Galactic center G objects as dust-enshrouded stars near the supermassive black hole

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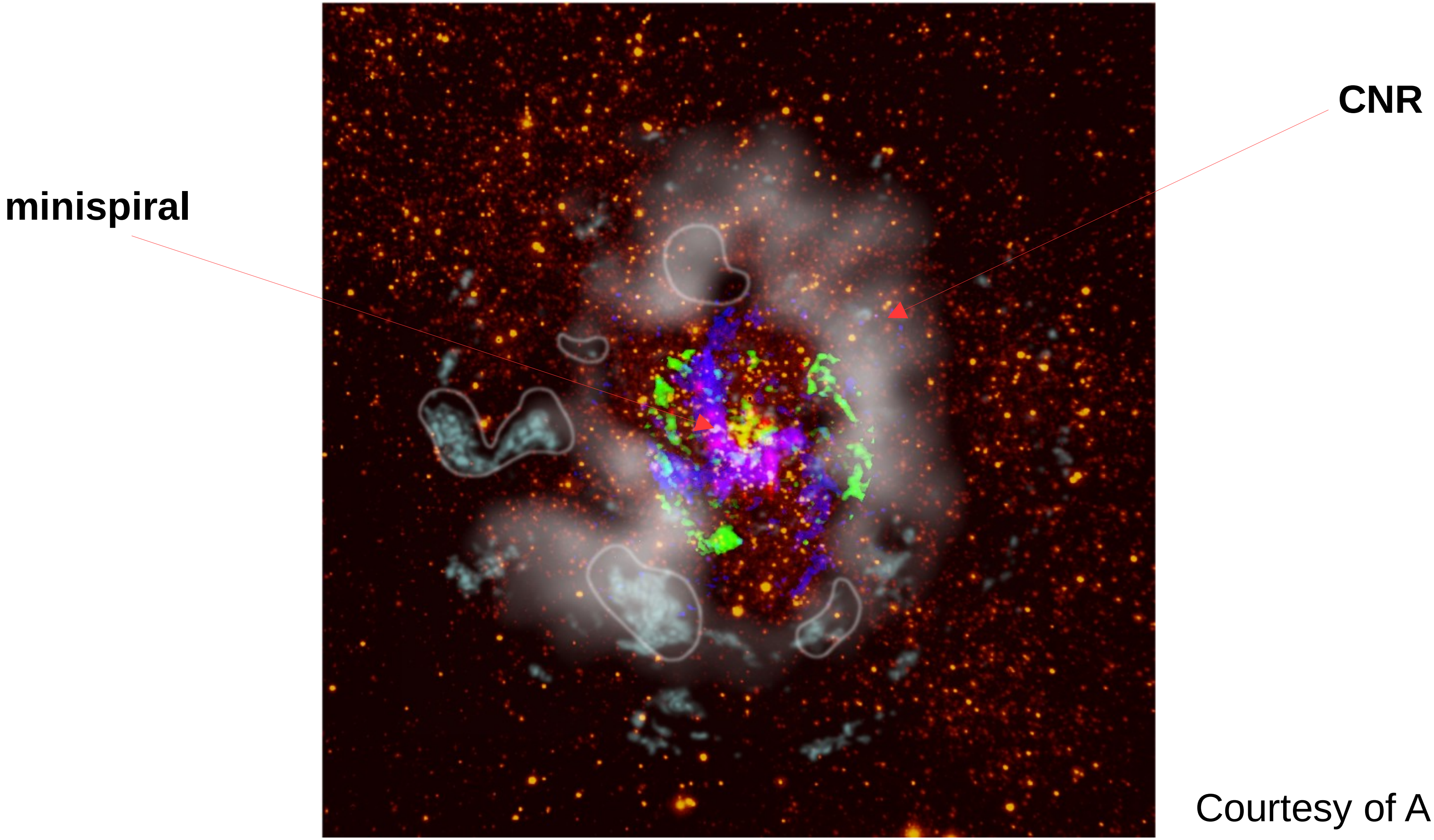
17th Marcel Grossmann Meeting - Session : Latest results from Galactic center observations
Pescara, July 11, 2024

Galactic Center – multiphase environment

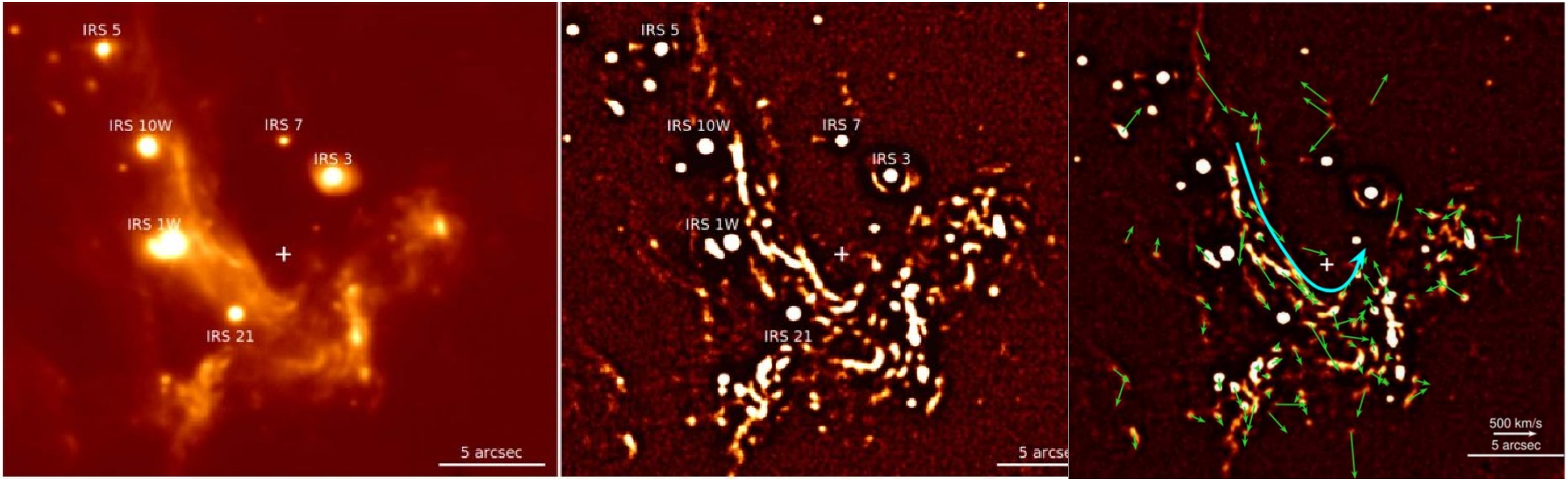
- Stars coexisting with colder dust and gas
- **Circumnuclear ring-CNR > *1.5 pc***
- **Minispiral filaments** within the **central Cavity < *1.5 pc***



Courtesy of A. Eckart

Galactic Center – multiphase environment

- Detection of dusty structures in mid-infrared
- Stellar sources with dusty envelopes and compact dusty filaments along the Minispiral northern arm

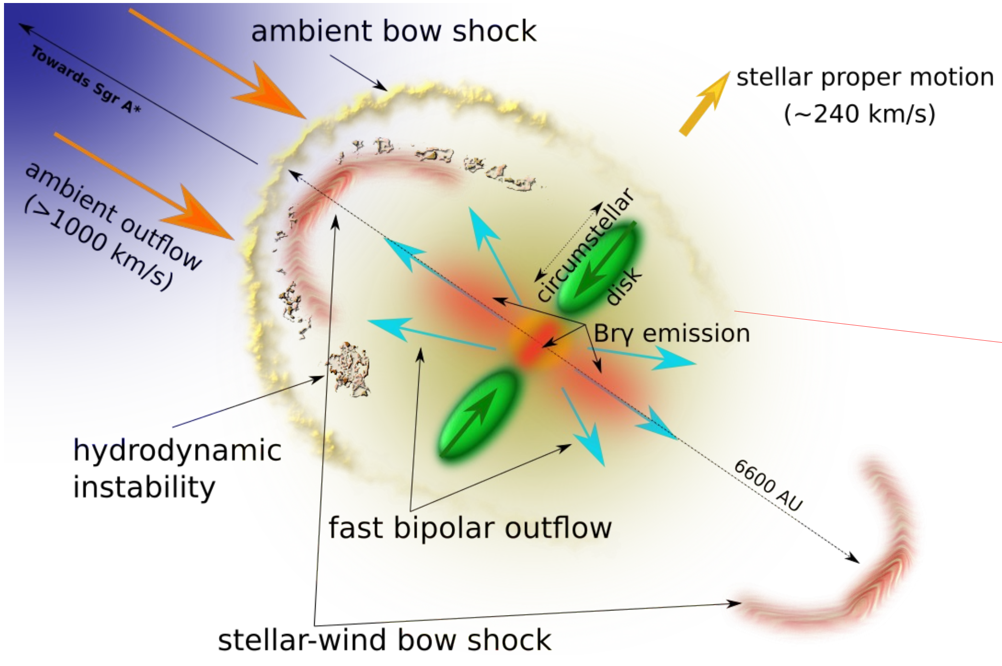


- Recent comprehensive analysis of mid-infrared (*N*-band) sources, including proper motions and spectral indices performed by **Bhat, Sabha, Zajaček et al. (2022)**

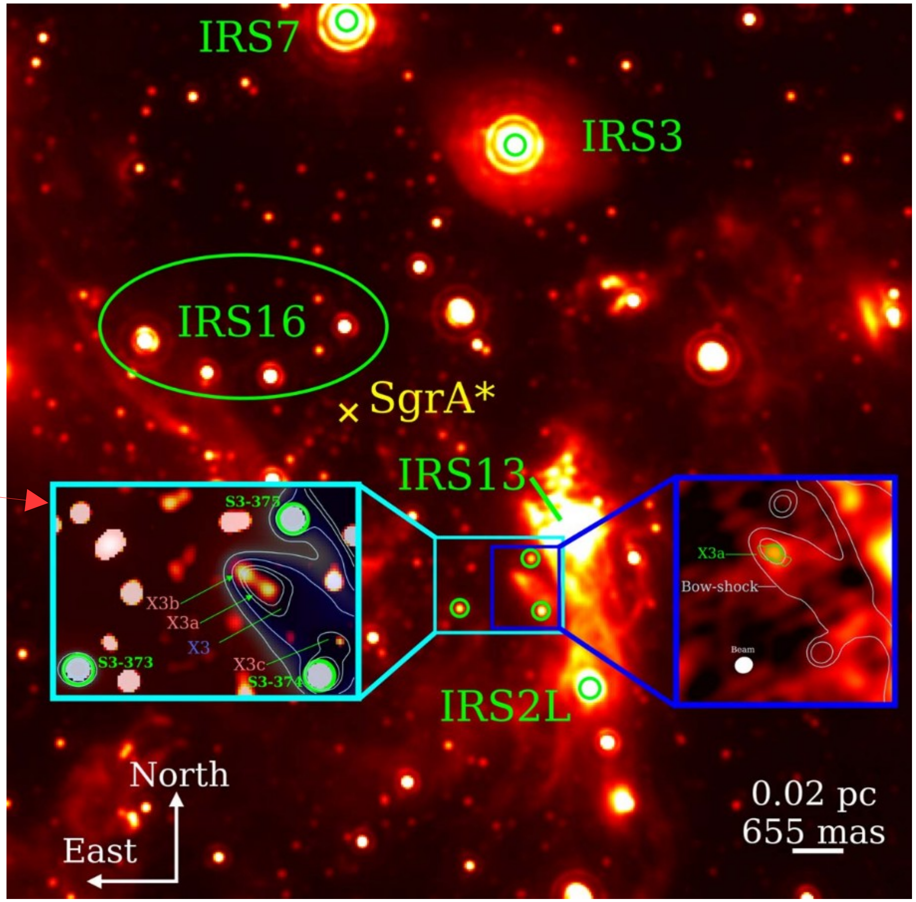
Galactic Center – multiphase environment

Dust-enshrounded star in the GC

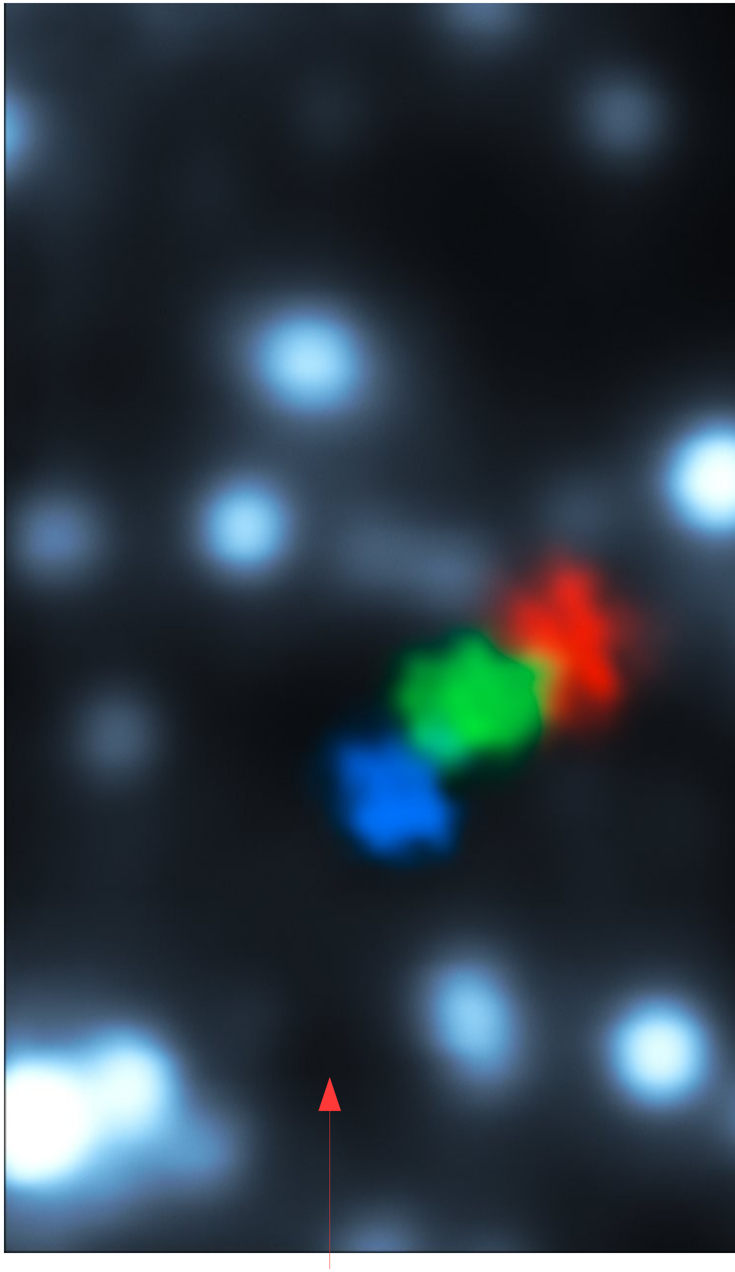
1) Interaction with the denser circumnuclear medium (stellar bow shocks)
2) Circumstellar dusty envelope: young stellar objects, binary merger products, evolved stars
3) Combination of 1) and 2)



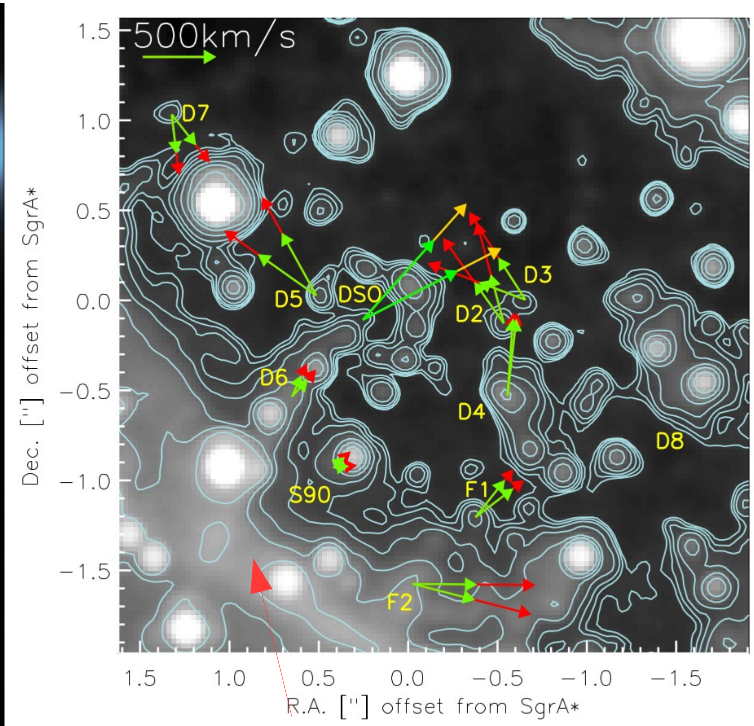
Example: X3 source (Peissker et al., 2023)



...G2 object appeared...approaching the Galactic center

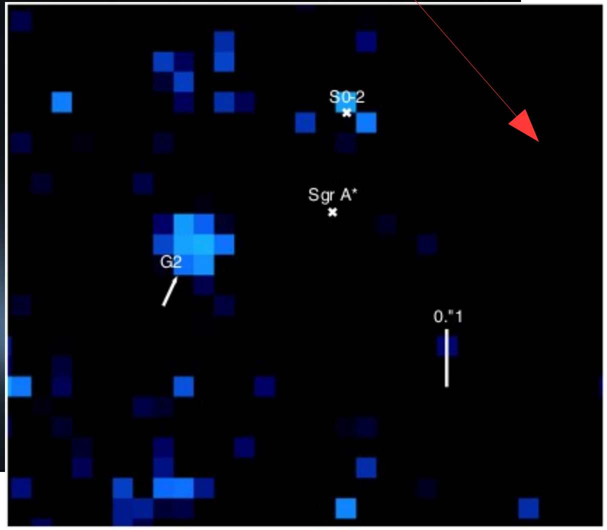


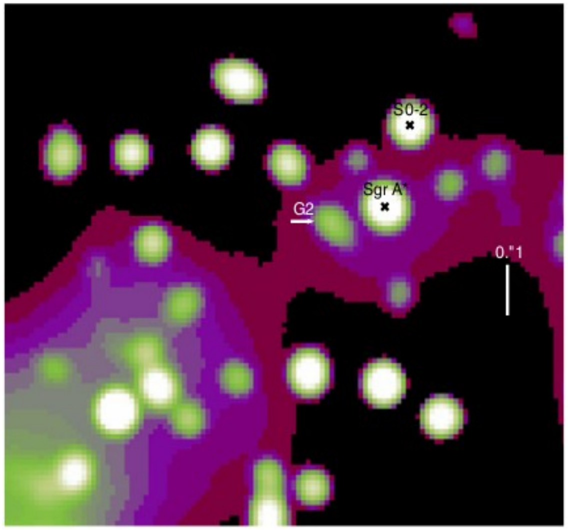
Gillessen et al., 2012



Eckart et al., 2013

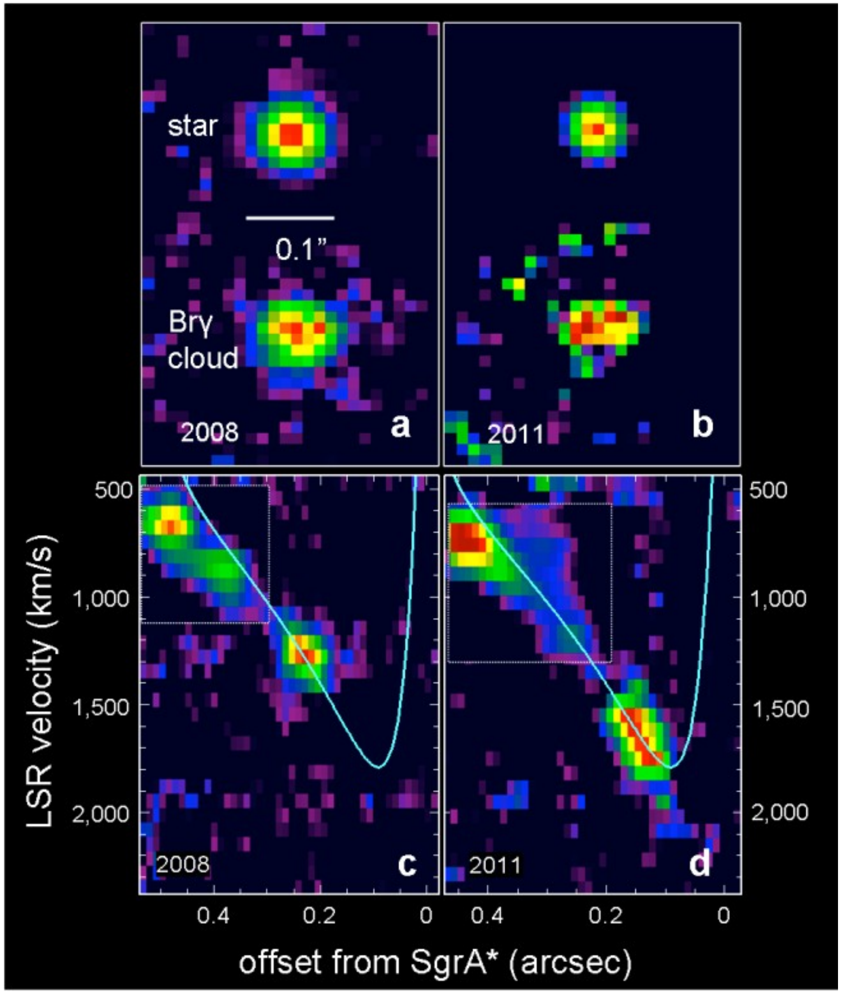
Phifer et al., 2013



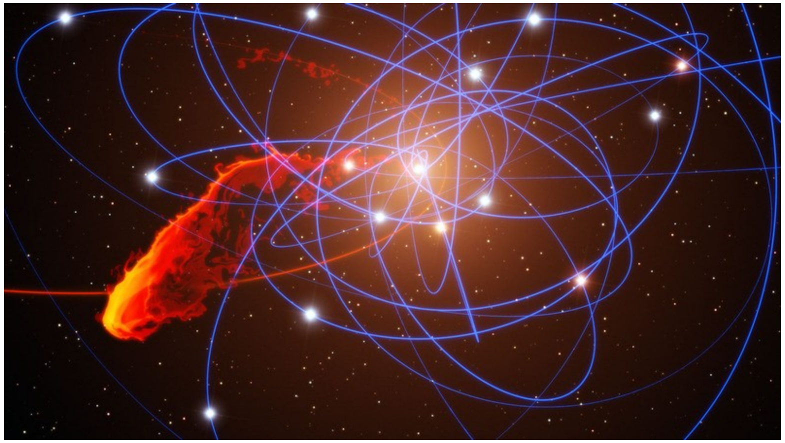


...G2 object appeared...approaching the Galactic center

Unusual appearance:
- **source of broad emission lines**
- **effective temperature of ~600-800 K**



Gillessen et al., 2012



Proposed to be **a gas cloud that is being tidally stretched**

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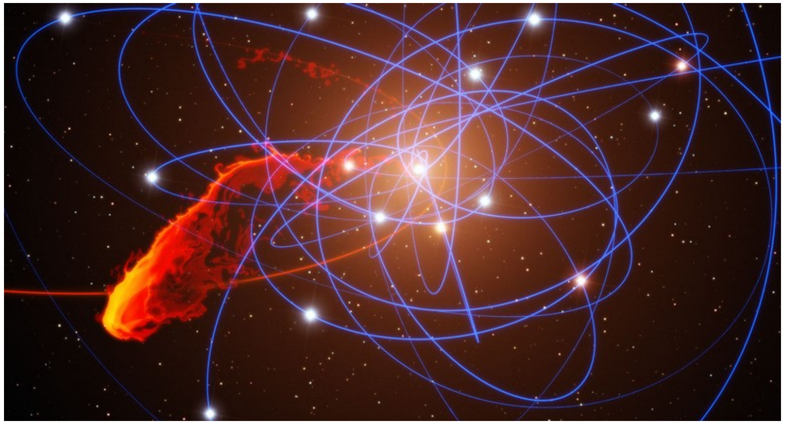


- Gas cloud – an attractive scenario
- should have led to an increased accretion (outflow)
- Unstable
- Expected prolongation and significant structural changes during the monitoring

Evaporation timescale

Burkert et al. (2012)

$$\tau_{\rm evap} \sim 1 \left(\frac{n_{\rm c}}{10^6\,{\rm cm^{-3}}}\right)\left(\frac{R_{\rm c}}{100\,{\rm AU}}\right)^2\left(\frac{T_{\rm h}}{10^8\,{\rm K}}\right)^{-\frac{5}{2}}\left(\frac{\log\Lambda}{30}\right)\,{\rm yr}\,,$$

$$\tau_{\rm evap} \approx 64\,{\rm yr}\left(\frac{r}{10^{16}\,{\rm cm}}\right)^{1/6}\left(\frac{M_c}{1.7\times10^{28}\,{\rm g}}\right)^{1/3}$$

Kelvin-Helmholtz timescale

$$\tau_{\rm KH} = \frac{\lambda_{\rm KH}}{v_{\rm shear}}\frac{1+r_\rho}{\sqrt{r_\rho}} = 4.95\left(\frac{\lambda_{\rm KH}}{100\,{\rm AU}}\right)\left(\frac{v_{\rm shear}}{3000\,{\rm km\,s^{-1}}}\right)^{-1}\frac{1+r_\rho}{\sqrt{r_\rho}}\,{\rm yr}\,,$$

Tidal timescale

$$\tau_{\rm tidal} = \sqrt{\frac{2R_{\rm c}}{|a_{\rm tidal}|}} = \frac{r^{3/2}}{\sqrt{GM_{\rm BH}}} = \left(\frac{r}{r_{\rm g}}\right)^{\frac{3}{2}}\frac{GM_{\rm BH}}{c^3} \simeq 0.624\left(\frac{r}{10^4\,r_{\rm g}}\right)^{\frac{3}{2}}\left(\frac{M_{\rm BH}}{4\times10^6\,M_\odot}\right)\,{\rm yr}\,.$$

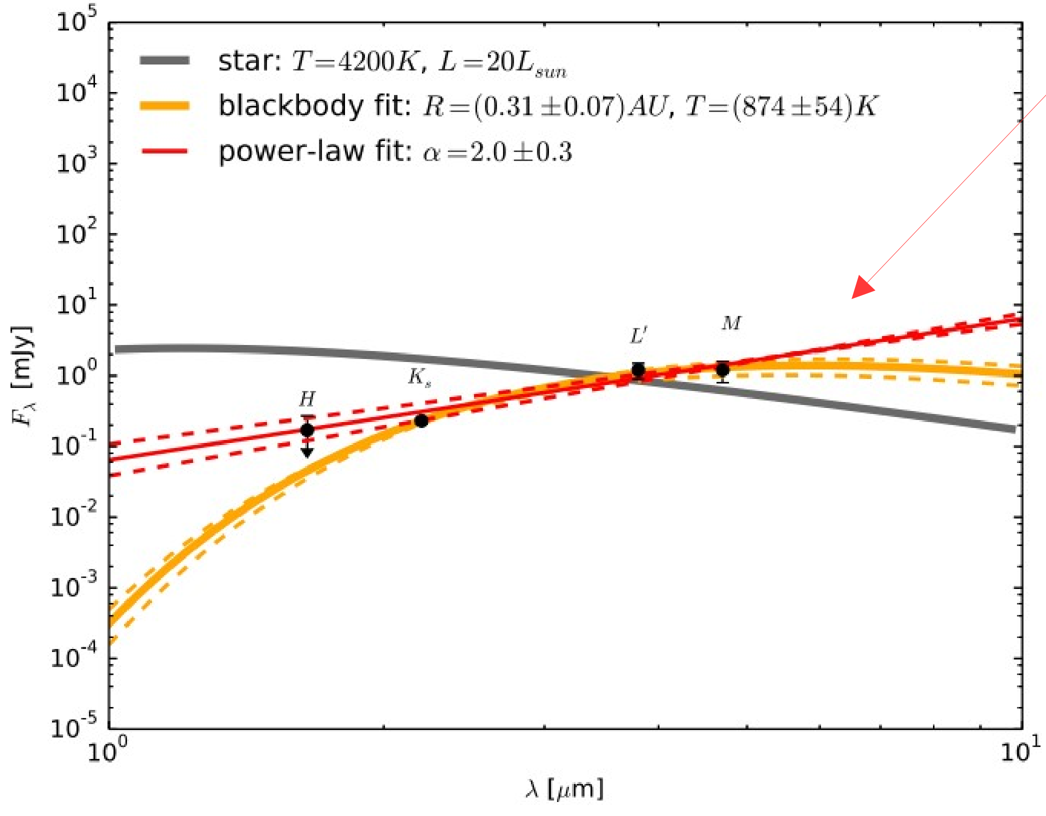
A coreless cloud is a transient feature in the hot ionized medium. There are also difficulties to form it (wind-wind collision in close binaries, see Diego Calderon’s talk)

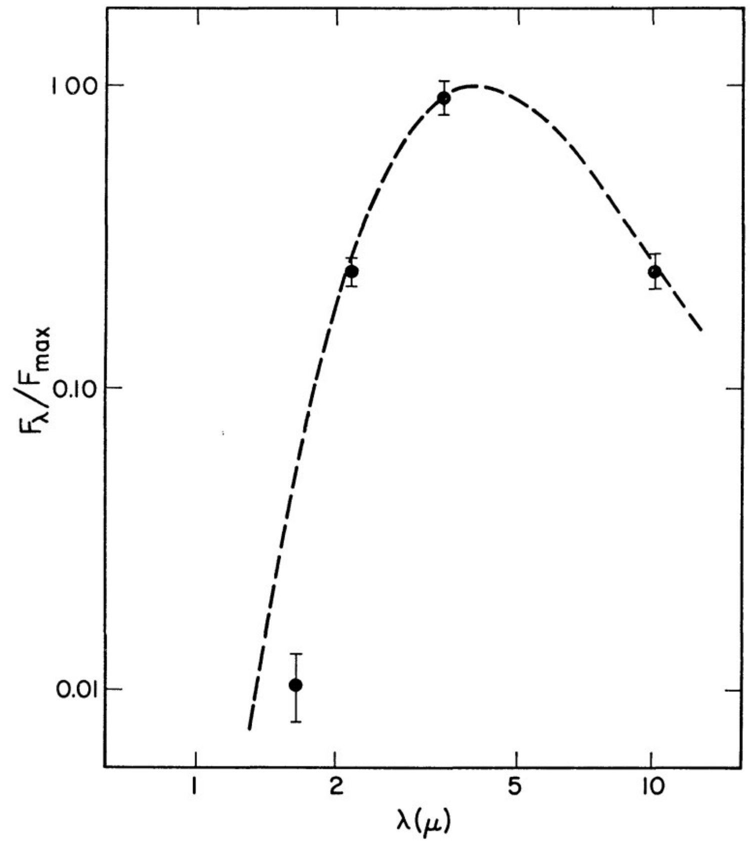
...G2 cloud appeared...approaching the Galactic center

Unusual appearance:
- source of broad emission lines
- effective temperature of ~600-800 K

- unusual SED in comparison with S stars:
Could it be a dust-enshrouded star?

Similar to SEDs of protostars
(e.g. Becklin-Neugebauer object)





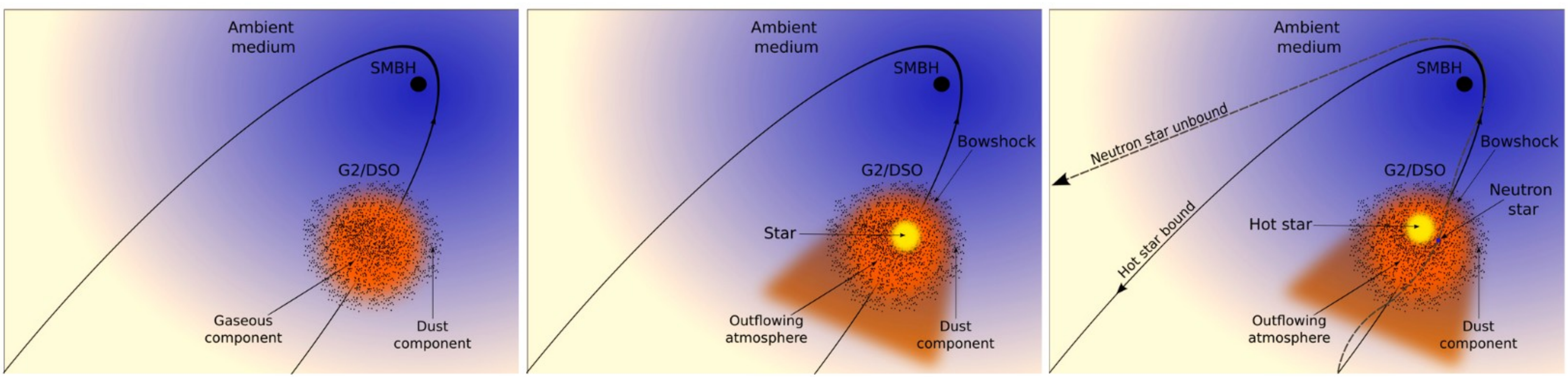
...G2 cloud appeared...approaching the Galactic center

- In Zajaček et al. (2014), we decided to compare **two scenarios**:

  core-less cloud vs. **dust-enshrouded star/binary**

- We also analyzed a binary with a common envelope as a plausible model

Michal Zajaček et al.: Dust-enshrouded star near supermassive black hole



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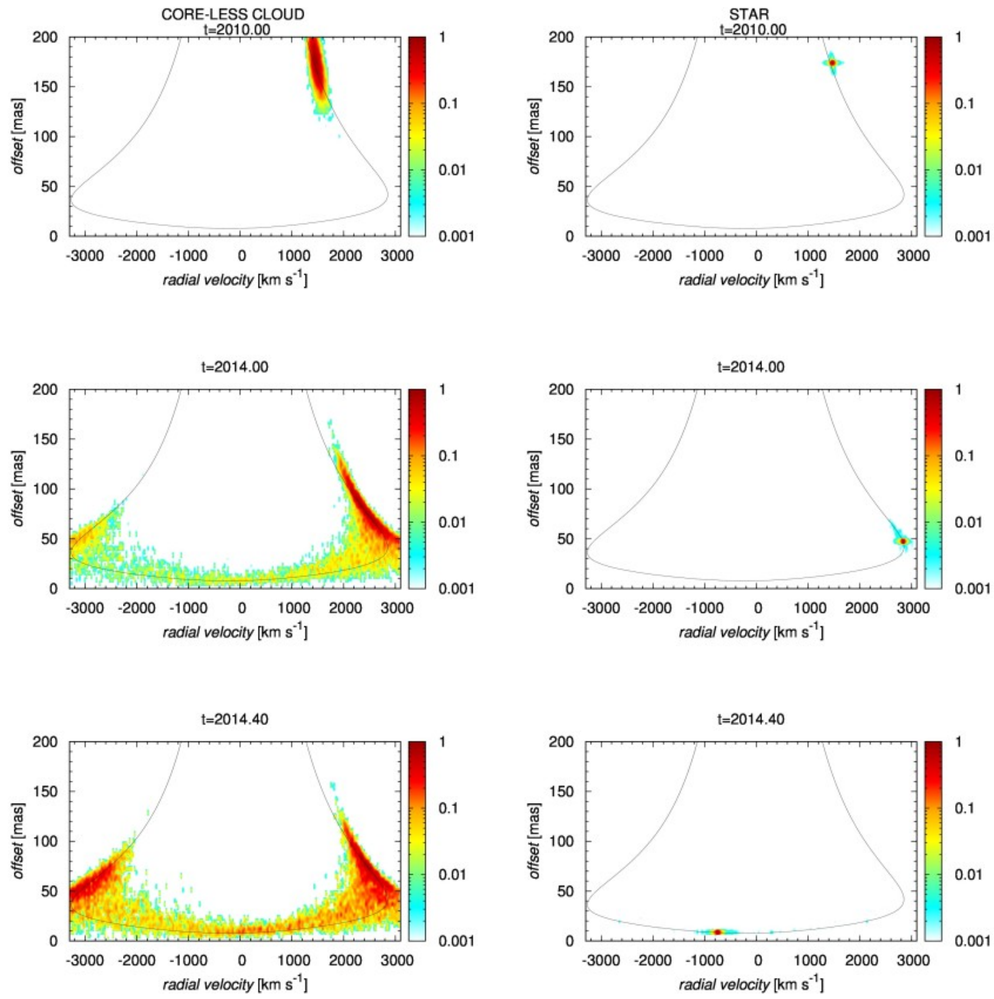
- In Zajaček et al. (2014), we decided to compare two scenarios:

core-less cloud vs. **dust-enshrouded star**



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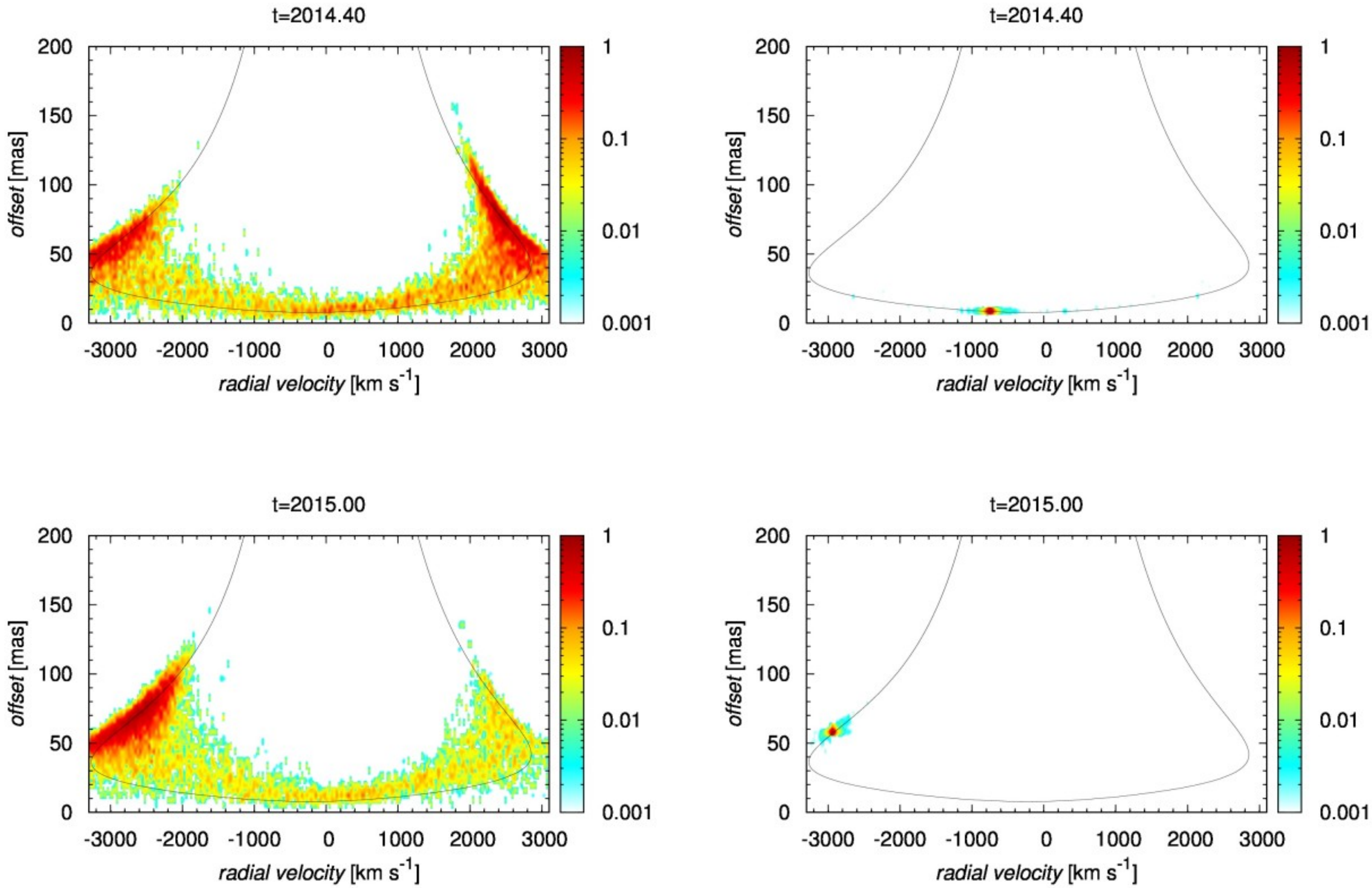
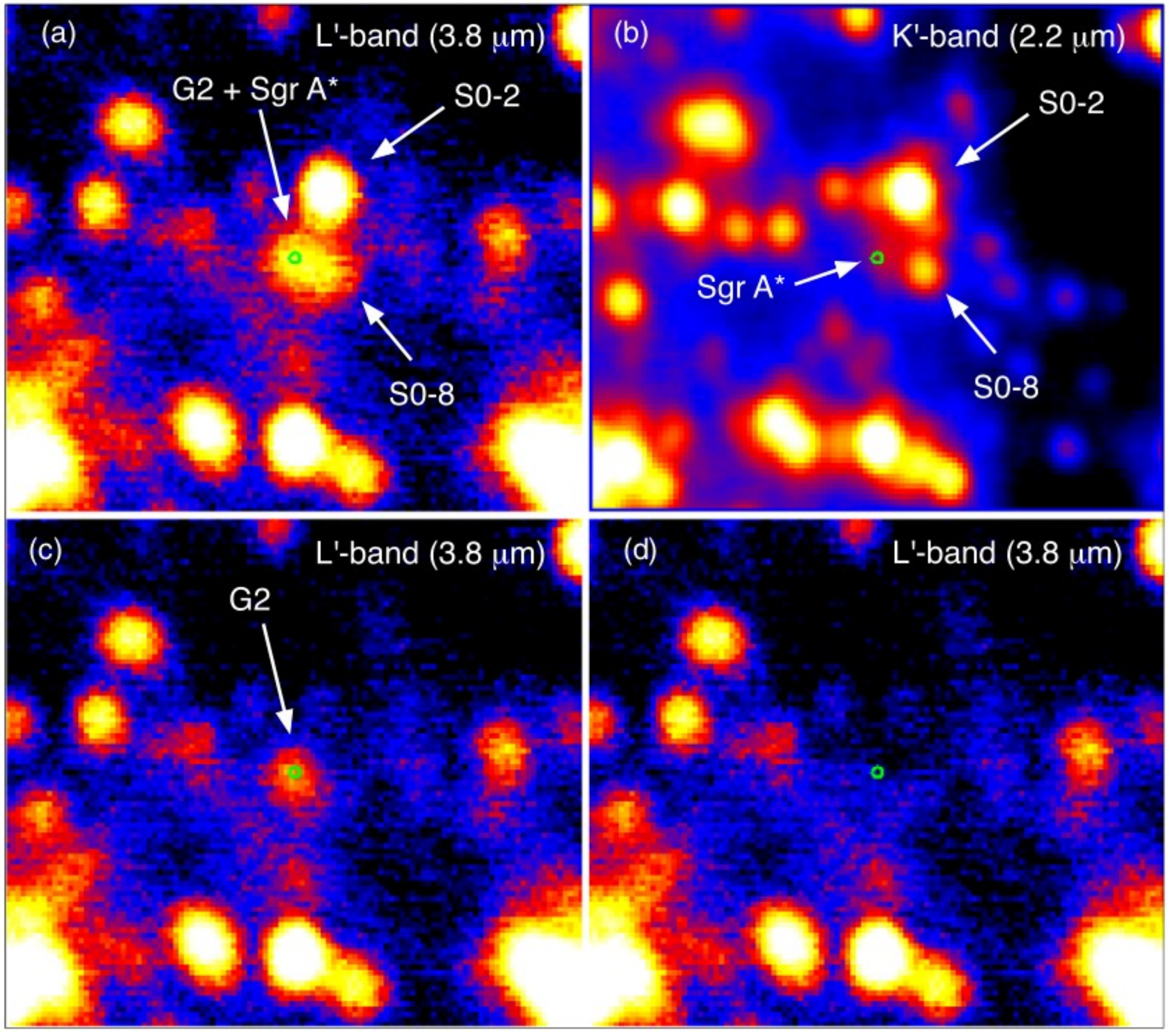


G2 as a dust-enshrouded star

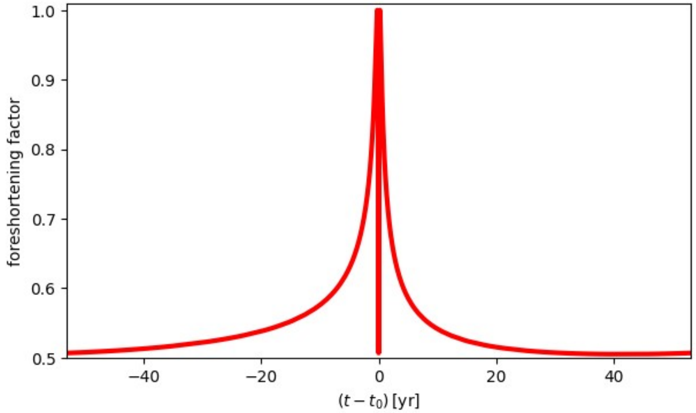
- Support for the dust-enshrouded star scenario:

G2 survived the pericenter passage in 2014



Witzel et al. 2014
-G2 as a compact *L*-band source during the periapse
- no significant change in *L*-band flux density

At the pericenter,
the foreshortening factor is 1,
hence we should see the "true" lengthscale of the source



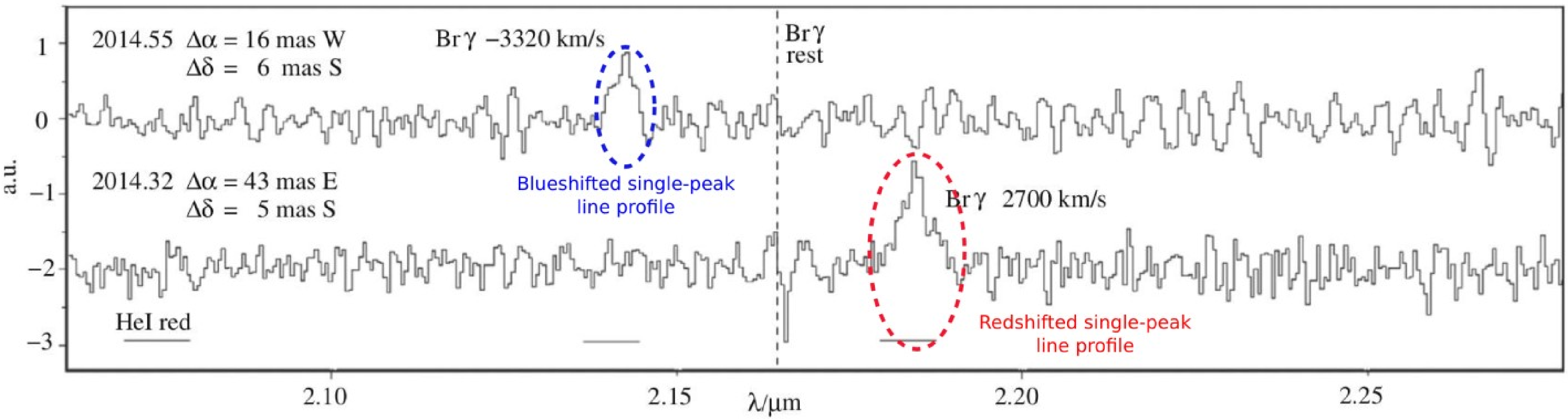
G2 as a dust-enshrouded star

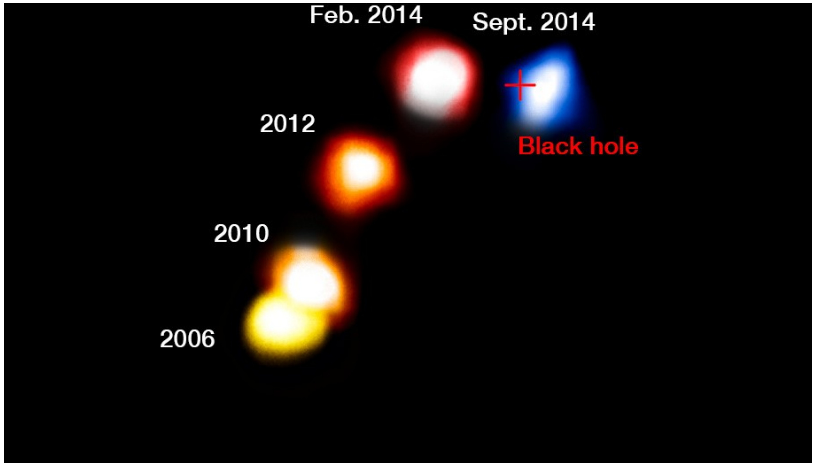
- Support for the dust-enshrouded star scenario:

G2 survived the pericenter passage in 2014

Valencia-S., Eckart, Zajaček et al. 2014

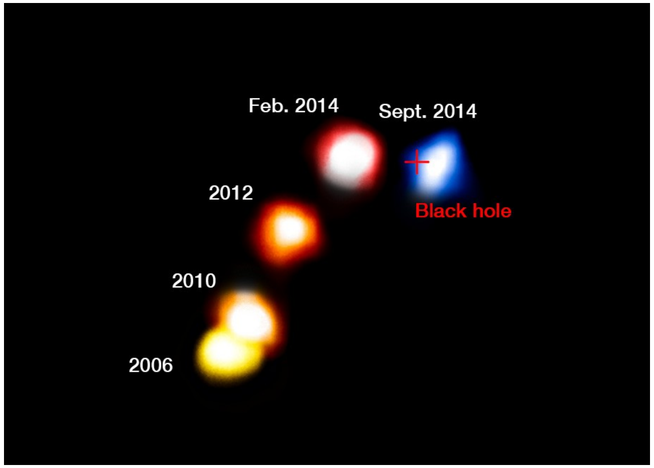
G2 as a compact Br-gamma line-emitting source – no signs of tidal prolongation

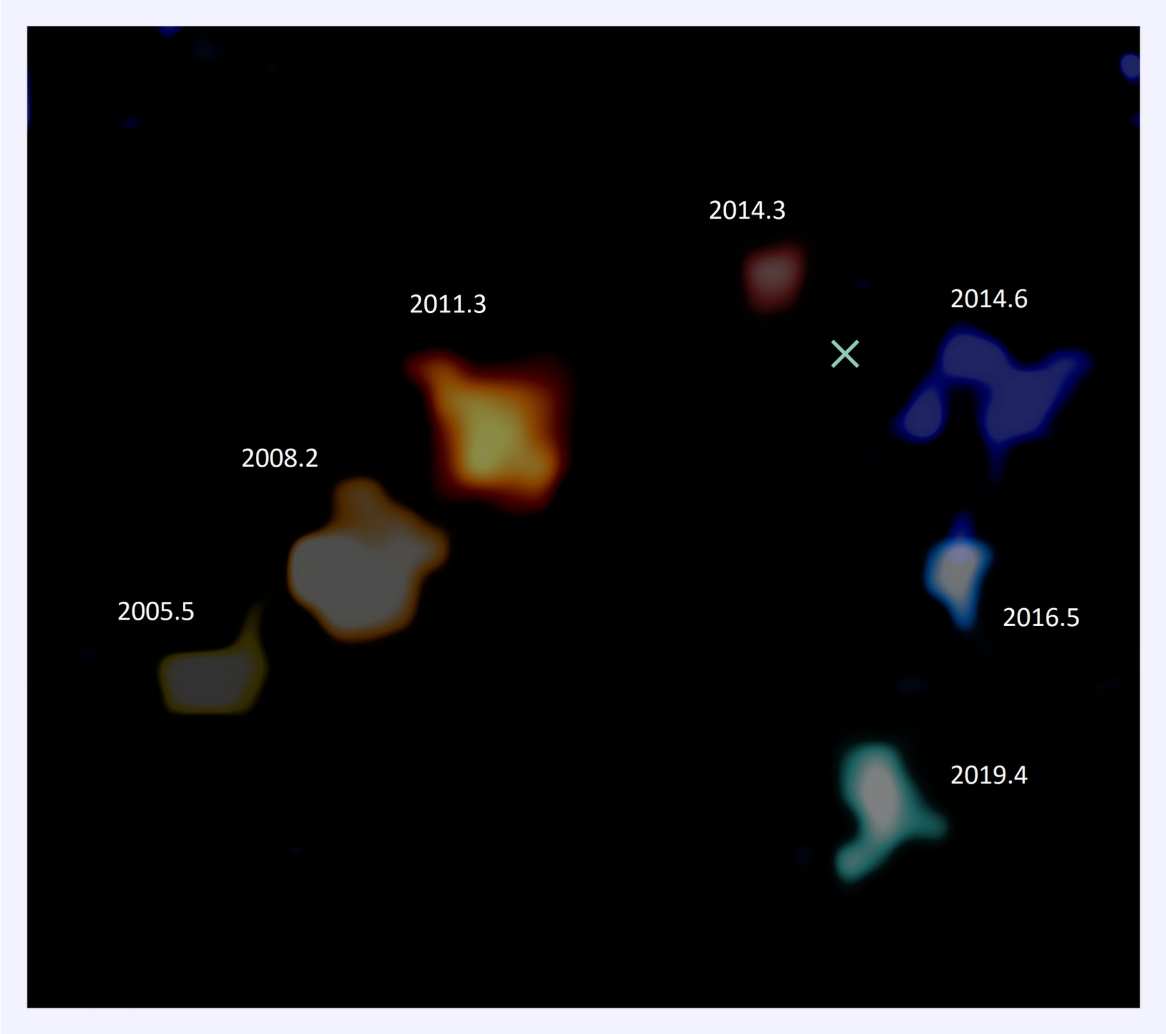




G2 as a dust-enshrouded star

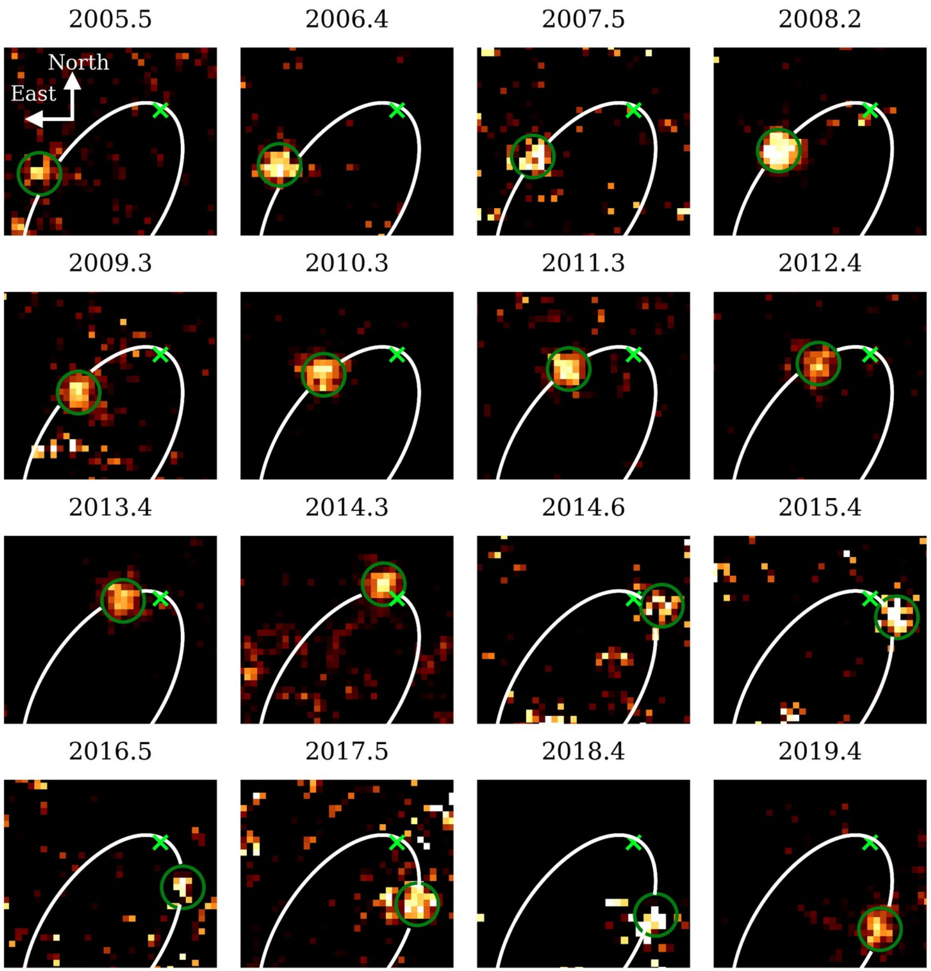
- Until now, the kinematics is consistent with a dust-enshrouded stellar object
- No significant deviation from the Keplerian orbit between 2005-2019
- No signs of evaporation or shredding by hydrodynamic instabilities/compact shape
- Br-gamma line emission evolution; see **Peissker et al. (2021)**





G2 as a dust-enshrouded star

- Until now, the kinematics is consistent with a dust-enshrouded object (self-gravitating)
- No signs of evaporation or shredding by hydrodynamic instabilities
- Br-gamma line emission evolution; see Peissker et al. (2021)



Orbital element	Best-fit value
a [mpc]	17.23 ± 0.20
e	0.963 ± 0.004
inclination [deg]	120.32 ± 2.40
Argument of pericenter [deg]	92.81 ± 1.60
Longitude of ascending node [deg]	63.02 ± 1.37
Closest approach [yr]	2014.43 ± 0.01

P~106 years

q~131.5 AU

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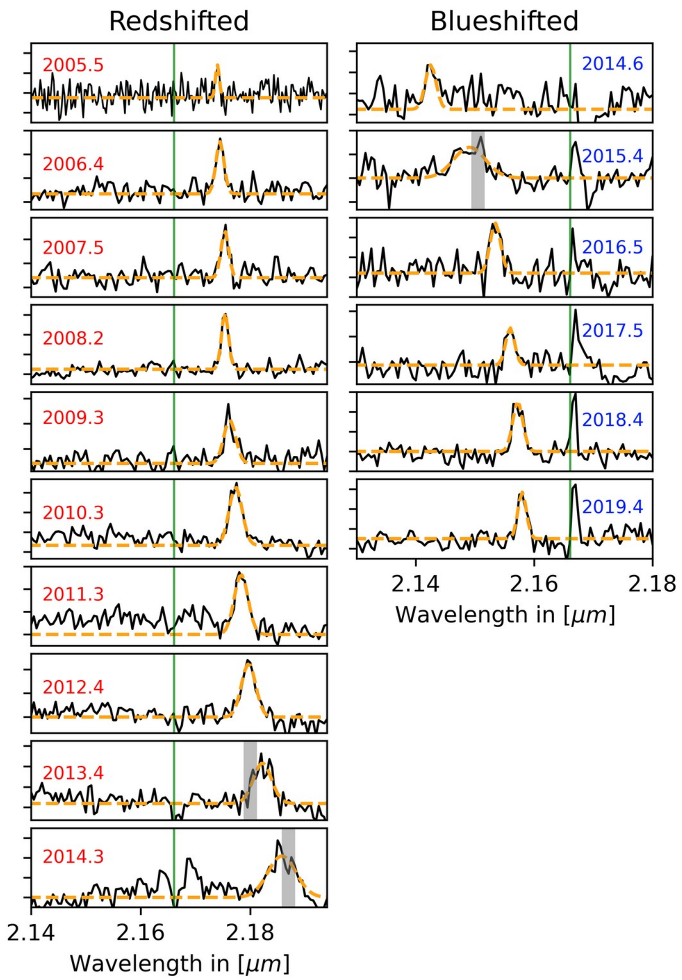

G2 orbit around the Galactic center

- Gas cloud should start deviating from the initial Keplerian orbit (?)

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https://doi.org/10.3847/1538-4357/aaf4f8

CrossMark

Detection of a Drag Force in G2's Orbit: Measuring the Density of the Accretion Flow onto Sgr A* at 1000 Schwarzschild Radii

S. Gillessen[1], P. M. Plewa[1], F. Widmann[1], S. von Fellenberg[1], M. Schartmann[1,2], M. Habibi[1], A. Jimenez Rosales[1], M. Bauböck[1], J. Dexter[1], F. Gao[1], I. Waisberg[1], F. Eisenhauer[1], O. Pfuhl[1], T. Ott[1], A. Burkert[1,2], P. T. de Zeeuw[1,3], and R. Genzel[1,4]

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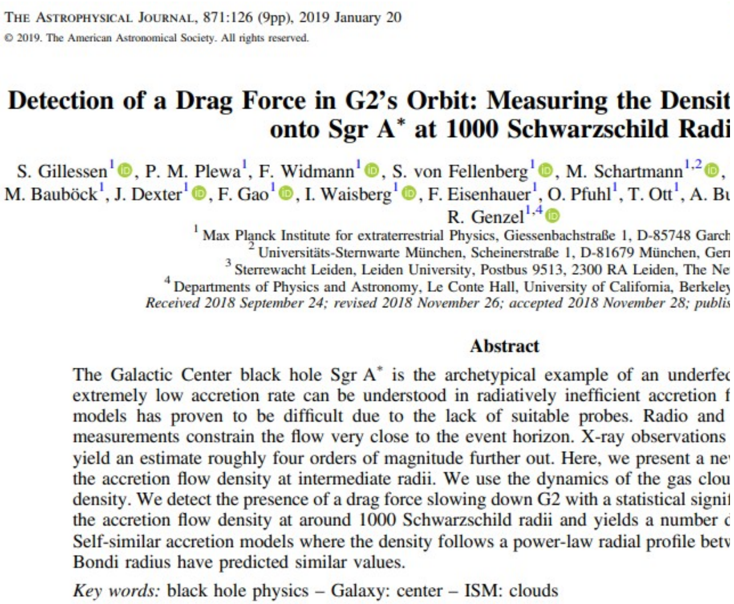
Abstract

The Galactic Center black hole Sgr A* is the archetypical example of an underfed massive black hole. The extremely low accretion rate can be understood in radiatively inefficient accretion flow models. Testing those models has proven to be difficult due to the lack of suitable probes. Radio and submillimeter polarization measurements constrain the flow very close to the event horizon. X-ray observations resolving the Bondi radius yield an estimate roughly four orders of magnitude further out. Here, we present a new, indirect measurement of the accretion flow density at intermediate radii. We use the dynamics of the gas cloud G2 to probe the ambient density. We detect the presence of a drag force slowing down G2 with a statistical significance of $\approx 9\sigma$. This probes the accretion flow density at around 1000 Schwarzschild radii and yields a number density of $\approx 4 \times 10^3$ cm^{-3}. Self-similar accretion models where the density follows a power-law radial profile between the inner zone and the Bondi radius have predicted similar values.

Key words: black hole physics – Galaxy: center – ISM: clouds

G2 orbit around the Galactic center

- In Zajaček et al. (2014) we suggest the deviation from the Keplerian due to the three-body dynamics



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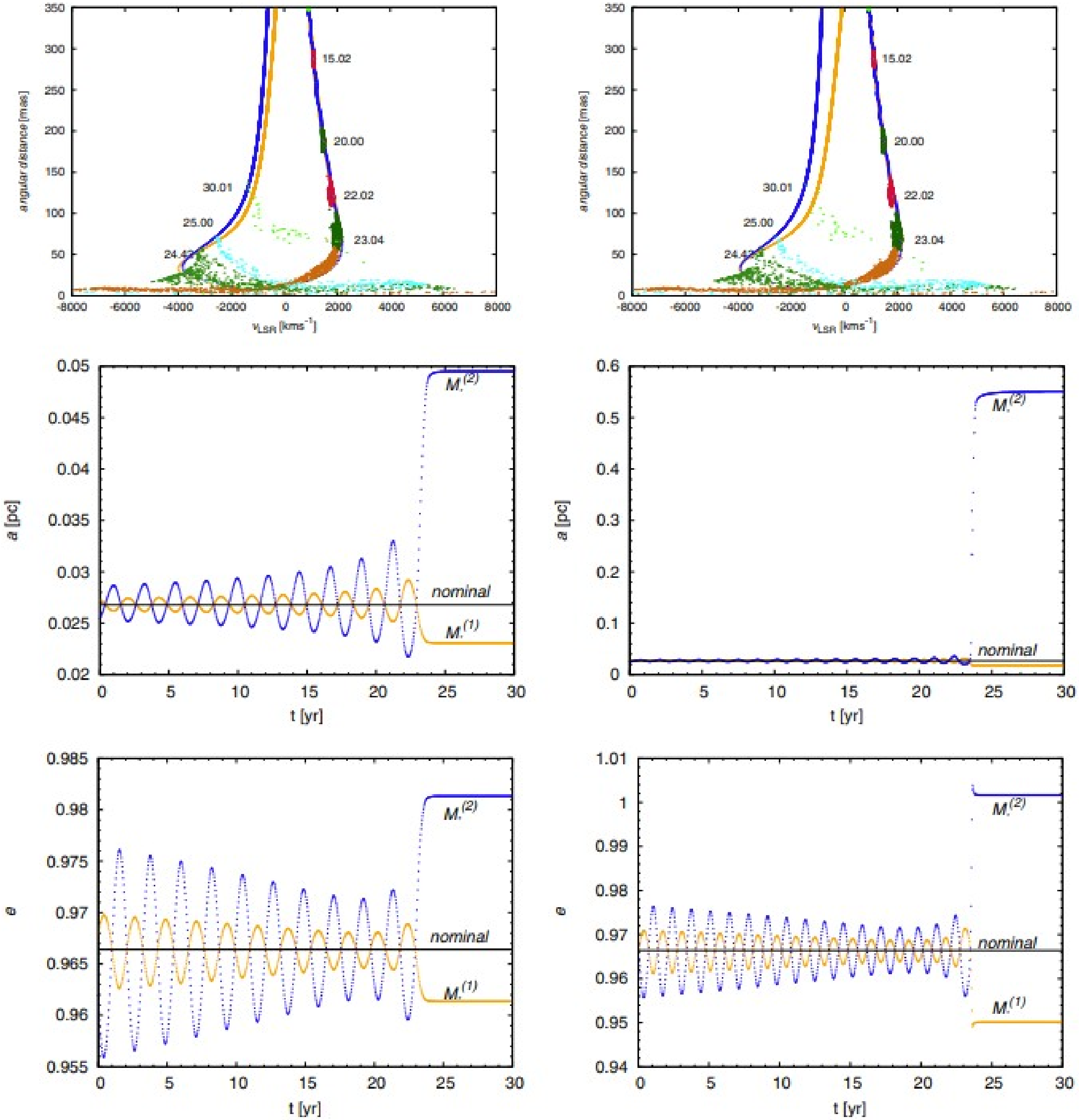
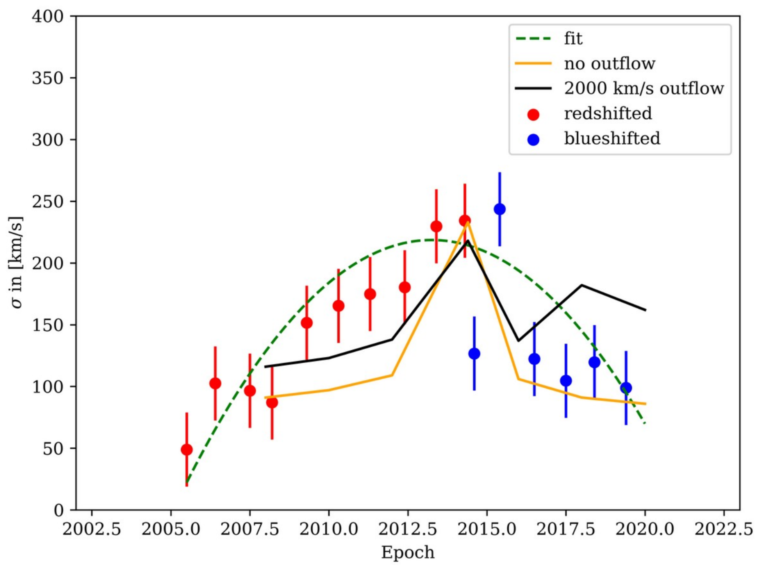
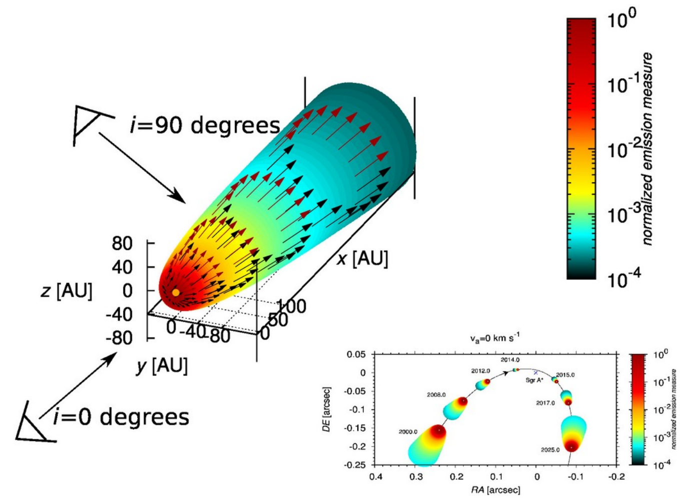
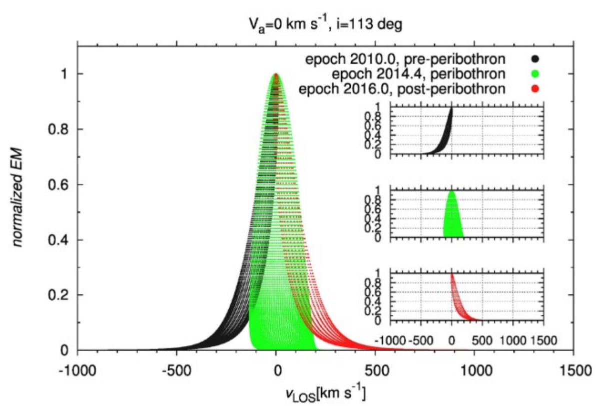


G2 as a dust-enshrouded star

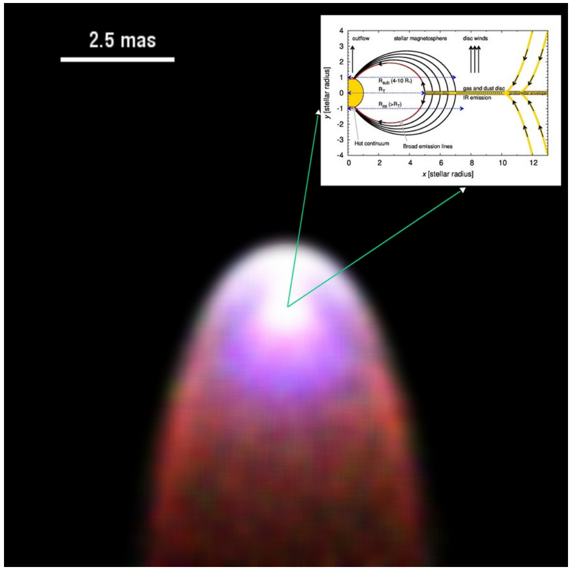
- Until now, the kinematics is consistent with a dust-enshrouded stellar object
- Br-gamma line width increases up to the pericenter, then decreases; see **Peissker et al. (2021)**
- Consistent with the Br-gamma line being associated with the bow shock (**Zajaček et al. 2016**)





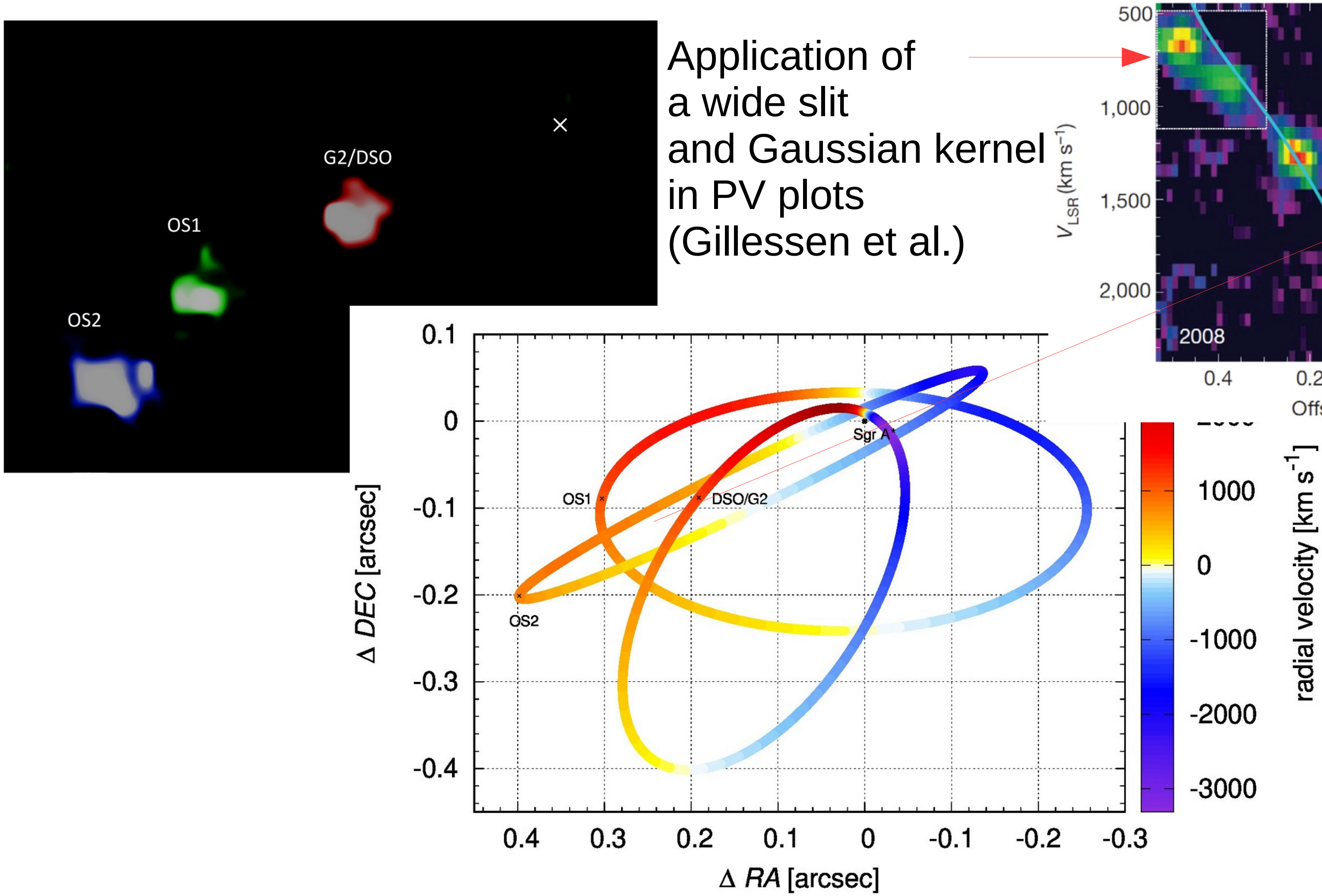


Outflow velocity	Velocity span at EM = 0.5						
	2008.0	2010.0	2012.0	**2014.4**	2016.0	2018.0	2020.0
(km s^{-1})	(km s^{-1})	(km s^{-1})	(km s^{-1})	(km s^{-1})	(km s^{-1})	(km s^{-1})	(km s^{-1})
0	91	97	109	**233**	106	91	86
2000	116	123	138	**218**	137	182	162

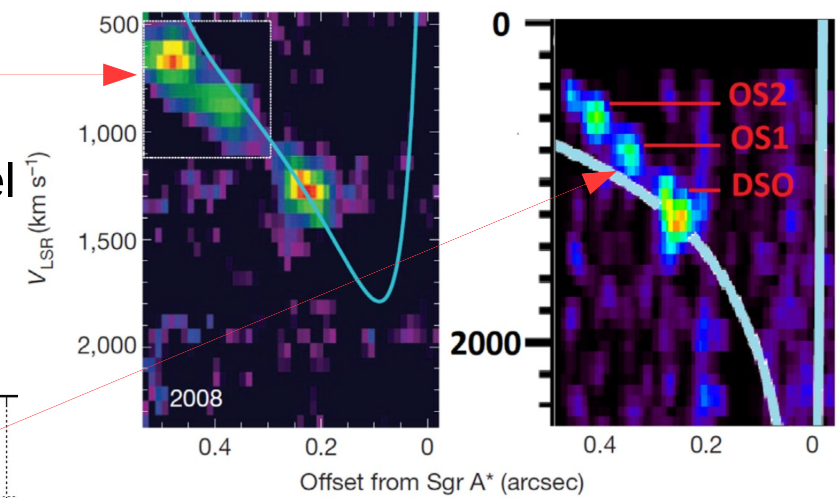


G2 as a dust-enshrouded star

- Other sources – **OS1 and OS2** - moving independently in the field of view of G2/DSO
- At certain epochs before the pericenter (~2008), OS1 and OS2 were redshifted and contributed to an apparent "tail" feature in position-velocity plots

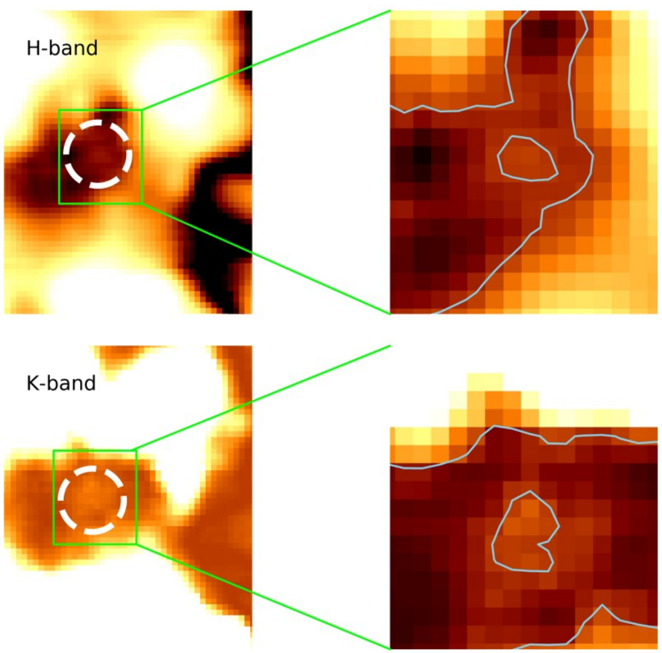


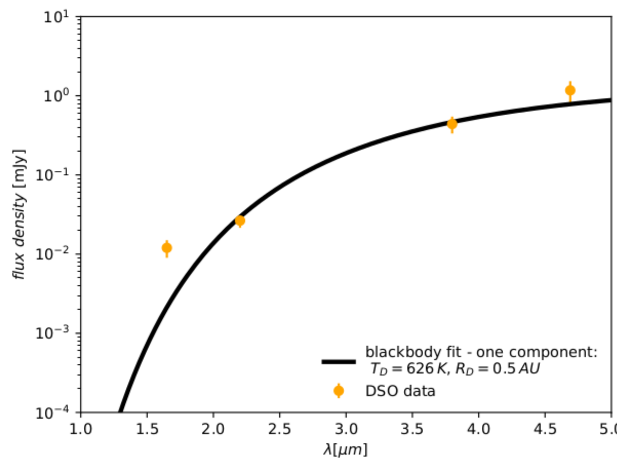
Application of
a wide slit
and Gaussian kernel
in PV plots
(Gillessen et al.)

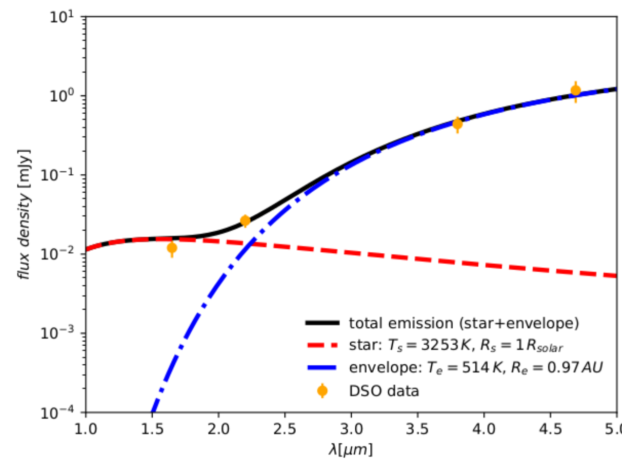


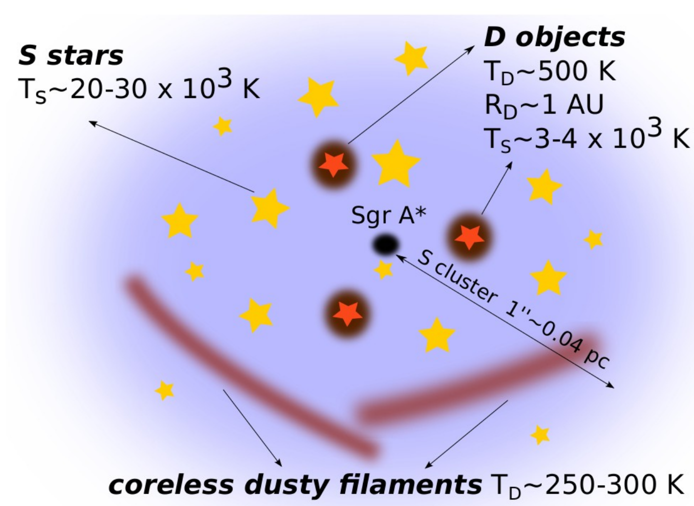
G2 as a dust-enshrouded star

- DSO detected in stacked *K*- as well as *H*-band images, see **Peissker et al., 2020**
- SED fitted better with a **two-component SED** (with a star)

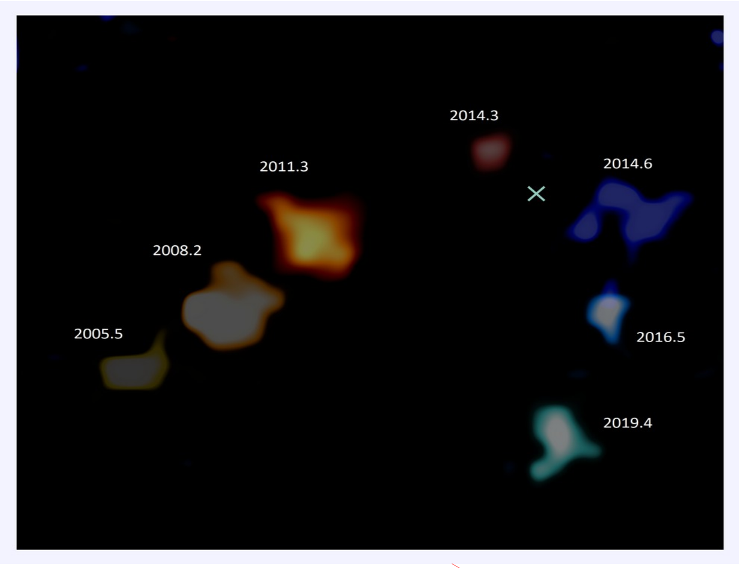




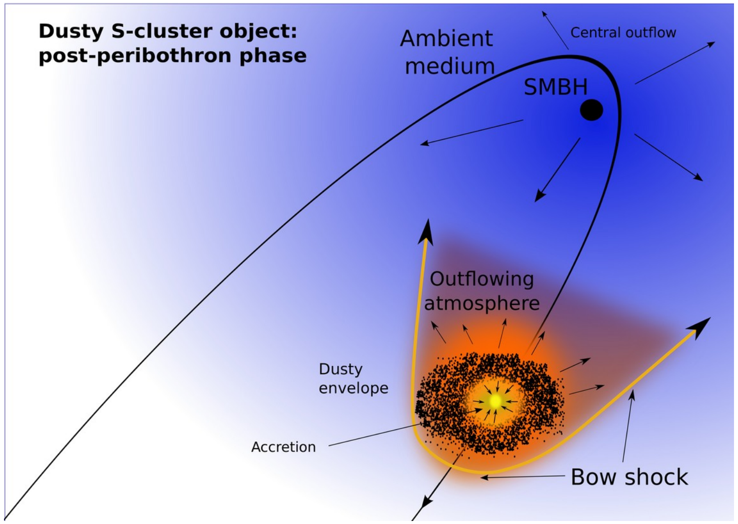




Interpretation as a dust-enshrouded star



Young stellar objects



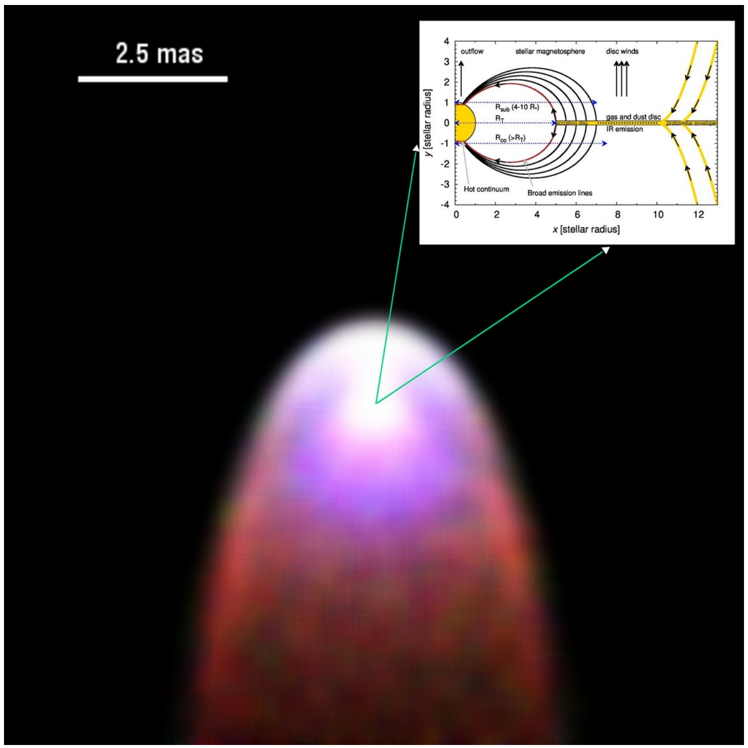
Common features
- dense, optically thick dusty envelope
- emission lines
- bow shock

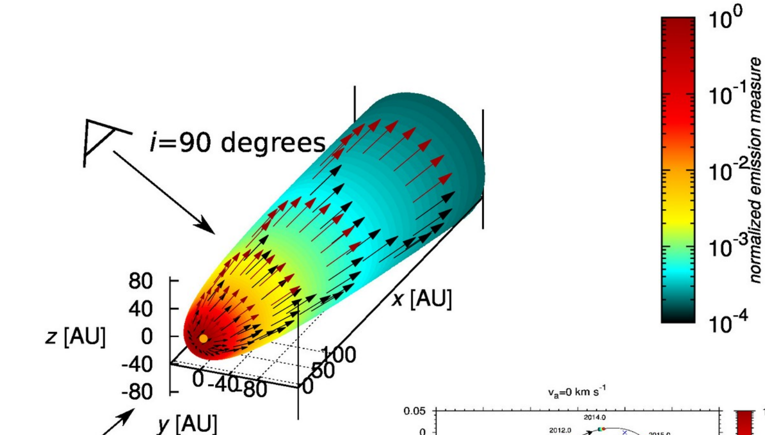
Binary mergers (see Anna Ciurlo's talk)

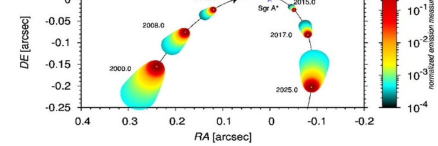
Differences
- different production rates

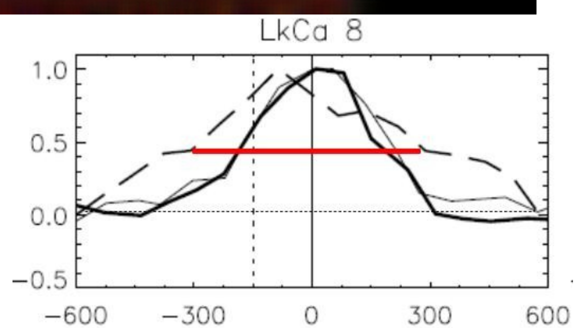
G2 as a dust-enshrouded star

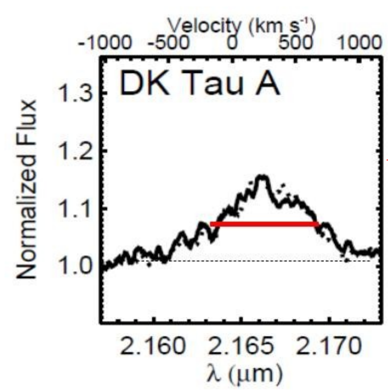
Br-gamma line could partially originate in the **bow shock** or in the **magnetospheric accretion flow** (see also **Zajaček et al. 2017** for the dust-enshrouded star model)







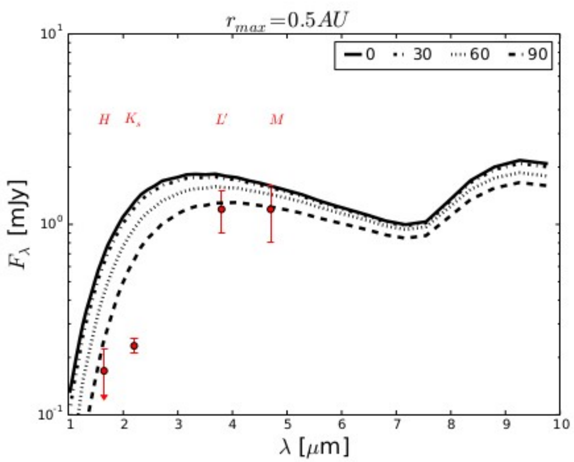


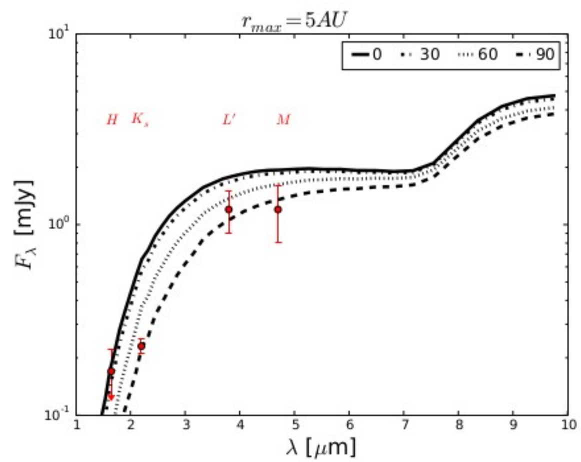


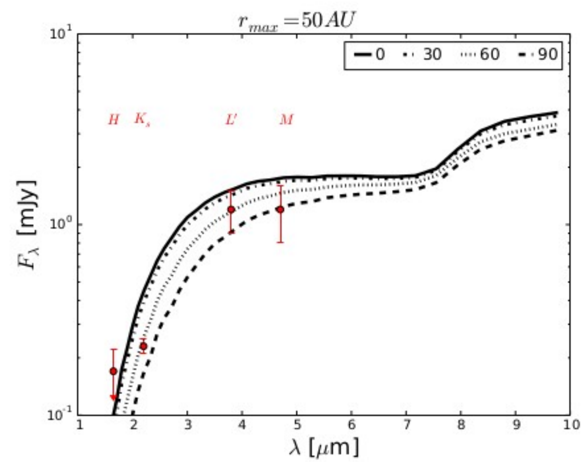
Broad Br-gamma emission line for nearby YSOs

Interpretation as a dust-enshrouded star

- 3D MCMC radiative-transfer model (Zajaček et al., 2017) including dust reprocessing of the emission of the central can reproduce well the NIR and the MIR properties of the G2 source
- broad-band NIR continuum is consistent with the SED of a young, accreting star with the envelope of 5 AU and the accretion rate of 10^{-7} M_{sun}/year



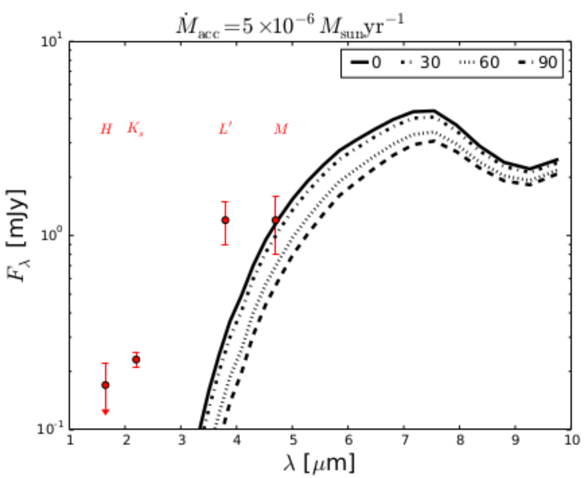


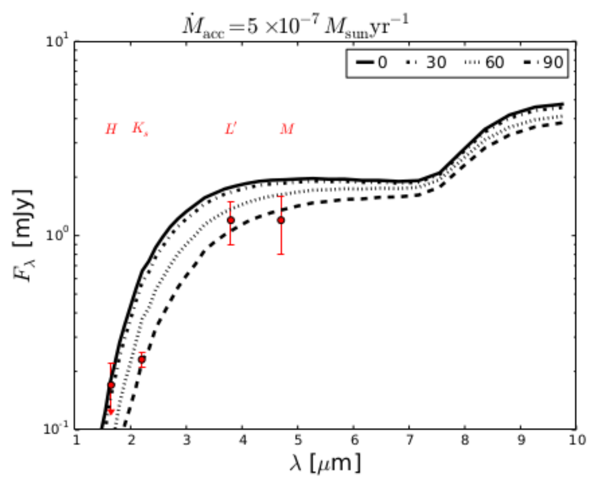


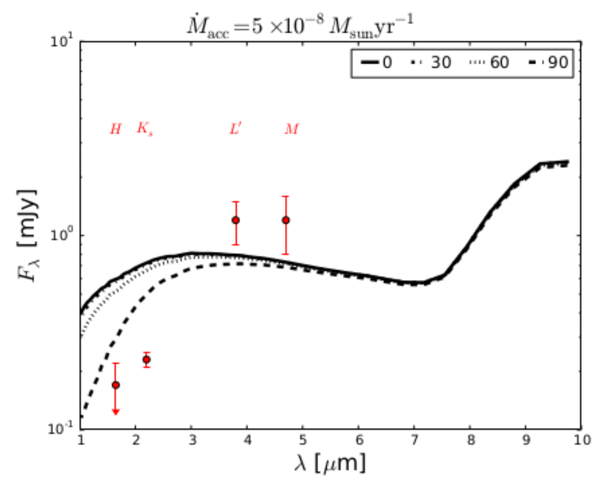
Increase in envelope size

Decrease in accretion rate

Model of young, accreting star (flattened *Ulrich* envelope)

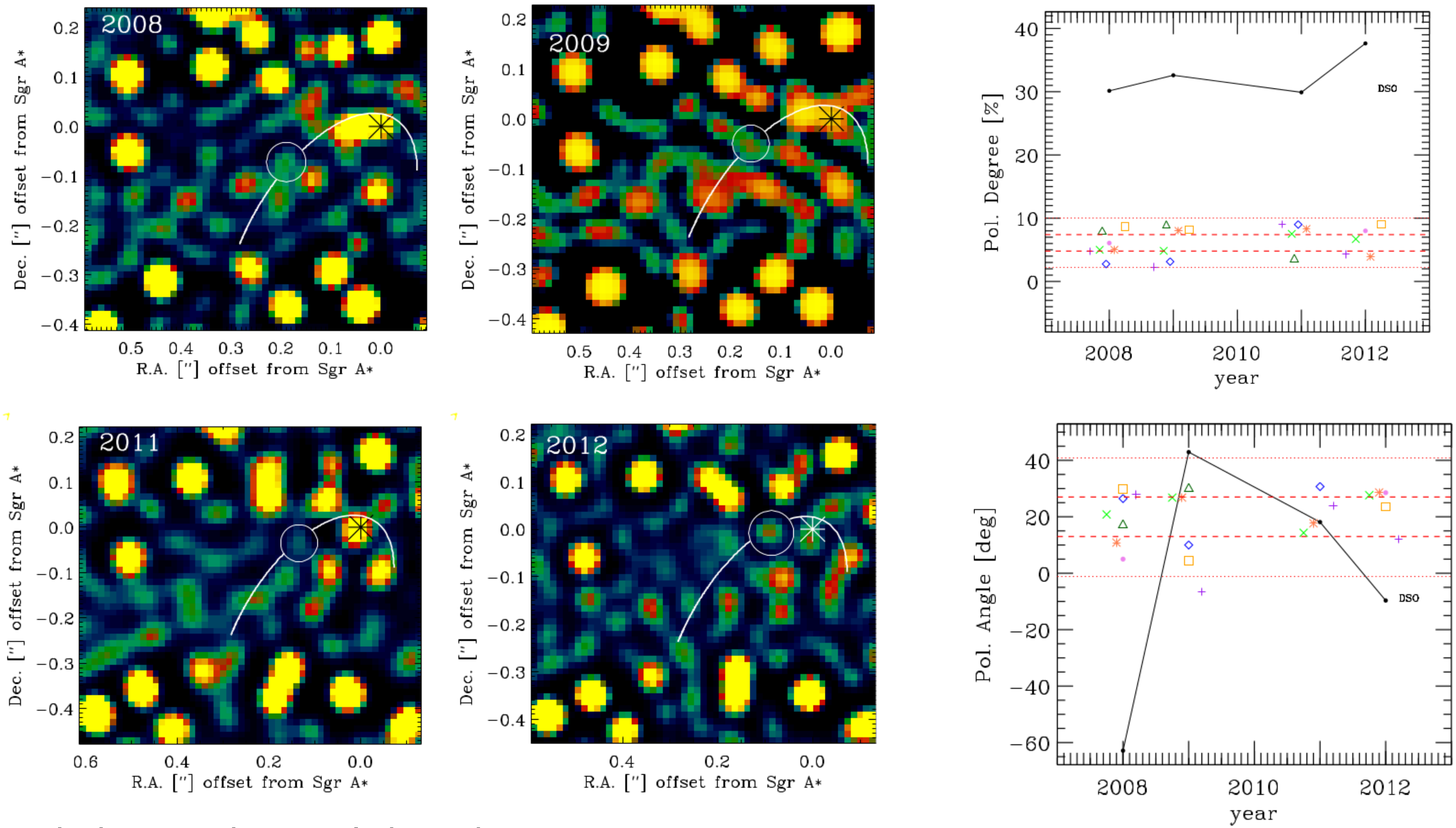






Interpretation as a dust-enshrouded star

- Polarized *K*-band emission detected by **Shahzamanian et al. (2016)** can be reproduced as well using the bow-shock dusty component/non-spherical dusty components



Shahzamanian et al. (2016)

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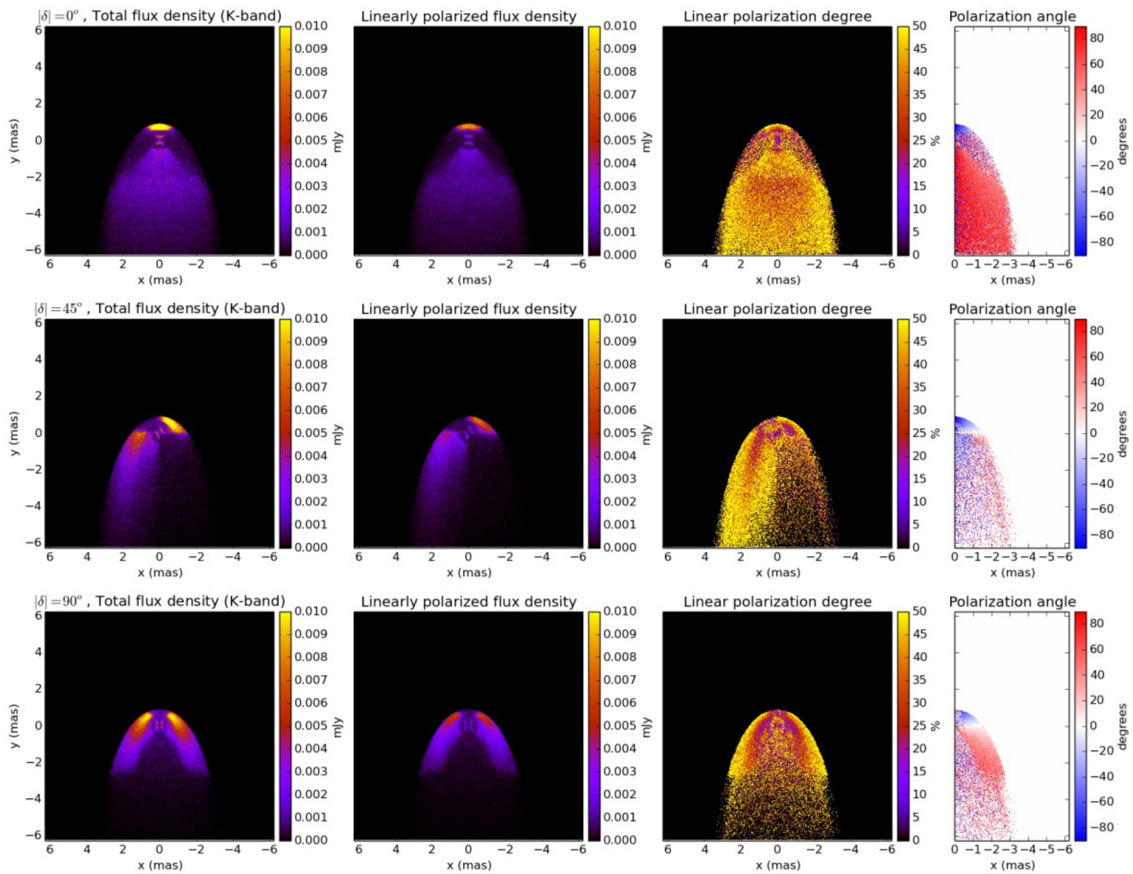
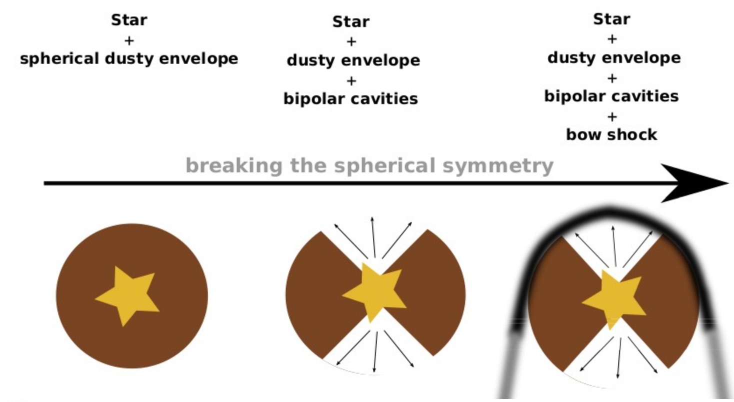
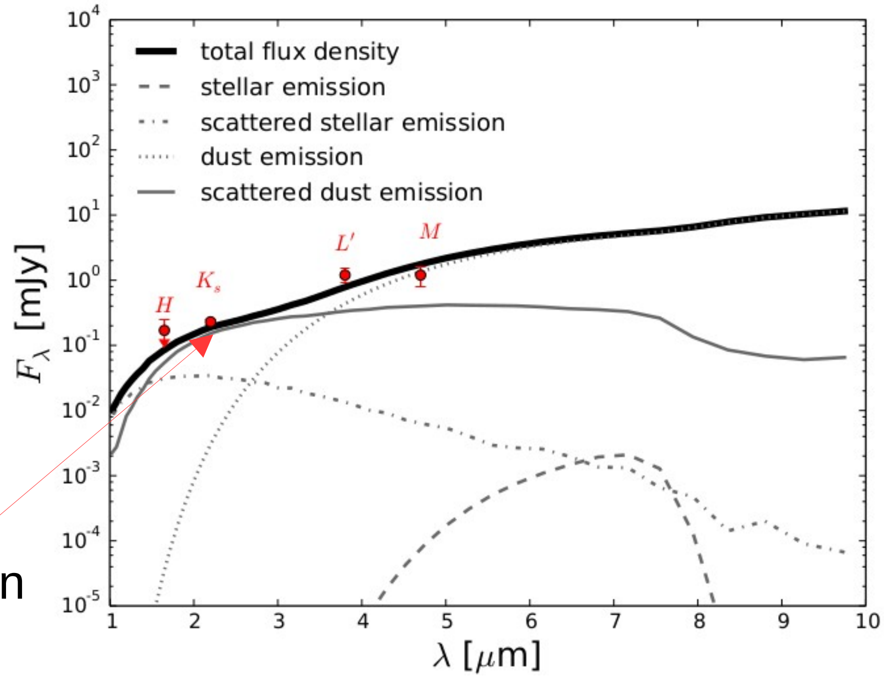


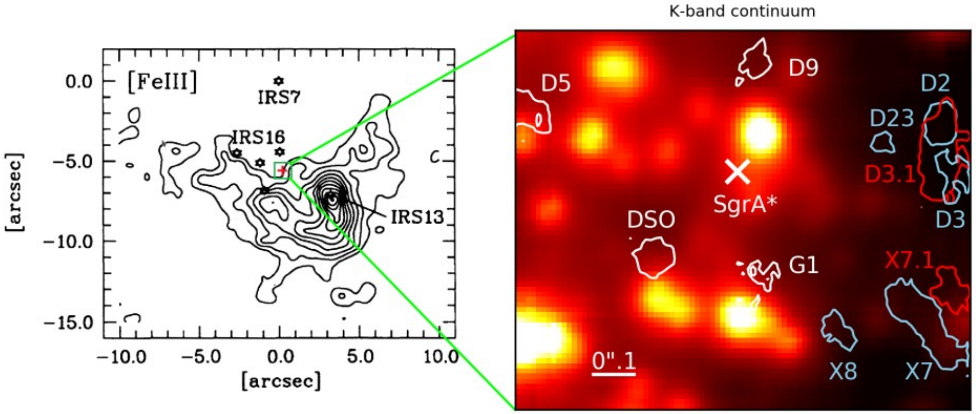




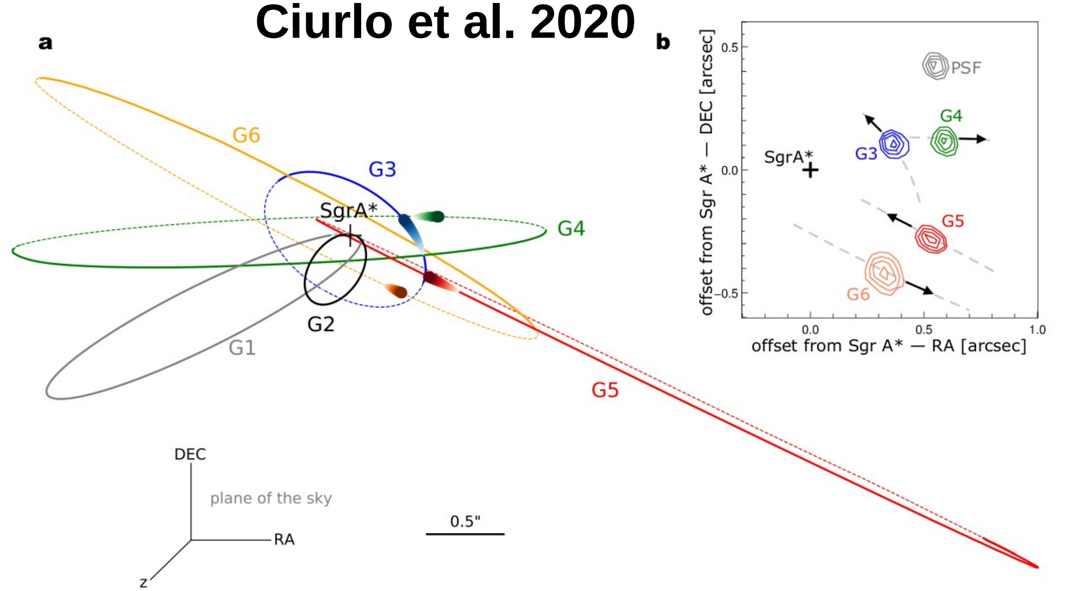
scattered dust emission dominates in K_s band

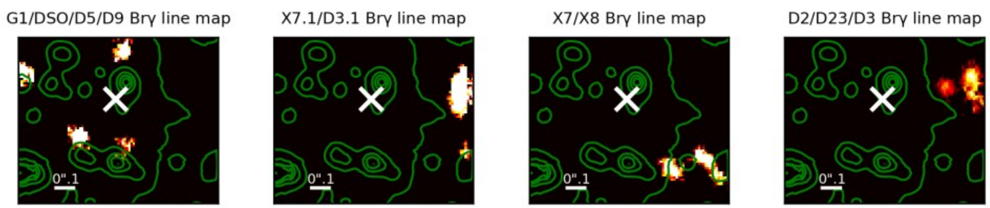
Zajaček et al. (2017)

More line-emission dusty sources in GC



Ciurlo et al. 2020



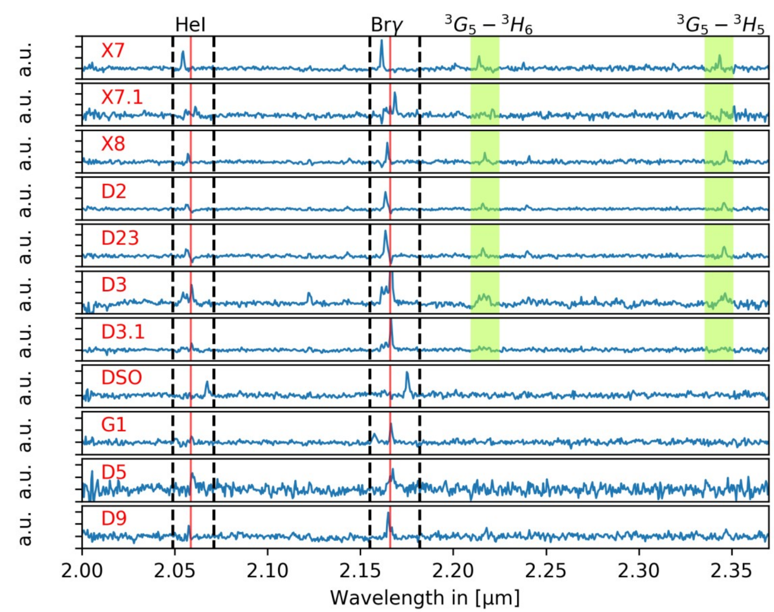


Continuum

Line map

Peissker et al. 2020

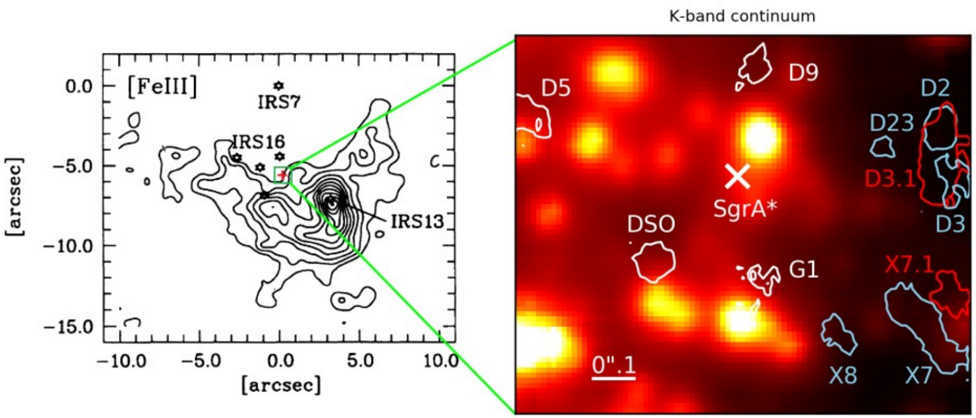
Near-infrared spectrum



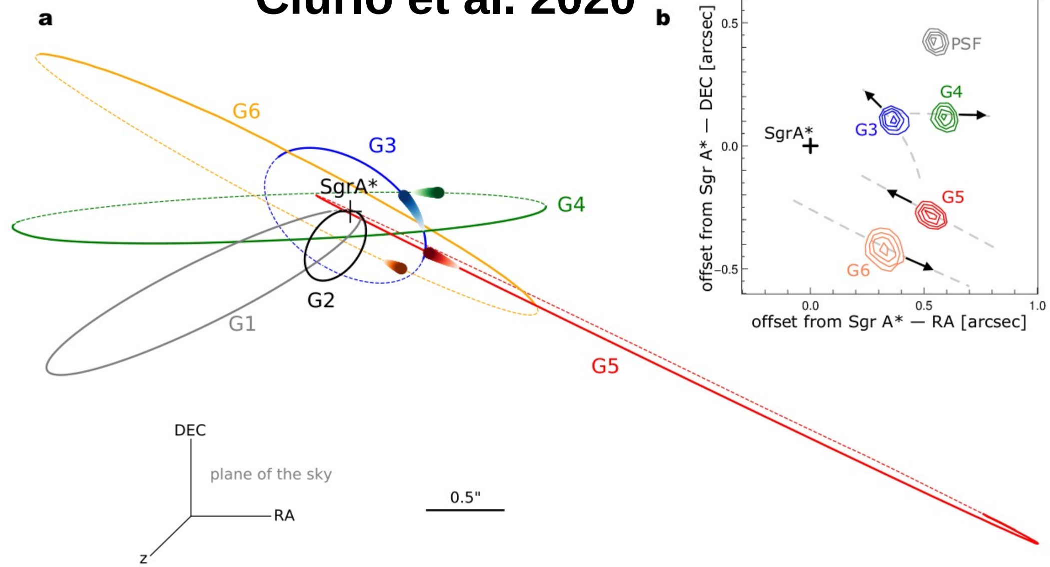
[FeIII] emission sources

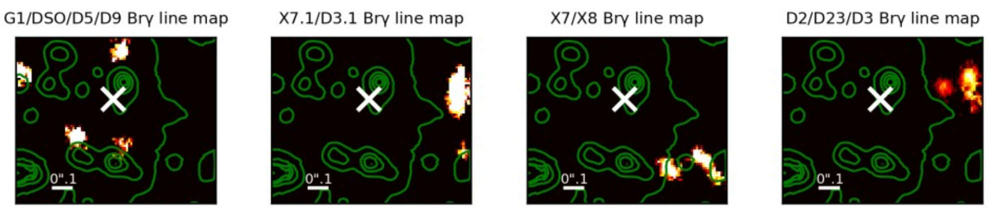
Source with no *[FeIII]* emission

More line-emission dusty sources in GC



Ciurlo et al. 2020



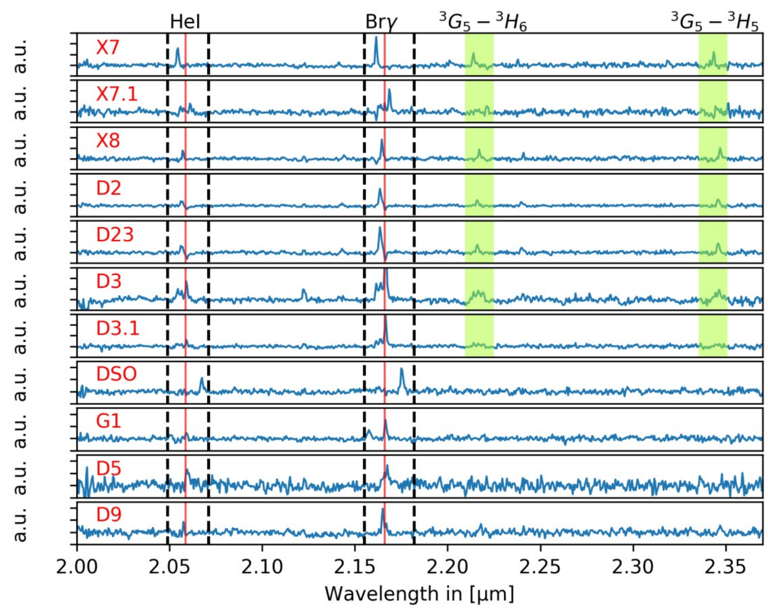


About other G objects, see **Anna Ciurlo's talk**
About G1, see **Maria Melamed's talk**

Continuum
Line map

Peissker et al. 2020

Near-infrared spectrum



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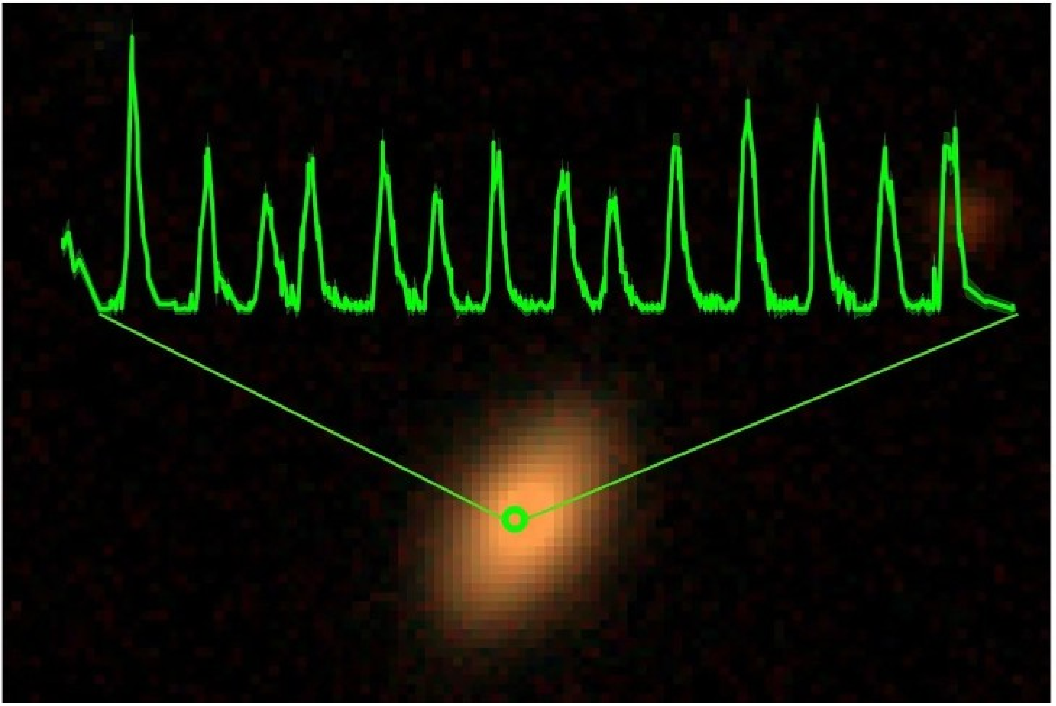
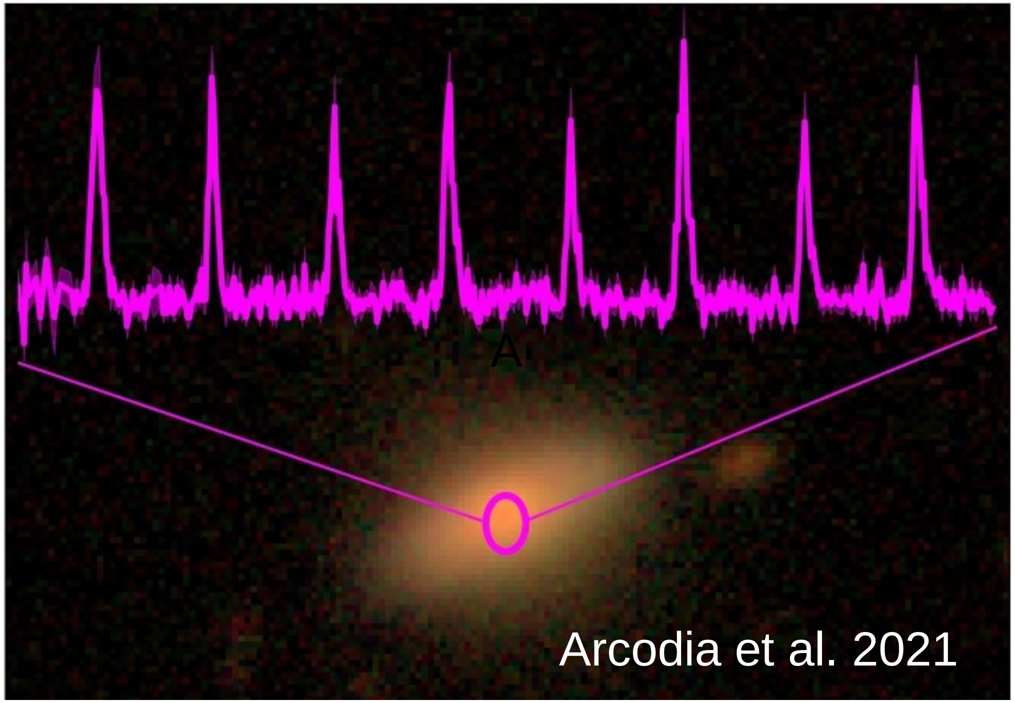
Source with no *[FeIII]* emission

What about other nuclei?

X-ray quasiperiodic eruptions (QPEs) – soft X-ray bursts repeating every few hours





Candidate sources
GSN 069: 9 hours
RX J1301.9+2747: 3.6 and 5.6 hours
eRO-QPE1 18.5 hours
eRO-QPE2   2.4 hours
<u>Swift J0230 ~20 days</u>

Models involving an orbiting star
Krolik & Linial 2022
Suková et al. 2021
Metzger, Stone, and Gilbaum 2022 – interacting EMRI
Linial & Metzger 2023
King, A. 2022

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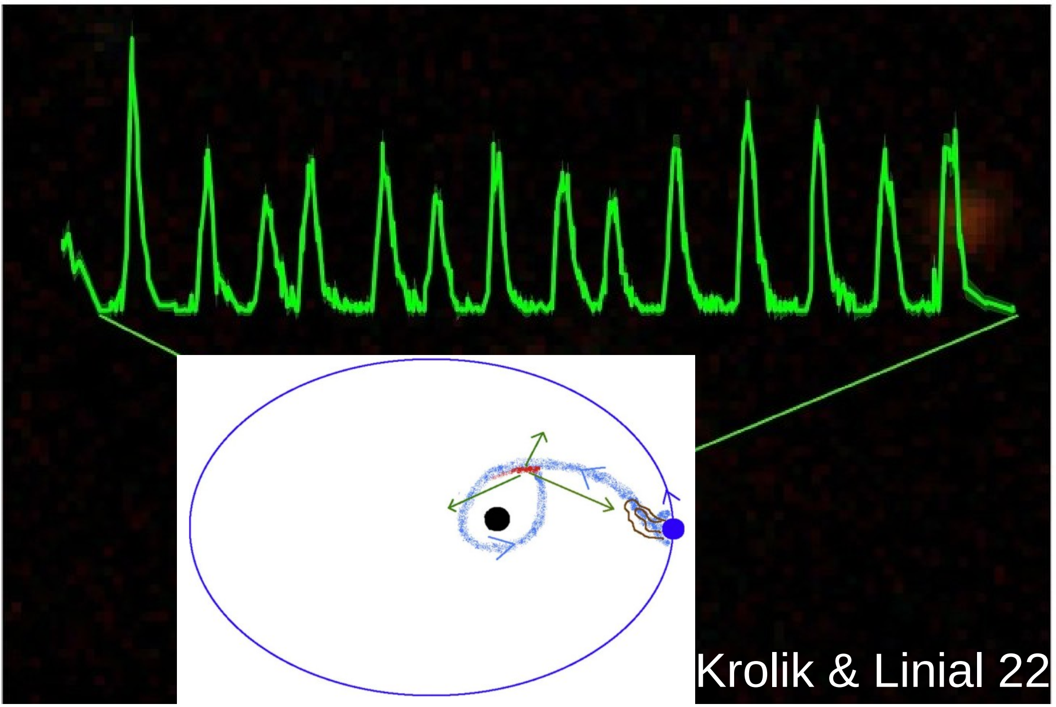

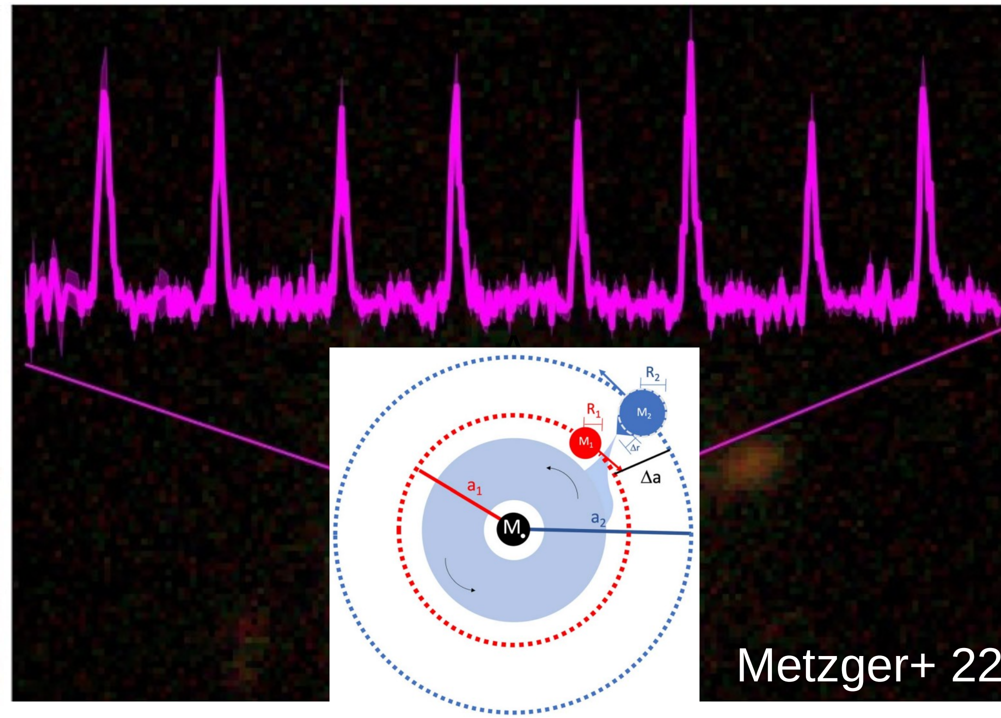

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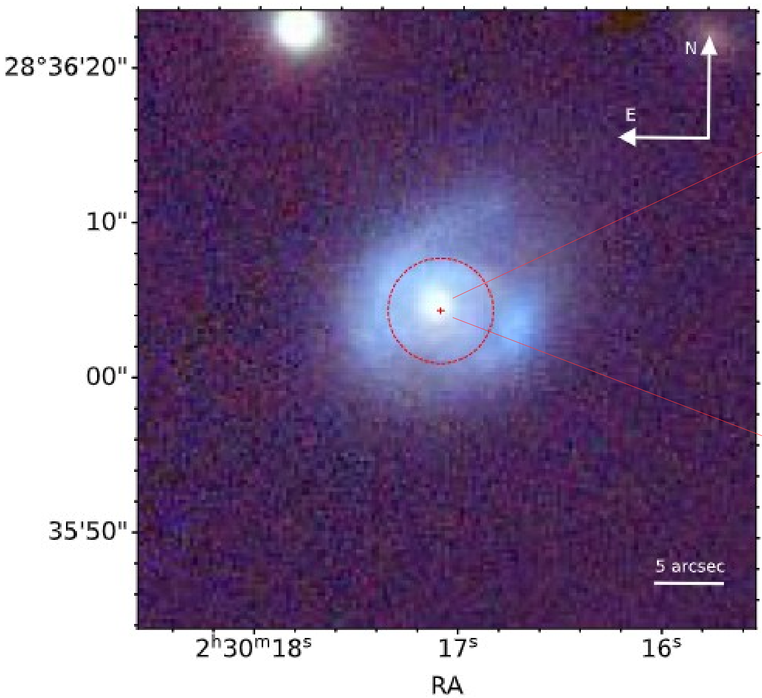
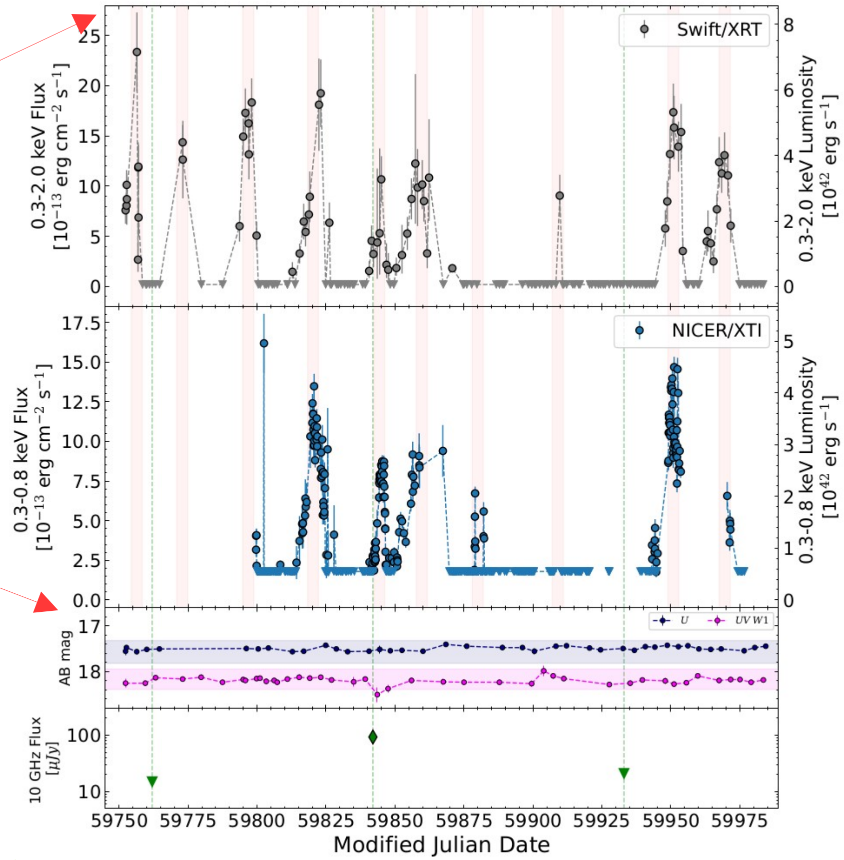
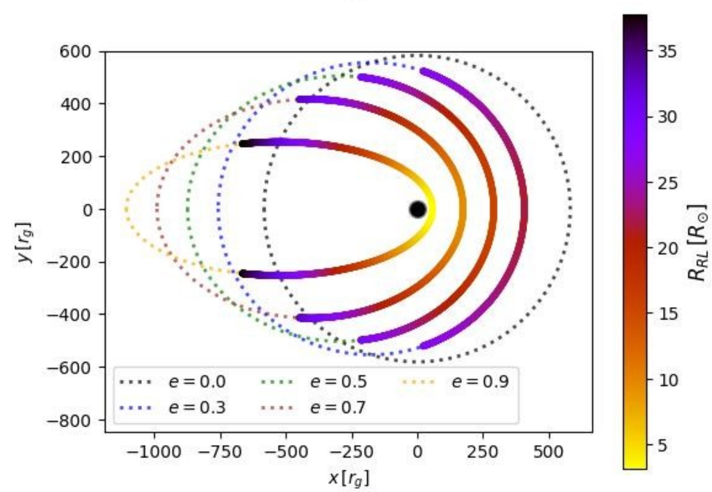
What about other nuclei?

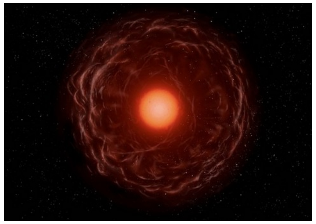
Swift source J0230+28 – the first candidate for hosting a big star of 30 Solar radii orbiting the SMBH at ~500 r_g







Star of about 30 Solar radii~0.1 AU

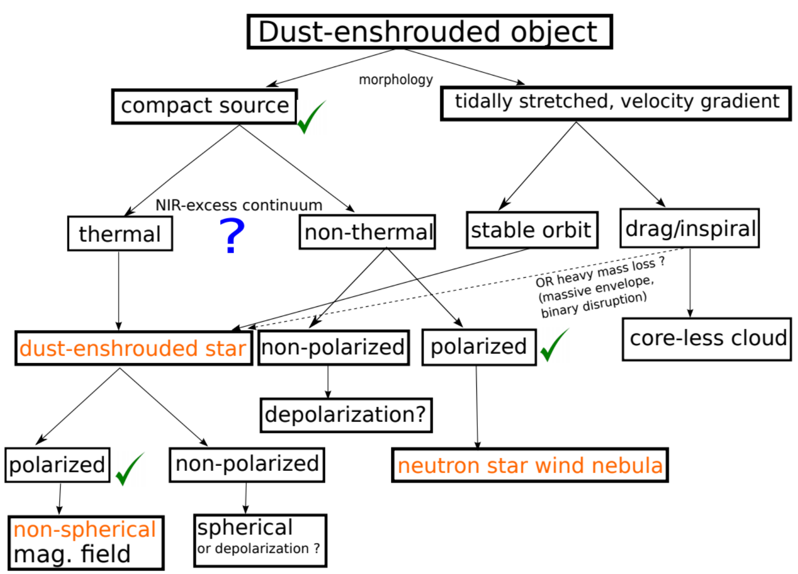


Guolo, Pasham, Zajaček et al., Nature Astronomy, 2024

Summary

- The evolution of the G2 source is consistent with the **stellar model** in the years 2005.5 – 2019.4
- **No significant changes of the orbital elements**
- Br-gamma emission: stable, no signs of significant tidal stretching or gradual evaporation
- Br-gamma line gets mildly wider towards the pericenter and gets narrower after → consistent with the changing viewing angle of the bow shock
- Polarization in Ks-band implies non-spherical envelope (bow shock, cavities)
- Improving prospects of detecting signatures of other stars, including G2-like objects, in **extragalactic systems (QPEs, QPOs, QPOuts)**

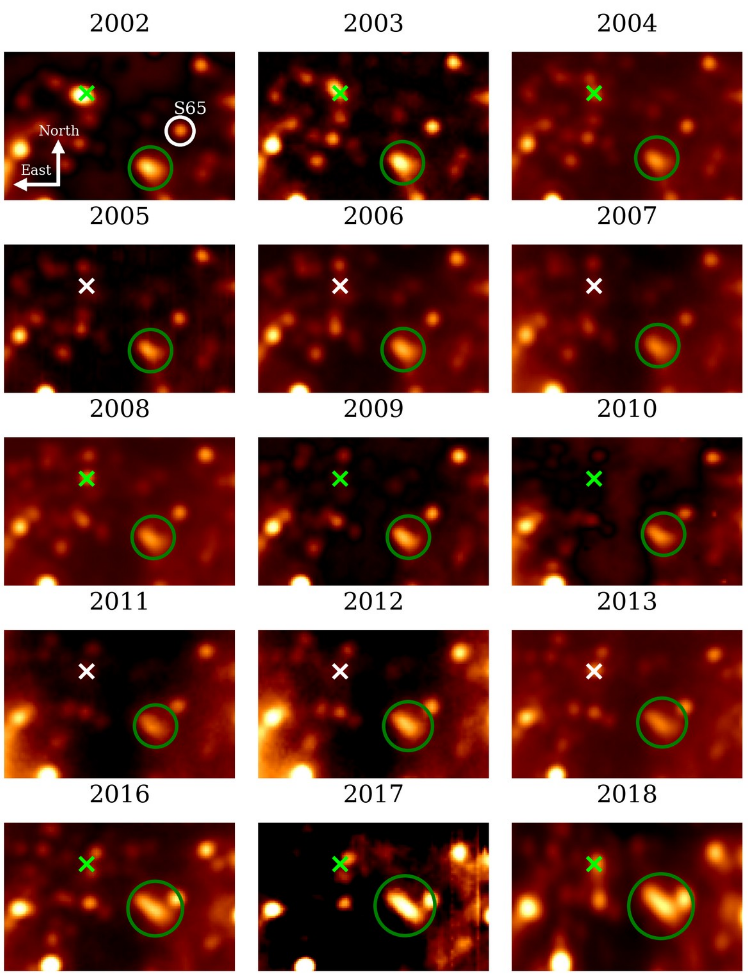
Flow chart for G objects:

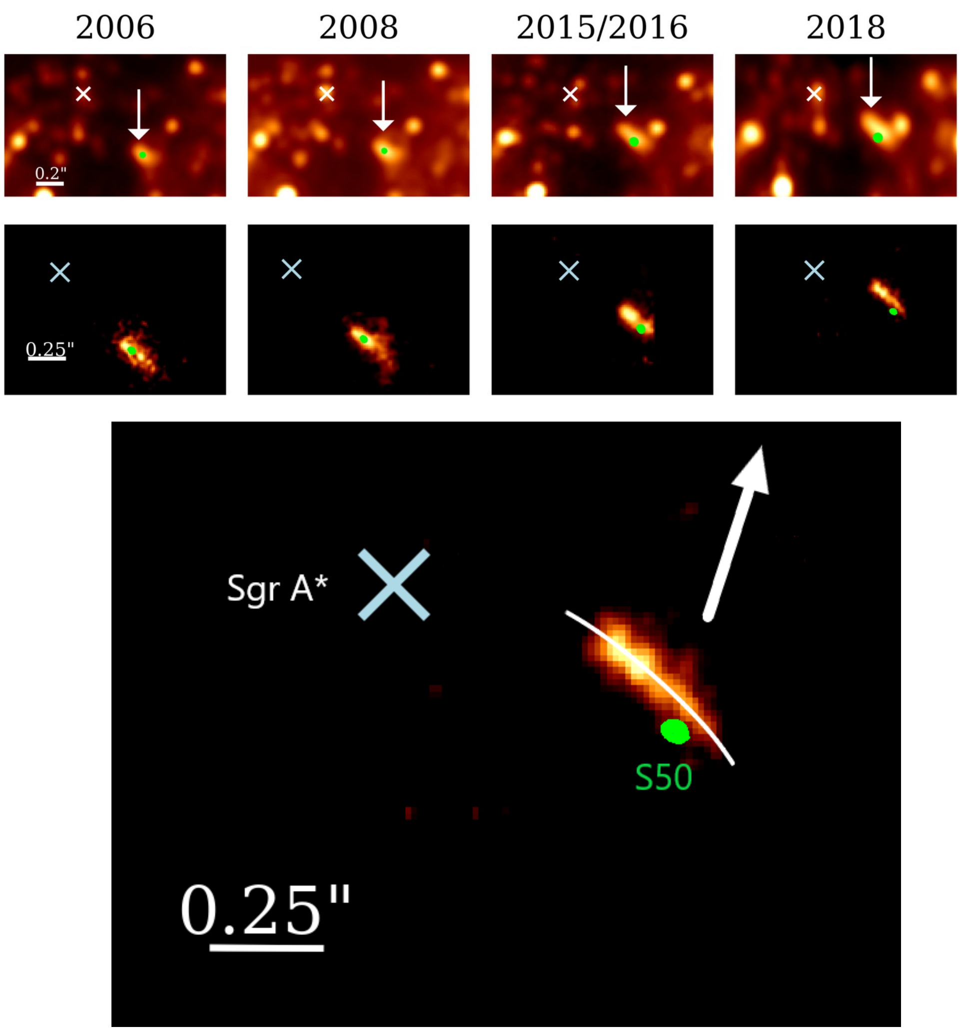


BRNO

Outlook: Resolved dusty object X7

- **X7:** an object within the S cluster whose envelope is resolved in *L*-band continuum and *Br*-gamma line emission
- potential association with **S50** (comoving till 2009)
- envelope reveals signs of shredding, elongation, and detachment from S50
- see **Peissker, Ali, Zajaček et al. 2021** for details





BLR cloud stability