Quantum Assisted Intensity Interferometry: Unlocking Ultra-High-Resolution Astrophysical Phenomena

Quantum Assisted Intensity Interferometry:

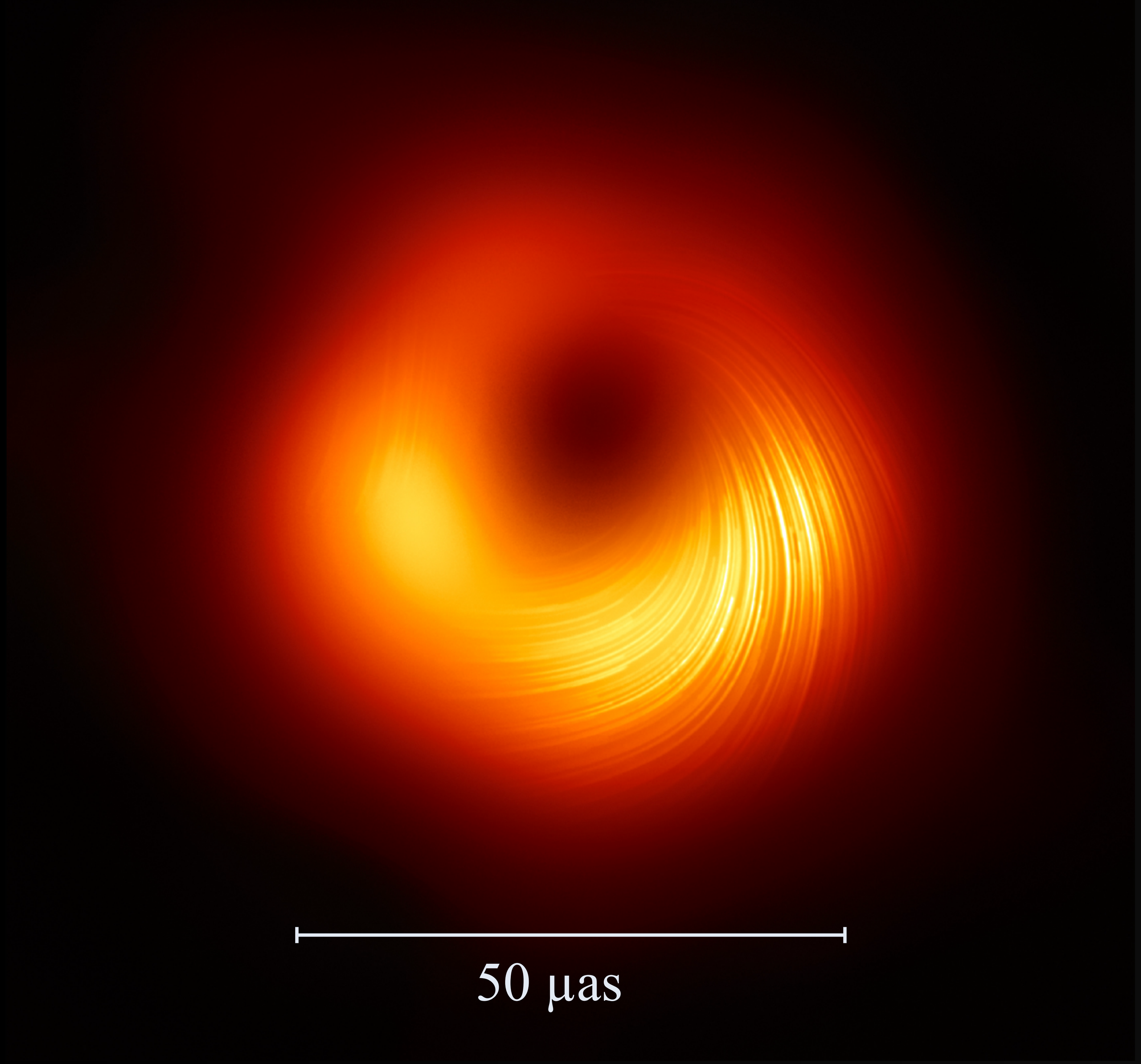
Unlocking Ultra-High-Resolution Astrophysical

- *Interested in witnessing a supernova explosion or measuring the accretion disk of a binary system or an active galactic nucleus (AGN)?*
- *How about observing the inner jets of Blazars?*
- *If you are interested how these once-elusive phenomena are now within reach, let me show you how it possible with Quantum Assisted Intensity Interferometry*

UNIVERS… DE GEN… FACULTÉ DES SCIENCES

The Picture of the decade

M87 imaged with polarised light



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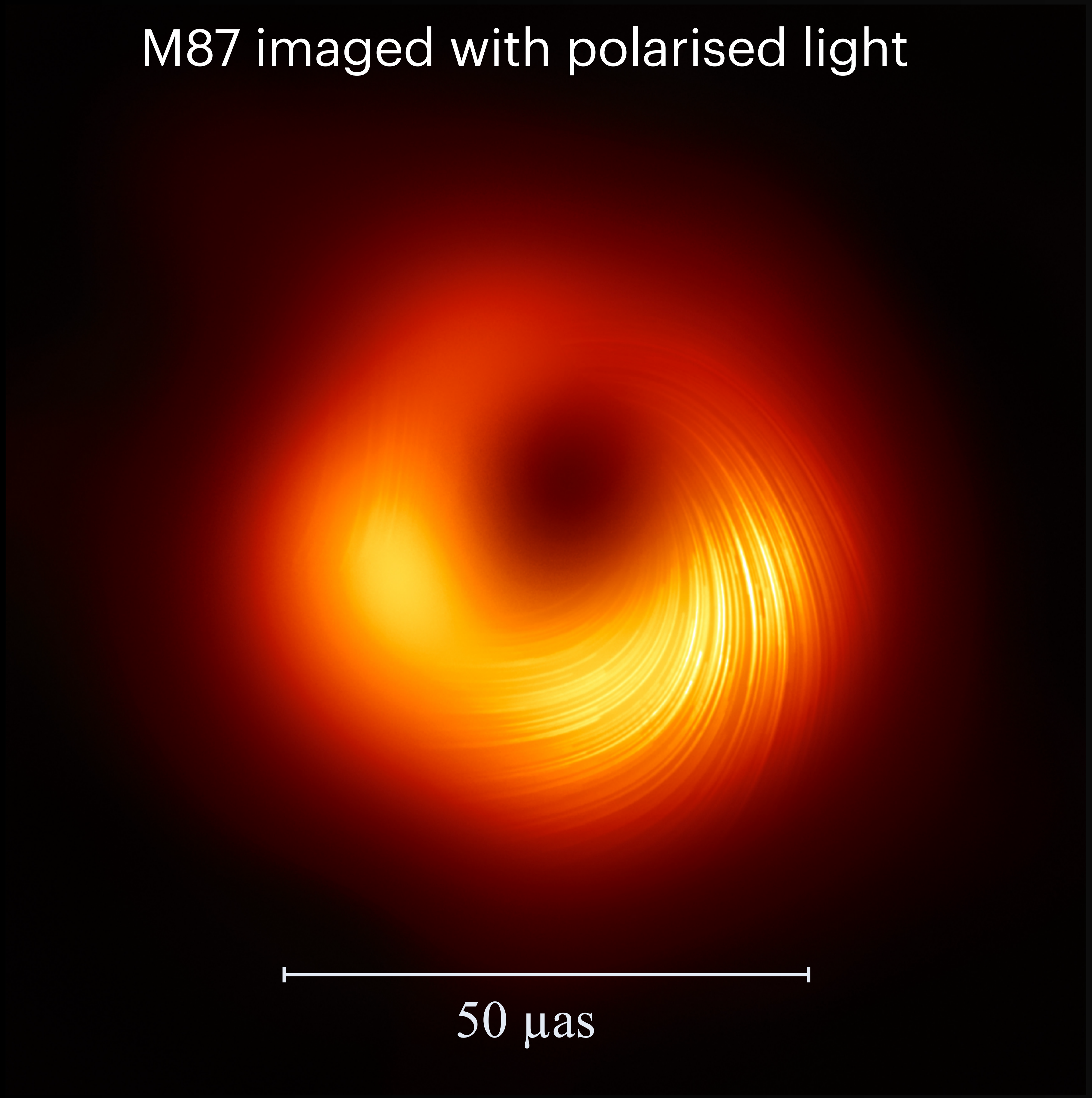

- *Achieved in radio by VLBI (Very long baseline interferometry) ~10'000 km baselines*
- *Amplitude interferometry*

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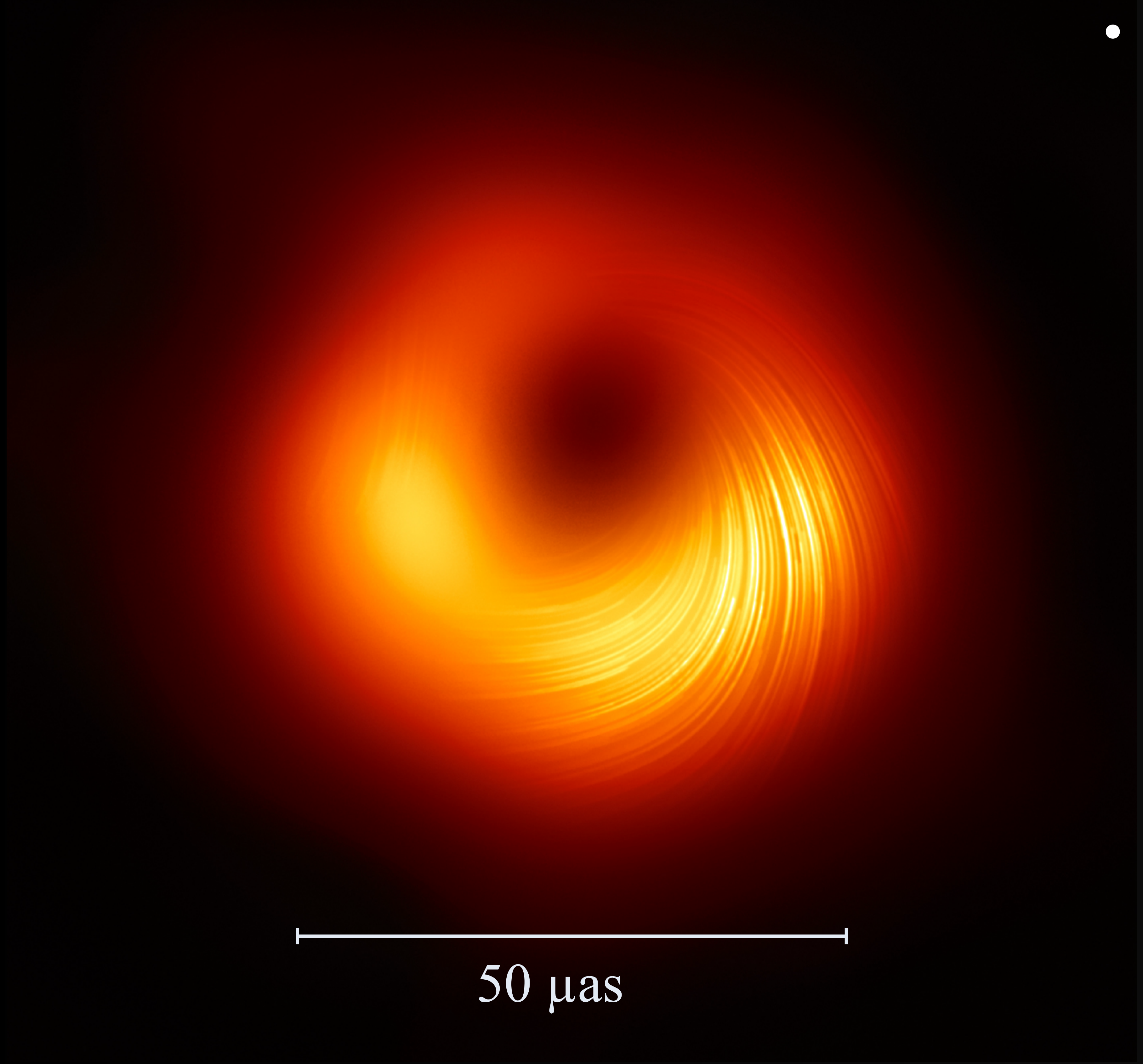

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- Ordinary Imaging Resolution $\sim \lambda / D$ D = *telescope diameter:*
  - Human Eye/Radio Telescopes: ~arcminutes
  - Optical Telescopes: ~50 milliarcseconds (mas)

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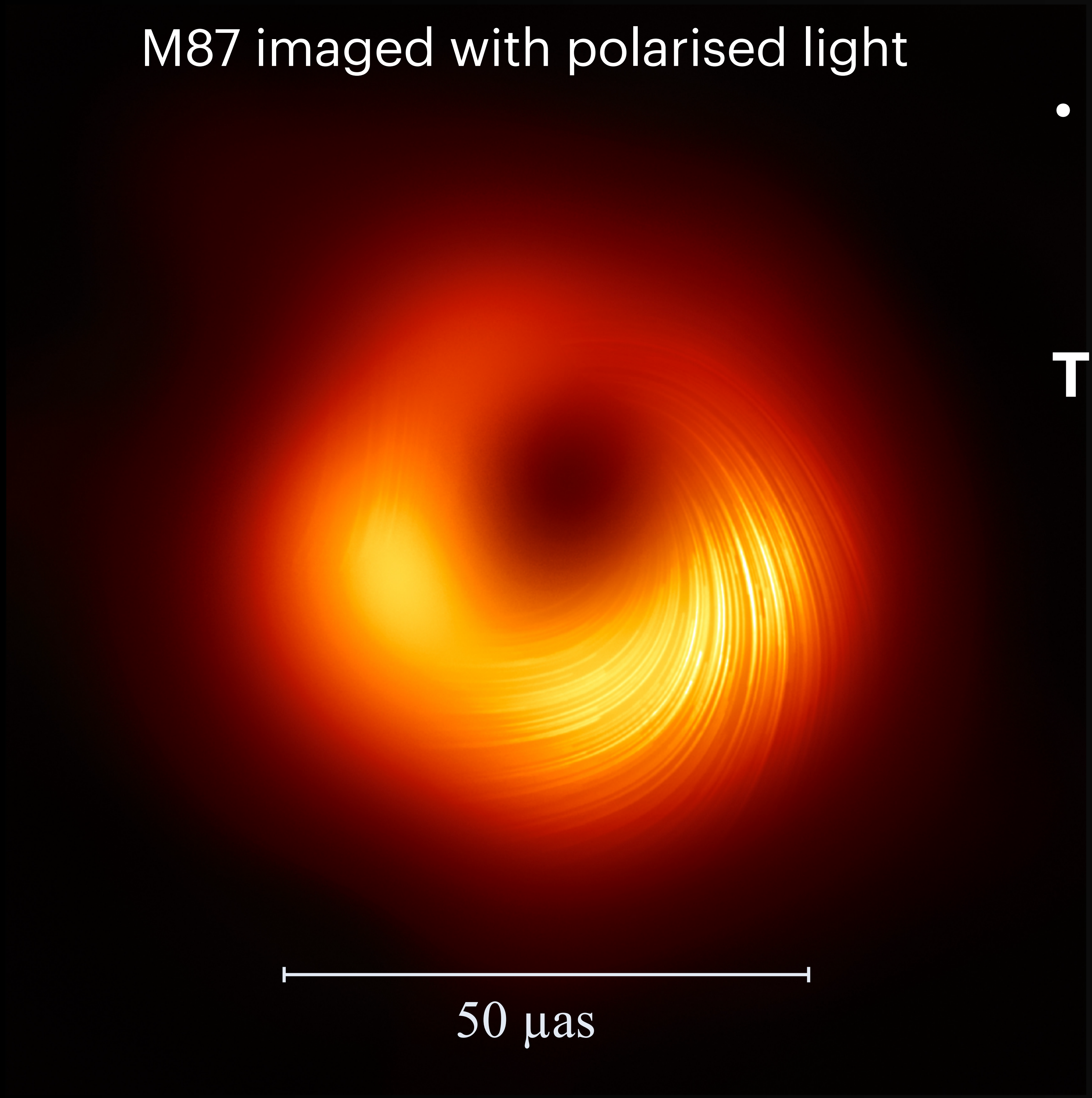

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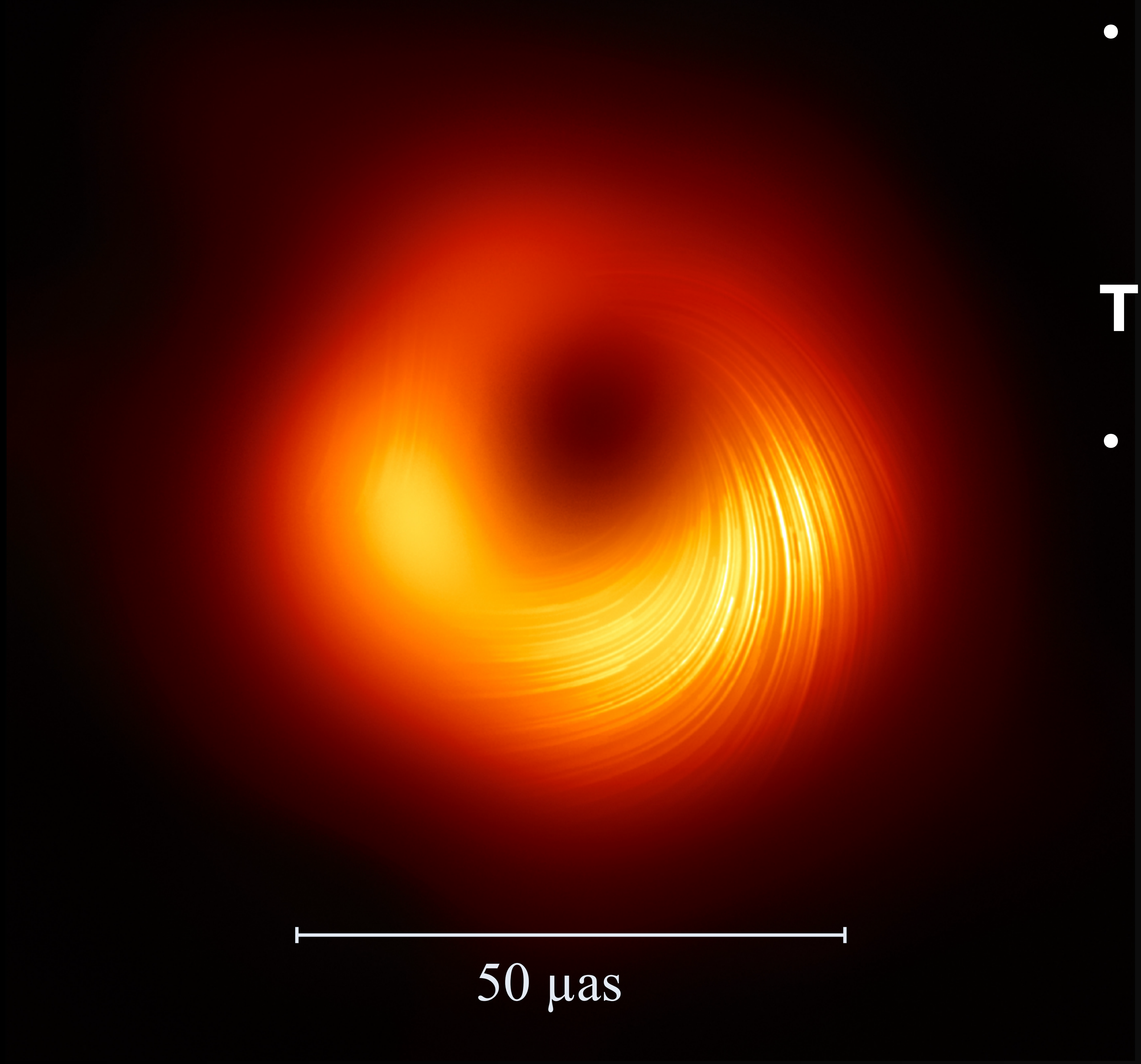

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  - ✓ Longer baselines = Higher angular resolution ⇒ $\sim 50\ \mu as$
  - ✗ No directly make images
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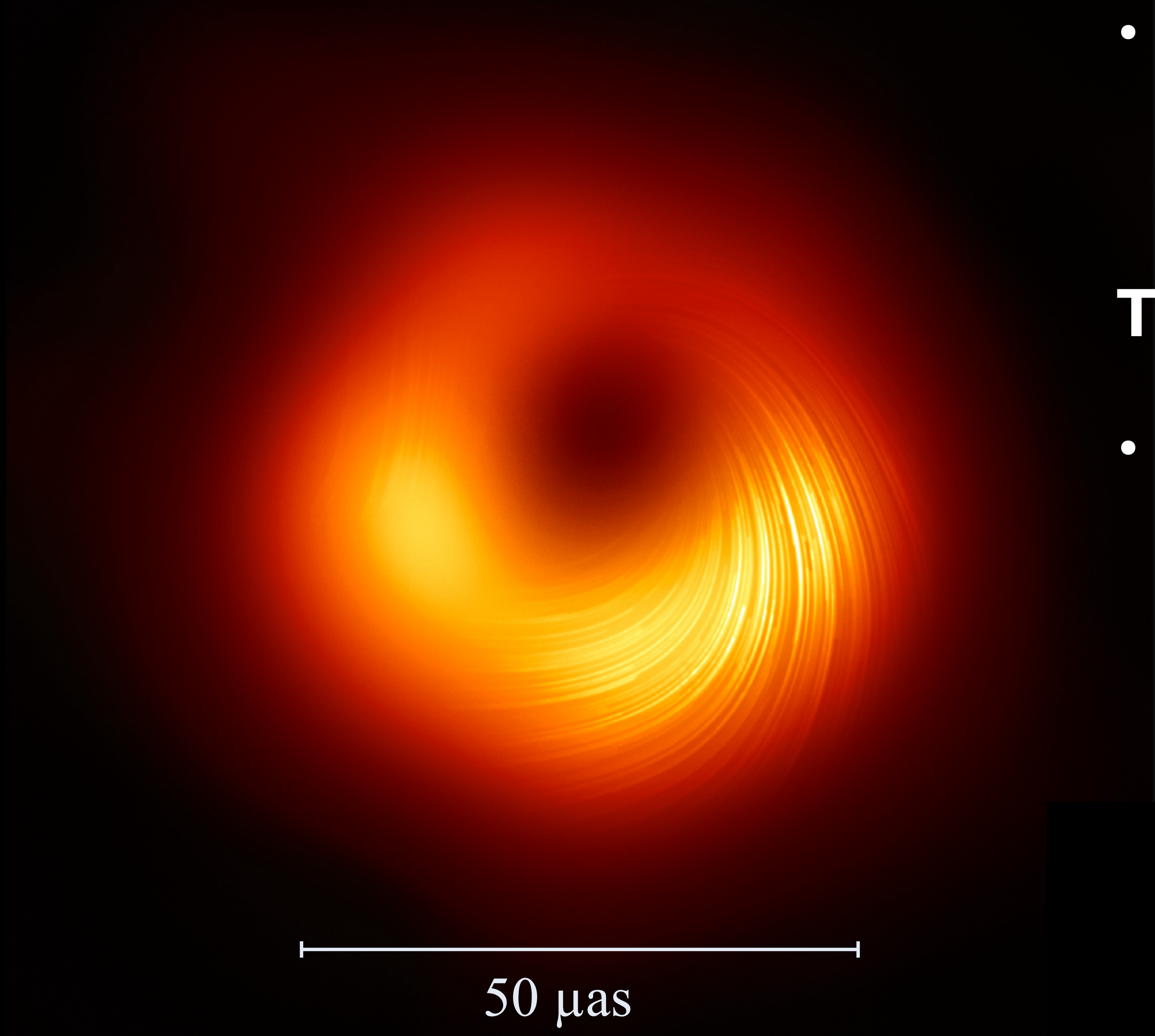

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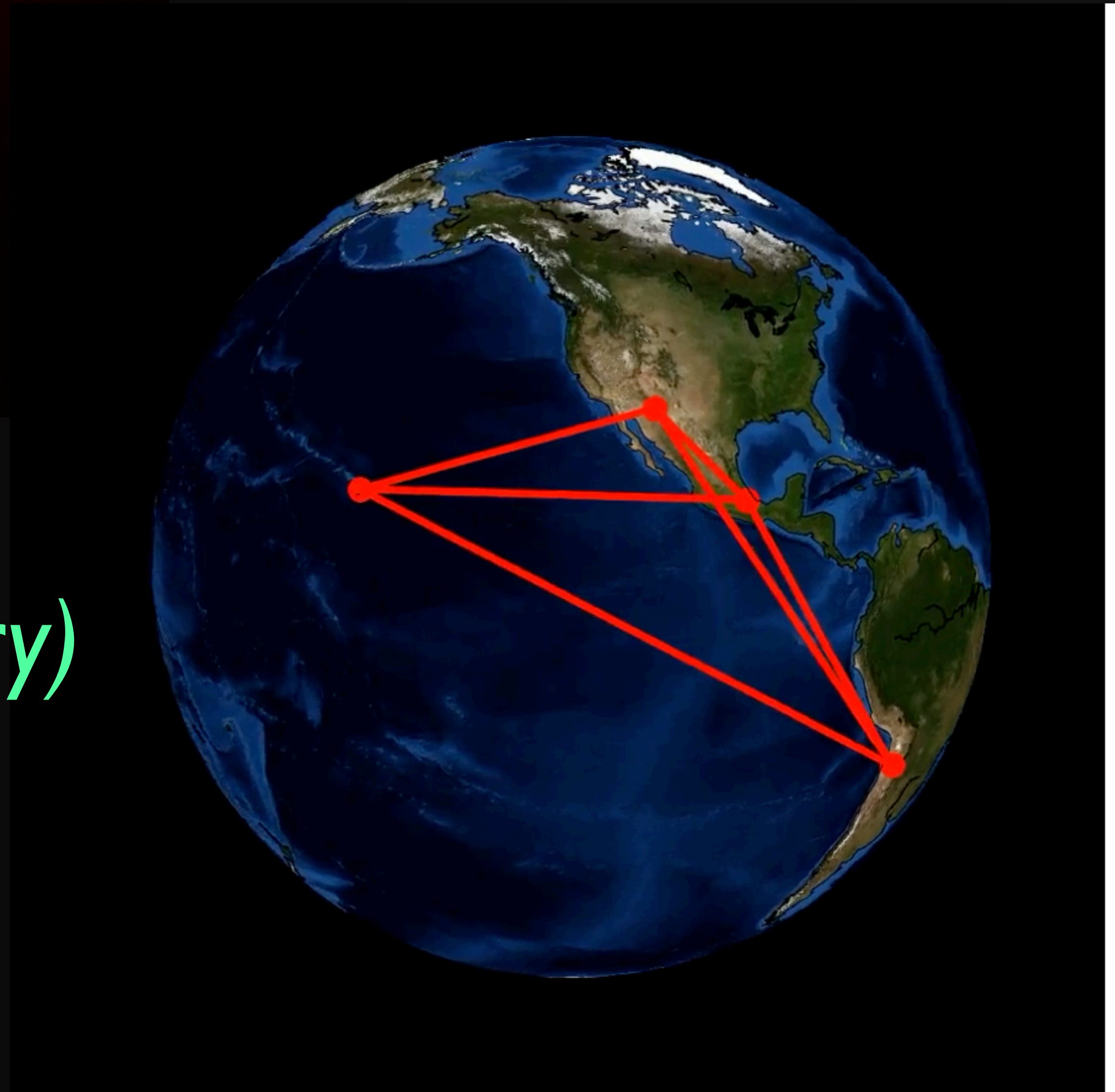

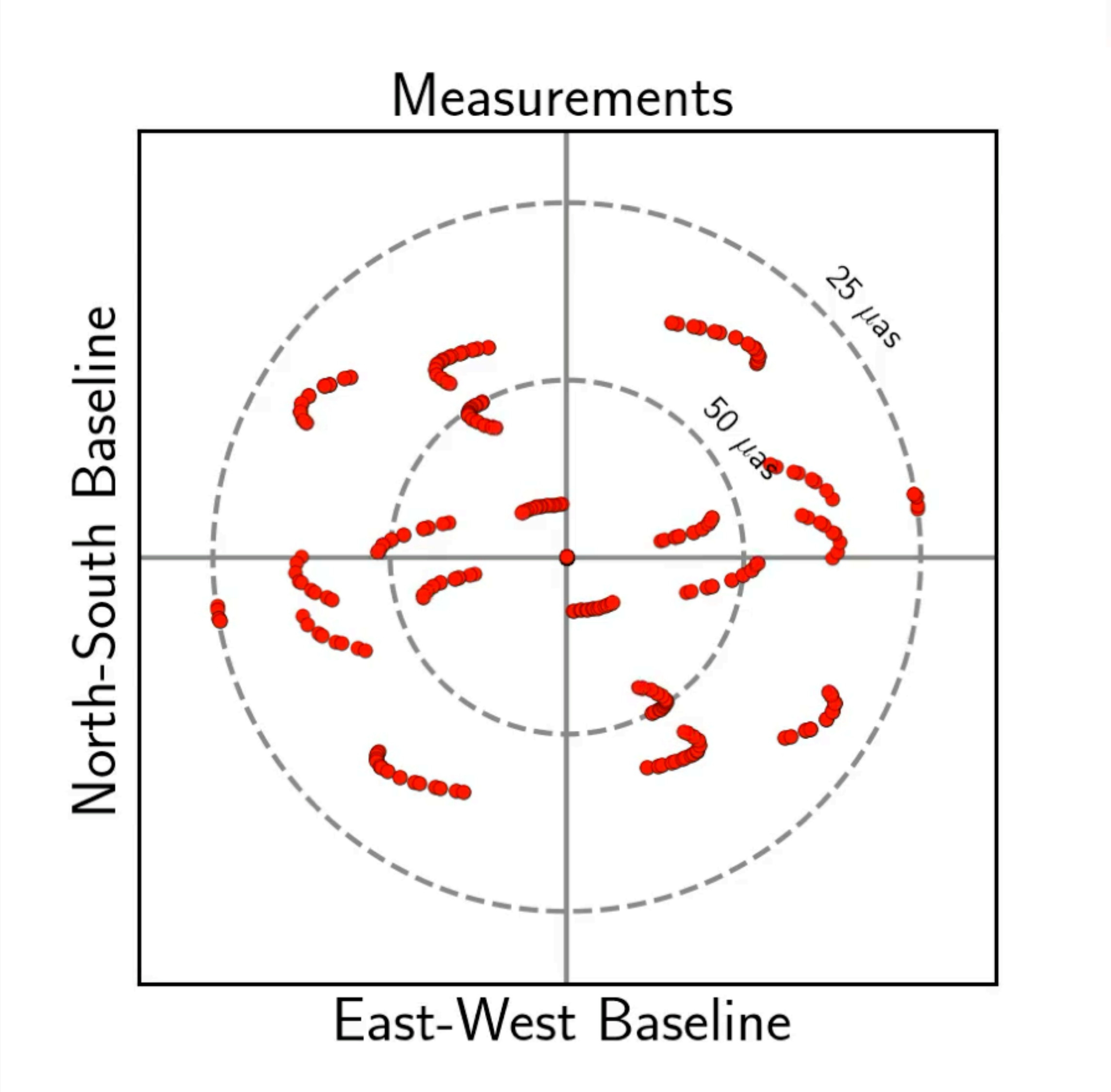

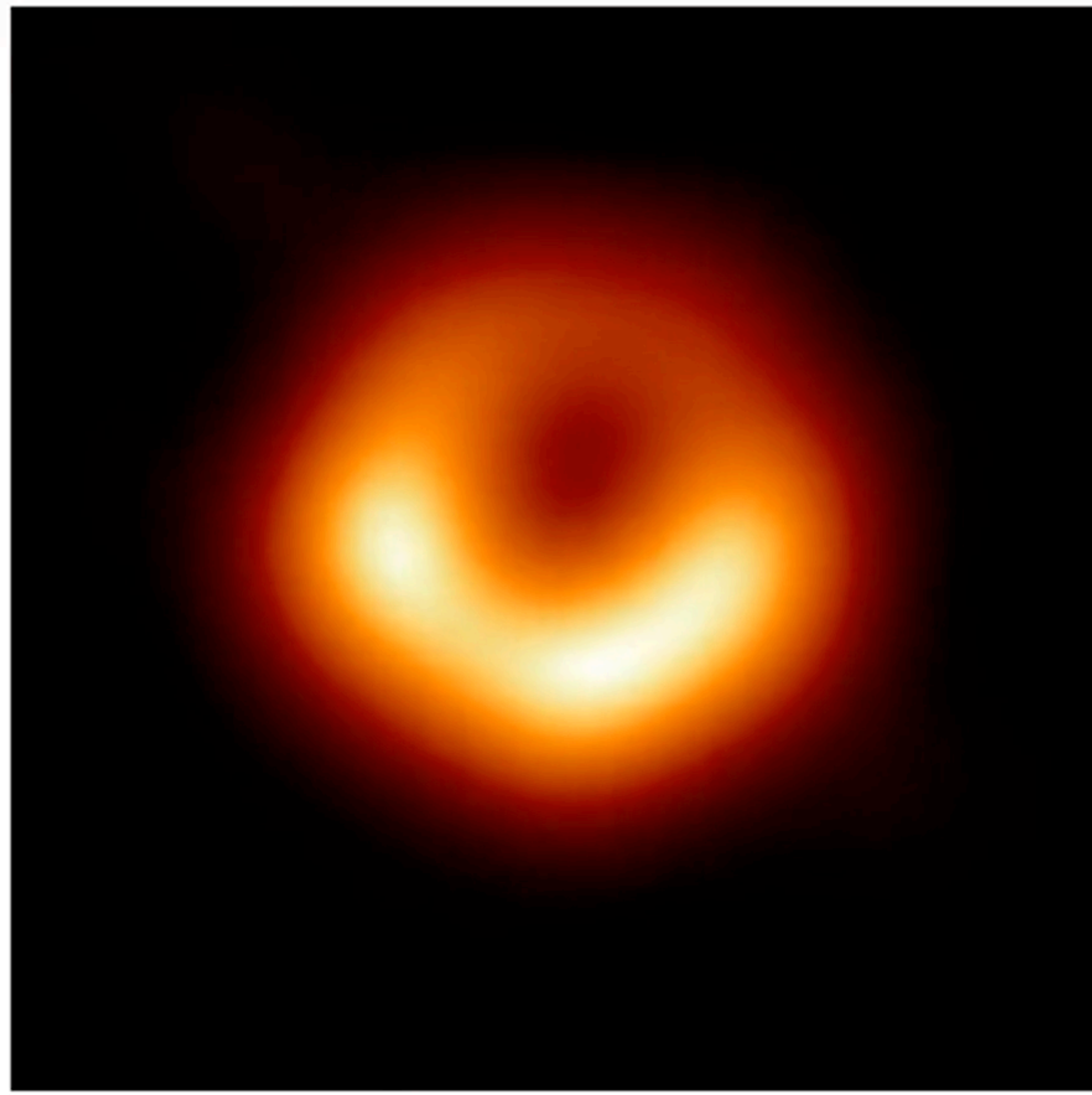

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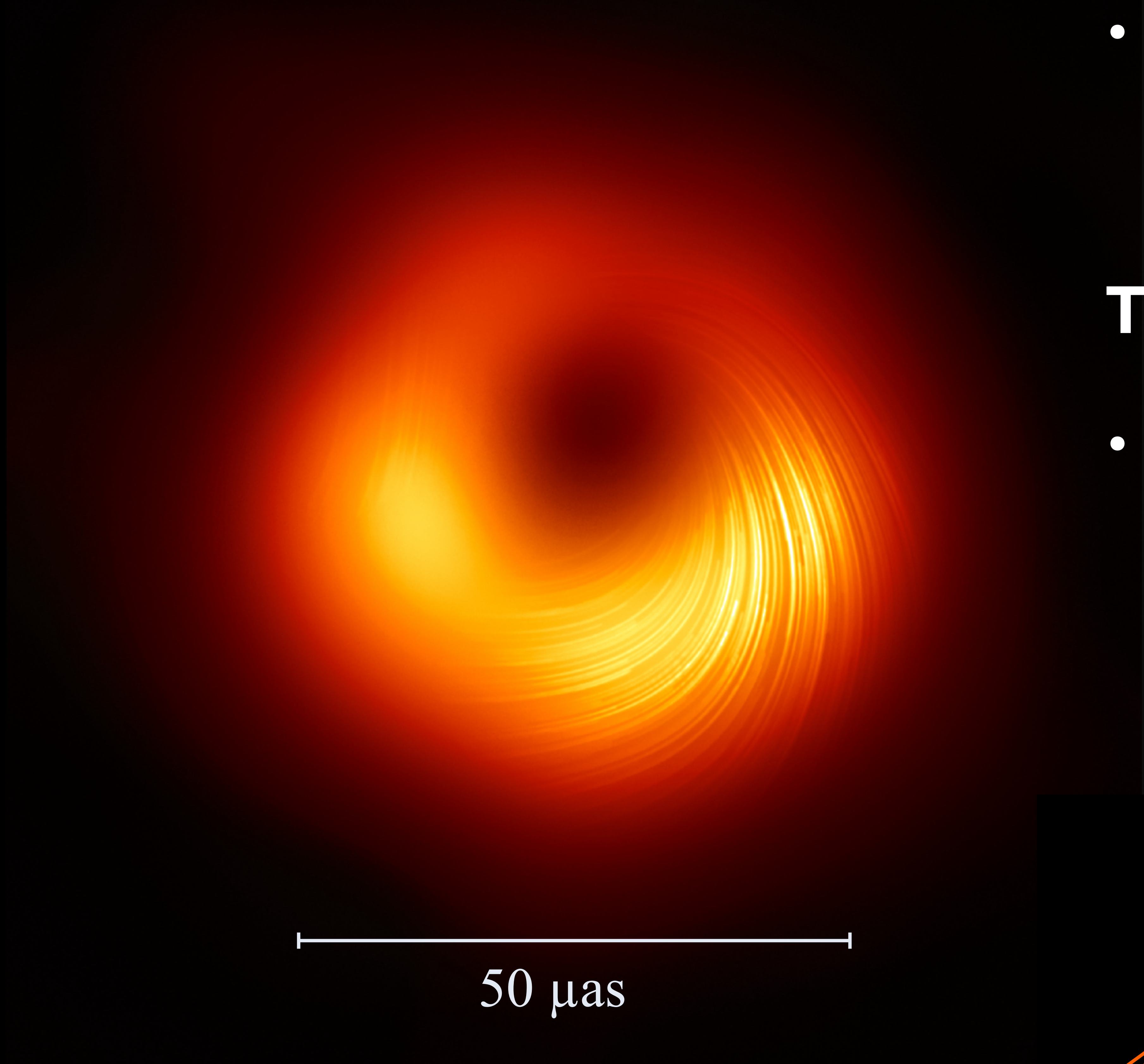

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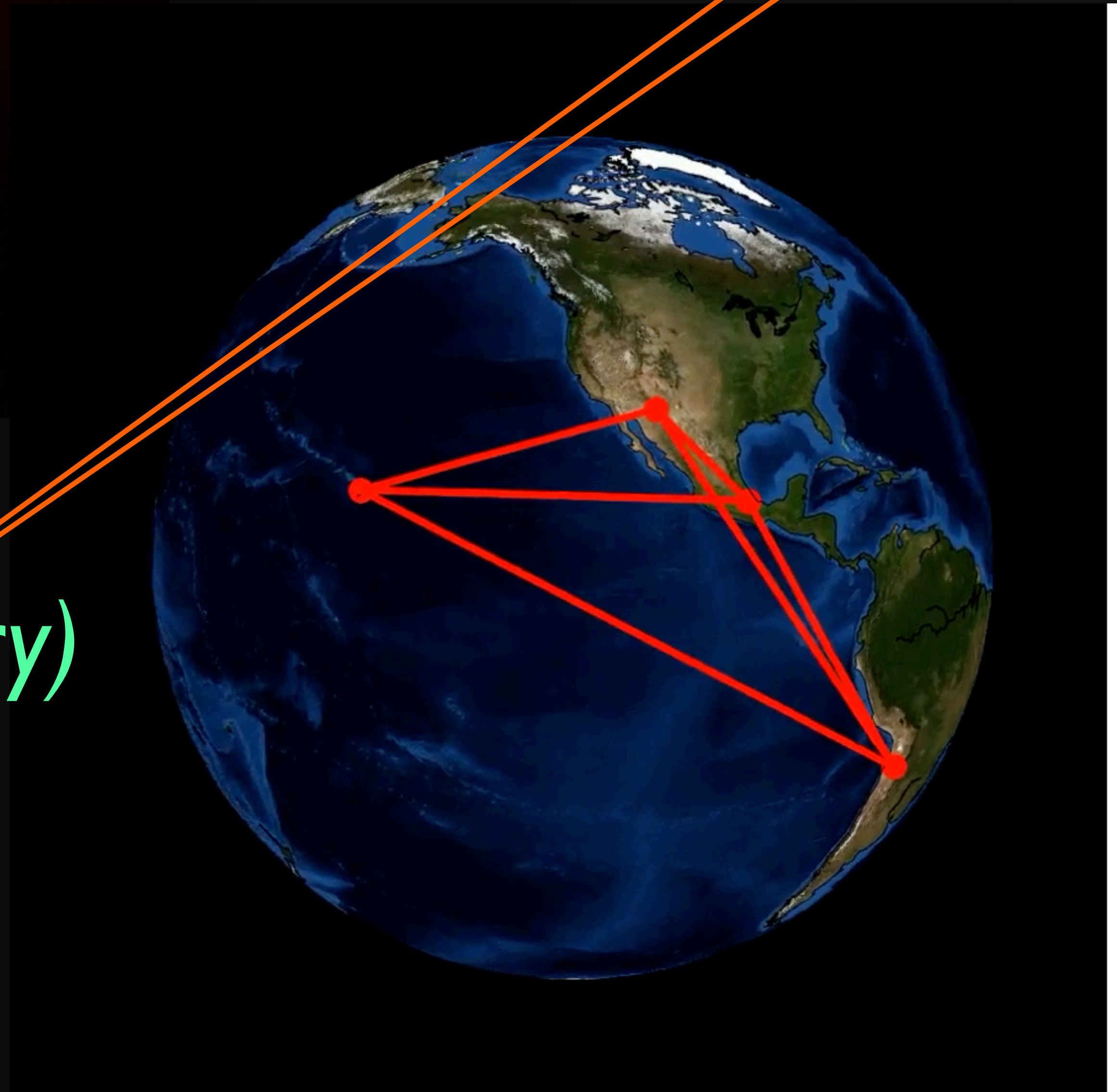

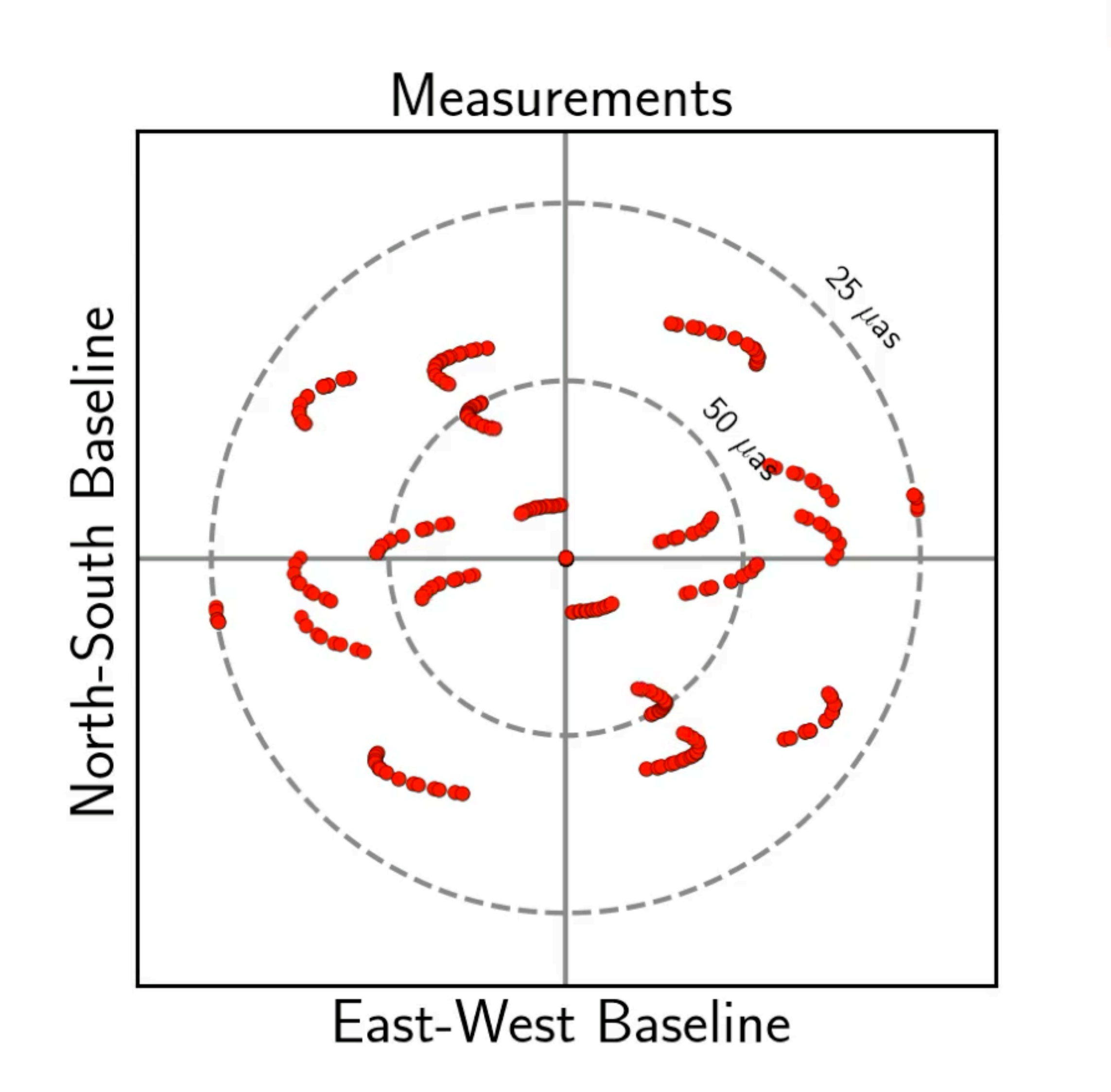

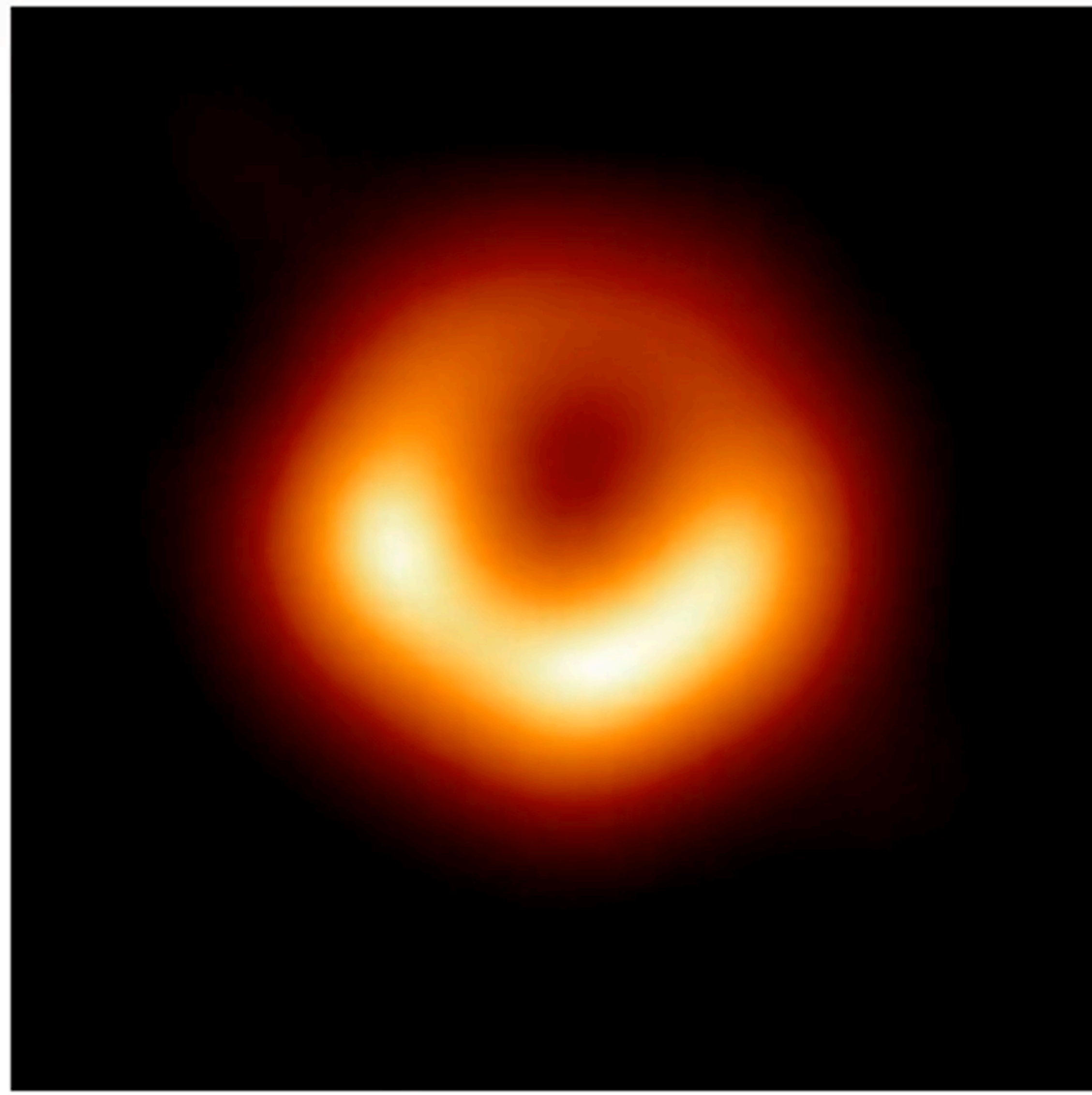

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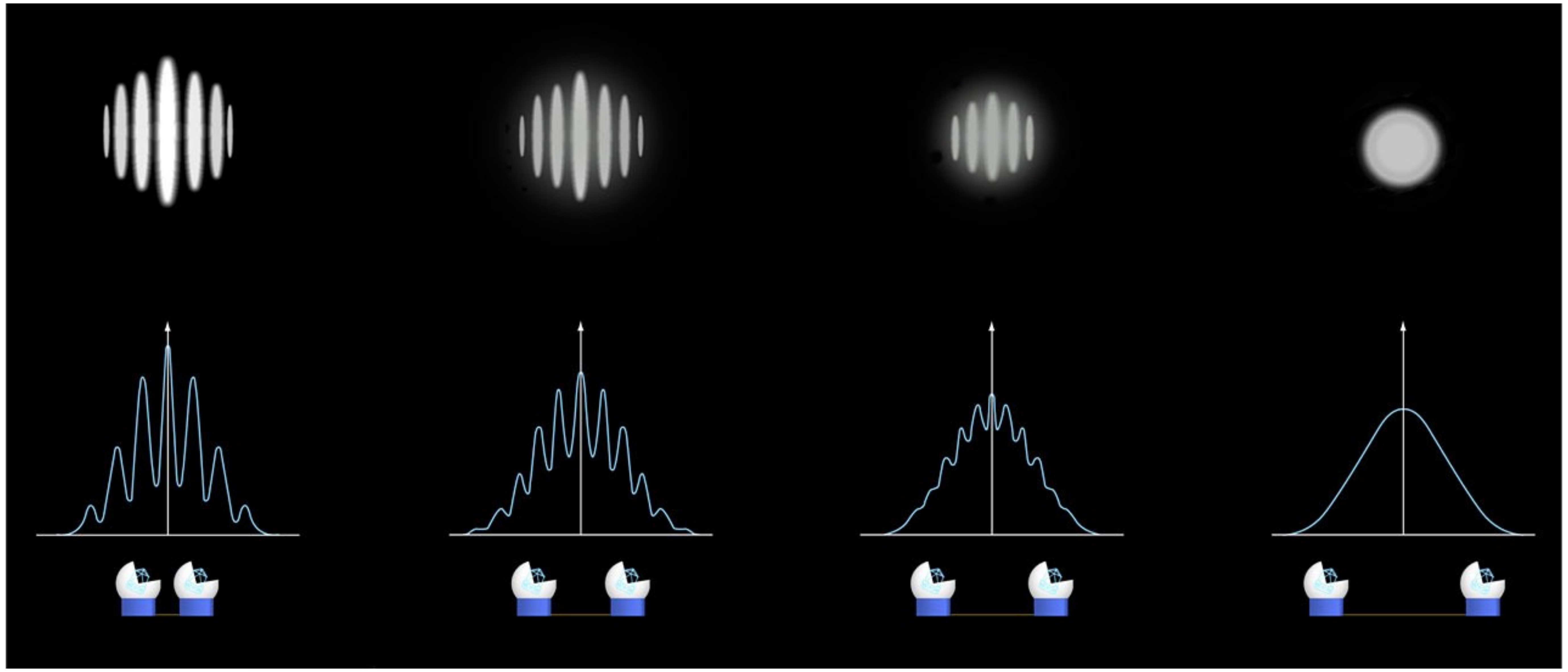

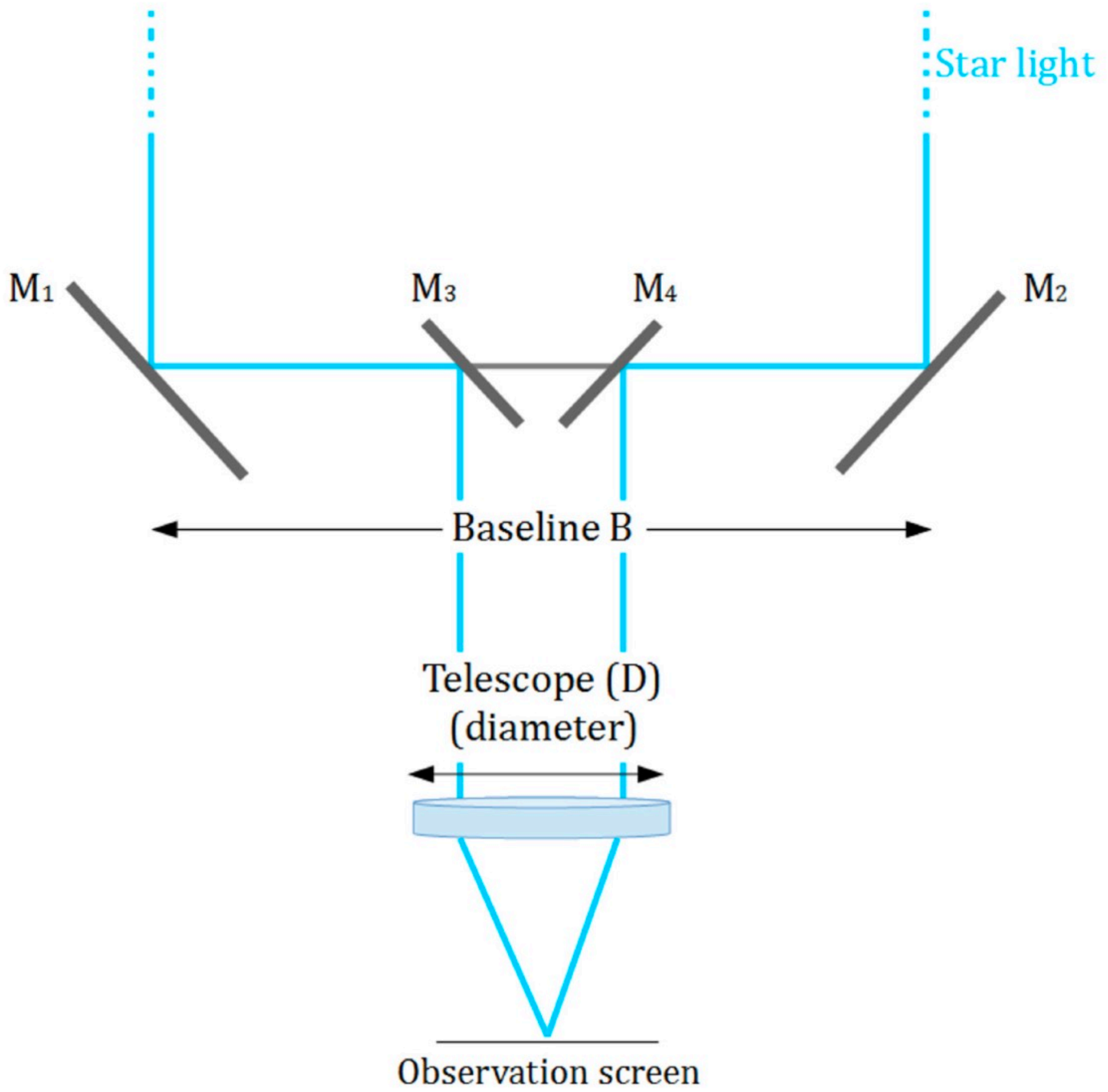

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Optical of interferometry is currently limited to:

- Baseline of hundreds of meters (light path), 100 µas.
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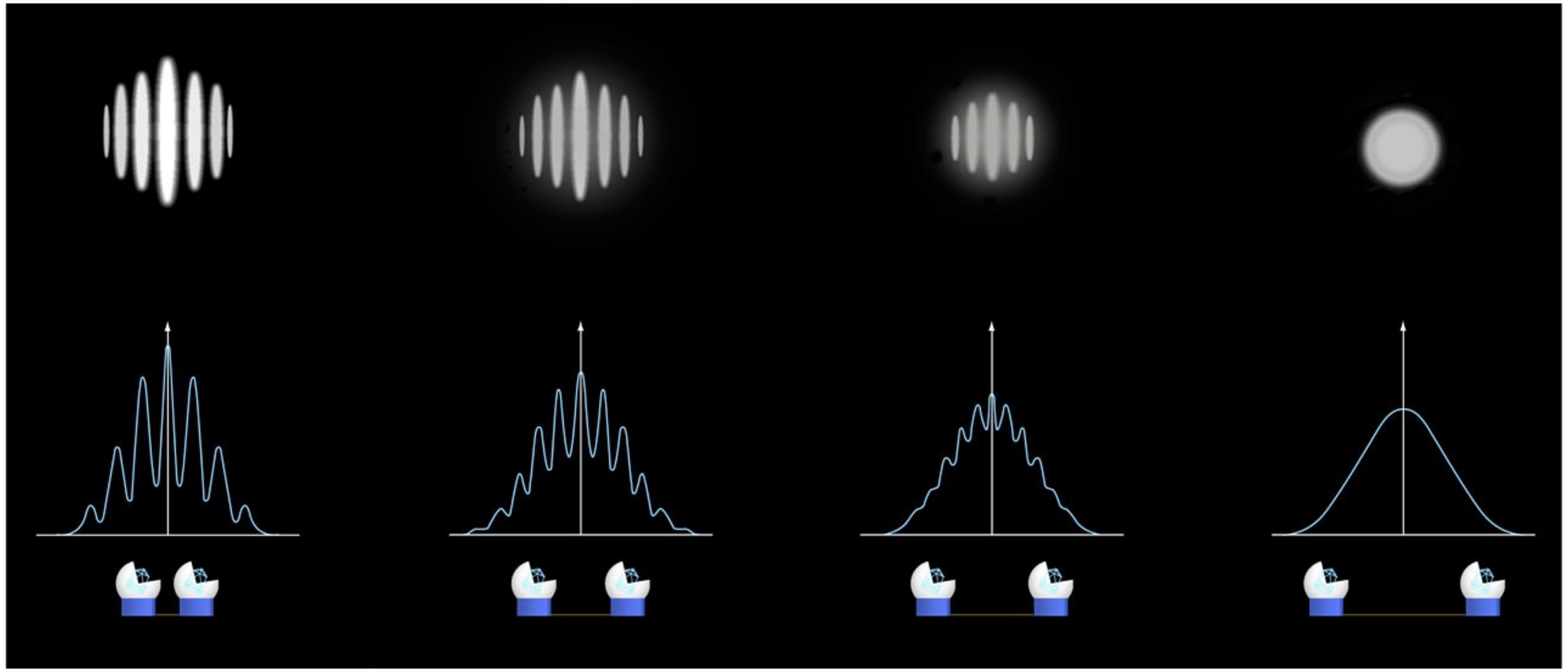
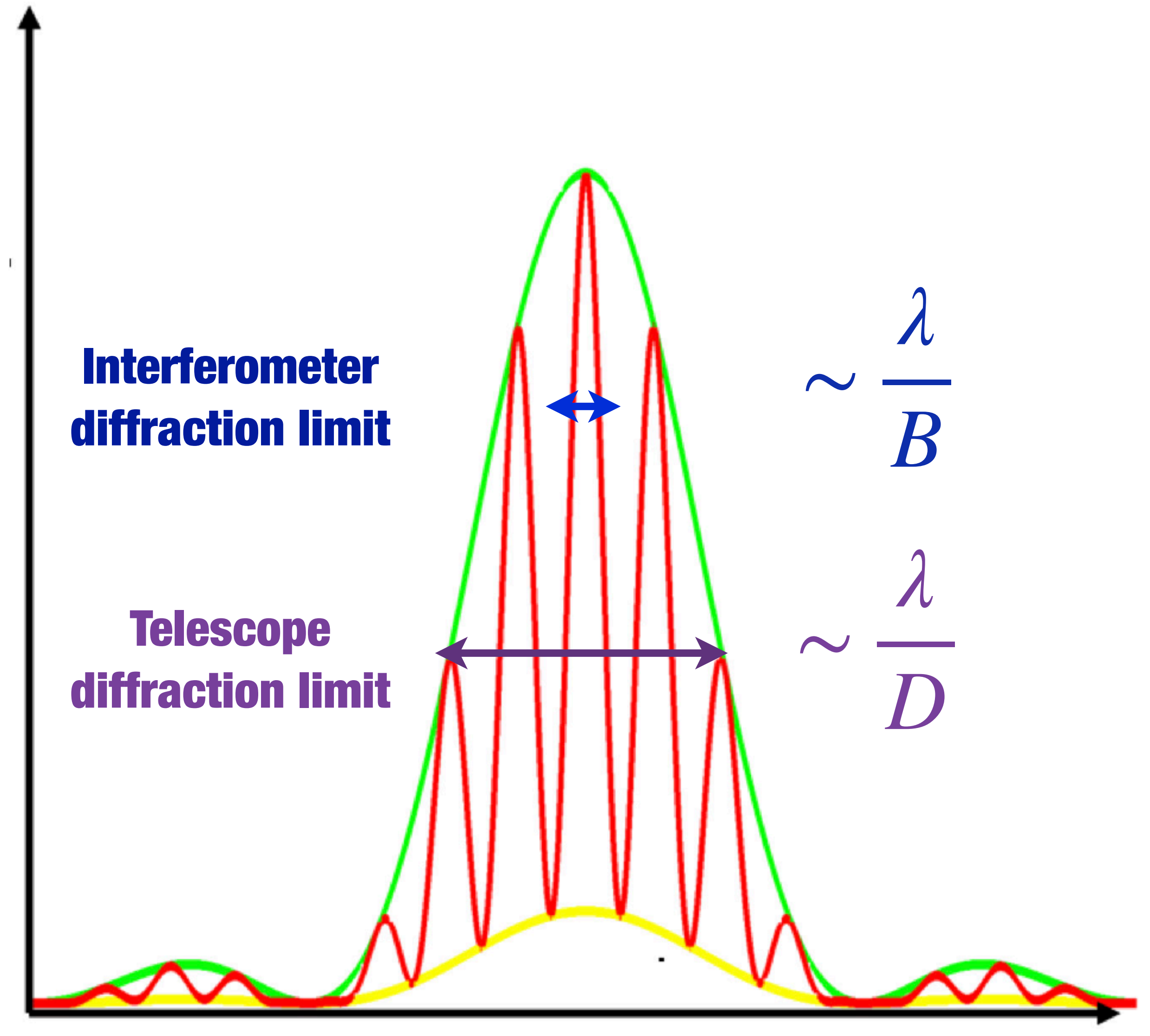
Double slit fringe visibility =2 point source





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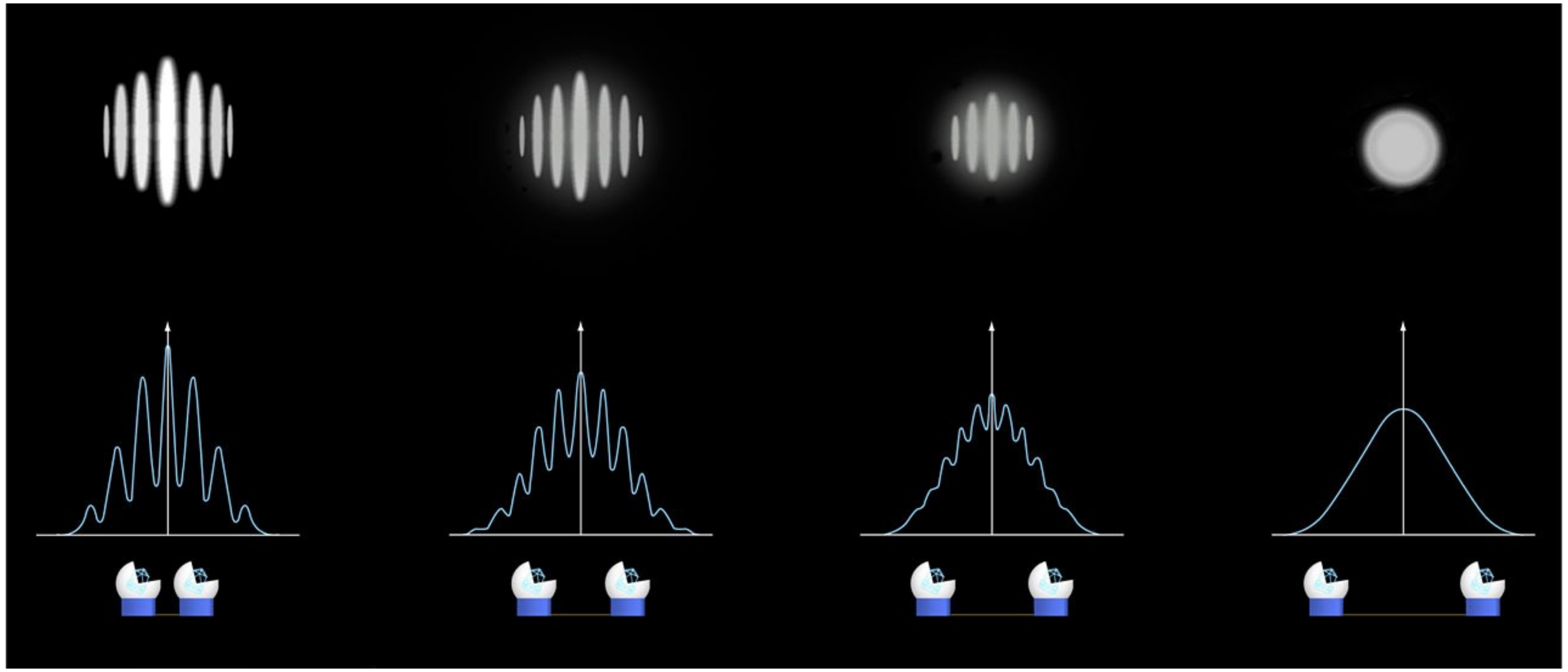

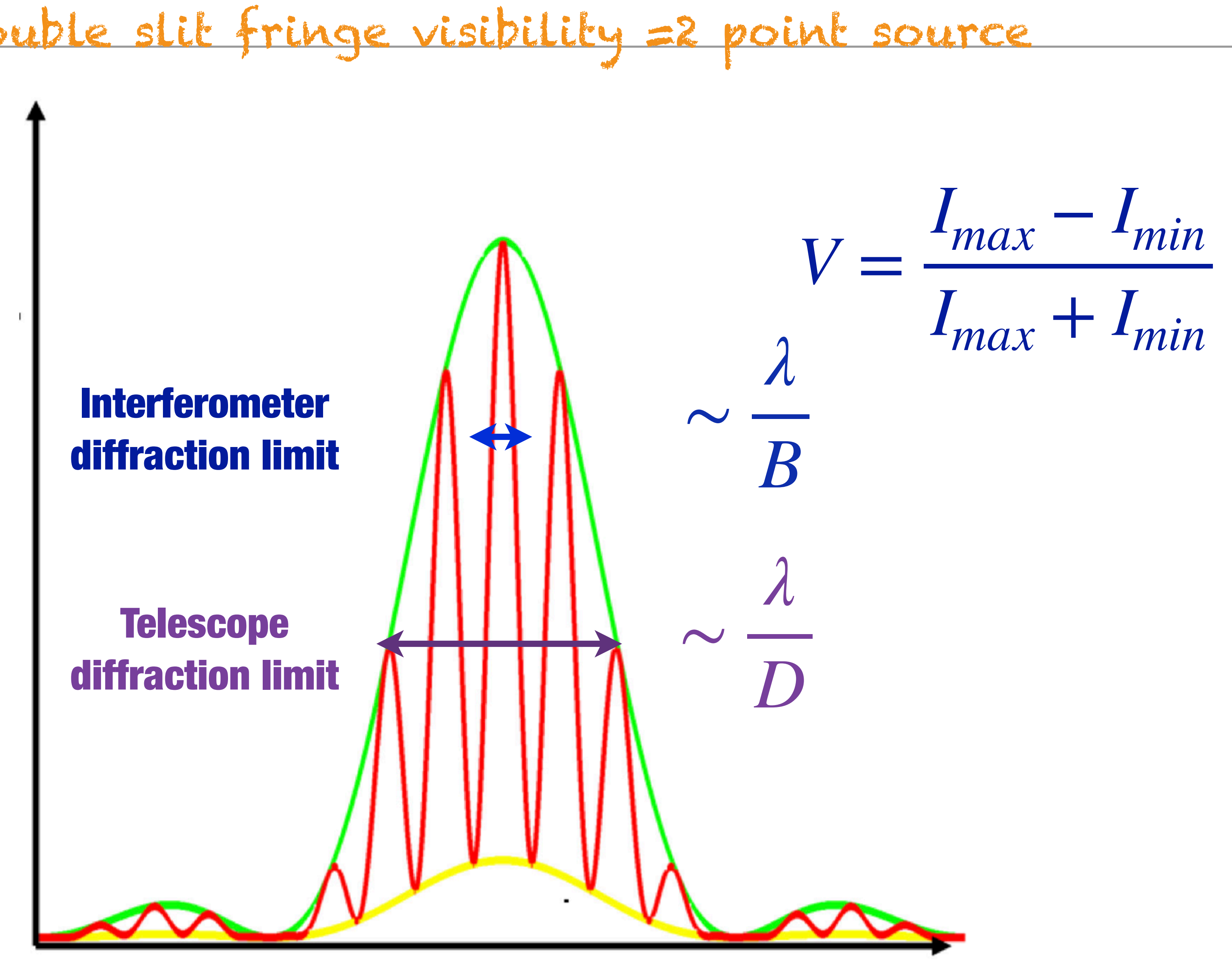

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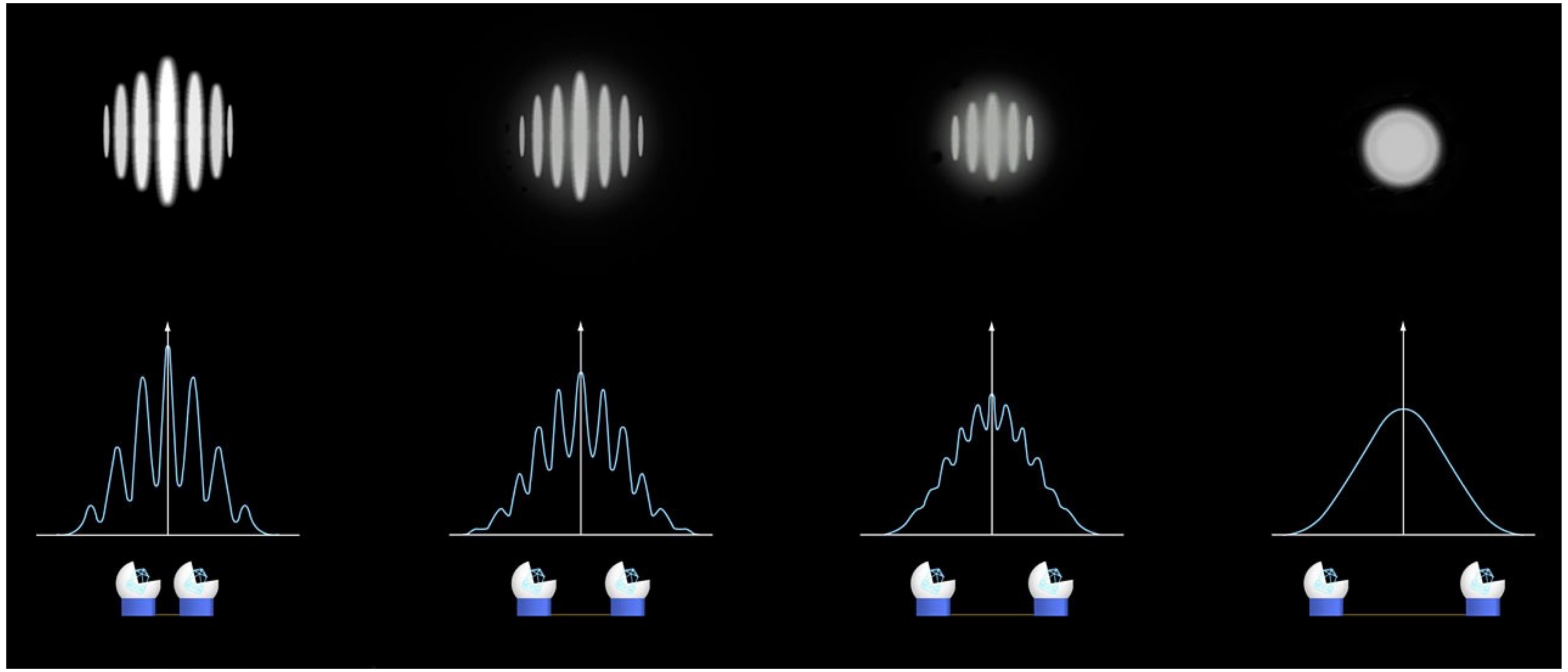

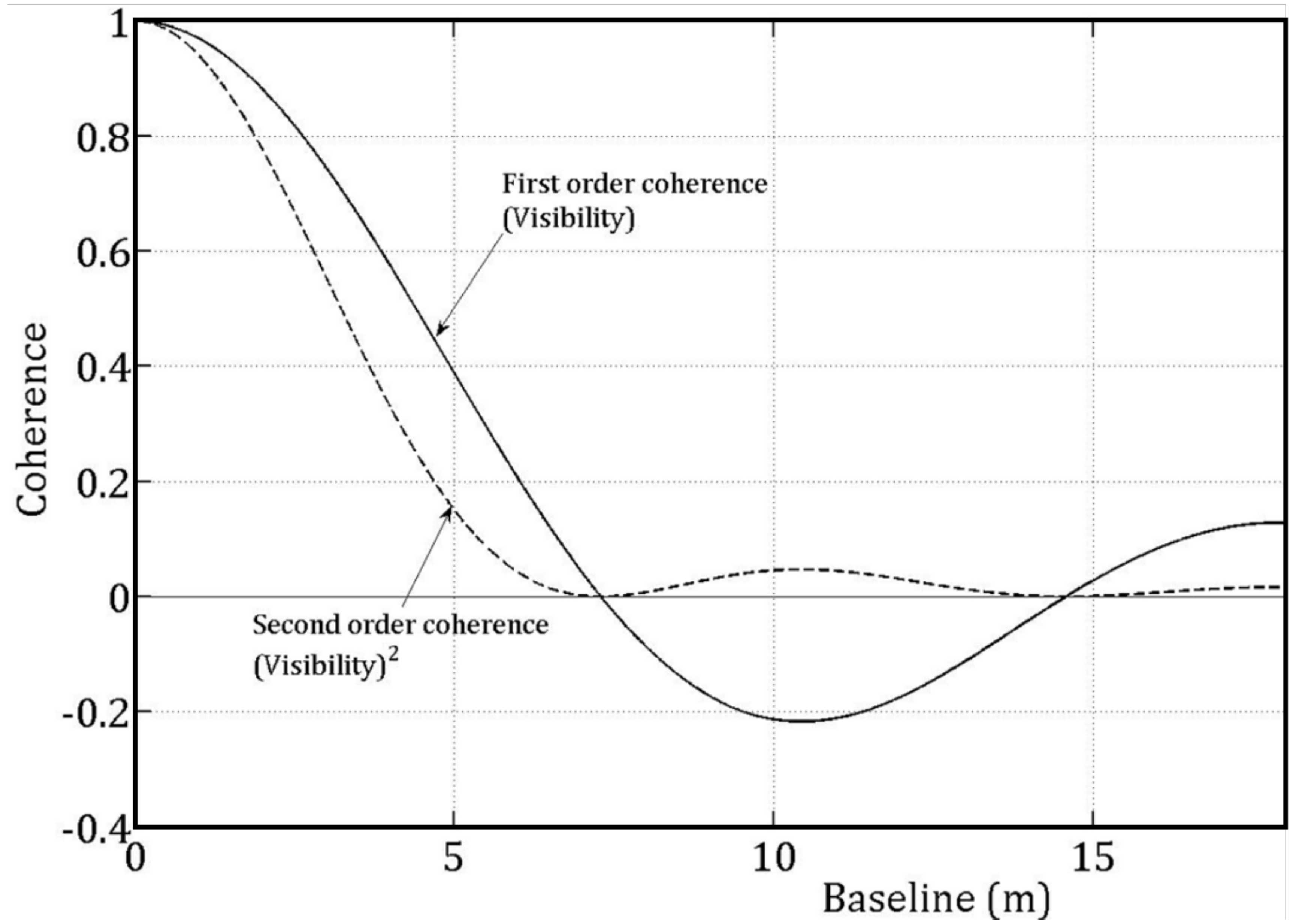

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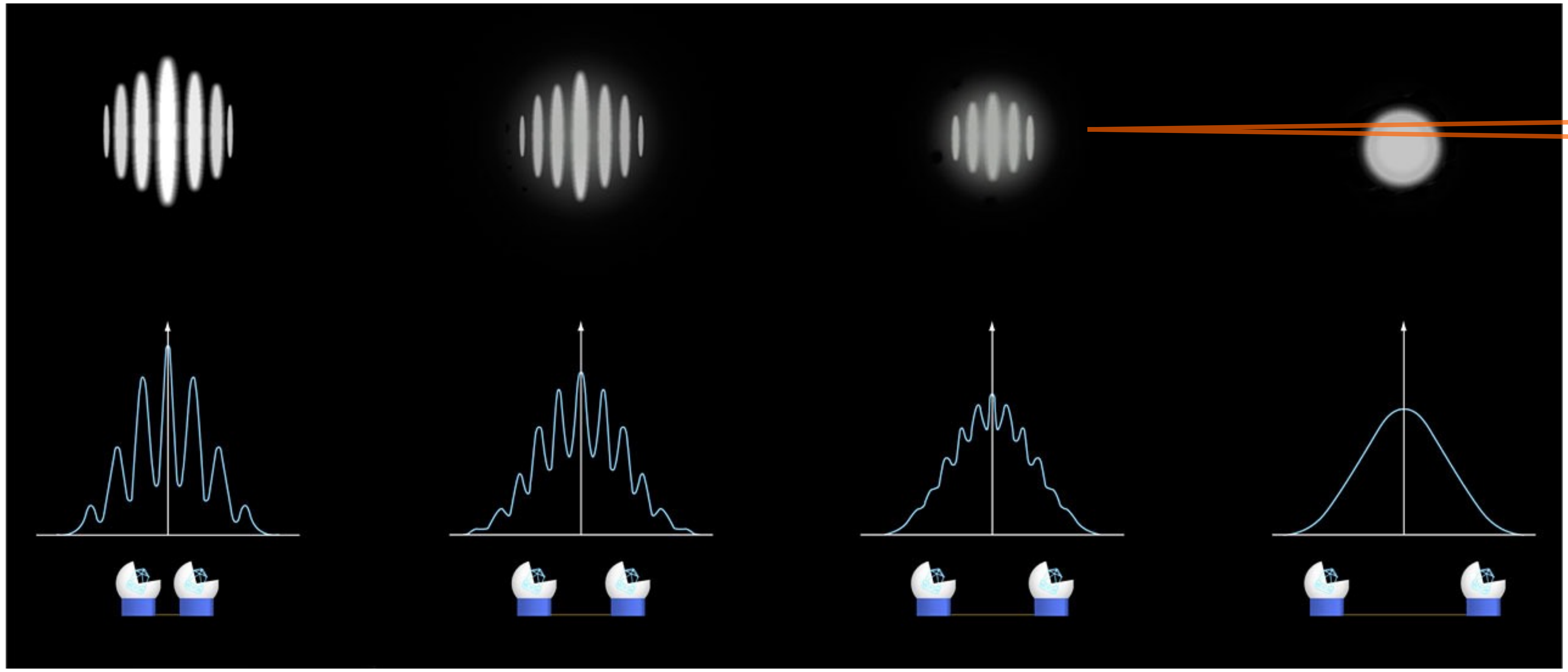

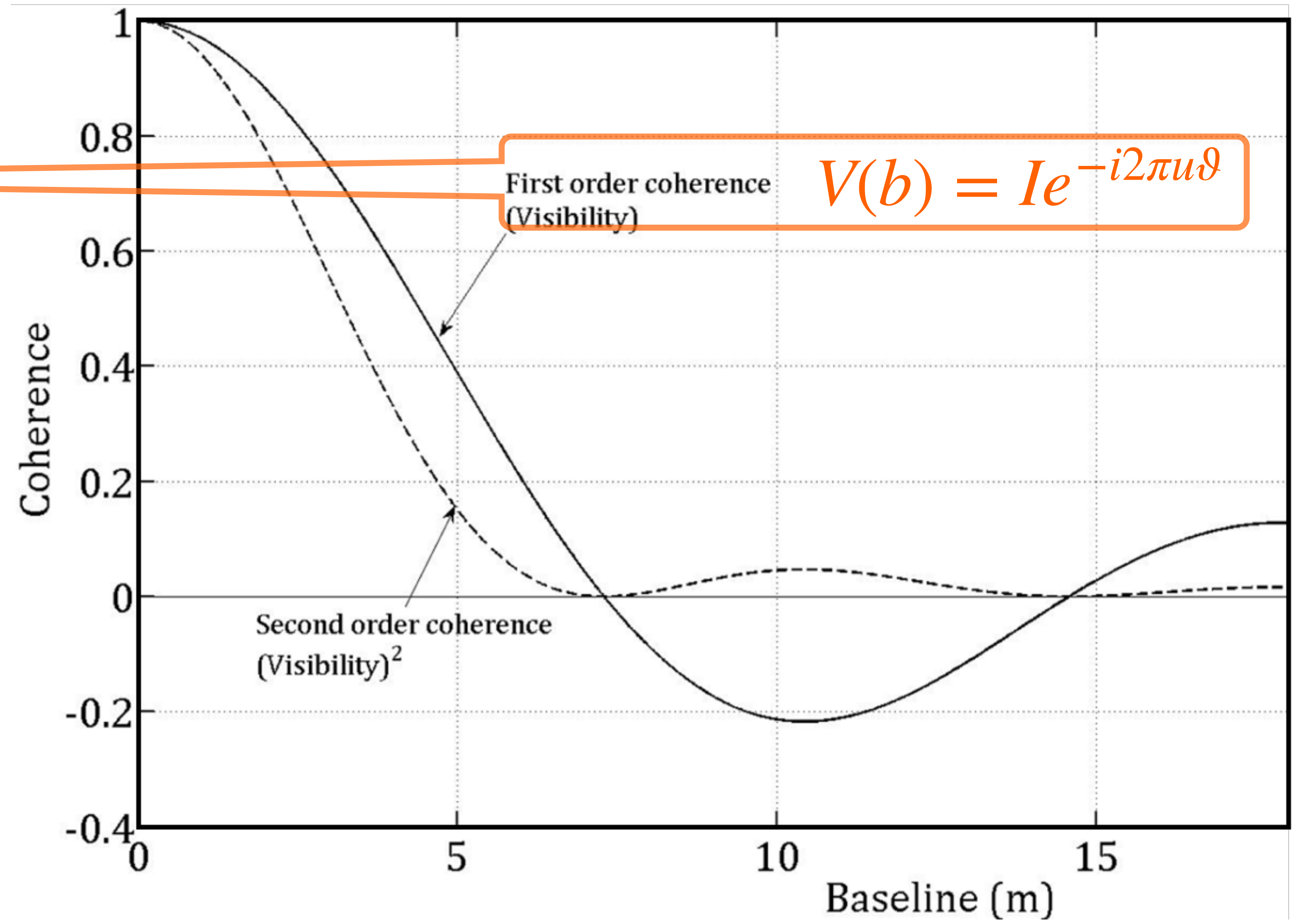

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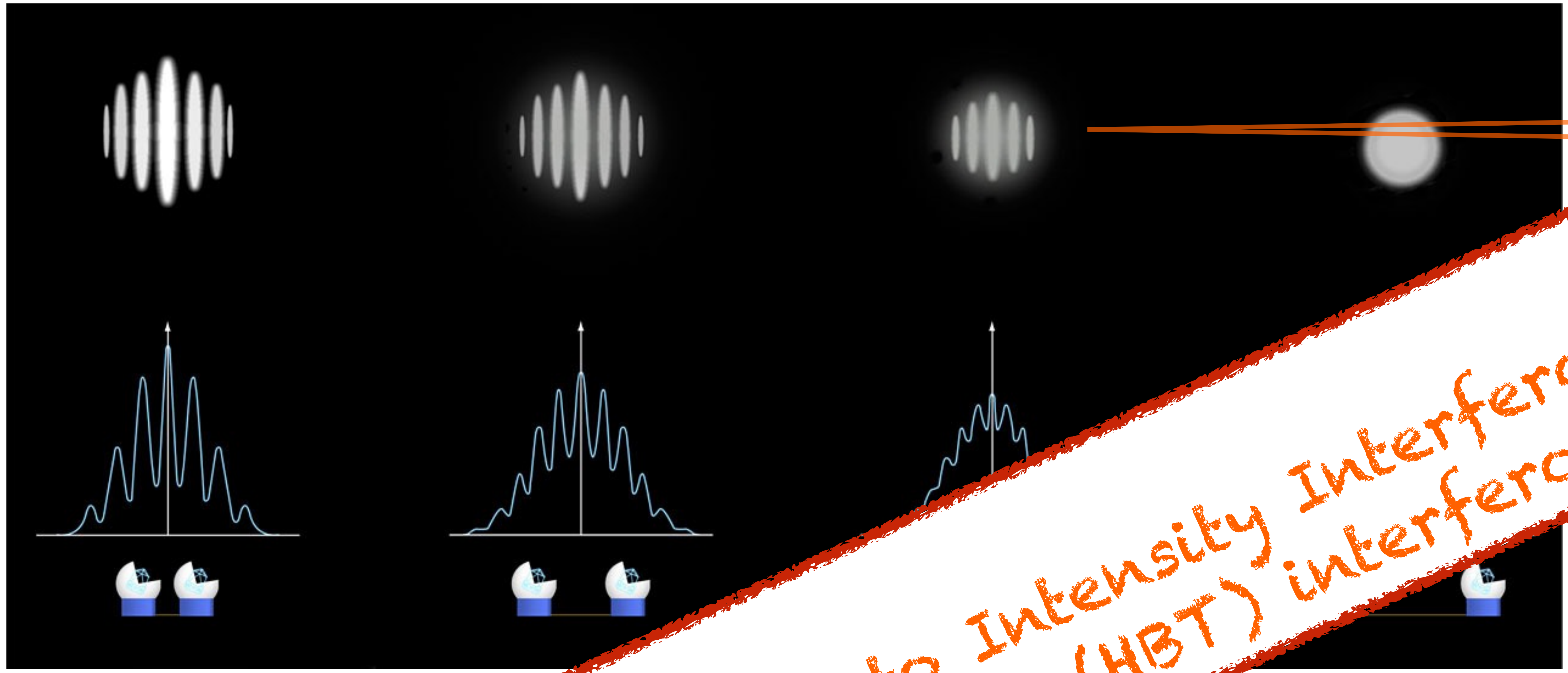

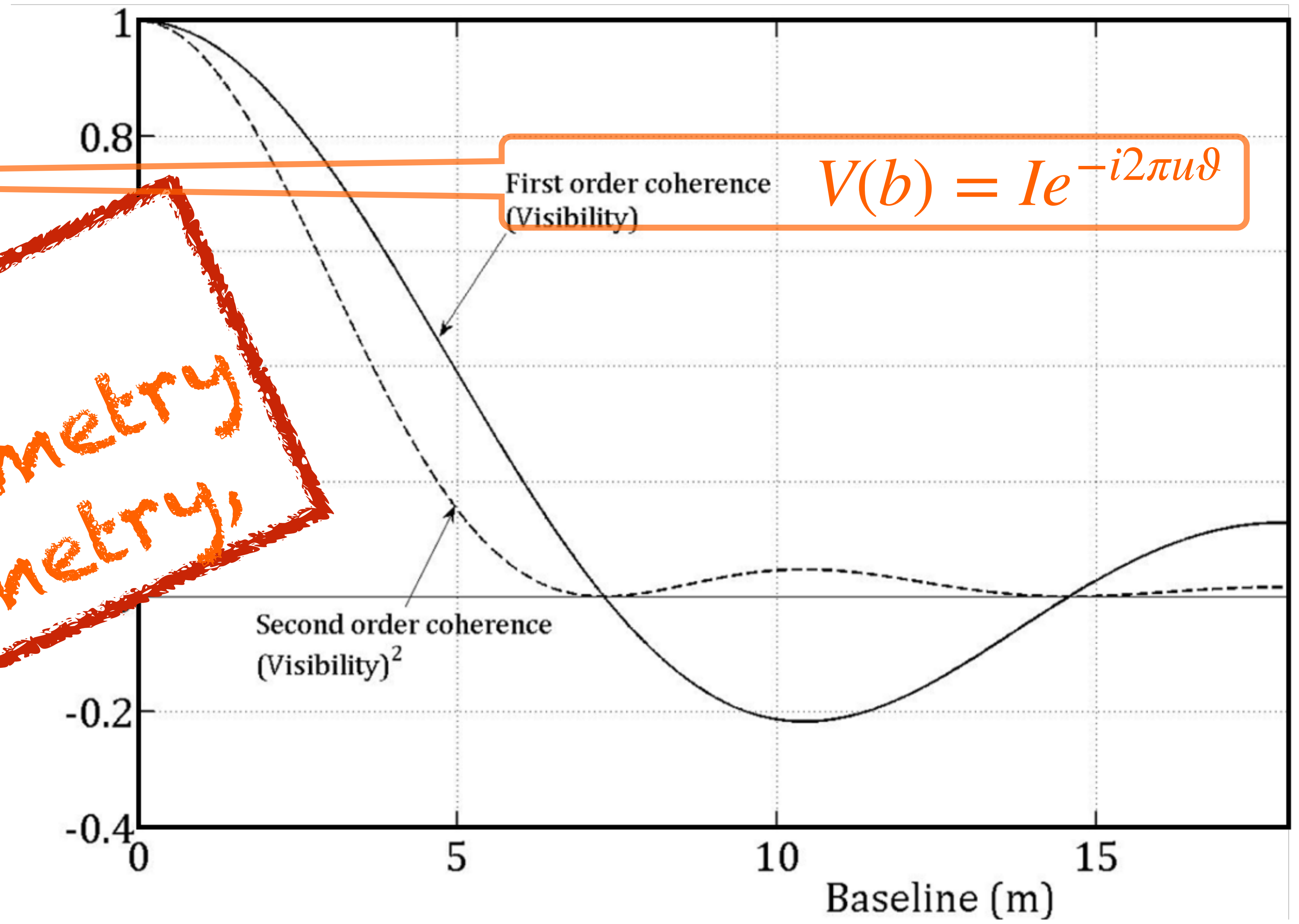

Solution!!
from Amplitude to Intensity Interferometry
Hanbury Brown-Twiss (HBT) interferometry,

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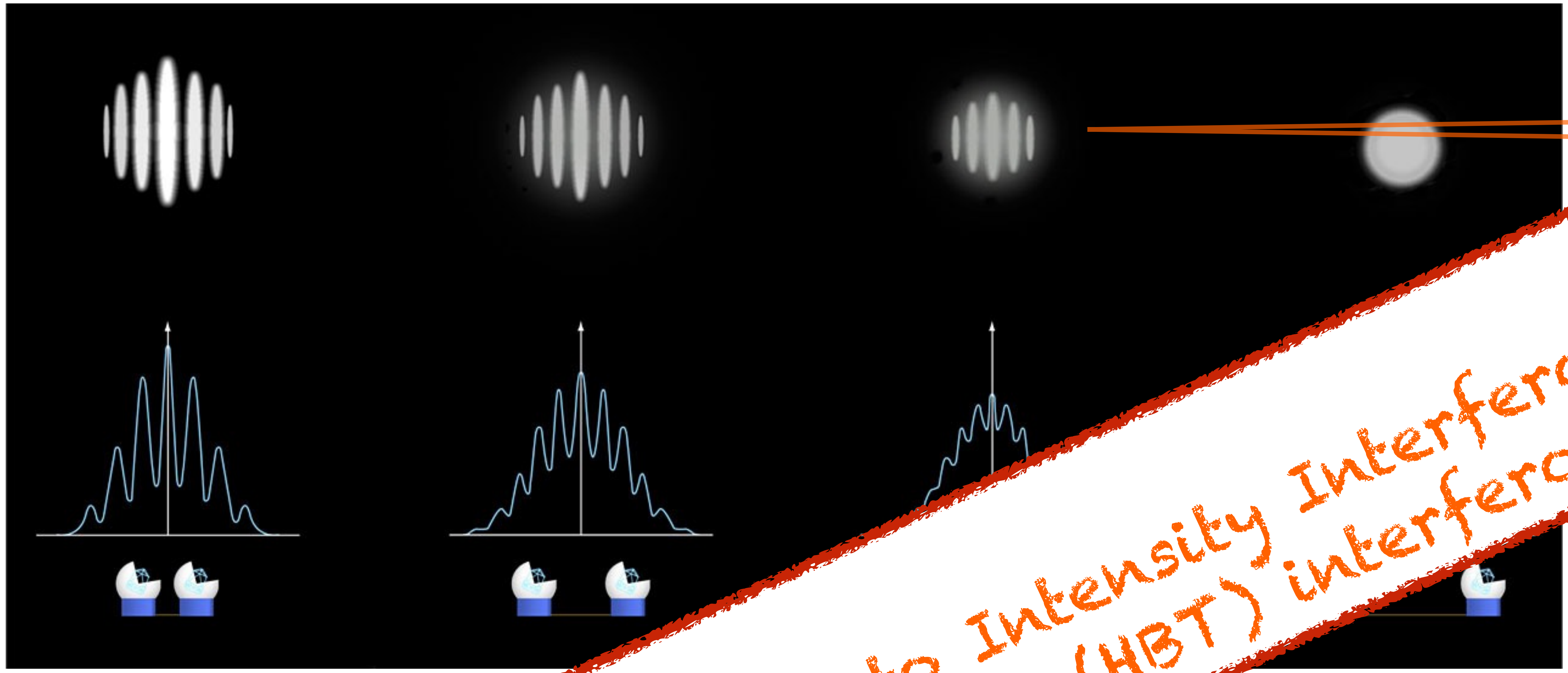

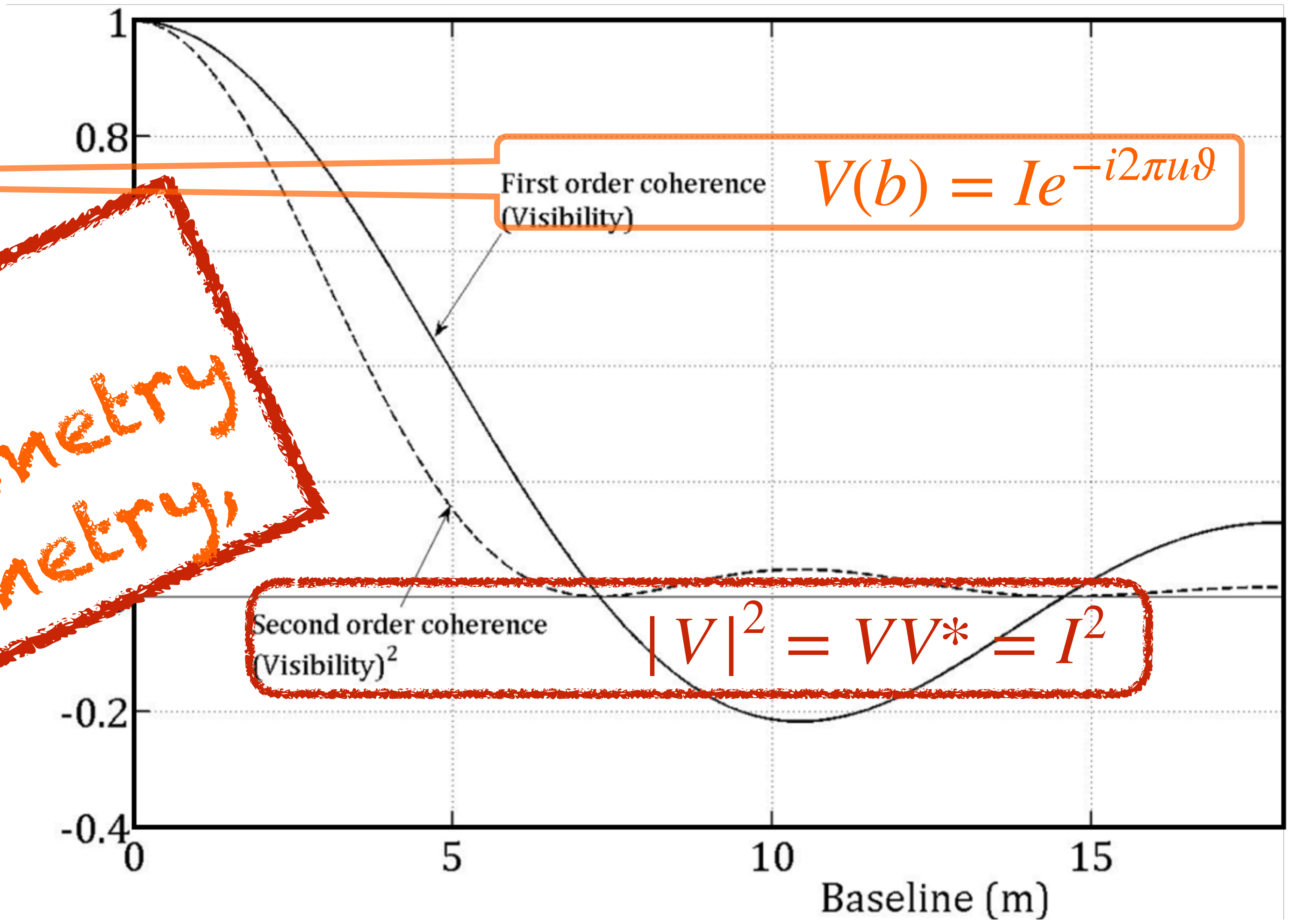

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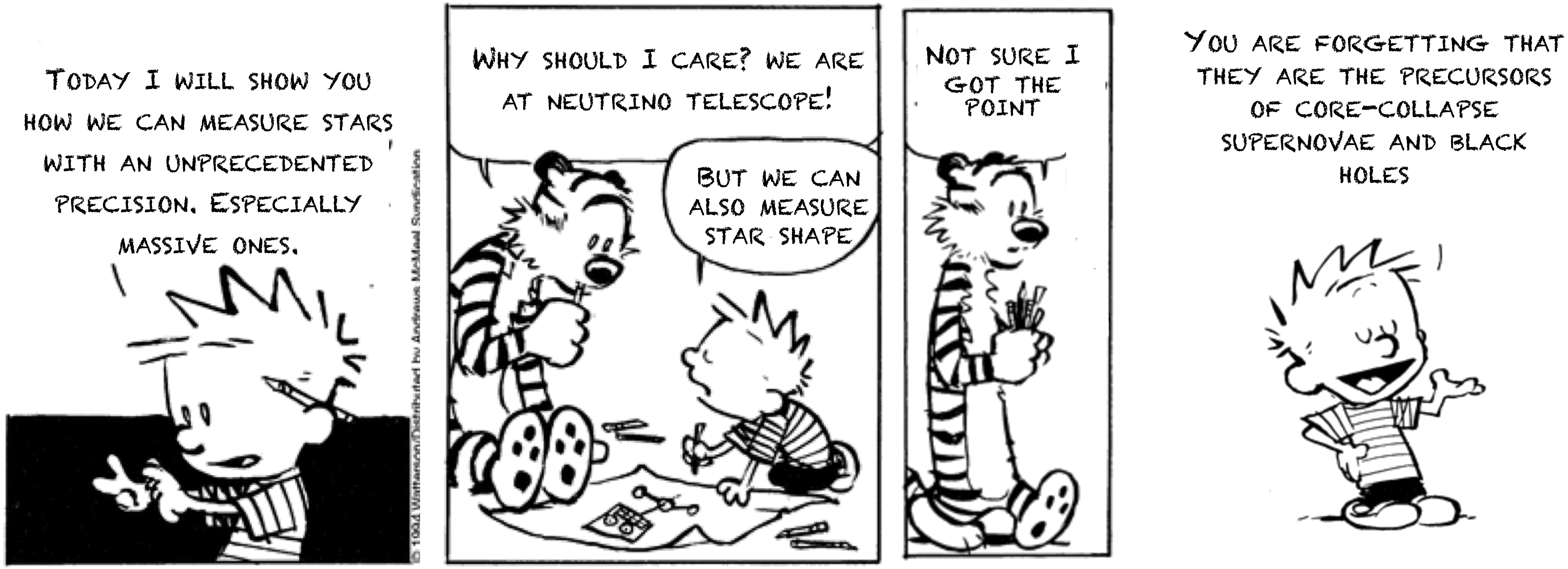
Measuring Diameter and shape of astrophysical objects

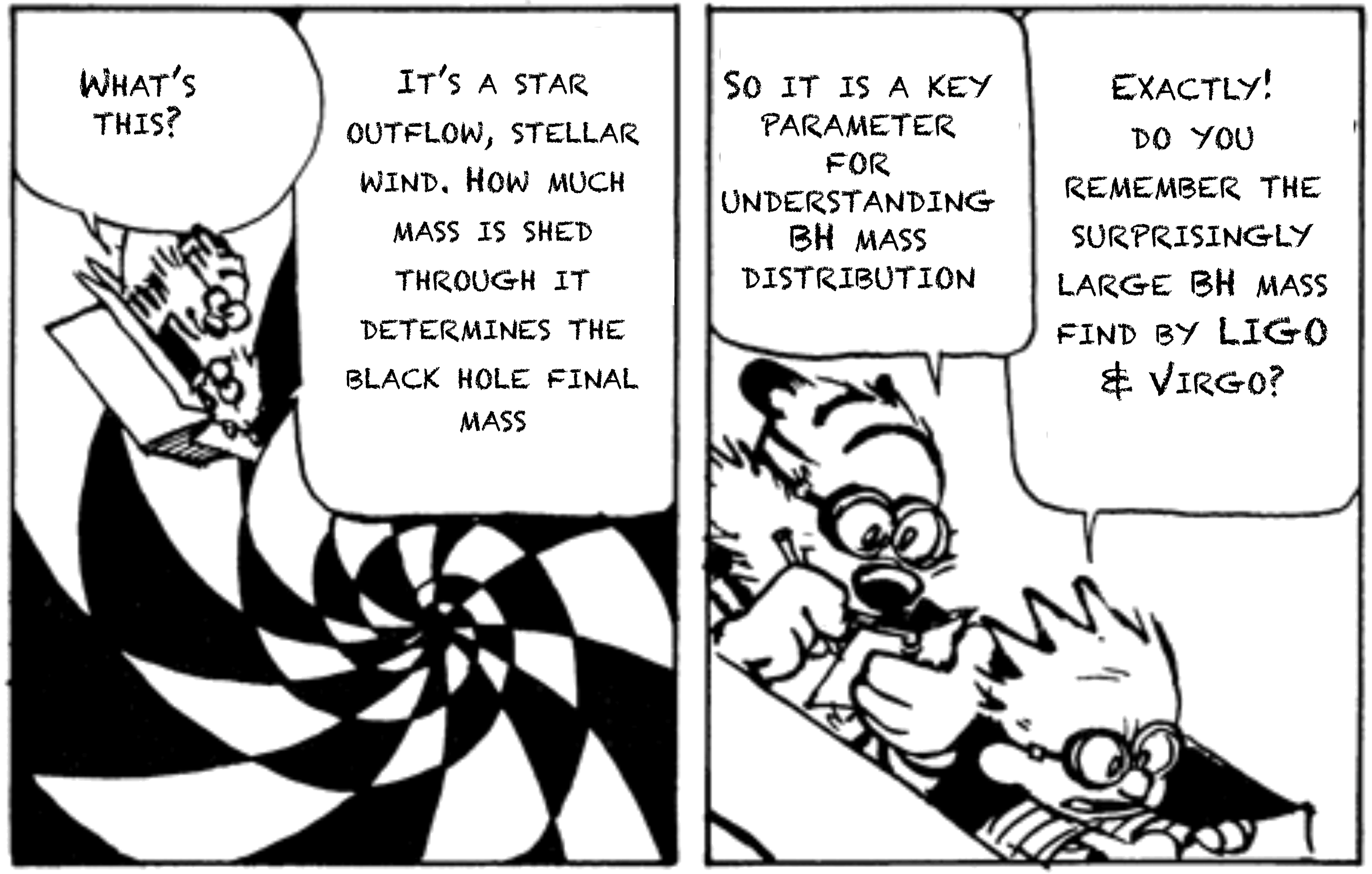


NEUTRINO PRODUCTION IN POPULATION III MICROQUASARS
https://doi.org/10.1016/j.astropartphys.2021.102557

NEUTRINO-DOMINATED ACCRETION AND SUPERNOVAE
https://iopscience.iop.org/article/10.1086/431354/pdf

GAMMA-RAYS AND NEUTRINOS PRODUCED AROUND MASSIVE BINARY SYSTEMS BY NUCLEI ACCELERATED WITHIN THE BINARIES
https://articles.adsabs.harvard.edu/pdf/2013ICRC...33.3447B

Stellar outflows and Wind

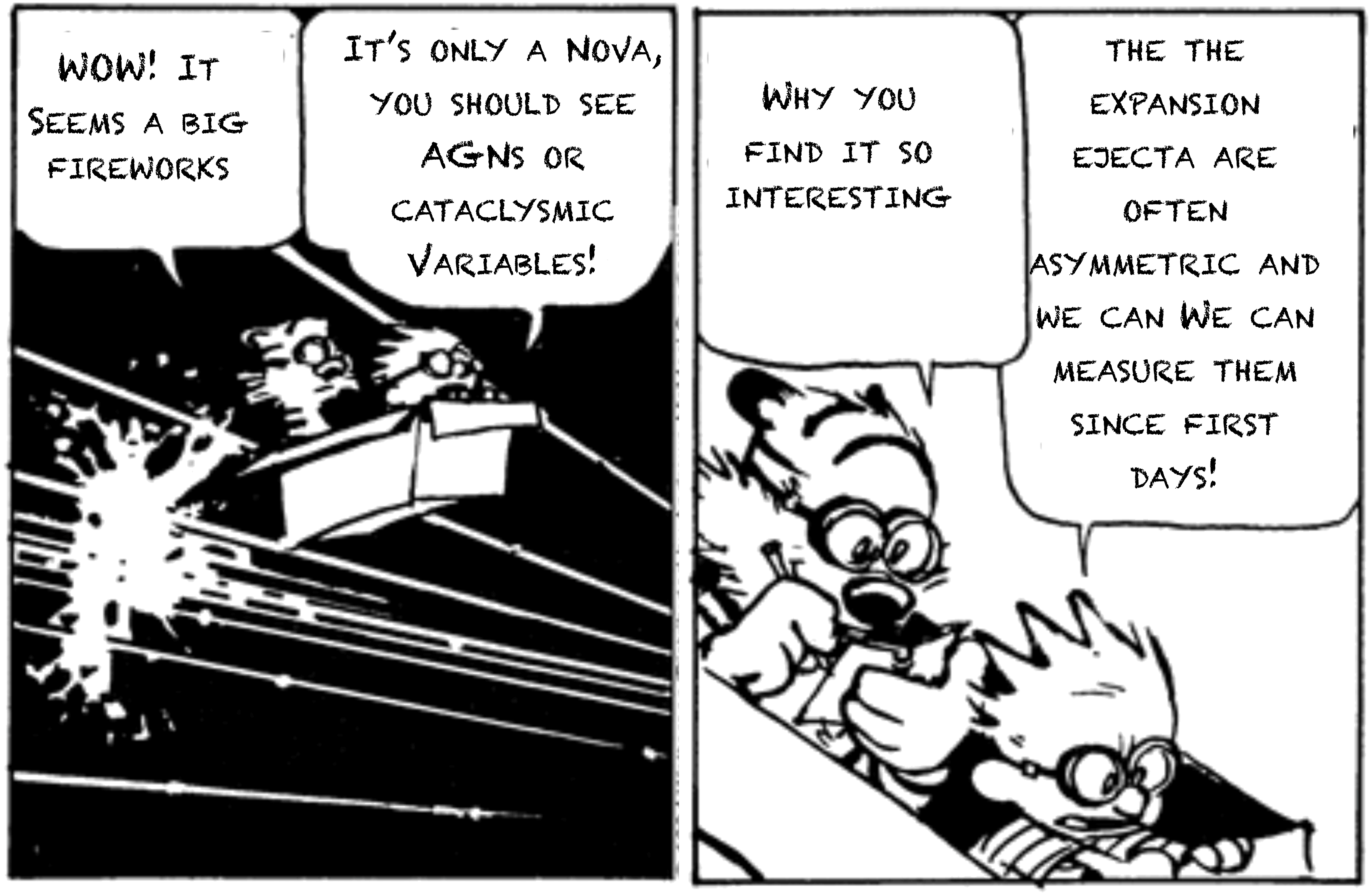


High Energy Neutrino Emission from Global Accretion Flows around Supermassive Black Holes
https://pos.sissa.it/444/1522/pdf

New Insights into Classical Novae
https://arxiv.org/pdf/2011.08751

Classical Be Stars
Rapidly Rotating B Stars with Viscous Keplerian Decretion Disks
https://arxiv.org/pdf/1310.3962

Novae & Cataclismic Variable



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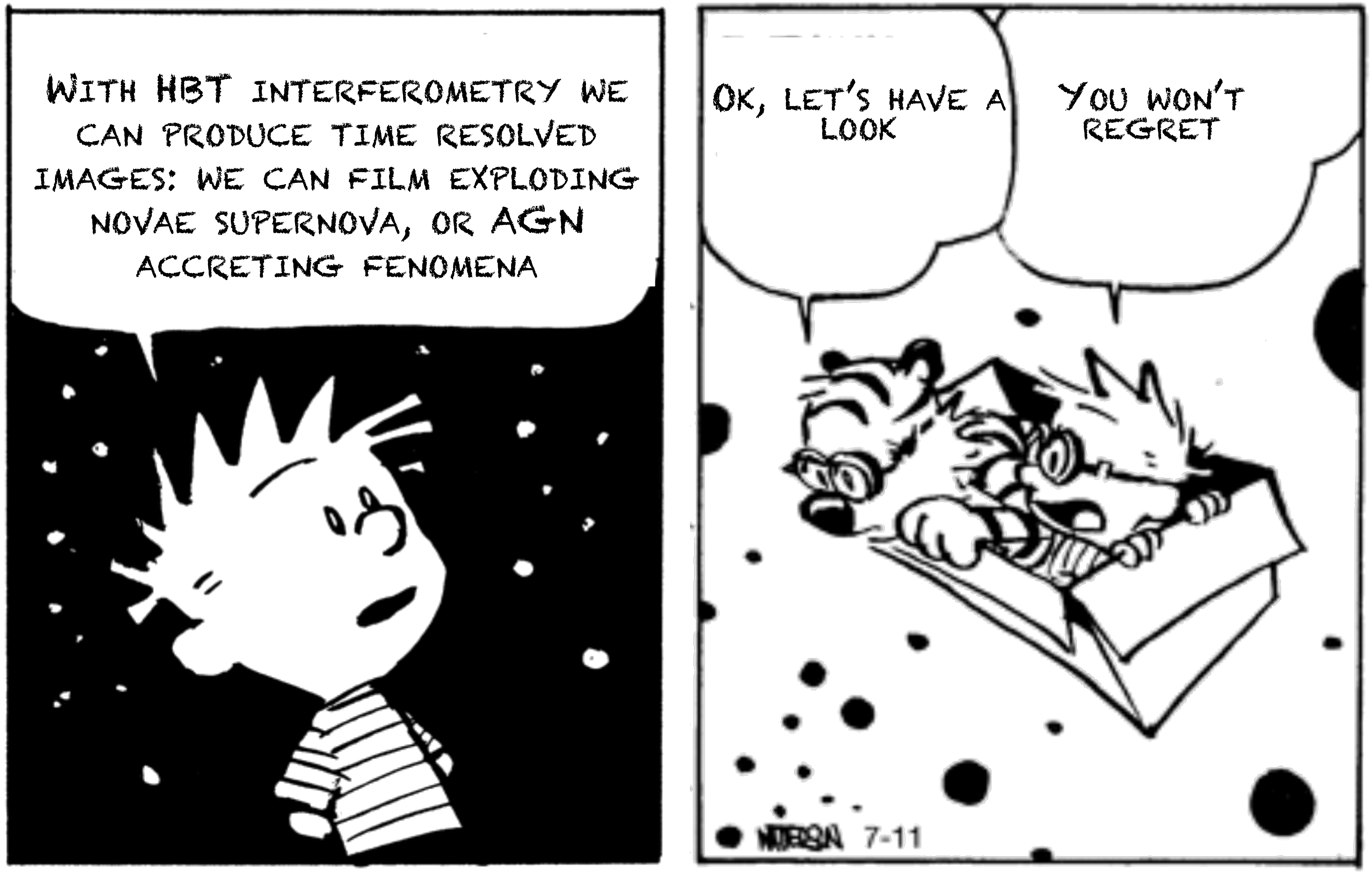
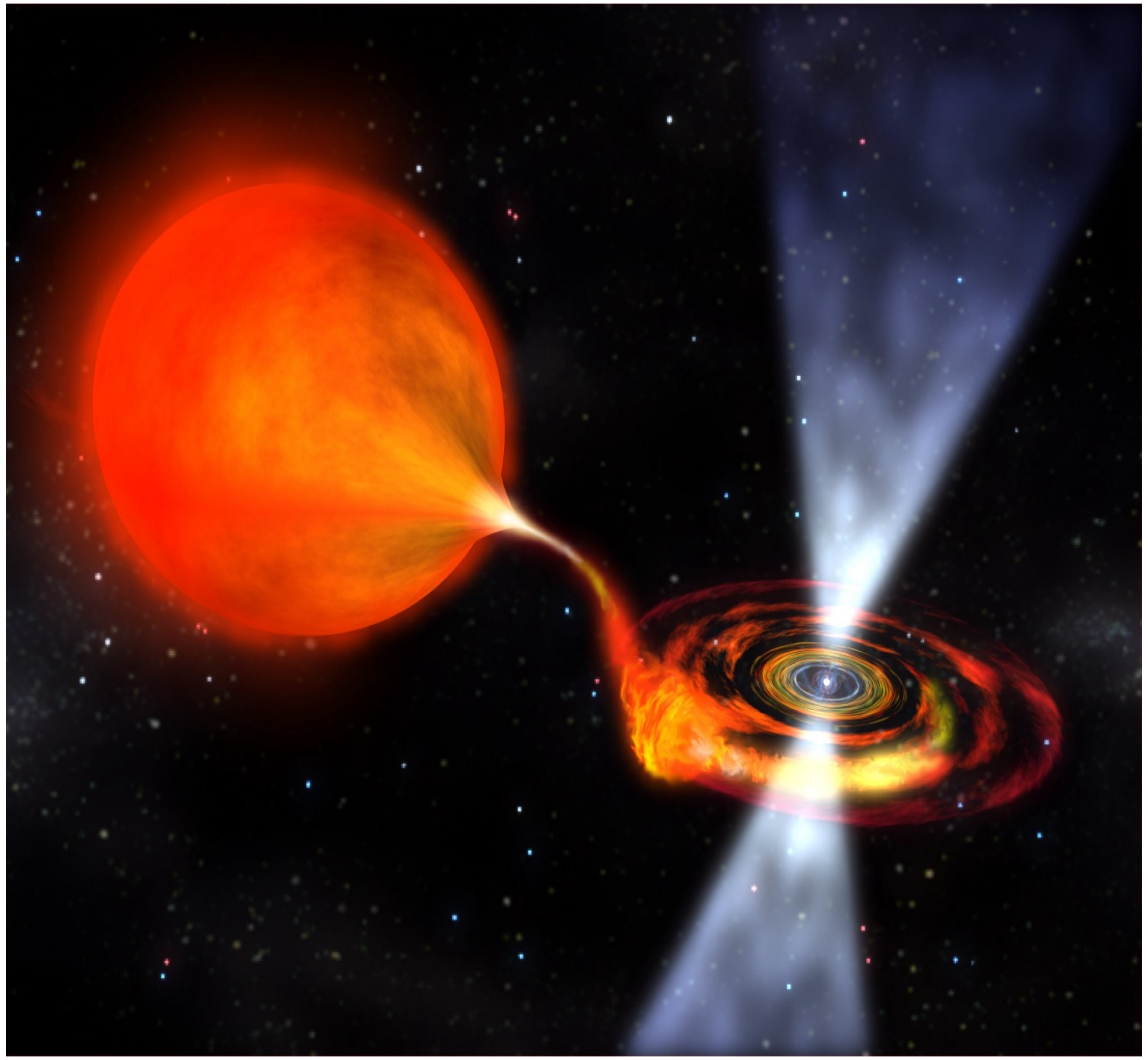
Filming the universe





Intensity Interferometry - pure quantum physics

THE
PRINCIPLES
OF
QUANTUM MECHANICS
BY
P. A. M. DIRAC

Dirac 1930

Wave - particle duality is the key

Each photon then interferes only with itself.
Interference between two different photons never occurs.

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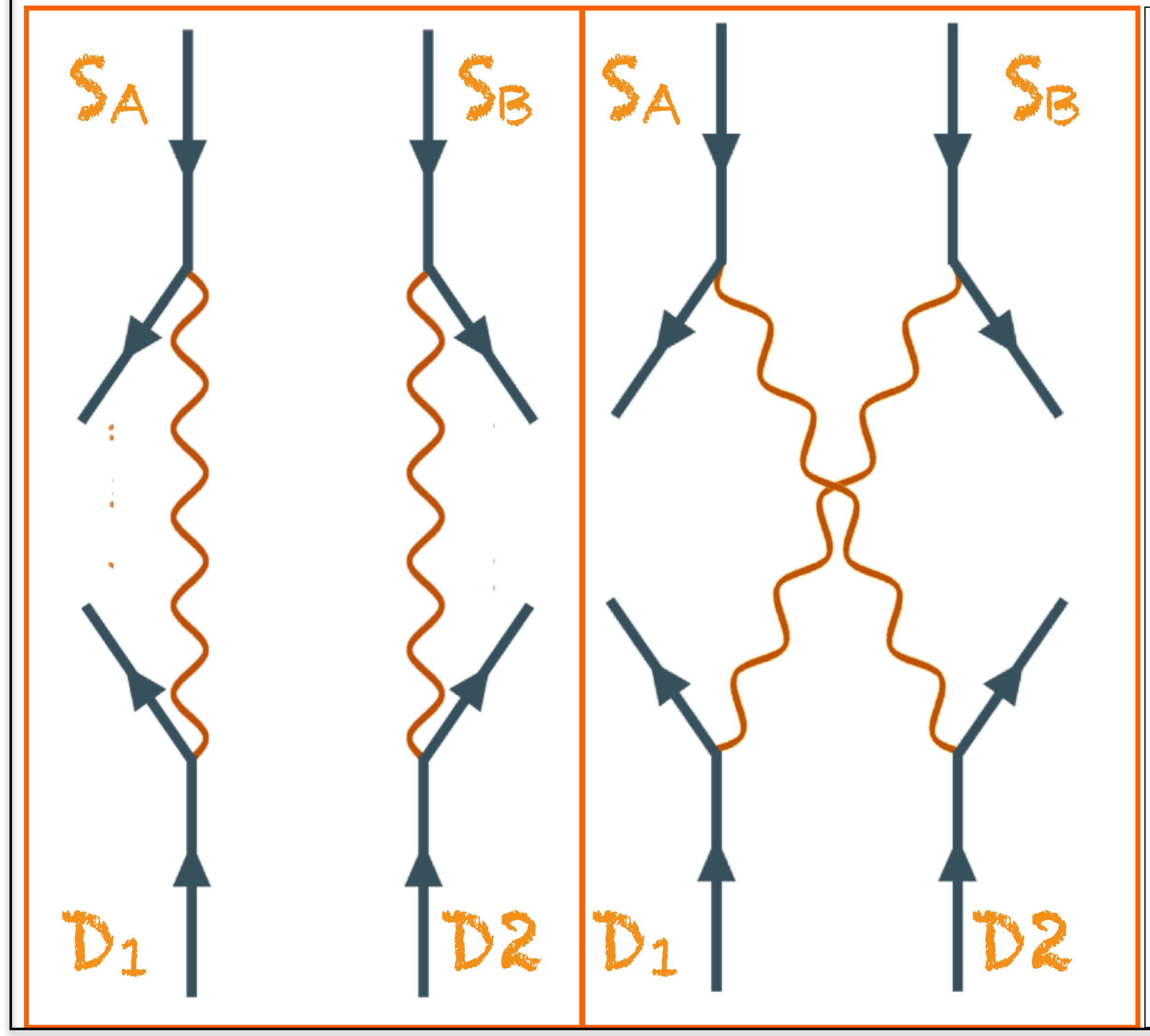

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- Incoherent light when detected at 2 different point in space show correlation in space and time ! ⇒ Intensity interferometry
  - Method used IN radio astronomy as measured correlations **immune to severe fluctuation**s **due to atmosphere big pros!**).
- Photons are bosons (fermions)
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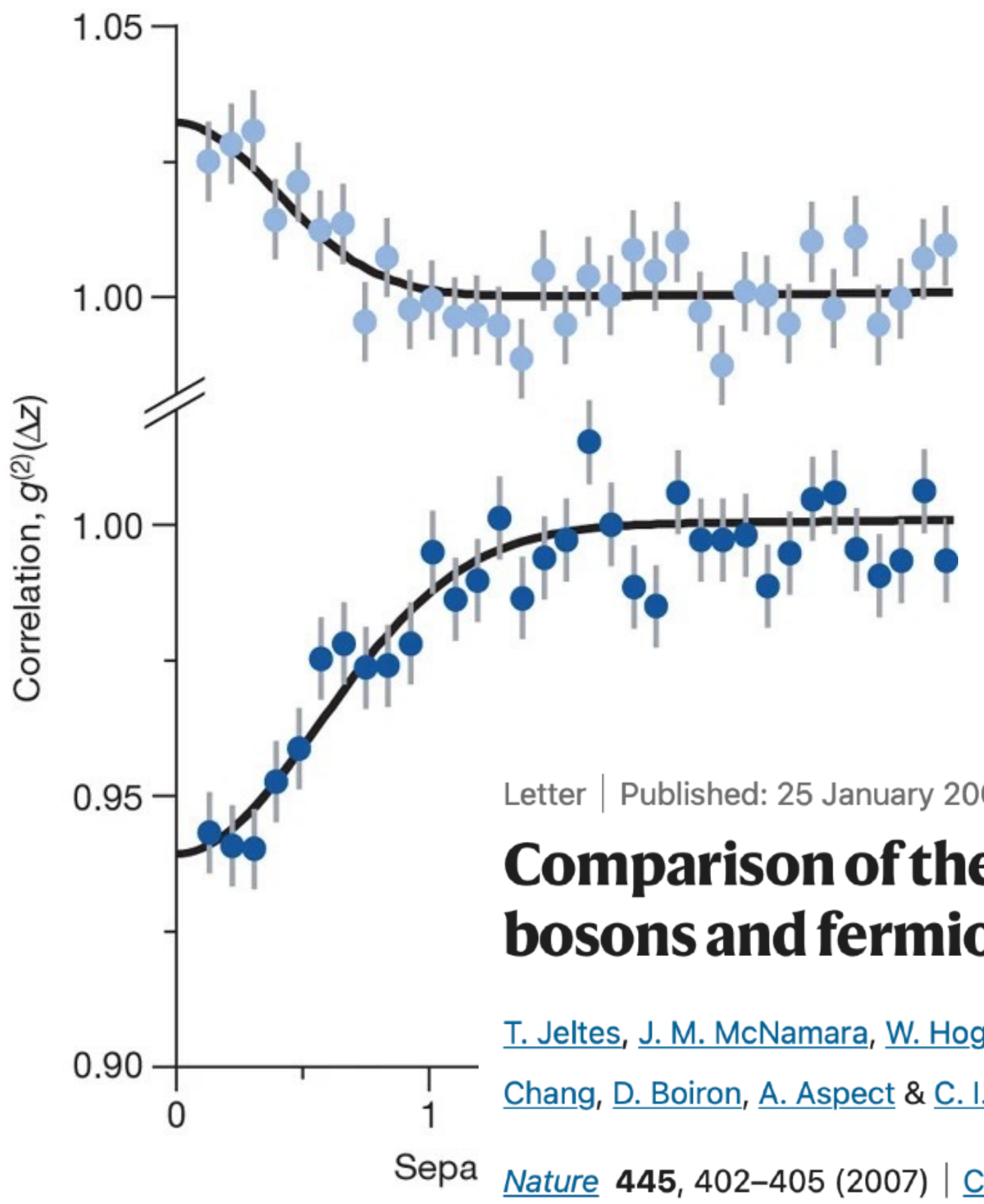

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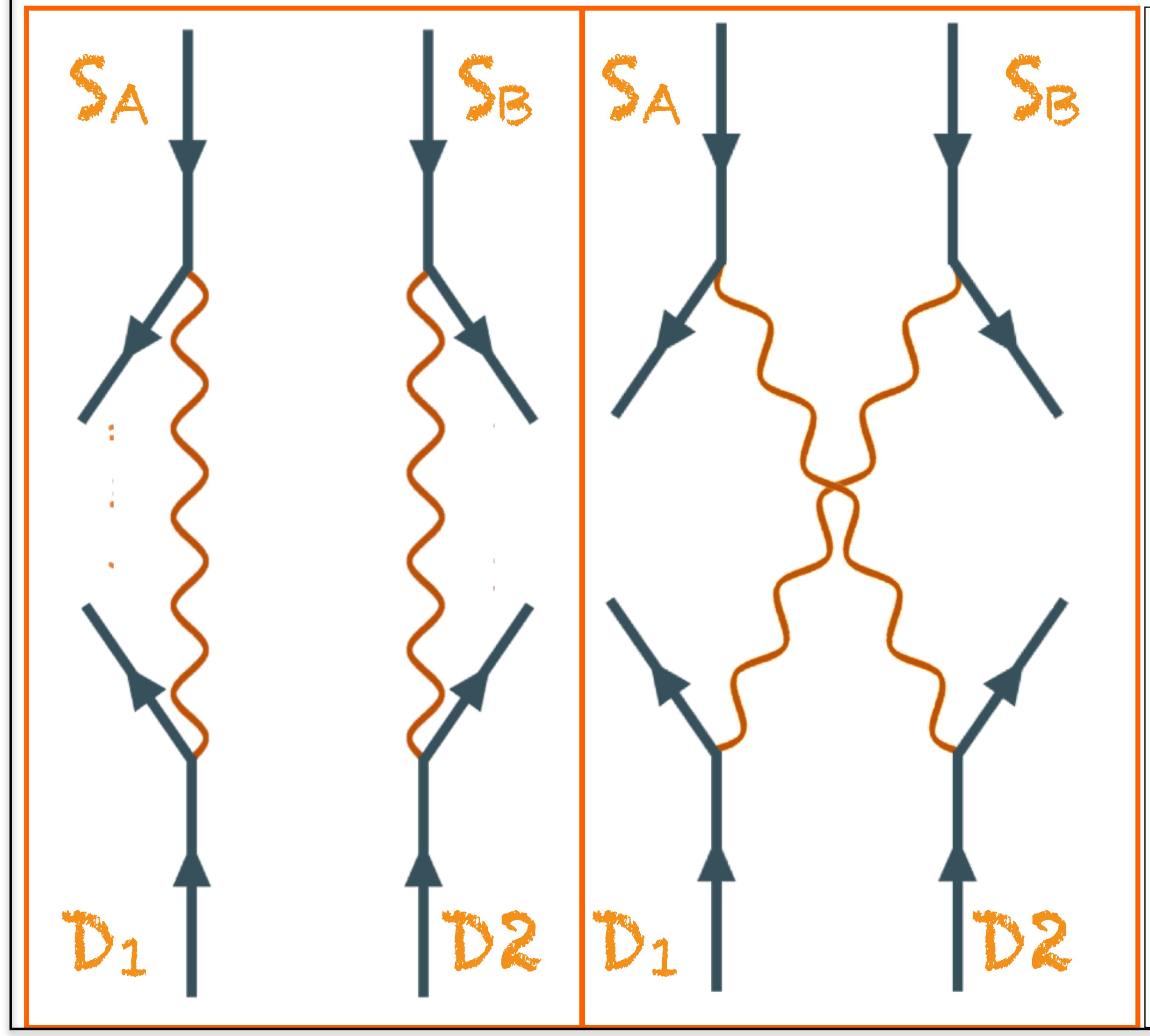
Letter | Published: 25 January 2007

Comparison of the Hanbury Brown–Twiss effect for bosons and fermions

T. Jeltes, J. M. McNamara, W. Hogervorst, W. Vassen, V. Krachmalnicoff, M. Schellekens, A. Perrin, H. Chang, D. Boiron, A. Aspect & C. I. Westbrook

Nature **445**, 402–405 (2007) | Cite this article



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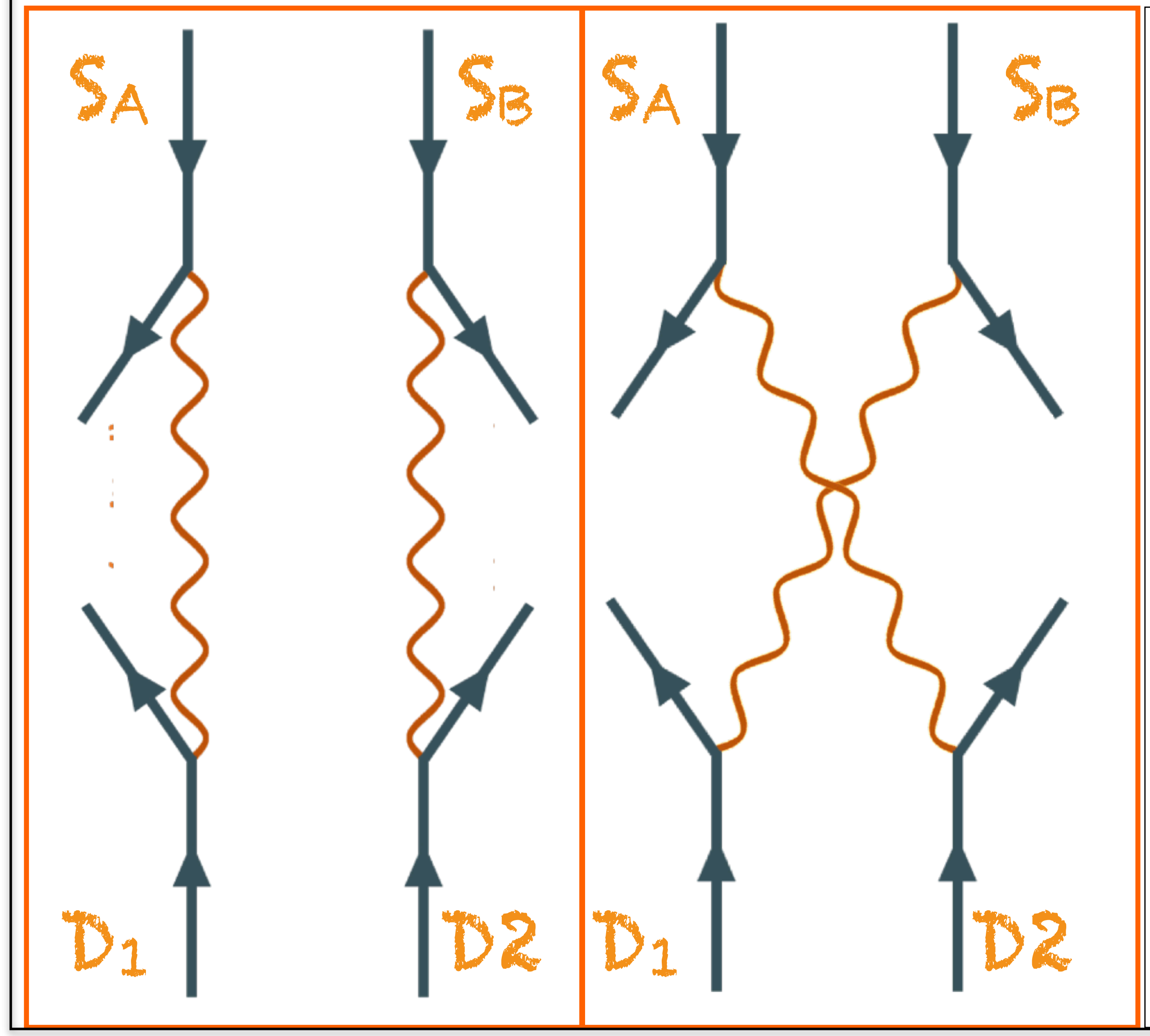

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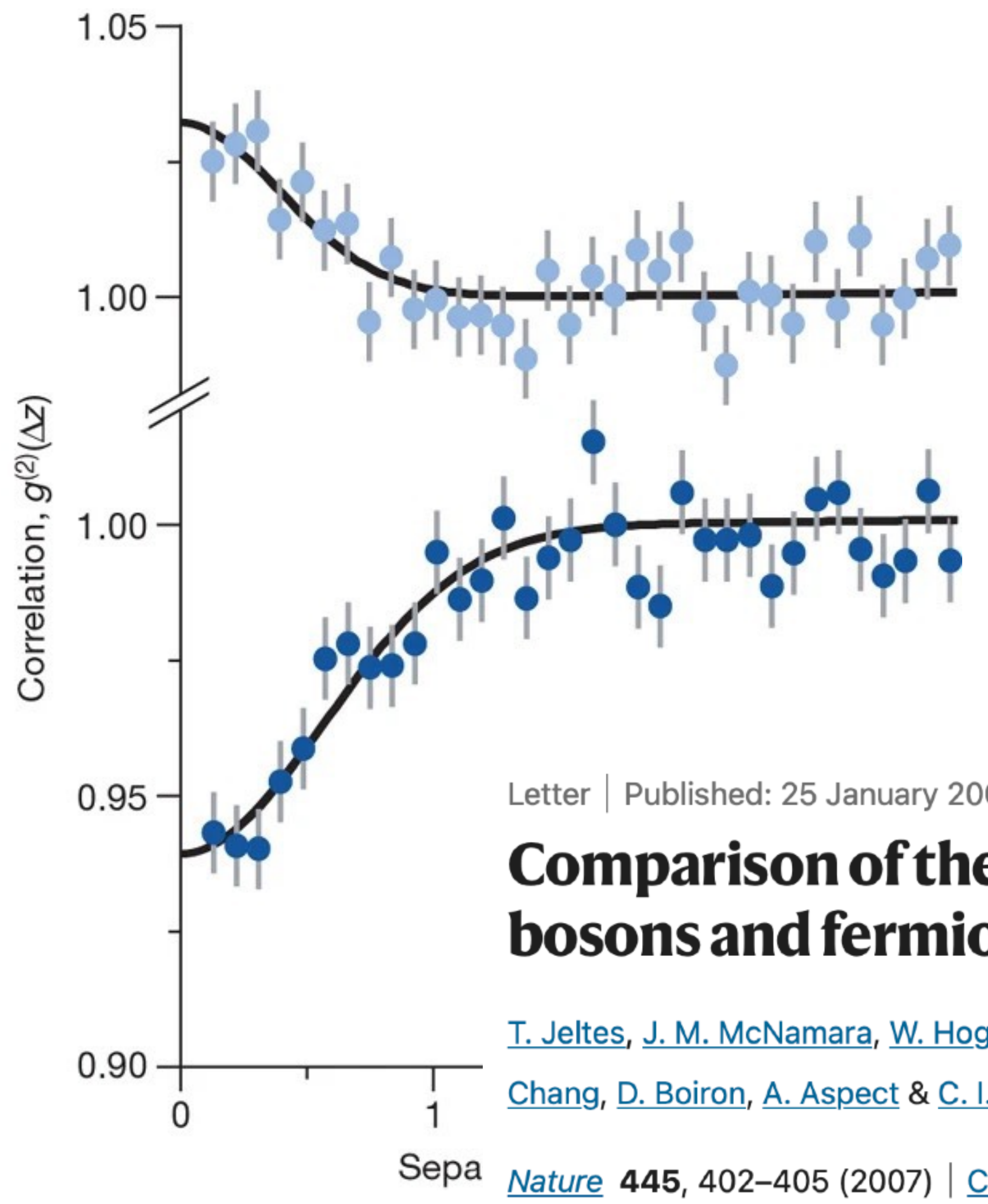

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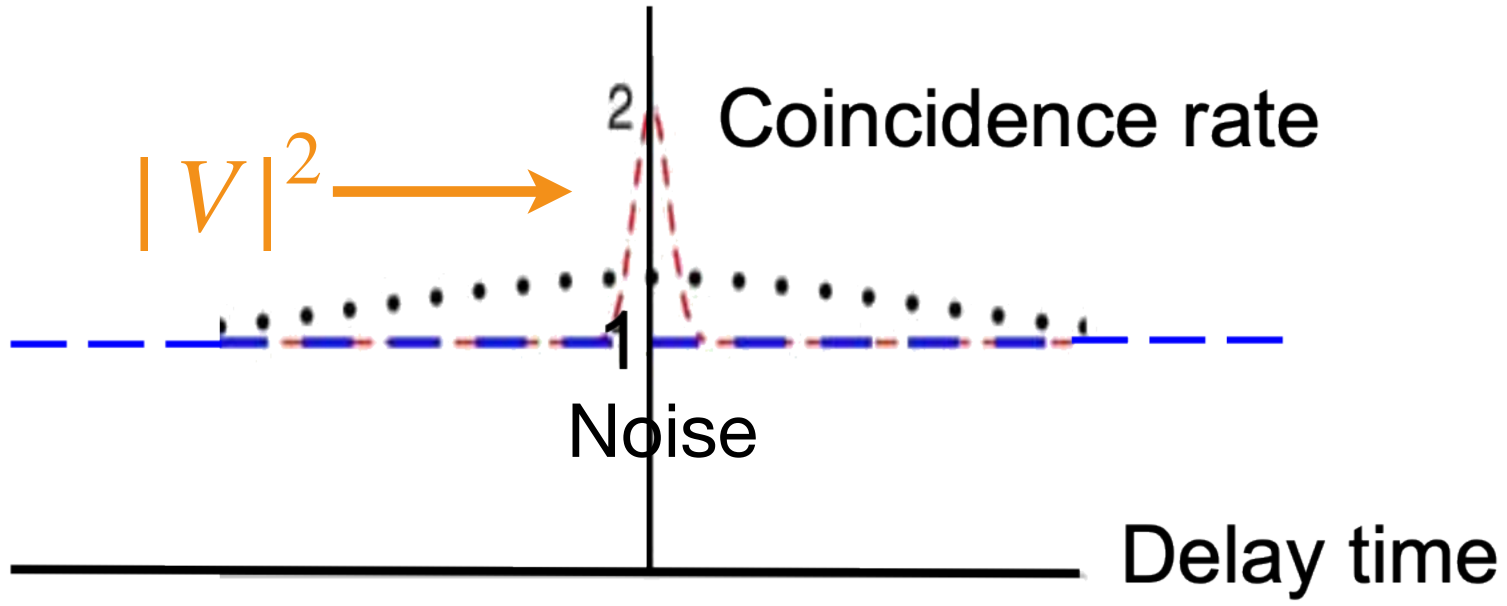
Visibility = 2nd order correlation

$$g^{(2)} = \frac{\pi^{(2)}(\mathbf{r_1}, t; \mathbf{r_2}, t+\tau)}{\pi^{(1)}(\mathbf{r_1}, t) \cdot \pi^{(1)}(\mathbf{r_2}, t+\tau)} = 1 + \left| g^{(1)} \right|^2$$



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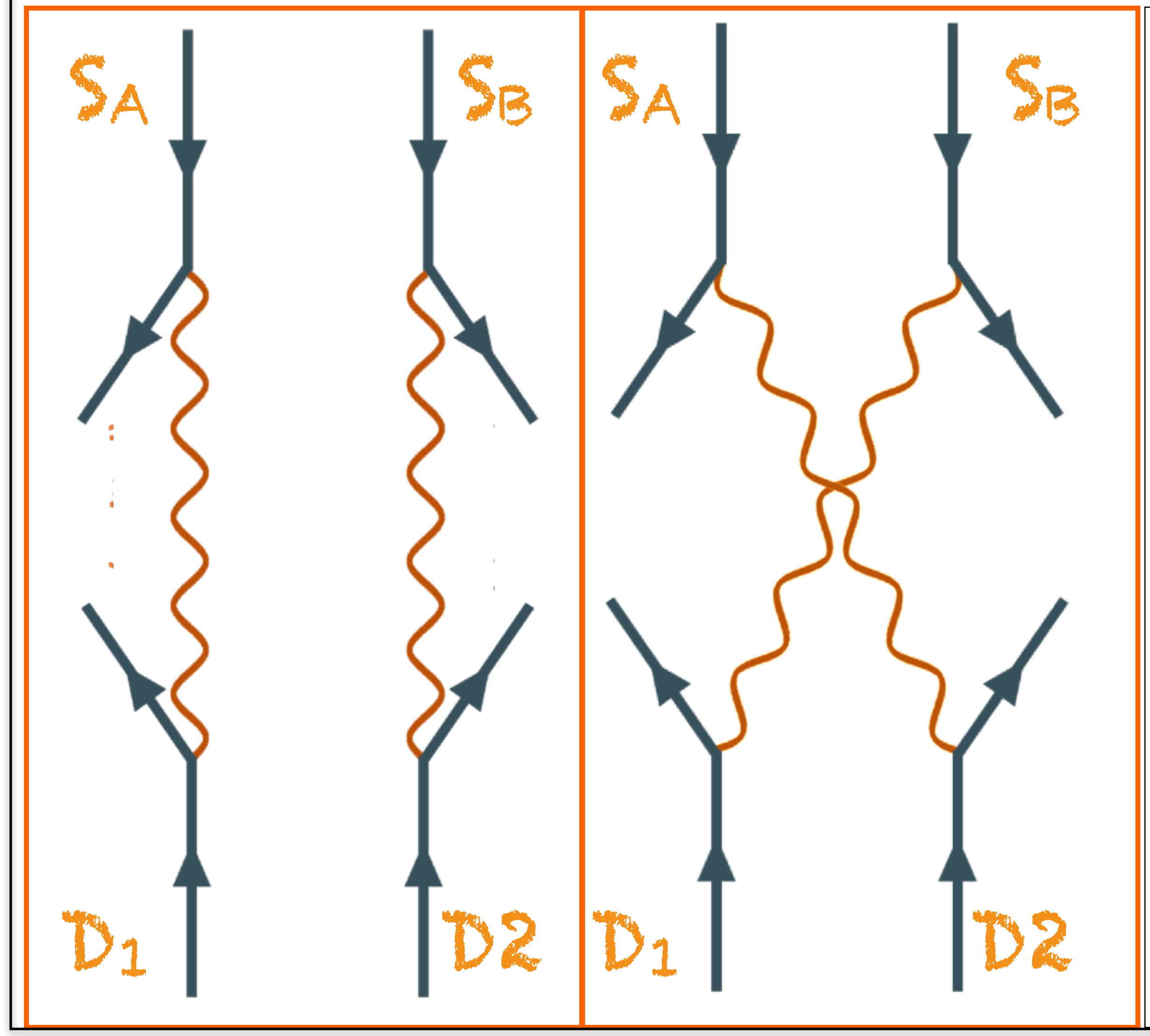

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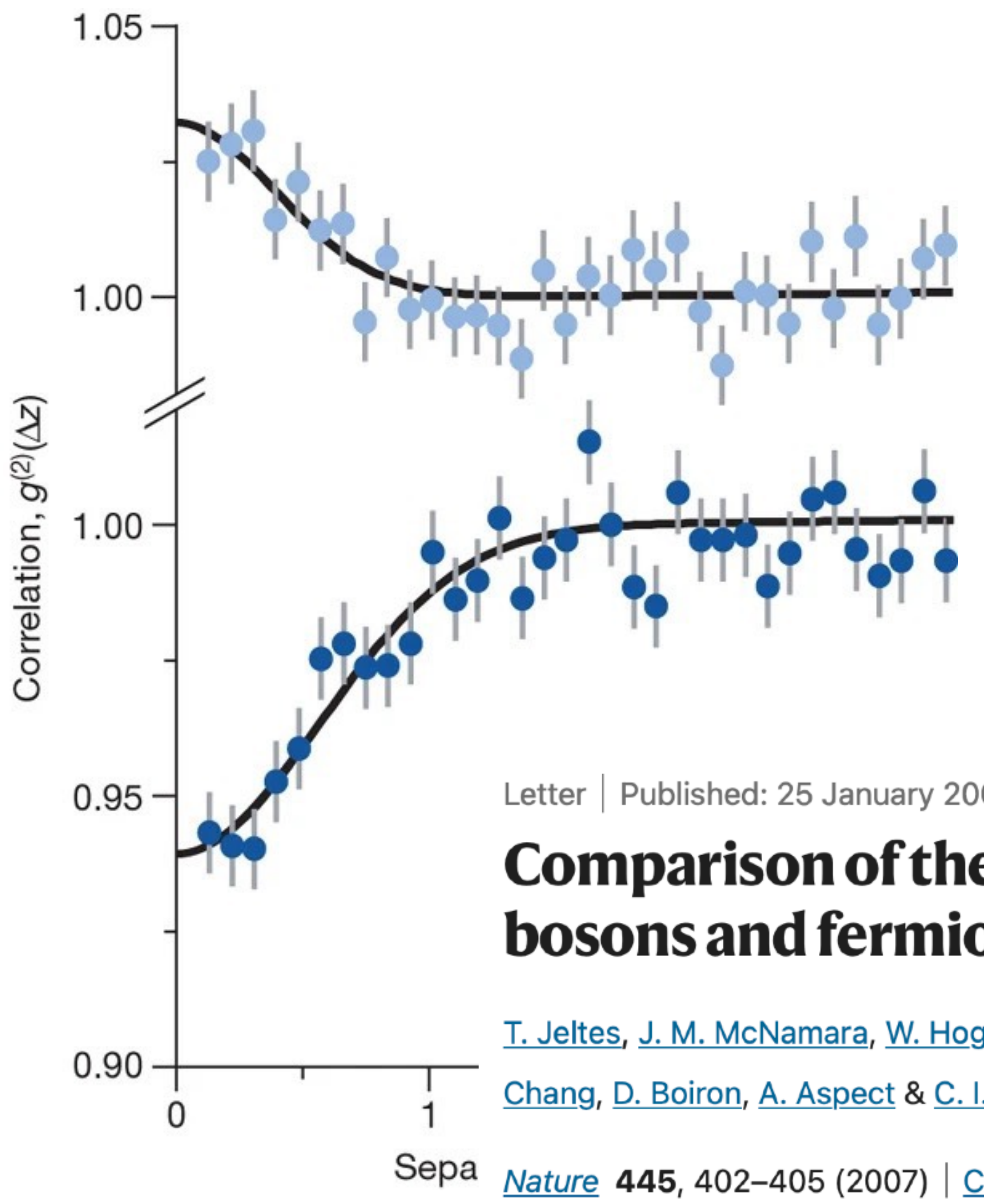

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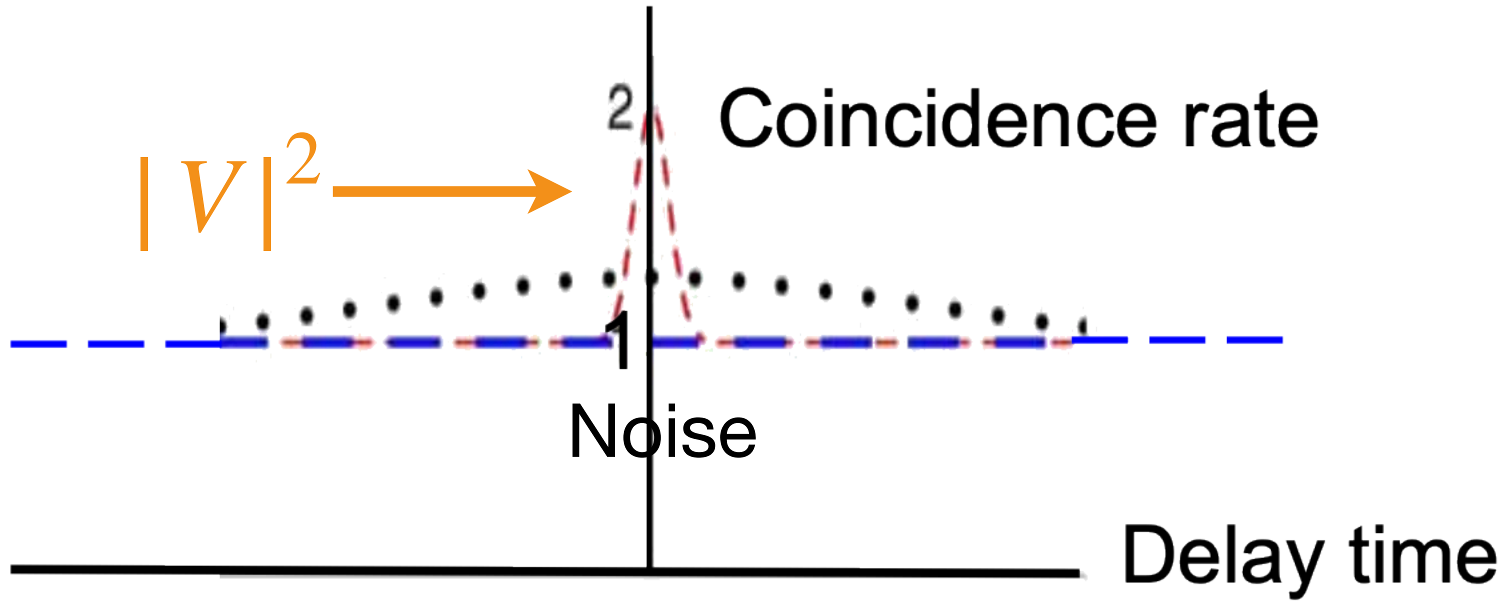

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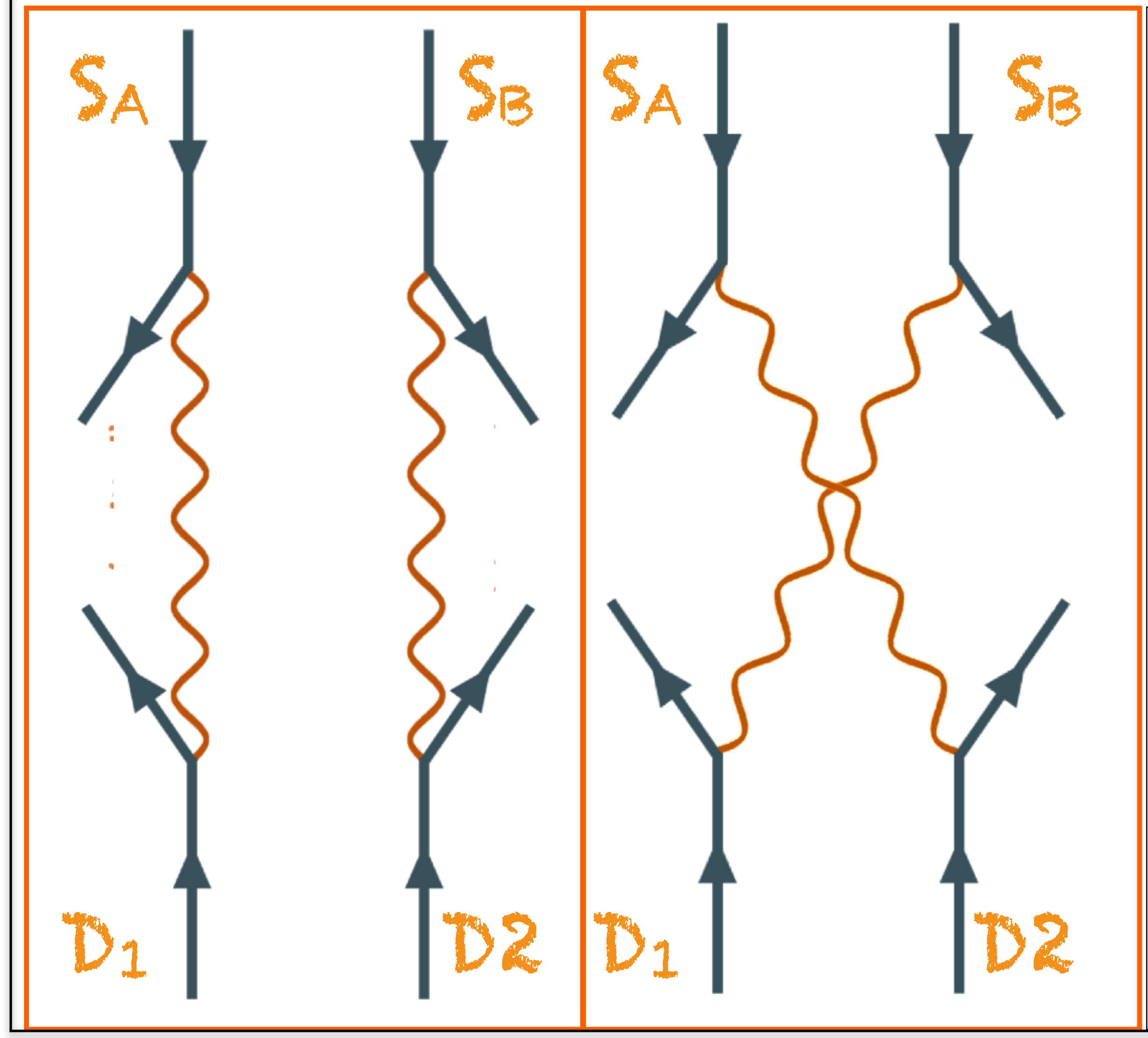

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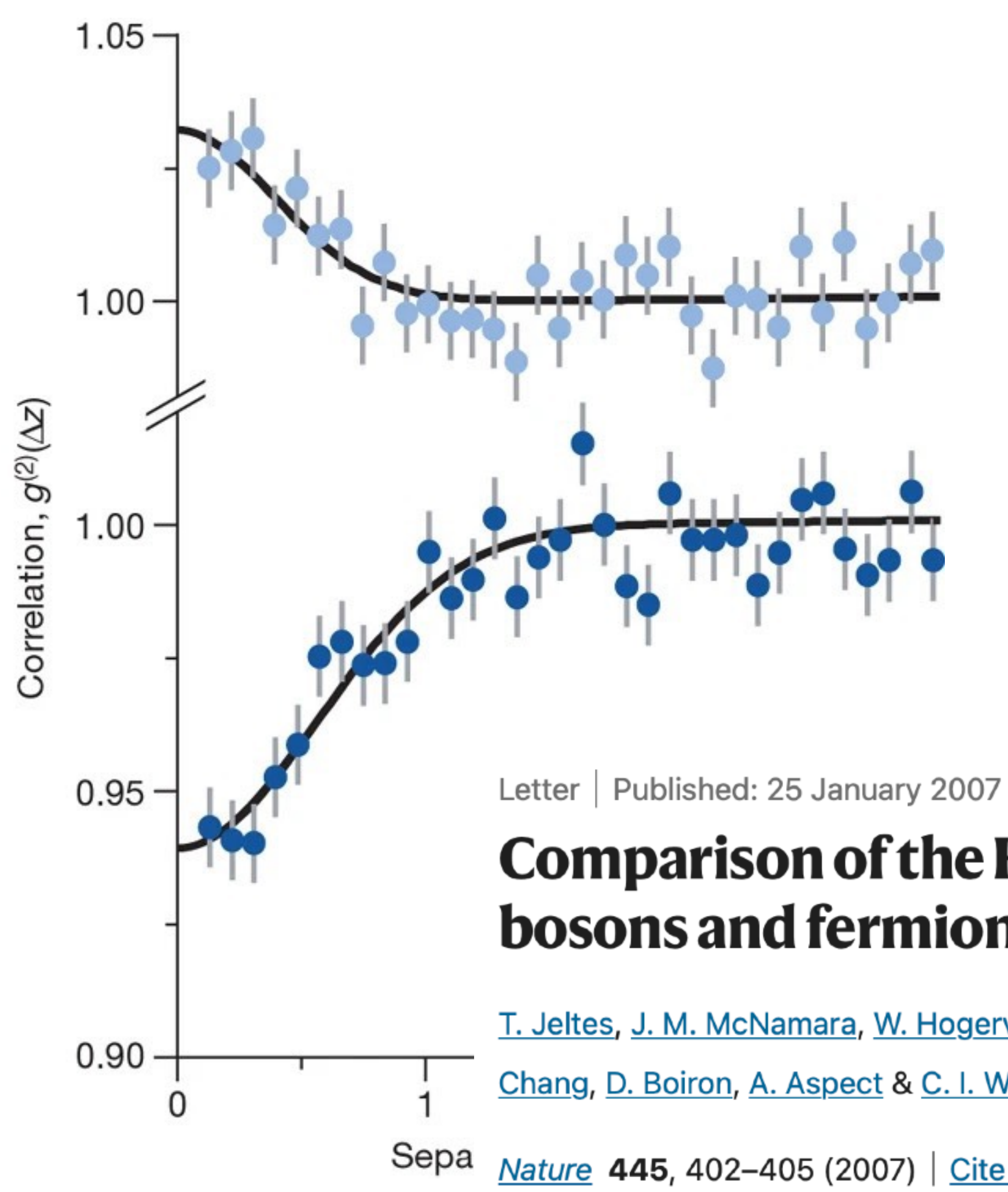

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Letter | Published: 25 January 2007

Comparison of the Hanbury Brown–Twiss effect for bosons and fermions

T. Jeltes, J. M. McNamara, W. Hogervorst, W. Vassen, V. Krachmalnicoff, M. Schellekens, A. Perrin, H. Chang, D. Boiron, A. Aspect & C. I. Westbrook

Nature **445**, 402–405 (2007) | Cite this article

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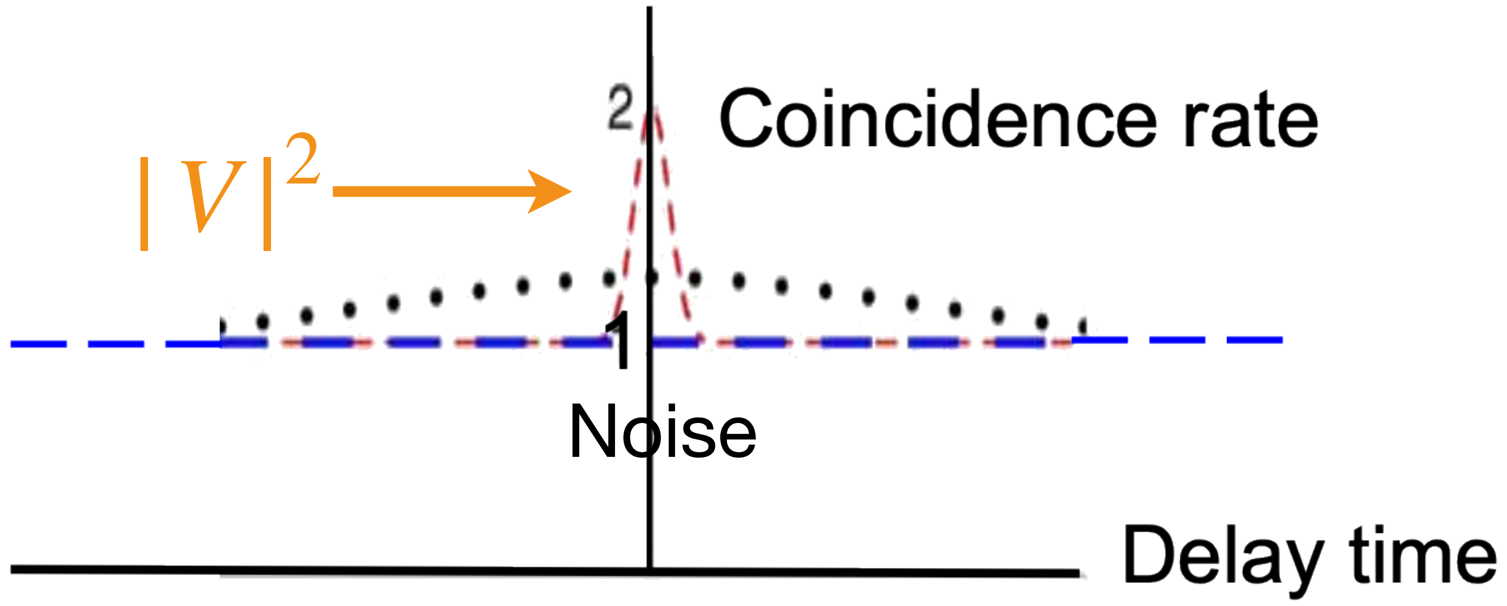

Glauber 1961

Intensity Interferometry - pure quantum physics

THE
PRINCIPLES
OF
QUANTUM MECHANICS
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Dirac 1930

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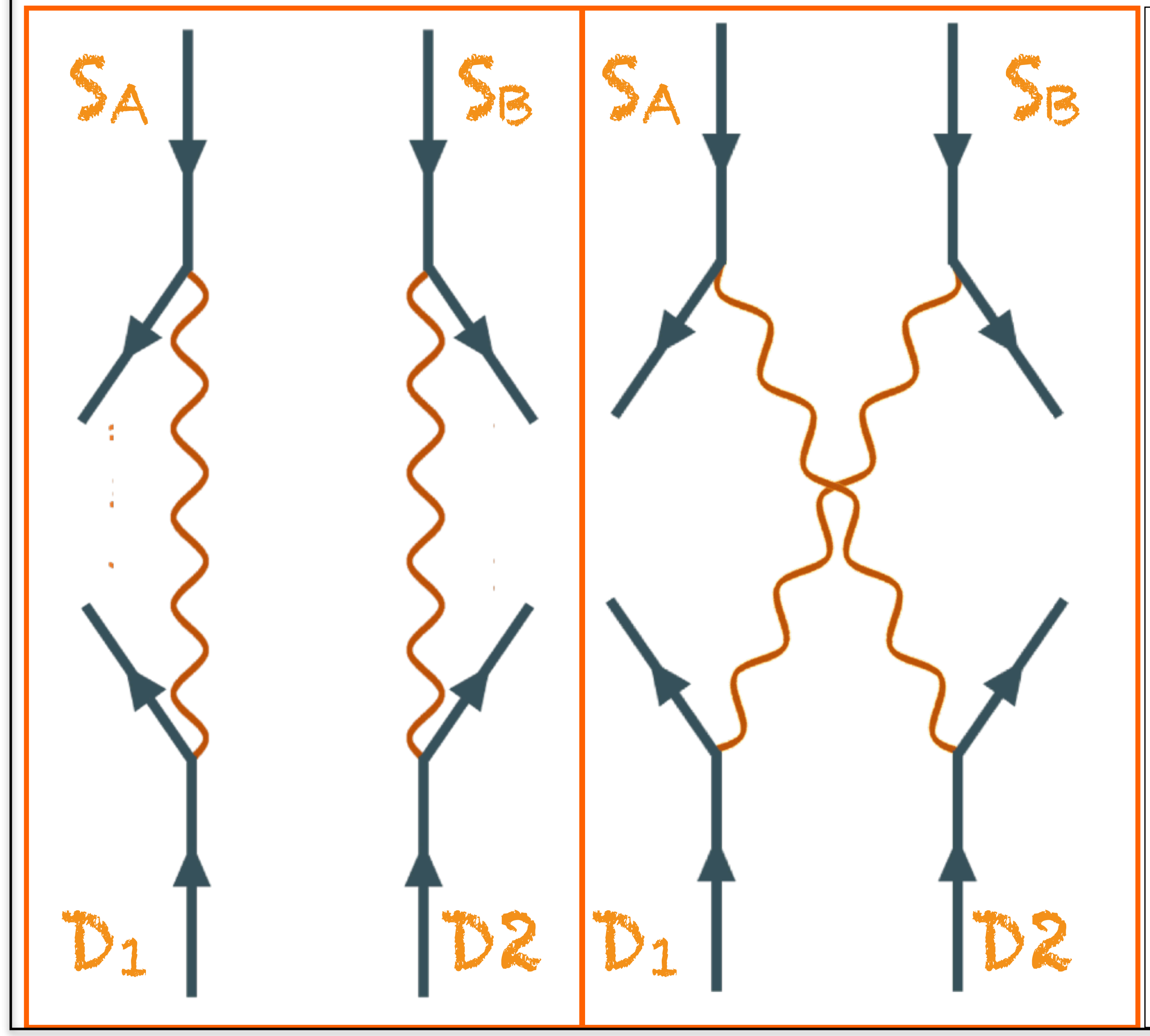

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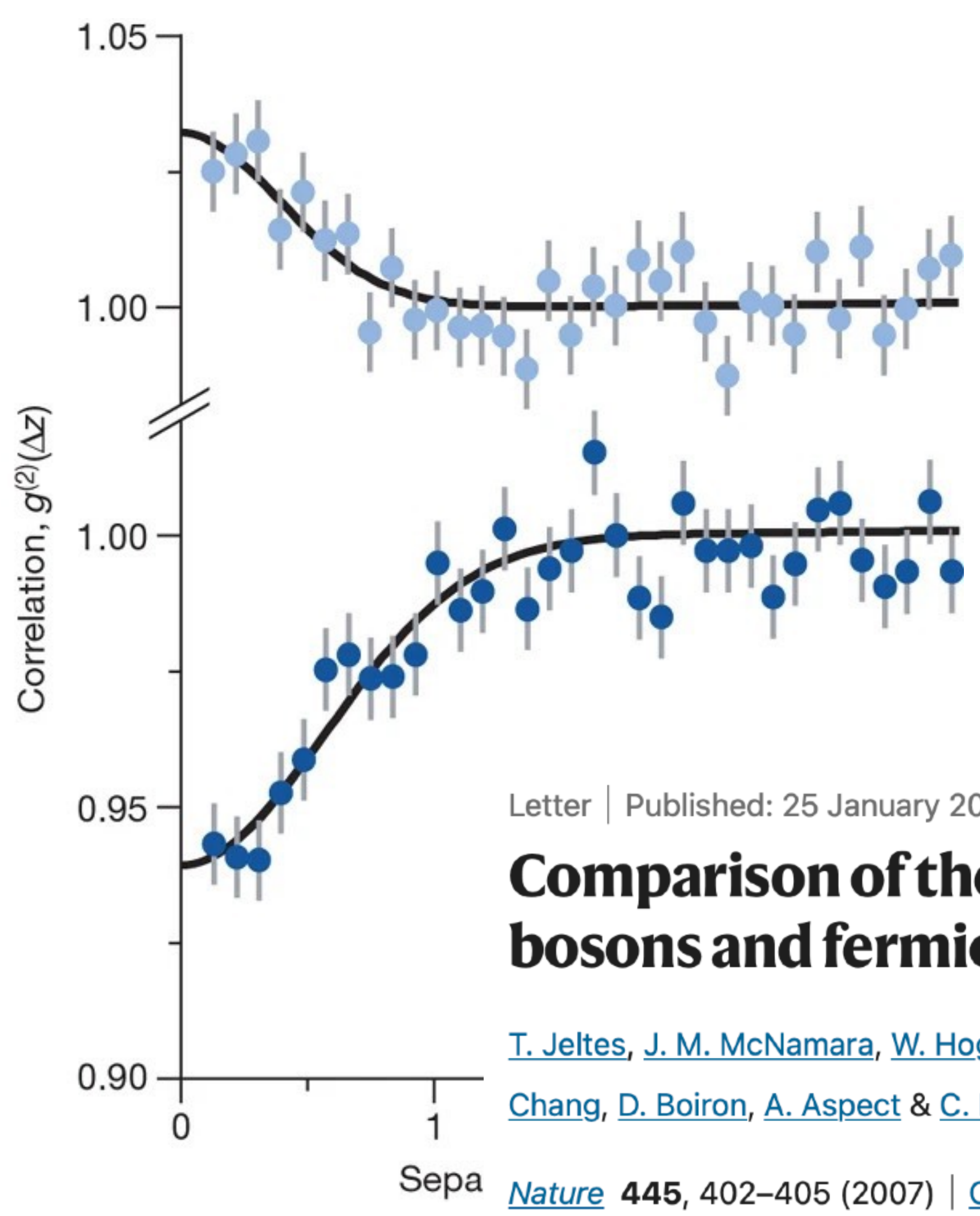

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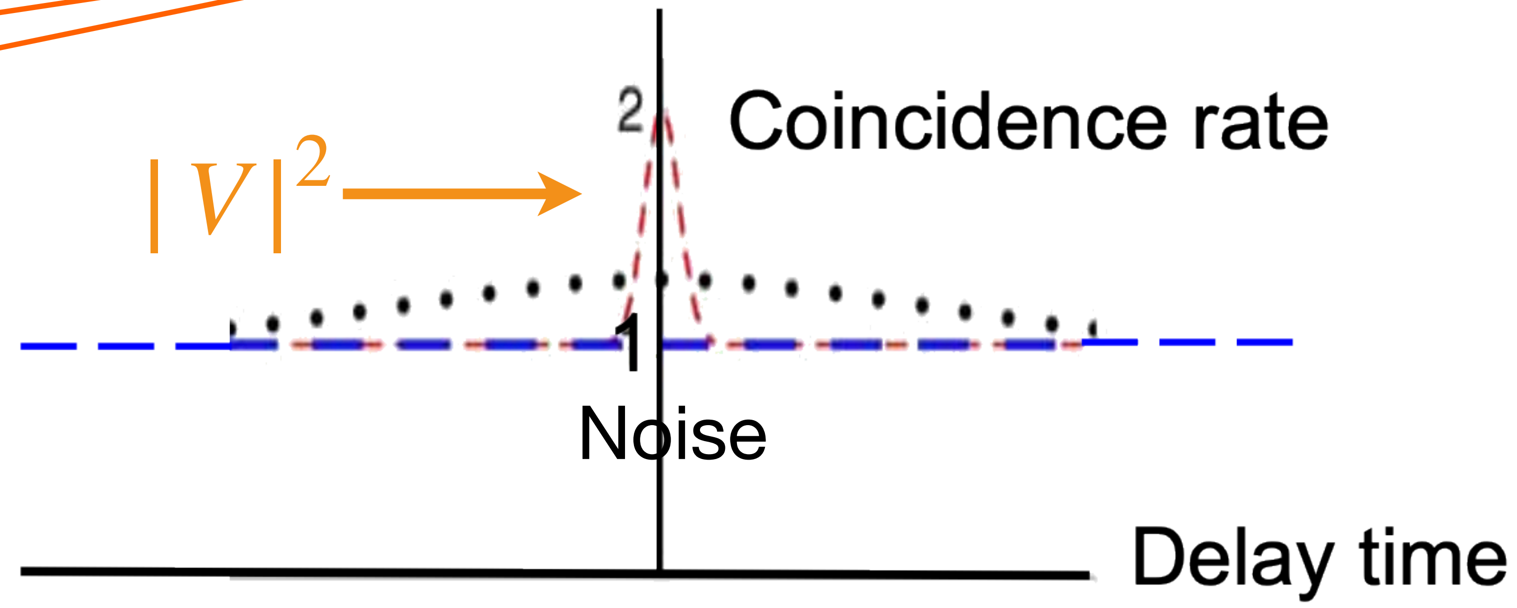

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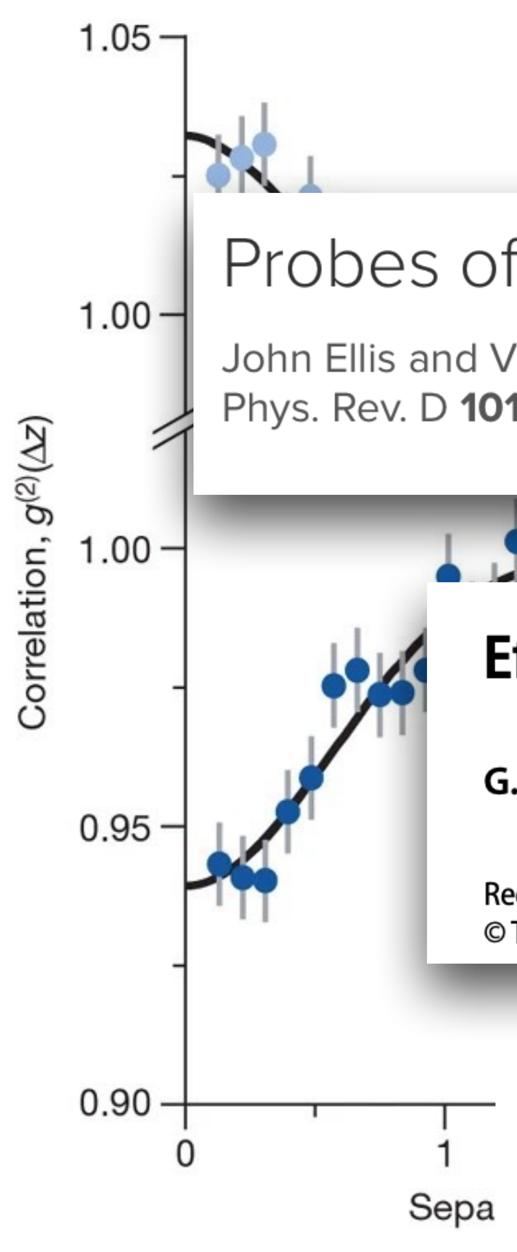

Probes of gravitational waves with atom interferometers

John Ellis and Ville Vaskonen

Phys. Rev. D **101**, 124013 – Published 9 June 2020

Effect of gravitational wave onto stellar intensity interferometry

G. Hong[1] · K. Y. Choi[1] · J. Hwang[1] · K. H. Lee[1] · C. H. Lee[2] · I. H. Park[1] · C. D. Rho[3]

Received: 20 October 2022 / Accepted: 22 November 2022 / Published online: 6 February 2023

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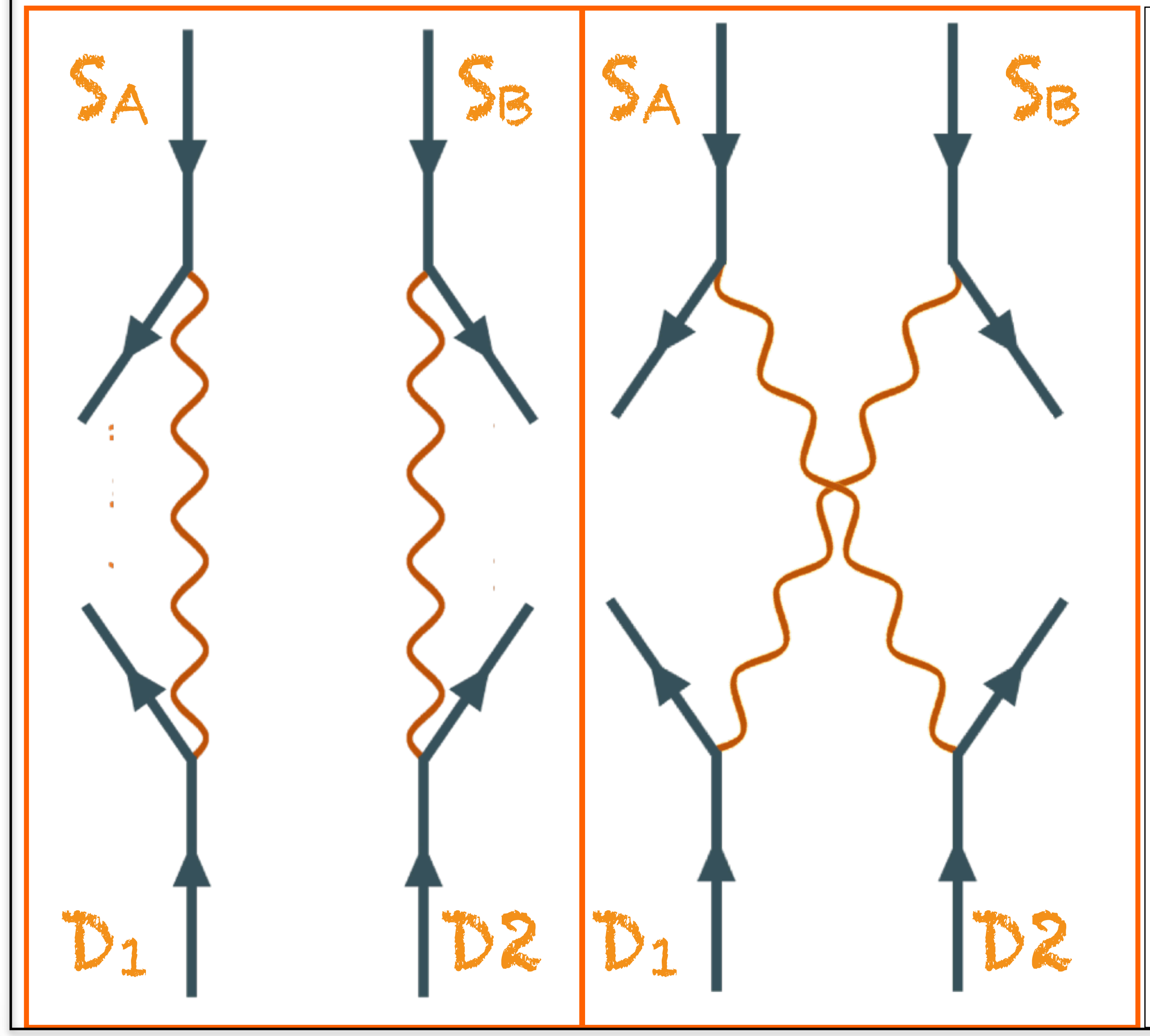

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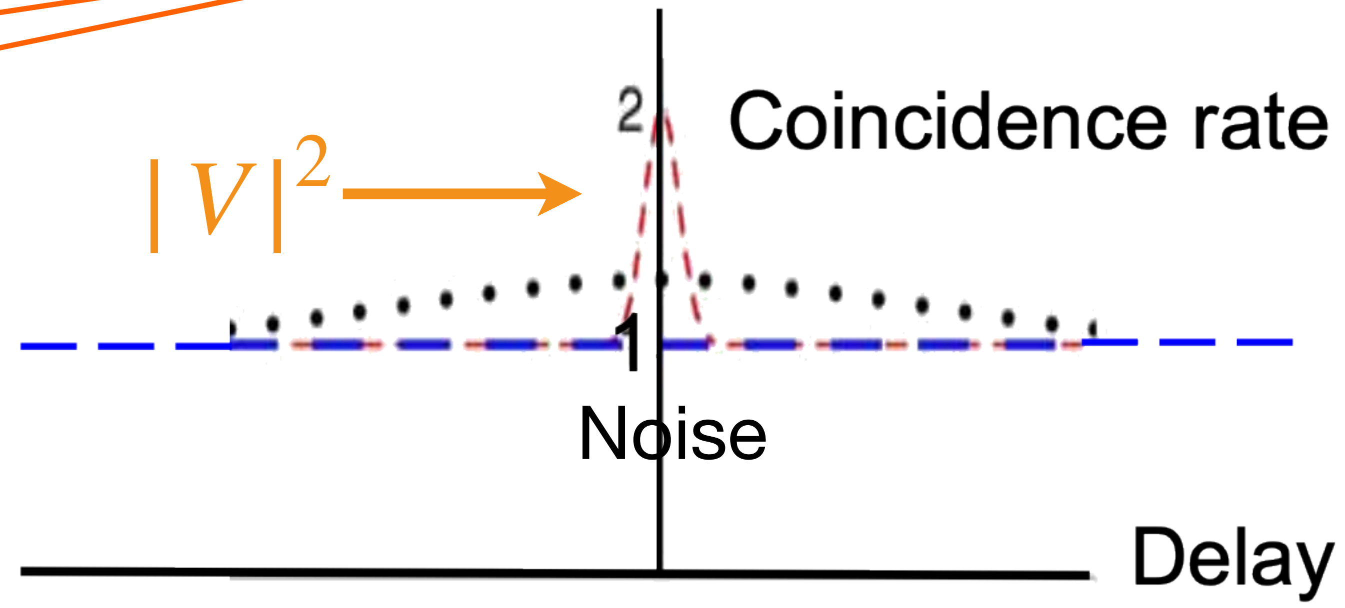

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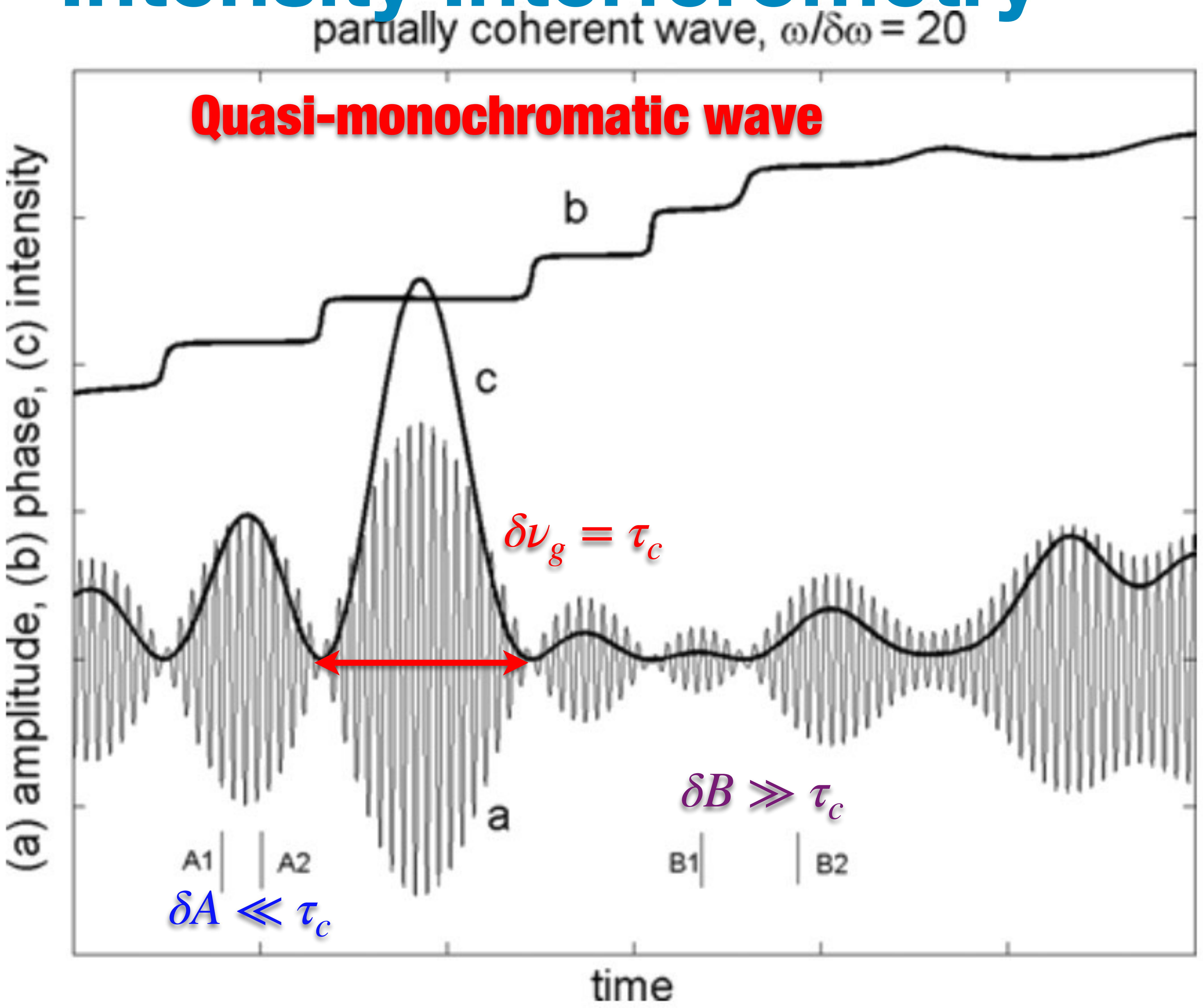

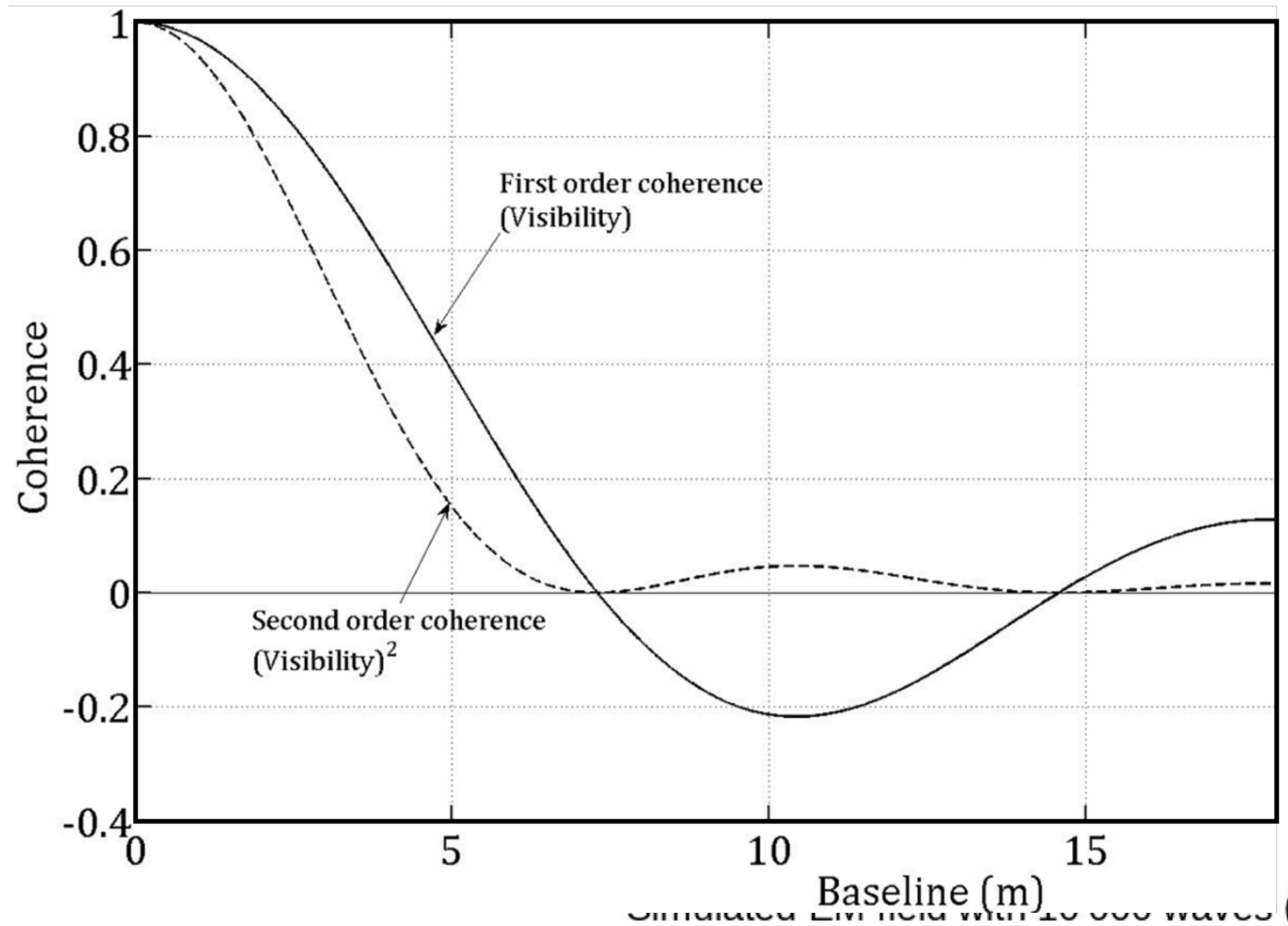

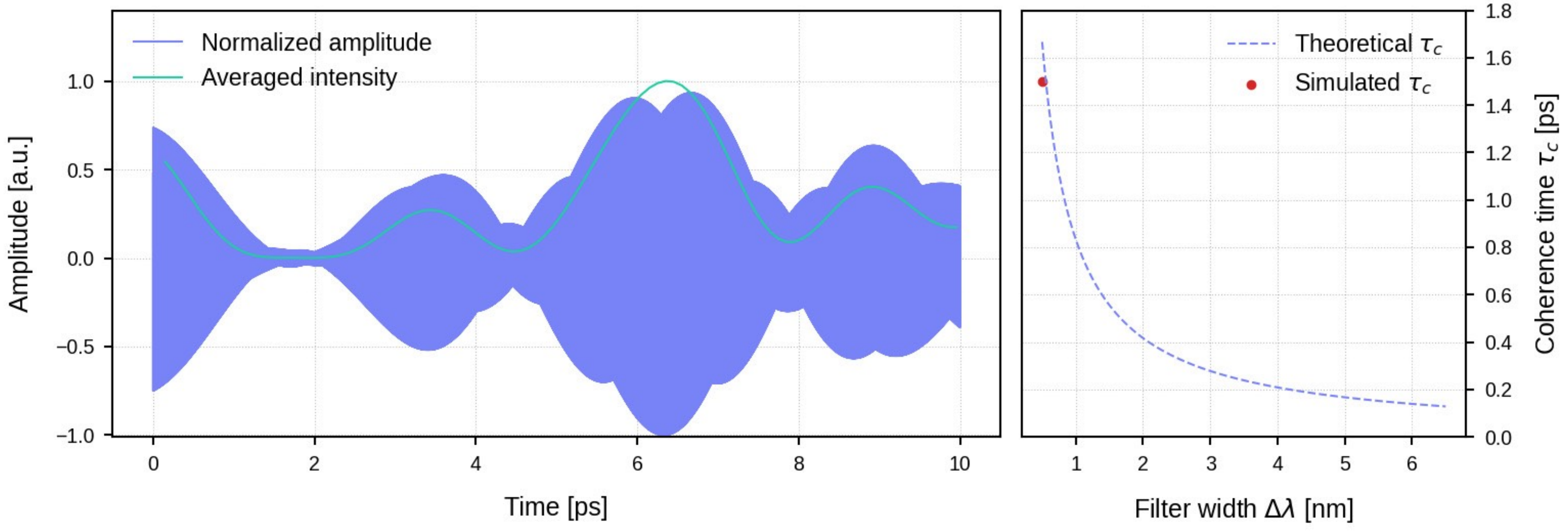

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Physics Today Vo. 55 , 7 (2002)

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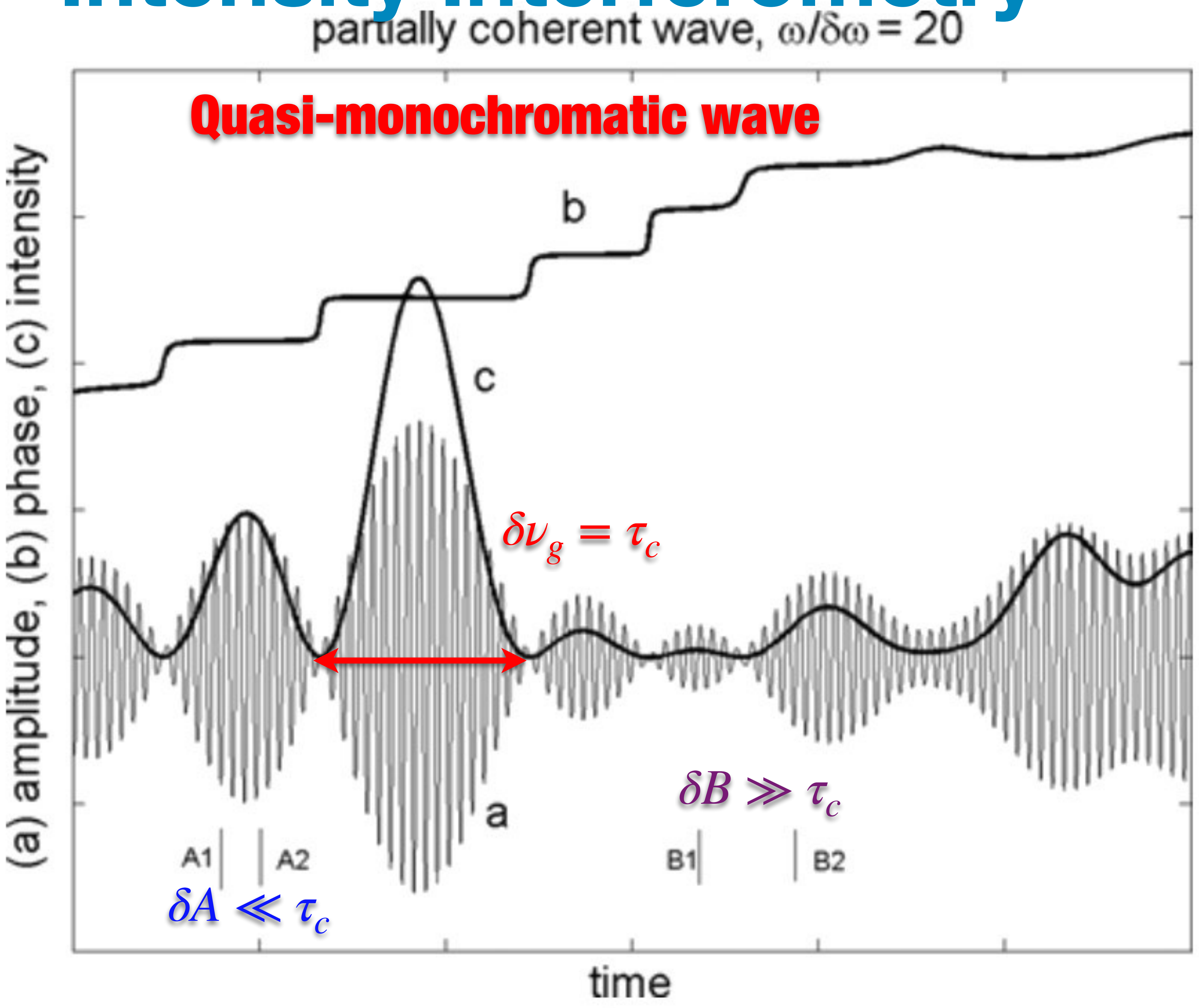

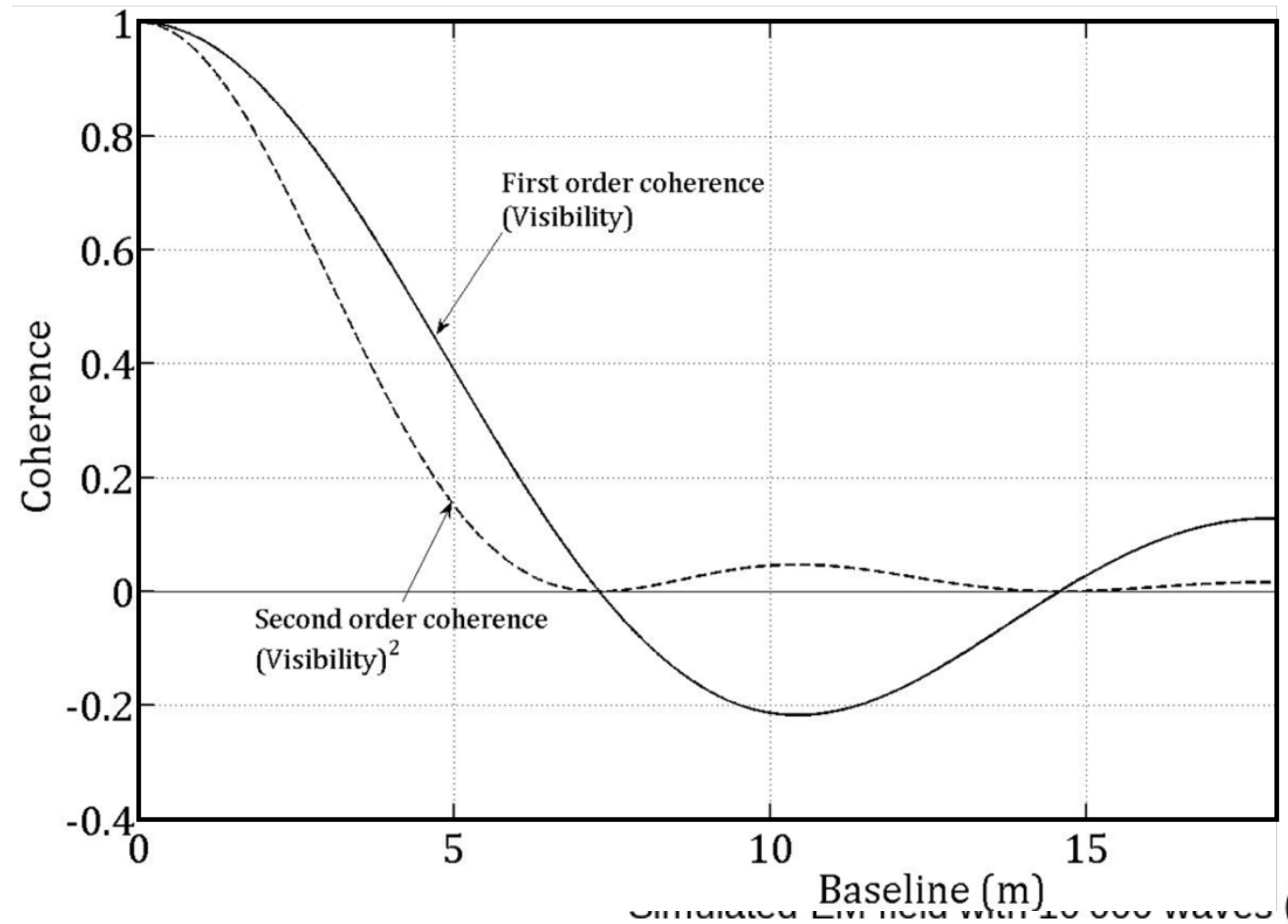

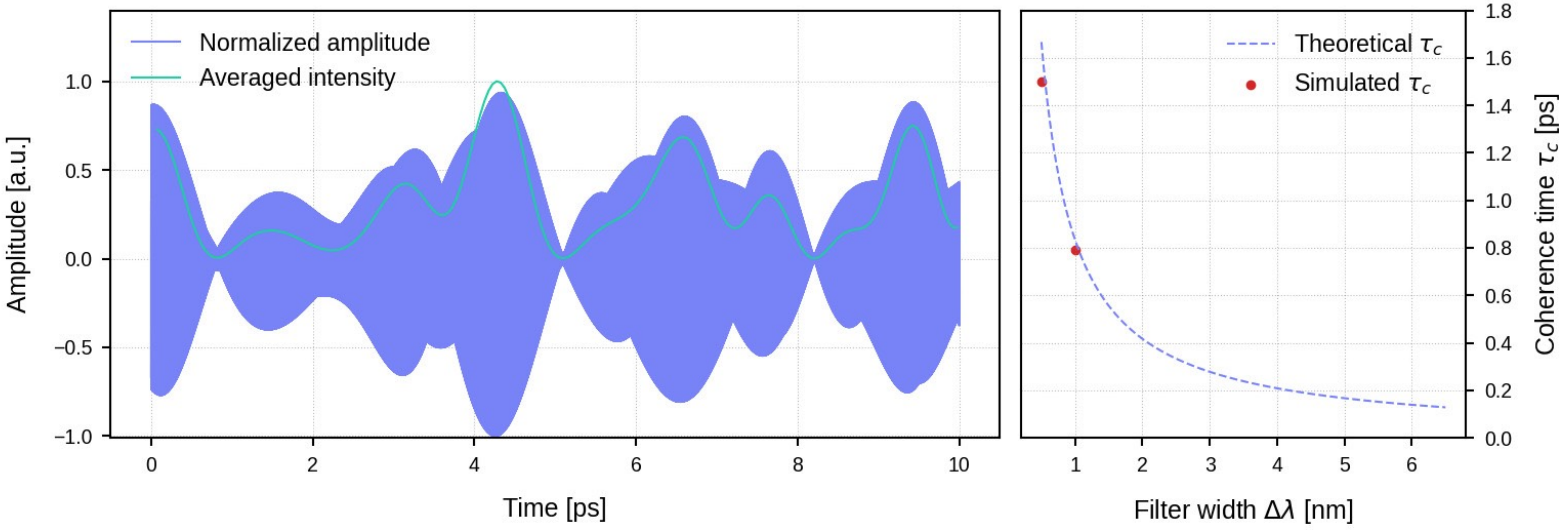

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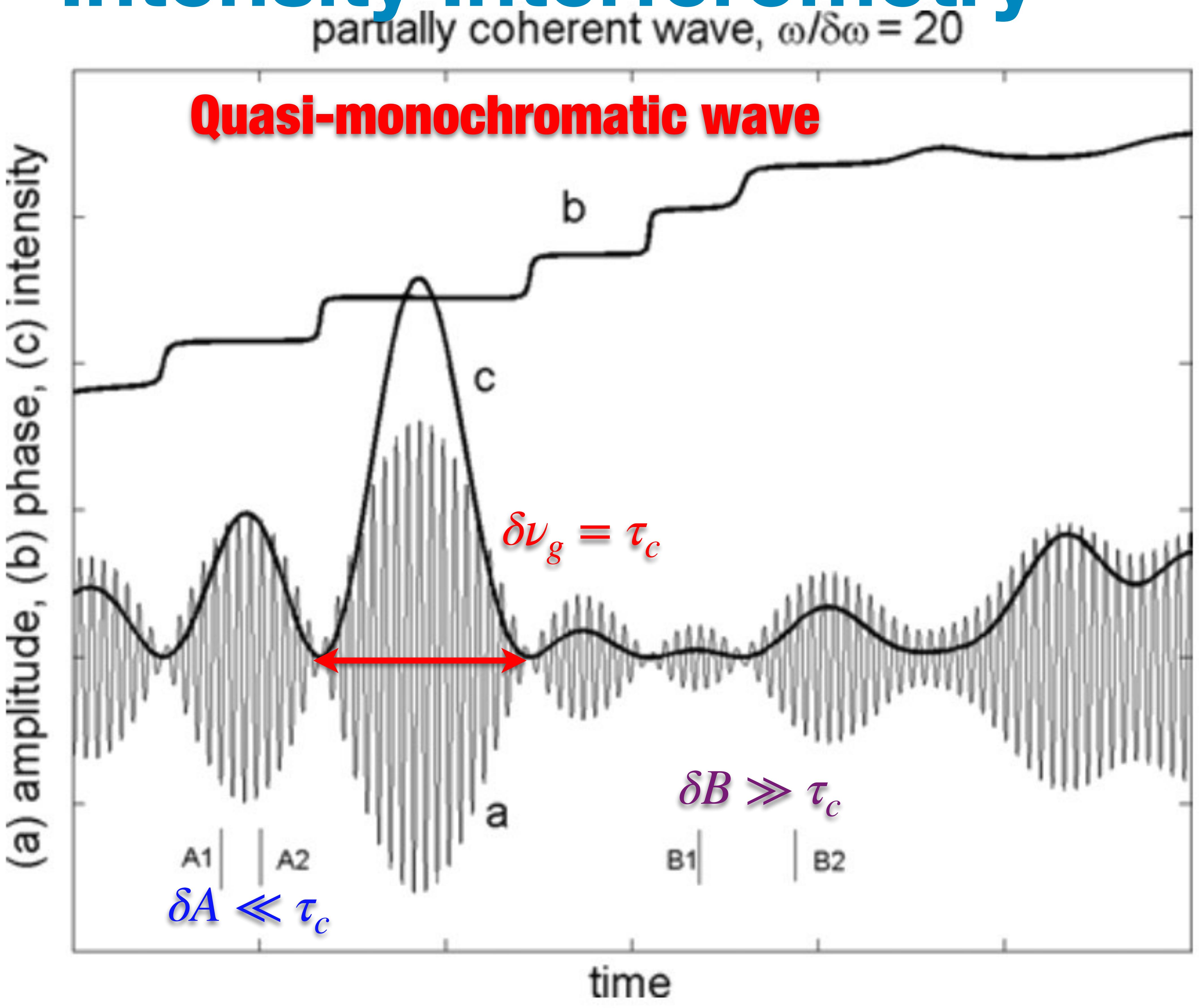

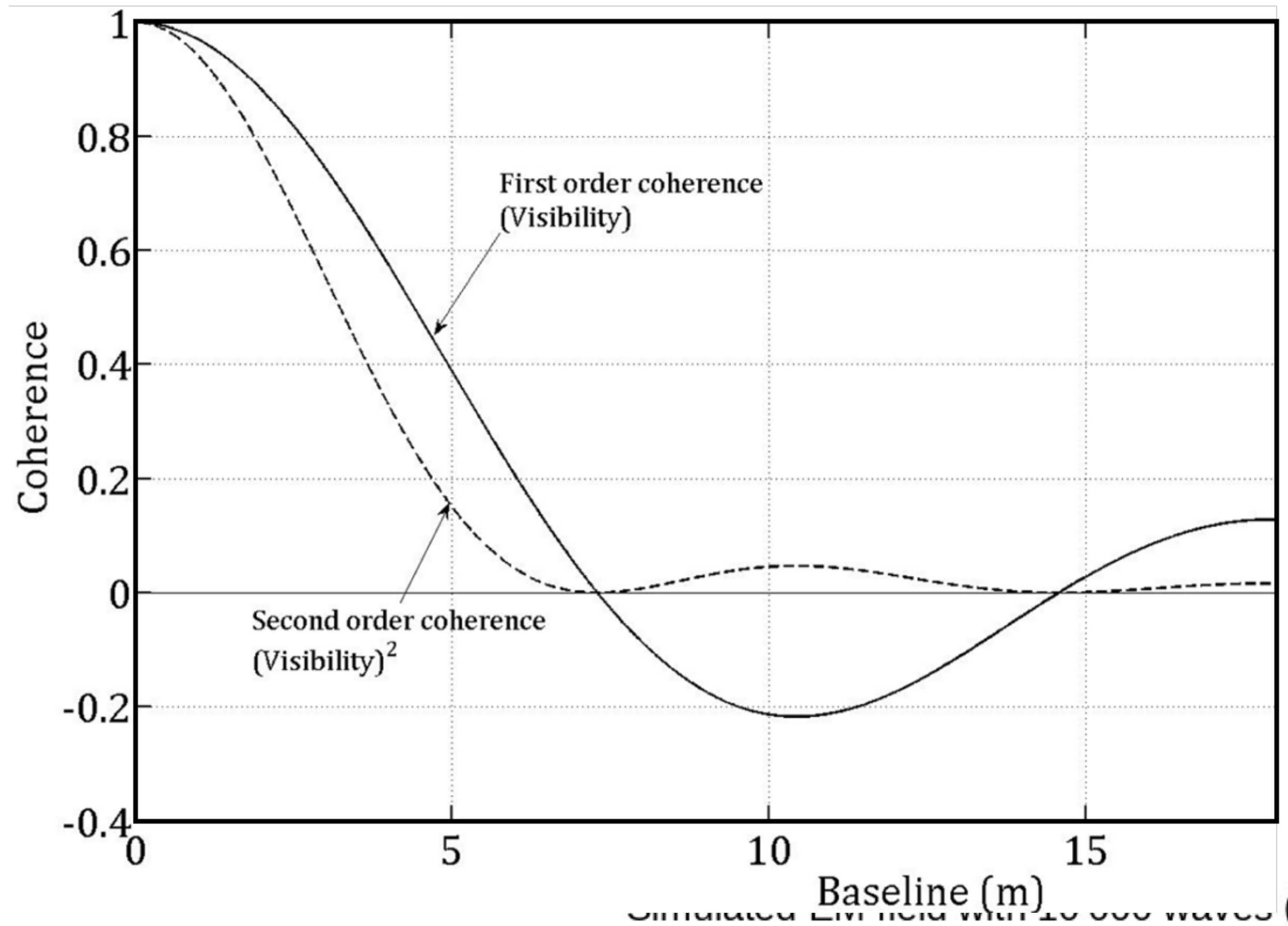

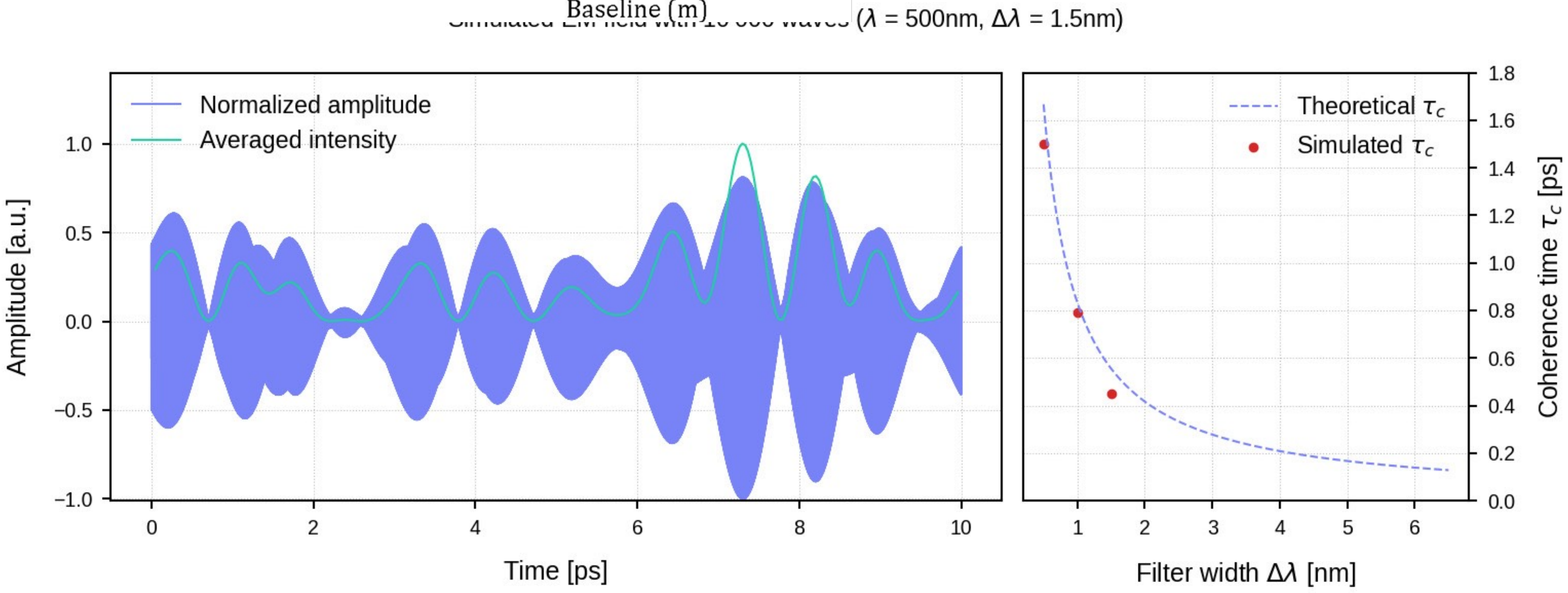

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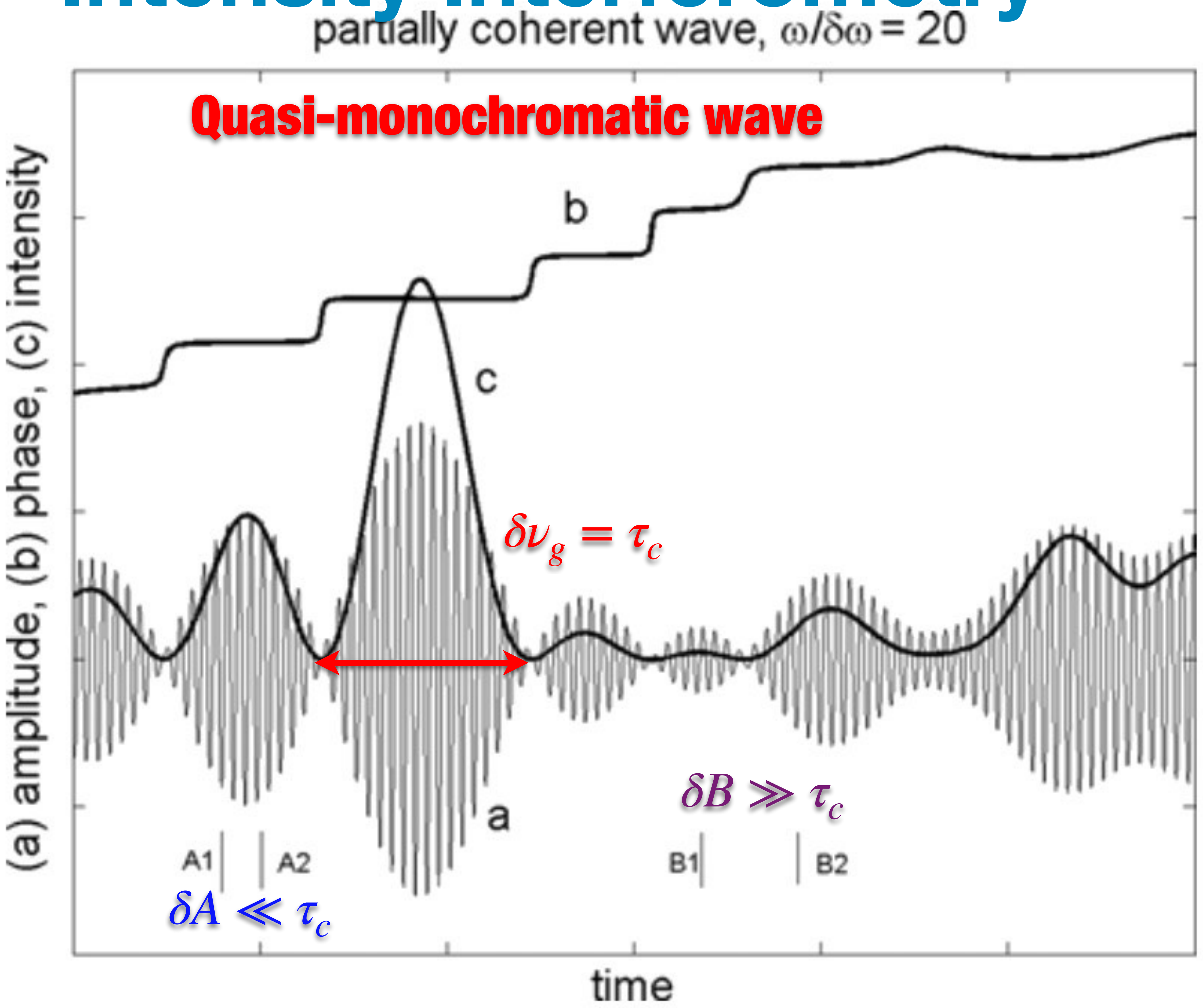

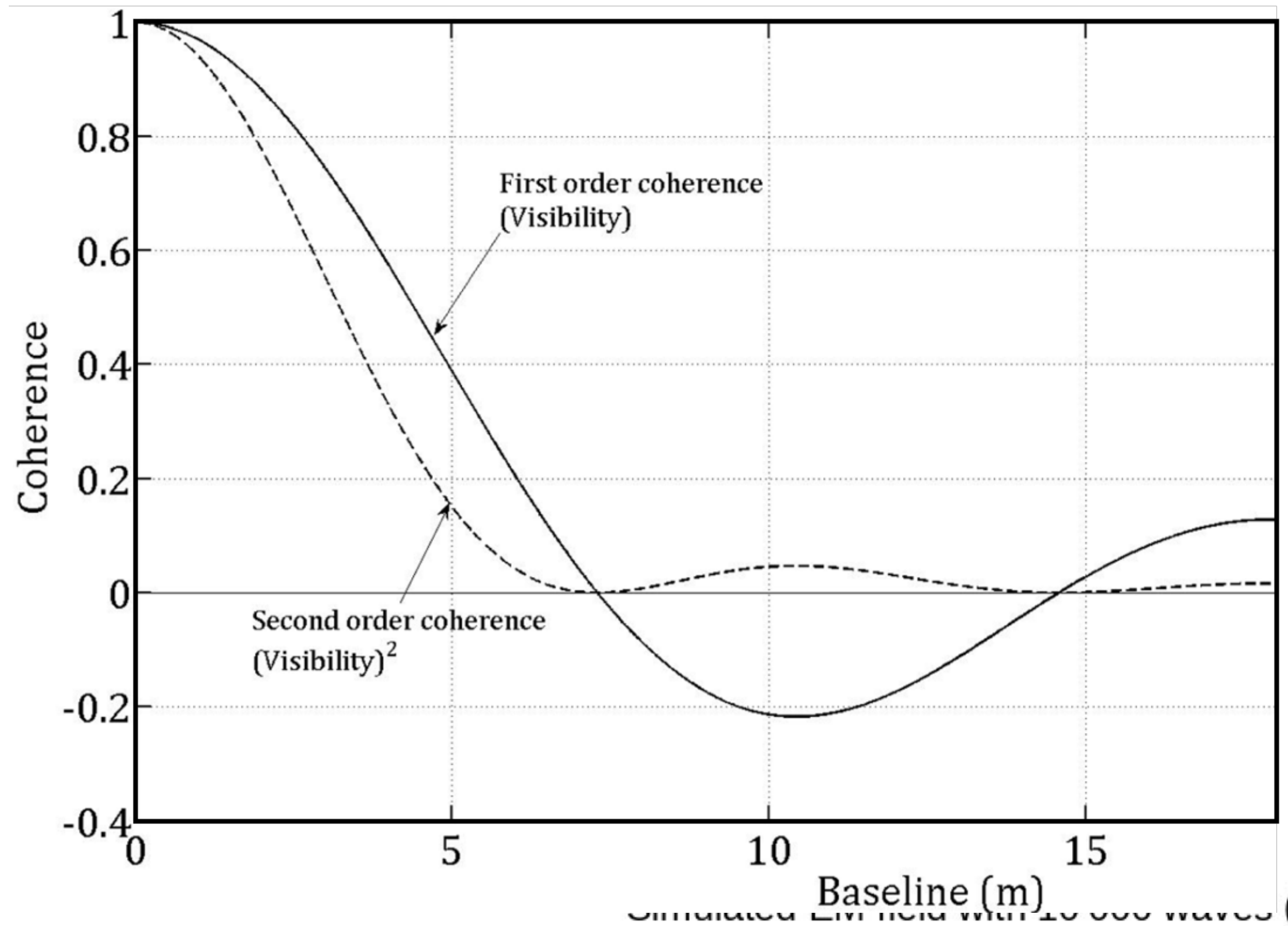

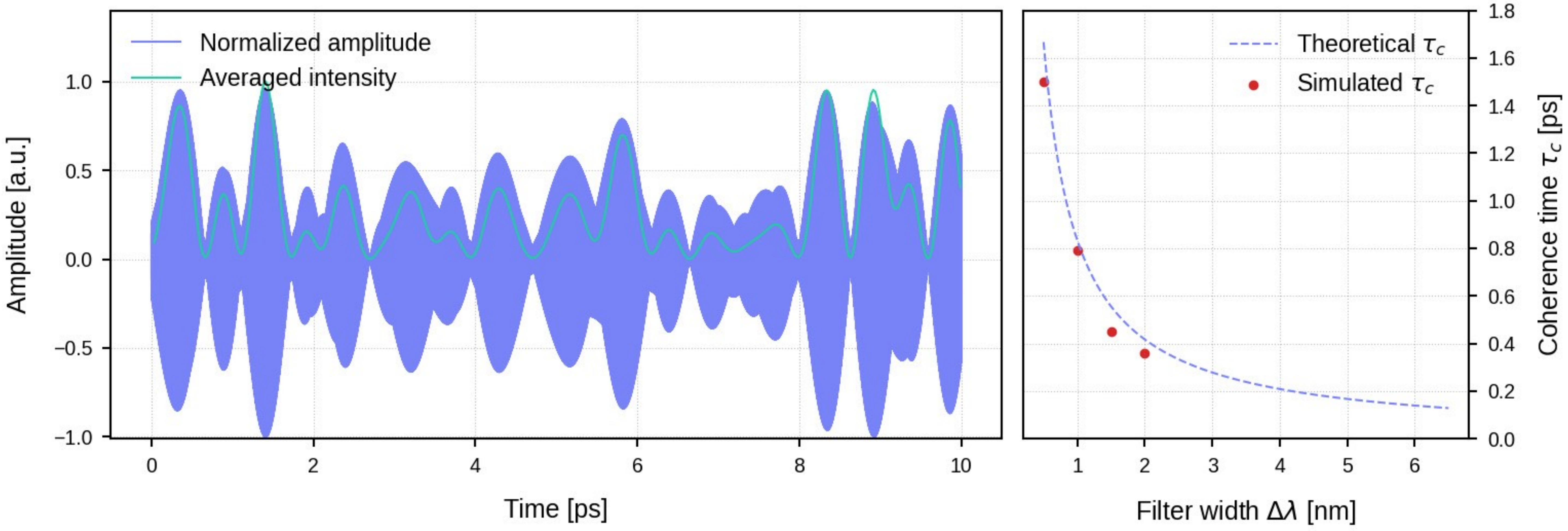

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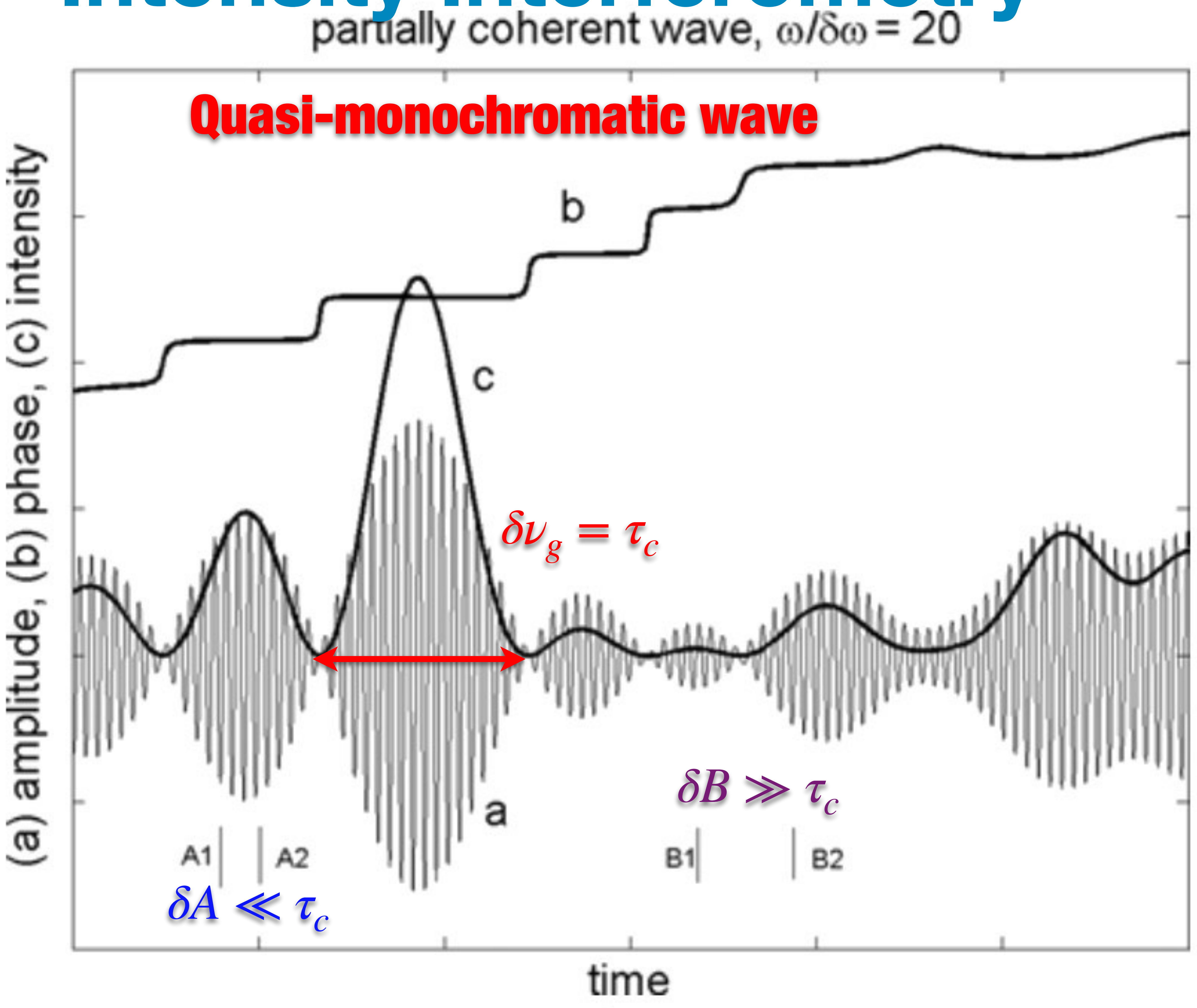

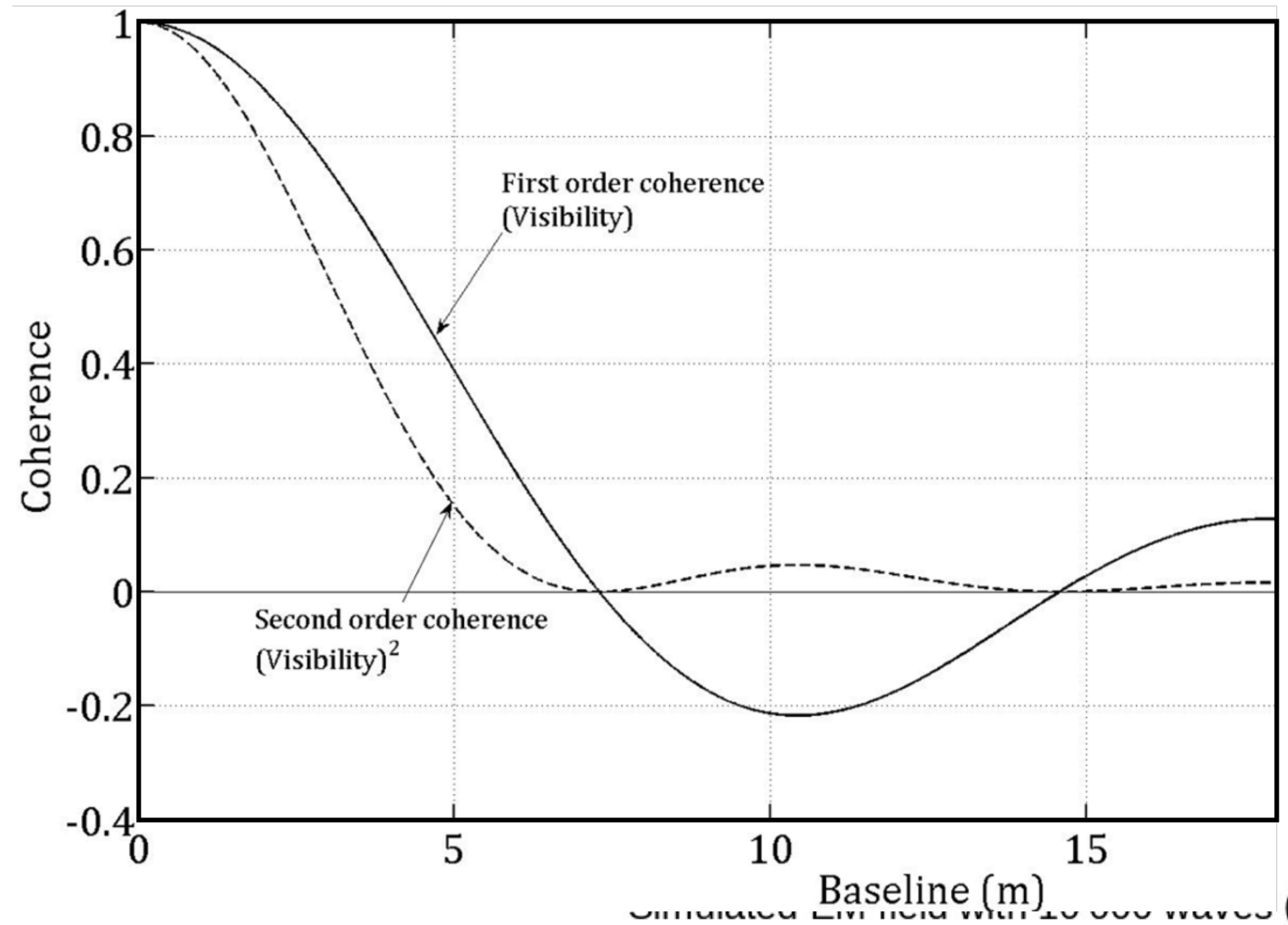

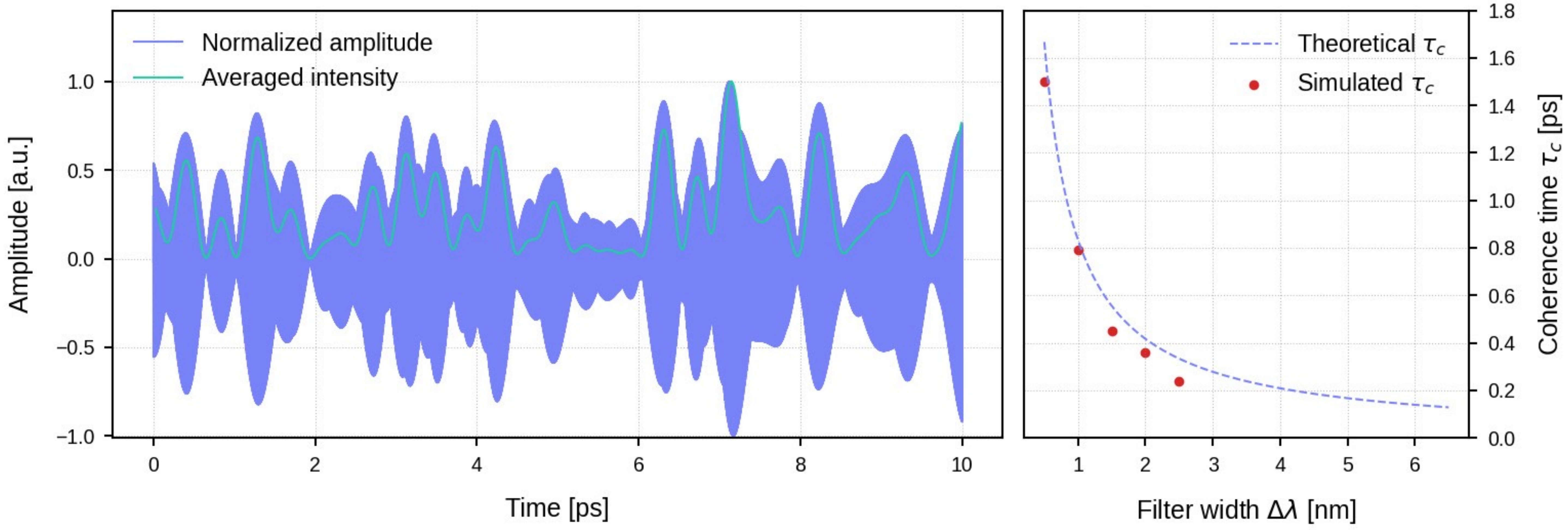

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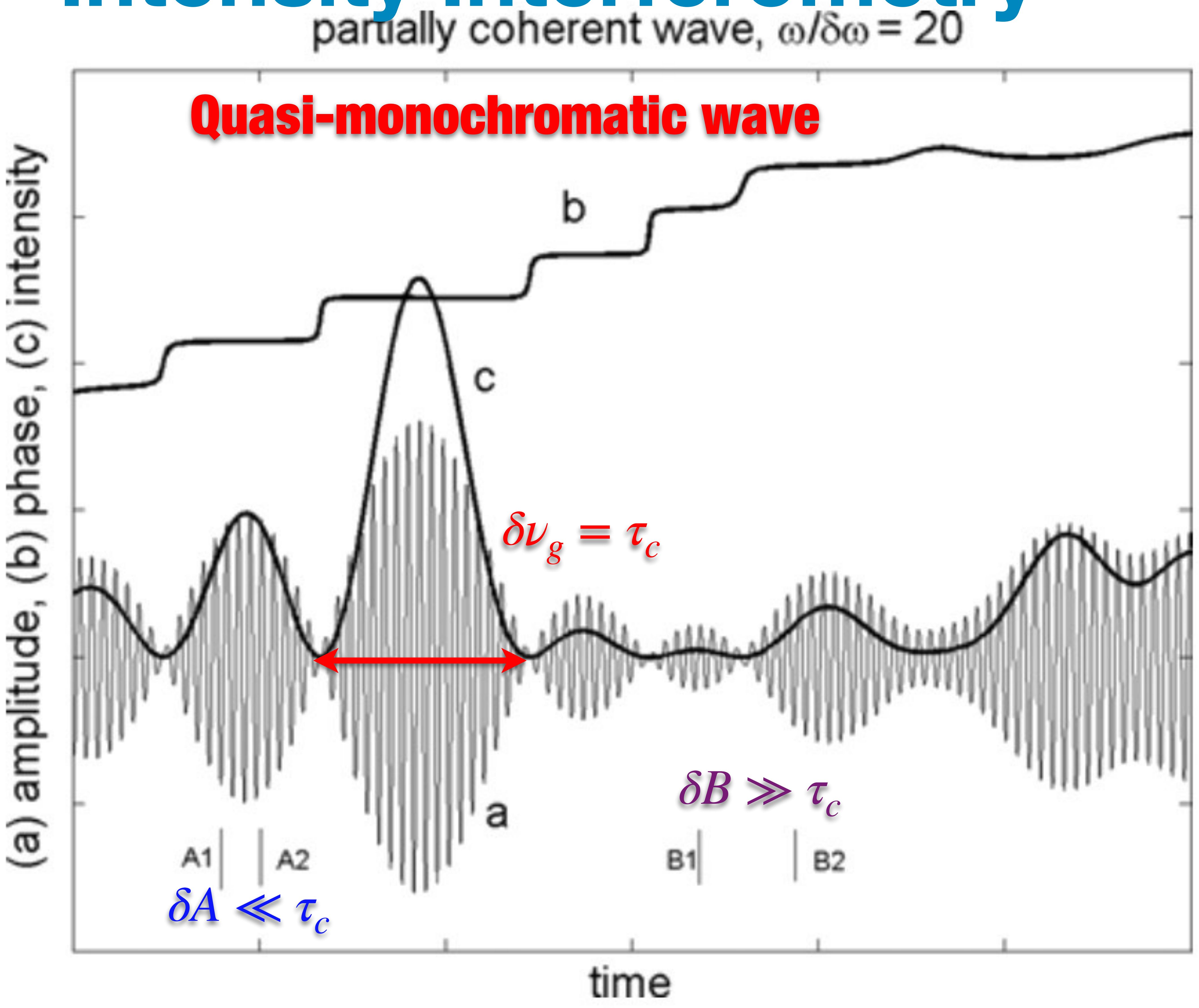
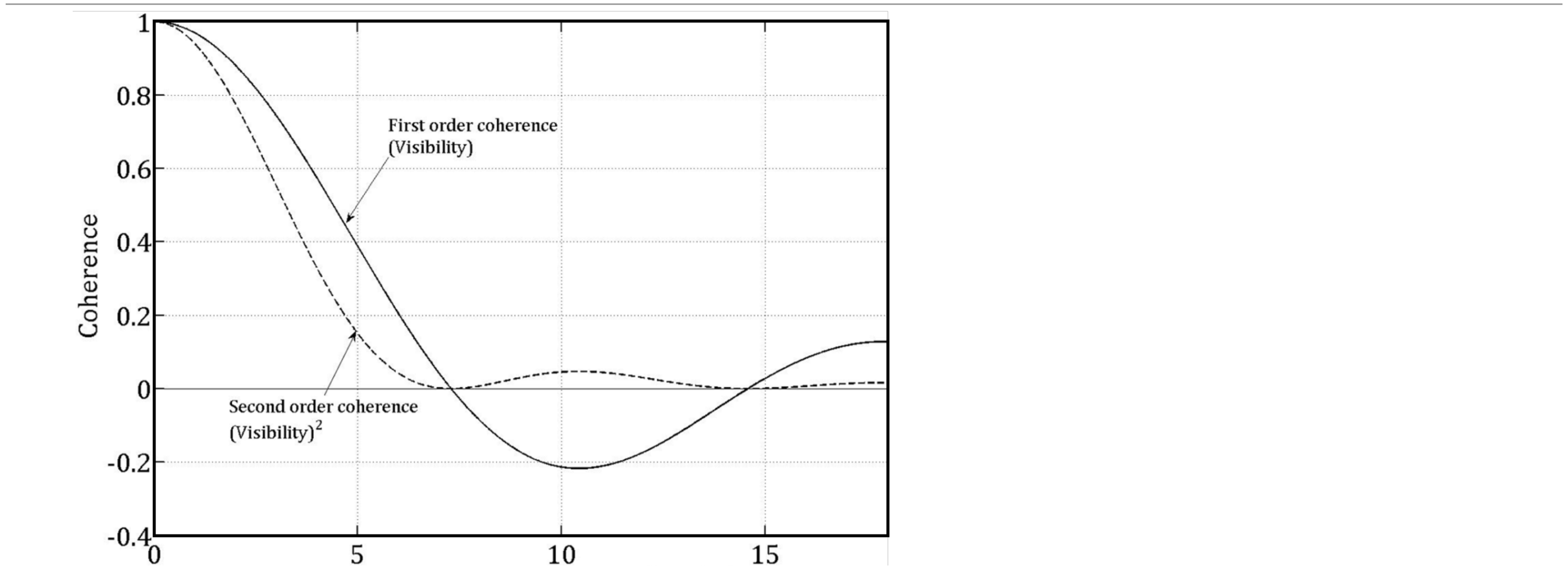
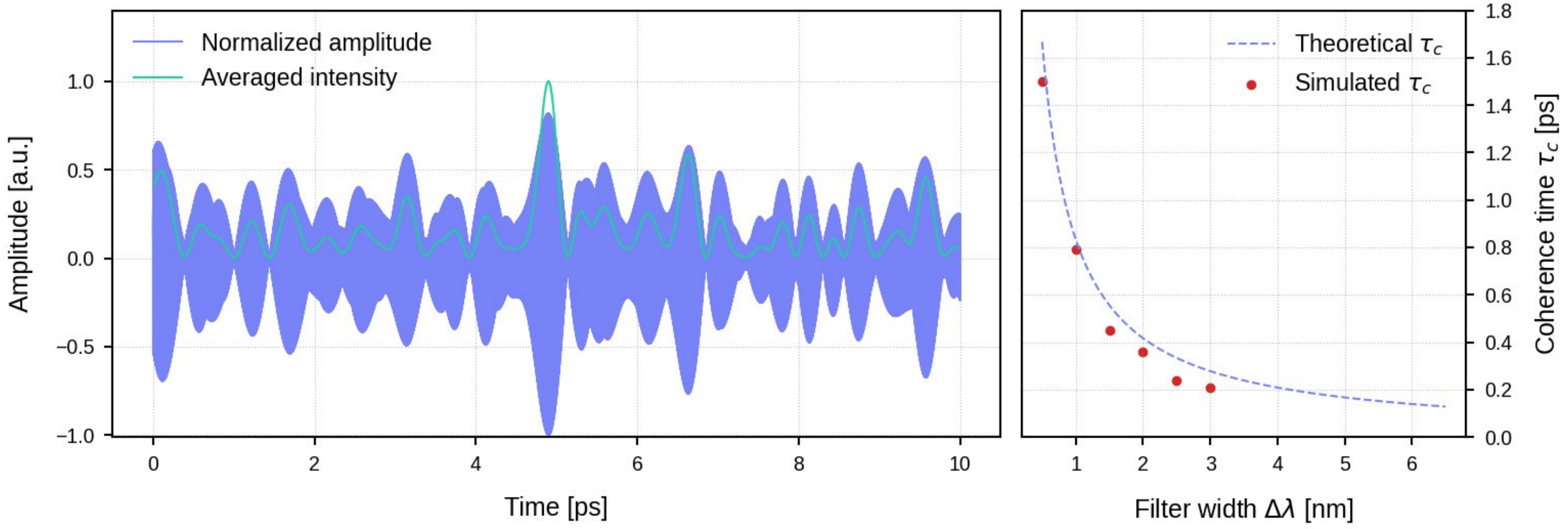




Simulated EM field with 10'000 waves (λ = 500nm, $\Delta\lambda$ = 3.0nm)



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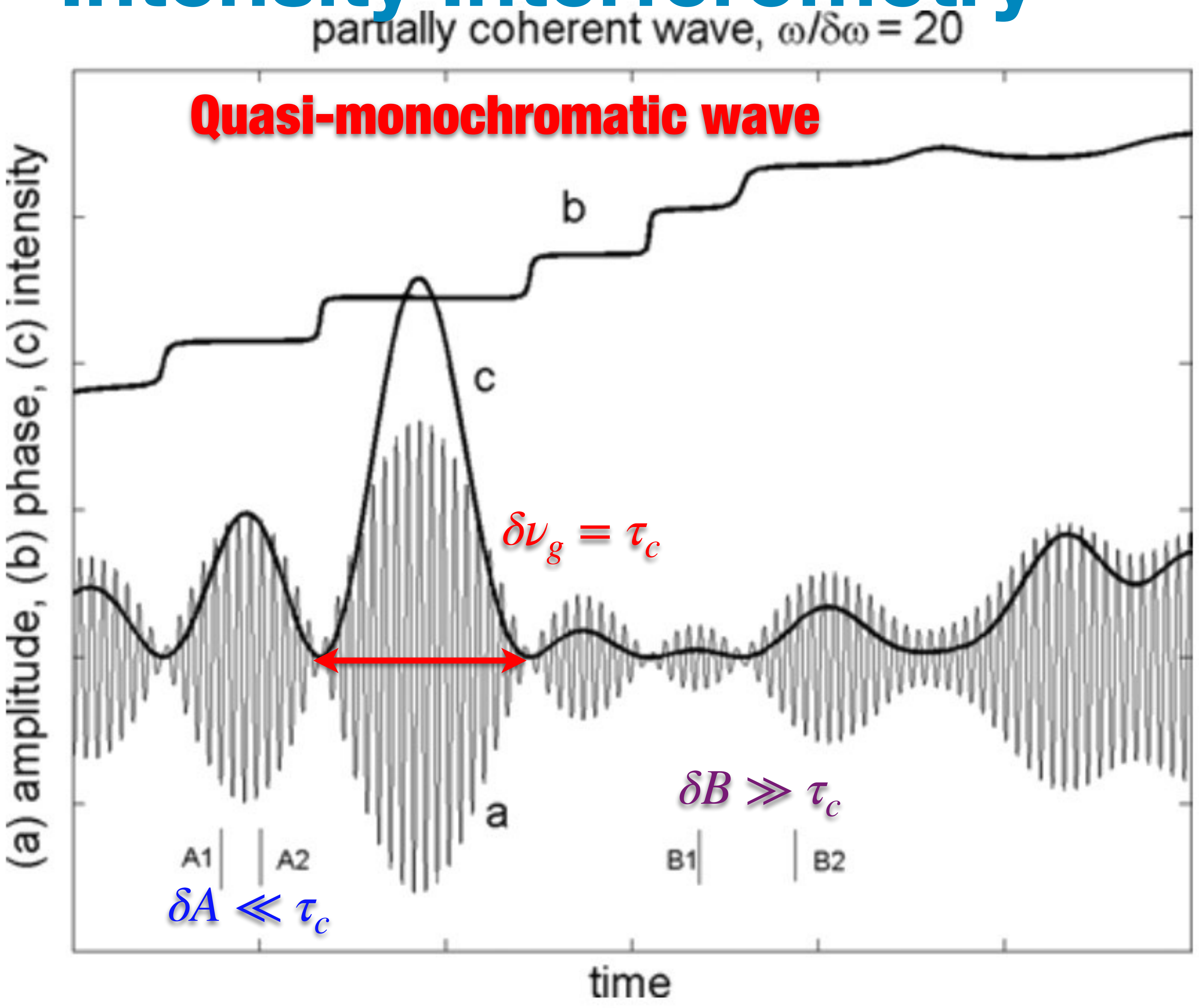

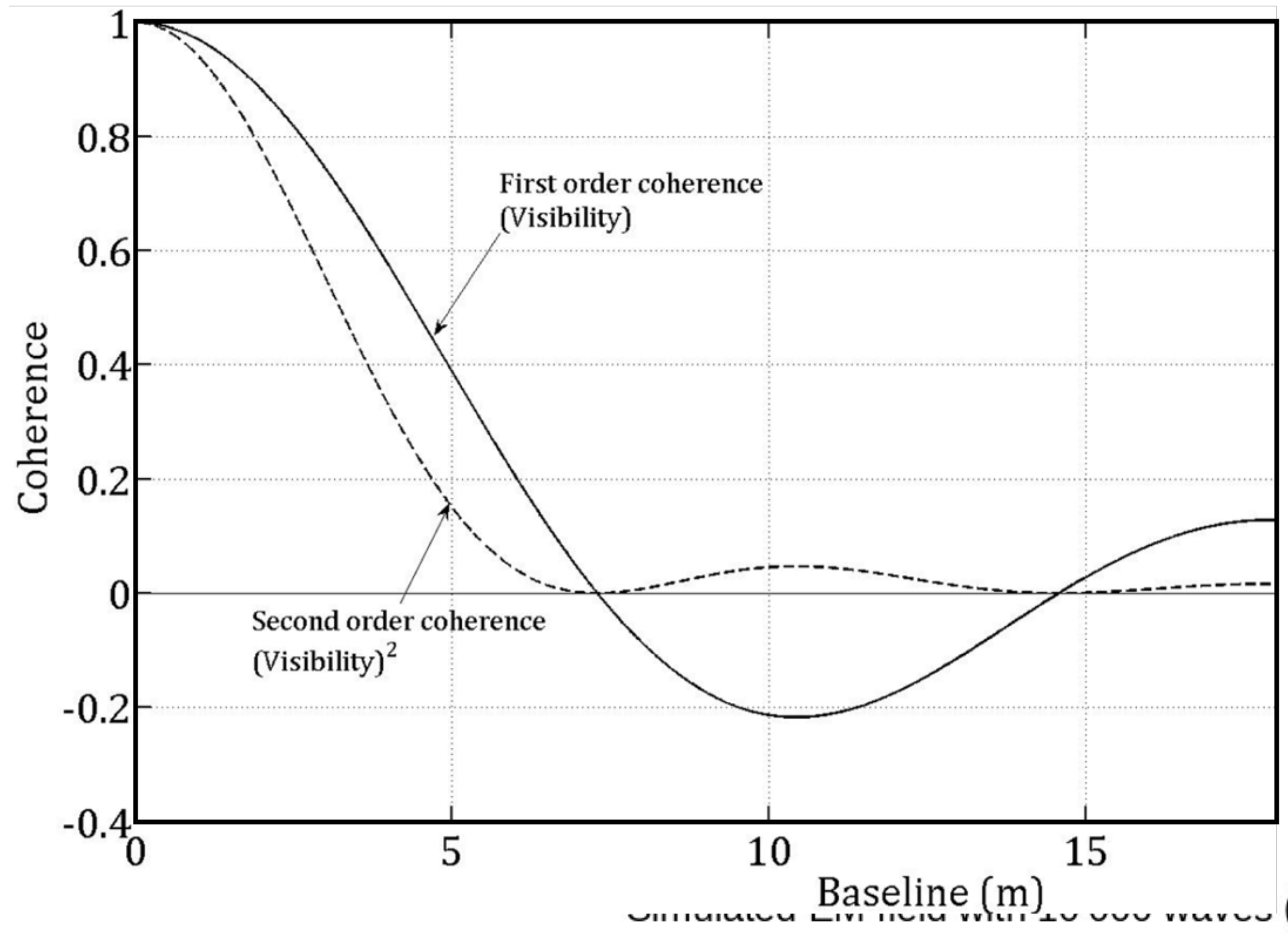

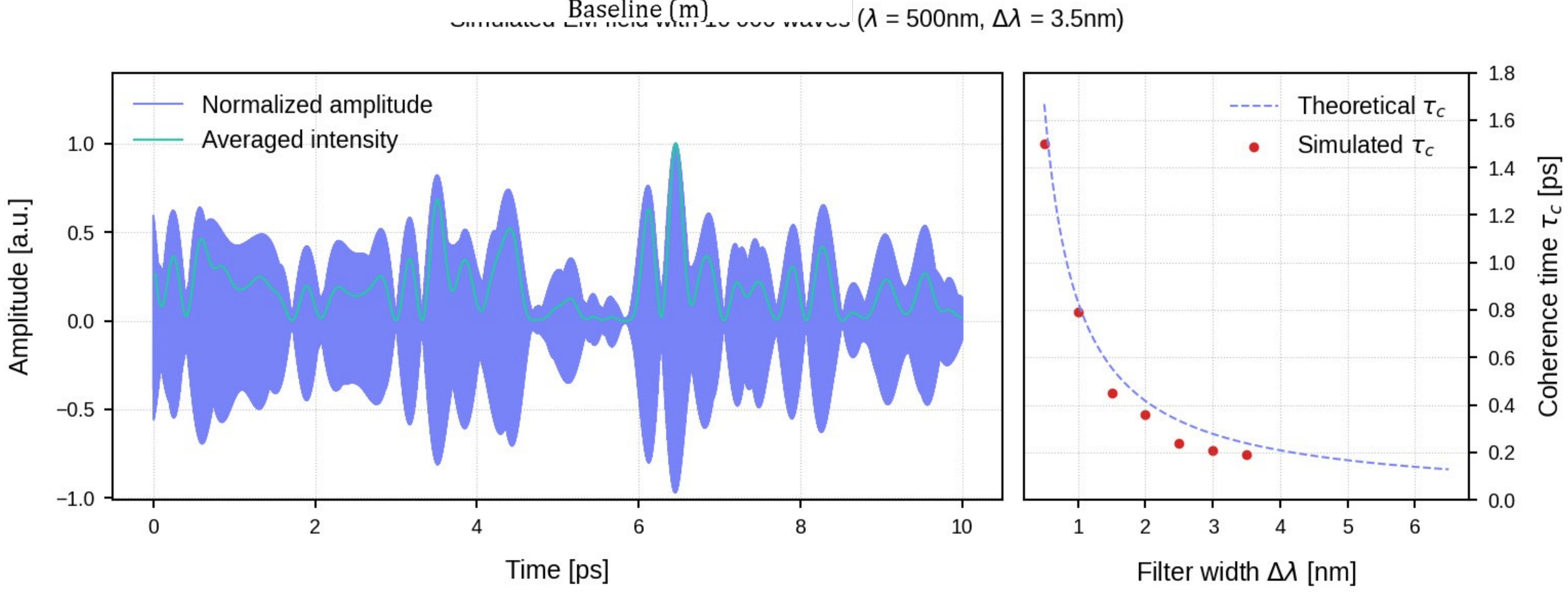

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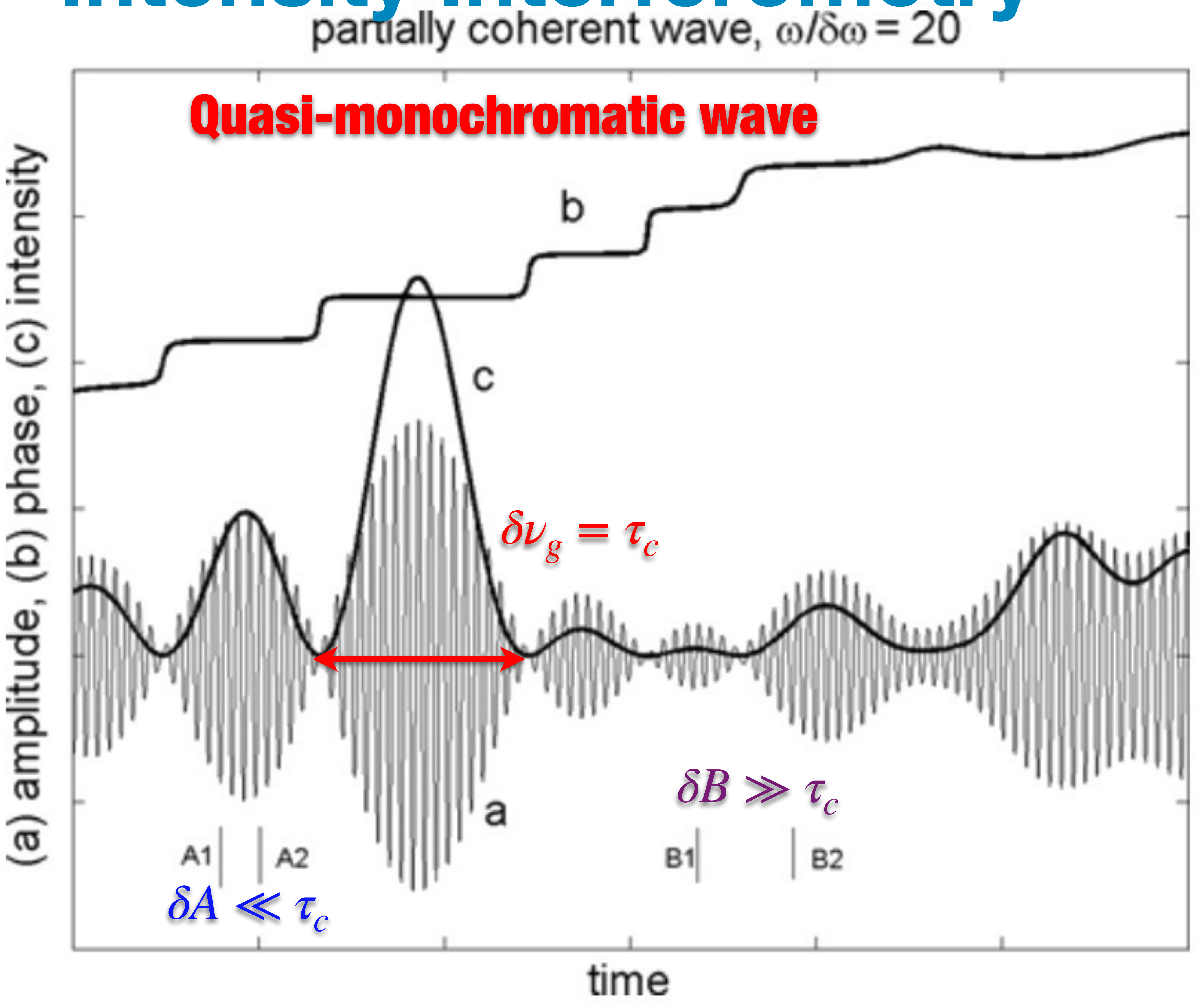

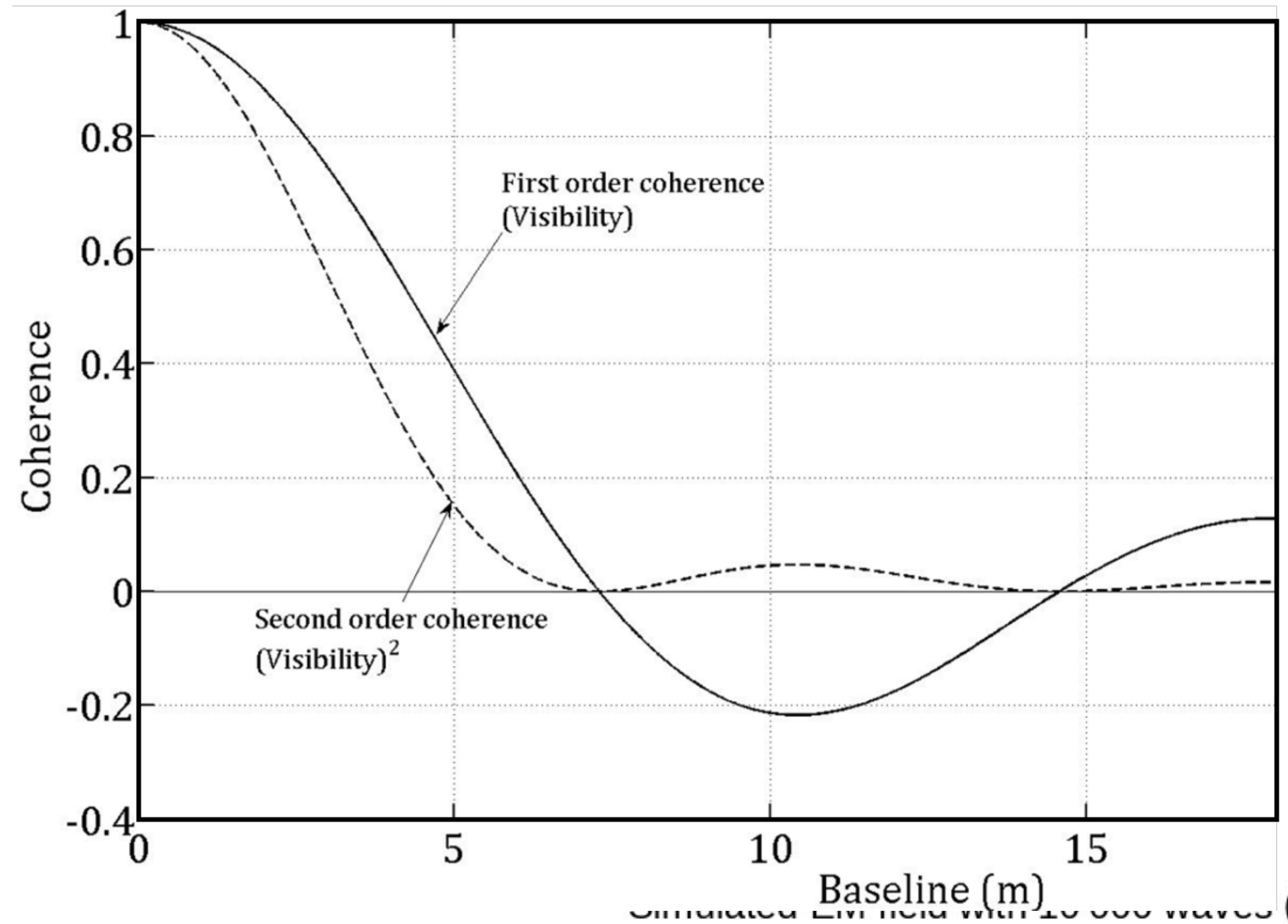

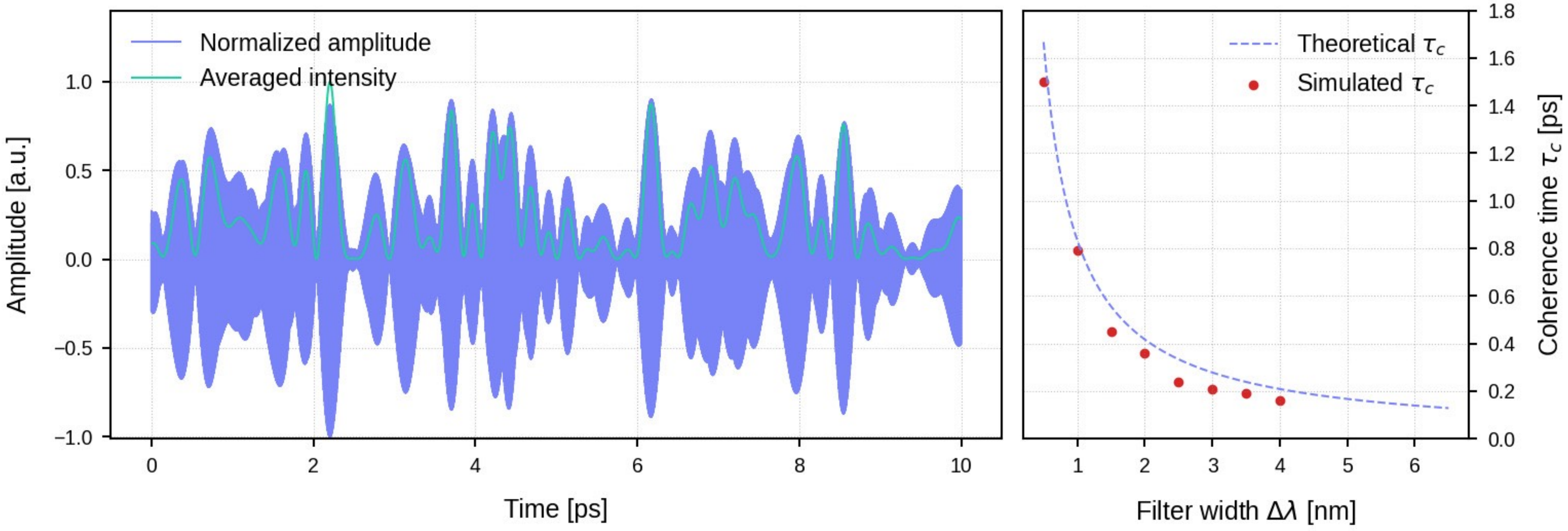

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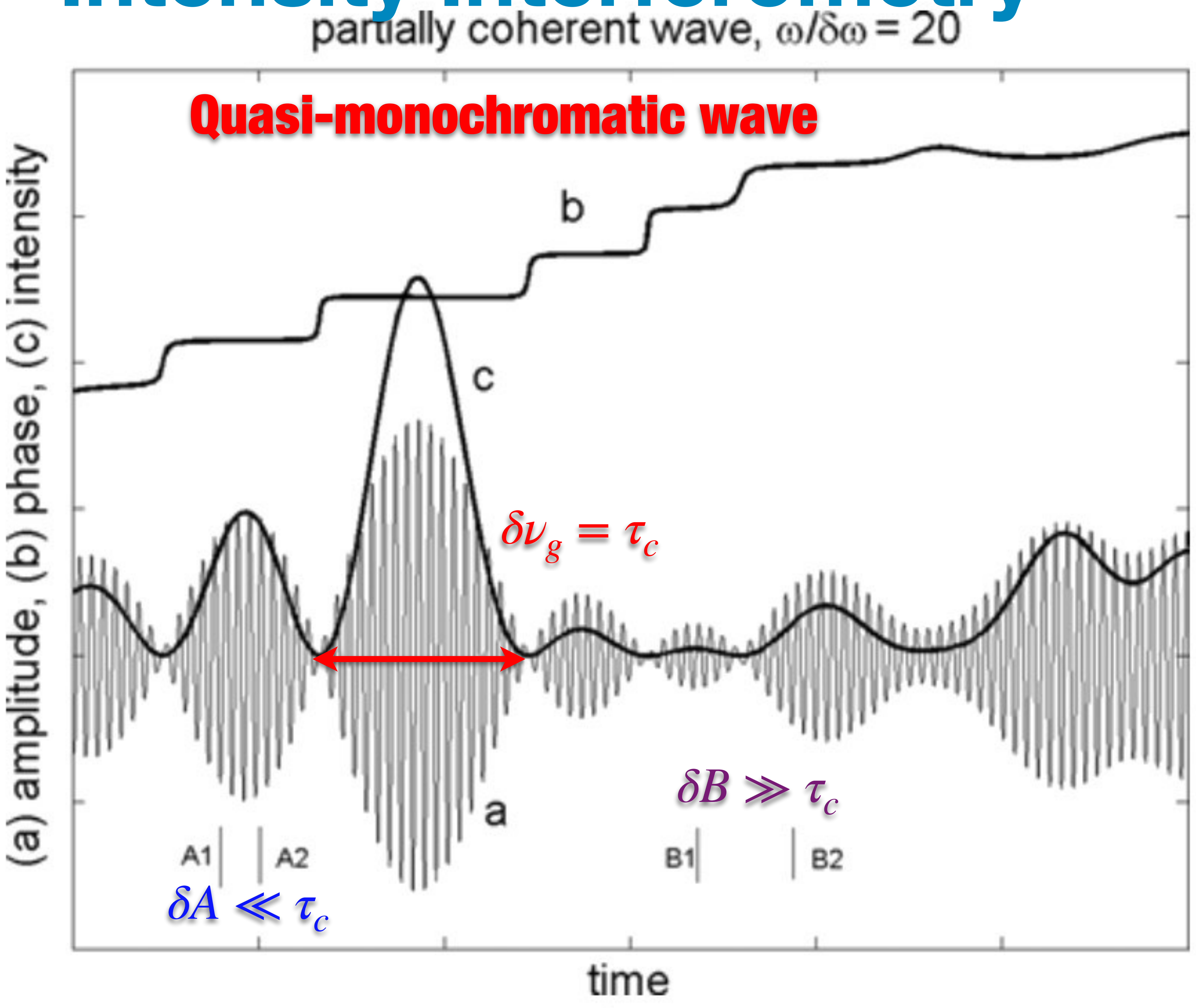

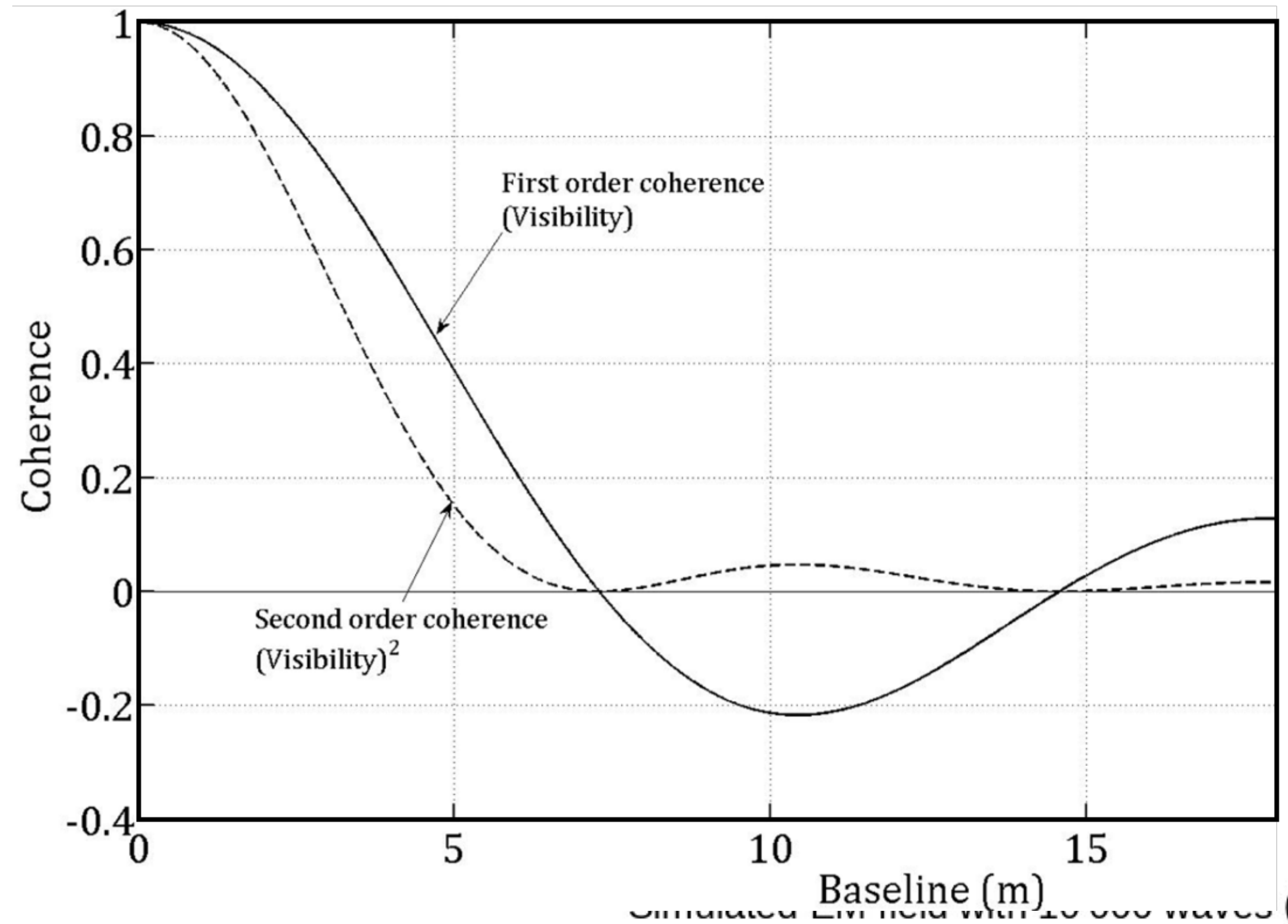

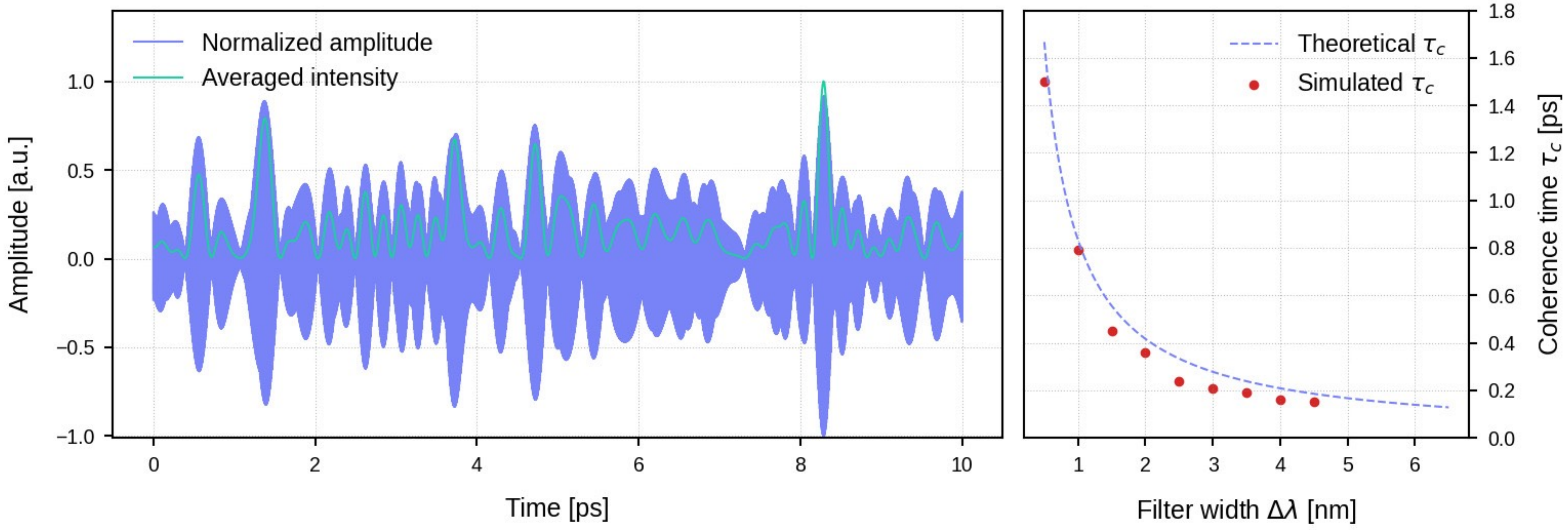

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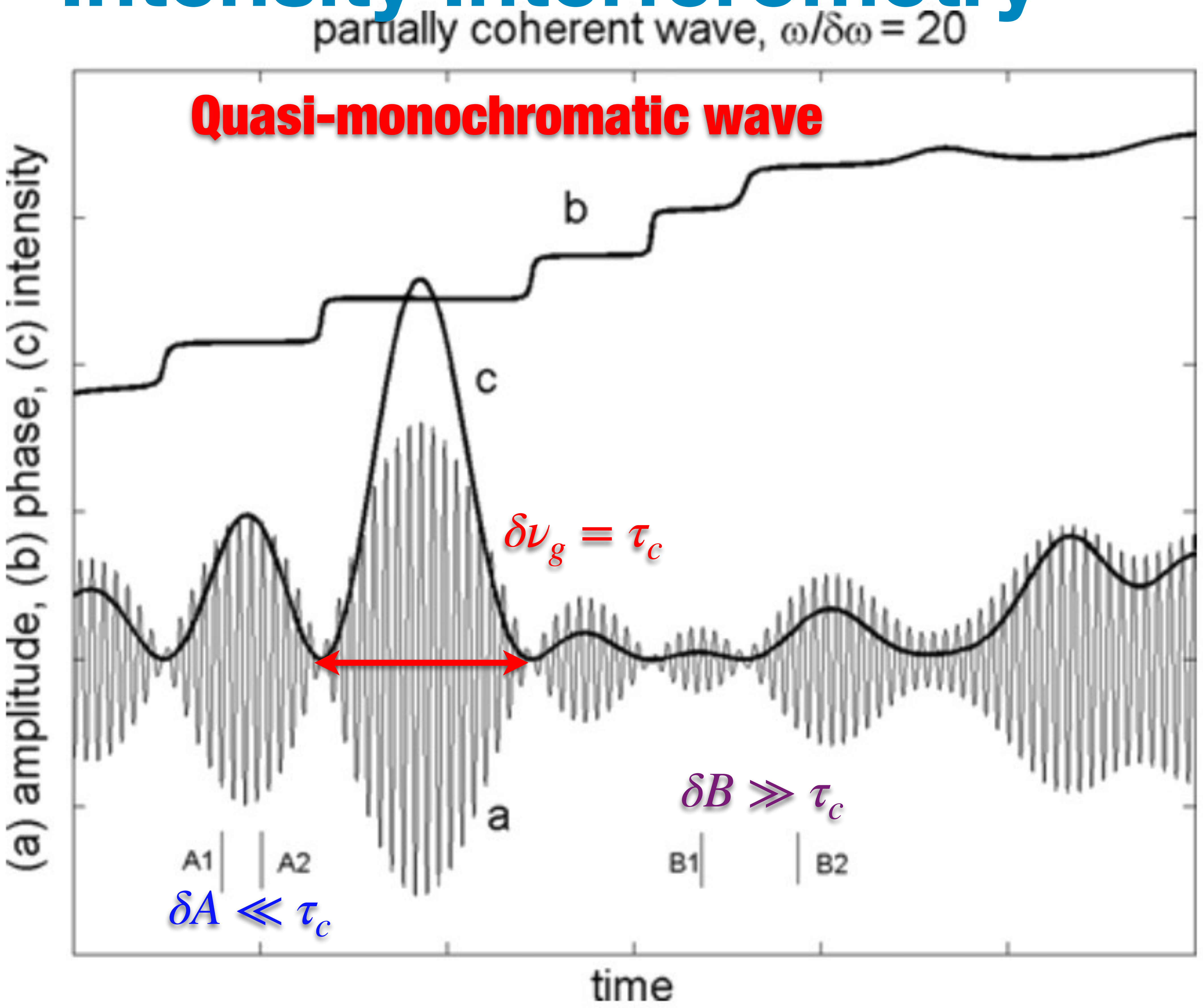

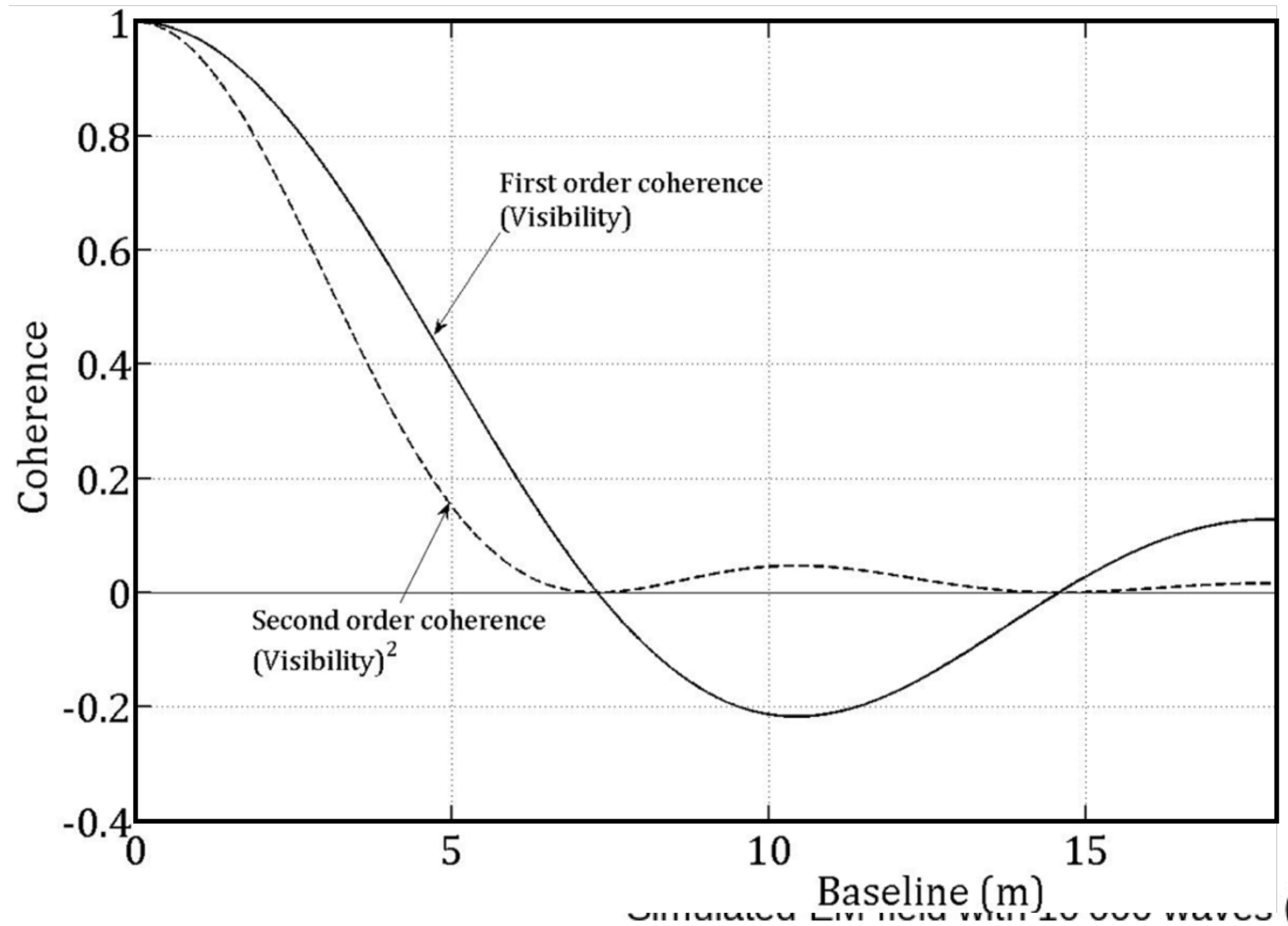

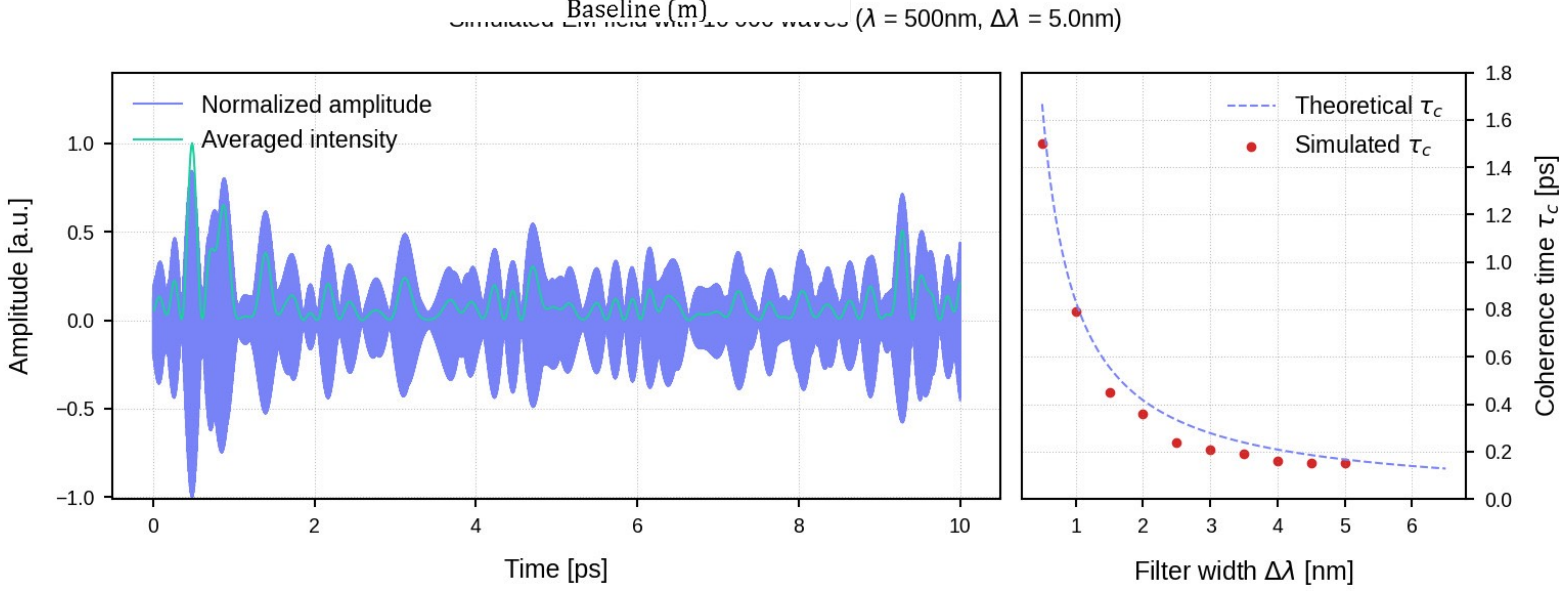

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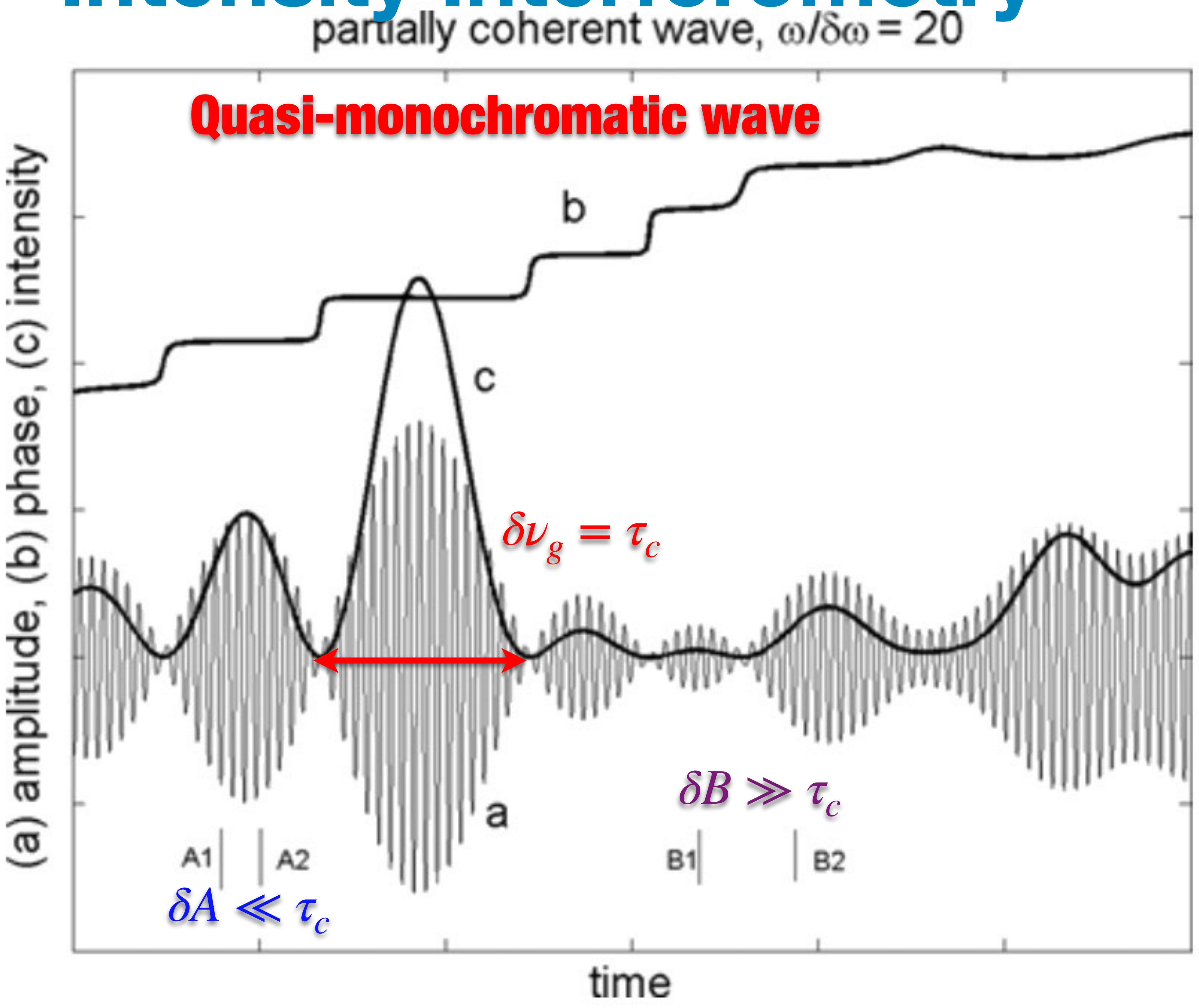

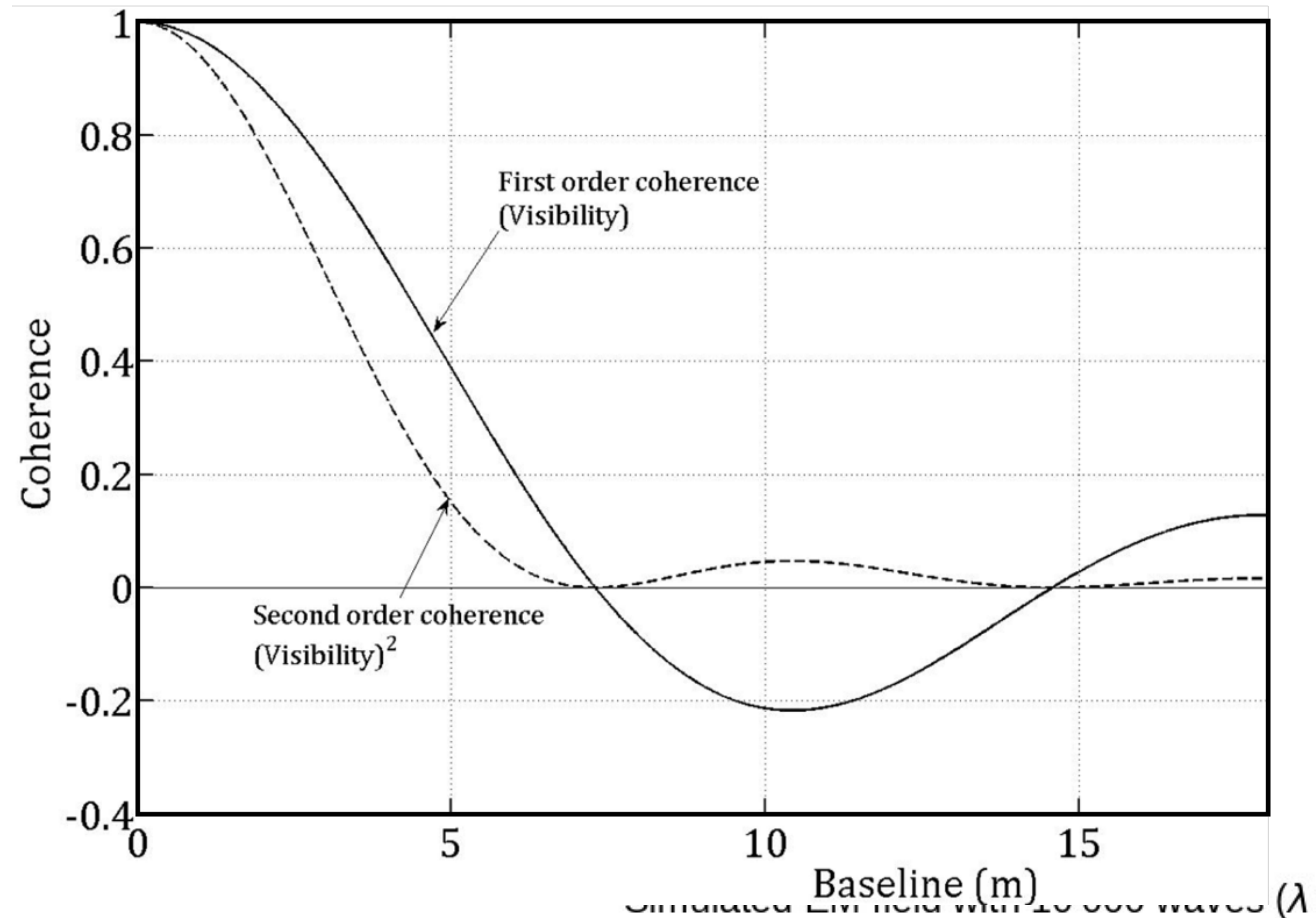

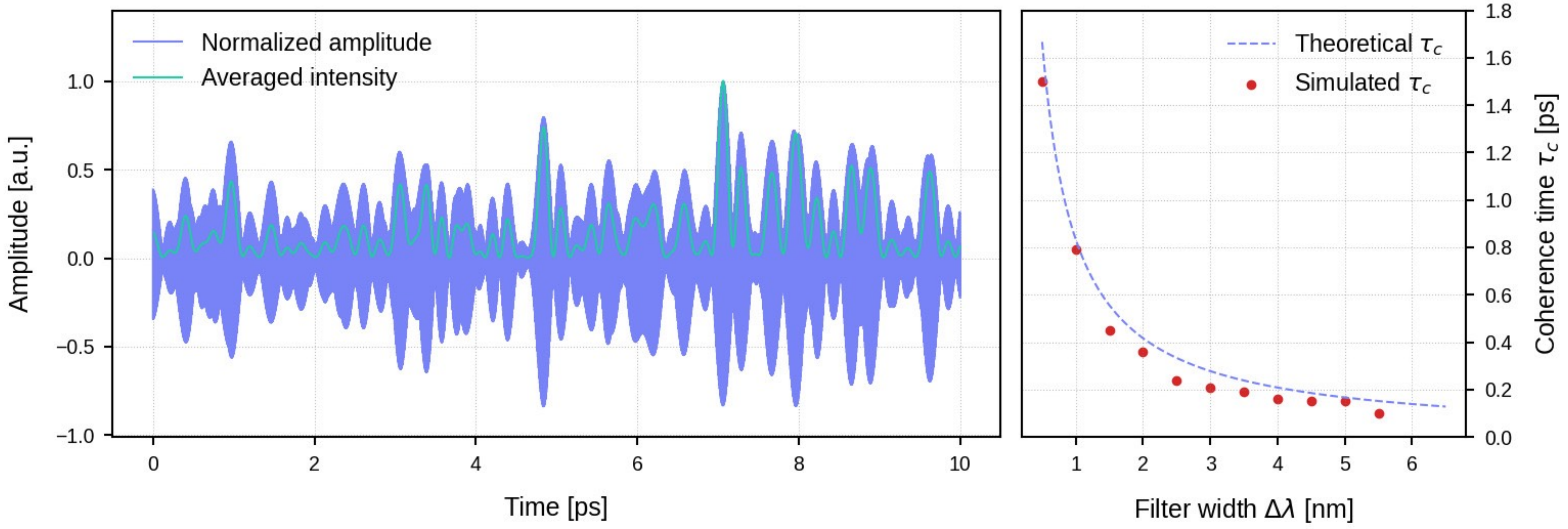

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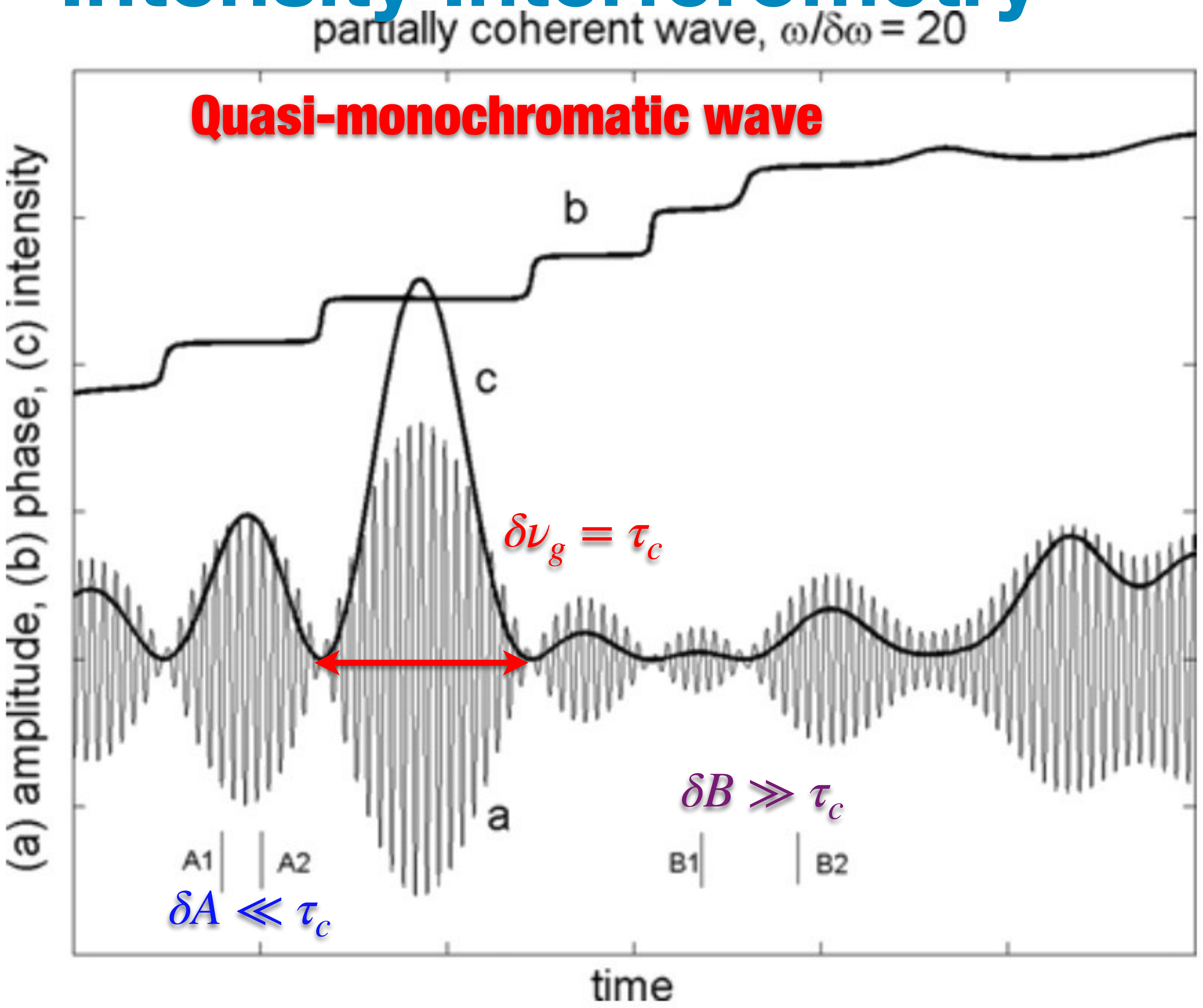

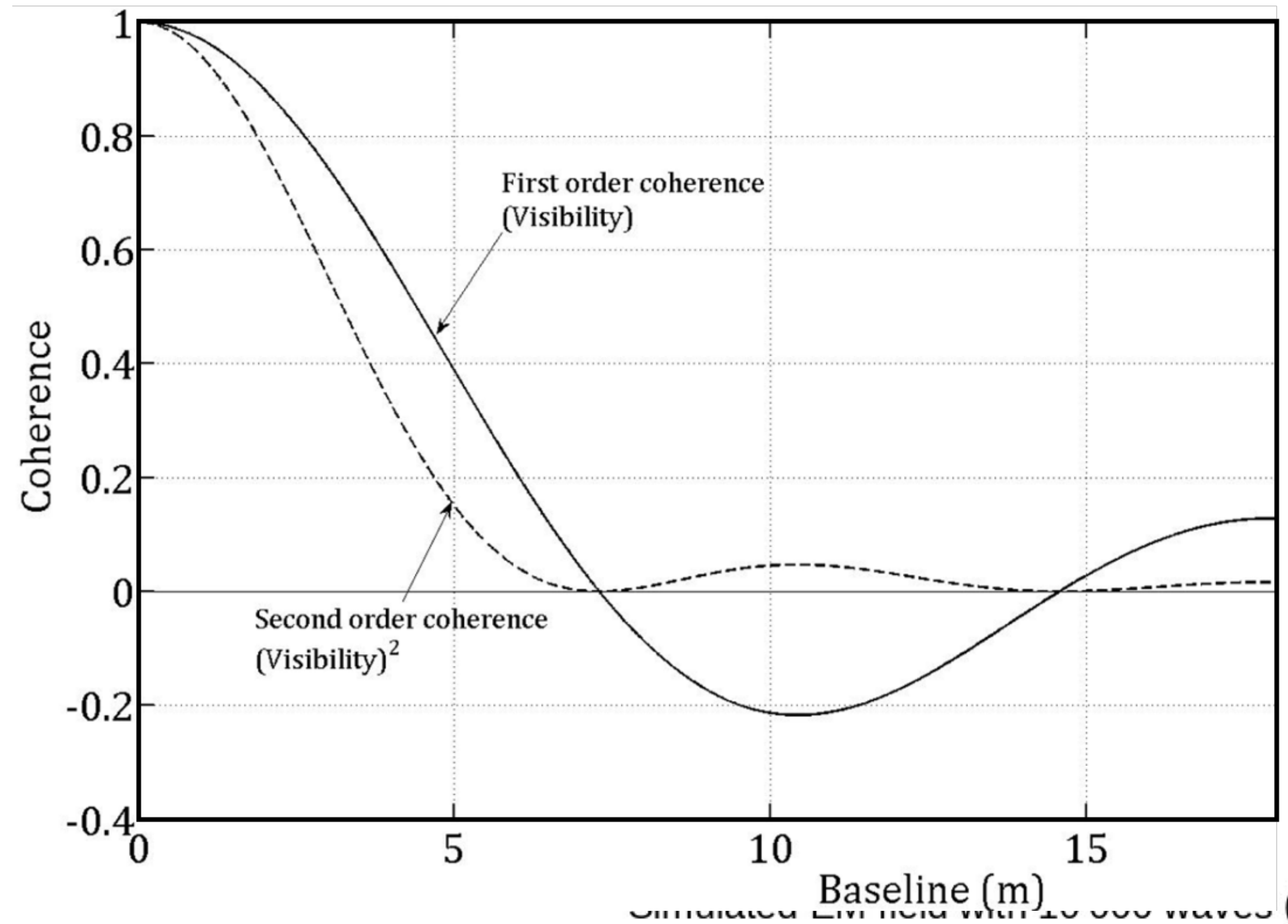

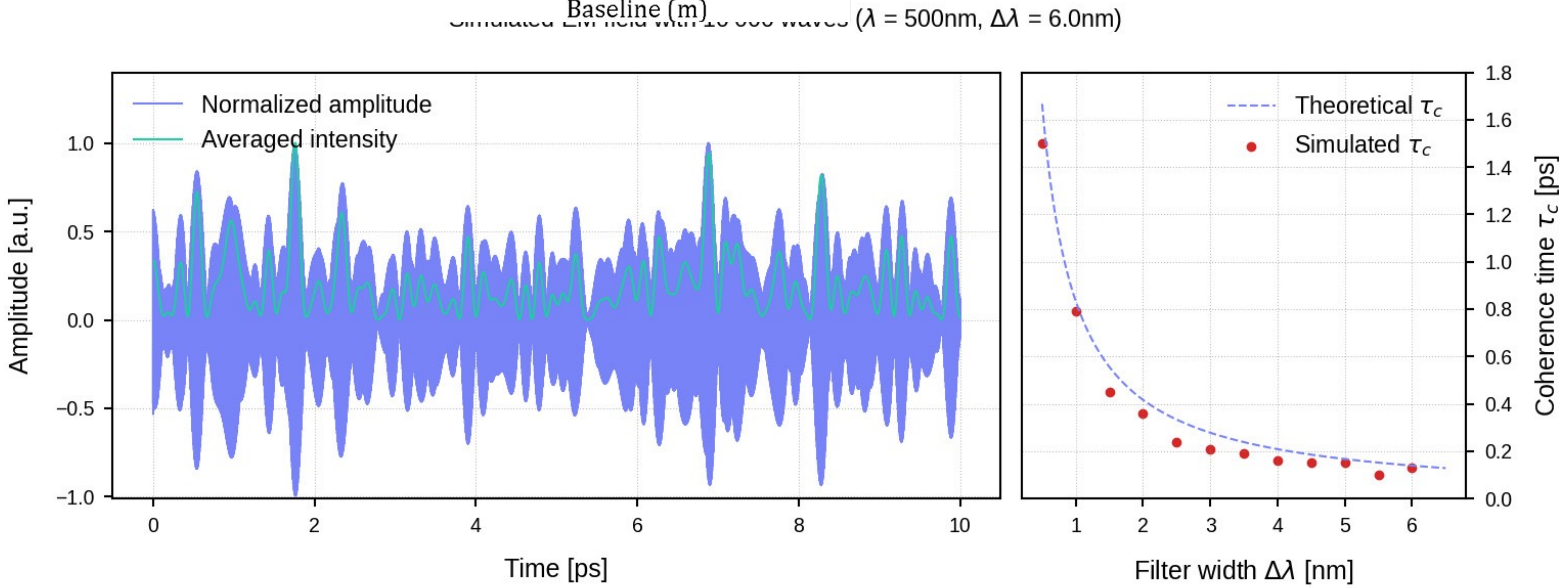

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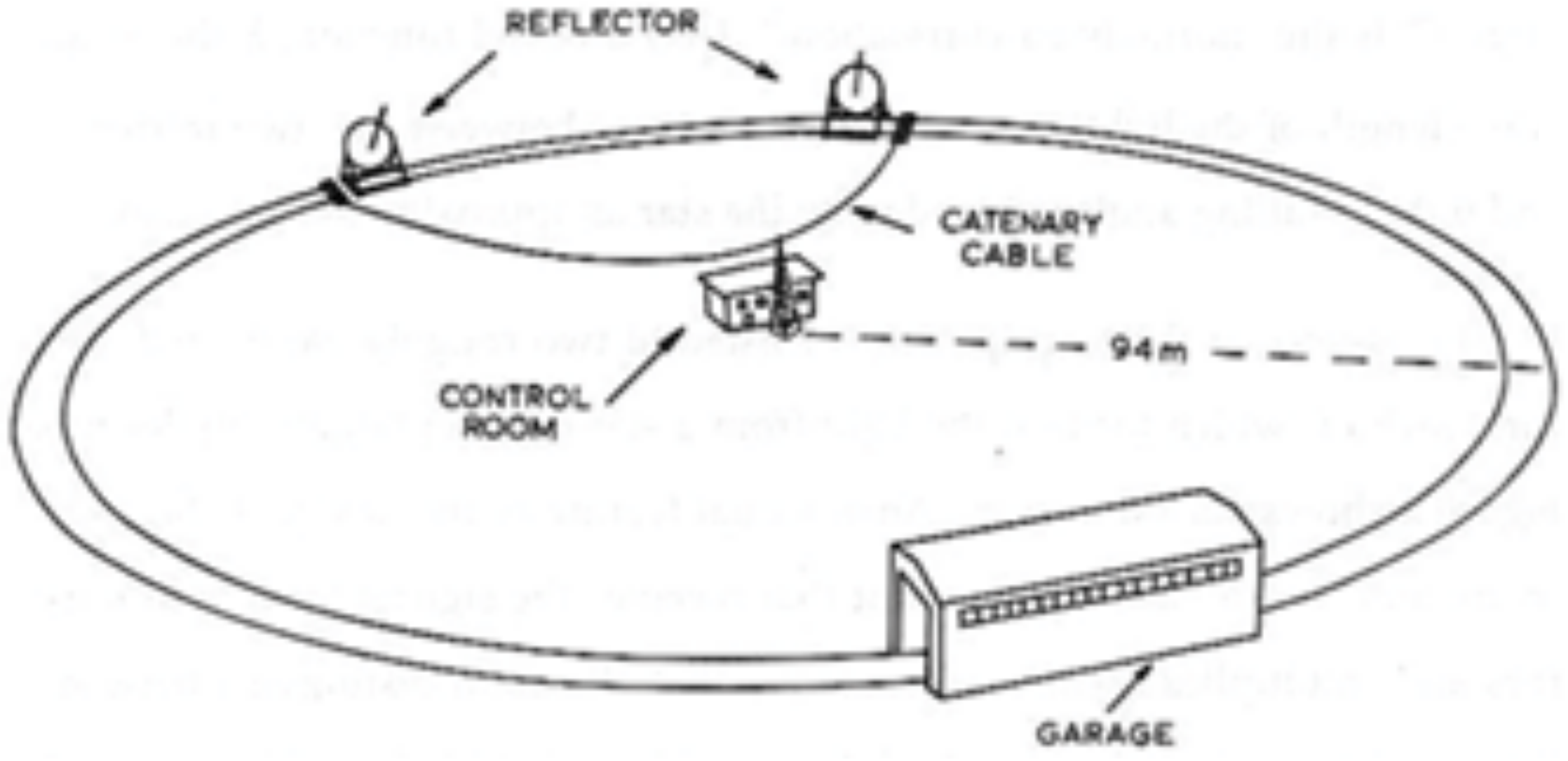
The History - The Narrabri Interferometer



Feynman Versus Handbury

…. Caltech colloquium at which Hanbury talked about it, and **Richard Feynman jumped up and said, “It can’t work!”** In his inimitable style, Hanbury responded, “Yes, **I know. We were told so. But we built it anyway, and it did work**.” Late that night, Feynman phoned and woke Hanbury up to say “you are right.” He also wrote a letter in which he magnanimously admitted his mistake and acknowledged the importance of this phenomenon that, at first sight, appears counterintuitive, even to quantum theorists

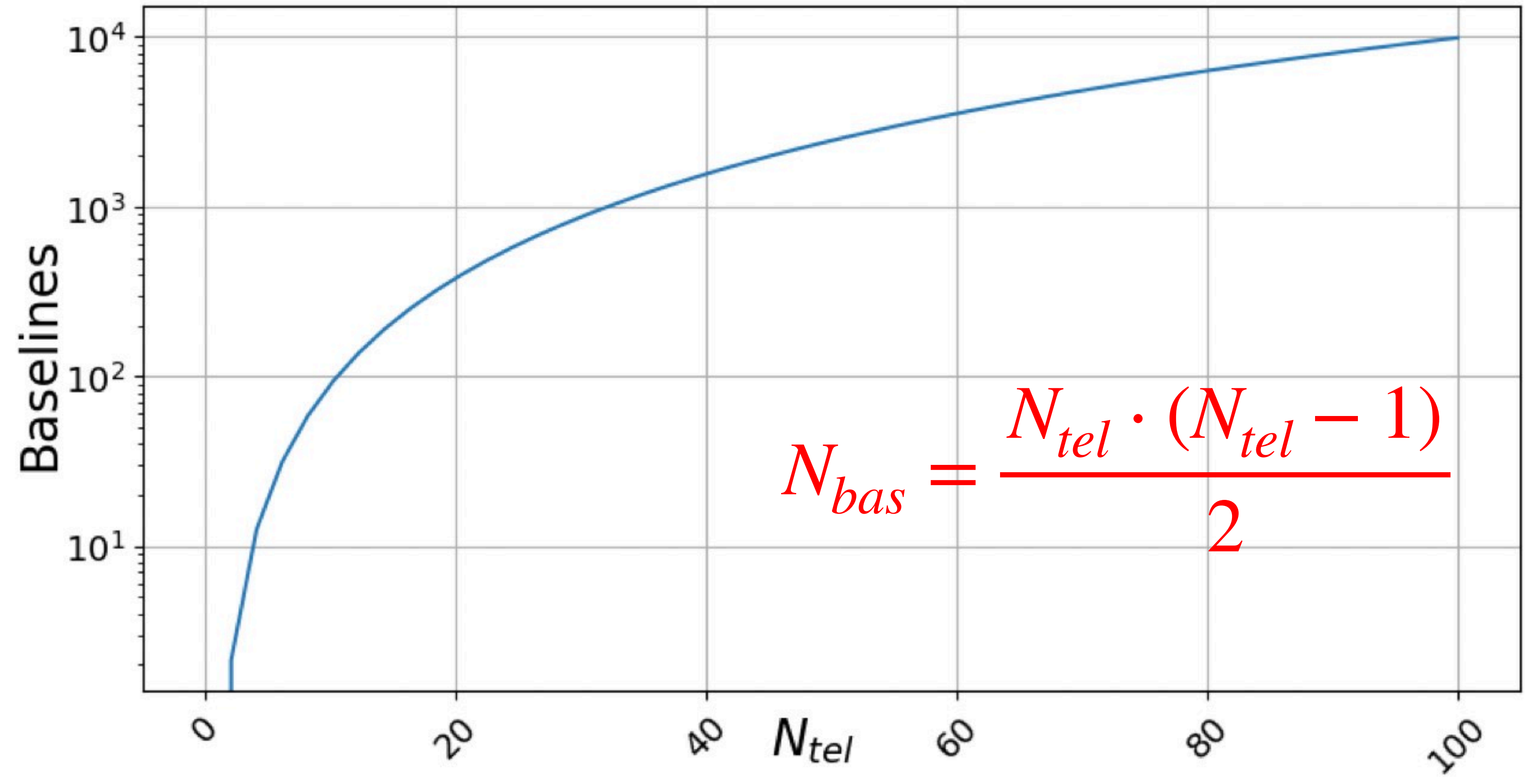
- From 1963 through 1974 direct interferometric
- measurements of the diameters of 32 single stars of O-F spectral type (Hanbury Brown et al. 1974; Hanbury Brown 1974)
- Then, Michelson interferometry took over

SNR: the driving design parameter HPR & HTR

$$SNR = n_\gamma \times \eta \times A \times \frac{\sqrt{T_0}}{\sqrt{\tau_c}} \times \frac{1}{\sqrt{\sigma_T}} \times |g^{(2)}|^2 \times \sqrt{N_{ch}^{\lambda}}$$

- Photon Flux $2.5^{m_\lambda} \cdot \Phi_0$ (n_γ)
- Detection efficiency (η)
- Mirror Area (A)
- Observation time (T_0)
- Coherence time (τ_c)
- Time resolution (σ_T)
- Spectral Channels (N_{ch}^{λ})

For arrays $\mathrm{SNR} = \sqrt{\frac{N_{\mathrm{bas}}}{2} \cdot N_{\mathrm{ch}}} \times \mathrm{SNR_B}$



$$N_{bas} = \frac{N_{tel} \cdot (N_{tel} - 1)}{2}$$

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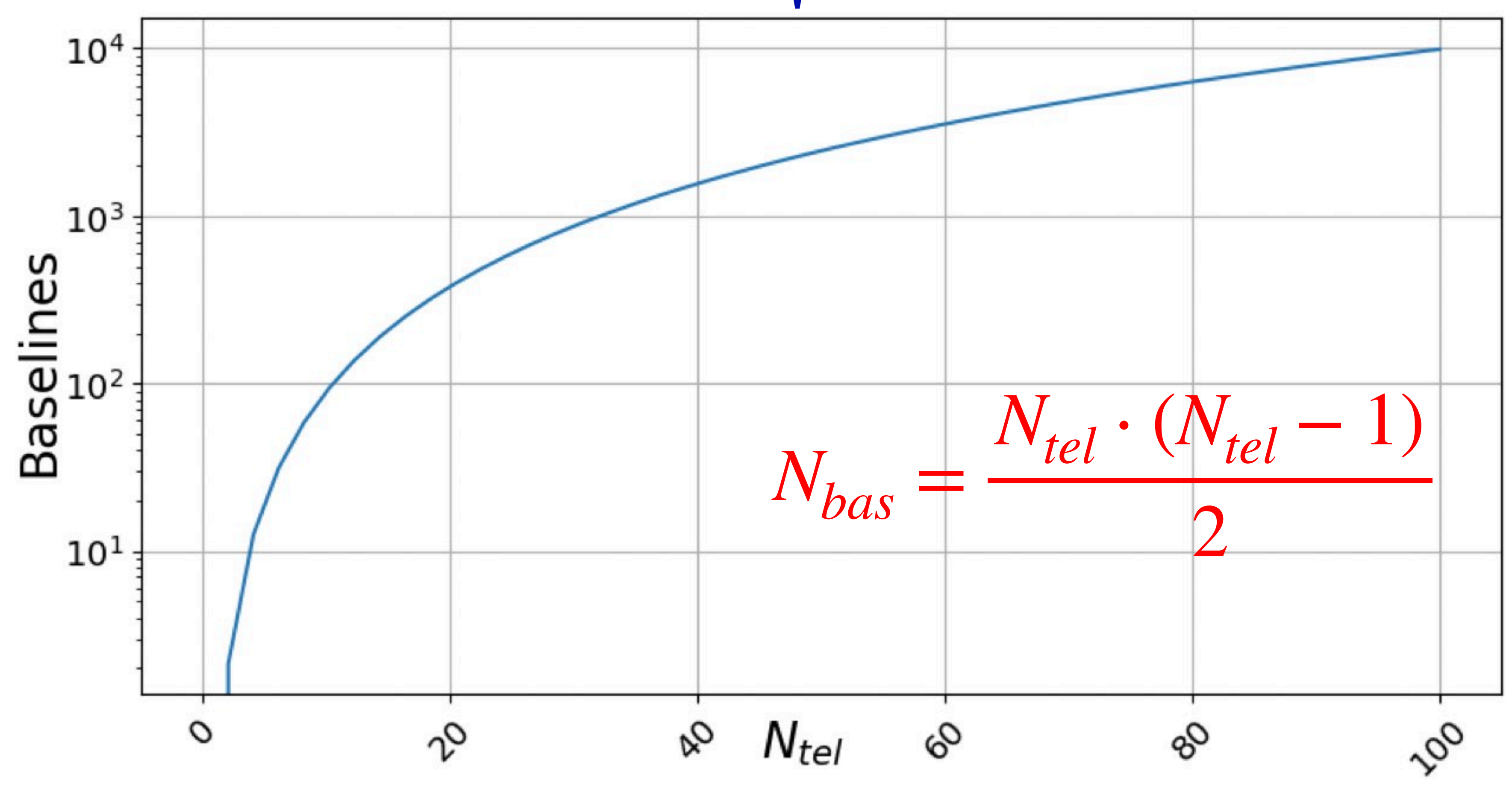


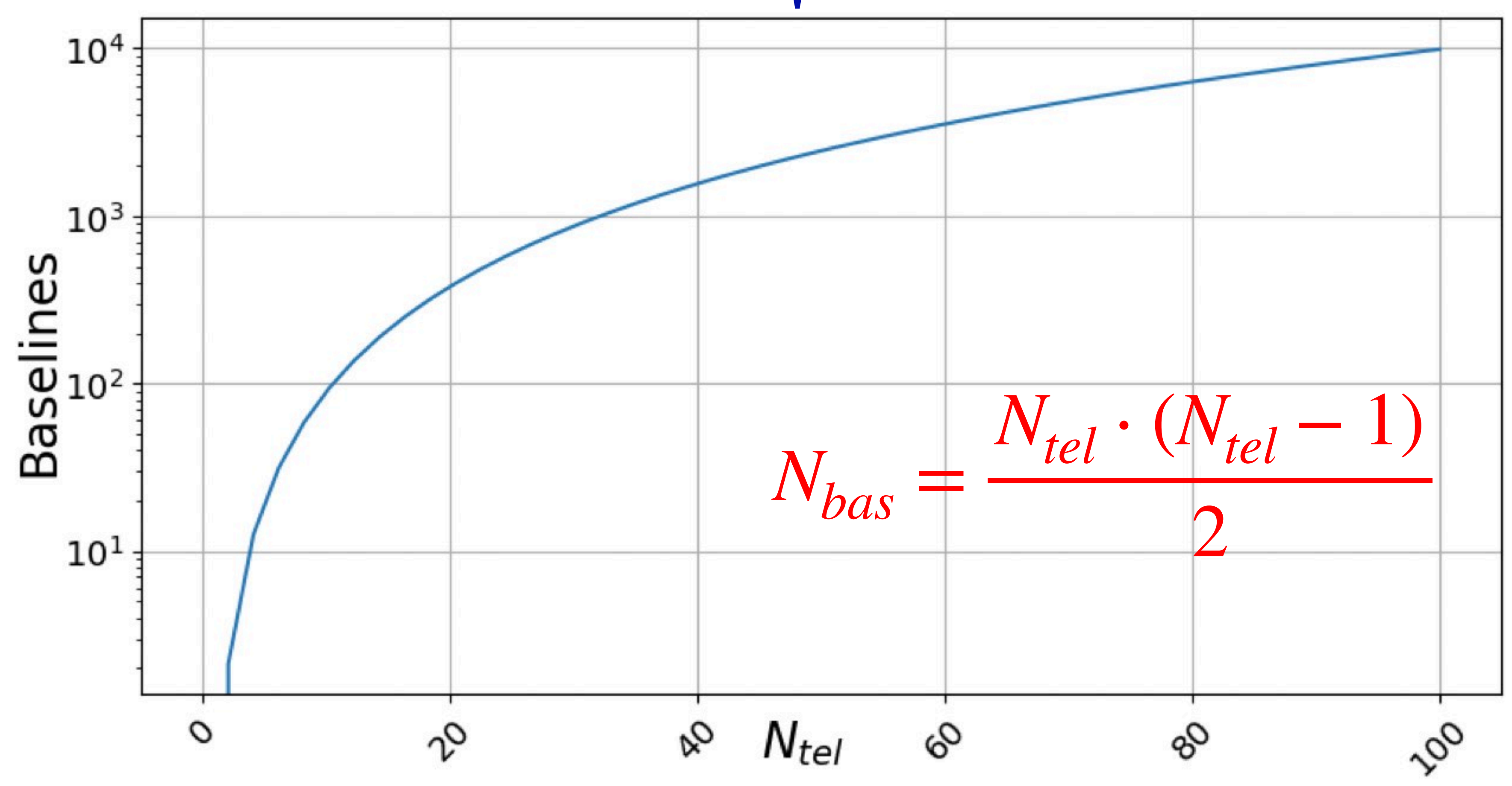
- ***Intensity counting***
  High photon rates (HPR)
  (*Cherenkov telescopes/ PMT HPD*)
  ✓Large area
  ✓Many Baseline
  ~Moderate time resolution (100 ps)
  ✗Few spectral channels

SNR: the driving design parameter HPR & HTR

$$SNR = n_\gamma \times \eta \times A \times \frac{\sqrt{T_0}}{\sqrt{\tau_c}} \times \frac{1}{\sqrt{\sigma_T}} \times |g^{(2)}|^2 \times \sqrt{N_{ch}^{\lambda}}$$

- Photon Flux $2.5^{m_\lambda} \cdot \Phi_0$ (n_γ)
- Detection efficiency (η)
- Mirror Area (A)
- Observation time (T_0)
- Coherence time (τ_c)
- Time resolution (σ_T)
- Spectral Channels (N_{ch}^{λ})

For arrays $\mathrm{SNR} = \sqrt{\frac{N_{\mathrm{bas}}}{2} \cdot N_{\mathrm{ch}}} \times \mathrm{SNR_B}$



- ***Intensity counting***
  High photon rates (HPR)
  (Cherenkov telescopes/ PMT HPD)

$$g^{(2)} = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle}$$

✓Large area

✓Many Baseline

~Moderate time resolution (100 ps)

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Photon Flux $2.5^{m_\lambda} \cdot \Phi_0$ | Mirror Area | Observation time | Spectral Channels

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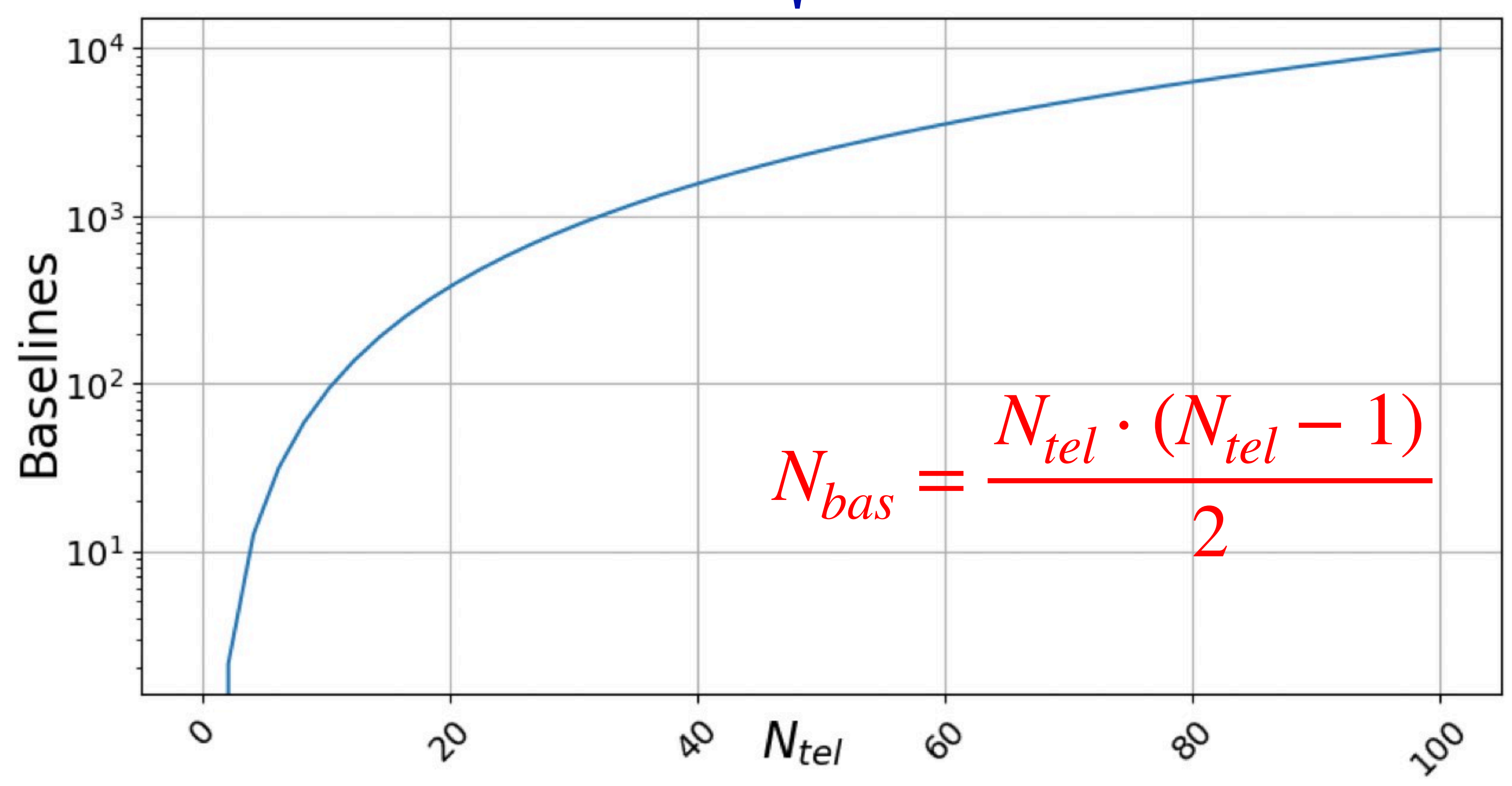

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  High time resolution (HTR)
  (*Optical telescopes /Quantum assisted SII*)

✘Small area
✘Few Baseline
✓High time resolution (100 ps)
✓Many Spectral channels

SNR: the driving design parameter HPR & HTR

Photon Flux $2.5^{m_\lambda} \cdot \Phi_0$

Mirror Area

Observation time

Spectral Channels

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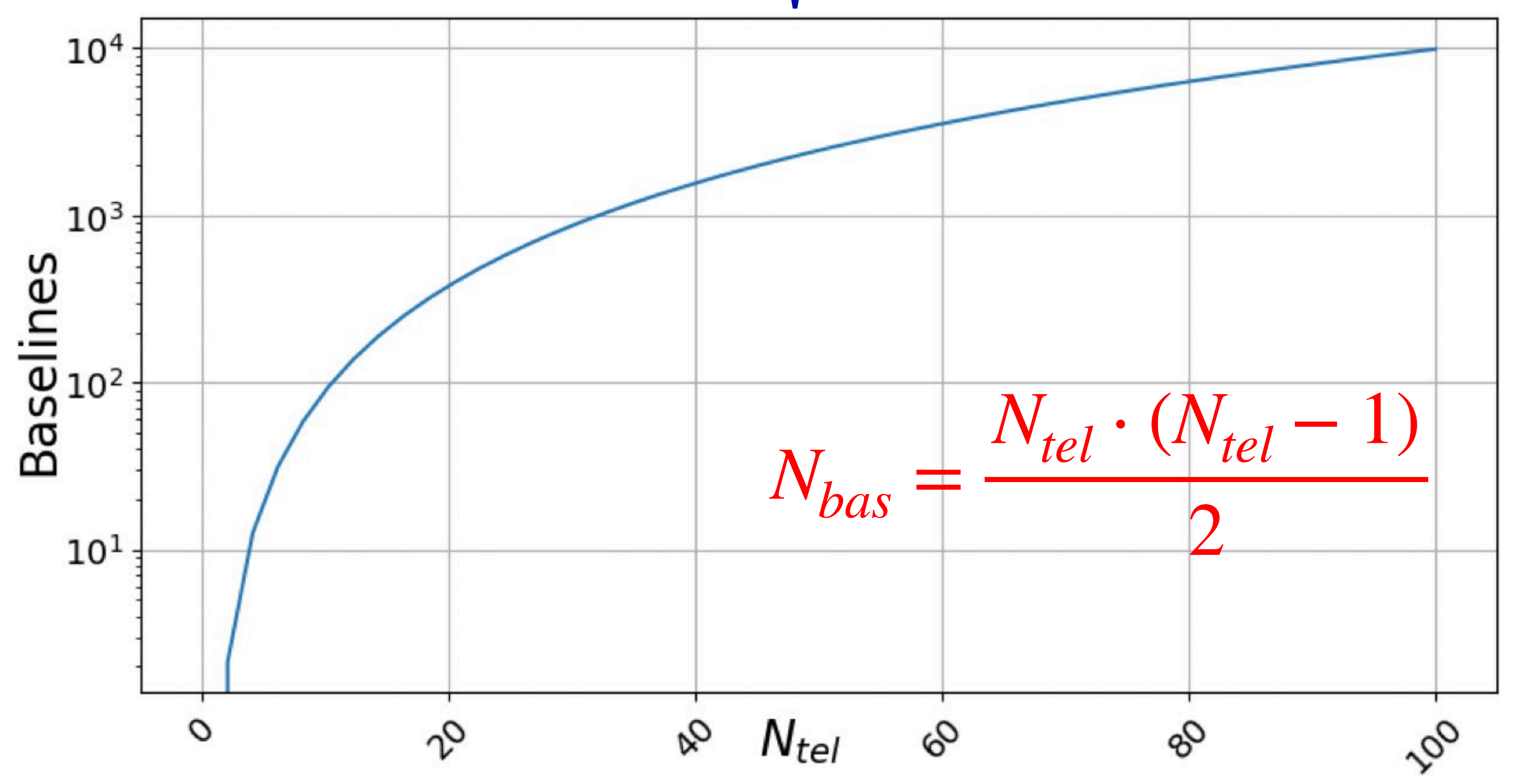

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- **Photon counting -**
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$$g^{(2)} = \frac{N_{12} \cdot n_\tau^T}{N_1 N_2}$$

✗Small area

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Current status MAGIC

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MNRAS **529,** 4387–4404 (2024)
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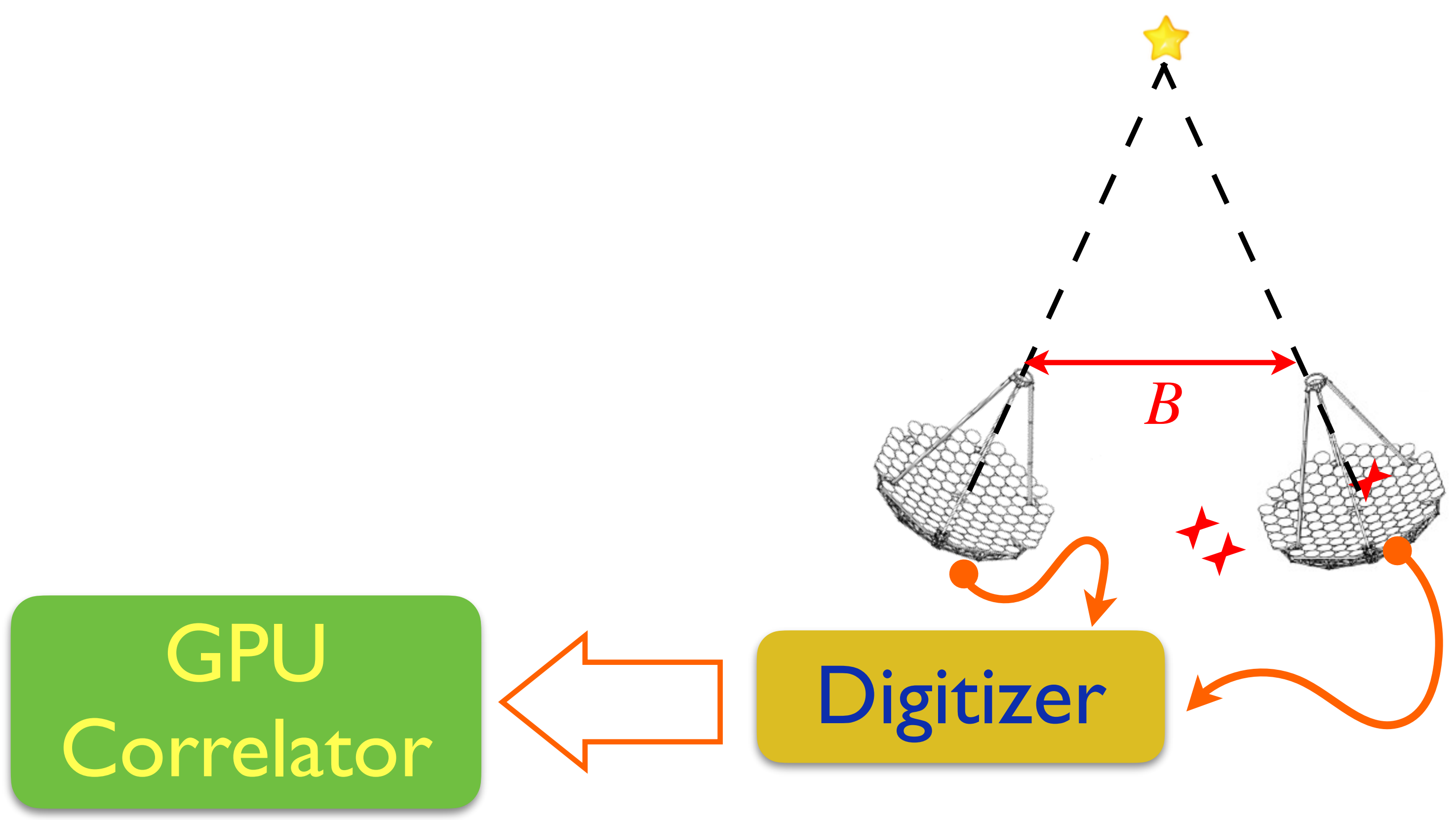

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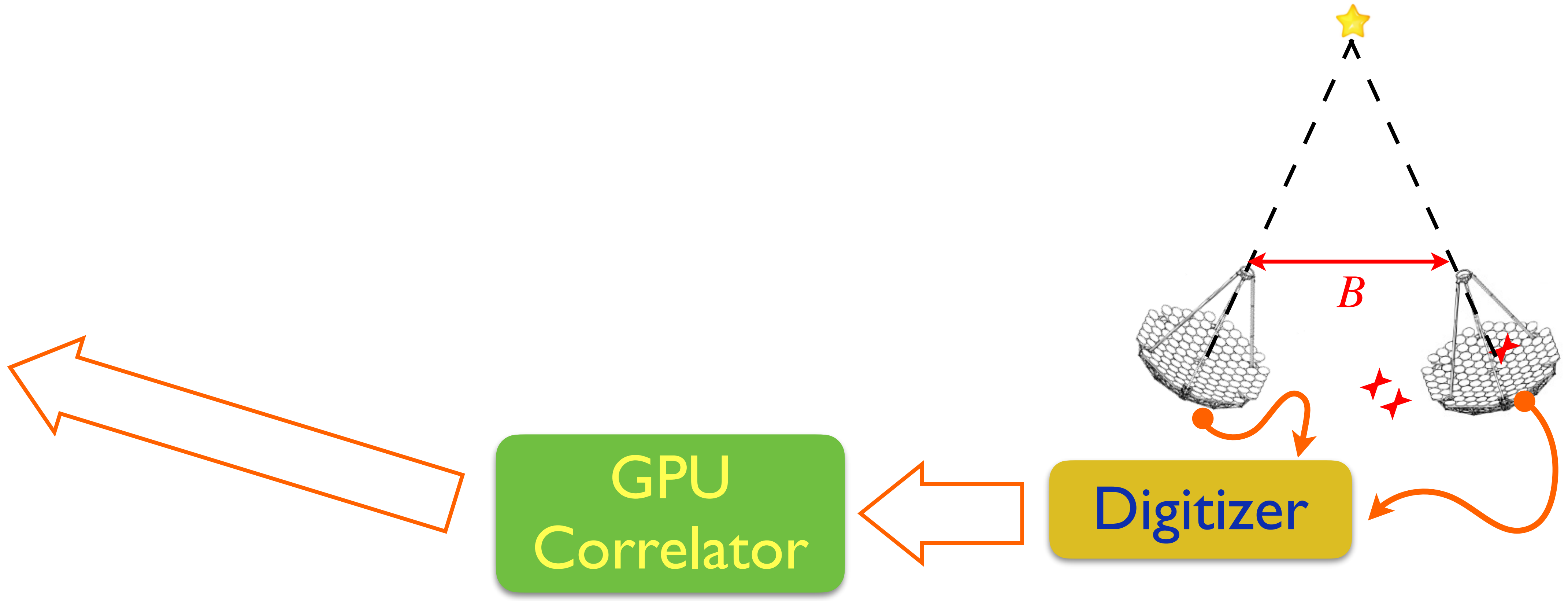

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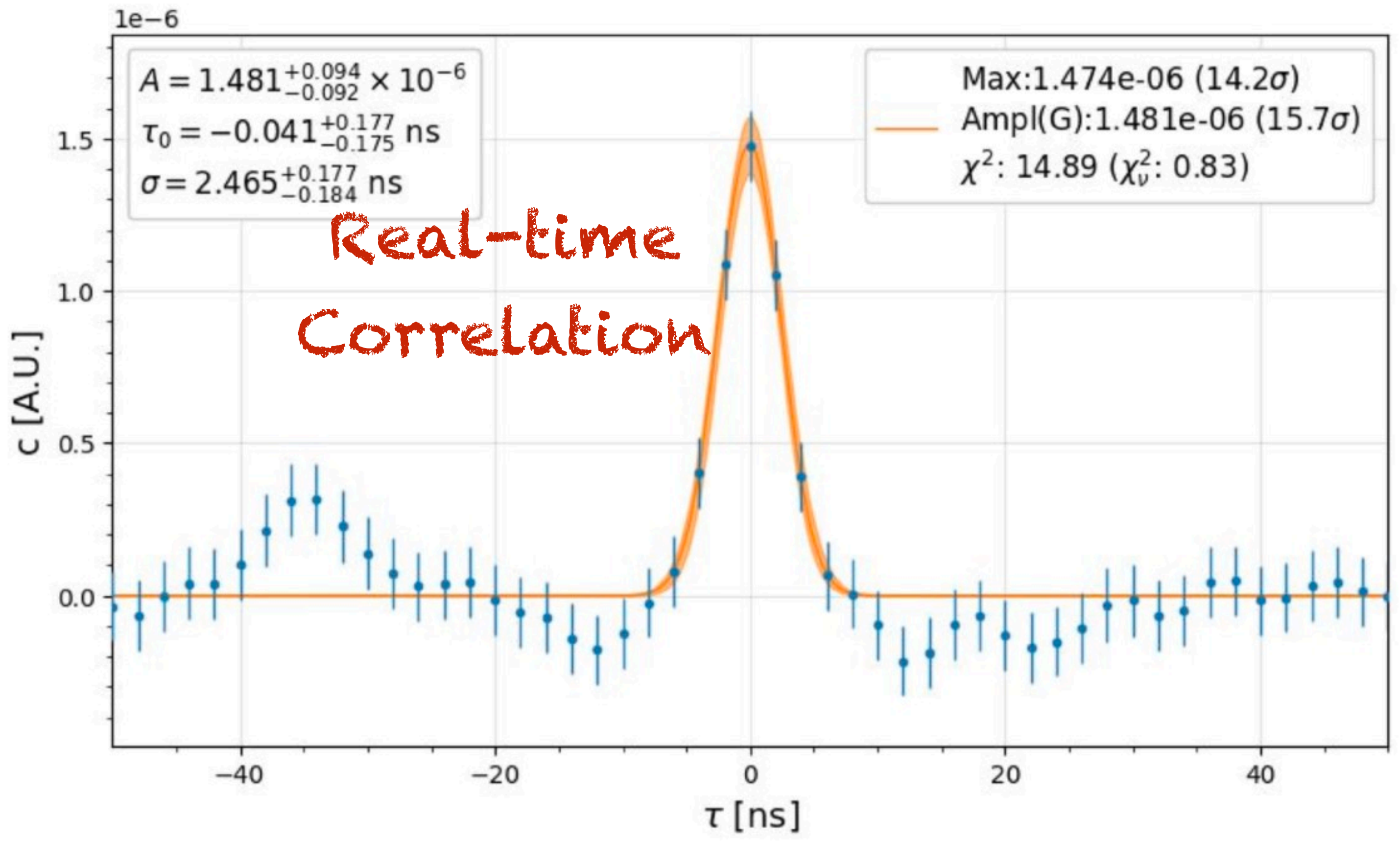

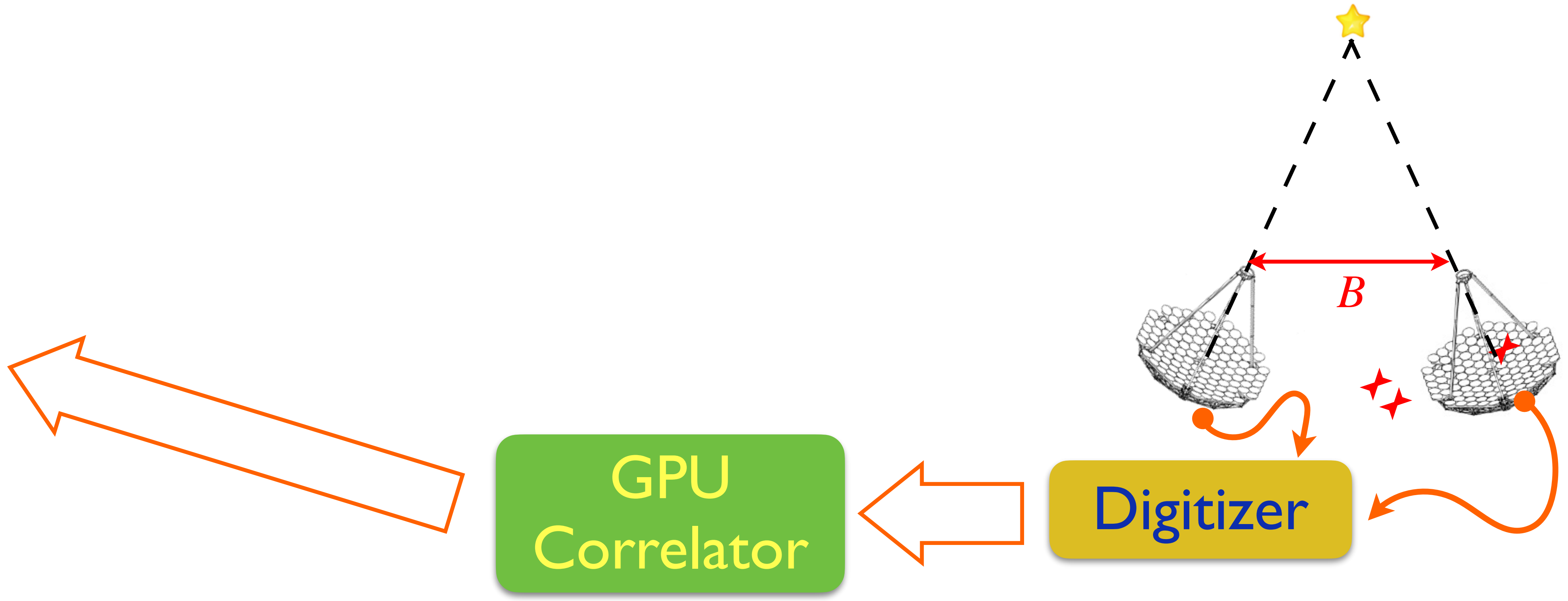

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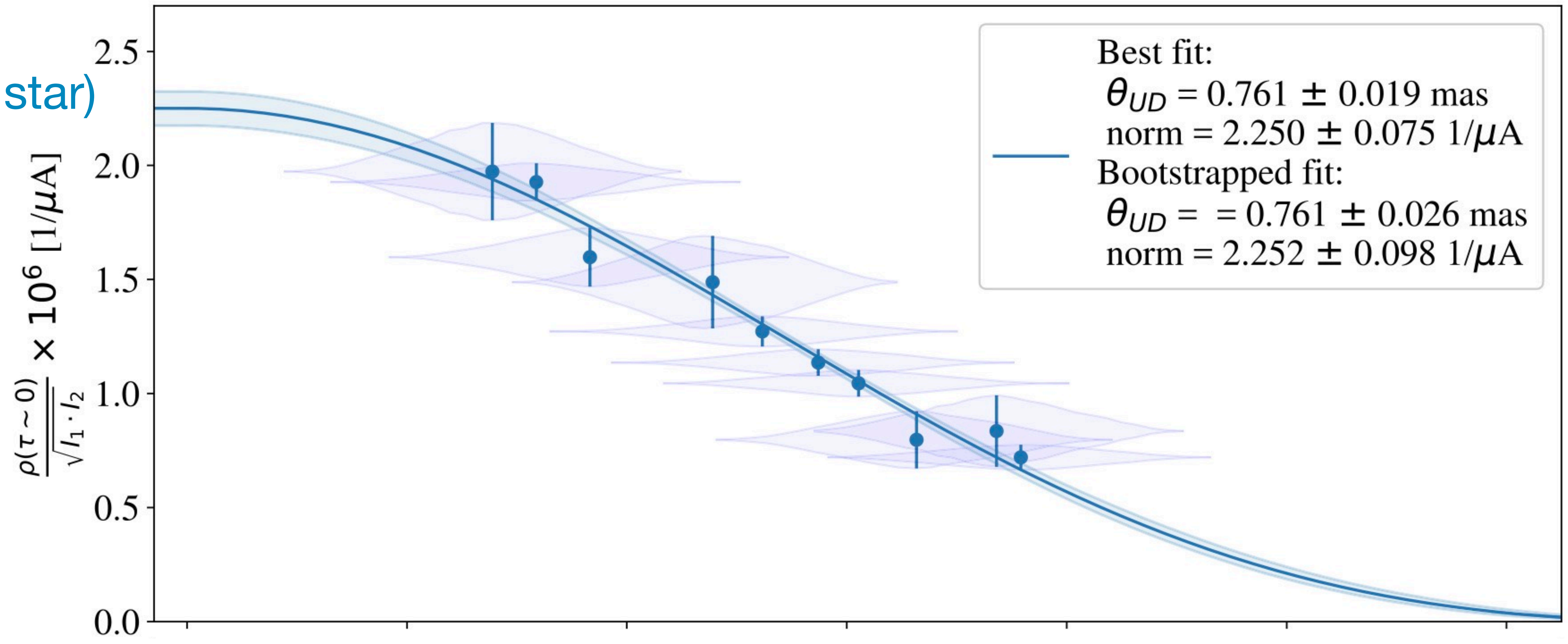

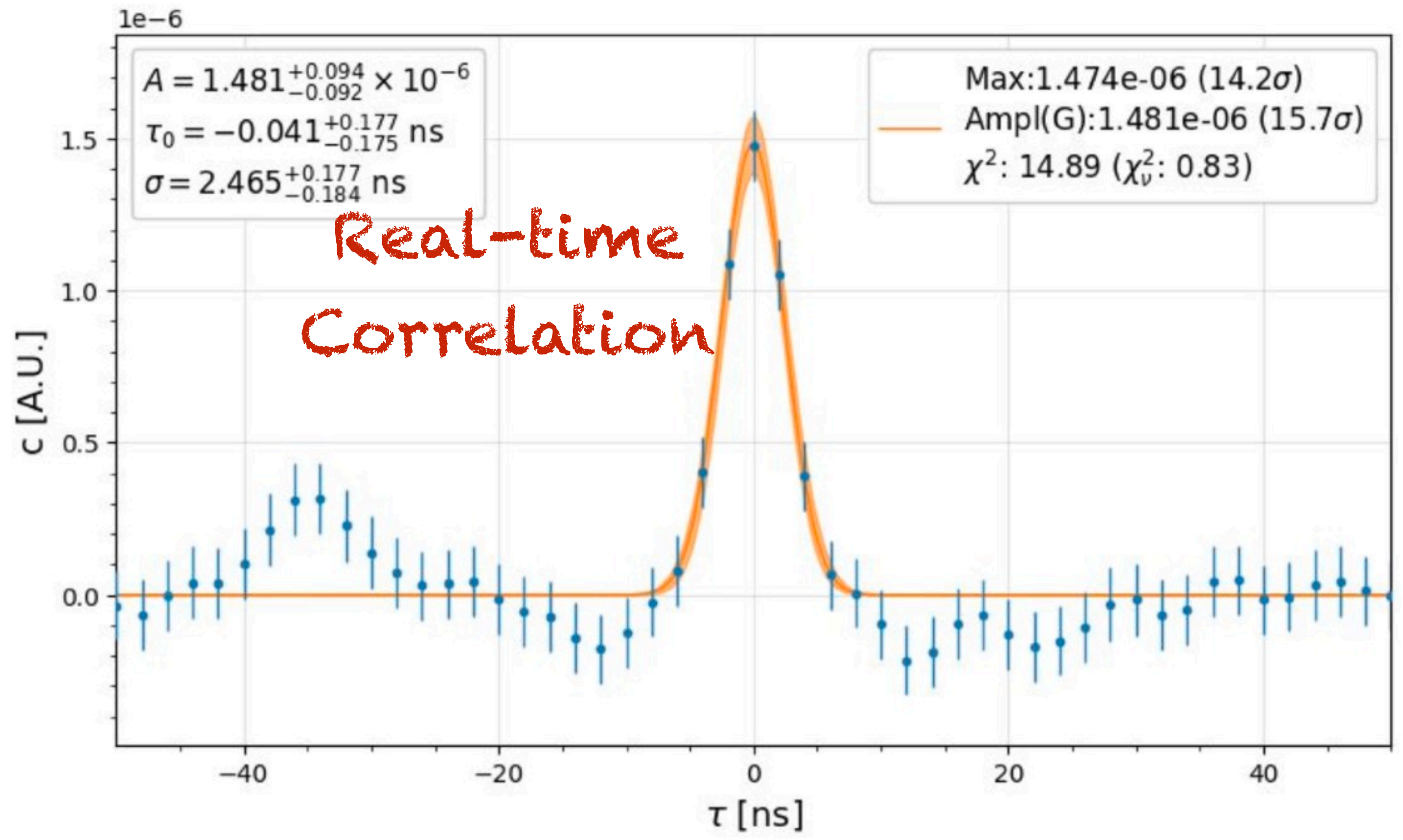

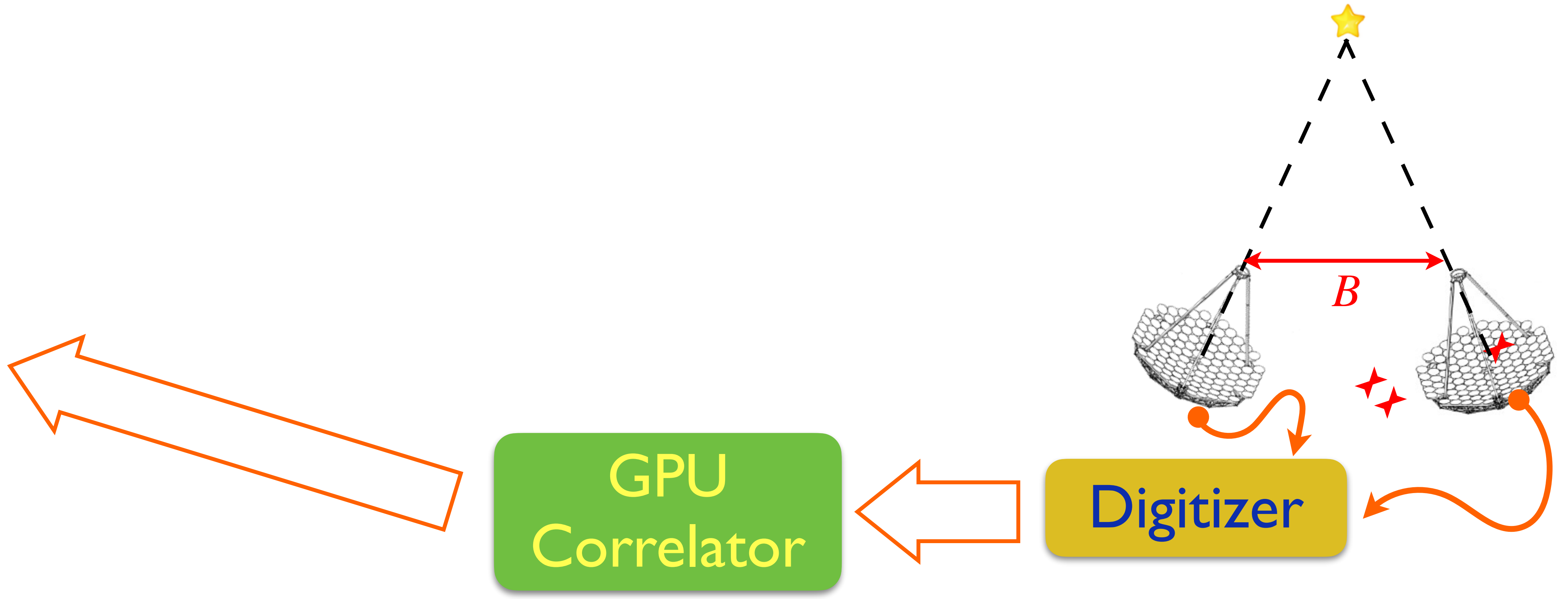

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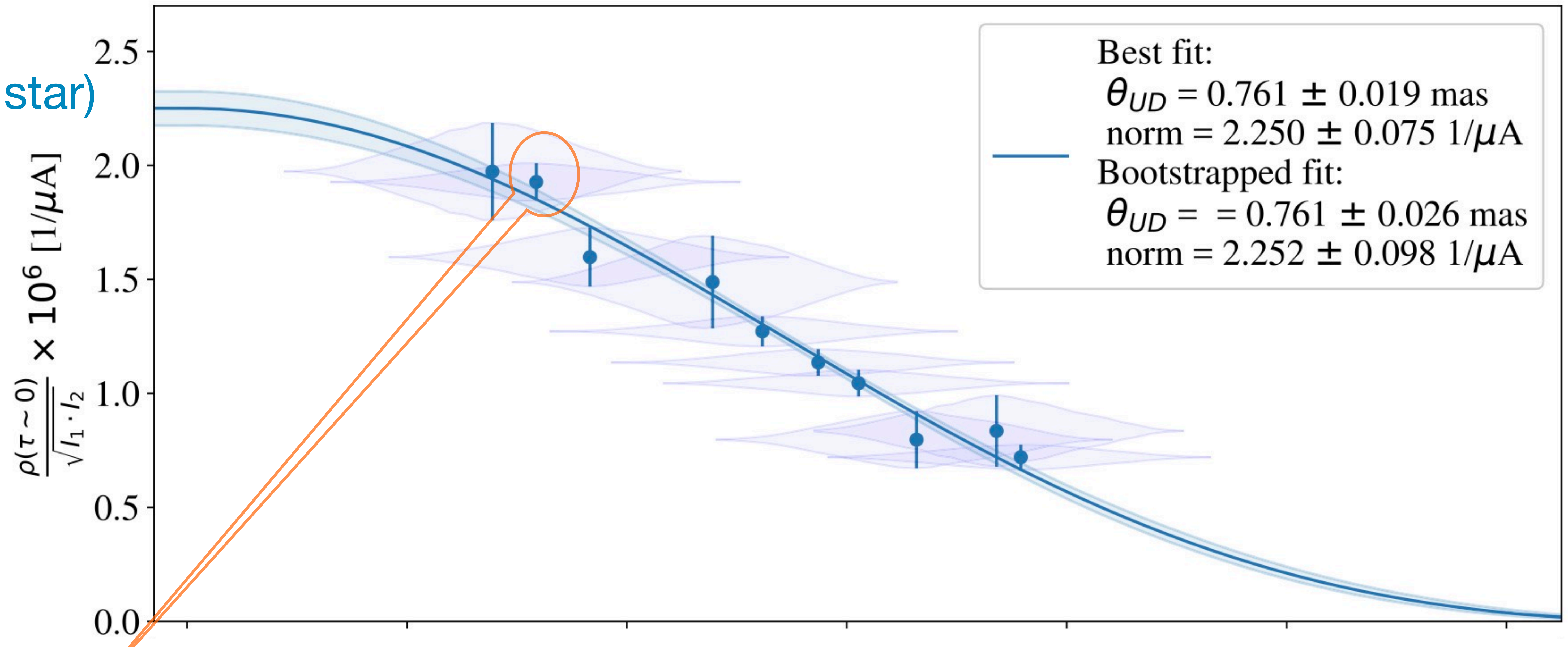

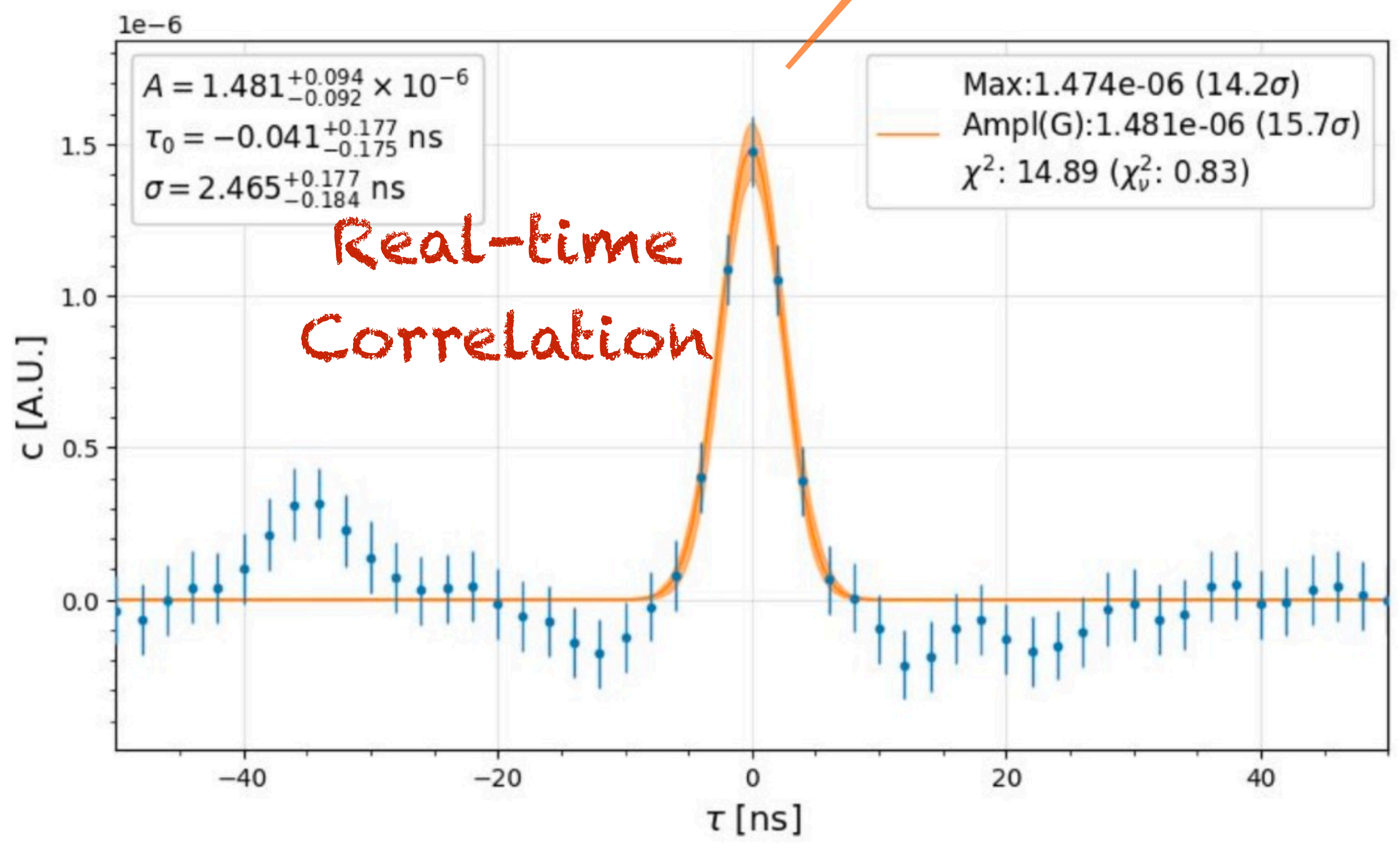

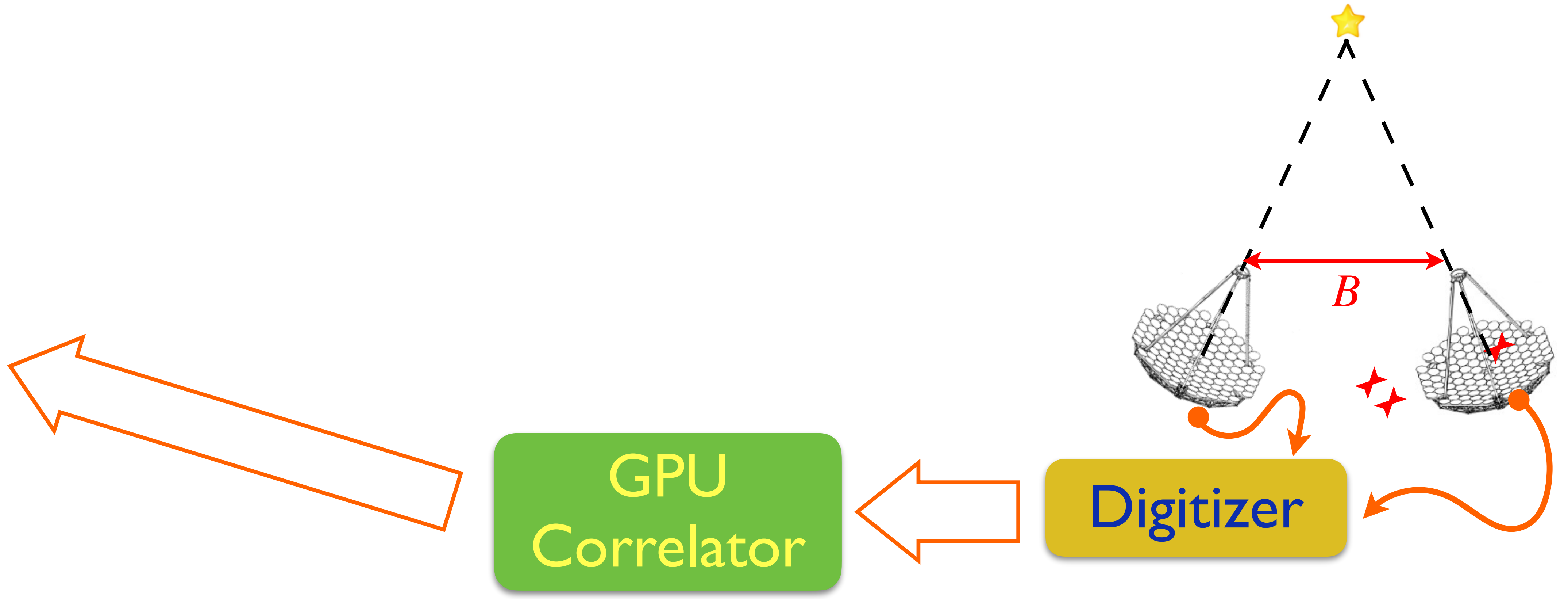

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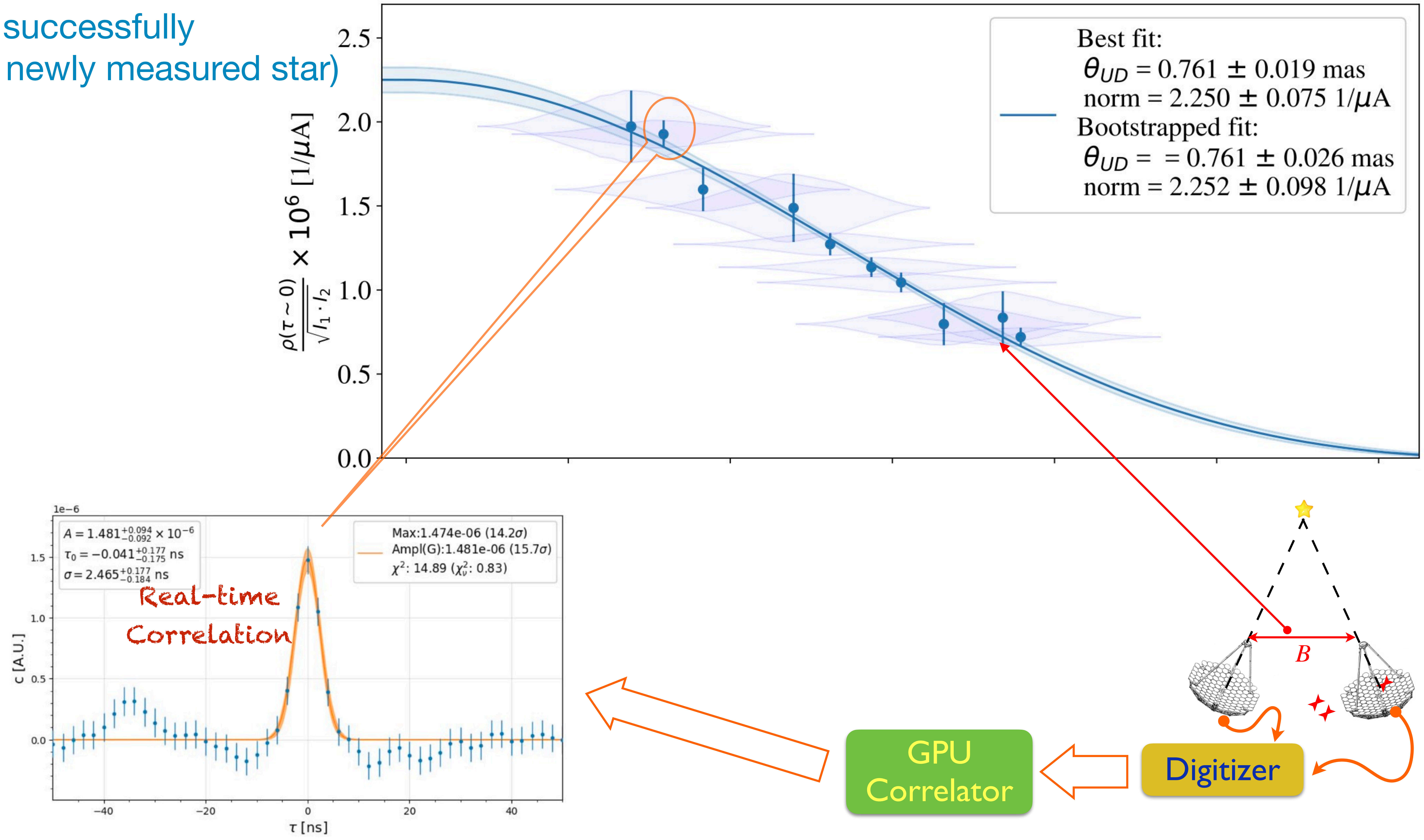

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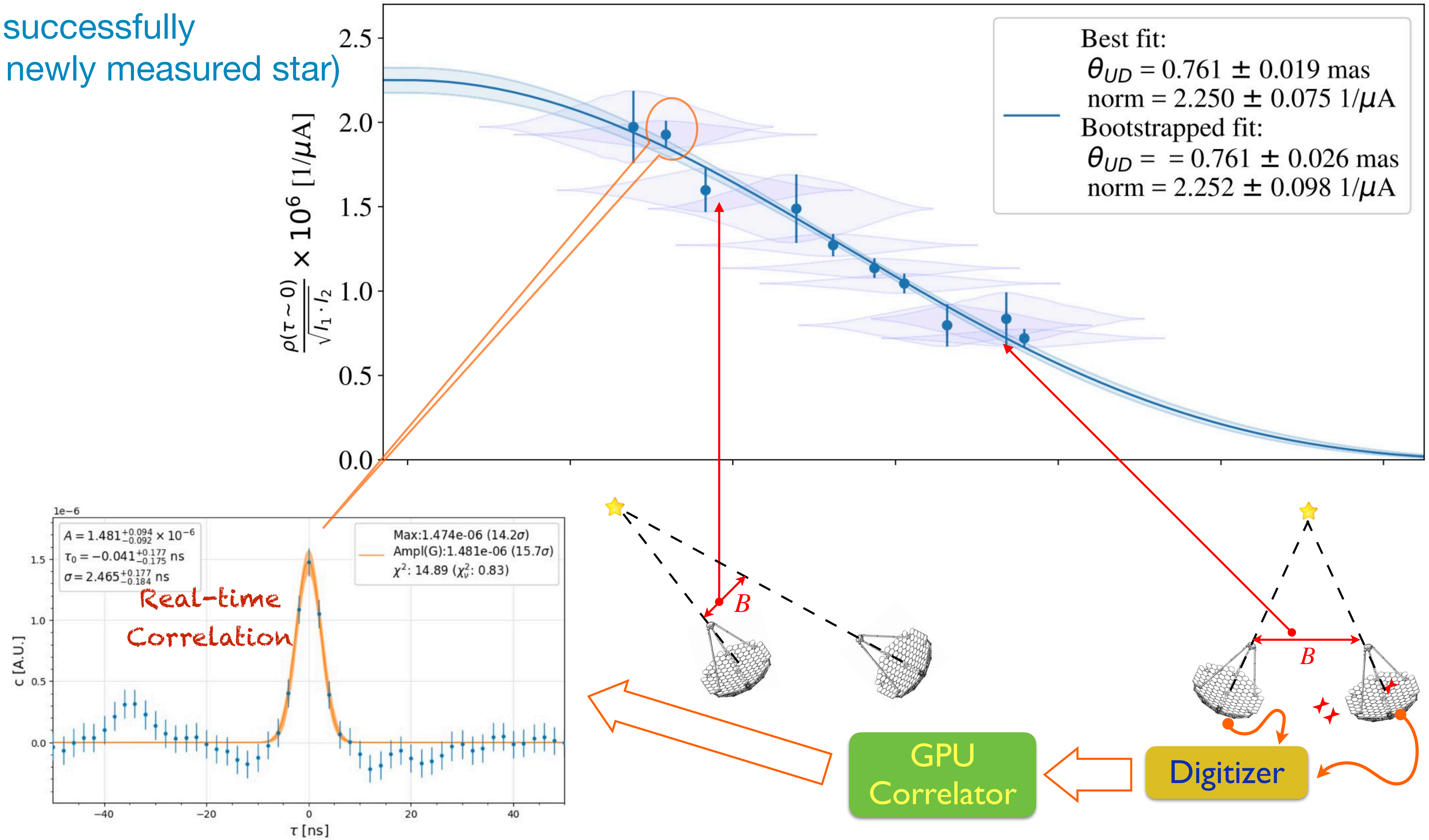

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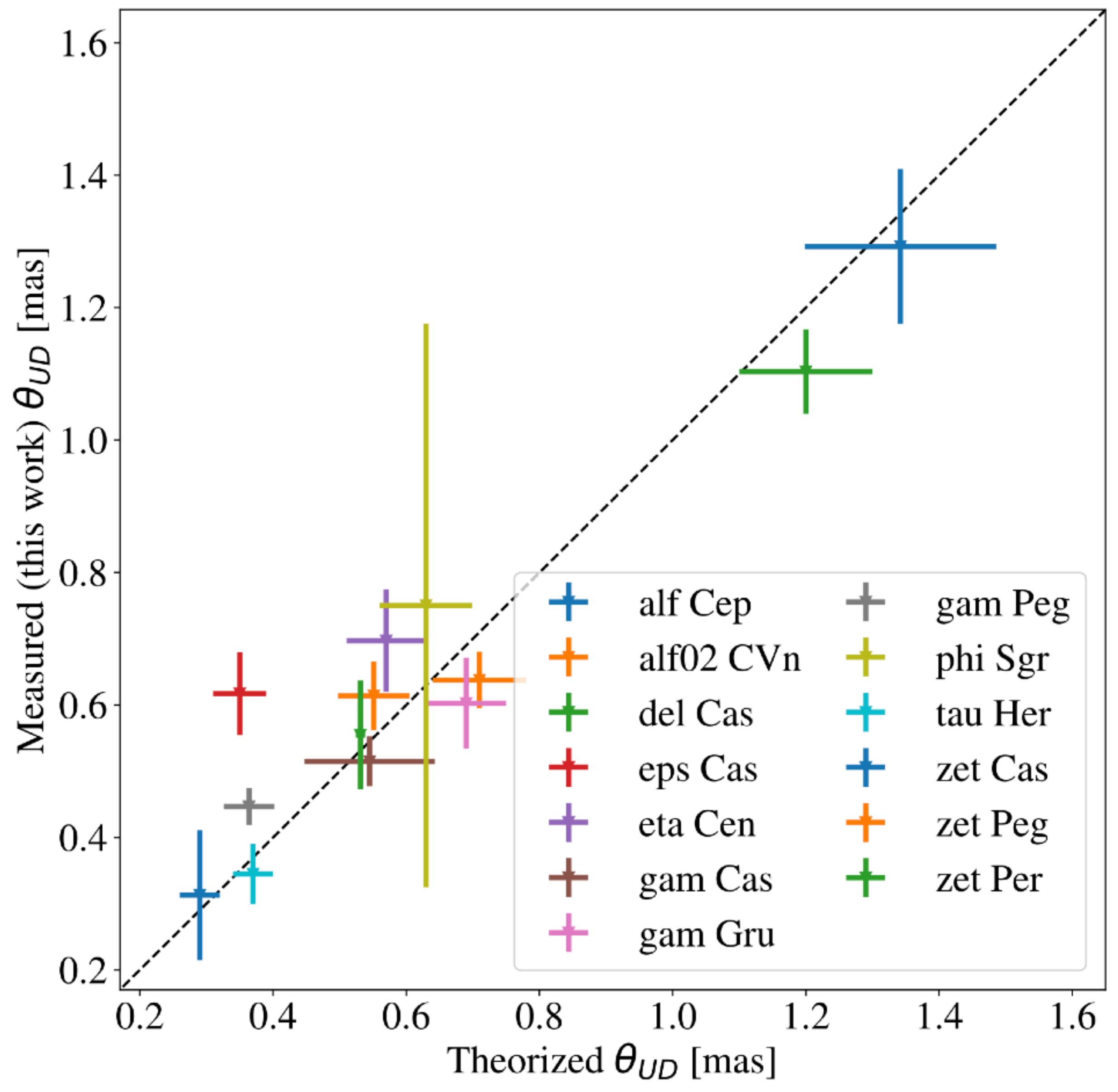

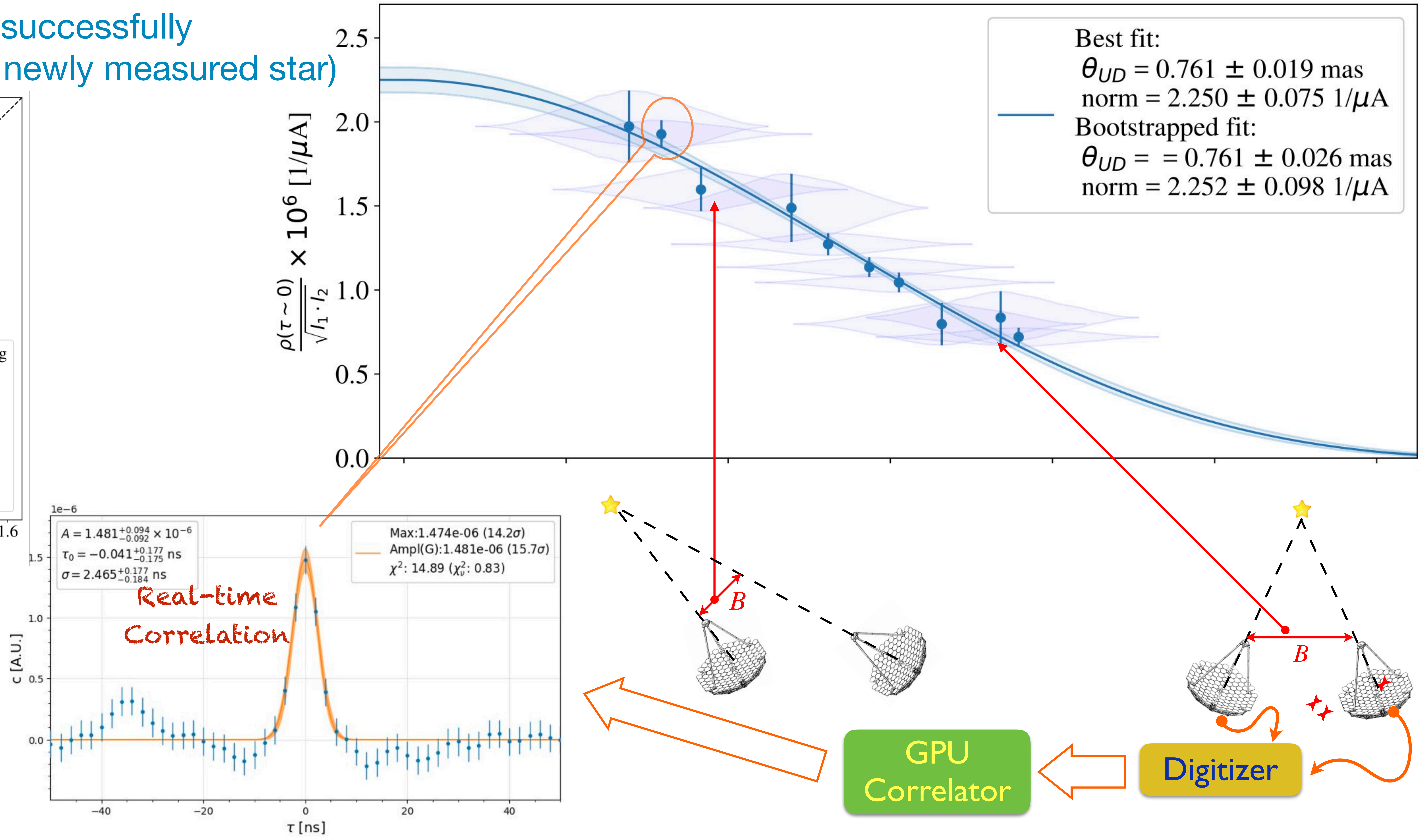

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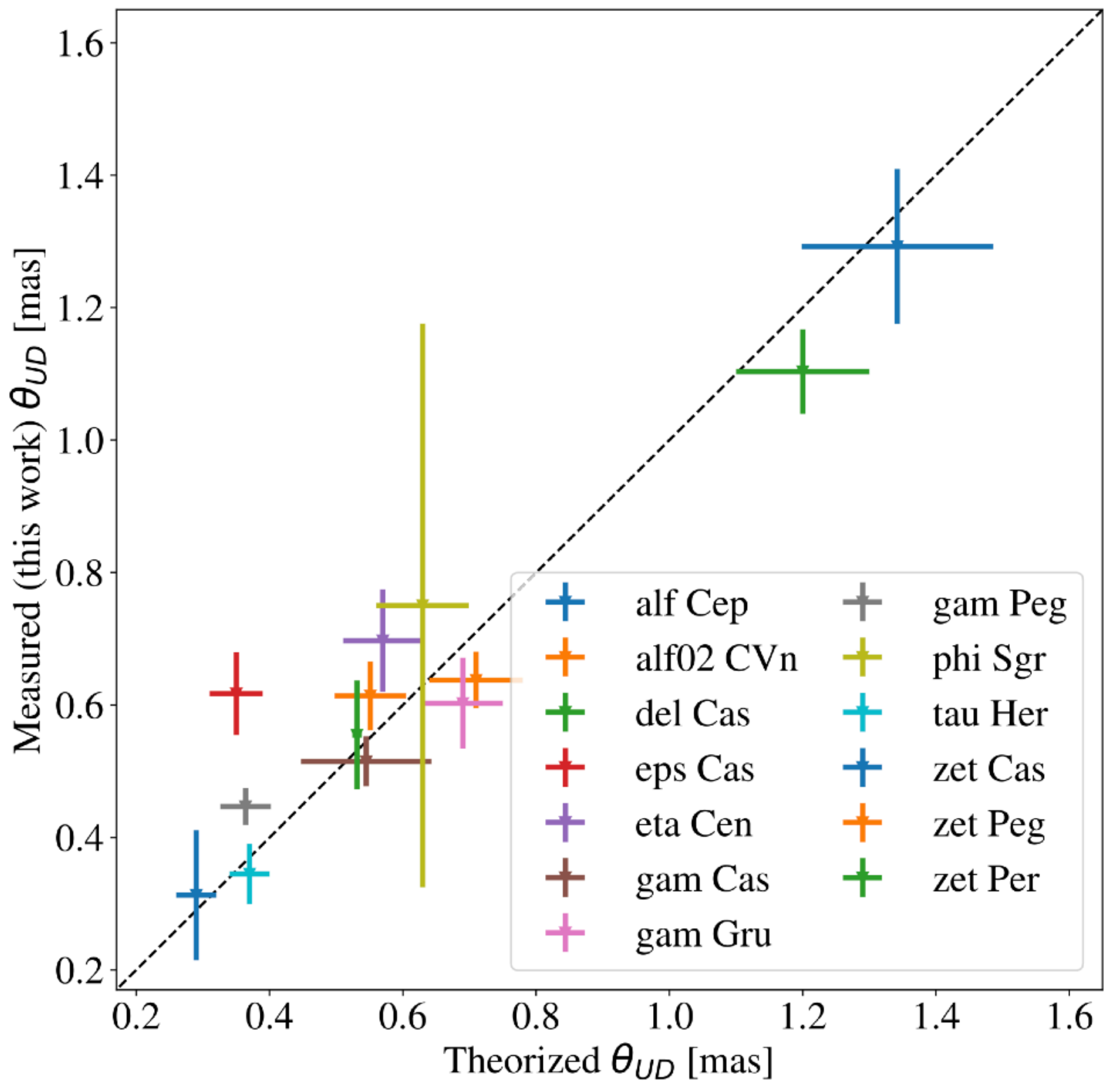

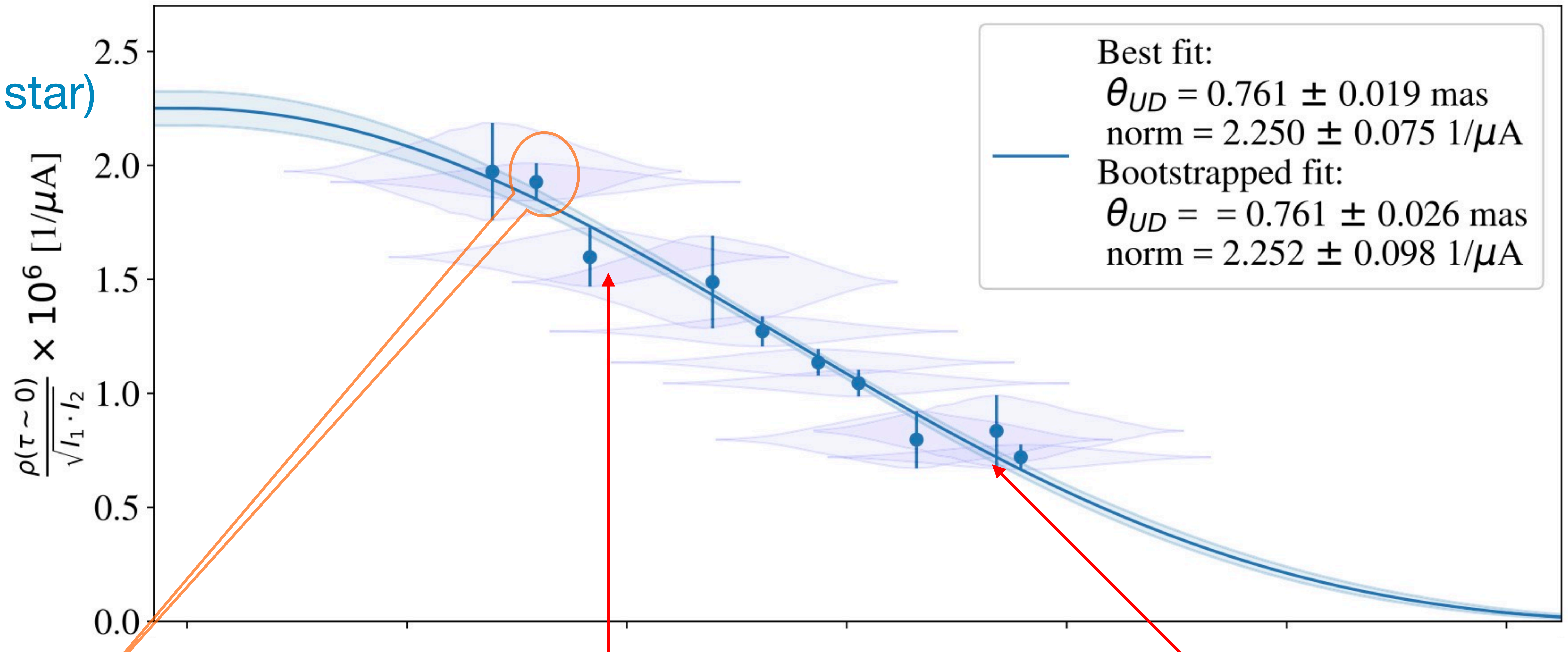

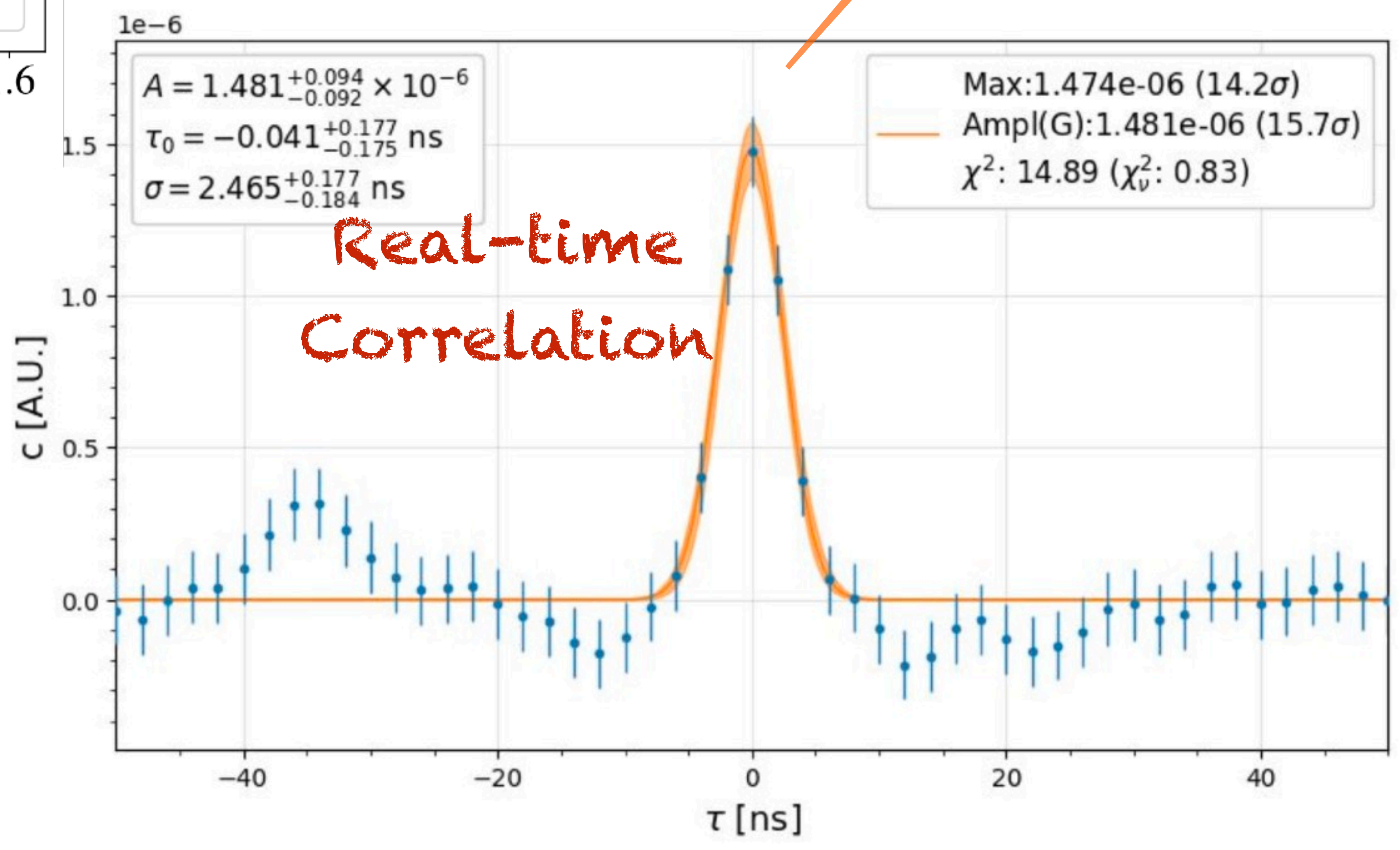

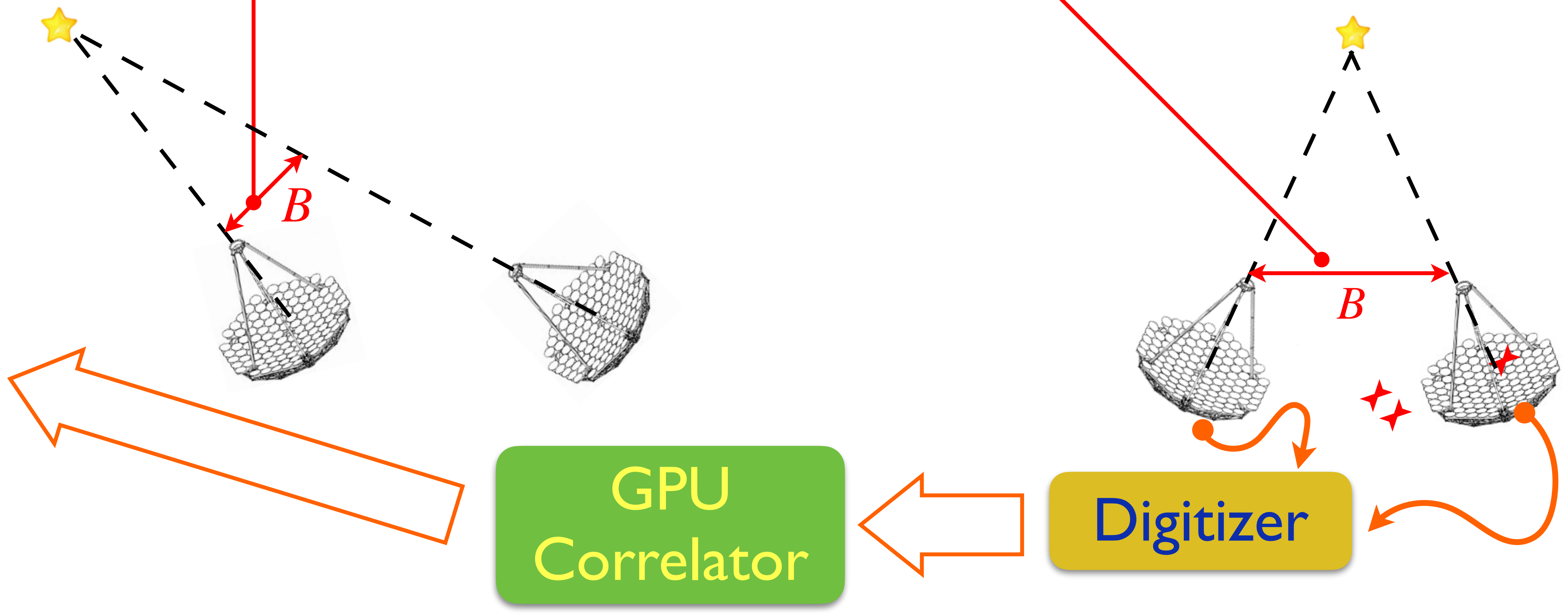

Sensitivity term	Value
Mirror area	236 m^2
Photo-detector QE ($\alpha(\lambda_0)$)	0.295
Optical efficiency ($q(\lambda_0)$)	0.304
Electronic bandwidth (b_ν)	125 MHz
Normalized spectral distribution (σ)	0.87
Noise factor (F)	1.15

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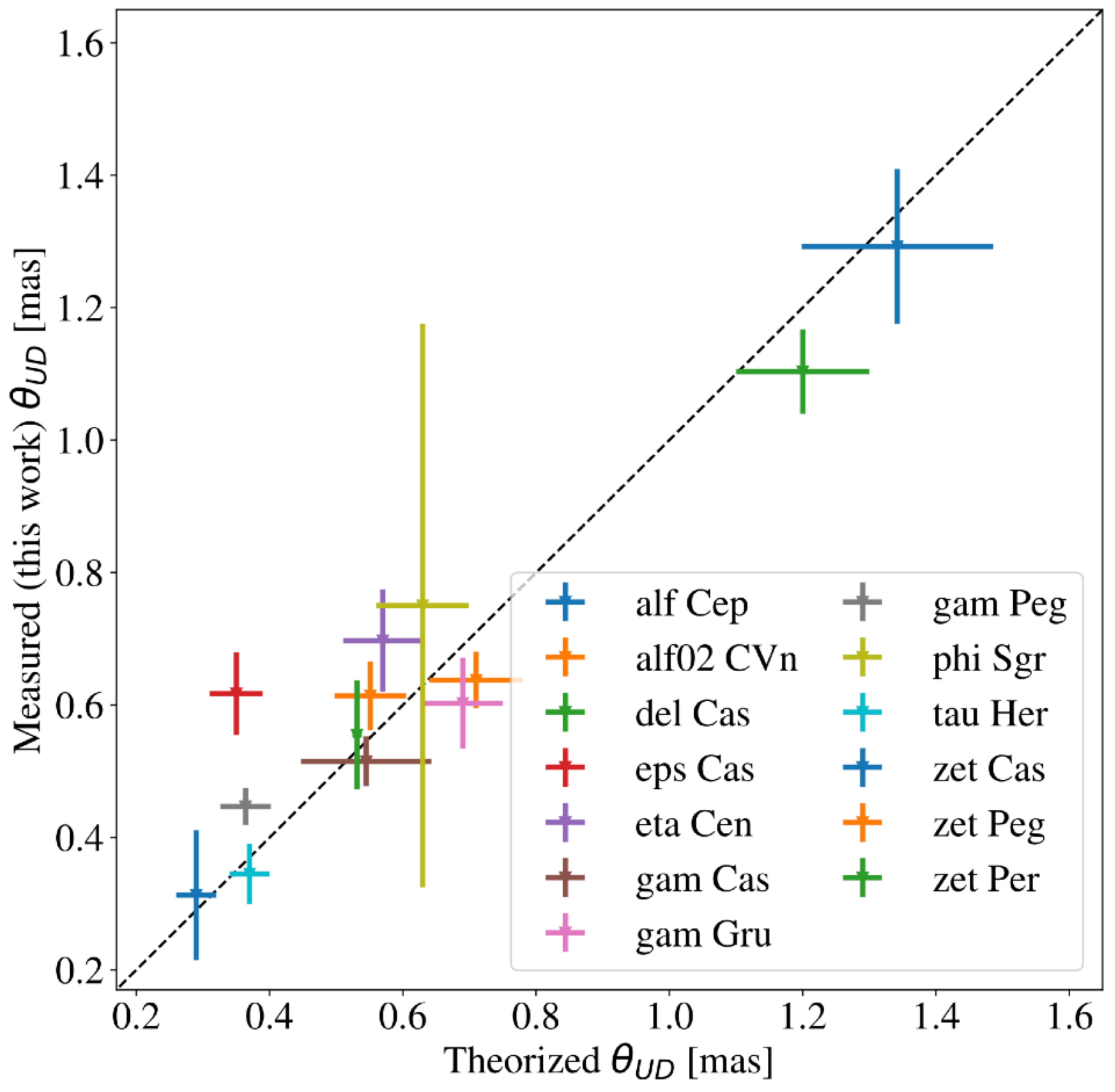

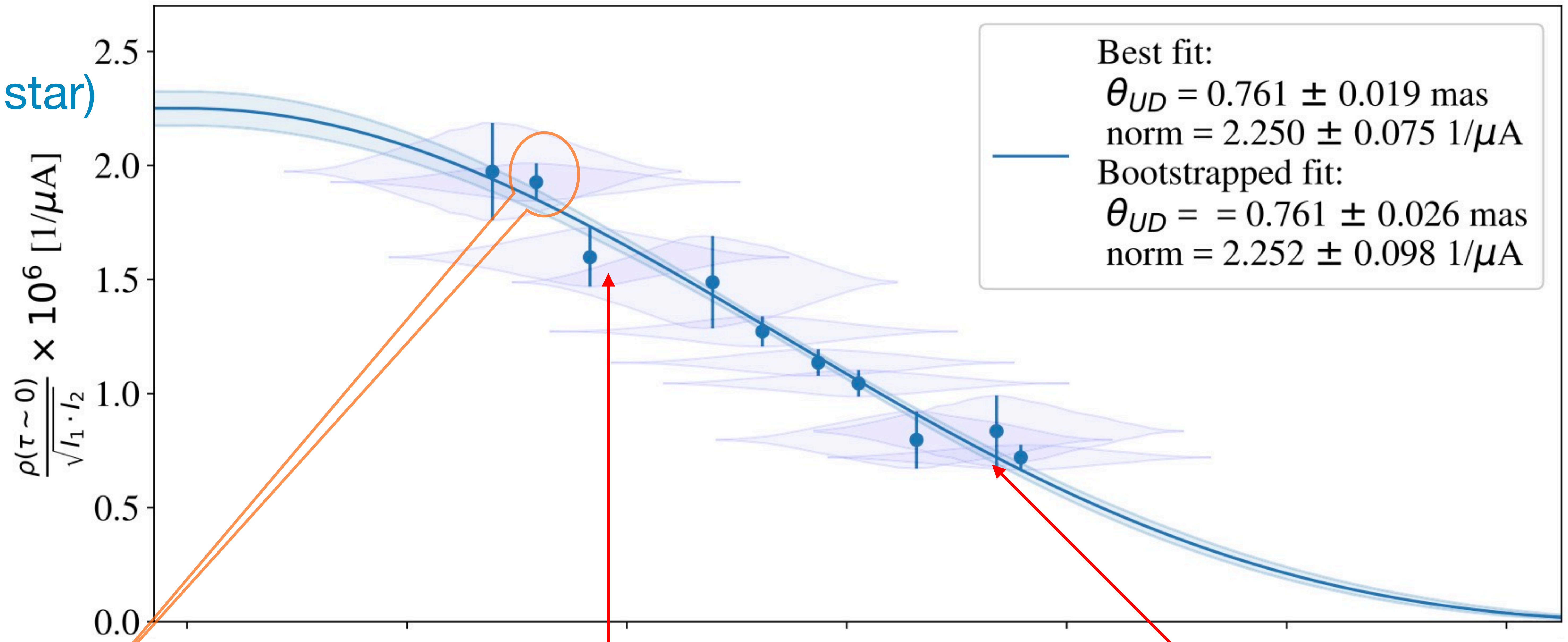

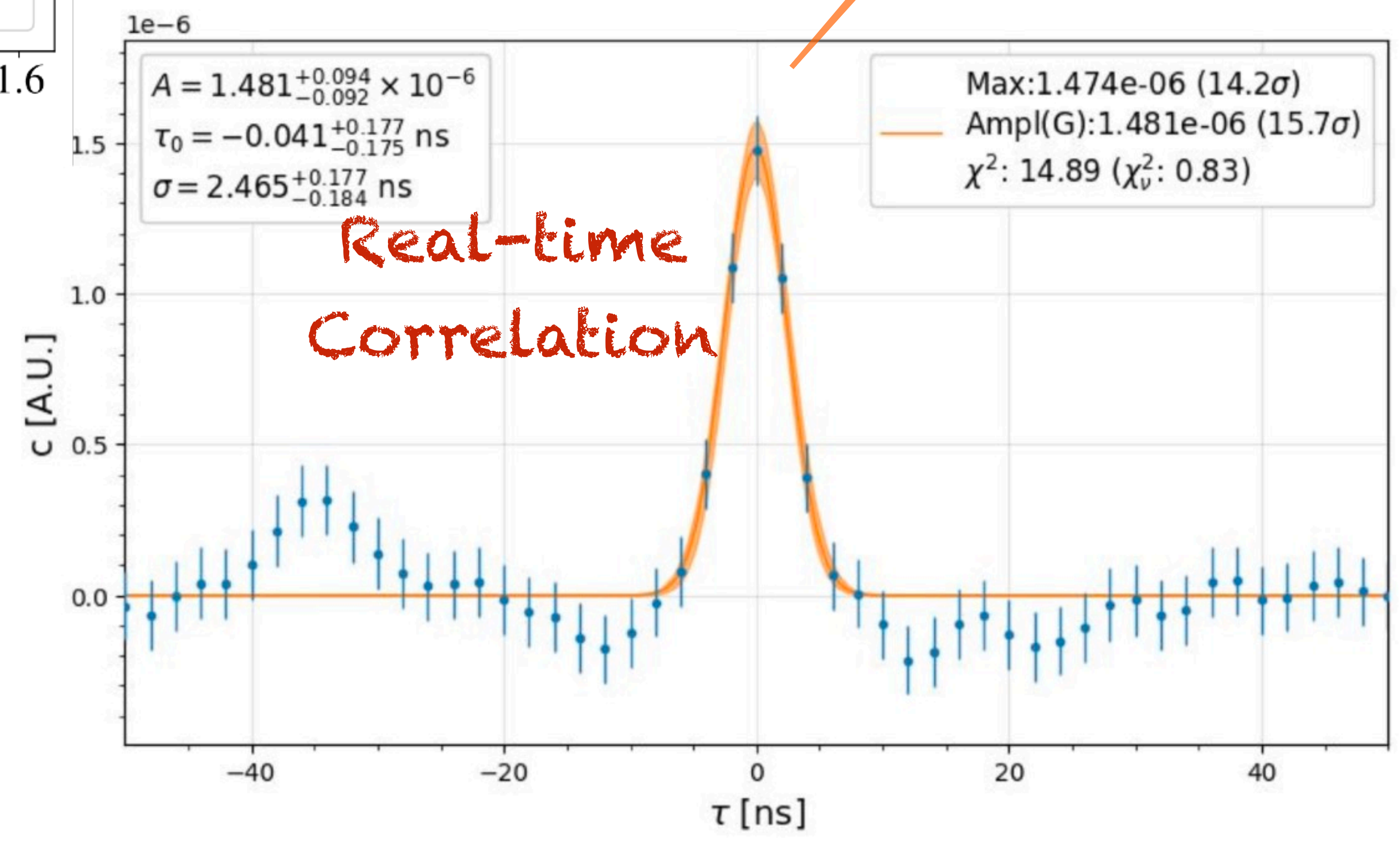

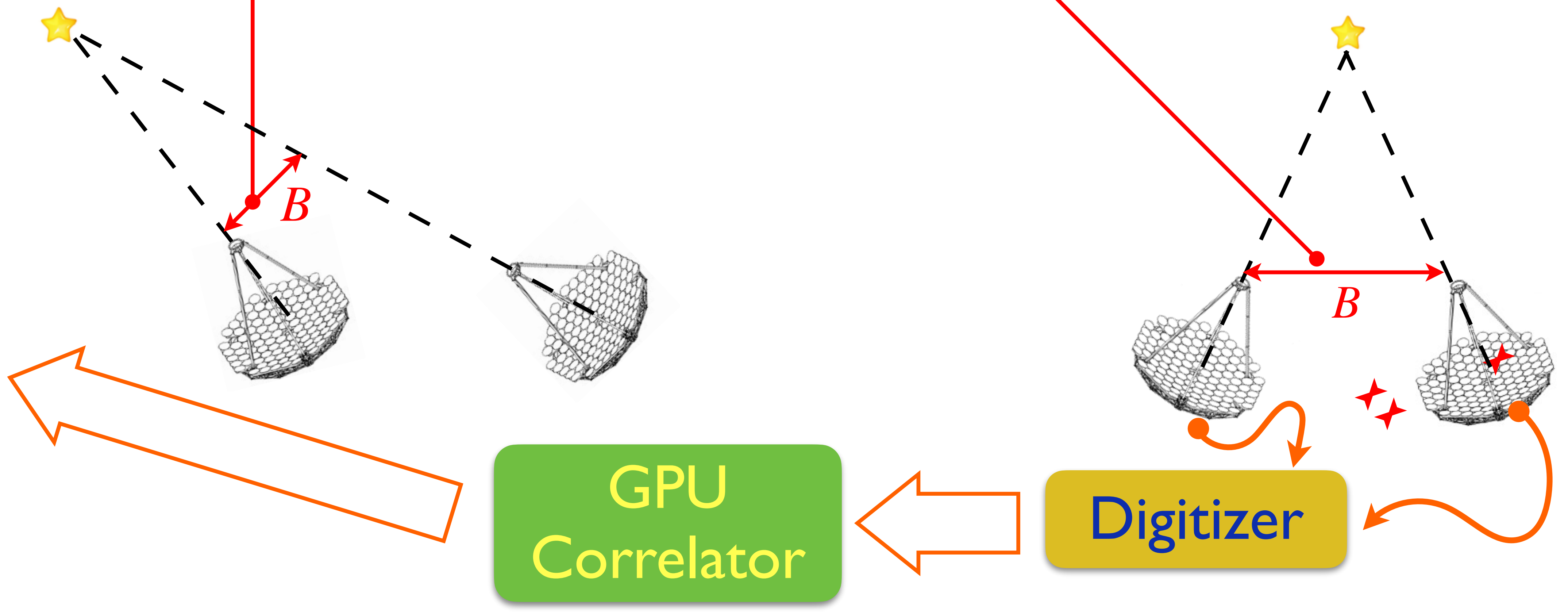

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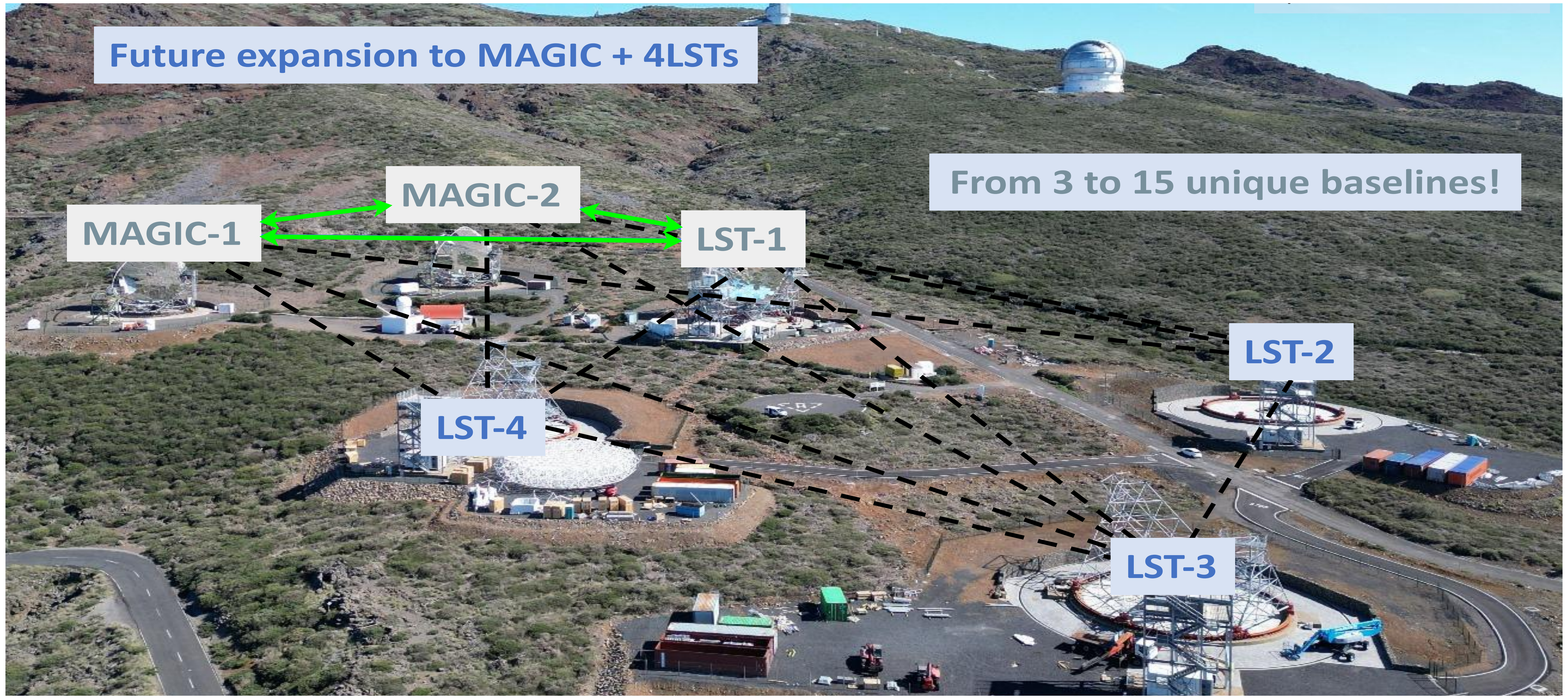
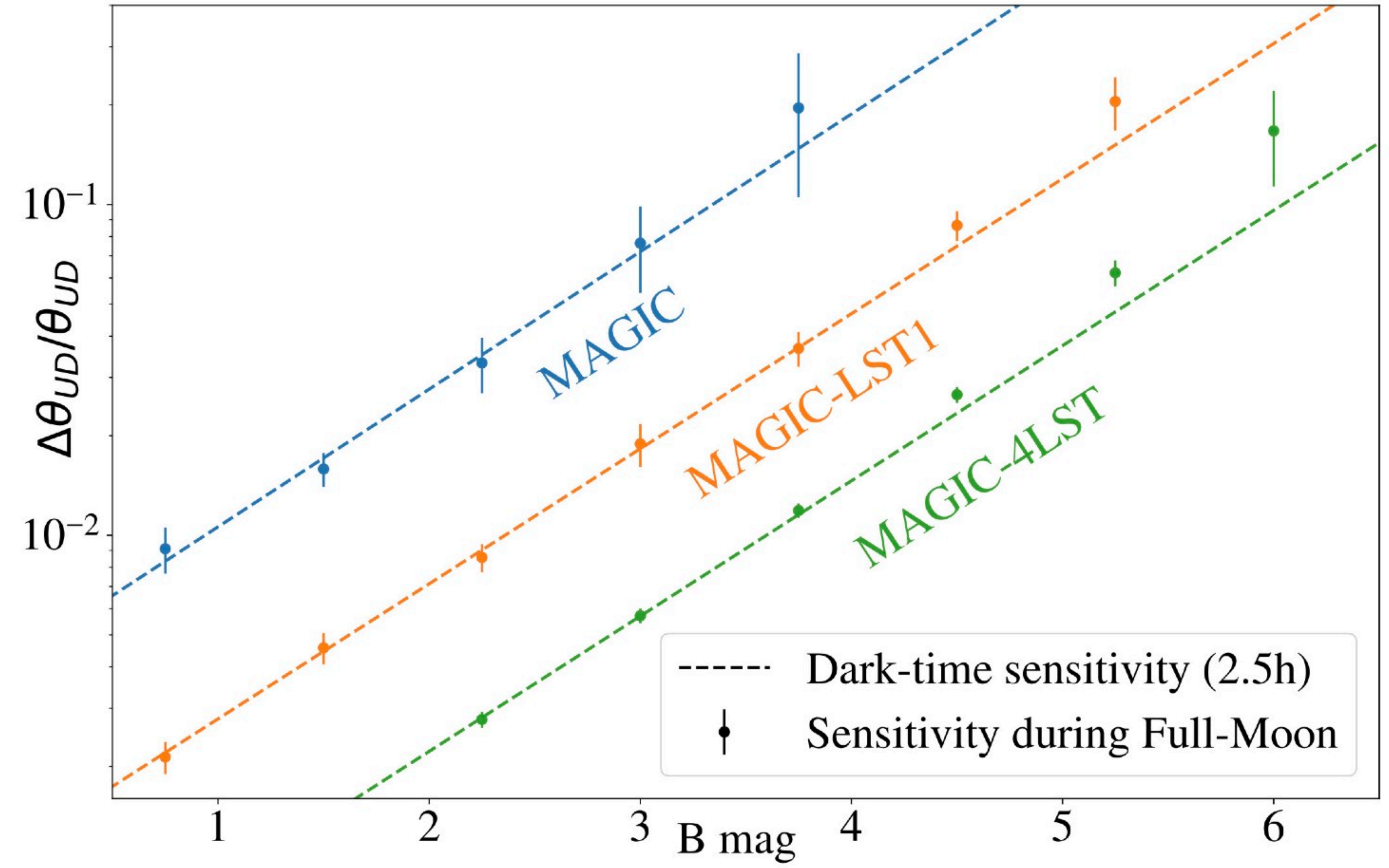
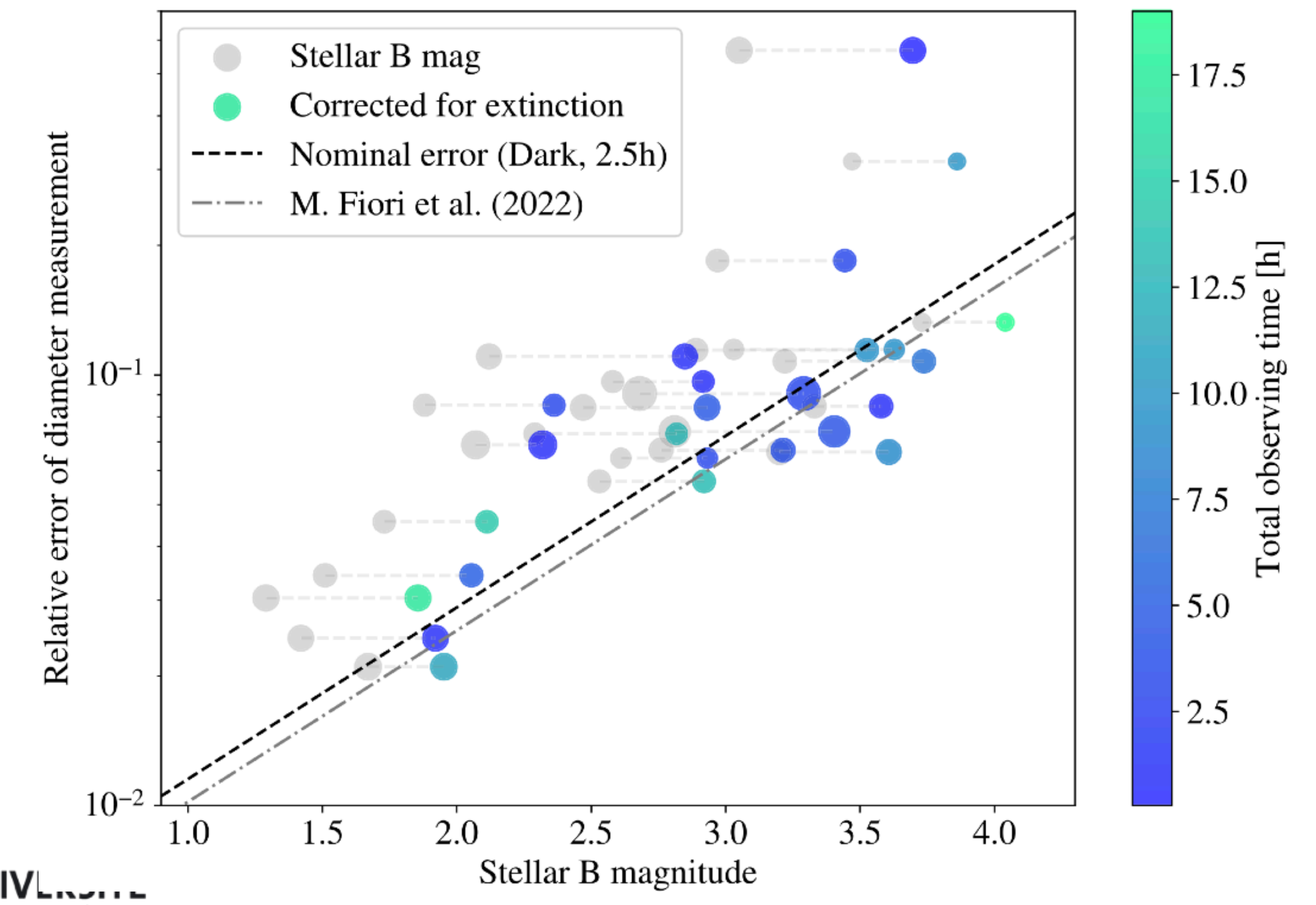
$$S/N = \alpha \cdot q \cdot n_\gamma(\lambda_0) \cdot |V(\lambda_0, d)|^2 \cdot \sqrt{b_\nu} \cdot F^{-1}\sqrt{T_0/2} \cdot (1+\beta)^{-1} \cdot \sigma(\Delta\lambda)$$

MAGIC + LST1







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- A significant improvement on sensitivity is expected even in full moon
- Lot of more physics possible with the addition of 3 more LST under construction at ORM observatory in la La Palma.
- This ‘instrument’ is a perfect ‘tool’ to explore the potentially and drive next generation of SII array …….. CTA? Something built on purpose?

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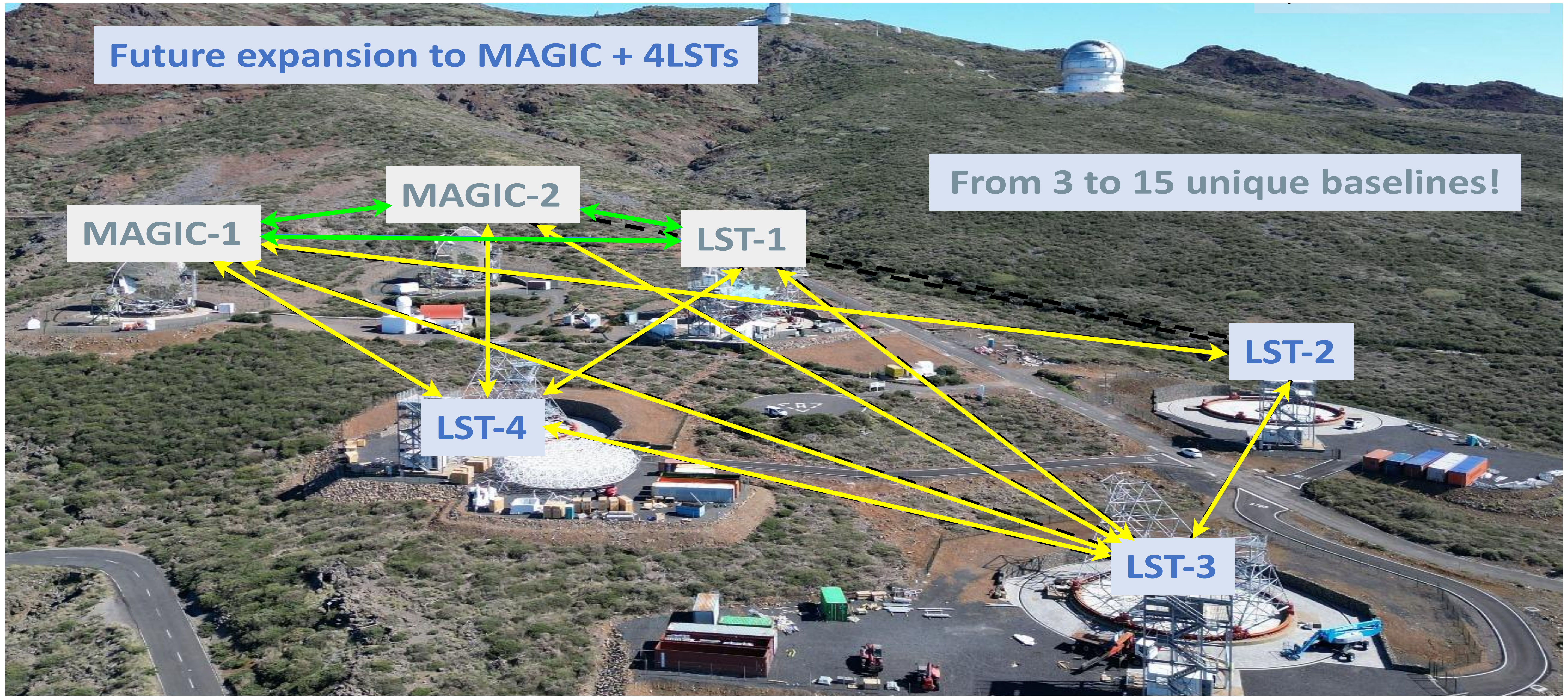

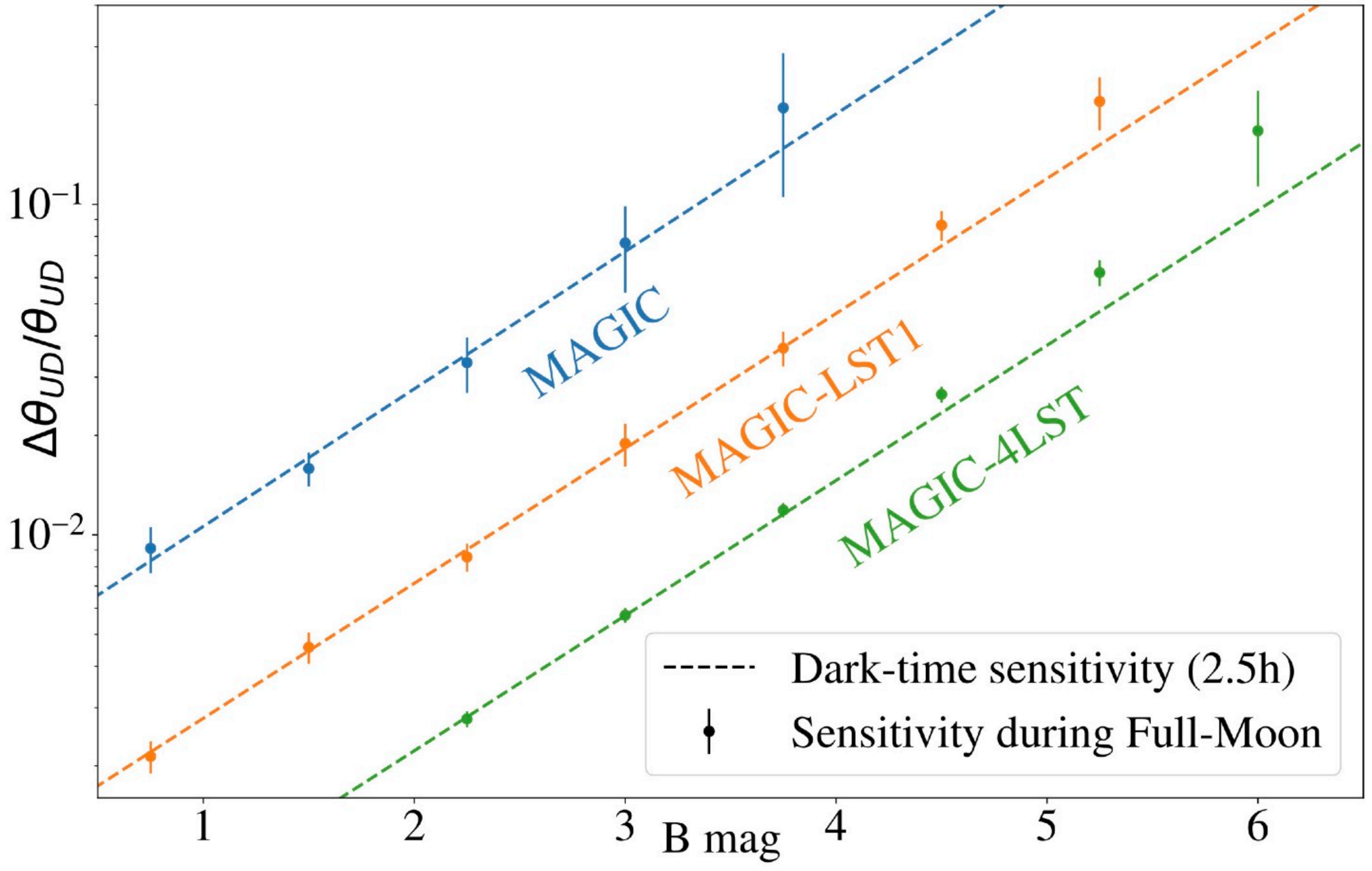

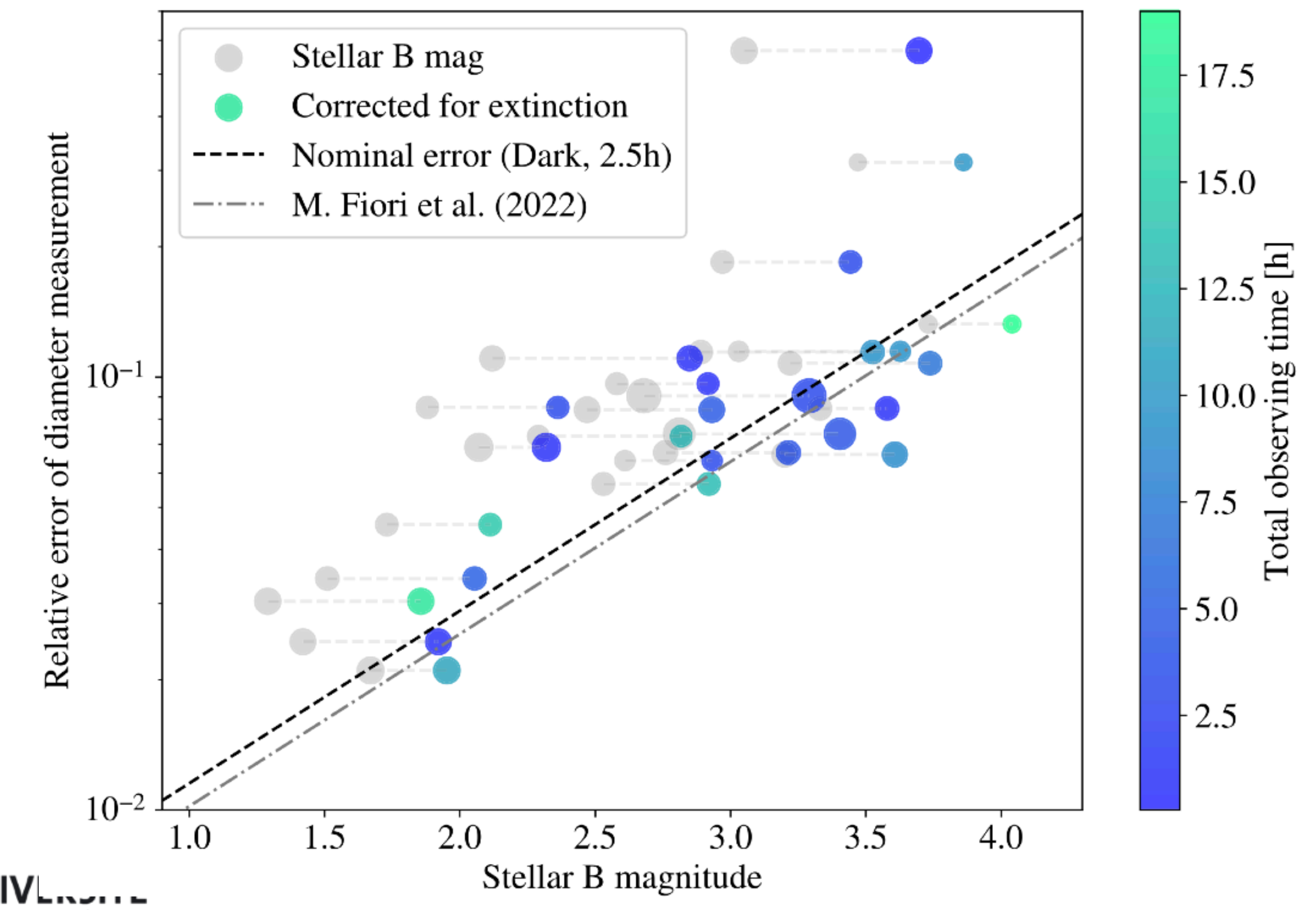

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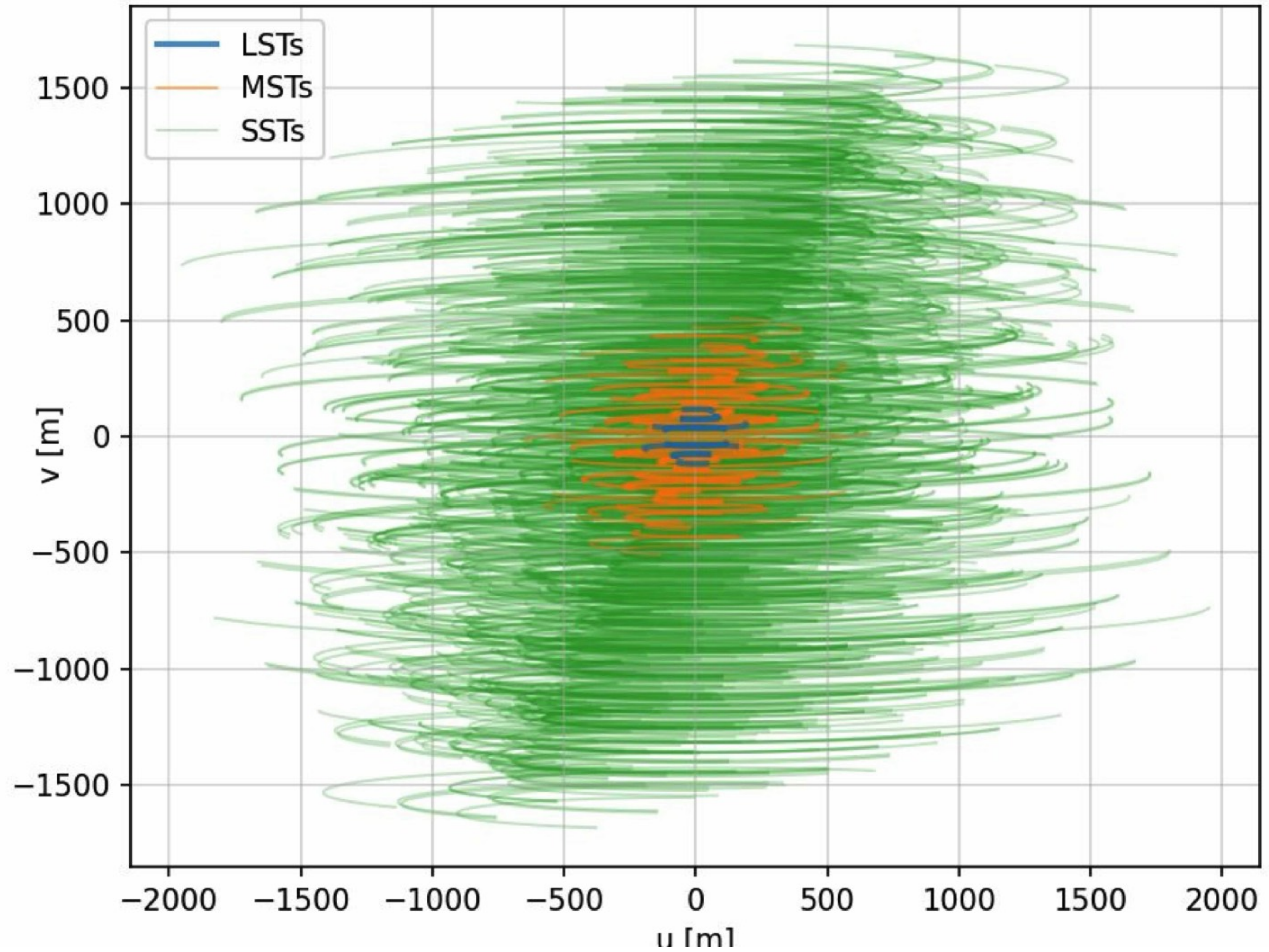
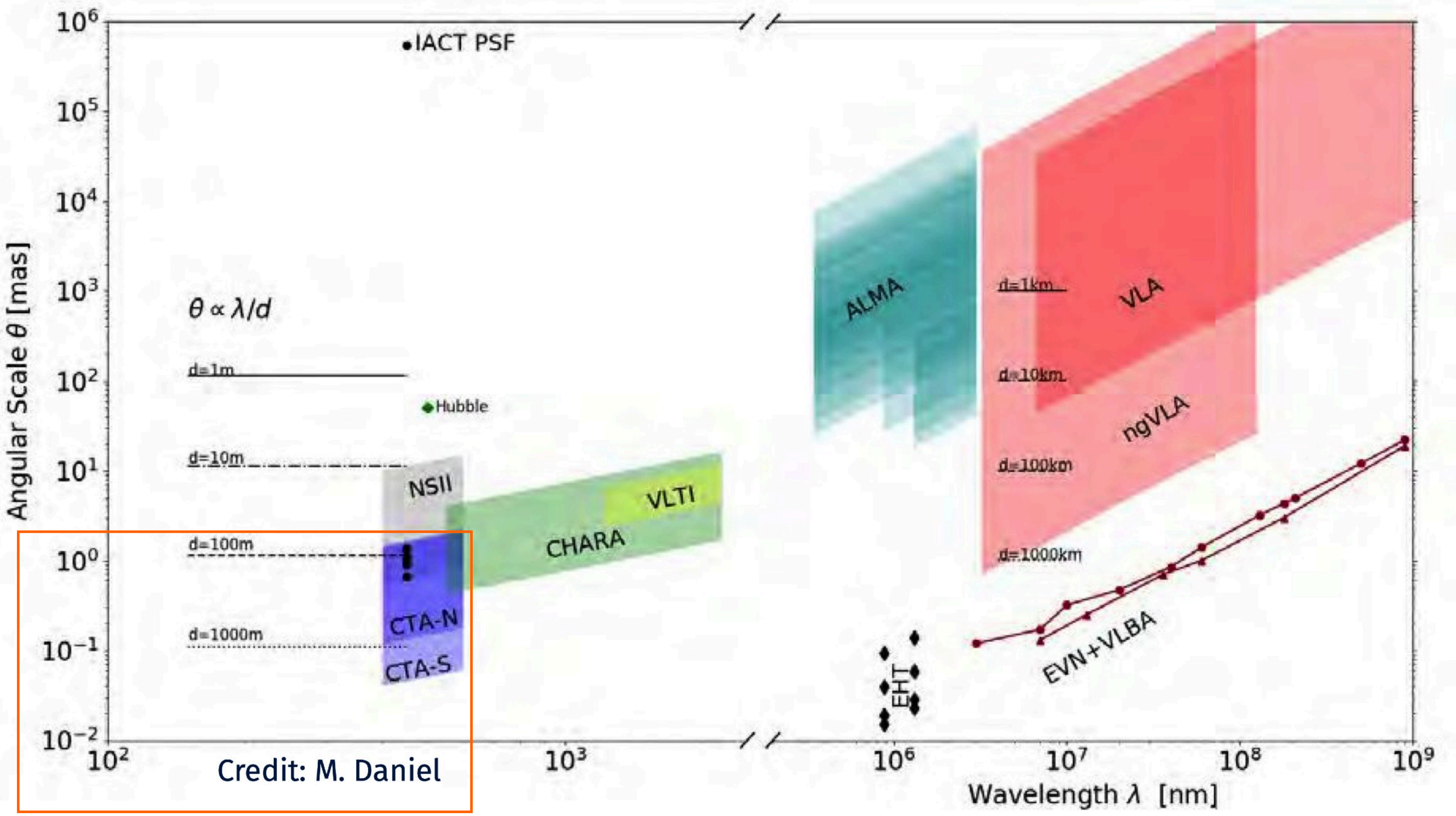
Future of SII with Cherenkov telescope



U-V high sampling



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  - Angular resolution~ 200 μas / <5 mag
- Depending on target and telescope type both type of approach
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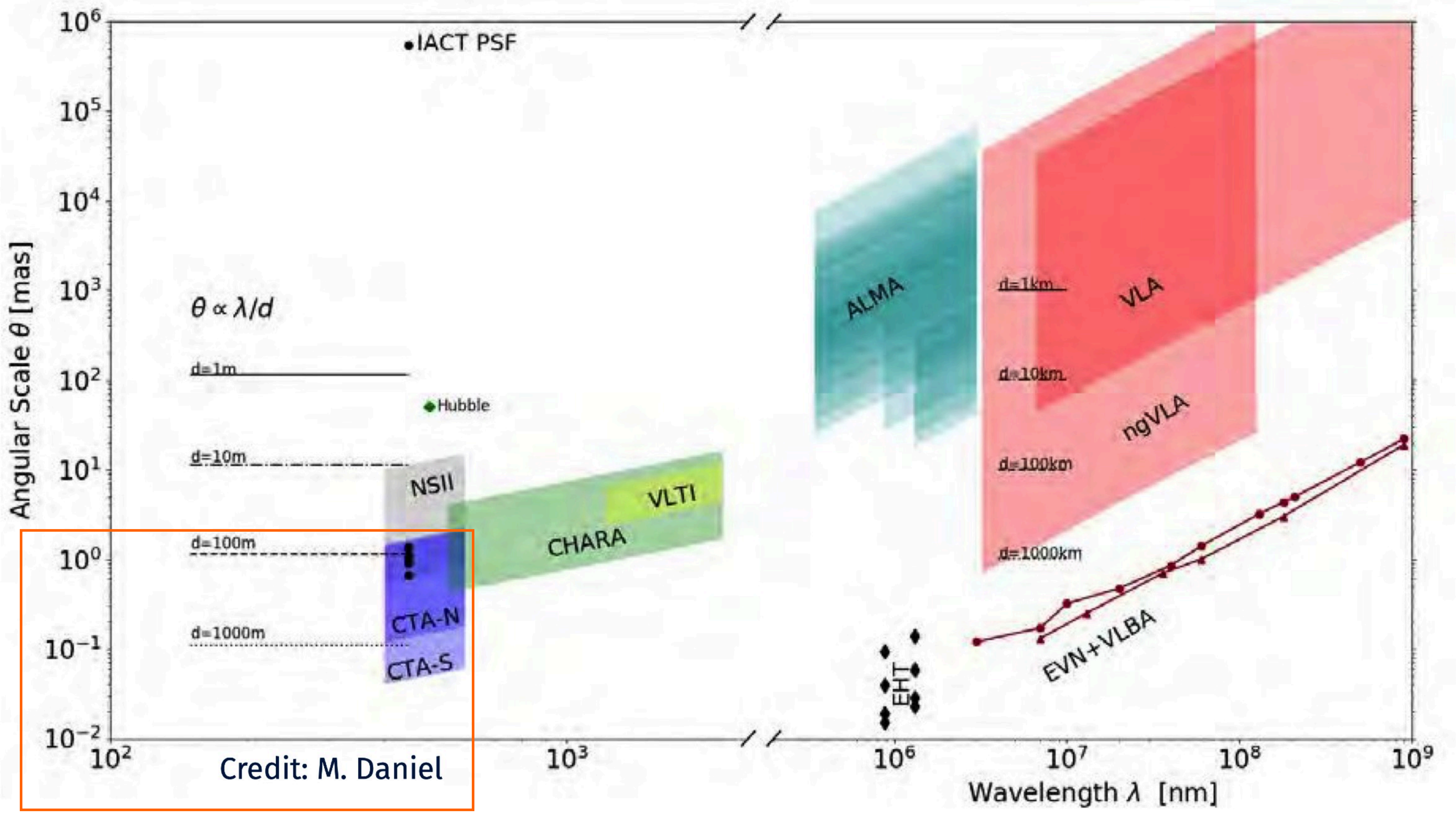

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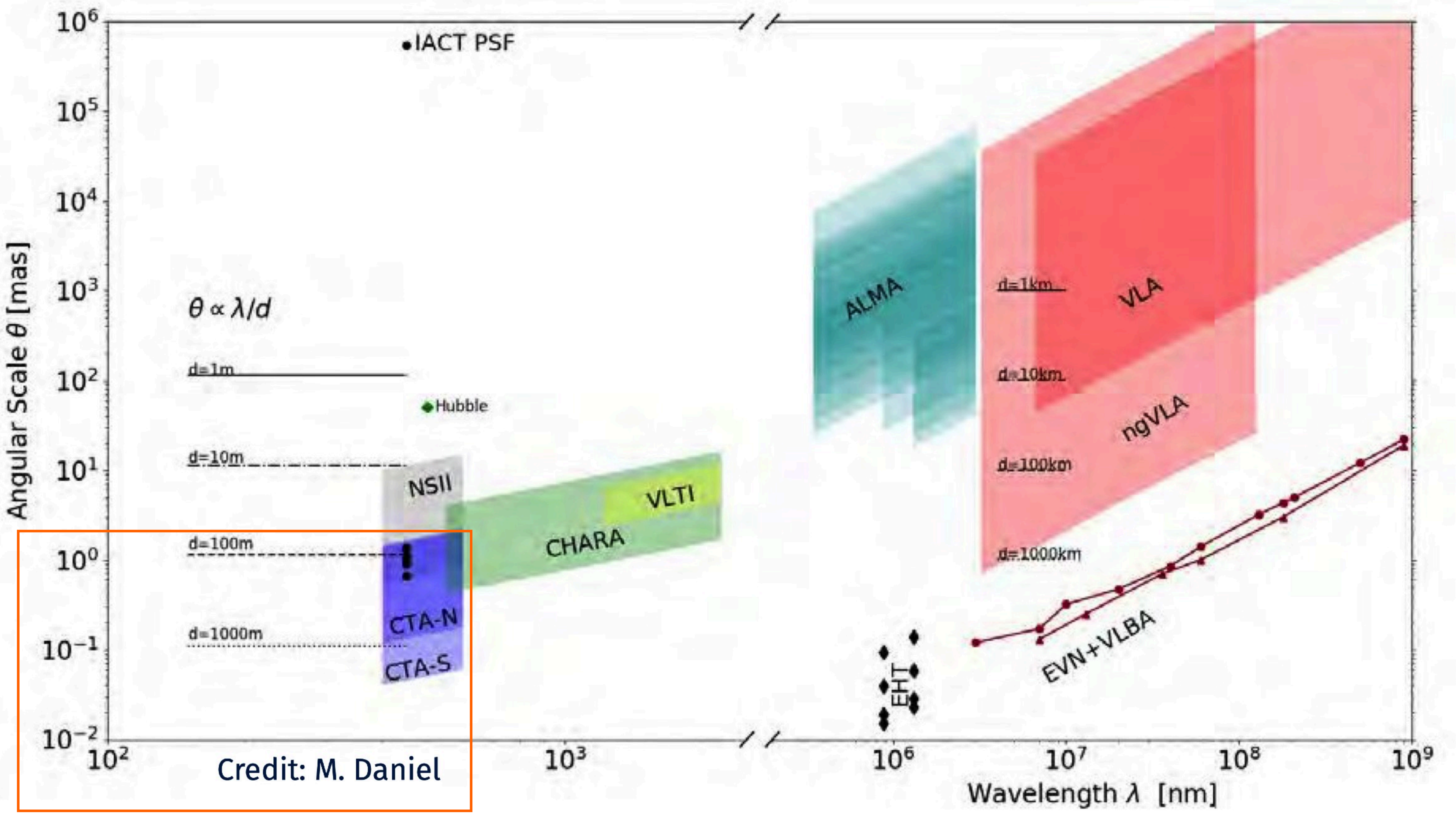

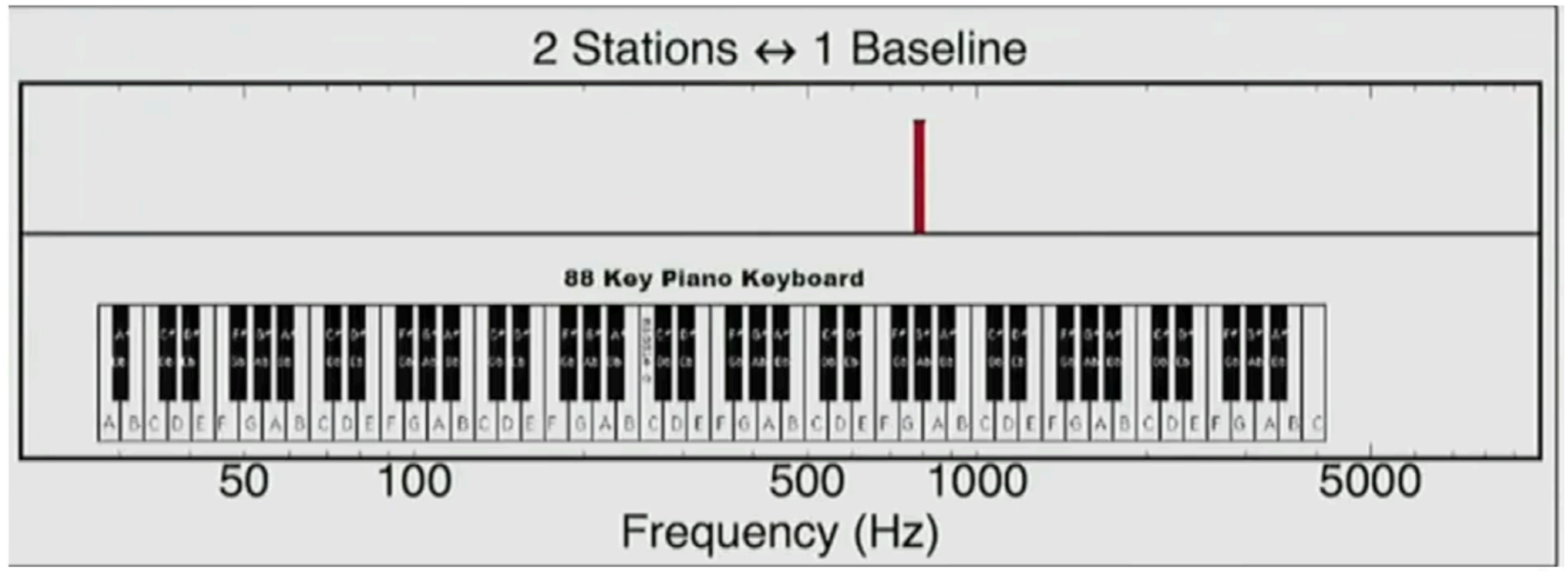

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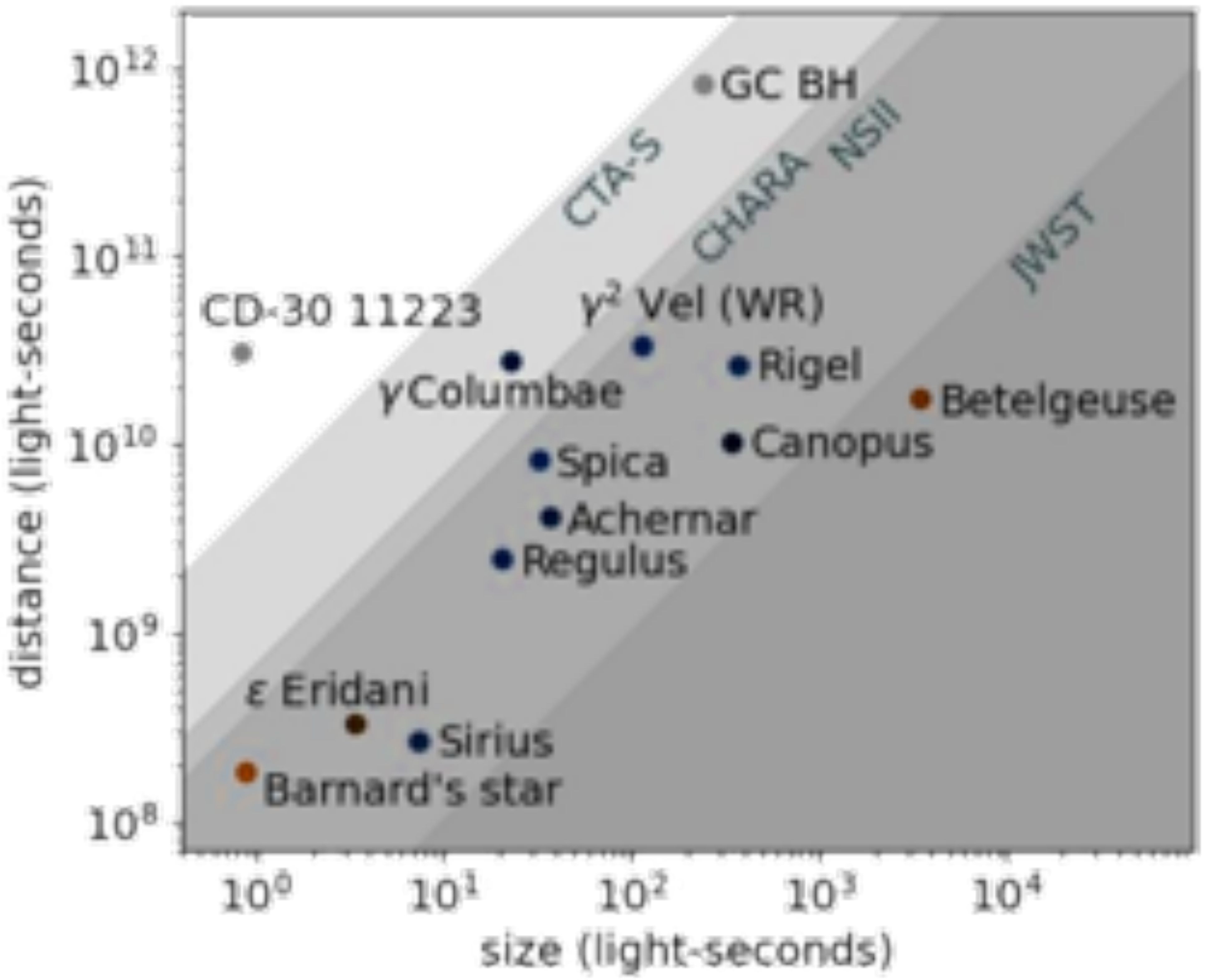

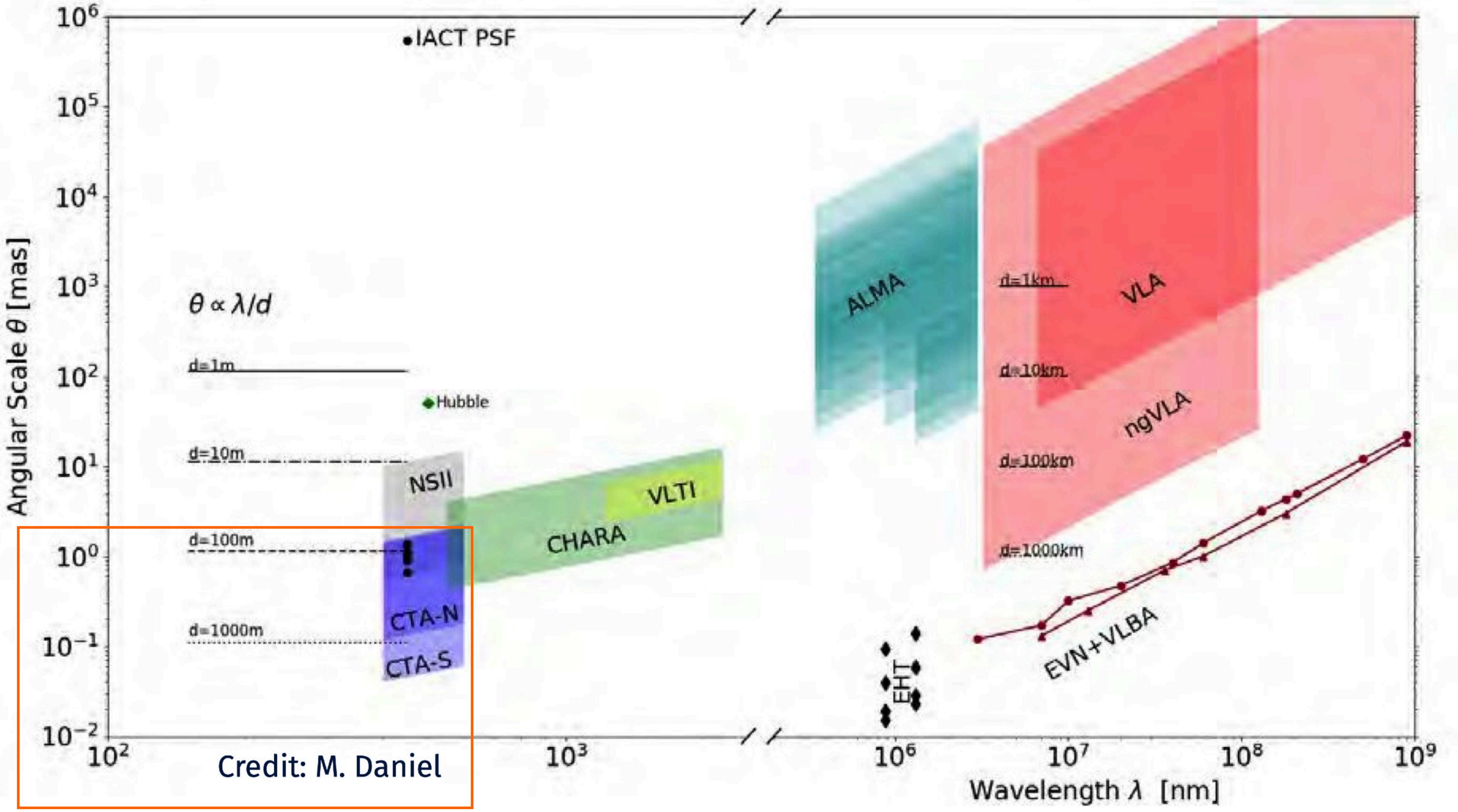

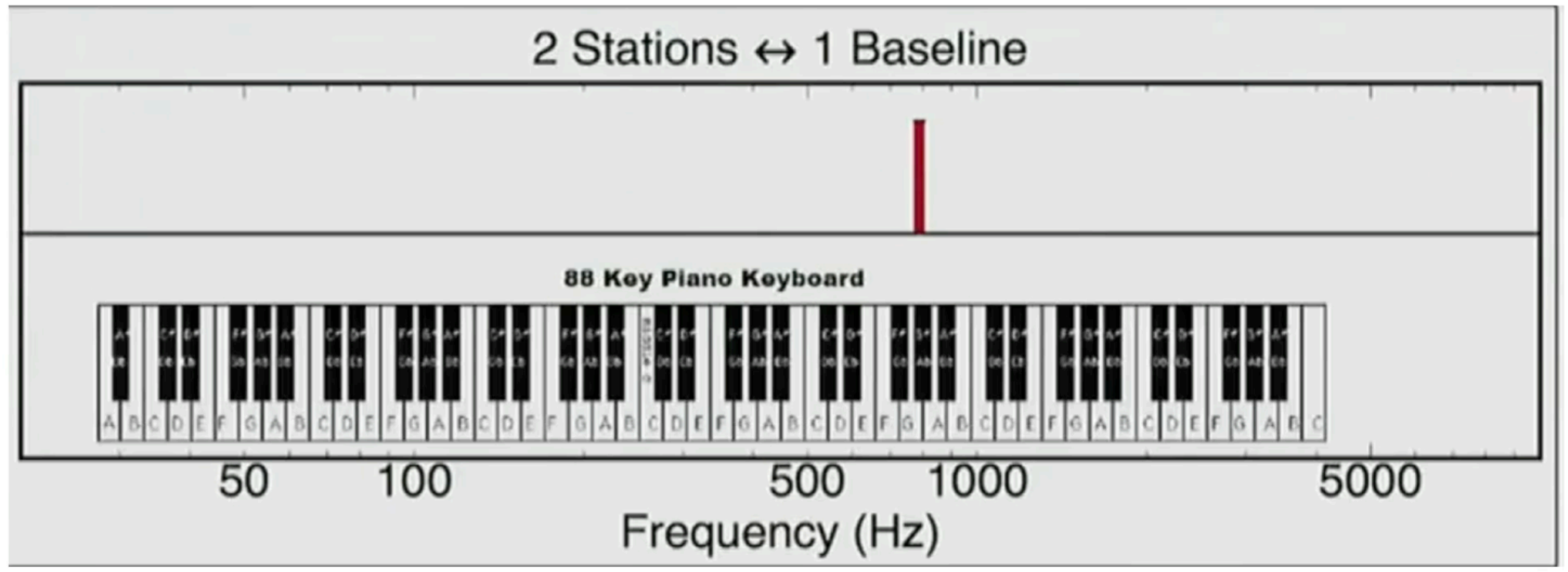

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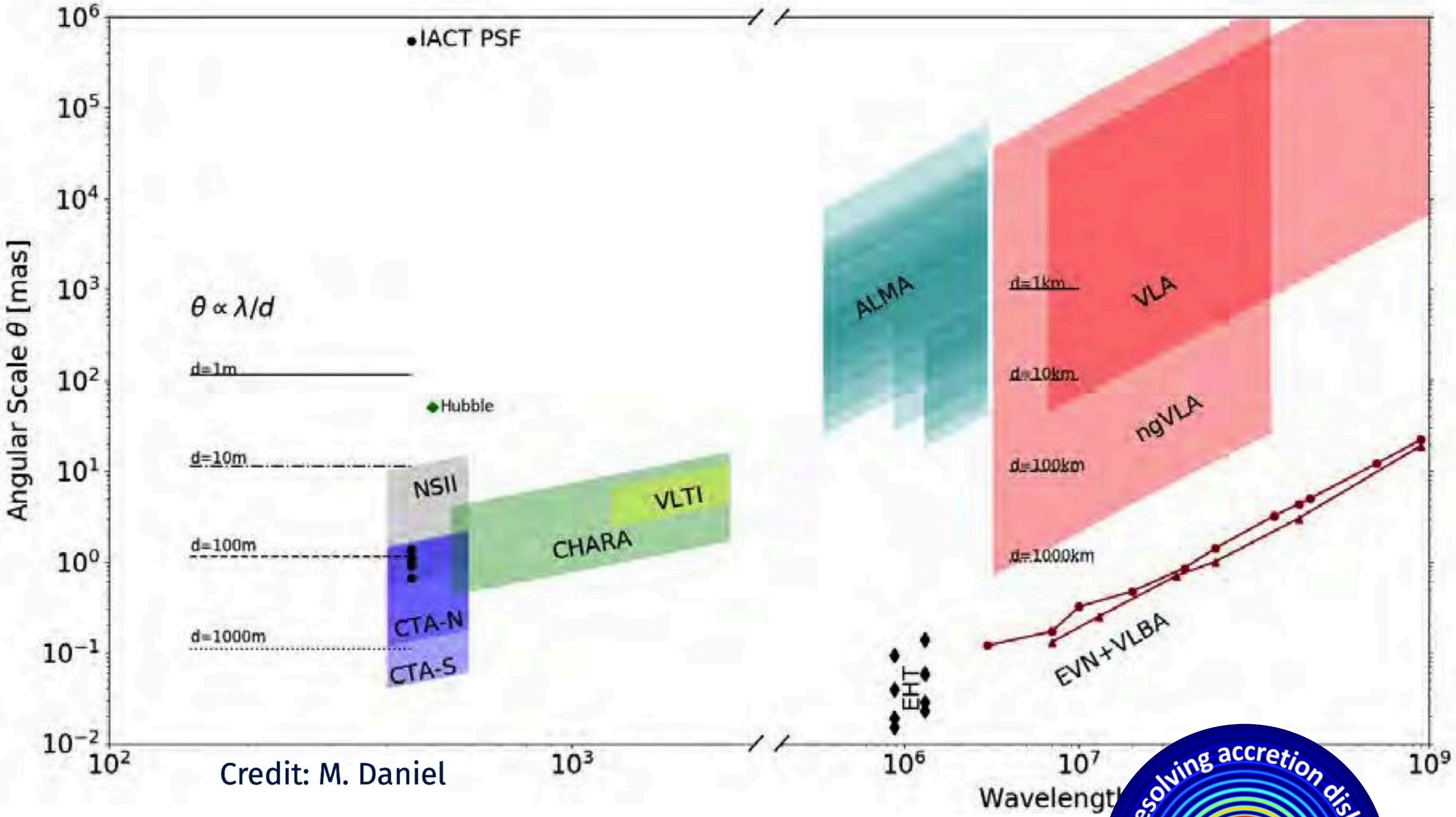
QUASAR - QUantum Astronomy for Super Angular Resolution

- Exploit new quantum technology is ps domain
  - SPADs ~ 20 ps
- Featuring Spectrometer
  - Many channel ⟹ Increase SNR
- Optical telescopes
  - Large surface, isochronous, small PSF
- Proof-of-concept on large optical telescope (~ several tenths of m^2) with baseline < km
  - Reach resolution <100 μas
  - For sources of magnitude < 8
- Next steps
  - Try to combine Optical and Cherenkov telescopes
- Future …… extremely large telescope baseline of thousands of kms!



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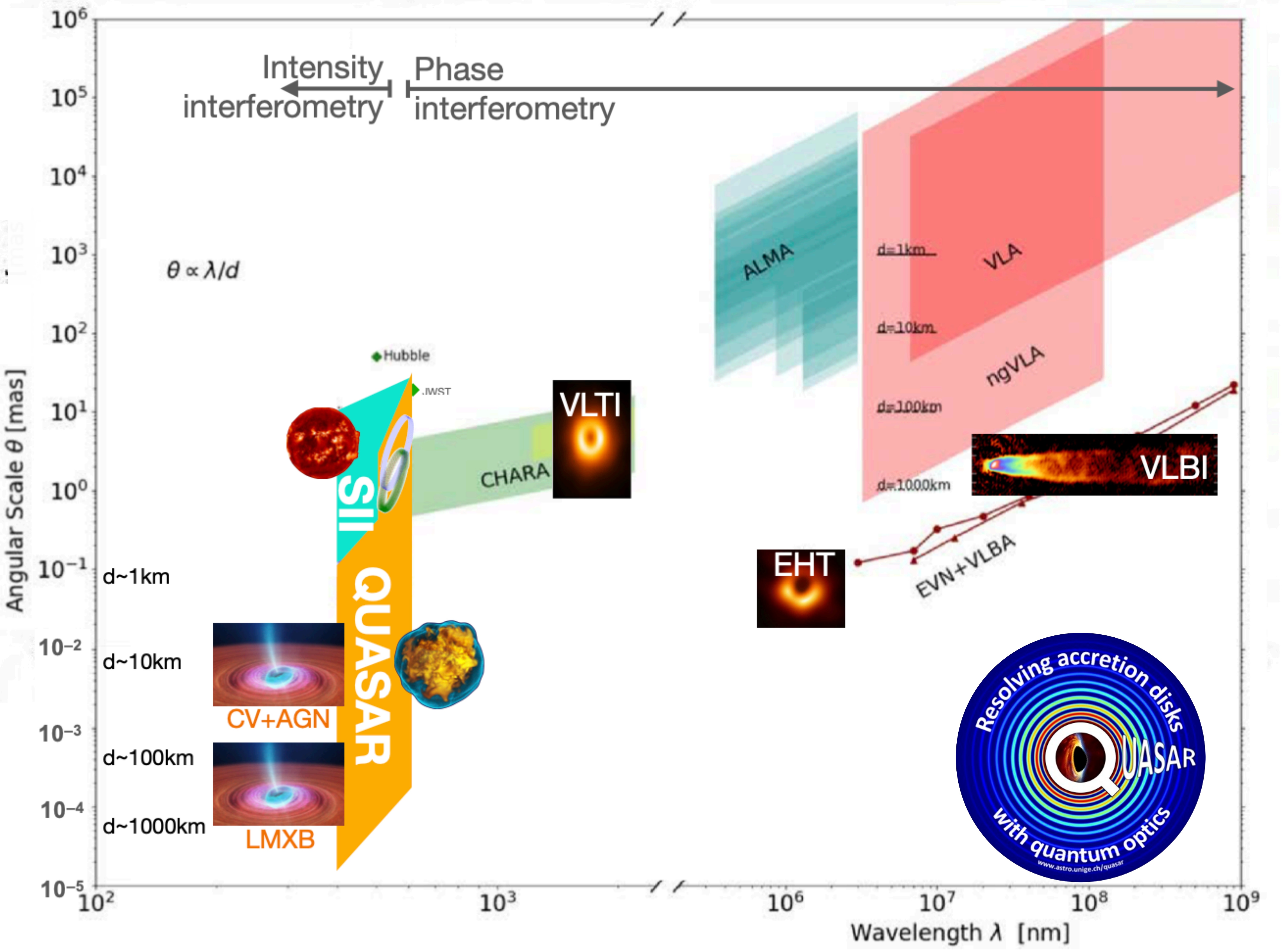
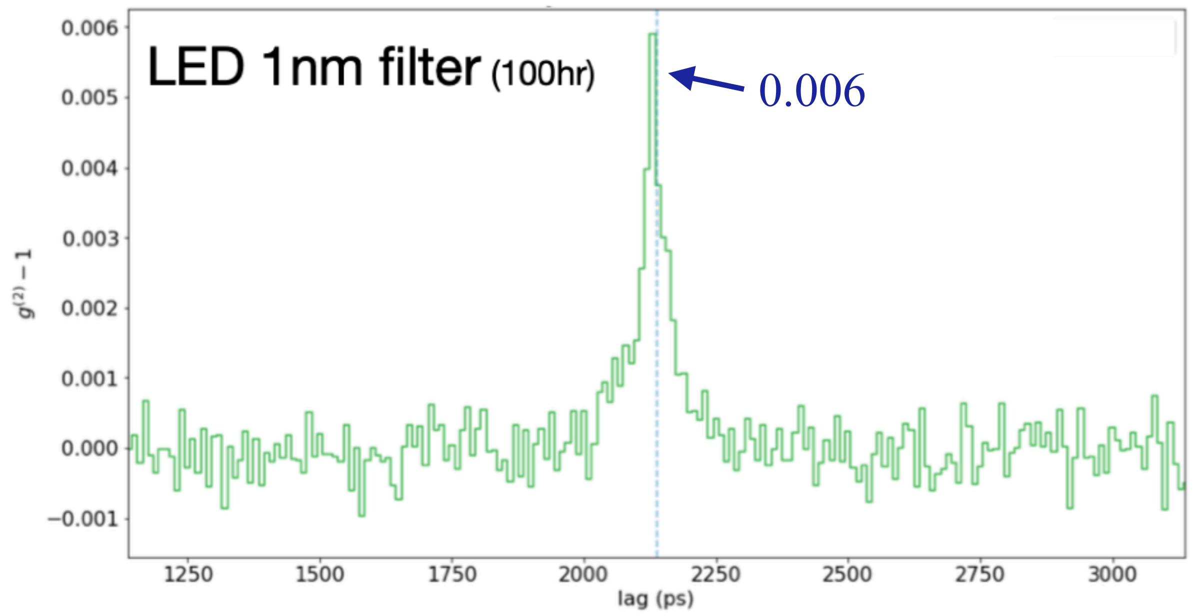


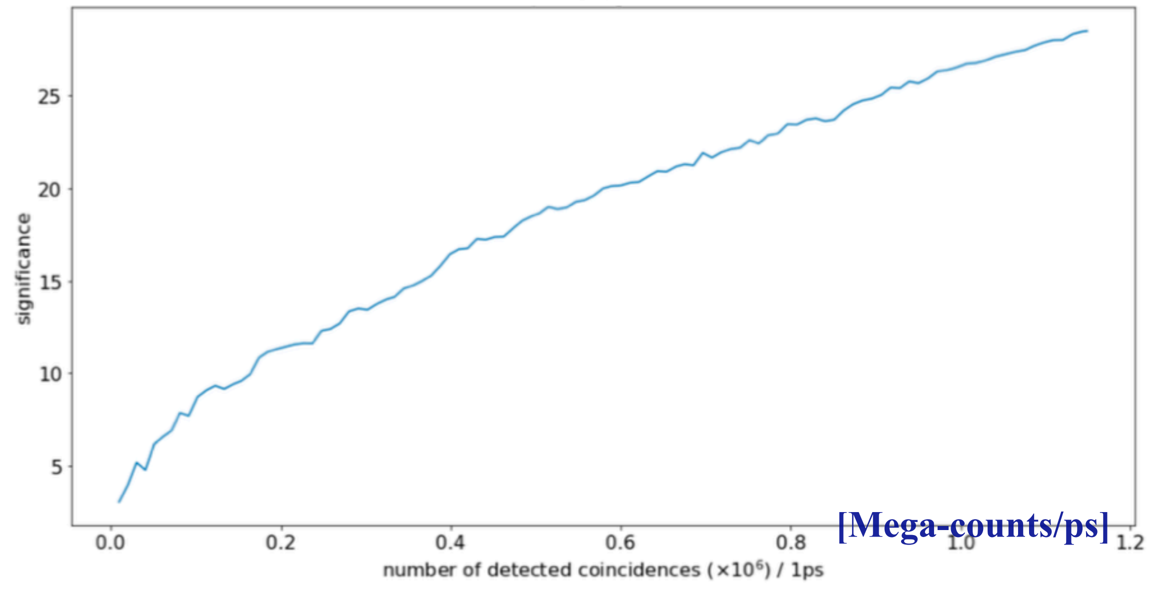
QUASAR challenges - time resolution/synchronisation

- Build a SPAD spectrometer of thousand channels with a digital output
  - Design on going, Foundry submission in few weeks, first prototype in Q1/2025

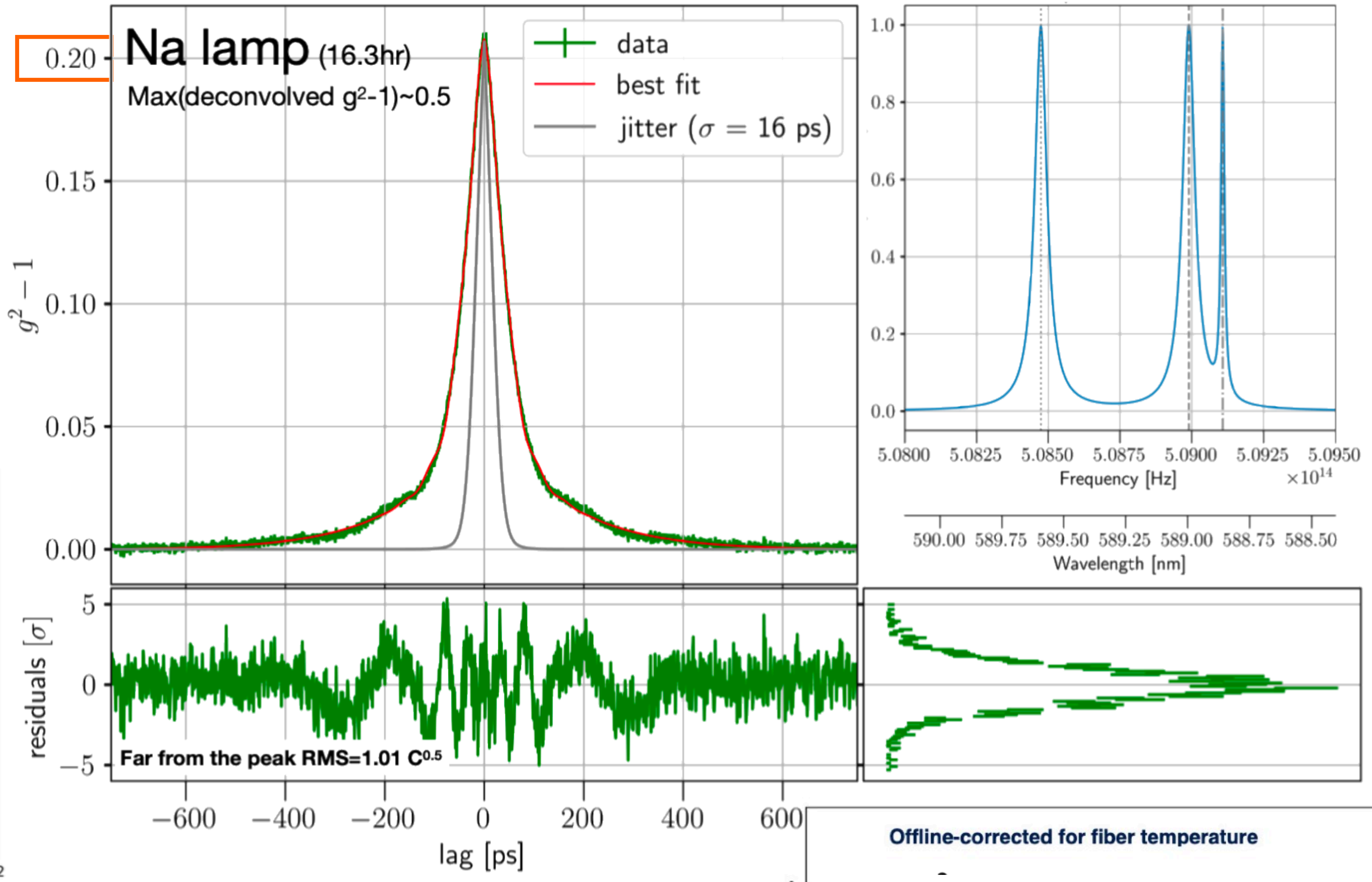
$$SNR \propto \frac{\sqrt{T_0}}{\sqrt{\tau_c}} \times \frac{1}{\sqrt{\sigma_T}} \times \sqrt{N^{\lambda}_{ch}}$$

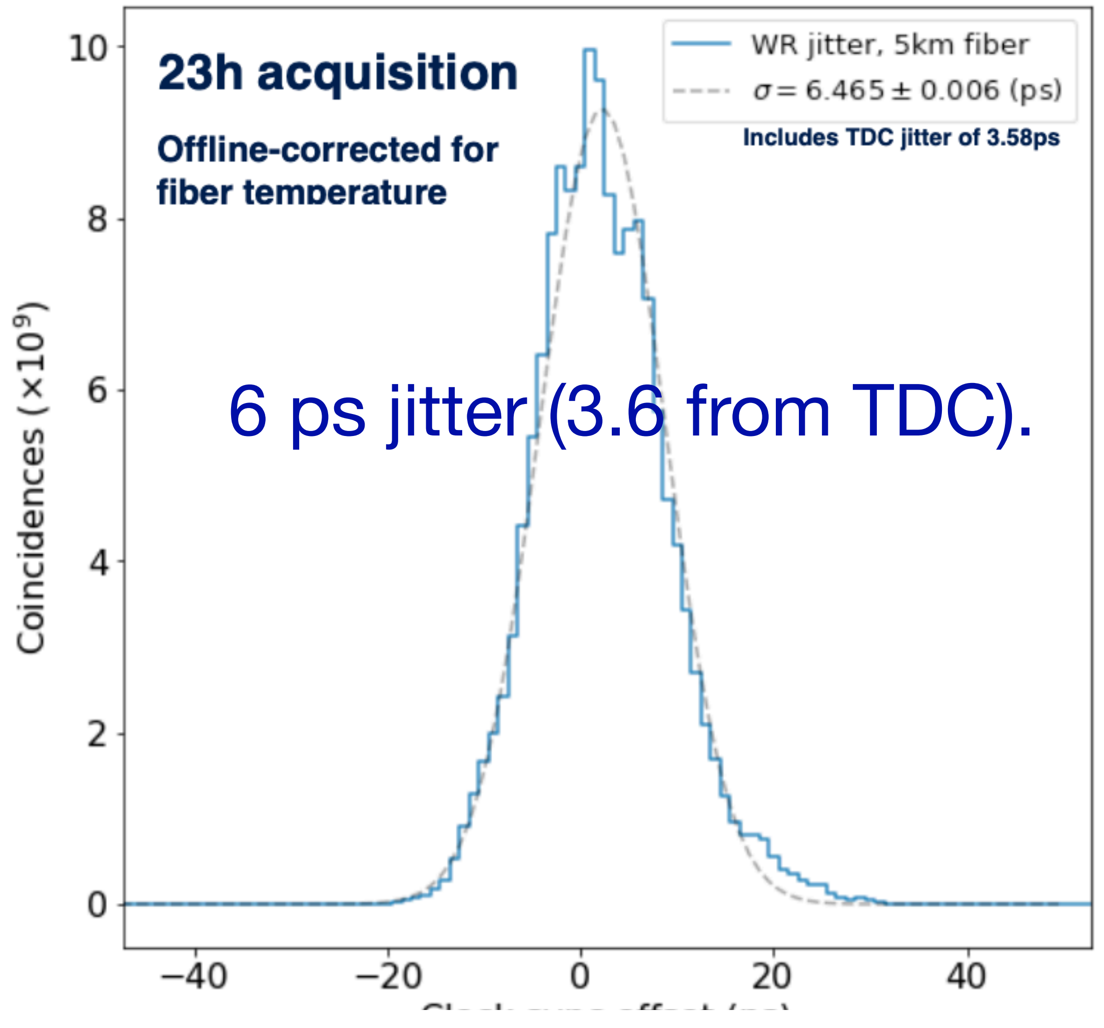
Low g² HBT peak (stellar g2 will be 5x stronger)



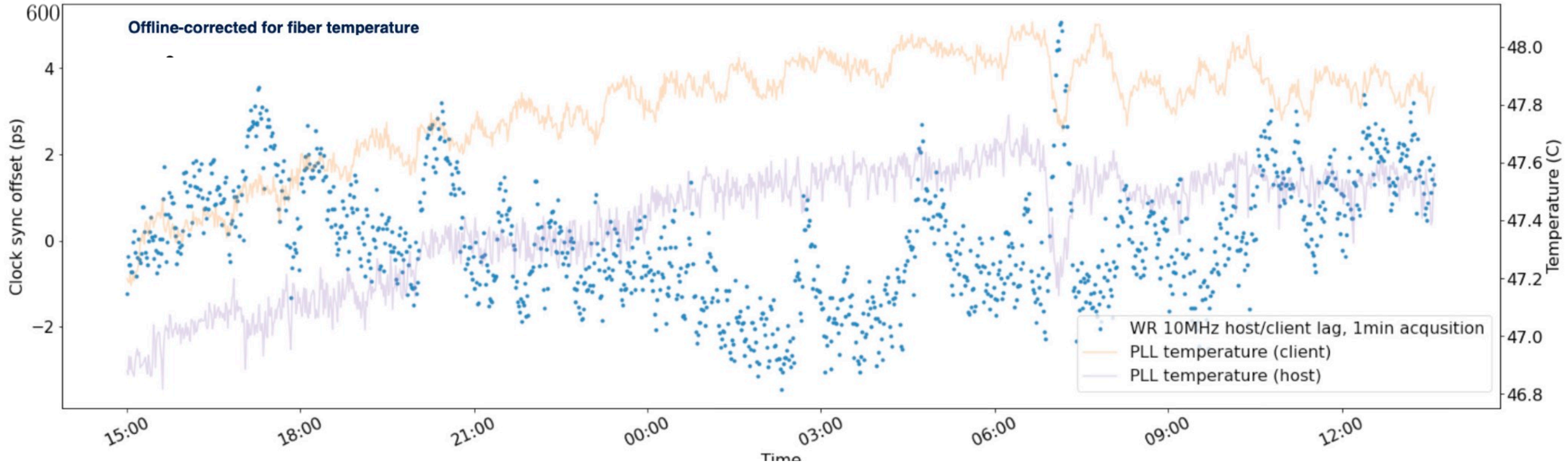


The highest S/N HBT peak (stellar g2 will be 10x smaller)



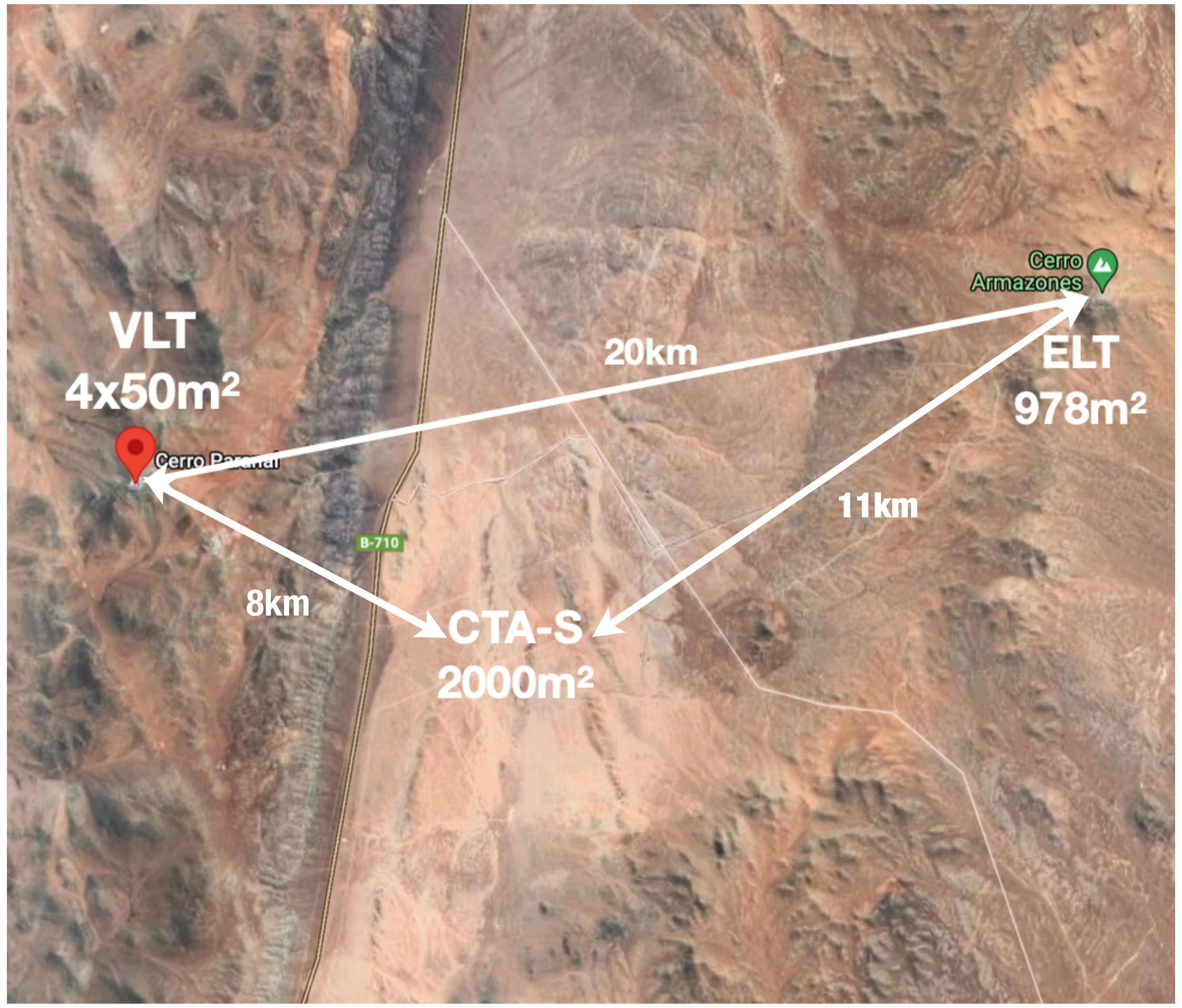


Timing synch with WR over 5 km fibre
Temp compensation can be improved to increase stability



What is achievable?

- ORM: (CTAO N)
  - GTC + WHT+ TNG :
    - $\Delta\vartheta \sim \frac{\lambda}{B} = \frac{400 \text{ nm}}{1273 \text{ m}}$ = 65 µas
- Paranal (CTAO S)
  - VLT-ELT
    - $\Delta\vartheta \sim \frac{\lambda}{B} = \frac{400 \text{ nm}}{10000 \text{ m}}$ = 4 µas
- This are theoretical maximum that can be achieved but there is a potential for a breakthrough



- **Combining Cherenkov and Optical ??**

$$SNR \propto \frac{A}{\sqrt{\sigma_T}} \times \sqrt{N_{ch}^{\lambda}}$$

✓ ***Cherenkov telescope will significantly increase the mirror area***

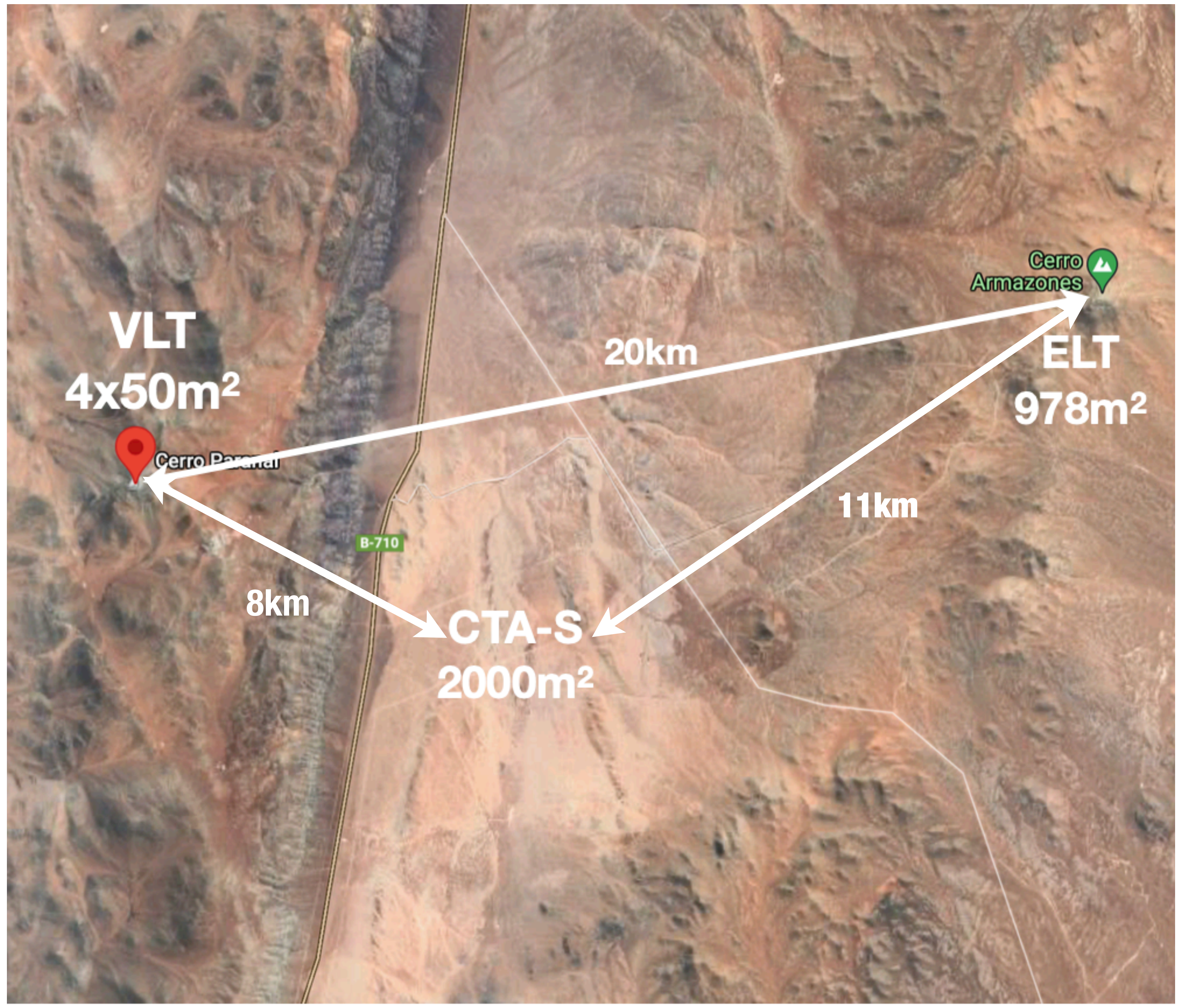
➡ Reach deeper magnitude

✘ ***The time resolution would be lower***

➡ SNR will anyhow improve

What is achievable?

- ORM: (CTAO N)
  - GTC + WHT+ TNG :
    - $\Delta\vartheta \sim \frac{\lambda}{B} = \frac{400 \text{ nm}}{1273 \text{ m}}$ = 65 µas
- Paranal (CTAO S)
  - VLT-ELT
    - $\Delta\vartheta \sim \frac{\lambda}{B} = \frac{400 \text{ nm}}{10000 \text{ m}}$= 4 µas
- This are theoretical maximum that can be achieved but there is a potential for a breakthrough



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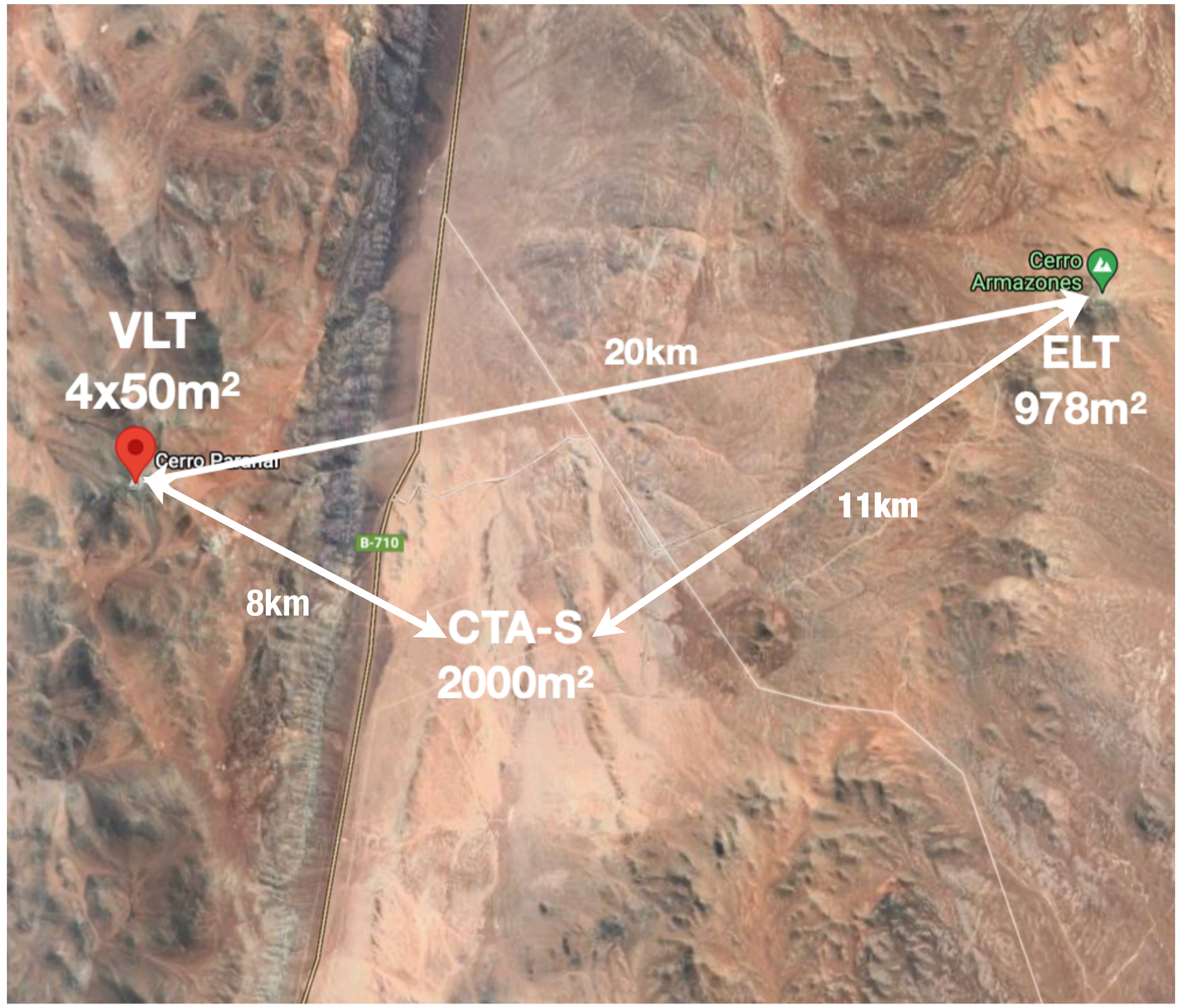

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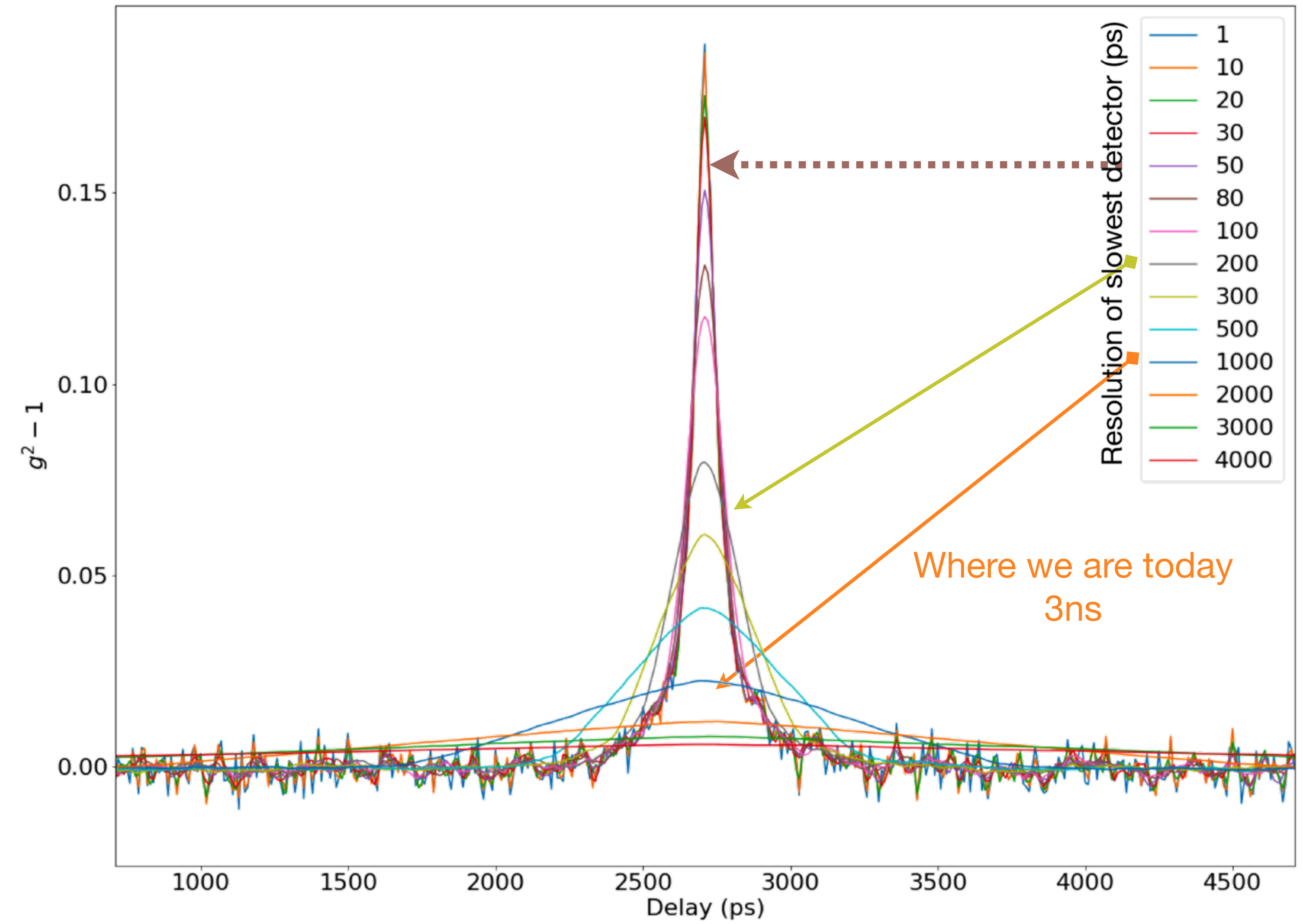
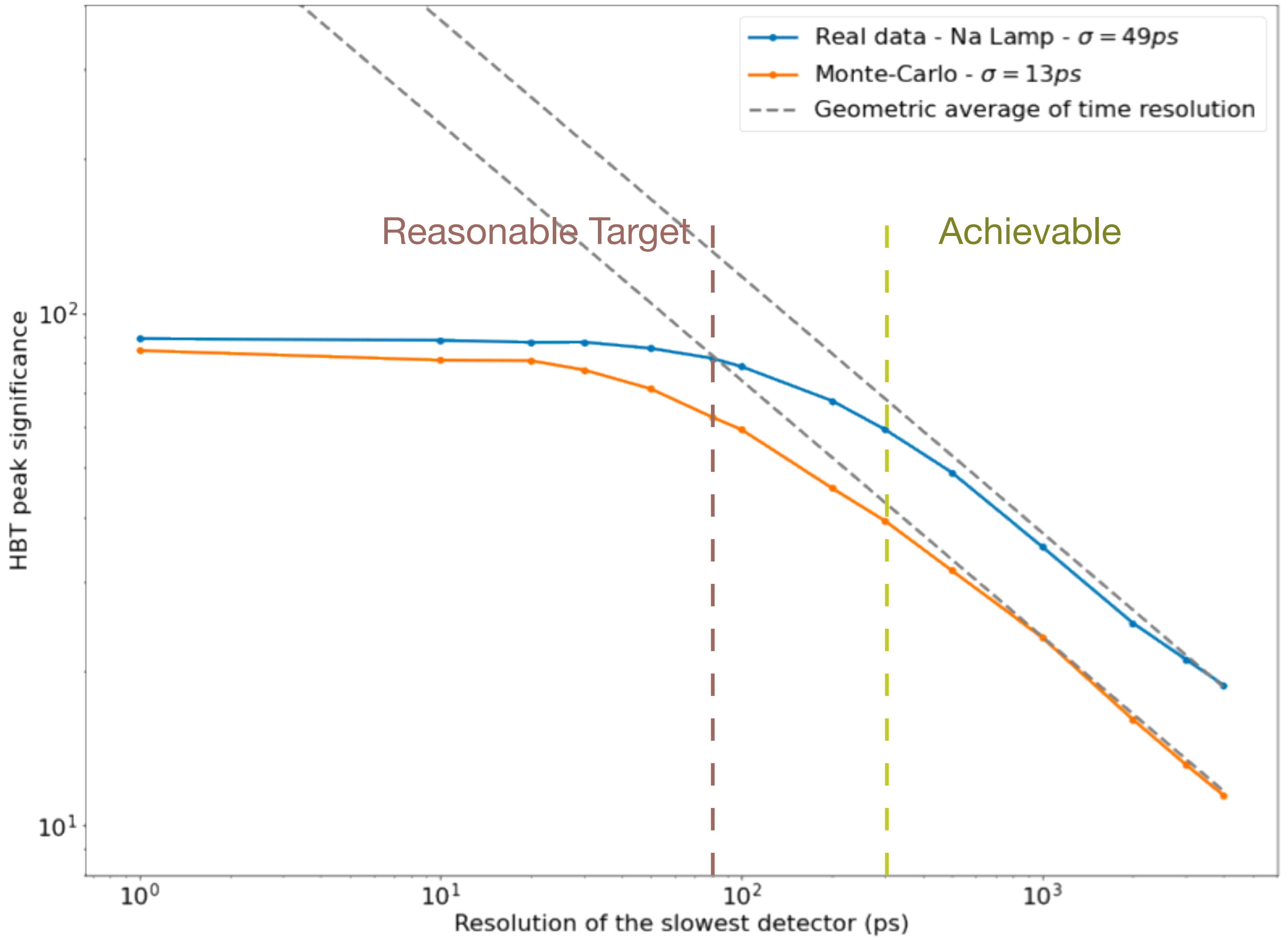
Combining Cherenkov and Optical ??

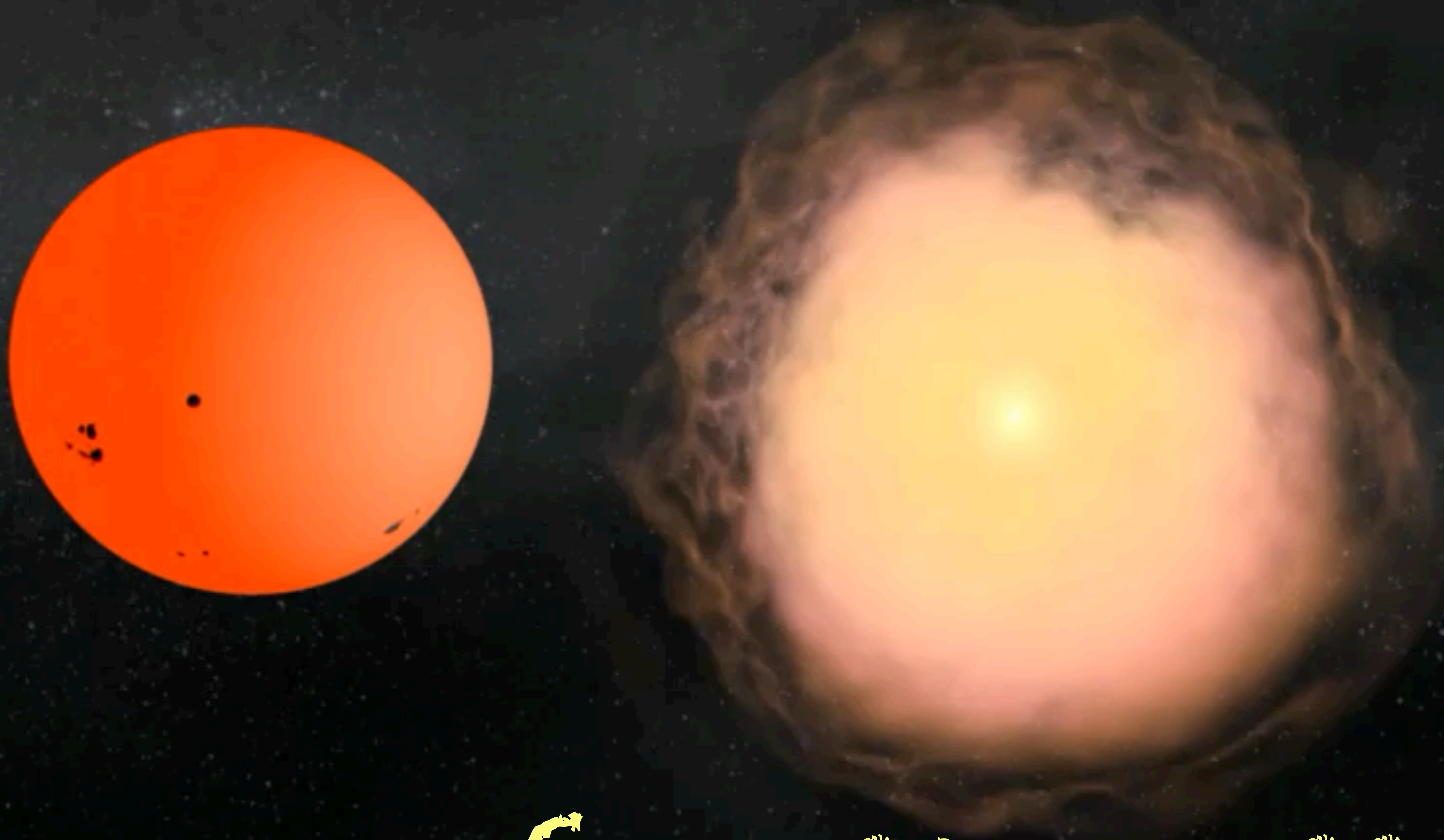
- The combination will reduce SNR and a good SNR can be achieved if the slowest detector is below 100 ps.
- Many technologies could provide it, but it's not trivial to change current cameras.
- At the moment, Cherenkov does HPR, but the combination can be easily achieved with HTR used in QUASAR.



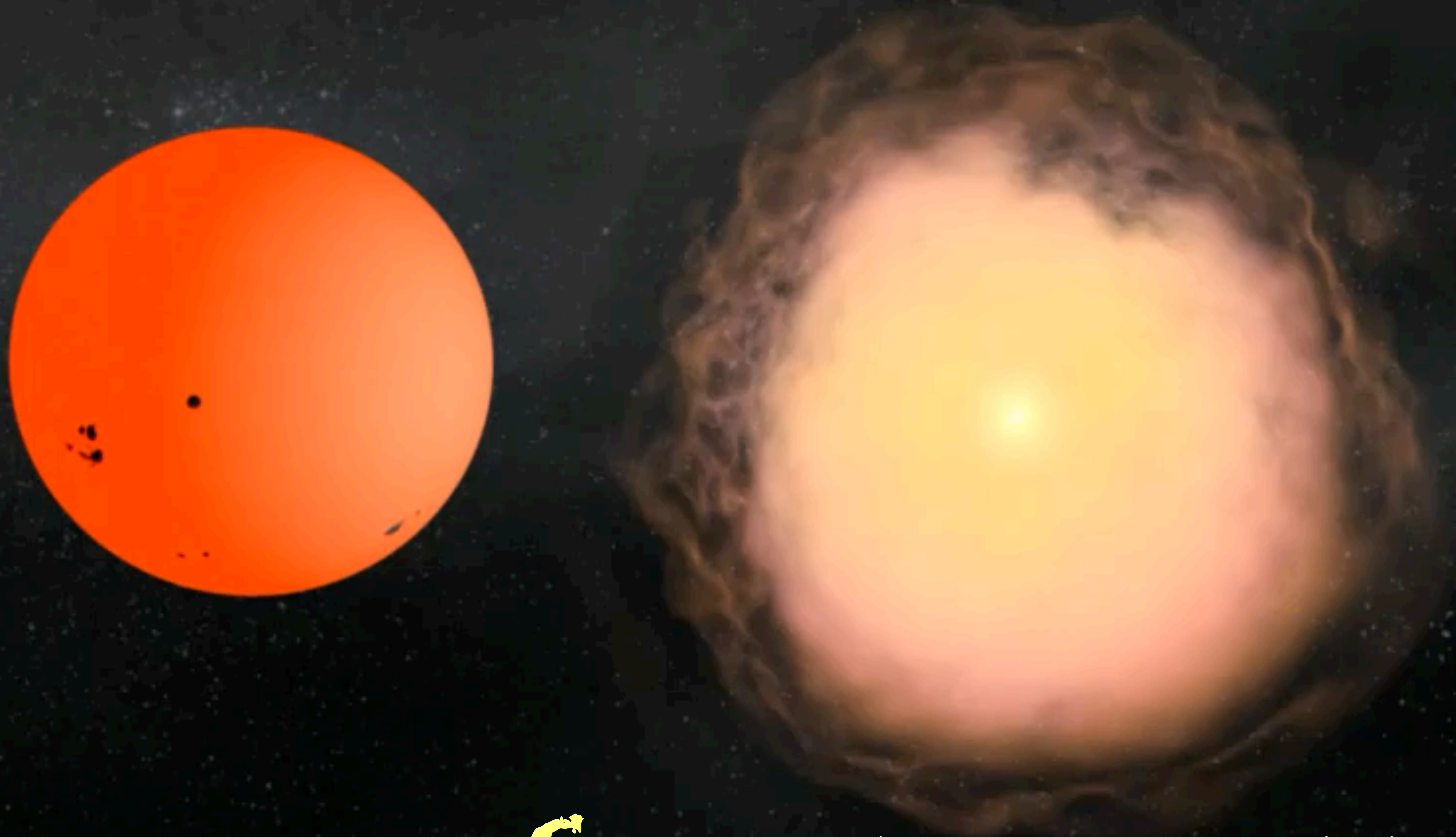


Measuring accretion disk: enabling new Science

- The possibility to go for µas-nas precision in optical it is clearly a breakthrough for astronomy but not only
- "All most luminous sources in astronomy are accretors" $\simeq$ "most of accretion disk are luminous"
  - Accretion flows around compact objects are important for gravitational physics,
    - resolved flows around compact objects $\Longrightarrow$ to probe general relativity / test theories of extraction of black hole spin energy,
    - improve our understanding of AGN central engines .
- This can be pushed to the limit … time-resolved images!
  - We could produce a film of an exploding supernova
  - Accretion of binary system , Black hole
  - AGN dynamic, or GRB evolution
- Gravitational Wave impact photon phase $\Longrightarrow$ 'see' GW
- What about neutrinos …. We cannot see but we can provide information on possible sources



Thanks for the attention



Thanks for the attention