Interstellar Scattering for Space VLBI

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Professor Emeritus at UCSB

Now living in Prescott, Arizona

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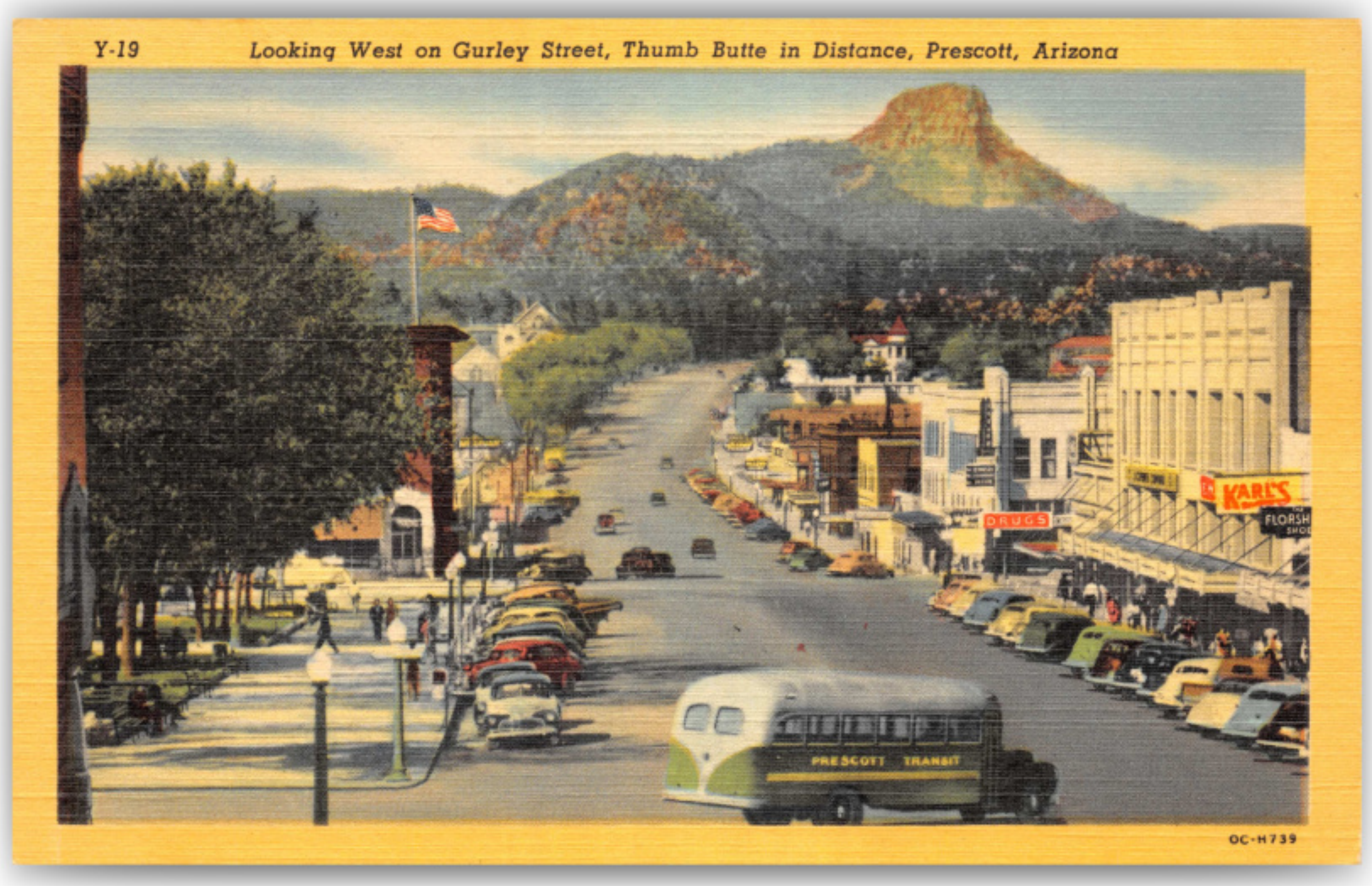

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- Scattering presents observational limits to imaging and angular resolution.
- Scattering also presents opportunities for novel observations, and to explain poorly-understood phenomena.
- Observational limits aren’t fully understood and may be simpler than now thought.
- How can future missions take best advantage of opportunities, but avoid pitfalls?

Outline

Review of Conventional Scattering

- Conventional and Fresnel lenses
- Kolmogorov spectrum
- Refractive vs diffractive scattering

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- Pulsars
  - Diffractive scattering
  - Cosmic prisms
  - Structure of pulsar emission
- Refractive scattering of AGN
  - Sgr A*
  - 3C273
- Scattering of H2O masers
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A New View of Scattering:

- Scattering for shorter paths & out of the Galactic plane

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A New View of Scattering:

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Concluding questions:

IDVs

FRBs

Scattering for future missions

2 kinds of lenses

Conventional lens

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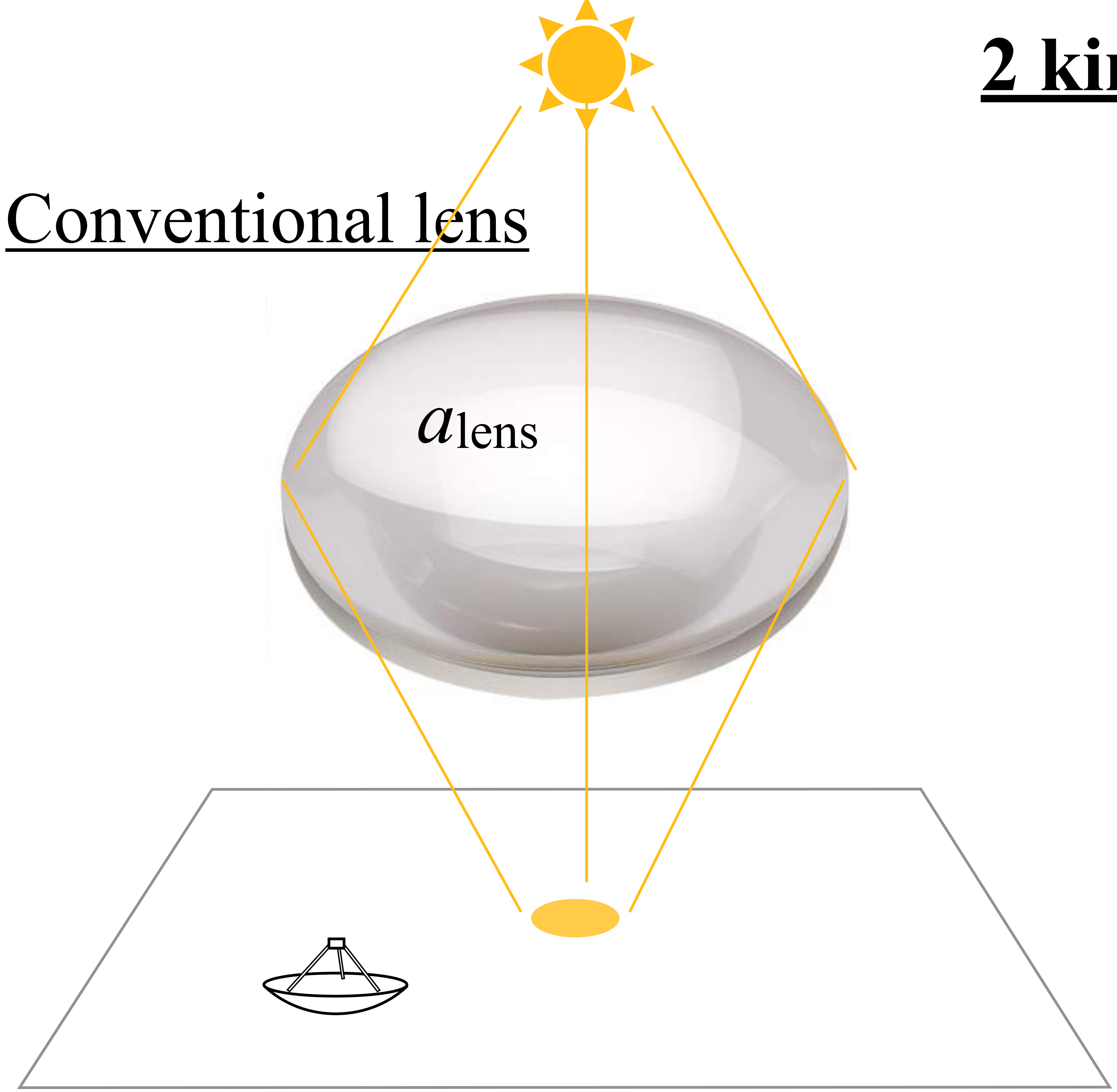
Conventional lens

Fresnel lens

2 kinds of lenses

Conventional lens



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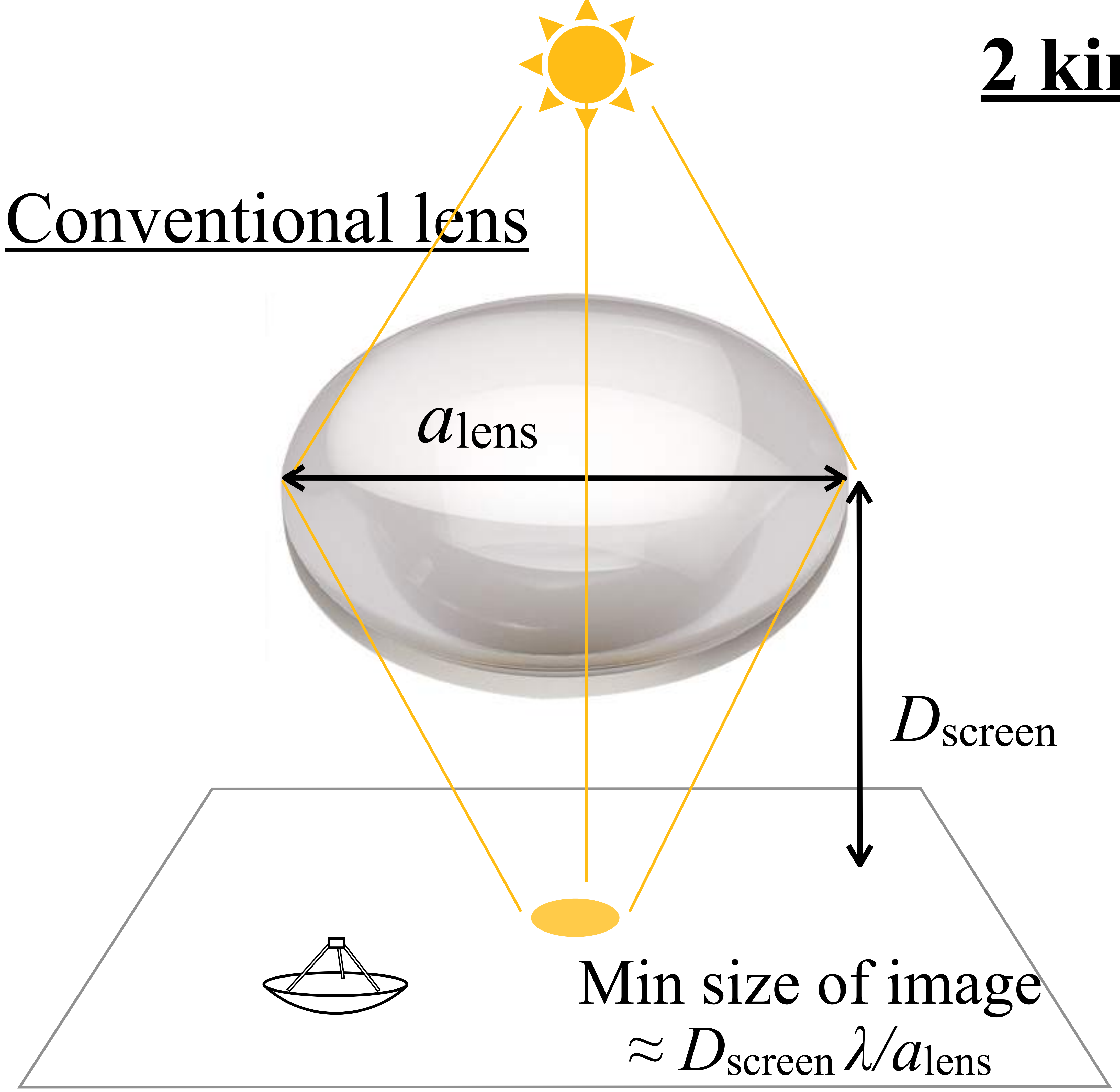

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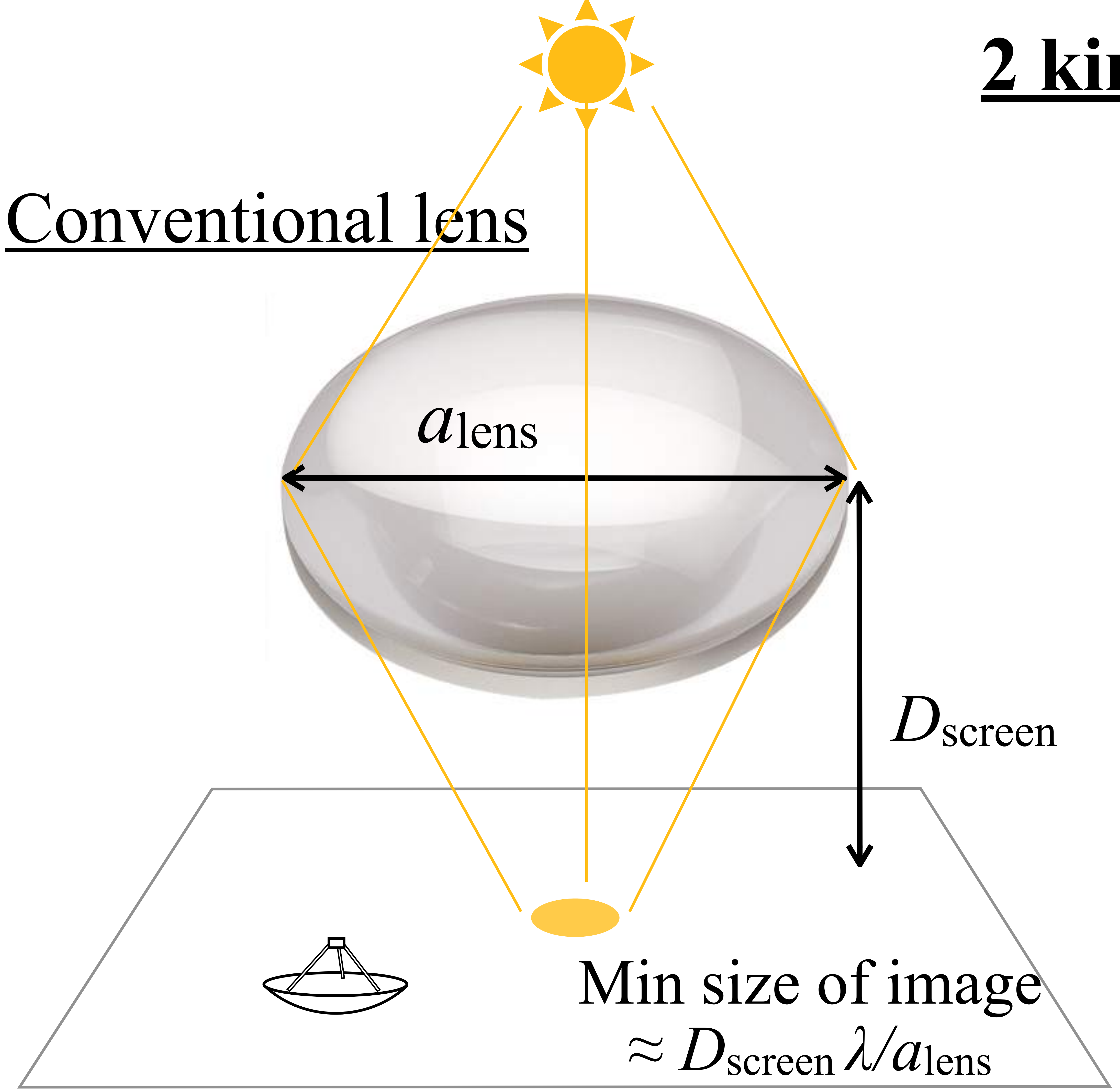

Phase-coherent: light waves from the source, at different points on the lens, cancel everywhere in the observer plane, *except* at the image.

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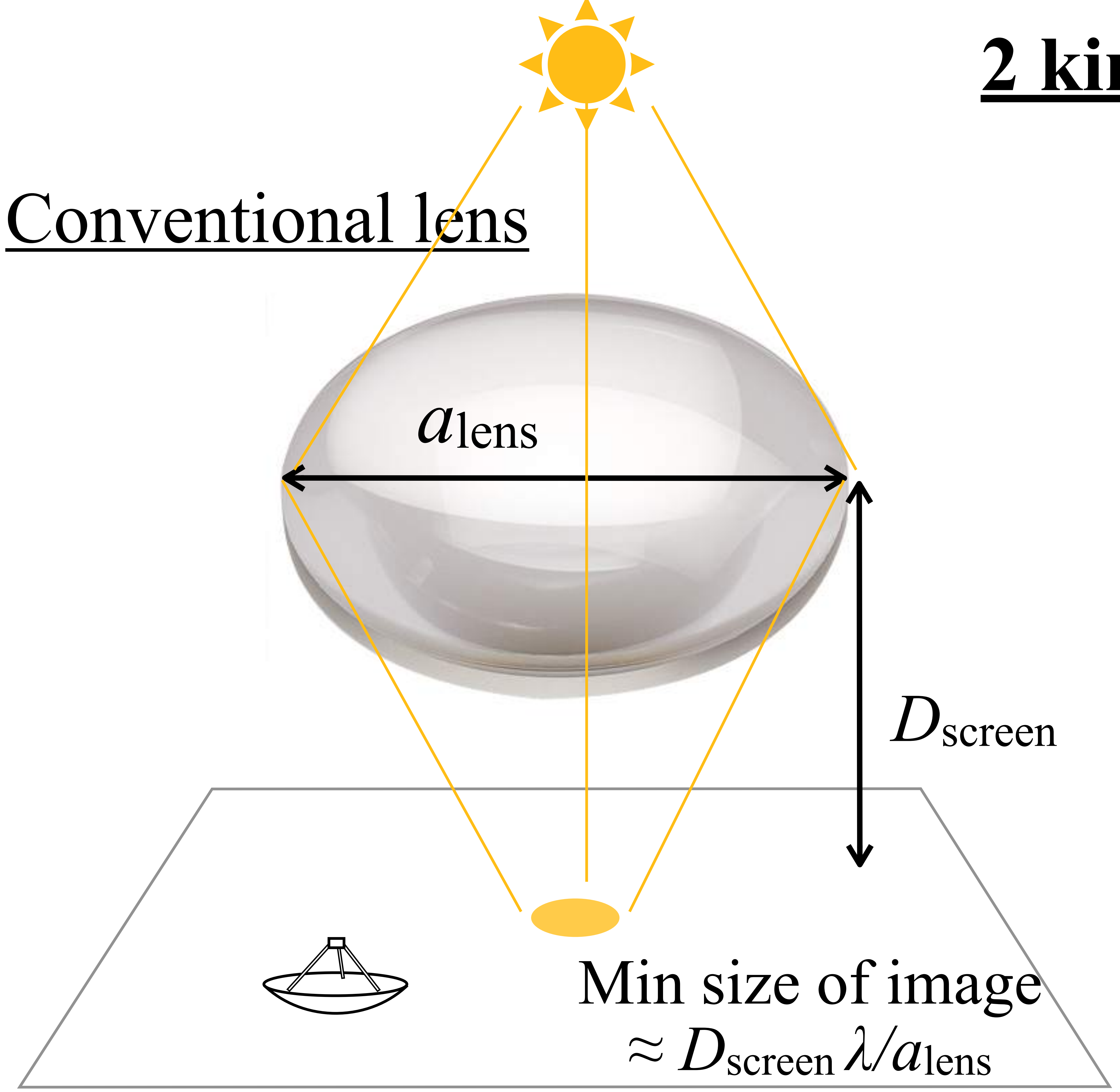

Phase-coherent: light waves from the source, at different points on the lens, cancel everywhere in the observer plane, *except* at the image.
The lens adds phases $\phi(x)$ that *cancel* the extra geometric phase ϕ_F for non-straight paths.

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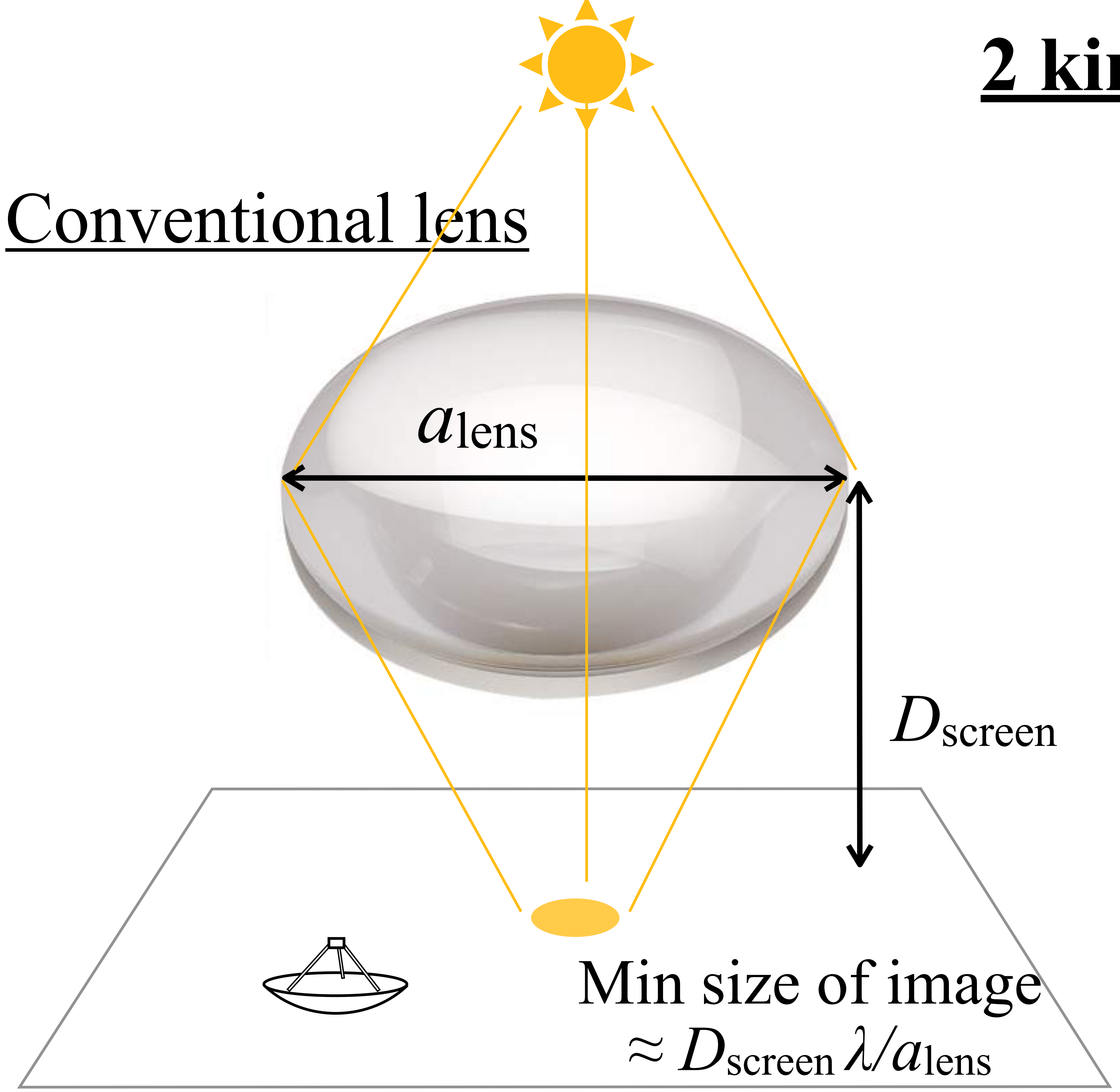

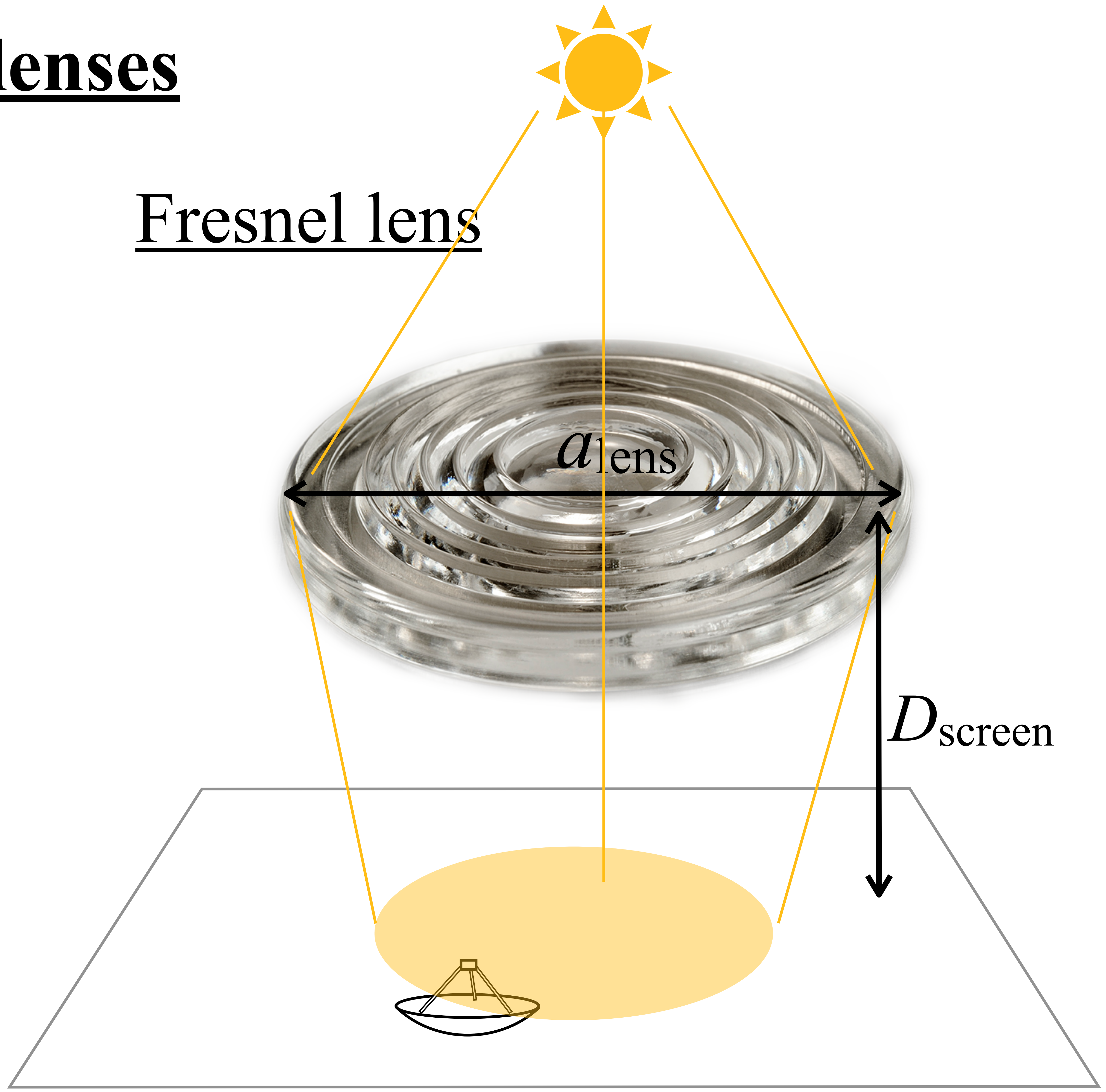

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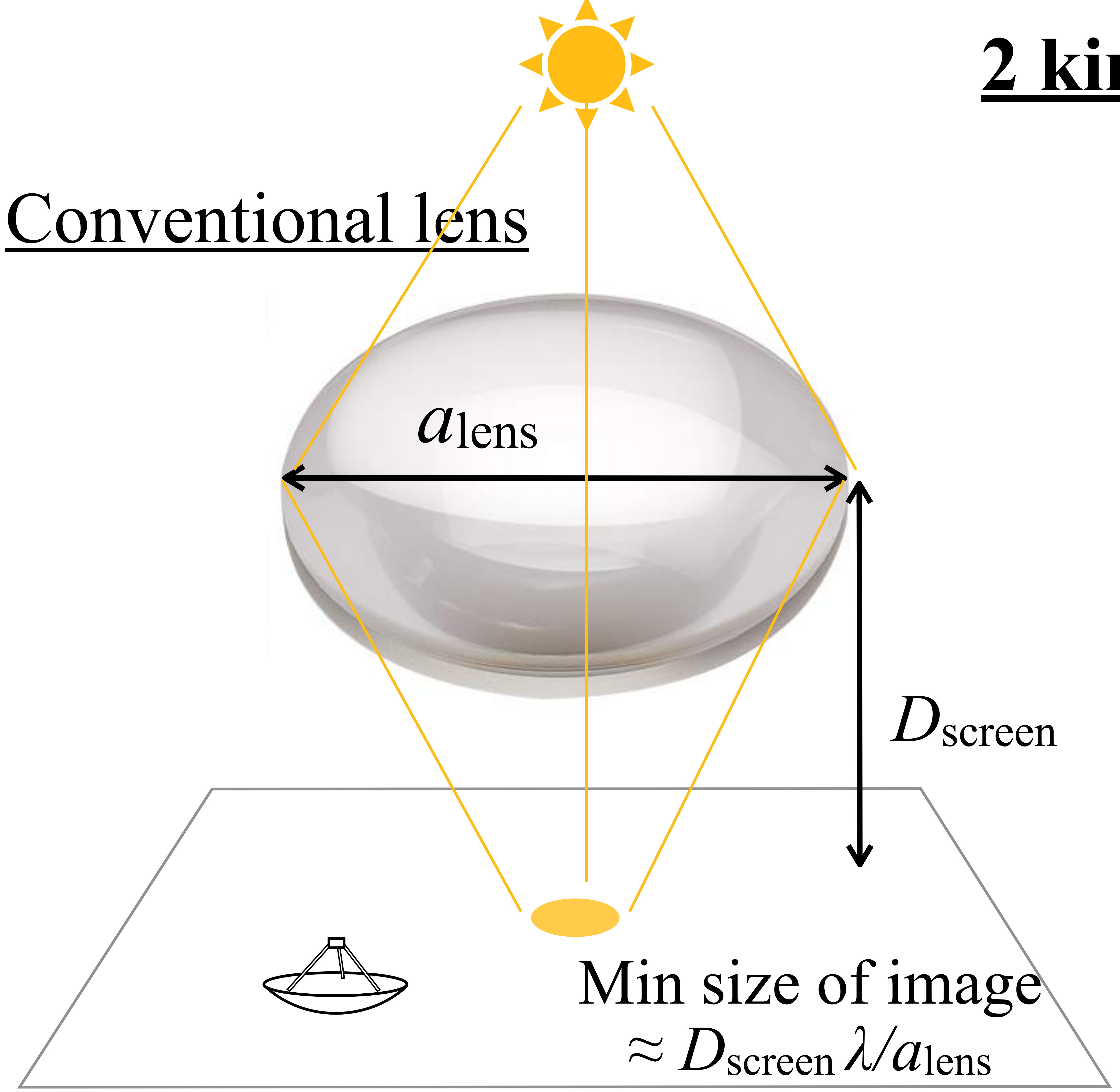

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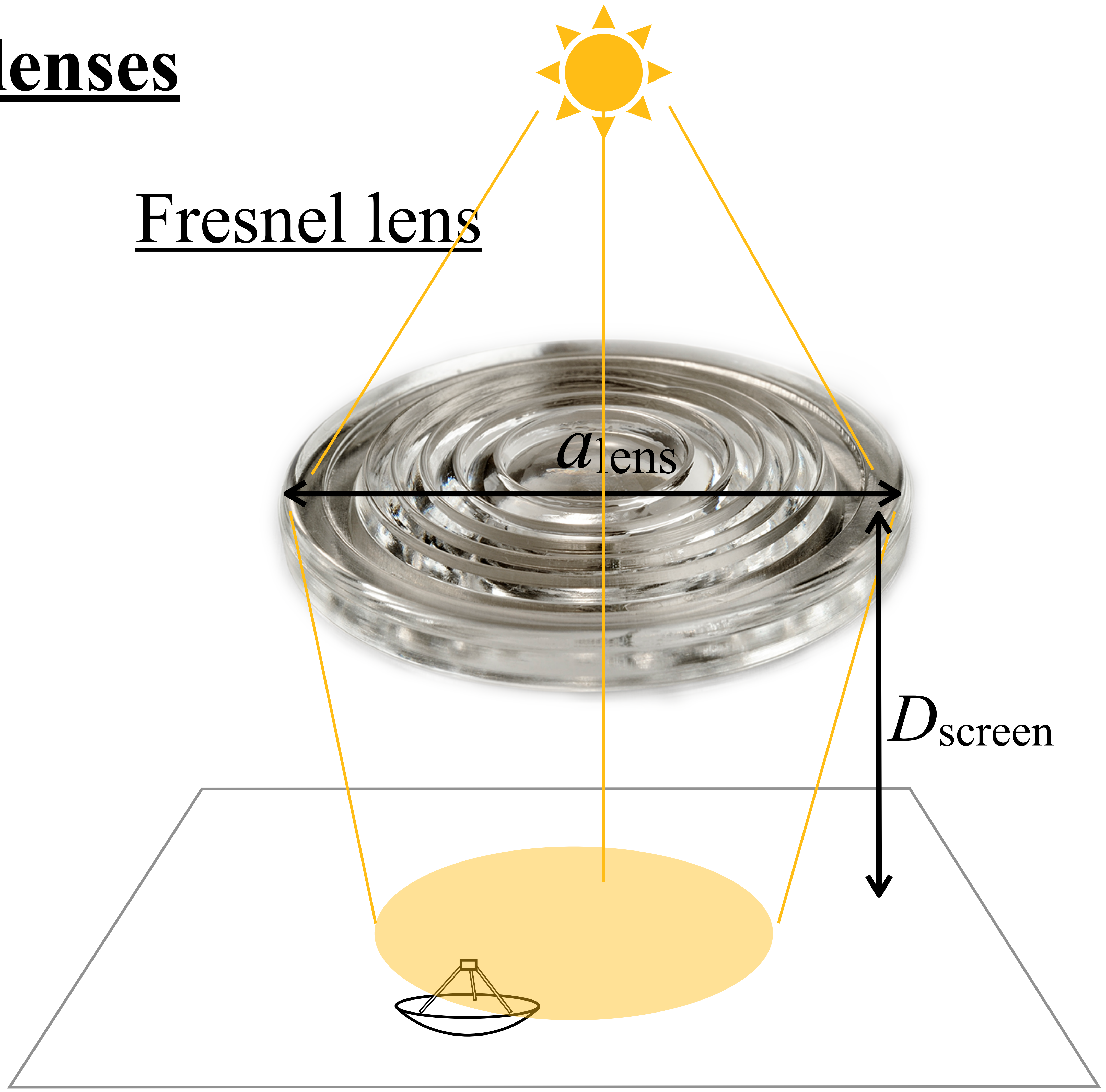

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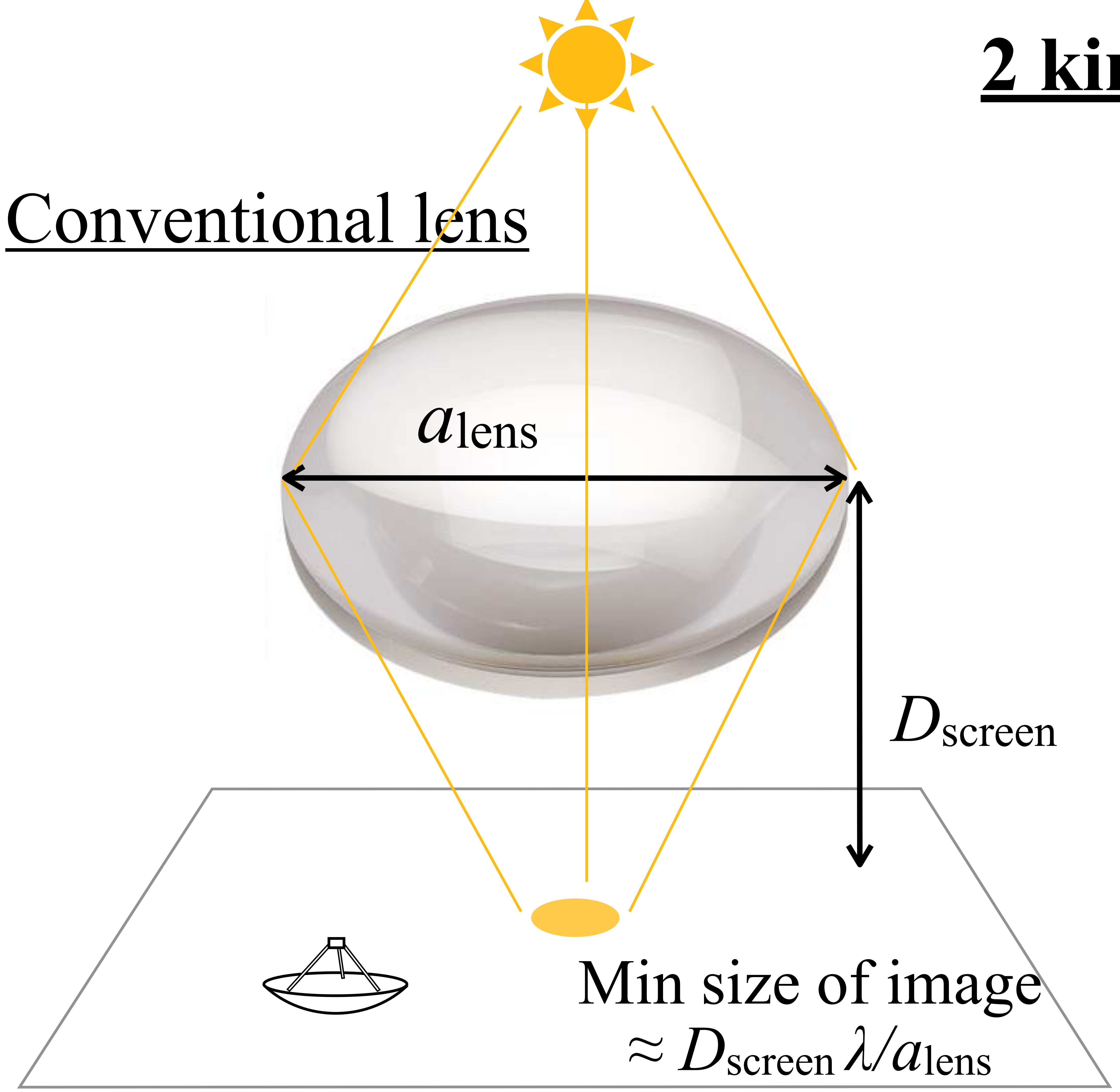

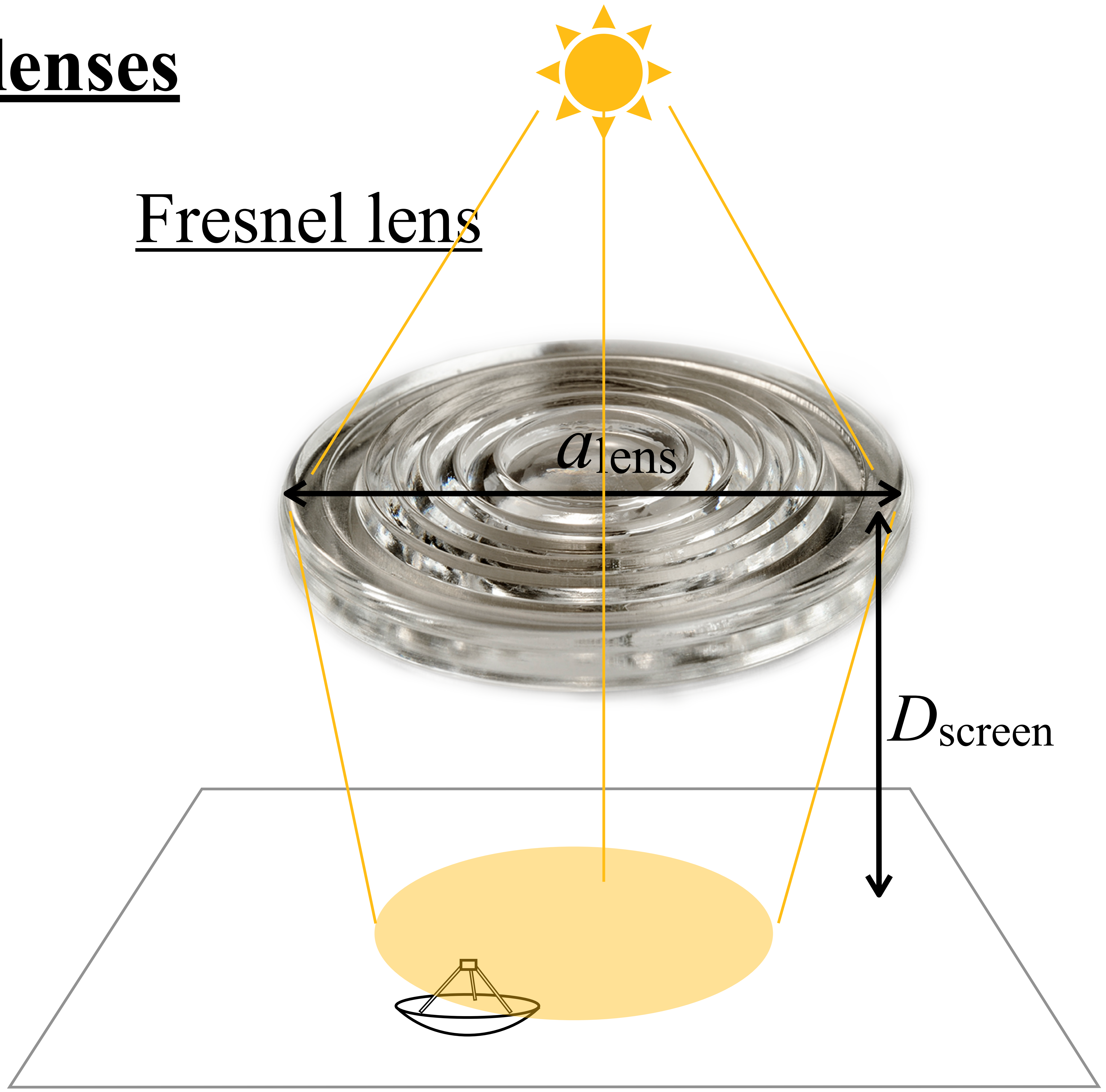

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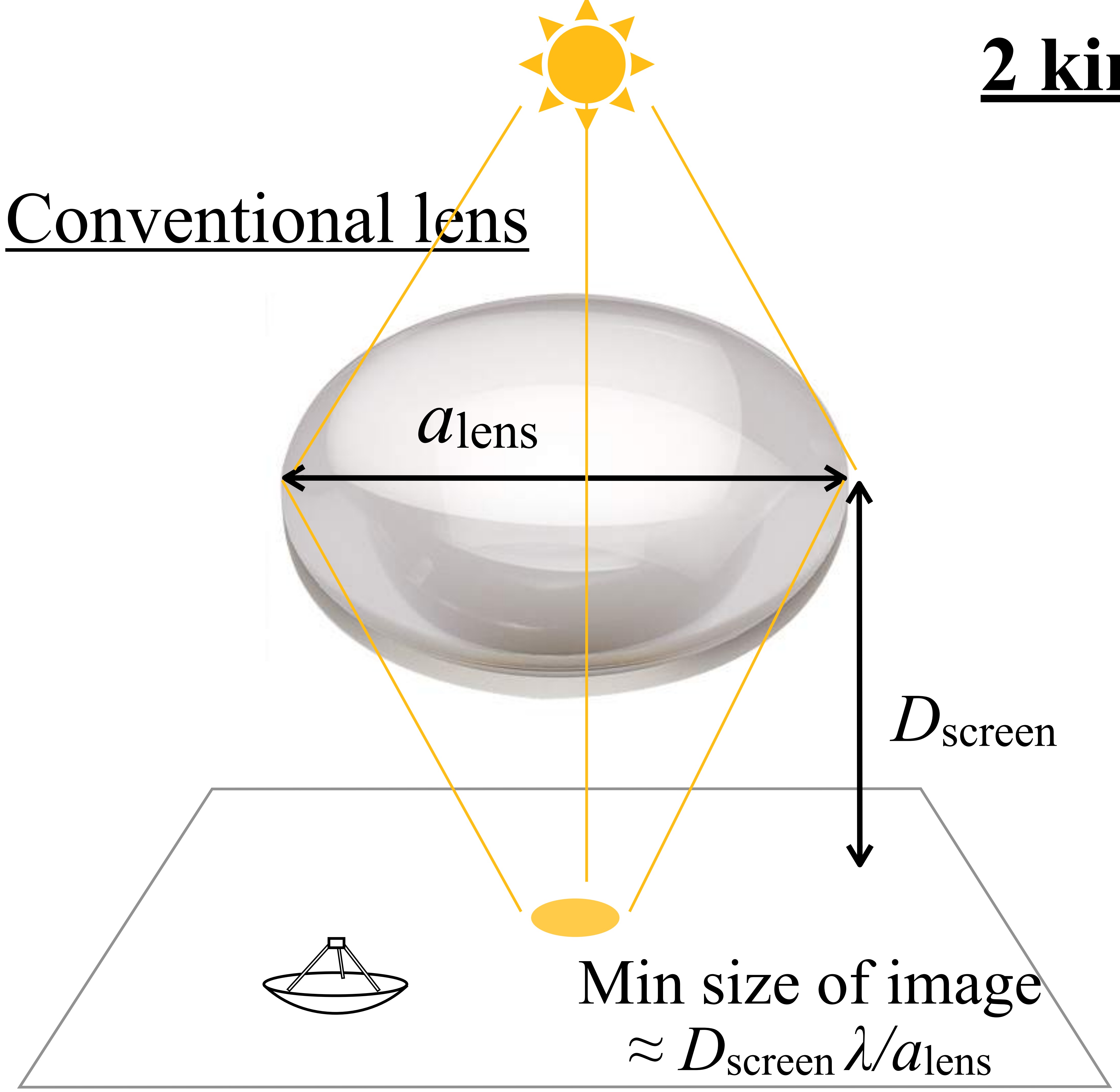

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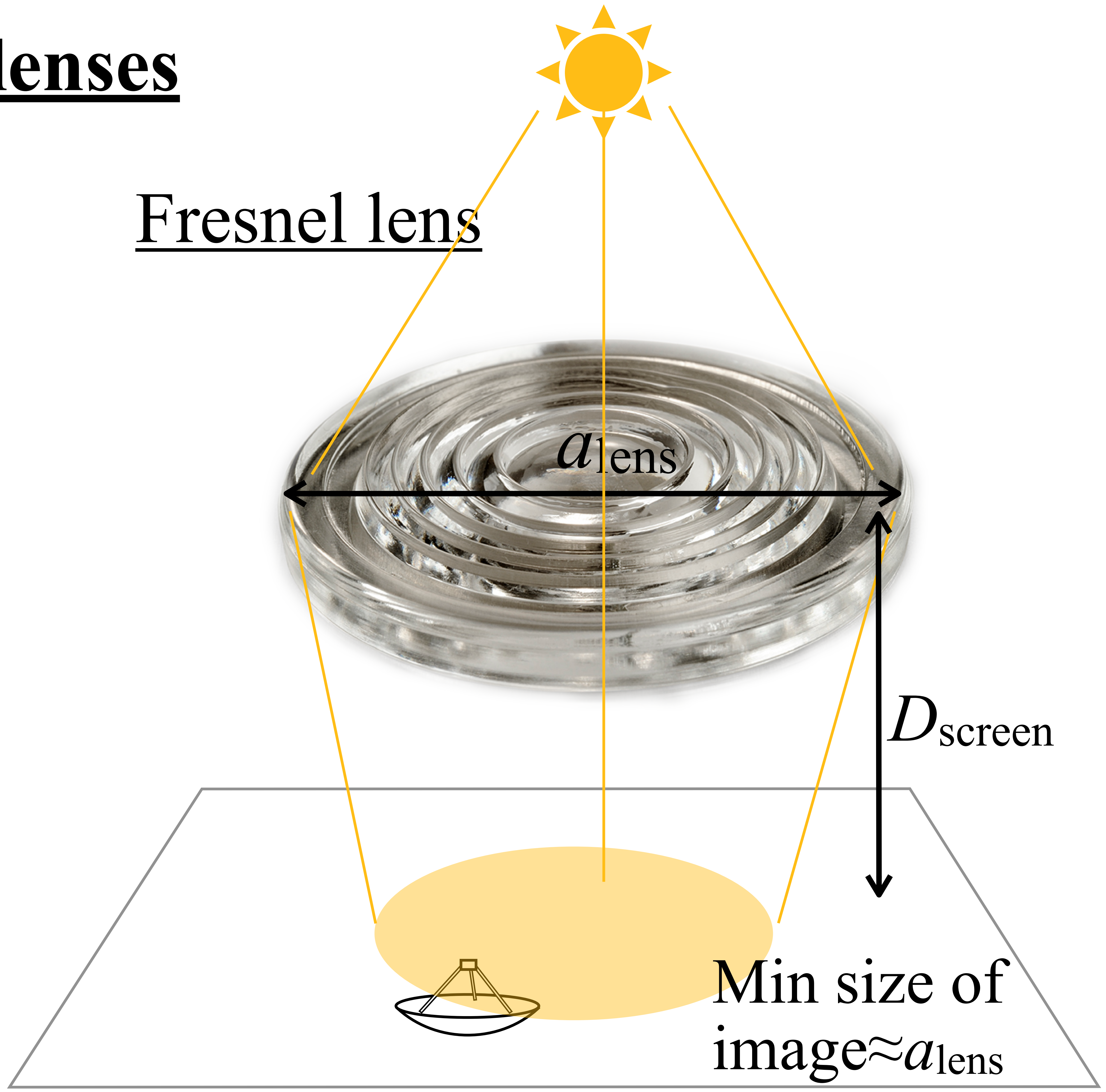

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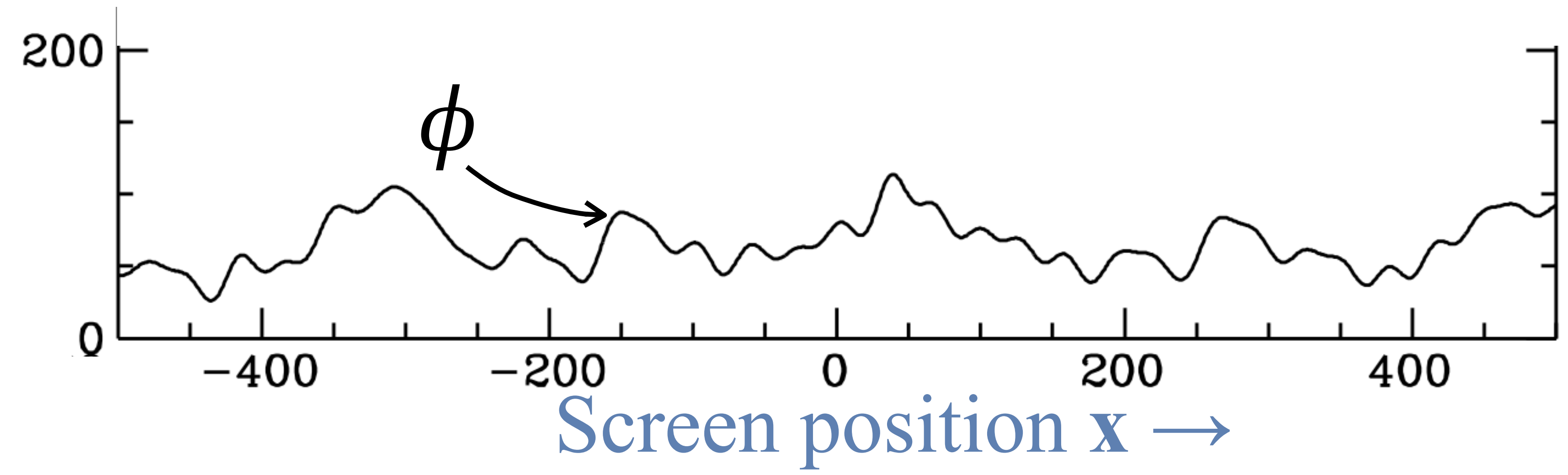

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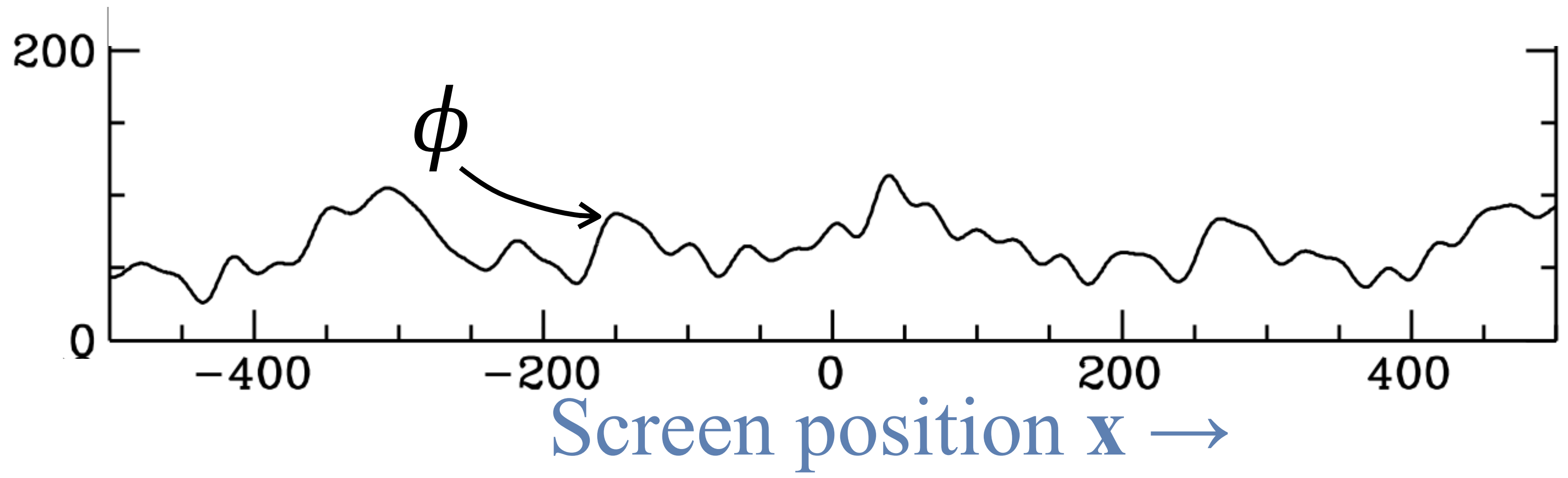
A correlation function describes screen phase:

$$\left\langle \left(\phi(\mathbf{x}+\Delta\mathbf{x}) - \phi(\mathbf{x})\right)^2 \right\rangle \propto |\Delta\mathbf{x}|^{\alpha}, \qquad \alpha = 5/3$$

For Kolmogorov turbulence: α=5/3

- Scaling arguments applied to fluid equations yield this value.



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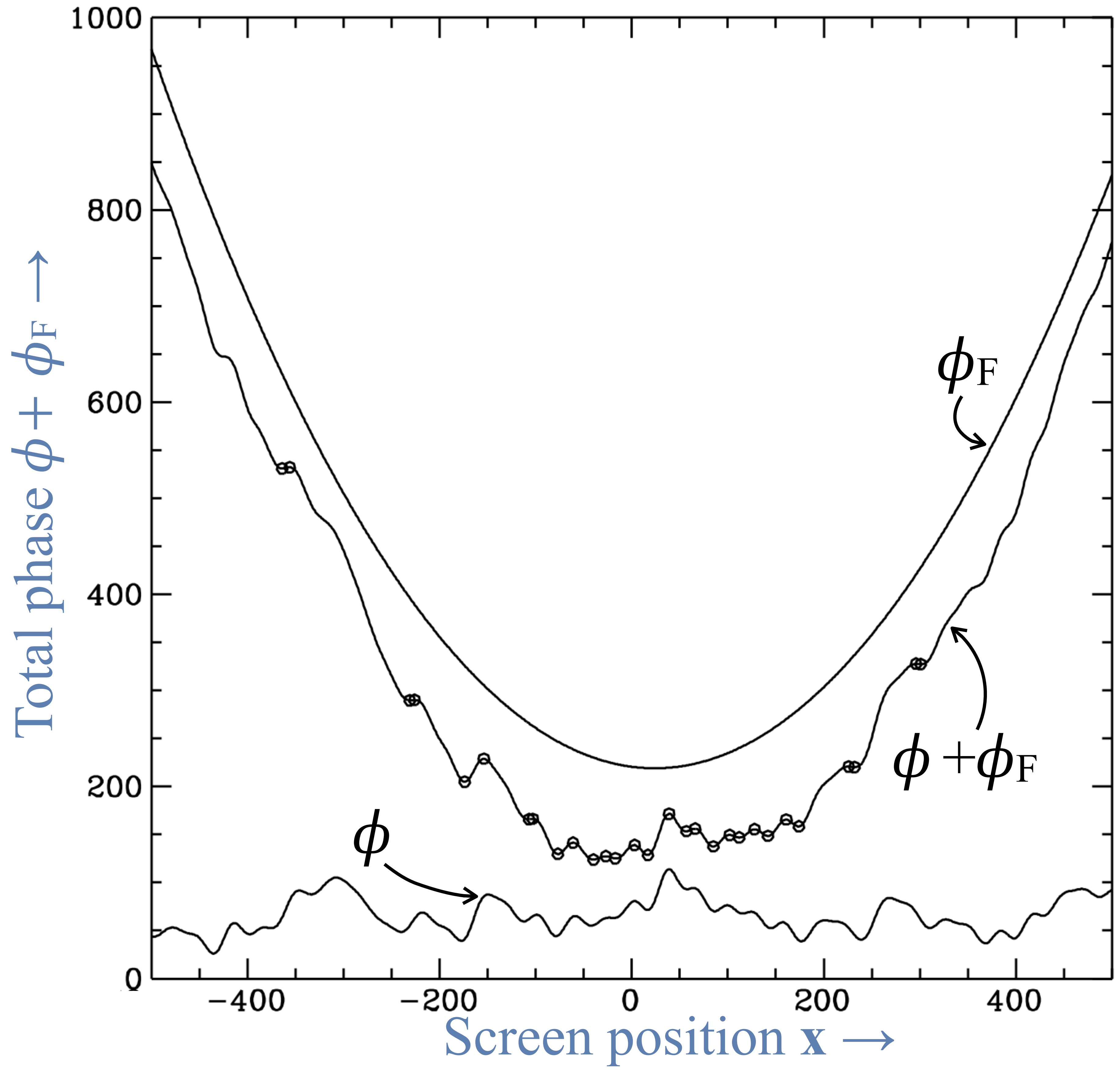

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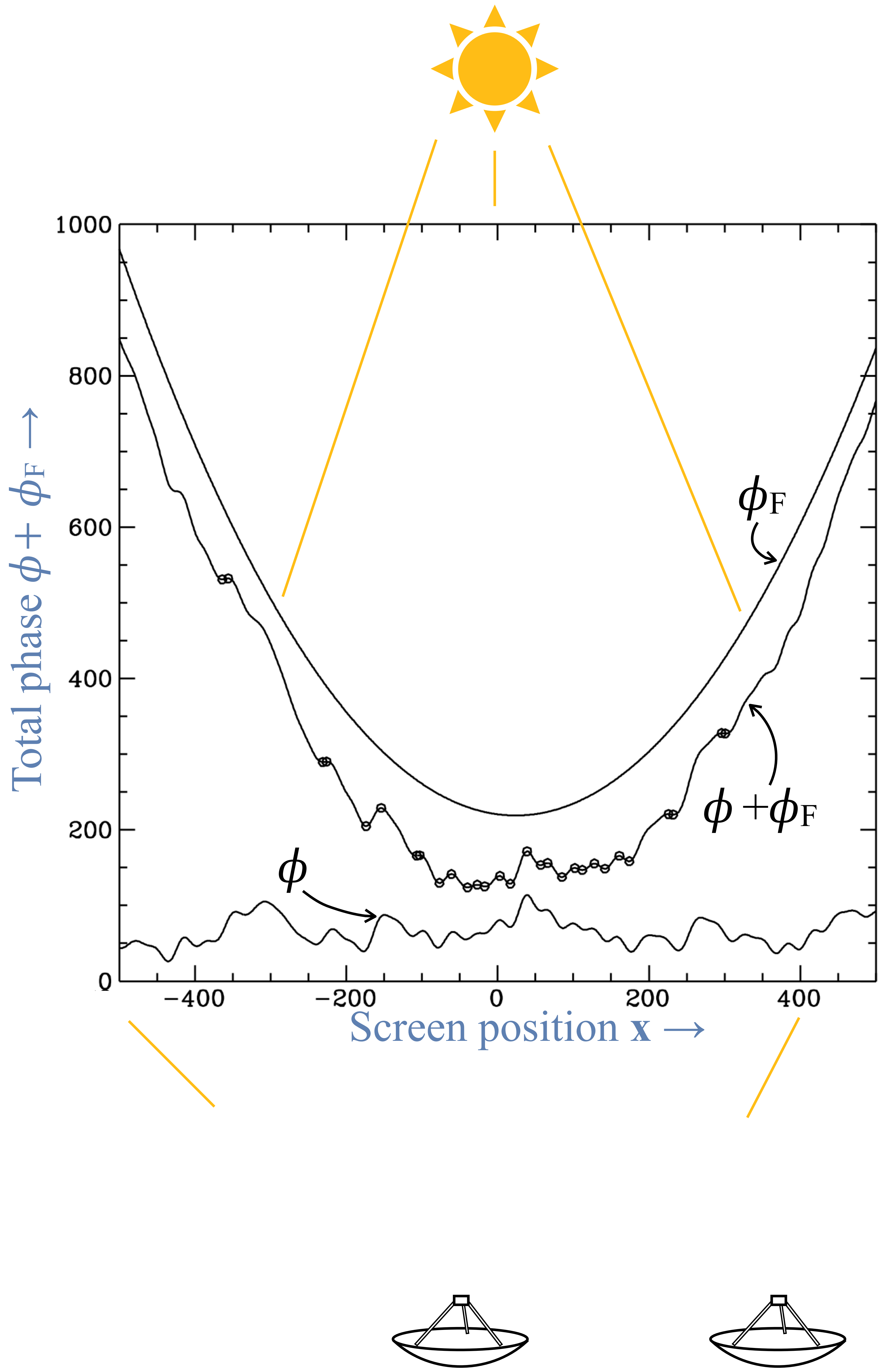

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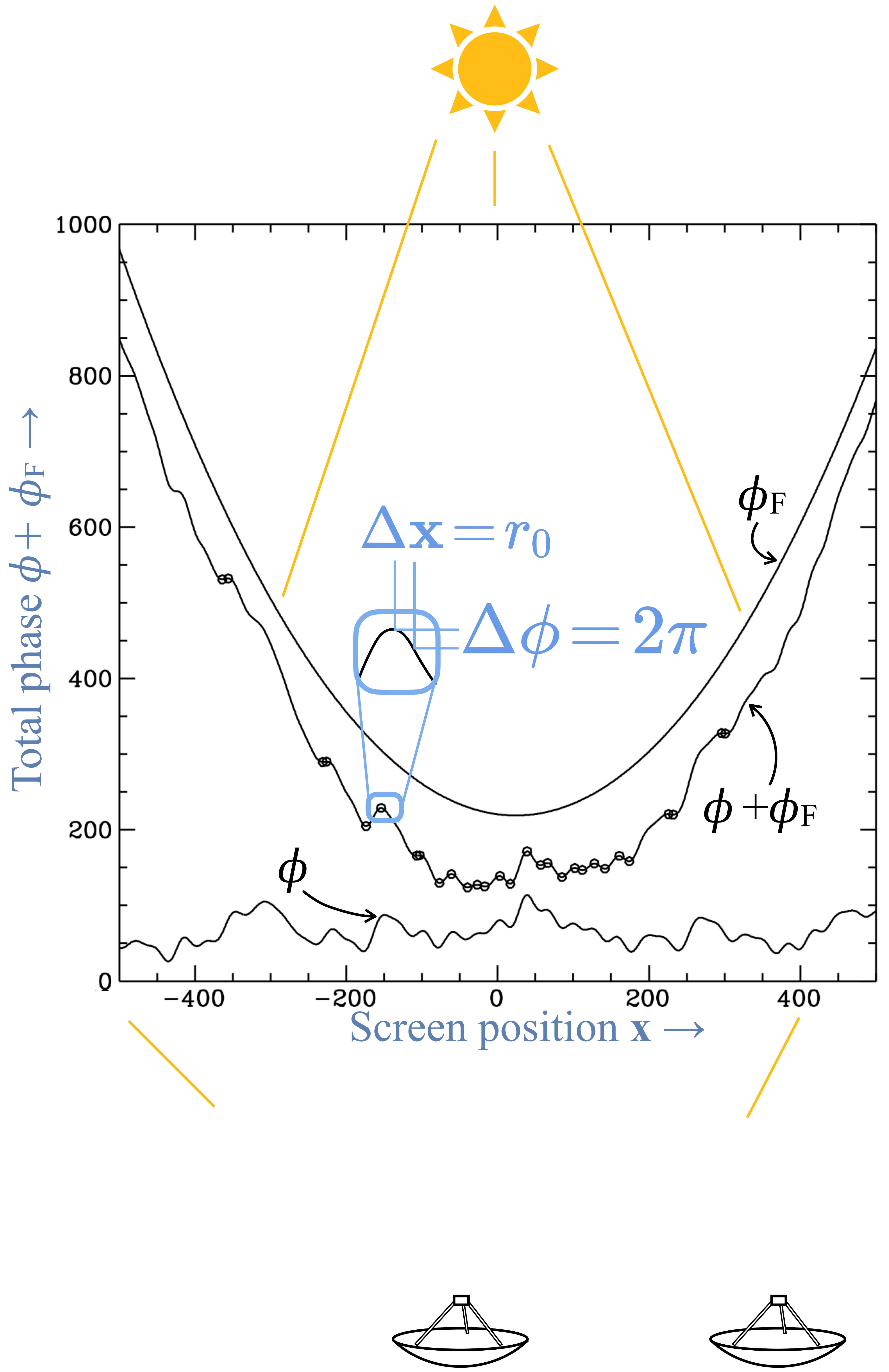

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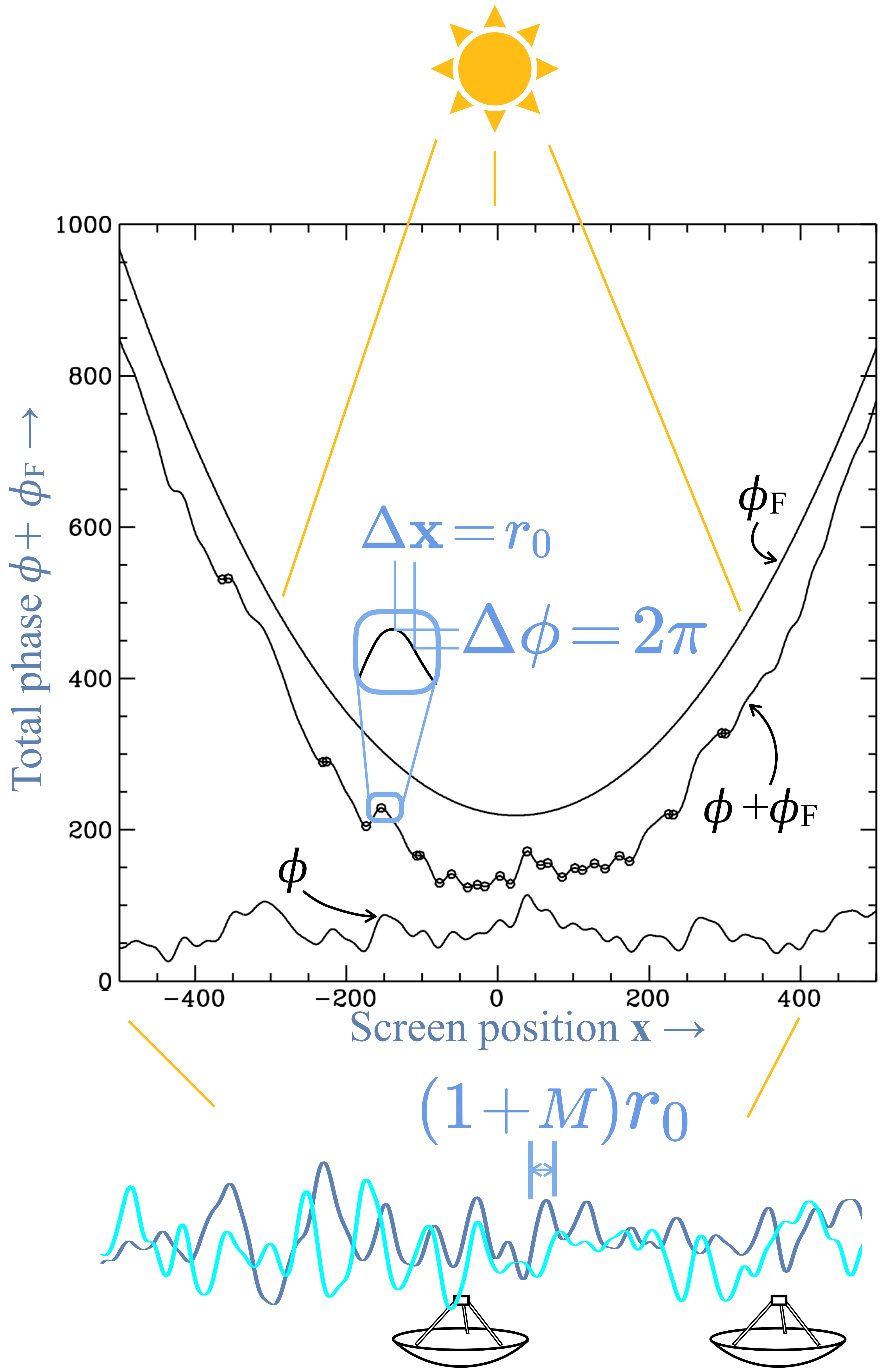

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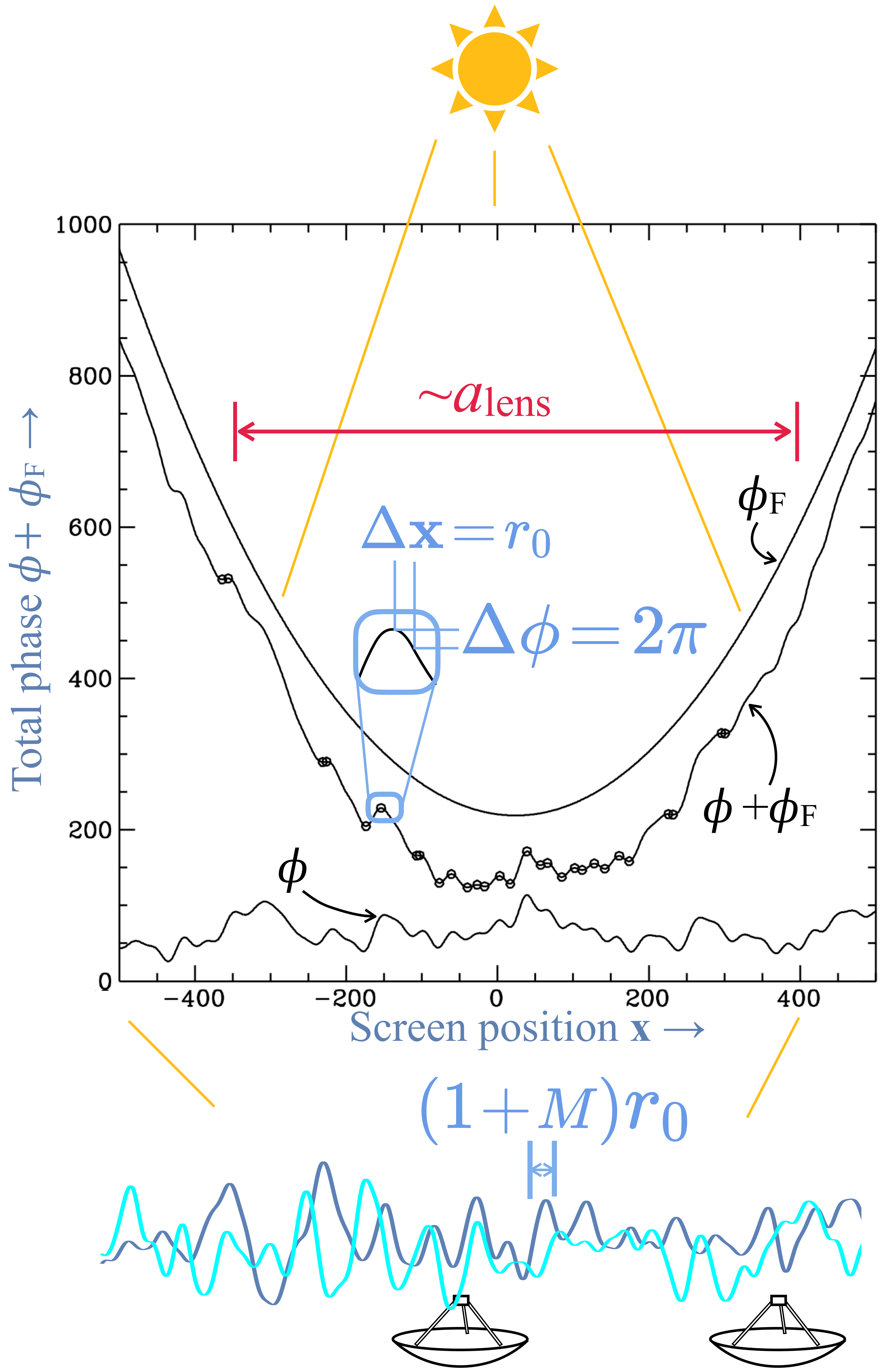

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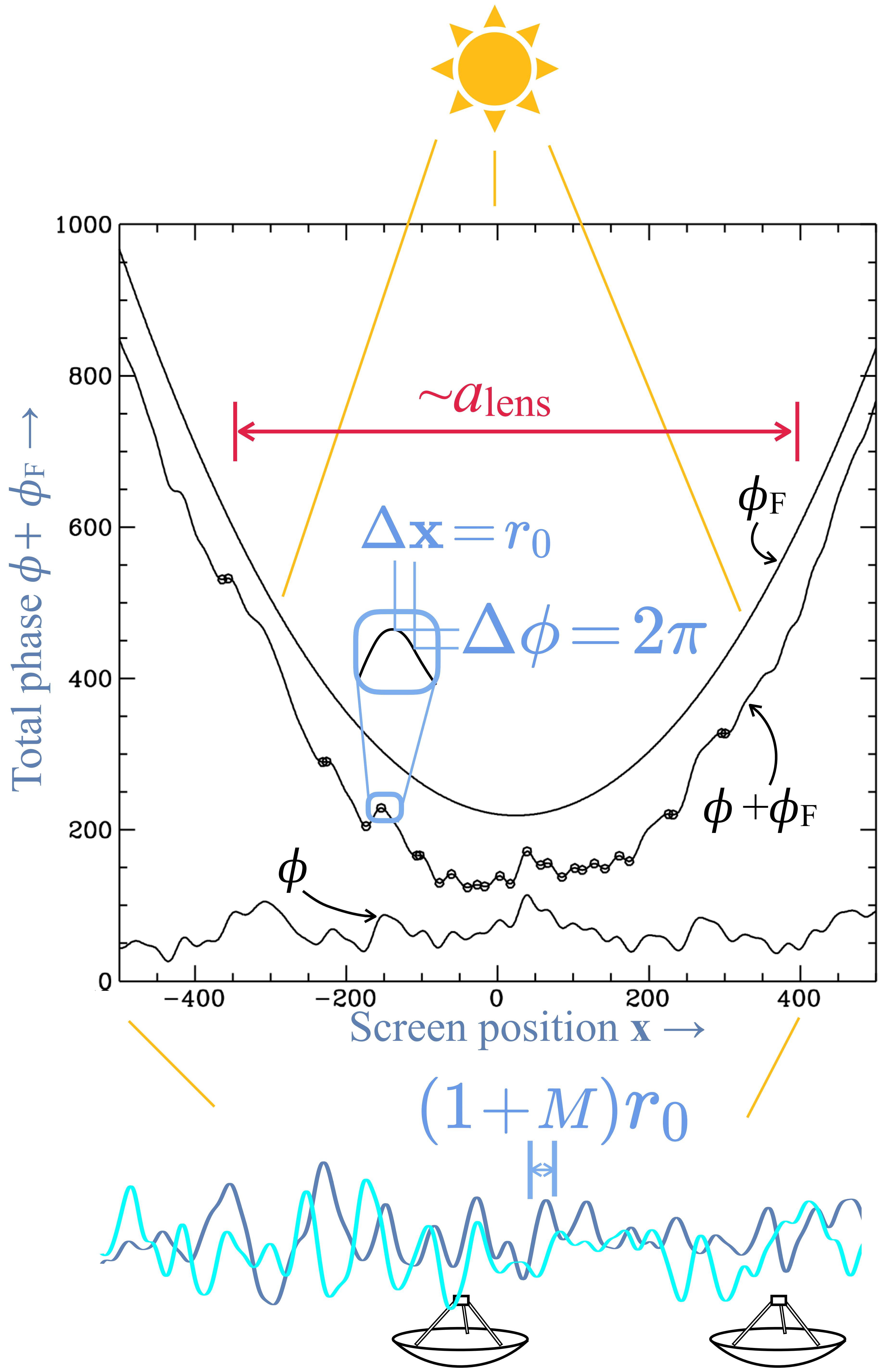

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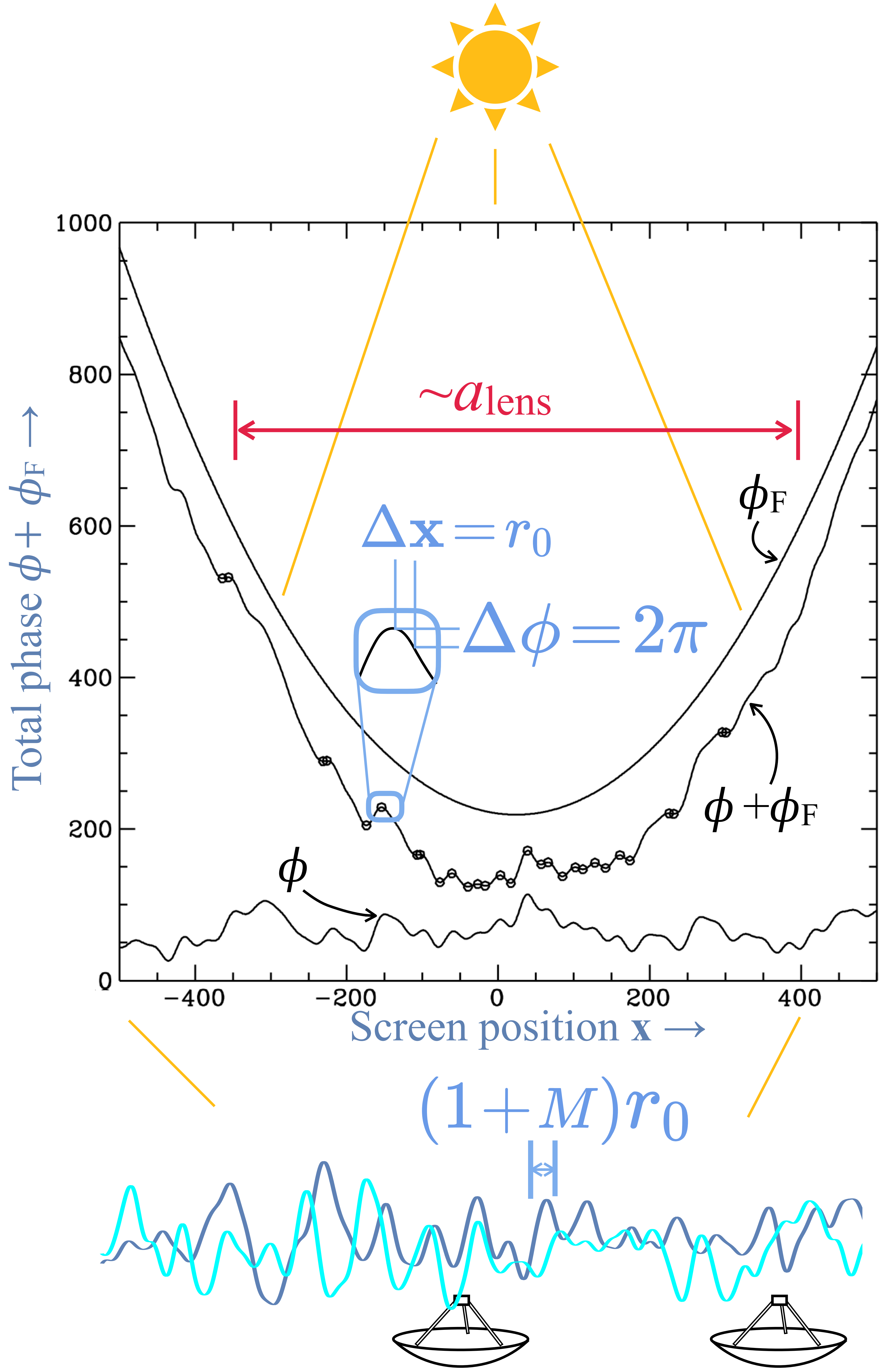

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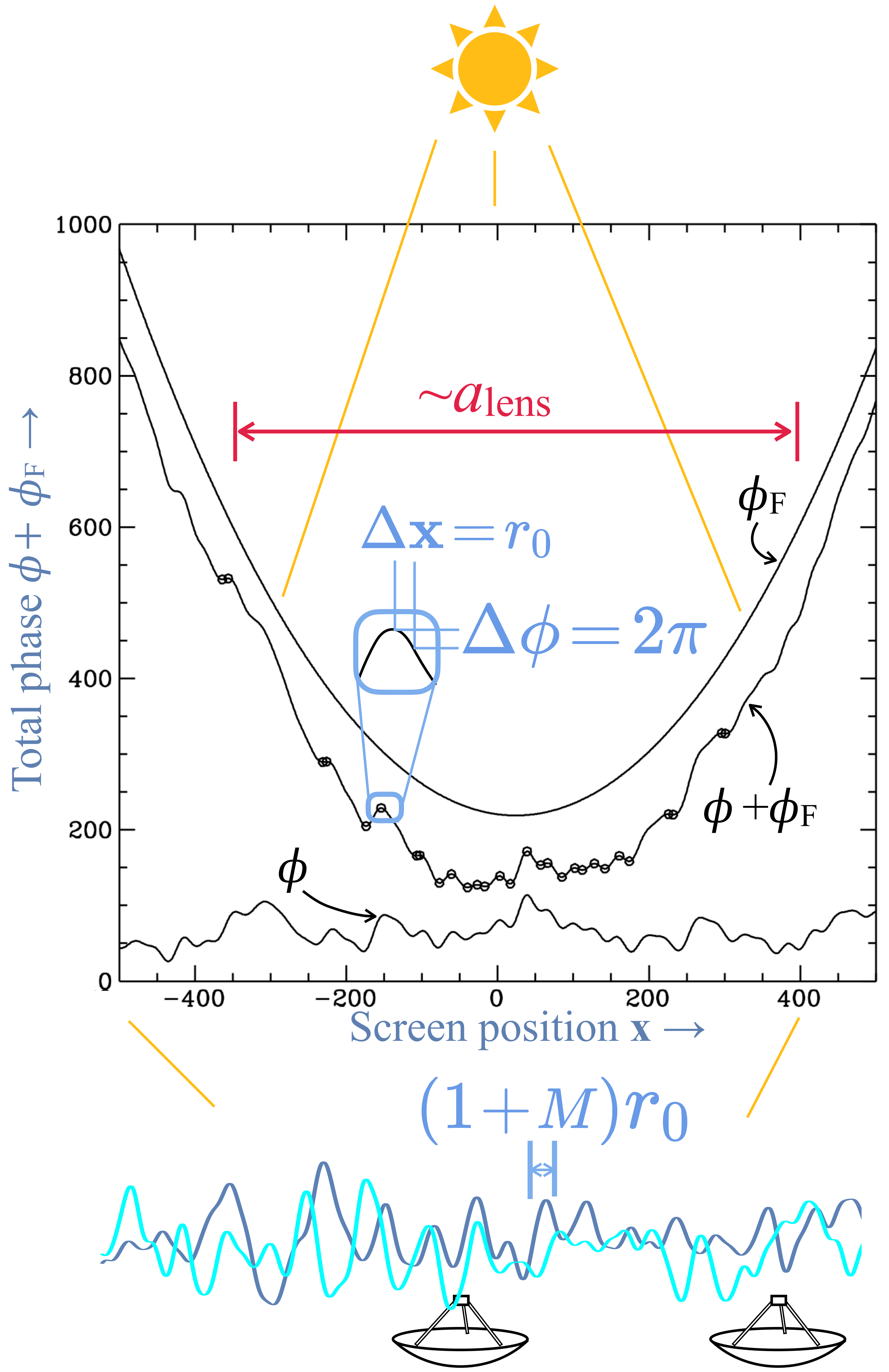

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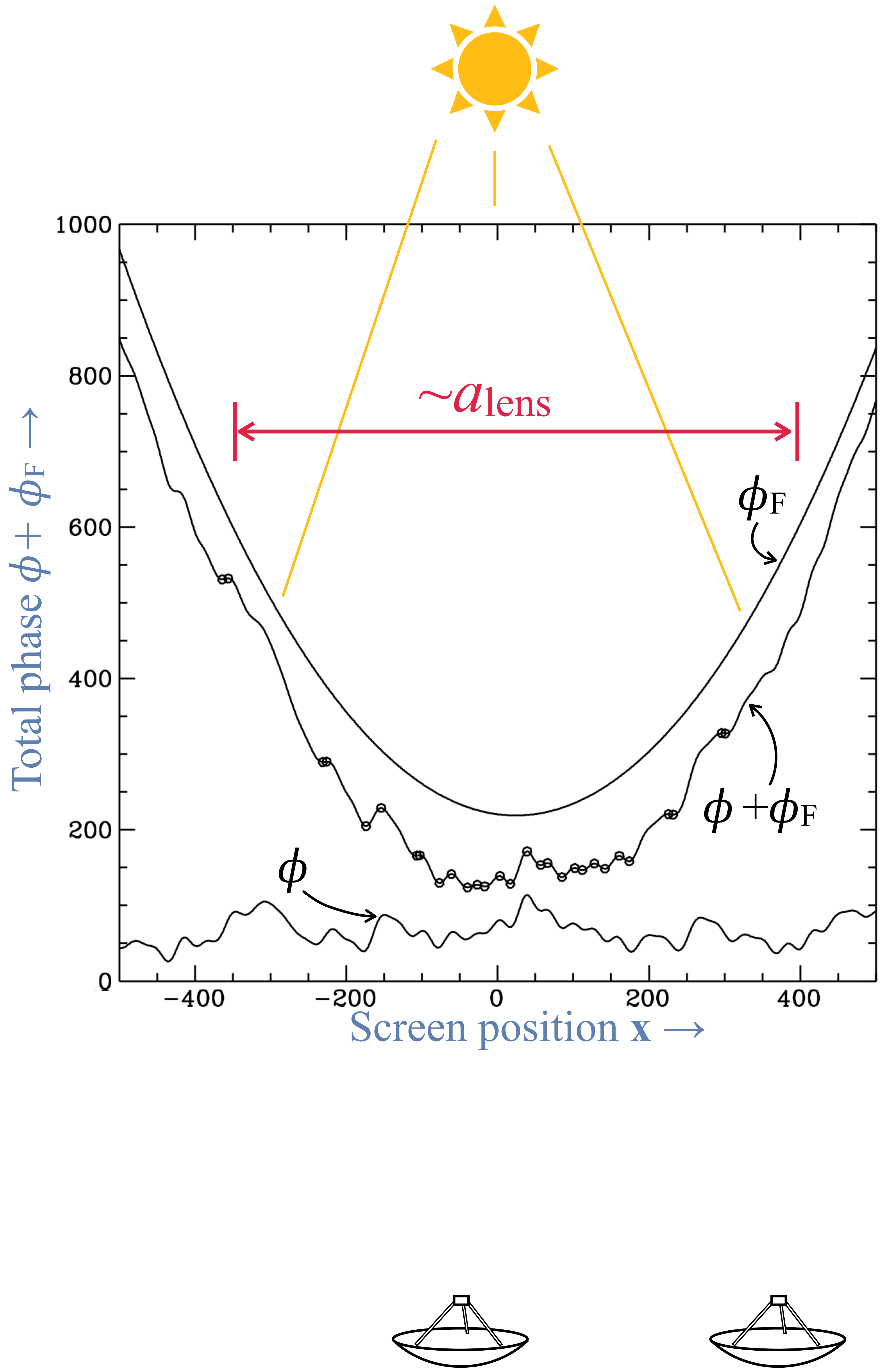

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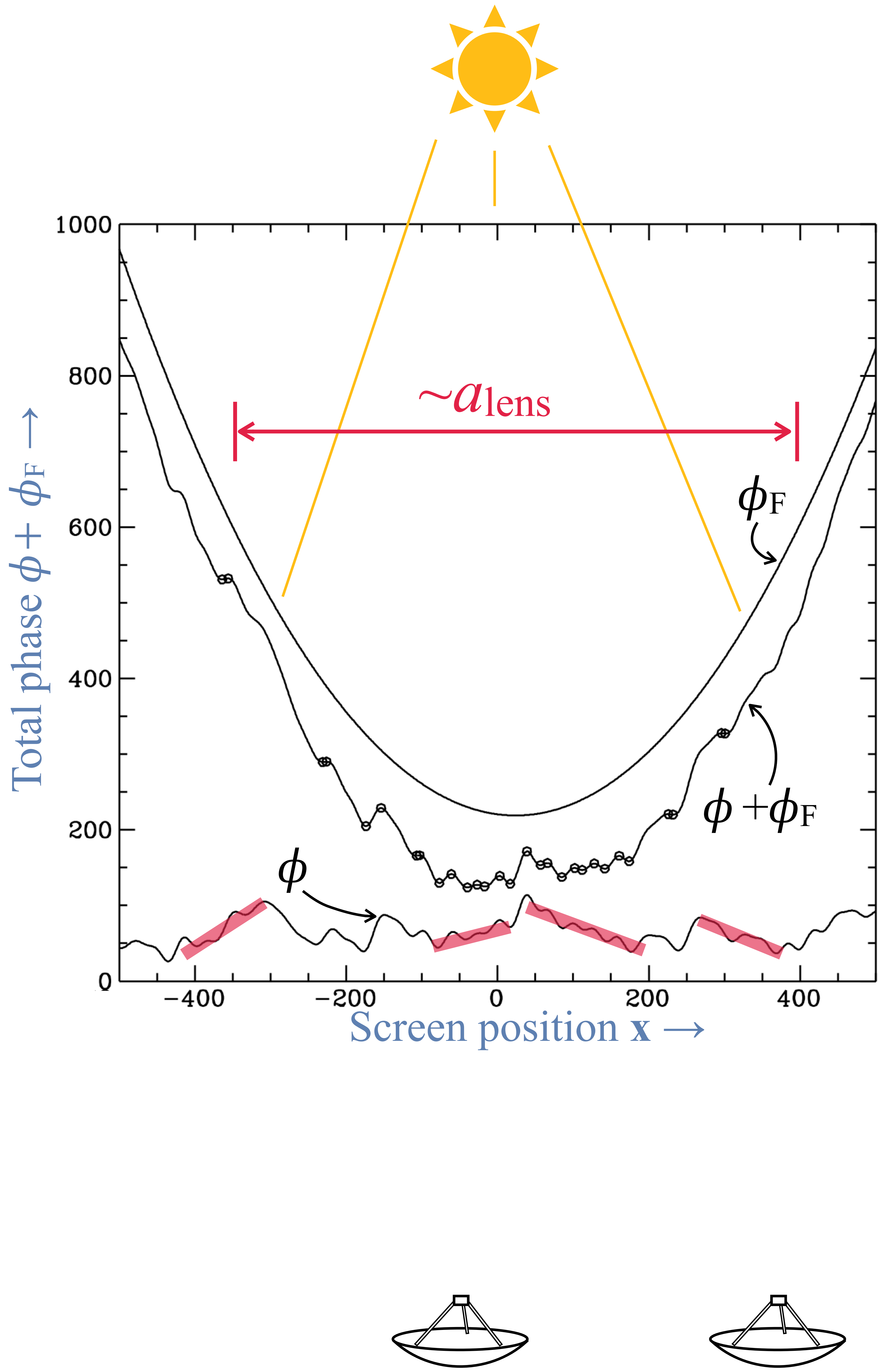

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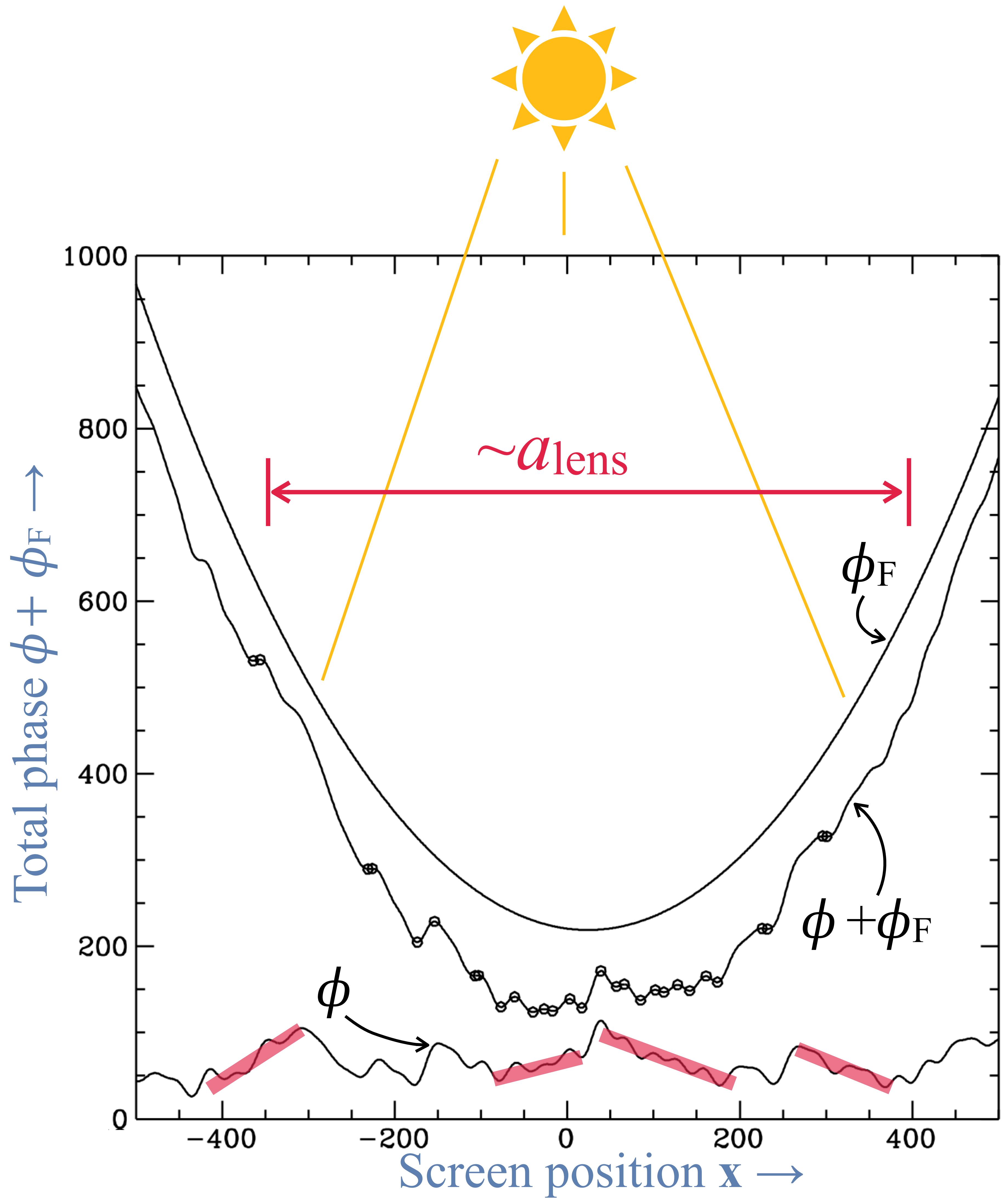

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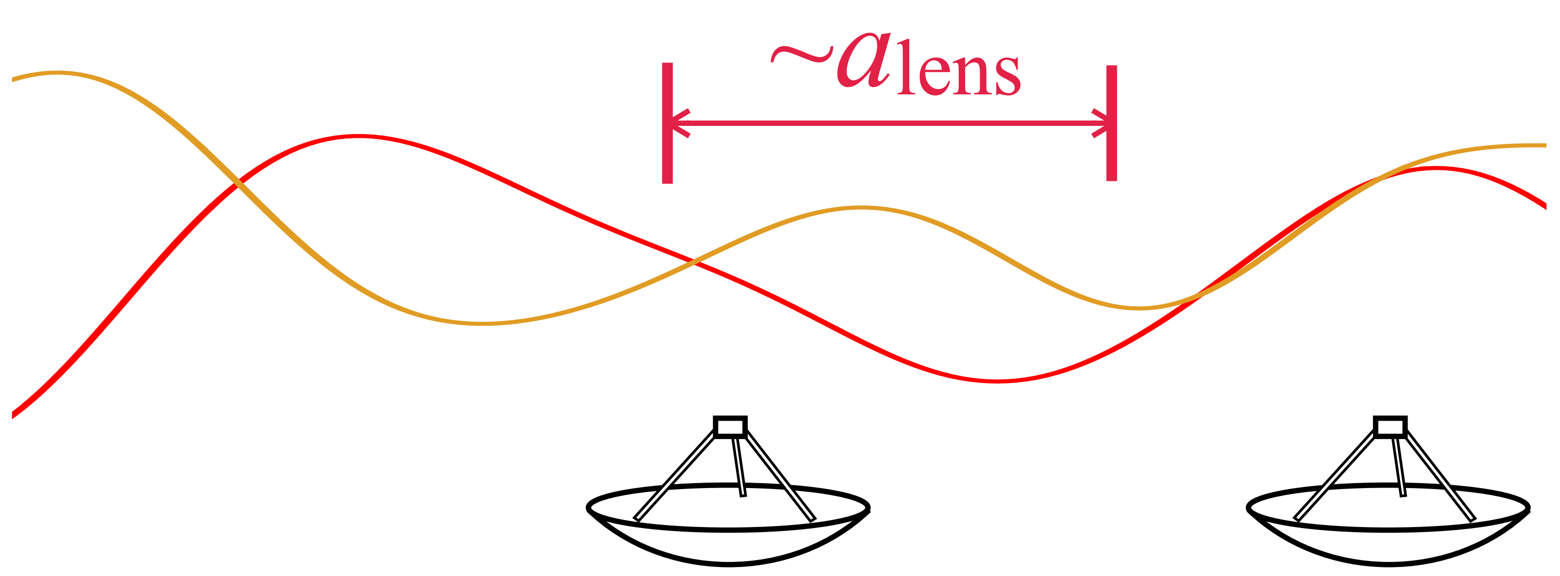

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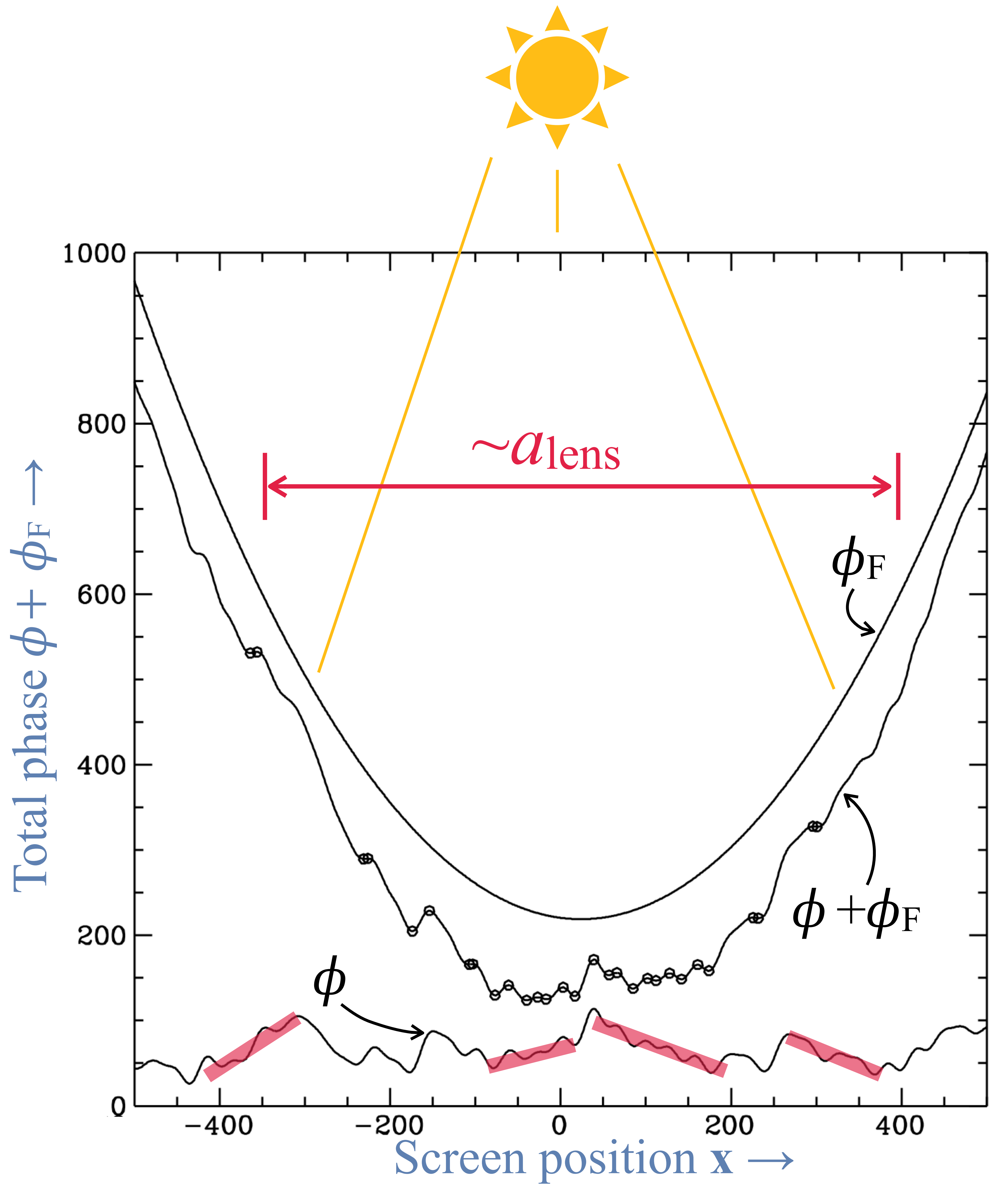

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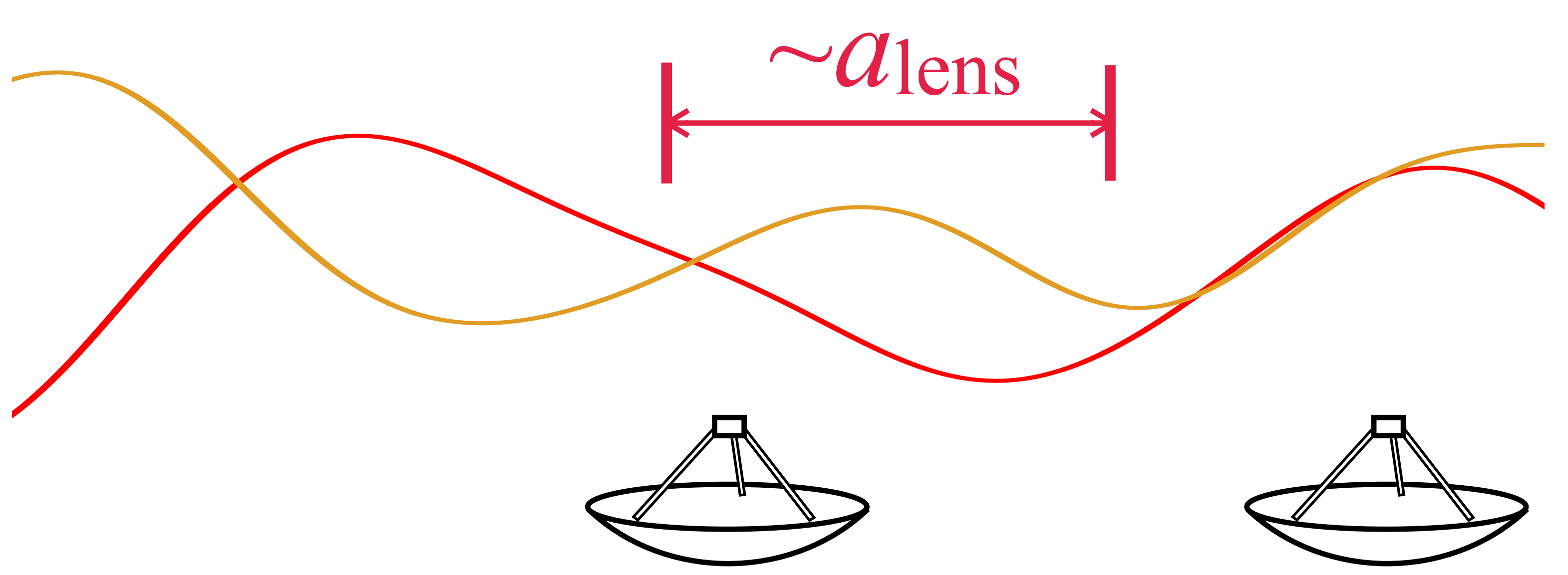

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Random images of size $\sim a_{lens}$ cover the observer plane.
Fractional bandwidth of images=$(\Delta\nu/\nu_{Obs}) \approx 100\%$

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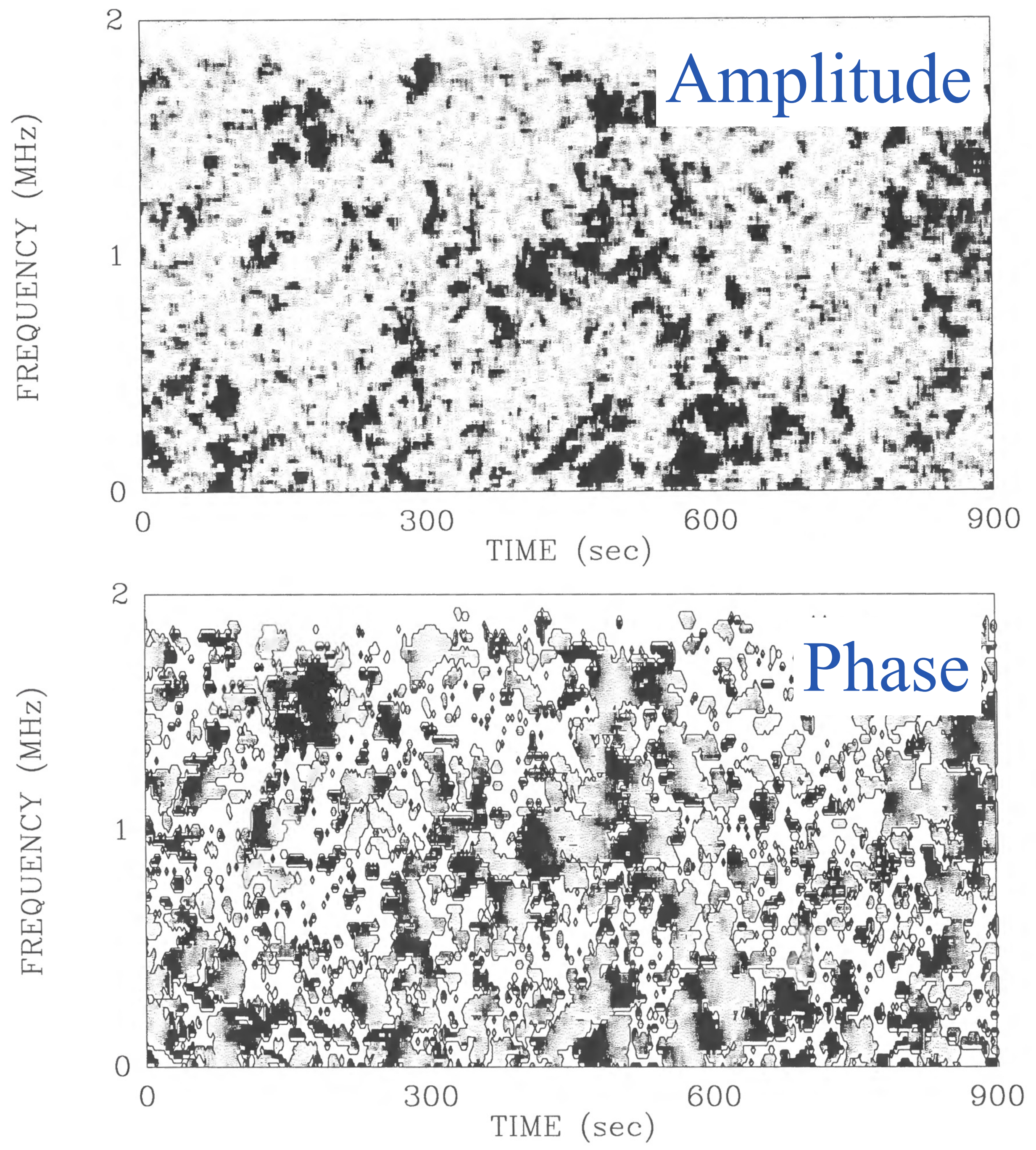

Vela Pulsar: Visibility on Tid-VSOP Baseline

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Space VLBI Can:
Sample more than one image ("scintle") and measure statistics of the diffraction pattern

2012 ApJ arXiv:1208.0039 Gwinn, Johnson, Reynolds, Jauncey, Tzioumis, Dougherty, Carlson, Del Rizzo, Hirabayashi, Kobayashi, Murata, Edwards, Quick, Flanagan, McCulloch
2016 ApJ arXiv:1501.04449 Gwinn, Popov, Bartel, Andrianov, Johnson, Joshi, Kardashev, Karuppusamy, Kovalev, Kramer, Rudnitskii, Safutdinov, Shishov, Smirnova, Soglasnov, Steinmassl, Zensus, Zhuravlev
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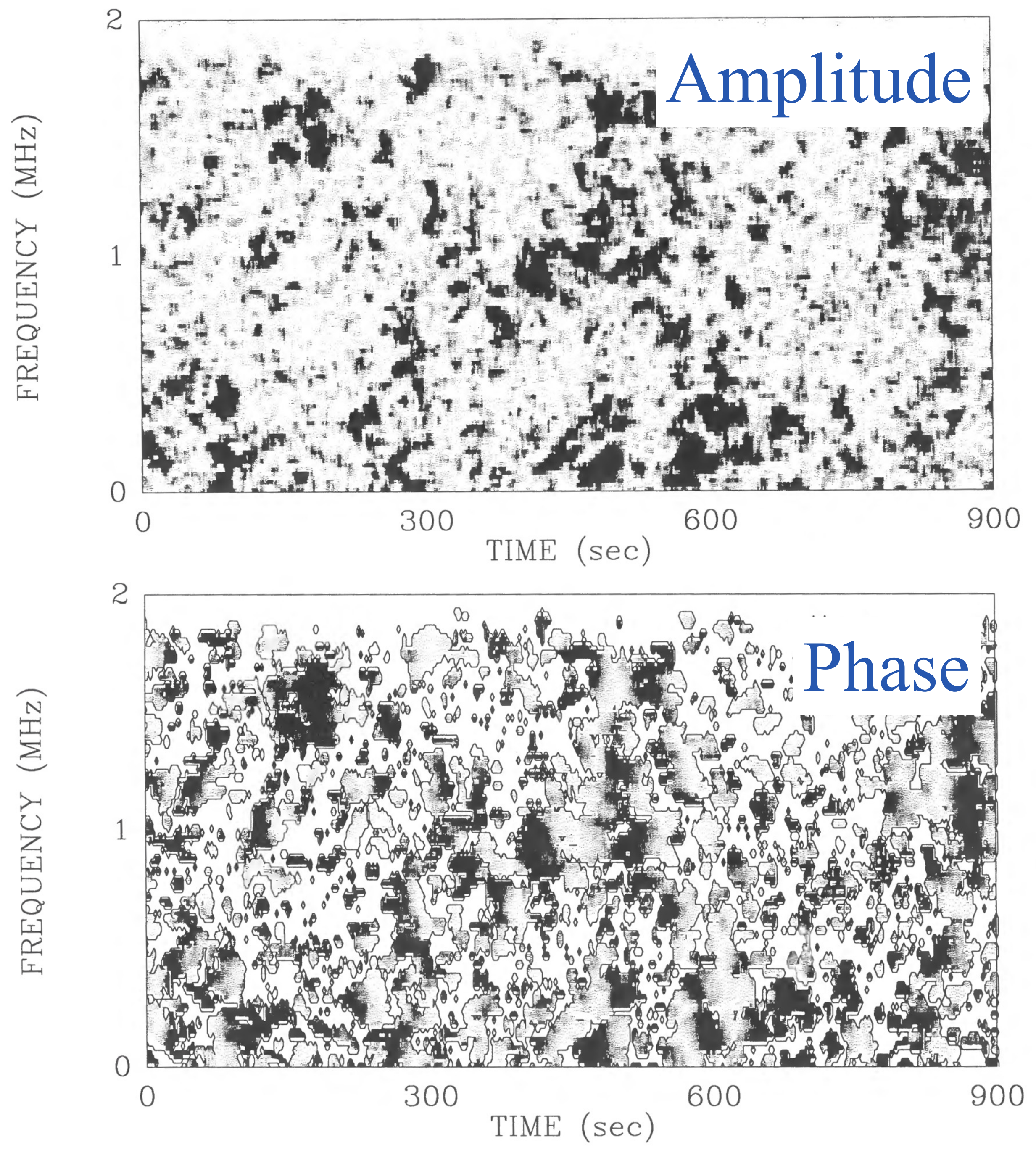

Vela Pulsar: Visibility on Tid-VSOP Baseline

Pulsars

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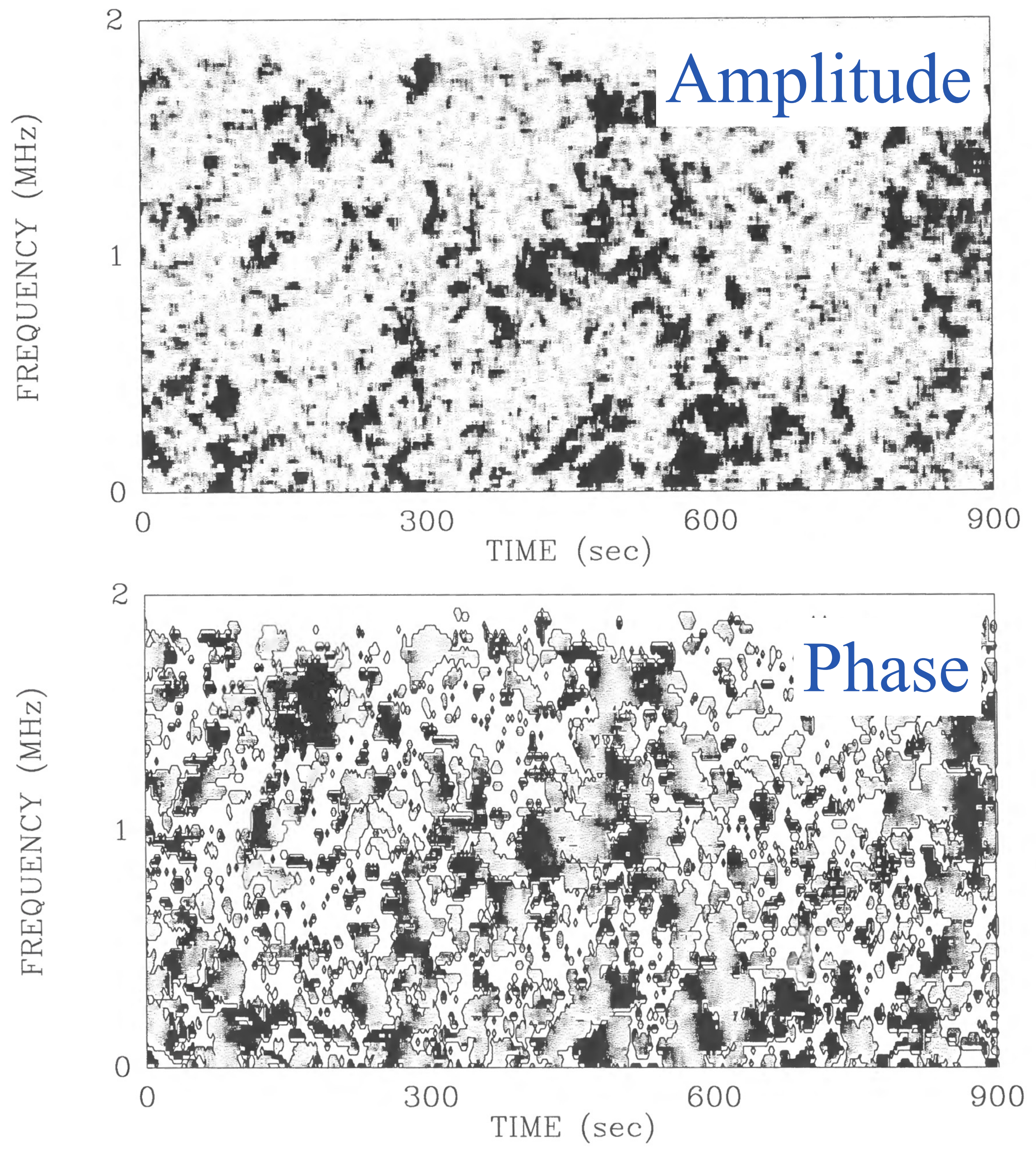

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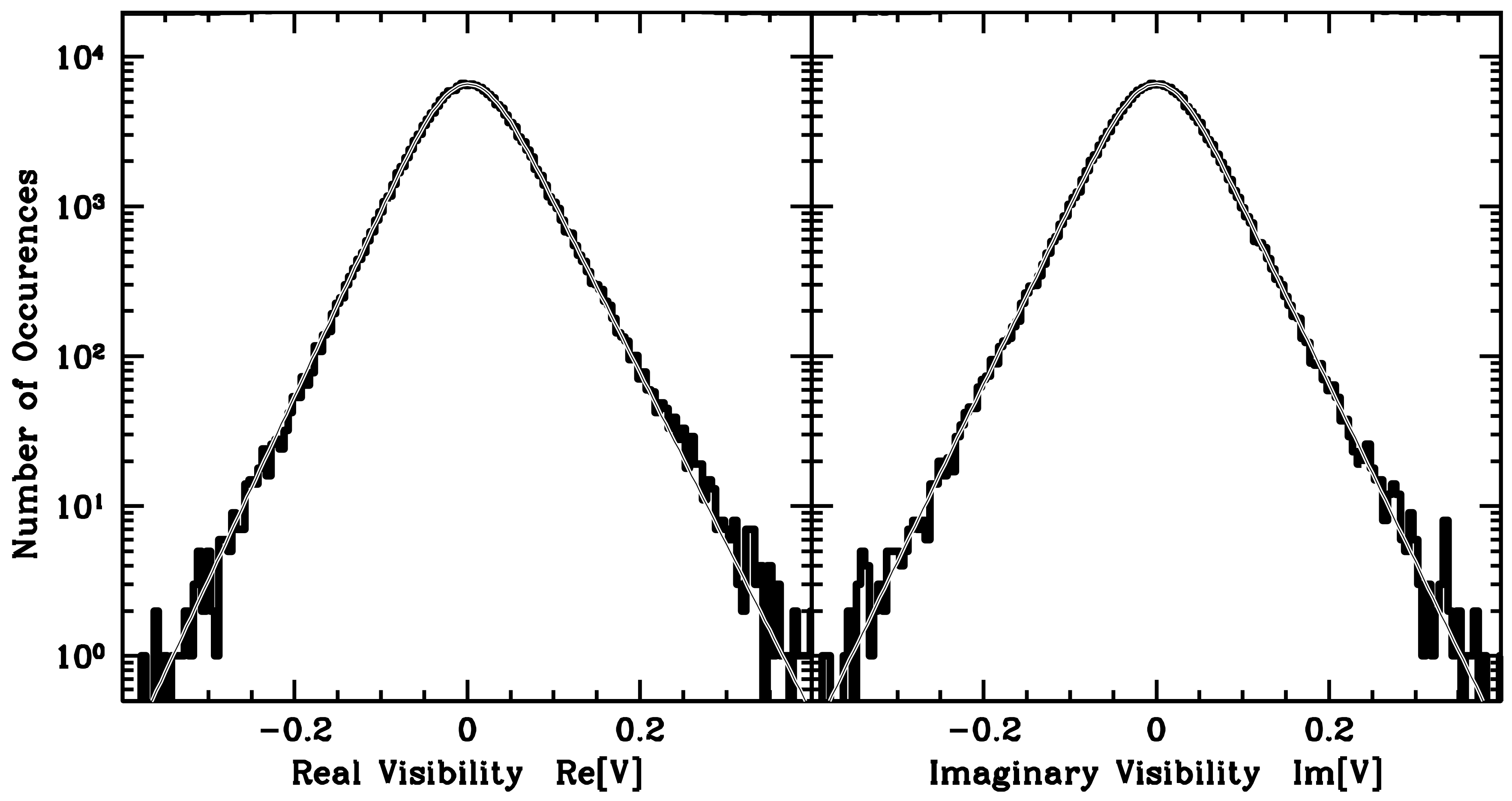

Observed distribution of visibility:
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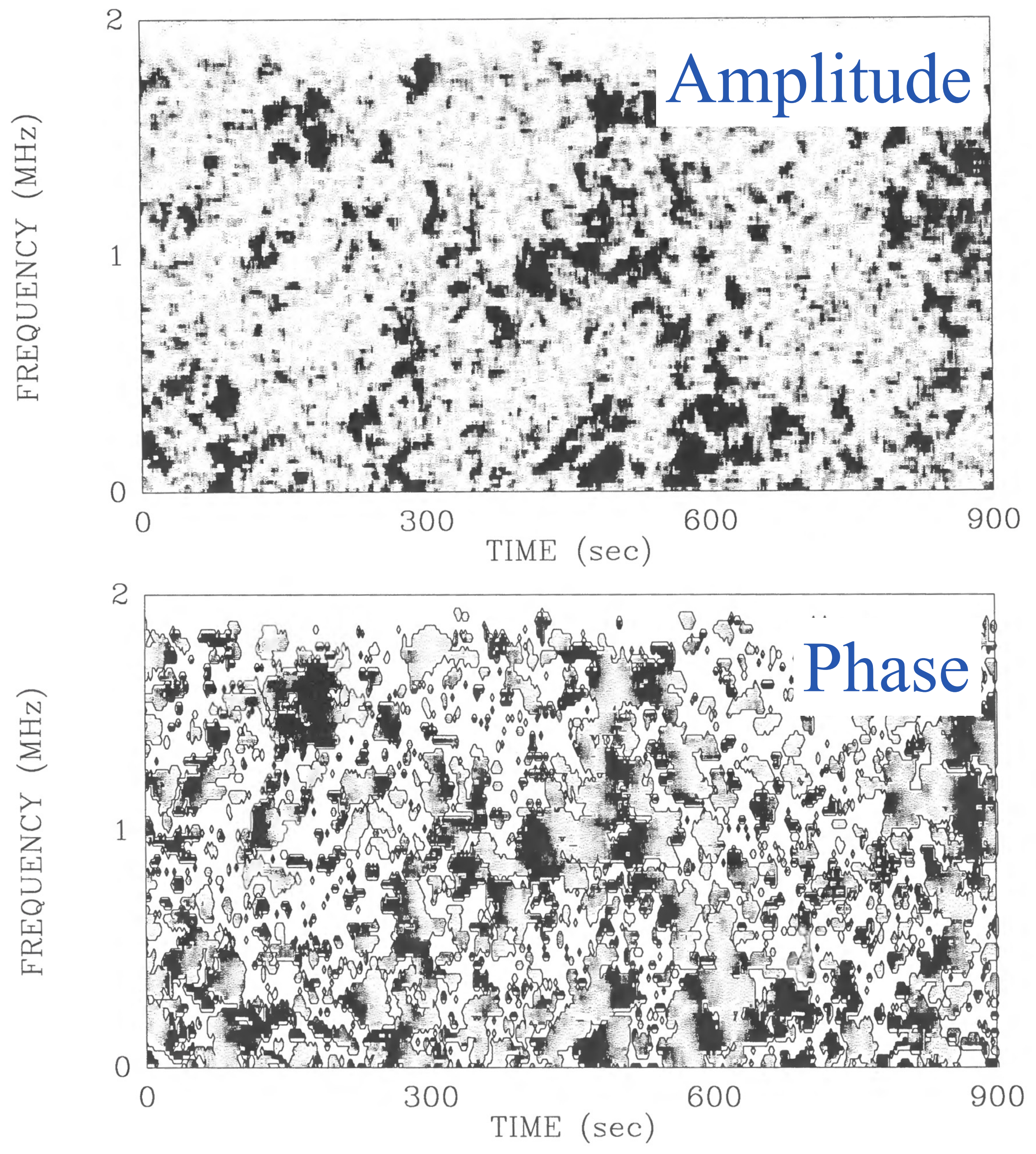

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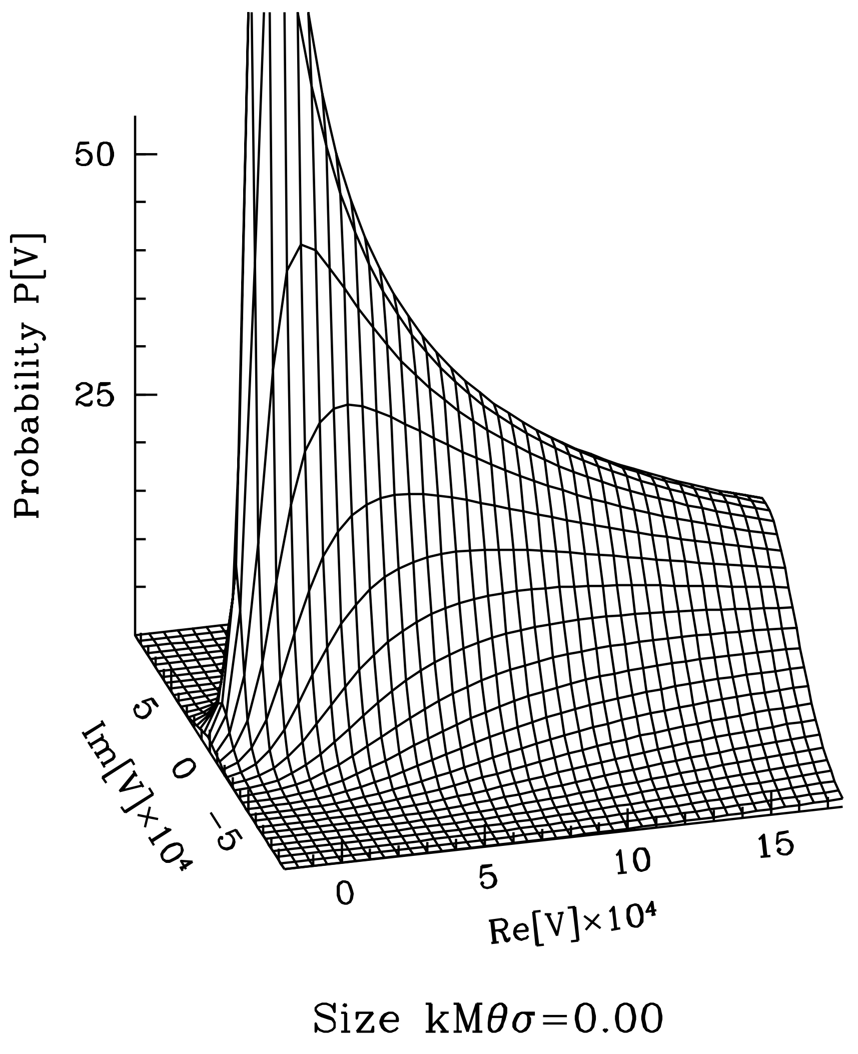
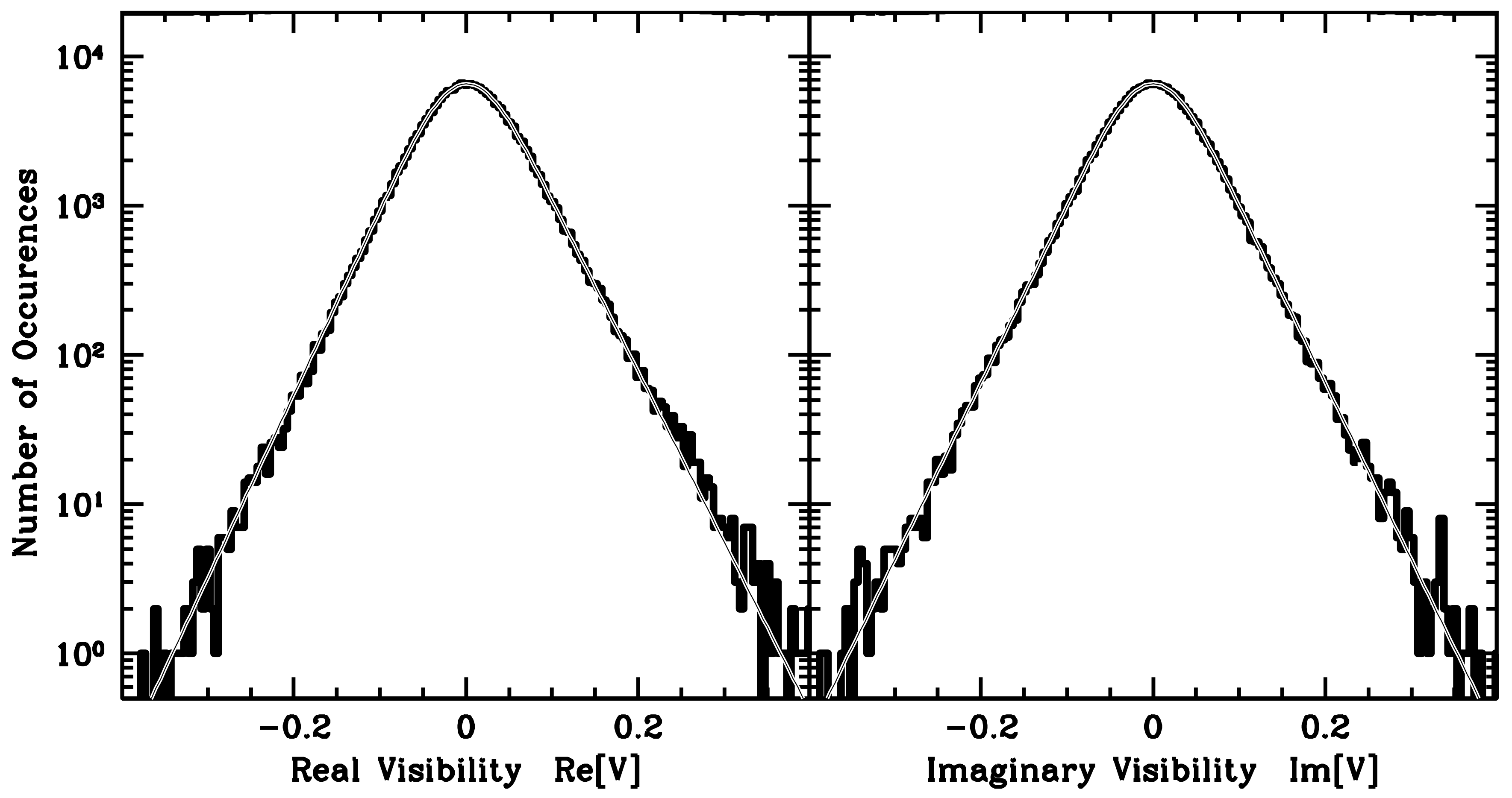


Theoretical distribution of visibility:
Medium baseline



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2016 ARep https://link.springer.com/article/10.1134/S1063772916090067 Popov, Andrianov, Bartel, Gwinn, Joshi, Jauncey, Kardashev, Rudnitskii, Smirnova, Soglasnov, Fadeev, Shishov
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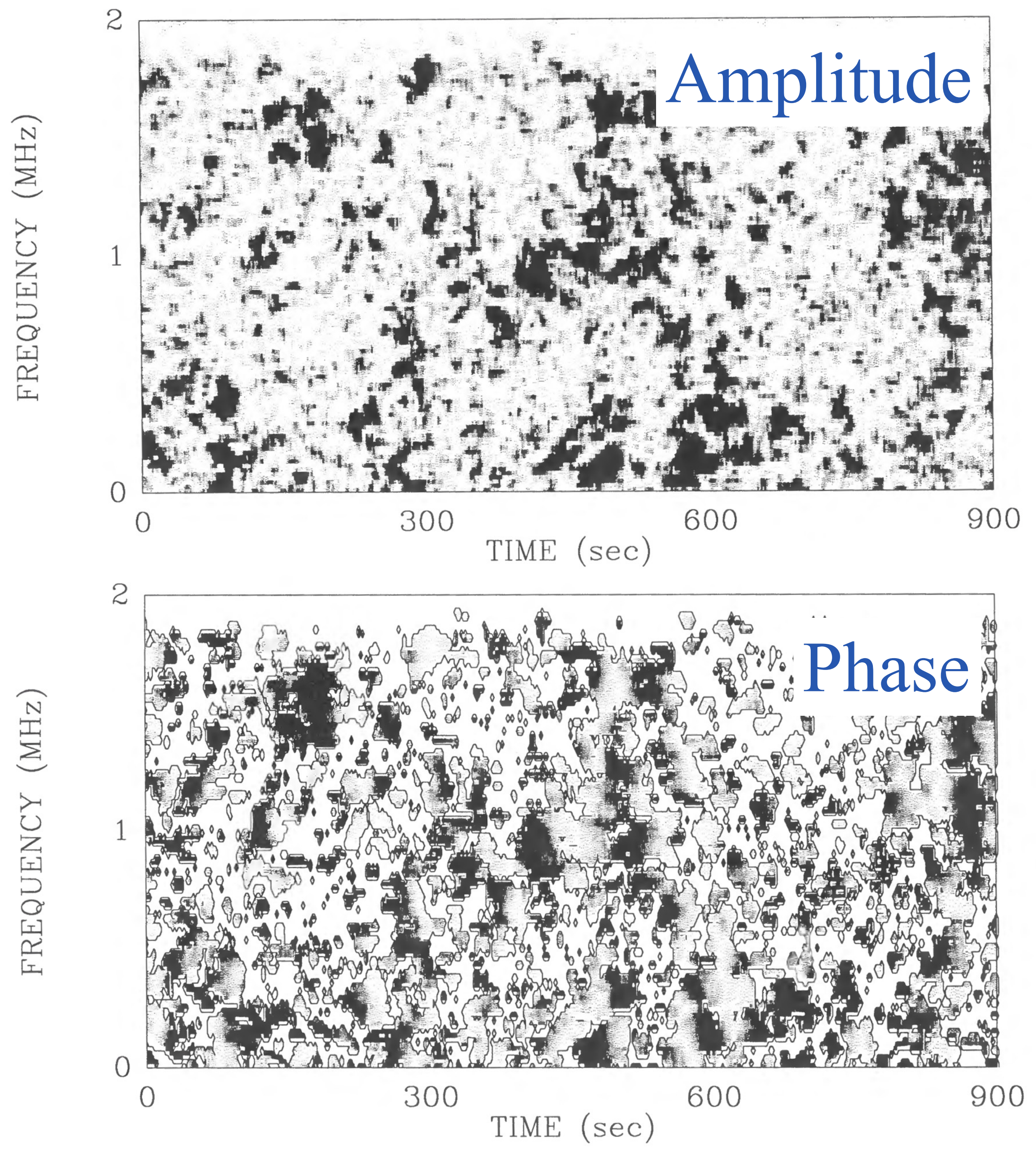

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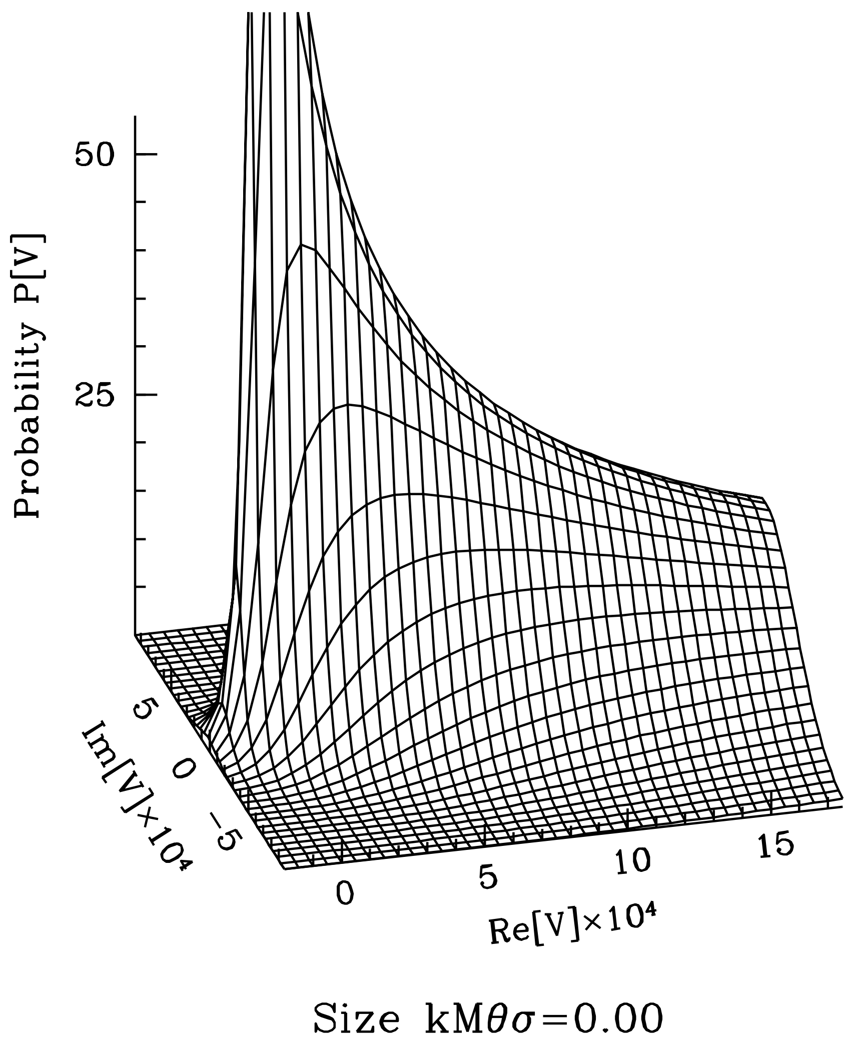

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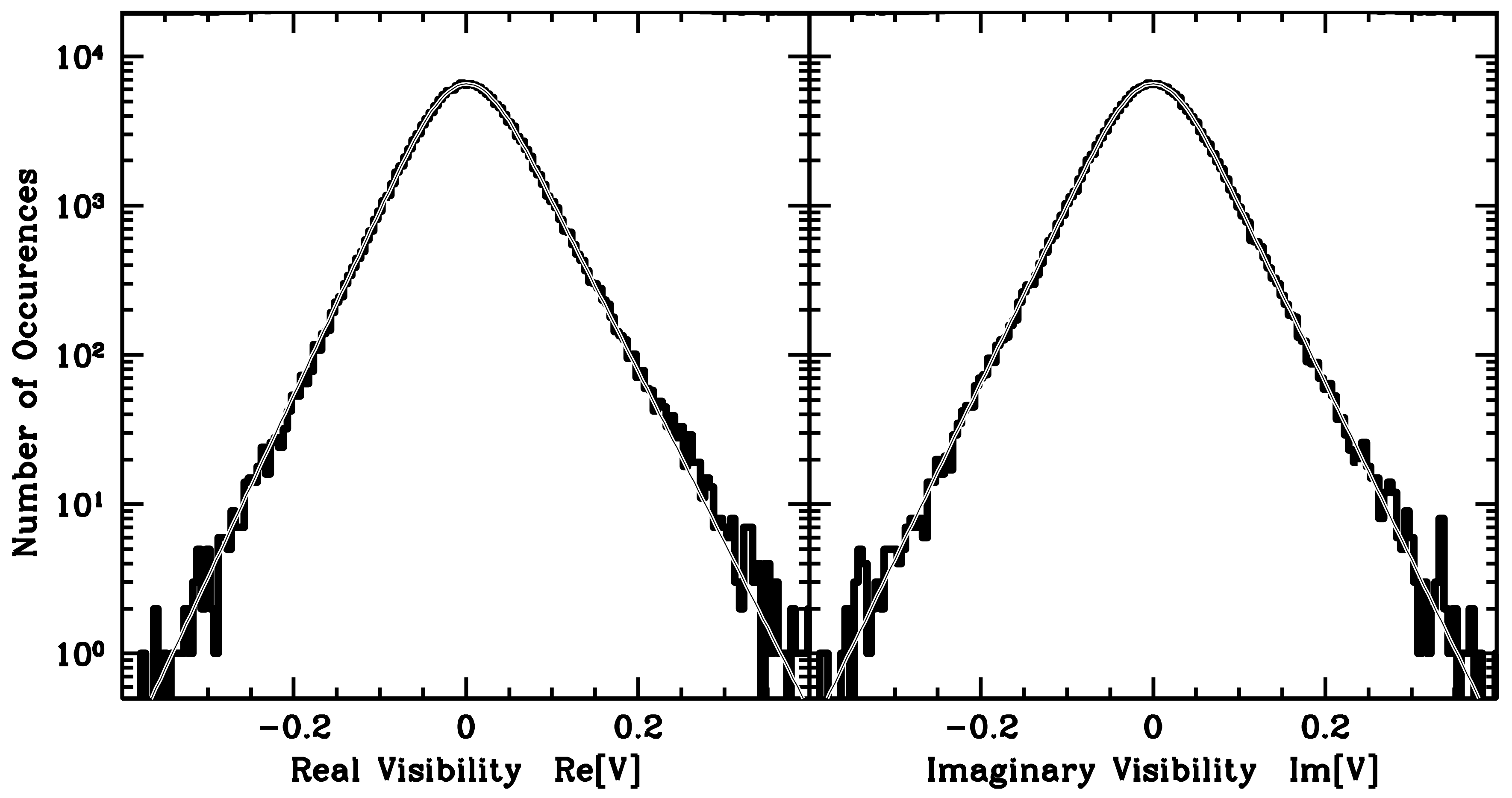

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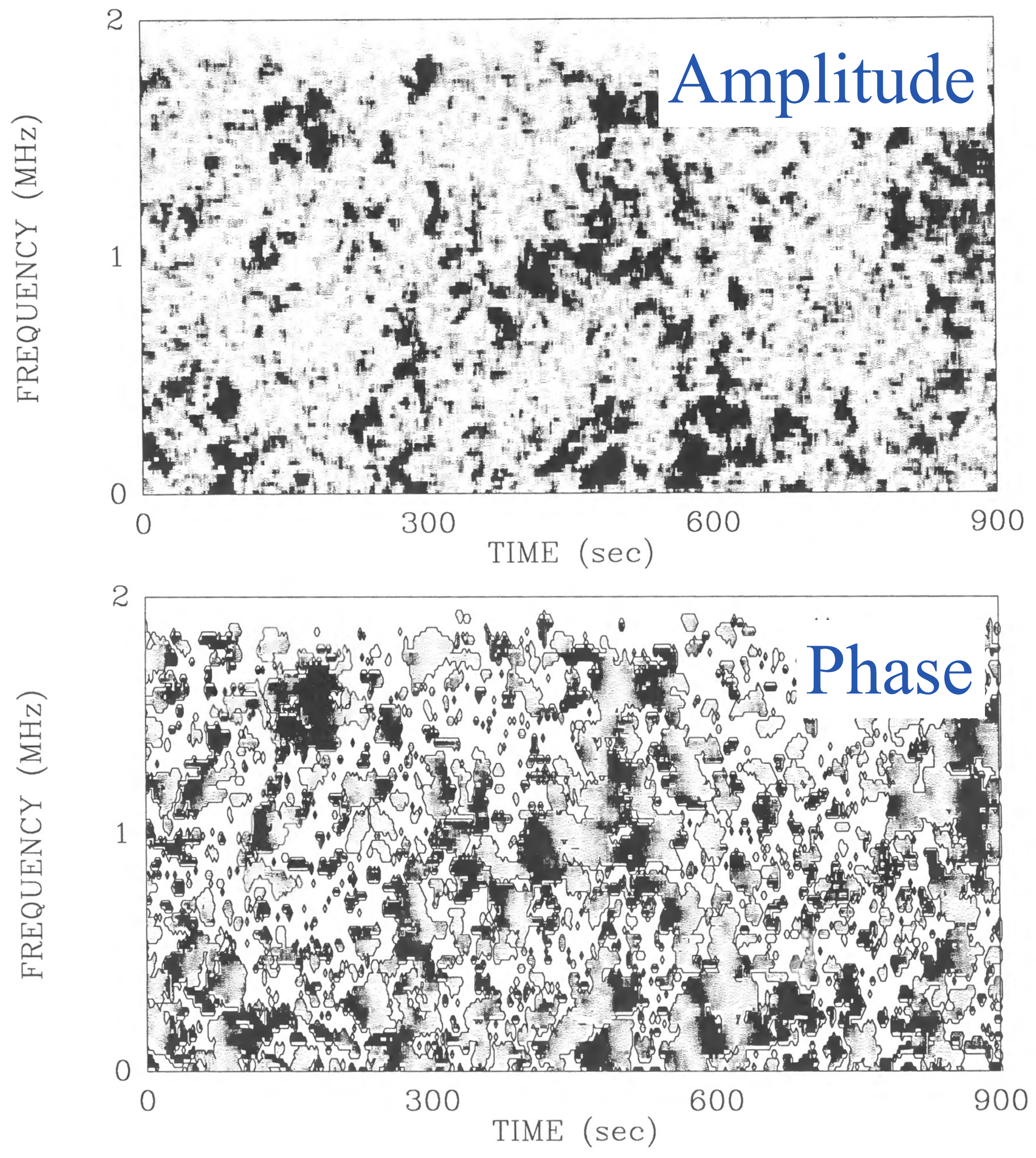

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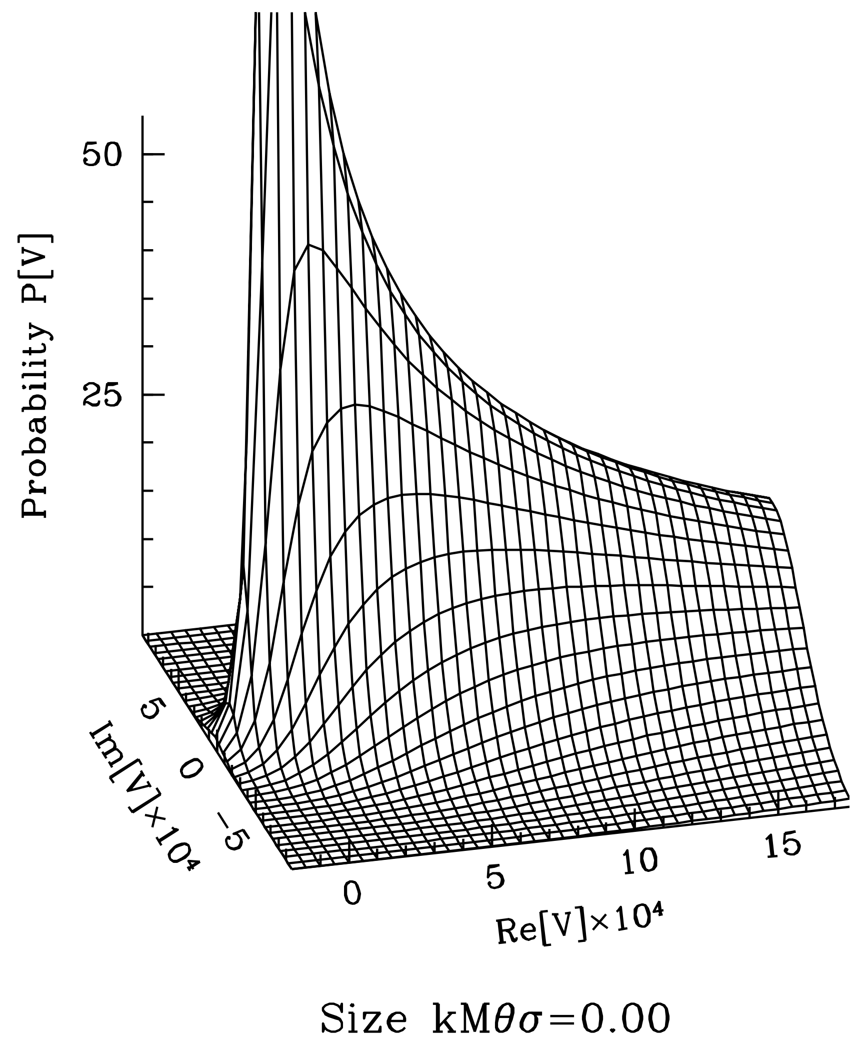

Theoretical distribution of visibility:
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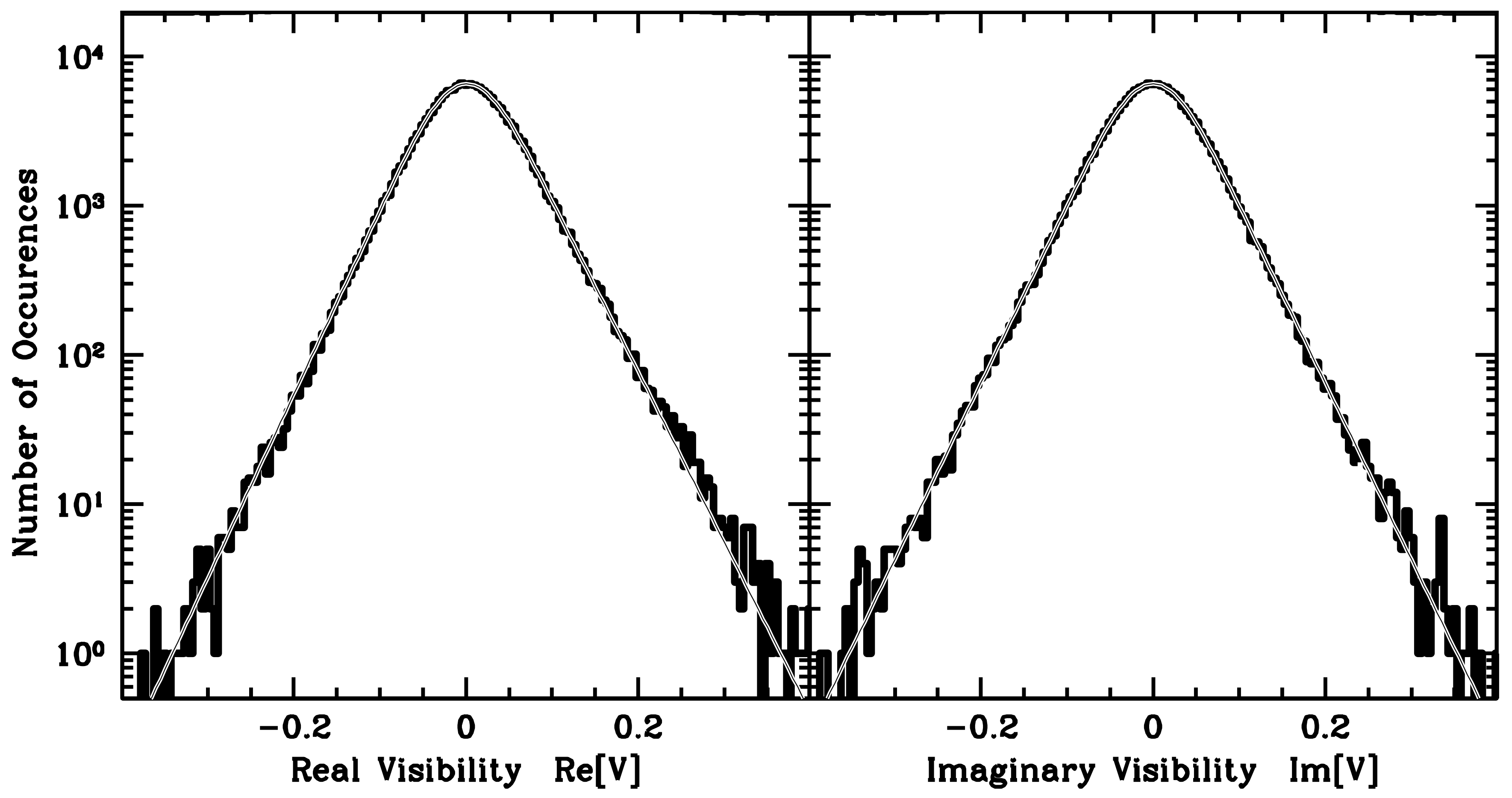

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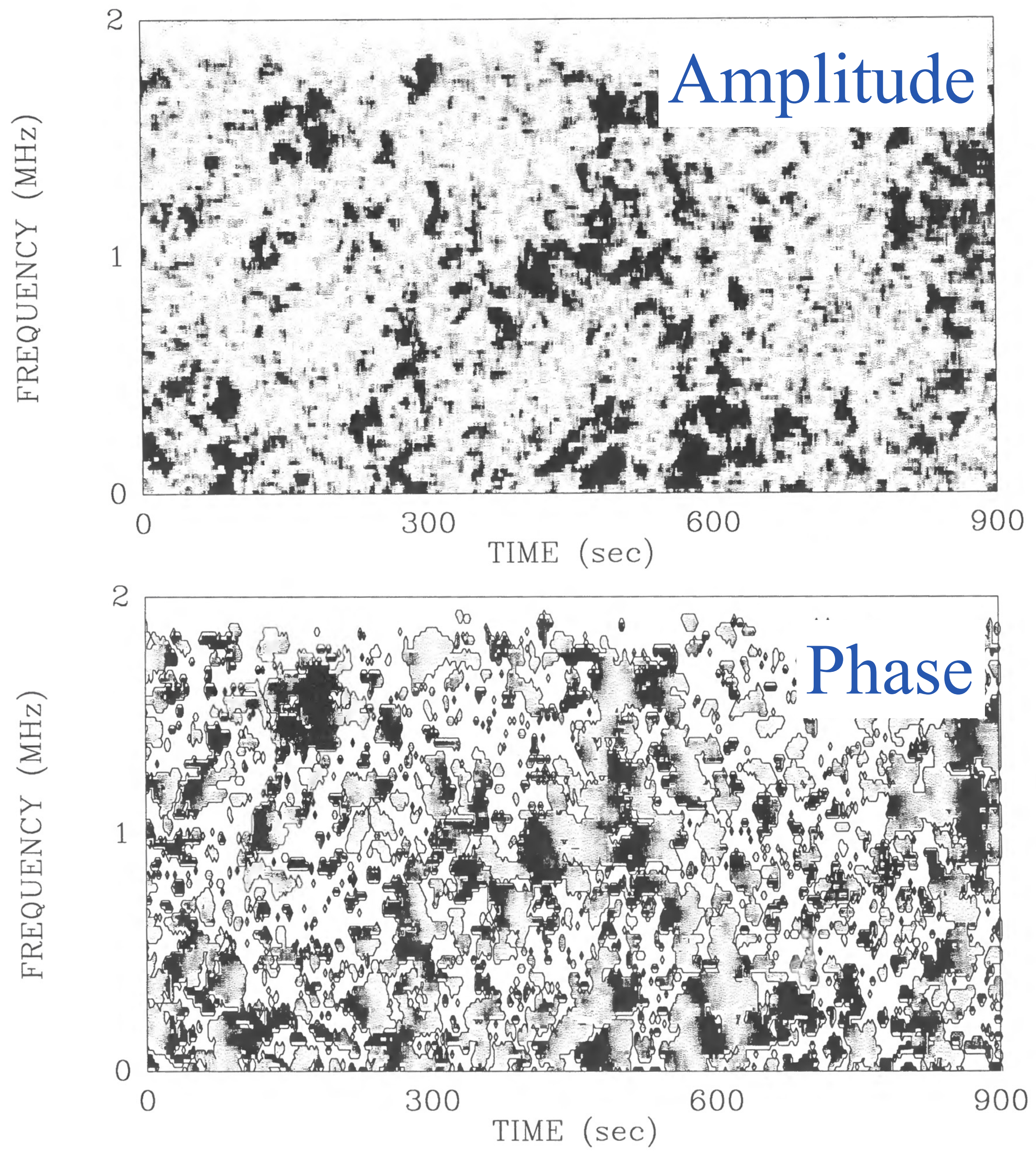
Estimate or set upper limits on size of pulsar emission region—role of space baselines?

2012 ApJ arXiv:1208.0040 Gwinn, Johnson, Reynolds, Jauncey, Tzioumis, Hirabayashi, Kobayashi, Murata, Edwards, Dougherty, Carlson, Del Rizzo, Quick, Flanagan, McCulloch



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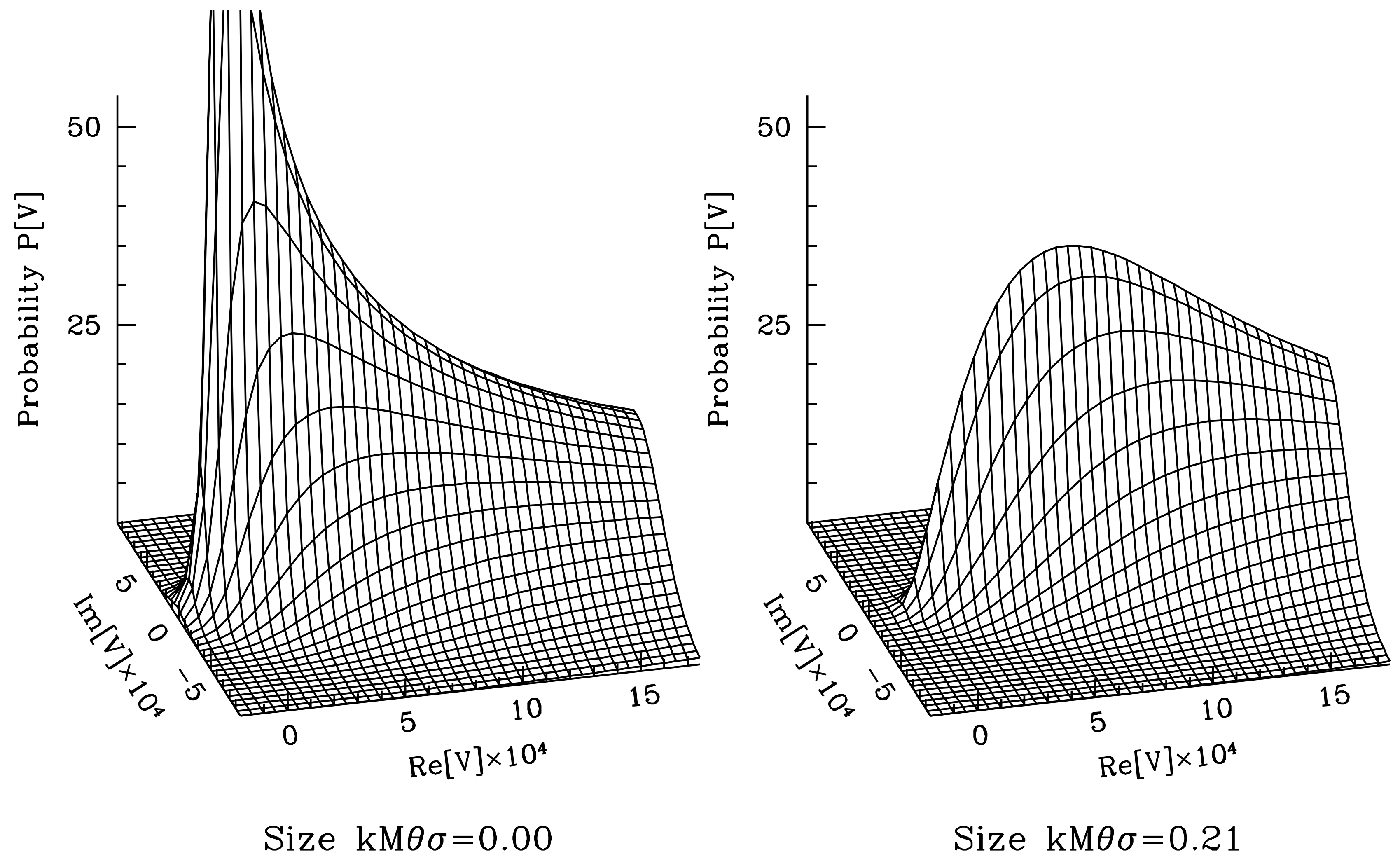
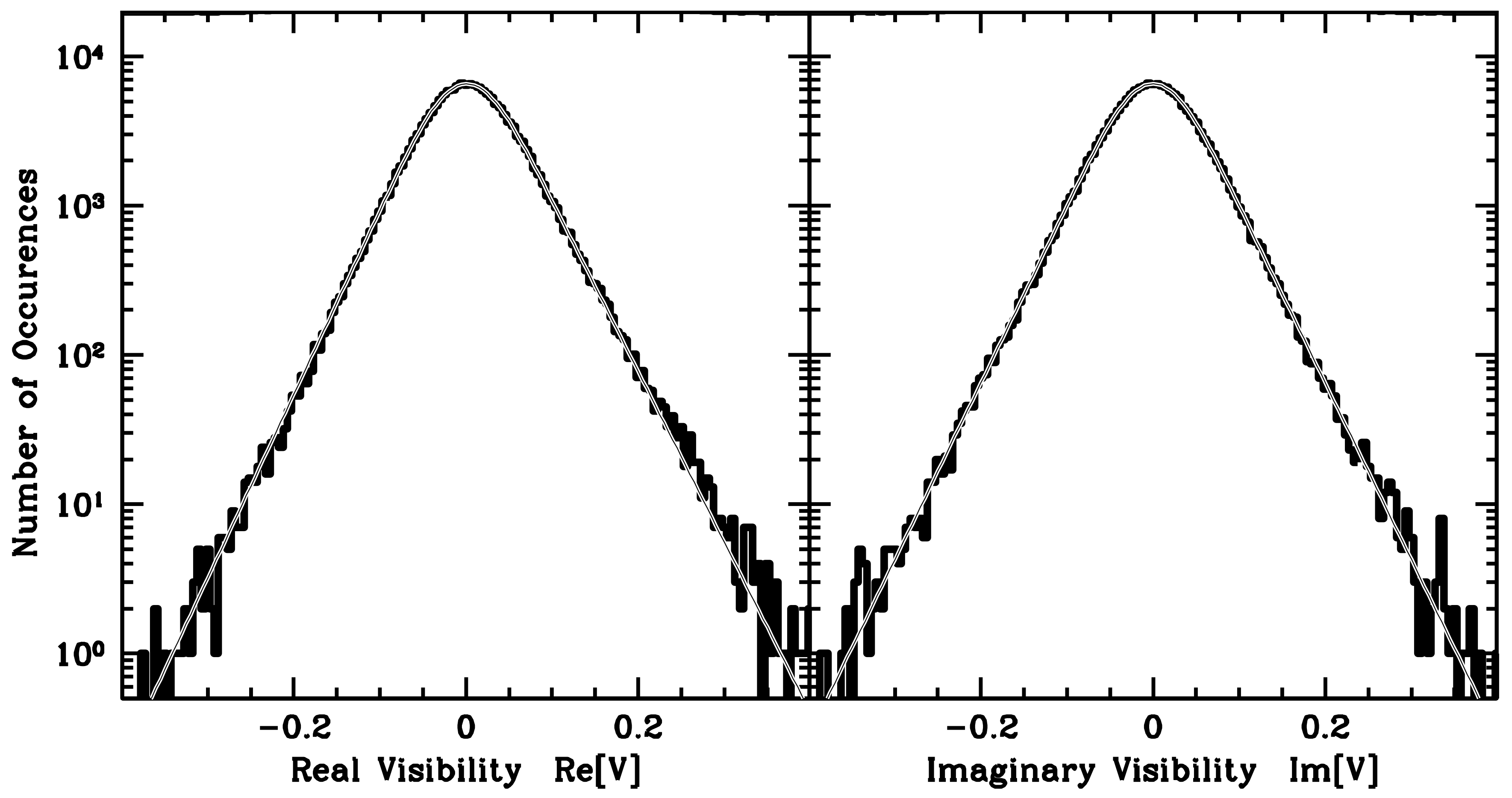


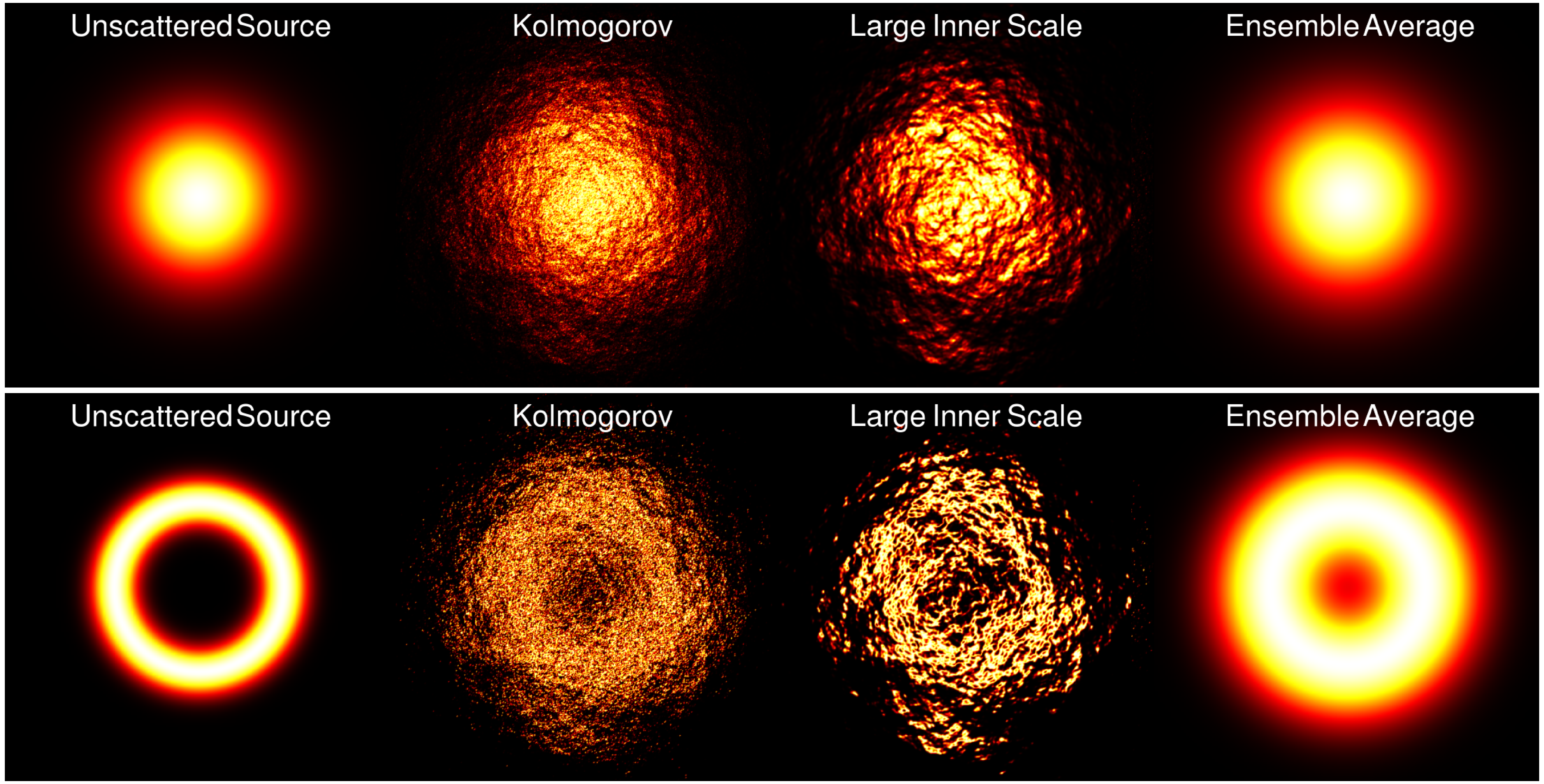
Theoretical distribution of visibility:
Medium baseline



Observed distribution of visibility:
Tidbinbilla-VSOP Baseline

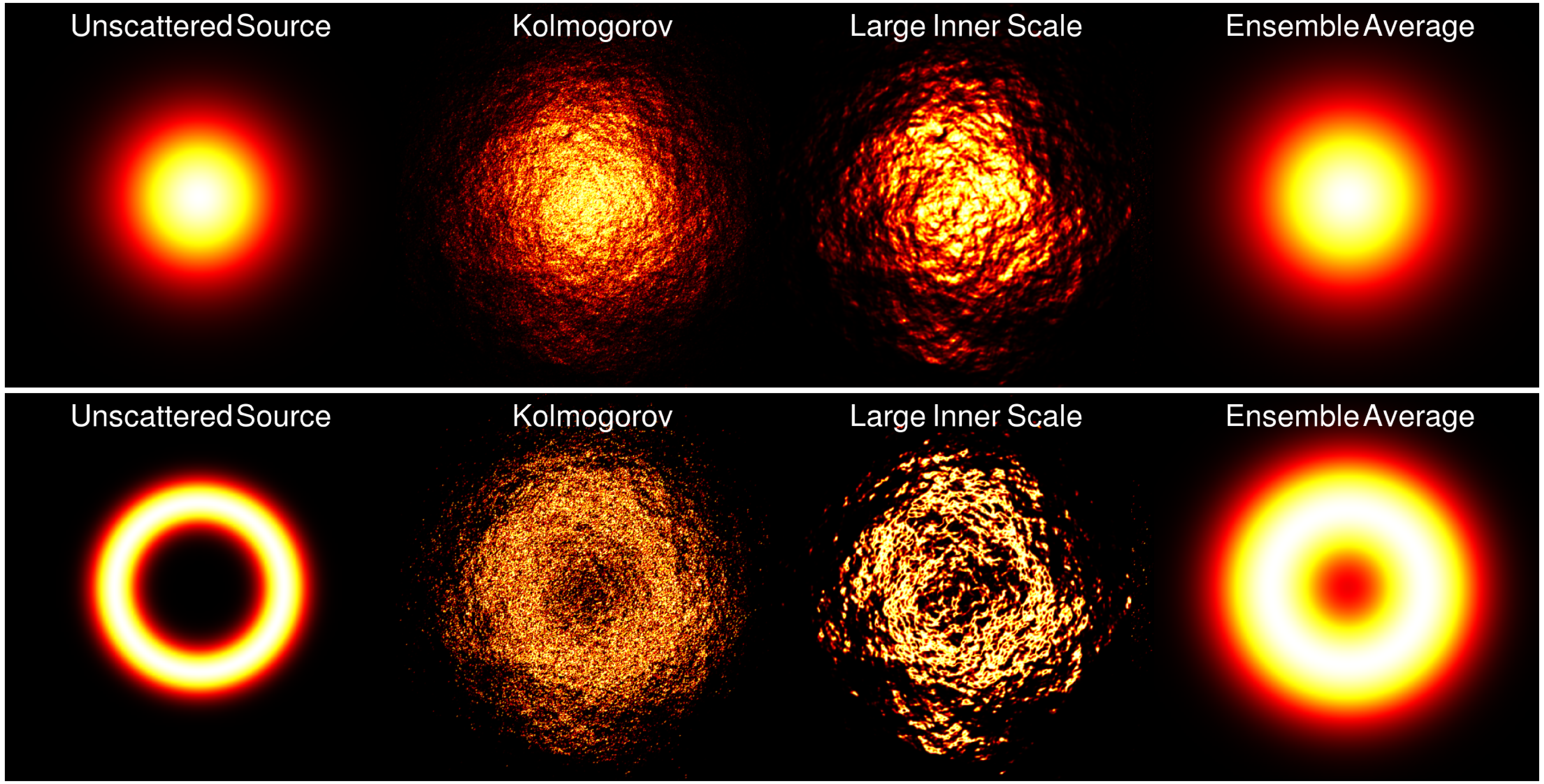

Unscattered Source
Ensemble Average
Unscattered Source
Ensemble Average

Scattering



Refractive Scattering

Refractive scattering is seen for compact sources smaller than $a_{\mathrm{lens}} \sim 1$ AU.



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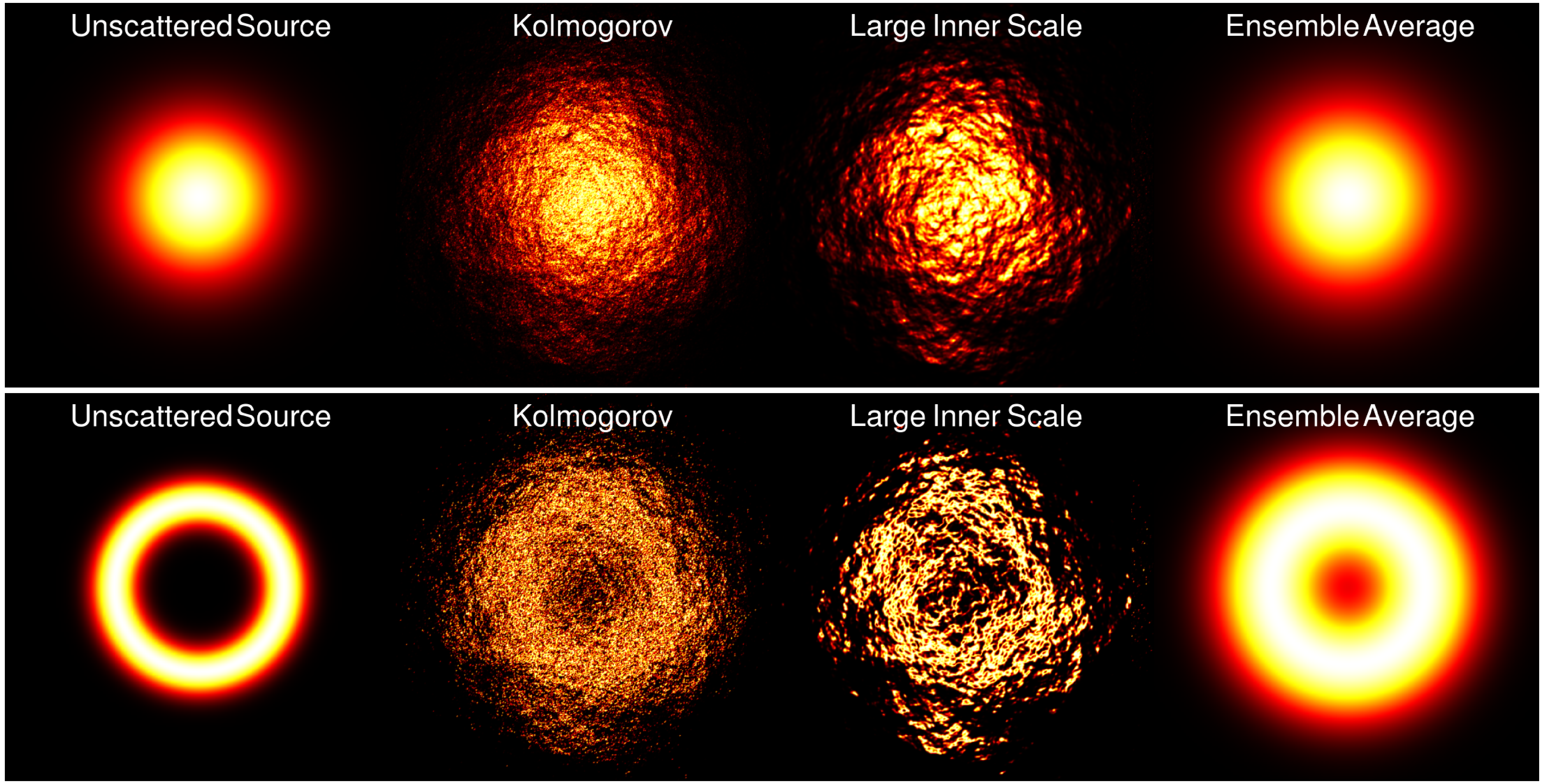

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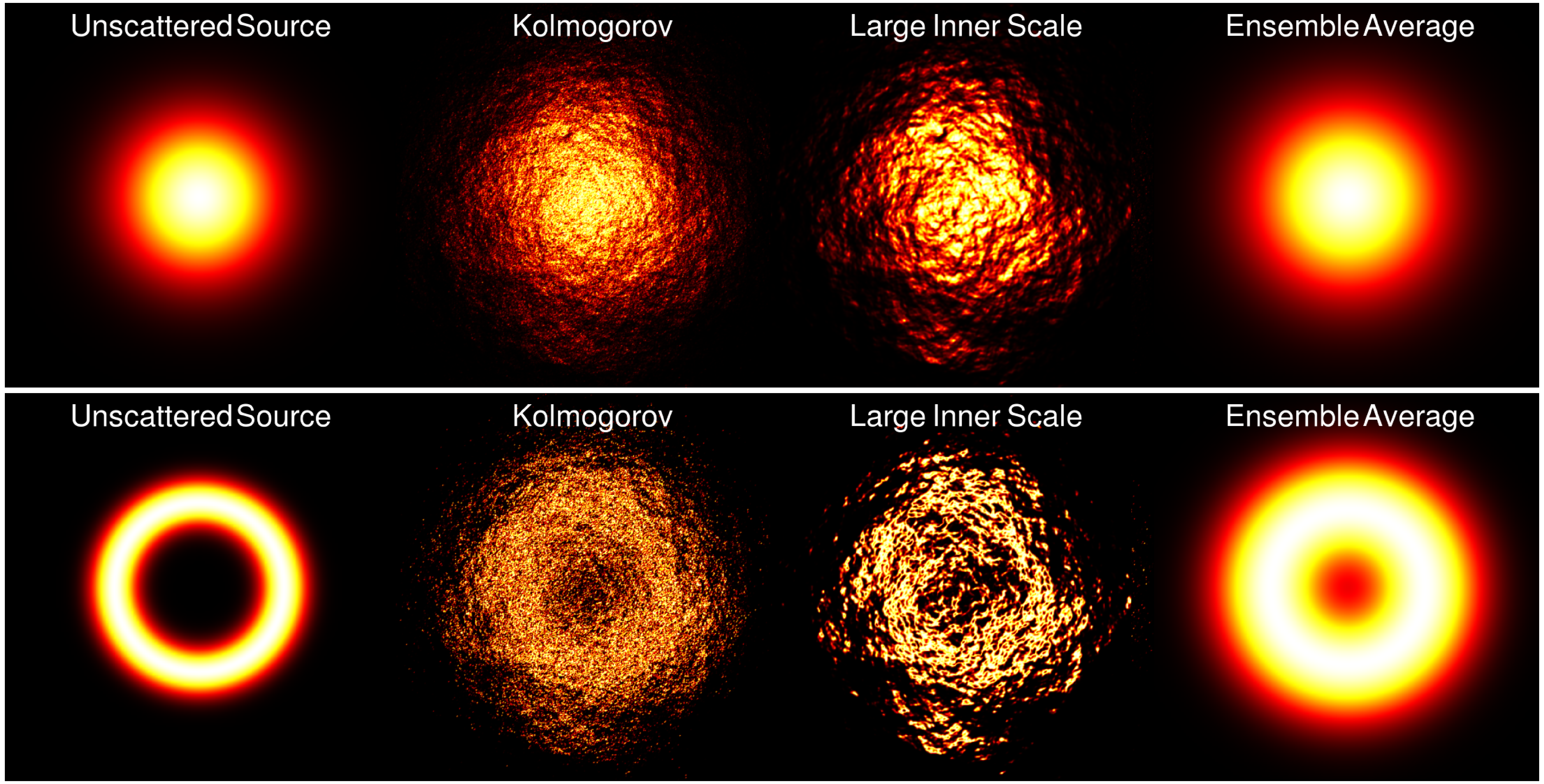

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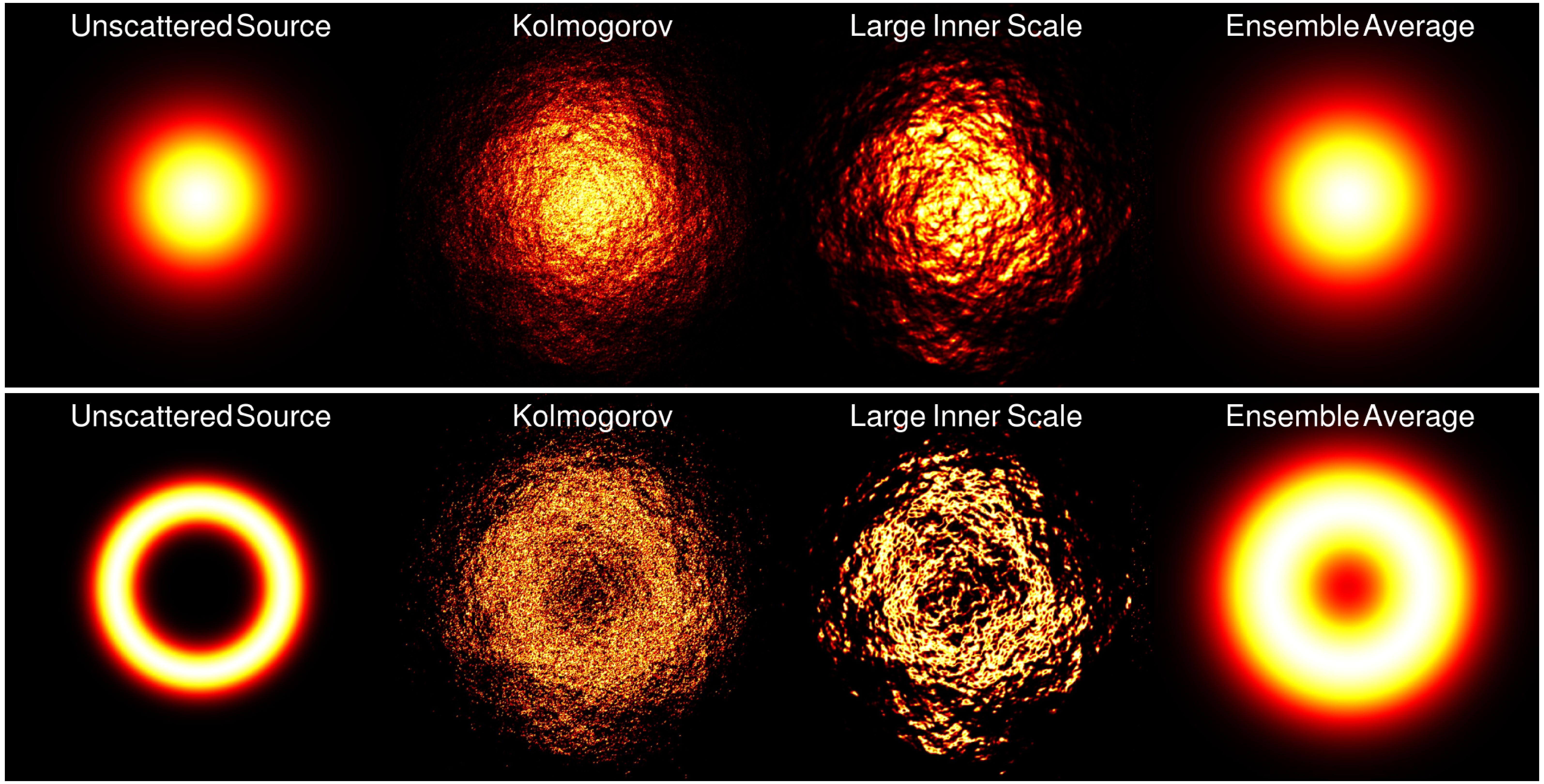

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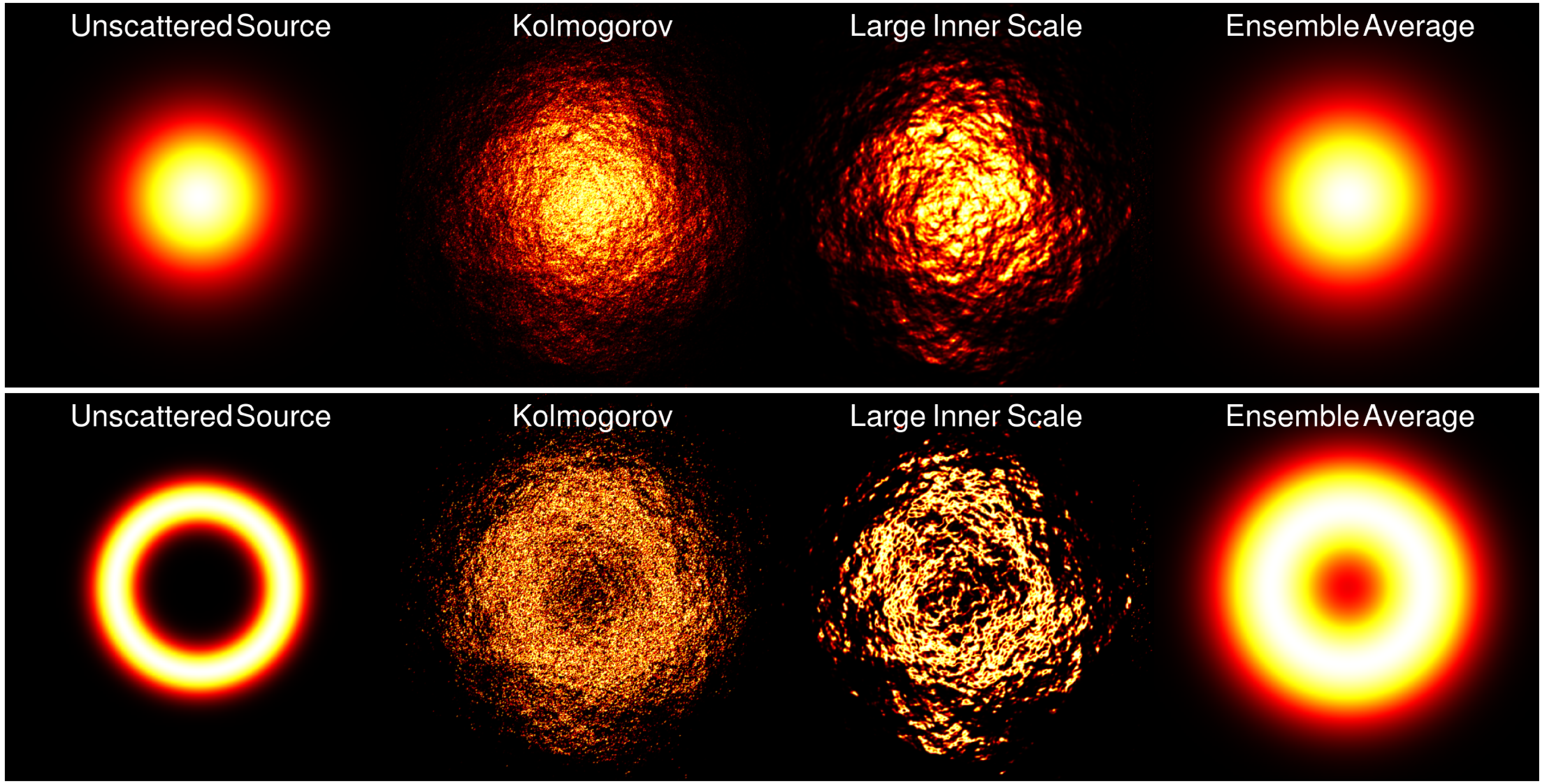
Refractive substructure changes only over times $t_{\text{Refractive}}$~weeks to months.



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The long-term average approaches the smooth "ensemble-average image."

Goodman & Narayan 1989 MNRAS https://academic.oup.com/mnras/article/238/3/995/1048426
Johnson & Gwinn 2015 ApJ arxiv:1502.05722

Refractive Substructure in the (u,v) Plane

Refractive scattering appears as noise atop the average visibility. Refractive “noise” is most apparent at long baselines, where the average image is resolved.

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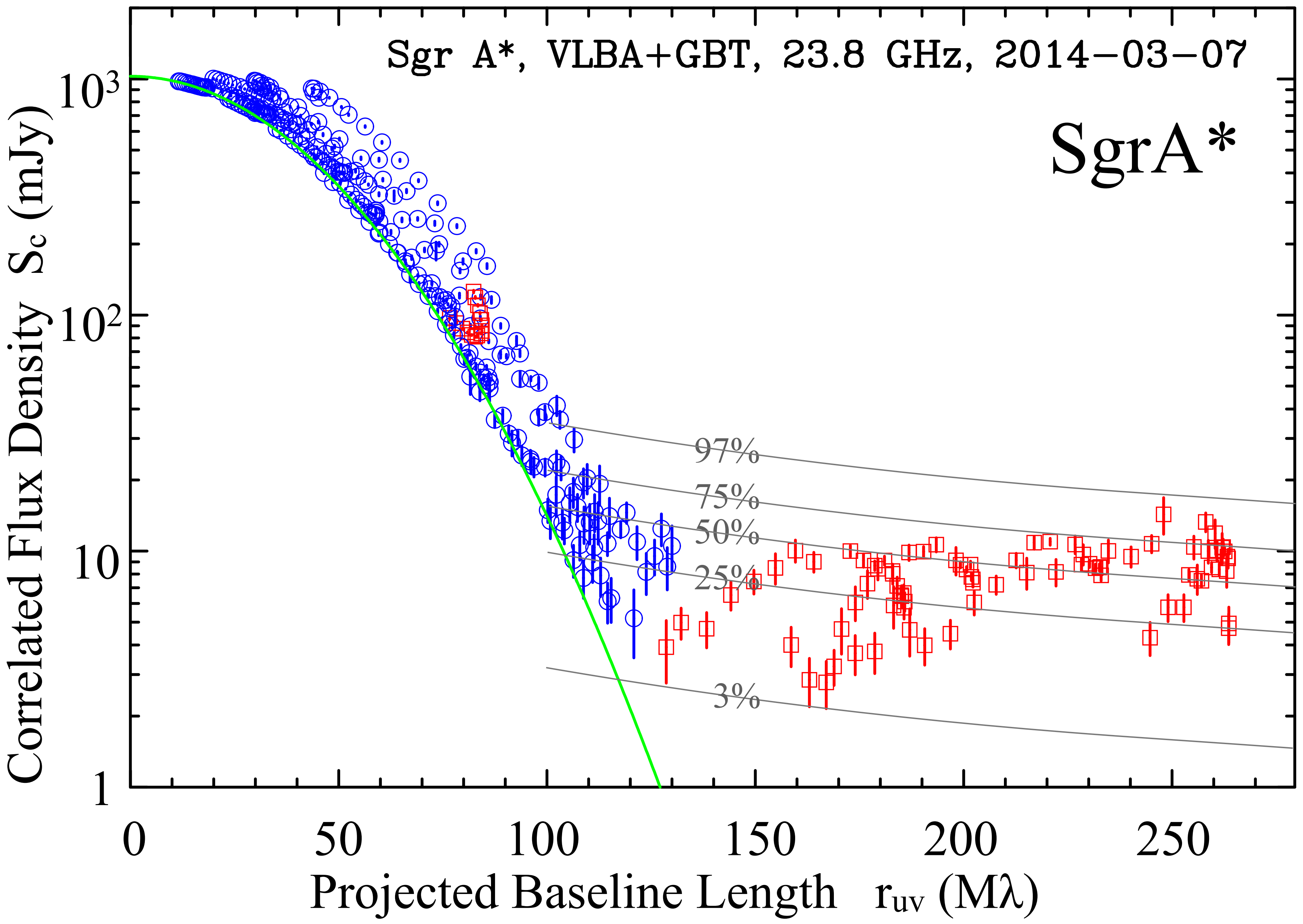

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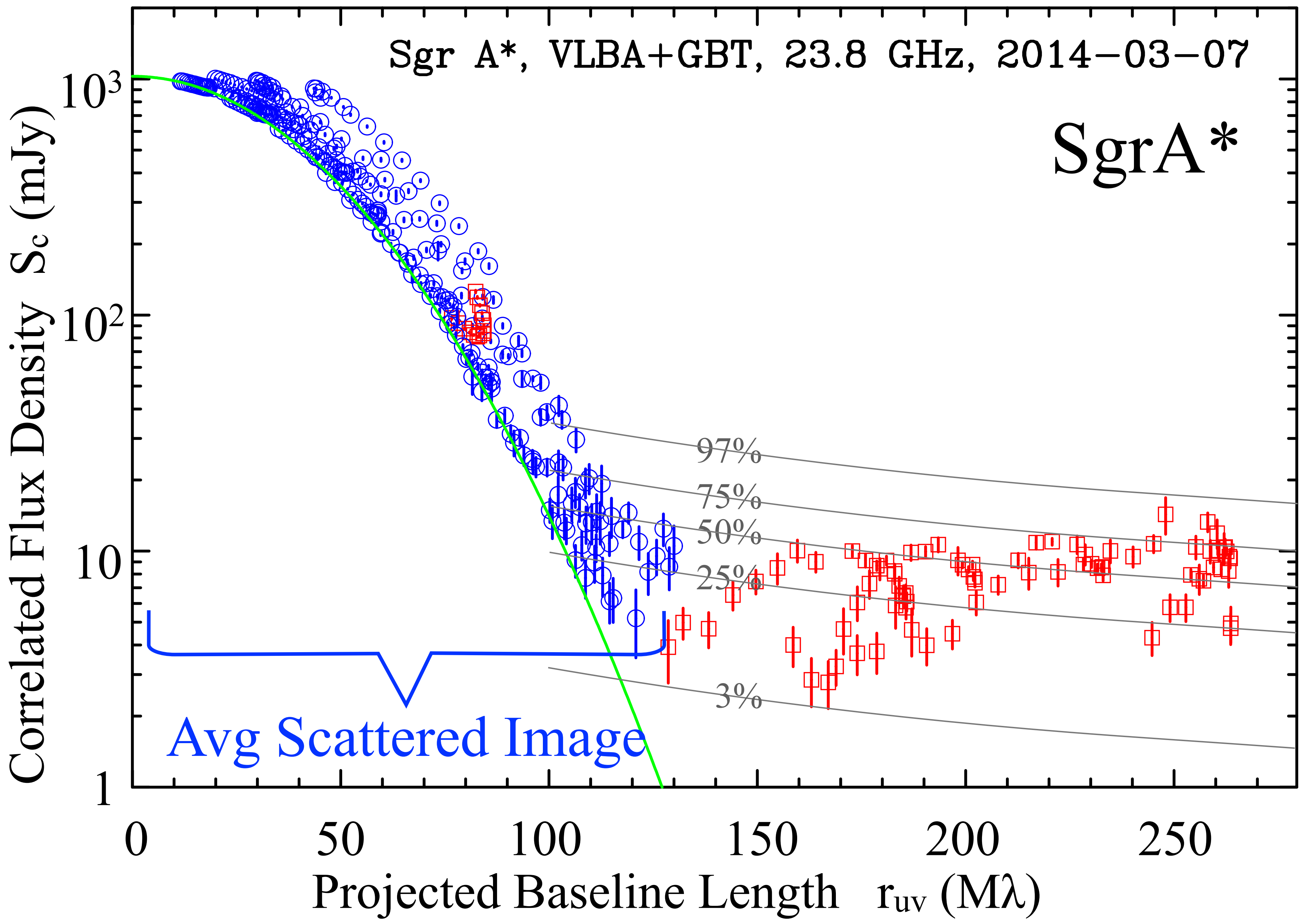

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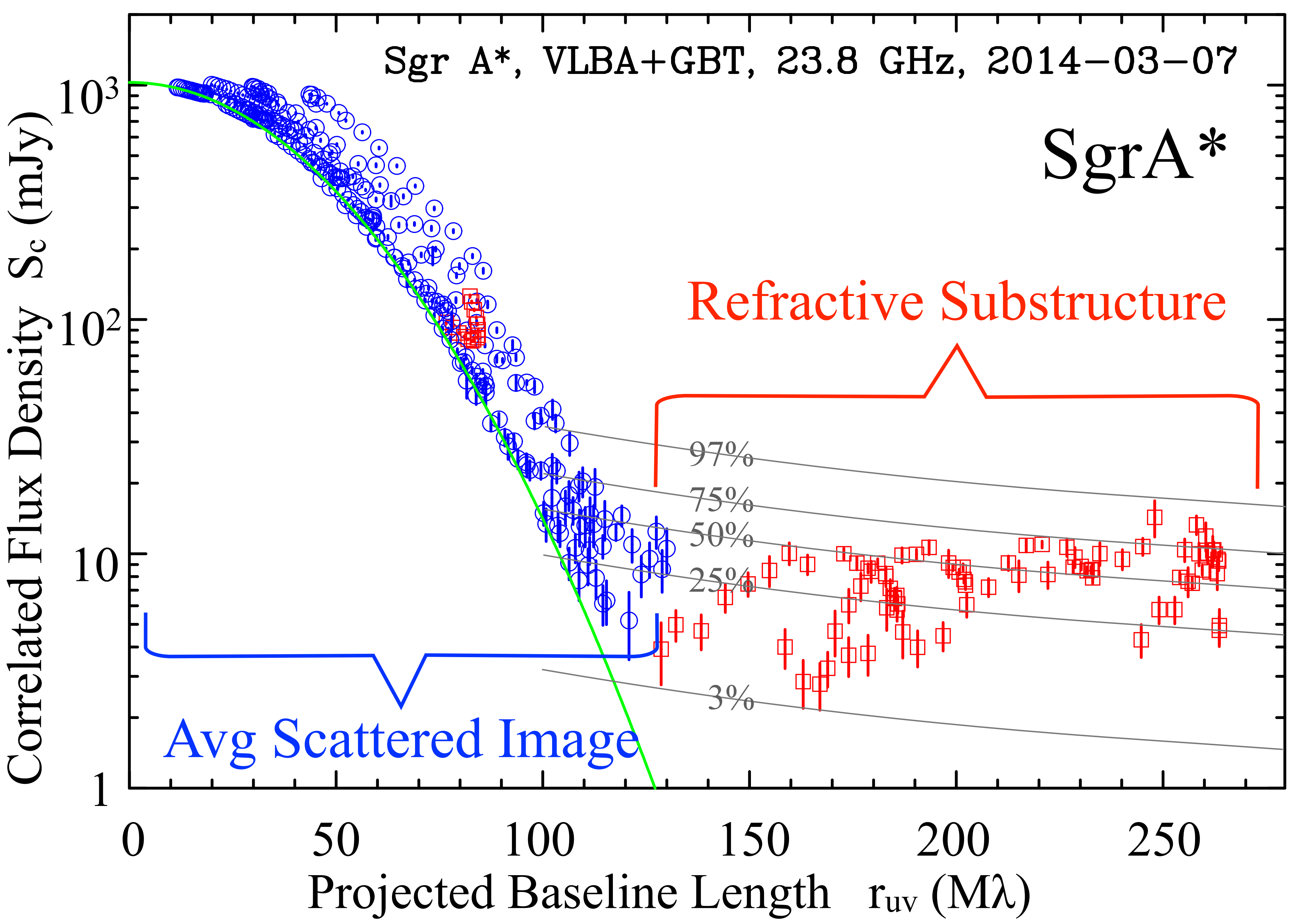

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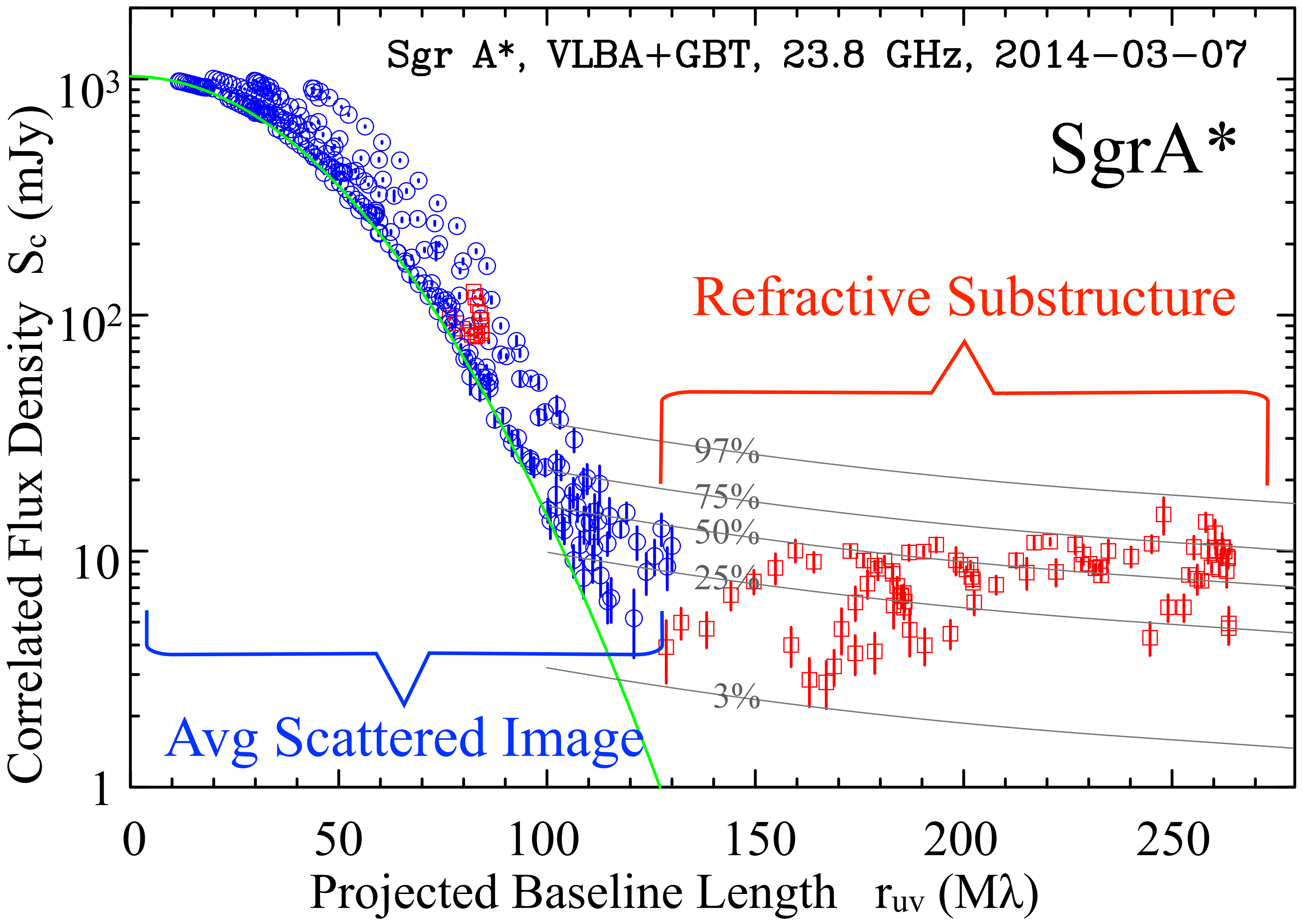

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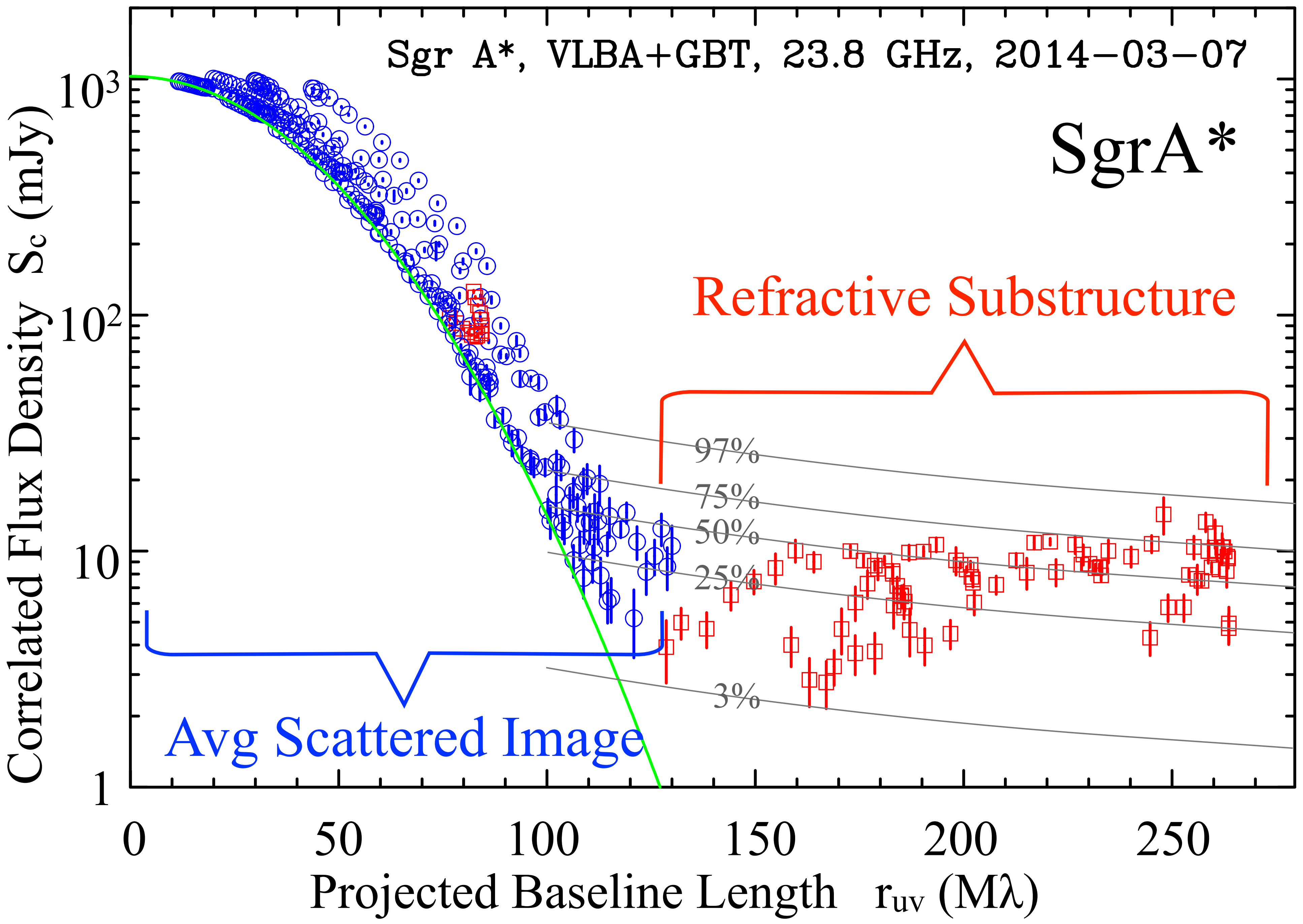

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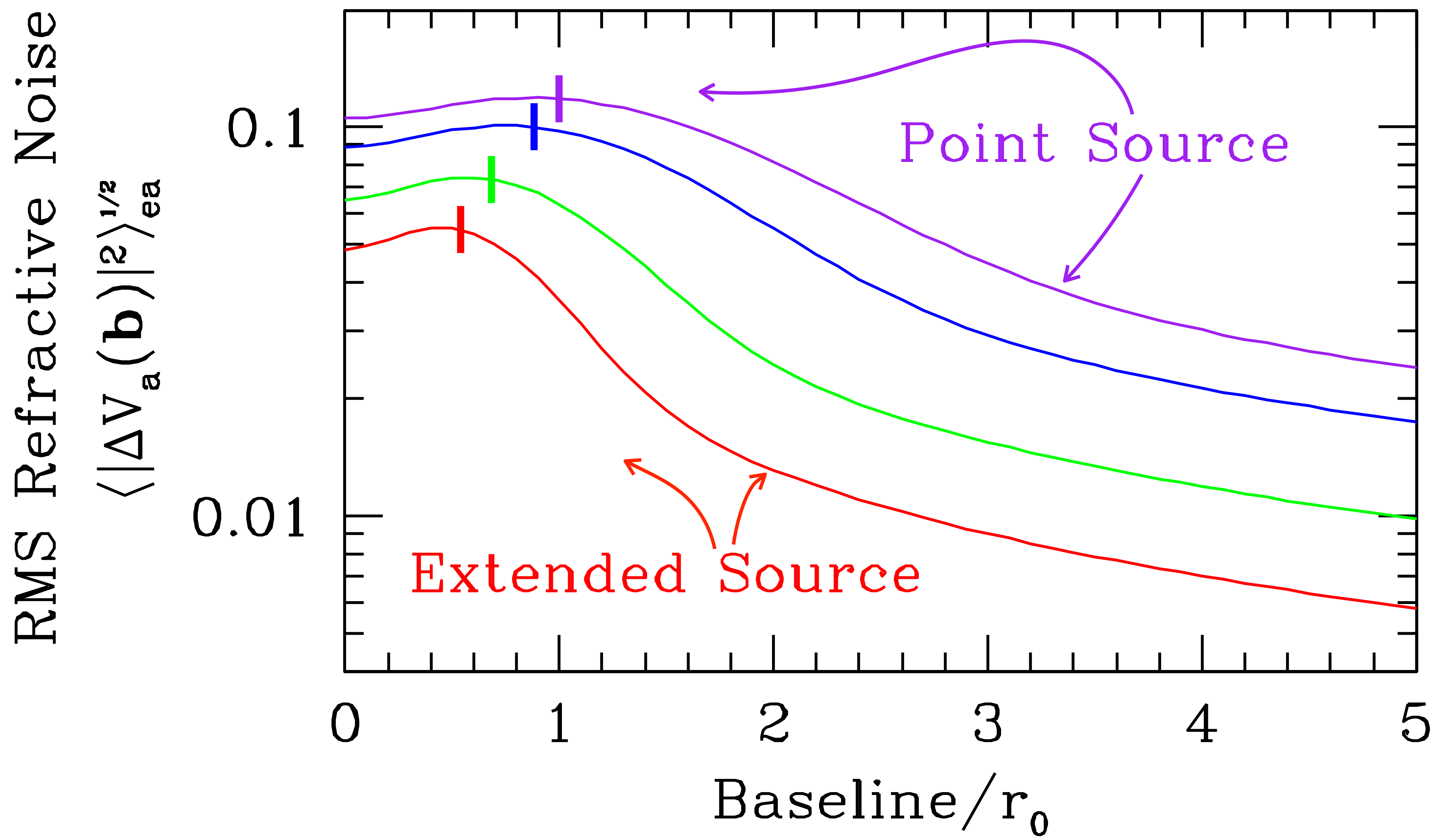

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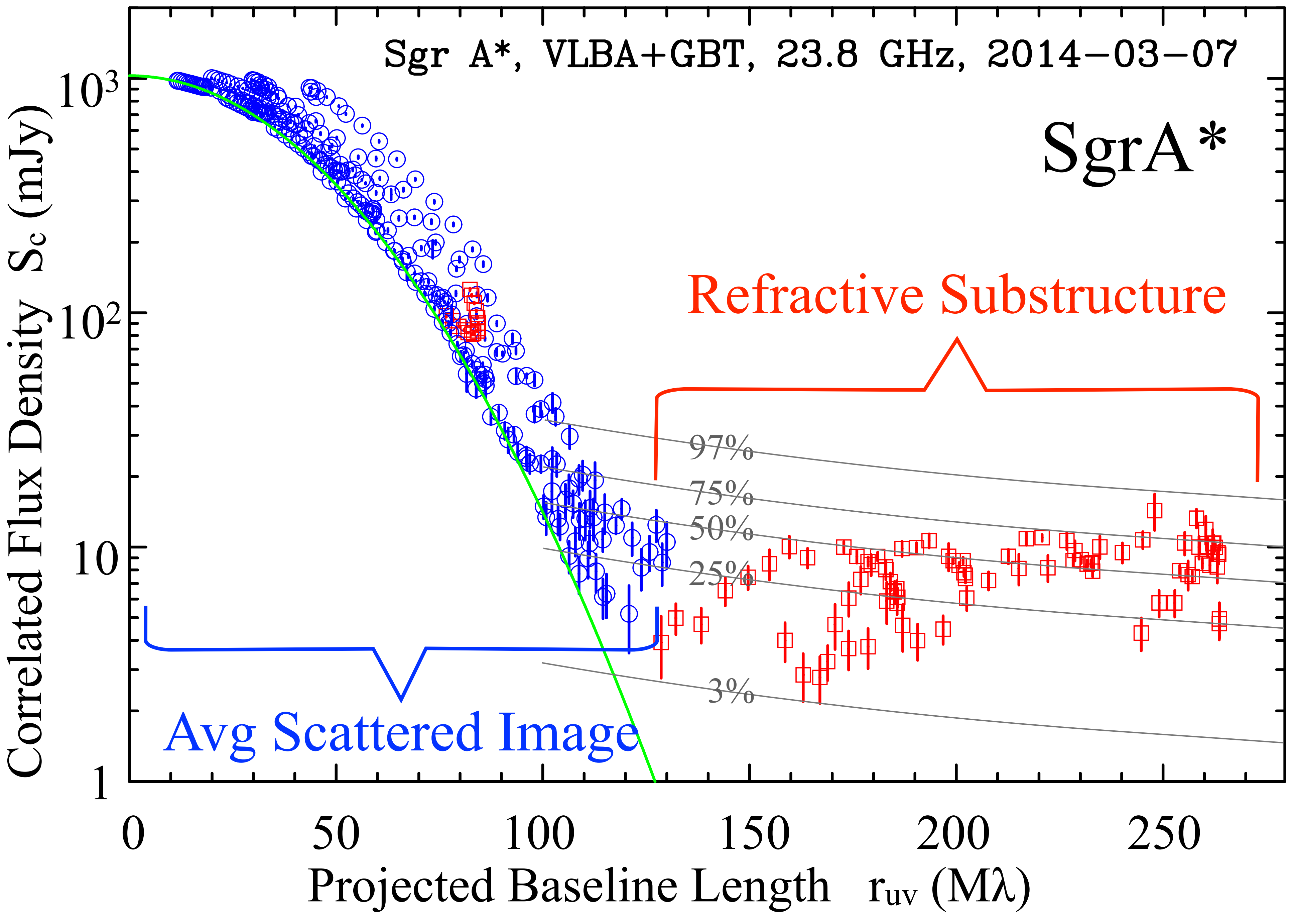

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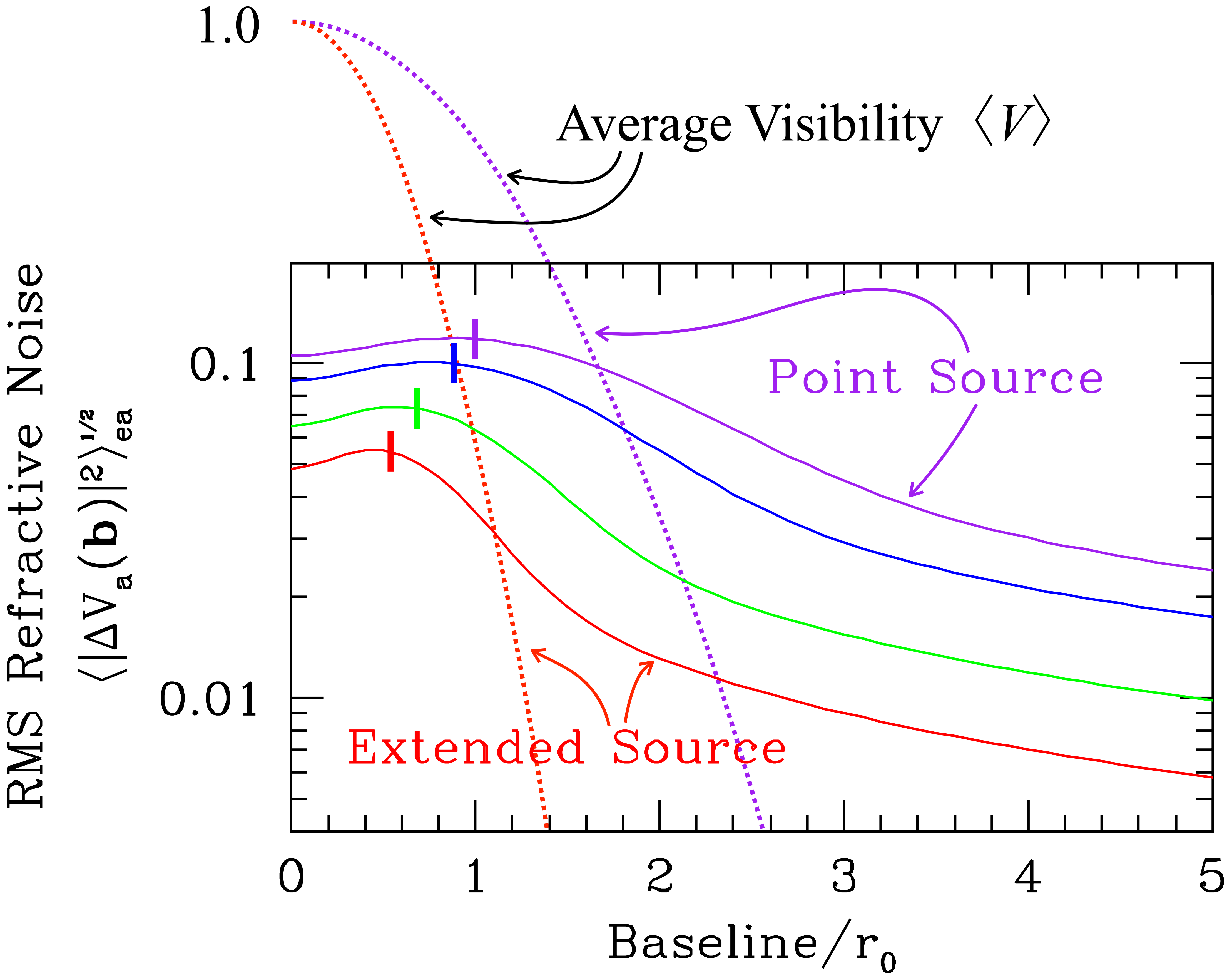

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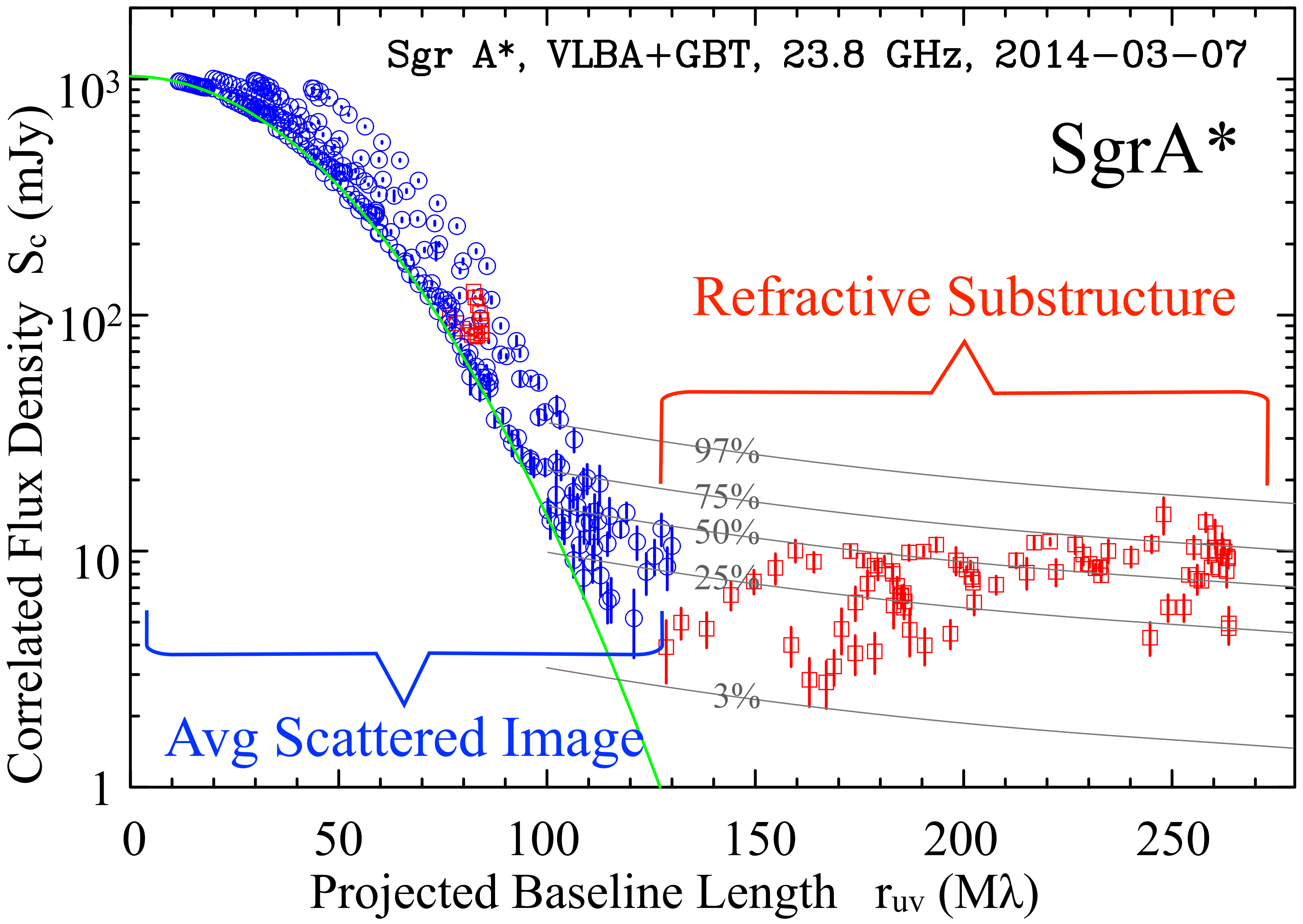

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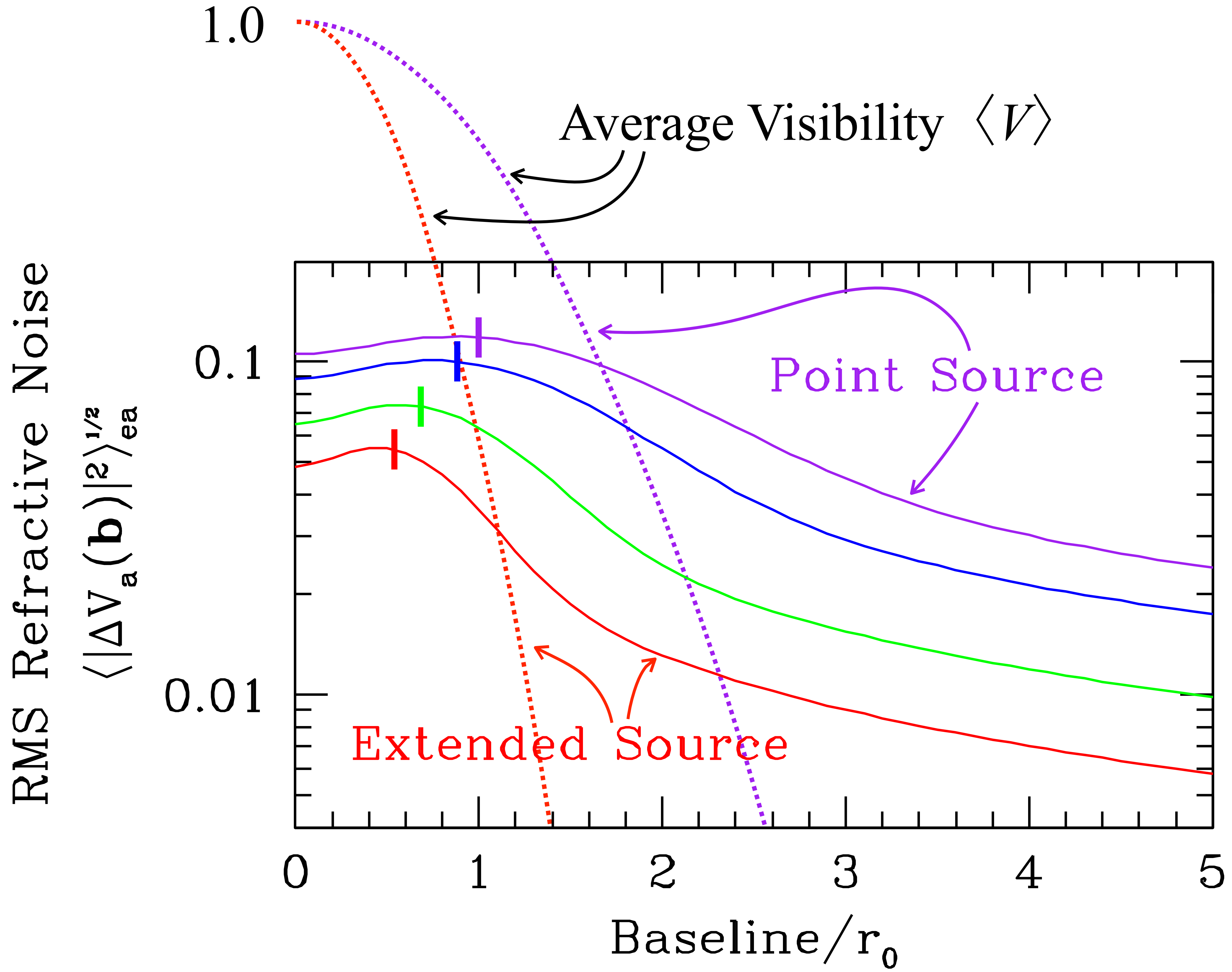

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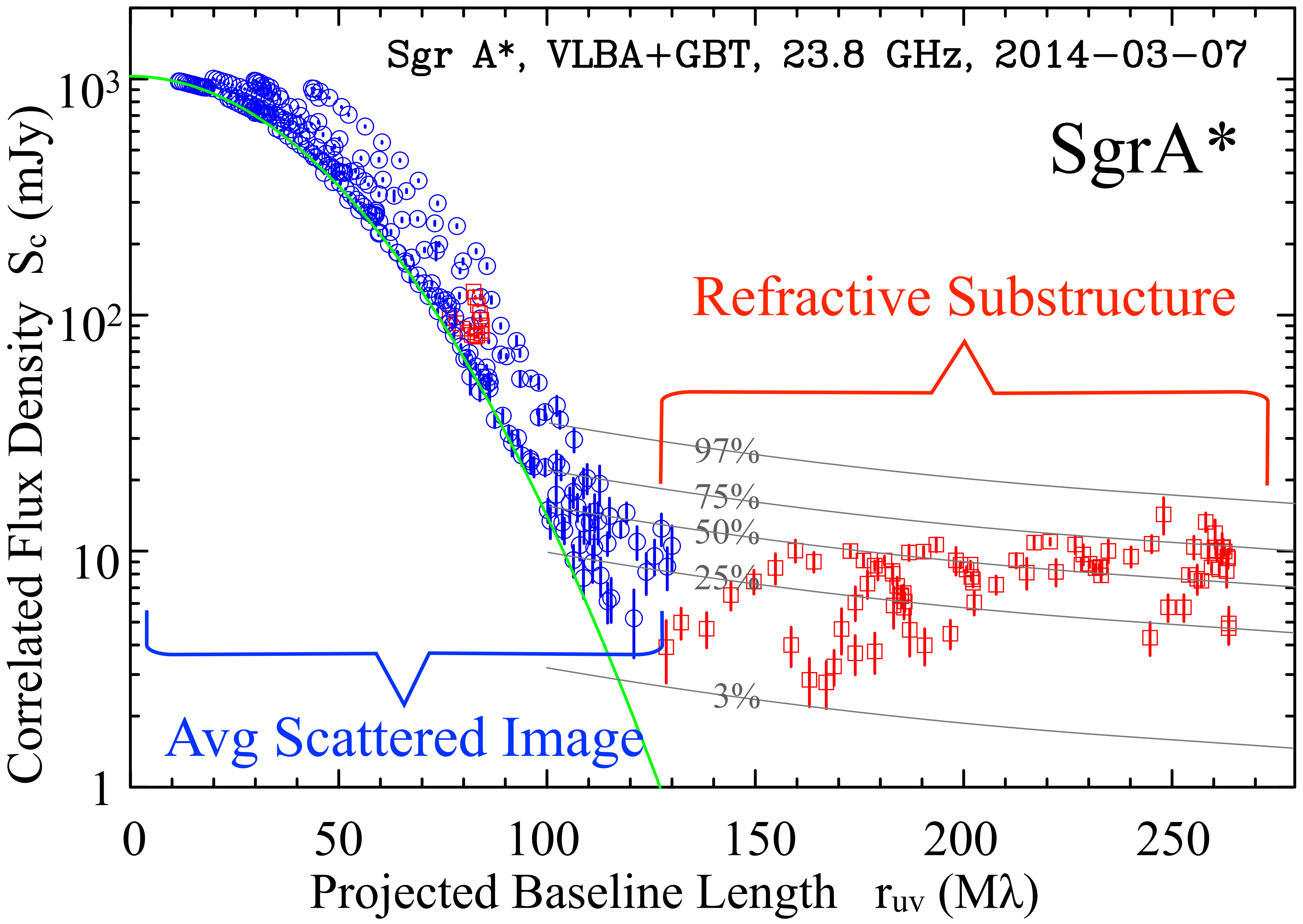

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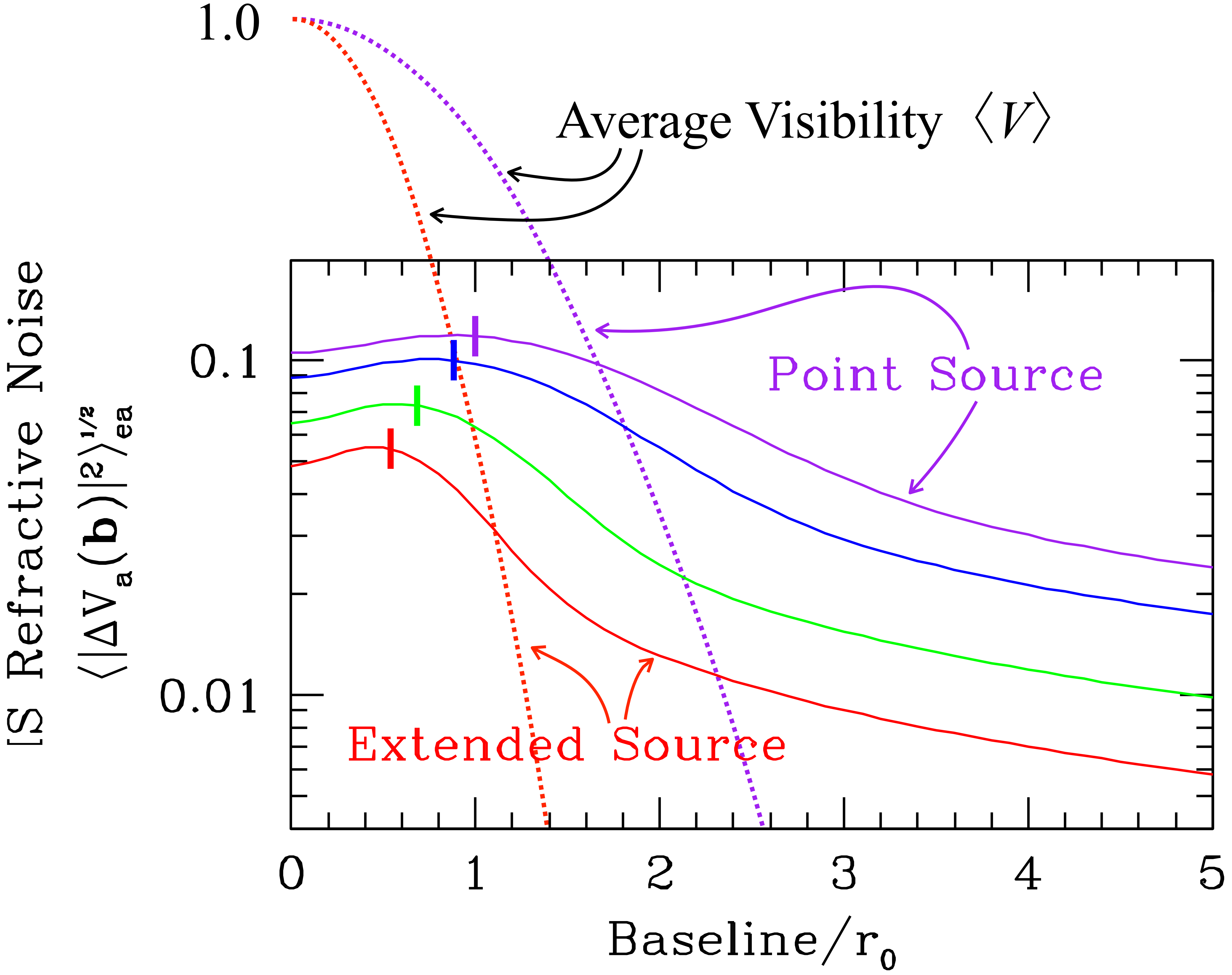

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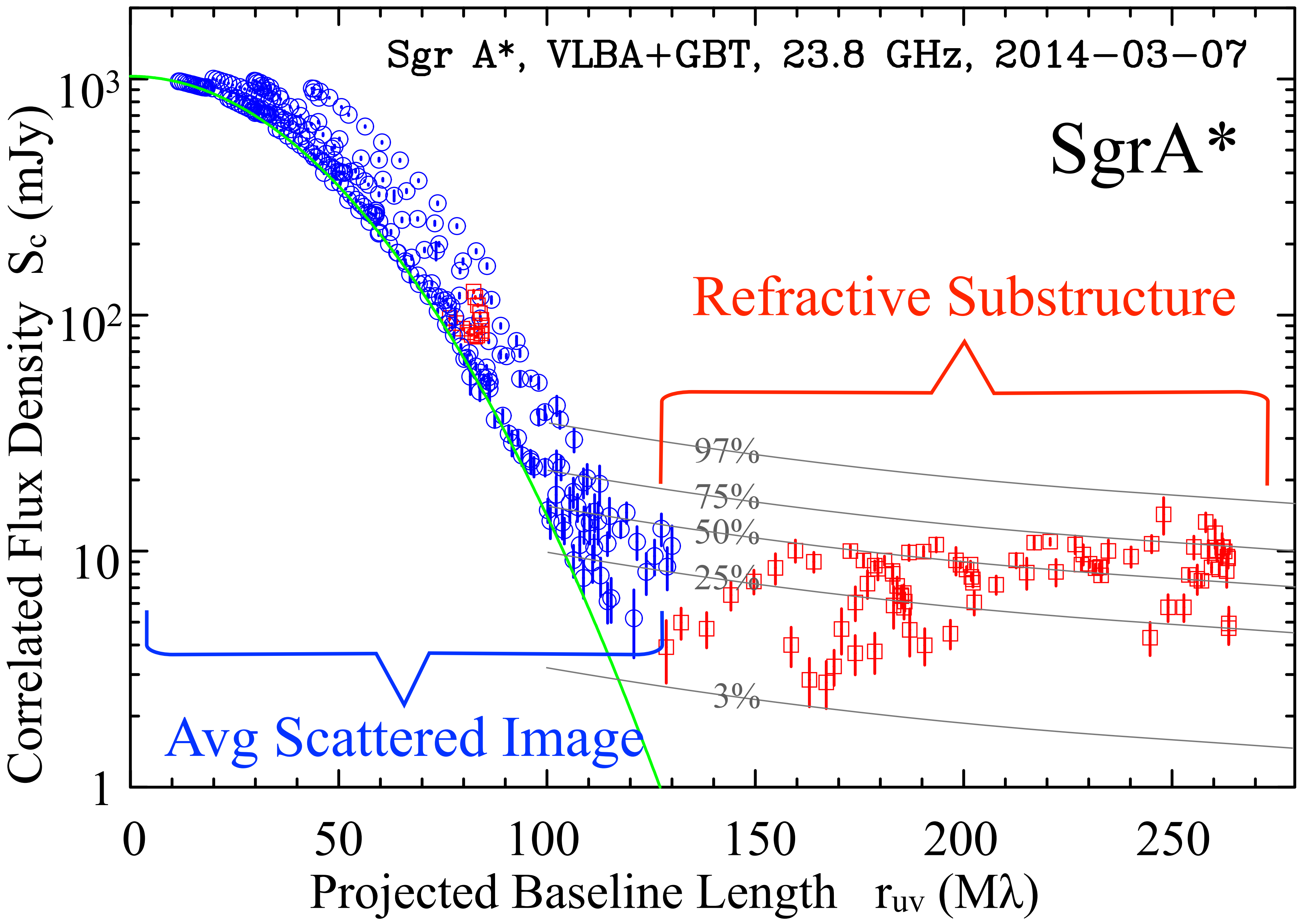
The index of turbulence α gives the strength of large-scale fluctuations (refractive noise) vs small-scale fluctuations (image broadening).

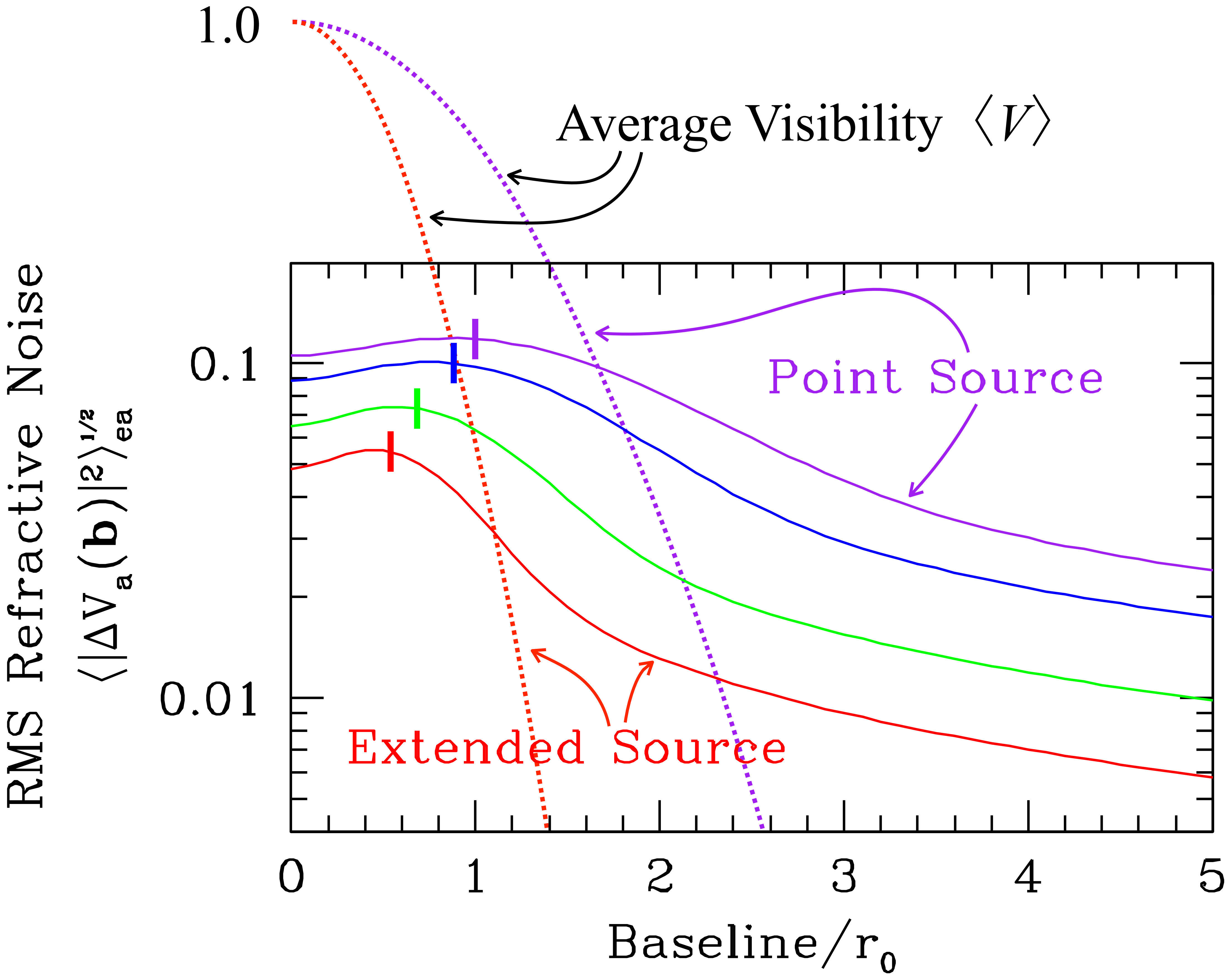
Refractive Substructure in the (u,v) Plane



Gwinn, Kovalev, Johnson, Soglasnov 2014 ApJ arXiv:1409.0530

Refractive scattering appears as noise atop the average visibility. Refractive "noise" is most apparent at long baselines, where the average image is resolved.

From refractive scattering of SgrA*, we can set limits on the intrinsic size of the source, and the index of the tubulence spectrum.



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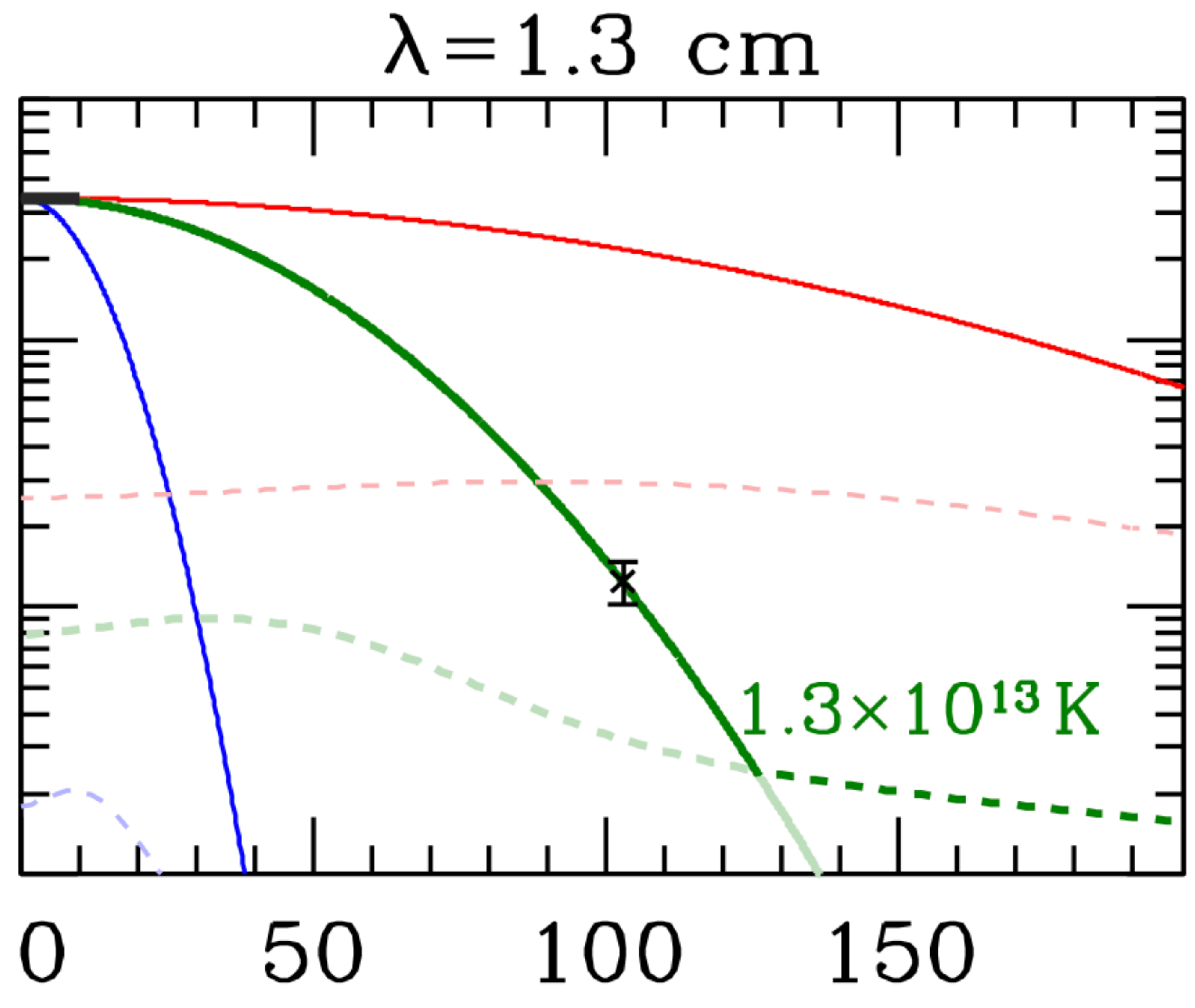
Larger intrinsic source size reduces refractive noise.

Johnson & Gwinn 2015 ApJ arxiv:1502.05722

Active Galactic Nuclei

3C273



λ=1.3 cm:
Visibility on 1.0×10^5 km baseline
is likely average scattered image.

3C273

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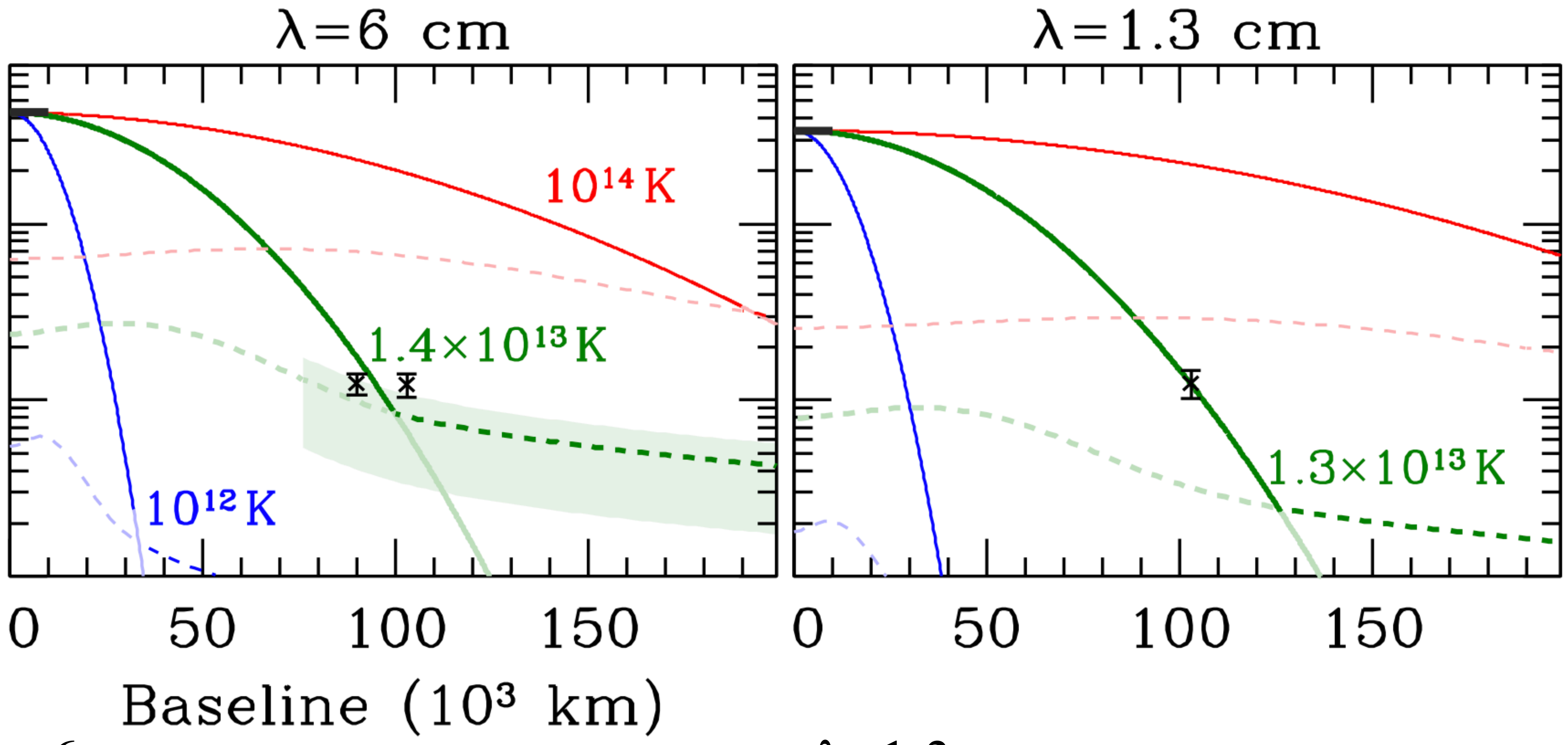

λ=6 cm:
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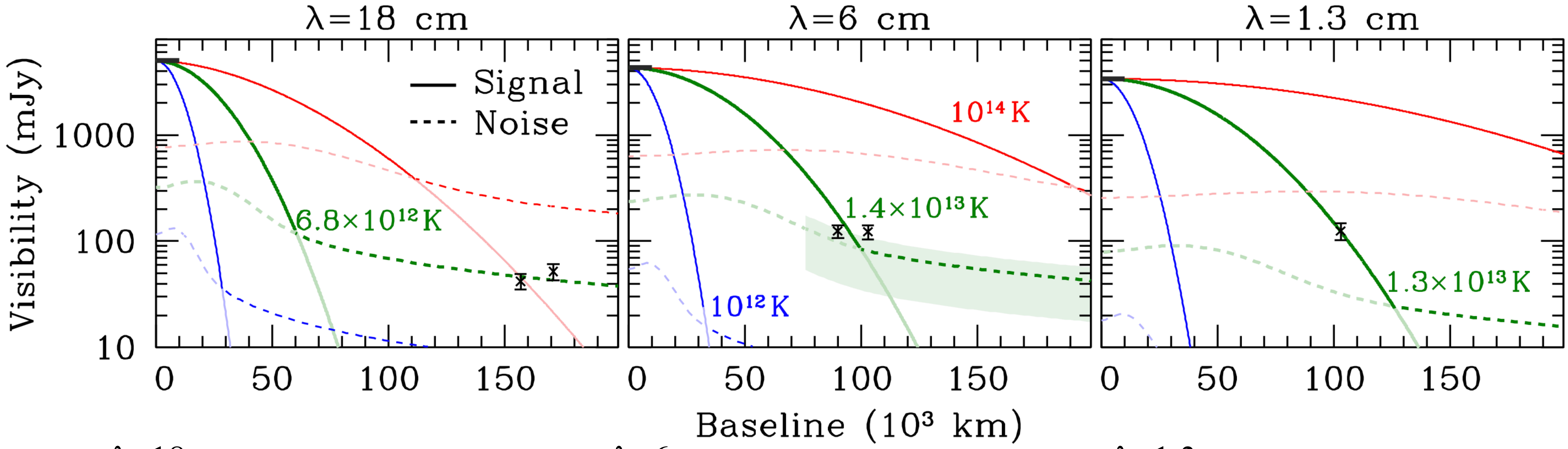

λ=18 cm:
Visibility on 1.5×10^5 km baseline is likely refractive noise.

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Visibility on 1.0×10^5 km baseline is likely average+refractive noise.

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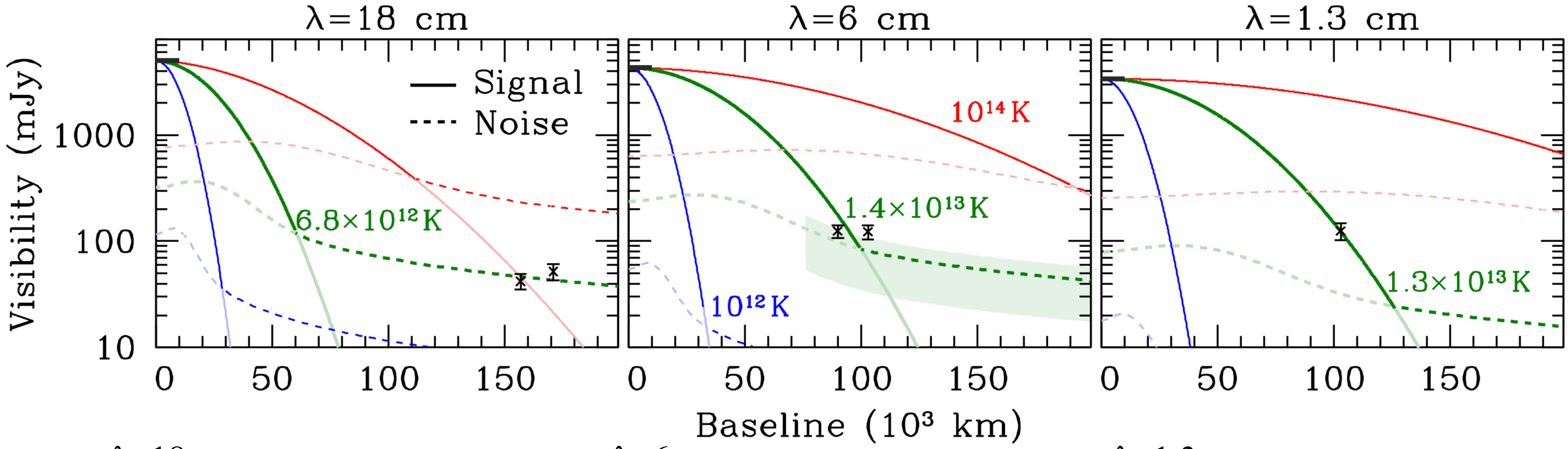

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These plots are from:

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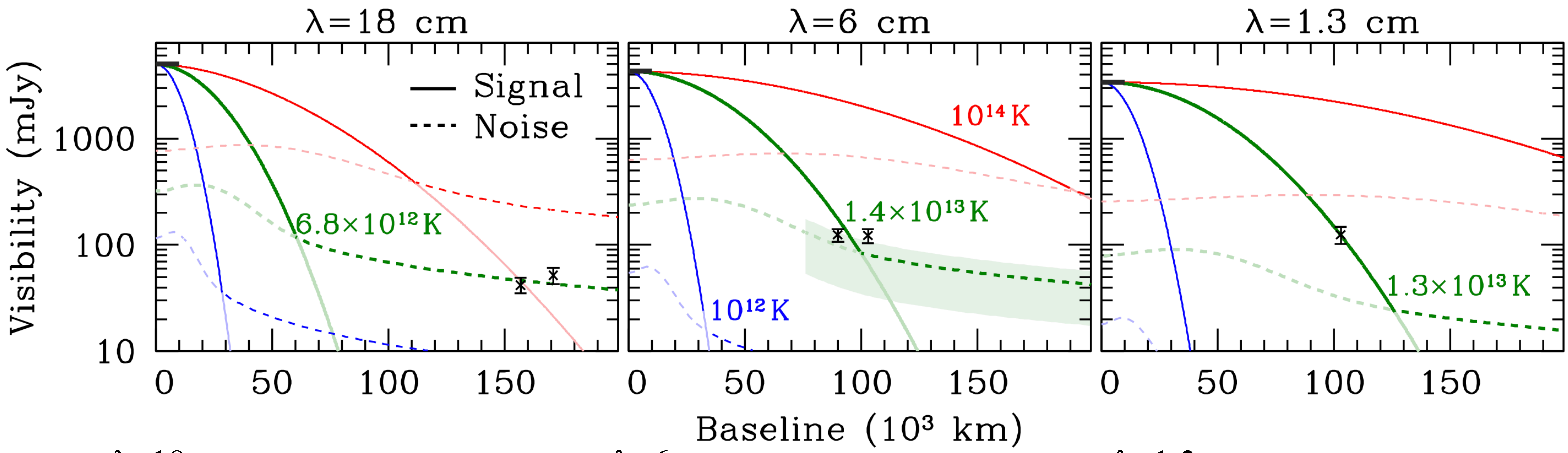

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Also see:

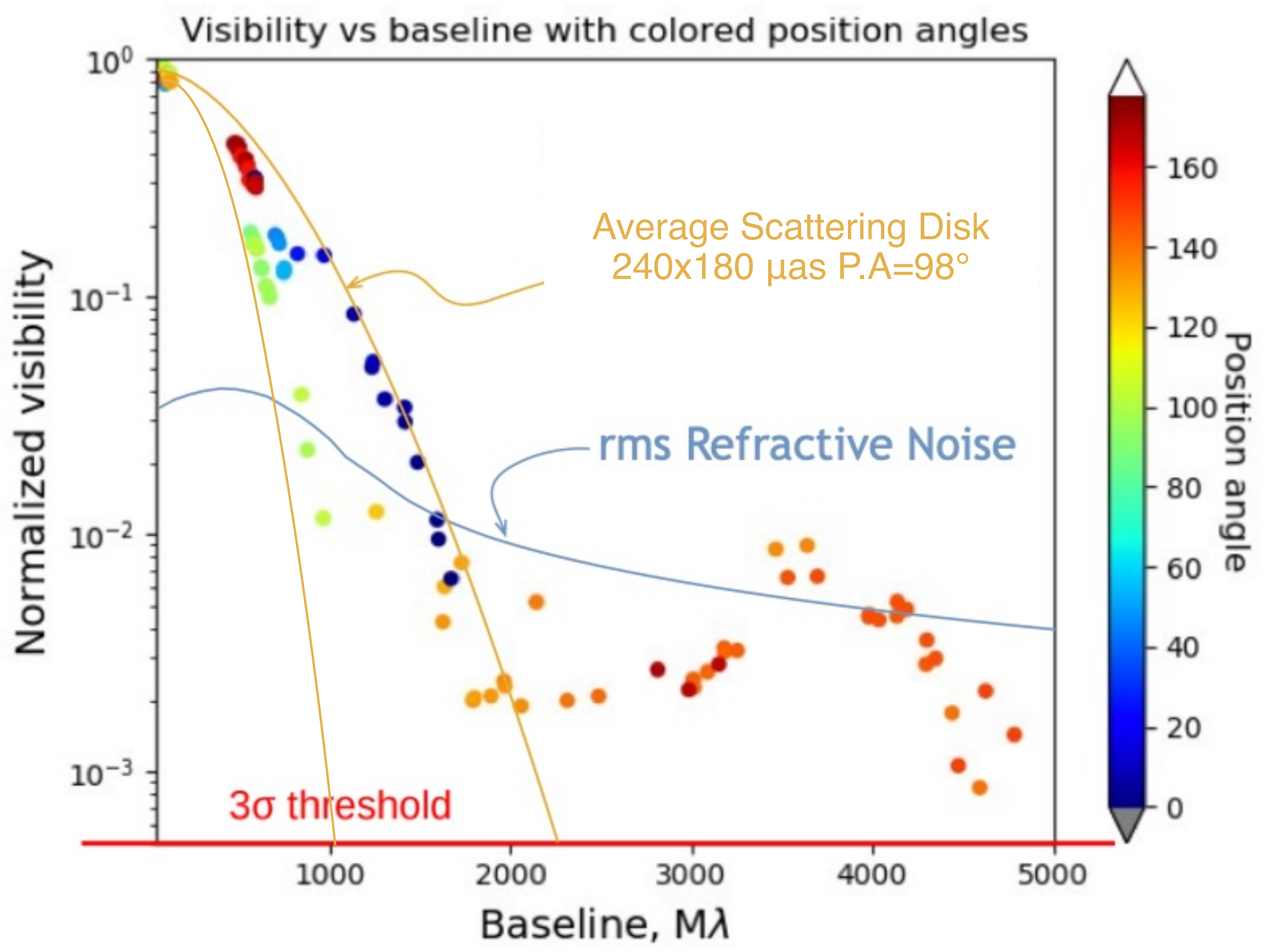
Kovalev, Kardashev, Kellermann, Lobanov, Johnson, Gurvits, Voitsik, Zensus, Anderson, Bach, Jauncey, Ghigo, Ghosh, Kraus, Kovalev, Lisakov, Petrov, Romney, Salter, Sokolovsky 2016 ApJ arXiv:1601.05806

Pilipenko, Kovalev, Andrianov, Bach, Buttaccio, Cassaro, Cimò, Edwards, Gawroński, Gurvits, Hovatta, Jauncey, Johnson, Kovalev, Kutkin, Lisakov, Melnikov, Orlati, Rudnitskiy, Sokolovsky, Stanghellini, de Vicente, Voitsik, Wolak, Zhekanis 2018 MNRAS arXiv:1711.06713

Scattered H_2O Masers in W49N

Masers lie in the Galactic plane.
More distant masers show effects of scattering — at distances≳1 kpc.

Scattered H2O Masers in W49N



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W49N distance=12 kpc ⇒ 1 AU=80 µas.

Shakhvorostova, Moran, Alakoz, Imai, Gwinn, Sobolev , Litovchenko, in preparation
Refractive Scattering of a Bright Maser Feature in W49N Observed on a 60,000 km VLBI Baselines

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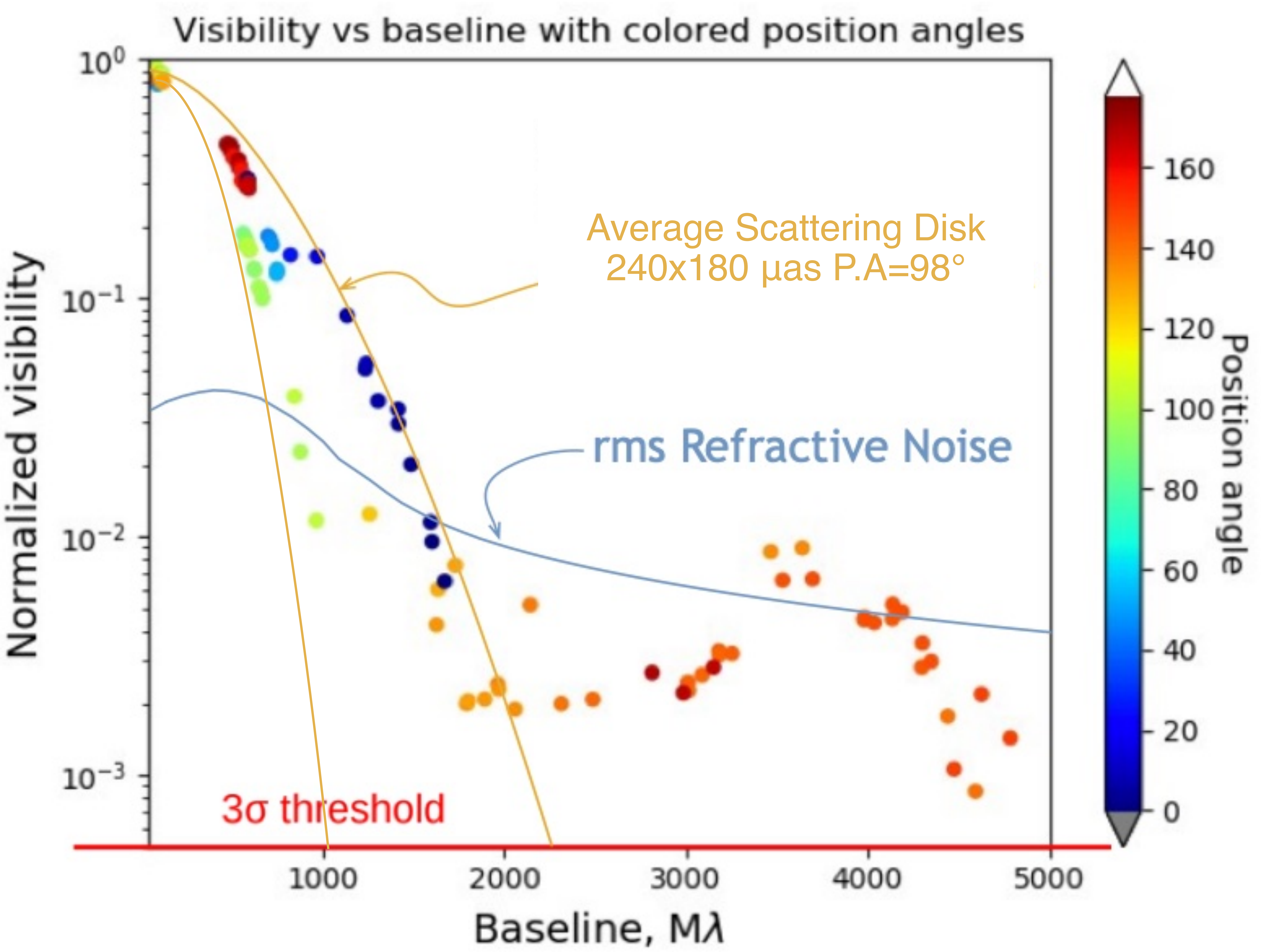

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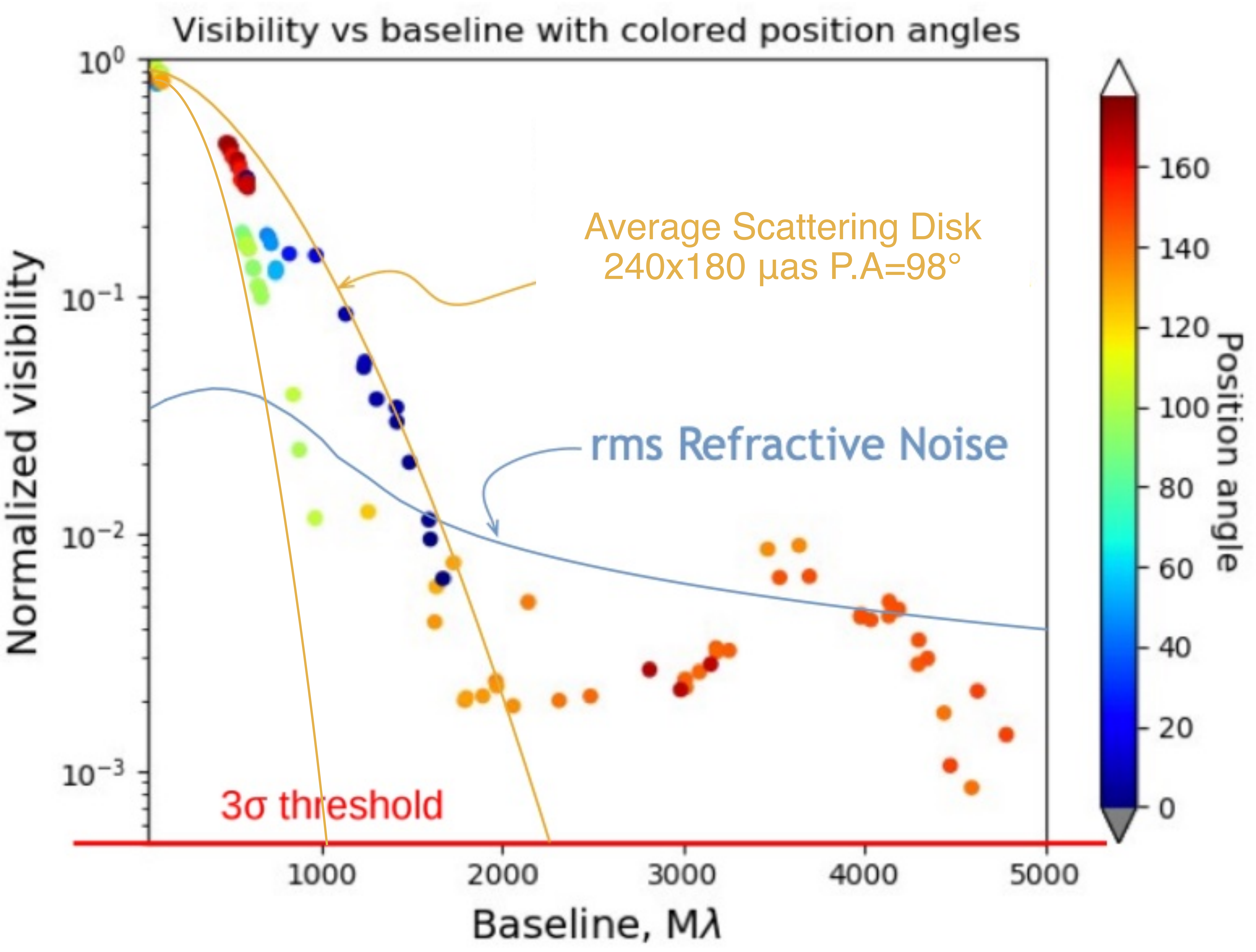

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Masers appear in clusters, so that they provide an opportunity to compare scattering on many nearby lines of sight. Masers have intrinsic structure at scales of about 1 AU— at least in some spectral channels.

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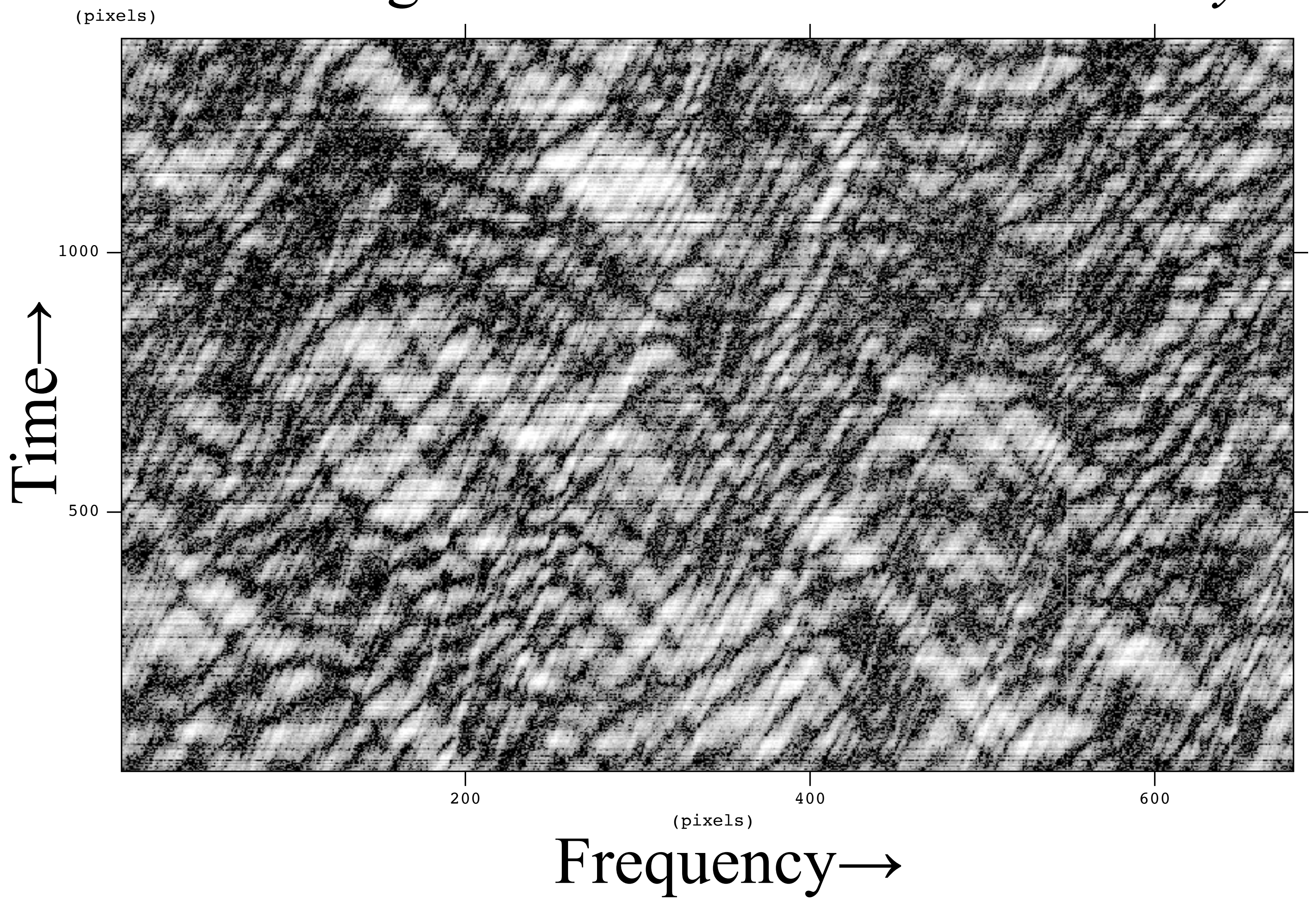
Scattering for paths < 1kpc, or at High Galactic Latitude

Modern single-dish observations show *very simple* diffraction patterns for pulsars at <1kpc.



Diffraction pattern for pulsar B0834+06
at the Green Bank telescope.

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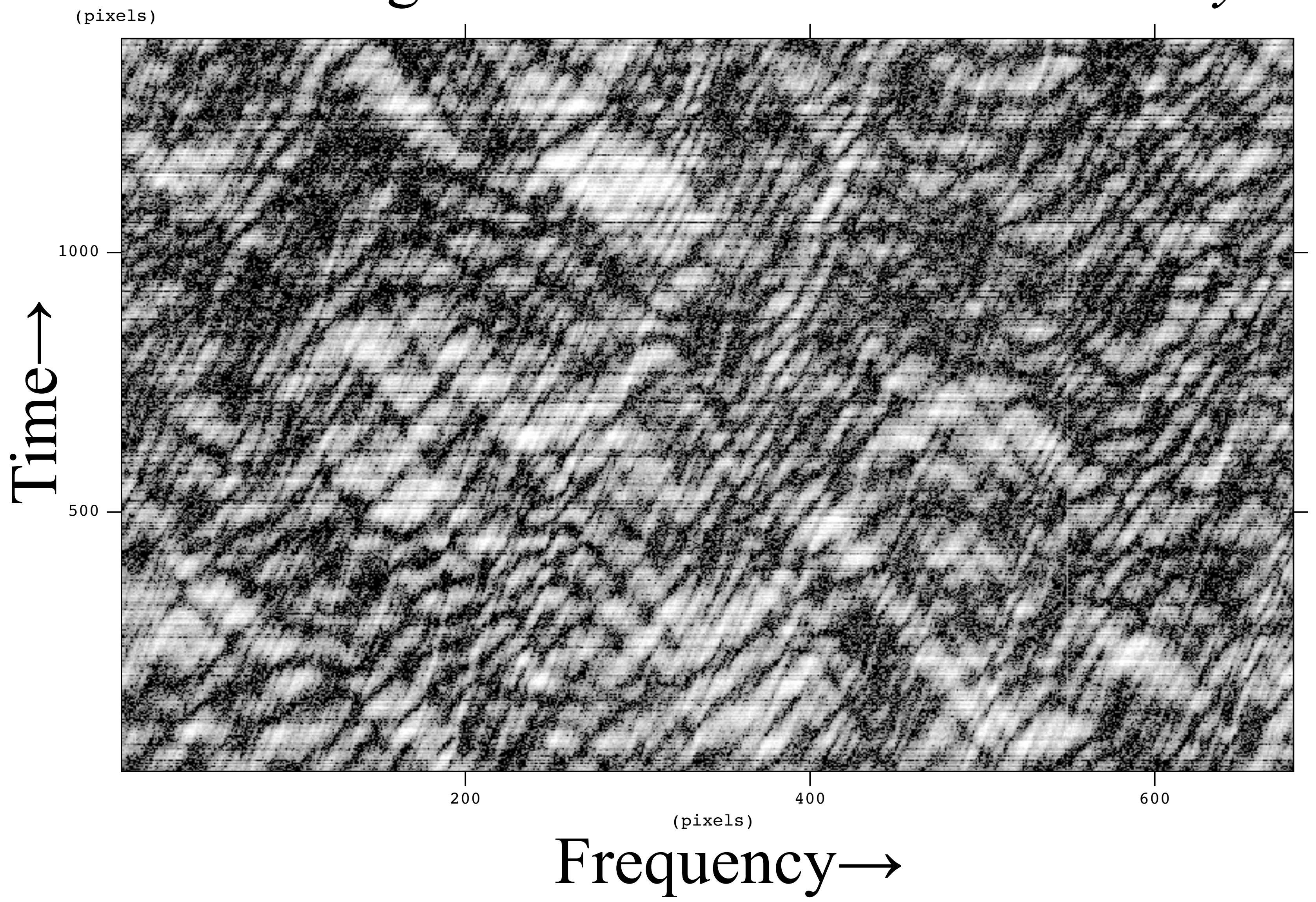

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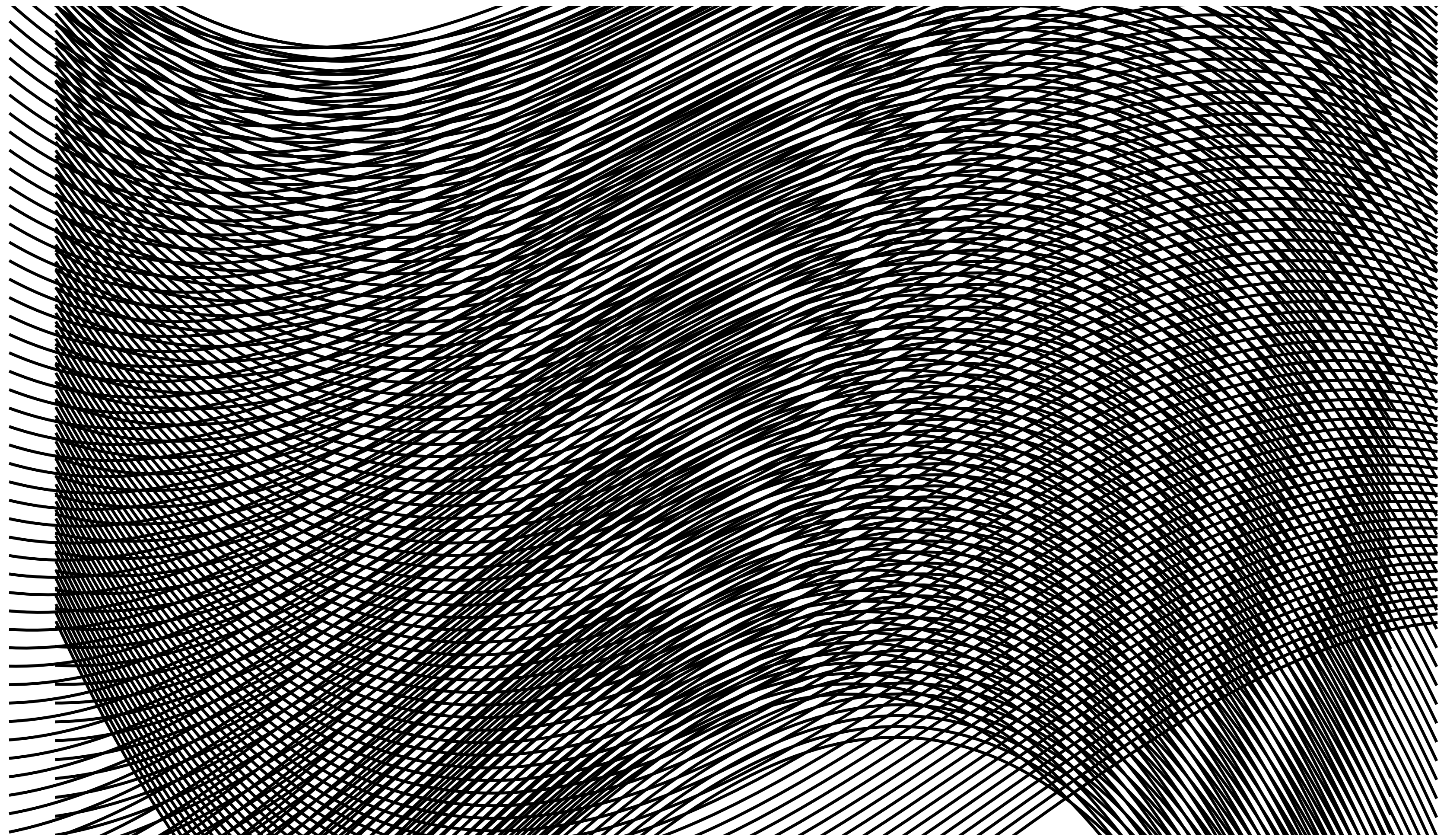

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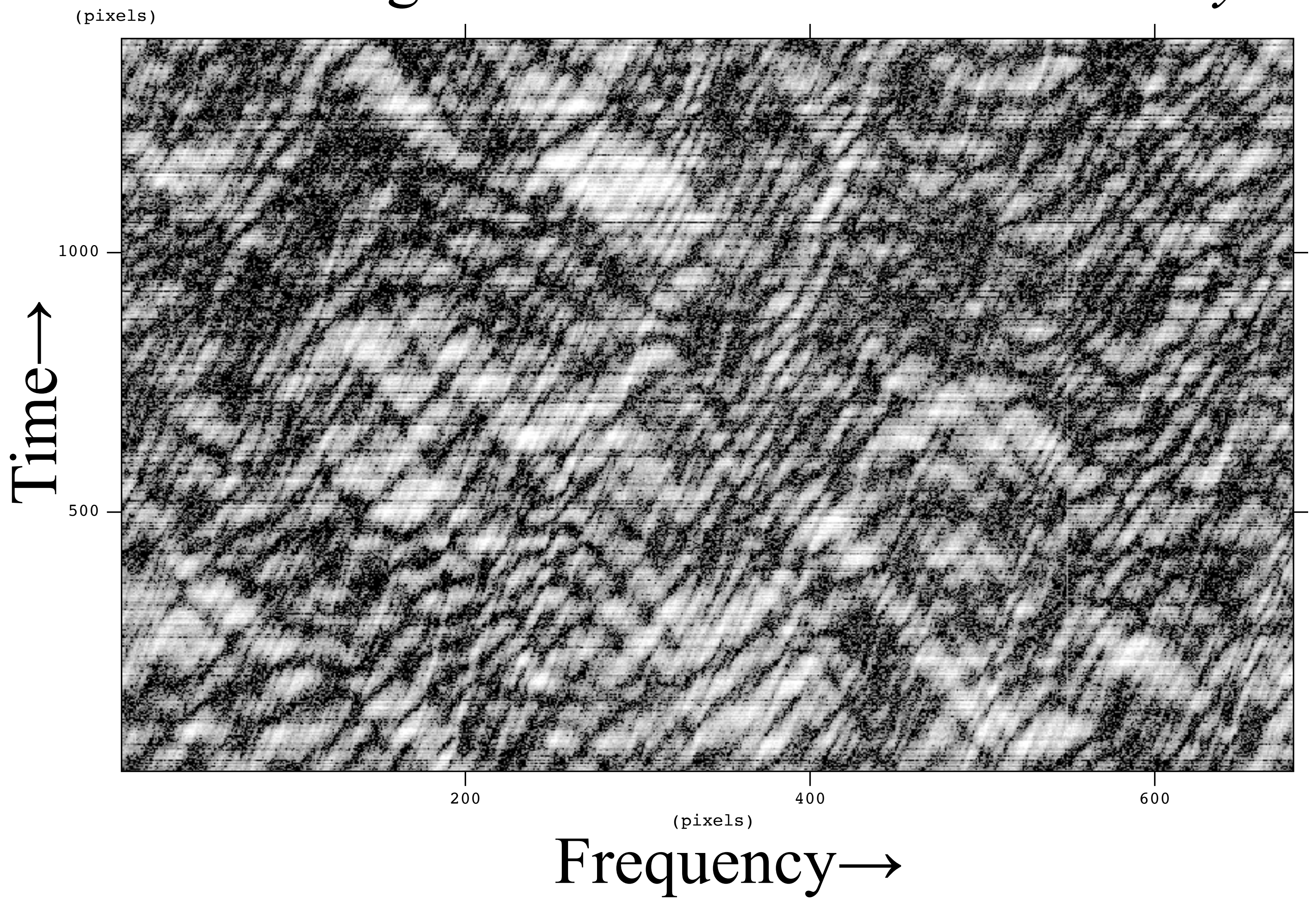

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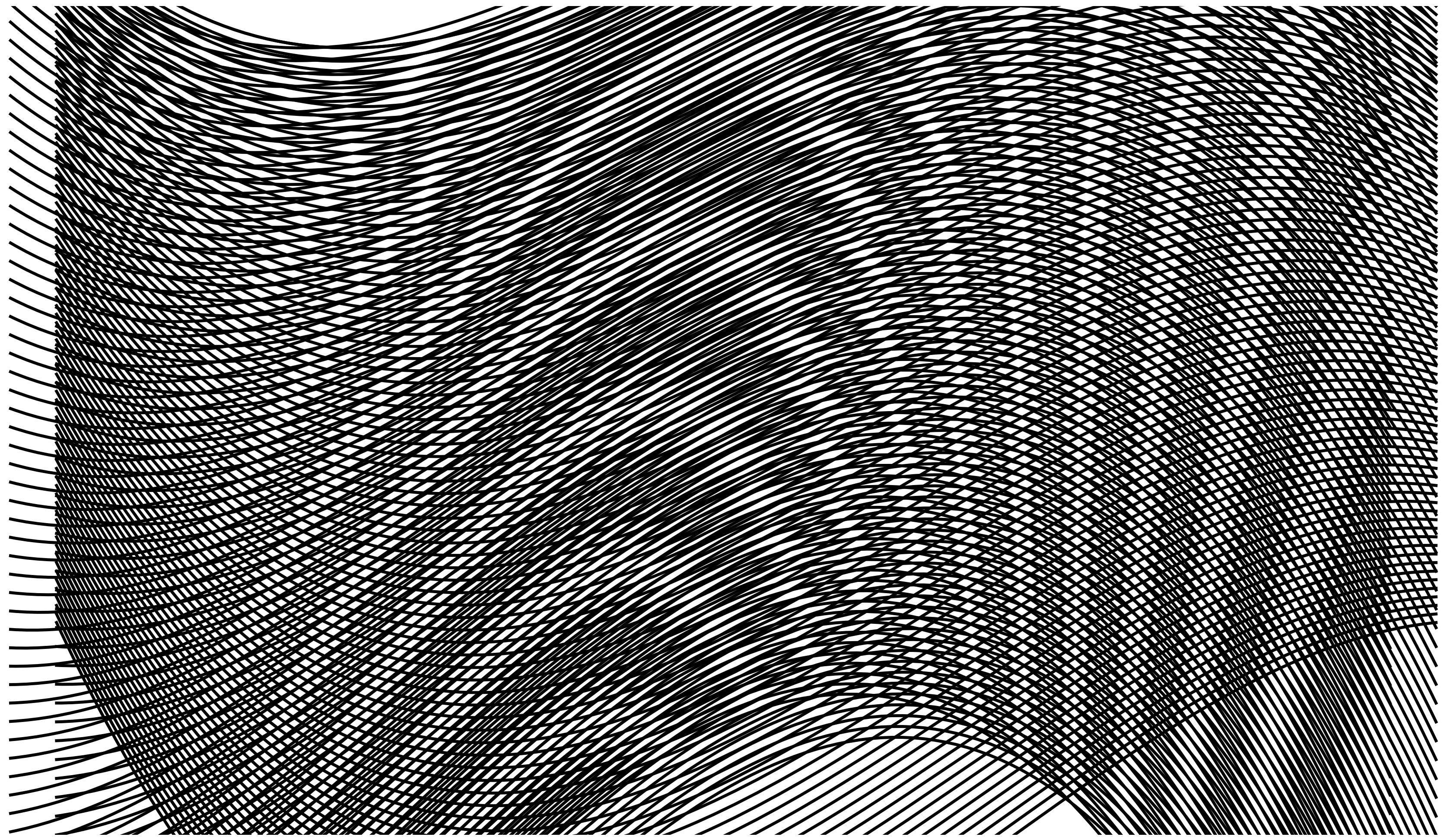

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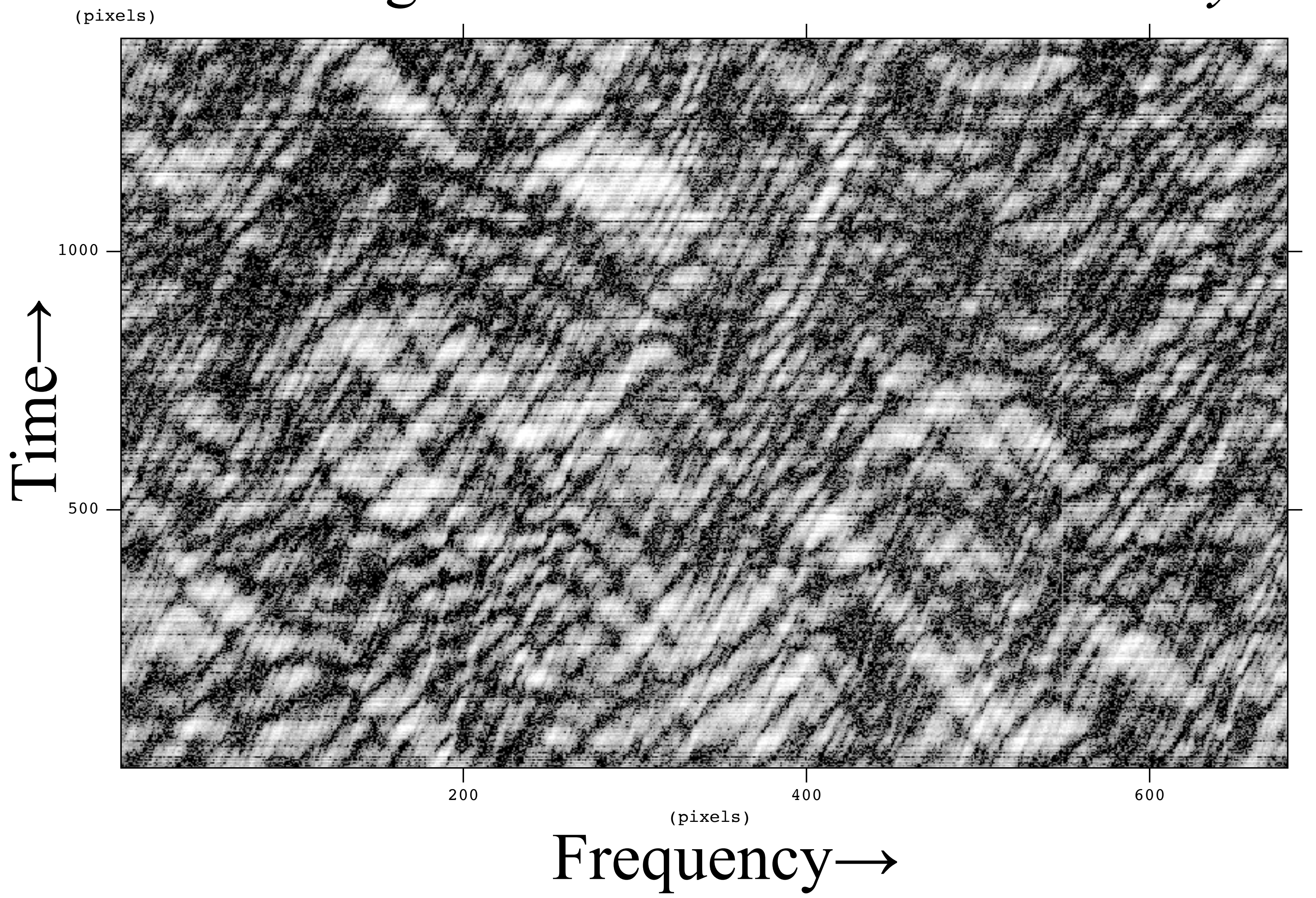

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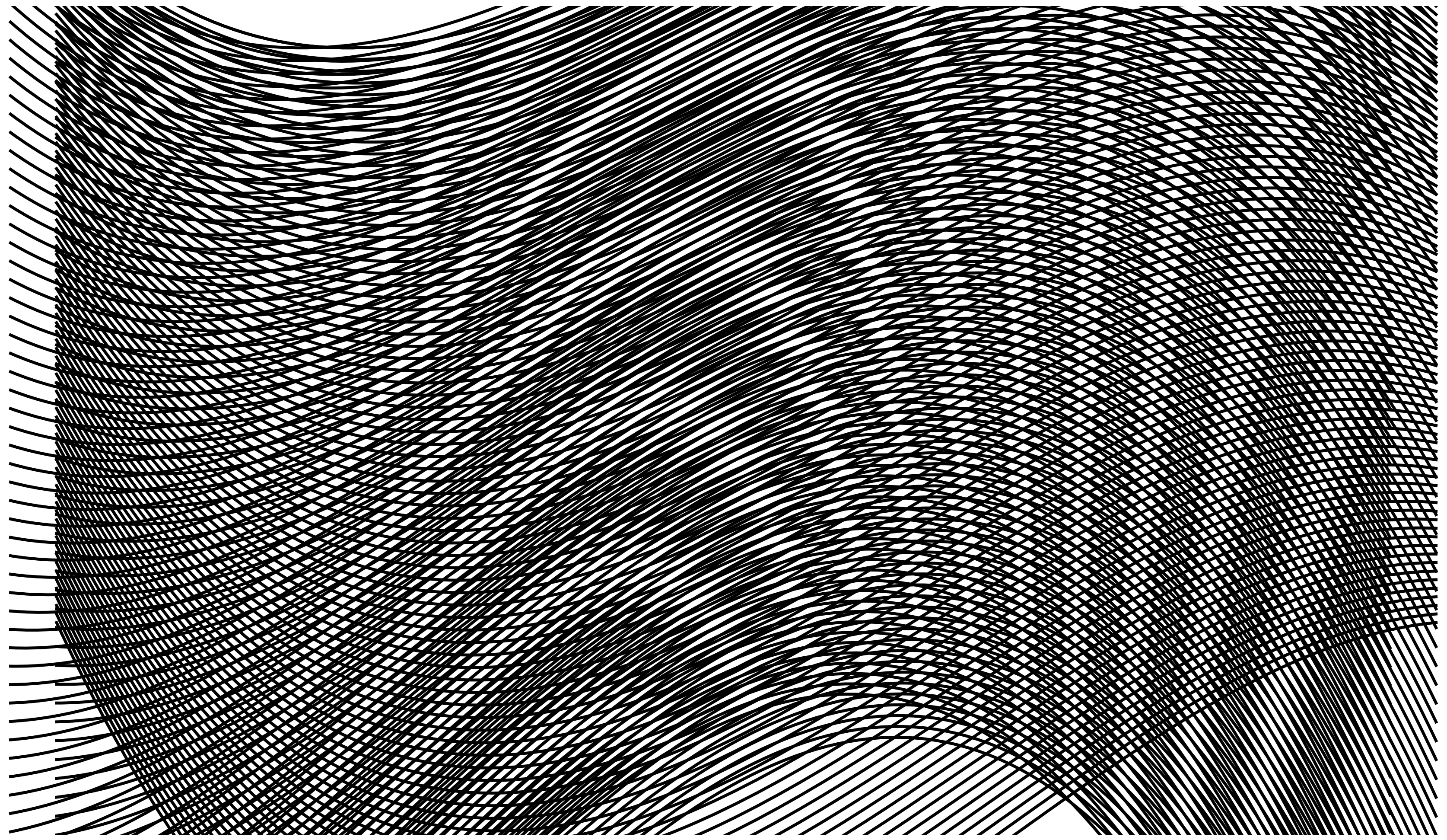

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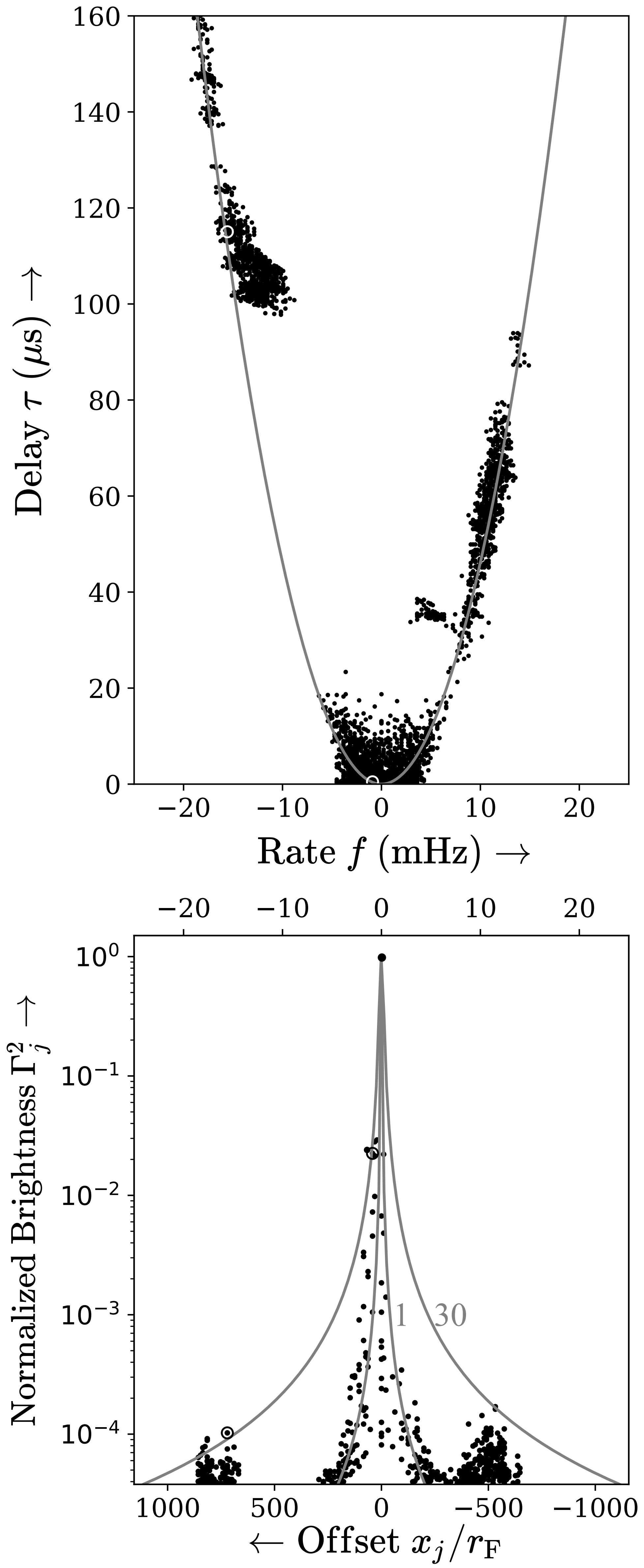

Gwinn & Sosenko MNRAS 2019

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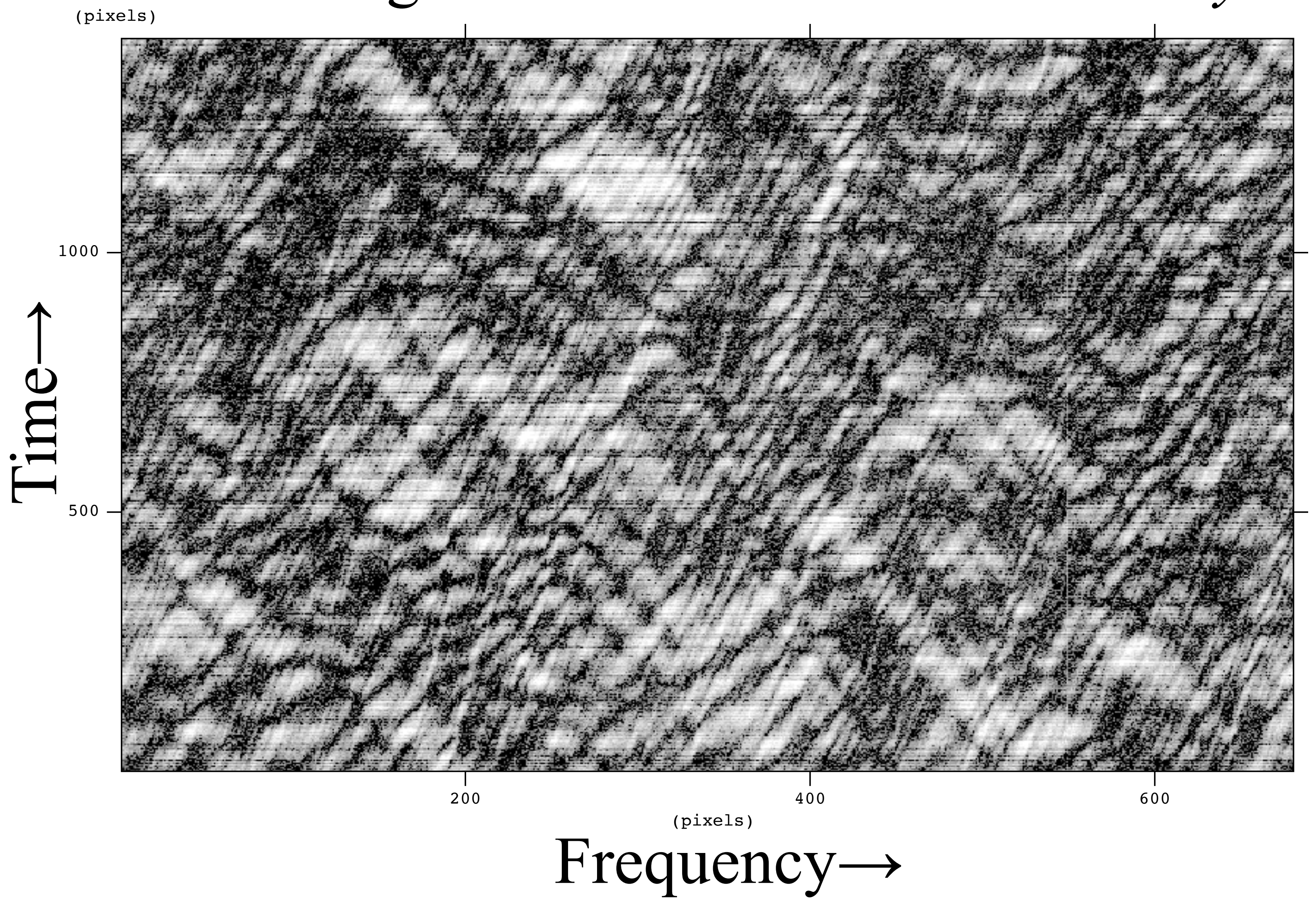

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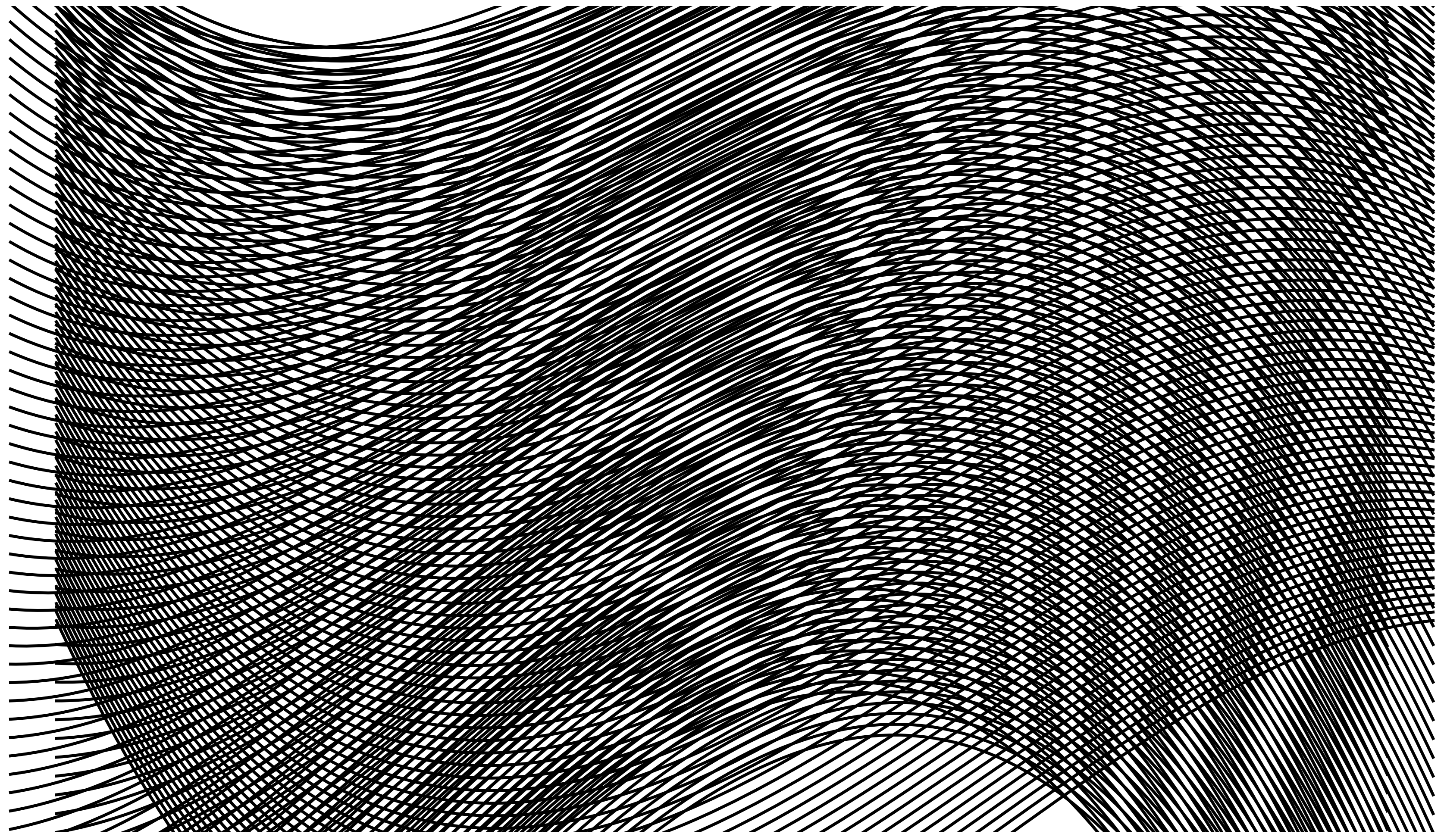

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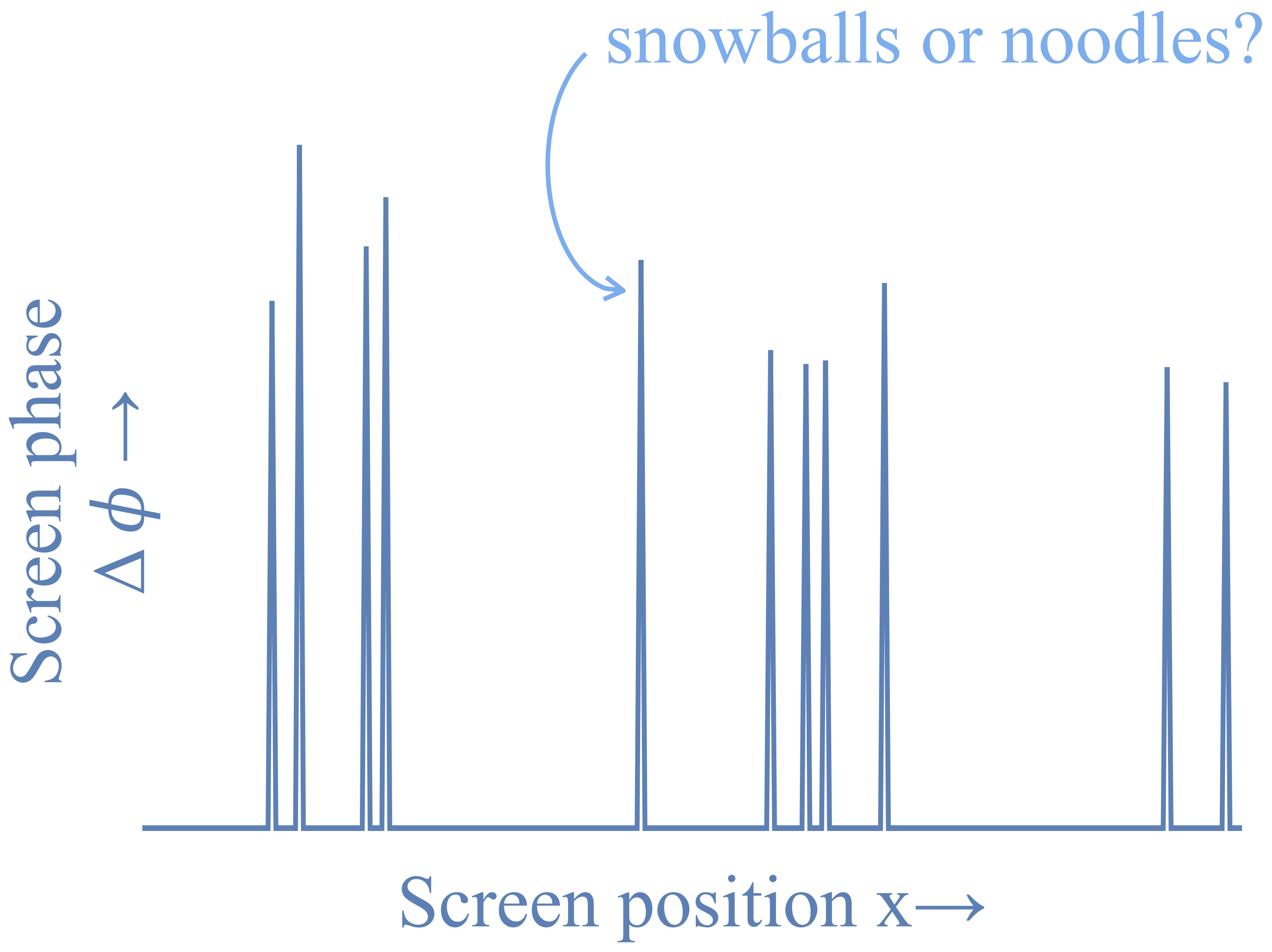

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Walker et al. 2004 (snowballs), Gwinn 2019a,b (noodles)

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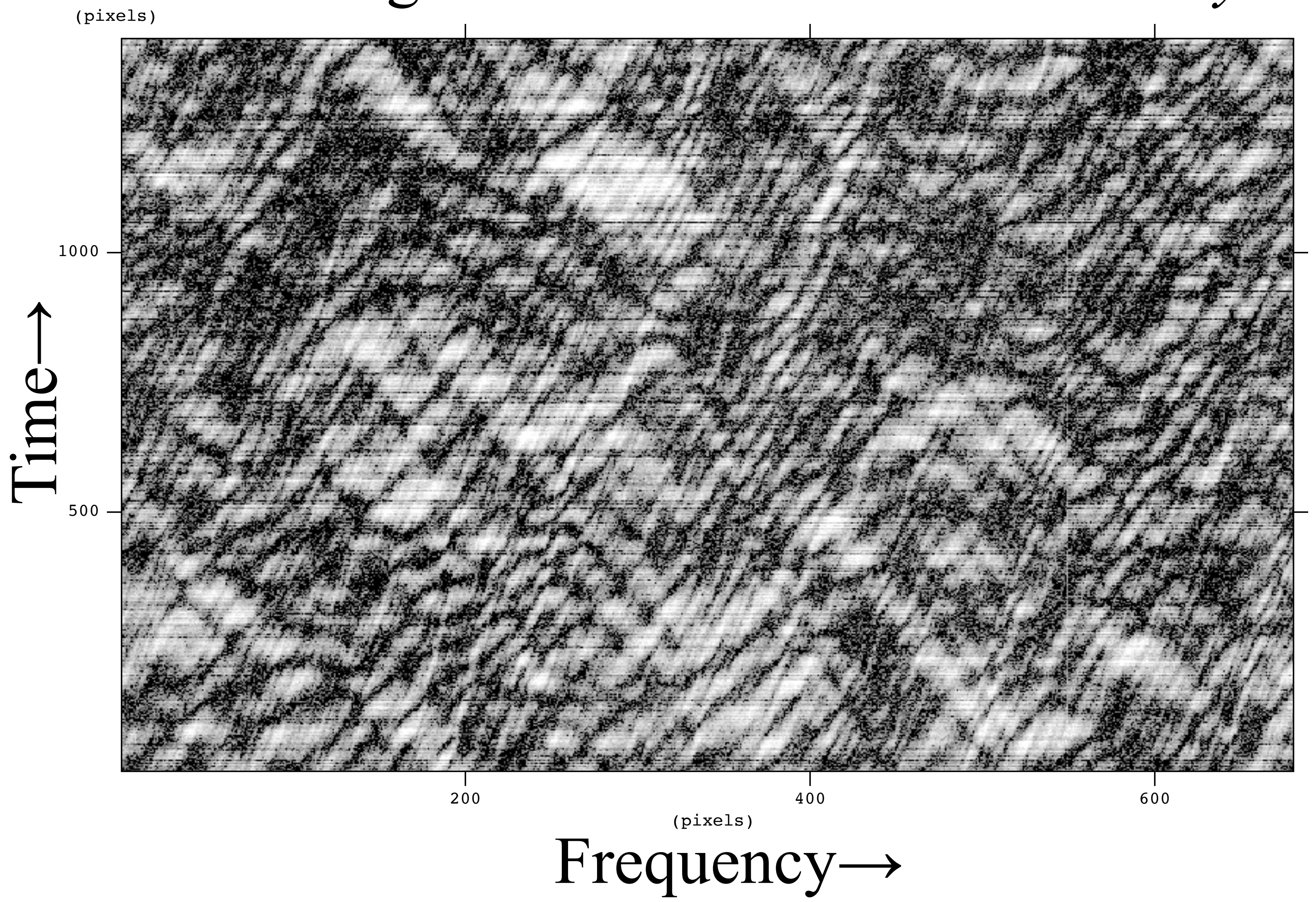

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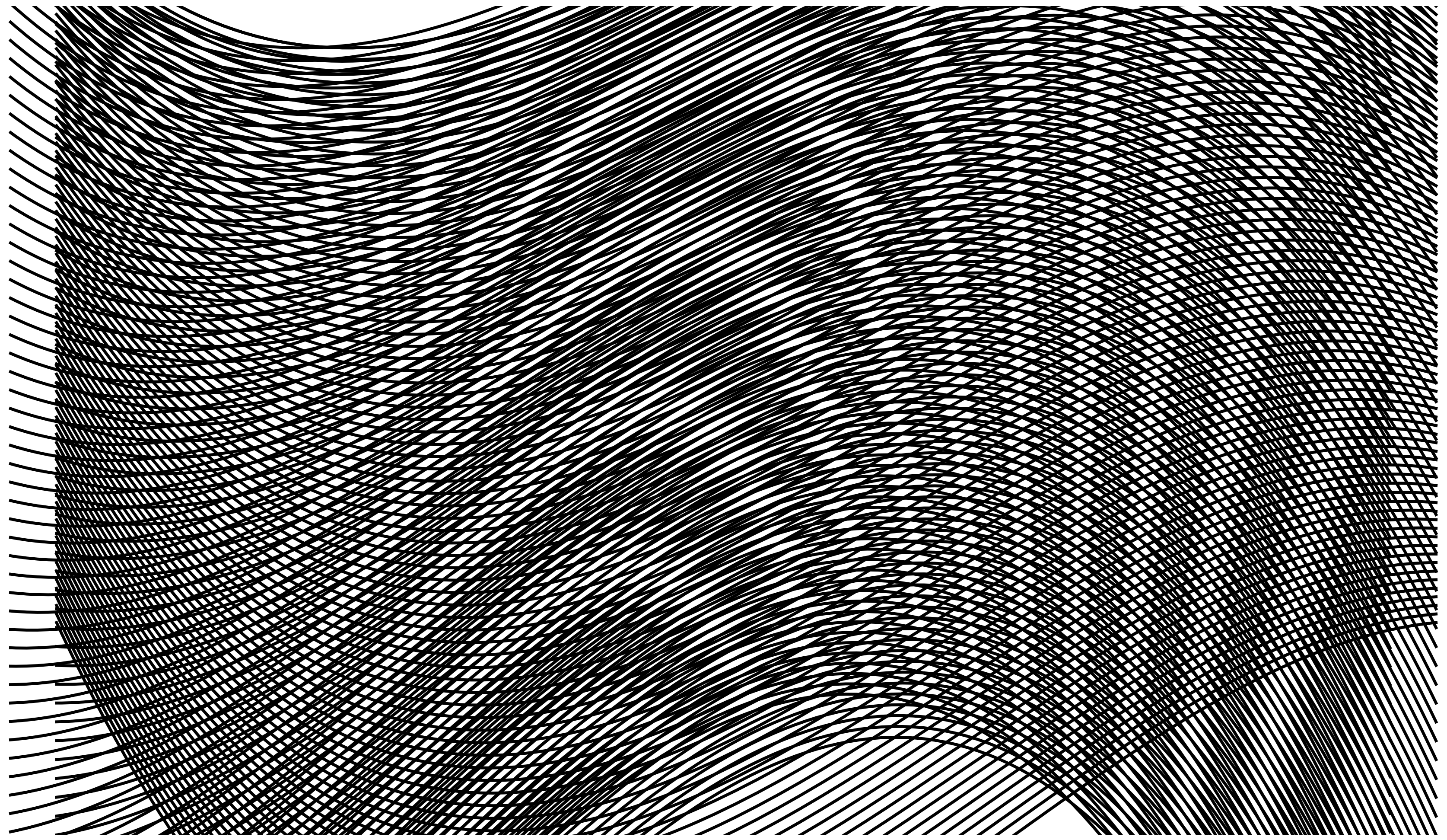

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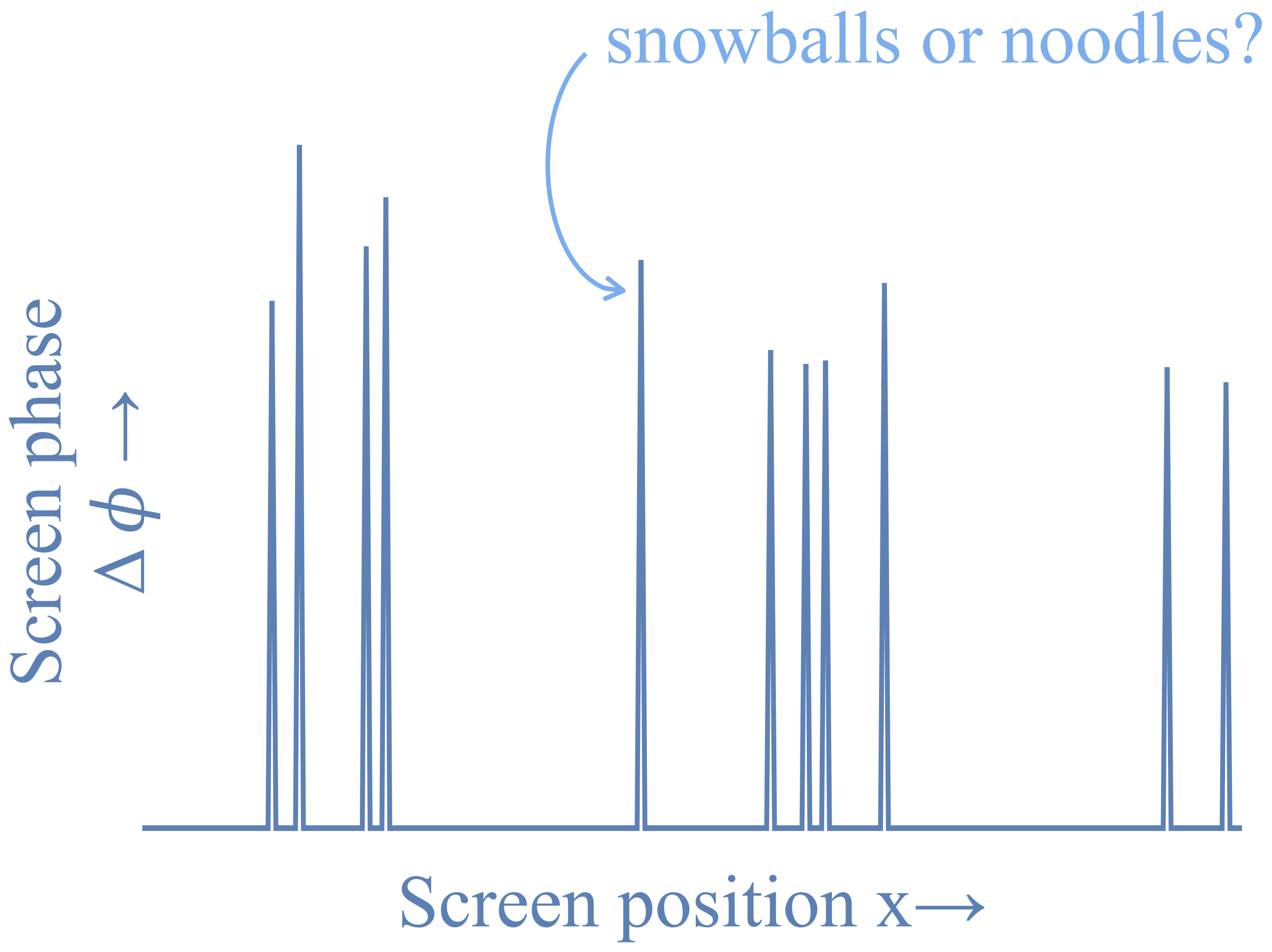

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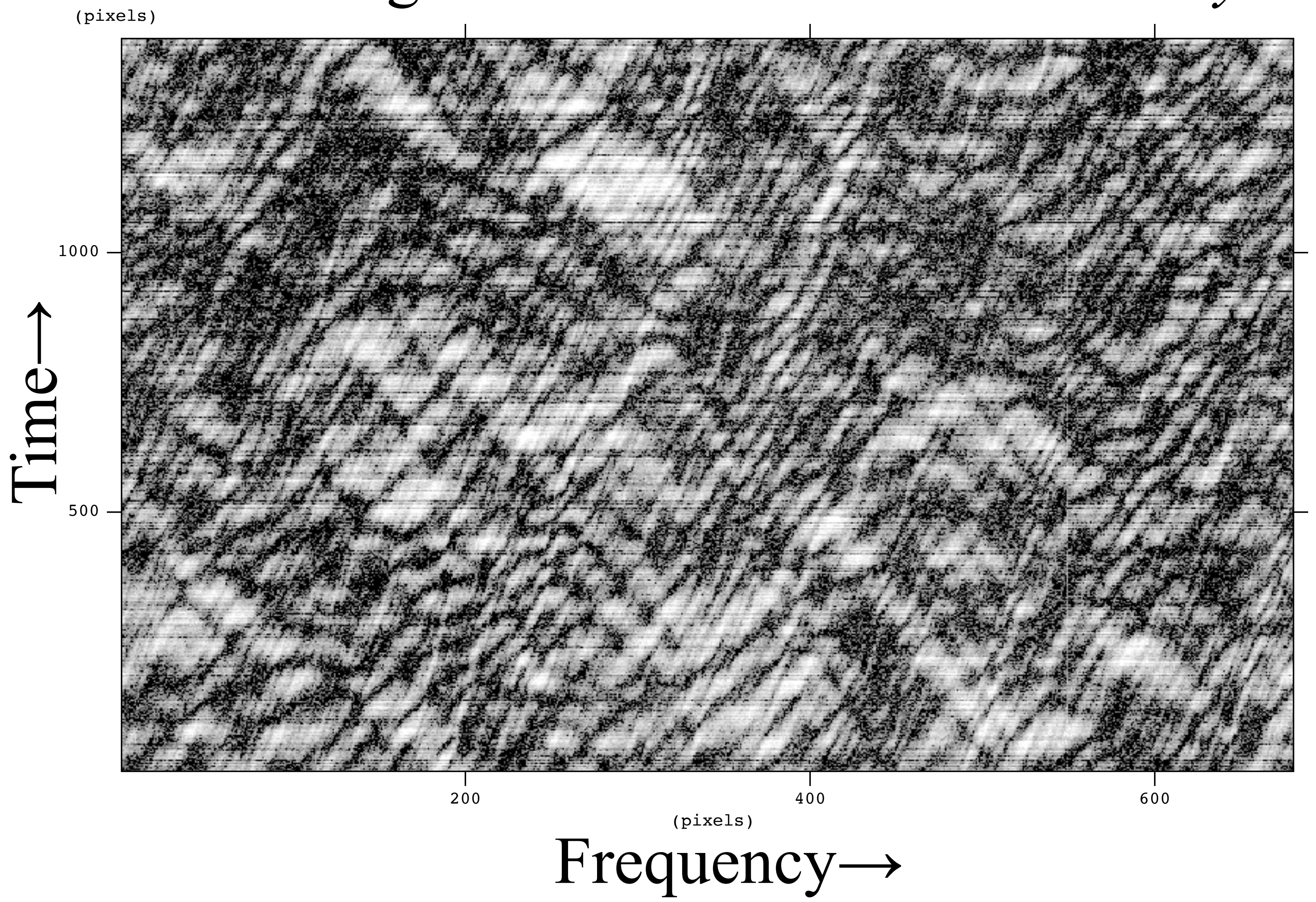

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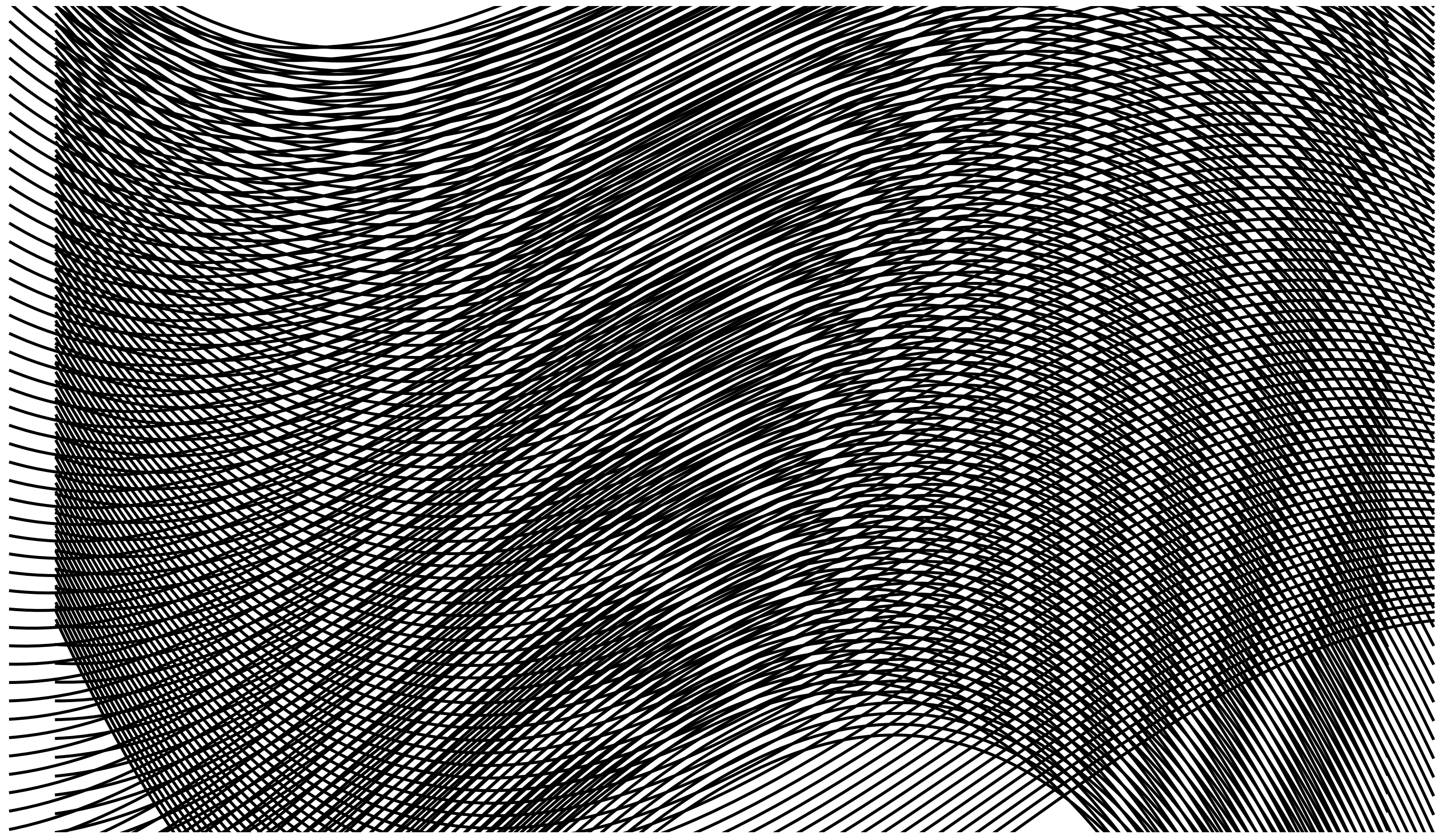

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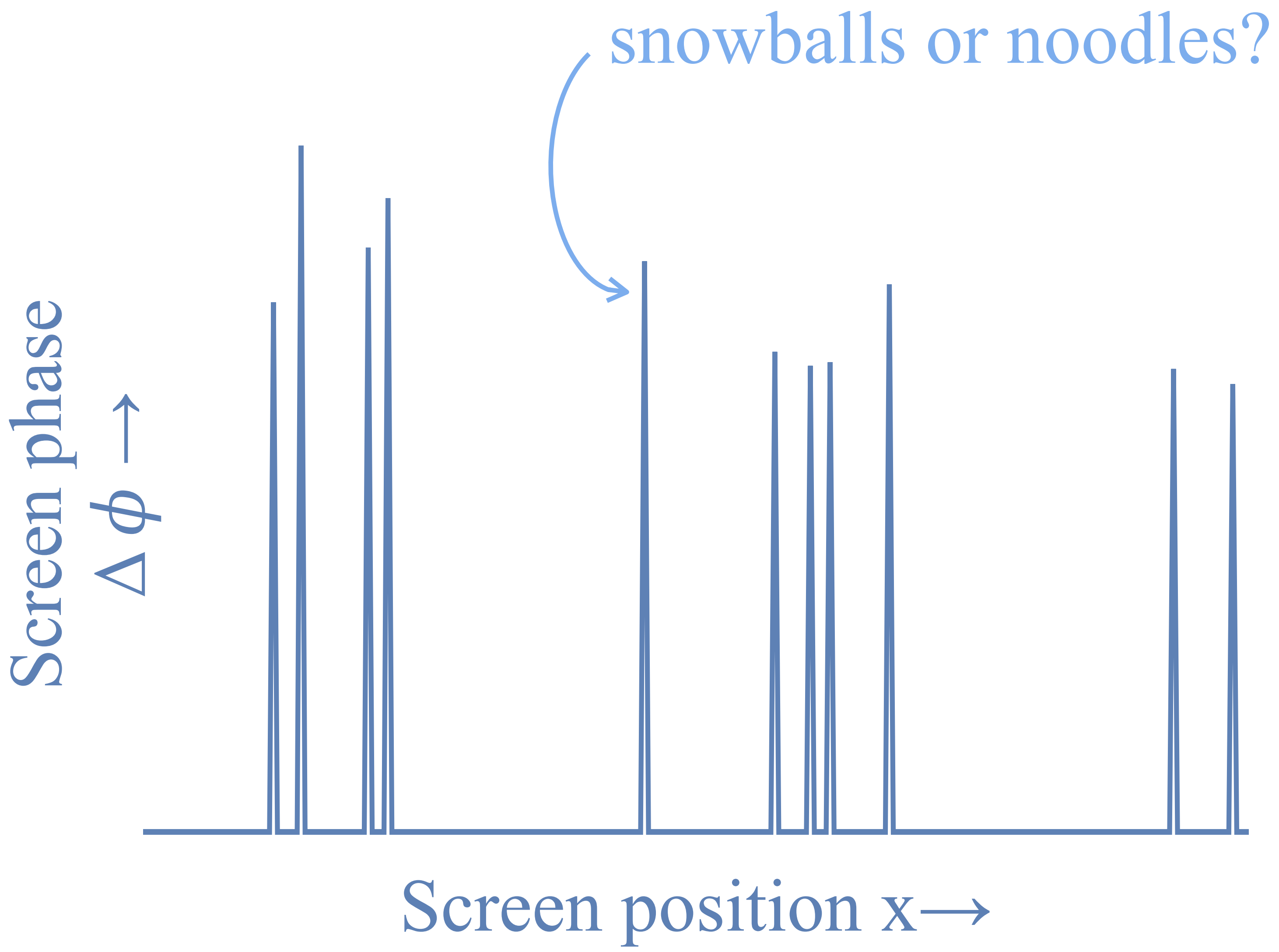

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- Ground-based VLBI tends to confirm this picture
- Despite several efforts, we did not attain sufficient sensitivity to observe parabolic arcs with RadioAstron-ground baselines

Next Generation VLBI Observations

Questions for you:

Noodles and Snowballs

- How would an extragalatic radio source appear, if seen through a screen containing just a few (<100) plasma noodles?
- Could effects of scattering by just a few scatterers be removed? What would that require?

  Interesting fact about convolution:

  Effects of scattering are always a convolution (sometimes averaged during or after observations). This is a code so simple that only a fool would use it to communicate over the Internet.

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Theoretical issues

- What does *refractive* scattering look like, if we drop the assumption that ϕ is drawn from a Gaussian distribution at each point?
- Can we gain more information on source structure, from refractive and diffractive scattering? What observations do we need?