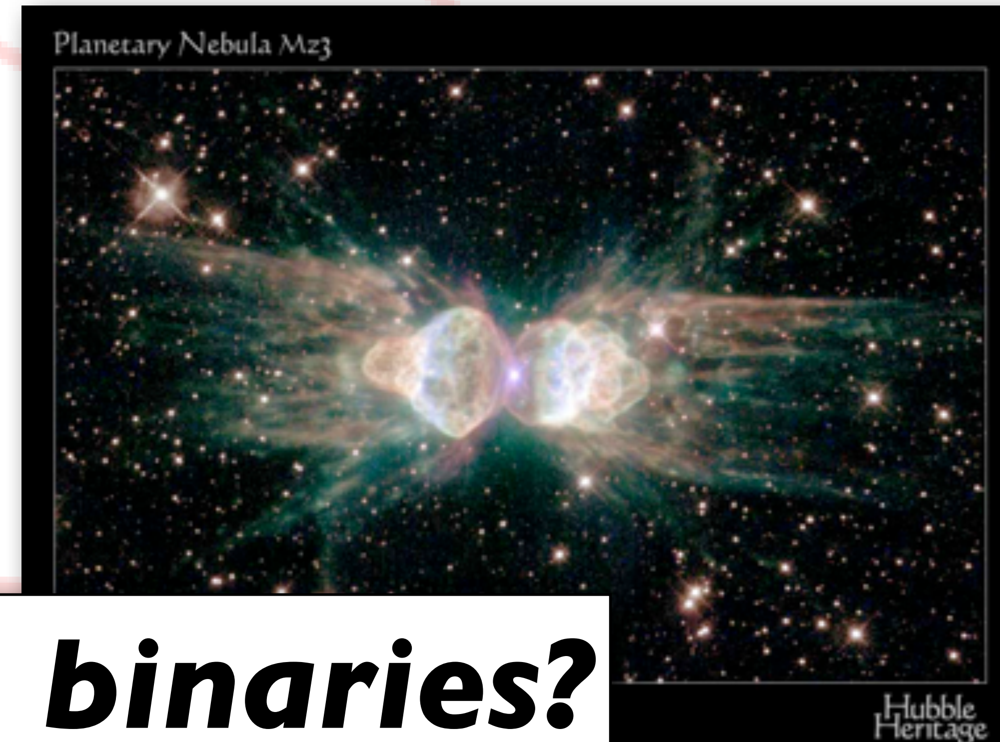

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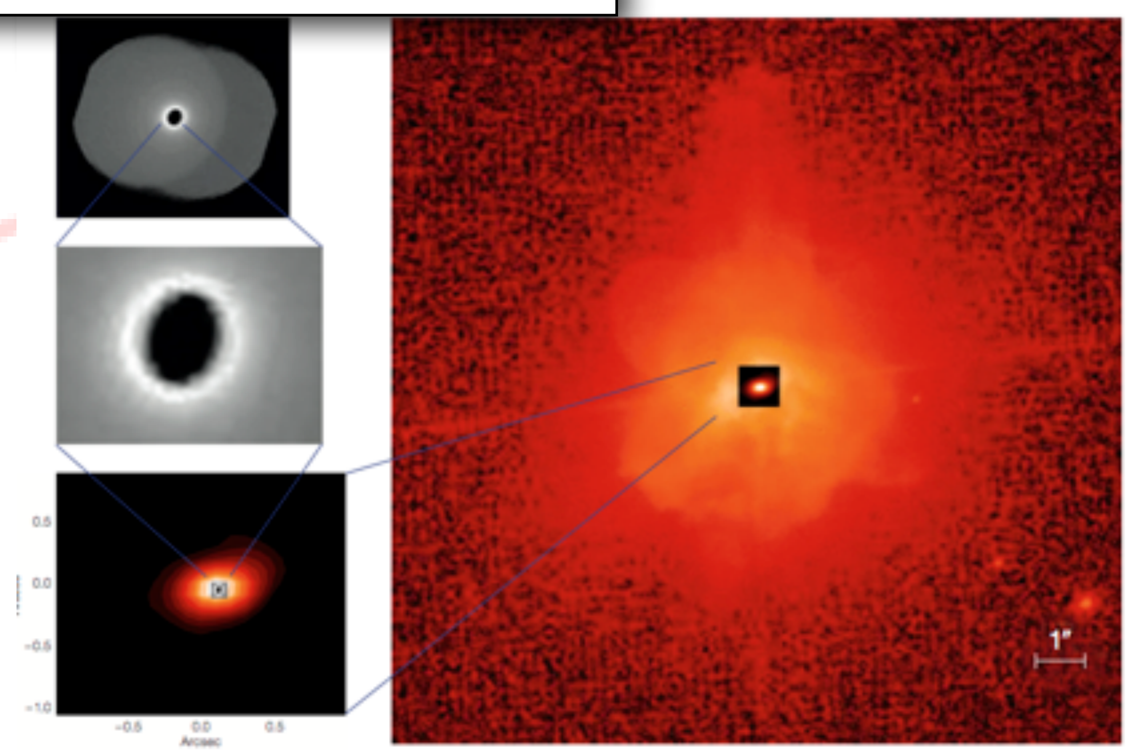
Where are the AGB binaries?



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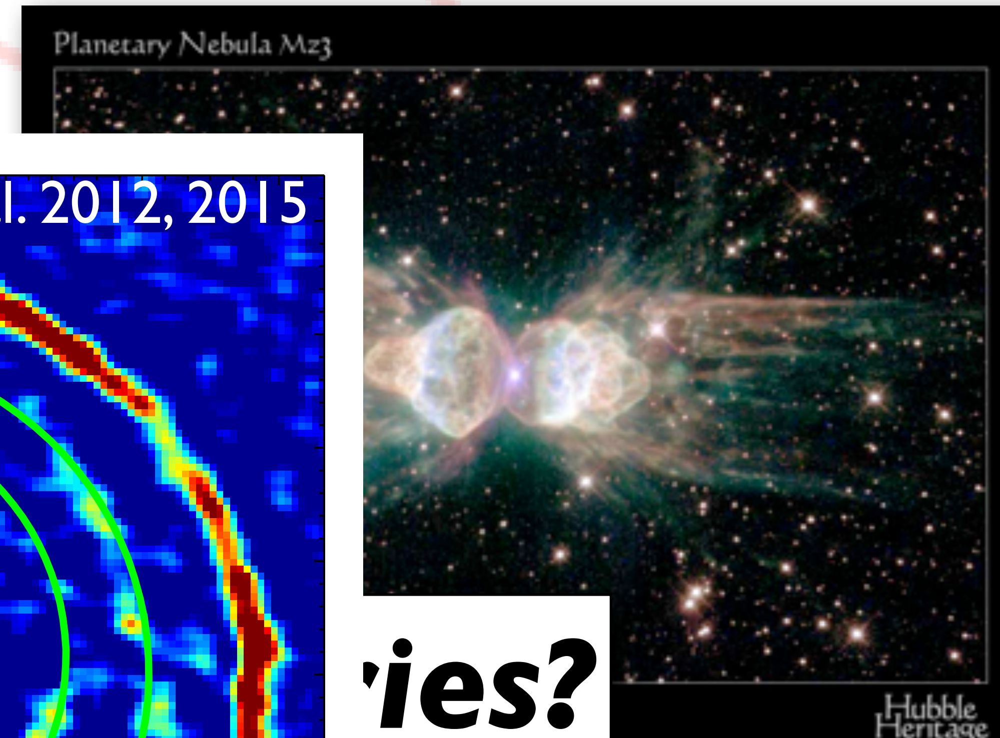

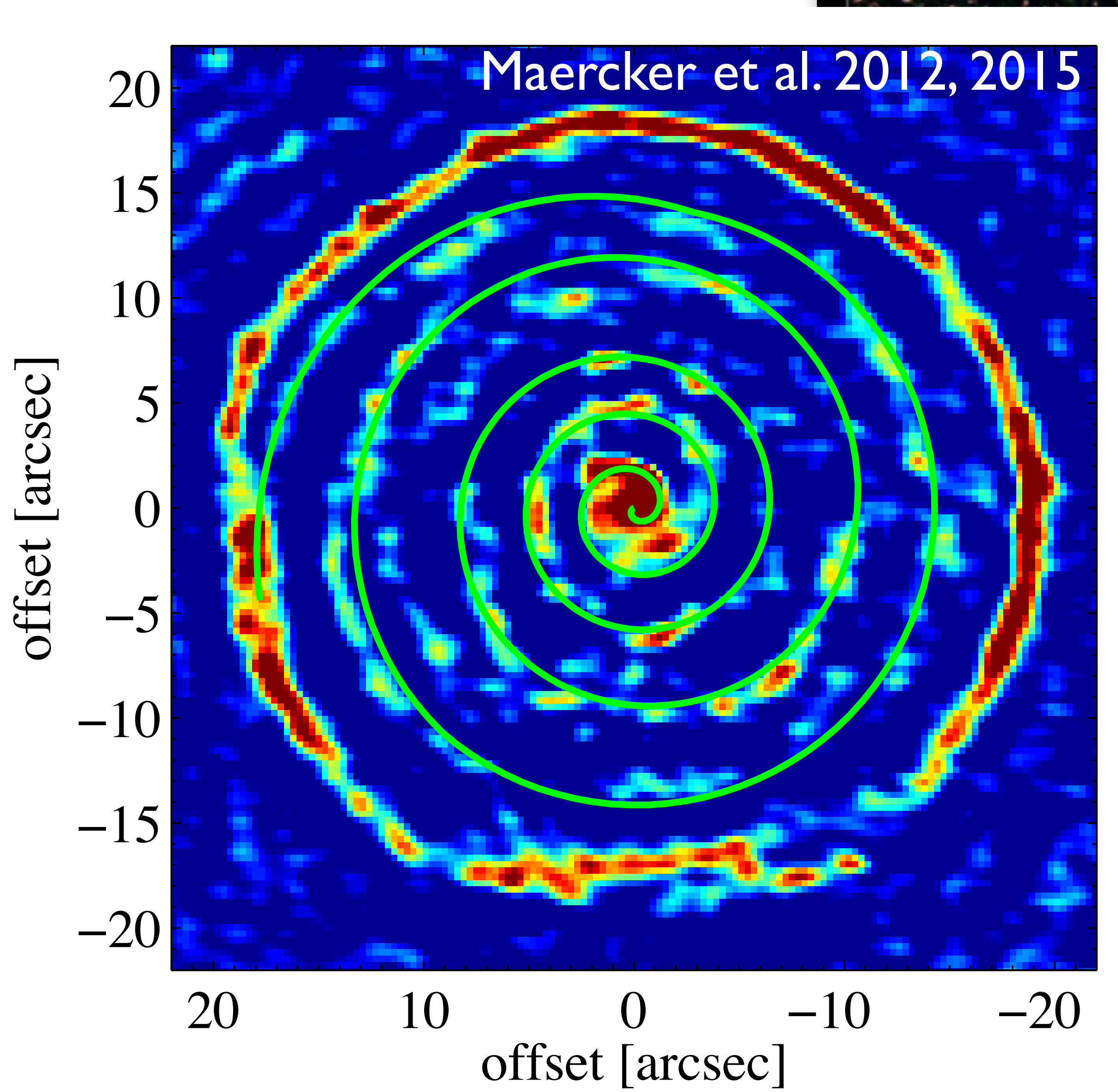

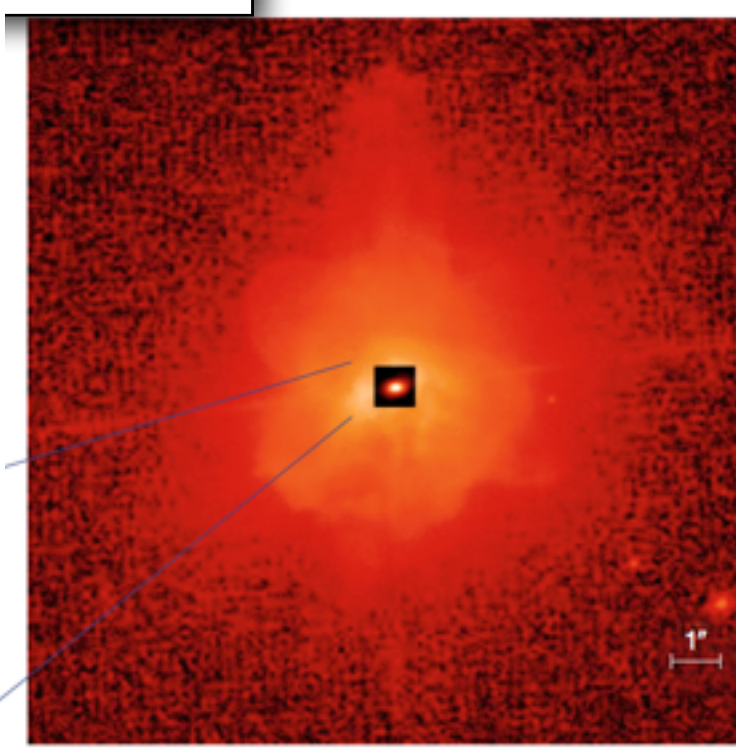

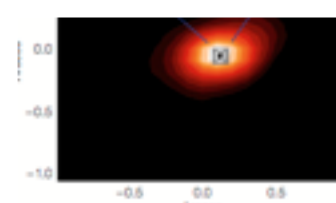

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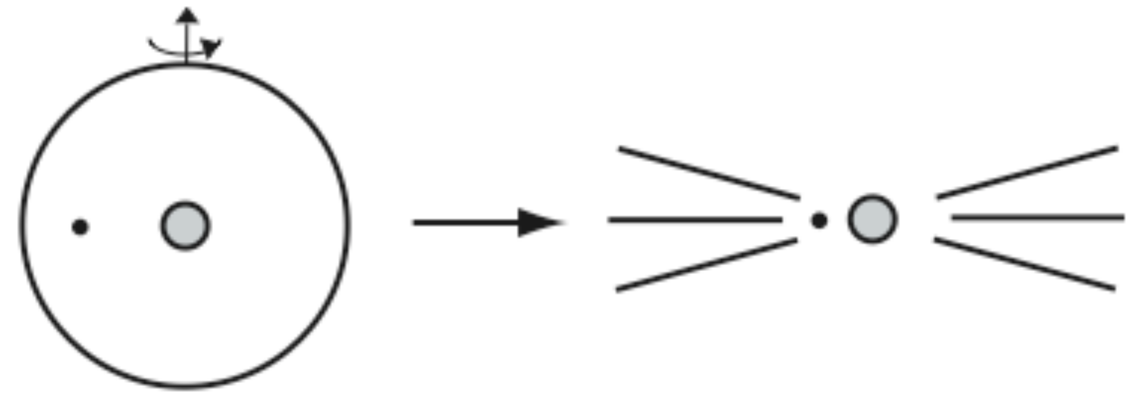
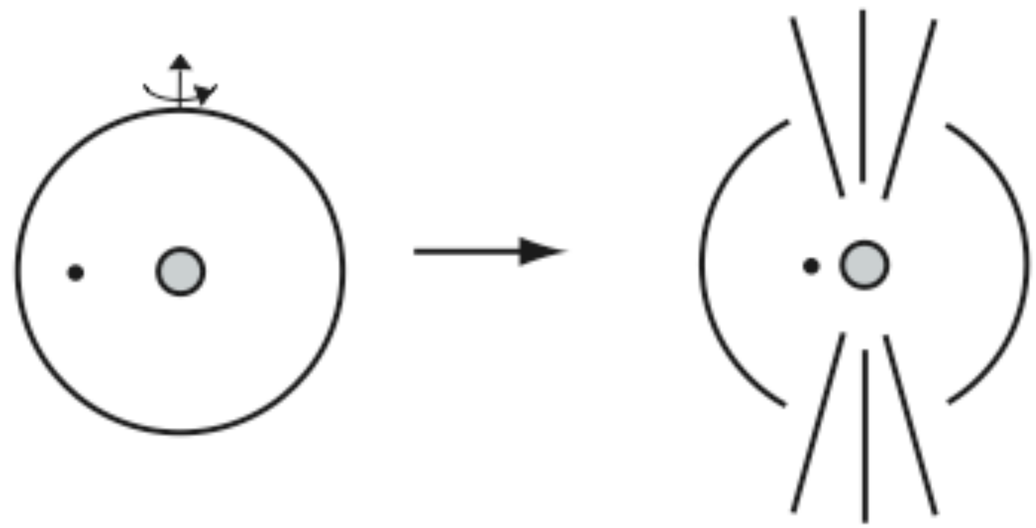
Shaping the envelope



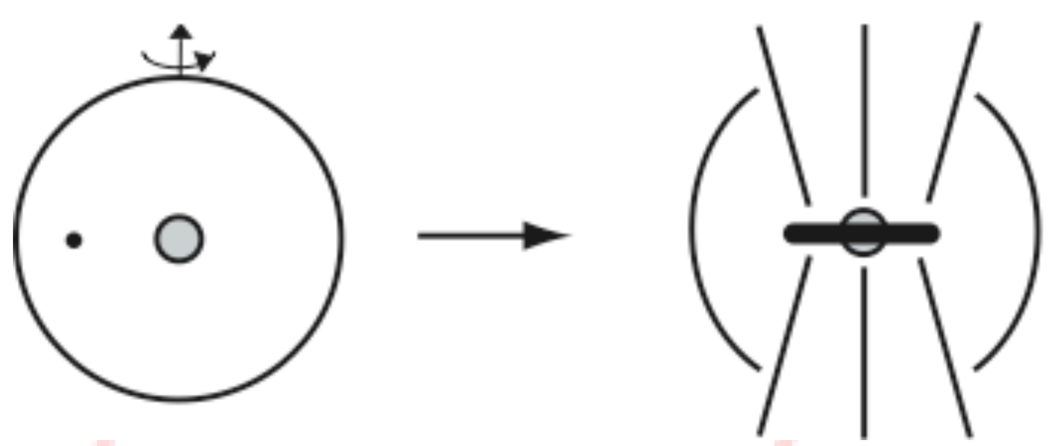
Direct Envelope Ejection

Outflow is predominately equatorial.



Dynamo Driven Ejection

Outflow is aligned around the rotation axis and is magnetically collimated.



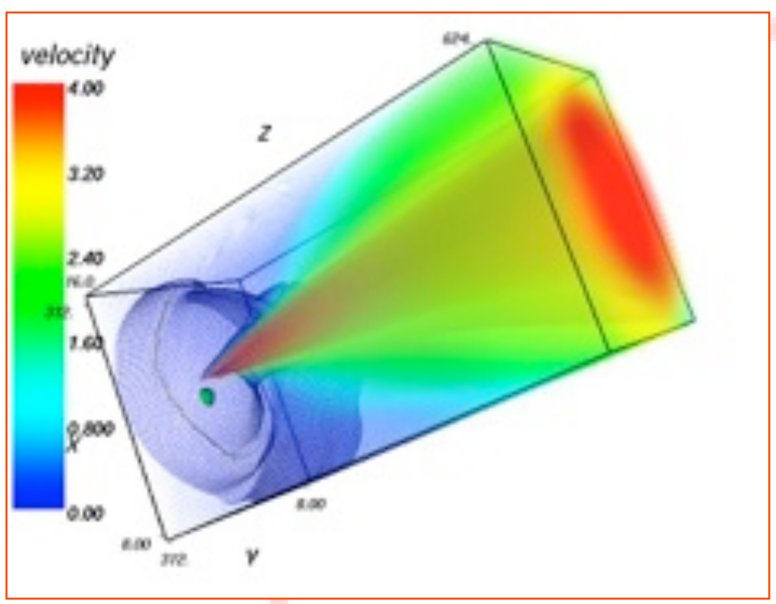
Disk Driven Ejection

Shred Secondary
Outflow is aligned with rotation axis.

Nordhaus et al. 2006

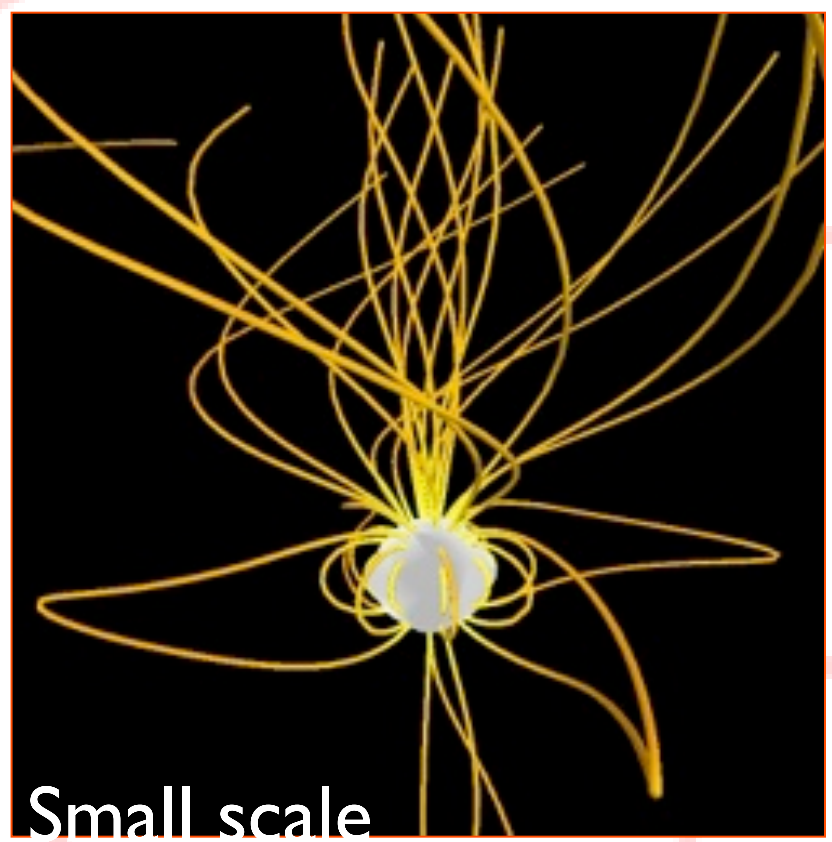
Shaping the envelope

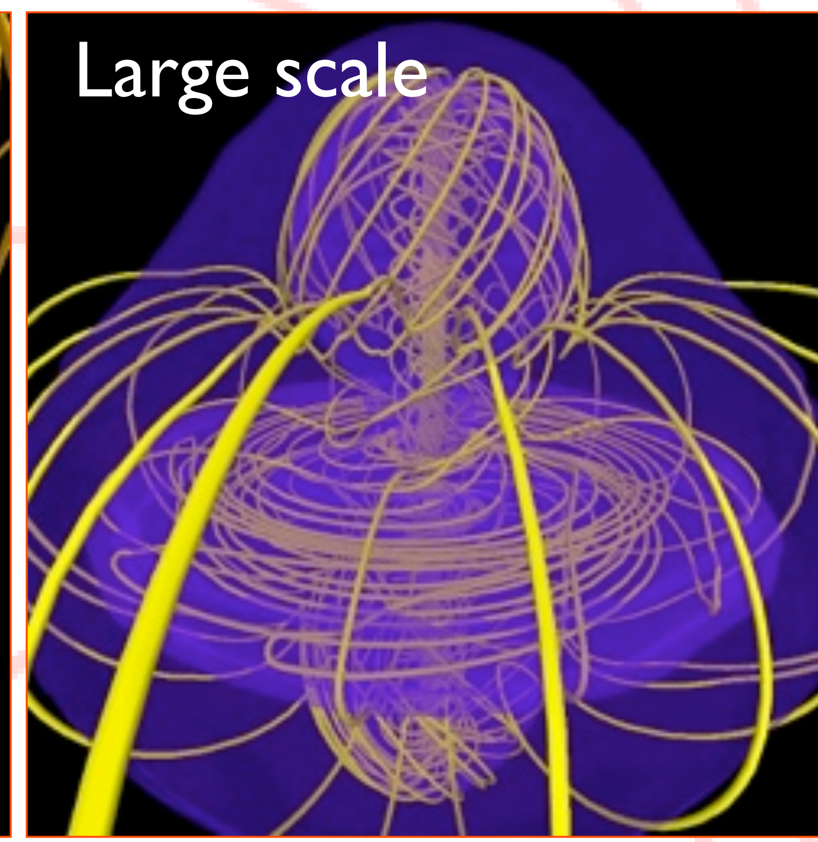
- MHD jet launching fairly well developed for YSOs
  - different models (e.g. Blandford & Paine 1985; Shu et al. 1994)
    - ‘Fling’ vs. ‘Spring’ (e.g. Frank, Blackman et al.)
    - Energetic estimates state typical values of few Gauss to launch PNe jets (e.g. Tocknell et al. 2013)
- Thermally driven jets? (e.g. Soker 2006)



Companion + disk

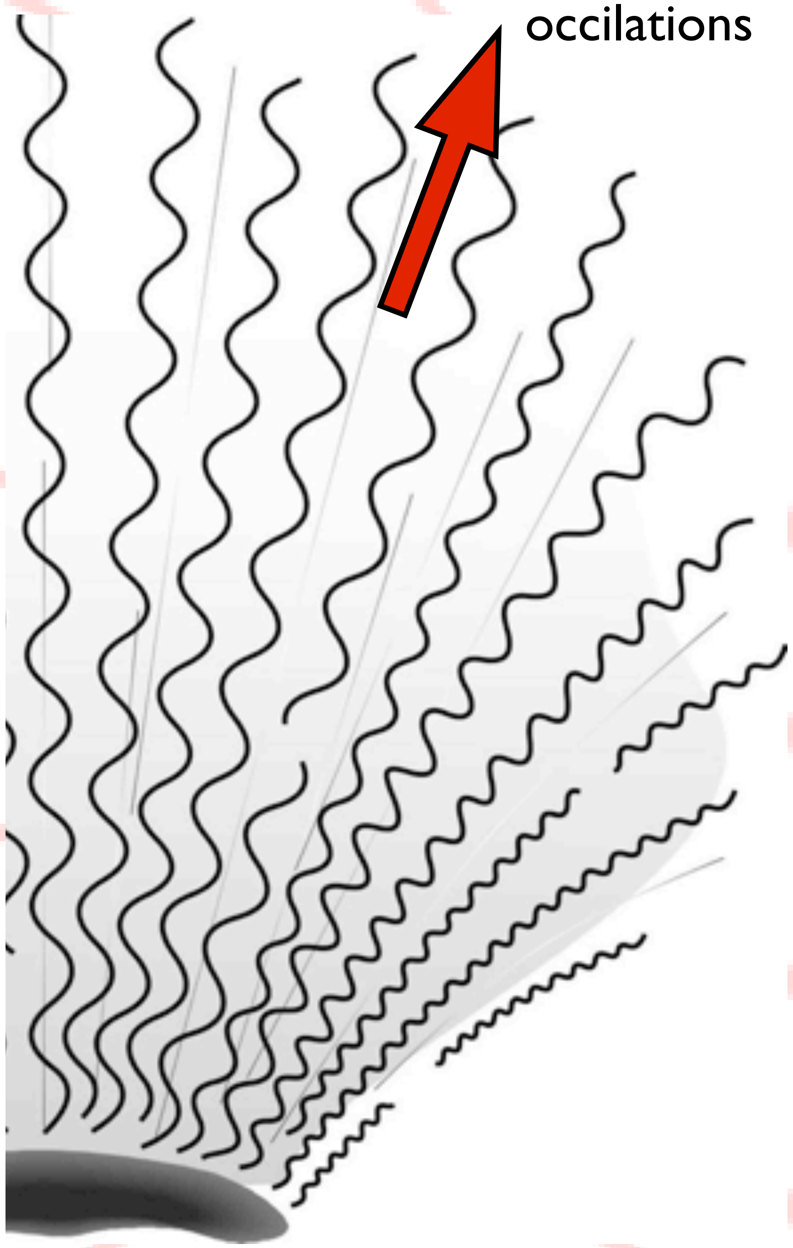
Single star





Alfvén-wave driven mass loss

- Low-frequency occilations of the magnetic field and coupled ions
  - injecting energy in the wind
- General Alfvén wind reaches too high velocity
  - AGB stars would naturally provide dissipation:
    - neutral gas interaction at lower temperatures
    - widening magnetic flux tubes
    - reflected waves
    - mode conversion for non-straight fields
- Potentially needed for supergiants, though hybrid models work for AGBs

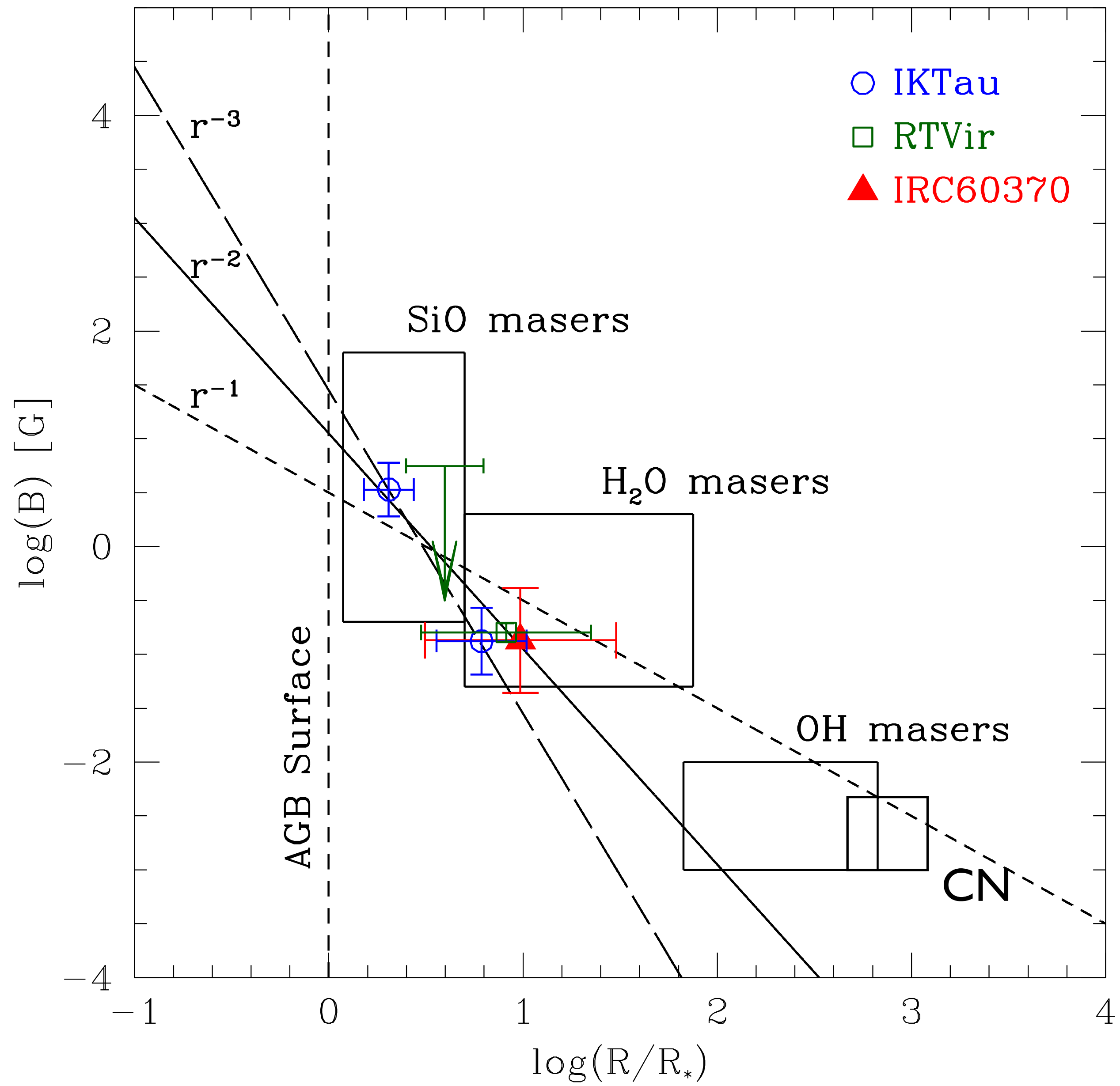


e.g. Hartmann & MacGregor 1980, Falceta-Gonçalves et al. 2006, (Hybrid models) Thirumalai & Heyl 2010

What do the observations tell us?

B-field strength AGB envelopes

- Oxygen rich:
  - SiO at 2 R*
    - B~3.5 (up to 10s) G [assuming Zeeman]
  - H_2O at ~5-80 AU
    - B~0.1-2 G
  - OH at ~100-10.000 AU
    - B~1-10 mG
- Carbon rich:
  - CN at ~2500 AU
    - B~7-10 mG



Leal-Ferreira et al. 2013
after Vlemmings et al. 2002,2005

Vlemmings et al. 2002, 2005
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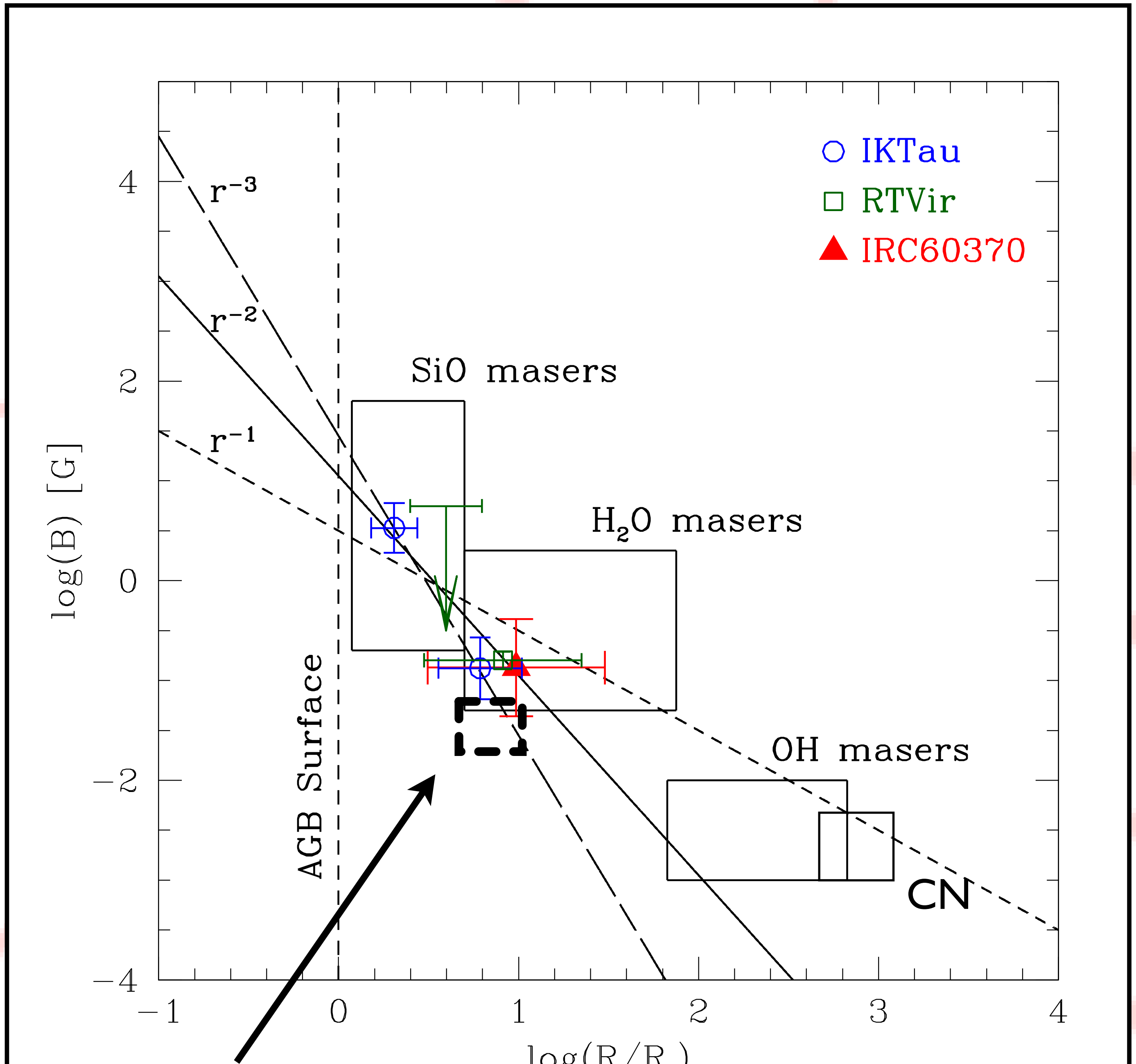

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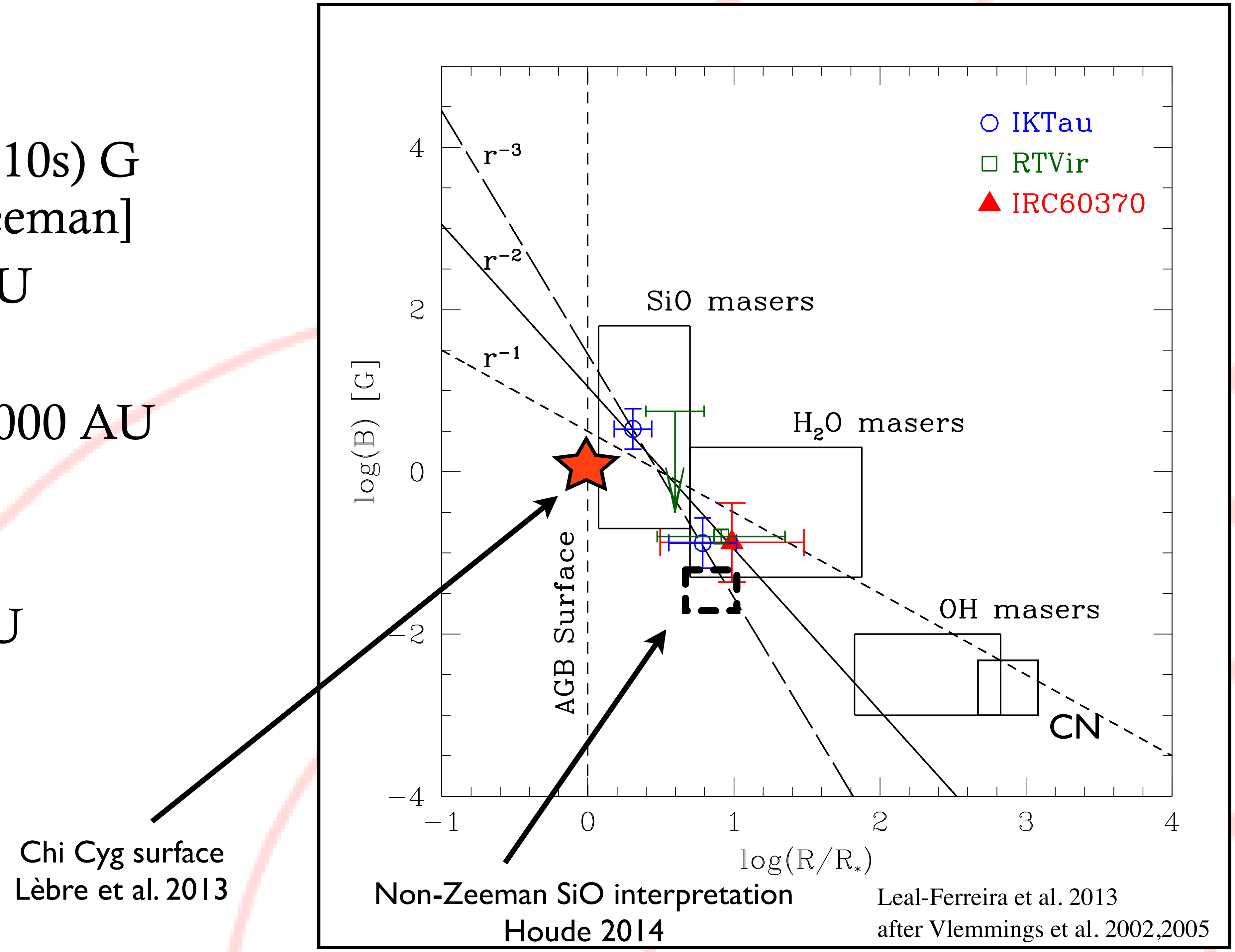


Energy densities

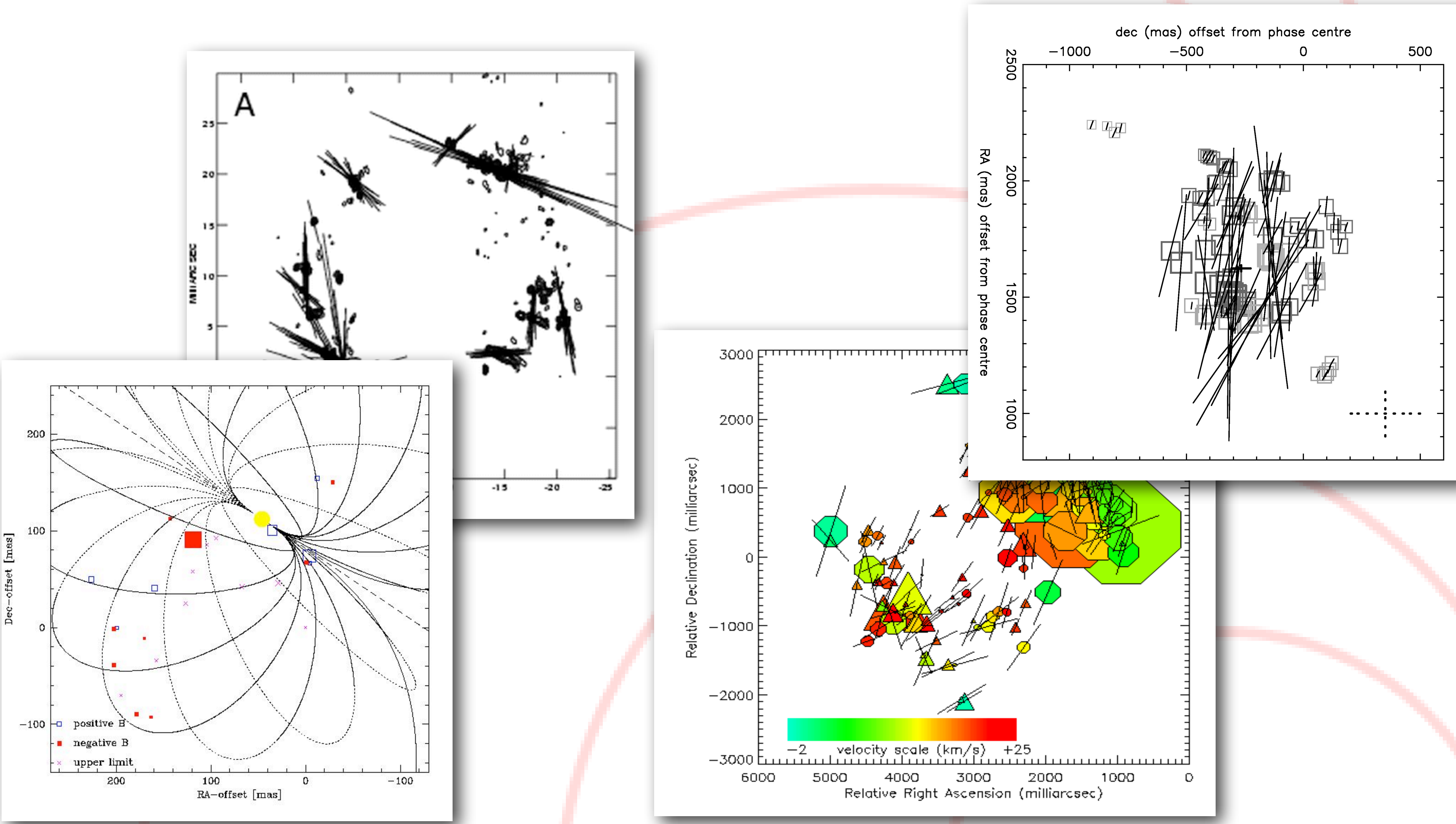
Maser	V_{exp} [km/s]	R_{star} [AU]	B [G]	n_{H2} [cm^{-3}]	T [K]	$B^2/8\pi$ [dyne/cm²]	nkT [dyne/cm²]	ρV^2_{exp} [dyne/cm²]	Alfvén Speed [km/s]
OH	~10	~500	~0.003	~10^6	~300	$10^{-6.4}$	$10^{-7.4}$	$10^{-5.9}$	~8
H_2O	~8	~25	~0.1-0.3	~10^8	~500	$10^{-3.3}$ - $10^{-2.4}$	$10^{-5.2}$	$10^{-4.1}$	~300
SiO	~5	~3	~3.5	~10^{10}	~1300	$10^{+0.1}$	$10^{-2.7}$	$10^{-2.5}$	~100
SiO non-Zeeman	~5 ~5 ~8	~10-15 ~10 ~20	~0.015 ~0.050 ~0.050	~7.5x10^8 ~7.5x10^8 ~7.5x10^7	~700 ~700 ~700	$10^{-5.0}$ $10^{-3.9}$ $10^{-3.9}$	$10^{-4.2}$ $10^{-4.2}$ $10^{-5.2}$	$10^{-3.6}$ $10^{-3.6}$ $10^{-4.2}$	
photo-sphere	~5		~1-10?	~10^{11}	~2500	$10^{[-1.4\ -\ +0.6]}$	$10^{[-1.5]}$	$10^{[-1.5]}$	~10
X Cyg	~3		2-3	~10^{10}	~2600	$10^{[-0.6]}$	$10^{-2.4}$	$10^{-2.9}$	

Magnetic energy dominates to ~50 AU ➡ 'launch' region ~50 R_i (Blackman 2009)

But: Ionization fraction in the inner envelope is low (~2x10^{-5}; Gaulain & Mauron 1996) so limited coupling until onset of ionization

Field morphology

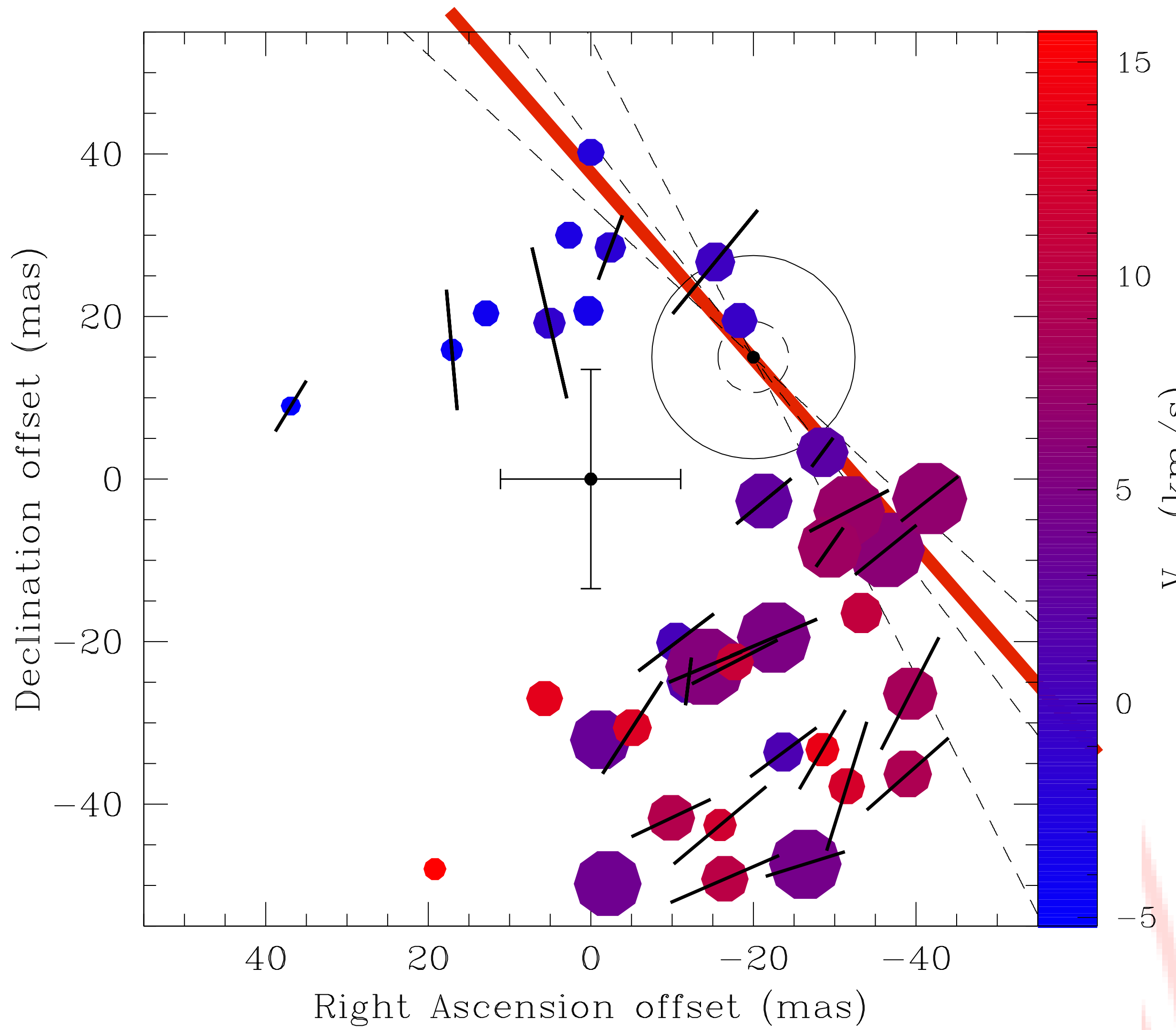
- Isolated pockets of compressed field lines, or a large scale field?
  - How to explain the similar structures seen over many hundreds of AU from the star?



Bains et al., Etoka et al. Kemball et al., Vlemmings et al.

Large scale fields (VX Sgr)

- SiO J=5-4 maser polarization
  - SMA observations at 215 GHz
  - Fits dipole field with: PA~220° and θ~40°
  - Consistent with water and OH observations
- Implies overall field shape maintained from few to 1000s of AU.



(Vlemmings et al. 2011 ApJ 728, 149)

Goldreich-Kylafis effect

- Linear polarization induced by anisotropic radiation field and small Zeeman splitting
- Traces B-field if Zeeman rate dominates

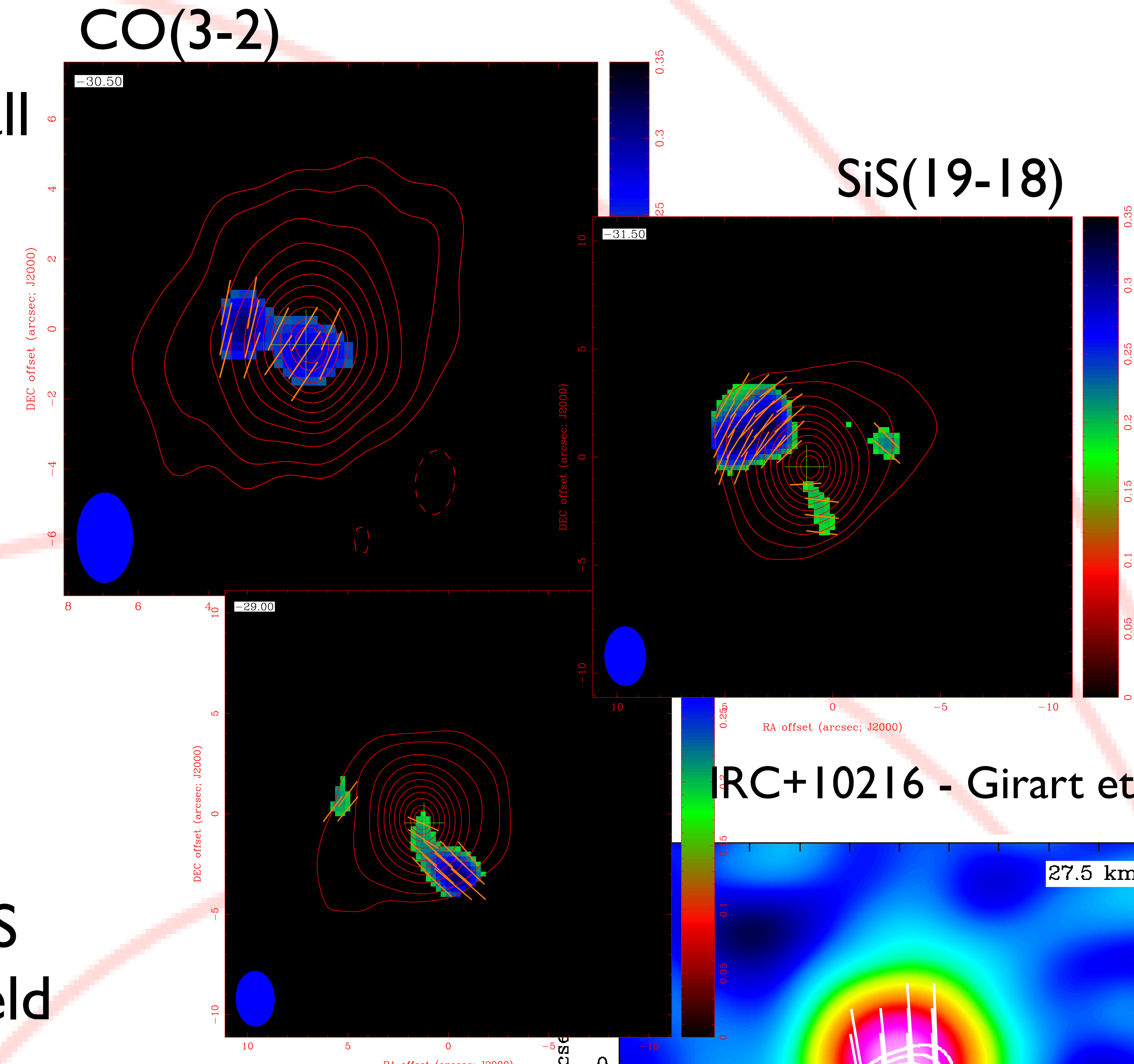
$$v_g = \frac{\mu B_0}{h} = 7.6 \times 10^{-4} \left(\frac{B_0}{10^{-6}\ \text{gauss}}\right)\left(\frac{\mu}{\mu_N}\right) \text{s}^{-1},$$

$$C = N_{\text{H}_2}\langle \sigma v_T \rangle = 9.4 \times 10^{-9} \left(\frac{N_{\text{H}_2}}{10^3\ \text{cm}^{-3}}\right)\left(\frac{T}{30\ \text{K}}\right)^{1/2} \text{s}^{-1},$$

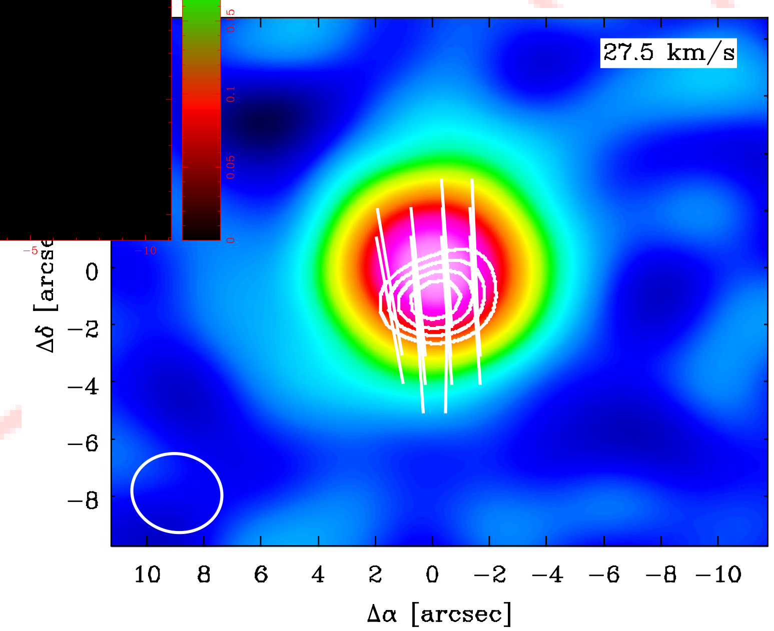
$$A_{a,b} = \frac{64\pi^4 d^2}{3h\lambda_r^3} = 1.8 \times 10^{-7} \left(\frac{0.26\ \text{cm}}{\lambda_r}\right)^3 \left(\frac{d}{0.1\ \text{debye}}\right)^2 \text{s}^{-1},$$

Kylafis 1983

- Observations indicates the CO, CS and SiO vectors trace magnetic field and not radiative anisotropies
- IK Tau shows consistent large scale field from thermal SiO out to CO(2-1)

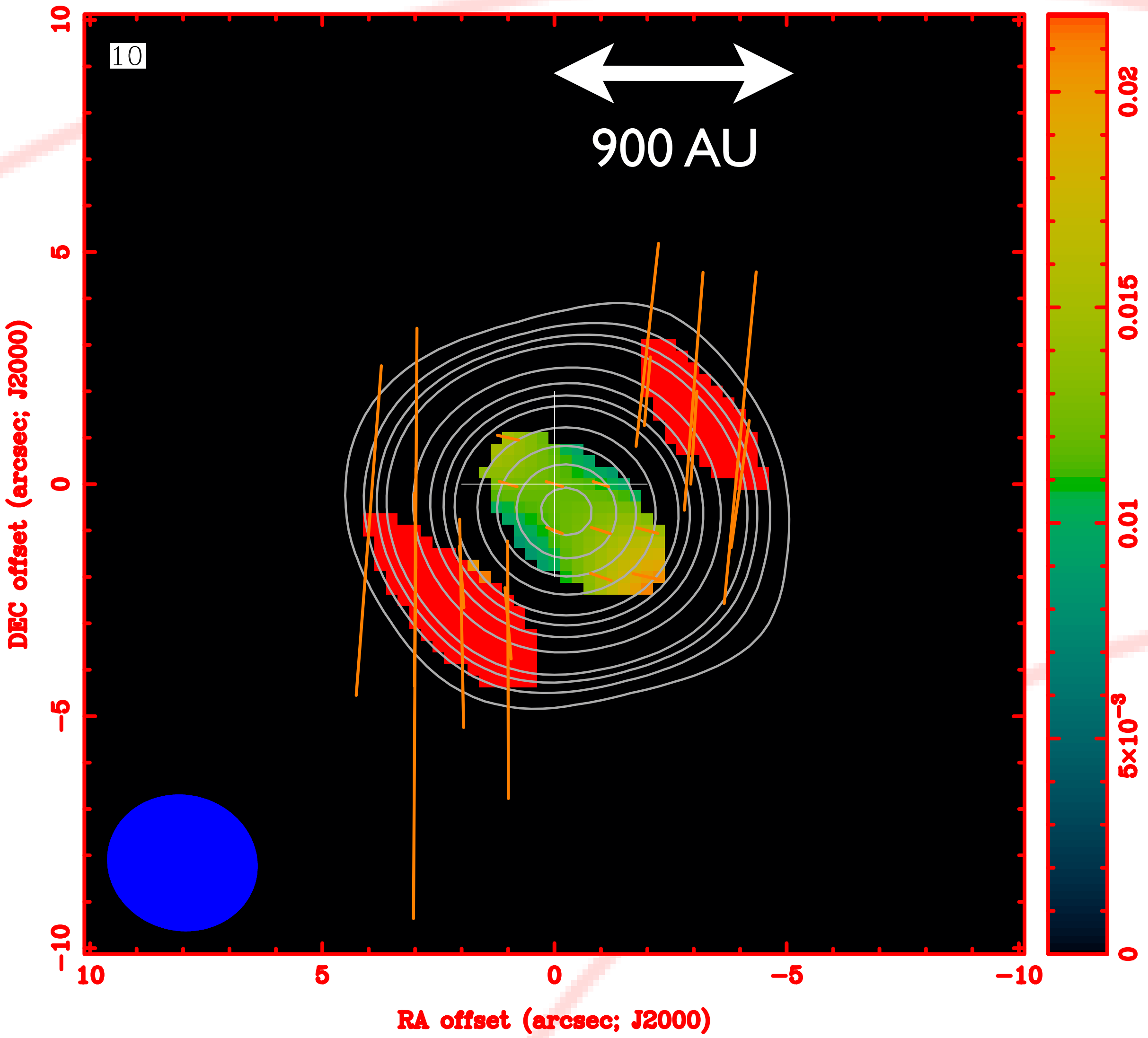


IRC+10216 - Girart et al. 2012



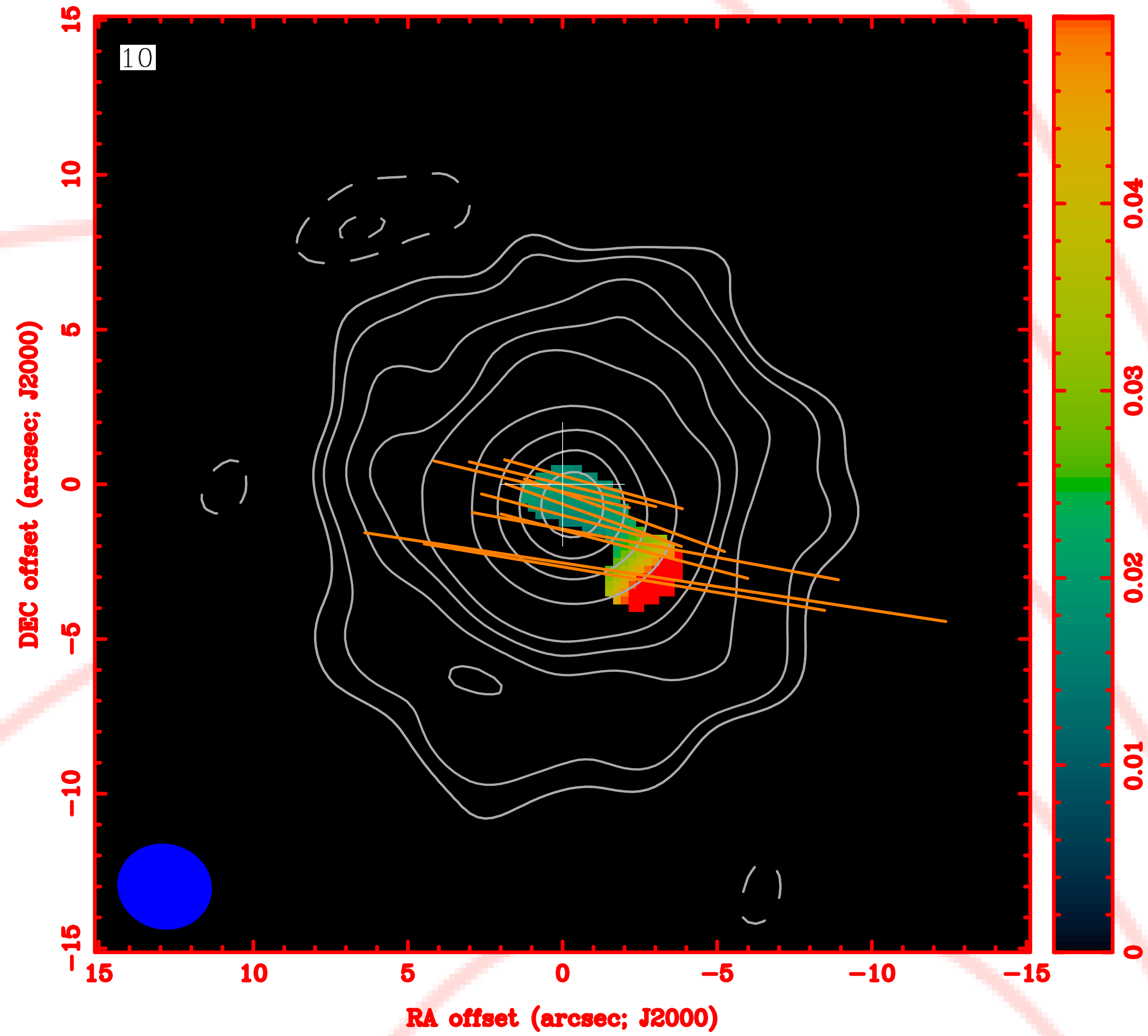
IK Tau SiO(5-4) - Vlemmings et al. 2012

Goldreich-Kylafis effect



SiO(5-4)

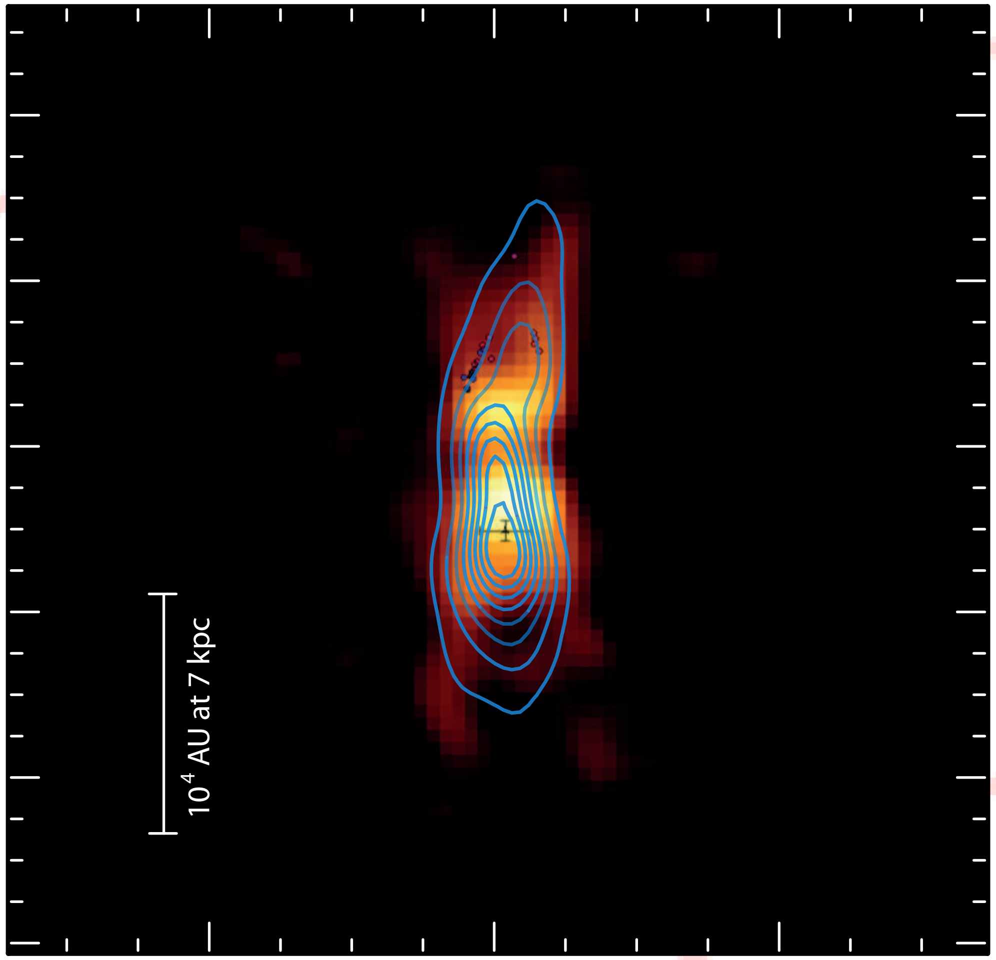
Chi Cyg - Tafoya et al. in prep.



CO(2-1)

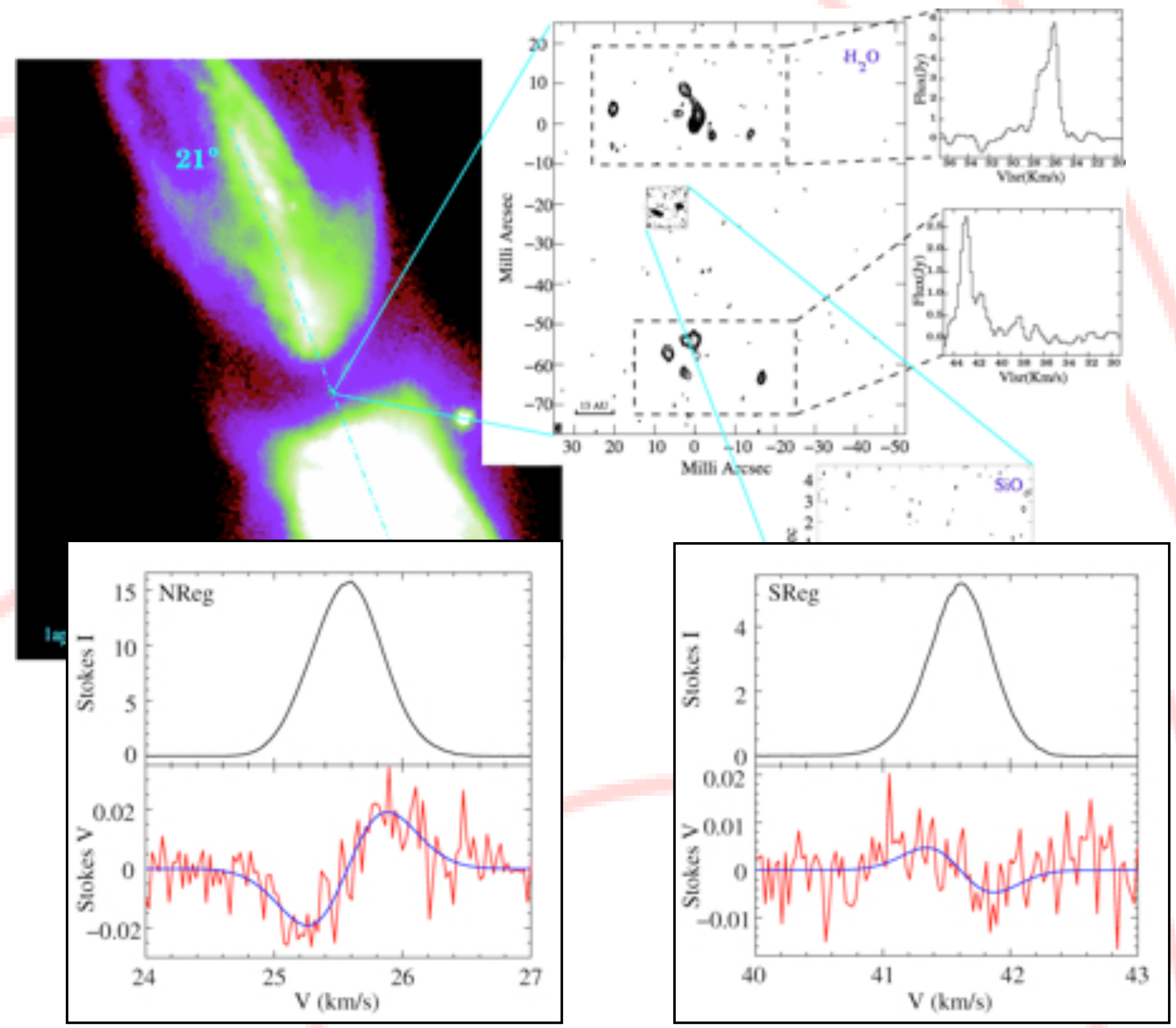
- ALMA will revolutionize this field!

post-AGB / p-PNe

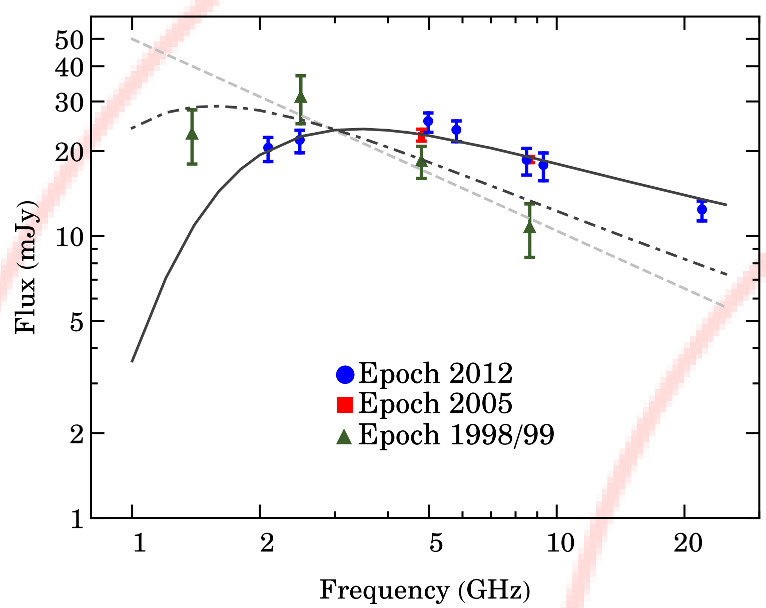


- Rotten Egg Nebula (symbiotic….)
- H_2O masers magnetic field measurement
  - Extrapolated ($B\varphi \propto r^{-1}$) surface magnetic field of B~3 G. (Leal-Ferreira et al., 2013)

Figure from Desmurs et al. (2007)



- IRAS 15445-5449 (Pérez-Sánchez et al. 2013)
- Synchrotron jet
  - Extrapolated ($B\varphi \propto r^{-1}$) surface magnetic field of B~13 G



Field origin

- Single stars:
  - Internal dynamo (Blackman et al. 2001)
    - differential rotation between core and envelope
    - rotation drained in 10-50 years (Nordhaus et al. 2006)
    - *Need to counteract energy loss*
      - *Convective energy (sun-like) model predicts magnetically dominated explosion*
  - Interaction with circumstellar disk
    - *But what is the origin of the disk ?*
- Binary stars:
  - Accretion disk amplification
  - Companion
- Localized stellar activity

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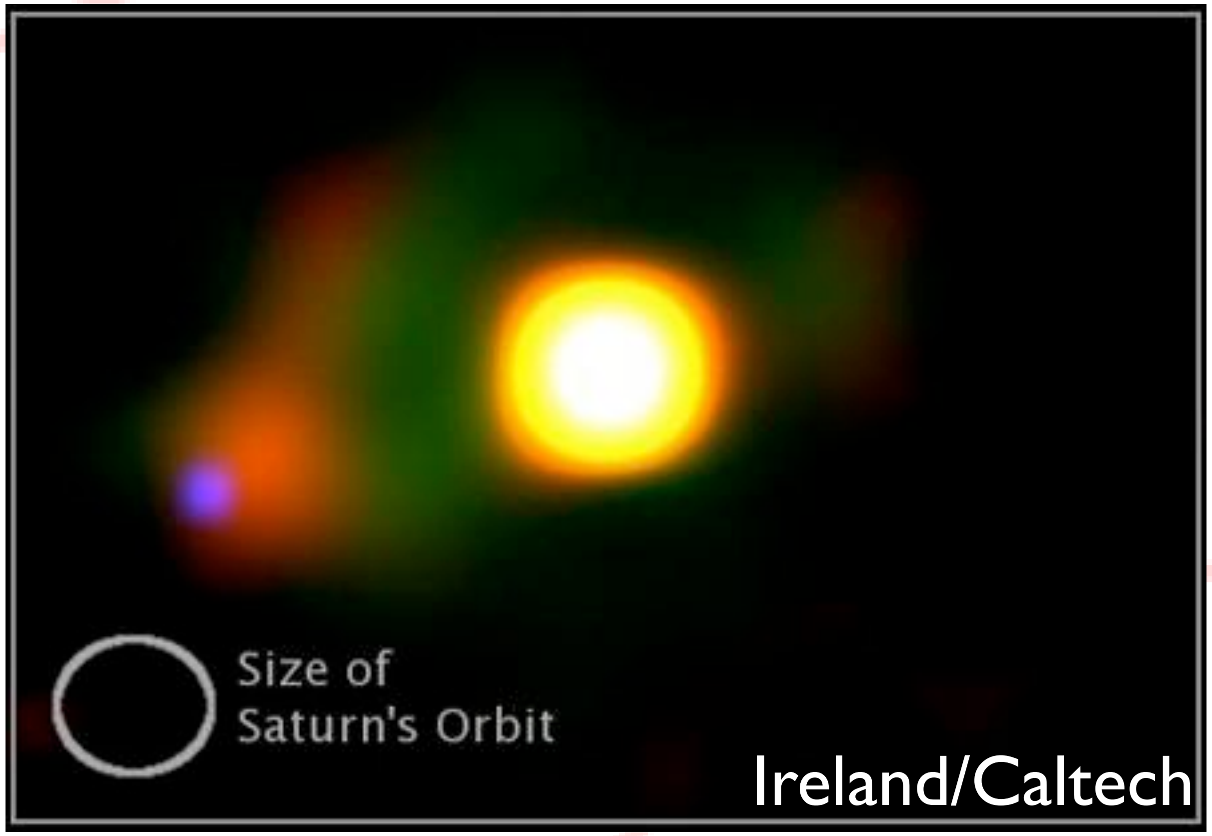
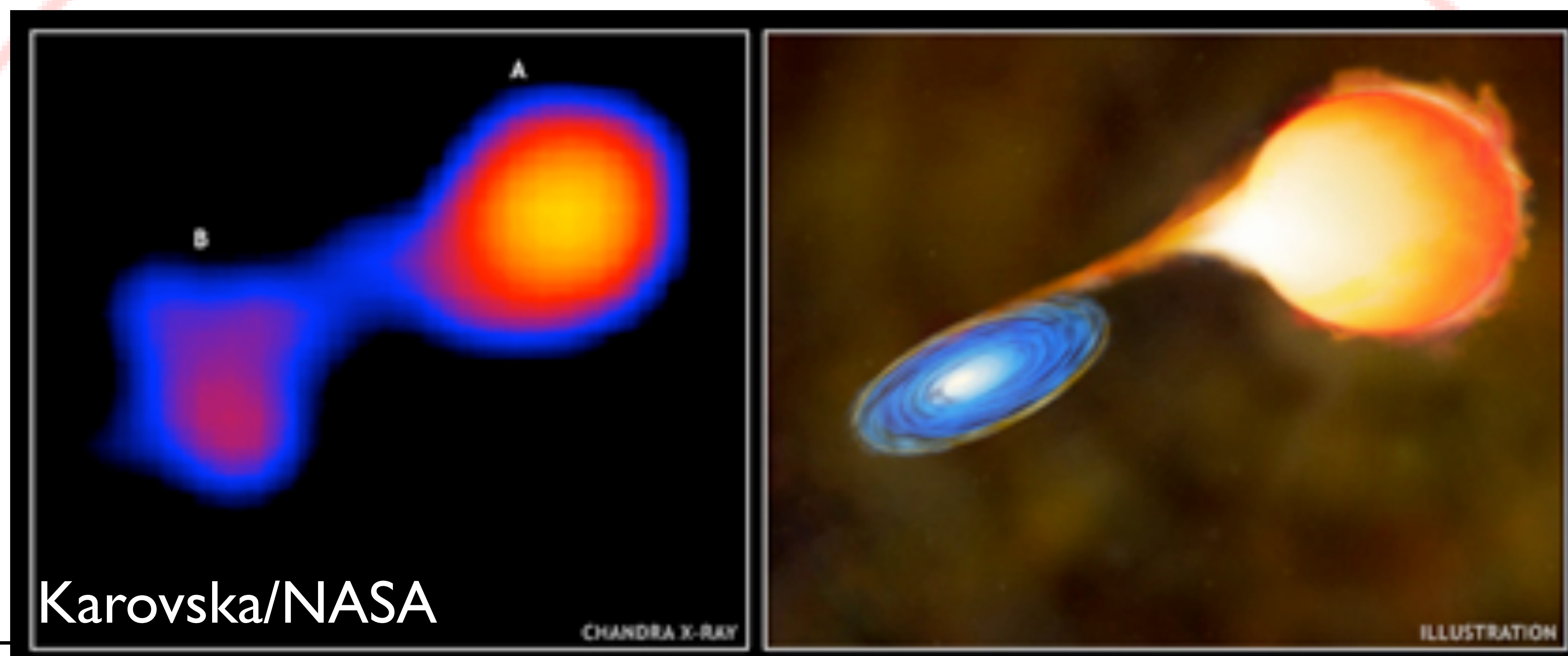
Resolving the stellar disc of Mira A with ALMA

Sofia Ramstedt, Eamon O'Gorman, Liz Humphreys, Markus Wittkowski,
Alain Baudry, Margarita Karovksa

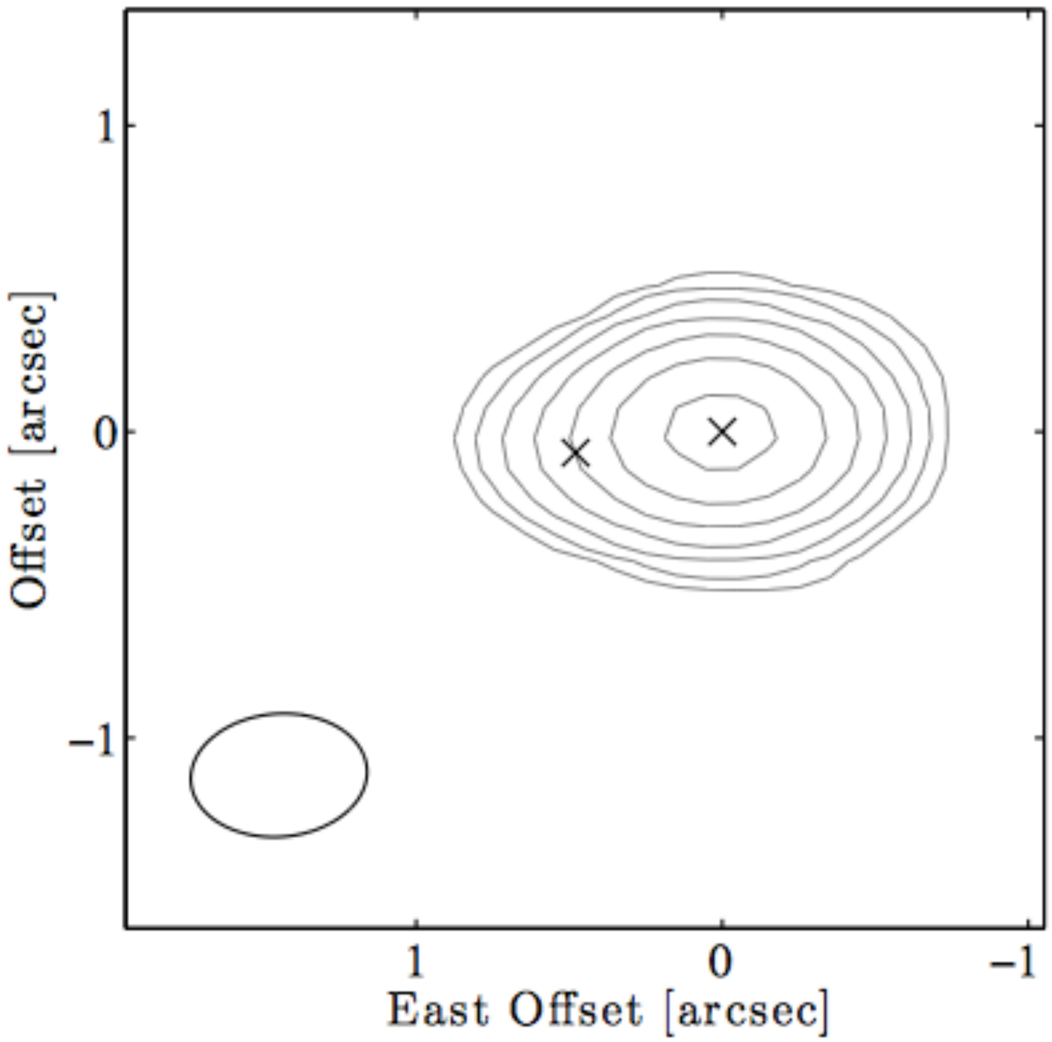
Interacting binary system



- Located at 92 pc
- Binary separation ~40 AU
- Accretion disk around Mira B formed from Mira A wind through Wind-Roche-lobe overflow?
- Both Mira A and B are X-ray and UV emitters



ALMA Long Baseline campaign: Mira



Band 7: Ramstedt et al. 2014

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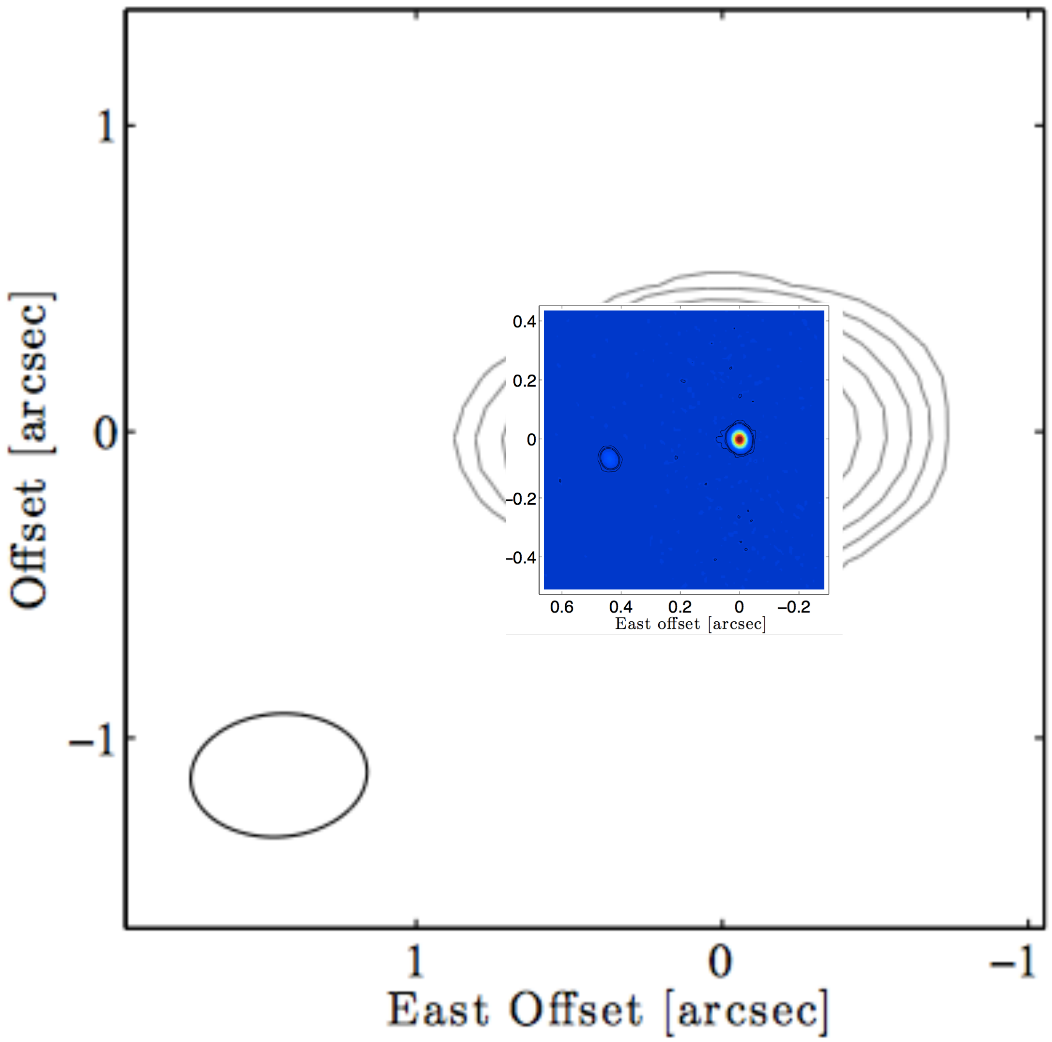

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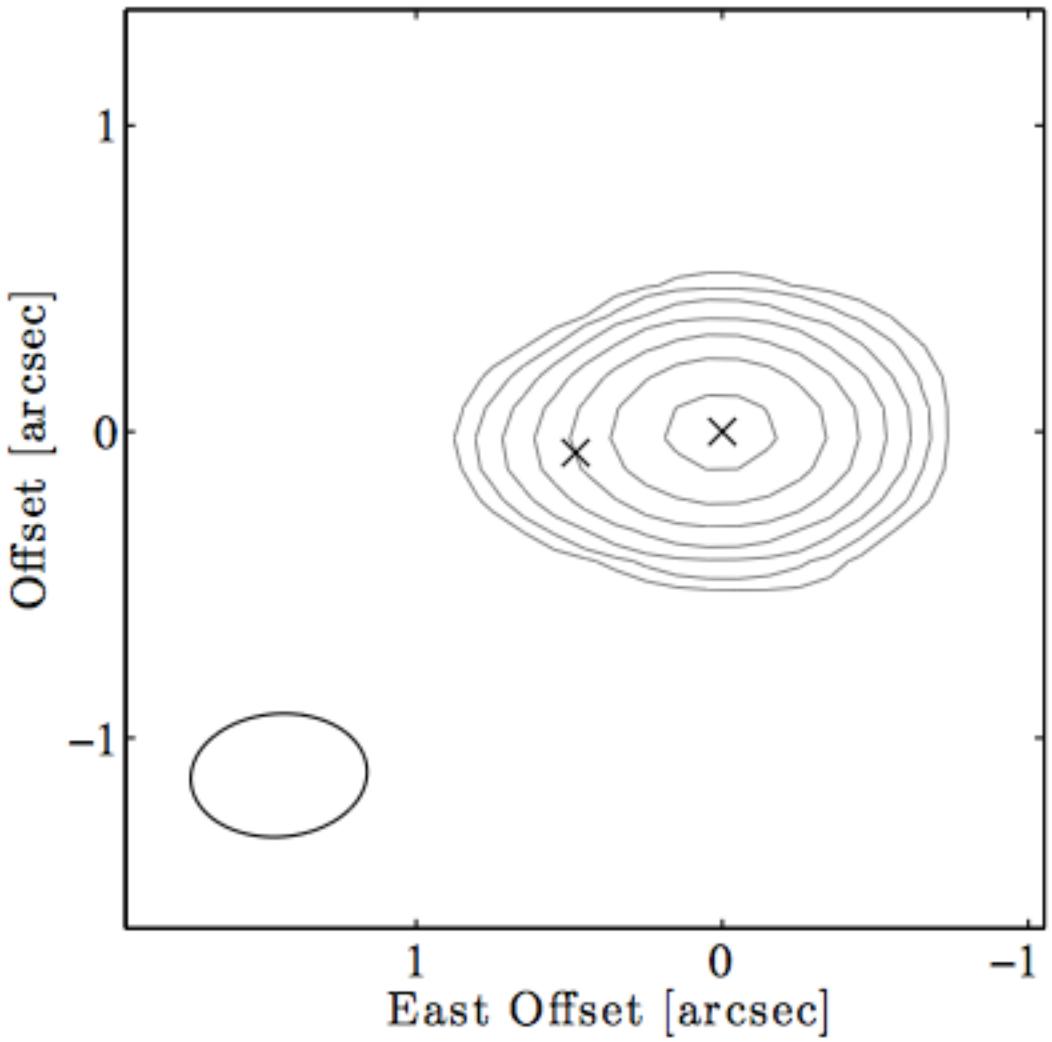

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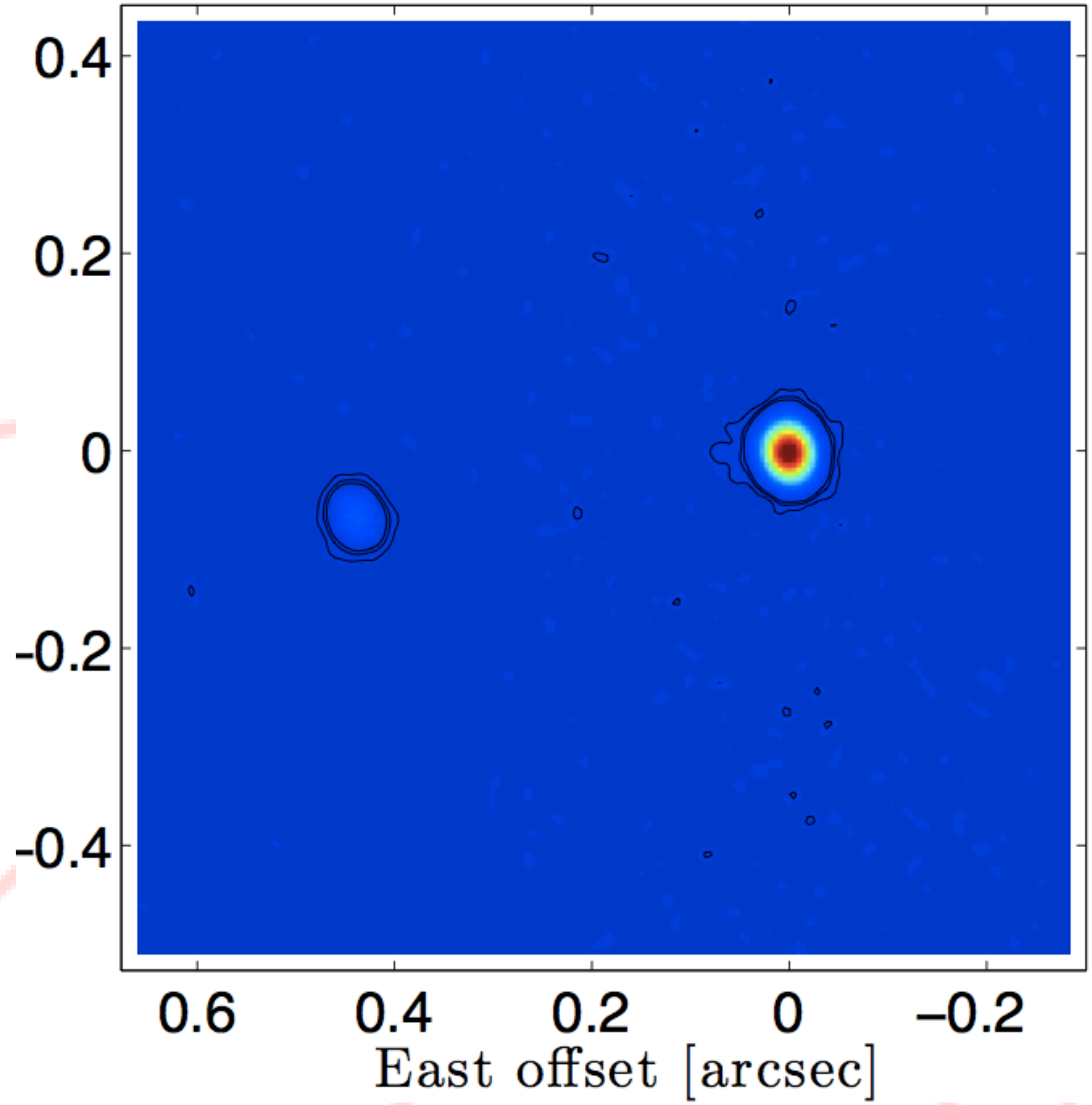
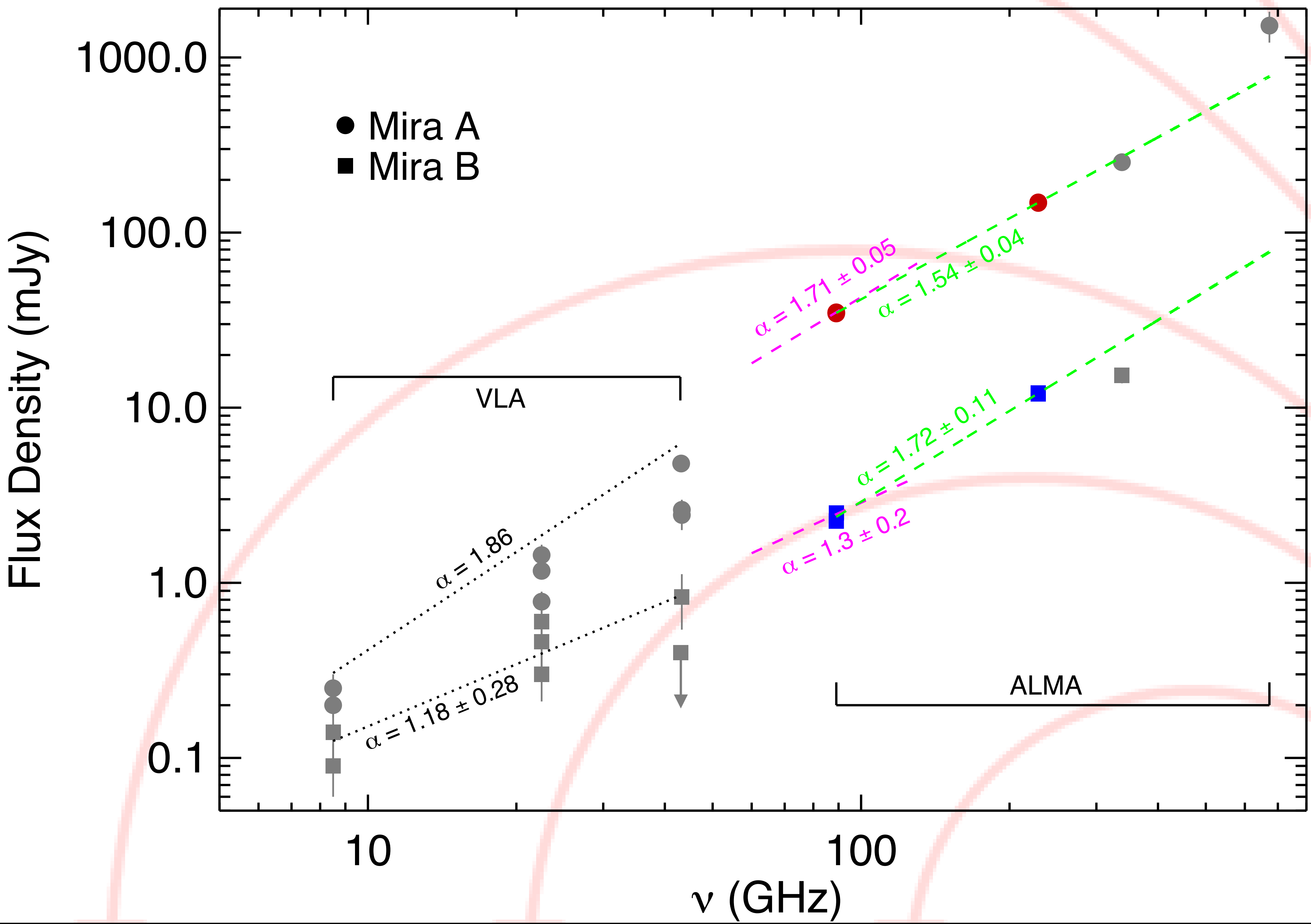
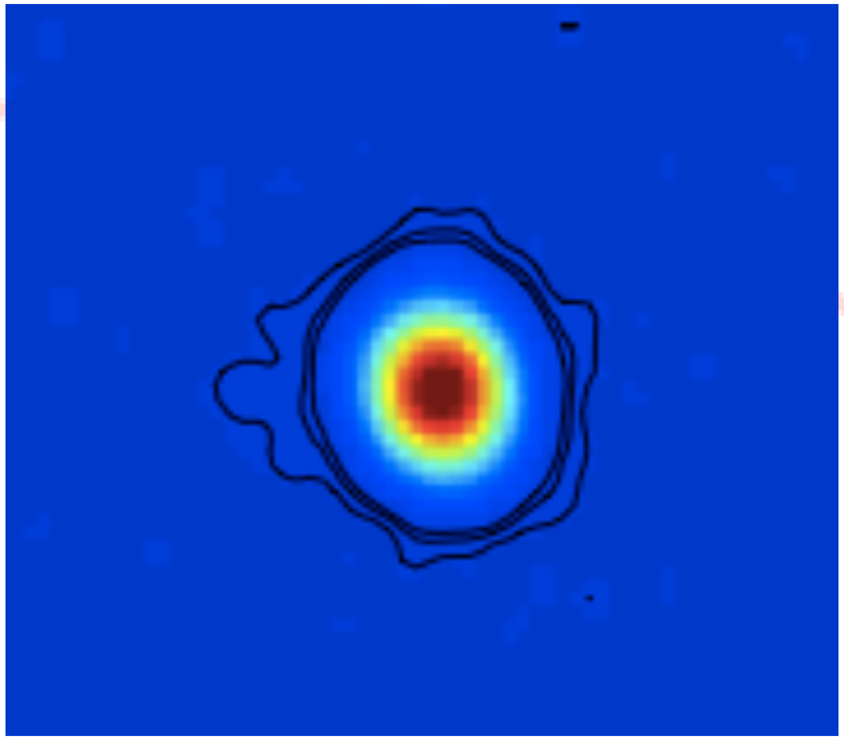


Band 6: Vlemmings et al., 2015

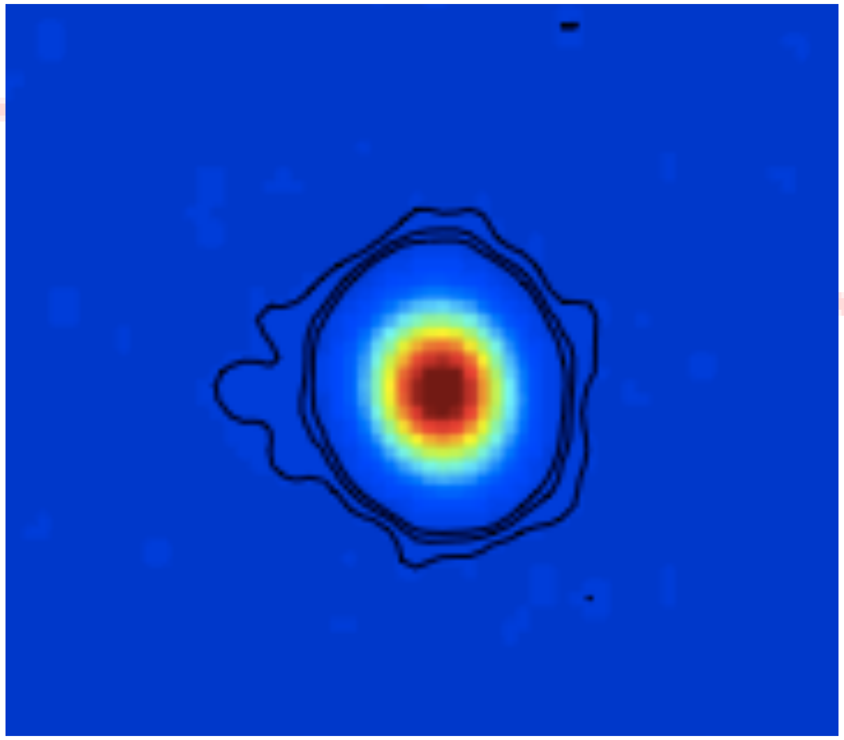
Spectral Index

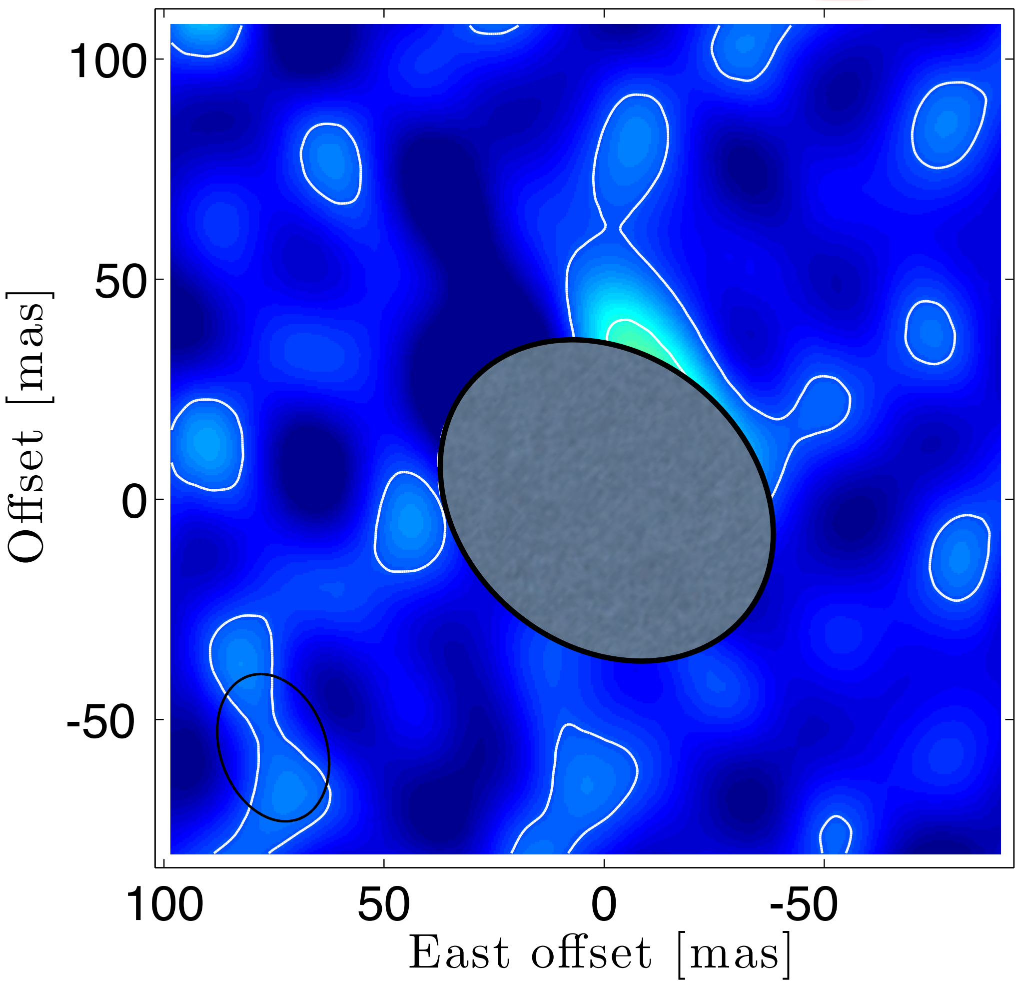


Mira A



Mira A





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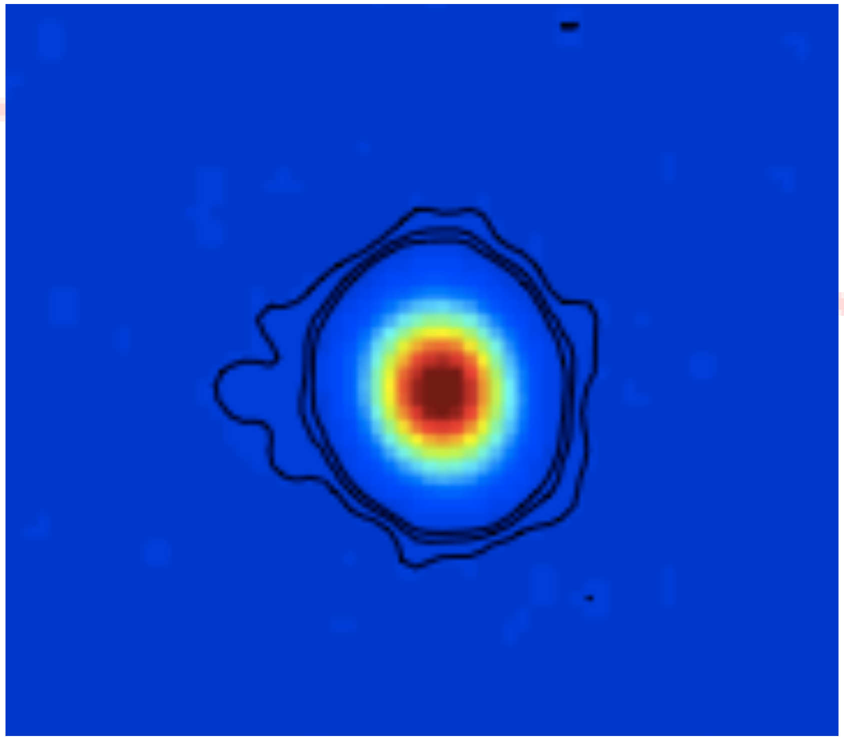

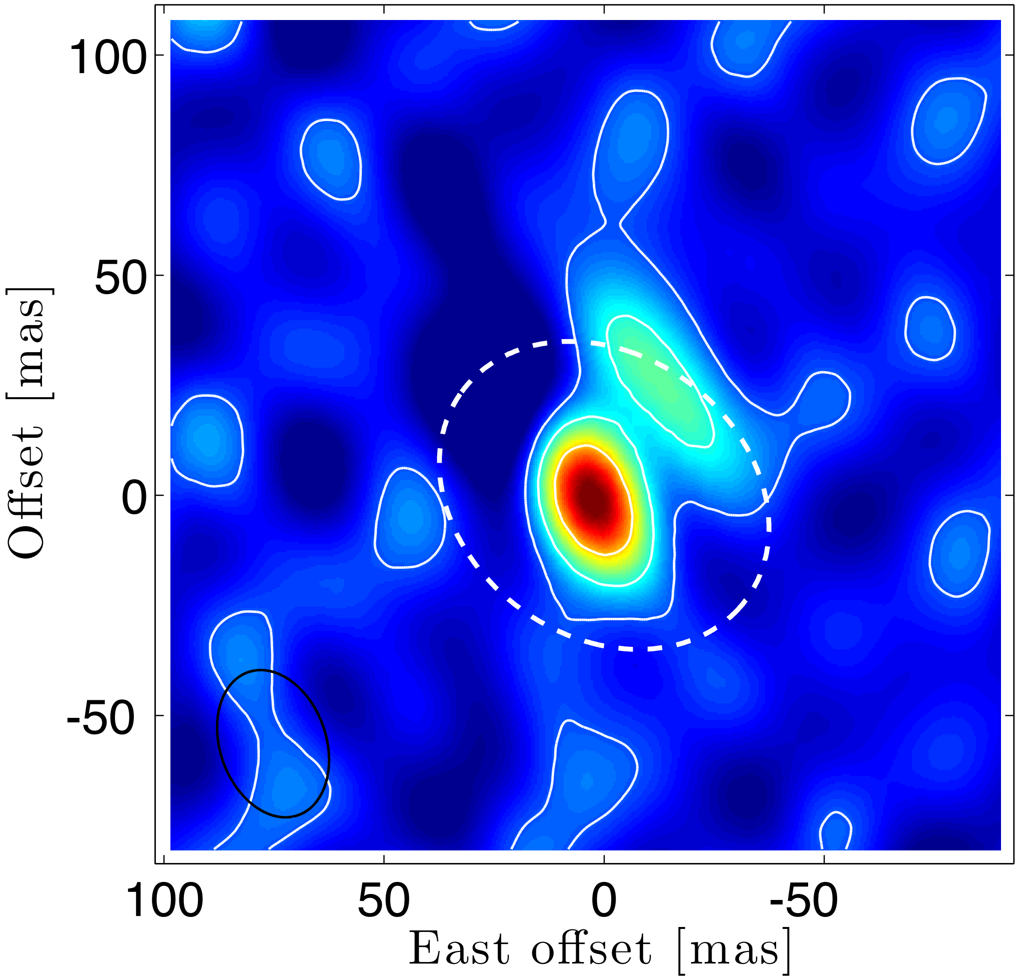

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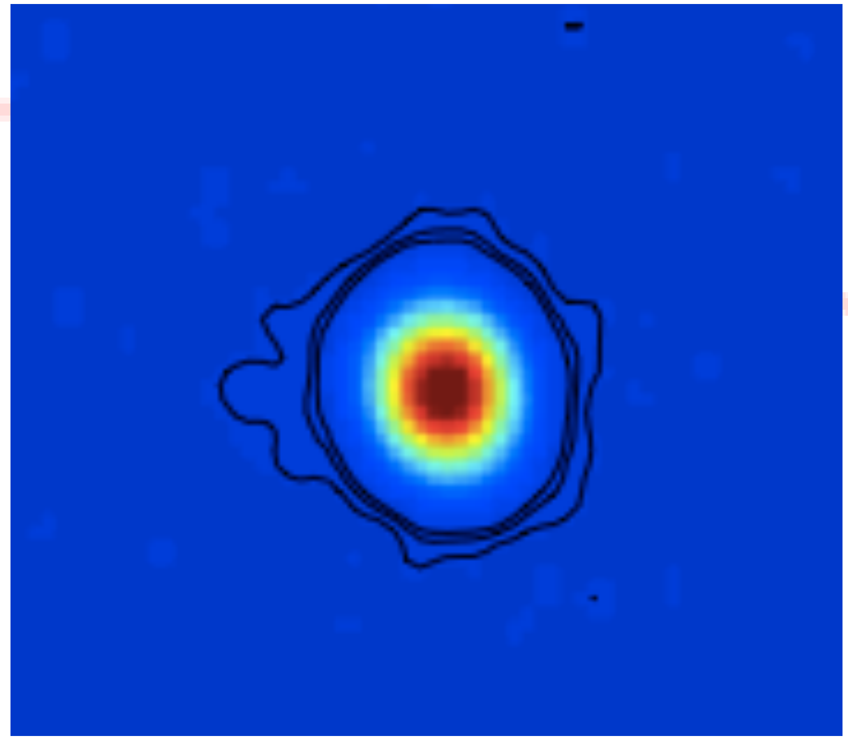

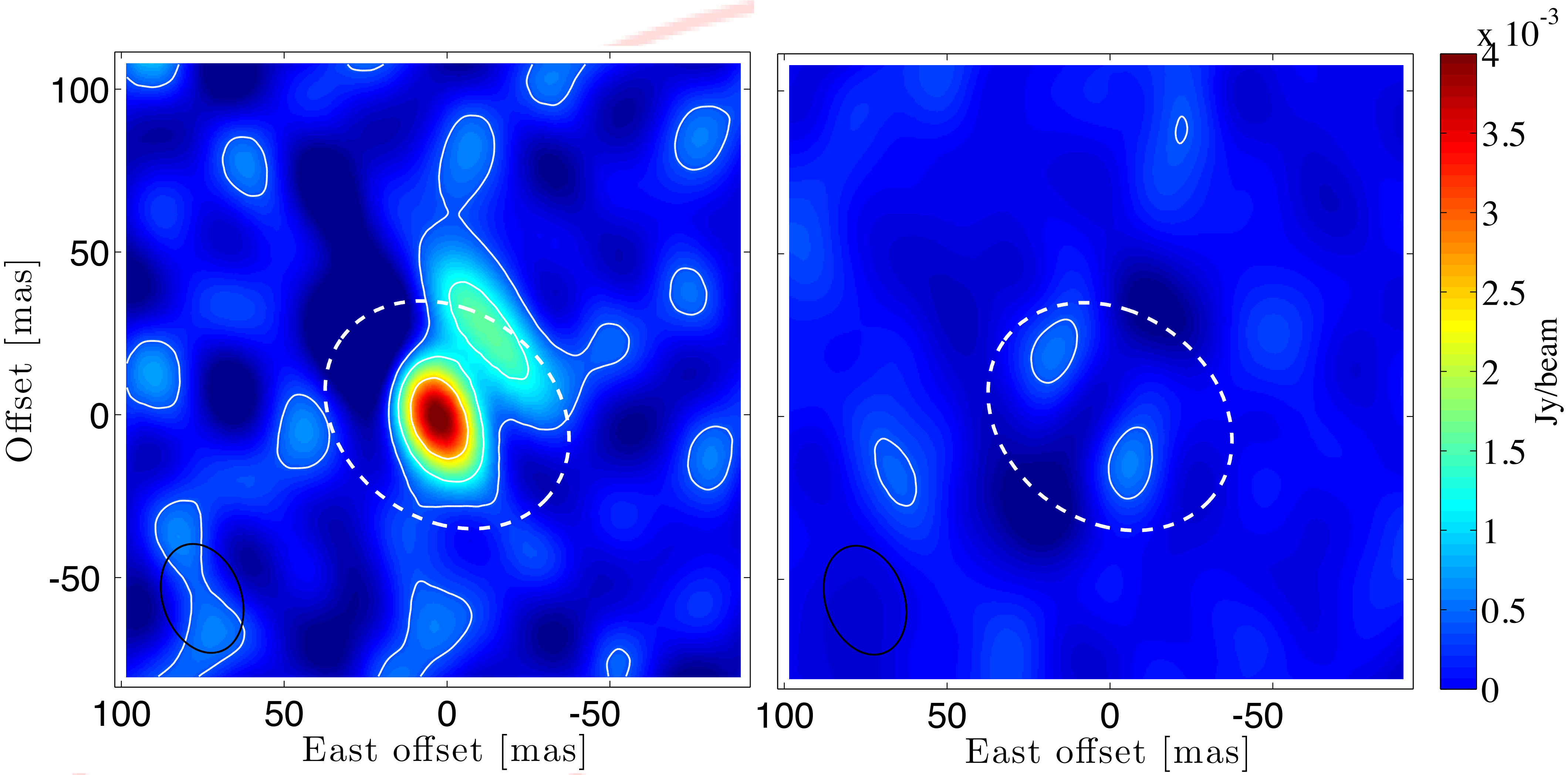

x 10^-3
4
3.5
3
2.5
2
1.5
1
0.5
0
Jy/beam
100
50
0
-50
Offset [mas]
East offset [mas]
East offset [mas]

Mira A stellar activity

epoch	ν [GHz]	shape	S_ν [mJy]	major axis / fwhm [mas]	axis ratio major/minor	position angle [°]	spectral index
Mira A							
17 Oct 2014	94.2	Disc	35.03±0.04	41.8±0.4	1.20±0.01	54±2	1.73±0.09
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
29 Oct 2014	228.67	Disc	137.8±0.2	43.28±0.07	1.13±0.02	51.0±0.5	…
	228.67	Gaussian	10.13±0.07	4.6±0.5	1.0	…	…
01 Nov 2014	228.67	Disc	140.0±0.2	43.36±0.06	1.12±0.02	50.8±0.6	…
	228.67	Gaussian	8.98±0.07	4.7±0.5	1.0	…	…

- Band 3 brightness temperature (~5000 K) > predicted (~2000 K) (Reid & Menten 1997)
  - Other (molecular) opacity sources?
- Elongation possibly due to non-radial pulsations
- Hotspot ~4.7 mas (area ff<0.01)
  - Brightness temperature ~10.000 K
    - Comparable to millimeter emission from Solar flares
    - Magnetic activity? (B-fields>100 G in ejecta)
      - related to X-ray and maser outbursts?

Conclusions

- **<u>Dynamically important large scale magnetic fields occur in the envelopes of evolved stars</u>**
    - SiO, H_2O and OH maser observations consistent with solar-type or dipole magnetic field
    - Alfvén waves can help drive mass-loss
    - Surface fields are consistent and a hotspot on Mira could be indicative of solar-like magnetic activity
- *<u>Questions:</u>*
  - How widespread are AGB magnetic fields (obs) ?
  - Is it dynamically important (obs/models) ?
  - What is the origin of the magnetic field (obs/models) ?
    - Single star dynamo, binary, heavy planet, disk interaction
  - Are magnetically collimated jets common features of the proto-planetary water fountain sources ?
    - Are they the explanation for asymmetric (bi-polar) PNe ?

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Magnetic fields ~~vs.~~ Binaries

And?

- *Questi*
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