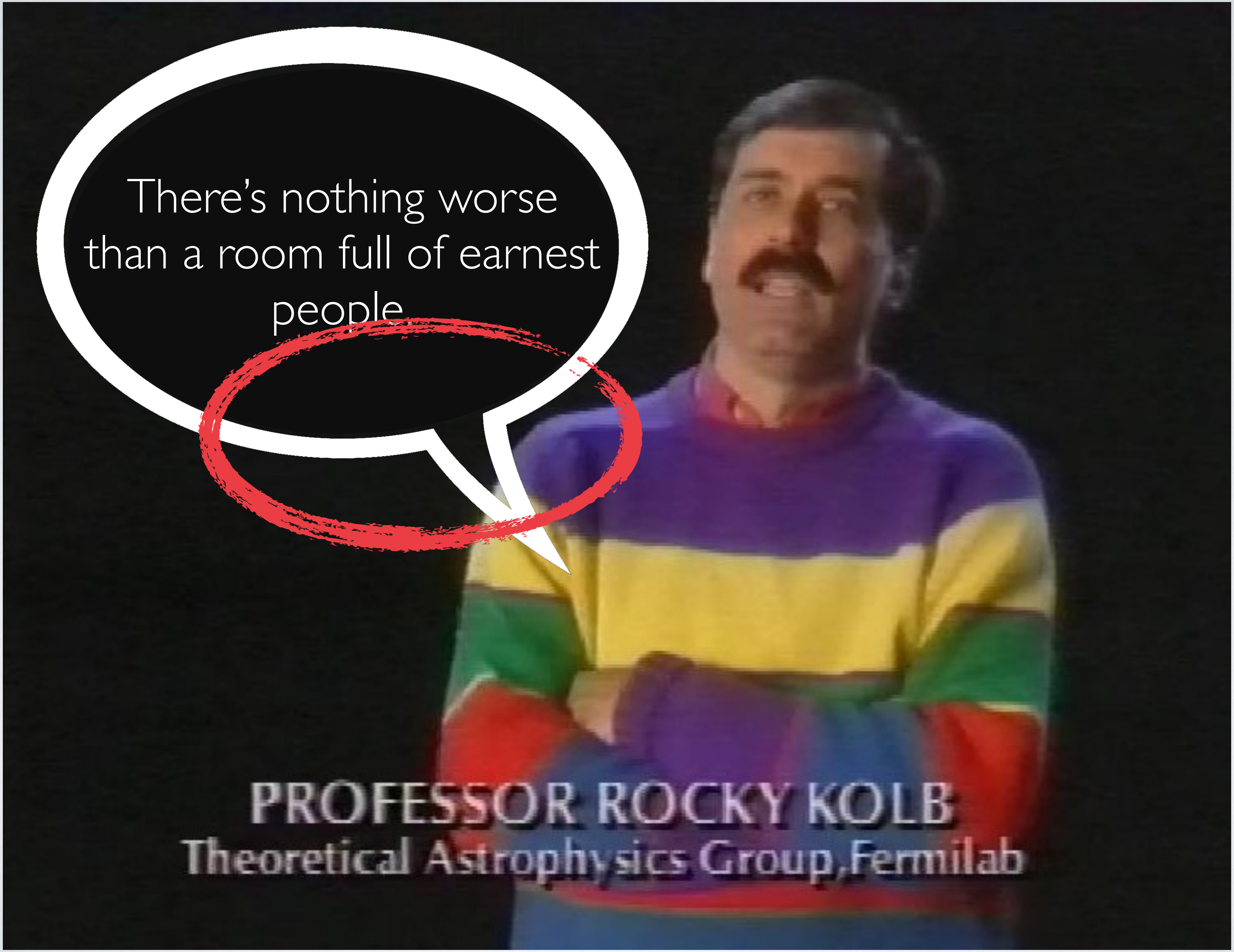
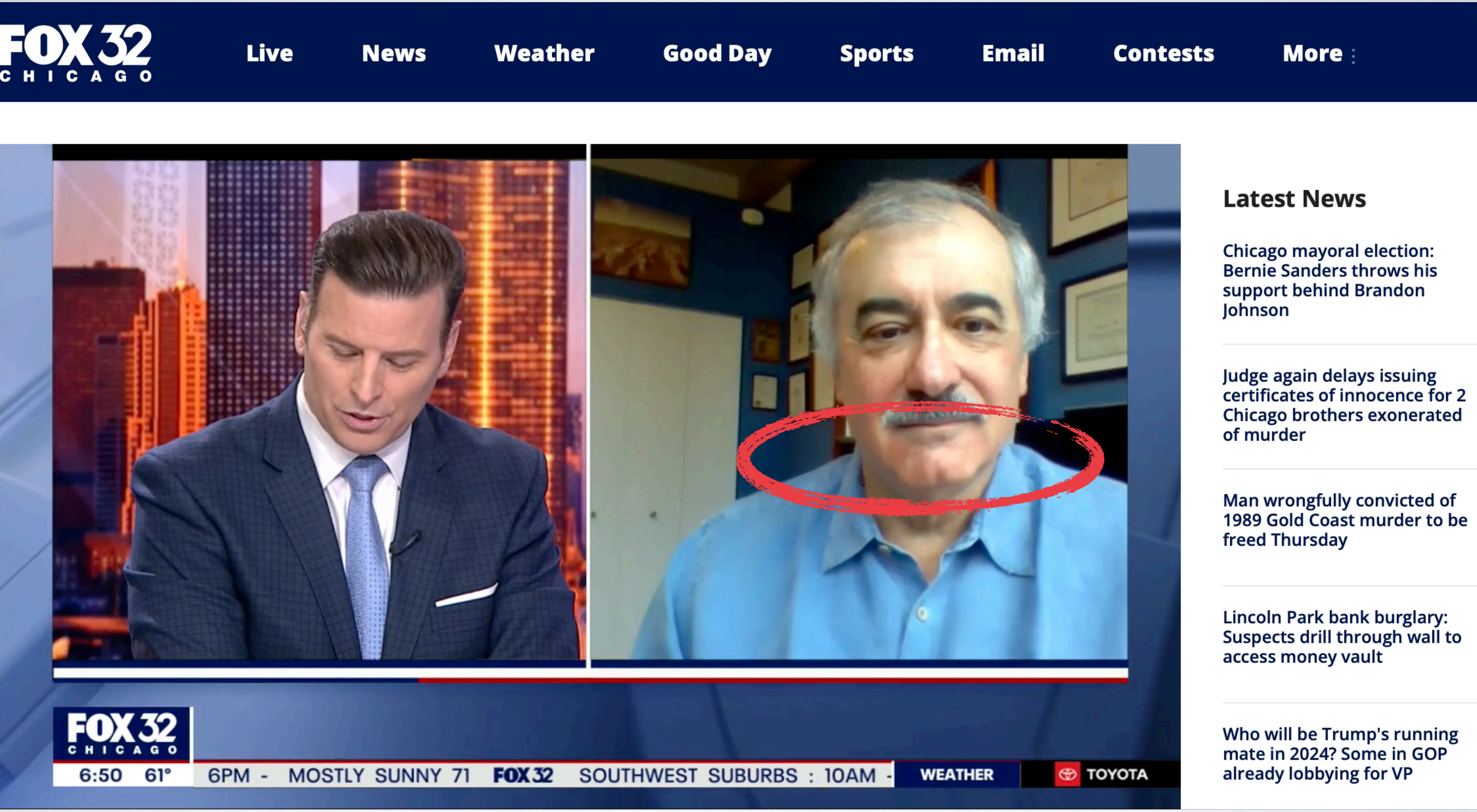
SEEING BETTER

Albert Stebbins
Fermilab

Rocky & Friends
Chicago, USA
2023-03-19


There's nothing worse than a room full of earnest people.
PROFESSOR ROCKY KOLB
Theoretical Astrophysics Group, Fermilab


FOX
&friends


FOX 32 CHICAGO
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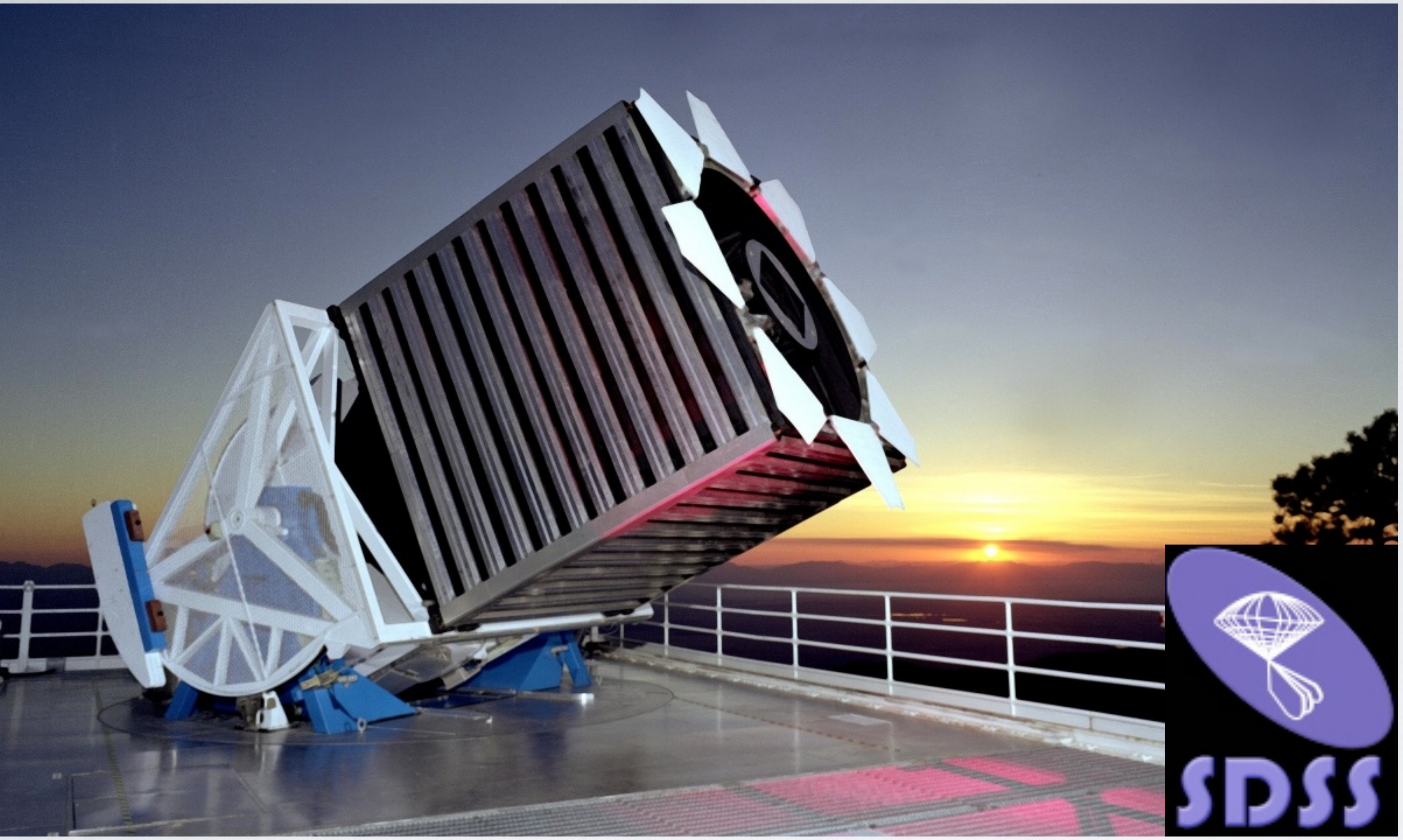
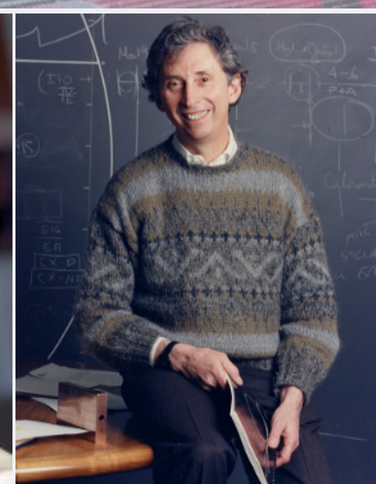
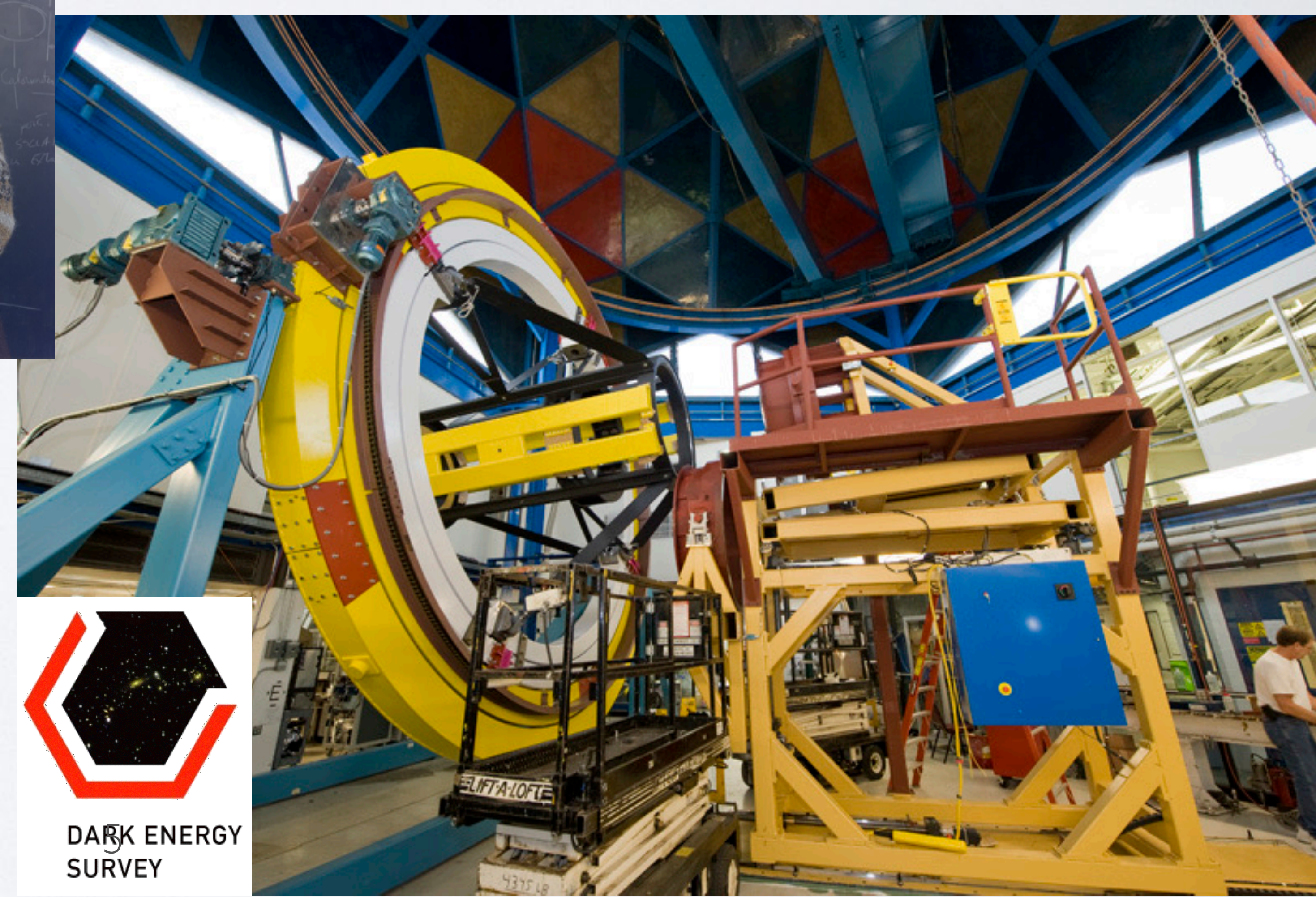
6:50 61°
6PM - MOSTLY SUNNY 71
FOX 32
SOUTHWEST SUBURBS : 10AM -
WEATHER
TOYOTA
Latest News
Chicago mayoral election: Bernie Sanders throws his support behind Brandon Johnson
Judge again delays issuing certificates of innocence for 2 Chicago brothers exonerated of murder
Man wrongfully convicted of 1989 Gold Coast murder to be freed Thursday
Lincoln Park bank burglary: Suspects drill through wall to access money vault
Who will be Trump's running mate in 2024? Some in GOP already lobbying for VP

Cosmology meets Big Data



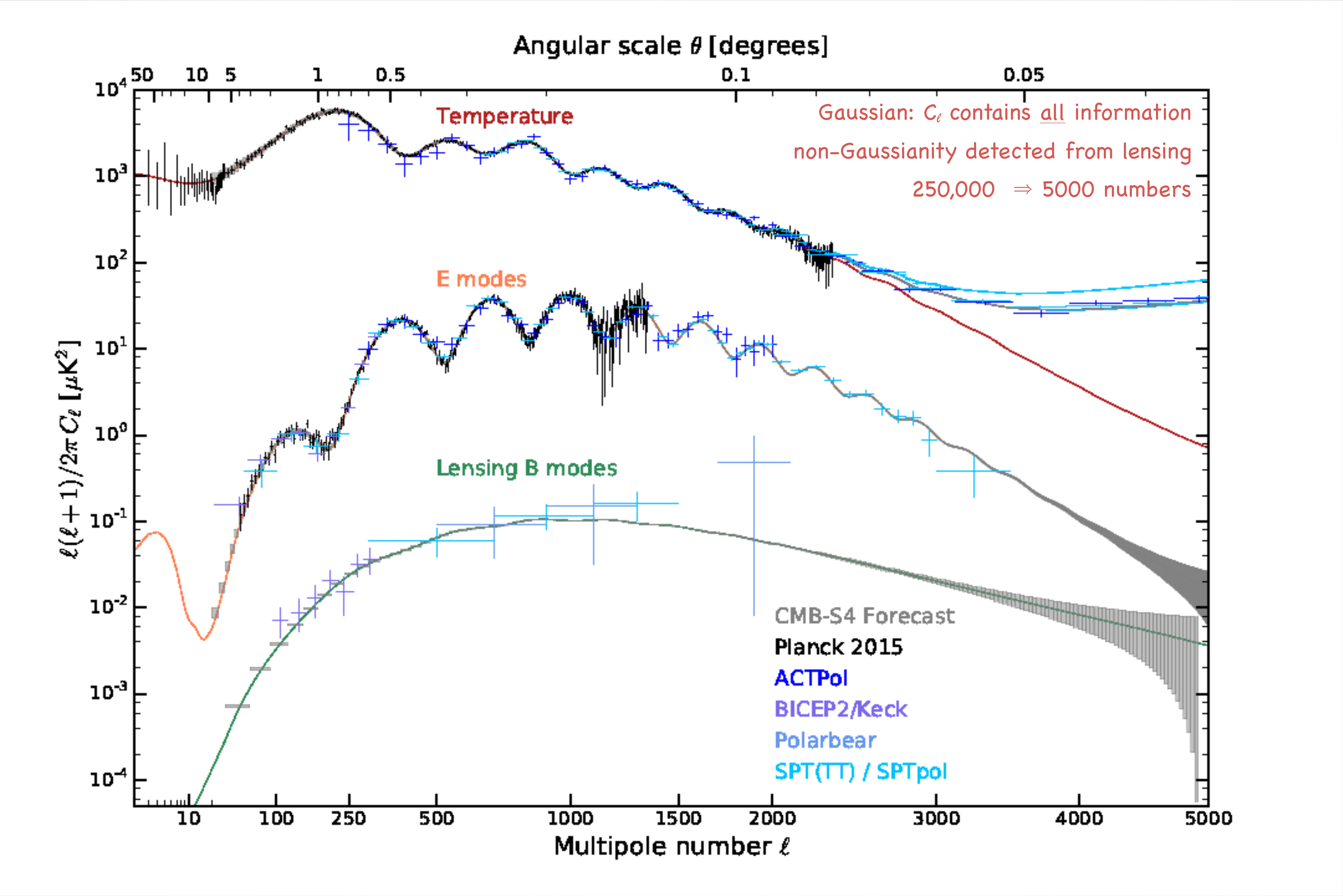
FERMILAB





DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

AMONG MOST SUCCESSFUL THEORIES OF MODERN SCIENCE

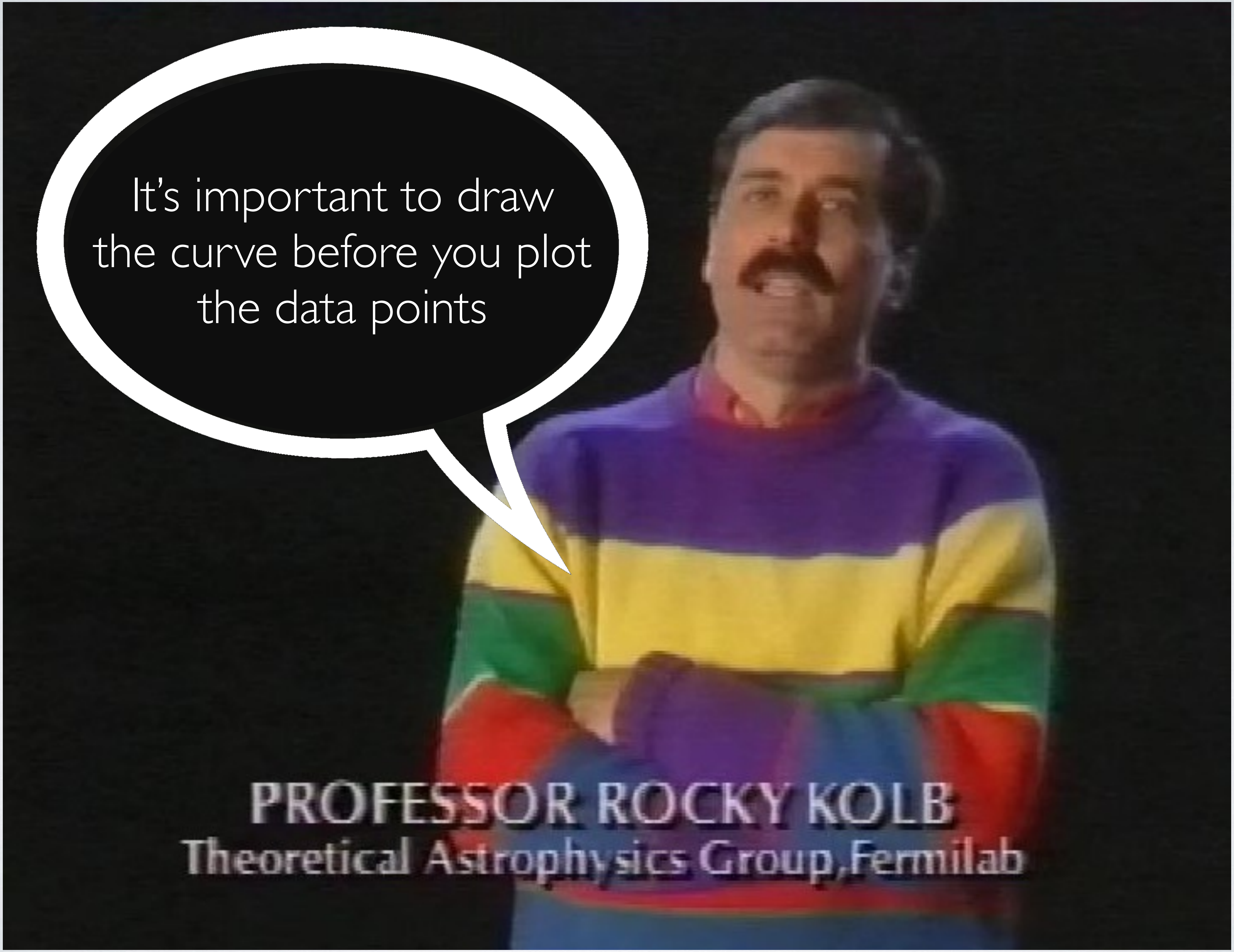


LIFE THE UNIVERSE AND EVERYTHING

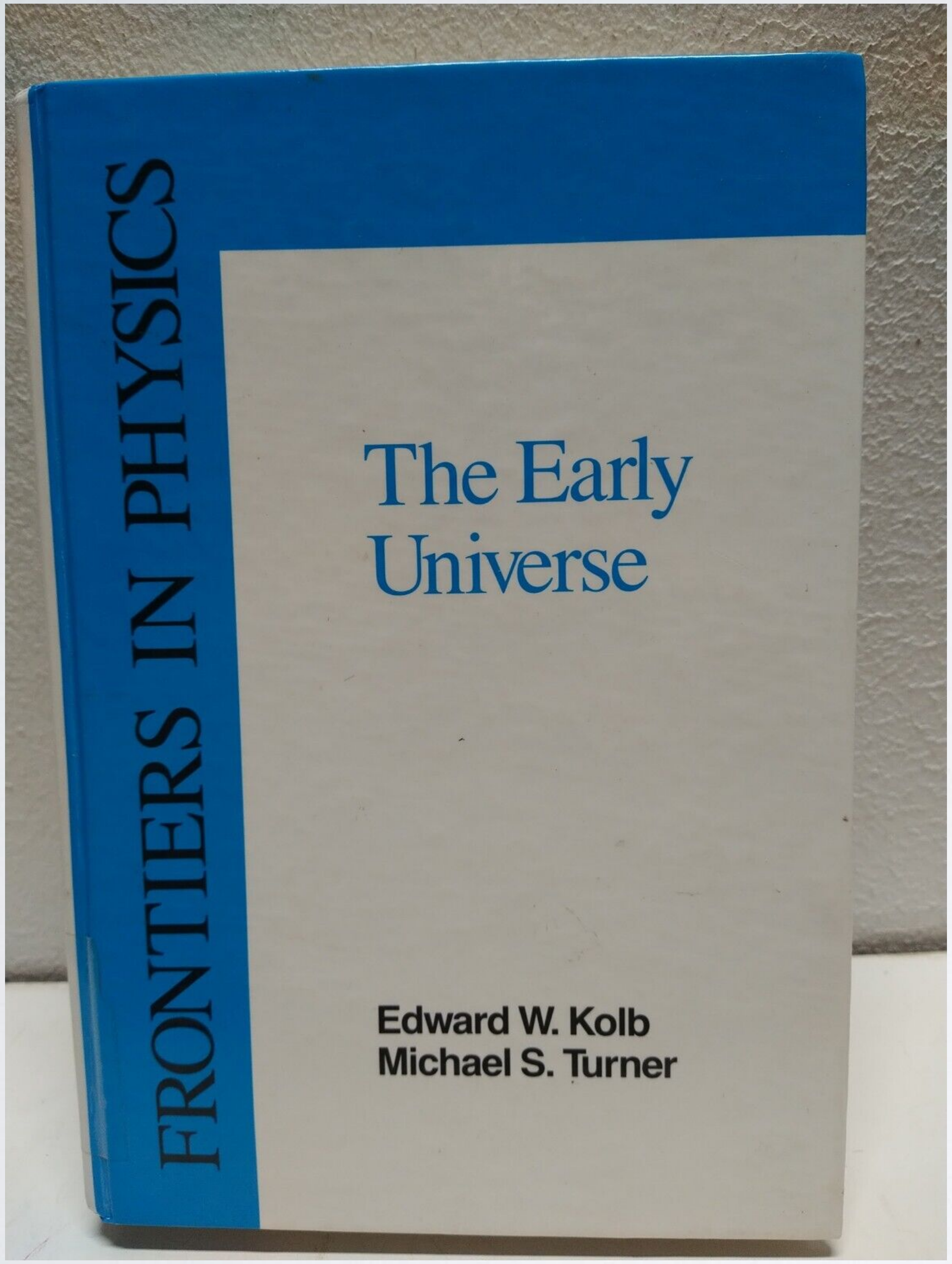
space-time geometry: homogeneous isotropic with no spatial curvature

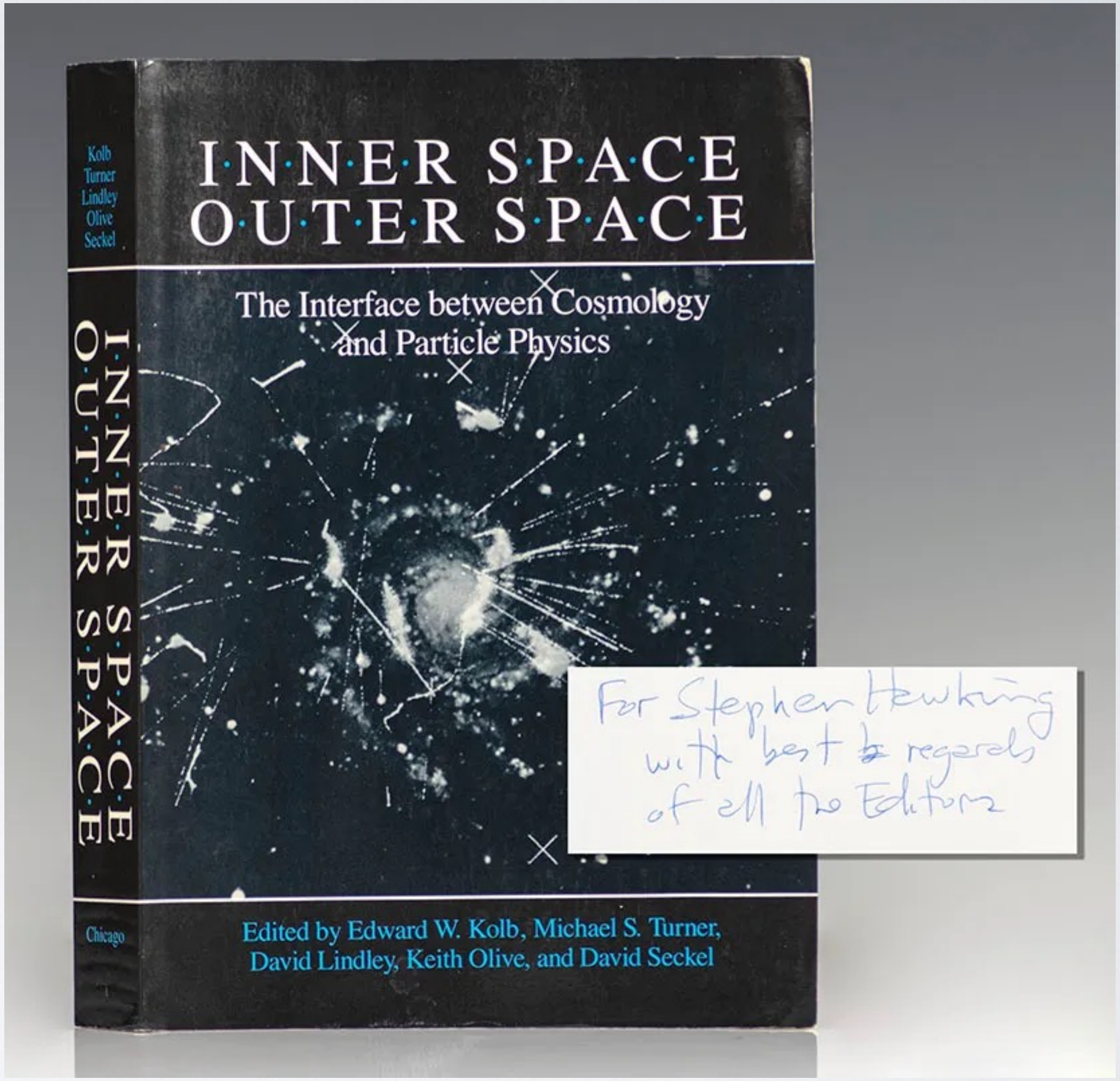
+ density inhomogeneities: adiabatic homogeneous isotropic Gaussian noise

		Parameter	[4] *Planck* TT,TE,EE+lowP
	baryons	$\Omega_b h^2$	0.02225 ± 0.00016
INVENTORY:	(cold) dark matter	$\Omega_c h^2$	0.1198 ± 0.0015
	Λ / dark energy	$100\theta_{MC}$	1.04077 ± 0.00032
	optical depth	τ	0.079 ± 0.017
ARRANGEMENT:	amplitude	$\ln(10^{10} A_s)$	3.094 ± 0.034
	slope	n_s	0.9645 ± 0.0049
NUISANCE:	expansion rate	H_0	67.27 ± 0.66
	photons	T_0	COBE/FIRAS 2.7255 ± 0.0006 K


It's important to draw the curve before you plot the data points
PROFESSOR ROCKY KOLB
Theoretical Astrophysics Group, Fermilab

LESS SUCCESSFUL THEORETICAL PROGRAM





Unwieldy Tomes

Encyclopédie (dictionnaire raisonné des sciences des arts et des métiers)

1751-1772 Diderot & d'Alembert (enlightenment / post-Jesuit thought)

post-classical theoretical cosmology

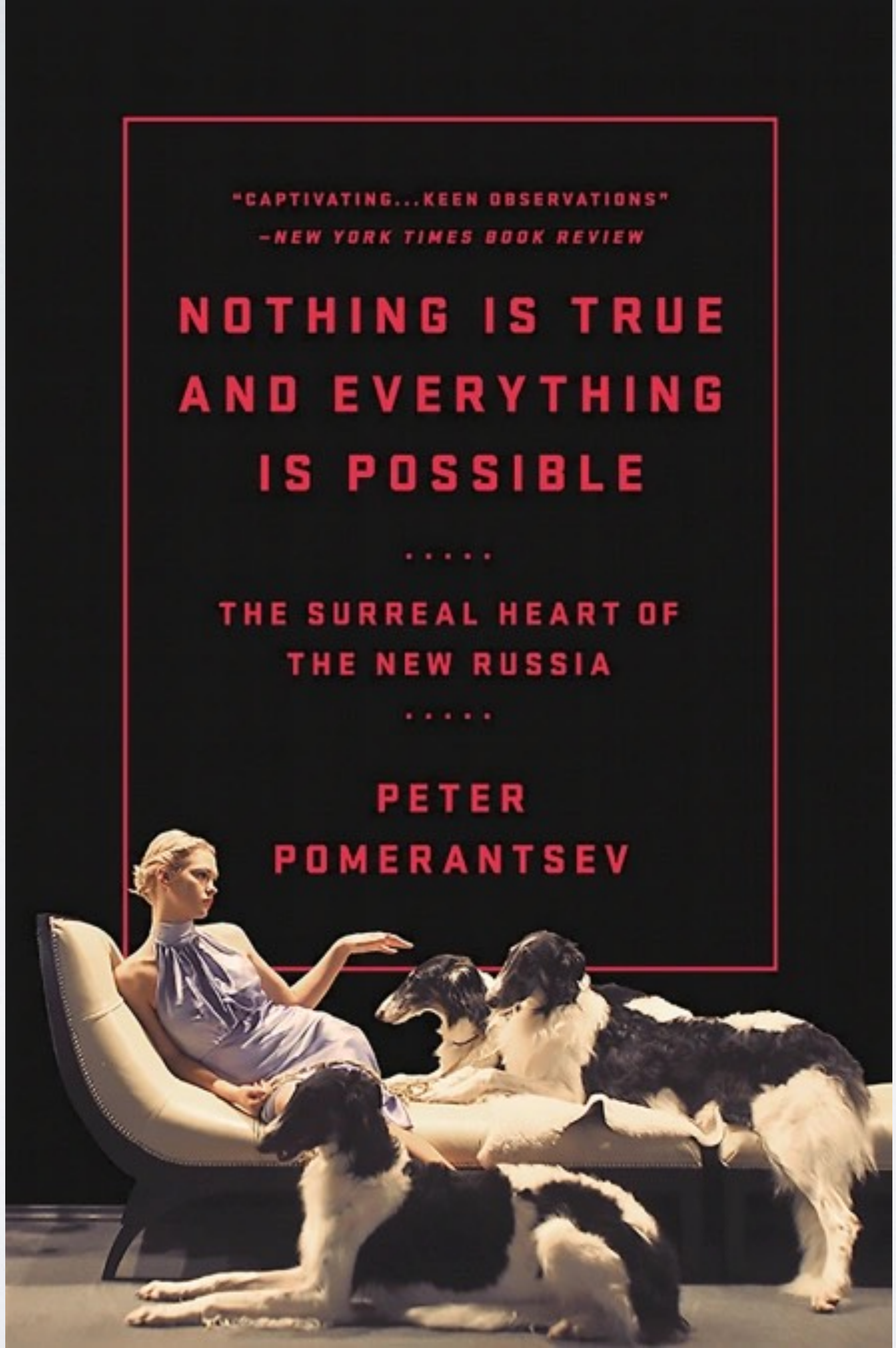
Encyclopædia inflationaris *2014 Martin Ringeval & Vennin*

Encyclopædia curvatonis *2015 Vennin, Kazuya &Wands*

Encyclopædia obscura materia *TBA*

Encyclopædia tenebris navitas *TBA*

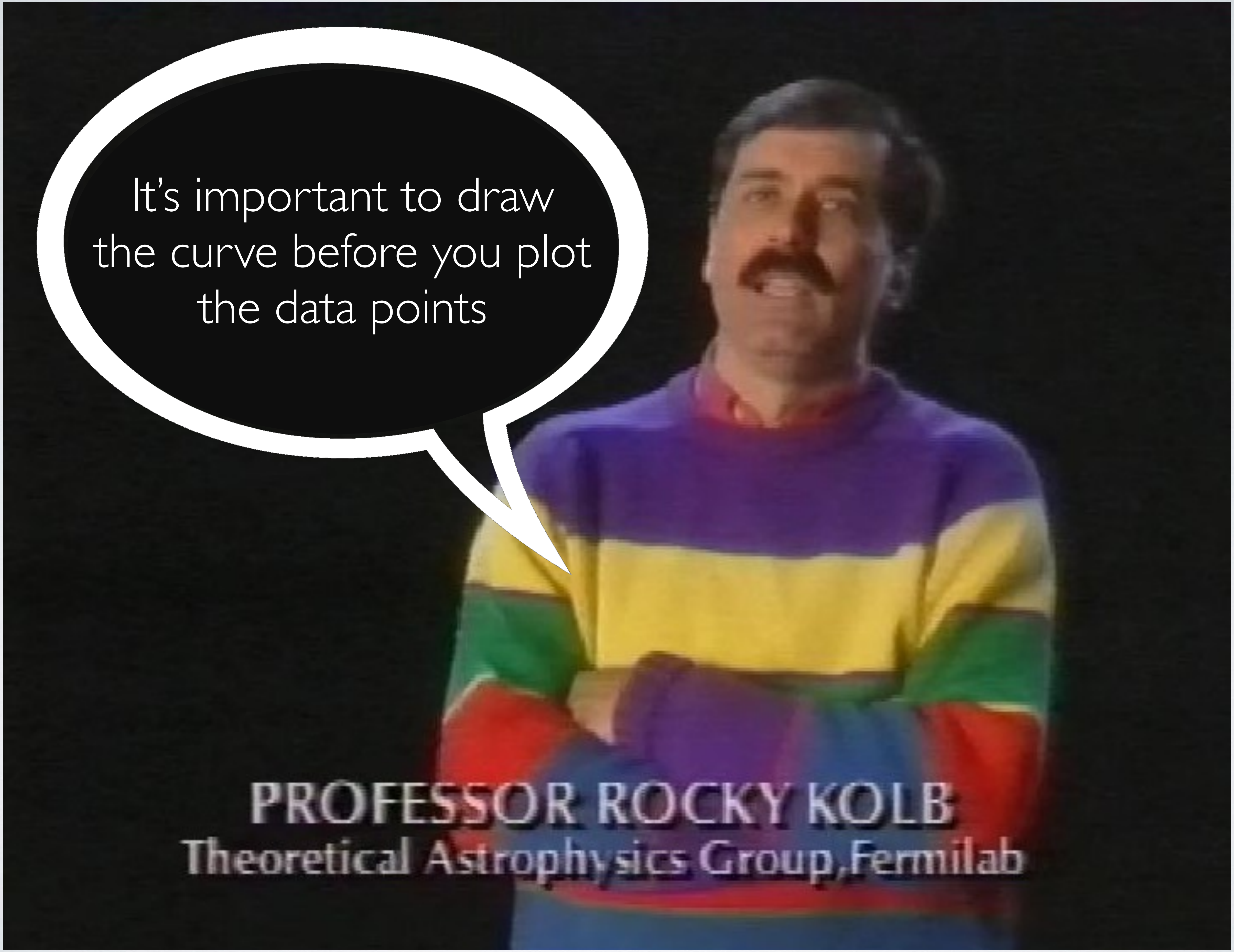
BSM


"CAPTIVATING...KEEN OBSERVATIONS"
—NEW YORK TIMES BOOK REVIEW
NOTHING IS TRUE AND EVERYTHING IS POSSIBLE
THE SURREAL HEART OF THE NEW RUSSIA
PETER POMERANTSEV

A BRIEF WORD FROM MY SPONSOR

FERMILAB THEORY SUMMER VISITORS' PROGRAM

- Postdoc/Faculty level active researcher
- 2-3 week stays (not short / few day visit)
- May-September 2023
- Local expenses covered (not travel)
- Nominal Deadline **31 March 2023**
- Consider Applying Today!
- **https://theory.fnal.gov/visiting-us/summer-visitors-program/**
- Program expected to continue annually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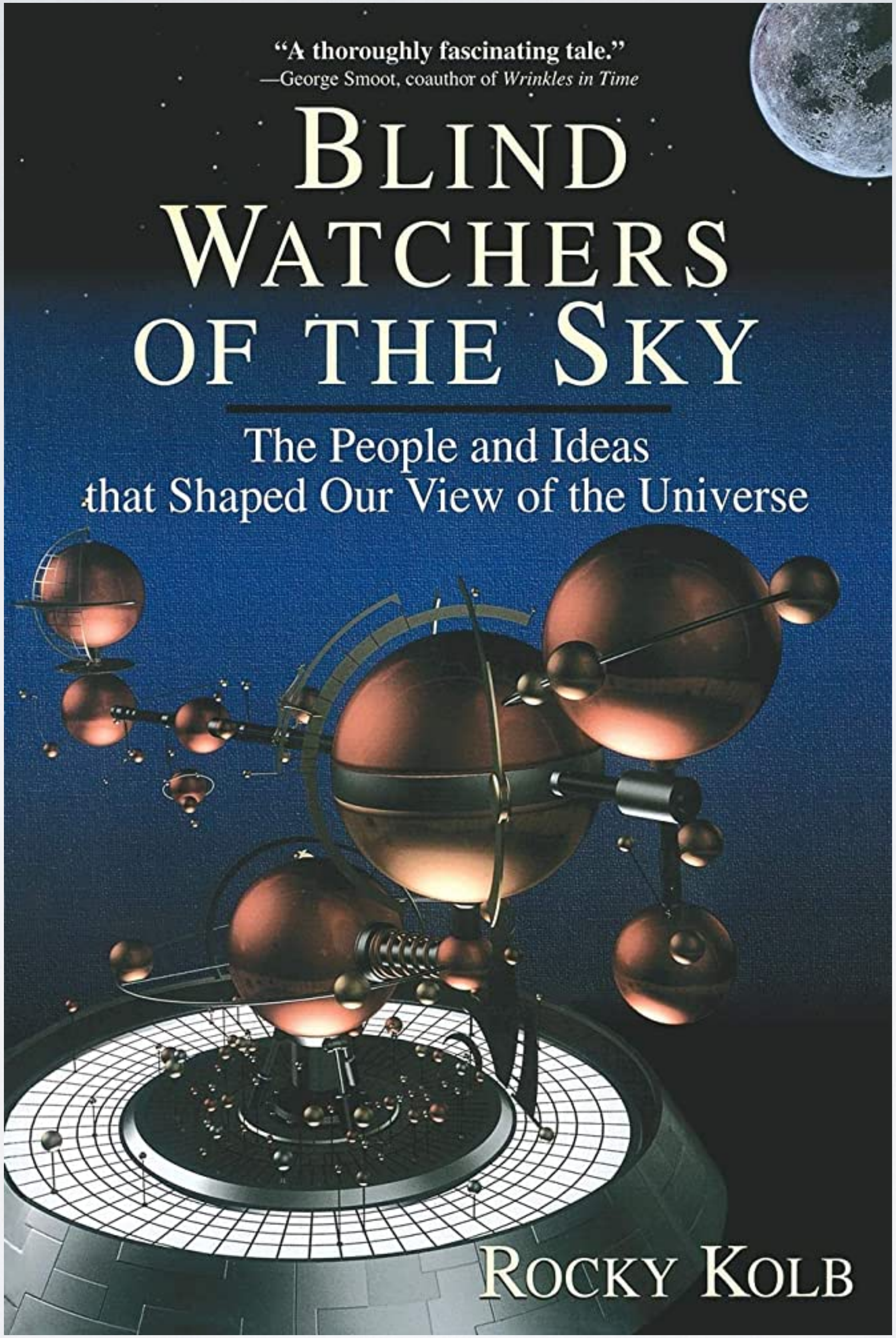
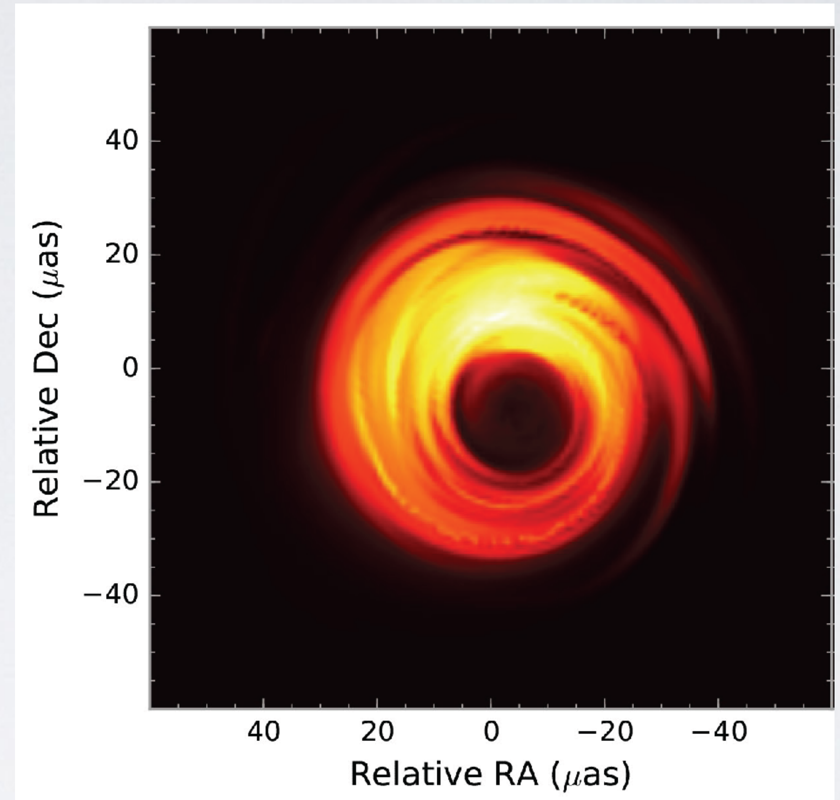

"A thoroughly fascinating tale."
—George Smoot, coauthor of Wrinkles in Time
BLIND WATCHERS OF THE SKY
The People and Ideas that Shaped Our View of the Universe
ROCKY KOLB

BUILD ASTRONOMICAL INFRASTRUCTURE

- Measure what you can measure much better than you could before.
  - if no strong arguments there is nothing there
- good chance you'll find something new.
- Prioritization?

ANGULAR RESOLUTION FRONTIER



- VLBI (radio)
  - probes ~1 milli-arcseconds
- single site Optical/InfraRed Interferometers
  - probes ~0.1-10 milli-arcseconds
- VLBI (mm) Event Horizon Telescope
  - probes ~10 micro-arcseconds

diffraction limit:

$\delta\vartheta \sim \lambda/b$

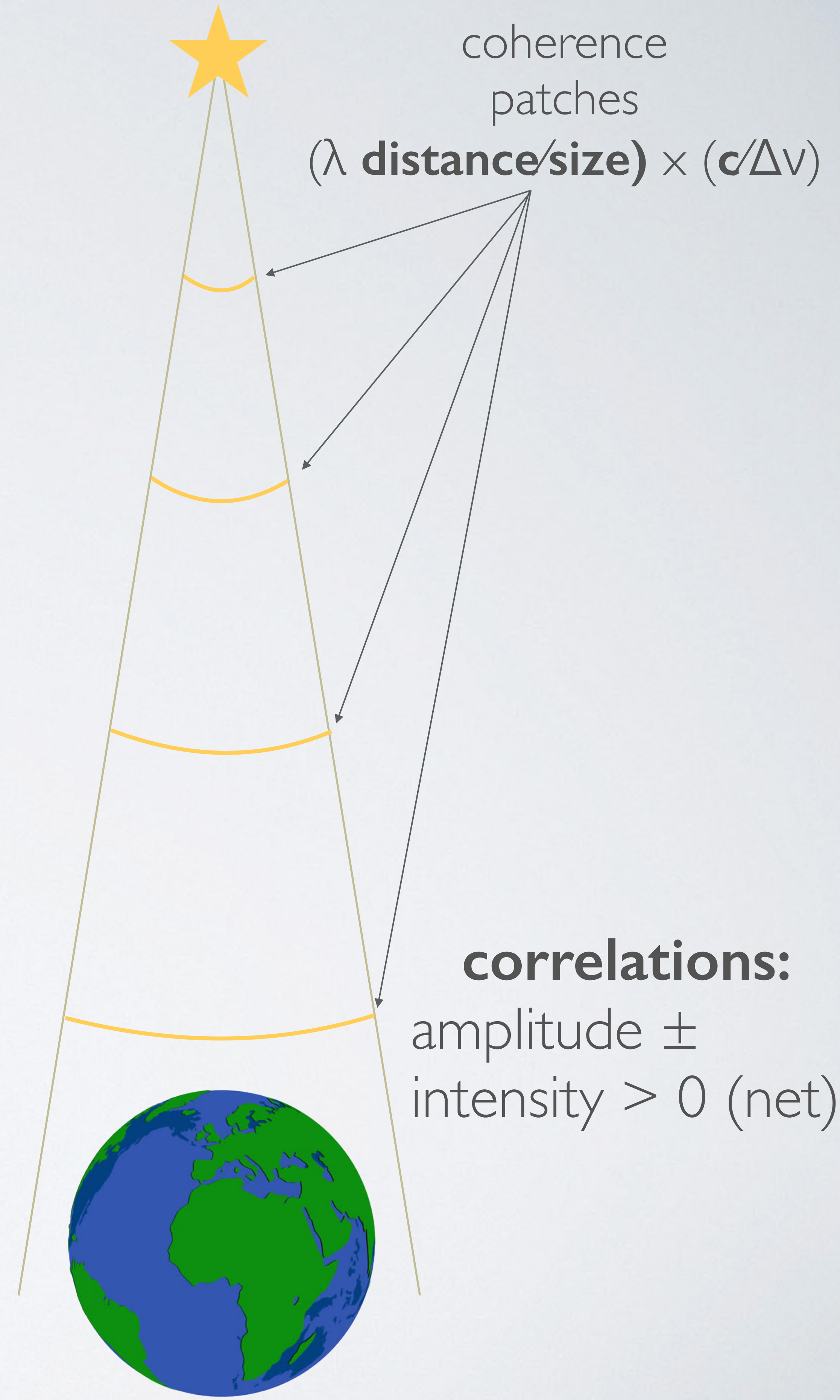
GROUND BASED IMAGING LIMITED BY EARTH SIZE :

BASELINE $\lesssim$10000KM

IN OPTICAL:

WAVELENGTH ~ 1 MICRON

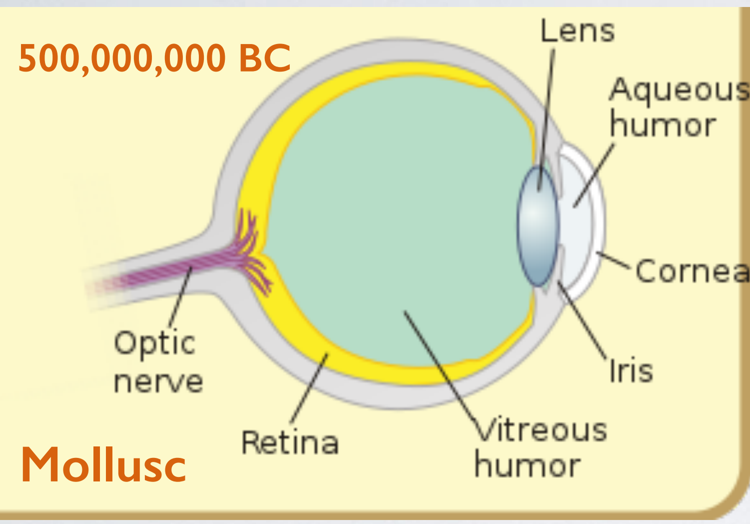
ANGULAR SCALE $\gtrsim$ 10^{-9} ARCSEC

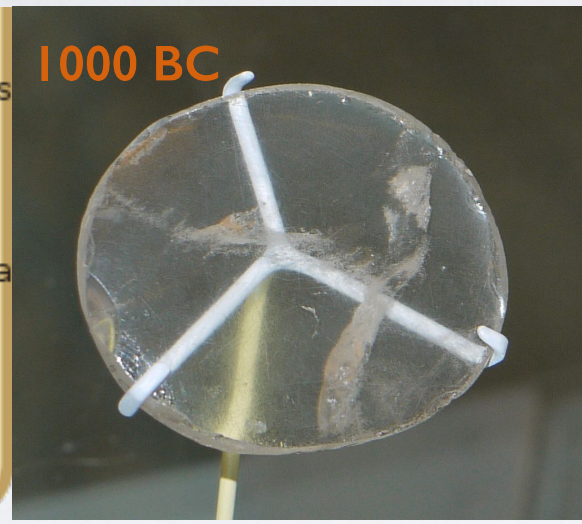


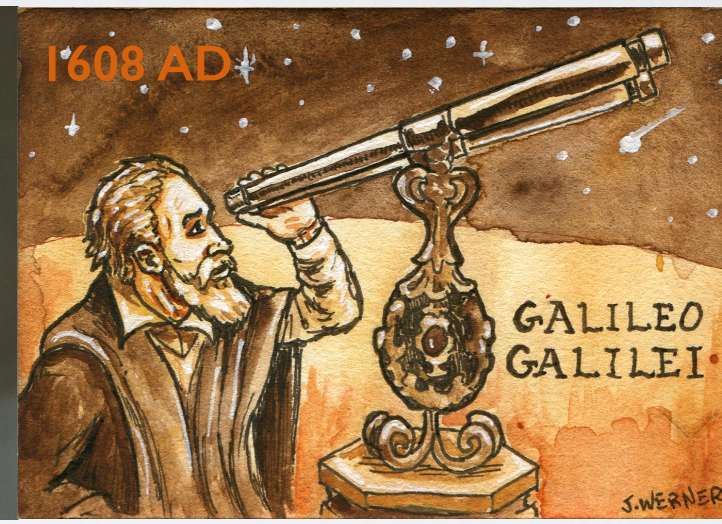
IMAGING

ANALOG

- **optically combine** waves from different transverse positions
  - on spatial scale better than one wavelength

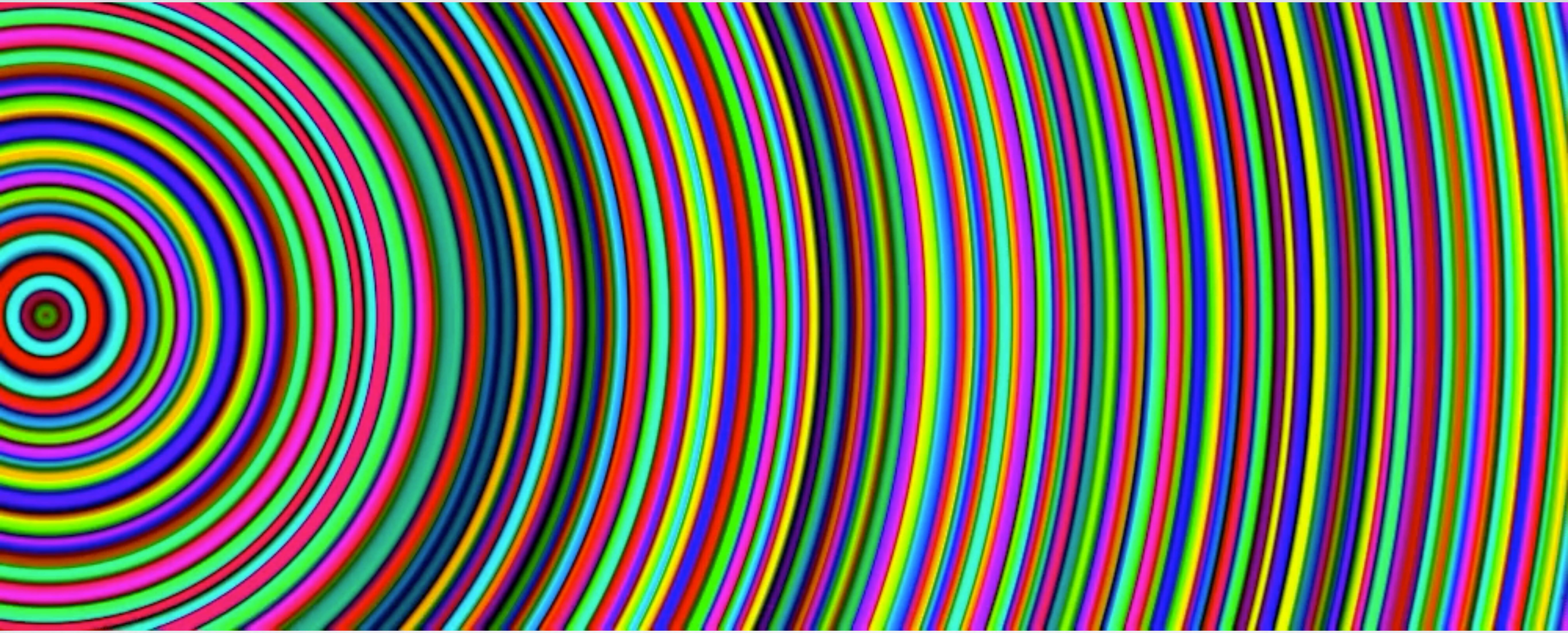






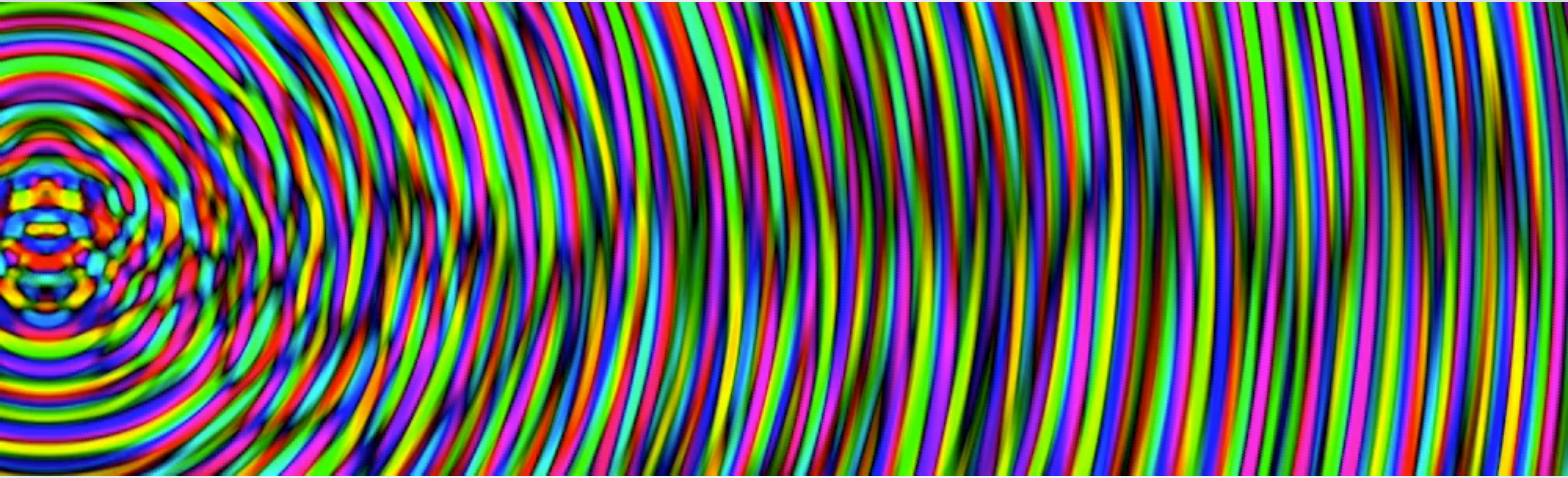
DIGITAL

IMAGING: TRANSVERSE CORRELATIONS



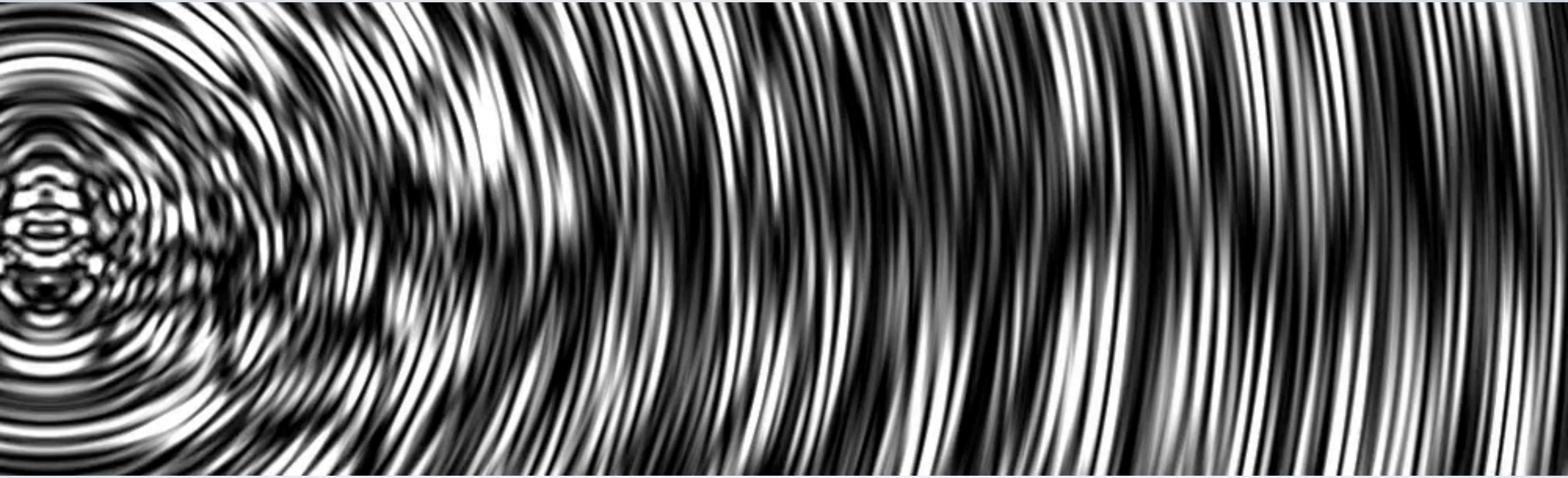
- "point" source "incoherent" source emitting wave
  - color gives polarization position angle, intensity gives amplitude
- line-of-sight correlation length ~λ for broadband emission
- **but** for point source transverse correlations infinite

IMAGING: TRANSVERSE CORRELATIONS



- "extended" "incoherent" source emitting wave
  - color gives polarization position angle, intensity gives amplitude
- line-of-sight correlation length ~λ for broadband emission
- **but** transverse correlations $b_{\perp} \sim \lambda / \vartheta \propto$ distance
- "image" encoded in transverse correlations

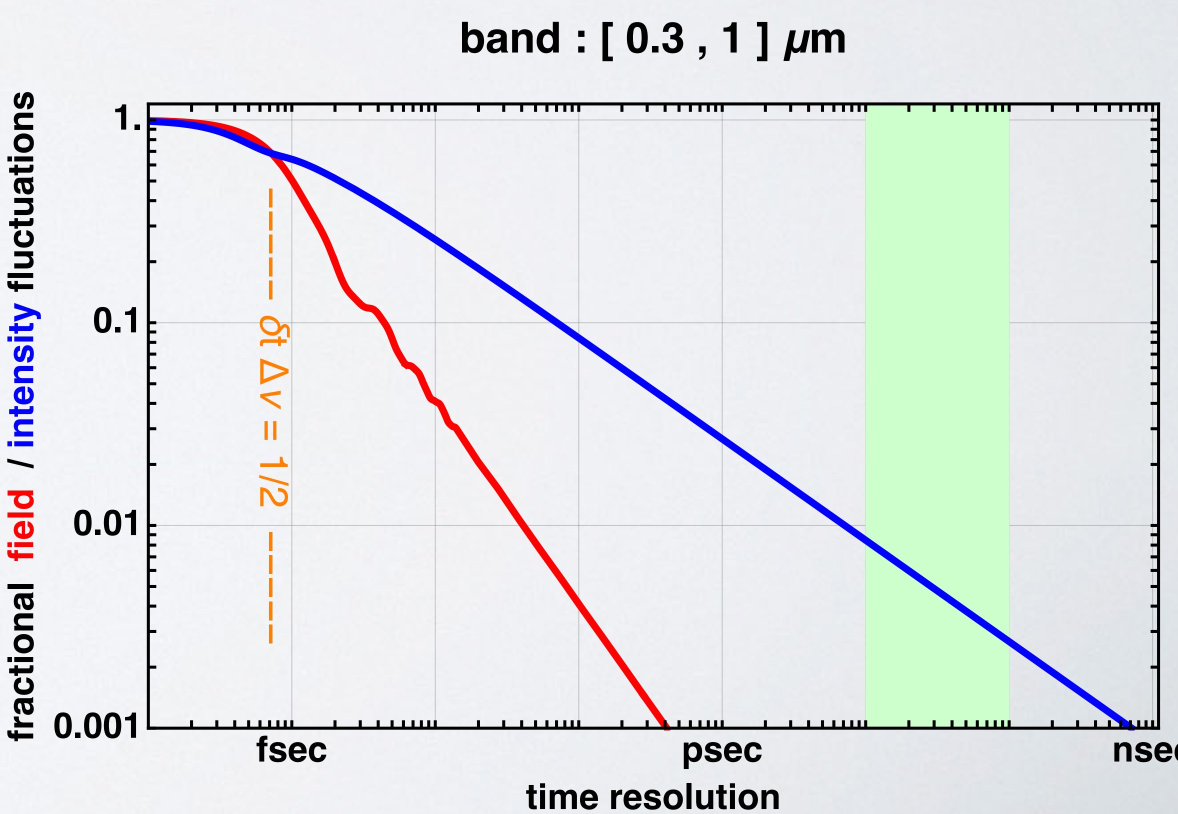
TEMPORAL INTENSITY CORRELATIONS✷



- field correlation power spectrum: $\mathbf{f}_\nu$ (flux density e.g. Janskies)
- intensity correlation power spectra (unpolarized)

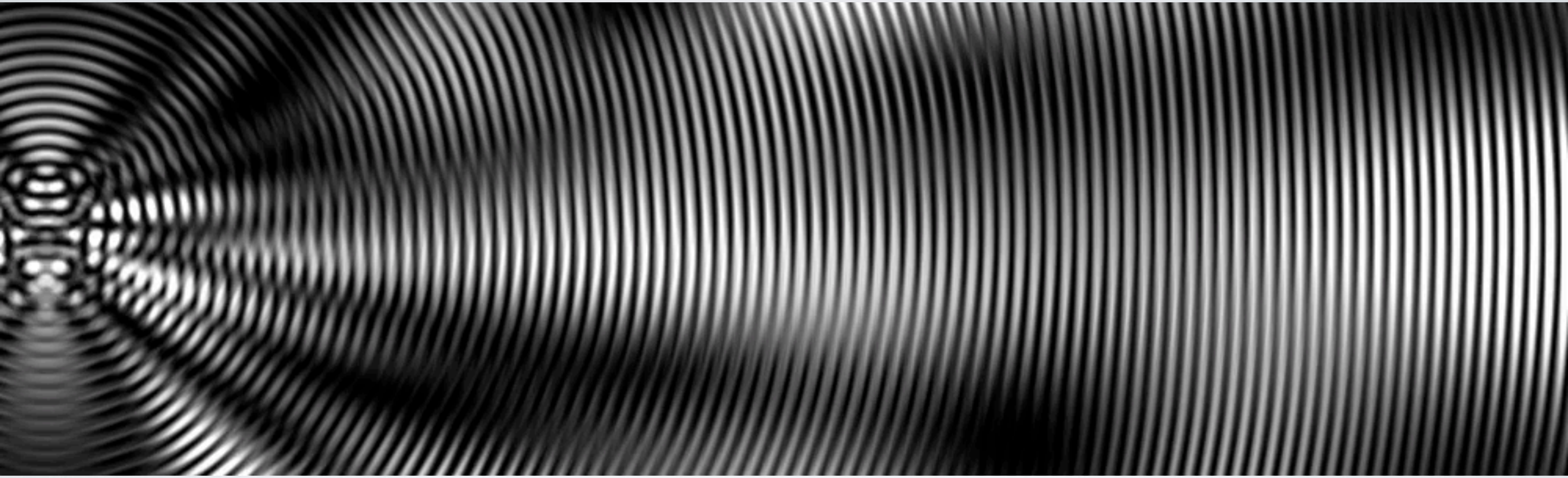
  $(\delta \mathbf{I}^2)_\nu = \frac{1}{4}\int d\nu' \, \mathbf{f}_{\nu'} \, \mathbf{f}_{\nu-\nu'}$

- intensity has more long duration correlations
- polarized emission increases $(\delta \mathbf{I}^2)_\nu$

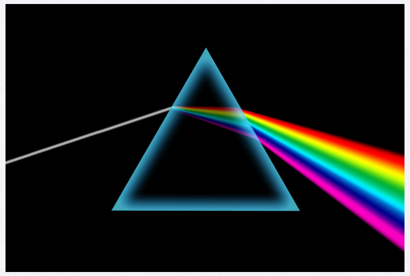


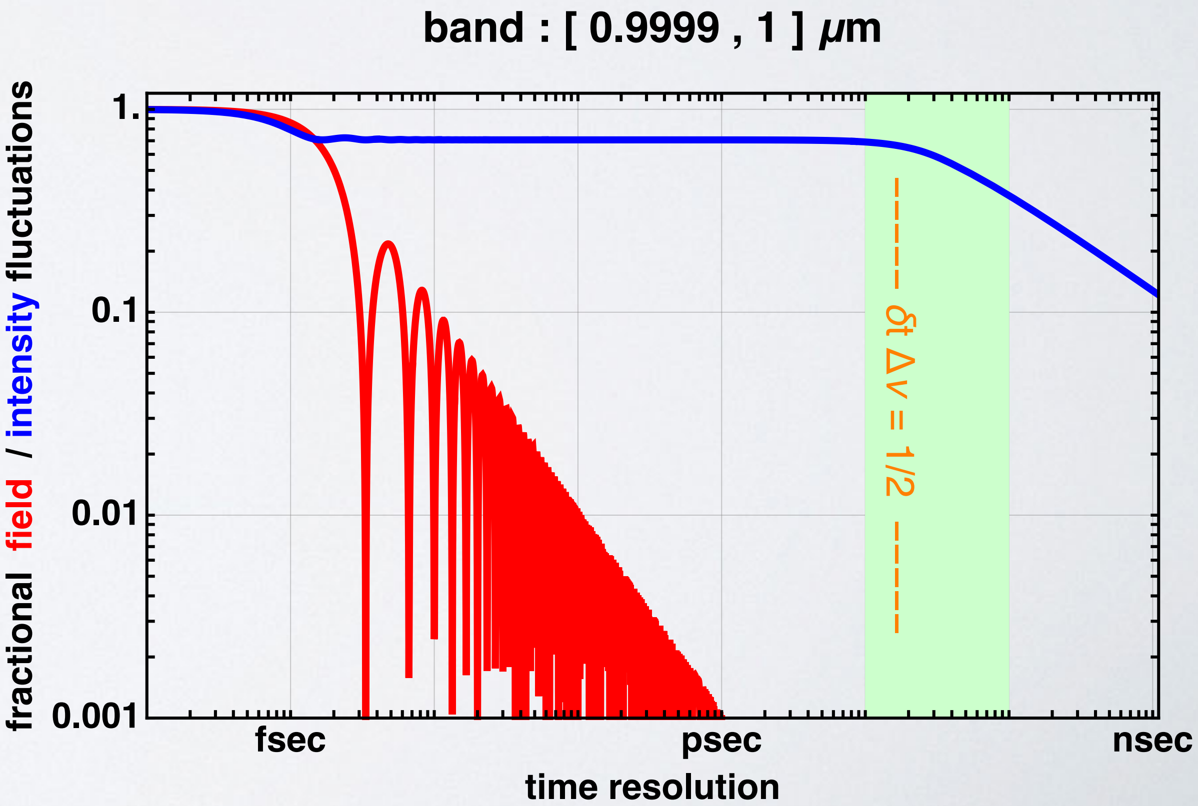
✷"Hanbury-Brown Twiss effect"

INCREASE TEMPORAL CORRELATION BY DECREASING BANDWIDTH



- convolution: $(\delta \mathbf{I}^2)_\nu = \frac{1}{4}\int d\nu' \, f_{\nu'} \, f_{\nu-\nu'}$
- intensity "mixes" radiation field with itself
  - "mixes down" to $\mathbf{1/\delta t \sim \Delta \nu}$
  - "mixes up" to $\mathbf{1/\delta t \sim 2\nu}$





- $\mathbf{R \sim \nu/\Delta\nu \gtrsim 10^4}$ ⇒ "quantum limit" $\delta\mathbf{t}\,\Delta\nu \lesssim \frac{1}{2}$

SIMULTANEOUS COUNT RATE

$$r_{12} = \delta t\, r_1\, r_2 \left(1 + 2\frac{\Phi}{m}\right)$$ "Gaussian" Radiation

- **r_{12}** rate of "simultaneous" counts
- **r_i** count rate
- **m** number of independent modes

$$m \cong 2\,\delta t\,\delta\nu$$ polarized counters

$$m \cong 4\,\delta t\,\delta\nu$$ unpolarized counters

$$\delta t\,\delta\nu \leq \frac{1}{2}$$ Schwarz Inequality

$$\Phi[\vec{\ell},\nu] \equiv |\phi[\vec{\ell},\nu]|^2$$ coherence function = intensity power spectrum

$$\phi[\vec{\ell},\nu] \equiv \tilde{I}_\nu[\vec{\ell}]]/f_\nu$$ correlation coefficient

$$\frac{r_{12}}{r_{12}^{\text{poisson}}} \leq 3$$

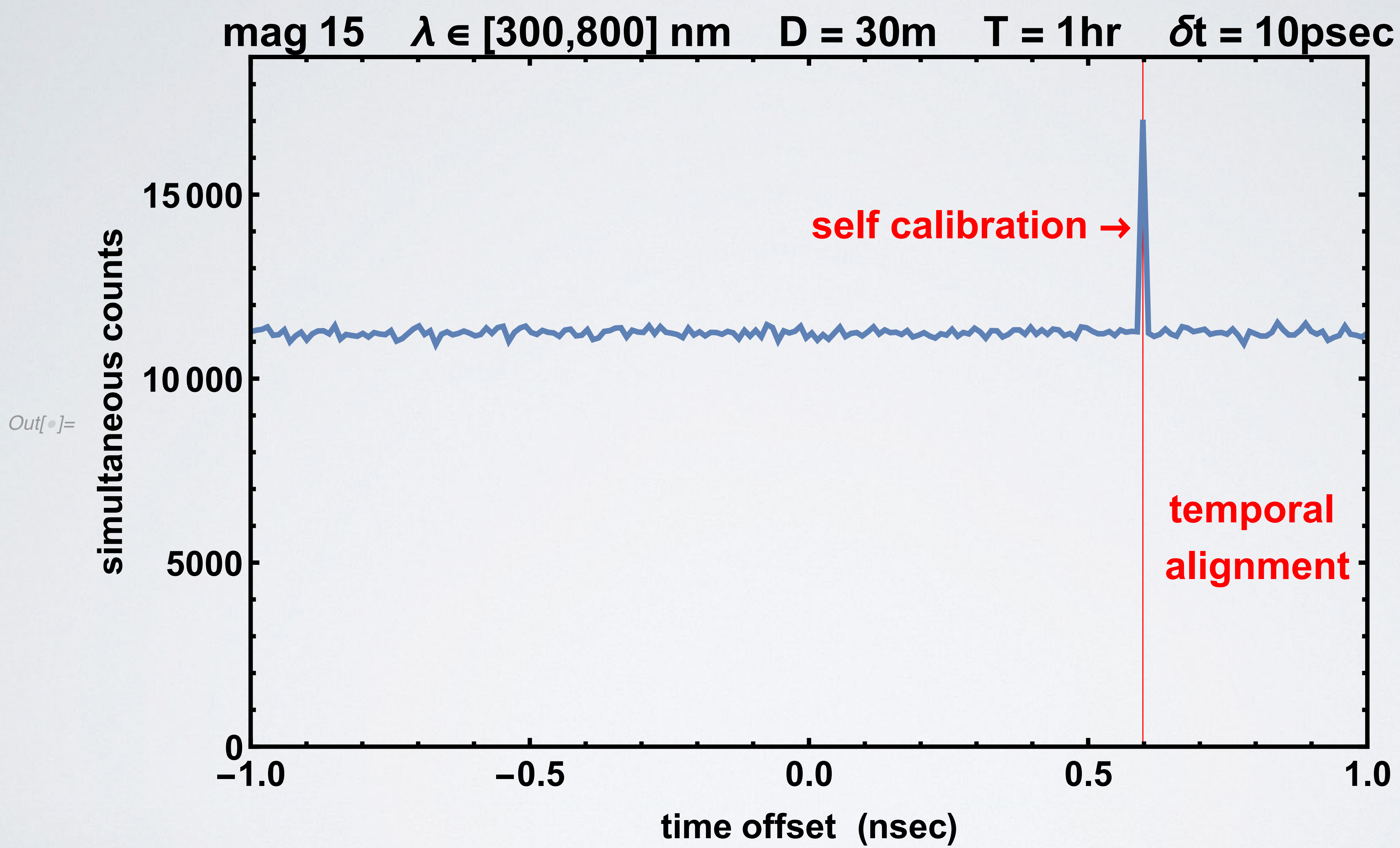
$$f_\nu = \tilde{I}_\nu[\vec{0}]$$ flux density (i.e. in Janskies)

$$\tilde{I}_\nu[\vec{\ell}] = \int d^2\hat{\mathbf{n}}\, e^{-i\,\vec{\ell}\cdot\hat{\mathbf{n}}}\, I_\nu[\hat{\mathbf{n}}]$$ Fourier transform of intensity pattern

$$\vec{\ell} = 2\pi\,\frac{\nu}{c}\mathbf{b}_\perp$$ angular wavenumber

$$\mathbf{b} \equiv \mathbf{x}_1 - \mathbf{x}_2$$ telescope baseline

MEASURE COHERENCE FUNCTION

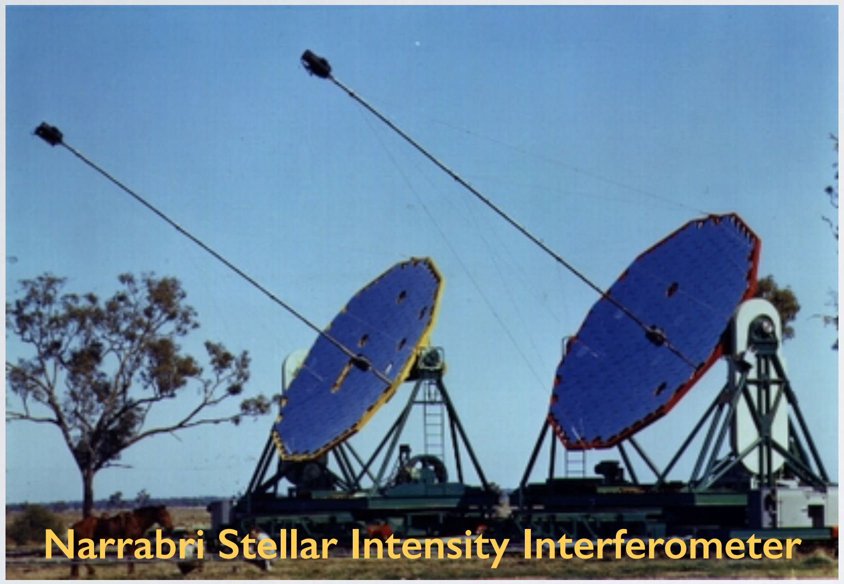


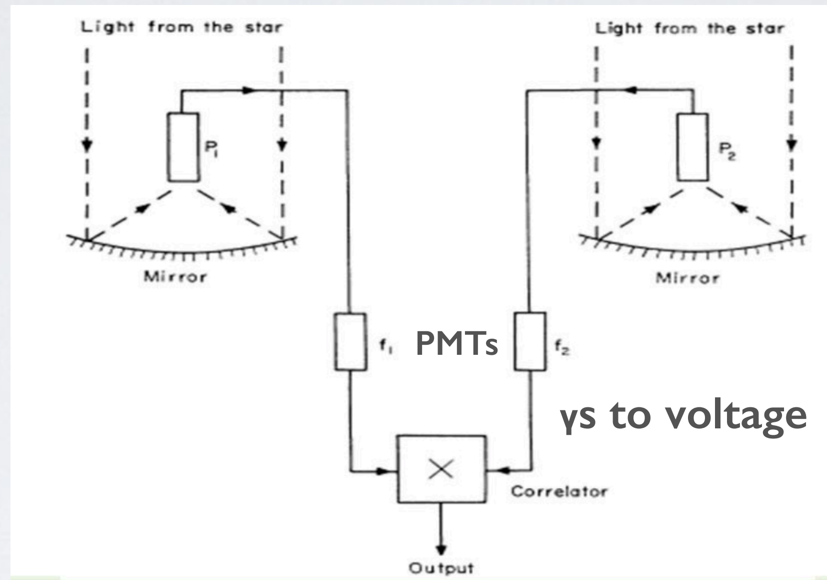
$$\Phi = \frac{m}{2} \frac{r_{12}}{\delta t \, r_1 \, r_2} - 1$$

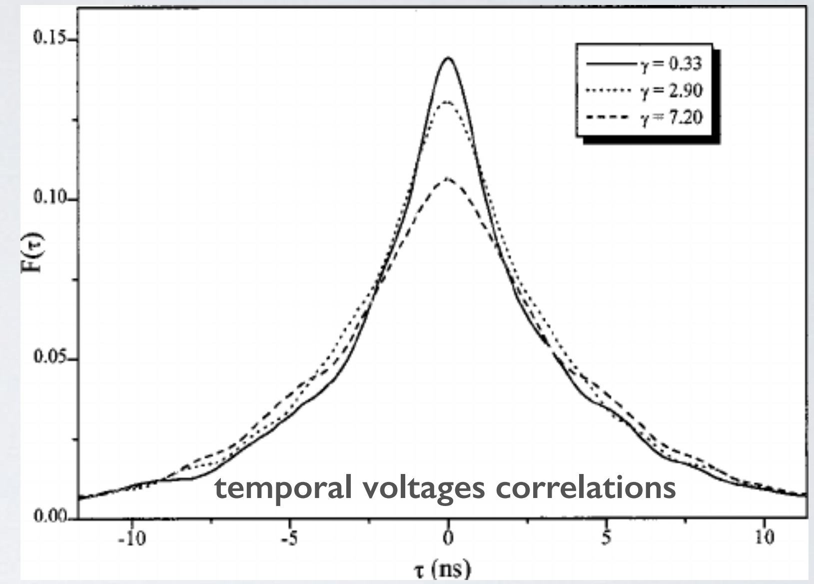
Use bright unresolved stars (Φ=1) as check and measure contribution from background light

HOW TO MEASURE INTENSITY CORRELATIONS

- ANALOG

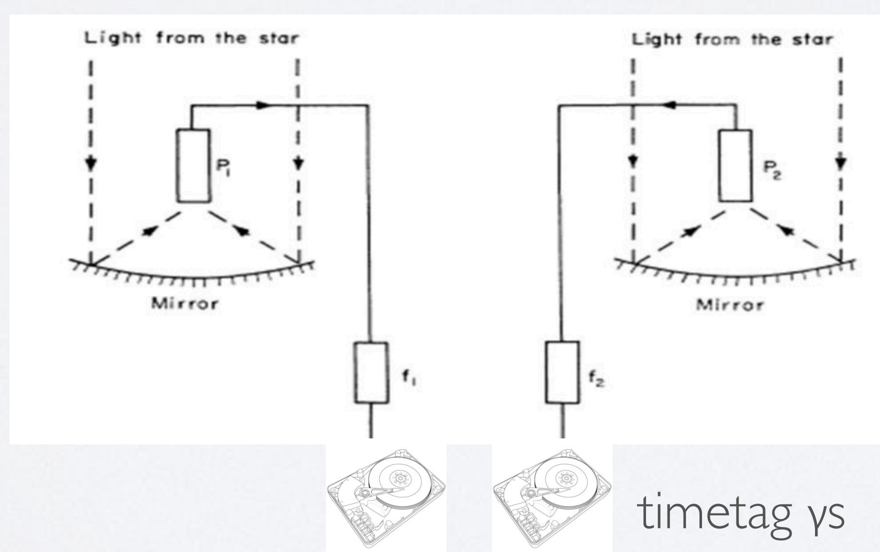






Analog method uses cables - not feasible for VLBII!

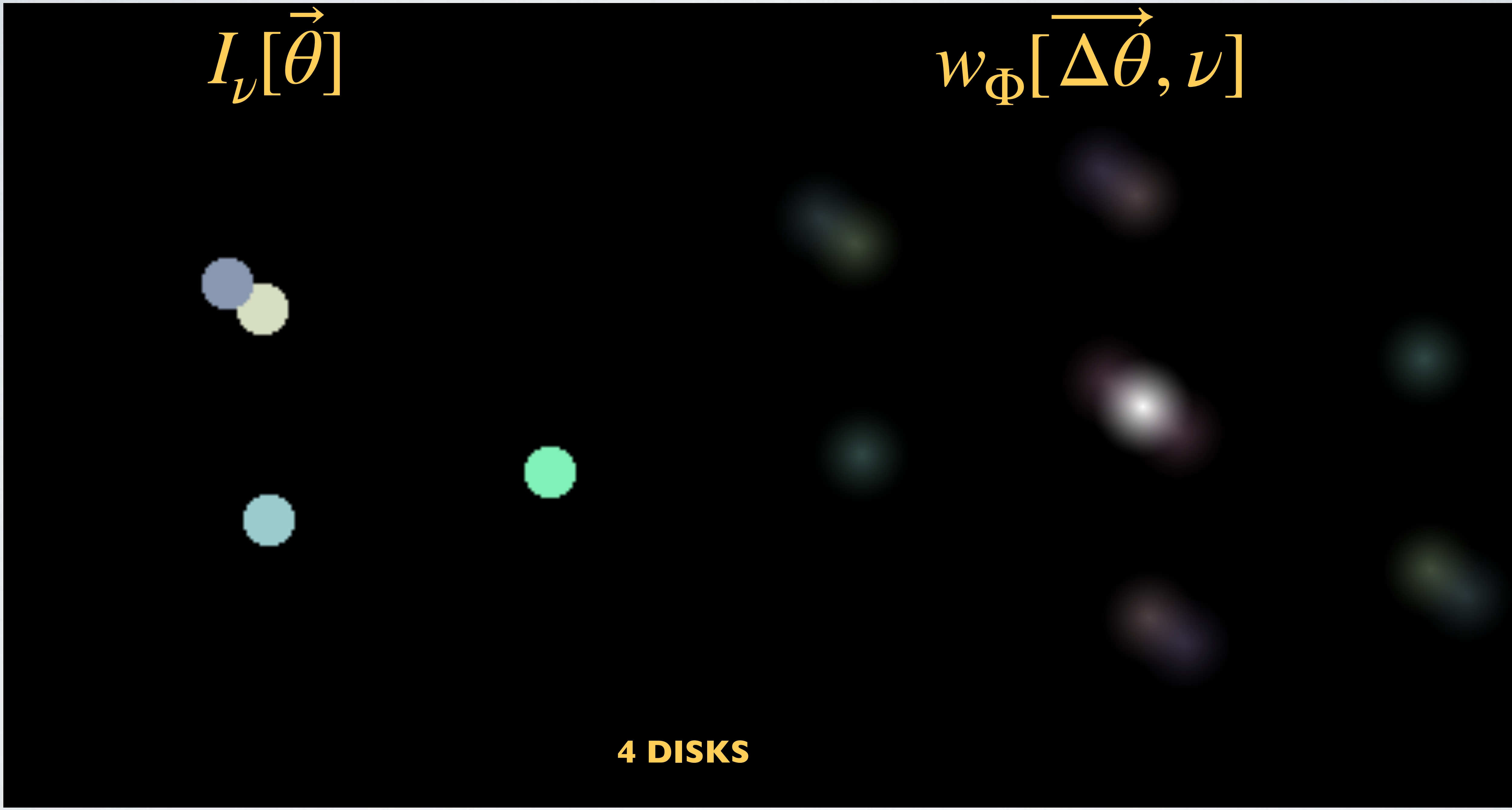
- DIGITAL



Digital method requires precise timing!
but
more practical for very long baselines

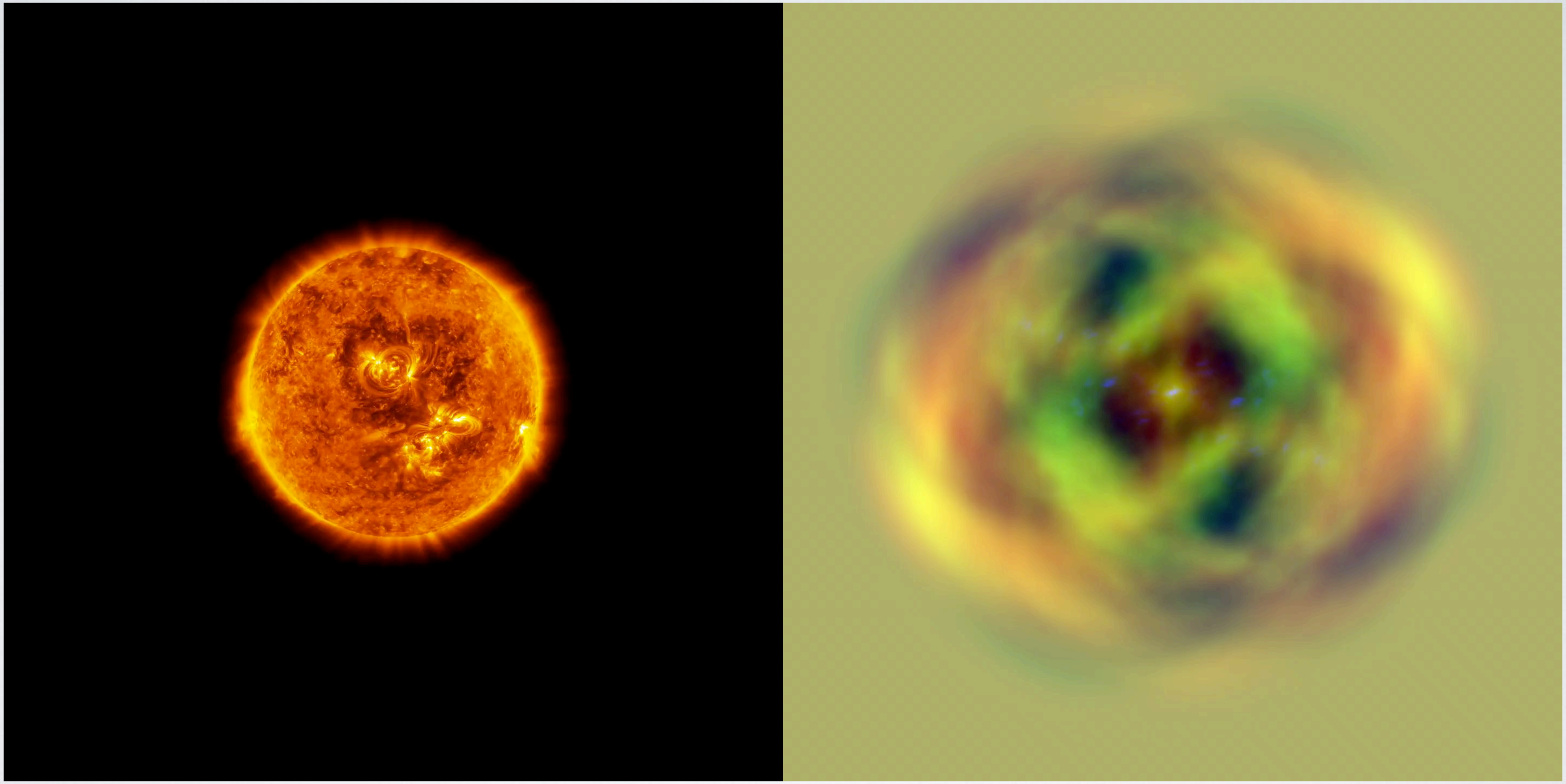
$\{ r_1, r_2, r_{12} \}$

COHERENCE CORRELATION FUNCTION



TIME DOMAIN COHERENCE

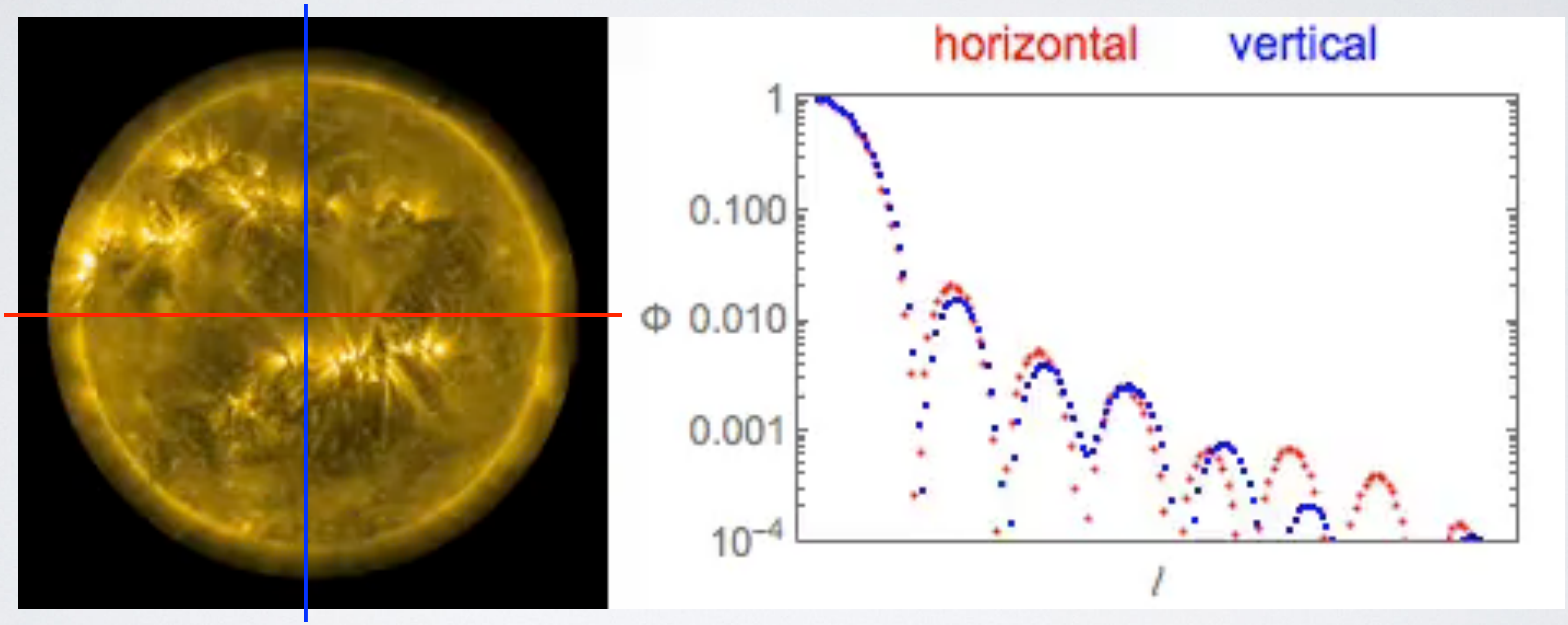
subtract temporal mean



COHERENCE FUNCTION FOR ONLY 2 BASELINES

rotating dynamic star [Sun from Solar Dynamics Observatory]

only two orthogonal baselines from 3 to 4 telescopes



in foreseeable future most II observations will only have a few baselines

ENABLING TECHNOLOGY

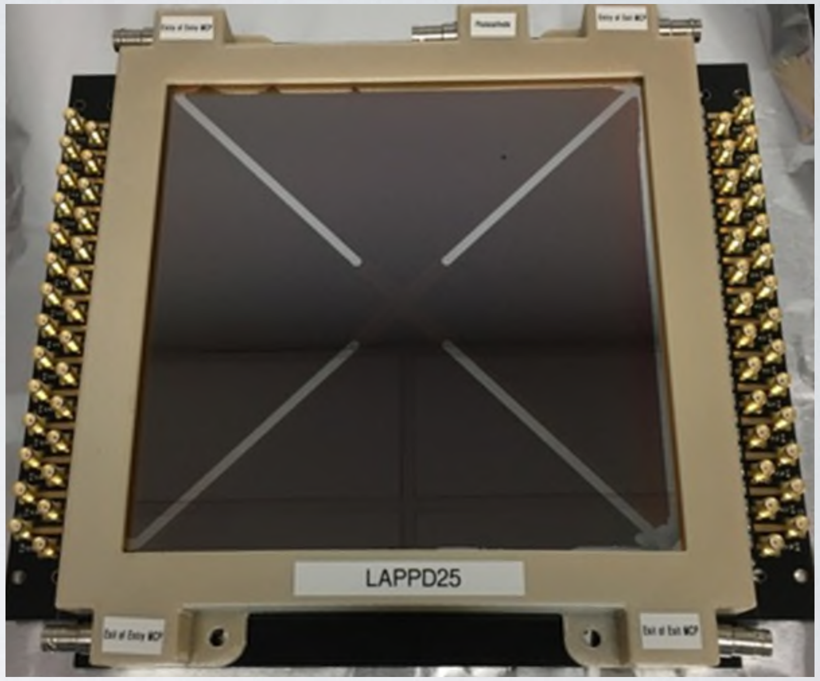
Intensity interferometry: measure excess rate of “coincident” photon counts from a single source at two (or more) widely separated locations.

Light should be separated spectroscopically before counting.

- large collecting area telescopes
- precise times of arrival
- accurate times of arrival
- detectors with large numbers of independent counters (i.e. pixels)

QUANTUM LIMITED DETECTOR: LAPPD?

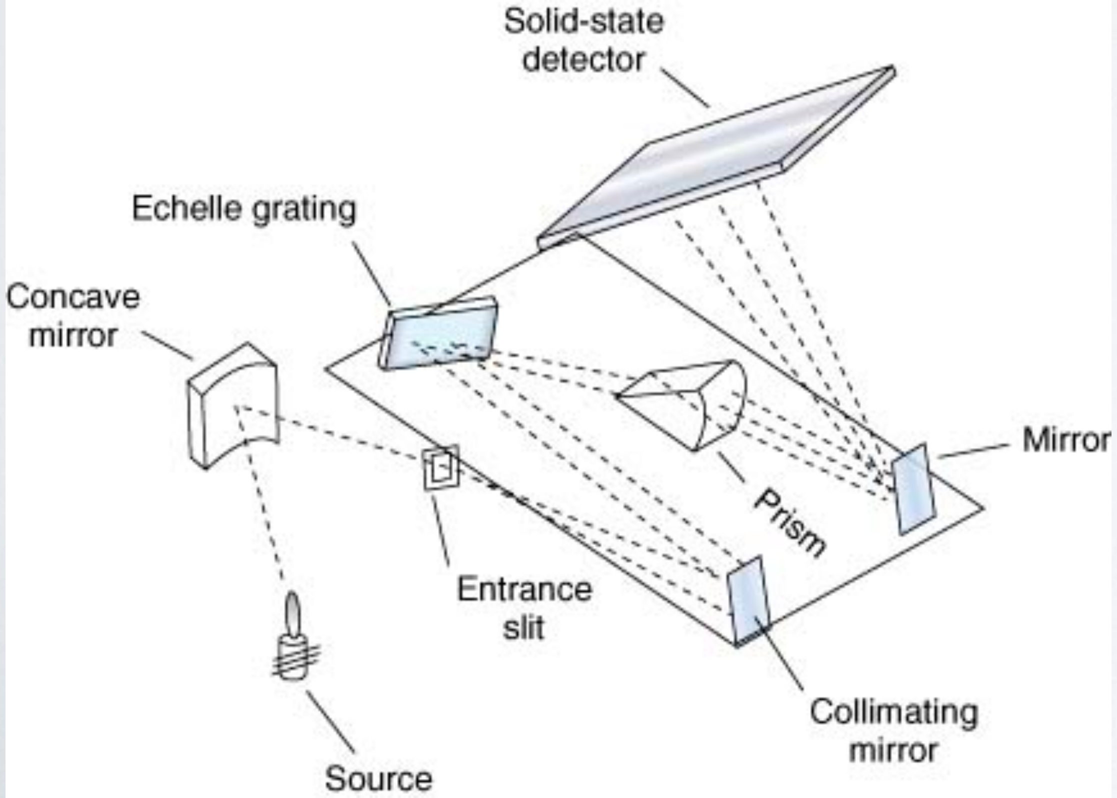
Large Area Picosecond Photon Detector

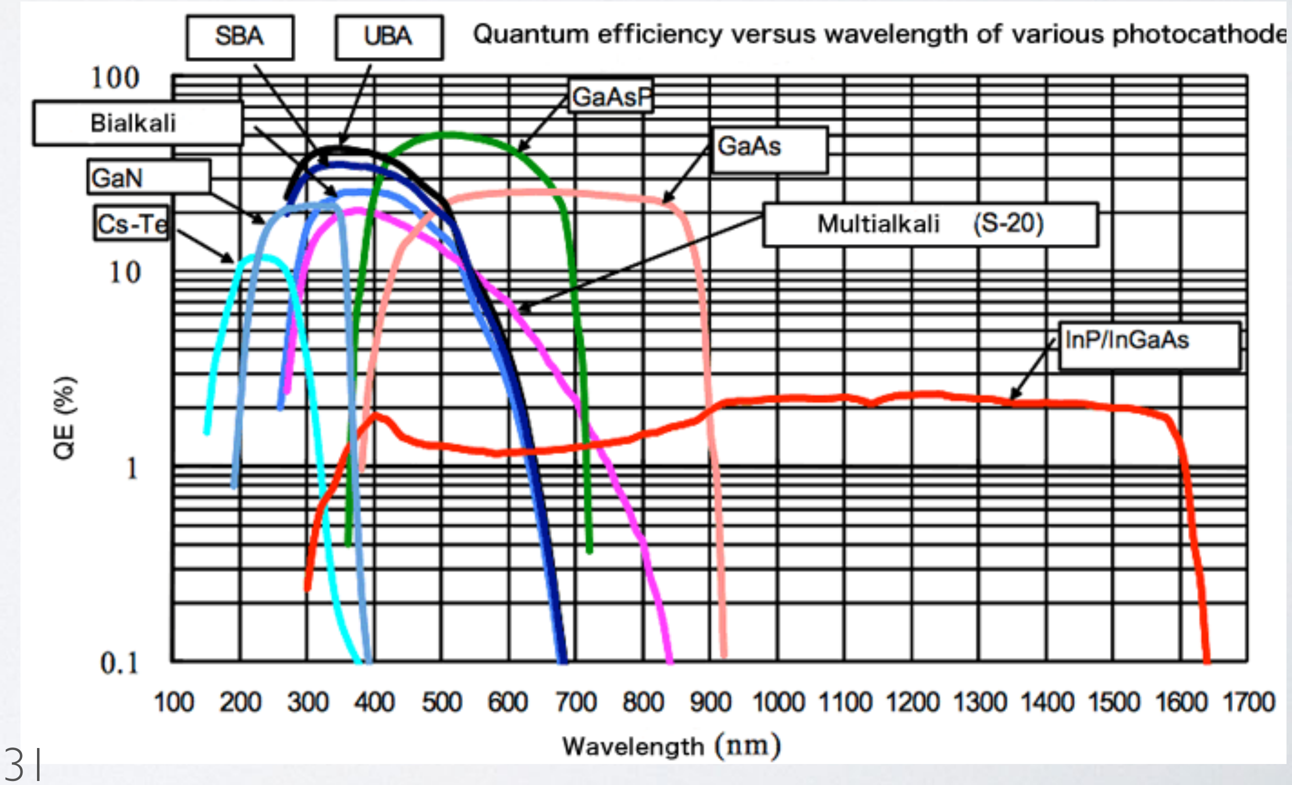


LAPPD could be off the shelf fast spectroscopic counters

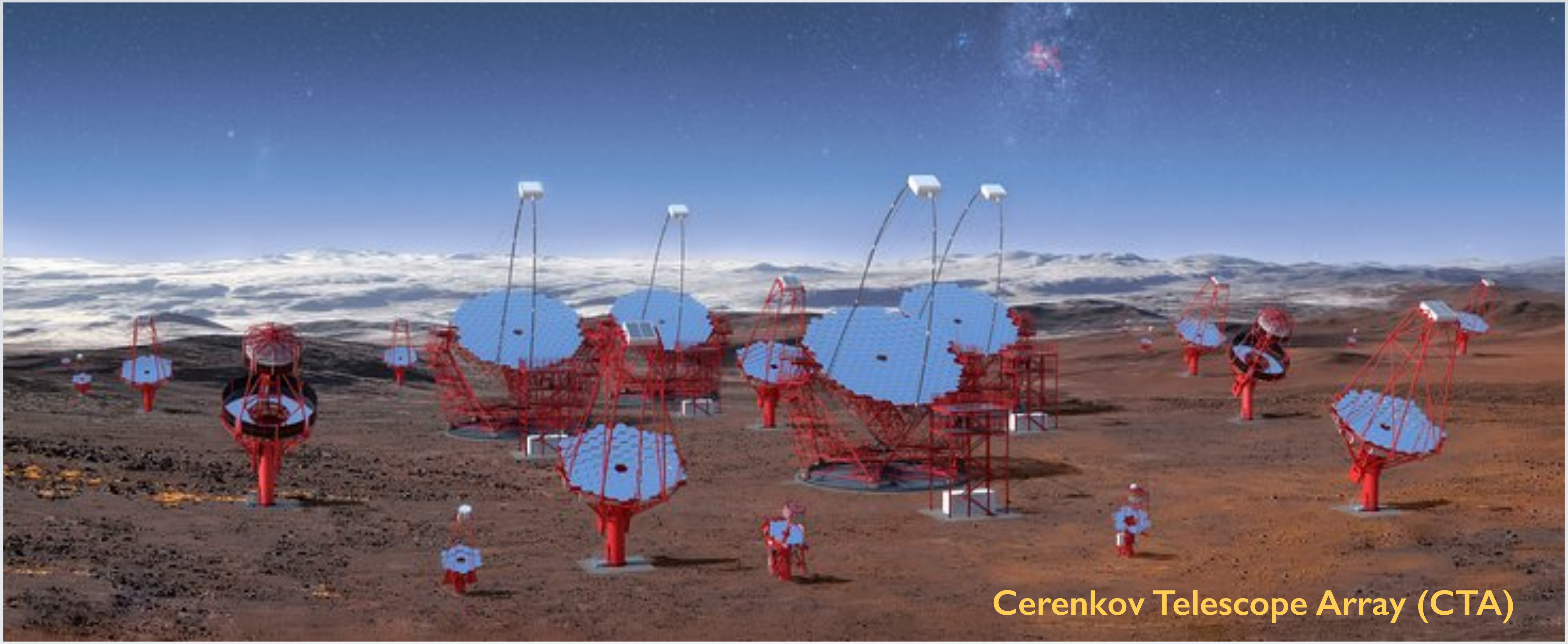
- precise timing capability (<100psec)
- $>10^4$ resolution elements for spectroscopy on each device
- can handle large count rate (> million counts per second)
- off-the-shelf technology soon?
- Quantum Efficiency 20-40%?

alternately, SiPM, SPAD, SNSPD, …



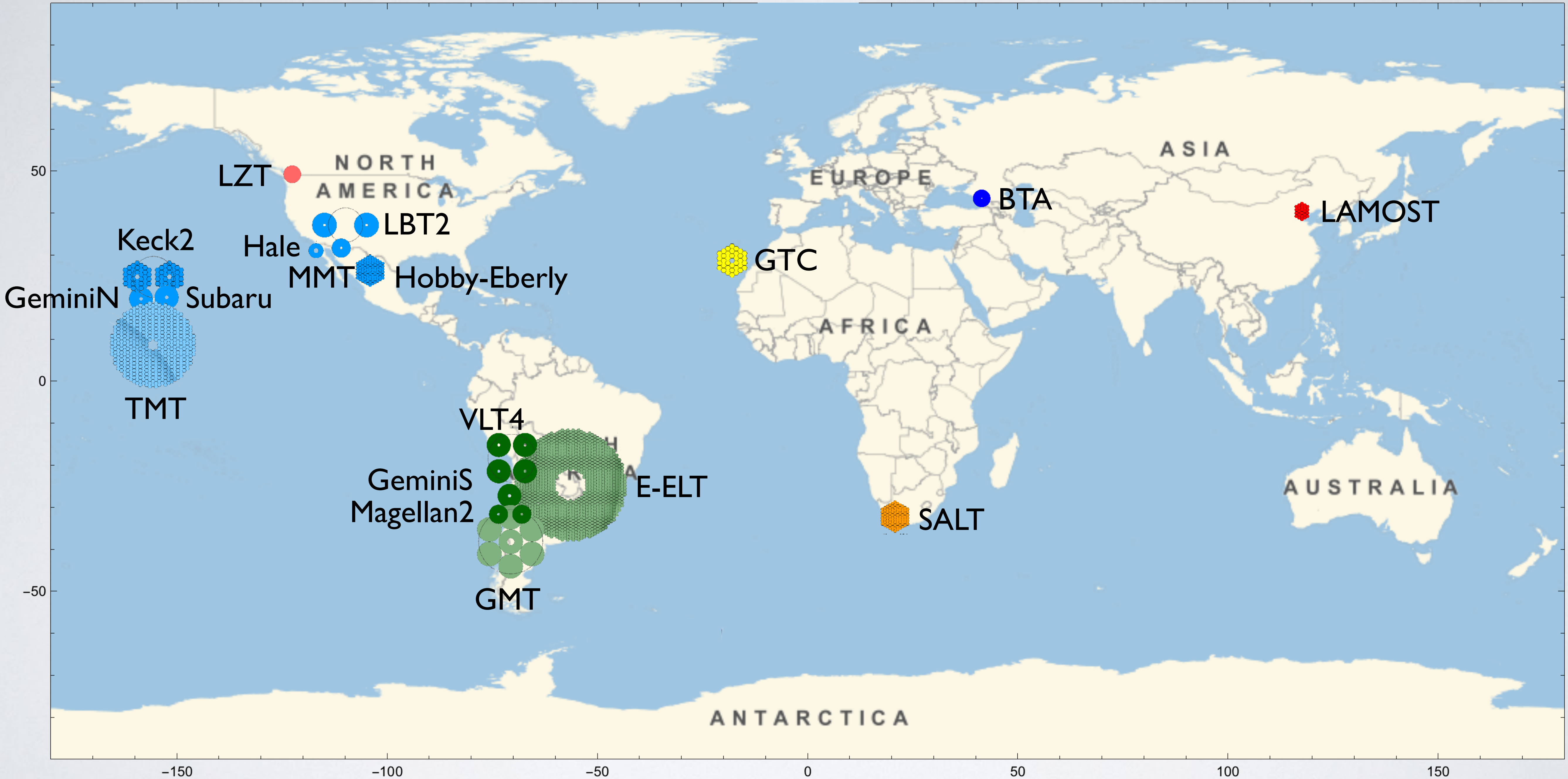


COLLECTING AREA = GLASS



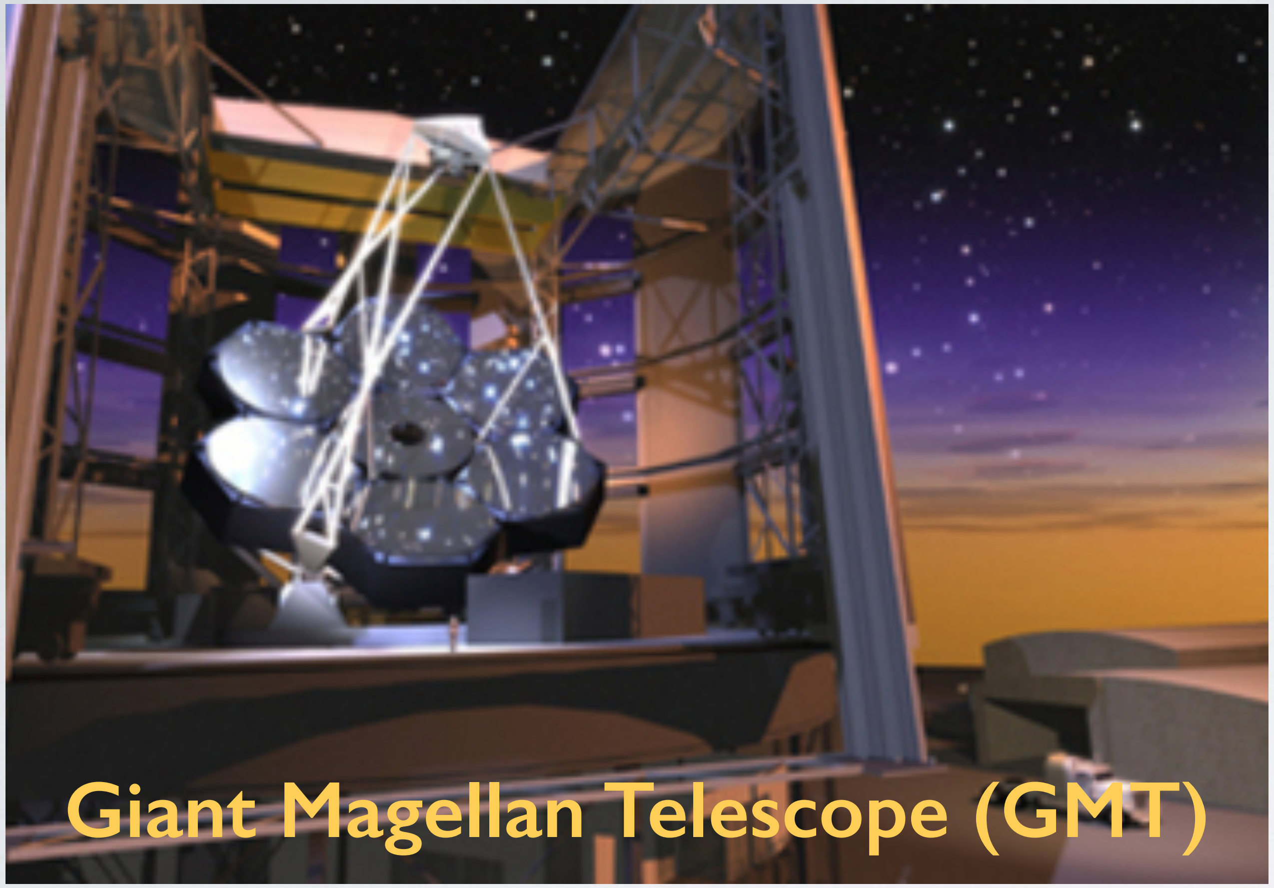
BIG GLASS

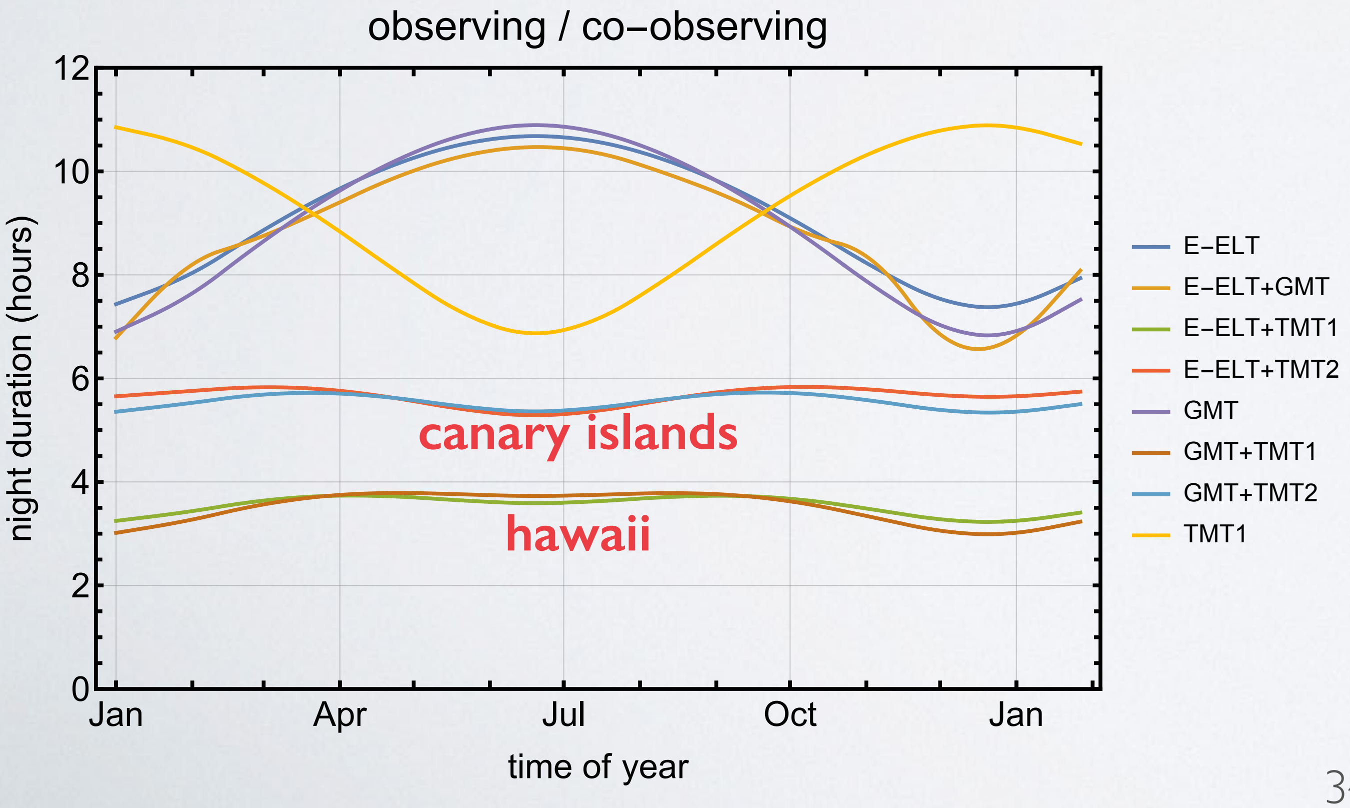
APERTURE "DIAMETER" ≥ 200"

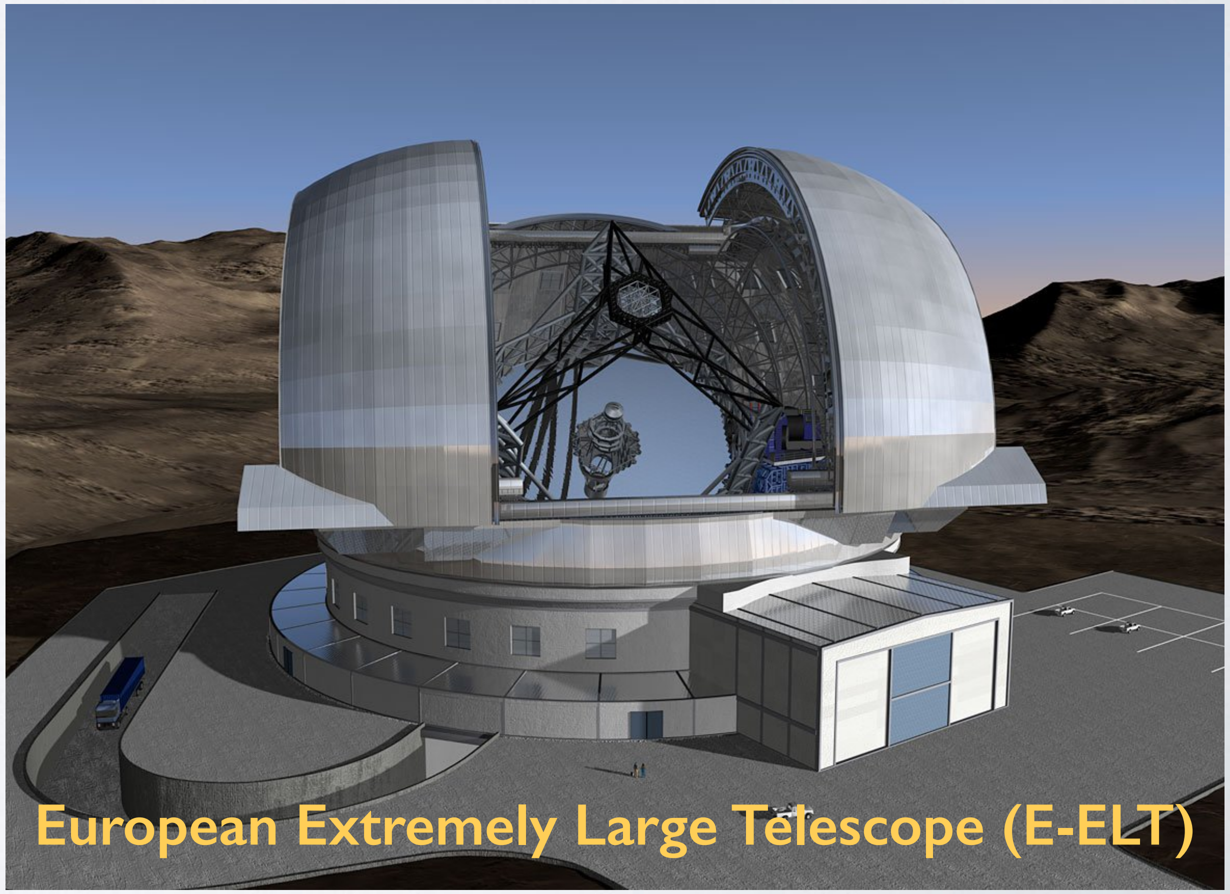


VLBII: VERY LONG BASELINE INTENSITY INTERFEROMETRY

EXTREMELY LARGE TELESCOPES



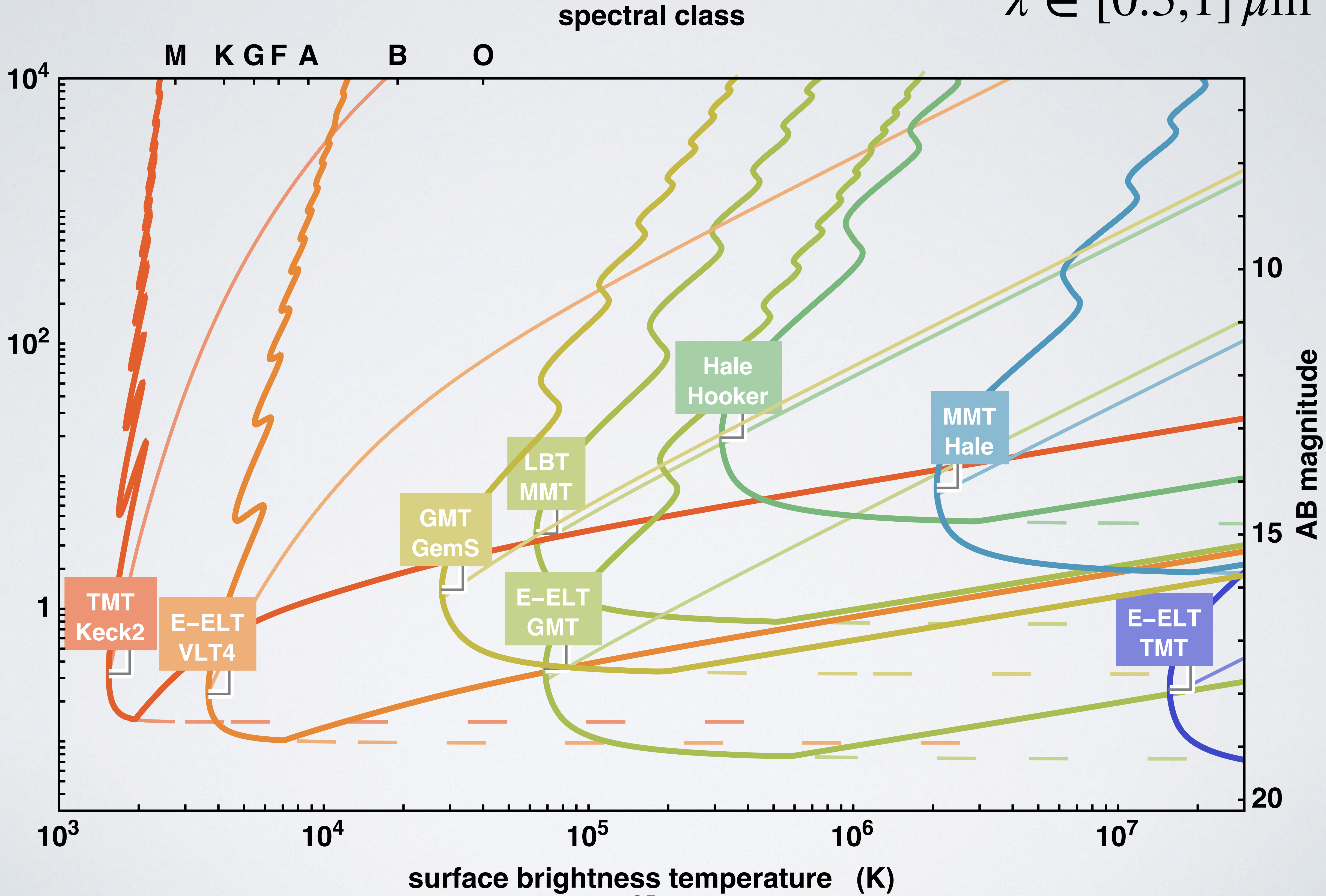




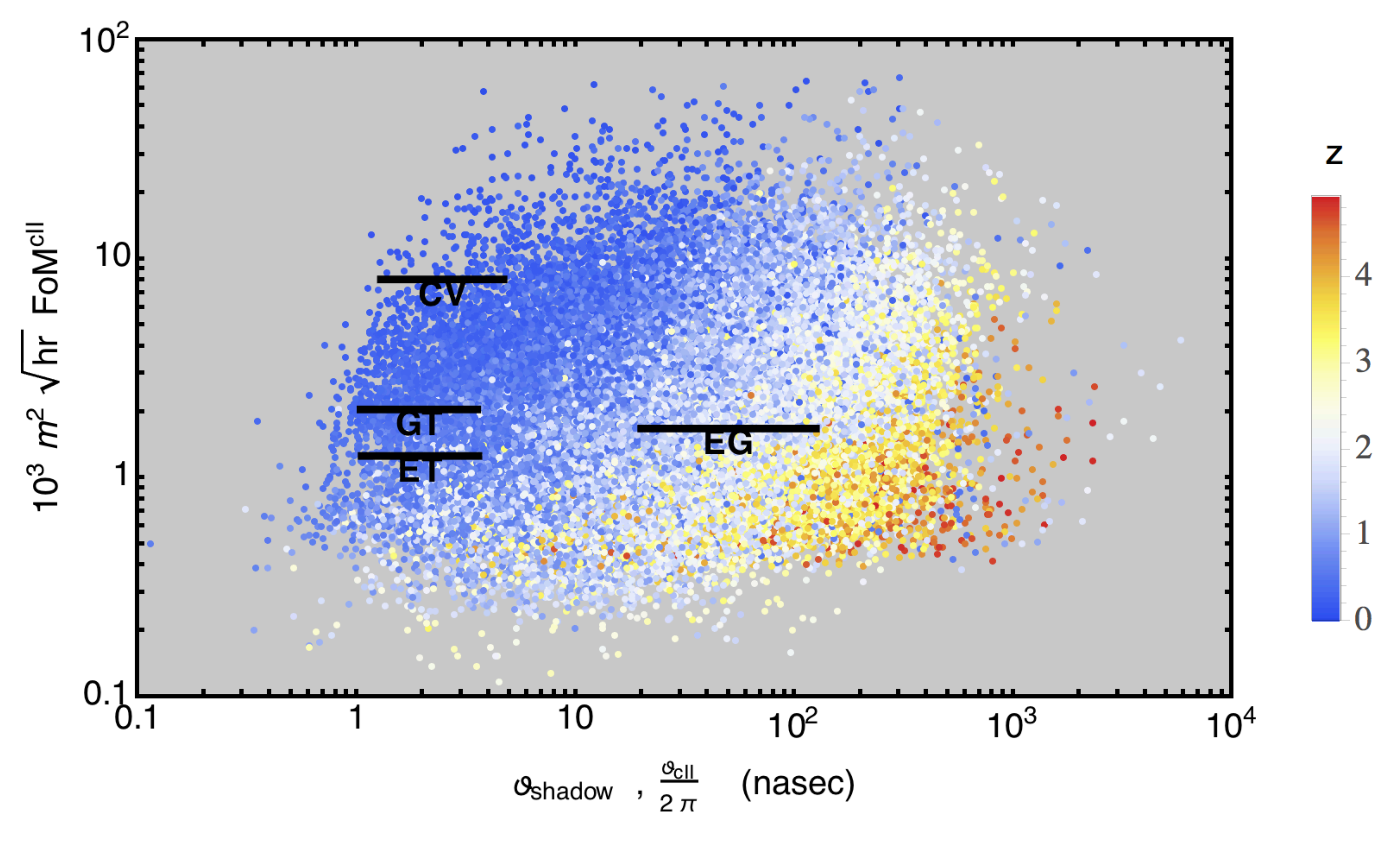
SURFACE BRIGHTNESS REQUIREMENTS

TEMPERATURE SENSITIVITY

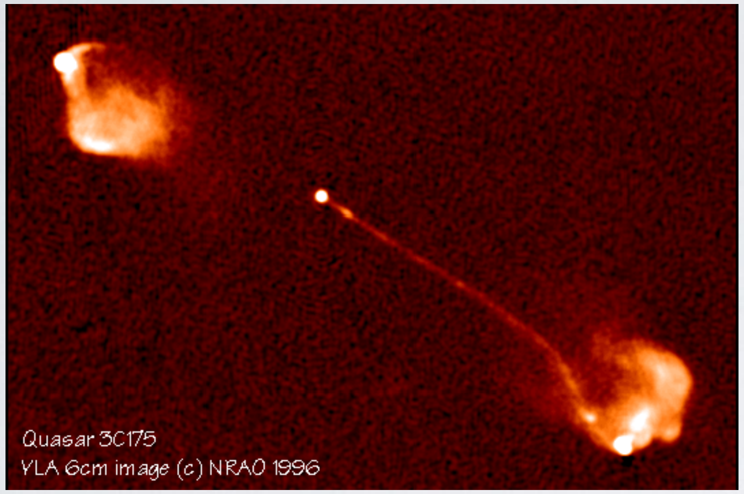
$$\lambda \in [0.3,1]\,\mu m$$

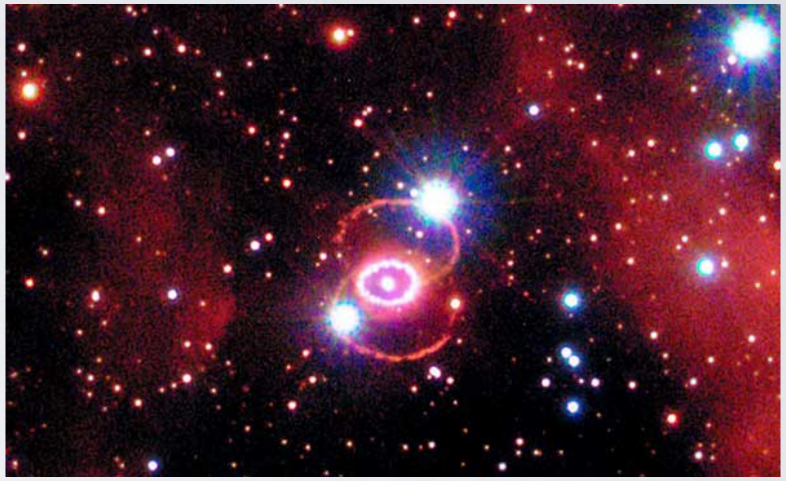


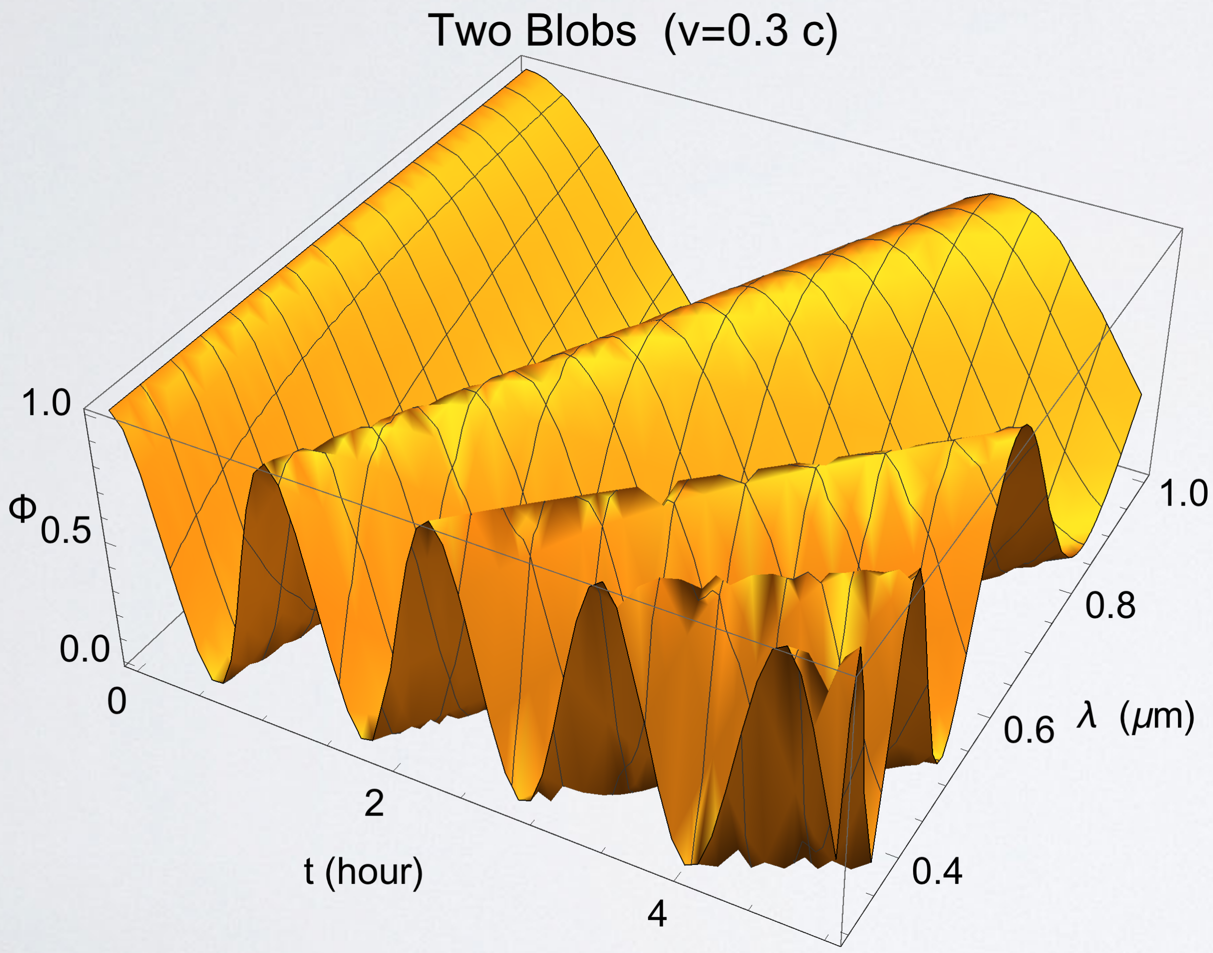
TARGET: SUPERMASSIVE BHS / QSO

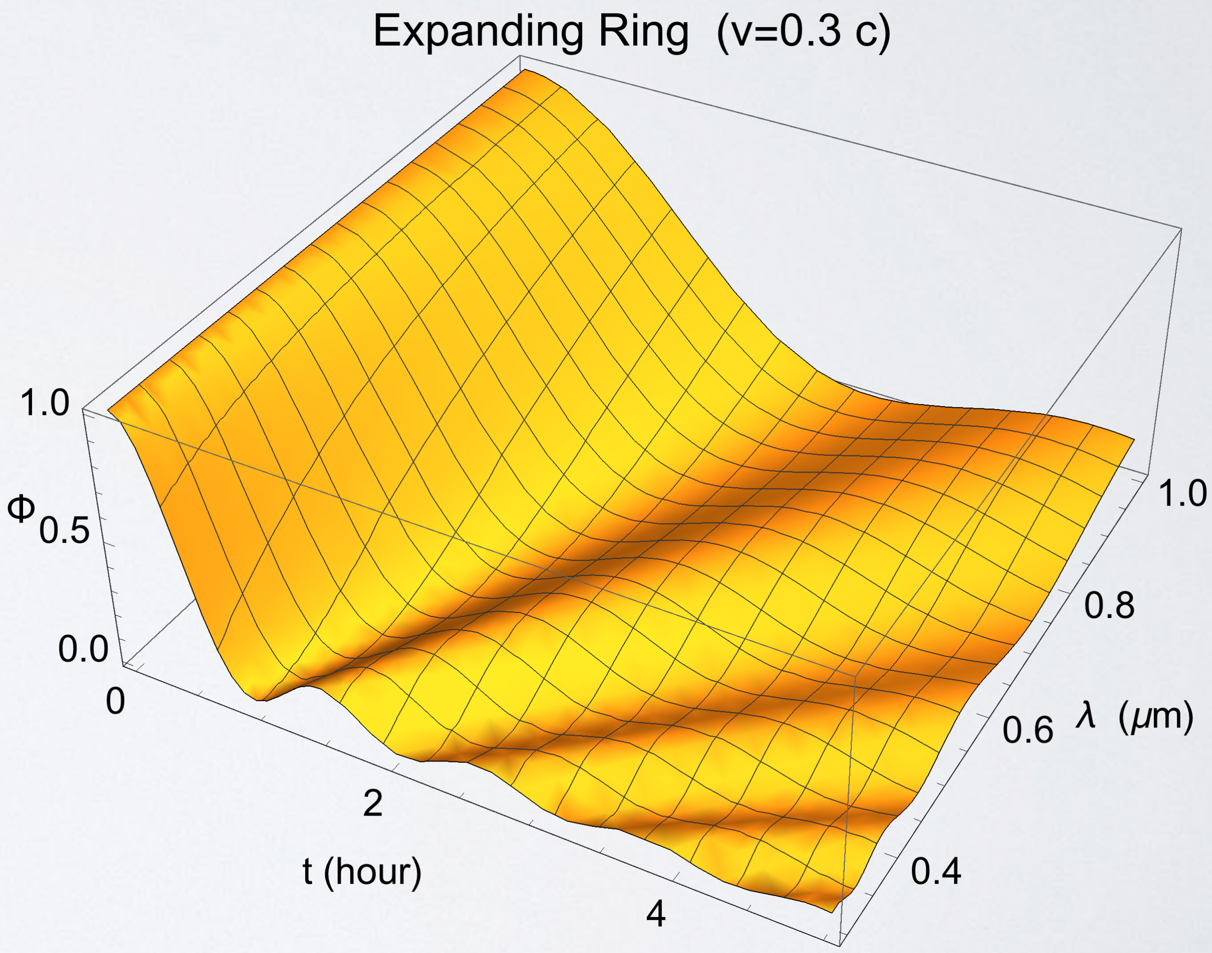


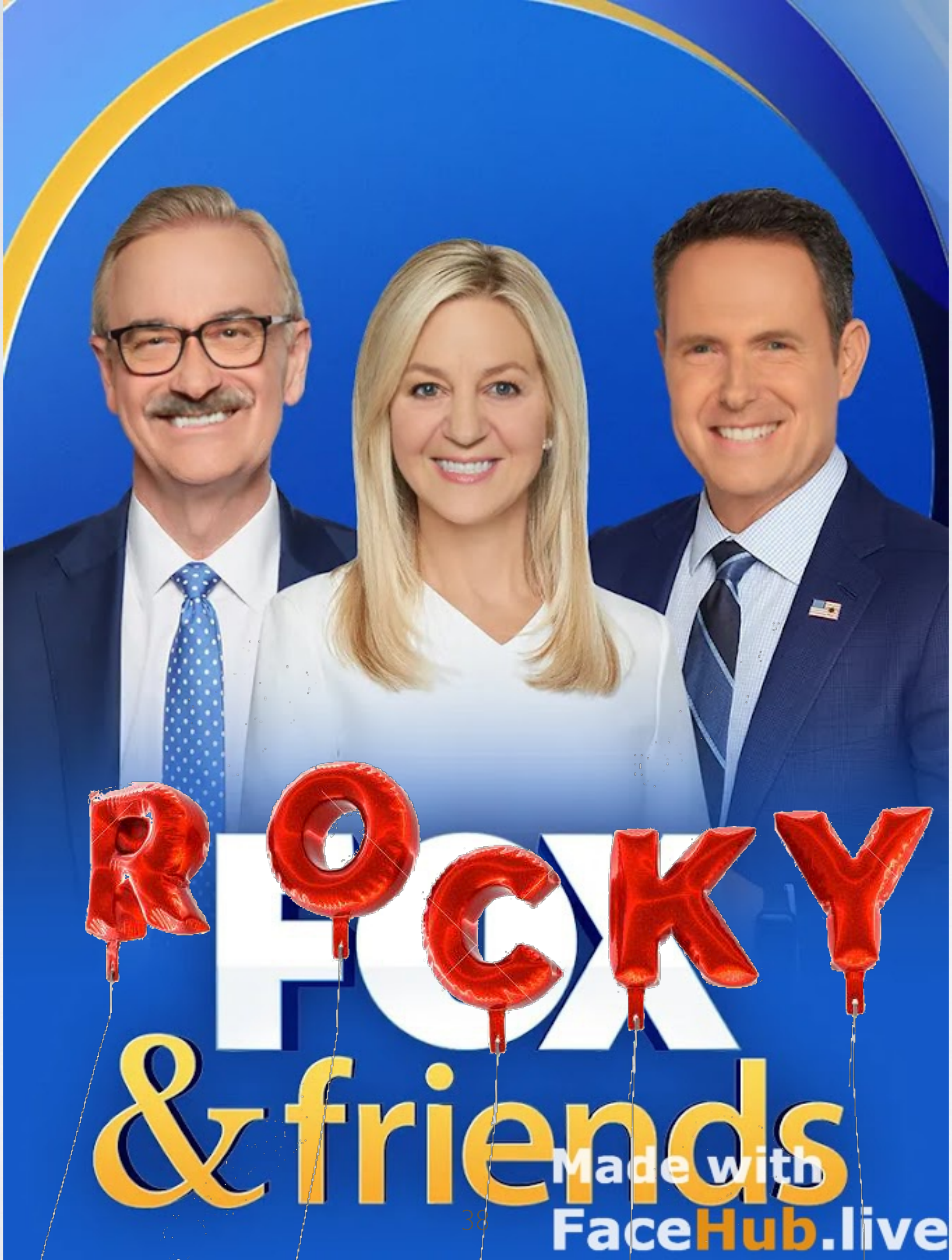
REAL TIME KILONOVAE







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