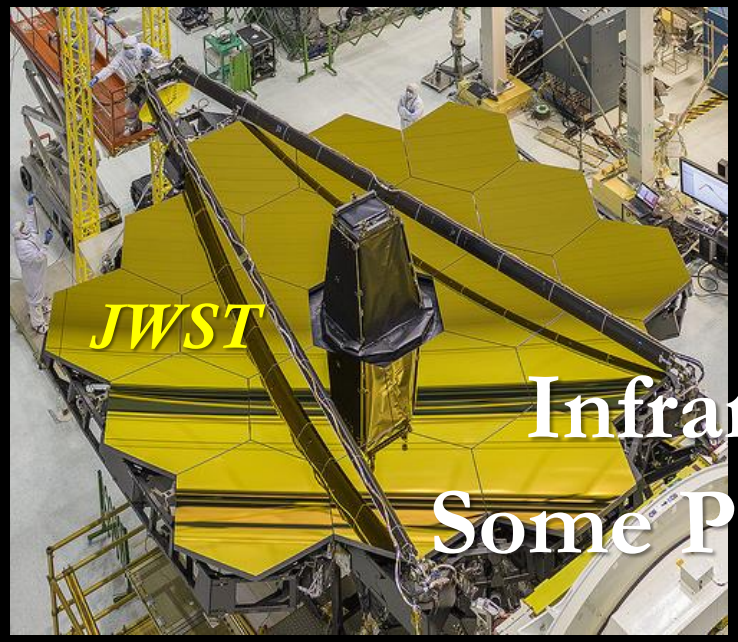
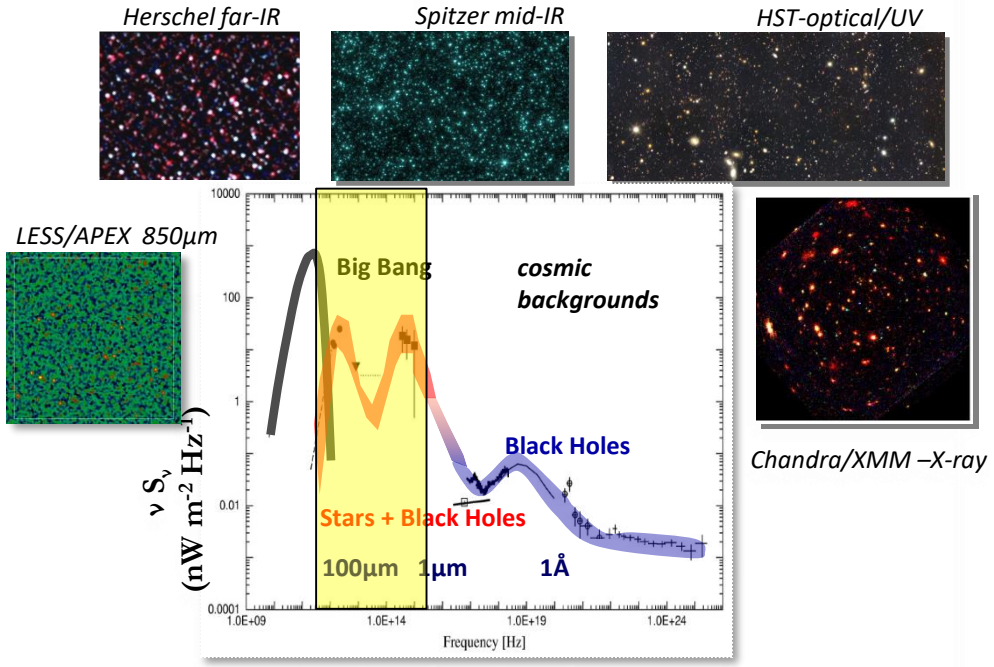


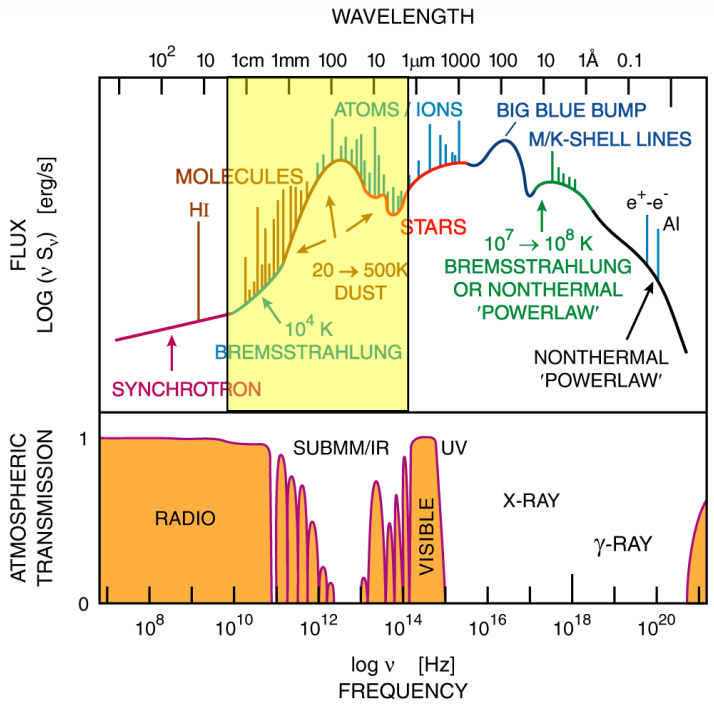




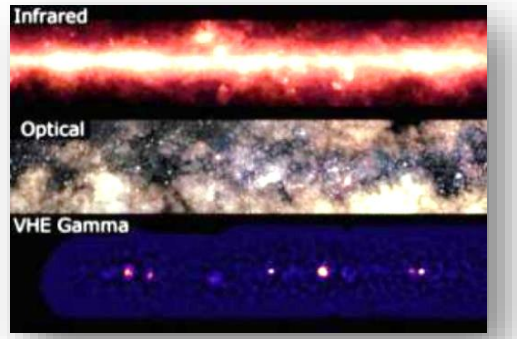
# Infrared to Millimeter Astronomy: Some Personal Comments on Status & Future Developments

*Reinhard Genzel*
*MPE & UCB*

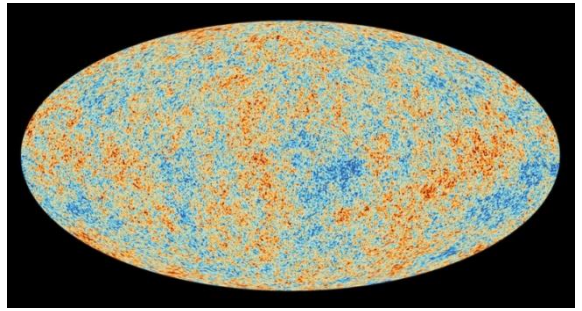




# Multi-Messenger Astronomy



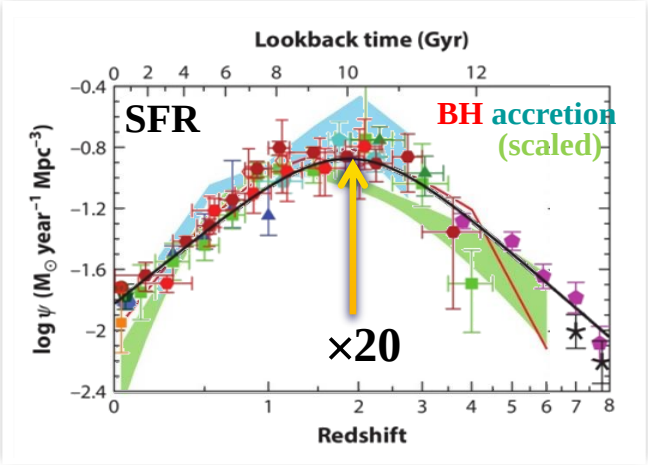

- dark matter: N-body simulations (+abundance matching), lensing, galaxy-galaxy correlation functions
- old/young stars: optical, near-IR SED + lines
- total luminosity, star formation: re-radiated UV/optical, in obscured regions: mid-/far-IR/submm SED
- AGN: X/γ-rays, cosmic rays, optical/IR lines, UV, optical, mid-IR, submm- to radio continuum emission
- hot and warm ISM/CGM/IGM: X-rays + EUV continuum & lines
- ionized ISM/CGM: optical/UV, IR emission/absorption lines
- atomic ISM: UV absorption, 21cm line emission, 158μm [CII] line
- molecular ISM: mm/submm emission lines, far-IR absorption lines & dust emission
- galaxy kinematics: optical/millimeter line emission, optical/near-IR, mm (CO)
- stellar absorption lines, 21cm HI line emission, γ-rays, cosmic rays
- stellar/AGN feedback: UV/optical to mm line emission, X/γ-rays, cosmic rays, Supernovae
- gravitational processes: gravitational waves, stellar & gas motions

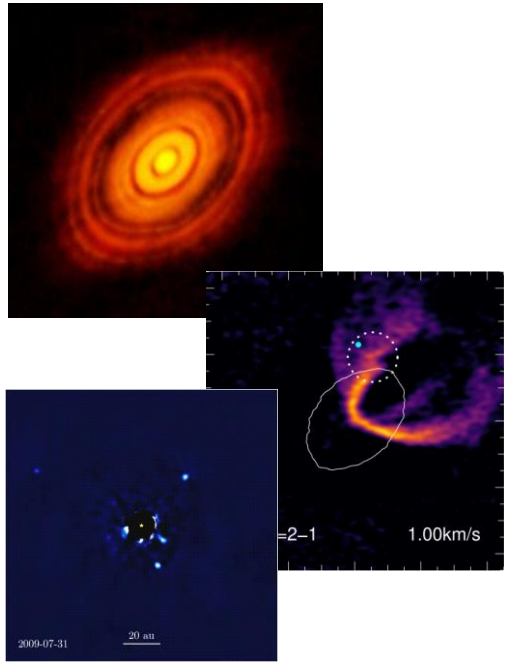
# Recent Highlights IR to MM Astronomy



## Cosmology & Galaxy Evolution:

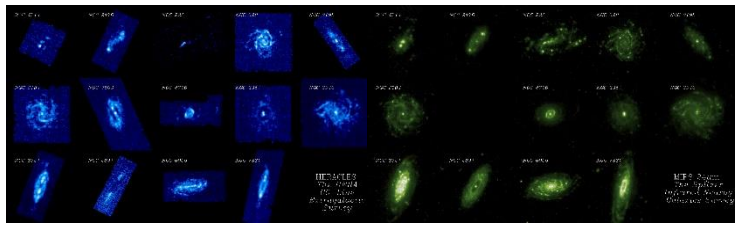
- Confirmation and precision measurements of the ΛCDM standard model of Large Scale Structure: WMAP, Planck, BAO with SDSS/BOSS/DES
- "Equilibrium Growth Model" of galaxies across cosmic time from HST/Spitzer/Herschel/ALMA imaging and spectroscopic follow-up with IFUs on VLT/Keck and CO on ALMA/NOEMA
- Cosmic co-evolution of galaxies and their central super-massive black holes
- Epoch of 're-ionization' (z~8-10) from WMAP/Planck & deep imaging surveys

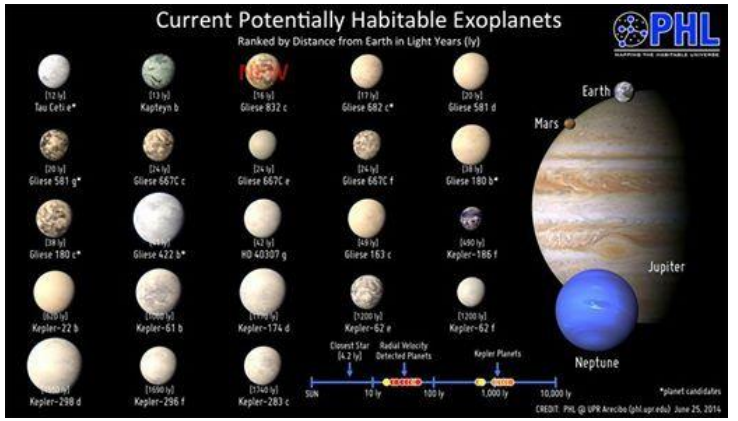



## Star & Planet Formation, Exoplanets:

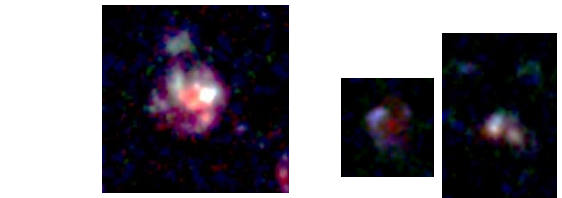
- Cloud scale resolved studies of the dense ISM & SF in nearby galaxies with Herschel, NOEMA & ALMA
- Spatially resolved studies of protoplanetary disks with ALMA
- Census of super-Earths and potentially habitable planets with Kepler
- Atmospheric composition of young hot Jupiters with Spitzer, GPI/Sphere and GRAVITY@VLT

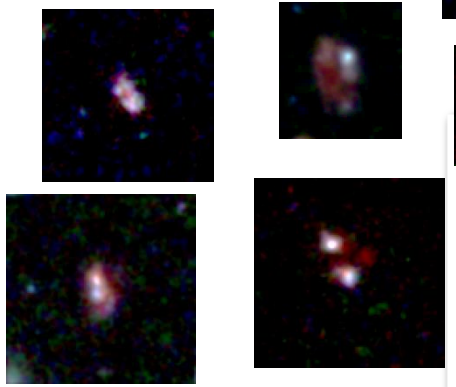


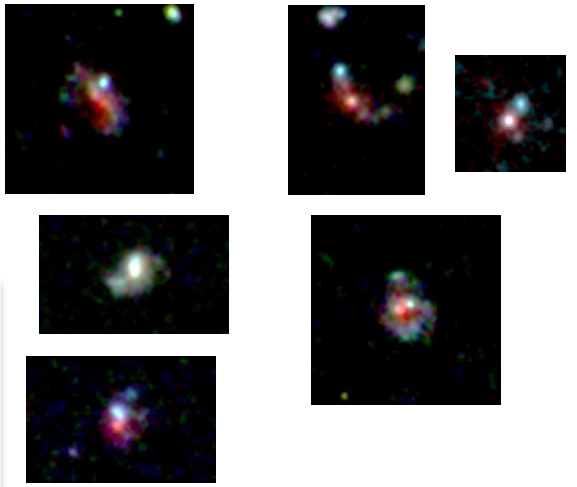


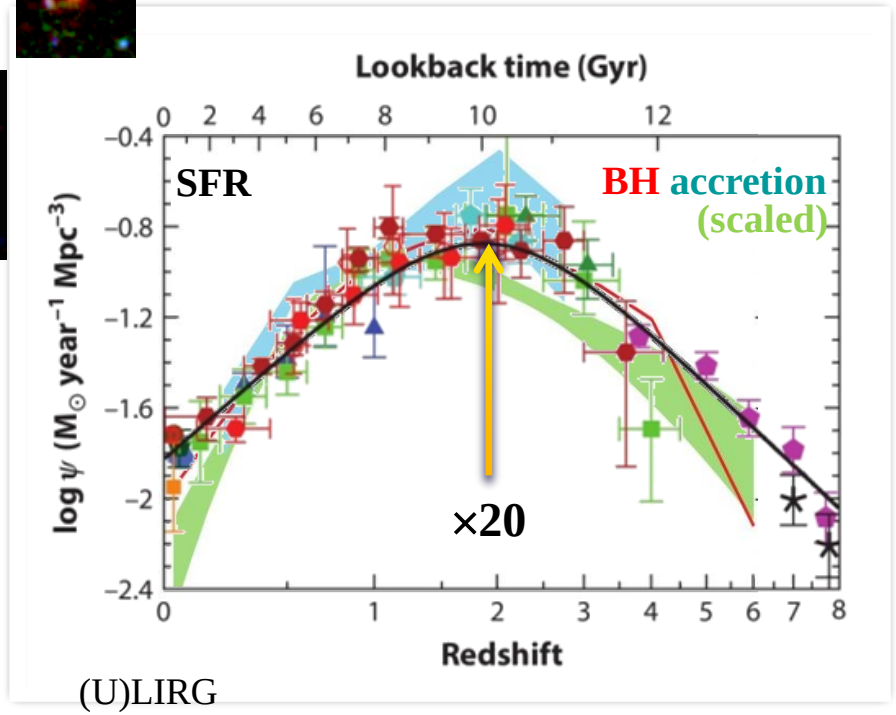
# ‘Cosmic Noon’: The Peak of the Galaxy Formation Epoch

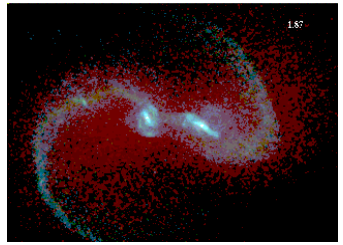
*Nature or Nurture?*







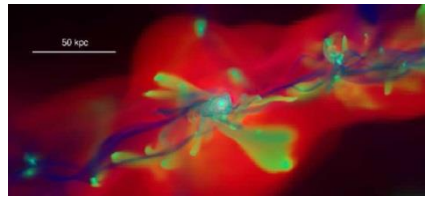


(major) mergers
& starbursts
rate ~ 20-30%

(U)LIRG
luminosities common

*Madau & Dickinson14*



semi-continuous
accretion from halo
(including minor
mergers)
& disk instabilities
rate ~ 60-80 %


Madau +96, Lilly +96, Steidel +96, Cowie +95,Giavalisco +96, van den Berg 96, Hopkins & Beacom 2006, Soifer +08, Rees & Ostriker 77, Silk 77, White & Rees 78, Kauffmann +93, Steinmetz & Navarro 03, Springel +05, Hopkins +03-09, Robertson & Bullock 08, Sanders & Mirabel 96, Dekel & Birnboim 03,06, Keres +05, 09, Nagamine +05, Davé 07, Elmegreen +05, 07, 09, Kitzbichler & White 07, Naab +07, Governato +08, Ocvirk +08, Dekel +09, 12, 13, 14, Ceverino + 12, Agertz +09, Guo +09, 11, Teyssier +10, Bournaud 2010, Davè +11a,b, 12, Kauffmann +10, Elmegreen 12, Vogelsberger +13, Genel +14, 15, Sijacki +14, Schaye +14, Hopkins +12, 14, Nelson +14, Keres +15

# Evolution of Star-Forming Galaxies along the "Main Sequence"

NEWFIRM

KROSS

(z)-COSMOS

CANDELS

muse

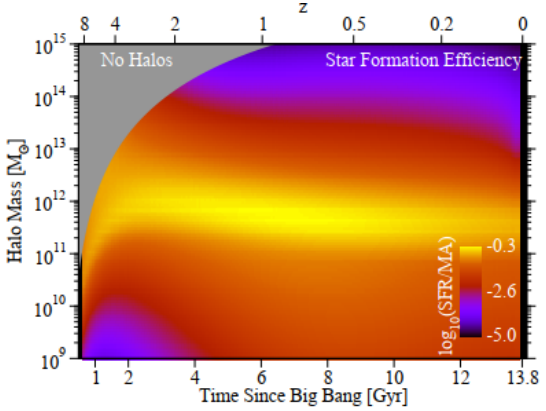
VVDS

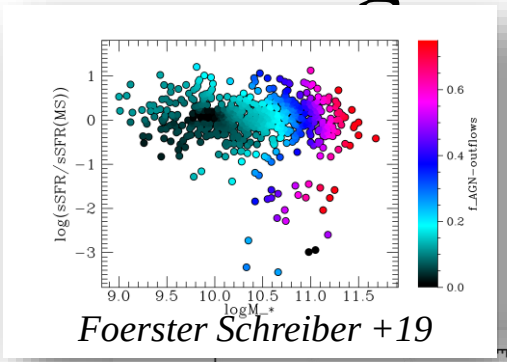
3D HST

SINS/zC-SINF AO Survey

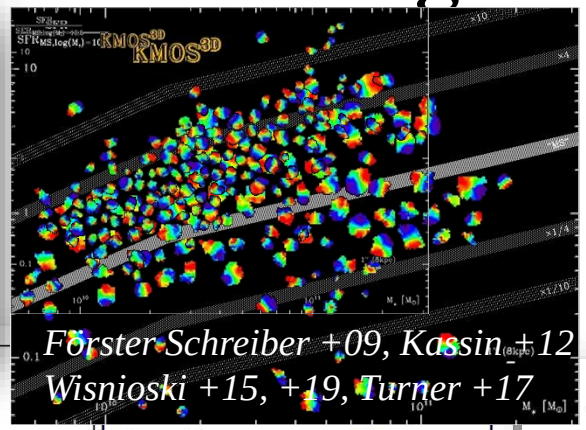
KMOS$^{3D}$

*Behroozi +09, +12, Moster +13*

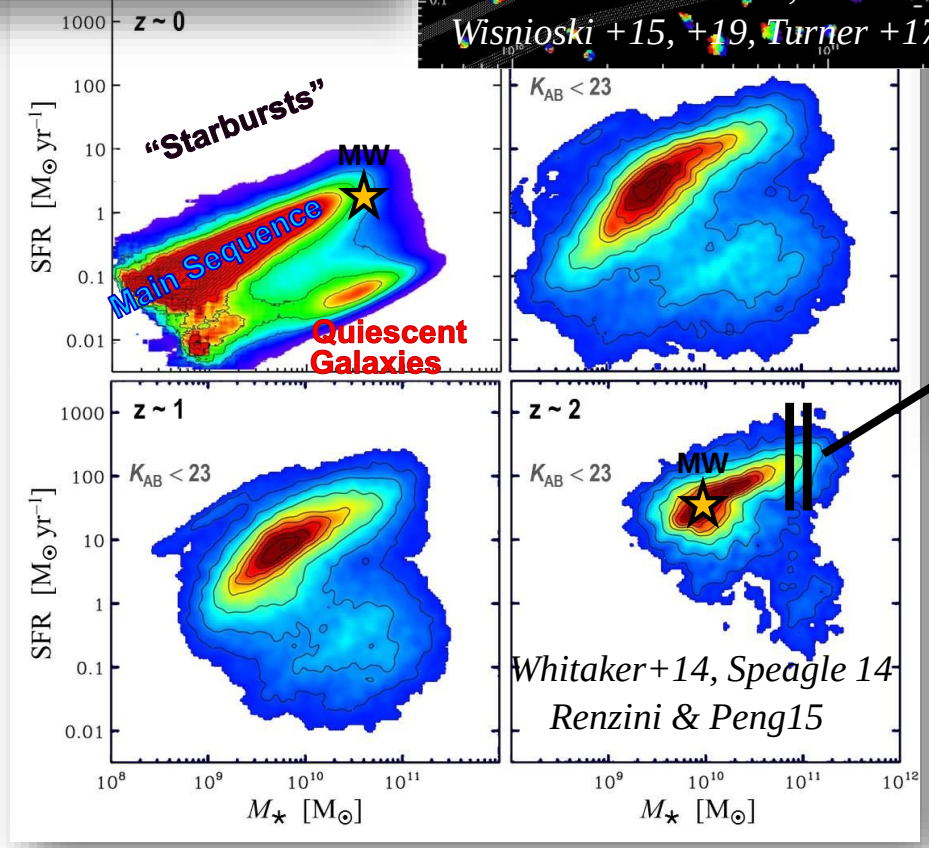


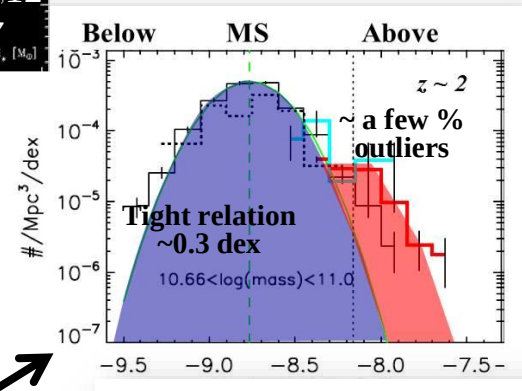

*Foerster Schreiber +19*



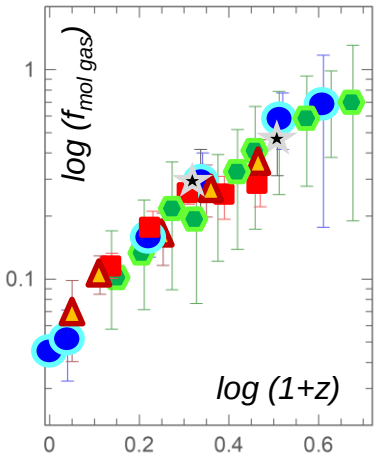

*Förster Schreiber +09, Kassin +12*
*Wisnioski +15, +19, Turner +17*




*Whitaker+14, Speagle 14*
*Renzini & Peng15*

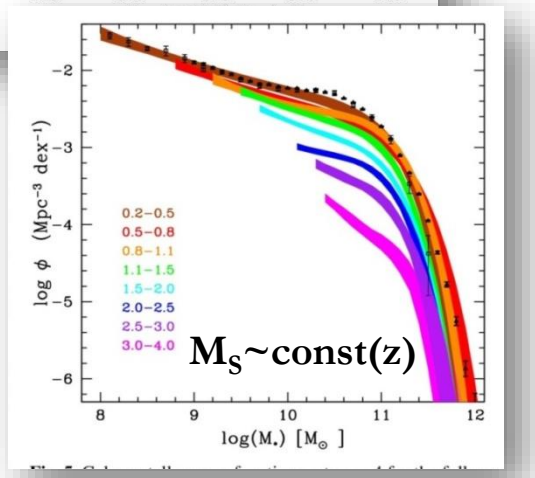



*Rodighiero +11*
*Schreiber +16*




*Genzel +15*
*Scoville +17*
*Tacconi+18*

*1400 SFGs*
*z=0-4*
*CO*
*dust (FIR)*
*dust (submm)*




*Muzzin +13*


Rudnick+03,06, Adelberger+04, Brinchmann +04, Noeske+07, Schiminovich+07, Elbaz+07, Daddi+07, Franx +08, Marchesini+09, Shankar+09, Ilbert+10,13, Peng+10, Brammer+11, Rodighiero+11,14, Caputi+11, Gonzalez+11, Karim+11, Magnelli+11,13, Wuyts+11, Whitaker+12,14, Muzzin+13, Stark+13, Speagle +14, Renzini & Peng15, Schreiber +16, Davies +19, Harrison +17, Tacchella +15, +17, Behroozi +09, +12, +15, Moster +11, +13, Förster Schreiber +09,11,14,19, Stott+14, Wisnioski +15, +19, Genzel +08, +11, +14, +17, Kassin +07, +12, Simons +15, +17, Burkert +16, van Dokkum +13, +15, Peng +10, +13

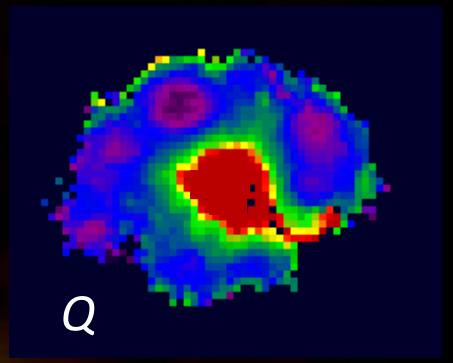
# Evolution of Early Gas Rich Disks

$$\left(\frac{\sigma}{v_d}\right) = \left(\frac{h_z}{R_{disk}}\right) \underset{Q\sim 1}{=} \frac{Q f_{gas}}{\sqrt{2.3}}$$

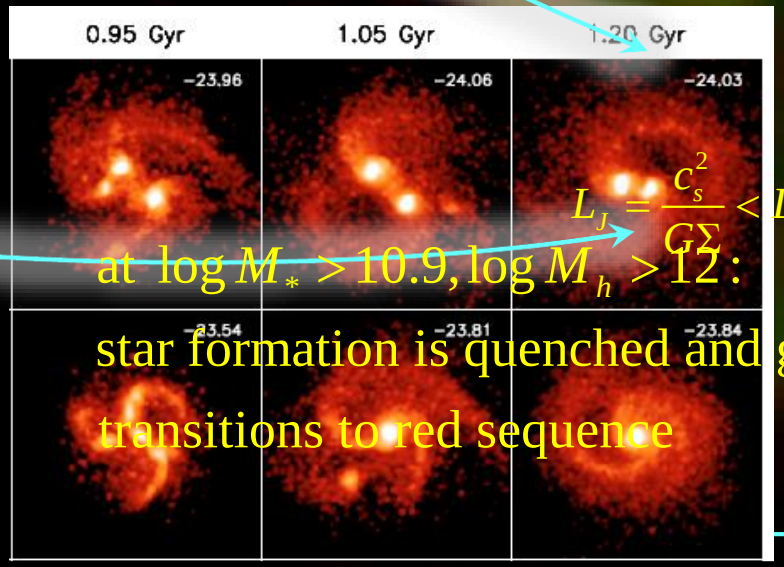
$$M_{Toomre} \propto f_{gas} M_R \times (1+z)^{2.3}$$

$$M_{Toomre} \sim f_{gas}^2 M_{disk} \sim 10^9\ M_\odot$$

R ~ 1kpc



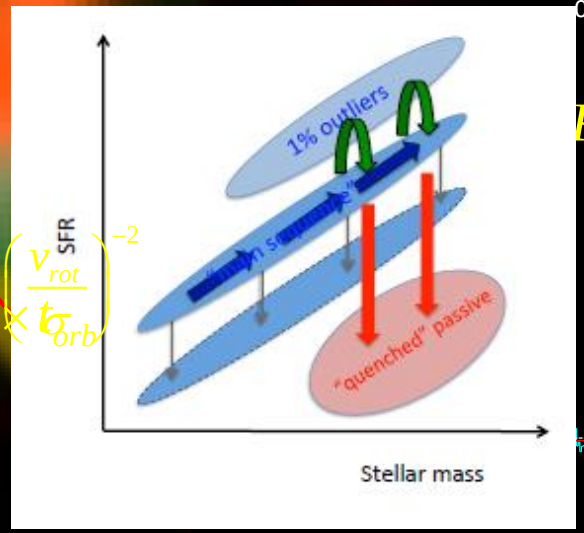





$$L_J = \frac{c_s^2}{G\Sigma} < L < L_T = Q \times \left(\frac{\pi^2 v_d^2 G\Sigma}{\sigma}\right)^2 \times \left(\frac{v_{rot}}{t_{orb}}\right)^{-2} \approx t_{radial}$$

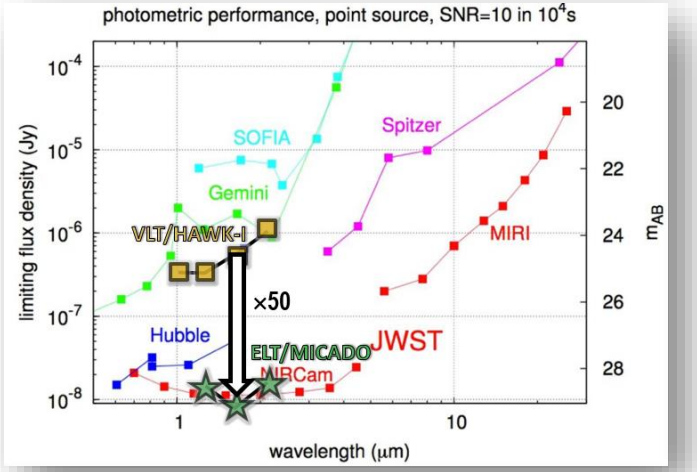
at $\log M_* > 10.9, \log M_h > 12$:

star formation is quenched and galaxy transitions to red sequence

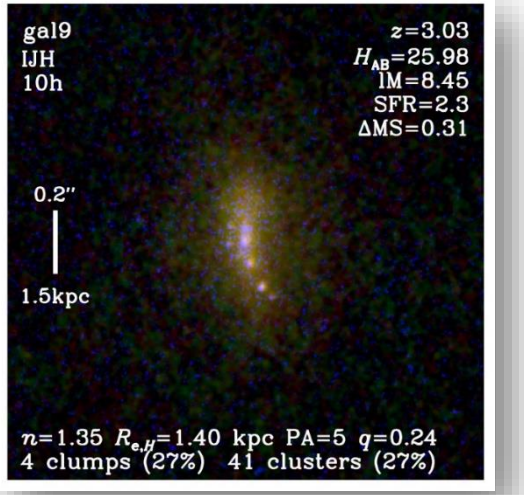



5 kpc

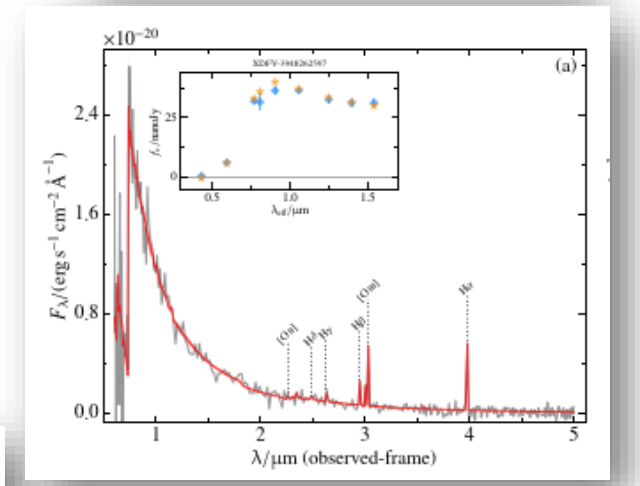

Noguchi 1999, Immeli +04, Bournaud +07, Elmegreen +07, 08, Dekel +09b, Genzel +08, 11, 13, Bournaud +11, Krumholz & Burkert 10, Ceverino +10, Foerster Schreiber +11a,b, 13, Swinbank +11, Wisnioski +12, Newman +12a,b, Bouche + 10, Dutton +10, Brammer +11, Nelson + 12, 14, Kriek + 11, Lilly +13, Fang +13, Mo, Mao & White 1998

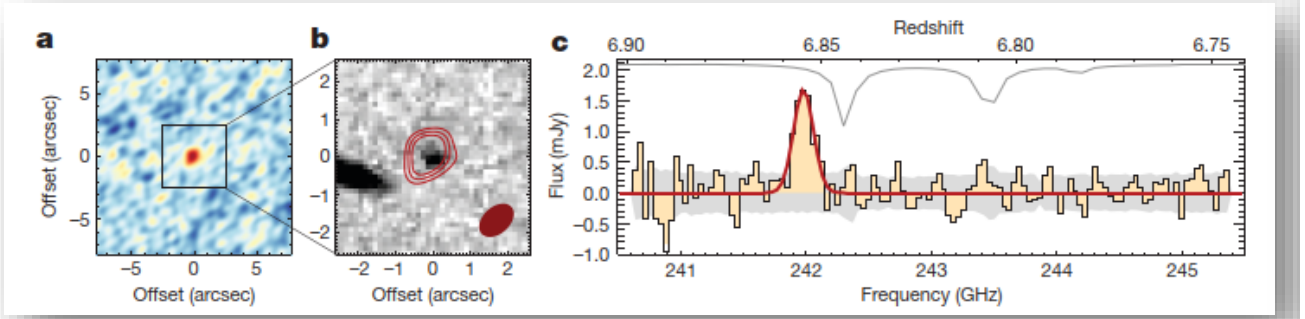


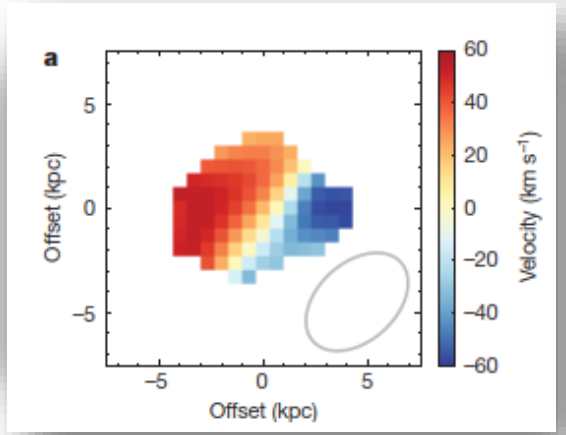

# The Next Decade in Galaxy Evolution




- Pushing from cosmic noon to re-ionization with JWST & ALMA/NOEMA
- High-z galaxies under the microscope: physical processes on < 1kpc scale with ALMA/NOEMA, VLT(I) and ELTs (MICADO, HARMONY, IRIS)
- Statistically robust census of evolving populations from z=7 to 0 with Keck, VLT, Subaru, Euclid, WFIRST & JWST
- Galaxy- MBH Co-evolution on mass selected samples, as a function of $L_{Edd}$
- Does AGN feedback dominate galaxy quenching near the Schechter mass?

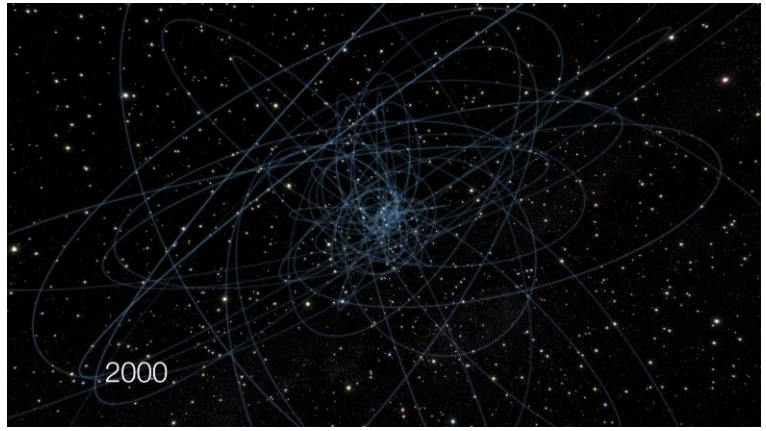


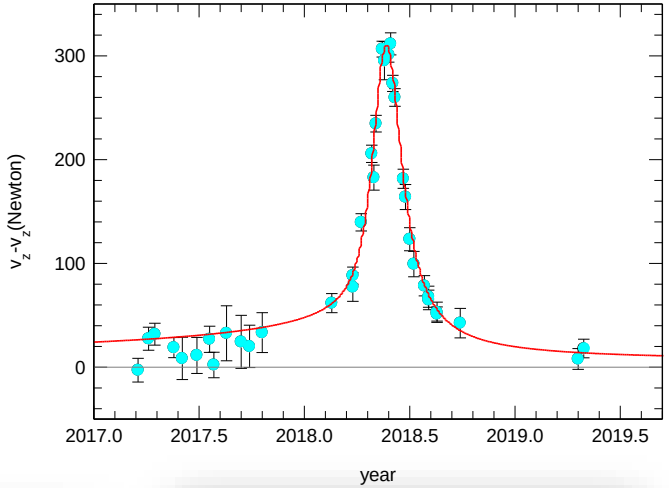

Smit et al. 2018, Chevallard et al. 2018, Davies et al. 2018, Foerster Schreiber et al. 2019

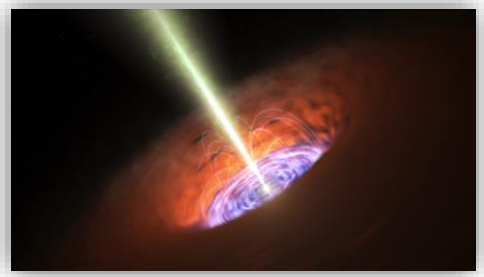
# Recent Highlights IR to MM Astronomy

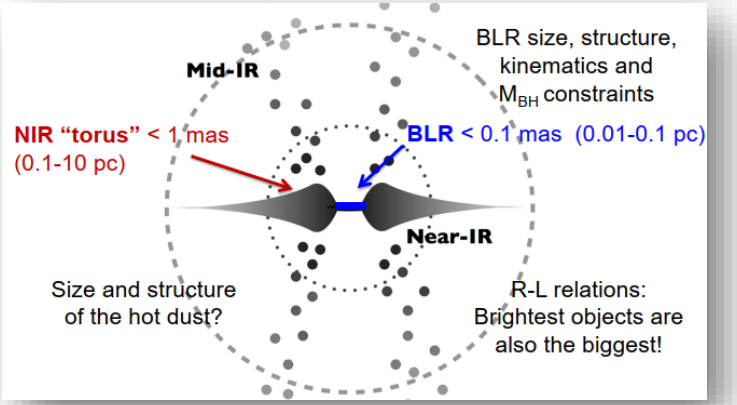


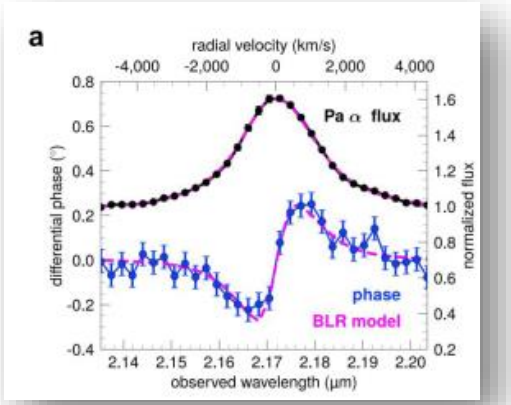

**Black Holes, Active Galactic Nuclei and Tests of GR:**

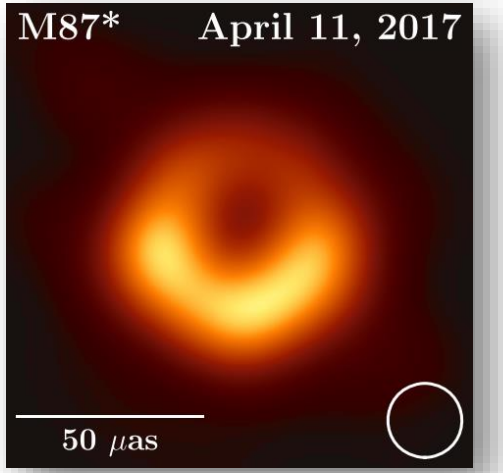
- Stellar Orbits in the Galactic Center show that SgrA* is a 4.1x10$^6$ $M_{sun}$ black hole, beyond any reasonable doubt, and deliver precision tests of GR near a super-massive BH
- The first results of the Event Horizon Telescope (EHT) demonstrate the existence of a 1.3mm photon ring/shadow in the 6.5x10$^9$ $M_{sun}$ super-massive black hole in M87
- Differential μarcsec-spectro-astrometry with GRAVITY spatially resolves the broad line region of the famous QSO 3C 273 and delivers a direct mass determination at sub-parsec scales



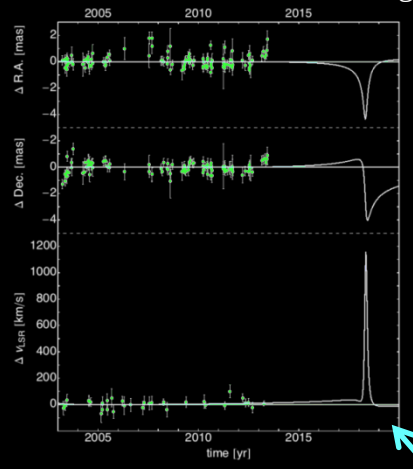


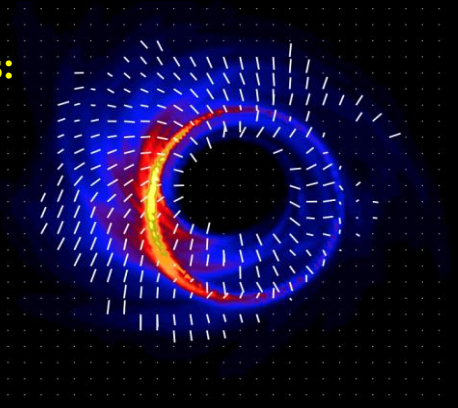



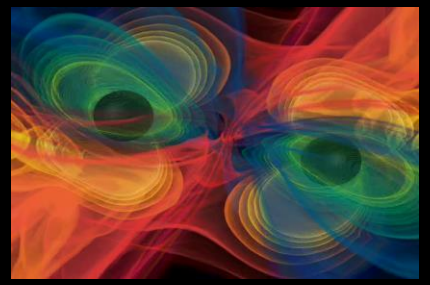
# Massive Black Holes: Inward Bound

**testing GR near massive black holes:**
submm-VLBI (Event Horizon Telescope)
infrared interferometry (GRAVITY)
pulsars
30m-class telescopes
X-ray spectroscopy
gravitational waves



$$\theta_{shadow} \overset{GR}{\underset{\neq f(i,a)}{=}} (5.2 \pm 0.2) \times \frac{2GM_\bullet}{c^2 \times R_0}$$



Quadrupole moment of metric, no hair & gravitational waves

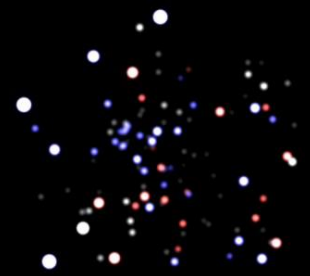
Strong curvature: shadow

spin from L-T precession

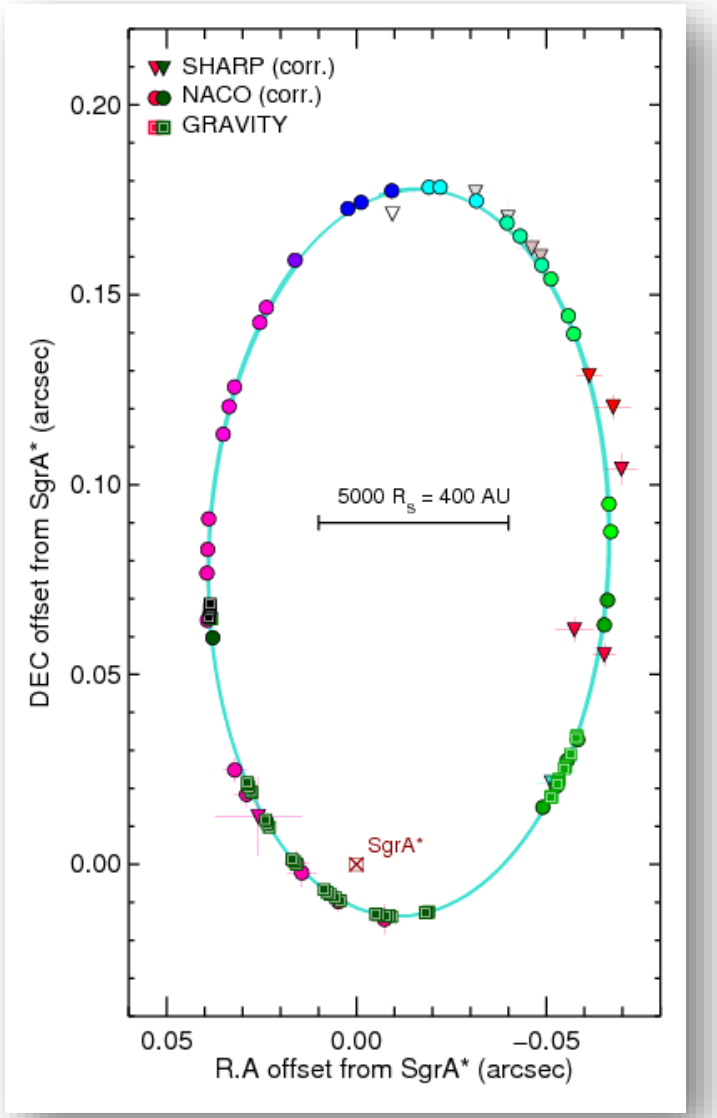
relativistic prograde precession

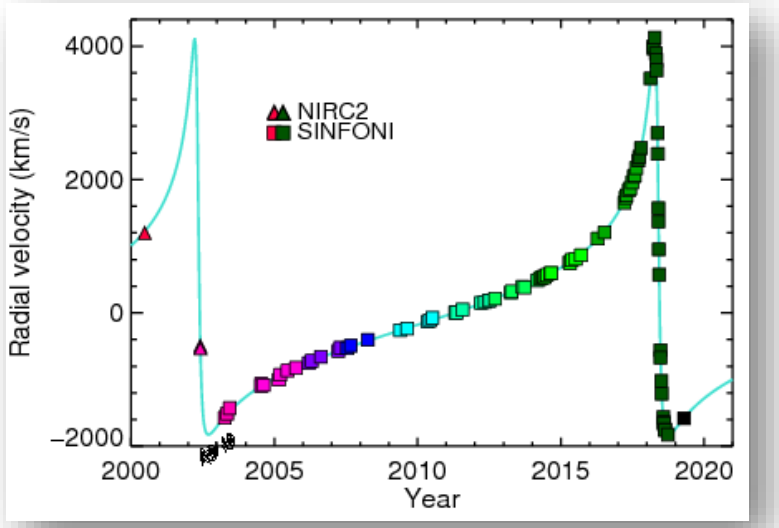
PPN (1) in radial velocities

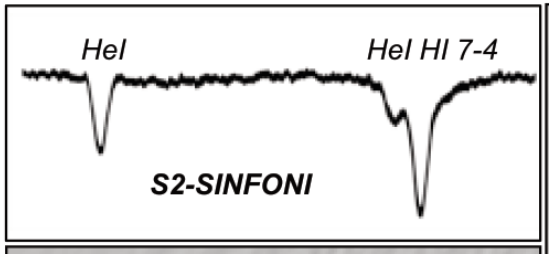
5
4
3
2
1

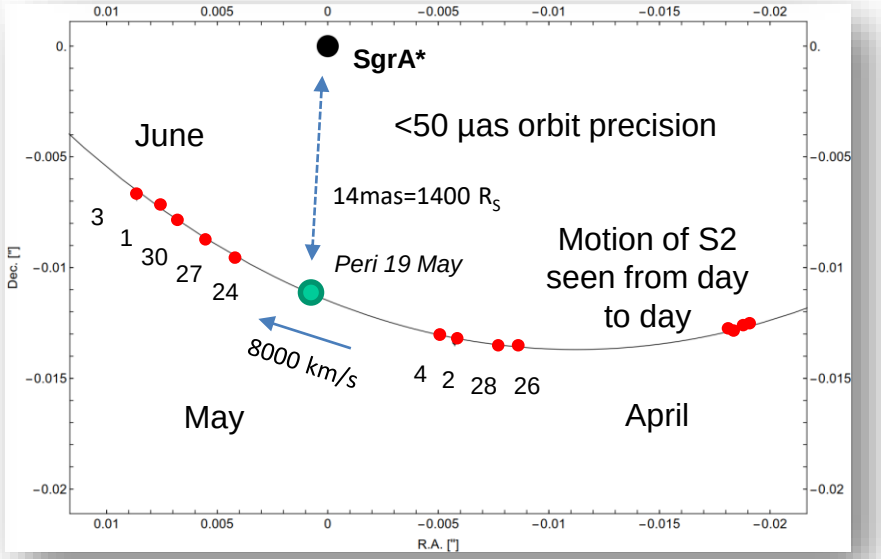


# 27 years of S2 observations



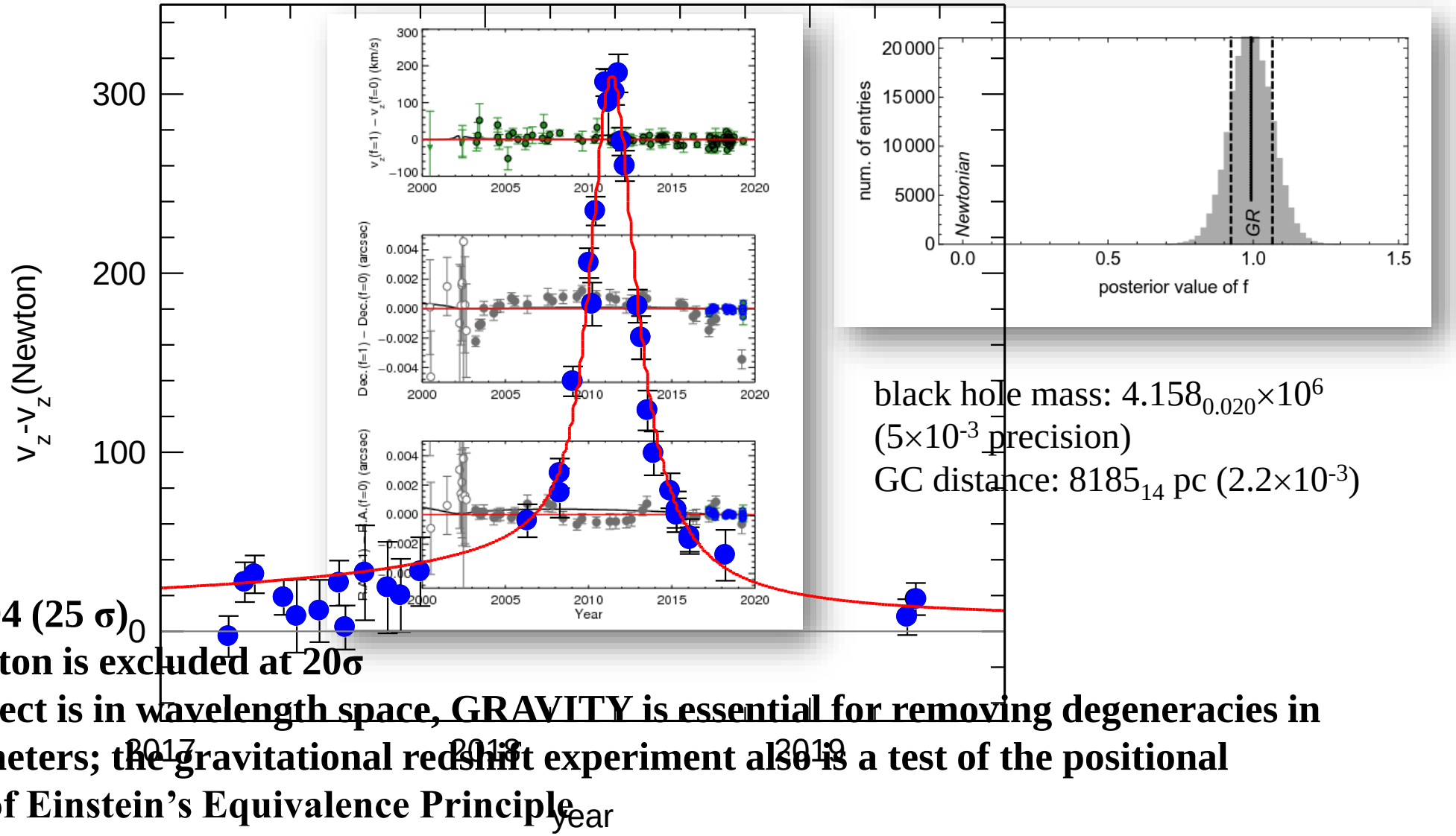




Schoedel et al. 2002, Ghez et al. 2003, 2008, Gillessen et al. 2009, 2017,GRAVITY collaboration+18a, A&A 615, L10

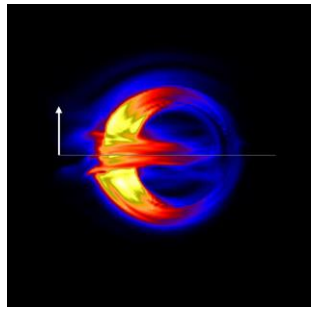
# GR effects in the orbit of S2: gravitational redshift




black hole mass: $4.158_{0.020} \times 10^6$
($5 \times 10^{-3}$ precision)
GC distance: $8185_{14}$ pc ($2.2 \times 10^{-3}$)

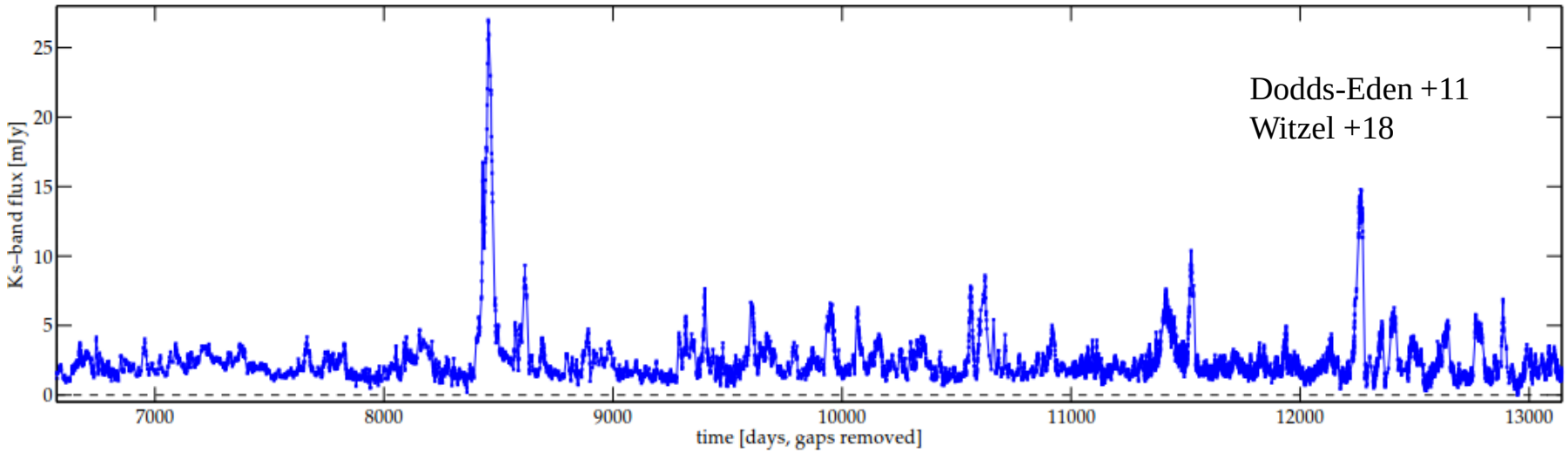
**$f = 1.05 \pm 0.04$ $(25\ \sigma)_0$**
**Kepler/Newton is excluded at 20σ**
**although effect is in wavelength space, GRAVITY is essential for removing degeneracies in other parameters; the gravitational redshift experiment also is a test of the positional invariance of Einstein's Equivalence Principle**

GRAVITY collaboration+18, A&A 615, L15, GRAVITY collaboration +19, A&A in press

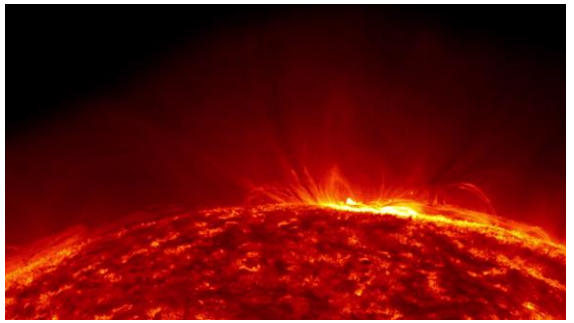


# Detection of Orbital Motions near SgrA*s ISCO

Astr. & Astrophys. 2018, 618, L10



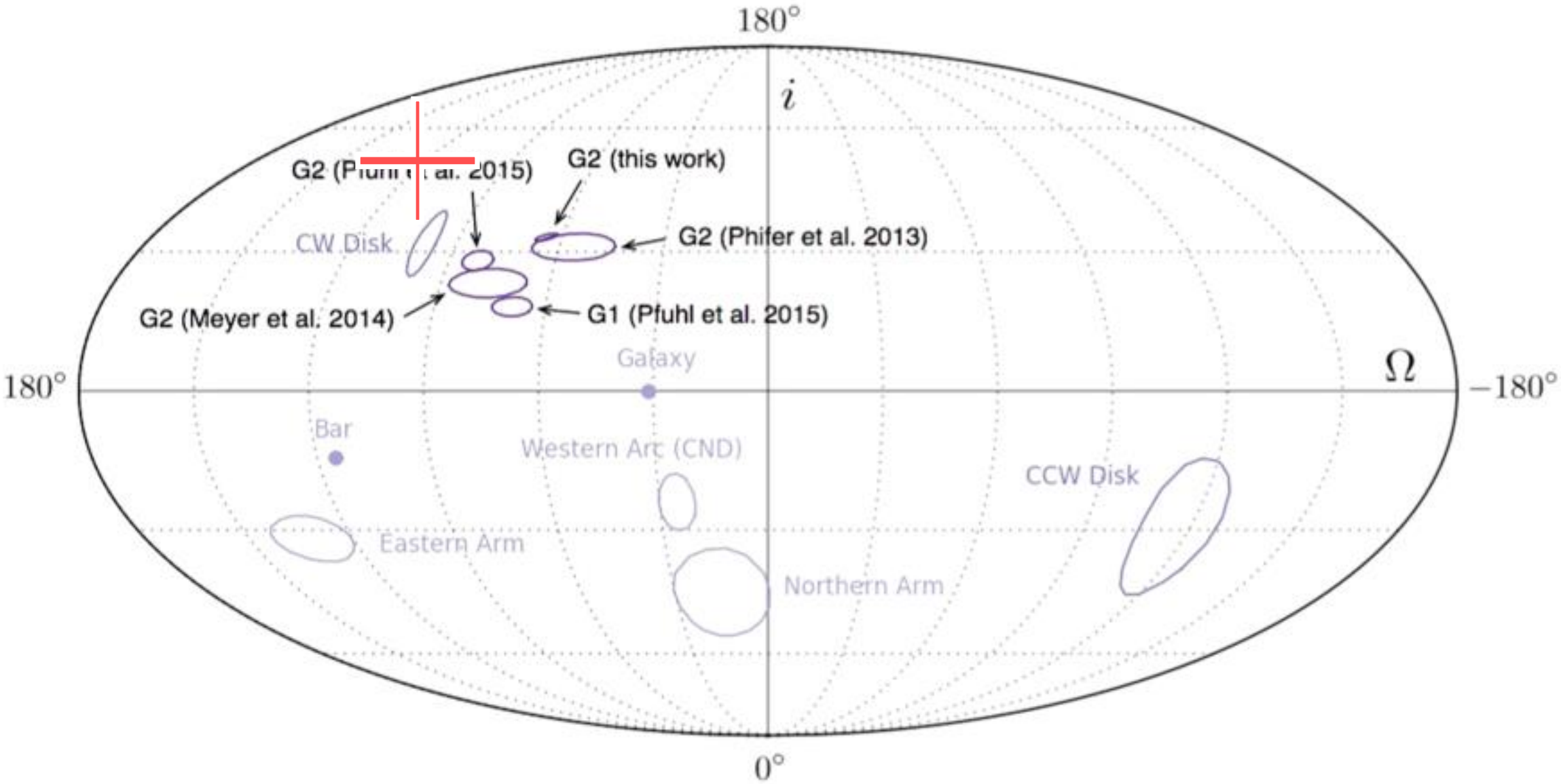

Continuously variable near-IR synchrotron emission ($\gamma \sim 10^3$) in innermost accretion zone at R~10 $R_g$: orbiting hot spots due to magnetic reconnection/shocks ?

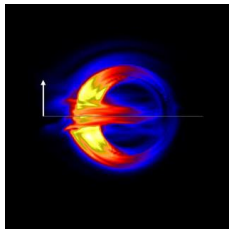


solar flare

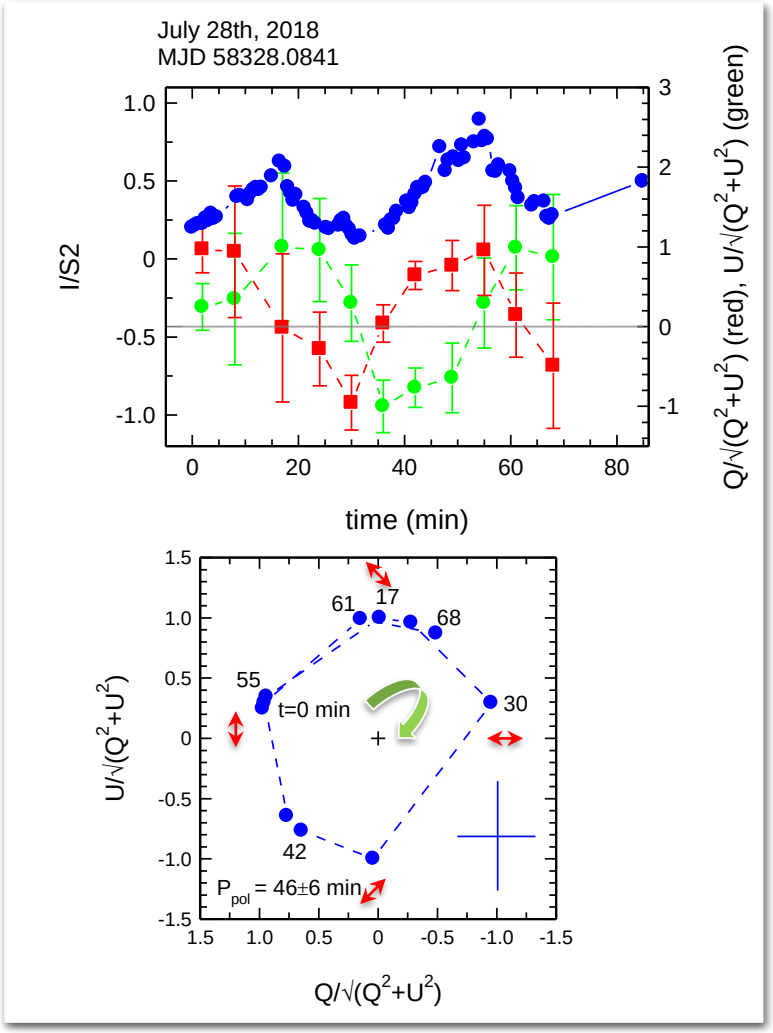
*Baganoff +2001, Genzel et al. 2003, Ghez et al. 2004, Do et al. 2008, Dodds-Eden et al. 2009, 2010, Ponti et al. 2017, Witzel et al. 2012. 2018,* ***Broderick & Loeb 2005, 2006****, Hamaus et al. 2009, Markoff et al. 2001, Yuan et al. 2004, Moscibrodzka et al. 2015, Dexter et al. 2013, Doeleman et al. 2008, Broderick et al. 2011, Johnson et al. 2017, Ponti et al. 2017*

# Orientation of the inner accretion zone

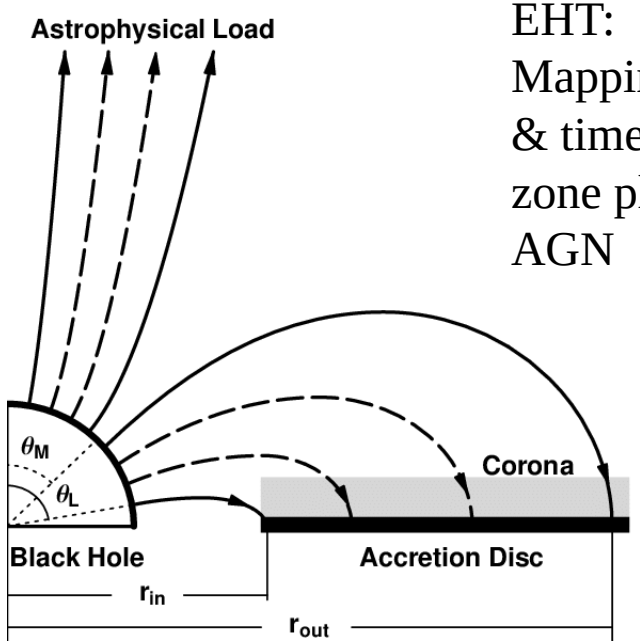




# Polarization loops with the same period as the orbital period



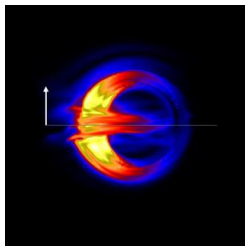

→ strong poloidal field

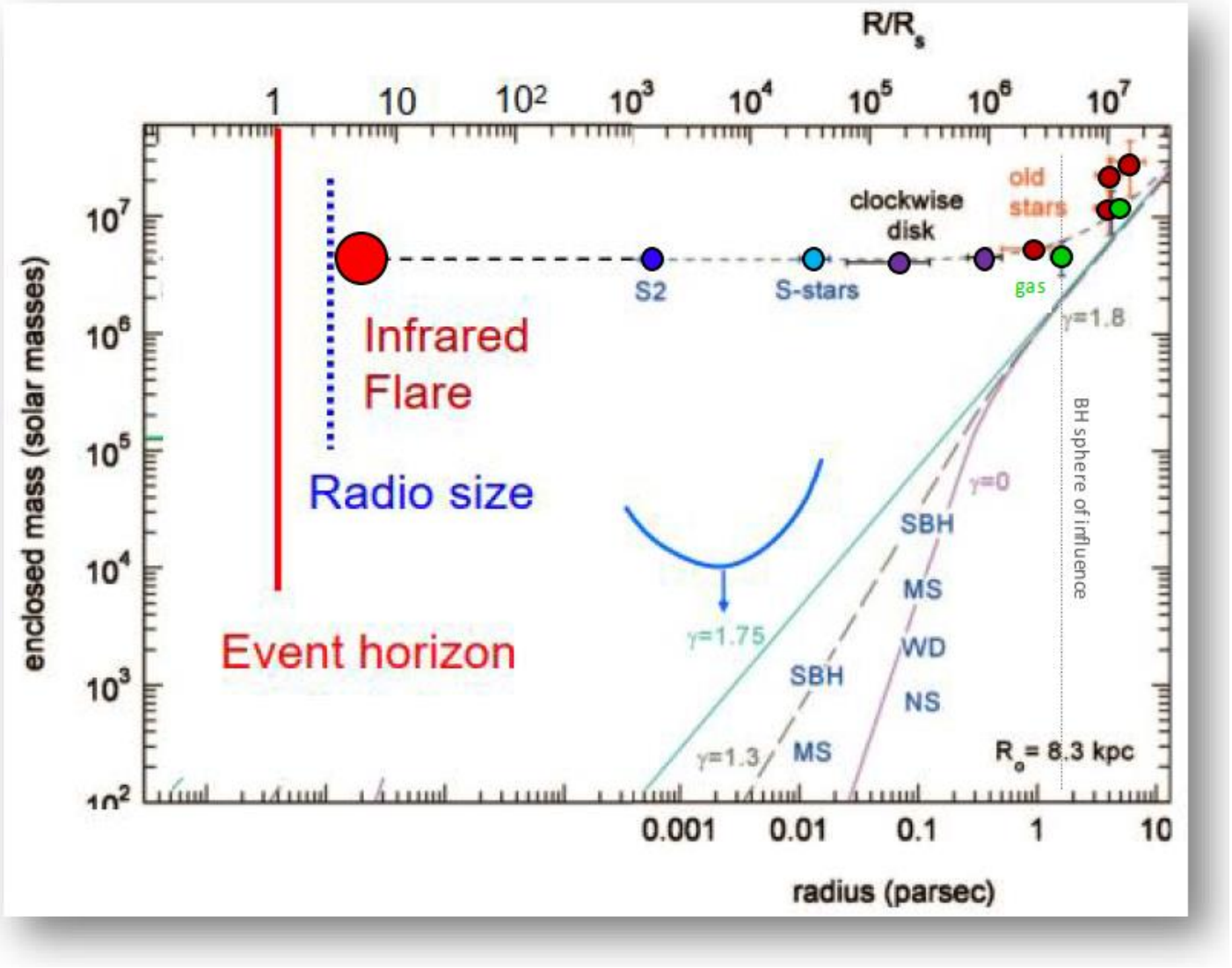



Future work with GRAVITY & EHT:
Mapping the structure, kinematics & time evolution of the accretion zone plasma in SgrA* and nearby AGN

GRAVITY collaboration 2018b, A&A 618, L10,
Marrone PhD Thesis Harvard 2006

# Orbital motions in relativistic zone are consistent with hypothesis that SgrA* is a Kerr Black Hole



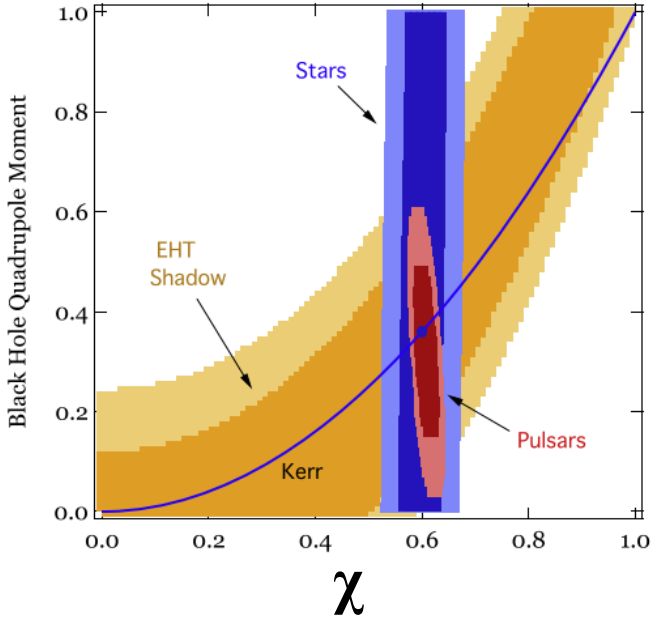


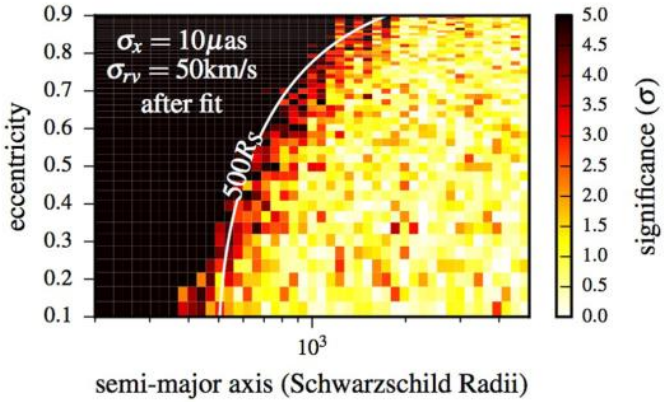

GRAVITY collaboration 2018b, A&A 618, L10, 2019c

# Testing the 'no-hair' theorem with GRAVITY, EHT & pulsars

**EHT**: precision determination of centroid displacement D/M and deviation from circularity A/M

$$\left(\frac{A}{M}\right) = \left[0.84 \times \varepsilon + 0.36 \times \chi^2\right]$$




**GRAVITY & SINFONI** : multi-year precision determination of orbit of a star inside S2 and determination of spin parameter χ

$$\Delta\Phi_{per\ orbit} = f_{SP} \times 3\pi\left(\frac{R_s}{a(1-e^2)}\right) + f_{LT} \times 2\chi\left(\frac{R_s}{a(1-e^2)}\right)^{3/2}$$

$$\left(\frac{q}{M}\right) = -\left[\chi^2 + \varepsilon\right]$$

Kerr (no hair): $\varepsilon$=0

Johannsen & Psaltis 2010 a,b, Johannsen 2016, Psaltis, Wex & Kramer 2016, Johannsen et al. 2016, Zhang et al. 2015, Waisberg et al. 2018 , EHT collaboration et al. 2019