Adaptive Optics: Observations & Prospects for AGN Studies

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- Adaptive Optics Concepts & Techniques
- QSOs at High and Low Redshift
- **The Galactic Center**
- **Nearby AGN**
- **Future Perspectives**

Phrases to avoid

'quiescent AGN' is an oxymoron

'active AGN' is a tautology

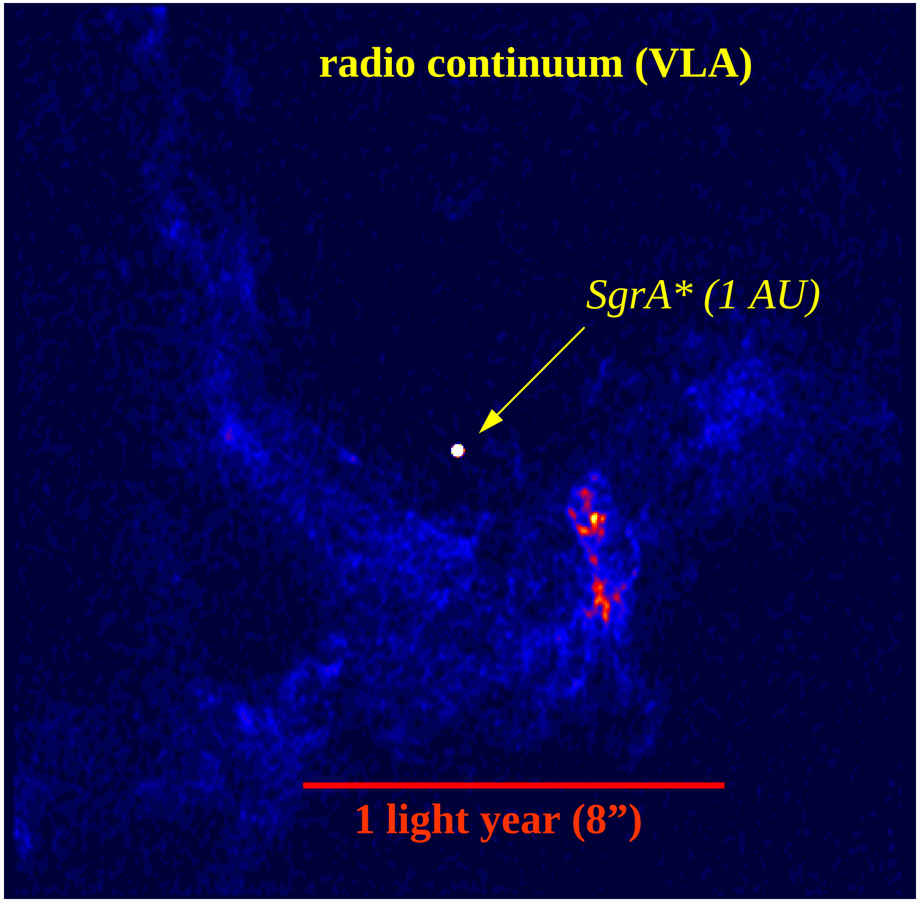
3. The Galactic Center

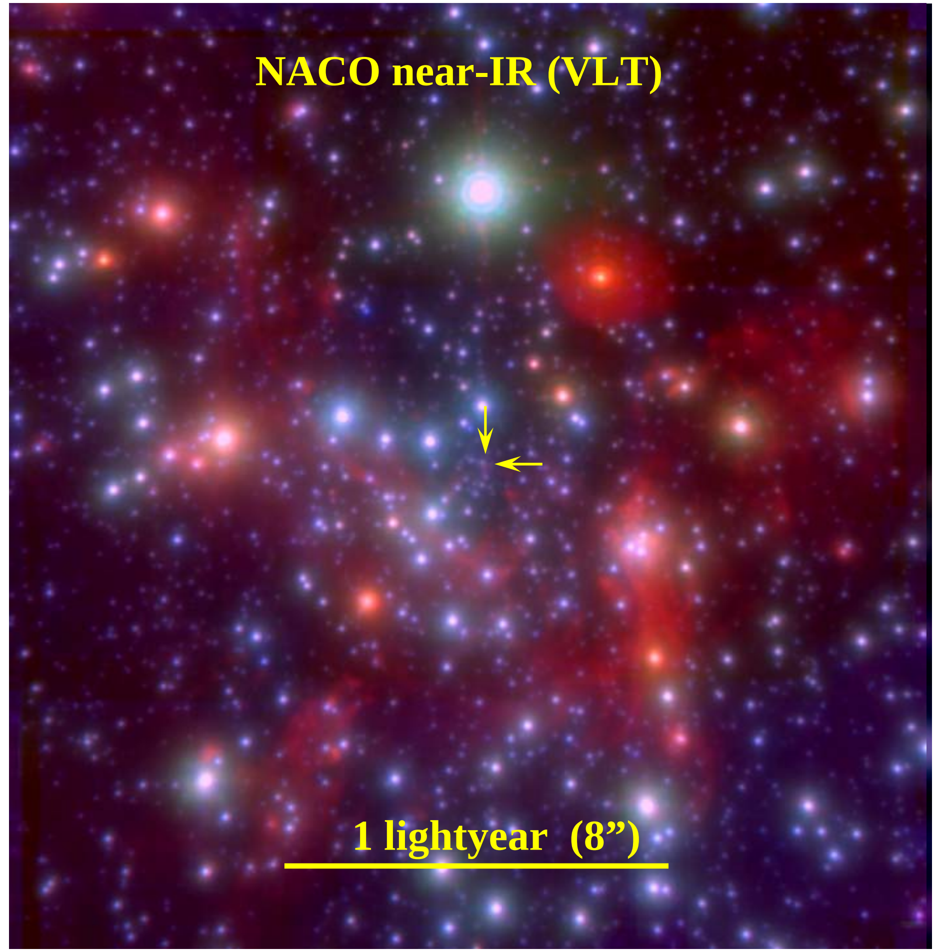
main references:
everything published in the last few years by

Genzel's group at MPE, Germany
Ghez's group at UCLA, USA
Eckart's group at Uni Köln, Germany

- Stars & their Orbits
- Paradox of Youth
- Why so faint?
- Infrared & X-ray Flares
- Next Steps into the Galactic Center

The Galactic Center

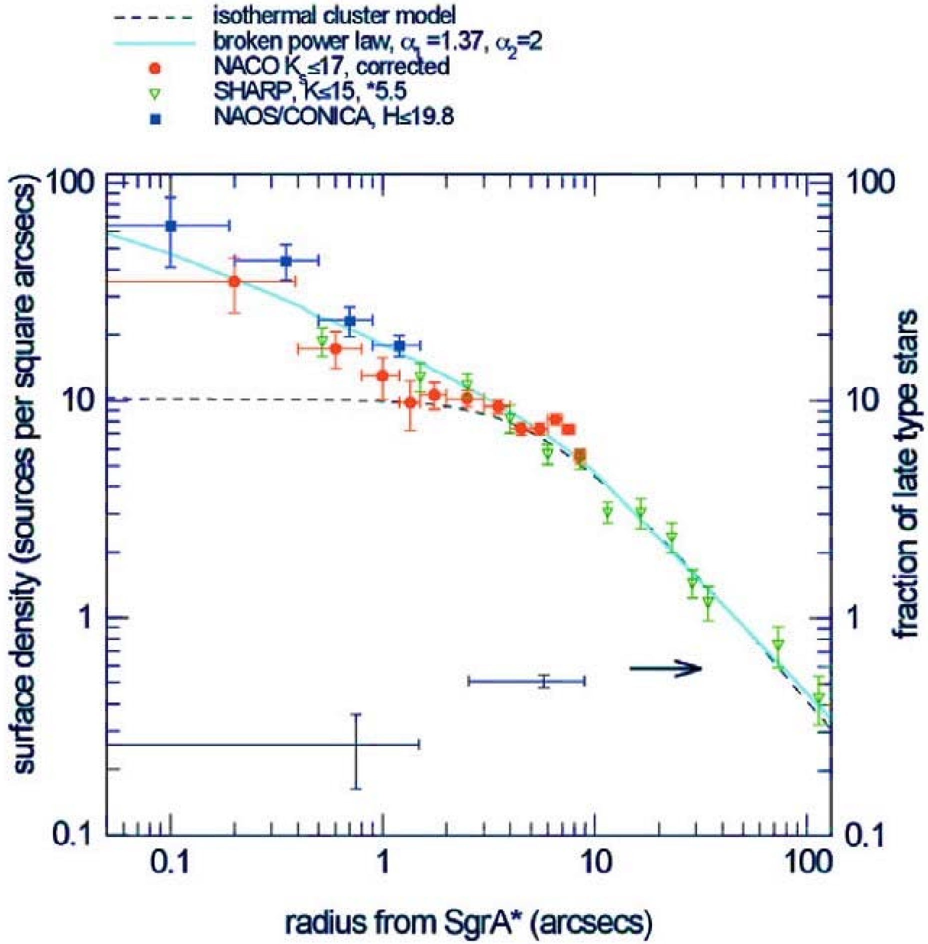




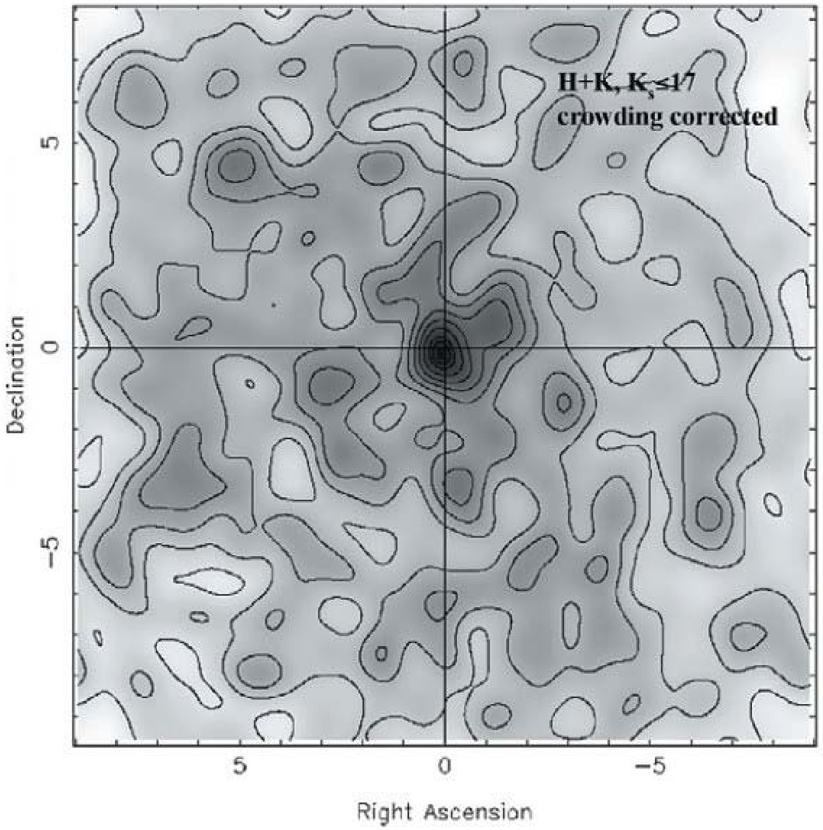
- proper motion 6mas/yr in galactic plane
- after accounting for sun's motion, residual is 0.4+/-0.9km/s
- SgrA* contains >10% of central mass

e.g. Reid et al. 2004

Density of Stars



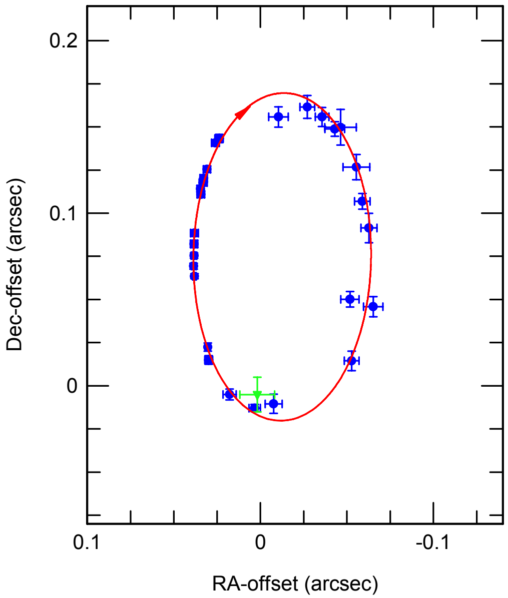
e.g. Ott et al. 2003,
Schoedel et al. 2006

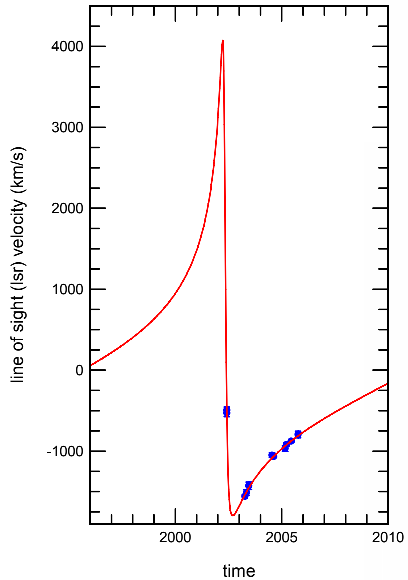


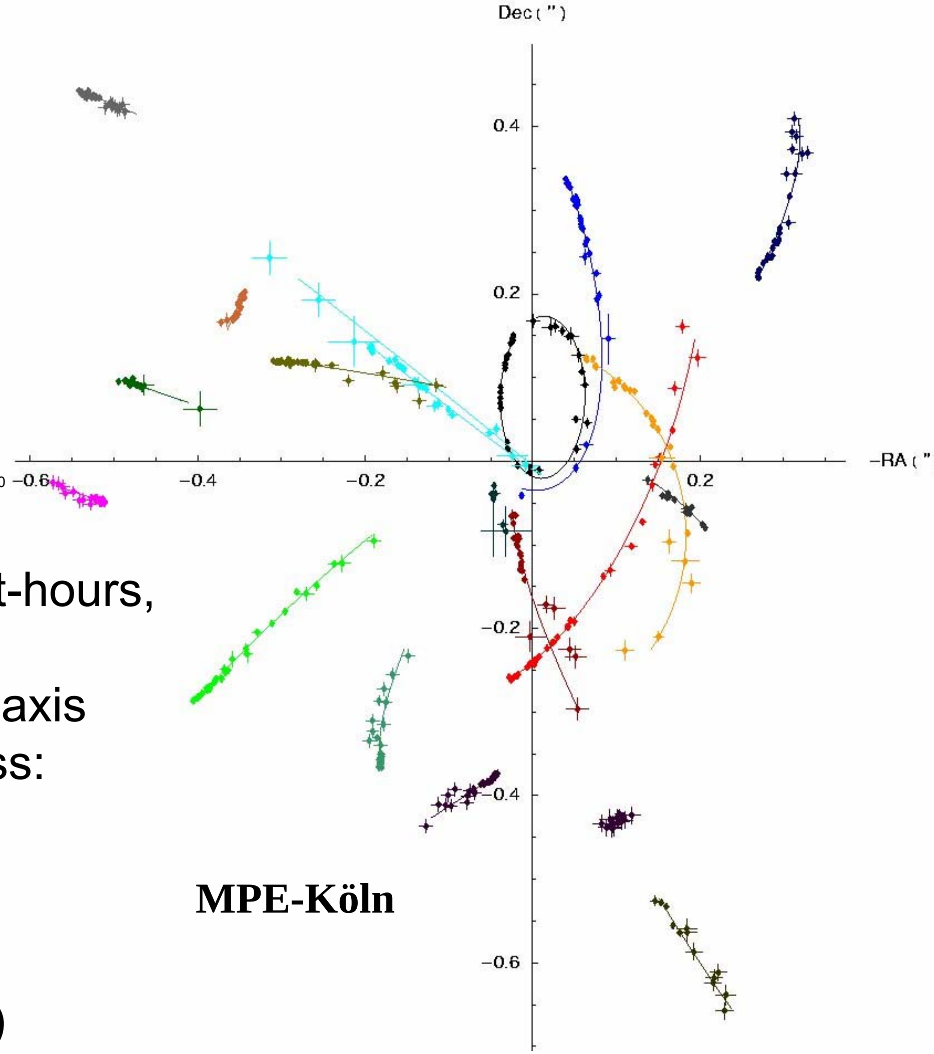
central stellar density exceeds expectations from an isothermal cluster, reaching about $10^8 M_{sun} pc^{-3}$ within 0.5” of SgrA*. This is consistent with theory of stellar cusp formation, except timescales are wrong.

stellar cluster is centered on SgrA* to within +/-0.2” (note that the light peaks on IRS7, which is a very bright complex)

Proper & Radial Orbital Motions







S2 closest approach to SgrA* was 17 light-hours, at which point it had velocity 8000km/s.
15.2yr orbital period & 4.4mas semimajor axis give, with Kepler's 3rd law, the central mass:

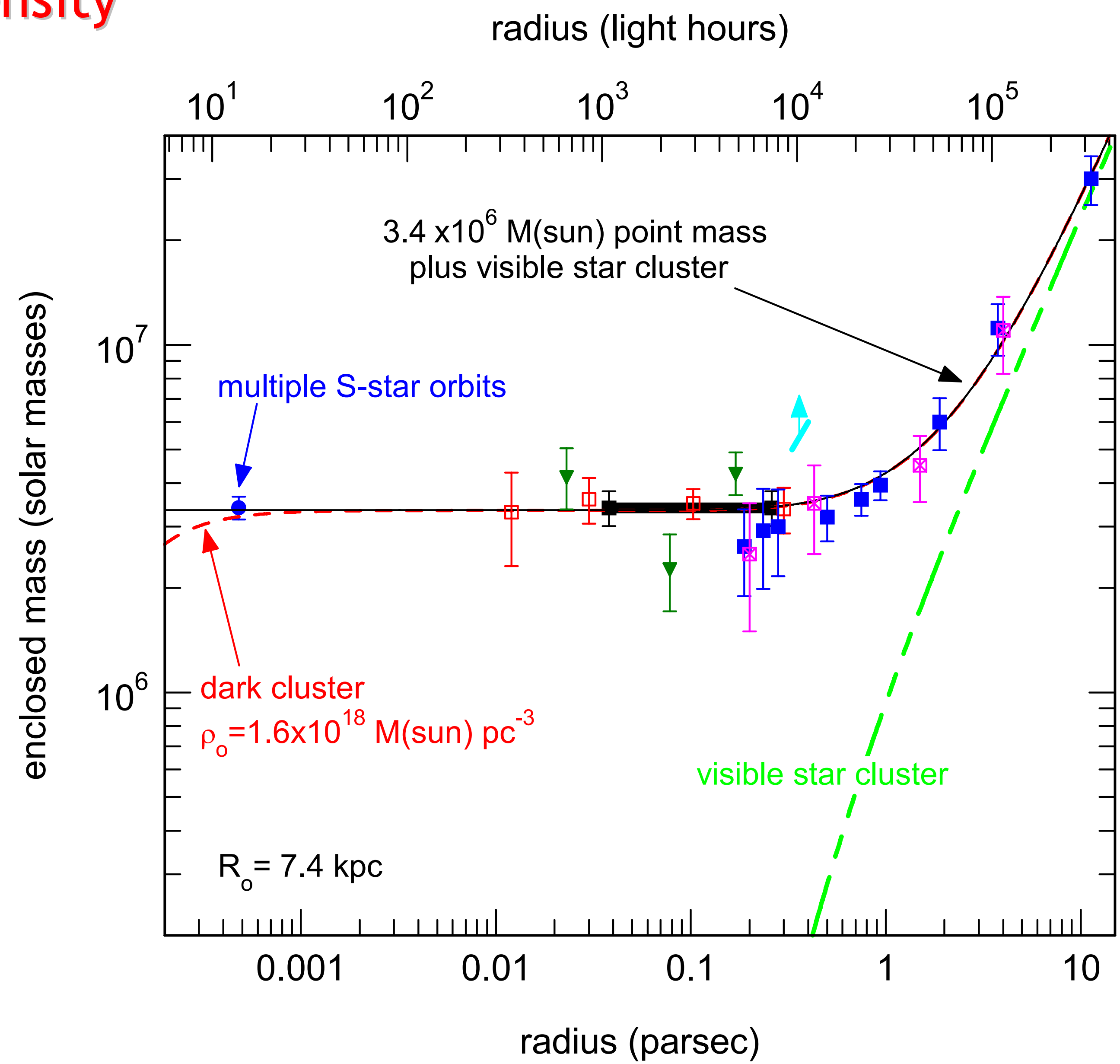
$$\left(\frac{P}{2\pi}\right)^2 = \frac{a^3}{G(M+m)}$$

M_o 3.4 ±0.24 (±0.3) 10^6 ($M_\odot$)
R_o 7.4 ±0.23 (±0.5) (kpc)
(mass contained within a few light hours of SgrA*)

e.g. Eisenhauer et al. 2005

Central Mass Density

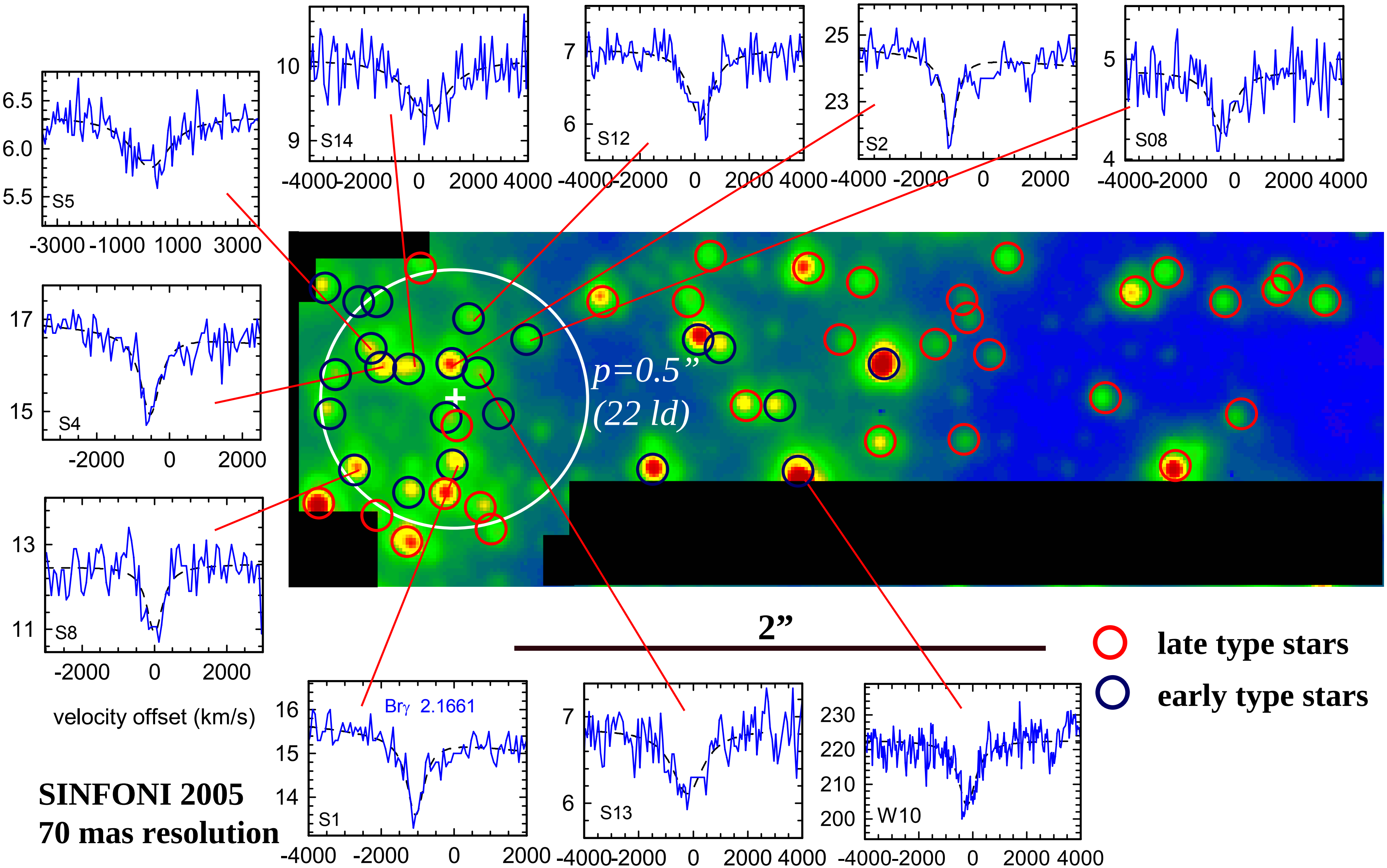
Hypothesis for a dark cluster of low mass stars, neutron stars, or black holes can be rejected since its density would imply a lifetime of only 10^5 yrs, but stars in the centre are much older.



e.g. Eisenhauer et al. 2005, Ghez et al. 2005

Paradox of Youth

>90% of all K<16 stars in the central cusp are young main sequence B stars



SINFONI 2005
70 mas resolution

Paradox of Youth

Normal, non-coherent, two body relaxation requires 150Myr for stars to migrate to central parsec. This is too slow: longer than the main sequence lifetime of stars >2 M_{sun} (e.g. S2 is 15M_{sun} with lifetime ~10Myr). So how did they get there?

local star formation:
tidally disrupted 'dispersion ring' evolving into a star forming accretion disk.
problem: very high densities

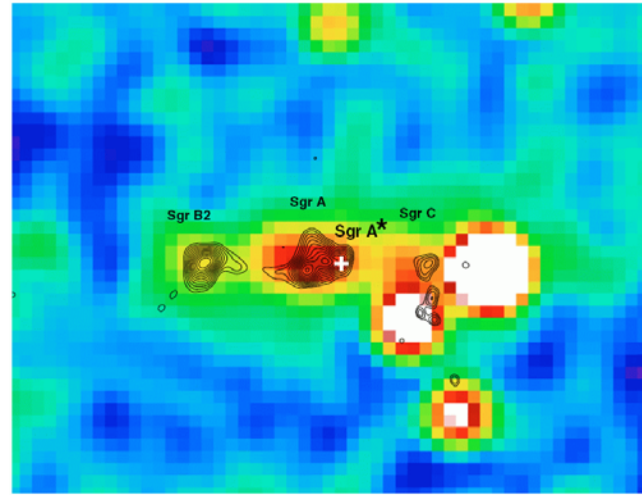
external formation:
transport by in-spiraling massive cluster.
problem: very large cluster mass and density

transport by scattering:
star/stellar-BH scattering
problem: large number of stellar BHs, large number of B stars on eccentric orbits

old stars masquerading as youths:
rejuvenation by merging or stripping
problem: merger number & rates, speed of stars, normalcy of S stars

Why is SgrA* so Faint?

- dM/dt: ~10^{-3} $M_{\odot}yr^{-1}$ at R~50 pc
  ~10^{-4} $M_{\odot}yr^{-1}$ at R~1 pc
  ~$10^{-5..6}$ $M_{\odot}yr^{-1}$ at R~0.01 pc
  ~10^{-8} $M_{\odot}yr^{-1}$ at R_s~$3x10^{-7}$ pc
- dM/dt ~10^2 times greater ~$10^{2.5}$ years ago
- dM/dt strongly dependent on angular momentum distribution of stars in central cusp; & highly variable

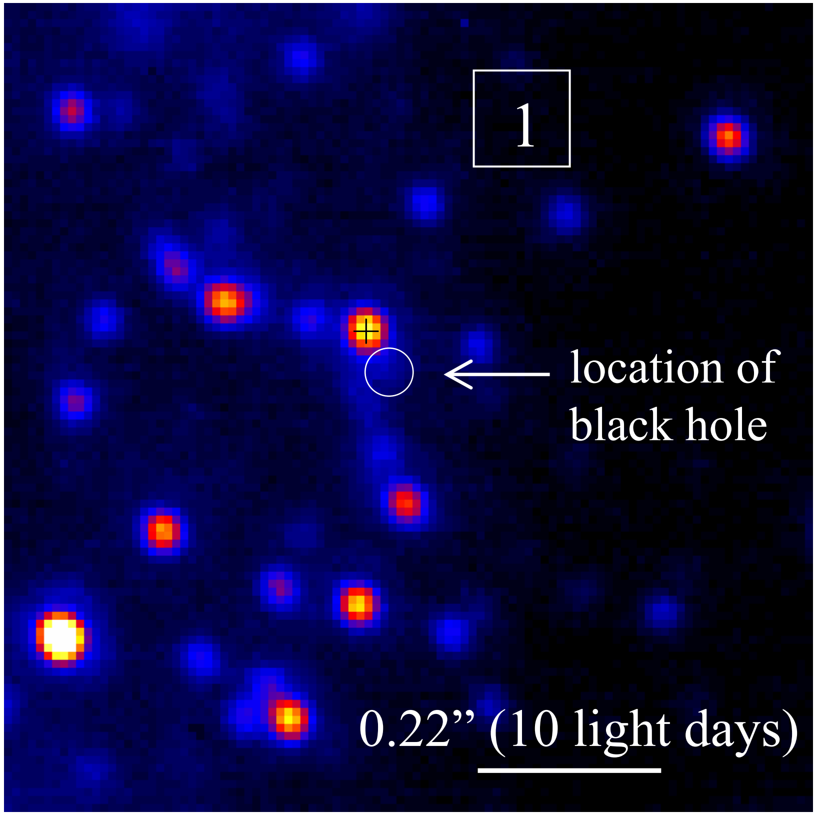


Hard X-rays compton scattered & reprocessed by nearby molecular cloud suggest SgrA* was low luminosity AGN (~10^{39} erg s^{-1} at 2–200 keV) 300-400 yrs ago. (Revnivtsev et al. 2004)

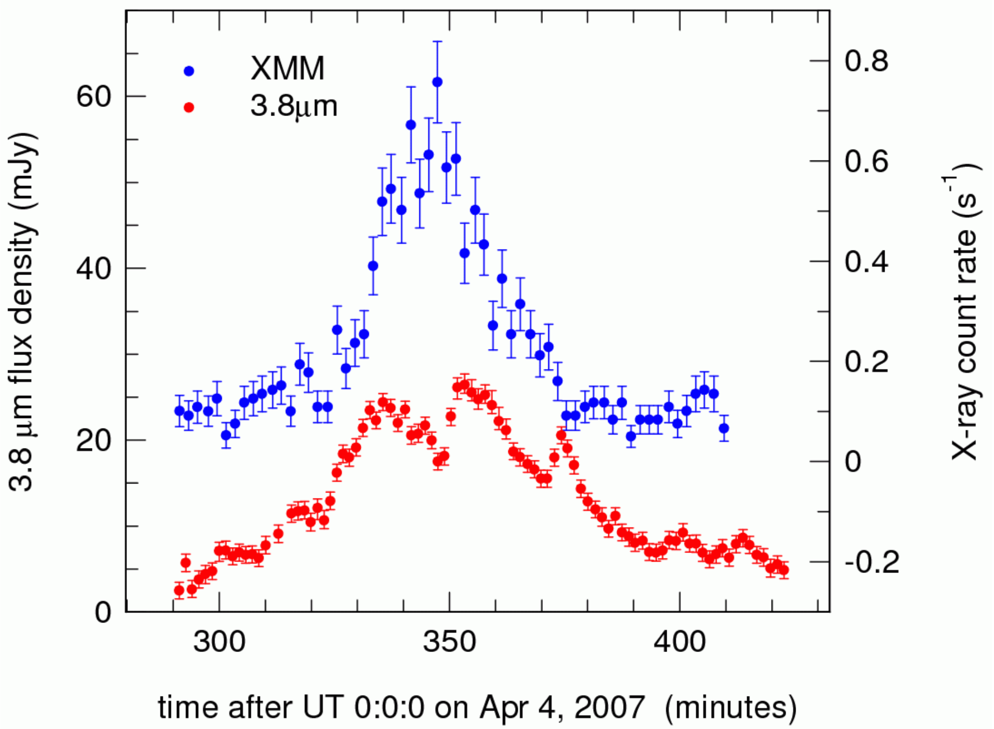
Cuadra & Nayakshin 2006 model:

- fast 700km/s young stellar winds; slow 200km/s winds; orbital motion of stars
- mean accretion rate onto BH $3\times10^{-6}M_{sun}yr^{-1}$ but with considerable variability
- gas has 2-phase structure: hot X-ray emitting gas & cold filaments, which settle into a disk; slow winds create cold gas clumps which introduce the variability

Infrared and X-ray Flares

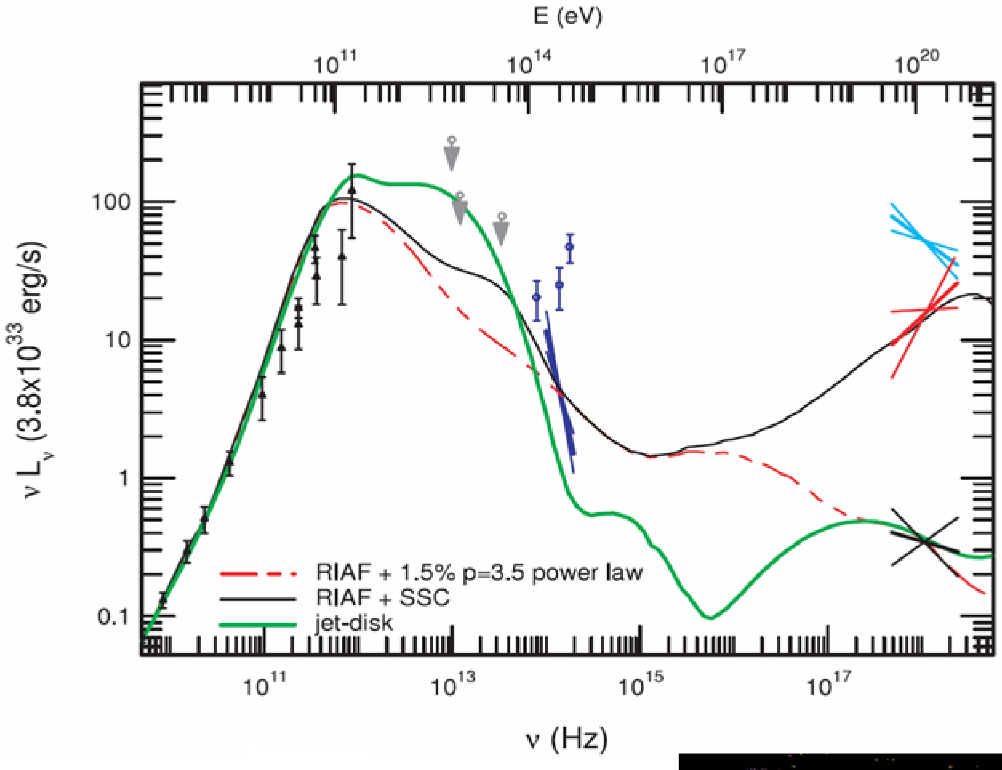


NACO (VLT) H-band, 40 mas resolution 1min per image (Genzel et al. 2003)



D. Porquet, G. Hasinger, *priv. comm.*

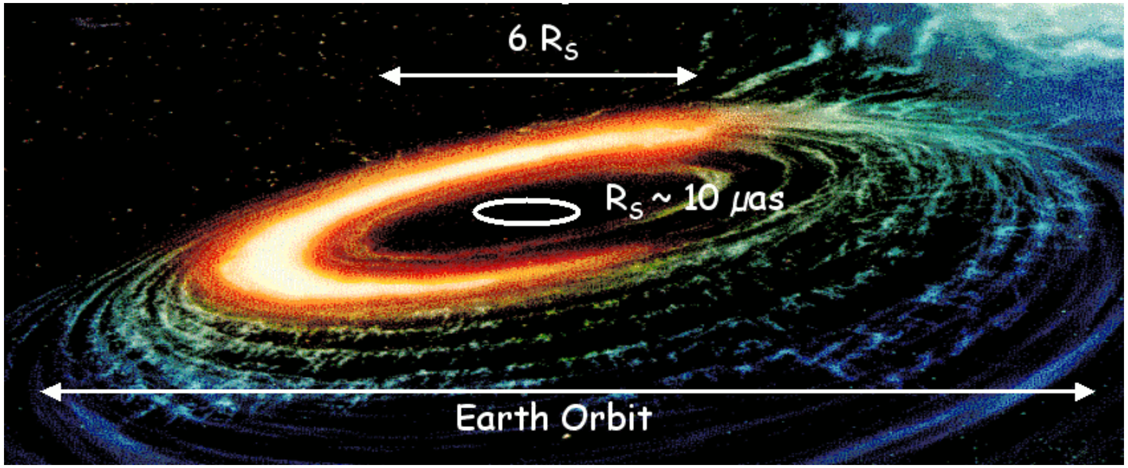
What causes the Flares?



Infrared emission is caused by an increase of the non-thermal tail of highly relativistic electrons (synchrotron models) due to transient heating/acceleration; emission is strongly affected by doppler effect, beaming, lensing, etc…

orbiting hotspot: t~17min

synchrotron emission:
$t \sim 8\text{min}\ B_{30}^{-3/2}\ \lambda_2^{1/2}$



Next Steps into the Galactic Center: GRAVITY

Periodicity within flare light-curve suggests matter on last stable orbit, believed to be a compact spot of hot gas emitting synchrotron radiation.

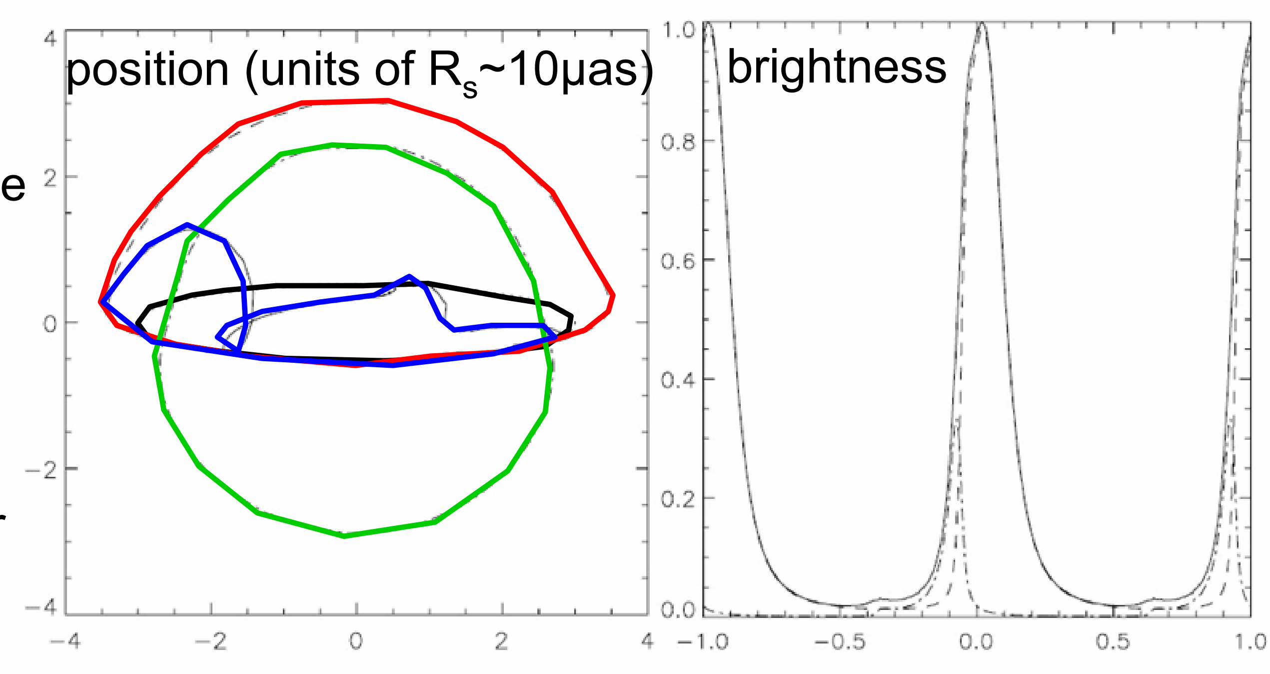
GRAVITY can probe General Relativity in the strong field limit by detecting motion of this gas around the black hole.

black: true orbit (80° inc.)

red: observed primary image

green: observed secondary image

blue: centroid (taking into account relative brightness, lensing, beaming, & doppler effects)



By observing many flares, one can improve statistics of centroid measurements & distinguish between different models

4. Nearby AGN

main references:
Davies, Mueller Sanchez, + (ApJ accepted)
Hicks, Davies, Mueller Sanchez, + (in prep)

- AGN at adaptive optics scales
- Black Hole Masses
- Obscuring Molecular Gas
- Nuclear Star Formation
- Feeding the Monster

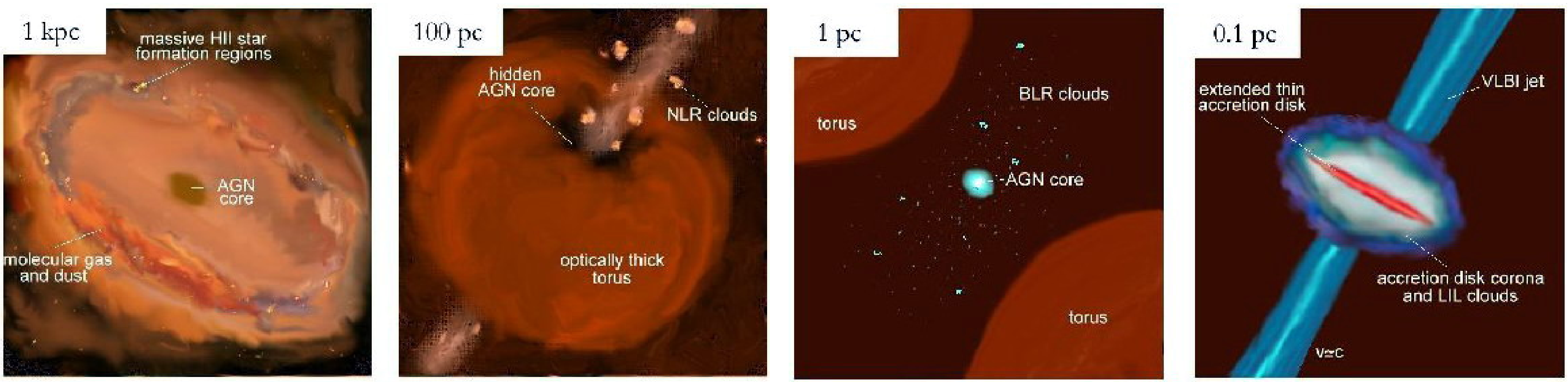
AGN at Adaptive Optics Scales

What physical scales can we study with adaptive optics?

examples	Distance	1”	50mas
NGC4945, Circinus, Cen A:	4Mpc	20pc	1pc
NGC1068, NGC3227, NGC1097	15Mpc	70pc	4pc
1 Zw 1	280Mpc	1.4kpc	70pc

What structures exist on those scales?

- circumnuclear region of host galaxy
- narrow line region
- torus & nuclear region of host galaxy
- broad line region
- black hole (sphere of influence)



NB: sizescales here are for a QSO

AGN at Adaptive Optics Scales

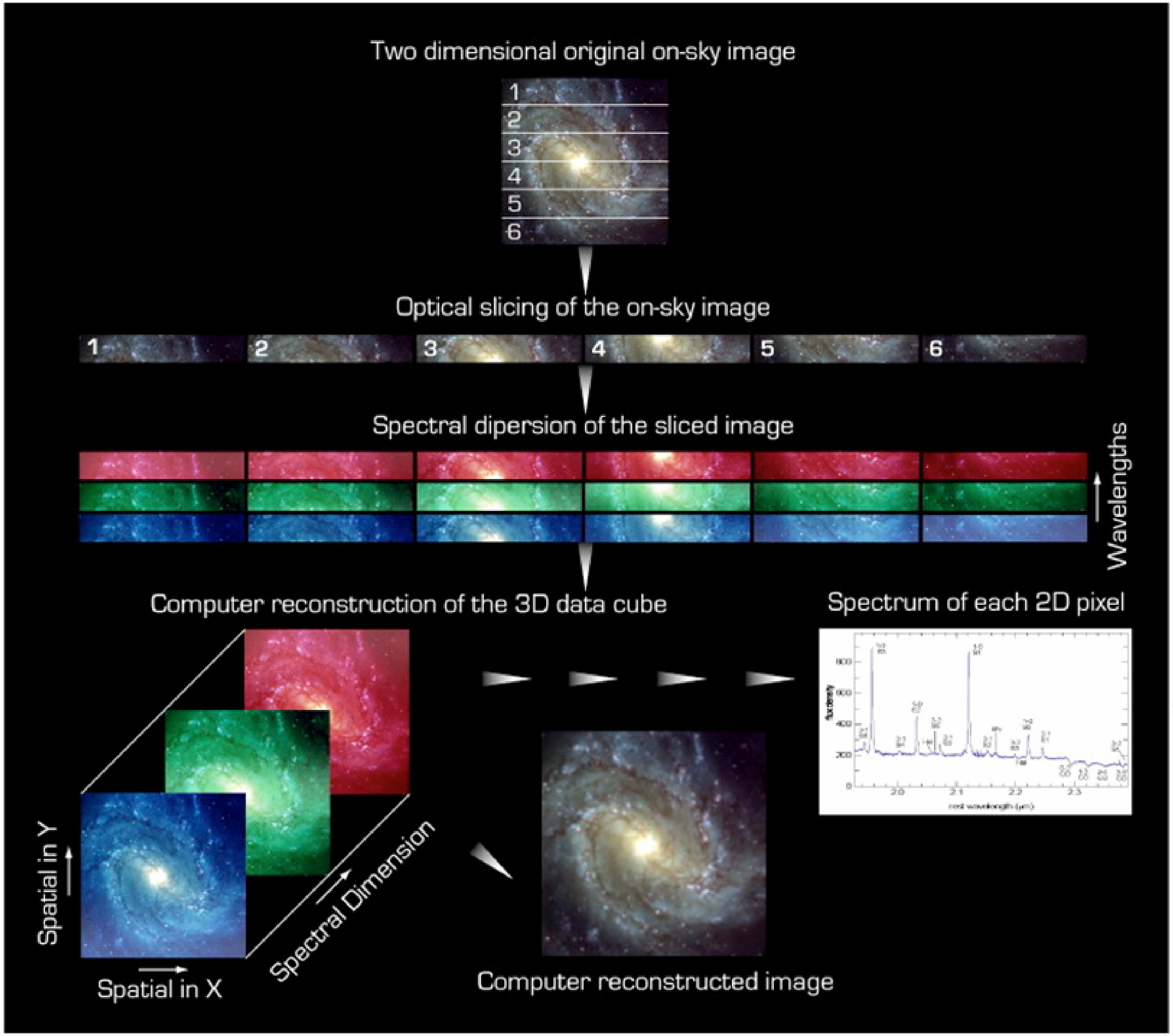
some open questions

- black hole mass from stellar dynamics to test reverberation masses (BLR geometry) & M_{BH}-σ relation
- distribution & kinematics of molecular gas; relation to obscuring material (torus); fuelling the AGN
- extent, intensity, & history of recent star formation and relation to AGN (impact on fuelling & feedback)

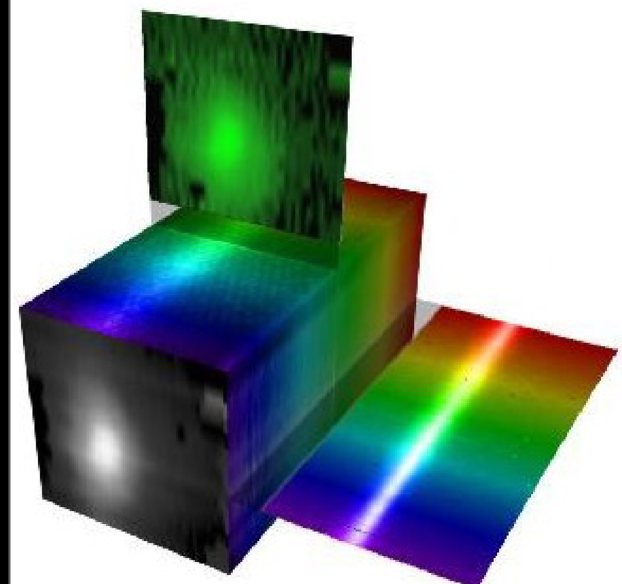
advantages of observing in the near infrared

- spatial resolution from AO (but not necessarily increased sensitivity)
- contrast against AGN
- reduced extinction wrt optical
- diagnostics for stars, ionised gas, & molecular gas

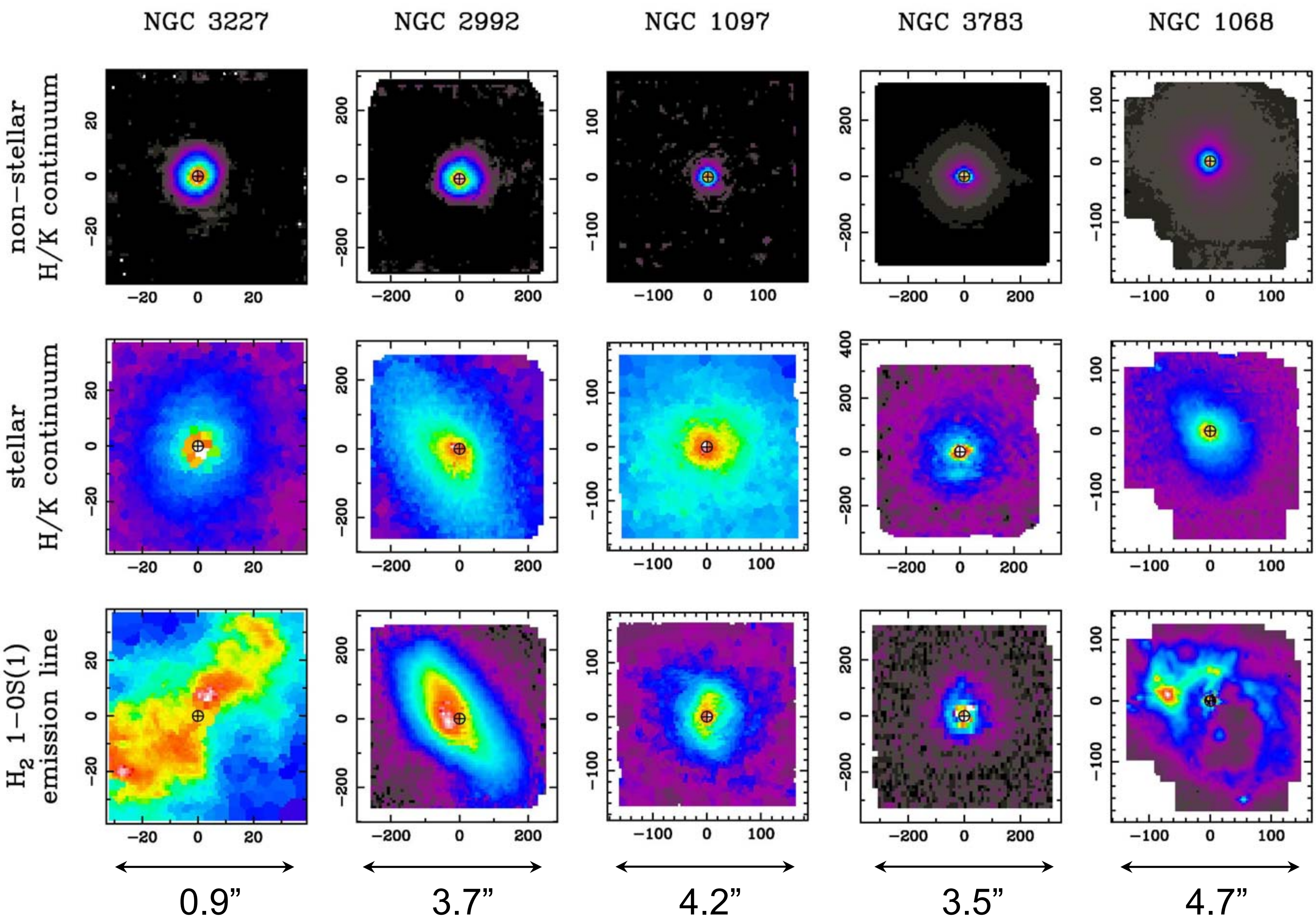
Integral Field Spectroscopy



- image slicing
- dispersion
- reconstruction
  into a datacube



SINFONI results



Black Hole Masses

what measurements are possible & how good are they?

• stellar proper motions	only our Galaxy so far (but soon also M31?)
• reverberation mapping	yielded most results
• masers	accurate but applicable to few galaxies
• gas dynamics	can be influenced by in/out flows
• stellar dynamics	ideal if radius of influence of black hole resolved

BH radius of influence

$$r_h \sim \frac{GM_{BH}}{\sigma^2} \sim 11.2 \left(\frac{M_{BH}}{10^8 M_{sun}} \right) \left(\frac{\sigma}{200 kms^{-1}} \right)^{-2} pc$$

but M-σ relation is

$$M_{BH} = 1.35 \times 10^8 \left(\frac{\sigma}{200 kms^{-1}} \right)^{4.02} M_{sun}$$

so to zero order

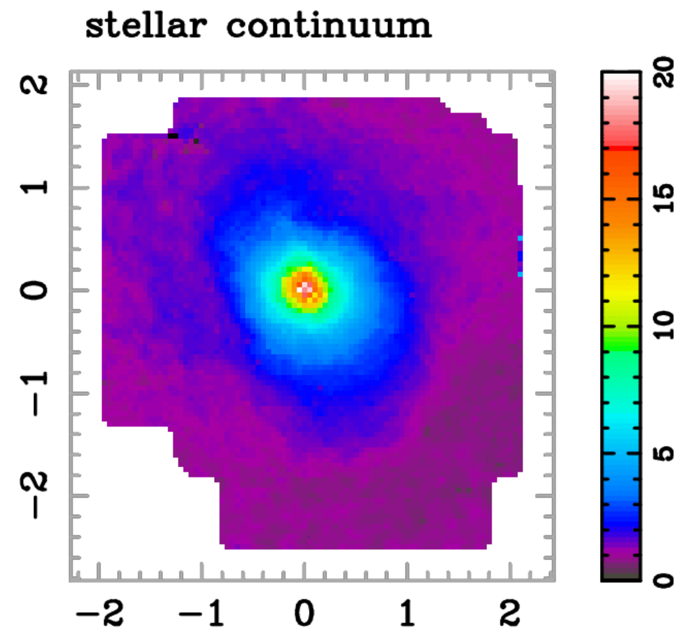
$$r_h \sim \left(\frac{M_{BH}}{10^6 M_{sun}} \right)^{0.5} pc$$

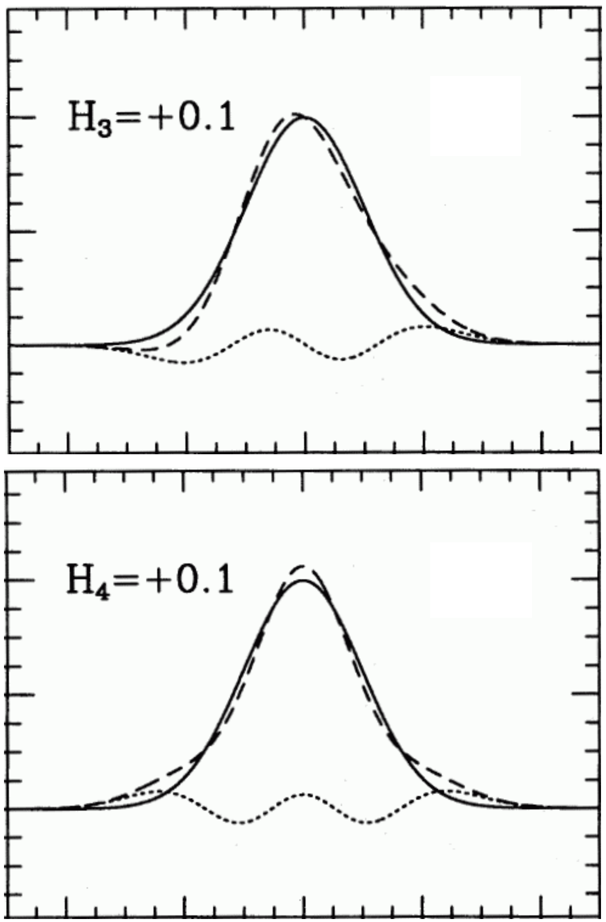
i.e. can resolve r_h in Seyfert galaxies out to ~20Mpc

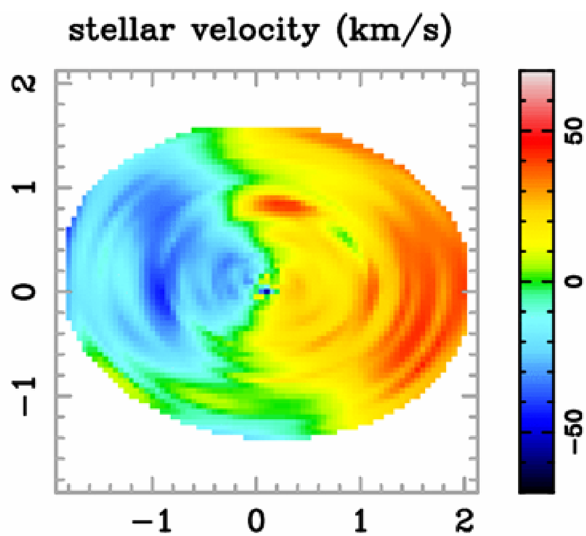
What do we need to measure?

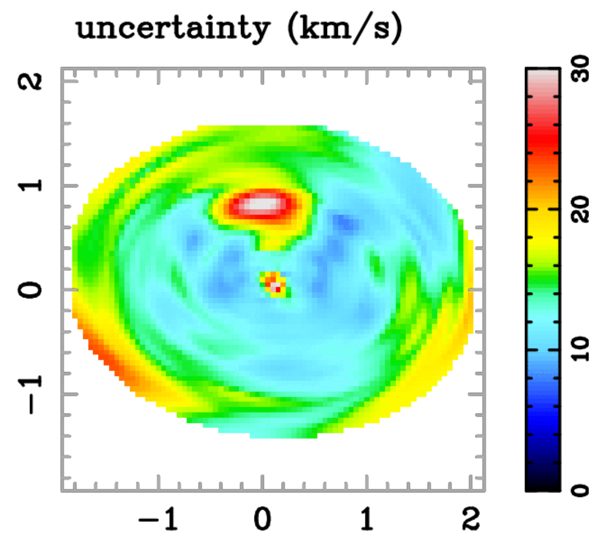
stellar kinematics:

- velocity
- dispersion
- ideally also Gauss-Hermite terms h3 & h4
  (if noise permits)





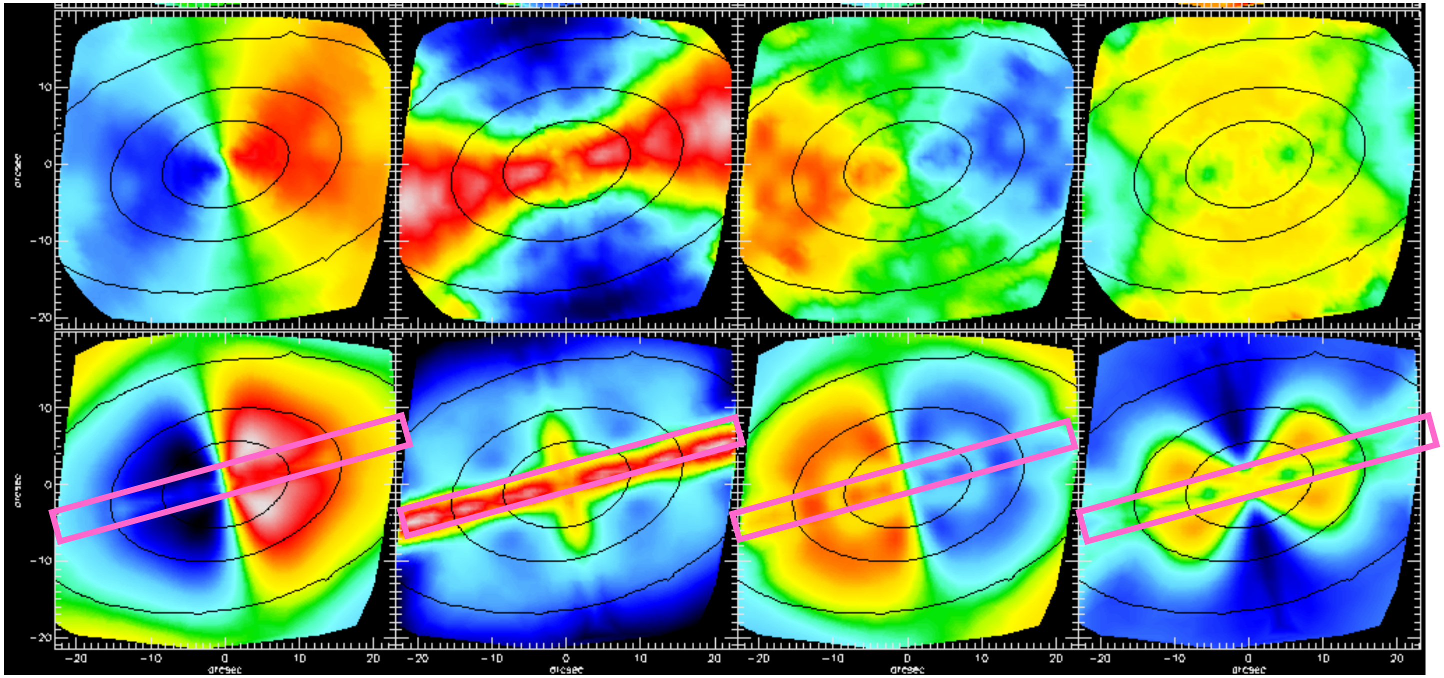




Importance of 2D kinematics

data & models from SAURON project

v σ h_3 h_4



symmetrized data for NGC4473

axisymmetric model based on longslit

v σ h_3 h_4

Schwarzschild (orbit superposition) modelling

Model

- start with a defined potential (for M_{BH}, M/L & distribution)
- follow equations of motion to build up a library of orbits
- create linear (non-negative) combination of orbits
- must match luminosity profile
- X^2 minimised wrt LOSVD

for NGC3227

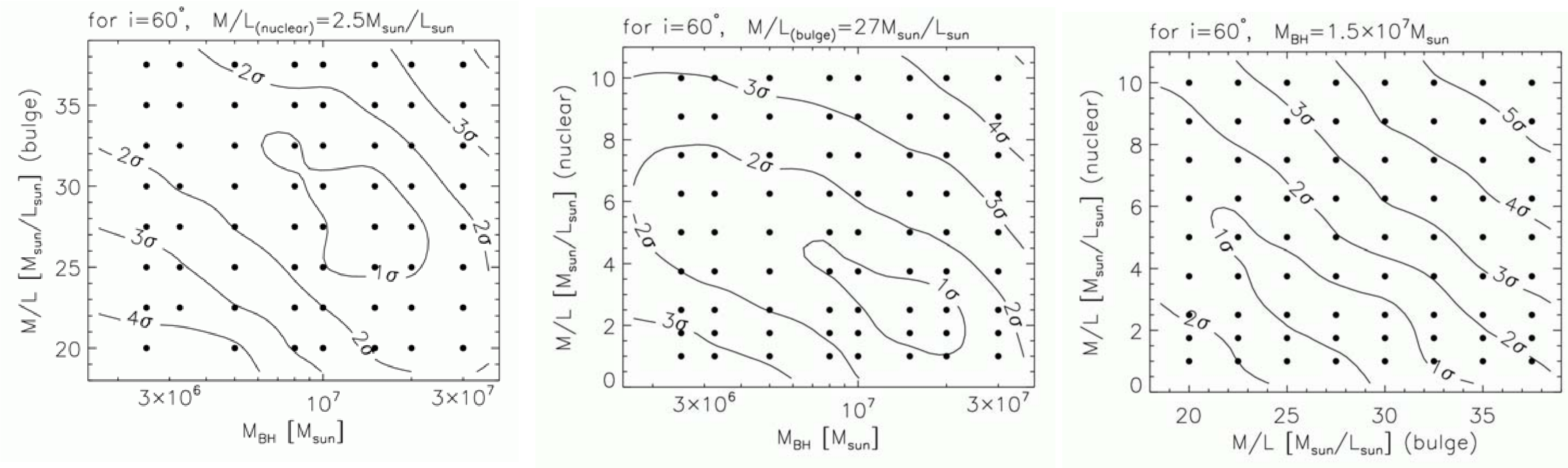
Mass-to-Light ratios

- 'disk' system – from star formation constraints
- bulge – in range 10-30 M_{sun} (Förster Schreiber et al. 2003)
- M/L_{disk}, M/L_{bulge}, and M_{BH} are varied independently to create a grid of models

Orbit Library

- 3300 library orbits in each direction (pro/retro-grade), sufficient for the LOSVDs, measured in 4 angular x 7 radial bins in each quadrant)
- inclination fixed at 60°
- mass distribution based on luminosity distribution & mass/light ratios of the 2 components

Results for M_{BH} in NGC3227



best fitting parameters:		from starburst modelling & expectations	
bulge M/L	27.5 M_{sun}/L_{sun}	bulge M/L	25-35 M_{sun}/L_{sun}
'disk' M/L	2.5 M_{sun}/L_{sun}	'disk' M/L	0.5 M_{sun}/L_{sun}
M_{BH}	1.5×10^7 M_{sun}		

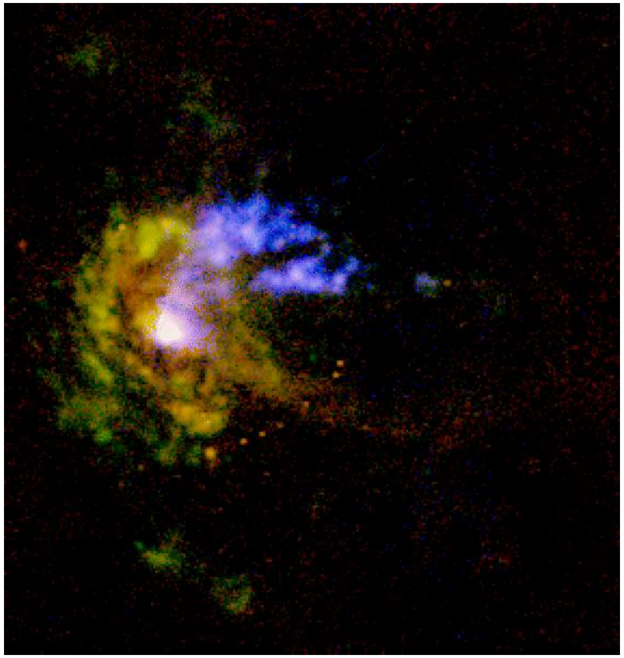
but doesn't include gas mass

consistency checks are important!

Obscuring Molecular Gas

What are the minimum criteria for the torus?

- consists of molecular gas (& dust)
- compact, size tens of parsecs
- optically thick, so as to obscure AGN when viewed edge on (column density at least 10^{22}cm^{-2})
- vertically extended, by several parsecs so as to provide collimation for ionisation cones

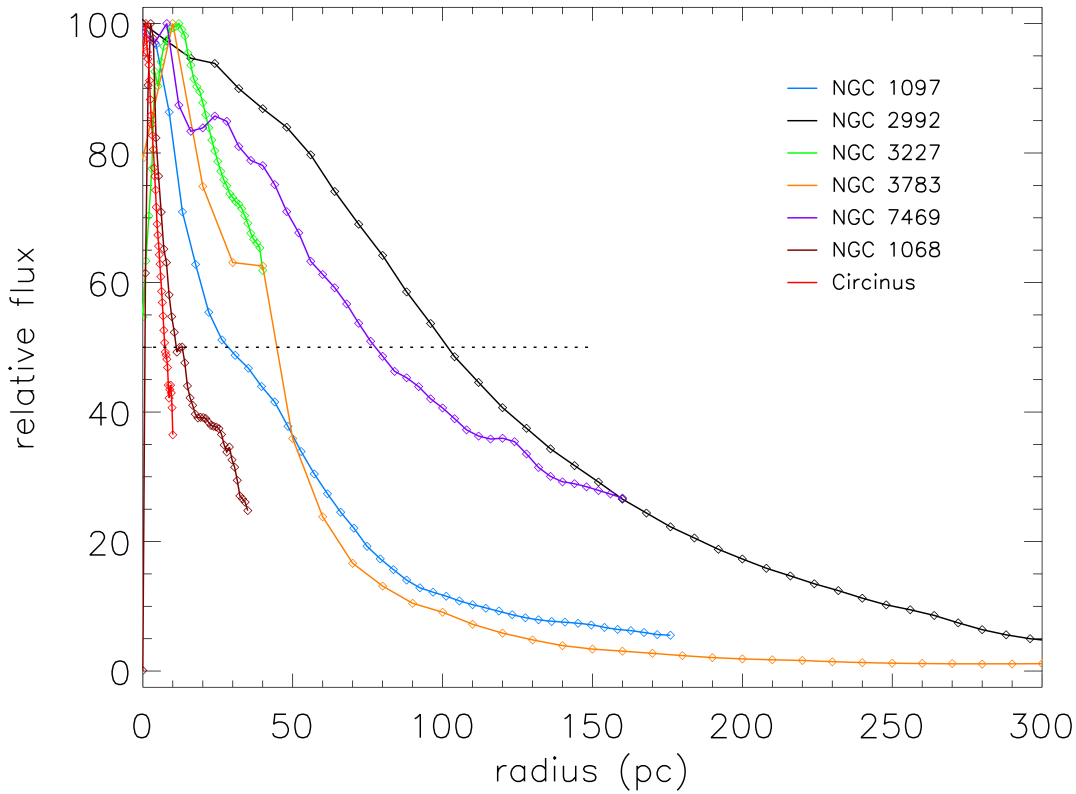


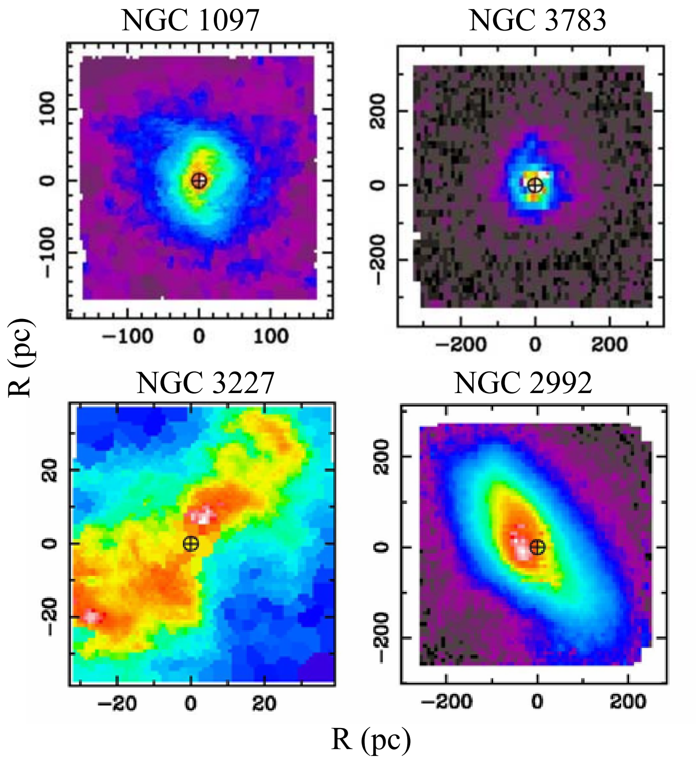
ionisation cone in Circinus is traced for ~15” = 300pc (Marconi et al 94)

[OIII] (blue)
Ha & [NII] (yellow)

Radial distribution of molecular gas

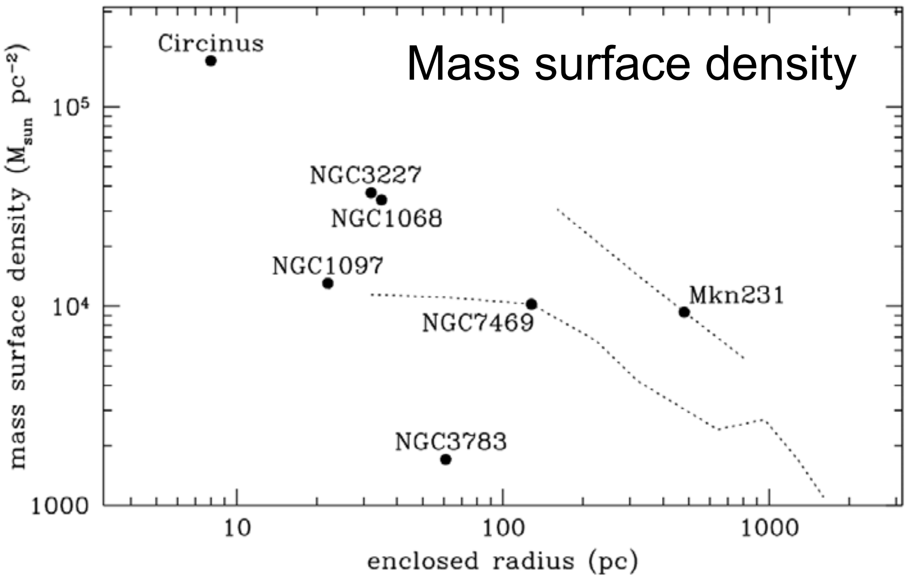
HWHM generally < 50pc

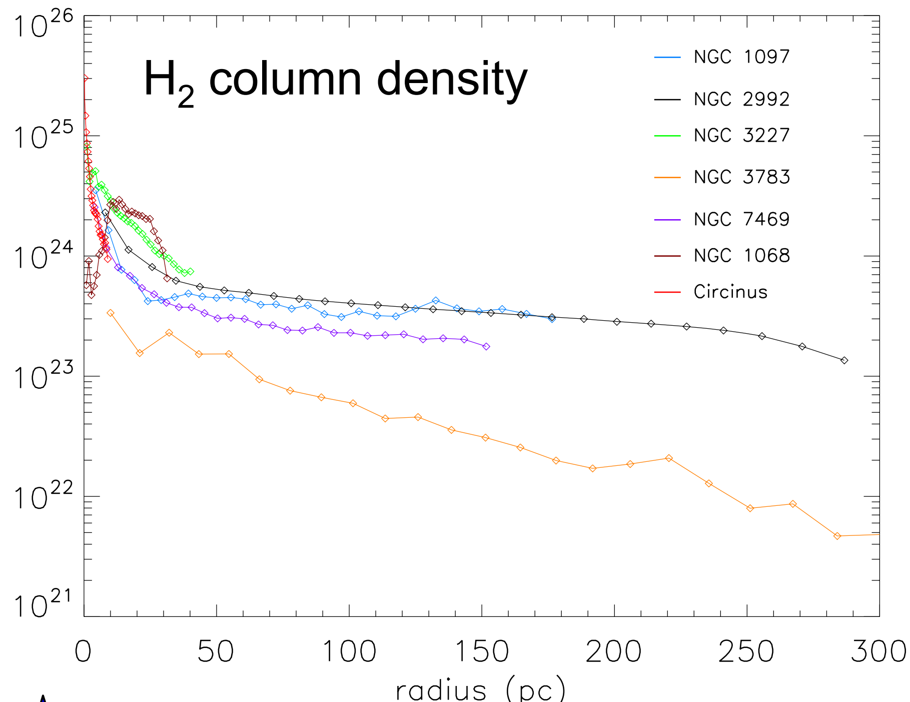




Column density of Molecular Gas

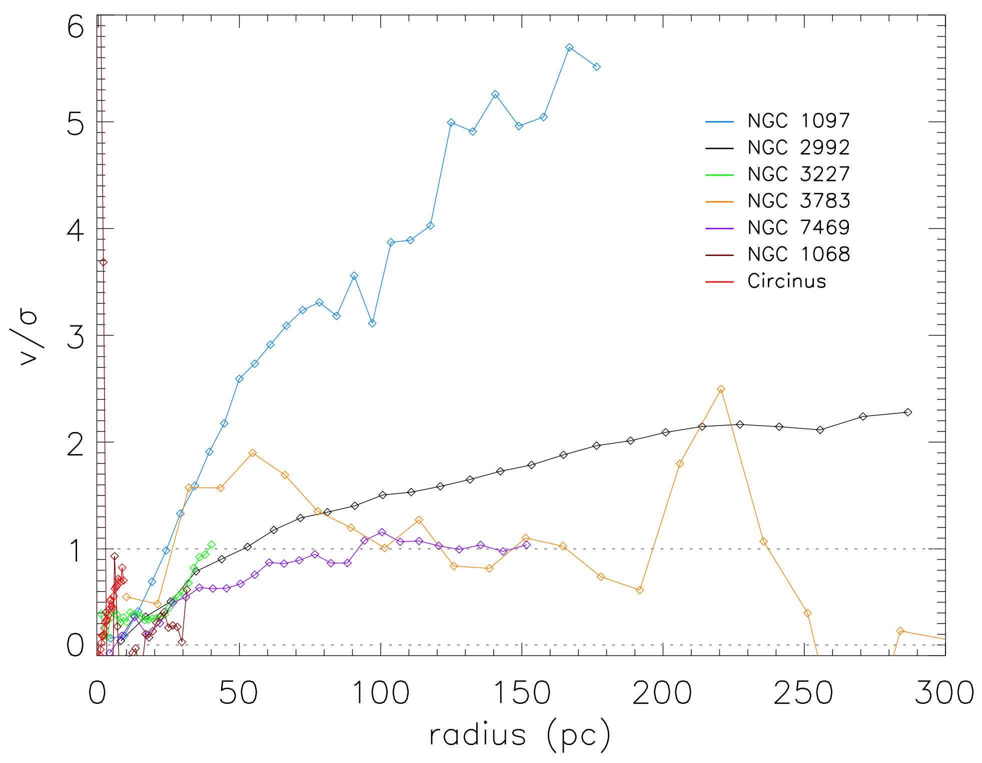
- estimate dynamical mass ~ $(V^2+3\sigma^2)R/G$
- assume gas fraction 10% (conservative)
- find column density $>10^{23}$ cm^{-2}
- this already implies the gas is clumpy – so as not to obscure lines of sight to the bulk of the star formation





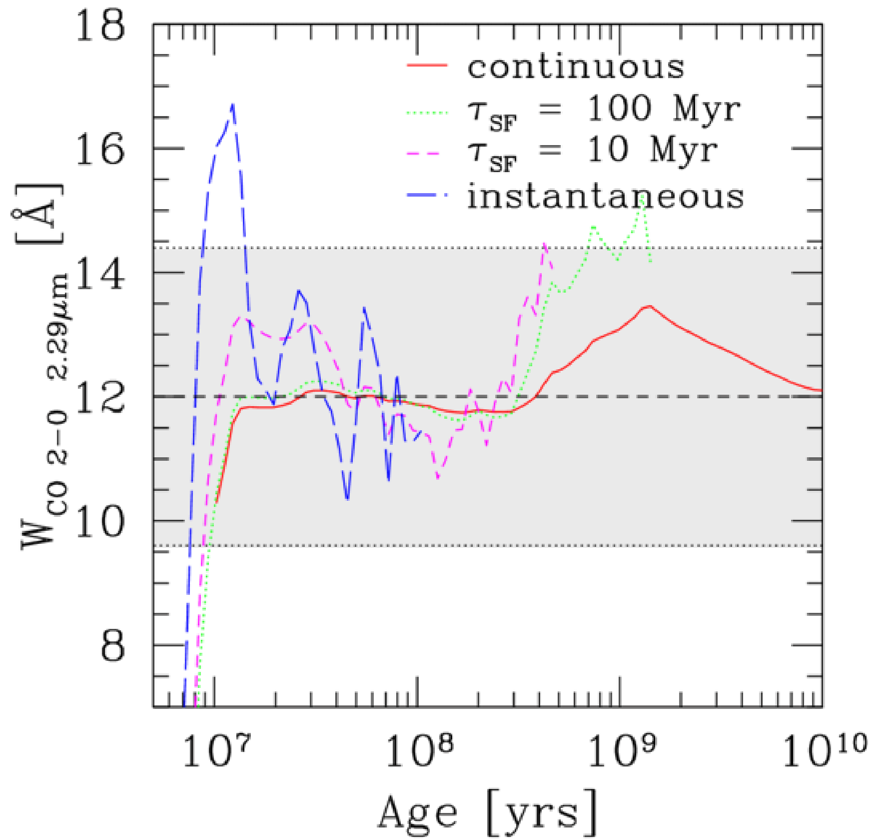
Scale height of Molecular Gas

- σ_{gas} ~ 50-100km/s in centers of these AGN
- but 1-0S(1) emission strongest for shock speeds 20-50km/s
- mm CO2-1 measurements of cold H2 also have large dispersions
- there are high dispersion 1-0S(1) lines in Orion: ‘bullets’
- bulk cloud motions must account for σ_{gas} in AGN
- distribution must be vertically extended

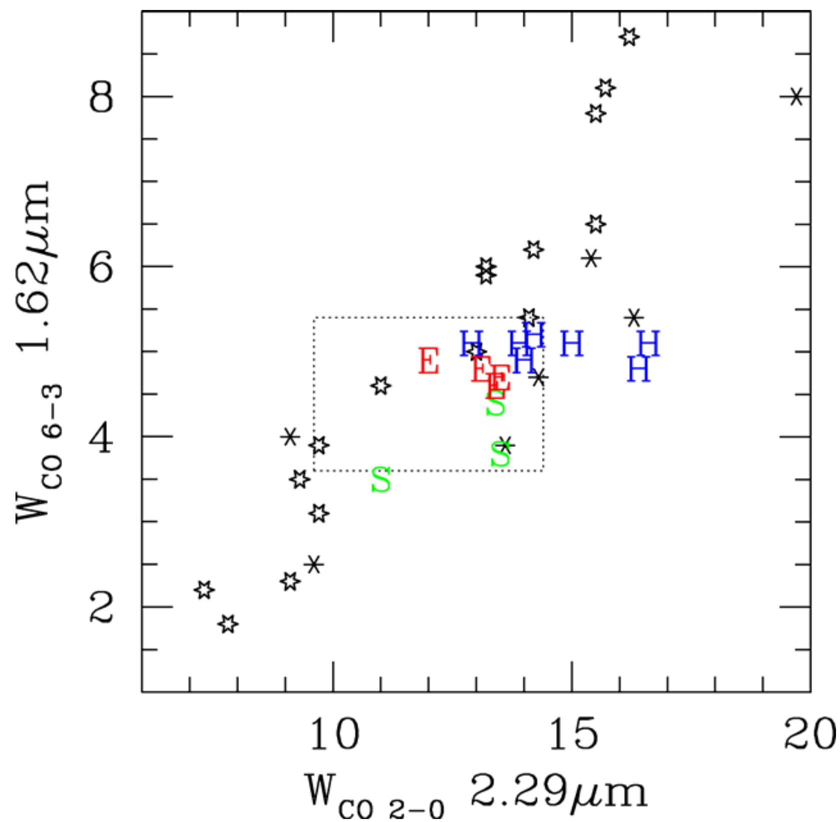


Nuclear Star Formation: correcting for dilution

It is possible to correct for dilution by AGN & estimate stellar continuum without knowing anything about the stellar population



STARS stellar cluster models
$W_{CO6\text{-}3}$ ~ 4.5Å & $W_{CO2\text{-}0}$ ~ 12Å



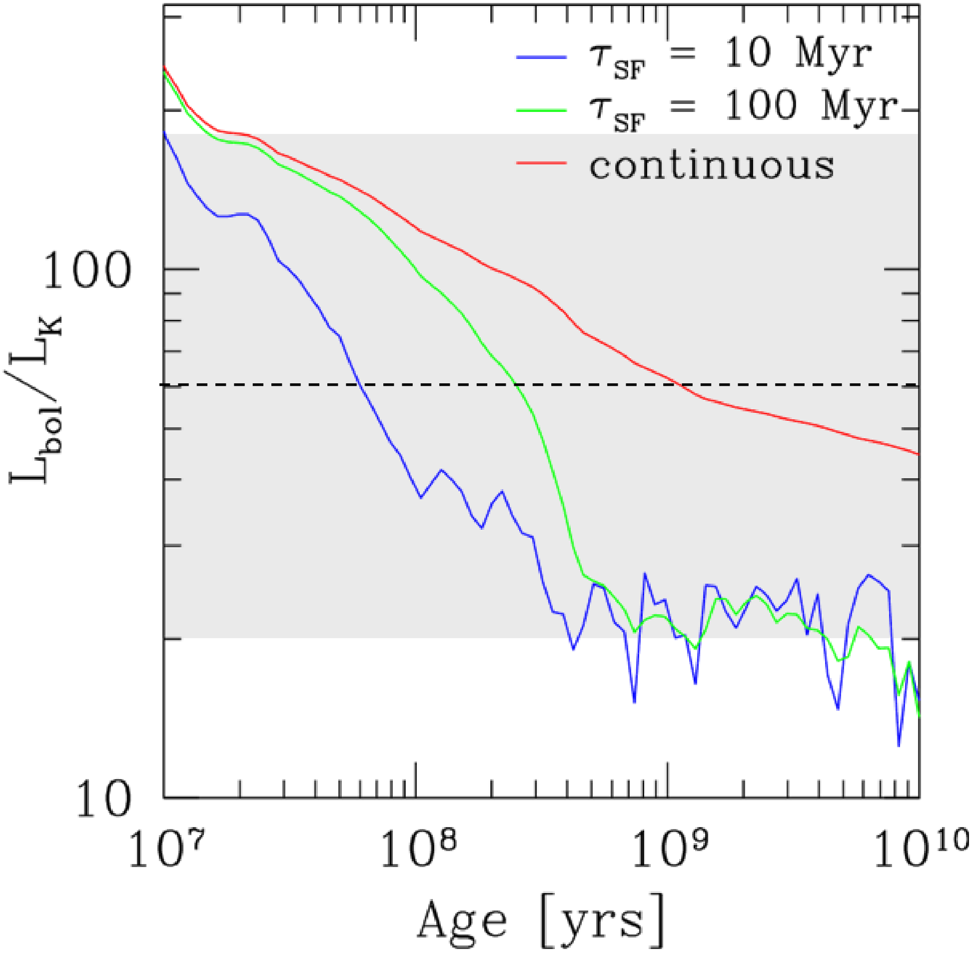
adapted from Oliva et al. 1995

can also run Starburst99 version 5.1 models: http://www.stsci.edu/science/starburst99/

Nuclear Star Formation: estimating L_{bol}

Estimating stellar bolometric luminosity is simple and robust

For the stellar continuum, it is possible to estimate L_{bol} from L_K to within a factor of 3 without knowing anything about the star formation history



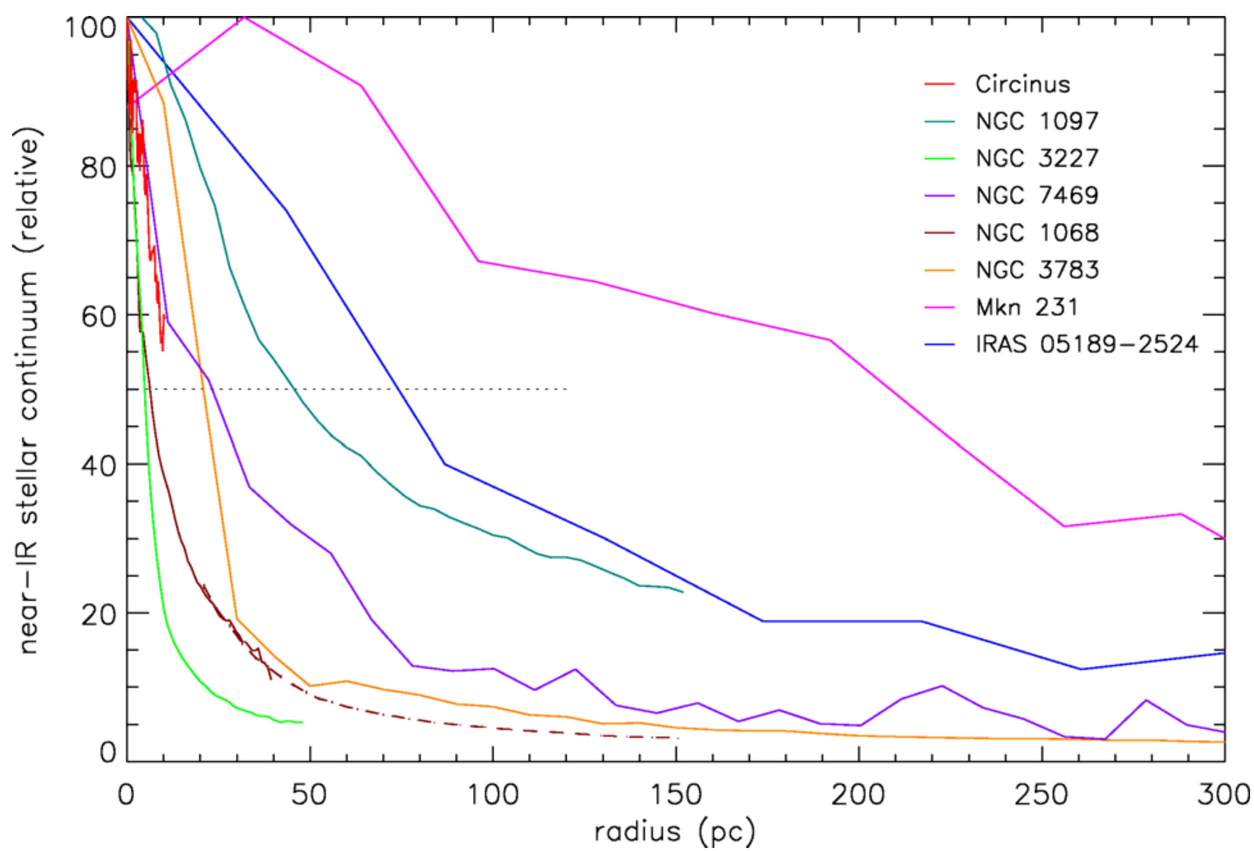
STARS stellar cluster models

Nuclear Star Formation: size & age

nuclear stellar continuum resolved in all cases

age is 10-300 Myr

but low $W_{Br\gamma}$ means star formation is no longer active

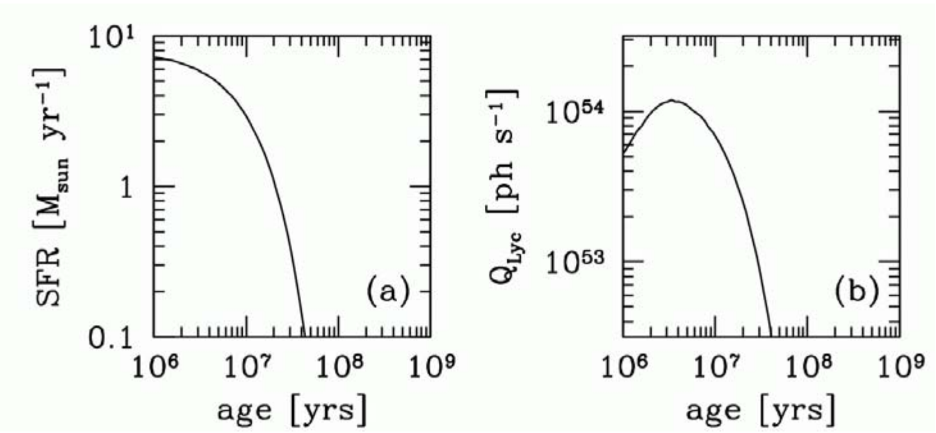


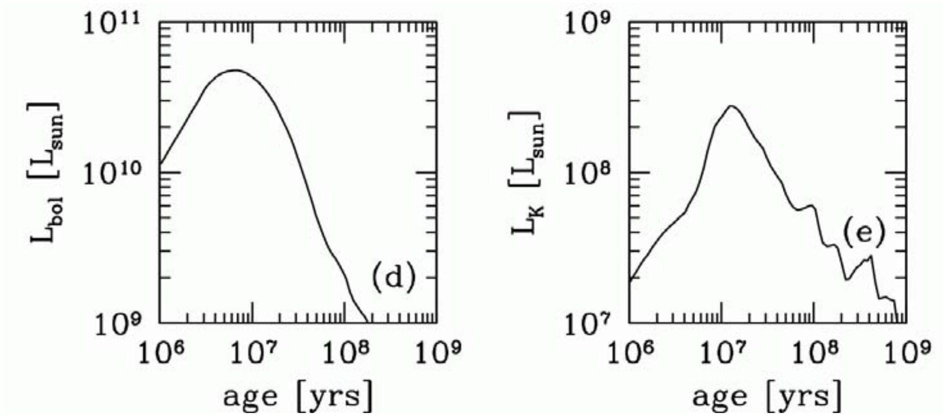
Cid Fernandes+ 04: central ~200pc of 79 nearby Seyfert 2s; 1/3-1/2 have experienced significant star formation in last few hundred Myr

Representative Stellar Cluster Model

STARS illustrative stellar cluster model:

for recent star formation which is no longer active, the luminosity was of order 10 times higher in the past – could have been source of heating to create the large velocity dispersions now seen





exponentially decaying star formation rate, τ_{SF}=10Myr

Brγ flux drops rapidly

normalisation set by $L_{bol} = 2\times10^9 L_{sun}$ at 100Myr

L_K similar to L_{bol}

can also run Starburst99 version 5.1 models: http://www.stsci.edu/science/starburst99/

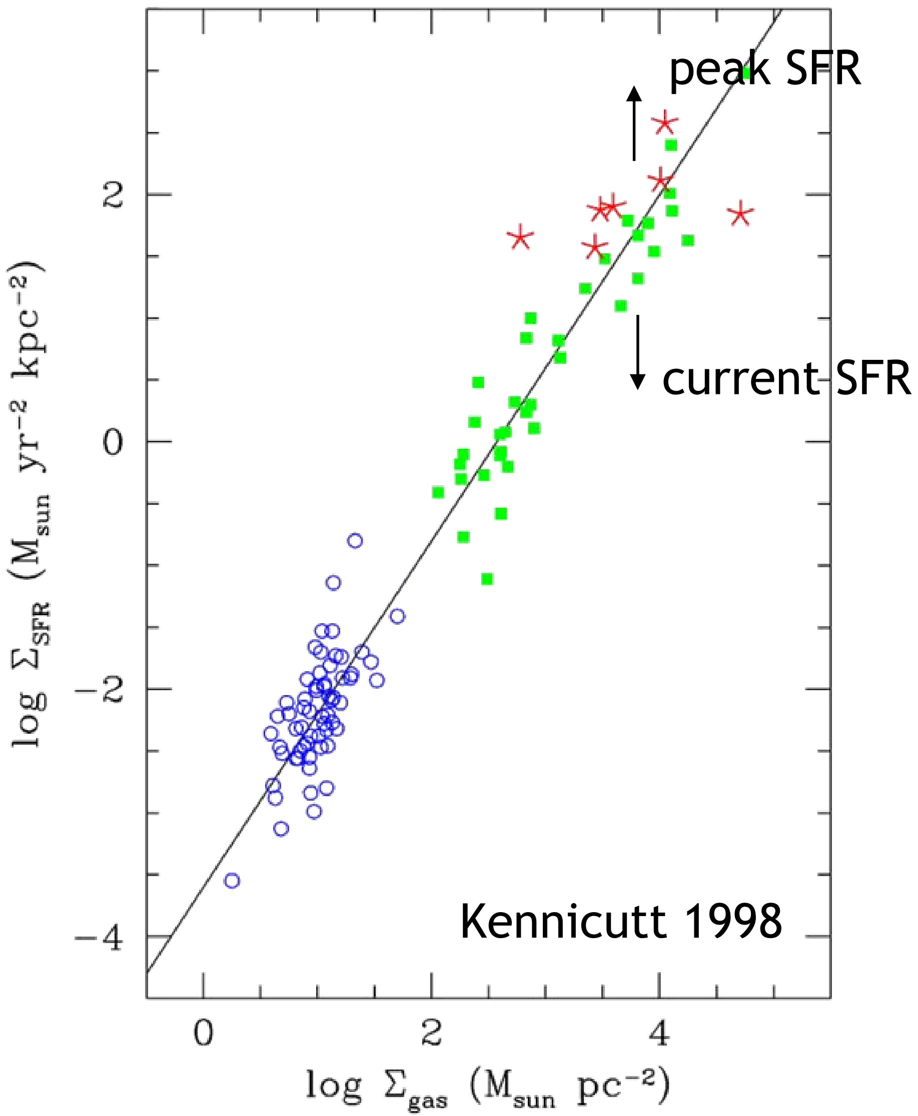
Kennicutt Schmidt Law

Nuclear starbursts lie on the Kennicutt Schmidt law

$\Sigma_{SFR} = 2.5\times10^{-4}\ \Sigma_{gas}^{1.4}$

when SFR is time averaged and 30% of dynamical mass is attributed to gas.

SFR is high because the gas surface mass density is high. As a result the star forming efficiency is also high.



A hypothesis for episodal star formation

(but see also results from numerical modelling: poster by N.Kawakatu)

- Gas accumulates in central 100pc
- Region cannot form stars due to high turbulence (Toomre criterion, $Q=\sigma\kappa/\pi G\Sigma$)
- Eventually, the high gas density leads to a high star formation rate
- Starburst is Eddington limited, generating a huge radiation pressure
- Because the efficiency is high, the starburst is short lived
- Starburst fades and is then dormant until gas is replenished

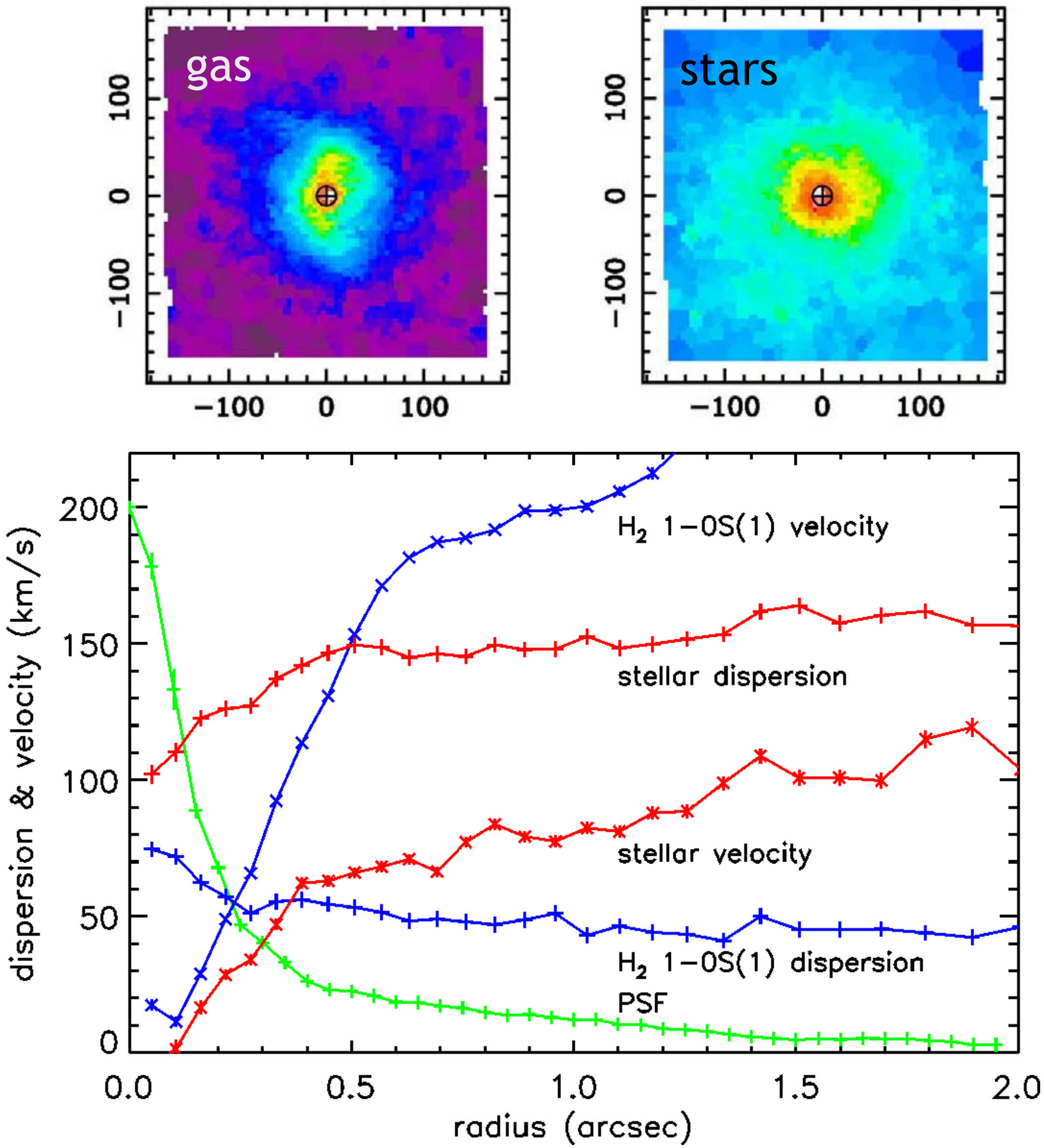
… but how is star formation related to the torus & the AGN?

A star-forming torus in NGC1097

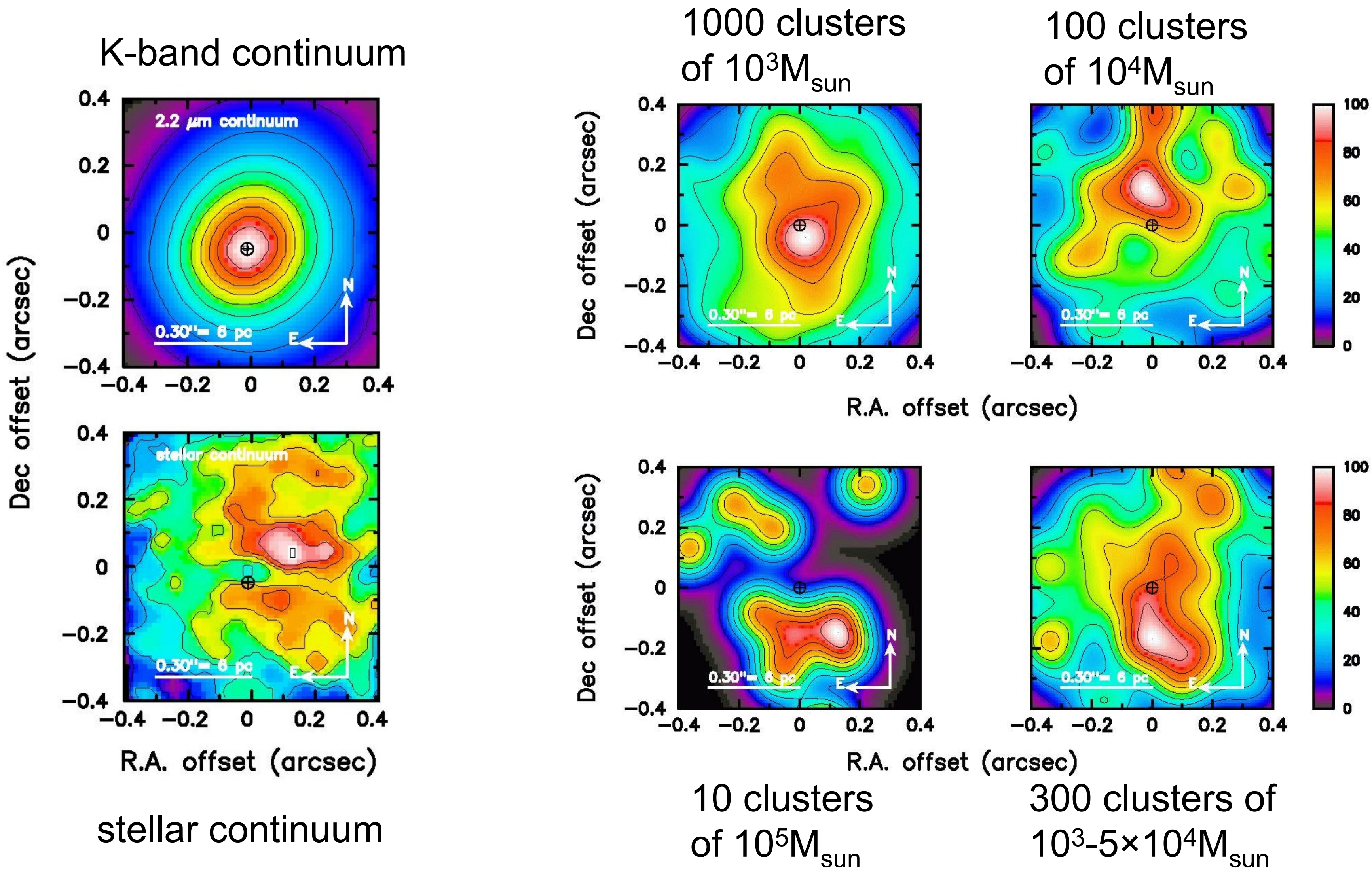
…but how is star formation related to the torus & the AGN?

- distributions similar
- kinematics similar
- gas & stars are mixed
- torus is forming stars

Star formation is probably inevitable and it will have a huge impact on the gas in the nuclear region



Nuclear Star Clusters in Circinus



Mueller Sanchez et al. 2006

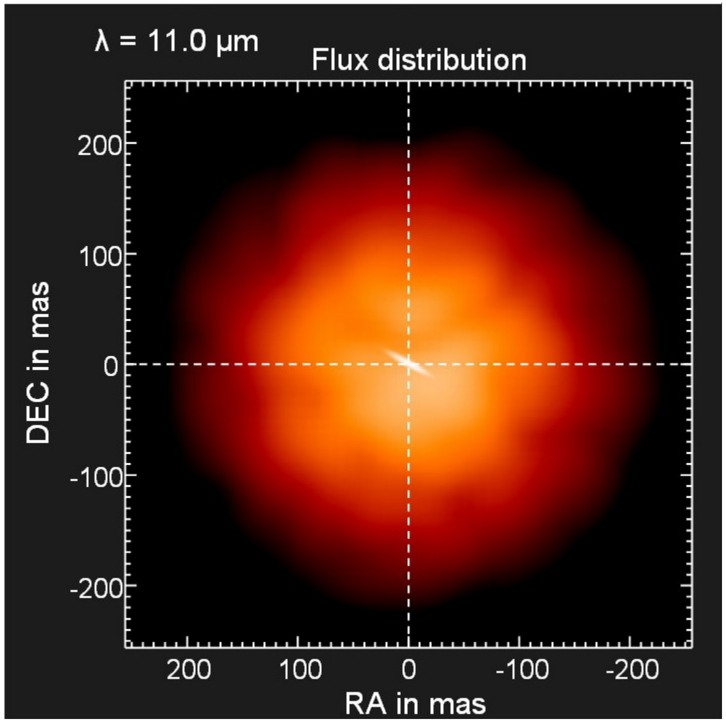
Clumpy Star Forming Torus

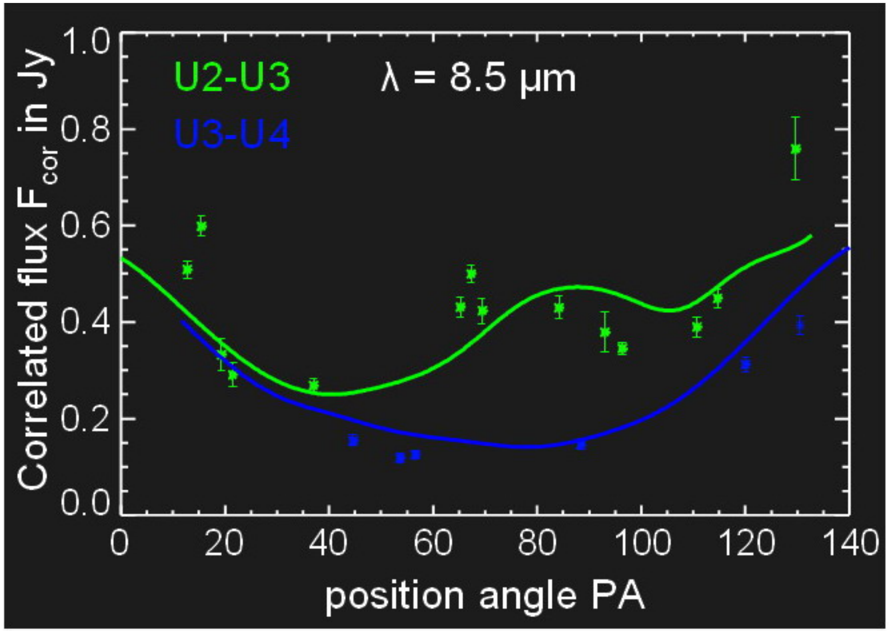
warm dust in Circinus (Tristram, PhD thesis 2007)

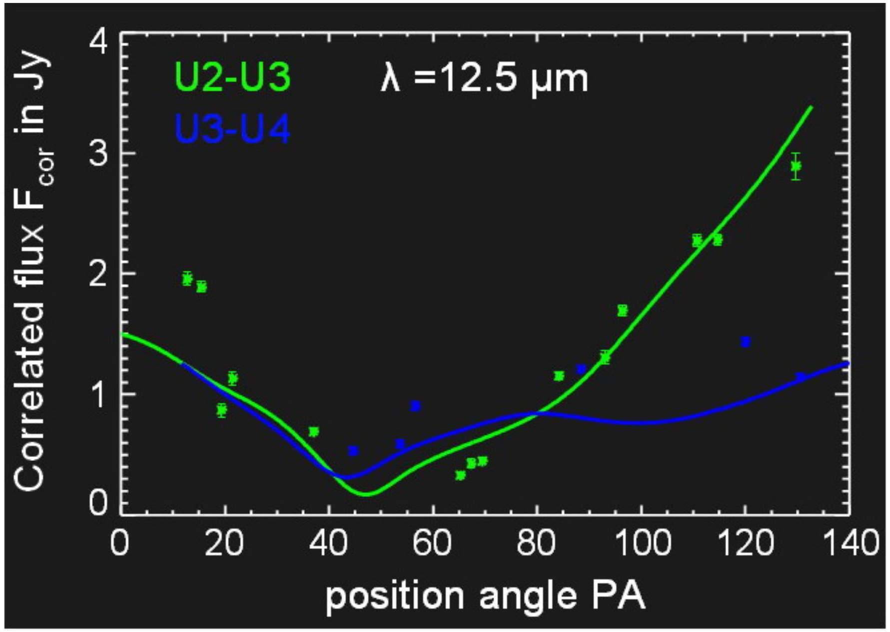
needs clumpiness to reproduce VLTI fringe visibilities

size of clumpy dust emission from VLTI: radius ~0.1”
size of clumpy stellar structure from AO: radius ~0.2”

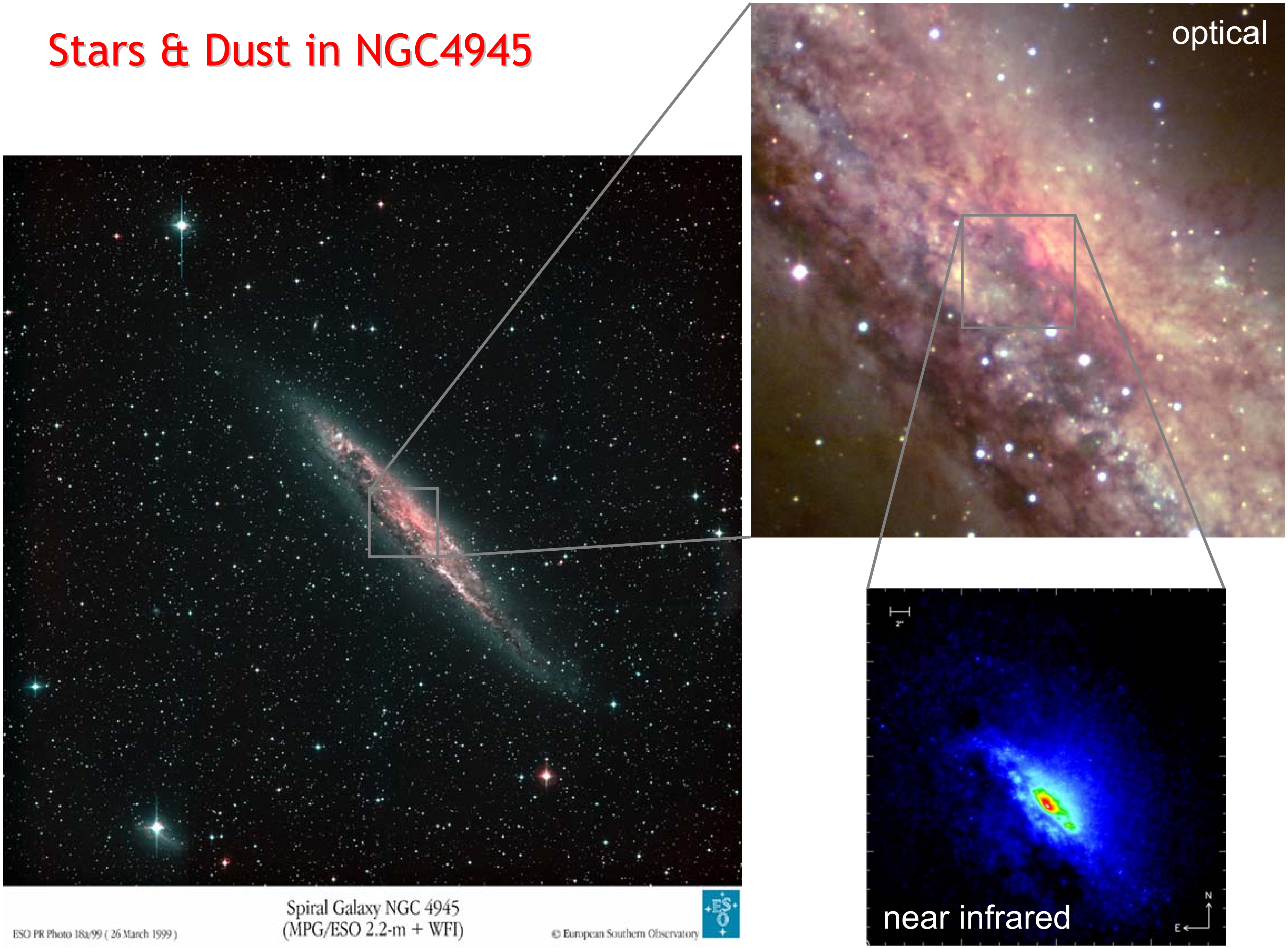
maybe this is dust heated by the stars





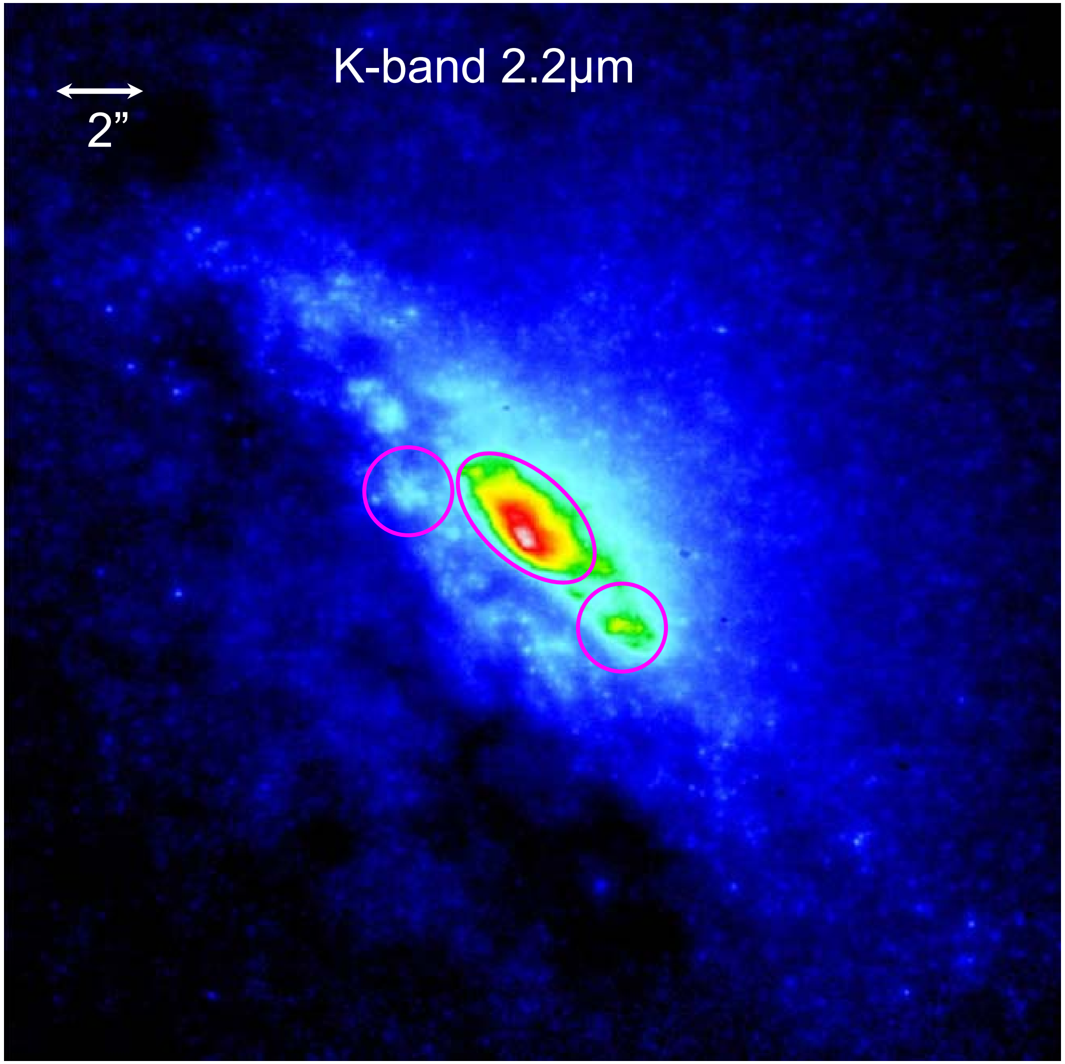


Stars & Dust in NGC4945

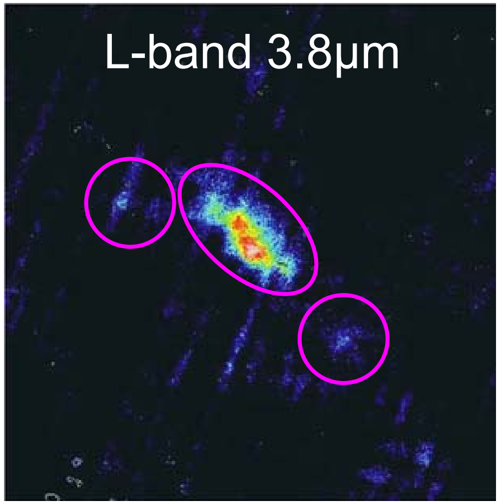


Stars & Dust in NGC4945

VLT LGSF commissioning results at a resolution of ~2pc show individual stars; massive star clusters are also visible



L-band shows warm dust emission & traces same structures as the stars, even on larger scales – confirmation that the dust is heated by stars rather than the AGN

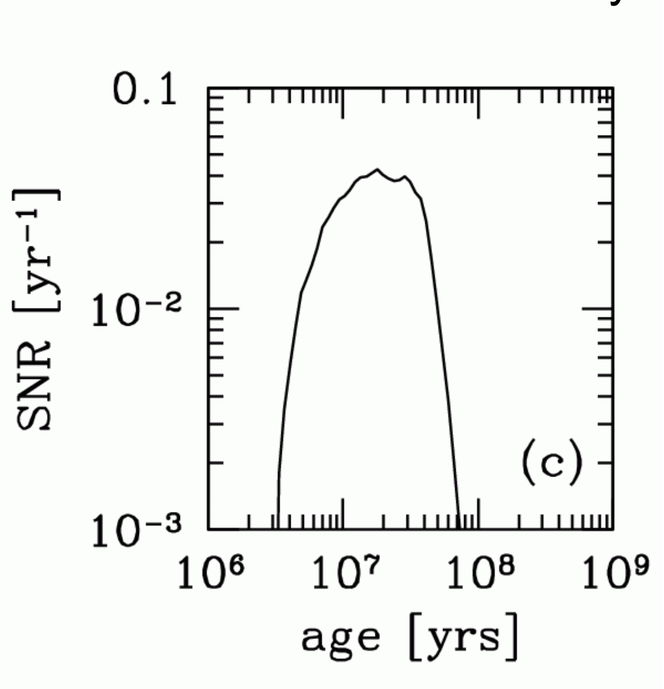


Feeding the Monster: the role of stellar ejecta

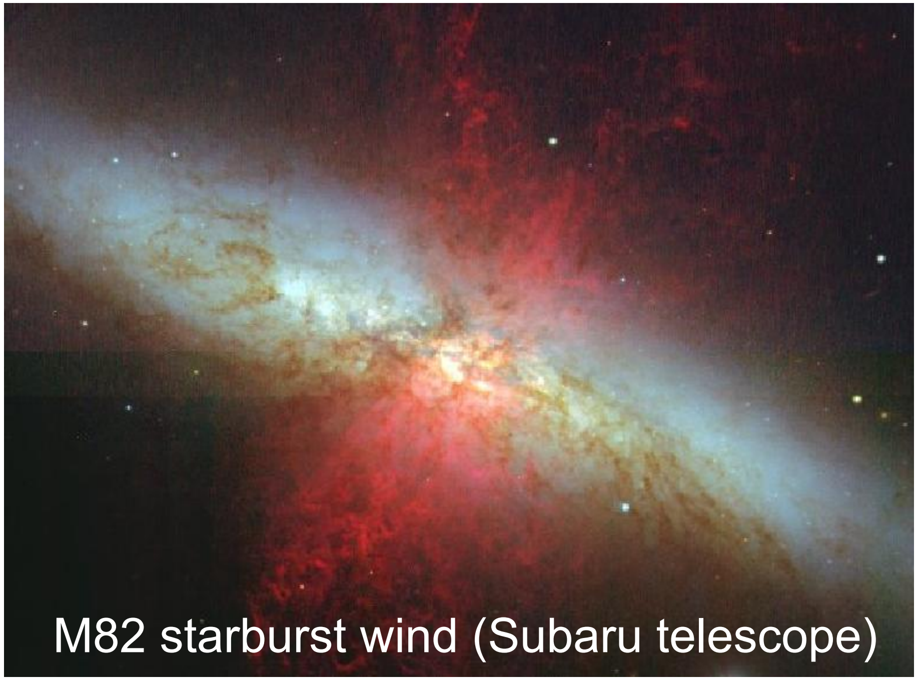
OB stars — significant mass loss, but at speeds of ~1000km/s and only for a short time;

in Galactic Centre, winds are partially responsible for stopping accretion (Ozernoy+96,97, Cuadra+06)

supernovae — ~10^6 SNe, at 10-50Myr, each ejecting ~$5M_{sun}$ at ~5000km/s; most likely outcome is a superwind rather than accretion



STARS representative stellar cluster model

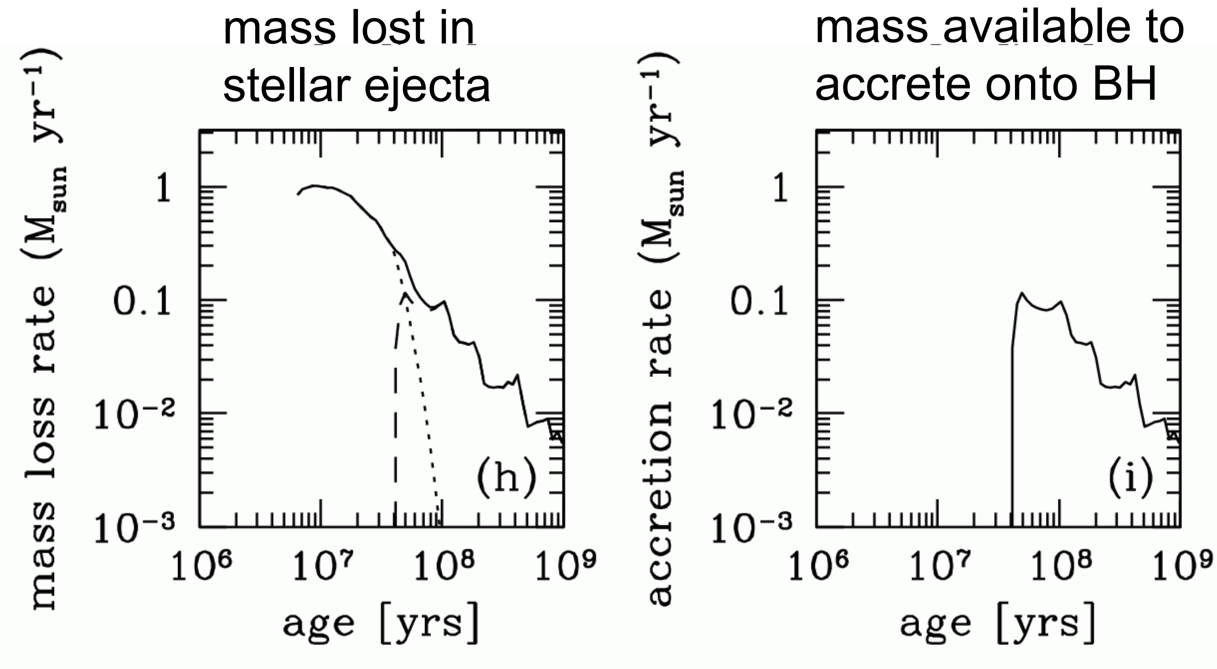


M82 starburst wind (Subaru telescope)

Feeding the Monster: the role of stellar ejecta

AGB stars

stars of 1-8M_{sun} reach AGB phase after ~50Myr;
winds have speeds of 10-30km/s and remain bound;
mass available >0.02M_{sun}/yr over timescale of 50-200Myr;
total mass ~$2\times10^7 M_{sun}$ over 1Gyr



STARS representative stellar cluster model

Bondi accretion

$$\dot{M}_{BH} = \frac{2\pi G^2 M^2 \rho}{V^3}$$

if gas is provided by a stellar wind

$$\rho_{wind} = \frac{\dot{M}_{wind}}{4R^2 V_{wind}}$$

$$\dot{M}_{BH} \propto V_{wind}^{-4}$$

5. Future Perspectives

AO has taken a long time to get going but is now standard at many observatories & even laser guide stars are becoming common

Here we look at a few different examples of where AO/interferometry might take us a little bit further

- MCAO on Gemini South
- LINC-NIRVANA on the LBT
- MUSE on the VLT
- GRAVITY on the VLT
- E-ELT

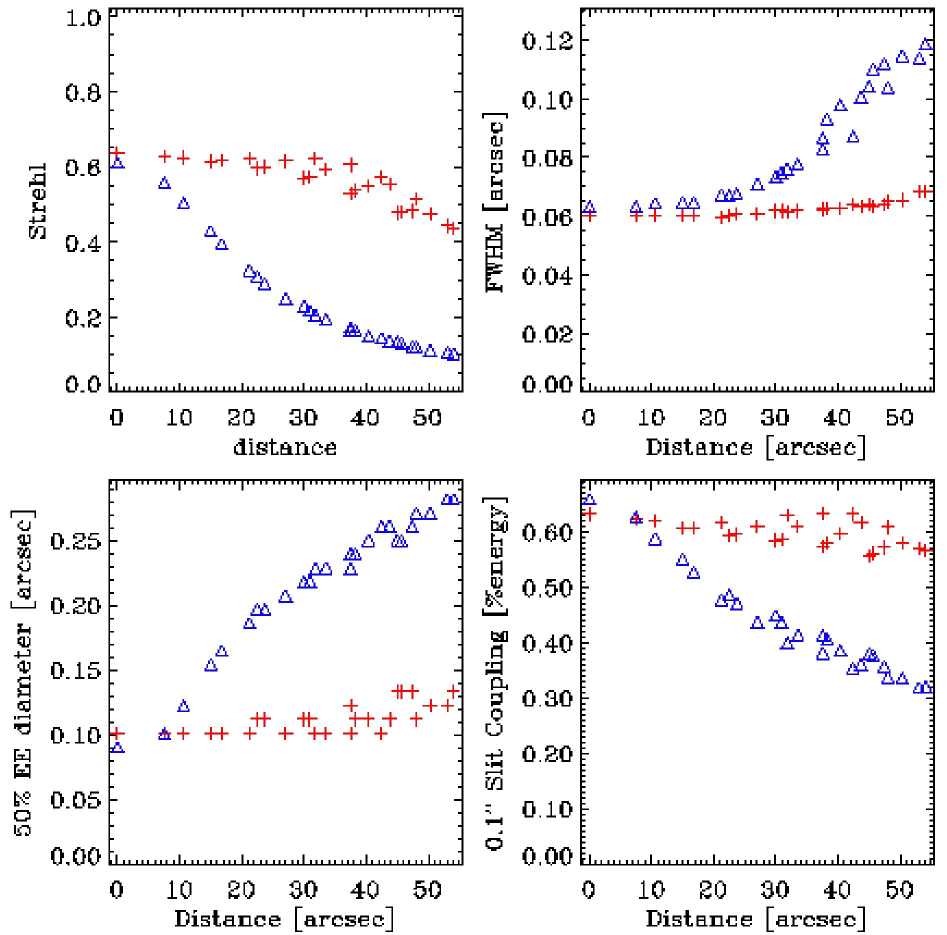
MCAO on Gemini South

adaptive optics:

- MCAO: 5 LGS and 3 NGS to control 3DMs
- diffraction limited imaging in JHK (30-60mas, predicting 45-80% strehl with variation of 2-6% across the field
- sky coverage for R=19mag guide stars: 15% at galactic pole, to >70% within 30° of galactic plane
- installation of LGS-MCAO in 2007

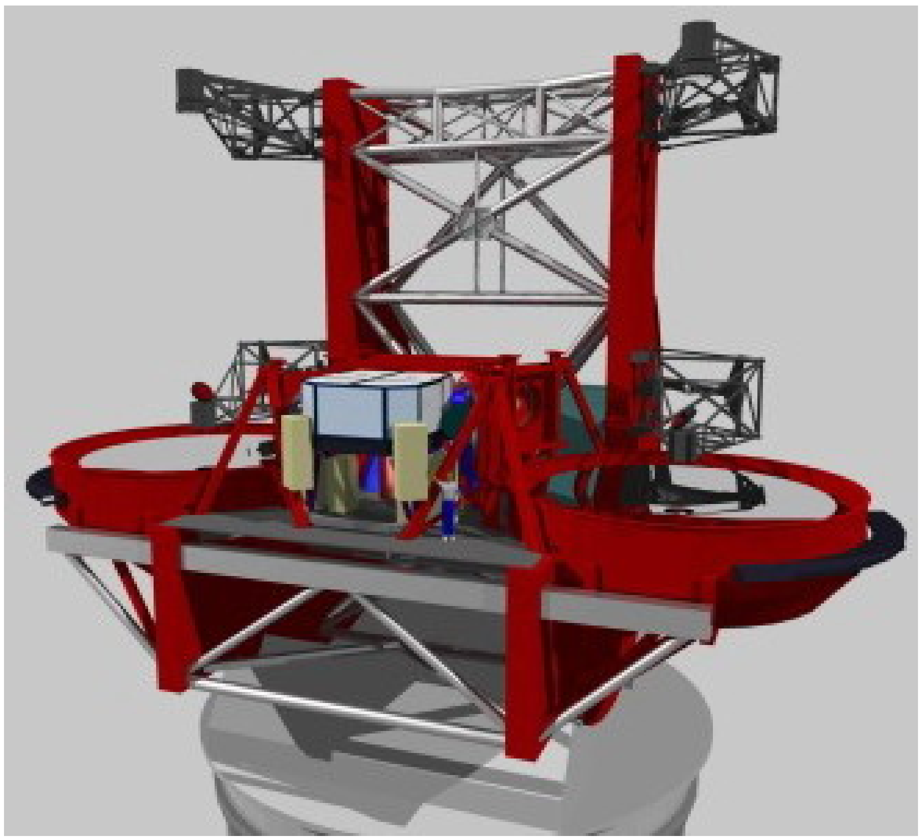
instruments:

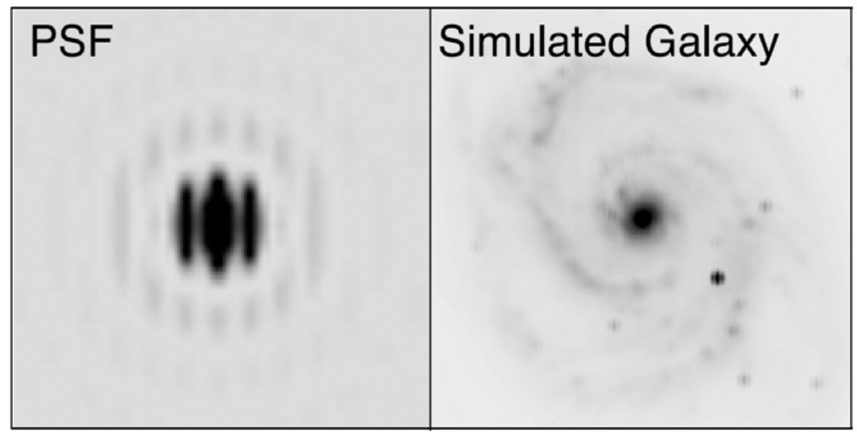
- multi-object spectroscopy at up to R~3000 with Flamingos2
- imaging with 80”x80” FoV sampled at 0.02” imaging at 1-2.5um with GSAOI



LINC-NIRVANA on the LBT

- LBT has two 8.4m mirrors with full diameter 23m, yields 10mas in J band
- LINC-NIRVANA* is a 1-2.5μm Fizeau interferometric beam combining imager which will use multiple natural guide stars to do MCAO
- SERPIL/LIINUS is a integral field spectroscopic upgrade



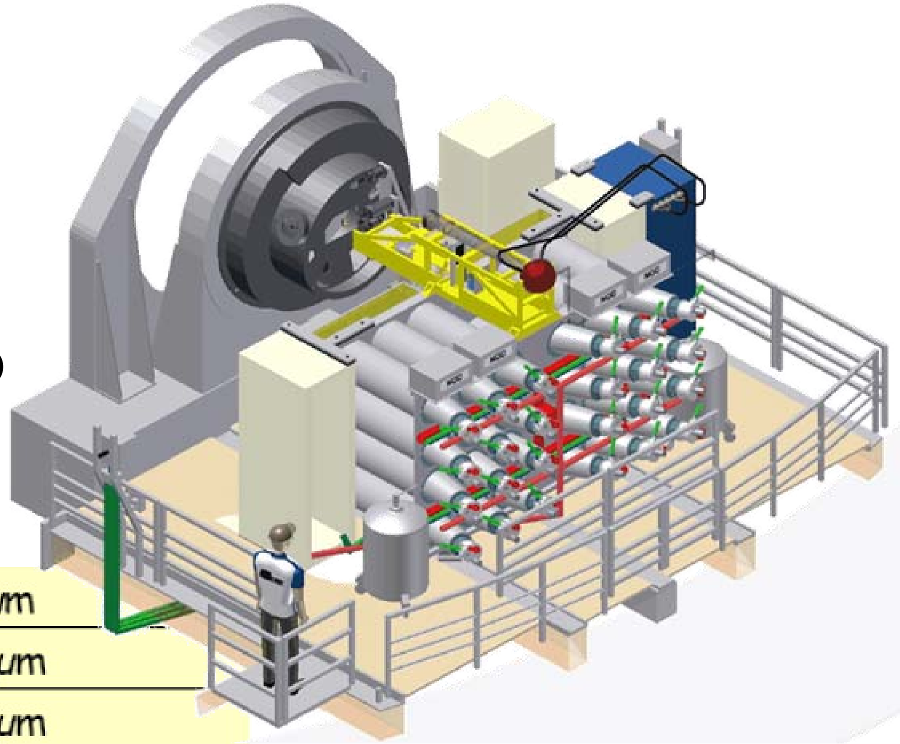


* Nirvana = "an ideal condition of rest, harmony, or joy"

MUSE on the VLT

first light planned for 2012

3 modes:
seeing limited, wide field AO, narrow field AO



specs for Wide Field AO mode

Spectral range (simultaneous)	0.465-0.93 μm
Resolving power	2000@0.46 μm
	4000@0.93 μm
Wide Field Mode (WFM)	
Field of view	1x1 $arcmin^2$
Spatial sampling	0.2x0.2 $arcsec^2$
Spatial resolution (FWHM)	0.3-0.4 arcsec
Gain in ensquared energy within one pixel with respect to seeing	2
Condition of operation with AO	70%-ile
Sky coverage with AO	70% at Galactic Pole
Limiting magnitude in 80h	I_{AB} = 25.0 (R=3500)
	I_{AB} = 26.7 (R=180)
Limiting Flux in 80h	$3.9\ 10^{-19} erg.s^{-1}.cm^{-2}$

24 detectors, each 4096^2 giving 400 million pixels

adaptive optics, at optical wavelengths, with high sky coverage (multiple LGS)

very deep exposures

GRAVITY on the VLT

VLTI will enable us to measure the size of the BLR

resolution of 100m baseline in K-band is 4mas → BLR can never be resolved
e.g. size of a BLR 3lightdays across at a distance of 10Mpc is 60μas
BLR in 3C273 is 390lightdays, which is 130μas

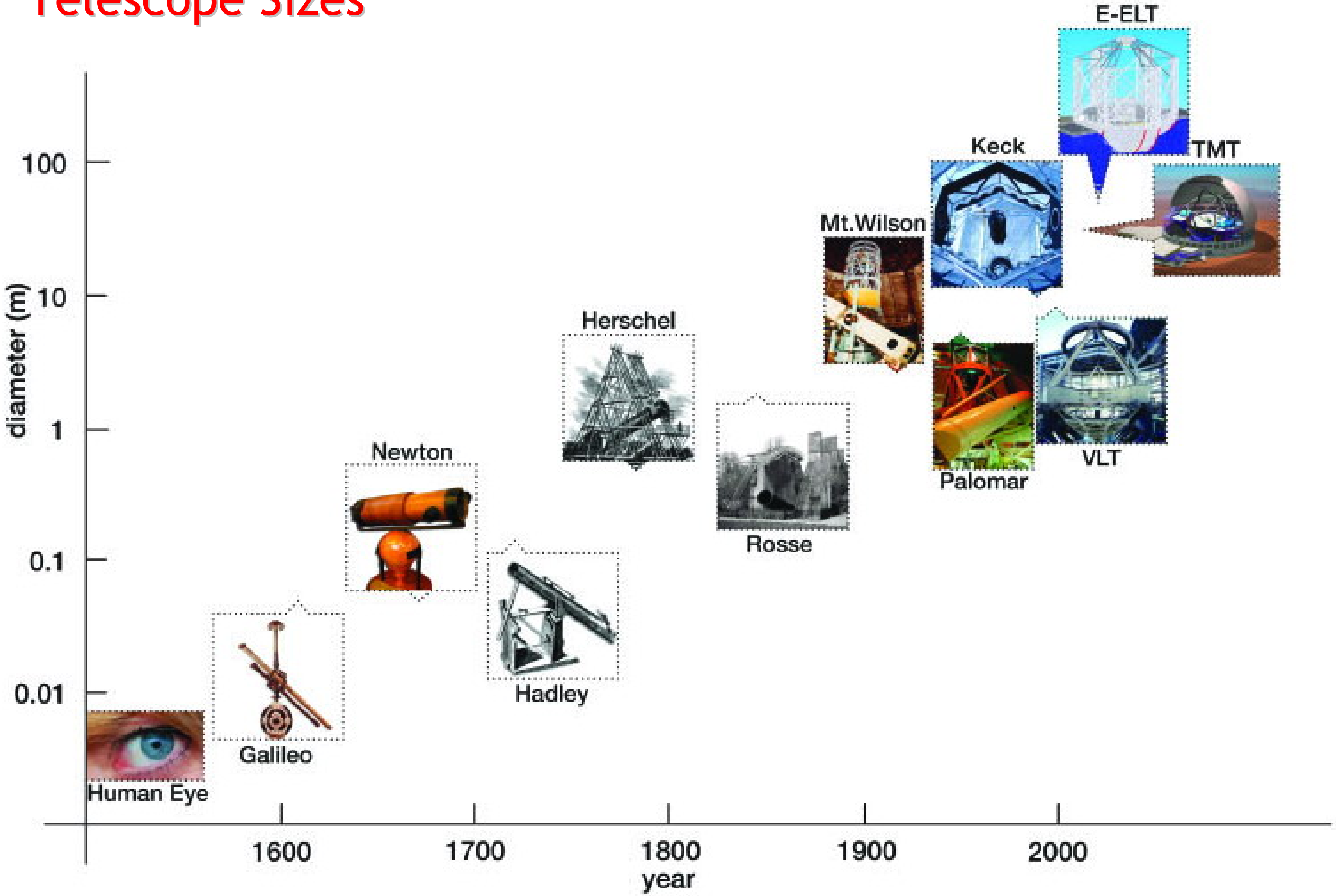
suggestion of flattening in 10-20% of BLRs → rotational signature

velocity gradient can be measured using 10μas astrometry & spectral capability, giving us

1. statistical estimate of fraction of BLRs with significant ordered rotation
2. measurement of size of BLR from velocity gradient
3. mass of central black hole (once inclination is known)

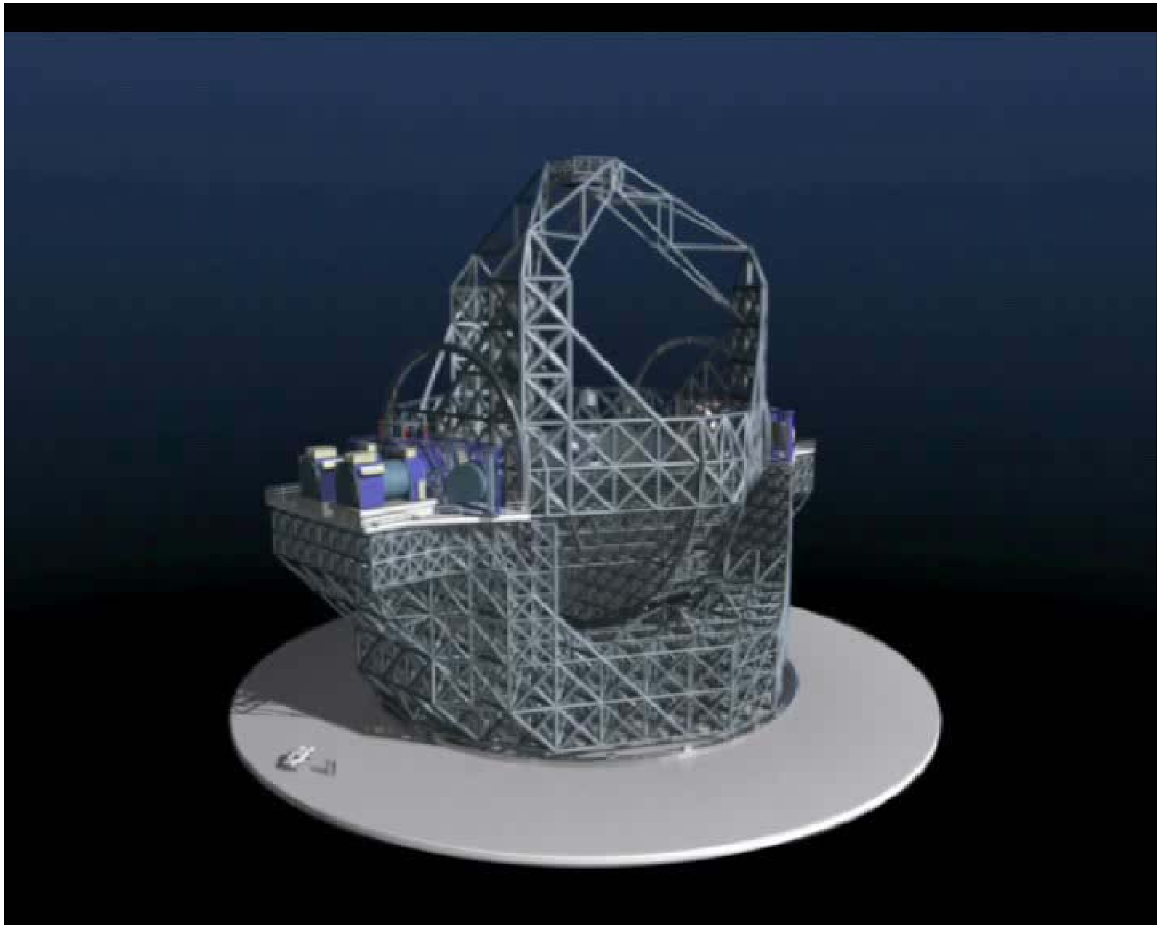
e.g. 3C273: red/blue channels (at +/-300km/s) will be 50μas apart

Telescope Sizes



E-ELT

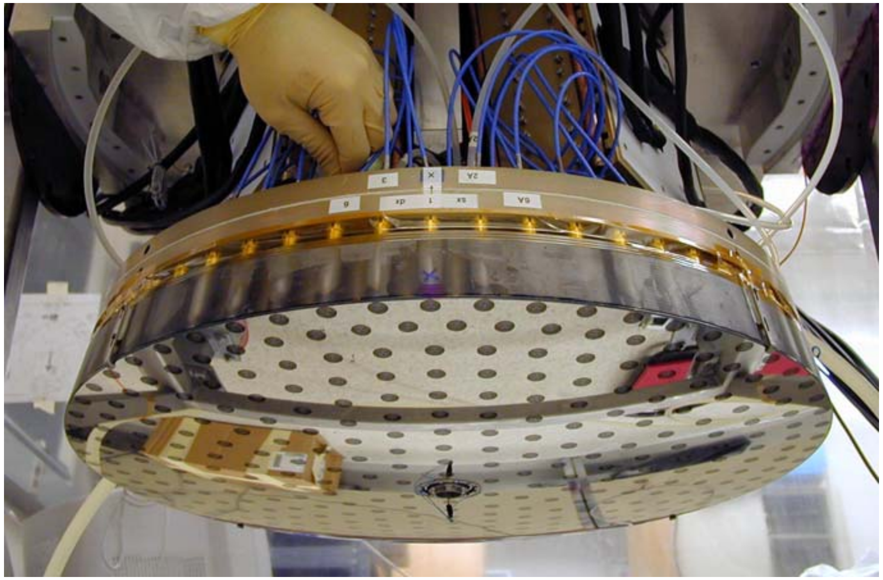
- merger of OWL & Euro50
- 42-m primary, 906 1.45m segments
- ~800MEuro
- 5500 moving tons
- site not yet chosen



- 2006, Dec: ESO council approval for phase B (preliminary design)
- 2007, Oct: Technical Review
- 2009, Feb: System Review
- 2009, Oct: Construction Cost Review
- 2010: Construction begins
- 2017: Operations begin

E-ELT

Adaptive optics with laser guide stars will be 'standard' with many AO modes planned: SCAO, LTAO, MCAO, GLAO, MOAO, XAO



telescope	width	thickness	actuators
MMT	64cm	2mm	336
LBT	91cm	1.6mm	672
VLT	112cm	1.9mm	1170
ELT	*250cm*		*5000*

AO will give: 10mas resolution at 2μm; 6mas at J-band (1.25μm)

AO is actually necessary – optics size:

focal ratio of camera

$$f\,/\,number = \frac{206265 d_{pix}}{D_{tel}\theta_{pix}}$$

VLT instrument might have f/2.5; on ELT this would be f/0.5

size of spectrograph optics

$$D_{coll} = \frac{Rp\theta_{pix}D_{tel}}{206265(2\tan\theta_B)}$$

for KMOS, D_{coll}~5cm; LUCIFER, D_{coll}~12cm similar instrument for ELT, D_{coll}~30-50cm

Summary

- Adaptive Optics Concepts & Techniques

- QSOs at High & Low Redshift

- The Galactic Center
  - density of stellar cluster
  - orbits of stars
  - flares from the last stable orbit

- Nearby AGN
  - black hole masses
  - nuclear star formation
  - torus

- Future Perspectives
  - exciting new technological developments in the next few years