Theory of G2 cloud multi-wavelength emission

The Cloudy Life of the Galactic Center
http://arxiv.org/abs/1309.2282

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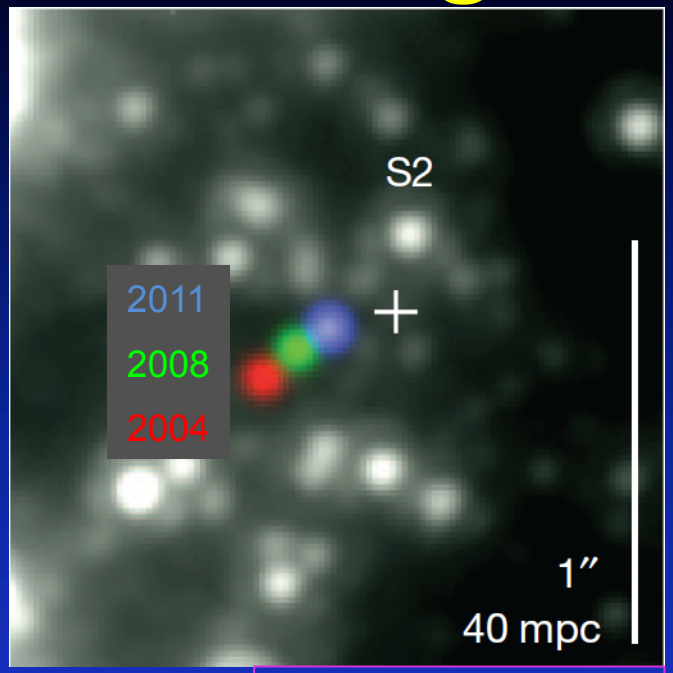
G2 gas cloud (is it a cloud?)



Gillessen et al. 2012

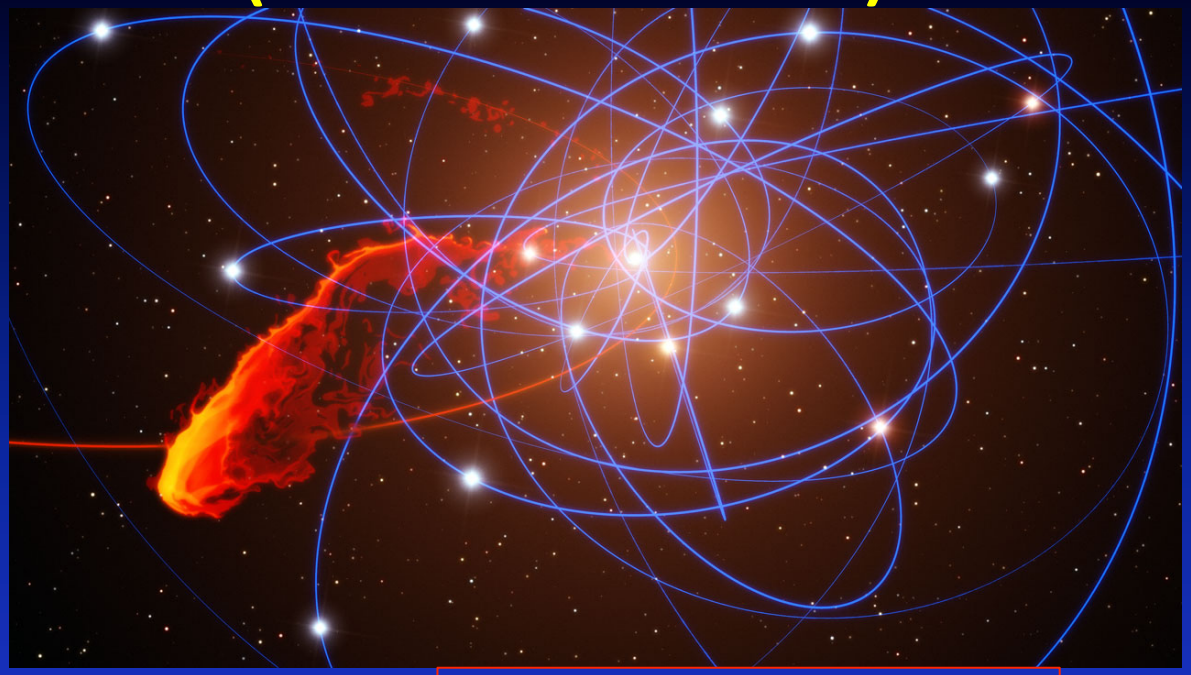


Image Credit: ESO/MPE/Marc Schartmann

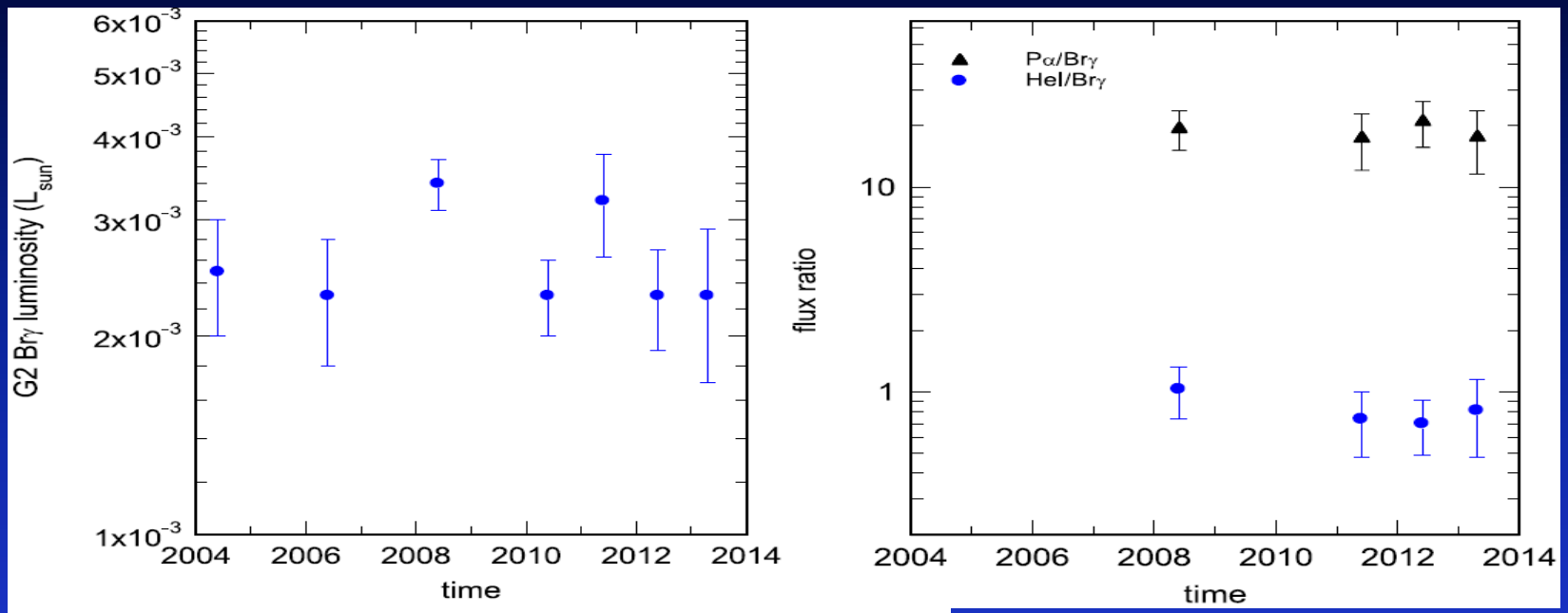
Features:

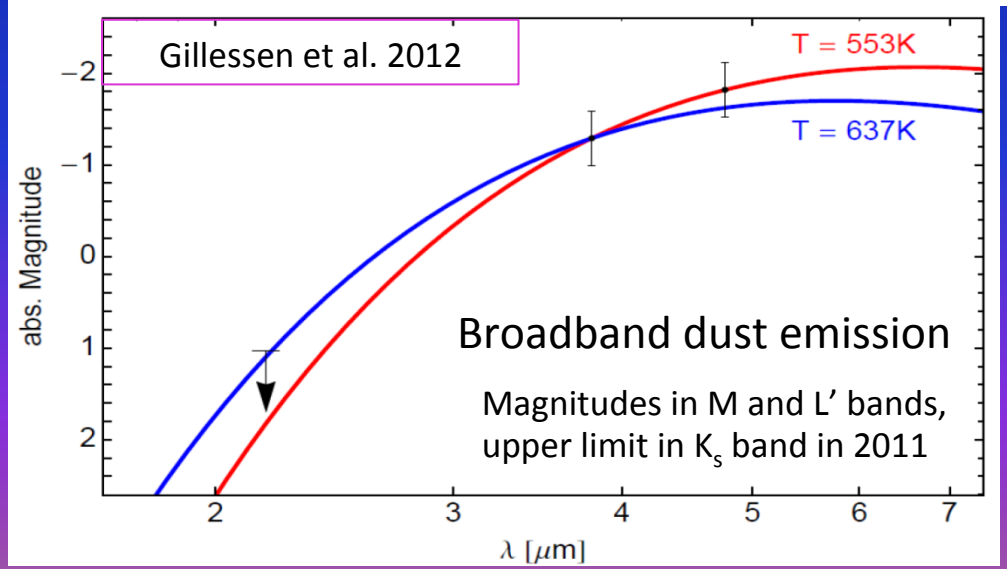
- Emission broadly consistent w/ photoionized gas cloud with density $n \sim 3 \cdot 10^5 cm^{-3}$ and mass $M \sim 3M_{Earth}$
- Being tidally disrupted on the way towards Sgr A*
- Non-trivial radiative signatures are expected from pericenter passage and the accretion of debris

Observed luminosities and magnitudes

Line luminosities in different years: Brγ, Paα, HeI

Gillessen et al. 2013b

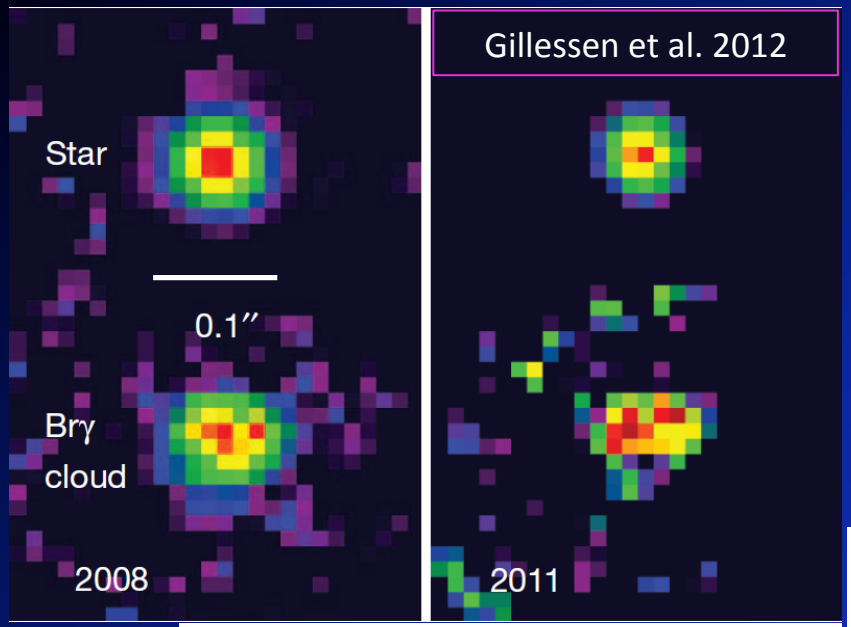




Observed 3 line luminosities
in different epochs
+ 2 broadband luminosities
+ K-band upper limit or detection?

Line luminosities stay constant

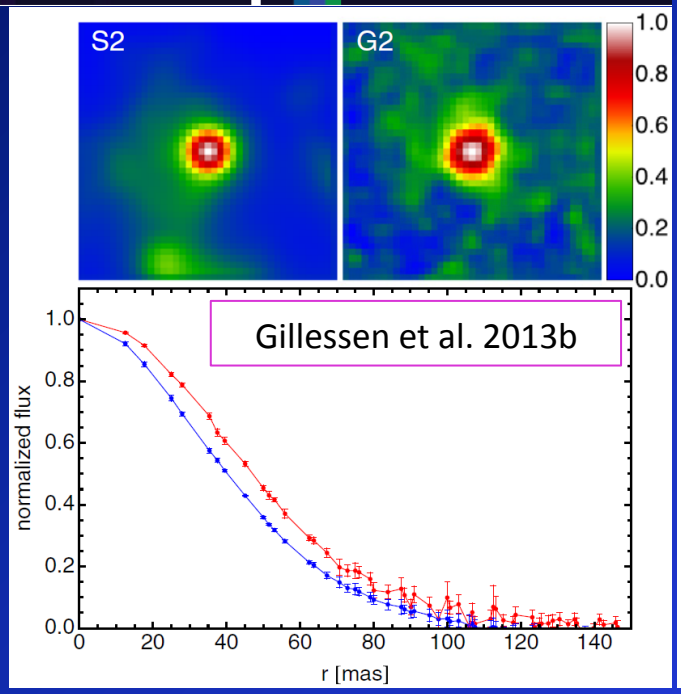
Observed spatial extent and velocities

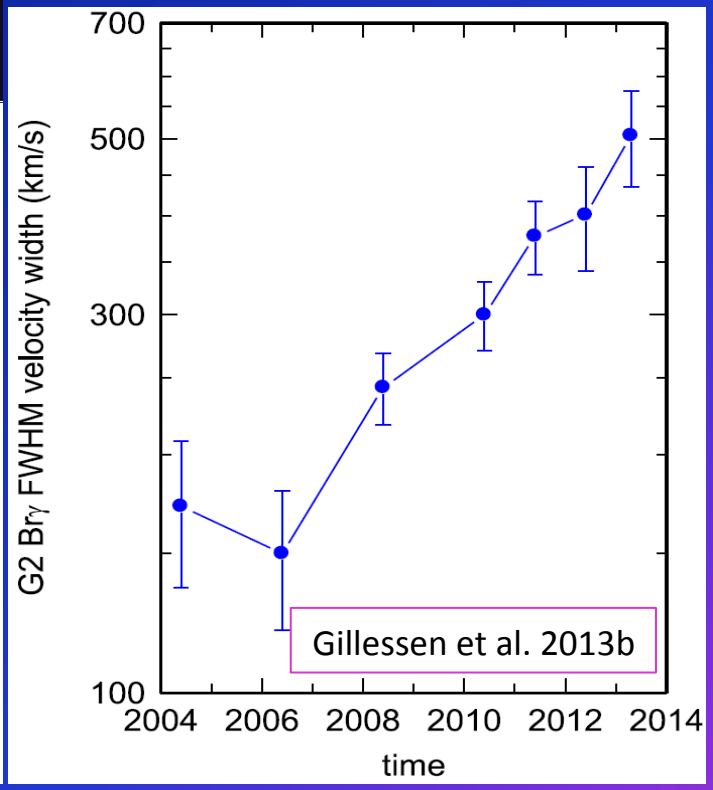


G2 is spatially extended w/ FWHM=42mas

Line widths give projected size d=40-60mas in 2008 and 2011 for new orbital parameters

talk by Leo Meyer





Outline

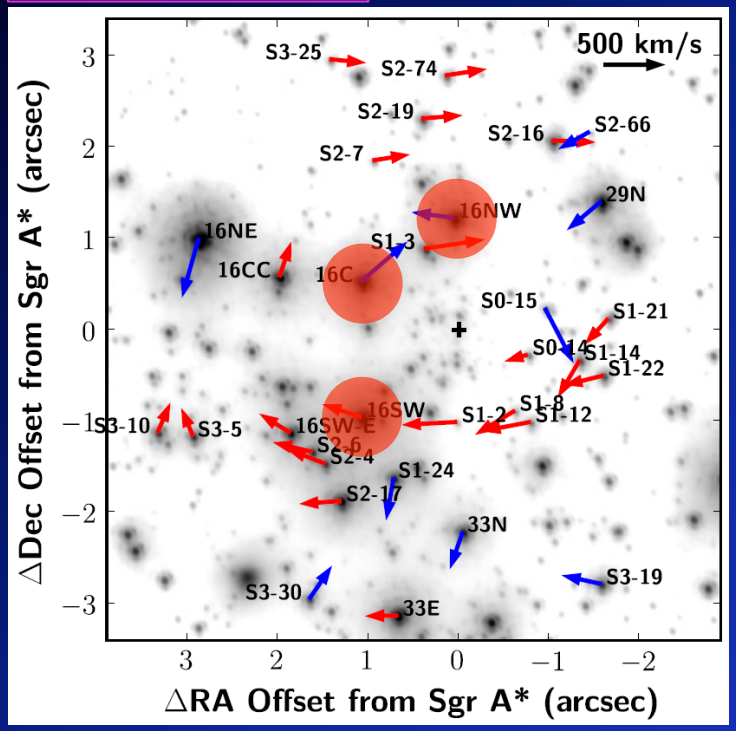
0. Assume G2 is a cloud (no central source).
1. Compute ionizing radiation from nearby stars.
2. Dynamical models + radiative transfer.
3. Fit the observations => cloud properties.
4. Discuss emission from pericenter passage.

Ionizing continuum

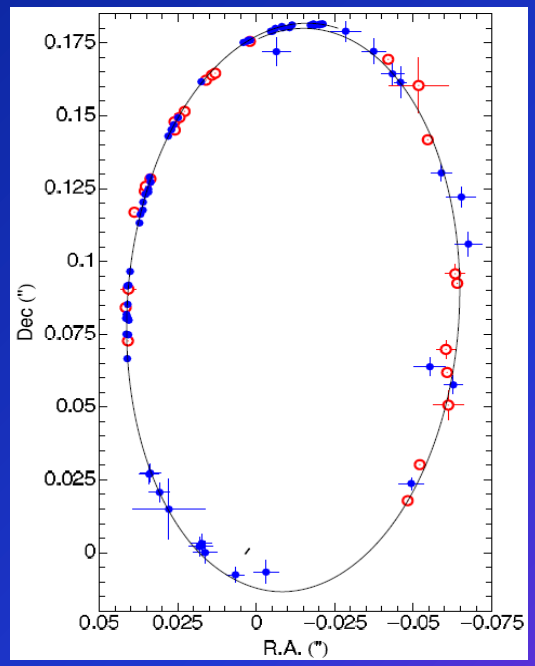
All WR stars + reported bright stars + S0-2 (sample complete to $M \geq 10 M_{Sun}$)

Paumard+2006, Martins+2007, Cuadra+2008

Lu+ 2009; Do+ 2013



Gillessen et al. 2009 – S0-2 star

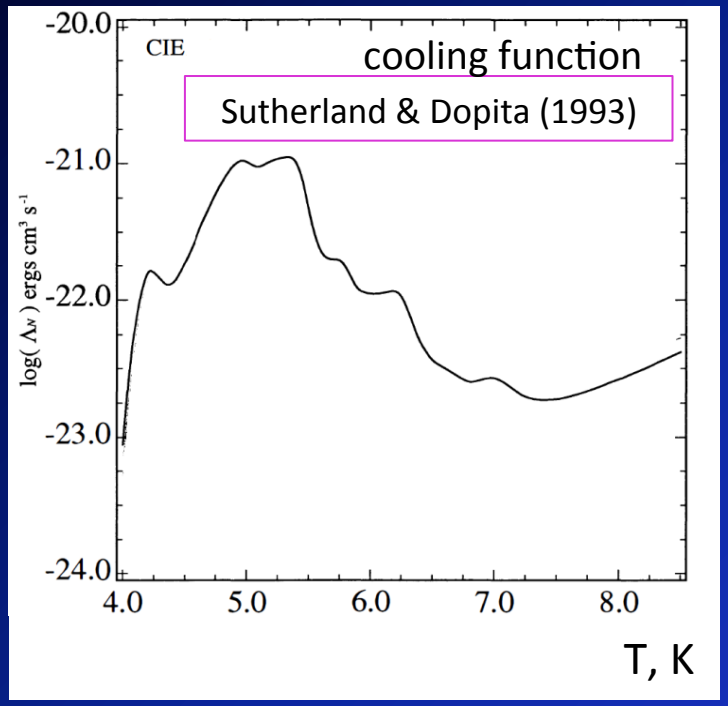


Ionizing flux F_{ion} vary little in 2004-2011 period

Quantity	In 2004 at G2	In 2008 at G2	In 2011 at G2	At G2 pericenter	In 2011 at Sgr A*
Distance from G2 to Sgr A*, arcsec [a]	0.59	0.43	0.30	0.020	...
Total flux[b,c], 10^4erg s^{-1}cm^{-2}	3.0 (75%)	3.5 (87%)	4.0 (100%)	5.7 (142%)	5.2 (129%)
S0-2 flux[b], 10^4erg s^{-1}cm^{-2}	0.26 (31%)	0.47 (57%)	0.84 (100%)	2.6 (306%)	2.0 (241%)
Total of IRS16NW, IRS16C, and IRS16SW fluxes[b], 10^4erg s^{-1}cm^{-2}	2.8 (86%)	3.1 (95%)	3.2 (100%)	3.2 (100%)	3.2 (100%)
S0-2 contribution to flux	8.4%	13%	21%	44%	39%

How to reproduce constant L(Brγ)?

Cloud temperature is **T~10⁴K**, above which cooling is substantial



Temperature is constant over large range of heating rates

Saitoh et al. 2013

G2 is always transparent in IR, but can have τ>1 to ionizing continuum: optically thick and optically thin cases

Only irradiated outer part of the cloud emits Brγ

A large amount of mass may be hidden from view!

optically thin – the entire volume emits

$L(\mathrm{Br}\gamma) \sim n\, m_{cloud}\, T^{-1} \Longrightarrow$ constant density n

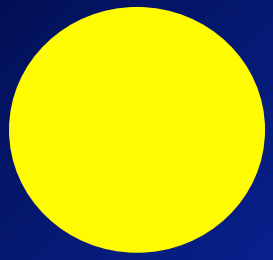
optically thick – reemits the absorbed light

$L(\mathrm{Br}\gamma) \sim F_{ion}\, S \Longrightarrow$ constant/slightly decreasing surface area S

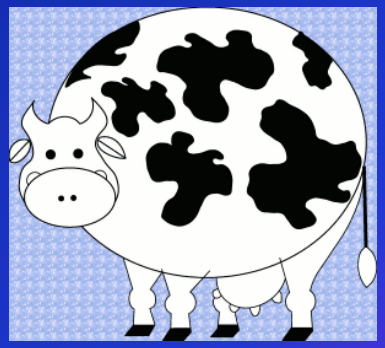
Dynamical models

Initially spherical cloud formed at 1'' distance

Spherical cloud (preserves shape)



The spherical cow
(in vacuum)



Tidally stretched

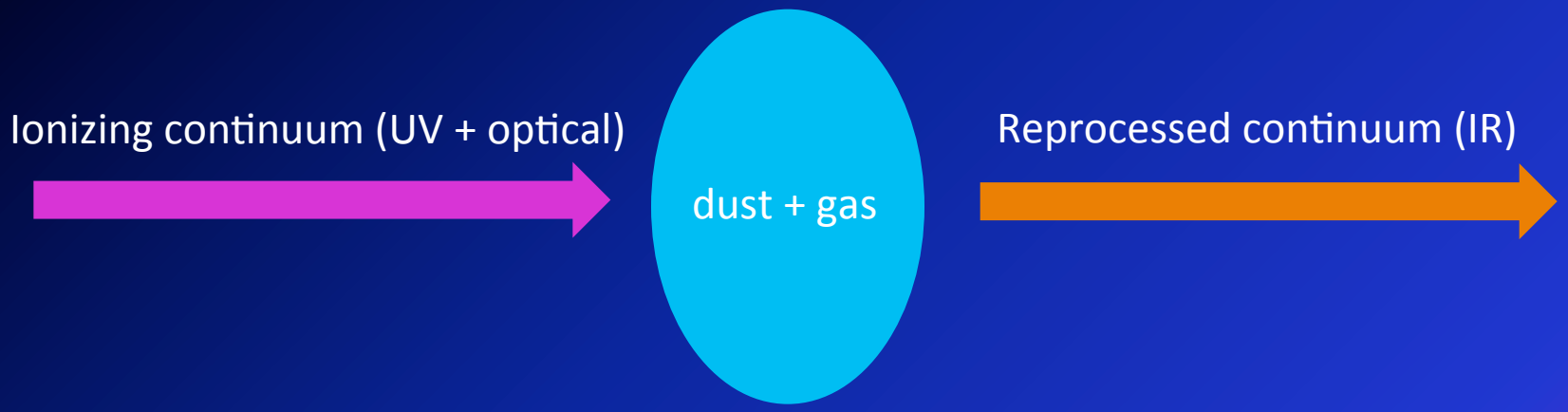
Unmagnetized tenuous cloud
(nova/protoplanetary disk)

Magnetically arrested

Magnetized tenuous cloud
(cooling stellar winds)

Magnetic pressure balances perpendicular gravity

Radiative transfer: CLOUDY code



CLOUDY code Ferland et al. 2013
Version 13 released this year.

- All ionization and collisional processes for many atomic species.
- Various distributions and compositions of dust grains.
- Full radiative transfer from radio to hard X-rays.

Tested clouds with a large range of (initial) densities
Tested 10nm graphite dust and ISM size grain distribution

Modeling + results

Line luminosities/ratios

Gas properties

- Paα/Brγ is always constant (same species)
- HeI/Brγ is consistent w/ data for broad range of density $n_{2011}=3\cdot10^4-10^7 cm^{-3}$
- Observed size => $n_{2011}>6\cdot10^4 cm^{-3}$
- Brγ line width is consistent

Broadband luminosities

Dust properties

- Small dust grains are self-consistently heated to T=500K
- ISM dust size distribution – a bit too red
- 10nm graphite grains – consistent L'-M color, predicts $m_{Vega}(K_s)=19$

Temporal evolution

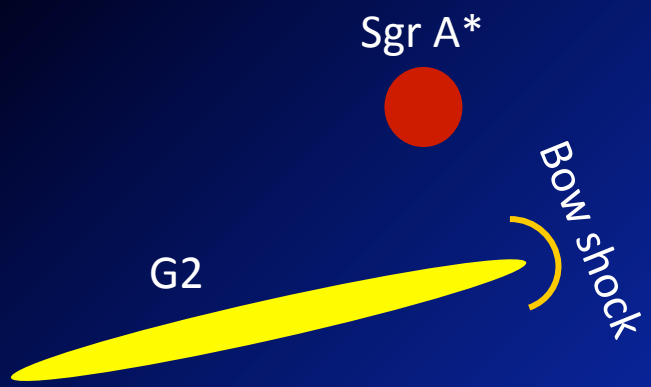
~~Spherical optically thin and thick~~ ← Not expected to preserve shape

~~Tidally stretched optically thick (100M_{Earth})~~ ← Tidal compression/ambient gas interaction => L(Brγ) rises

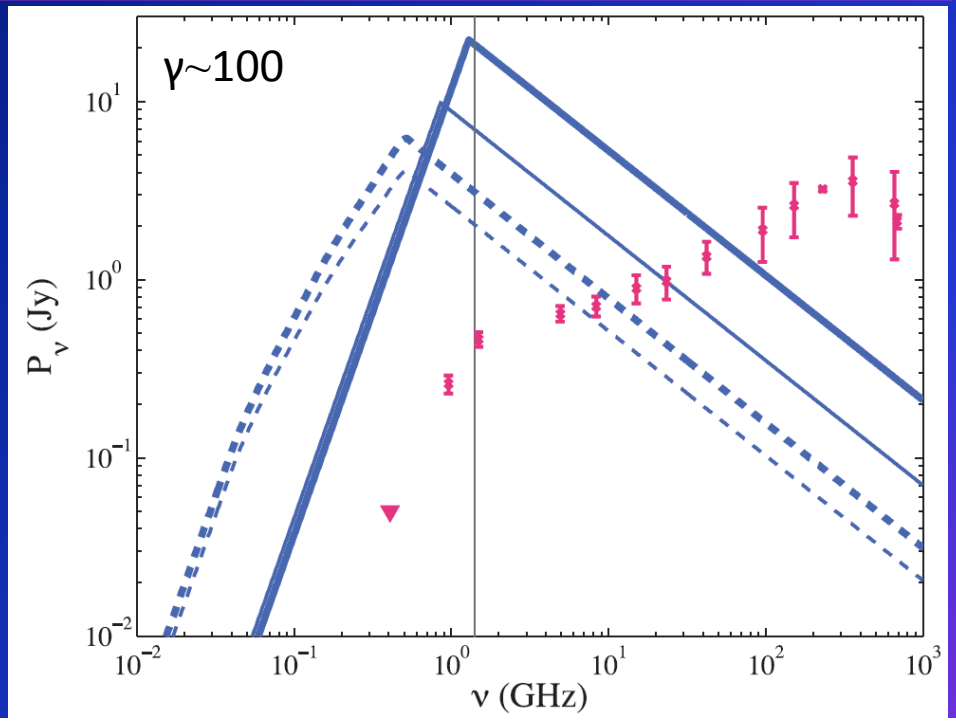
Magnetically arrested optically thin and ~~thick~~ (10-~~180~~M_{Earth}) ← Hard to form a large cloud? => 10M_{Earth} talk by Jorge Cuadra

Non-thermal emission at pericenter

Narayan et al. (2012); Sadowski et al. (2013a,b); Abarca et al. (2013)



Bow shock accelerates particles => synchrotron radio/IR/X-ray emission



X-ray luminosity $\nu L_\nu = 1.5 \times 10^{34} \left(\frac{\nu}{4\mathrm{keV}}\right)^{-0.1} \mathrm{erg\ s^{-1}}$

γ~10^6 electrons

Shcherbakov 2013

Actual observed fluxes are a factor of 20 lower

Bower et al. 2013

However, "overly optimistic" assumptions:

… Large cloud cross-section radius r=10^{15}cm

… Efficient particle acceleration

Non-thermal emission: reconciling theory and observations

1. Cloud is radially extended => bow shock at pericenter early? (late 2012/early 2013) ⬅ Radio/X-ray monitoring is continuous

2. Ambient density profile shallower than $n \sim r^{-1}$ ⬅ Better density profile $n \sim r^{-0.85}$ => 2x lower luminosity

Shcherbakov et al. 2012; also Wang et al. 2013

3. Smaller cloud cross-section ⬅ Best-fitting perp. radius $\rho = 4 \cdot 10^{14}$cm => 5x lower luminosity

Shcherbakov 2013

4. Lower acceleration efficiency ⬅ Efficiency can readily be 1.5% => 3x lower luminosity

Narayan et al. 2012

5. Weak acceleration in oblique shocks ⬅ Effectively lower cross-section => lower luminosity

Sadowski et al. 2013a

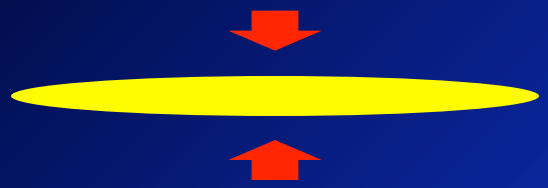
⬇

Non-detection of non-thermal bow shock emission is consistent with the cloud hypothesis

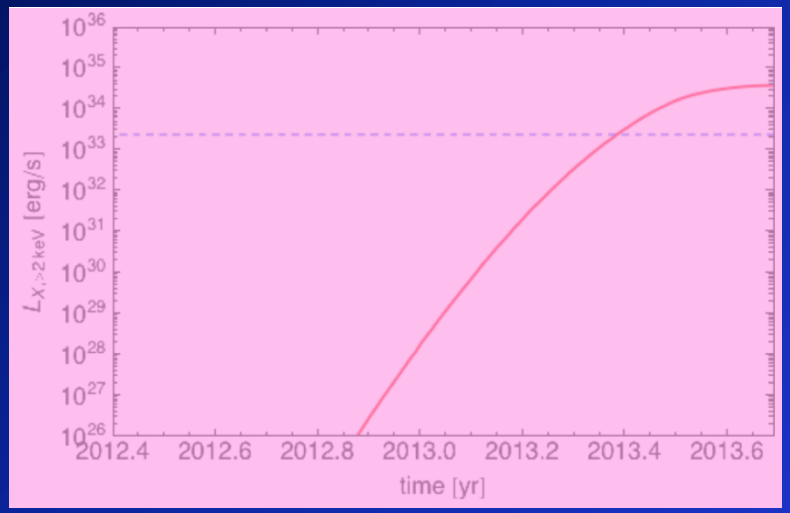
Thermal emission at pericenter

Squeezing in perpendicular direction by

- shock driven by ambient gas (gradual)
- tidal compression (gradual)
- tidal compression shock (sudden)



X-ray emission



Gillessen et al. 2013a

Not actually observed

Gas cools quickly =>
most emission is in IR lines/broadband

Saitoh et al. 2013; Ballone et al. 2013

Larger Brγ near pericenter, not observed
talk by Ballone

Magnetically arrested cloud

- Supported against ambient medium
- Weak tidal compression
- May only be weakly heated by B dissipation

May only exhibit a modest increase in IR lines and broad bands

What to expect after pericenter

Cloud mass is 4x larger => higher accretion rate?

But debris fallback is delayed

due to weaker interaction w/ ambient medium

- Magnetized cloud is less prone to Kelvin-Helmholtz instability
- Smaller cross-section and larger mass
- Ambient density is lower than used in numerical simulations

=> lower accretion rate, later onset

Numerical simulation
of magnetically arrested cloud
(is to be performed)

Conclusions

There is a scenario, which is
(1) self-consistent
(2) consistent with observations

Dynamics:

- spherical $10M_{Earth}$ cloud forms at 1'' via runaway cooling of stellar winds
- cloud is magnetically arrested => little compression at pericenter
- delayed onset of fallback accretion

Radiation:

- reproduces L(Brγ); HeI/Brγ; Paα/Brγ
- heated to T=500K small dust reproduces magnitudes in M, L', and K_s(?)
- non-thermal emission from bow shock is below detection threshold
- little/no thermal emission at pericenter

Looking forward to the bright future of G2