KISS: Extracting Science from Black Hole Images

Dana Simard

Lightning Talk: Interstellar Scattering

September, 2019

What is interstellar scattering?

Why is it a problem?

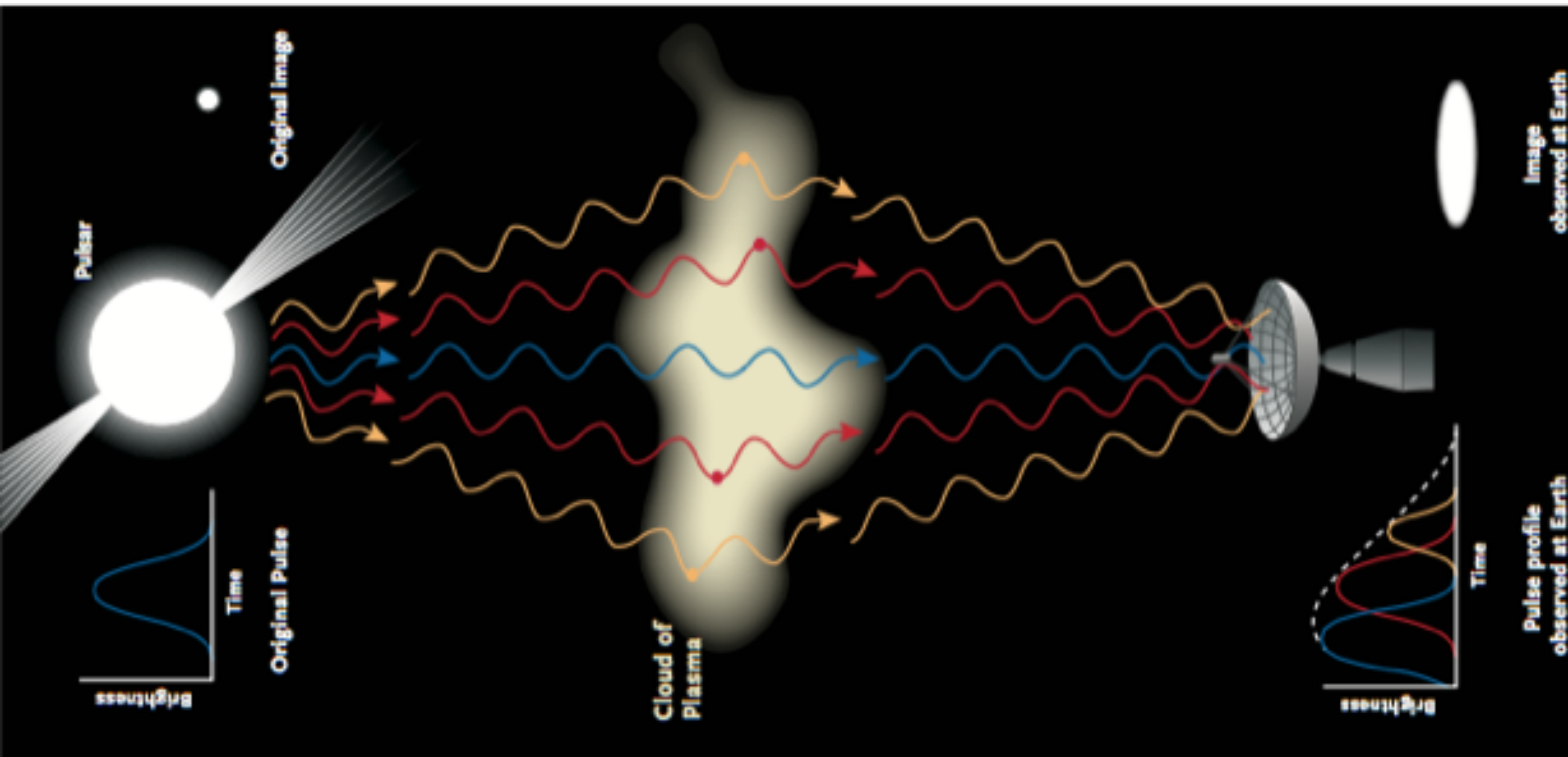
What can we do about it?

What about Sgr A* in particular?

Convener: TBD

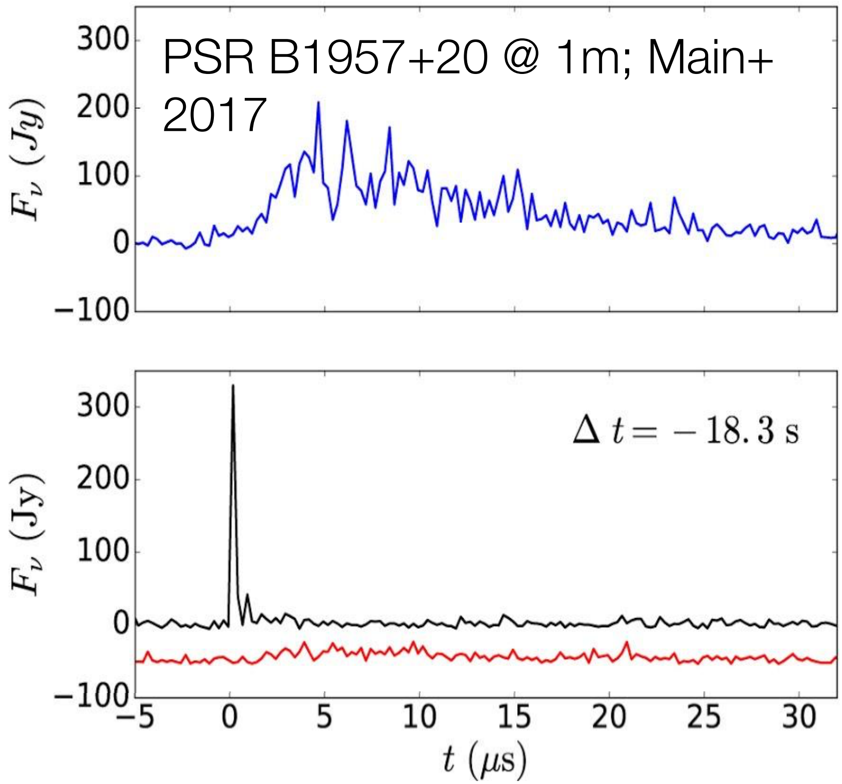
Interstellar scattering

Haggard & Bower 2016
Sky & Telescope



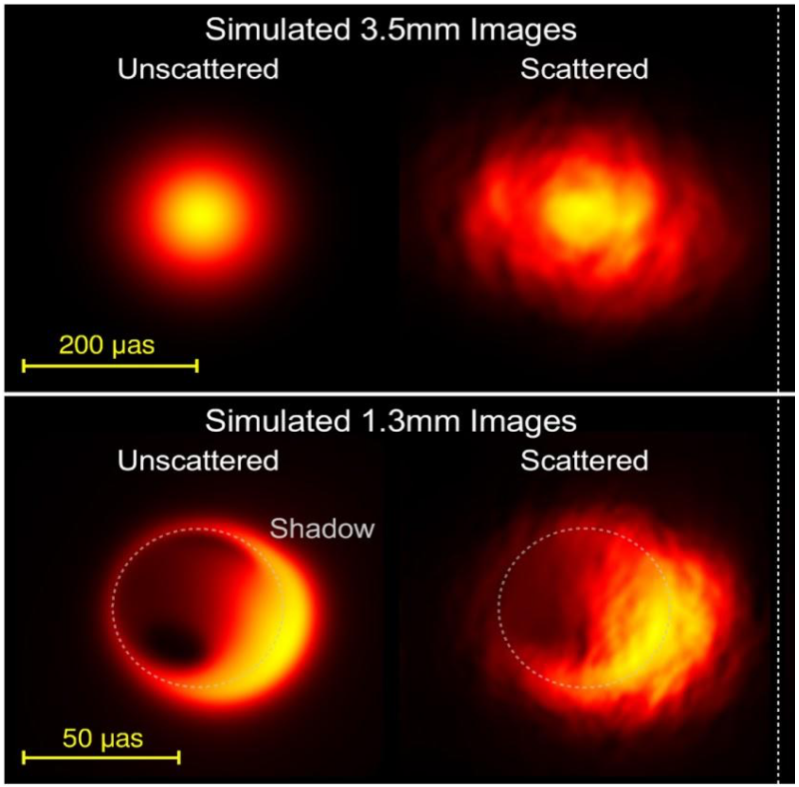
Why is it a problem?

Masks temporal information



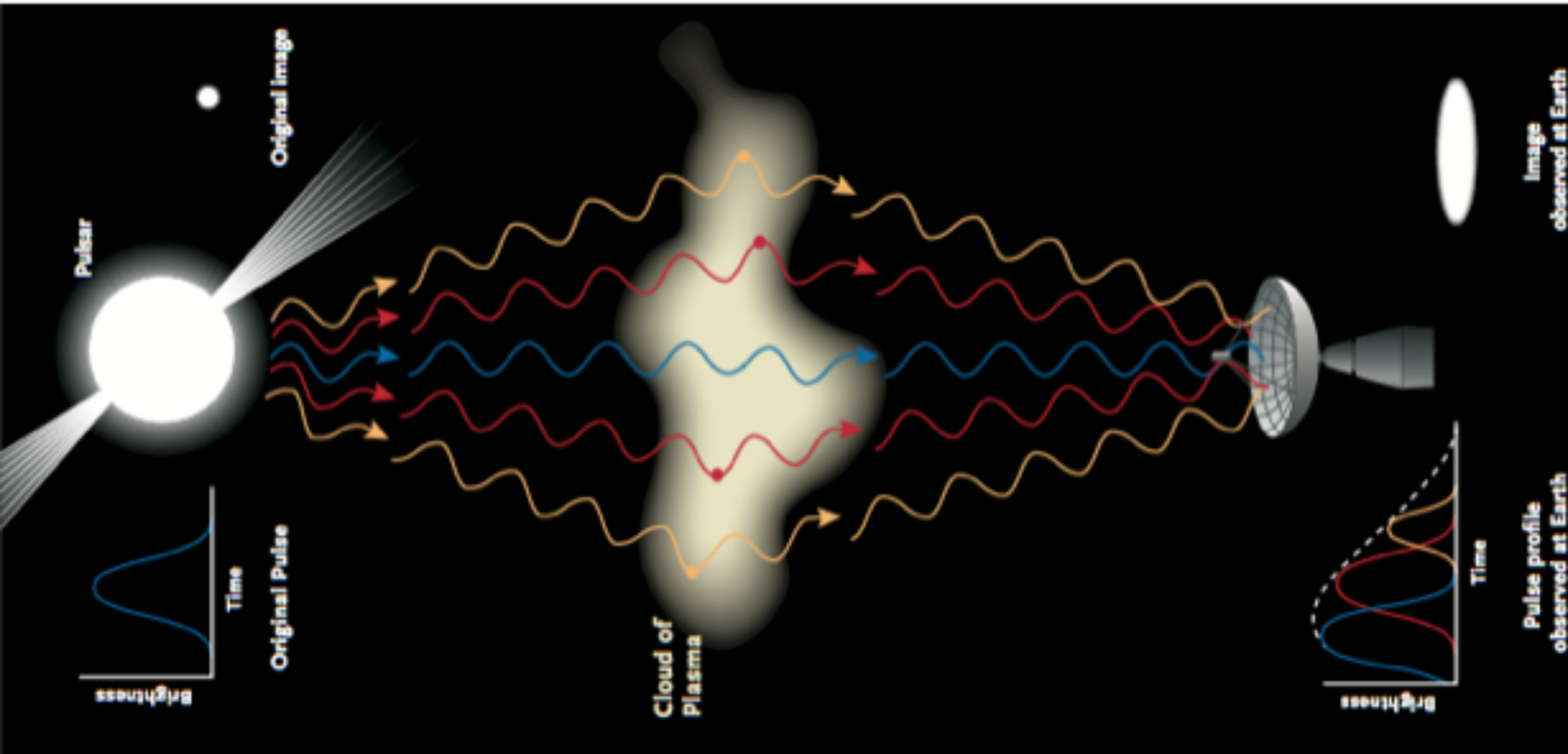
Masks spatial information

Johnson+ 2016



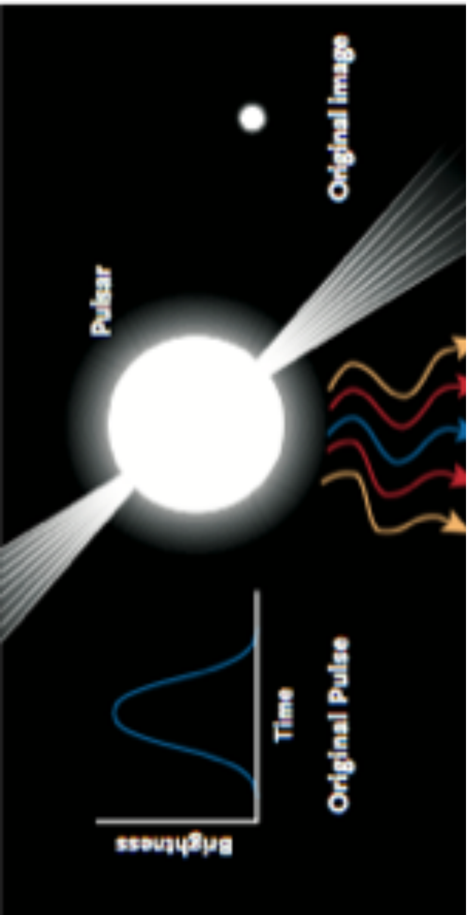
Interstellar scattering

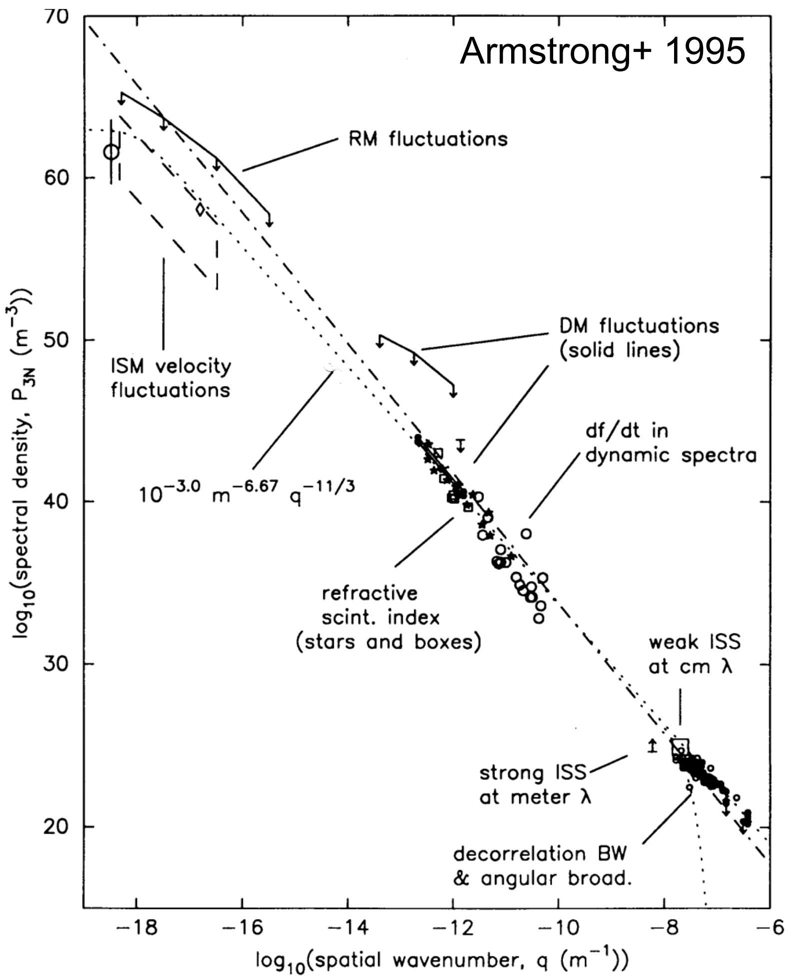
Haggard & Bower 2016
Sky & Telescope

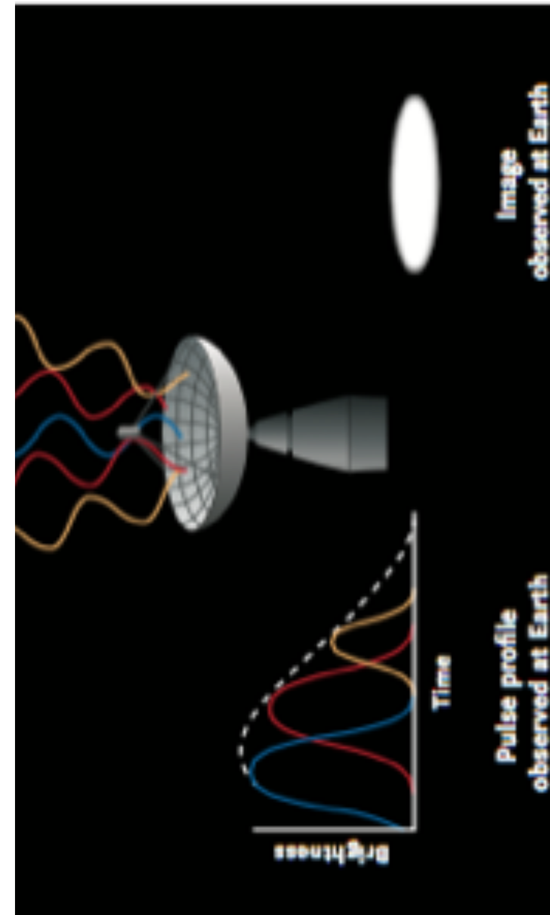


Interstellar scattering

Haggard & Bower 2016
Sky & Telescope

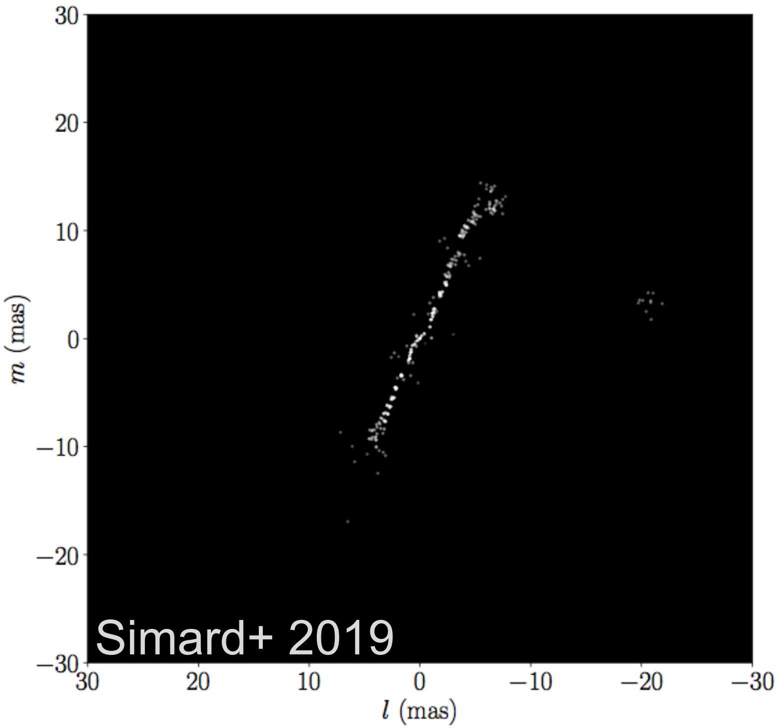






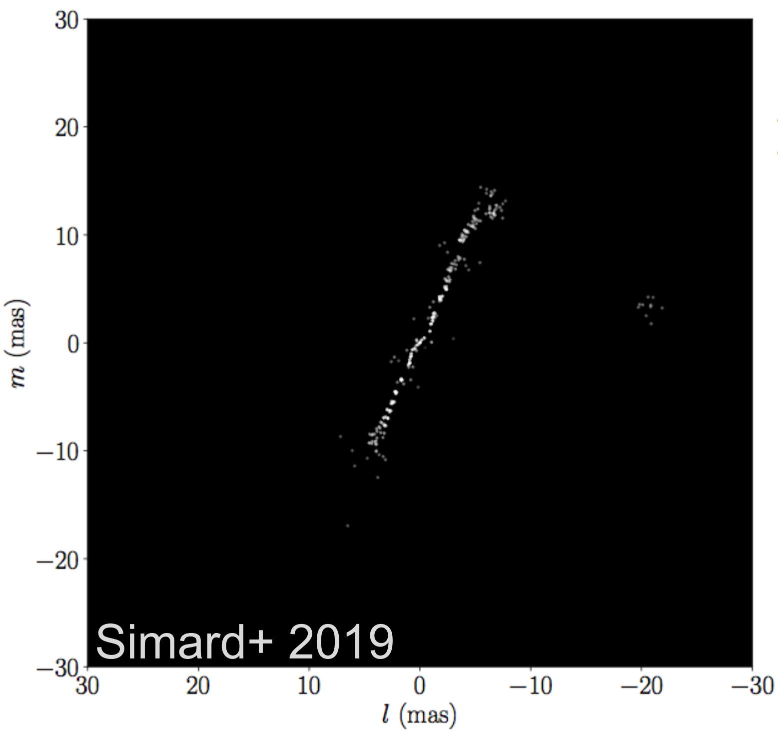
Insight from pulsars

Highly anisotropic scattering @ thin screens *(Stinebring+ 2001; Walker+ 2004; Putney+ 2006; Cordes+ 2006; Brisken+ 2010; many others)*



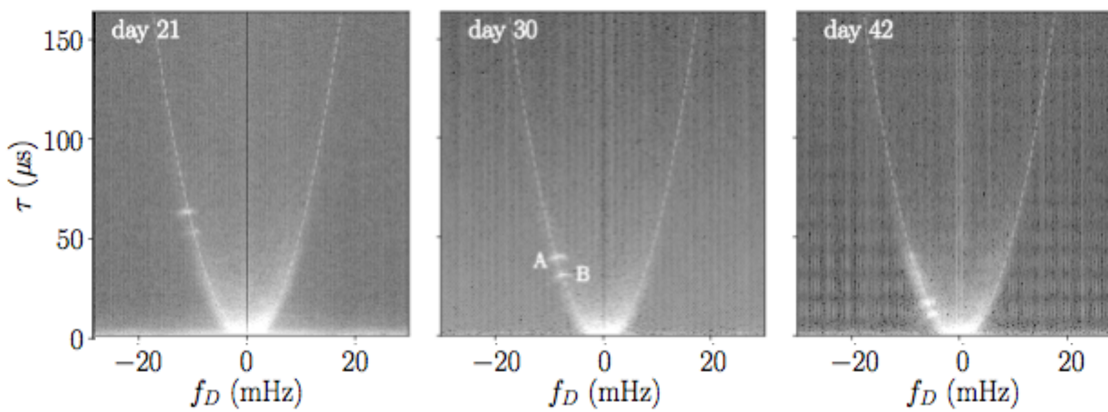
Insight from pulsars

Highly anisotropic scattering @ thin screens *(Stinebring+ 2001; Walker+ 2004; Putney+ 2006; Cordes+ 2006; Brisken+ 2010; many others)*



(As far as we can tell) plasma changing on >1 month timescales and shorter variation due to relative motion only. *(Hill+ 2005; Simard+ in prep.)*

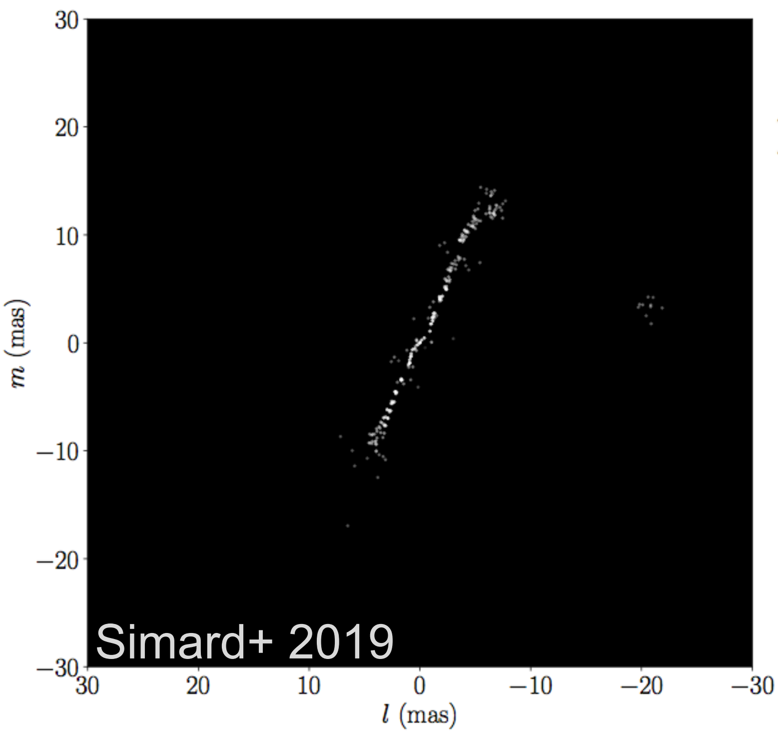
PSR B0834+06



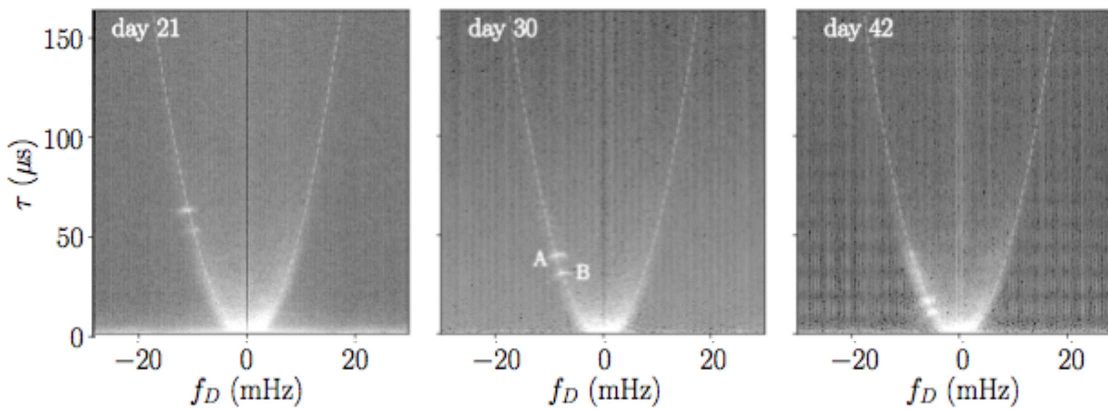
$$\nu \frac{d\tau}{dt} \propto \theta$$

Insight from pulsars

Highly anisotropic scattering @ thin screens *(Stinebring+ 2001; Walker+ 2004; Putney+ 2006; Cordes+ 2006; Brisken+ 2010; many others)*



(As far as we can tell) plasma changing on >1 month timescales and shorter variation due to relative motion only *(Hill+ 2005)* + achromatic to 1st order *(Brisken+ 2010)*
PSR B0834+06 *(Simard+ in prep.)*

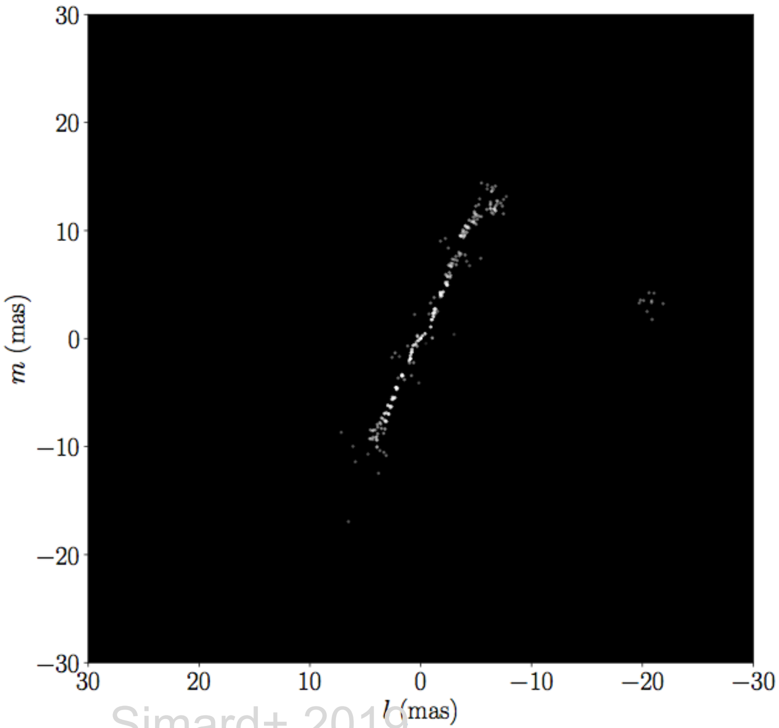


$$\nu \frac{d\tau}{dt} \propto \theta$$

Statistics of scattering constant over decades

- Used to map density structure in ISM (e.g. Cordes & Lazio 2001)
- Specific screens live for at least decades (Stinebring)

Insight from pulsars



Simard+ 2019

- Scattering may be entirely due to refraction
- Models still in two classes:
  - Filamentary *(e.g. Romani+ 1987; Gwinn 2019; Gwinn & Sosenko 2019)*
  - Sheets *(e.g. Romani+ 1987; Walker & Wardle 1987; Walker 2007; Walker+ 2017; Goldreich & Sridhar 2006; Pen & Levin 2014; Simard & Pen 2018)*

Models of scattering

1. Scattering dominated by thin screens: Distance to the screen
2. Scattering anisotropic: Size, axis ratio, orientation of scattered disk
3. Substructure in scattered image: Fluctuations in phase screen

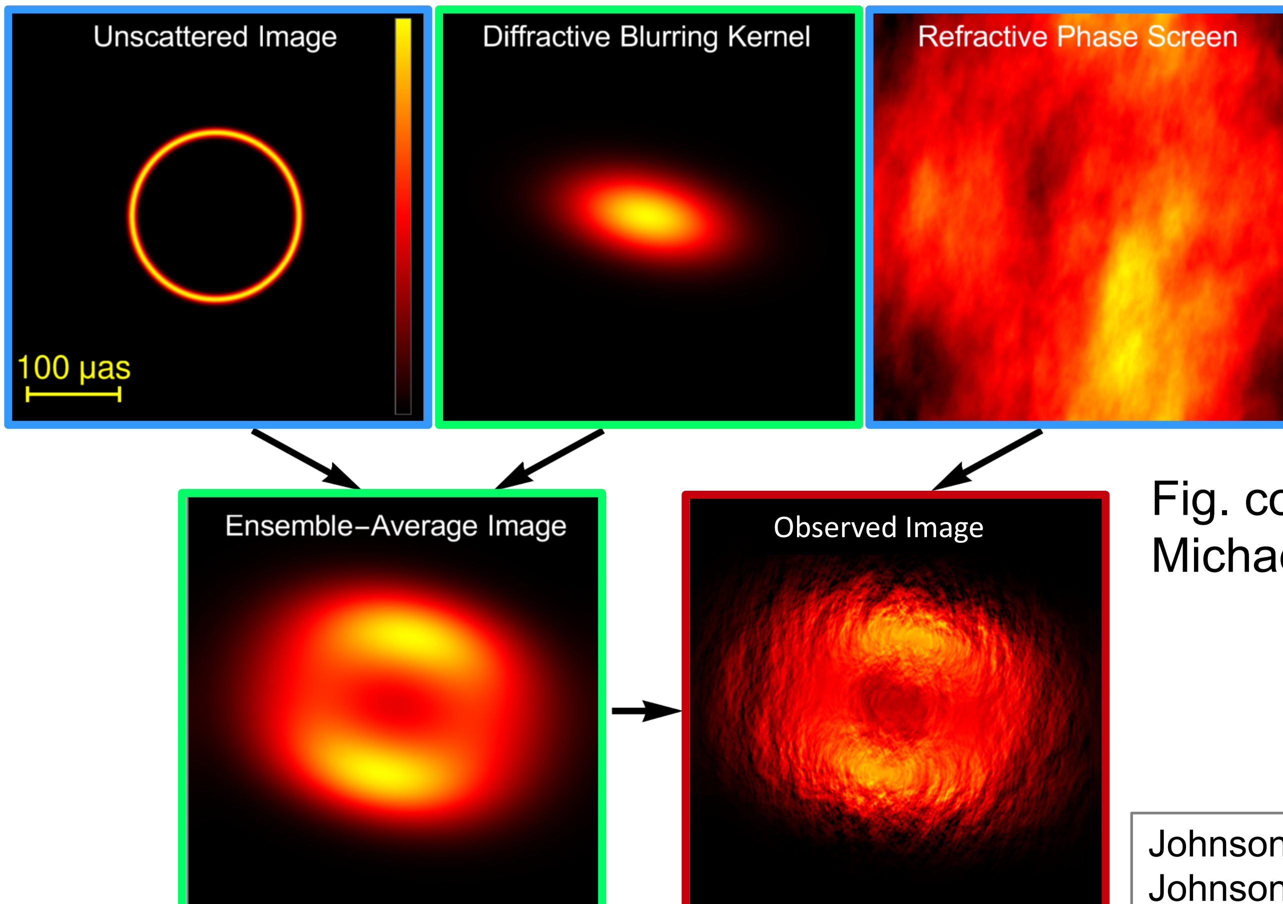
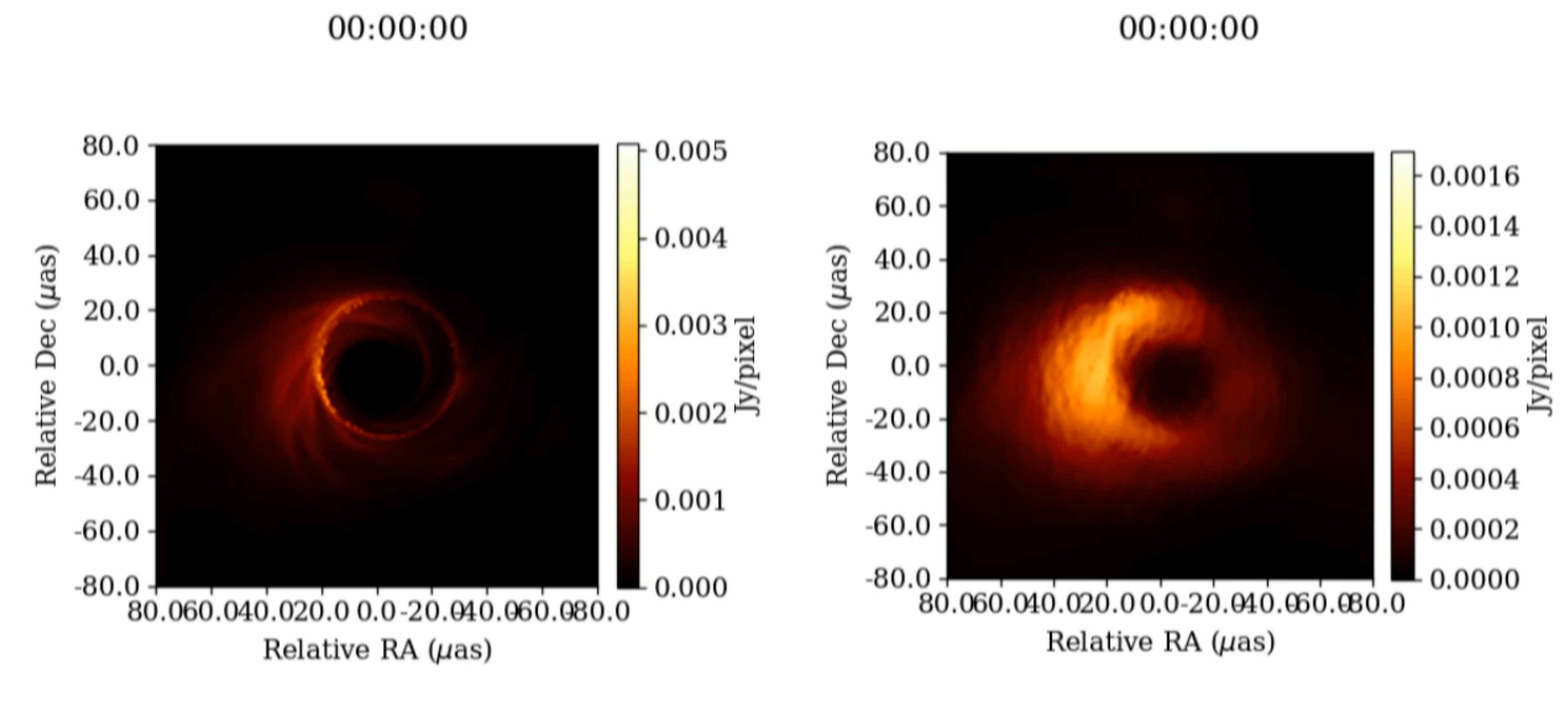


Fig. courtesy Michael Johnson

Johnson & Narayan (2016)
Johnson (2016)

Scattering and Time Variability of Sgr A*

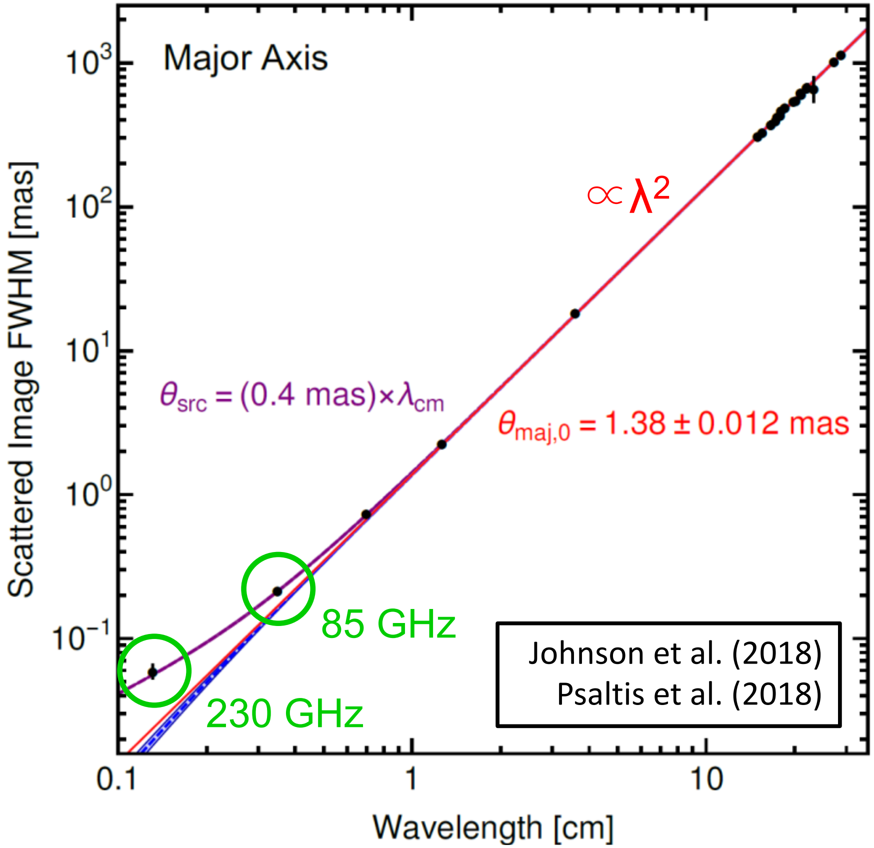


Slide courtesy of
Michael Johnson

Simulation of Sgr A* from George Wong

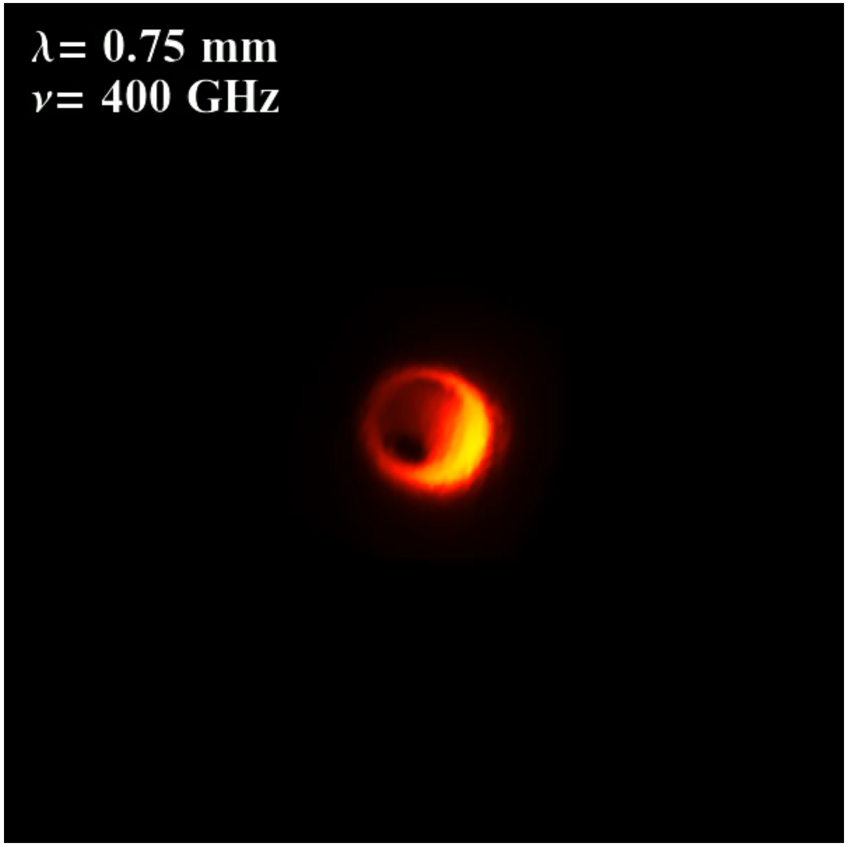
Interstellar Scattering of Sgr A*

Interstellar scattering affects the image size, asymmetry, and substructure for Sgr A*



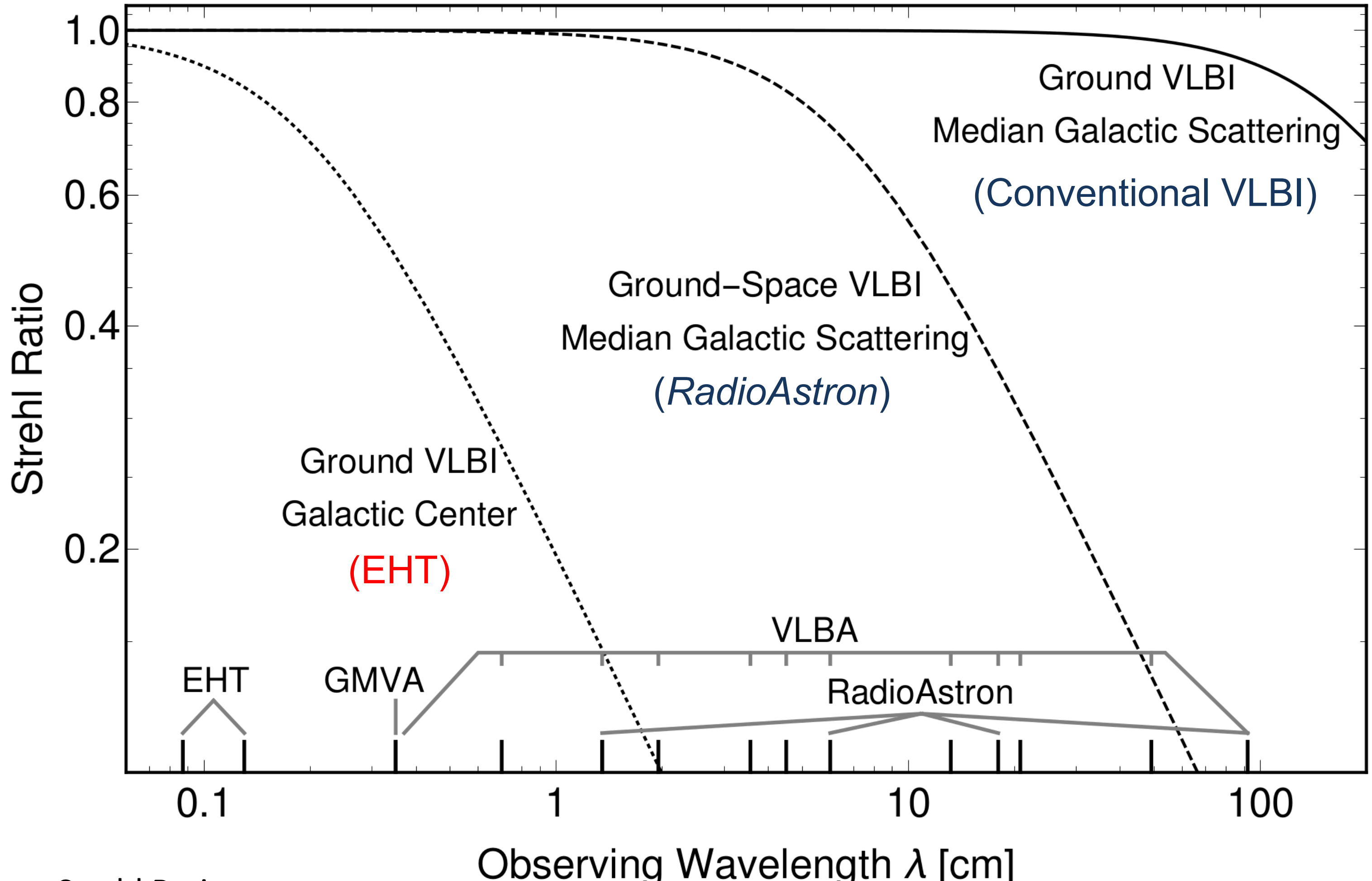
"All the interferometer observations [of Sgr A*] are consistent with the measured diameters being the result of interstellar scattering. This source has the largest interstellar broadening of any known source."

– Davies, Walsh, and Booth (1976)



The Radio Strehl Ratio

How important is scattering mitigation for the EHT?



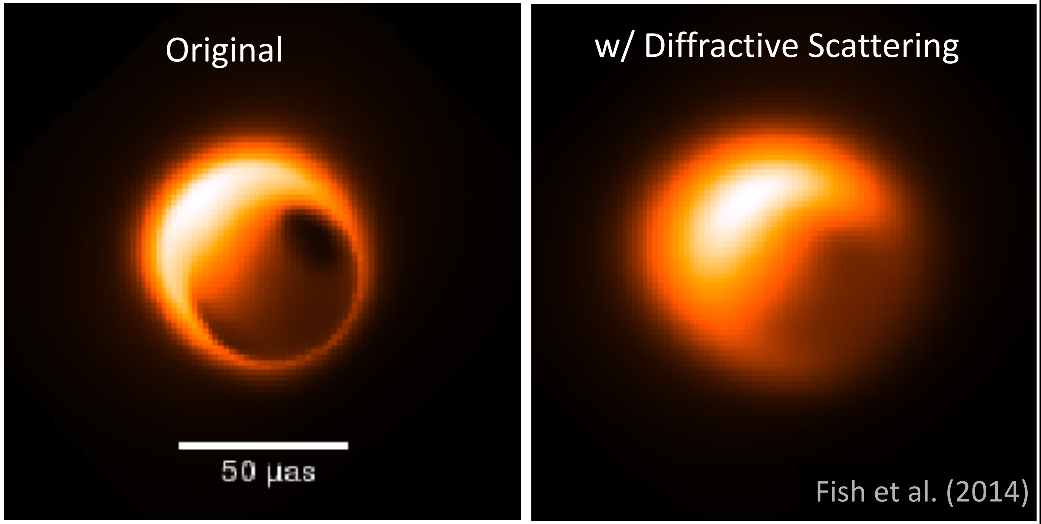
Strehl Ratio =
instrument's resolution with scattering as a fraction of the resolution without scattering

Effects of Scattering on Images

Two Branches of Interstellar Scattering

1. Blurring ("diffractive"):

- Stable over time
- Reduces signal on long baselines
- Decreases brightness temperature
- Weaker at higher frequencies



2. Substructure ("refractive"):

- Stochastic and time-variable
- Adds new "signal" on long baselines
- Stronger at higher frequencies
- Unexpectedly strong effect on VLBI!

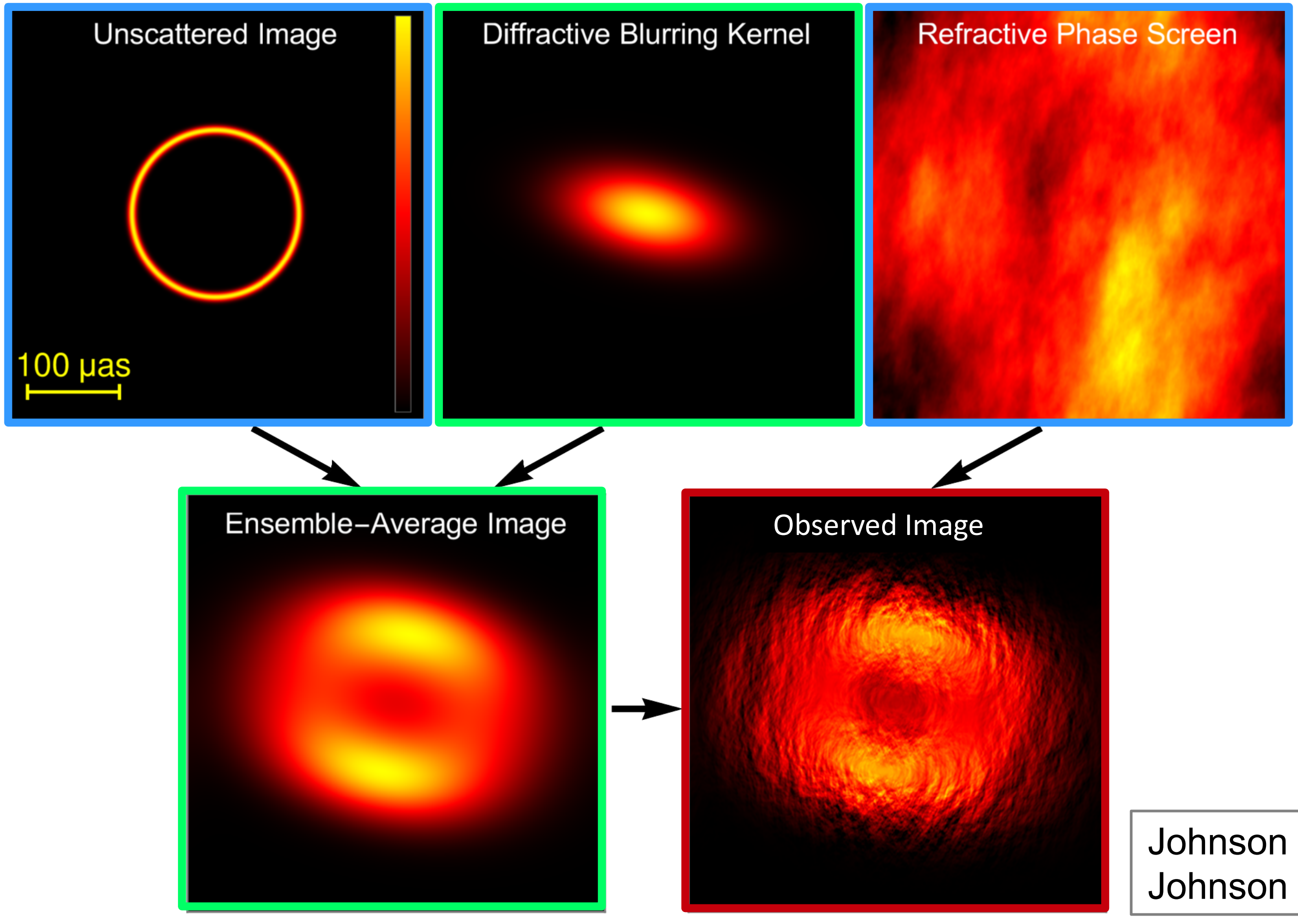
(Narayan & Goodman 1989; Johnson & Gwinn 2015)

A Simplified Scattering Framework

Scattering is most commonly described by turbulence governed by a single, unbroken power law

However, we can decouple the scattering into two dominant regimes (Blandford & Narayan 1985)

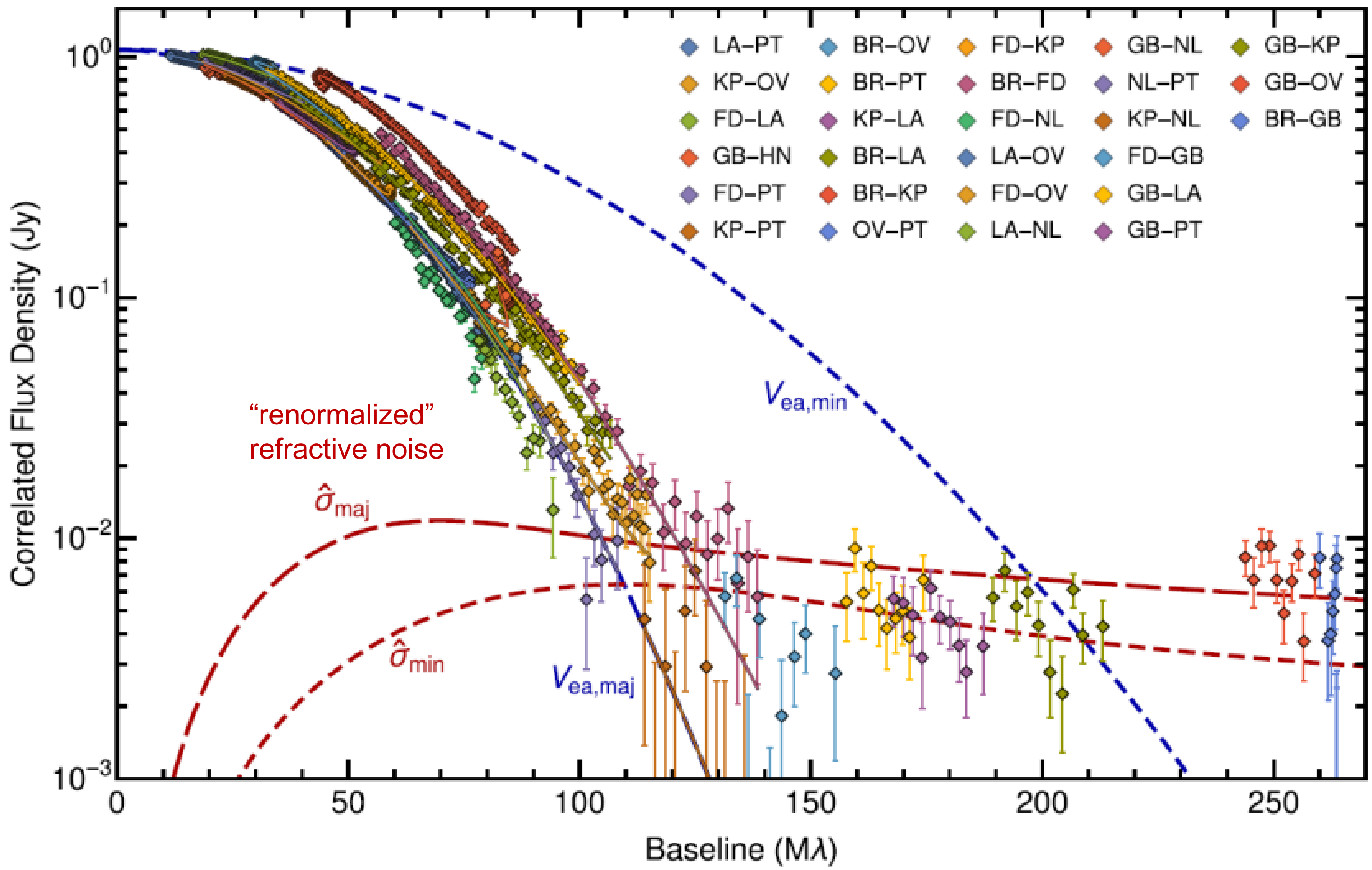
- Small-scale (“diffractive”) fluctuations can be replaced by their ensemble-average
- Large-scale (“refractive”) phase fluctuations can be treated as stochastic



Johnson & Narayan (2016)
Johnson (2016)

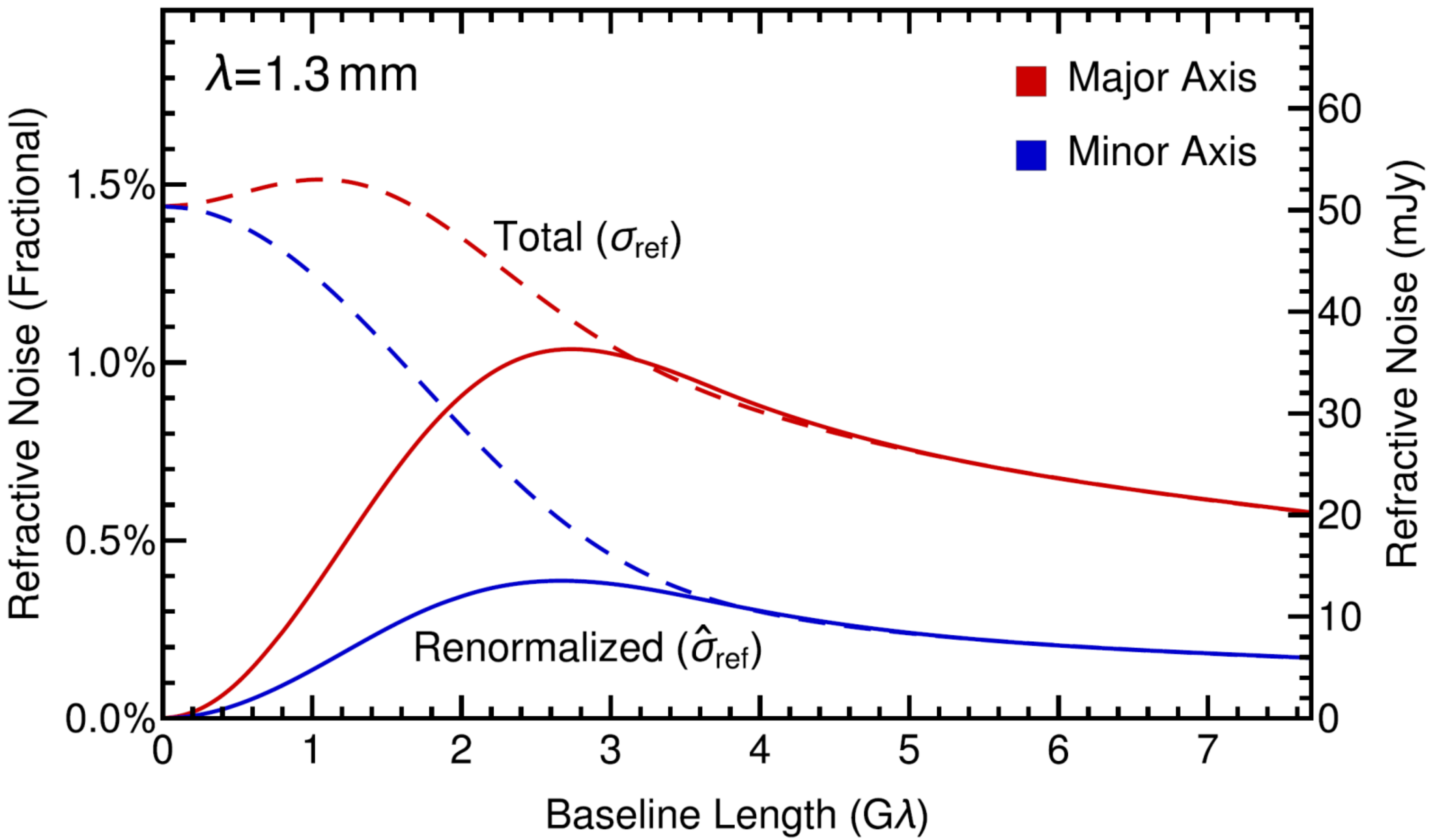
Refractive Substructure

Example: Sgr A* at 1.3cm

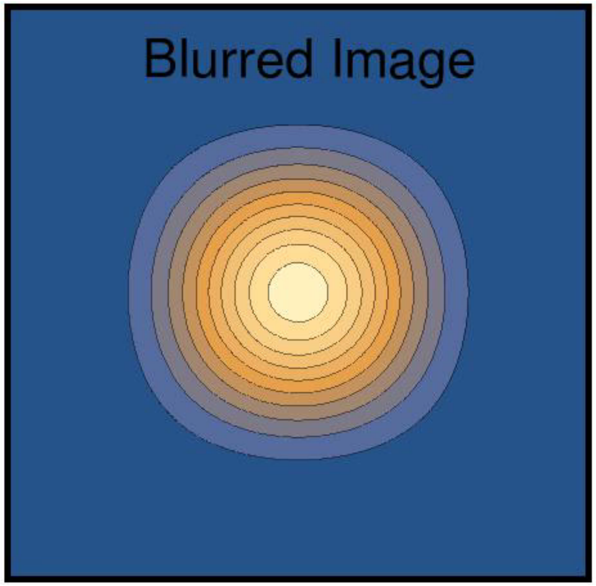


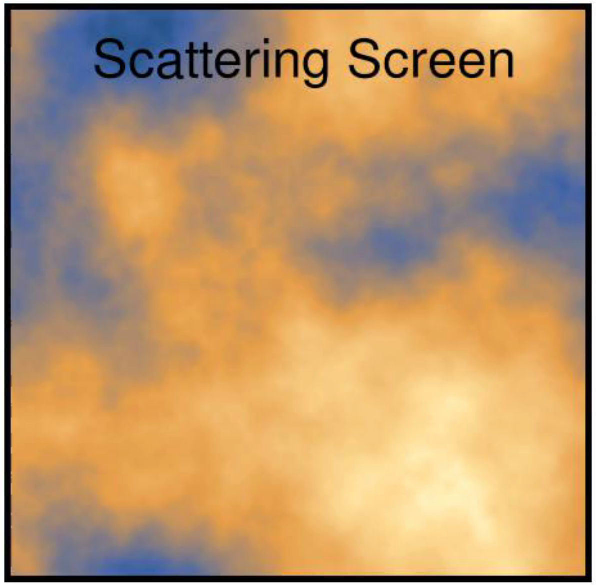
Refractive Substructure

Expected refractive noise at 1.3mm (for a Gaussian source)



One Mitigation Strategy: Model the Screen





The screen is ~constant even as the source evolves.

Need to model modes from the ~source size to the ~beam size

Total required modes could be ~10-100

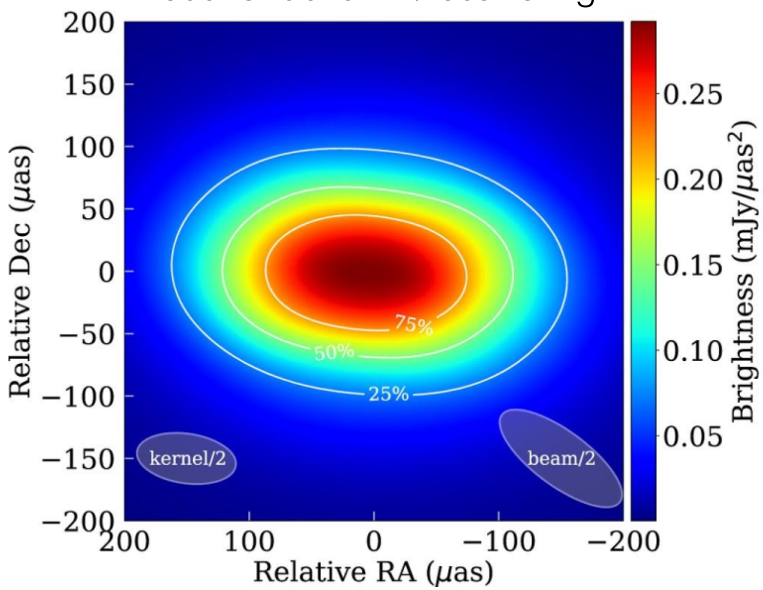
Ideal: Marginalize over these degrees of freedom

Models of scattering

1. Scattering dominated by thin screens: Distance to the screen
2. Scattering anisotropic: Size, axis ratio, orientation of scattered disk
3. Substructure in scattered image: Fluctuations in phase screen

Sgr A* @ 86 GHz; Issaoun+ 2019

Reconstruction w/ scattering



Reconstruction w/out scattering