# STOKES

# A Monte Carlo radiative transfer code for polarization modeling

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ASTRONOMICKÝ ÚSTAV

Akademie věd České republiky, v. v. i.

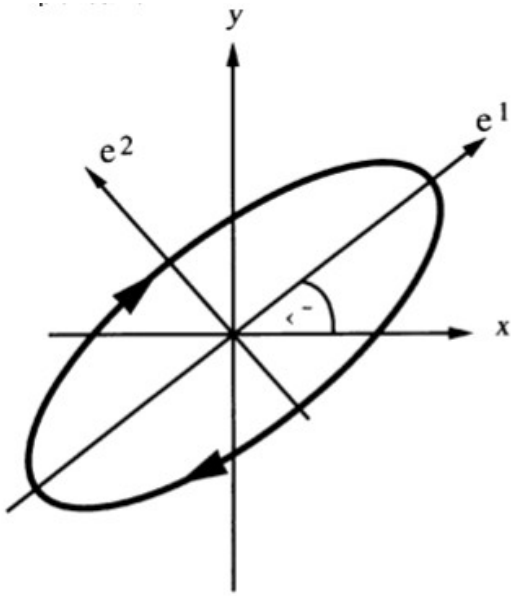
Observatoire astronomique de Strasbourg

# (Sir George) Stokes

Born : 13 August 1819
Died :1 February 1903

Irish mathematician, physicist, politician and theologian

Secretary, then president, of the Royal Society




(Campbell – Stokes) Etched Glass Sundial


Contributions to science :

- Fluid dynamics
- Chemical analysis
- Light
- Fluorescence
- Polarization

Stokes, G. G. 1852, Trans Cambridge Phil. Soc., 9, 339

# (Code) Stokes

Monte Carlo code designed to perform three-dimensional radiative transfer

Written in C/C++ (imaging routine in IDL) – Stokes formalism

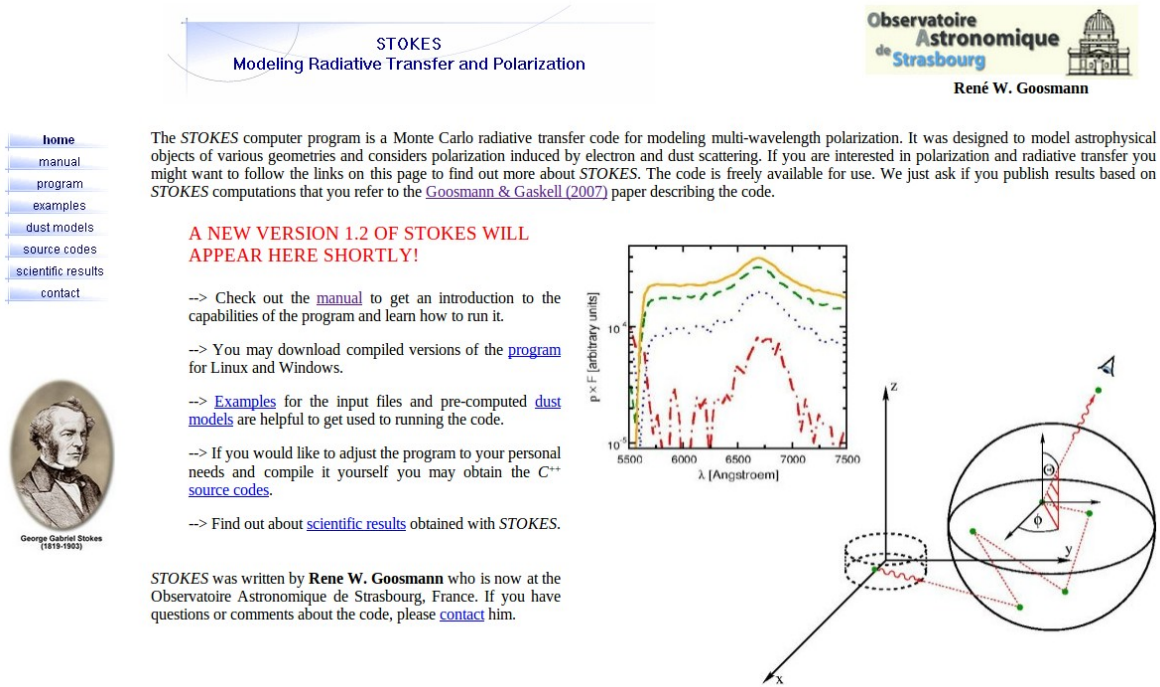
Created in 2004 to study the polarimetric signatures of Active Galactic Nuclei (AGN) in the optical / UV regime. Extended in the X-ray band (circa 2009)

Data cube of intensity+polarization as a function of 1- wavelength (spectroscopy), 2- sky position (imagery) and 3- time (variability)

Basic version publicaly available (http://www.stokes-program.info/)

Can be adapted to a large panel of objects / sources :

- Red super-giant stars
- X-ray binaries
- Galactic Center
- AGN



# Publications

Main papers:

- Goosmann & Gaskell, 2007, A&A, 465, 129
- Marin, Goosmann, Gaskell, Porquet & Dovciak, 2012, A&A, 548, A121

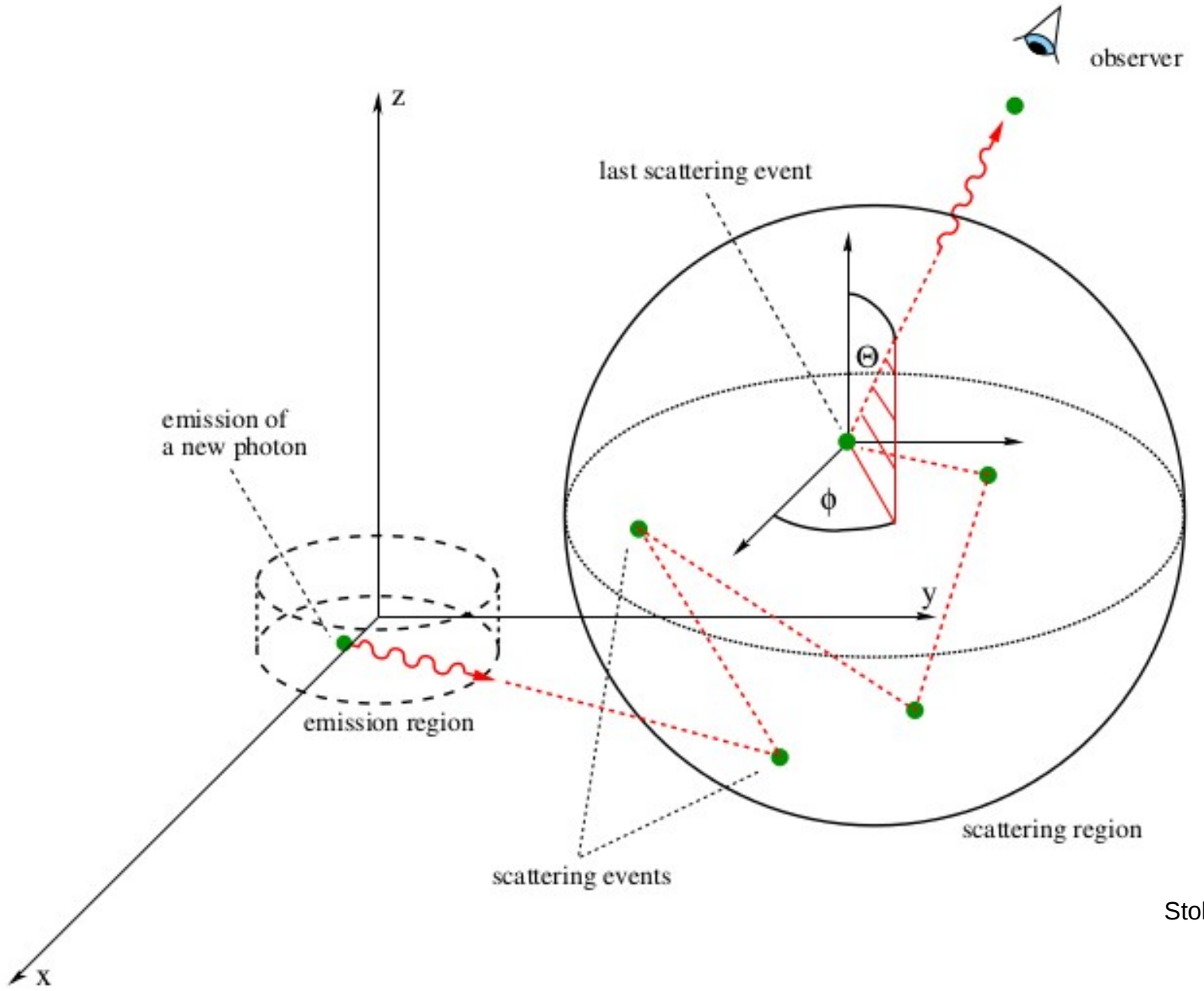
Various utilisations of STOKES so far:

- Exploring the Unified Model of AGN
- Off-axis irradiation and broad emission lines polarization in AGN
- Probing the origin of the iron Kα line around stellar and supermassive black holes
- Spectropolarimetric signatures from disk-born outflows
- Modelling the complex geometry of « changing look » AGN
- Constraining the layout of circumnuclear clouds in the Galactic center

Total (May 2014):

- 25 articles (refereed papers and proceedings)
- 96 citations

# A photon journey




Stokes manual

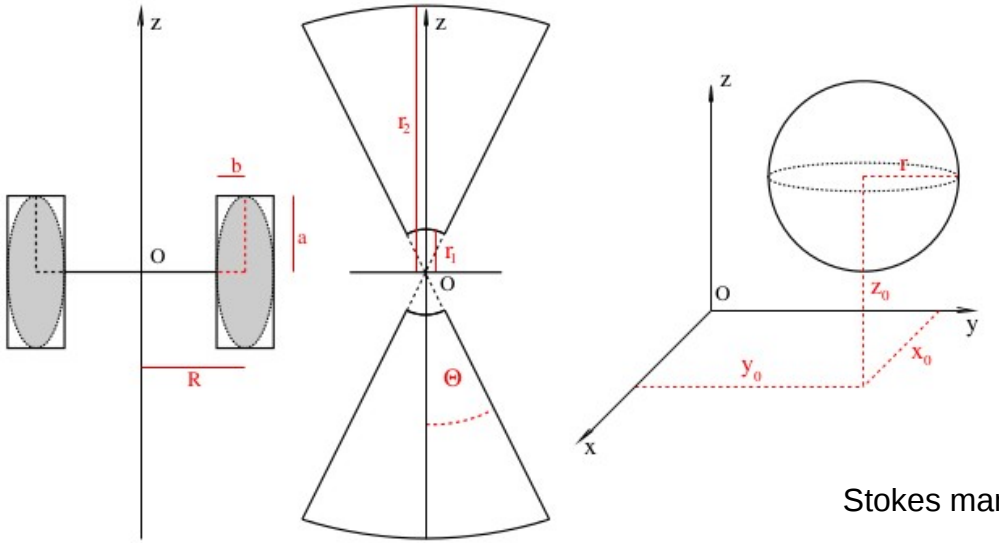
# Emission regions

SED:

- Power-law
- (multiple) black-body emission

Morphology:

- point-like
- cylinder
- slab
- double-cone
- torus
- segments




Stokes manual

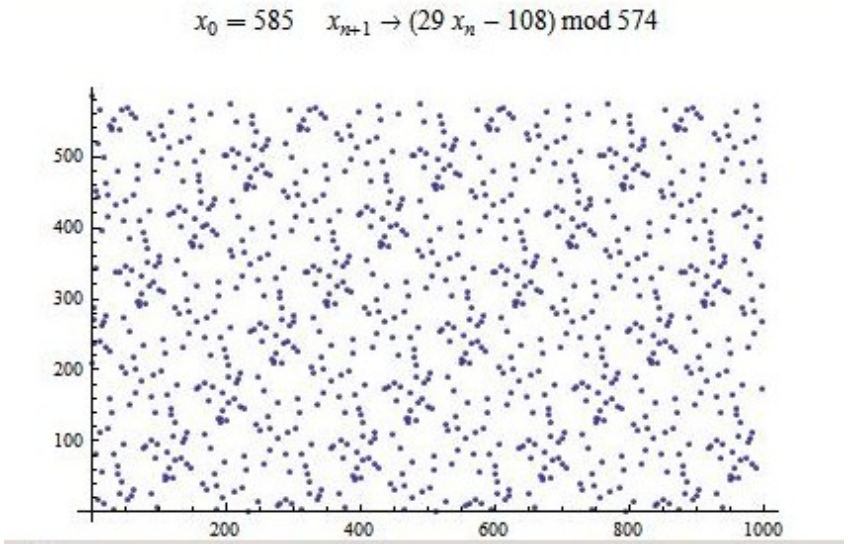
Waveband/energy band:

- optical/UV: 1400 – 10 000 Å
- X-rays: 0.8 – 300 keV

Parallel computing

# Impact of statistics

Importance of Random Number Generation (RNG) in radiative transfer codes




Usual RNG: Linear Congruential Generators (LCG)

→ fast and efficient only for short series (< $10^7$ photons)

→ loop back on series of values it has sampled before

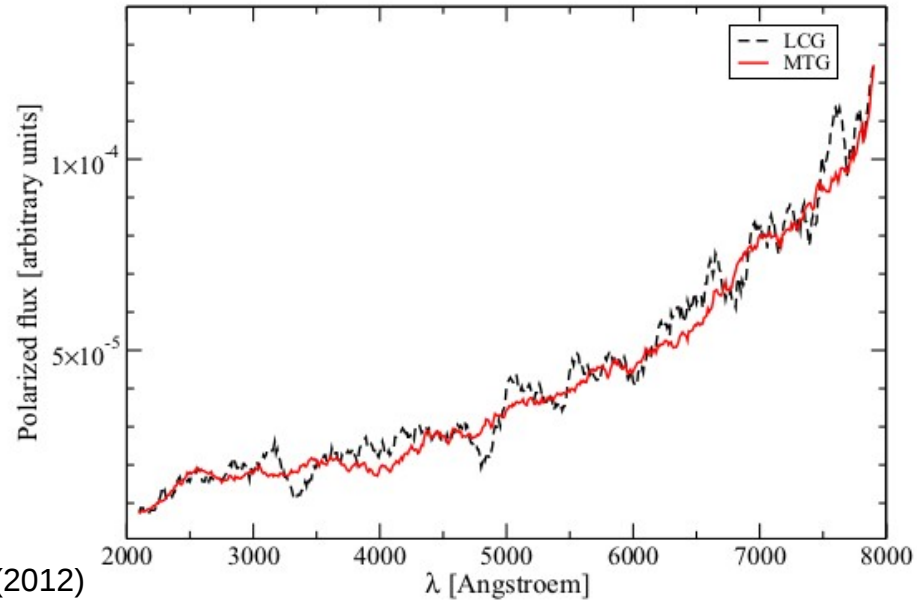
RNG implemented in STOKES: Mersenne Twister Generator (MTG)

→ generates pseudo-random numbers using a so-called twisted generalized feedback shift register

→ very high period of $2^{19937} - 1$

→ provides a 623-dimensional equidistribution up to an accuracy of 32 bits

→ passes the "Diehard" tests Marsaglia (1985)




Marin et al. (2012)

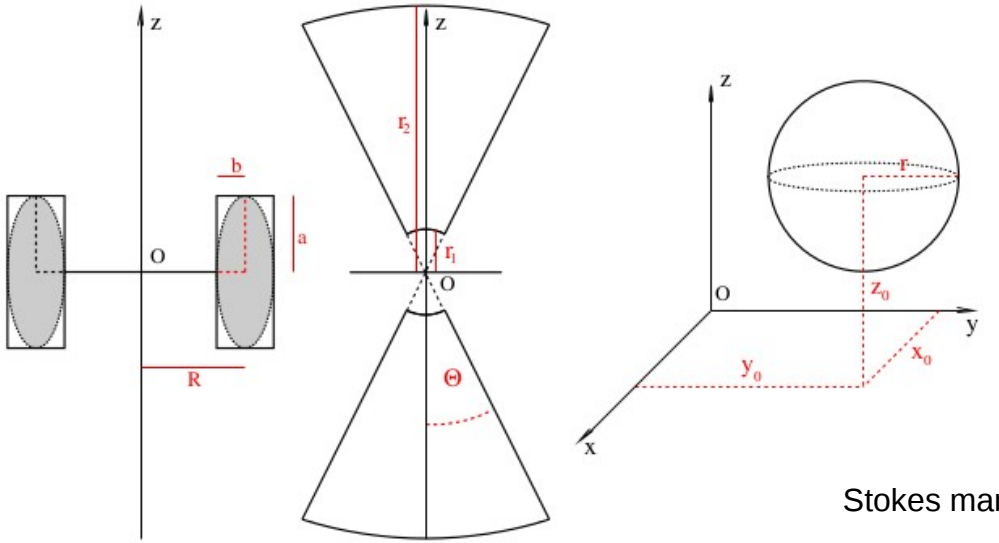
# Reprocessing regions

Composition:

- Dust (user-defined mixture)
- Electrons
- Atoms (from H to Ni)

Morphology:

- cylinder
- slab
- double-cone
- torus
- clouds
- disk-born winds




Stokes manual

Processes:

- Thomson/Compton/Mie scattering
- Radiative recombination
- Photoiozination / Fluorescence
- Dust / atomic absorption

3D velocity is implemented

Multiple-scattering (crucial for circular polarization)

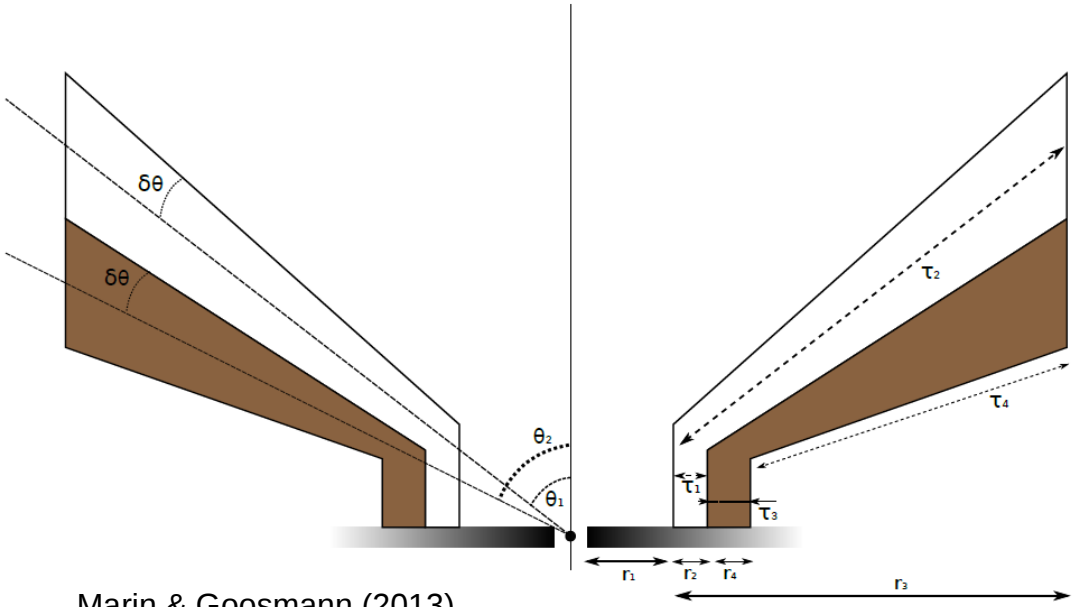
# Results

Photons stored in terms of Stoke's vector (I,Q,U,V) + t

Results processed with the module called ANALYZE

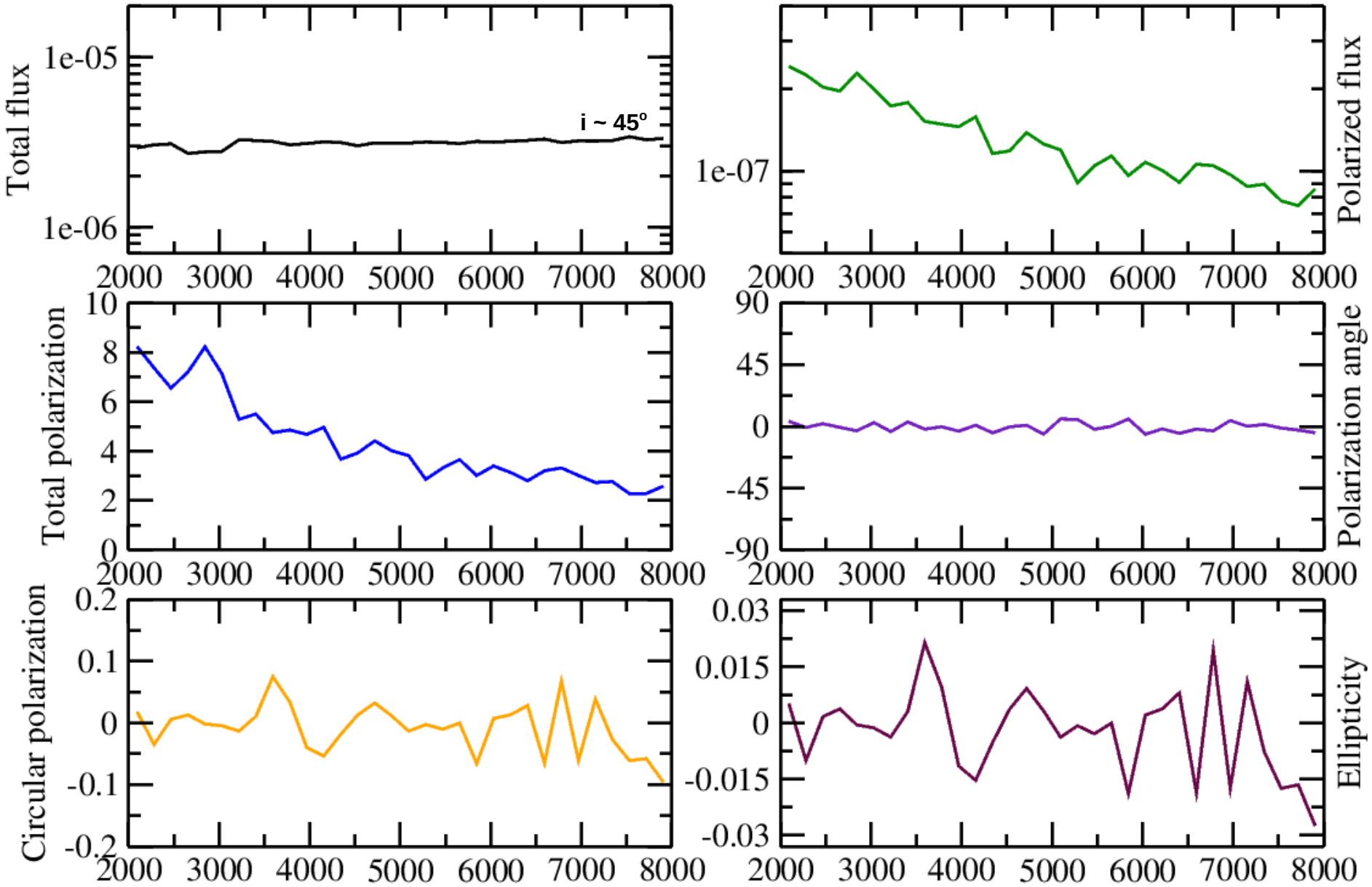
→ Total flux
→ Percentage of total polarization (linear + circular)
→ Polarized flux
→ Polarization angle
→ Percentage of circular polarization
→ Ellipticity
→ Polarization map
→ Time-lag

Example:
- Phenomenologically-based structure (Elvis 2000)
- Radiation-driven wind
- Bi-phased (WHIM / dust)
- Emission region off-axis

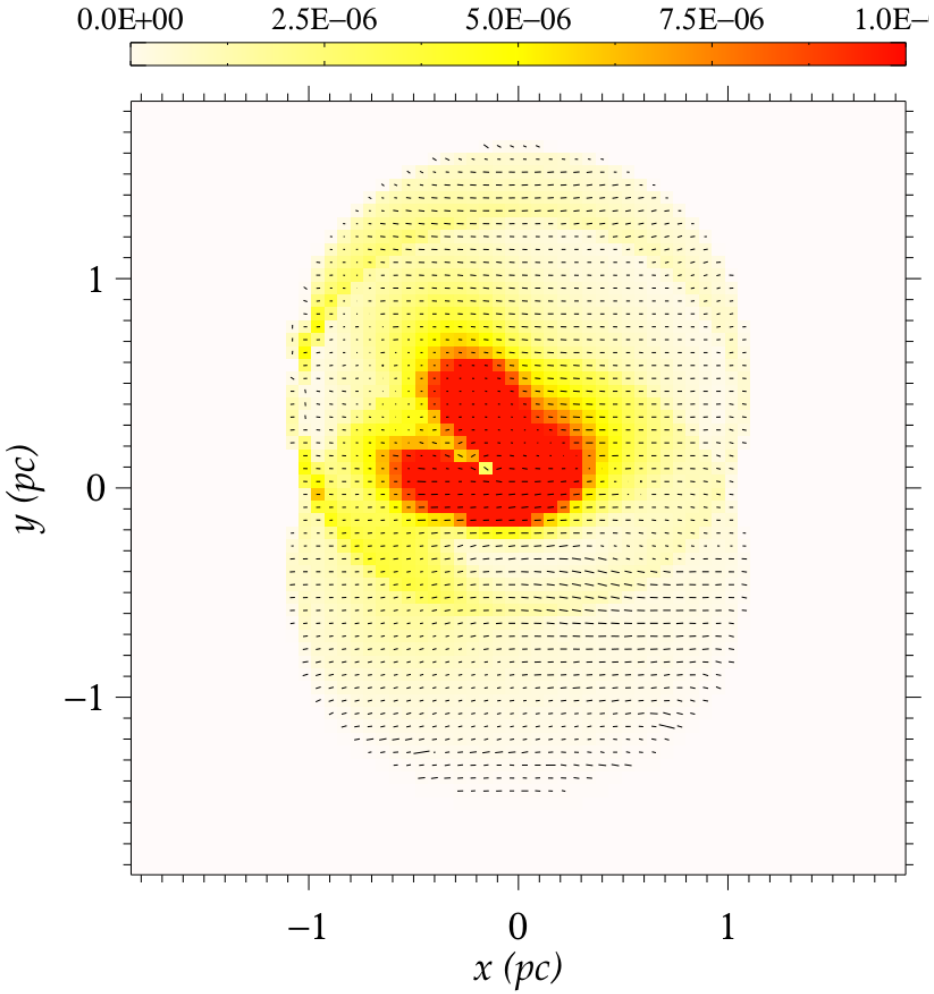


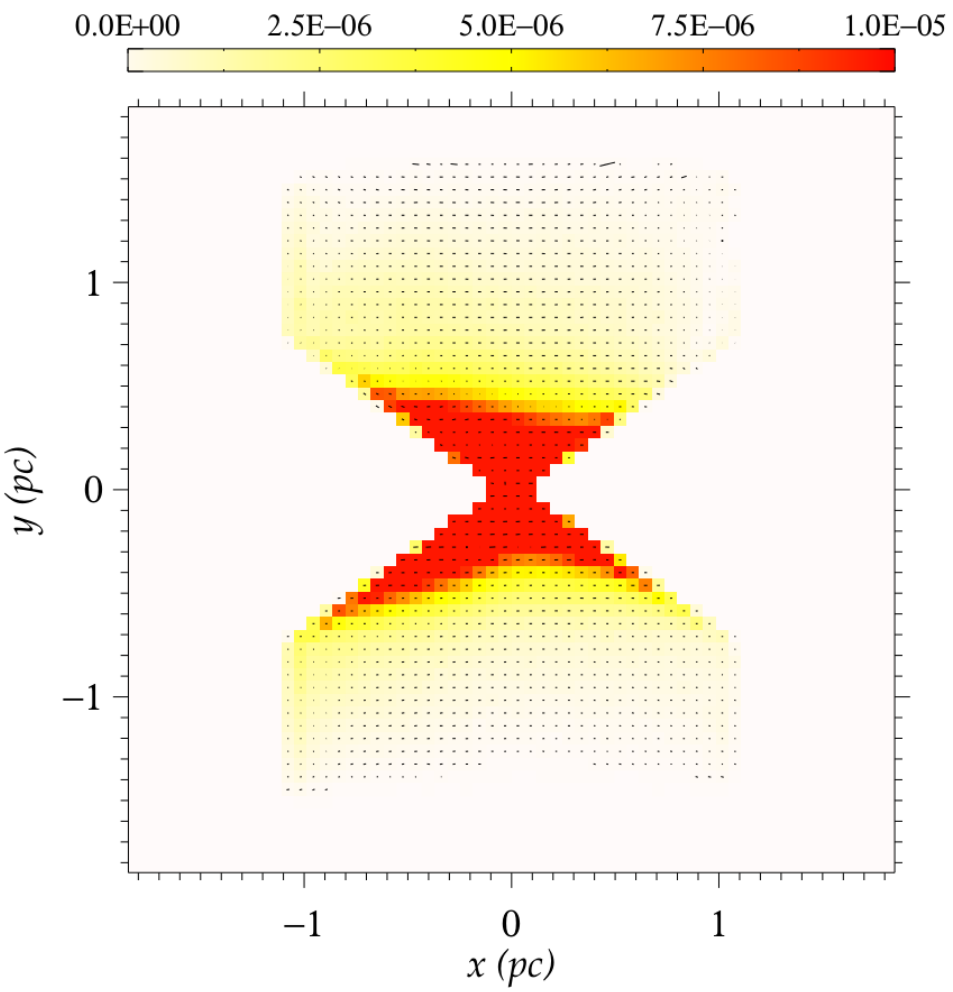

Marin & Goosmann (2013)

# Results


Total flux
1e-05
1e-06
i ~ 45°
1e-07
Polarized flux
Total polarization
Polarization angle
90
45
0
-45
-90
Circular polarization
0.2
0.1
0
-0.1
-0.2
0.03
0.015
0
-0.015
-0.03
Ellipticity
2000 3000 4000 5000 6000 7000 8000

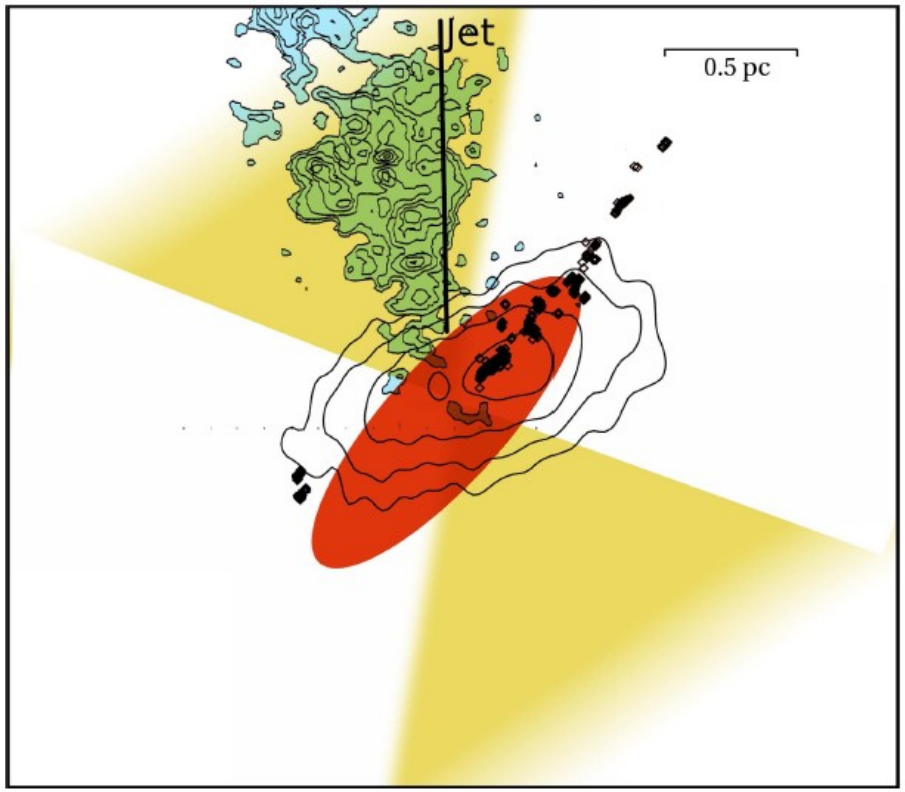
# Results




(Mie scattering removed)

# Probing (unusal) AGN with polarimetry




Raban et al, (2009)

NGC 1068 = one of the best examples of archetypal Seyfert-2

Compact dusty torus: 0.45 × 1.35 pc

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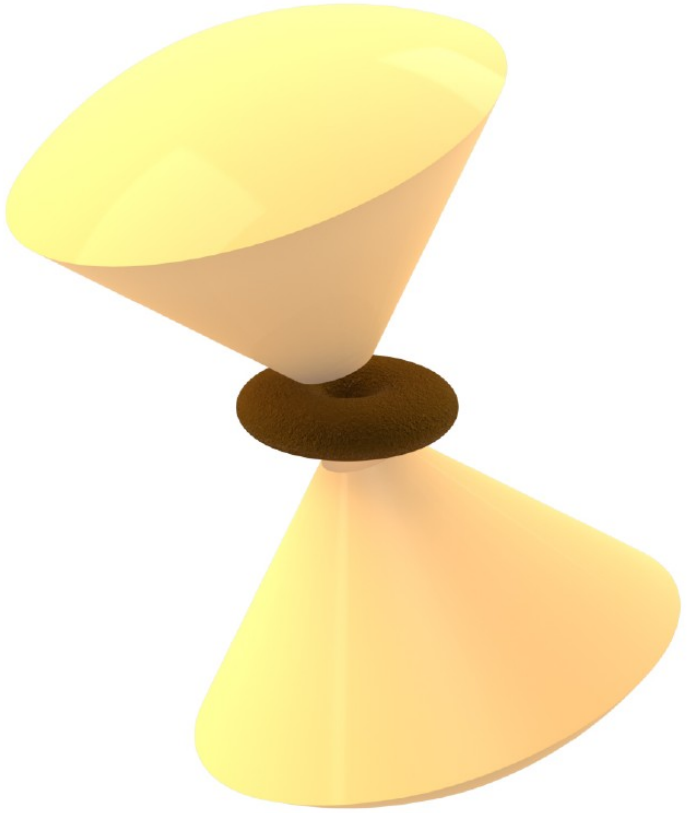
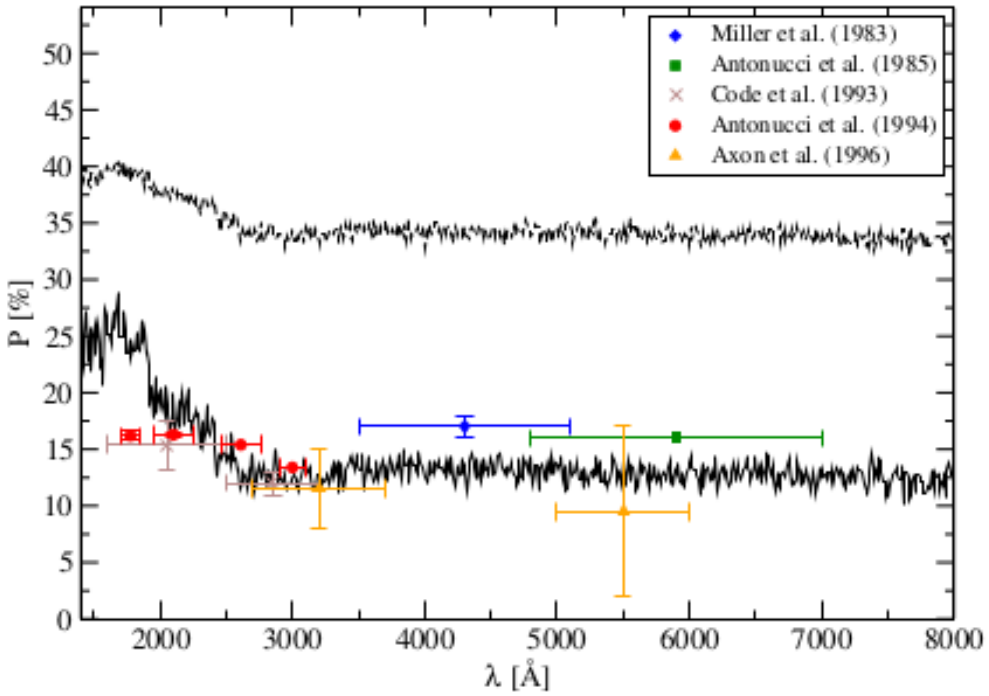


Marin, Goosmann & Dovciak (2012)

Principal hypothesis: the polar outflows sustain the same half-opening angle as the dusty torus

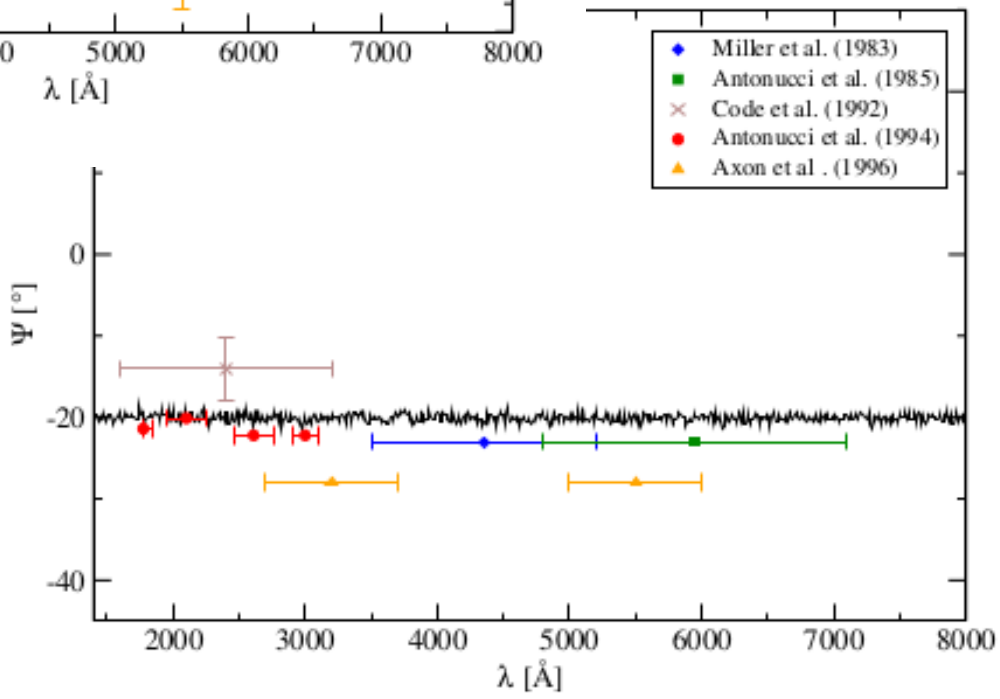
Raban et al. (2009) → polar winds (represented as a bi-conical structure) are inclined with respect to the obscuring torus axis

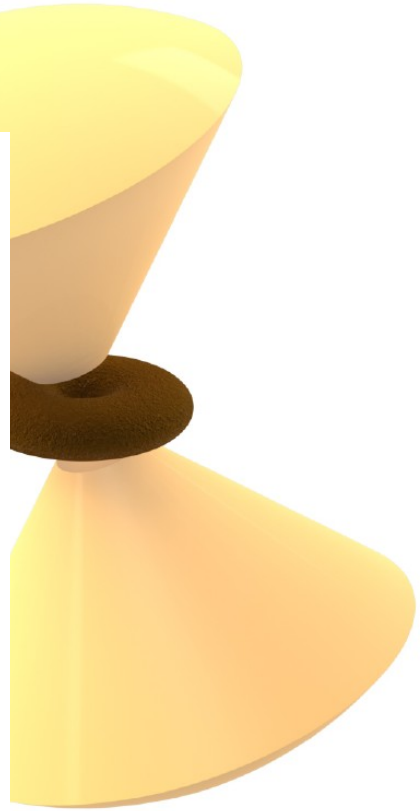
# Probing (unusal) AGN with polarimetry




Marin et al, (in prep.)

Polarization degree and polarization angle as 2 independent and complementary informations

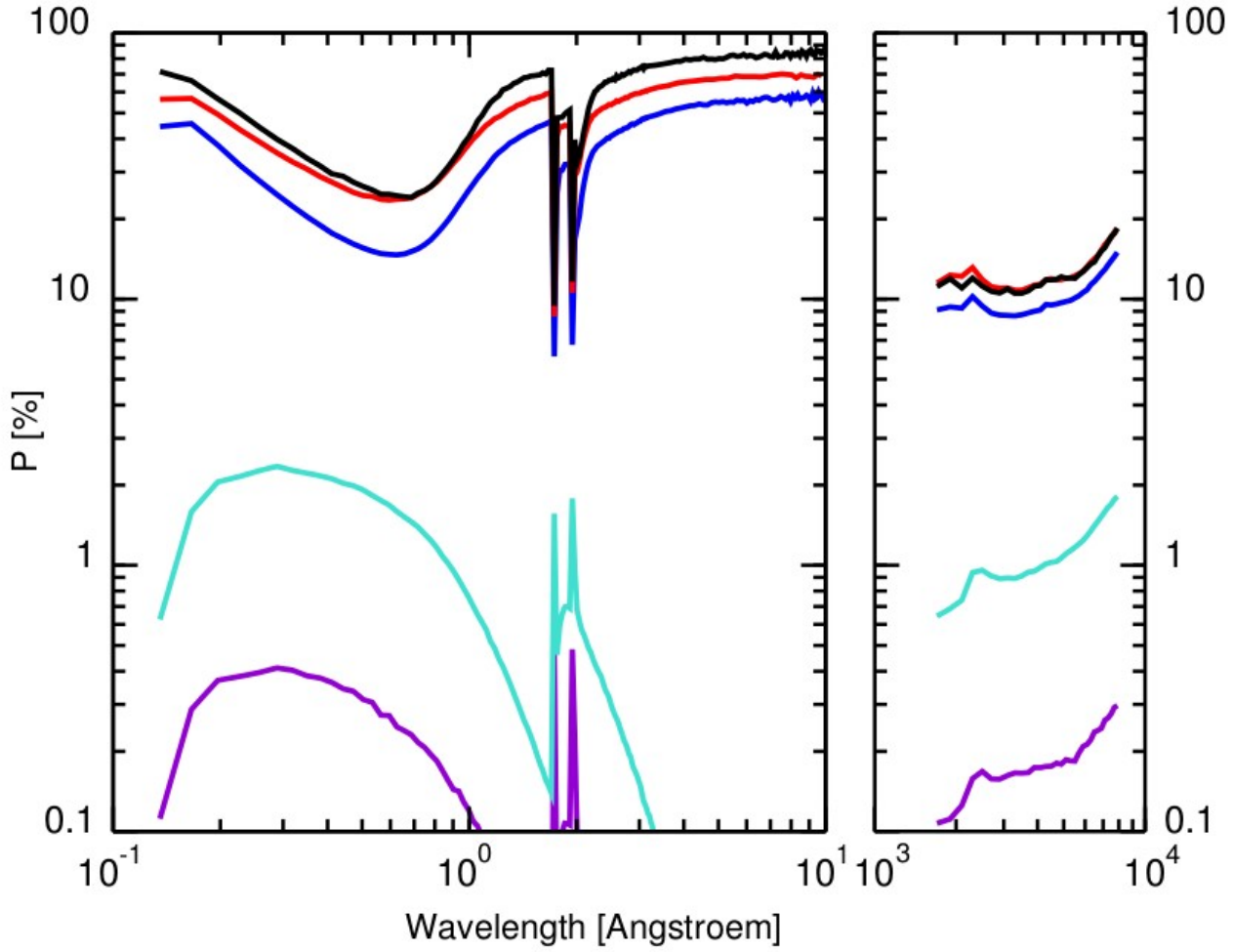


Constraining the 3D geometry of the tilted outflows with polarimetry

# Multi-wavelength polarimetry

To probe the geometry and kinematics of emission and scattering regions, it is important to provide consistent and simultaneous polarization models in the optical/UV and the X-ray band

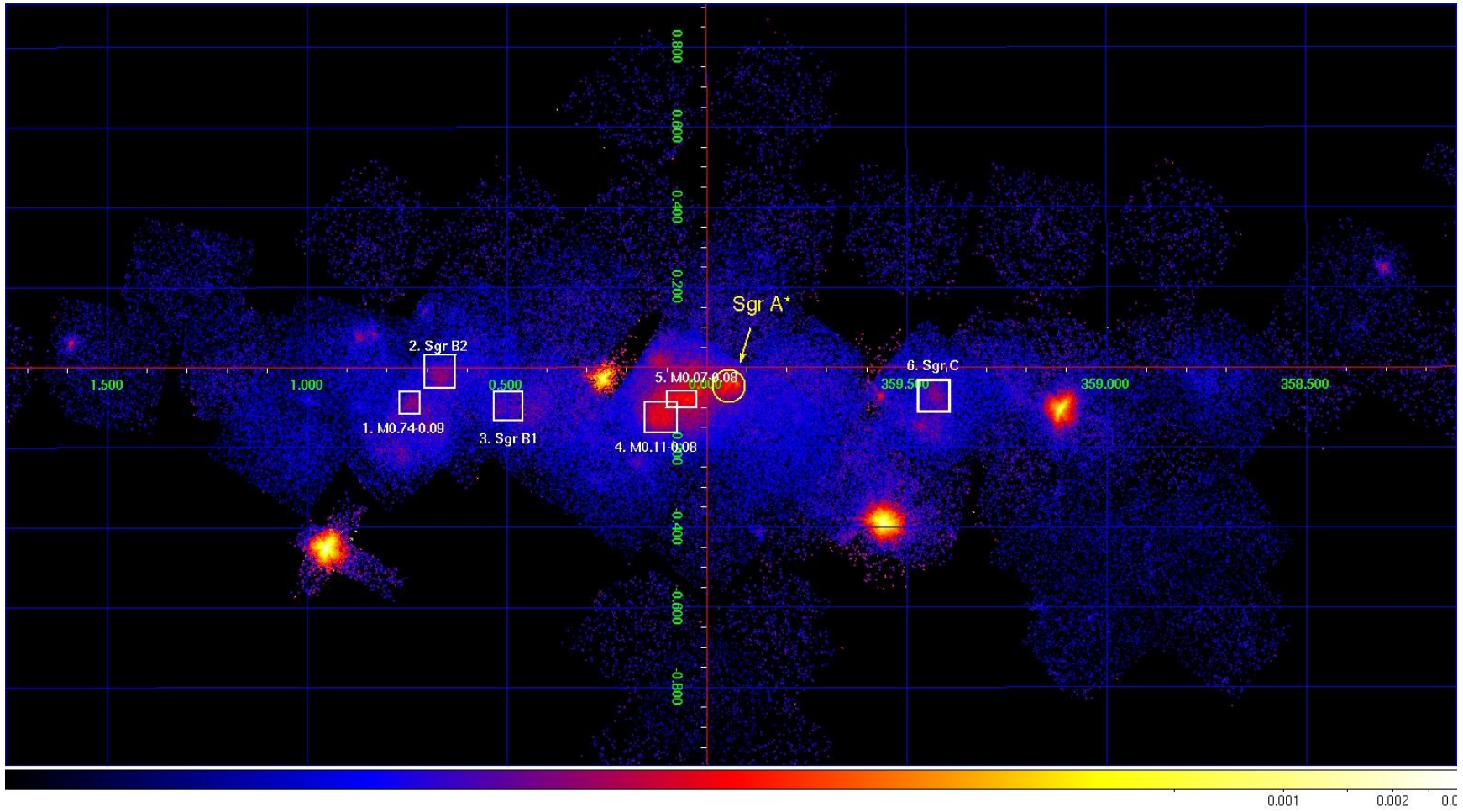



Goosmann (2009)

# Promoting X-ray polarimetry

The actual context of the Galactic Center

- 3D location of Sgr A*, Sgr B2, Sgr C … ?
- Are Sgr B2 and Sgr C reflecting past Sgr A* emission ?



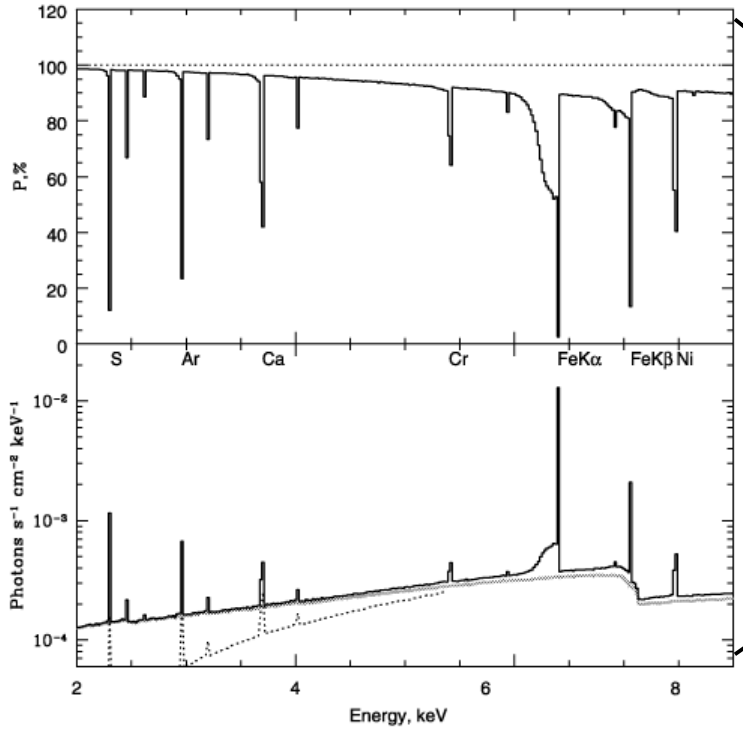

JAXA – Suzaky X-ray map of the GC

# Promoting X-ray polarimetry

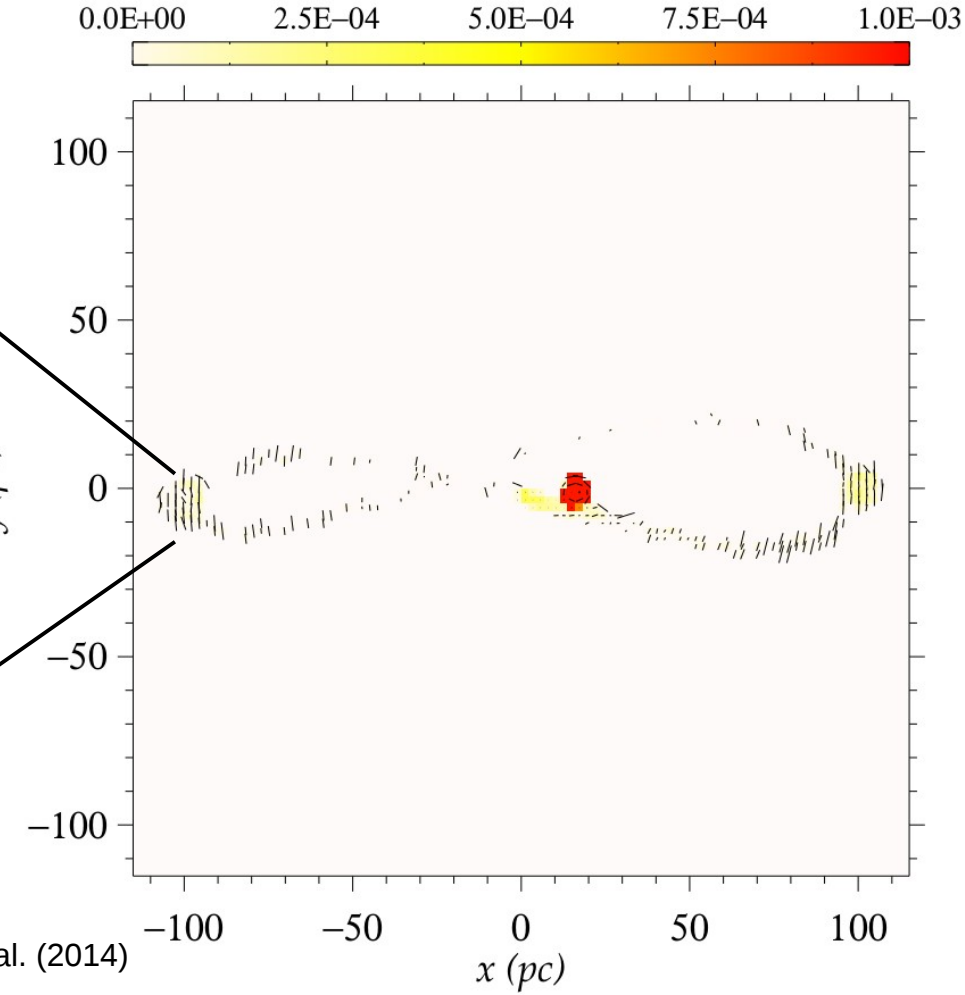
The actual context of the Galactic Center

- 3D location of Sgr A*, Sgr B2, Sgr C … ?
- Are Sgr B2 and Sgr C reflecting past Sgr A* emission ?

X-ray polarimetry can bring answers




Churazov & Sunyaev (2002)




Marin et al. (2014)

# Synergy with other codes

Potential coupling with :

MoCa – F. Tamborra, G. Matt, S. Bianchi
IDL code (interactive and vectorized), modular and fully special relativistic (Klein-Nishina cross-section, Juttner distribution …)
→ to include special relativity


SKIRT – M. Stalevski, M. Baes
3D Monte Carlo radiative transfer code (photon packages)
Temperature, kinematic, adaptative grid, variety of reprocessing geometry
→ to include infrared mechanisms

Polarization to be implemented