European efforts towards the EHT

Ciriaco GODDI
BlackHoleCam Project Scientist

Radboud Universiteit Nijmegen

Black Hole Cam

VLBI Tradition in Europe

First detection of Sgr A at 1.4mm with a single baseline IRAM PV-PdBI*

Krichbaum et al. 1998

ASTRONOMY AND ASTROPHYSICS

LETTER

Astron. Astrophys. 335, L106–L110 (1998)

Letter to the Editor

VLBI observations of the galactic center source Sgr A* at 86 GHz and 215 GHz

T.P. Krichbaum[1], D.A. Graham[1], A. Witzel[1], A. Greve[2], J.E. Wink[2], M. Grewing[2], F. Colomer[3], P. de Vicente[3], J. Gómez–González[3], A. Baudry[4], and J.A. Zensus[1]

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Outline

- mmVLBI Workshop at ESO (2012)
- European White Paper on mmVLBI (2014)
- ERC Synergy Grant to BlackHoleCam (BHC) (2014)

I will not review:

- EU contributions to the ALMA phasing project. *See V. Fish talk*
- λ 1mm-VLBI at APEX, PV, and PdBI. *See F. Gueth talk*
- GMVA operations, plans for joint ALMA-GMVA observations. *See E. Ros talk*

Workshop at ESO

"mm-wave VLBI with ALMA and Radio Telescopes around the World"

Garching, June 2012

- 61 scientists from the EU and 5 from outside
- From black holes to star formation
- *Strong EU science interest in a mm-VLBI facility*

Falcke et al. 2012

European White Paper on mmVLBI

Future mmVLBI Research with ALMA: A European vision

Editorial Board

R.P.J. Tilanus[23,2], T.P. Krichbaum[44], J.A. Zensus[44,51], A. Baudry[7], M. Bremer[29], H. Falcke[23,44], G. Giovannini[26,14], R. Laing[15], H. J. van Langevelde[39,2], W. Vlemmings[48]

Contributing authors:

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Tilanus et al. 2014, arxiv:1406.4650

European White Paper on mmVLBI

Future mmVLBI Research with ALMA: A European vision

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- outlines a possible roadmap toward a future global mm-VLBI collaboration
- summarizes the science interests of the European users
  - ✧ *NOT a restatement of the science case for the APP (Fish et al. 2013)*

Tilanus et al. 2014, arxiv:1406.4650

European White Paper on mmVLBI

About 50 different projects were submitted from 160 researchers

- Imaging the event horizon of the BH at the center of the Galaxy.
- Studying the origin of AGN jets and jet formation.
  See Gomez, Kadler, Krichbaum talks
- Testing General Relativity (GR) and/or searching for alternative theories.
  See Boller's poster
- Cosmological evolution of galaxies and Black Holes, AGN feedback.
- Masers in the Milky Way - in evolved stars and star-forming regions.
  See Colomer's and Richards' Talks, and Humphreys' poster
- Extragalactic emission lines and astro-chemistry.
- Redshifted absorption lines in distant galaxies and study of their ISM.
- Pulsars, neutron stars, and X-ray binaries. *See Kramer's talk*
- Testing cosmology and fundamental physical constants.

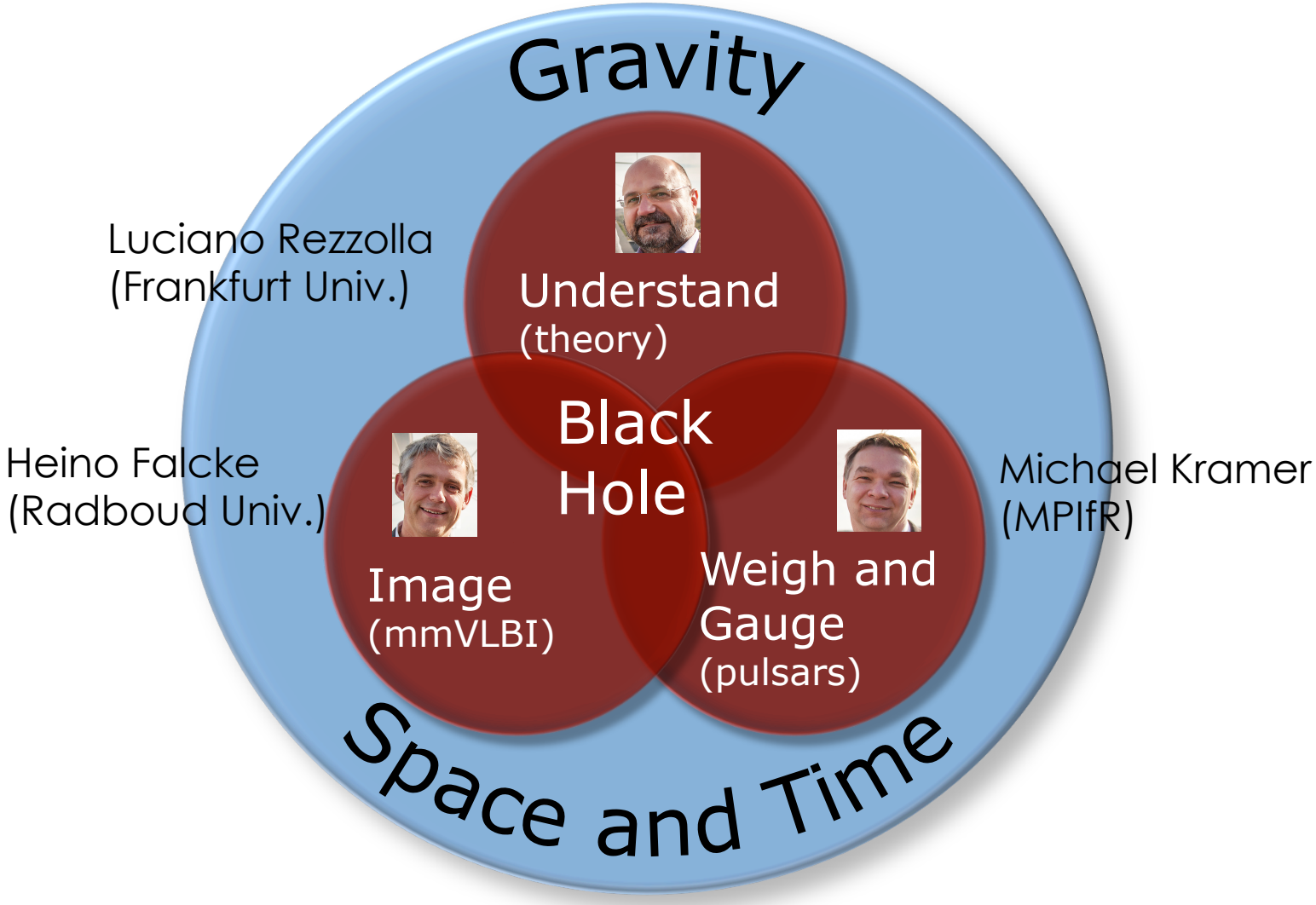
See V. Fish talk

Tilanus et al. 2014, arxiv:1406.4650

ERC Synergy Grant
BlackHoleCam Project

Black Hole Cam

European Research Council (ERC) awarded a "Synergy Grant" for 14 M€ for 6 years

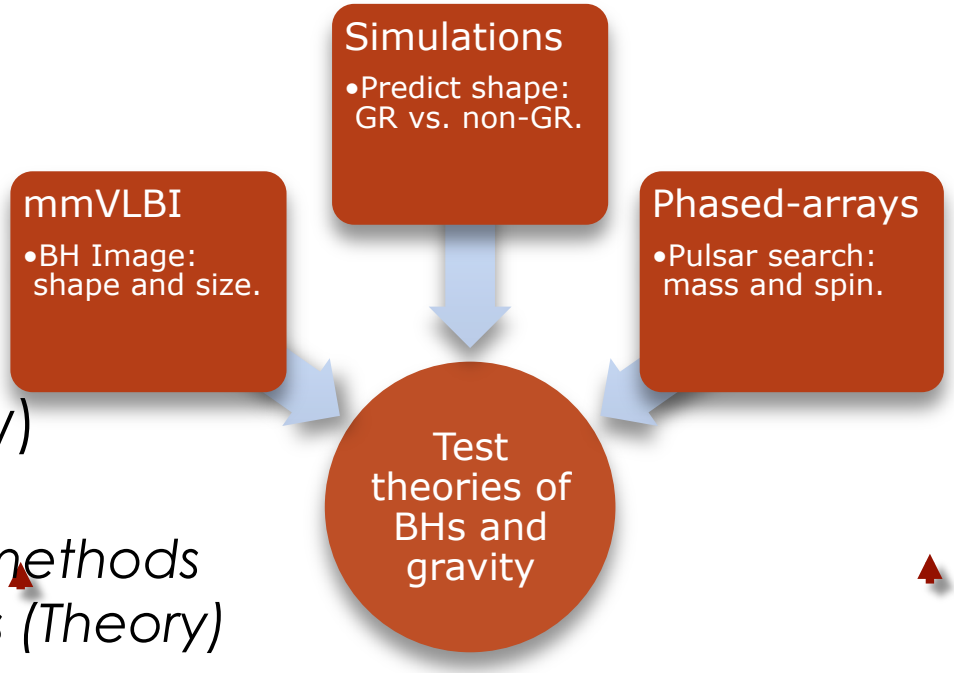


European partners

EHT partners

BHC Work Plan

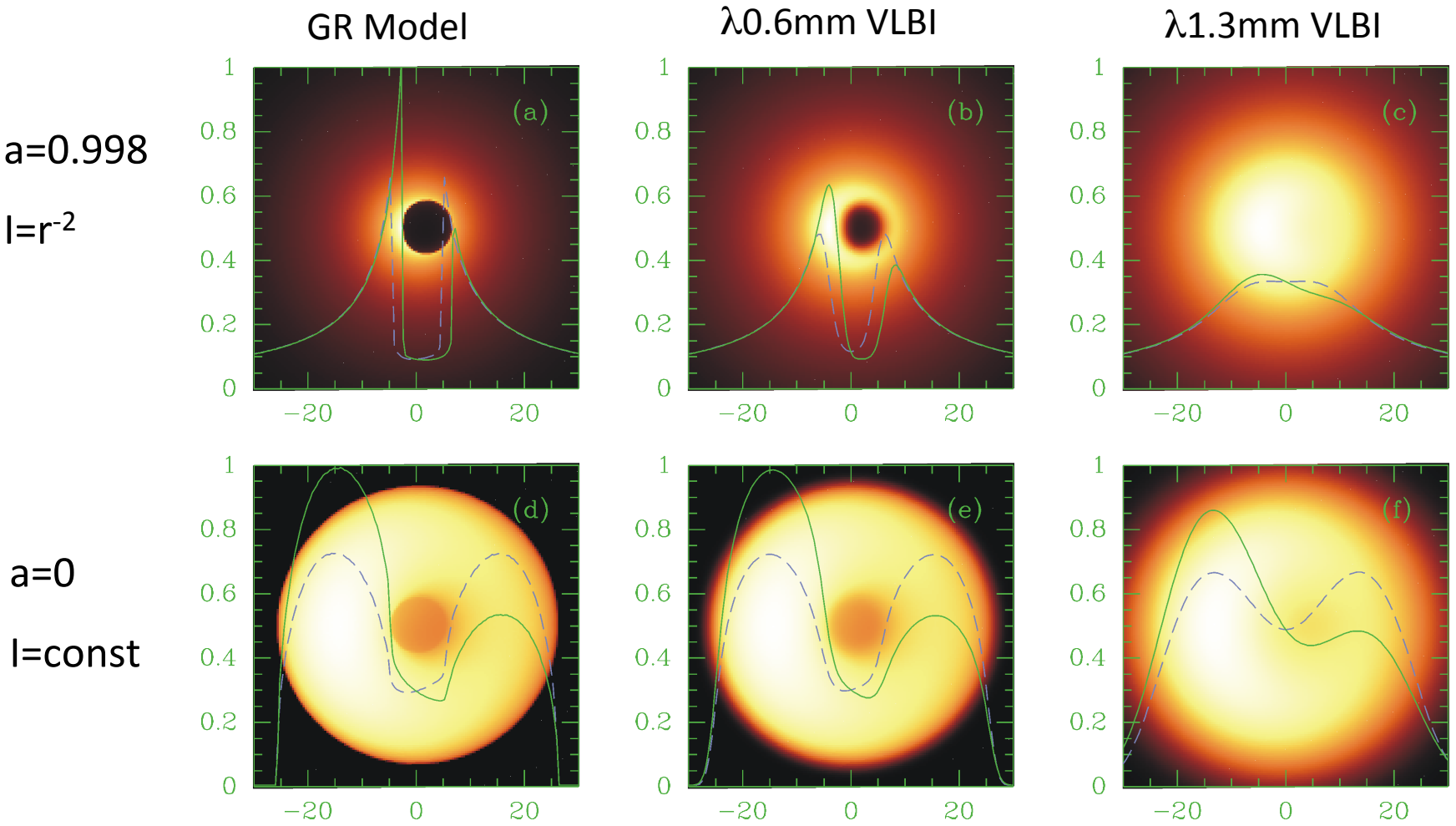
- BH shadow images (EHT)
- Pulsar timing (phased-ALMA)
- Stellar orbits (GRAVITY)
- Numerical Simulations (Theory)



Cross-correlation of the different methods and interpretation of observations (Theory)

<u>Ultimate goal</u>:
Measurements of mass/spin of Sgr A, spacetime around a BH, fundamental test of the validity of GR*

The Shadow of a Black Hole



(Falcke, Melia, Agol 2000)

Theory

- ✓ explore physical conditions of flow near Sgr A*
  - GRMHD Simulations of accretion flows onto a BH
- ✓ simulate emission from accretion flows on Sgr A*
  - Radiative transfer models (ray tracing)
- ✓ explore predictions of alternative theories of gravity
- ✓ production of observational predictions using detector simulations

GRMHD simulations of BHs

General relativistic magnetohydrodynamic (GRMHD) codes with particle acceleration

Nijmegen Group

Lead: Moscibrodzka

- *HARM(3D)* (Noble et al. 2007)
- radiative-transfer + ray-tracing
- astrophysical community investigating accretion flows around BHs

Frankfurt Group

Lead: Rezzolla

- *Whisky* (Rezzolla et al. 2010)
- radiative-transfer + ray-tracing
- GW community driven by fundamental-physics goals

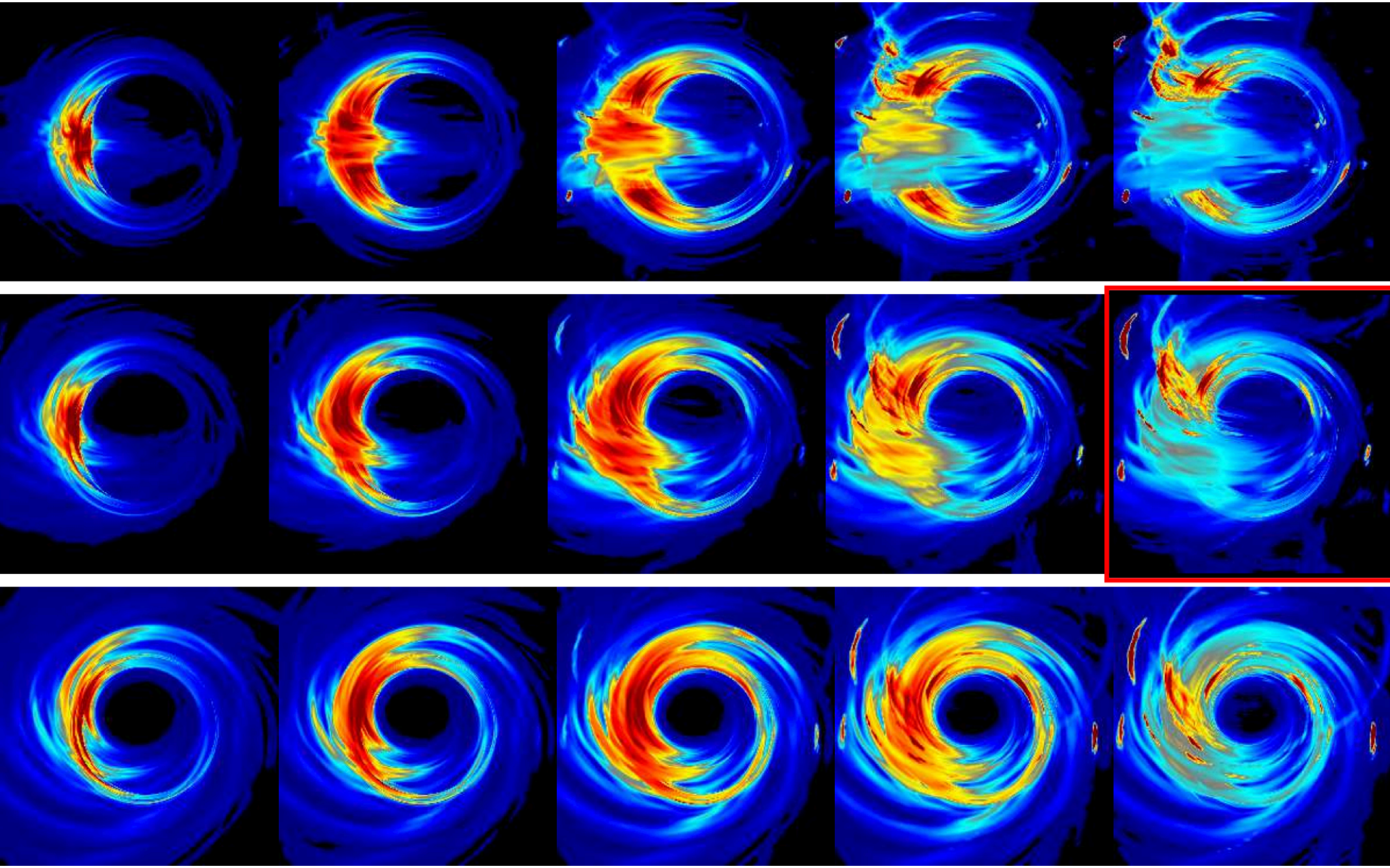
\+ *BH perturbation theory, alternative theories of gravity*

Use tools in both theoretical physics and astrophysics!

GRMHD simulations of BHs with *HARM-3D*

Disk-dominated……

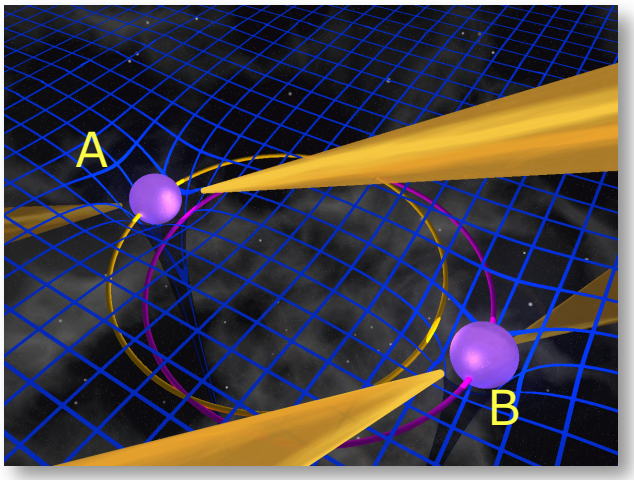
……Jet-dominated

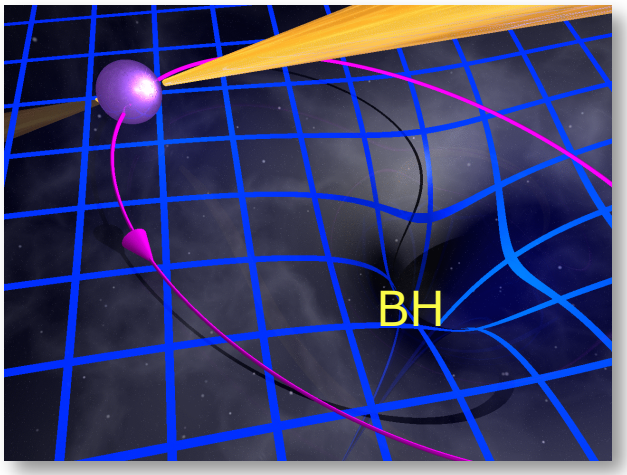


Single snapshot when varying:
T_e in disk and jet (left to right) & viewing angle (90° – 30° top to bottom)

Moscibrodzka et al.

Measuring masses with pulsars





- Binary pulsars test predictions of theories of gravity.
- We can gauge and weigh companion, e.g.:
  - Hulse-Taylor binary (Hulse & Taylor 1975)
  - Double Pulsar (Lyne et al. 2004)

    Pulsar A = 1.3381±0.0007 Solar Mass,

    Pulsar B = 1.2489±0.0007 Solar Mass.

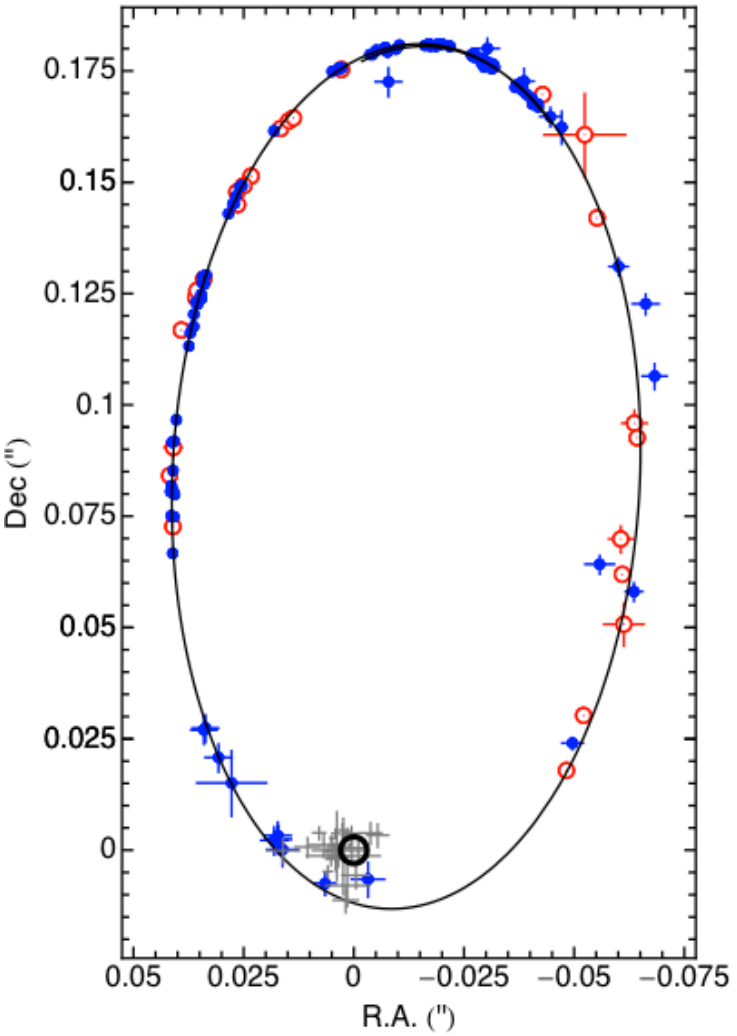
- Also possible with BHs!
- Ability to measure BH properties scales with mass.
- For few-million solar mass BH:

Mass with precision of 1:1,000,000
Spin with precision of 1:1,000.

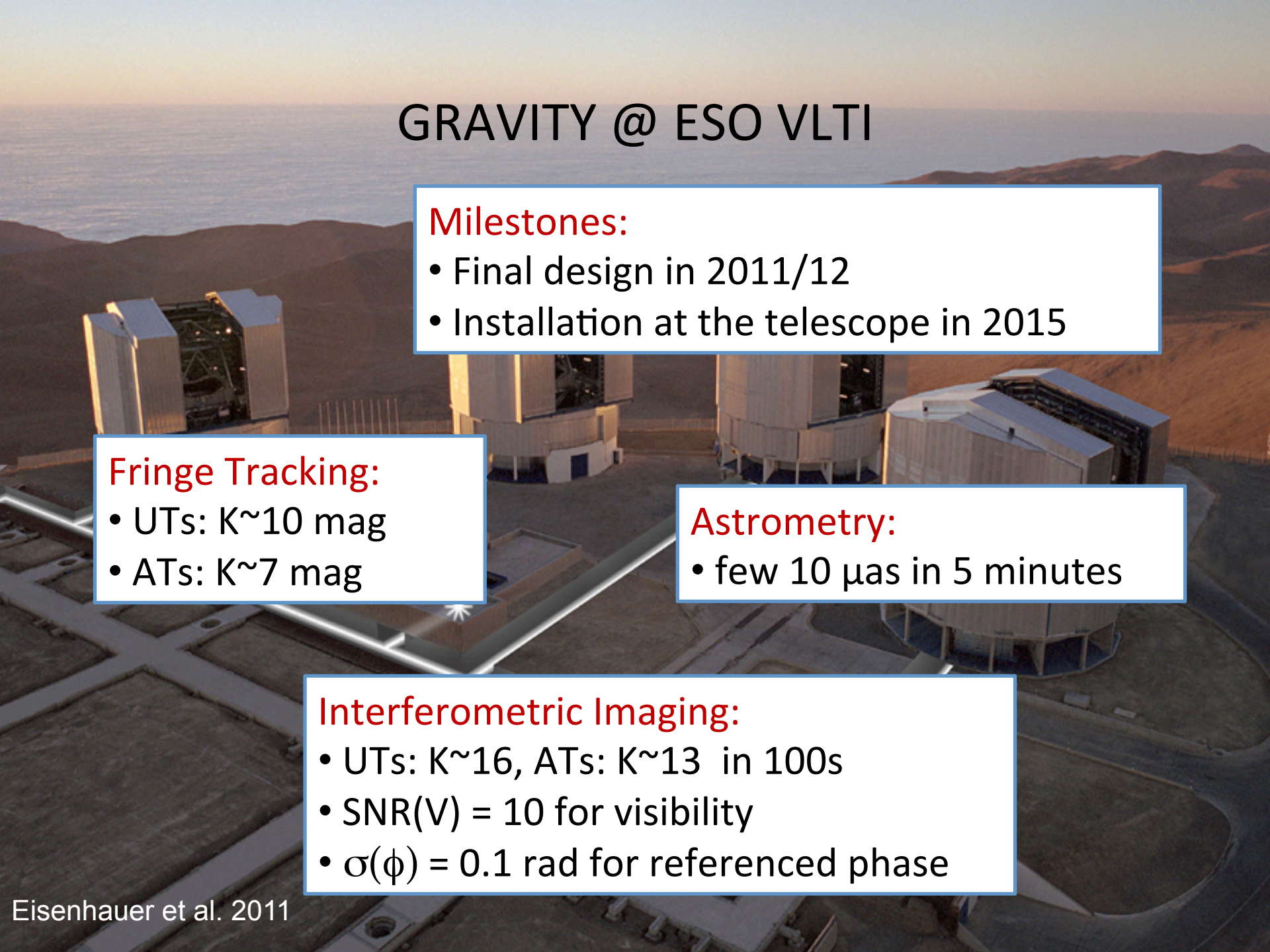
Courtesy of M. Kramer

Dark Mass in the Galactic Center

- Stellar proper motions have revealed a dark mass in the Galactic Center of 4 Million solar masses within the size of the solar system.
- The center of gravity coincides with Sgr A* within 215 R_s (15 AU).
- More stars could be at even tighter orbits, allowing one to measure more accurately mass and even spin.



Gillessen 2013, priv. comm.



GRAVITY @ ESO VLTI

Milestones:
- Final design in 2011/12
- Installation at the telescope in 2015

Fringe Tracking:
- UTs: K~10 mag
- ATs: K~7 mag

Astrometry:
- few 10 μas in 5 minutes

Interferometric Imaging:
- UTs: K~16, ATs: K~13 in 100s
- SNR(V) = 10 for visibility
- $\sigma(\phi)$ = 0.1 rad for referenced phase

Eisenhauer et al. 2011

BHC Milestones

- Kick-off Meeting (8-9 Jan 2015)
- Assessing Work-Packages (WPs)
- Setting up Working Groups (WGs)
- Equipment for March 2015 EHT Campaign

see Tilanus Talk

Setting up Working Groups

1. Theory (and Astrophysics)
2. Data simulation
3. Data reduction pipeline and image analysis
4. Pulsars (+ ALMA phasing and data recording)
5. Data acquisition, eVLBI & correlation
6. Turn-key operations, dynamic scheduling, and remote control

WP1.Theory work plan

Theory will cover three distinct but interconnected aspects:

(i) modelling of the dynamics and emission from astrophysical plasmas (*jets* and accretion *disks*) around BHs

- Extending now 3D GRMHD simulations (Nijmegen)
  - New HC computer cluster and expanded storage have been installed at RU
  - Started Oct 1
  - Lead: Monika Moscibrodzka (+Nijmegen theory group)

(ii) modelling of the signatures that different theories of gravity make on such dynamics and emission

- Mathematical framework for description of shadow in generic theories of gravity (Frankfurt)
  - Started Oct 1
  - Lead: Luciano Rezzolla (+Frankfurt theory group)

(iii) production of observational predictions using detector simulations

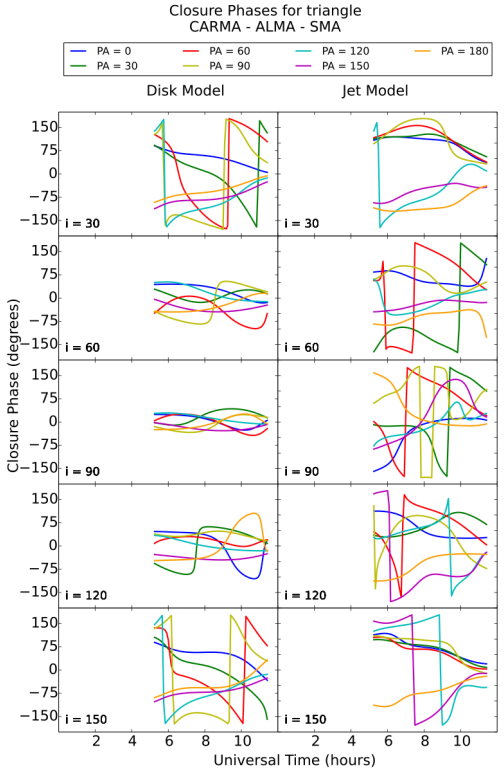
- build a large database synthetic images of the BH shadow

WP2. Software to Simulate VLBI Observations

Pipeline created by the Nijmegen group:

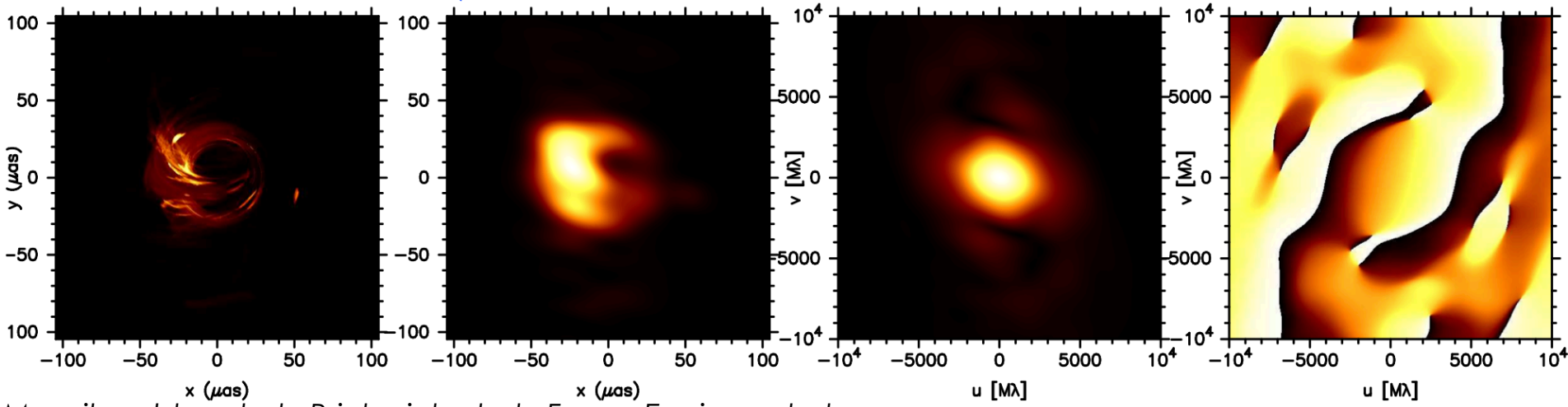
- extracts observables from GRMHD images:
  visibility amplitudes and phases, closure phases
- included in the pipeline ISM scattering effects, atm. effects, instrumental noise for arbitrary VLBI configurations

  People: Moscibrodzka, C. Brinkerink, R. Fraga-Encinas



Work in progress on **new software**:

- package of choice: MeqTrees, Maps,…?
- include polarization effects, calibration uncertainty,….
- develop radiative transfer model for polarized light (Radboud PhD T. Bronzwaer)
  - Leads: I. van Bemmel, M. Moscibrodzka



Moscibrodzka et al., Brinkerink et al., Fraga-Encinas et al.

WP3. Software data reduction/analysis pipeline

- ✓ Produce science quality images *and* non-imaging data

- ✓ Comparison among existing packages
  - AIPS, HOPS, Difmap, CASA, LOFAR software, PIMA, Miriad

- ✓ Package of choice: CASA
  - Fringe finder algorithm
  - VLBI gain calibration (Tsys, gain curves)
  - Sparse imaging algorithm?

- Started Oct 1.
- Lead: Ilse van Bemmel (+ JIVE software experts)

Please see I. van Bemmel's poster!

JIVE
JOINT INSTITUTE FOR VLBI IN EUROPE

WP4. Pulsar search with phased-ALMA

- Experience in using phased-up interferometers for the observations of pulsars (LEAP project).
- Similar data acquisition needs for the VLBI and pulsar communities (high-bandwidth digital equipment and storage solutions).
- Design and build a unified recorder system that can serve both communities at mm-wavelengths.
- Standard pipeline searching the data for pulsars + timing analysis
  - Start date: TBD
  - Lead: Gregory Desvignes (+MPIfR Pulsar group)

See Michael Kramer's talk this afternoon!

Max-Planck-Institut für Radioastronomie

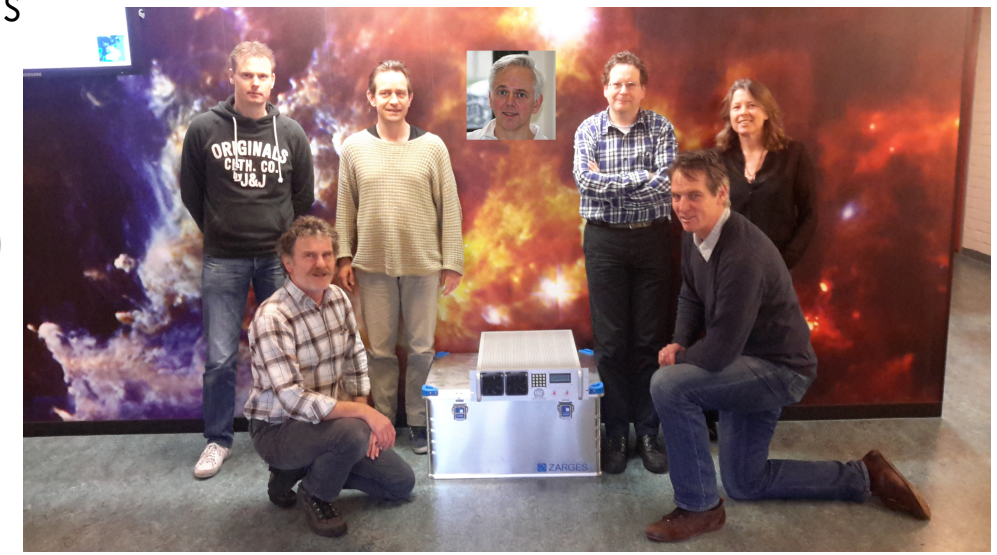
Data acquisition, Operations

- WP5. Near real-time software correlator and eVLBI interface
  - (Automatically) send data-snippets, e.g. on calibrators, to correlator for near real-time correlations
  - Implements ability to verify a functional array prior and during observations
  - Started Oct 1: port eVLBI capability from Mark5 to Mark6
  - Lead: Arpad Szomoru (+JIVE specialists)

- WP.6 Software package for remote control and dynamical scheduling/alerting
  - turn-key operations to interact smoothly with ALMA
  - Integrate mmVLBI with standard observing modes and allow for rapid switching
  - Start date: TBD
  - MPIfR Pulsar Group

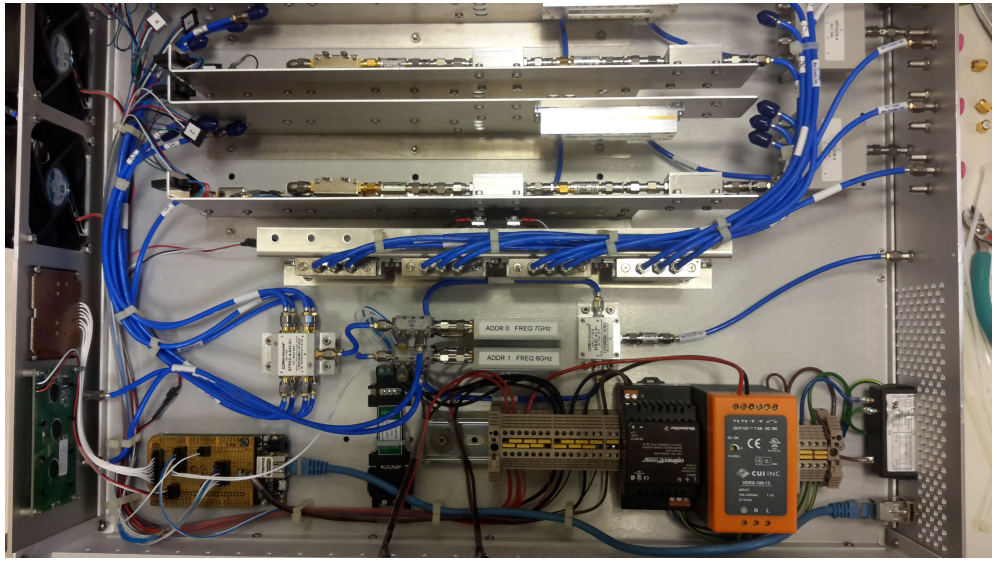
Installation of next-gen. mmVLBI units for EHT

- 64 Gbps (16 GHz) downconverters backends & recorders at the telescopes
- IRAM NOEMA beamformer (2017)
- March 2015 Campaign
- Lead: Remo Tilanus



SRON Groningen Team

Block down converter for the LMT just shipped to Haystack



- Built by SRON
- Filters by MPIfR
- Design by Haystack

See R. Tilanus talk!

BHC Kickoff Meeting

8-9th Jan 2015, Bonn

BlackHoleCam Kick-off Meeting Programme

January 8-9 2015, room 0.02, MPIfR, Bonn

Black Hole Cam

Thursday 8th

12:00 - 13:00 Lunch

13:00 - 13:05 Welcome

13:05 - 13:15 **Michael Kramer** (MPIfR) - *Introduction to BHC*

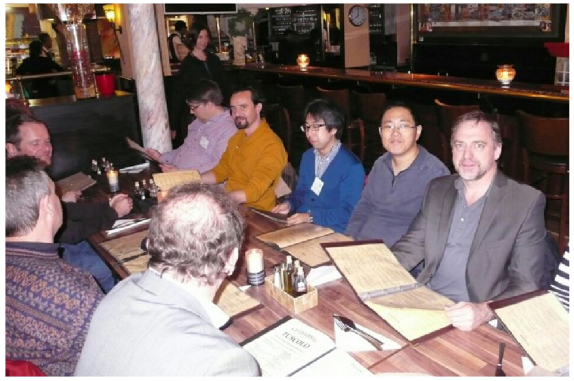
13:15 - 13:30 **Michael Kramer** (MPIfR) - *Pulsars*
13:30 - 13:45 **Luciano Rezzolla** (Frankfurt) - *Theory*
13:45 - 14:00 **Remo Tilanus** (Leiden/Nijmegen) - *Black Holes*

14:00 - 14:15 **Huib J. van Langevelde / Ilse van Bemmel** (JIVE) - *Software@JIVE*
14:15 - 14:30 **Robert Laing** (ESO) - *VLBI@ALMA*
14:30 - 14:45 **Frank Eisenhauer** (MPE) - *VLTI/GRAVITY*
14:45 - 15:00 **Eduardo Ros** (MPIfR) - *mm-VLBI at the MPIfR: the GMVA and beyond*

15:00 - 15:30 Coffee Break

15:30 - 15:45 **Remo Tilanus** (Leiden/Nijmegen) - *EHT Development, 2015 Spring Campaign*

15:45 - 15:55 **Monika Moscibrodzka** (Nijmegen) - *Theory Overview*
15:55 - 16:05 **Ziri Younsi** (Frankfurt) - *General Relativistic Radiative Transfer in Black Holes*



- 40 scientists from EU
- Science talks
- WP and management discussion

Conclusions and Outlook

- Broad scientific interest and ample support in EU for the development of an open-user global mm-VLBI facility.
- Various EU Institutions are contributing to the EHT project (MPIfR, IRAM, ESO, ERC,..) with resources, manpower, equipment, software, etc.
- Theoretical work and VLBI/Pulsar data analysis in BHC will help us interpret the EHT data (e.g. GR vs. non-GR)

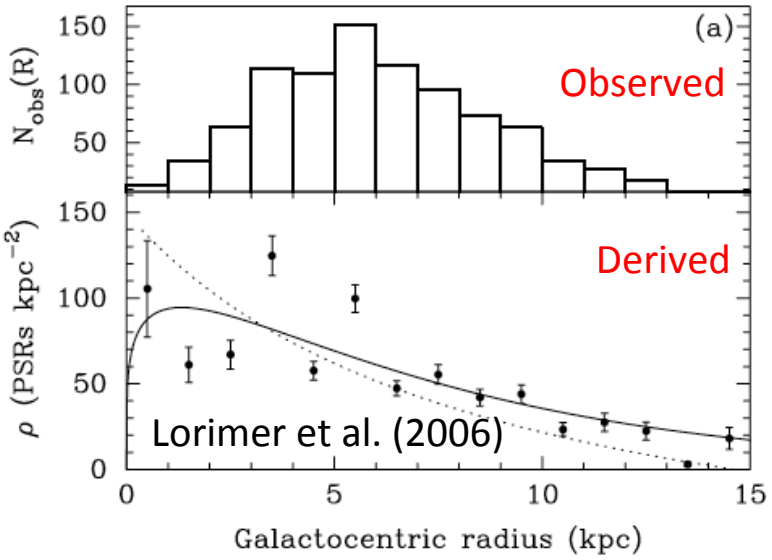
Let's all work together to make it happen!

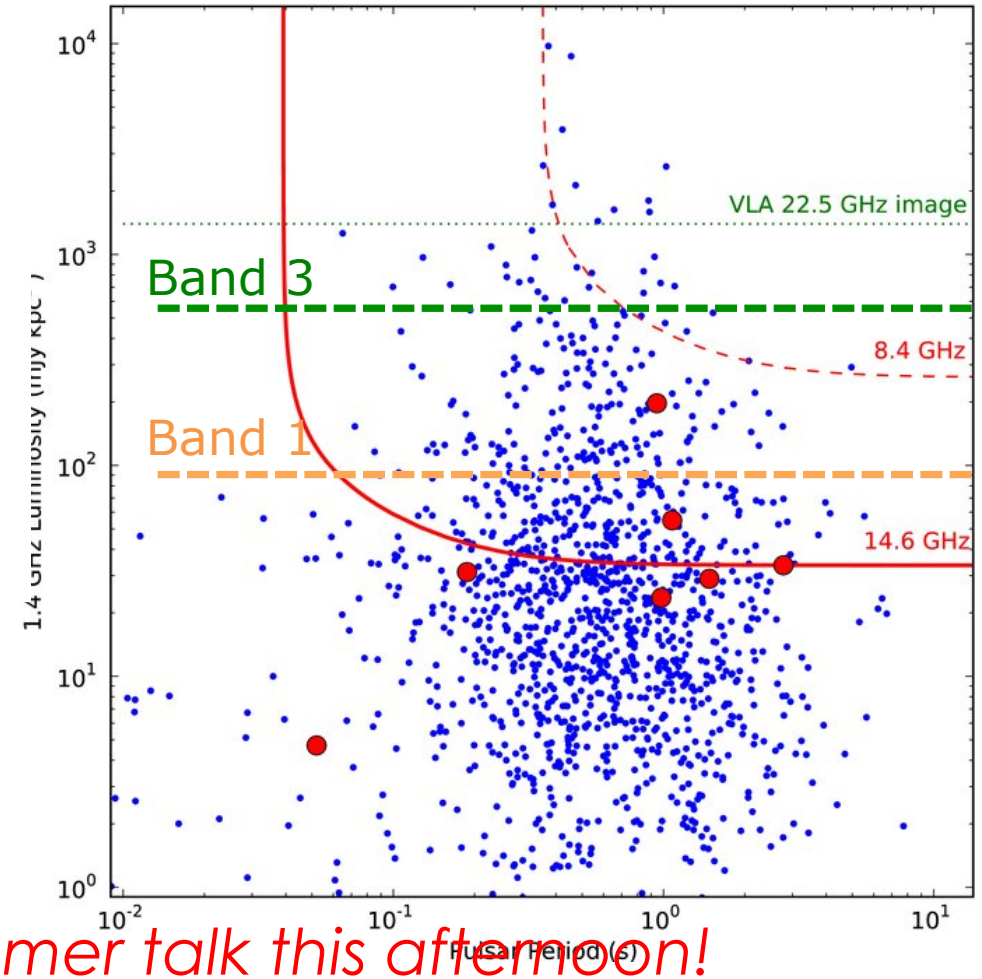
BACKUP

Finding GC pulsars with ALMA

- Until recently not a single pulsar had been found in the GC
- Is scattering too high? Maybe use ALMA for pulsars….

(Assuming 50 12-m dishes and compare it with the best searches)





Background: Macquart et al. (2010)

- Wharton et al. (2013) predict even up to 1000 pulsars in central parsec

See Michael Kramer talk this afternoon!

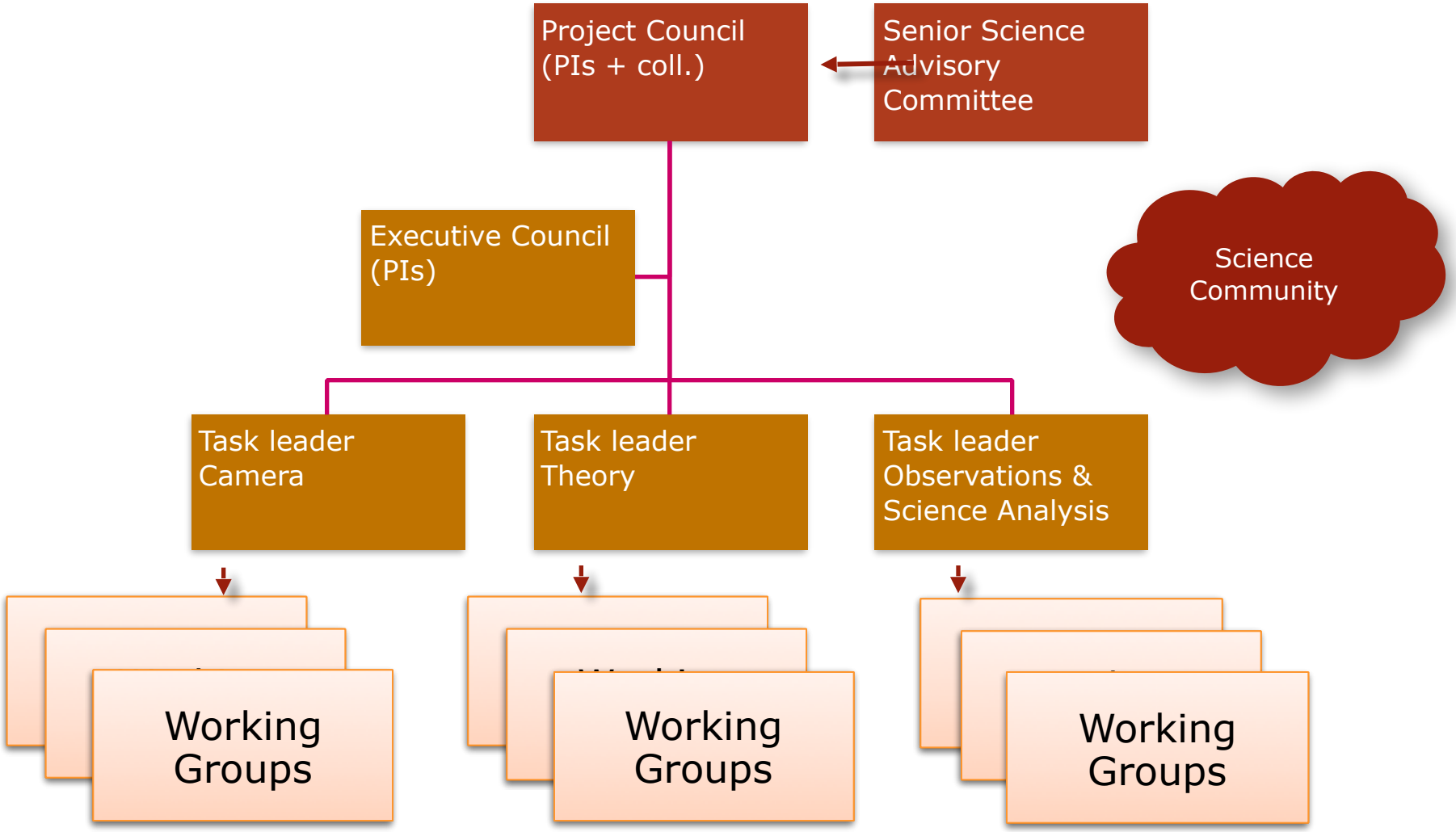
Summary slide BEFORE WP?

Putting things together: cross-validation of theory and observations

- Investigating constraints from combining pulsar, GRAVITY, and VLBI observations with theoretical predictions
- Comparison of the data with model predictions and analysis within our theoretical frame work

PLACE-HOLDER

Management Structure



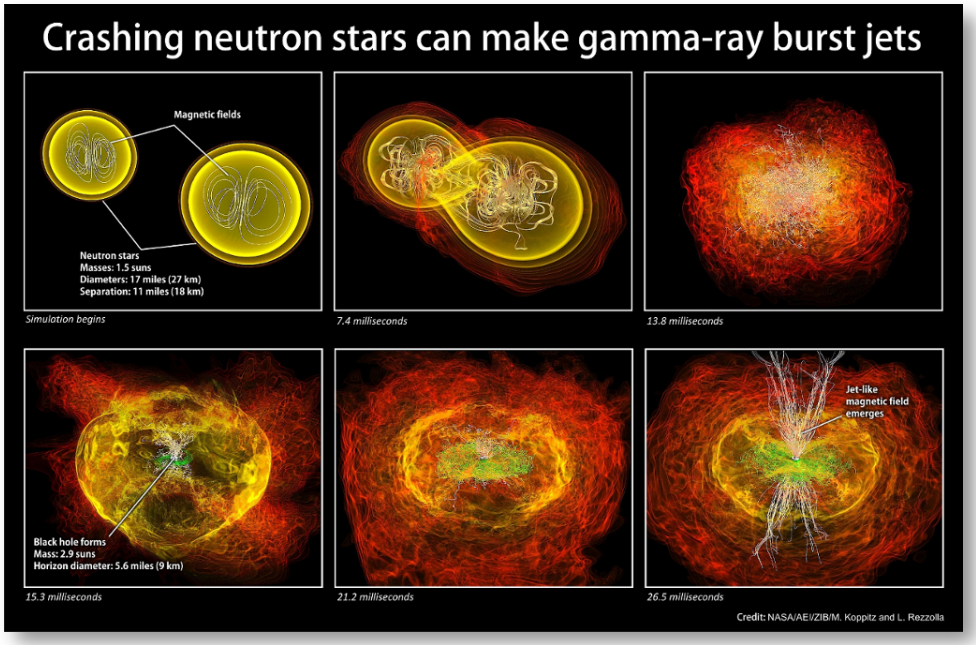
Theory and Observations

- Theoretically well studied: sophisticated numerical solution of Einstein equations + plasma dynamics.

- Theory more advanced than observations – are BHs just a theorist's toy?

- BHs are simplest objects – they are described by just two numbers:

  mass & spin!

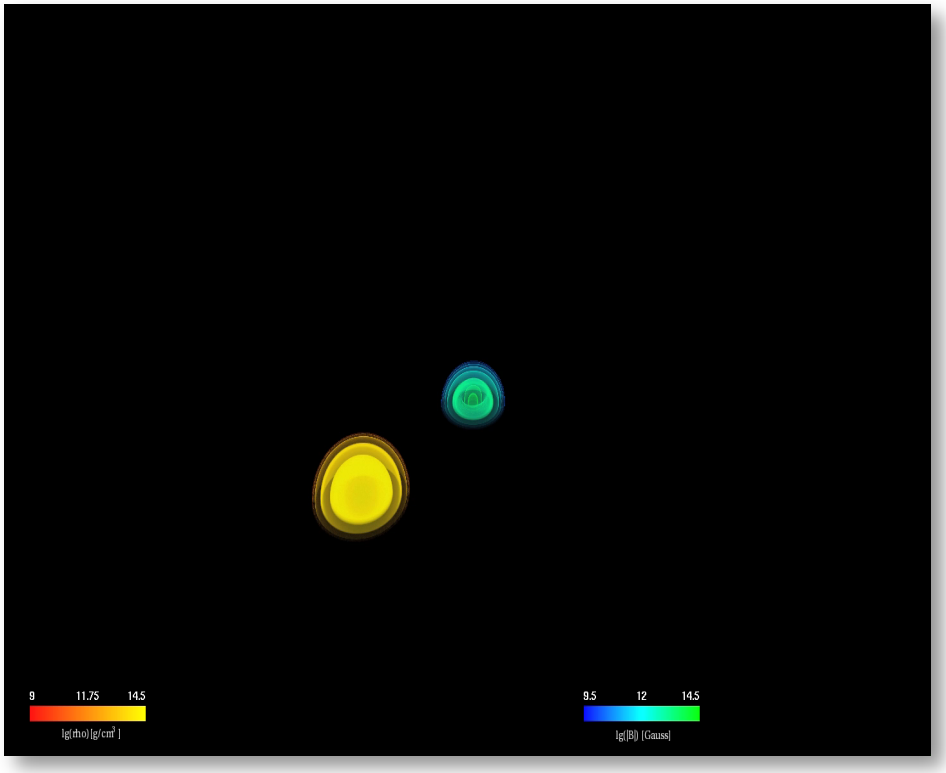


Rezzolla et al (2011)

Theory and Observations

- Gravity is well studied: Gravitational Wave (GW) community has developed sophisticated numerical solutions of Einstein equations + plasma dynamics.

- Theory is more advanced than observations – GWs will likely be measured, but Sgr A* may be the first real test of these tools!



Rezzolla et al (2011)

The Frankfurt theory team

- Luciano Rezzolla (Lead)
- Roman Konoplya — MHD simulations, jet launching, PIC
- Yosuke Mizuno — GR radiative transfer, ray tracing
- Oliver Porth — BH perturbation theory, alternative theories
- Ziri Younsi
- Alexander Zhidenko

The Nijmegen theory team

- Heino Falcke (PI)
- Monika Moscibrodzka (Lead) — BH physics, GRMHD simulations
- Elmar Koerding (Ass. Prof) — BH, compact objects physics
- Thomas Bronzwaer (PhD) — Radiative transfer
- Christiaan Brinkerink (PhD) — ……..
- Raquel Fraga-Encinas (PhD)

More details on simulations

- GRMHD Simulations of accretion flows onto a BH
  - Ideal-MHD equations
  - Zoo of models with various BH spins, B-field topologies

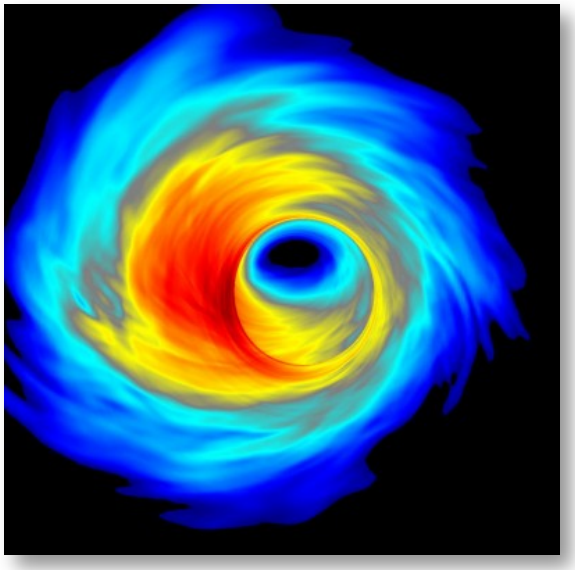
- Radiative transfer models
  - ray tracing schemes (follow light rays in curves space-time and solve RT eq. along photons geodesics trajectories)
  - all geometrical effects: light bending, Doppler boosts, light crossing time effect etc.
  - emission processes currently included: synchrotron + synchrotron self-absorption (mixture of thermal and nonthermal electrons: Maxwell + power-law DF), inverse-Compton scatterings (Klein-Nishina cross section), bremsstrahlung (optionally)
  - models can be differentiated by observations of BH systems at any wavelength (radio-X-ray, spectra and images)

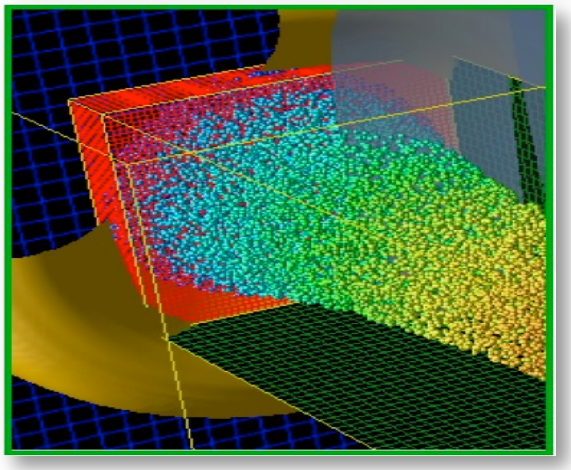
Perform numerical simulations

- use tools in theoretical physics *and* astrophysics.
- Detector simulation (simulated VLBI images)

GRMHD + particle codes

- In addition GRMHD codes are now well developed in astrophysics; link with observations is still weak
- Compare with GW tools
- Develop tools to couple GRMHD codes to PIC code to model particle acceleration
- End result matched with ray-tracing codes for realistic image synthesis for various physical conditions and gravity theories.





Noble et a. (2007)

The actual work plan

WP 2.1: 3D GRMHD simulations of accretion/jets systems with ray tracing, radiation transport, and particle acceleration, predicting theoretical images, spectra, and variability

D2.1.a: Comparative study of GRMHD codes [100,0,0].

D2.1.b: Systematic investigation of BH model parameter space via full 3D GRMHD codes [50,50,0].

D2.1.c: Extending 3D GRMHD with particle acceleration and radiation codes (semi-analytic and PIC) for comparison with observations [33,33,33].

WP 2.2: Investigation of alternative/expanded theories of gravity

D2.2.a: Imaging code for emission in arbitrary theories of gravity [0,60,40].

D2.2.b: Catalogue of BH images and emission properties in alternative theories of gravity [0,40,60].

D2.2.c: Framework for quantitative measurements of deviations from BH solutions in generic theories of gravity [0,20,80].

WP 2.3: Putting things together: cross-validation of theory and observations.

D2.3.a: Investigating constraints from combining pulsar, GRAVITY, and VLBI observations with theoretical predictions [33,33,33].

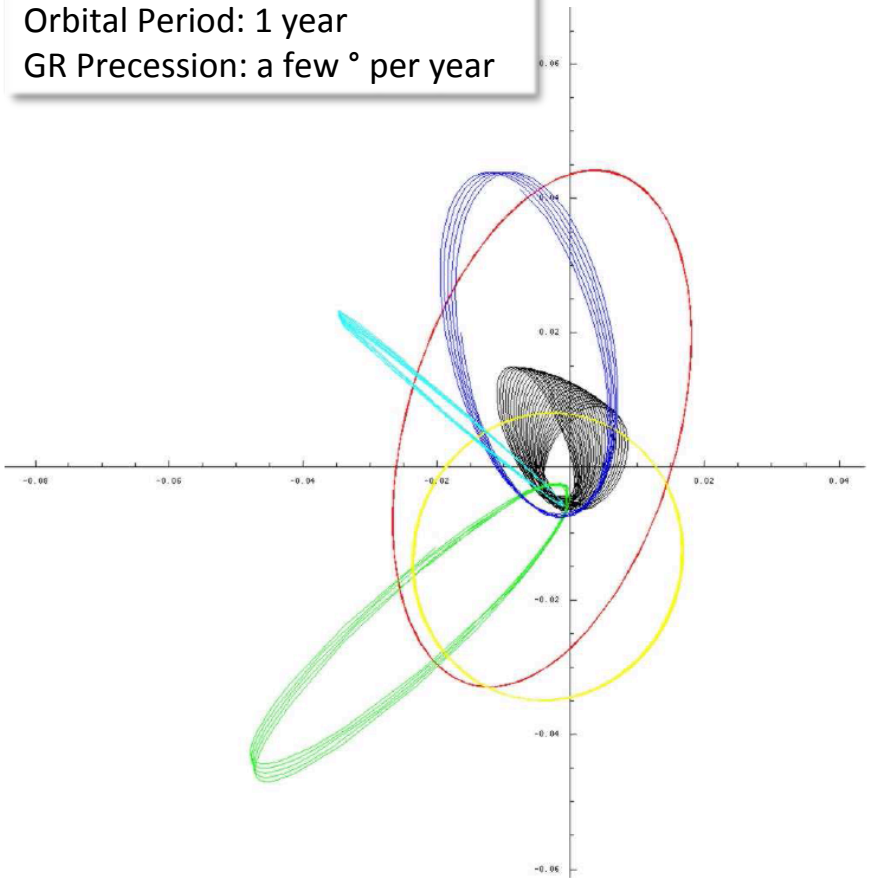
WP 2.4: Outreach, education, and science communication

D2.4.a: Production of (3D) animations, popular science articles, and materials for textbooks, webpages, and

Dark Mass in the Galactic Center

- Stellar proper motions have revealed a dark mass in the Galactic Center of 4 Million solar masses within the size of the solar system.
- The center of gravity coincides with Sgr A* within 215 R_s (15 AU).
- More stars could be at even tighter orbits, allowing one to measure mass and even spin.

Expected in central 100 mas:
~5 stars (K =17..19 mag)
Orbital Period: 1 year
GR Precession: a few ° per year



see also: Rubilar & Eckart (2001)

Theory work plan

- **build a large database** synthetic image of the shadow
- derive a (most) general parametric description of compact objects w/ *and* w/o horizon (not just Kerr BHs)
- given a theory of gravity (i.e. mass, spin, …? of BH), we will explore as much as possible the space of parameters:
  - flow geometries (spherical/disk)
  - magnetic field strength and topology
  - emission processes (disk? jet? flares?)
- determine how features obtained above change with different theories of gravity

Data Analysis and Simulation

- **D1.3.a**: automated VLBI software pipeline: 2 FTE Nijmegen, 3 FTE JIVE **[20,40,40]**.
- **D1.3.b**: mmVLBI simulation tool: 2 FTE Nijmegen (***Sec. 2.1.2***) **[50,50,0]**.
- **D1.3.c**: Pulsar search analysis pipeline for ALMA: 4 FTE Bonn (***Sec. 2.1.3)*** **[40,40,20]**.
- **D1.3.d**: Pulsar timing analysis pipeline working for ALMA:

Simulations

- Test null-hypothesis, new software
- Test sensitivity, atmosphere, image quality,…
- Package of choice: MeqTrees
  - Existing module for ionospheric phase errors
  - Existing EHT simulations
- Other institutes? Manpower? Separate WP?

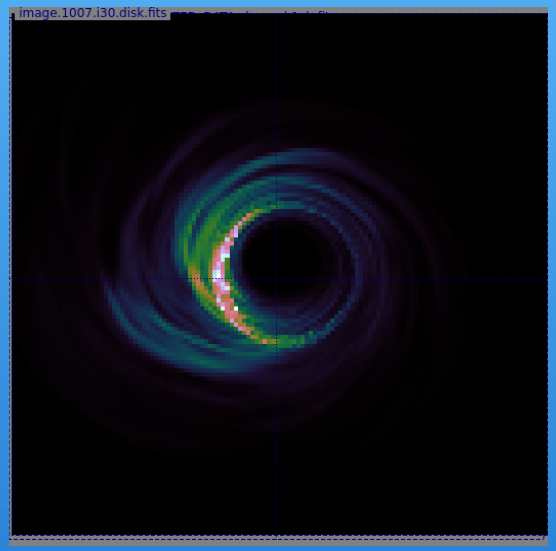
JIVE (& the EVN)

- EVN: European VLBI Network
  - Consortium of (European) Telescopes (>20 antennas
  - Covering range of frequencies from 18cm t
  - Operational approximately 60 days/year

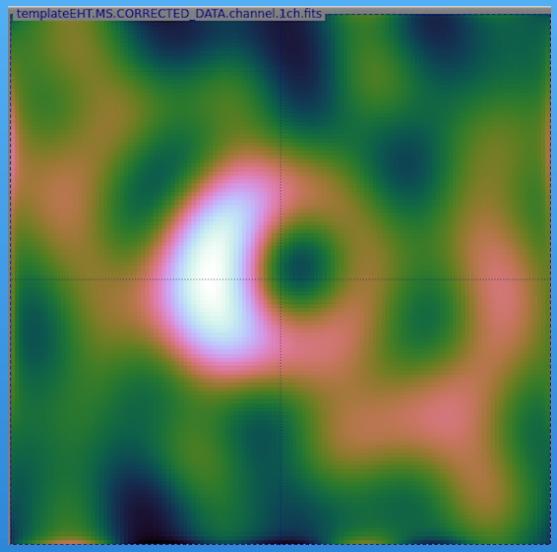
- JIVE: Joint Institute for VLBI in Europe
  - Data acquisition, correlation and processing
  - User support
  - User interfaces (Data product, Archive)
  - R&D to improve capabilities, Promote advance of V

c

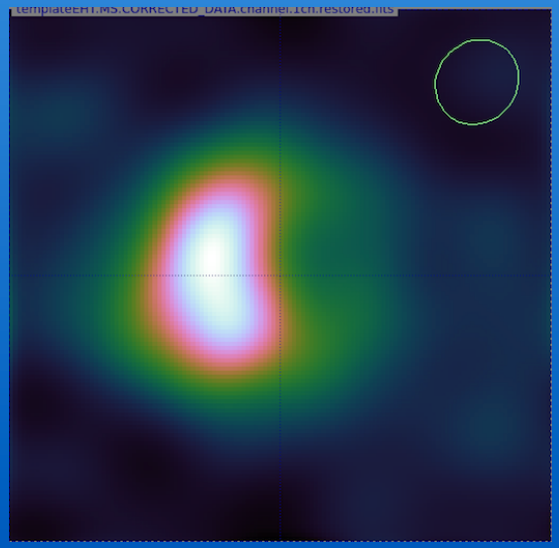
Simulations Nijmegen



EHT



Moscibrodska et al.



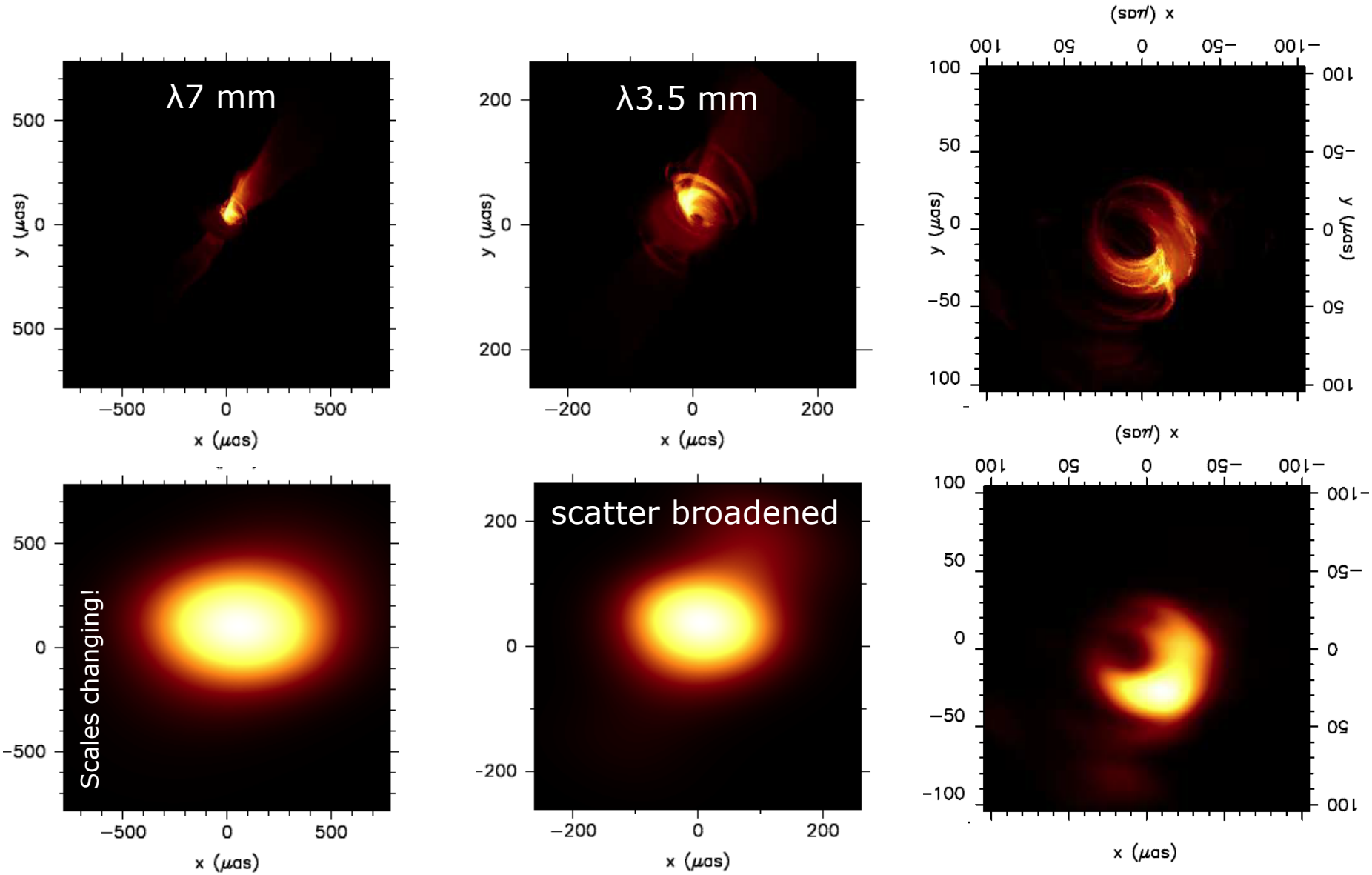
Courtesy:
Roger Deane

Contribution to the EHT

- Science / Theory?
- Software
- Upgrades of EHT stations (equipment and manpower)

SHOULD WE HAVE THIS SLIDE?
IF SO, WHERE SHOULD IT GO?

Effect of scatter broadening



Workpackages

SKIP?