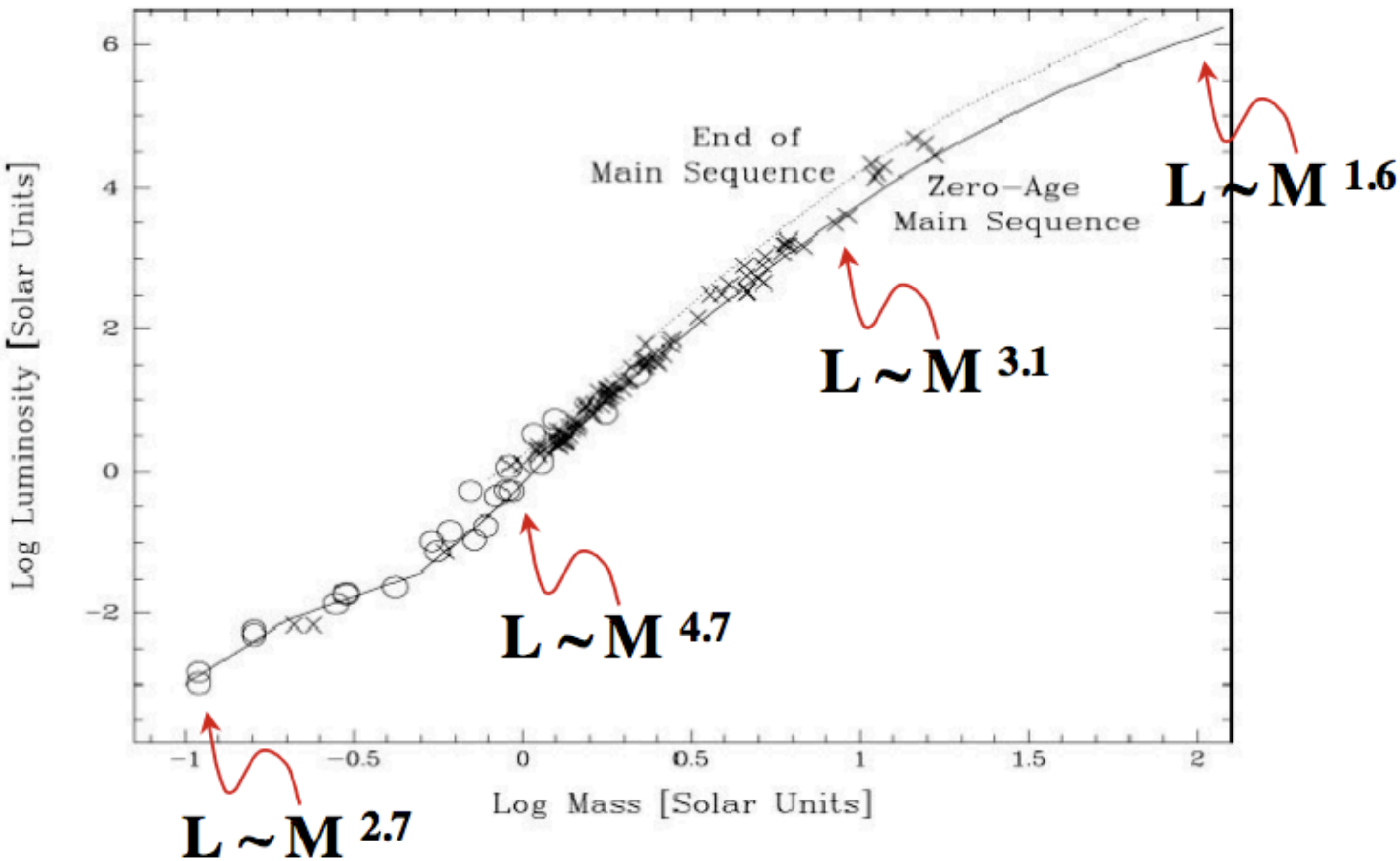
What do you see ?

First things first

- M –L relation

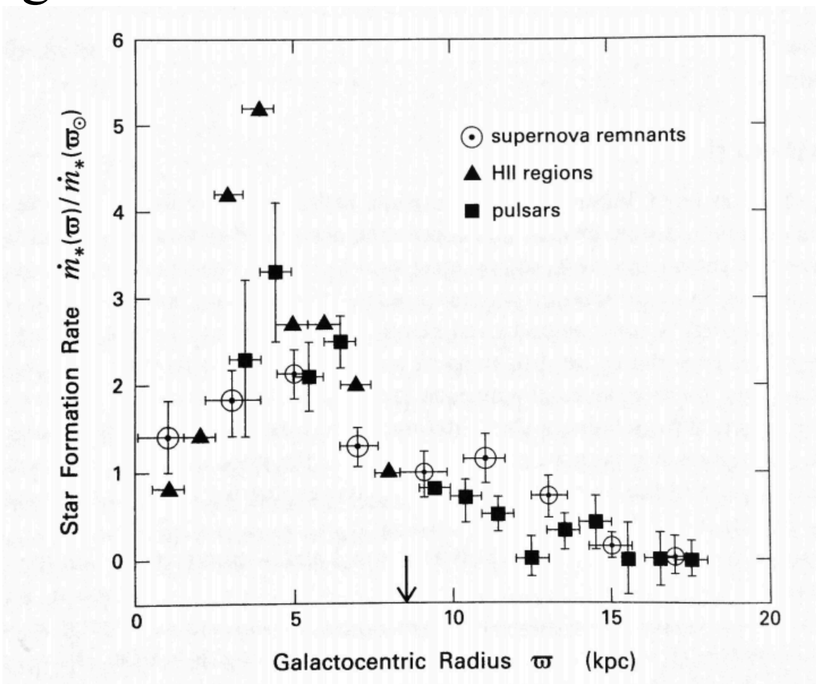


Star Formation in the Disk

- S.F. in the M.W. can be studied using:
  - Radio free-free emission: produced by e^- in HII regions, maps the ionizing photons and the surface density of O-B stars
  - Radio non-thermal emission (synchrotron): maps the location of SNRs ->SF of massive stars
  - Pulsar surveys: neutron star, distance measured via dispersion measurement, birthrate of massive stars
- The above method gives only the high mass end of the SFR
  - Use IMF to correct

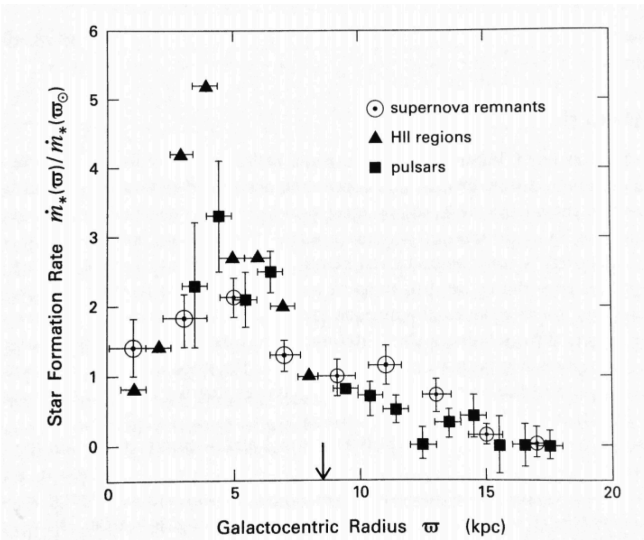
All 3 methods give comparable results

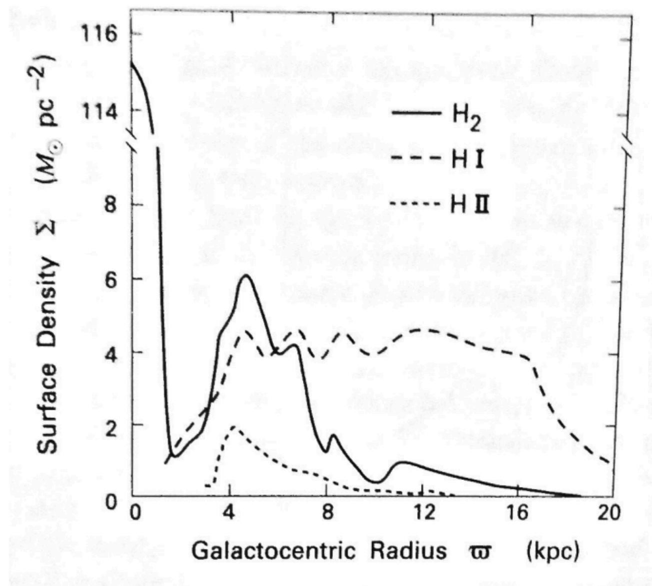
In the disk the SFR is ~4 $M_\odot$/yr



SFR and Gas Distributions

- Star formation should follow the H_2 distribution



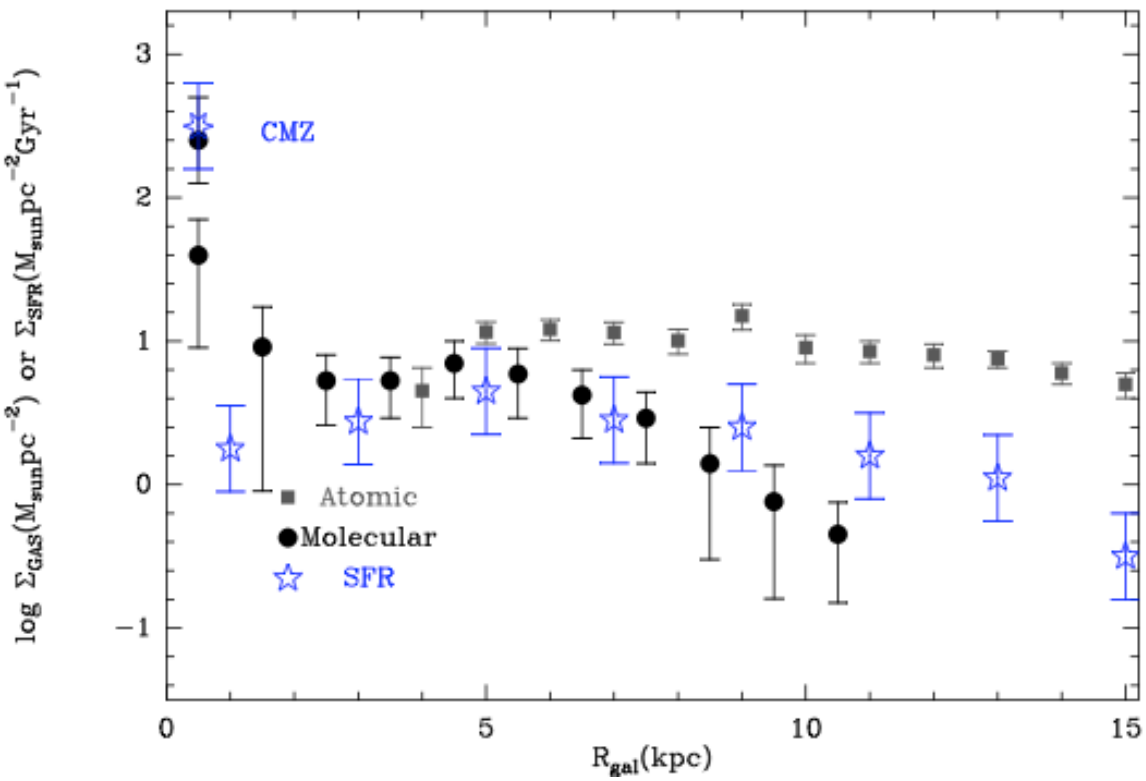


- Total H_2 is 2×10^9 $M_\odot$ at $4 M_\odot$/yr ->depletion time of ~5e8 yr!!
  - All the gas should have been converted into stars already!
- HI is more abundant (7×10^9 $M_\odot$), so there is a mechanism that transport HI and transforms (shields) it into H_2

Galactic Center

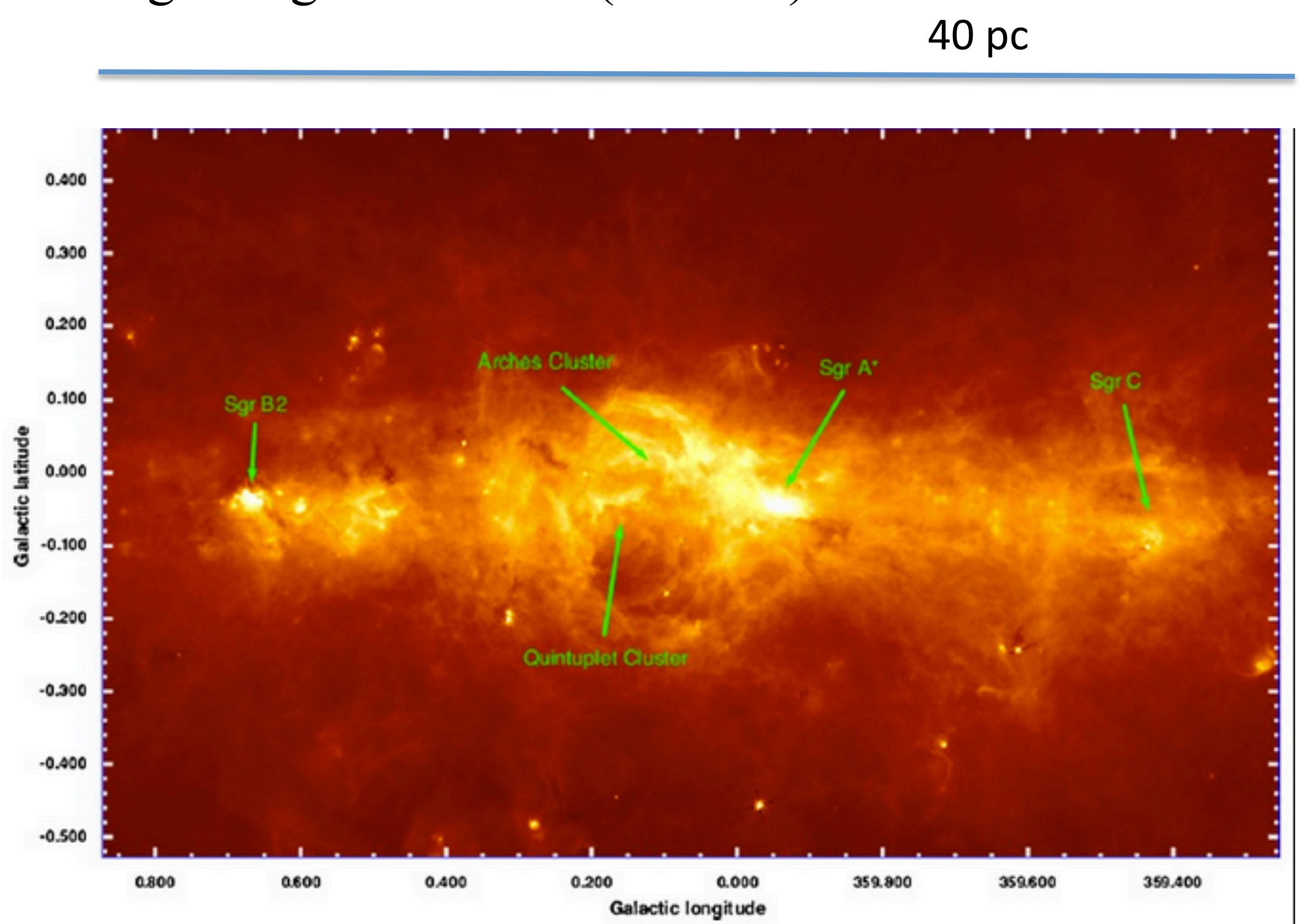
- Gas density increases towards the center of our Galaxy
  - Star formation has to as well

CMZ=central molecular zone



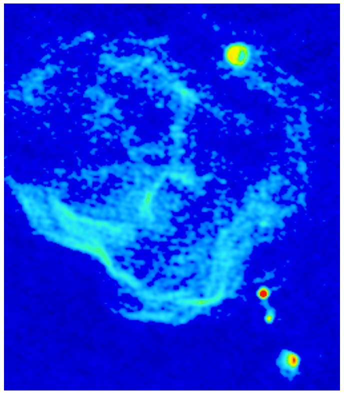
Galactic Center: CMZ structure

- Many GMCs with $M > 10^6\ M_\odot$
- High Temperatures : >=70 K
- Large Magnetic Fields (20 mG!)

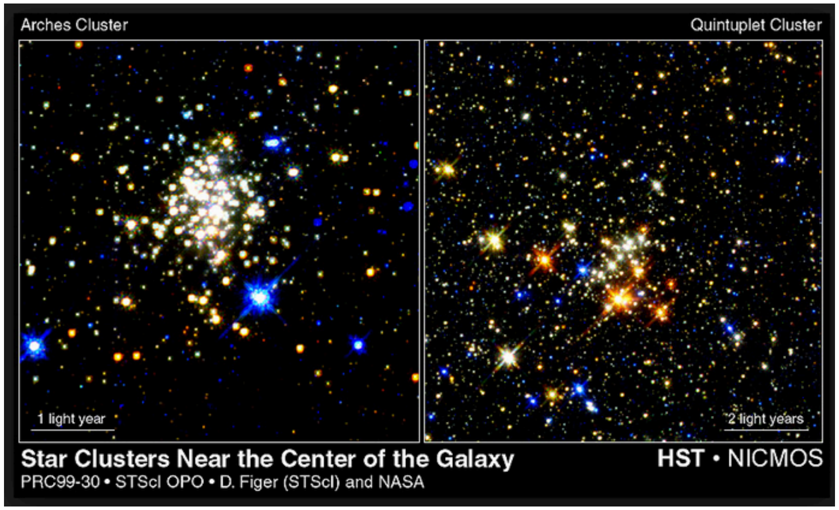


Stars

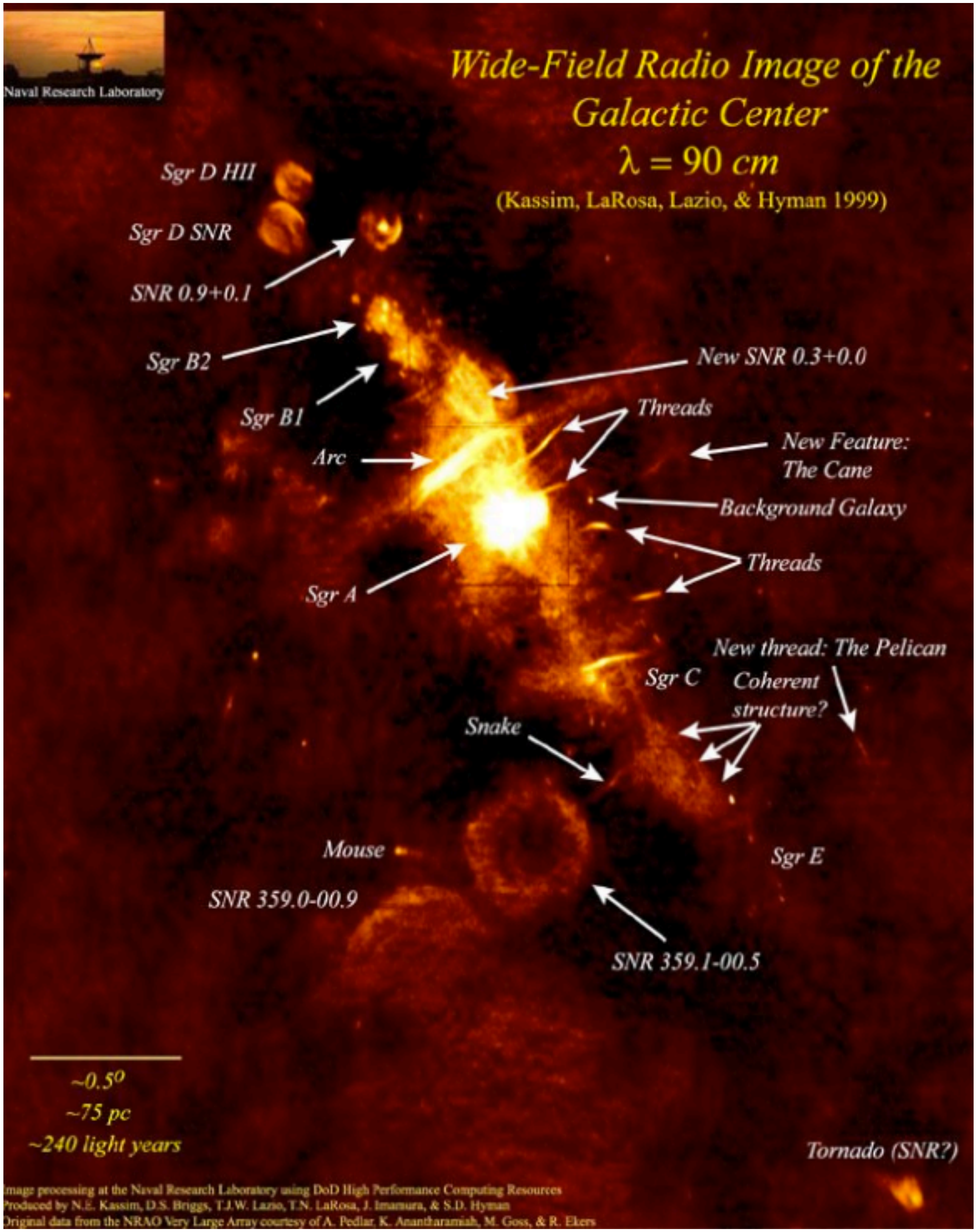
- Radio/FIR tracers yield SFR = 0.3 M/yr
  - 10% of the entire Galaxy ! Where do the stars come from ?
- VLA Interferometry reveals that Sgr B2 can be broken down in dozens of HII regions



- The most intense star formation happens in 3 clusters:
  - Central, Arches and Quintuplet
  - Each contains `hundreds' O-type stars
  - Believed to be old, they are instead very young (4e6 yr)

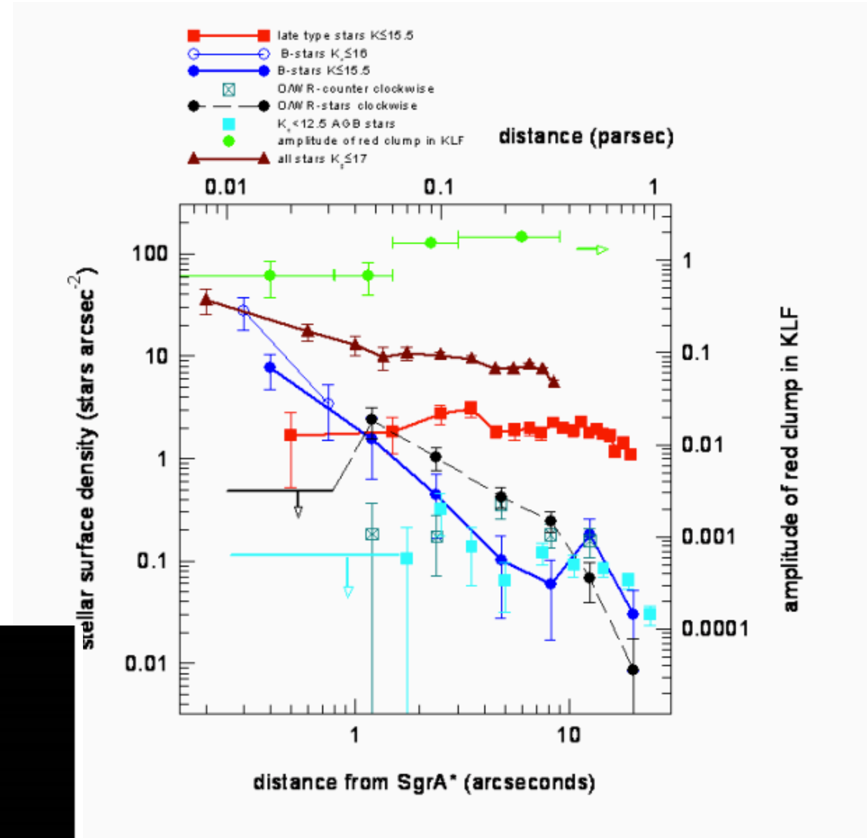


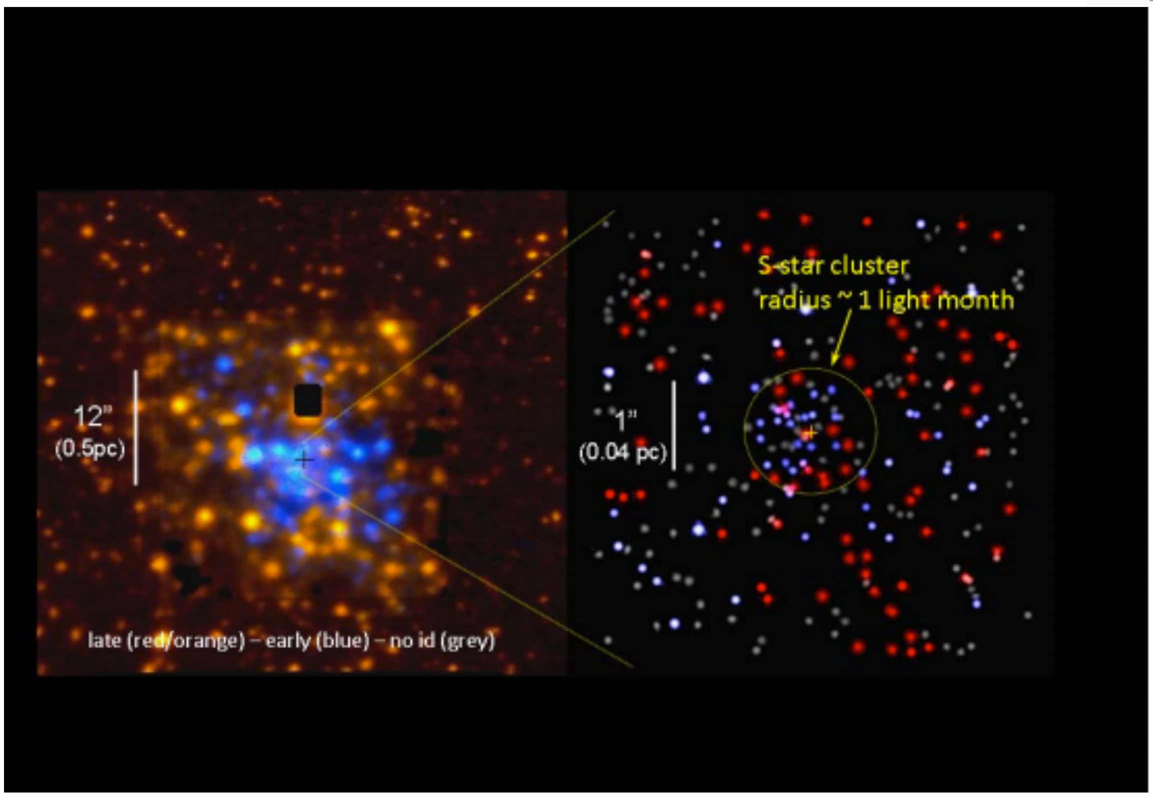
There needs to be constant gas inflow !!



Naval Research Laboratory
Wide-Field Radio Image of the Galactic Center
λ = 90 cm
(Kassim, LaRosa, Lazio, & Hyman 1999)
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
New SNR 0.3+0.0
Threads
New Feature: The Cane
Arc
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5
~0.5°
~75 pc
~240 light years
Tornado (SNR?)
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamiah, M. Goss, & R. Ekers

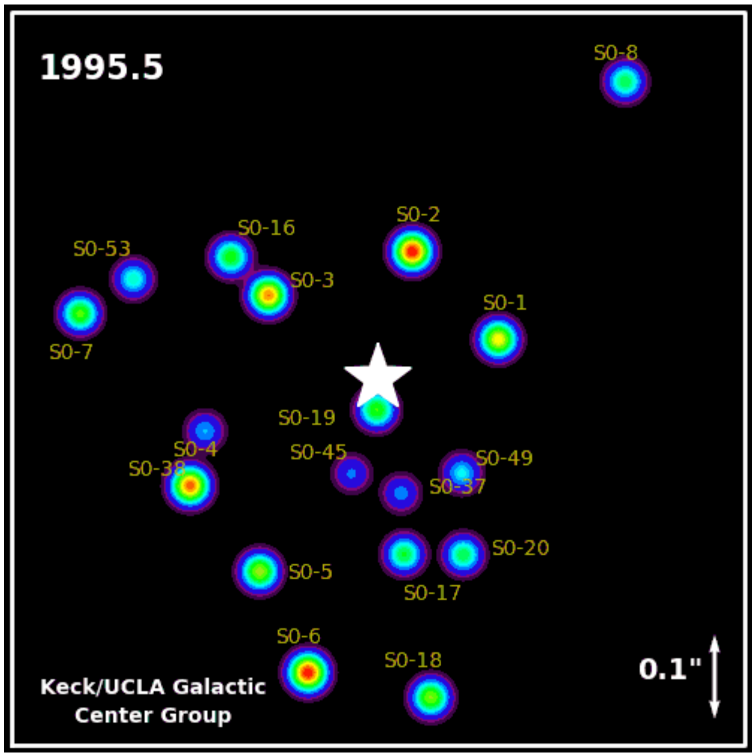
Genzel+2014


late type stars K≤15.5
B-stars K_s≤16
B-stars K≤15.5
O/WR-counter clockwise
O/WR-stars clockwise
K_s<12.5 AGB stars
amplitude of red clump in KLF
all stars K_s≤17
distance (parsec)
0.01
0.1
1
100
10
1
0.1
0.01
1
0.1
0.01
0.001
0.0001
1
10
stellar surface density (stars arcsec^{-2})
amplitude of red clump in KLF
distance from SgrA* (arcseconds)


12"
(0.5pc)
late (red/orange) – early (blue) – no id (grey)
1"
(0.04 pc)
S-star cluster
radius ~ 1 light month

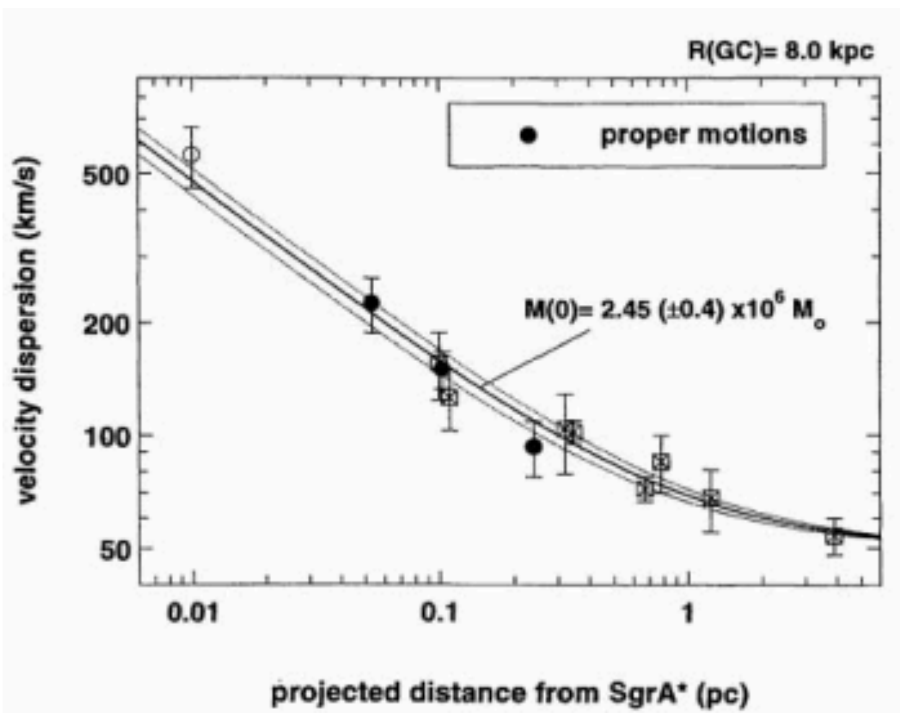
At the Center

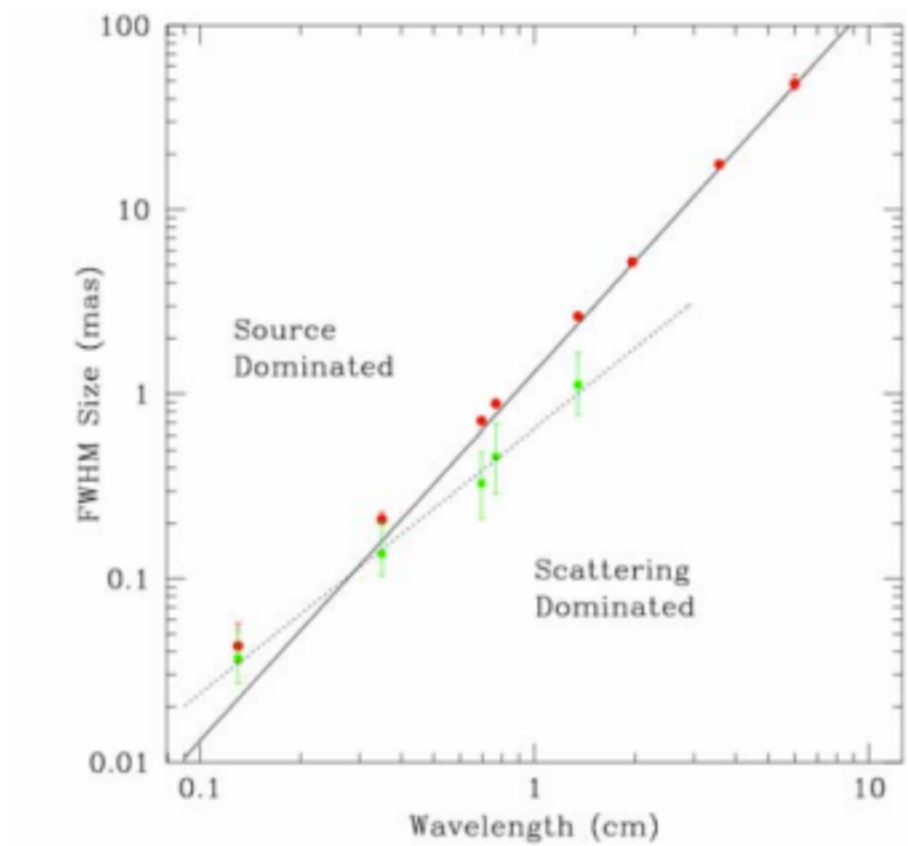
- Interesting things:
  - Observations of the Galactic center have revealed two paradoxes: there are far fewer old stars and many more young stars than expected based on theories.
  - Stars in the central ~0.04 pc (1") are on randomly distributed orbits.
  - Just outside the central arcsecond, there are many young stars orbiting the supermassive black hole in a common plane. These stars likely formed in a massive, gaseous disk in the central parsec.



The Mass of the Black Hole

- Measurements show stars follow Keplerian orbits around a compact mass
- VLBI interferometry showed that the source is <37μ-arcsec!
  - ~3 times the size of the event horizon for such BH
  -





Star formation around the B.H.

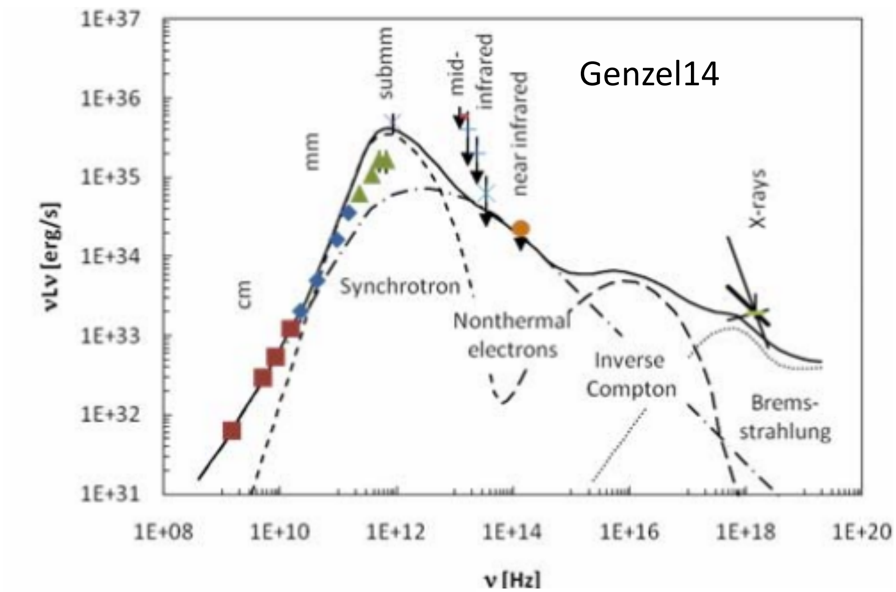
- Large population of young/massive stars
- Two hypotheses:
  - dense gas fell into the nucleus about 6 Myrs ago and formed a disk around the black hole (Morris 1993)
  - dense and massive star cluster formed outside the hostile central parsecs, subsequently spiraled into the nuclear region by dynamical friction and then finally was disrupted tidally there (Gehrard 2011)

- A self-gravitating disk can form stars
  - Instability to fragmentation and gravitational collapse (like the Jeans mass/length)
  - Controlled by the Toomre Q-parameter
  - Nayakshin, Cuadra & Springel (2007) perform SPH simulation and find that the accretion disk forms stars vigorously inside out

- What powers the Inner pc ?
  - The inner pc appears like a gigantic HII region (1e50 N_{lyc} ph/s) produced by an aging stellar population
  - No sign of much activity from the BHs

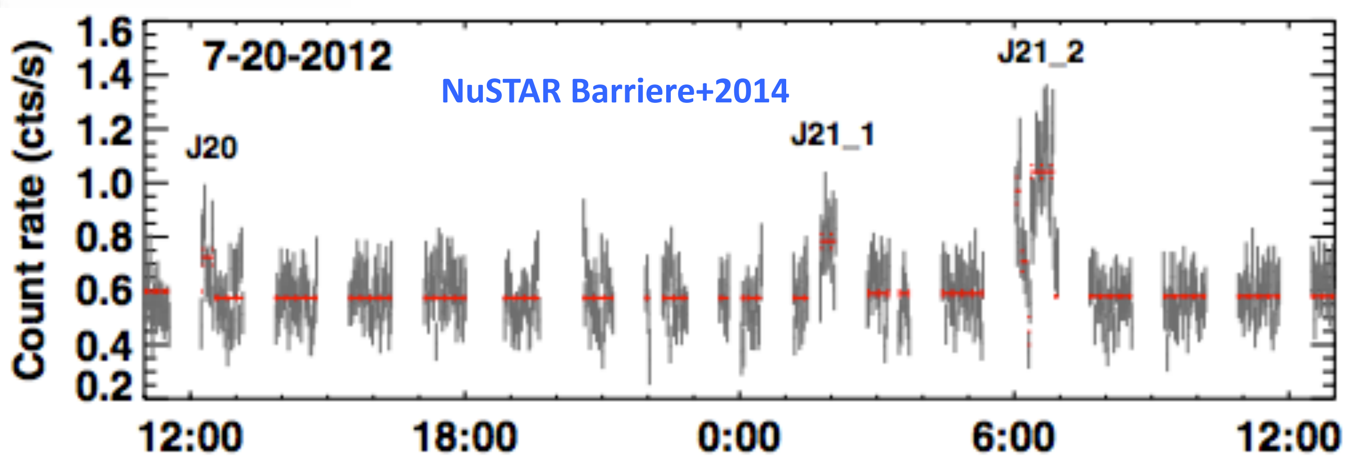
Black Hole Activity

- The Galactic Center black hole is most of the time in a ‘steady’ state, emitting ~ 1e36 erg/s predominately at radio and sub-mm



Compact source detected at all times: in radio

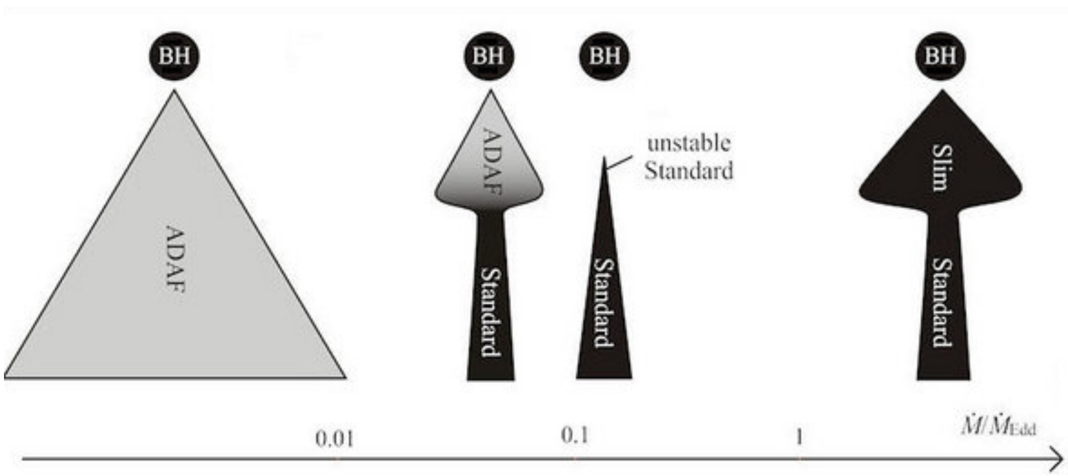
Emission is mostly synchrotron radiation from thermal electron

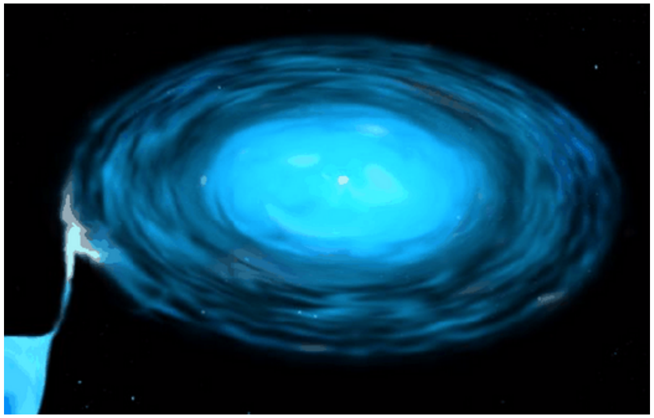


Few Words on Accretion Disks

- Accretion is important because
  - (a) it is a way for objects to grow
  - (b) it is a way for gravitational energy to be released
  - (c) it transports angular momentum via viscous dissipation
- Gas will settle into a disk : minimum energy configuration for a fixed angular momentum
- Eddington luminosity
  - Max energy a body can produce without blowing up (balance between radiation pressure and gravitational force)

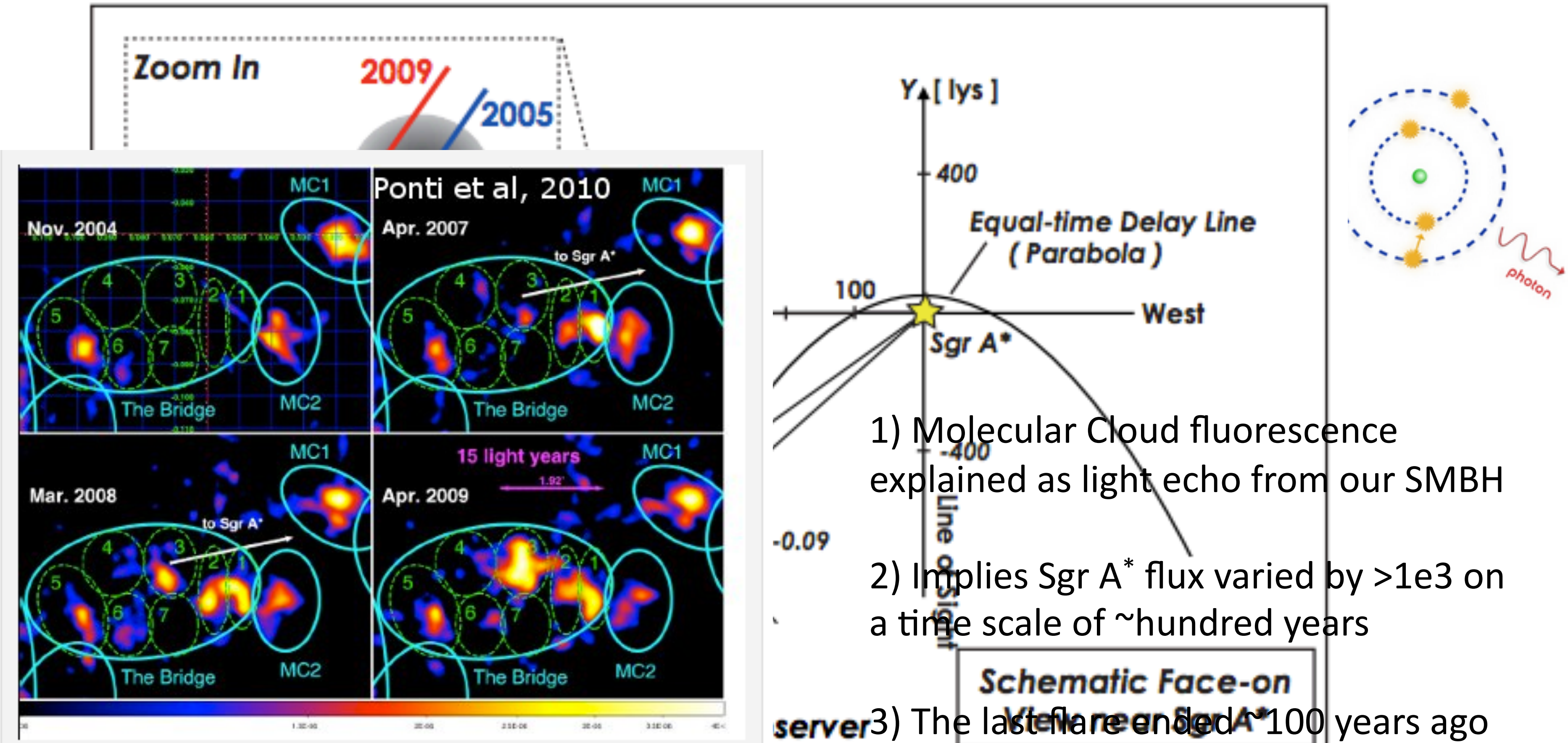
- The G.C. hole is sub-Eddington
  - Mass accretion rate of 10^{-9}-10^{-7} M/yr





Past Activity

- Was our black hole active in the past ?
- Iron K line: fluorescent emission from reflected radiation from e.g. disk/torus/molecular clouds



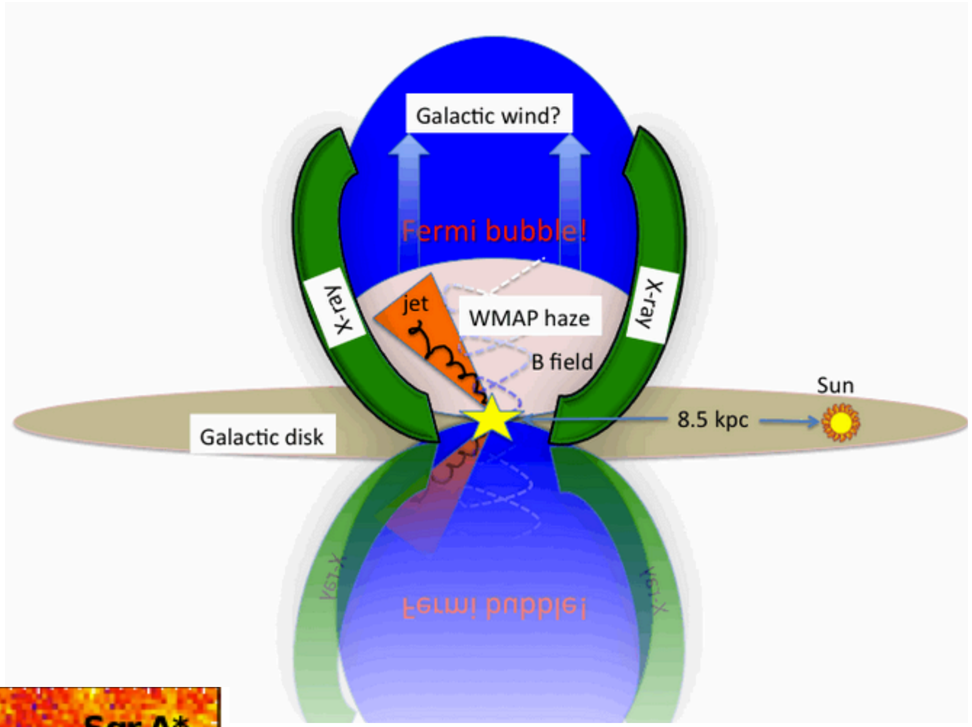
1) Molecular Cloud fluorescence explained as light echo from our SMBH

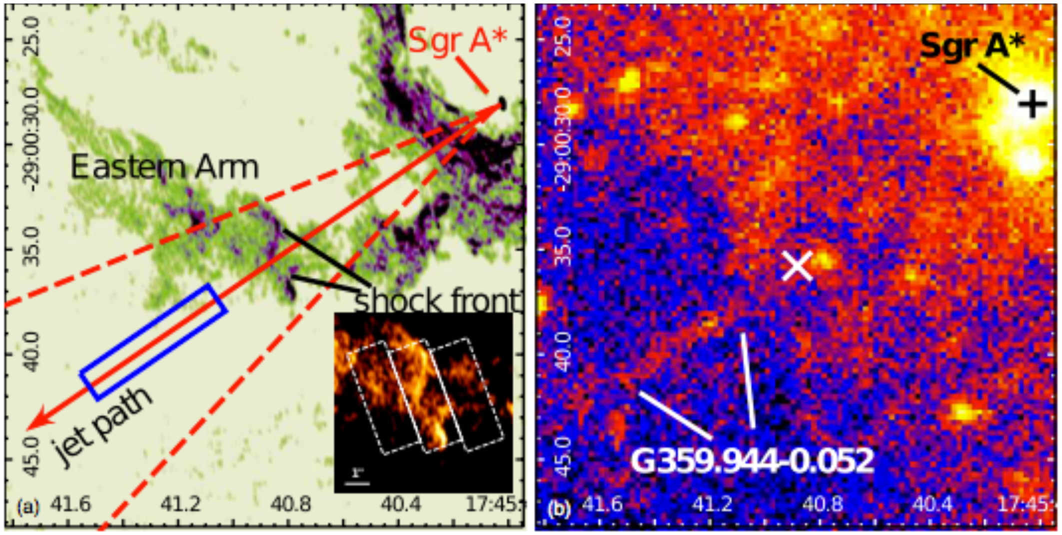
2) Implies Sgr A* flux varied by >1e3 on a time scale of ~hundred years

3) The last flare ended ~100 years ago

A superluminal X-ray echo travelling through the Galactic Centre molecular clouds (Ponti et al, 2010)

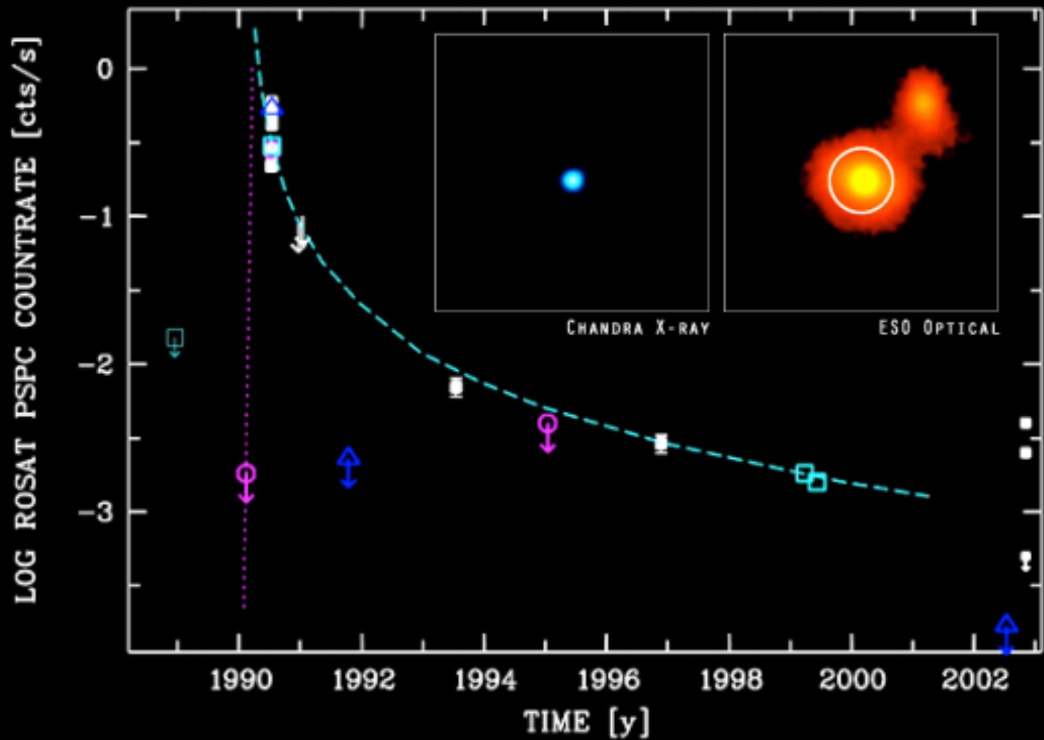
Past Activity





Tidal Capture and disruption events

A single star is captured and tidally disrupted by a black hole. After an initial flash of X-rays, there is a steady decline over a timescale of ~10 yr.



Light curves of 4 tidal capture events discovered by ROSAT.
Similar events have now being detected by Swift and by Galex/PanSTARRS!

Rees 1988

Komossa et al., 2004

I saw one as well ! ☺

Cappelluti, Ajello + 2010

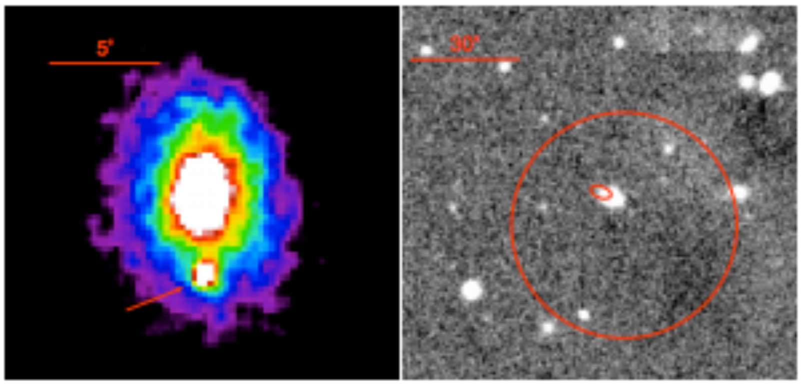


Fig. 1. *Left panel*: the *ROSAT*-PSPC 0.3–2.4 keV colour coded ima
of the field of A3571. The X-ray transient is indicated with the arr
Right panel: GROND image in the K_S-band of the region of the X-
transient, the *red circle* represents the *ROSAT*-PSPC error-box and
red ellipsoid is the Chandra confidence region.

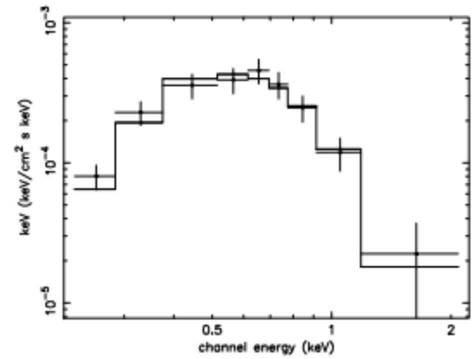


Fig. 2. The *ROSAT*-PSPC unfolded spectrum of the source
TDXFJ134730.3-325451 (crosses) and the best fit blackbody model

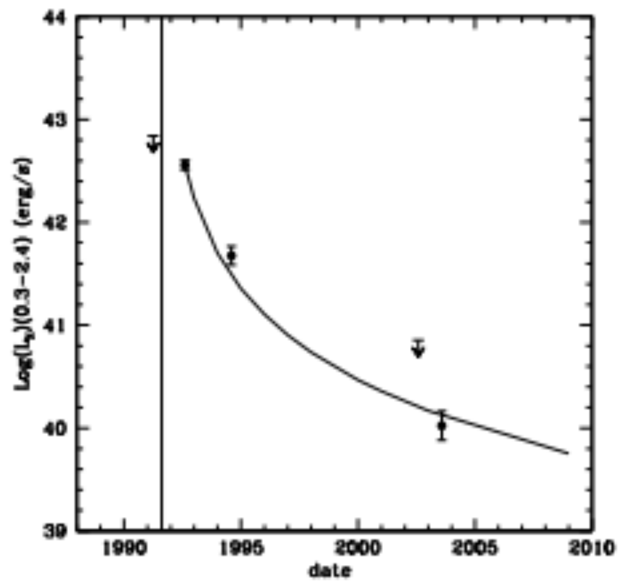
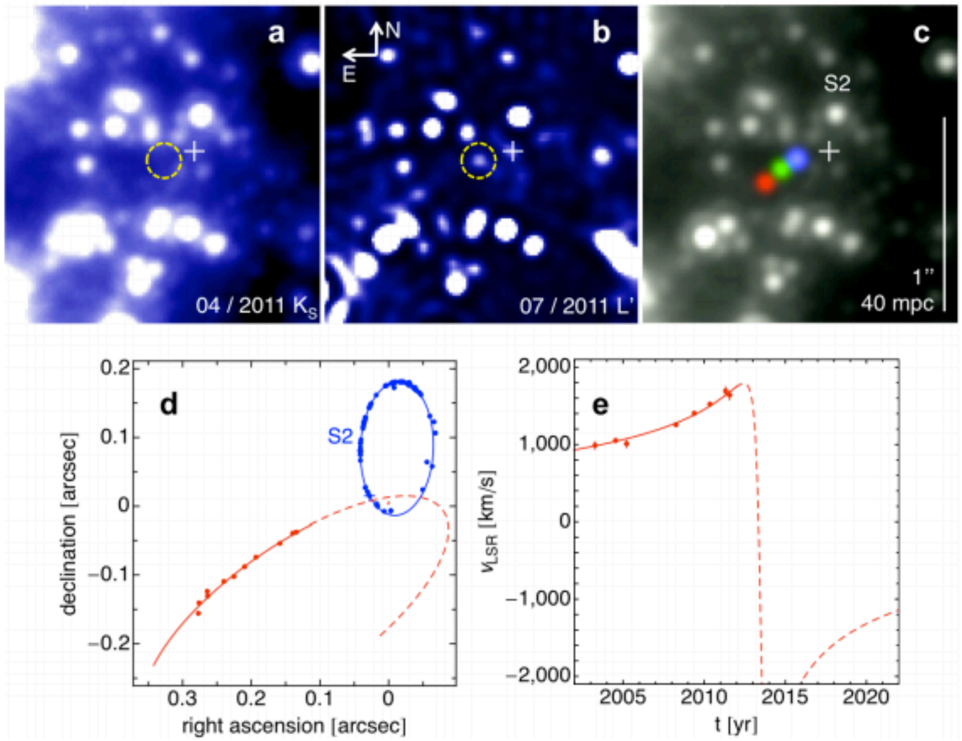


Fig. 4. The X-ray lightcurve of TDXFJ134730.3-325451. The *solid curve* represents the result of the power-law fit while the *vertical line* marks the expected begin of the flare.

G2 Cloud

Gillesen+2012 (Nature)



- Massive cloud approaching Sgr A*
  - Passing at a distance of only ~3000x size of the event horizon
  - Velocity increasing near perigee (from 1000 to 2000 km/s)
  - Tidal disruption can be expected in 2013 - 2014

G2 Cloud Approach

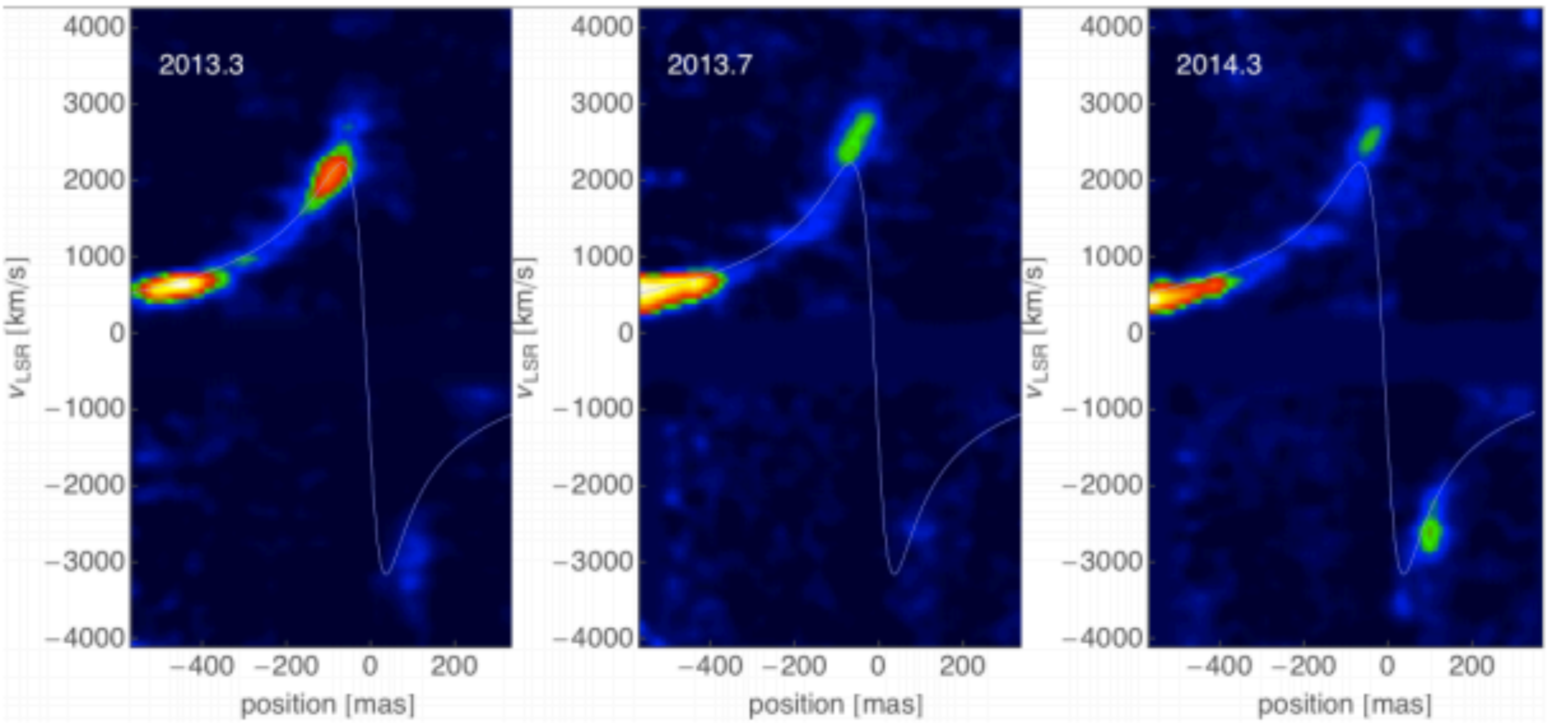


Figure 1: Comparison of the pv-diagrams from spring 2013 (data already presented in Gillessen et al. 2013b), late summer 2013 and spring 2014 (new data). The blue line corresponds to the Brackett-γ based orbit from Gillessen et al. (2013b), along which the pv-diagram is extracted. We have blended out the range between −660 km/s and +240 km/s to avoid emission from the mini-spiral (Paumard et al. 2004) visible at these wavelengths. The scaling is adjusted in each map individually to optimally show the structure of the gaseous emission; the maps cannot be compared photometrically to each other, but see section 3.2 and figure 2 instead.

G2 : Test particle simulation

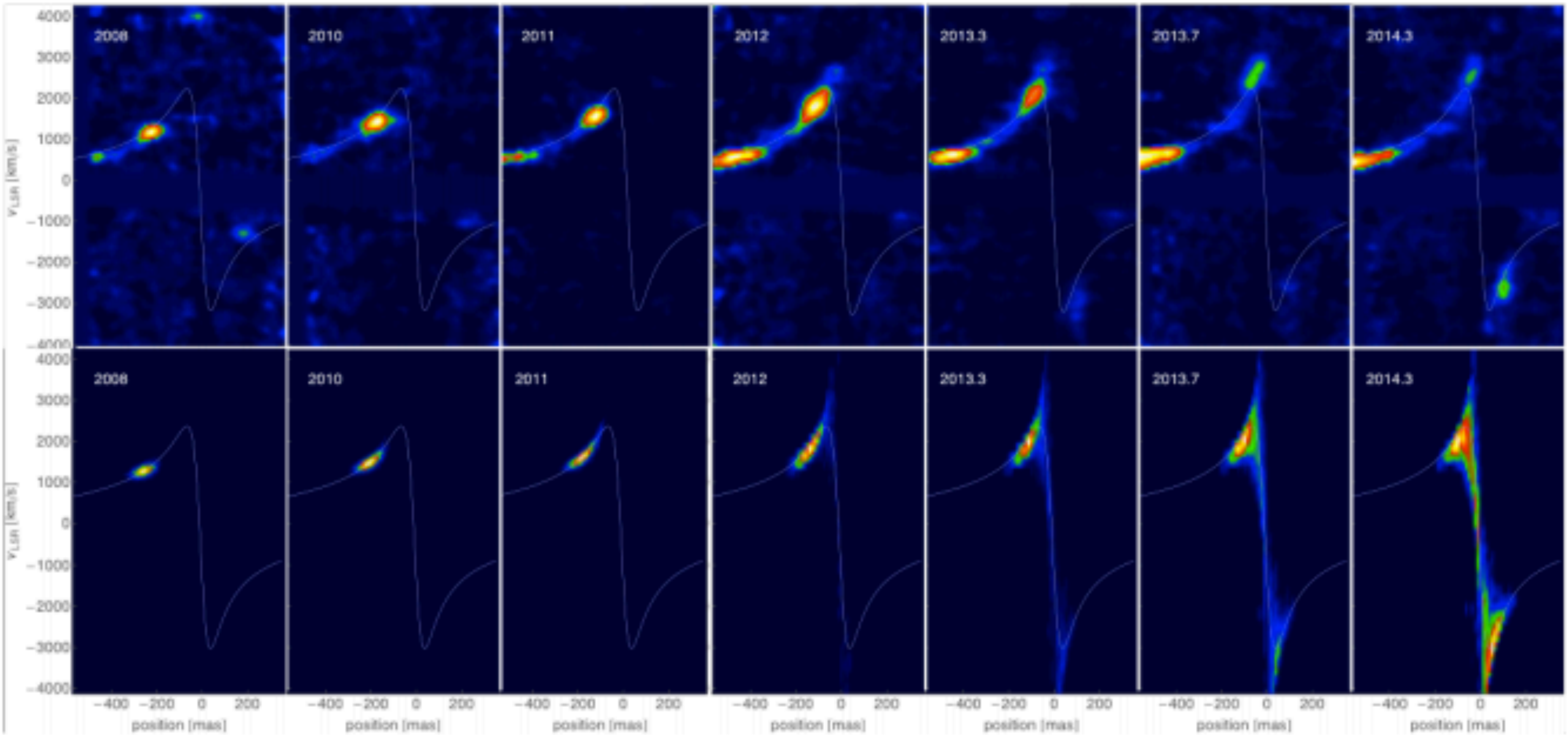
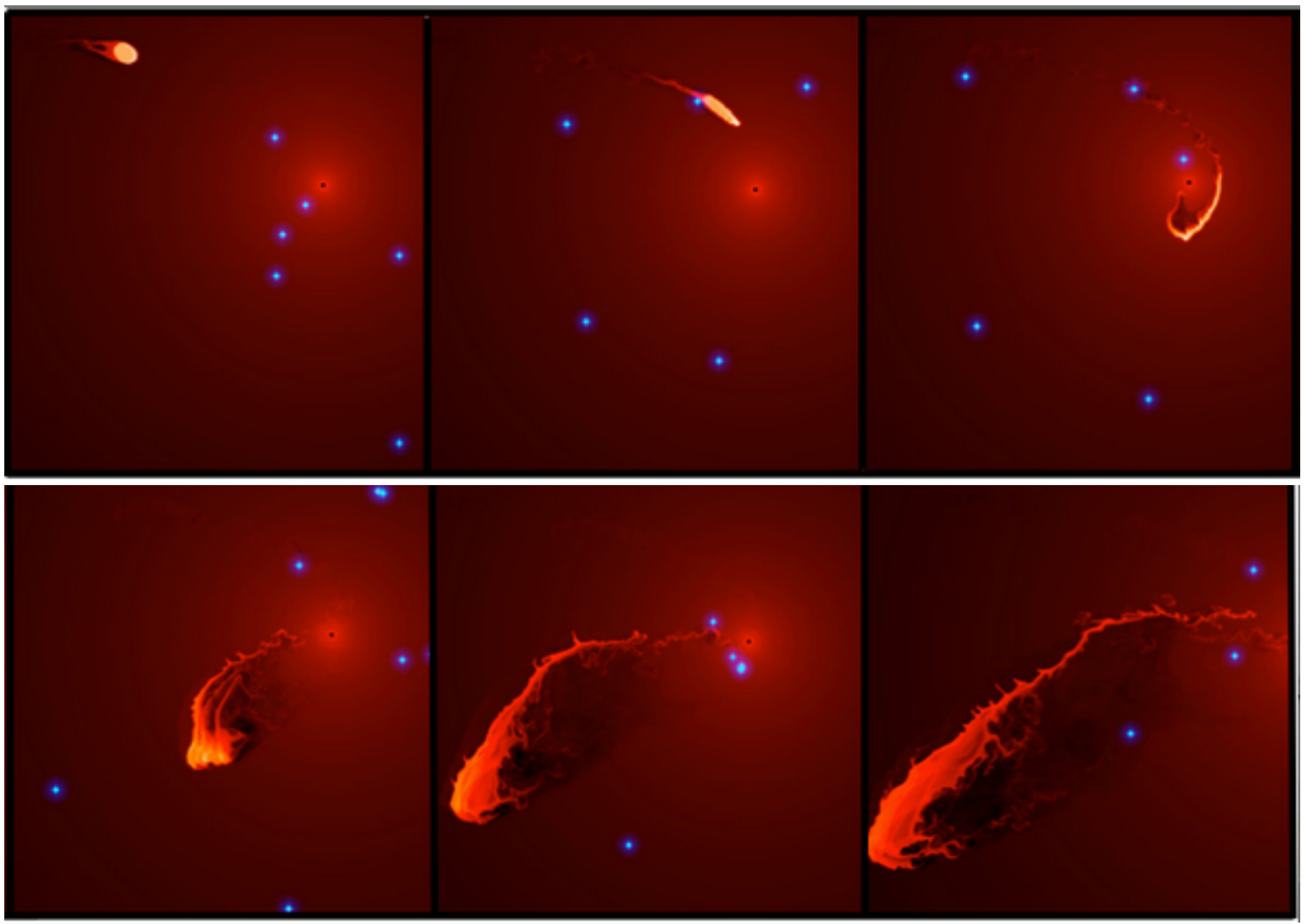


Figure 5: Comparison of the seven pv-diagrams from the epochs 2008, 2010, 2011, 2012, 2013/04, 2013/09 and 2014/04 (top row) with a test particle simulation (bottom row) of the same type as used in Gillessen et al. (2012). The scaling is adjusted in each observed map individually to optimally show the structure of the gaseous emission; the maps cannot be compared photometrically. The simulation plots show particle density.

G2 Cloud

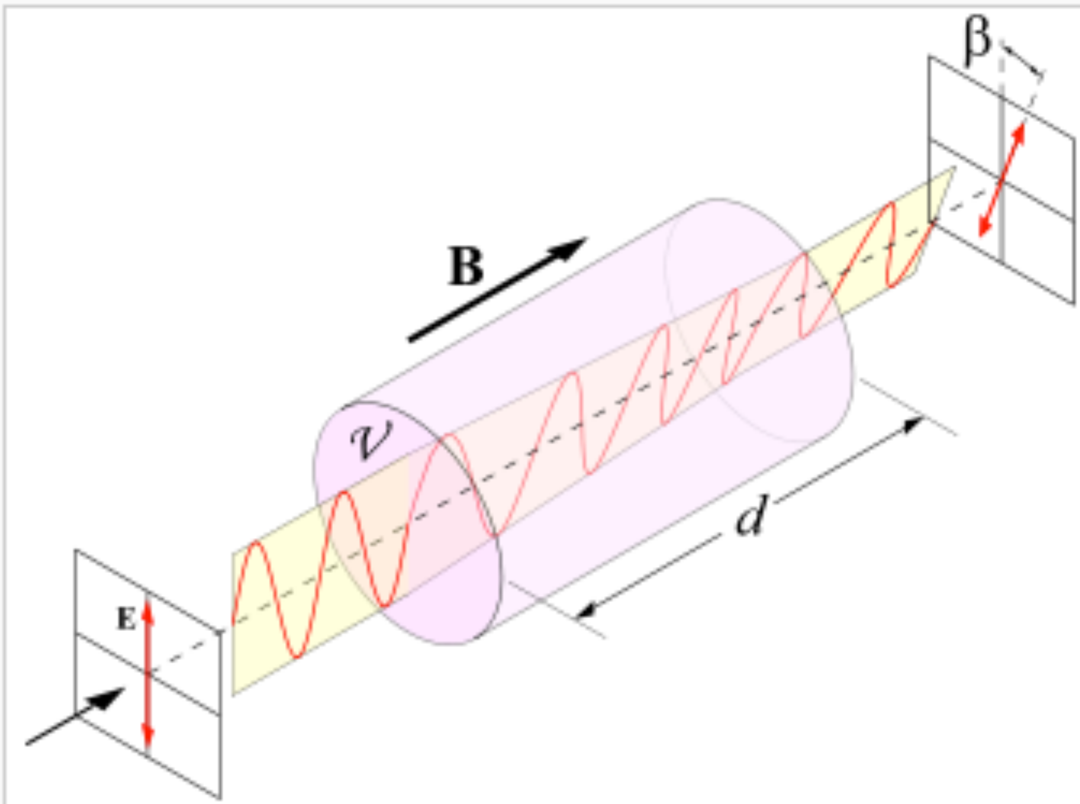
- G2 is at its closest approach, but yet still intact (Atel #6110, #6285)
- It implies it's denser than previously thought
  - E.g. hosts a star or is a star



All done for nothing ?

Eatough+13 (Nature)

- All the follow up led to the detection of a new pulsar in the G.C.
  - 3" away from Sgr A*



Polarization rotation due to the Faraday effect

All done for nothing ?

Eatough+13 (Nature)

- All the follow up led to the detection of a new pulsar in the G.C.
  - 3" away from Sgr A*

- Faraday rotation measurements lead to B>50μG

- If accreted down to the even horizon, this B field explains the observed emission from Sgr A*

Reading Assignment

- Star formation in the Galaxy
  - Chapter 19 in `The Formation of Stars' (Stahler and Palla)

- Galactic Center
  - http://casa.colorado.edu/~bally/ASTR6000_F11/Papers/GC_annurev.astro.34.1.645.pdf
  - Galactic Center Review: http://arxiv.org/pdf/1006.0064.pdf