INTENSITY INTERFEROMETRY W/ EXTREMELY LARGE TELESCOPES

using fast spectroscopic counters

cosmological fashion: *"black is the new dark"*

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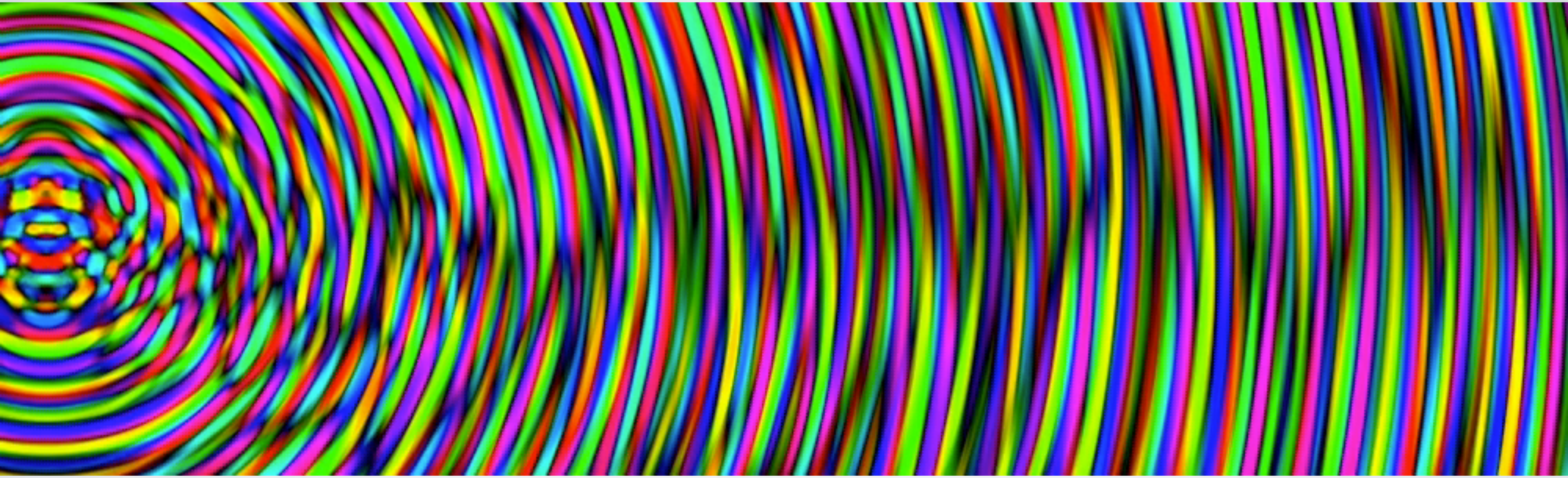
IMAGING: TRANSVERSE CORRELATIONS



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

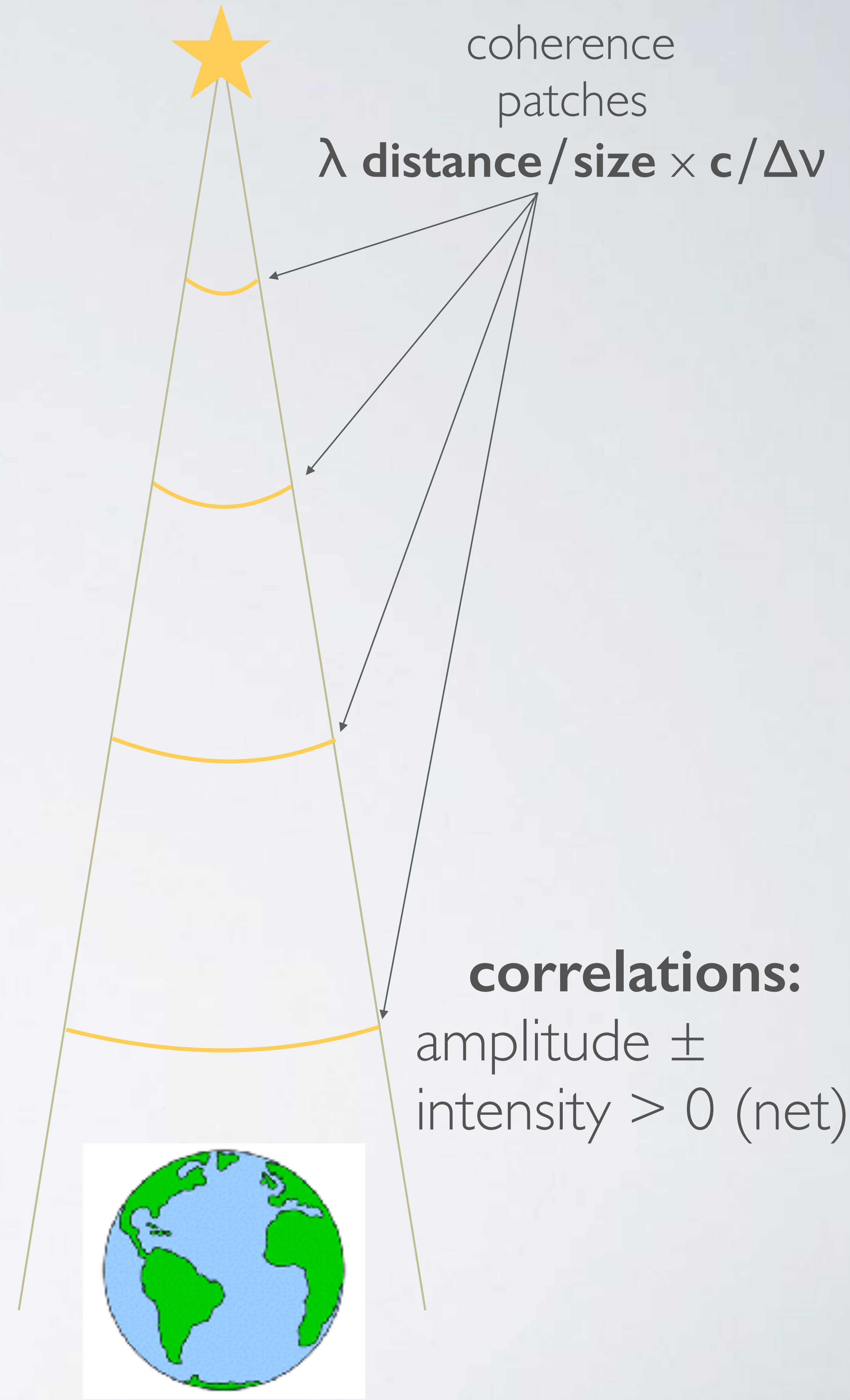
GROUND BASED IMAGING LIMITED BY EARTH SIZE :

BASELINE ≲10000KM

IN OPTICAL:

WAVELENGTH ~ 1 MICRON

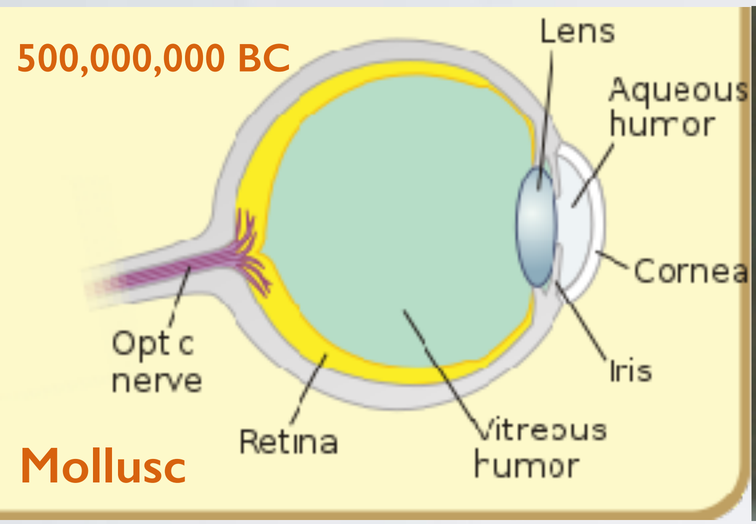
ANGULAR SCALE ≳ 10^{-9} ARCSEC

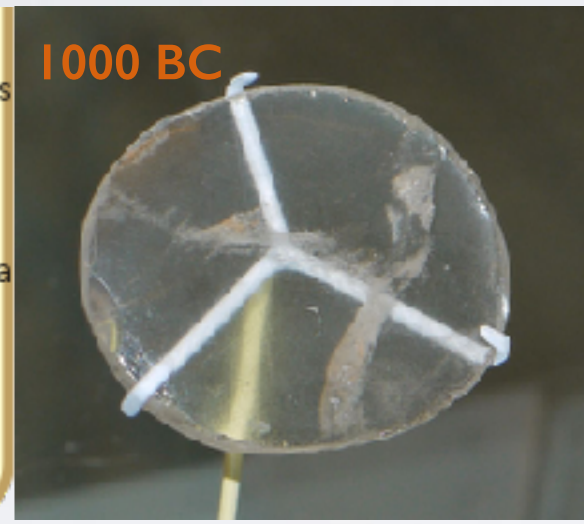


TWO WAYS OF IMAGING

ANALOG

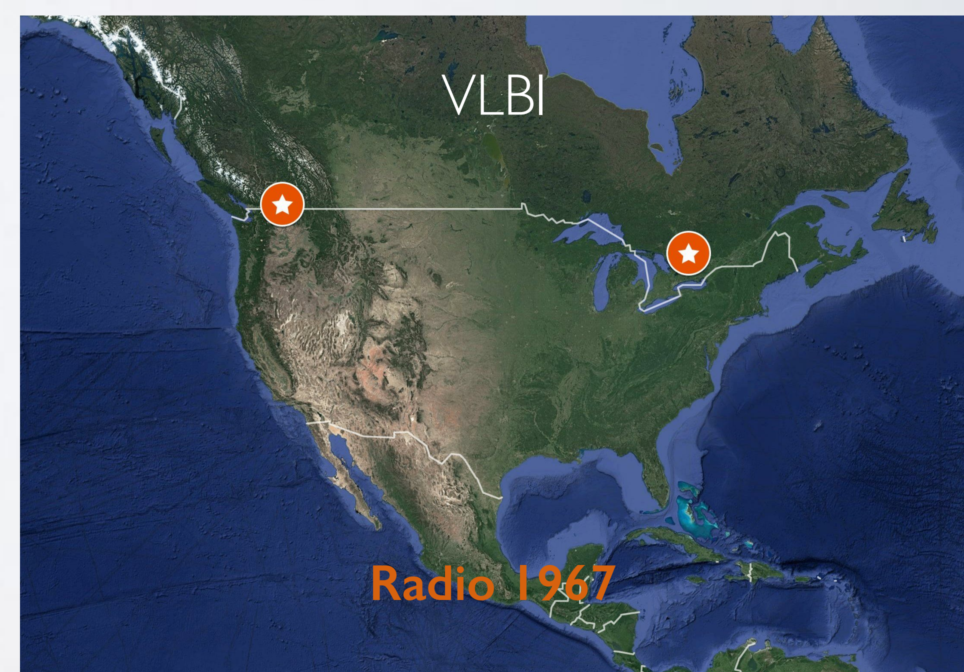
- **optically** combine wave from different transverse positions
  - on spatial scale better than one wavelength: $\lambda \ll 1\,\mu m$



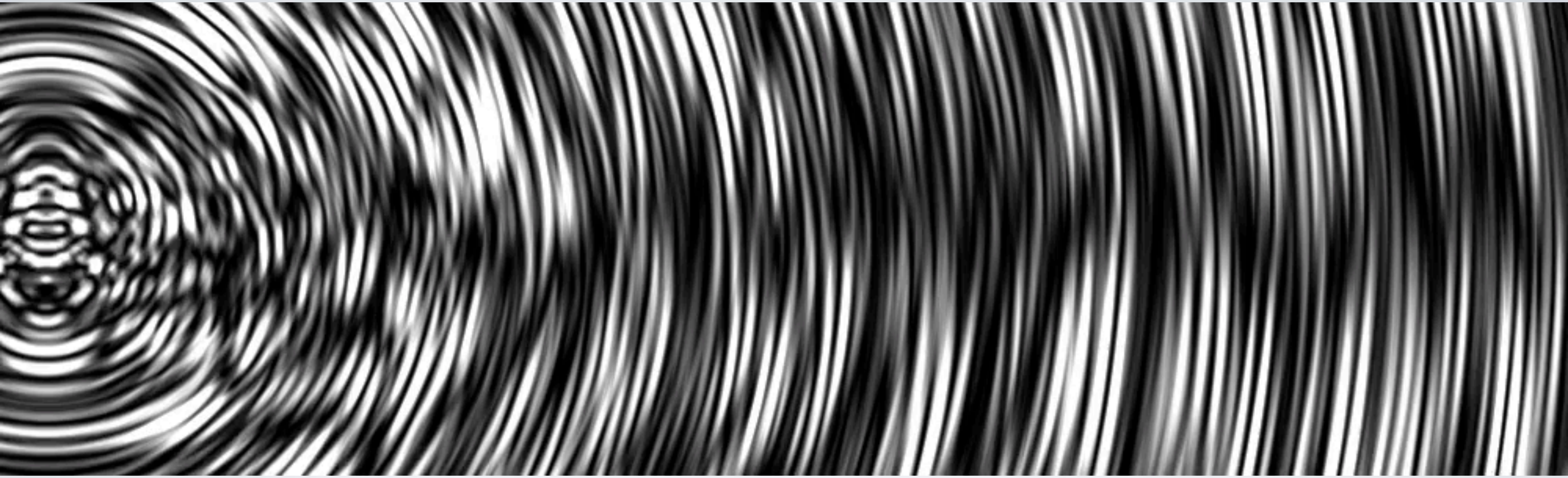


- **record** "waveform" at different transverse positions
- **ship** and compare
  - temporal scale: $\nu^{-1} \sim 10^{-15}$sec? **NOT!**
    - spectral filtering / mixing: $\Delta\nu^{-1} \sim 10^{-10}$sec
    - intensities **or**
    - **time tagged photons**

DIGITAL



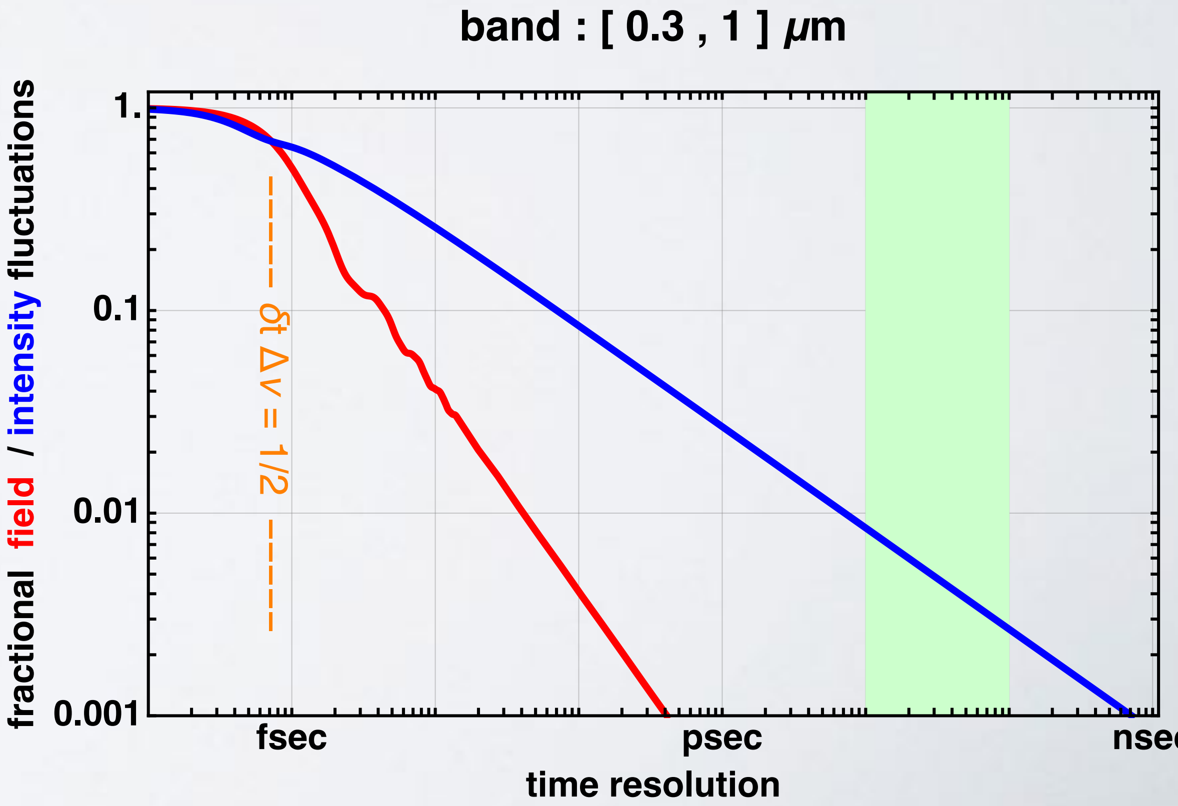
TEMPORAL INTENSITY CORRELATIONS



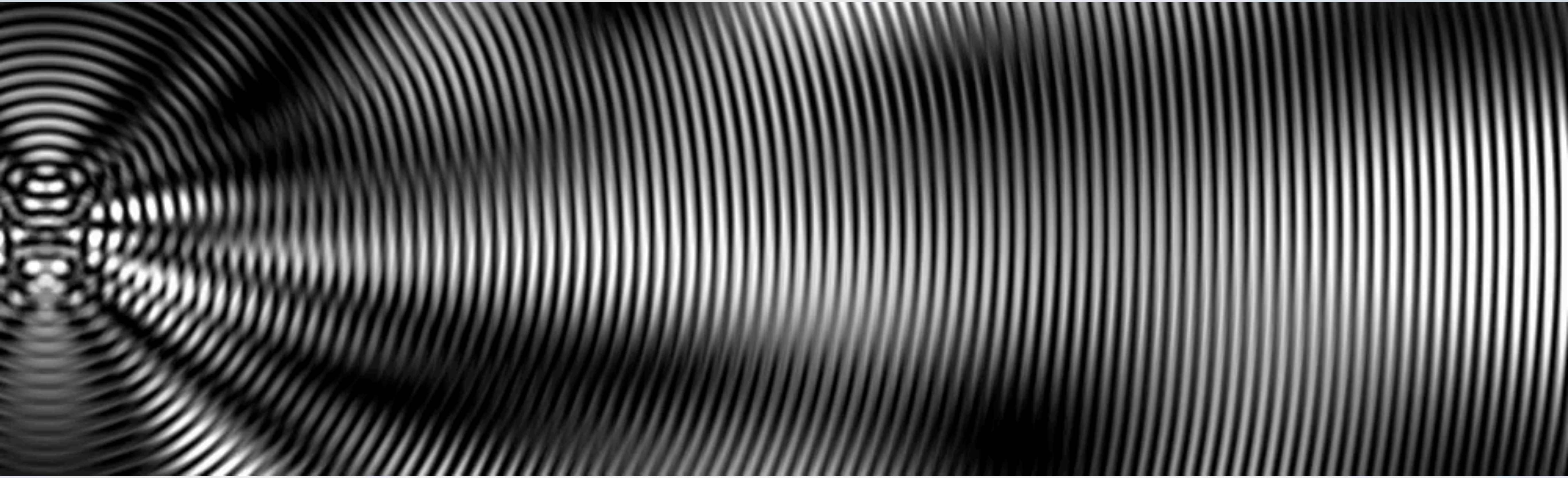
- field correlation power spectrum: f_ν (flux density / Janskies)
- intensity correlation power spectra (unpolarized)

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

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

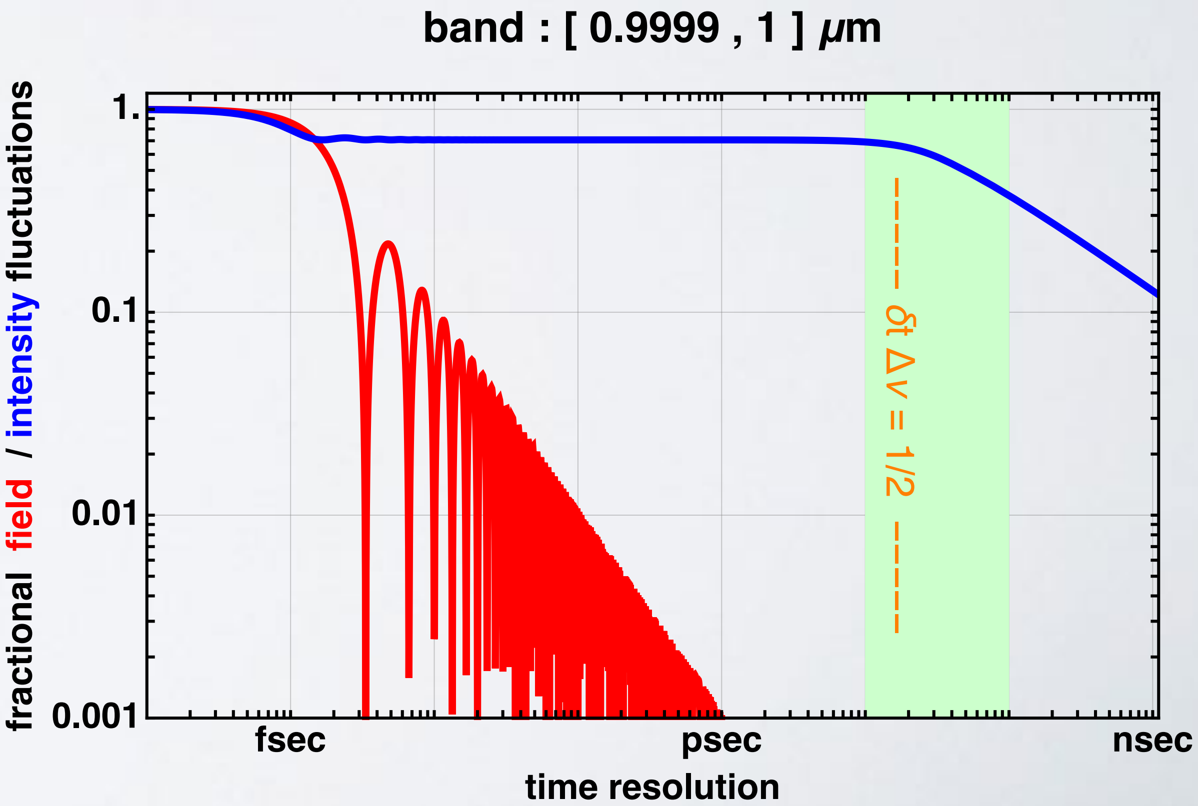


INCREASE TEMPORAL CORRELATION BY DECREASING BANDWIDTH



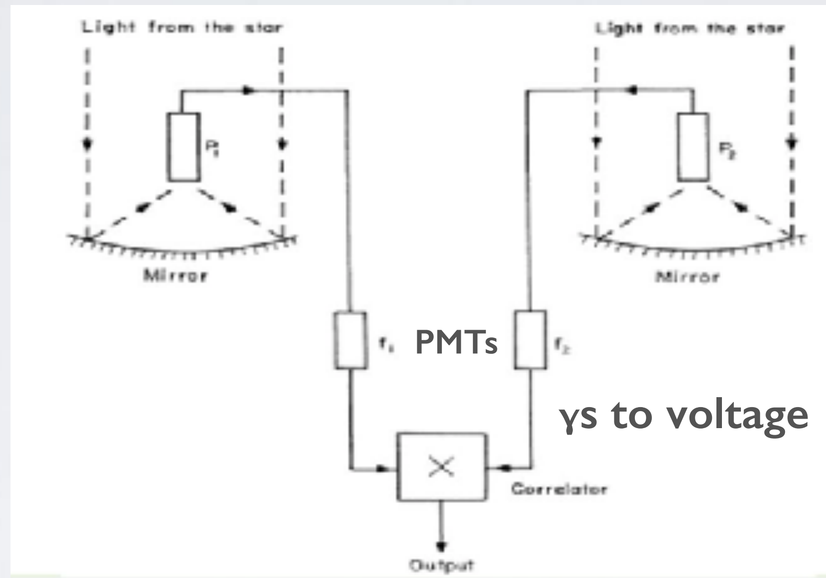
- convolution: $(\delta I^2)_\nu = \frac{1}{4} \int d\nu' \, f_{\nu'} \, f_{\nu-\nu'}$
- intensity "mixes" radiation field with itself
  - "mixes down" to $\mathbf{1/\delta t \sim \Delta\nu}$
  - "mixes up" to $\mathbf{1/\delta t \sim 2\nu}$

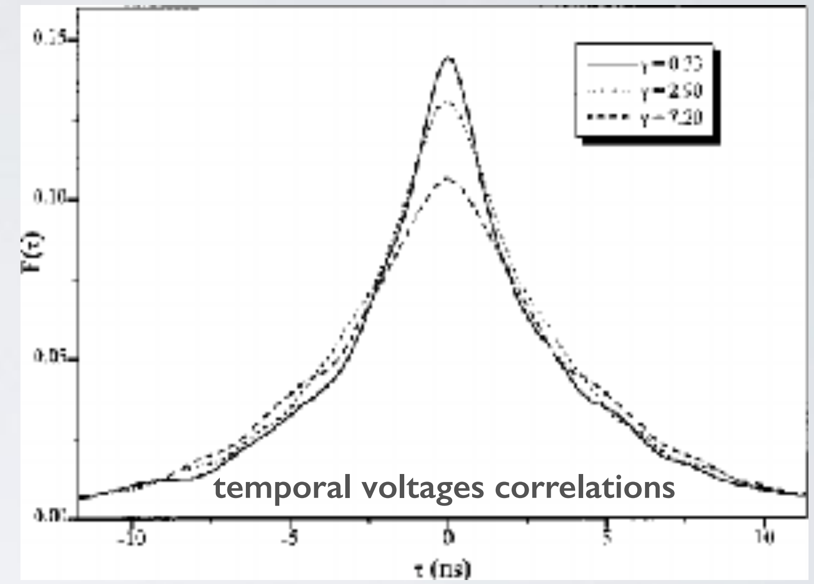
- $\mathbf{R \sim \nu/\Delta\nu} \gtrsim \mathbf{10^4} \Rightarrow$ "quantum limit" $\mathbf{\delta t \, \Delta\nu} \lesssim \mathbf{\frac{1}{2}}$



HOW TO MEASURE INTENSITY CORRELATIONS

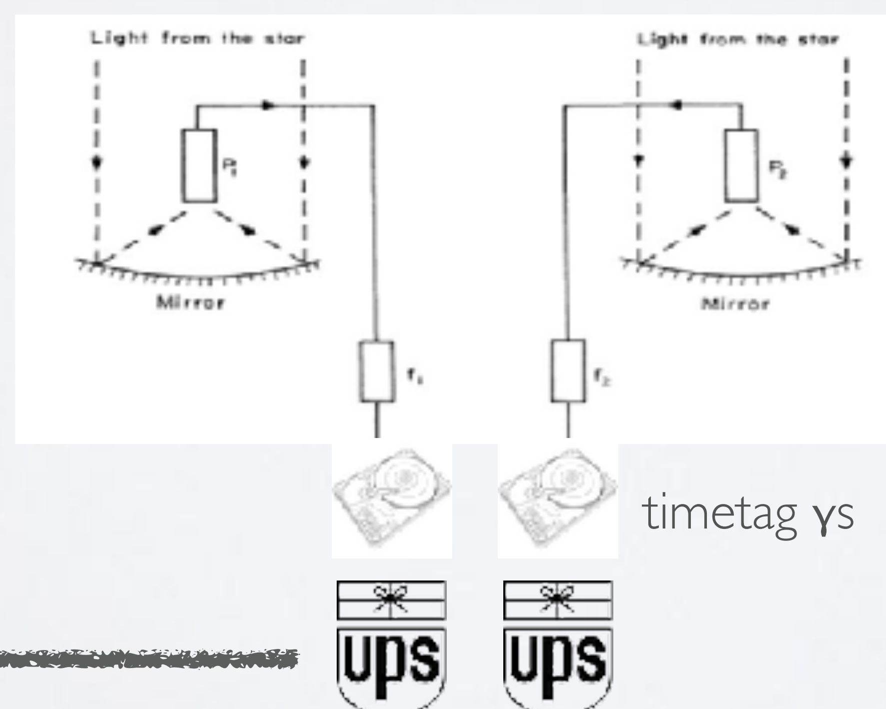
- ANALOG





Analog method uses cables - not feasible for VLBII!

- DIGITAL



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

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

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

$$\delta t\,\delta\nu \le \frac{1}{2}$$

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

$f_\nu = \tilde{I}_\nu[\vec{0}]$ flux density

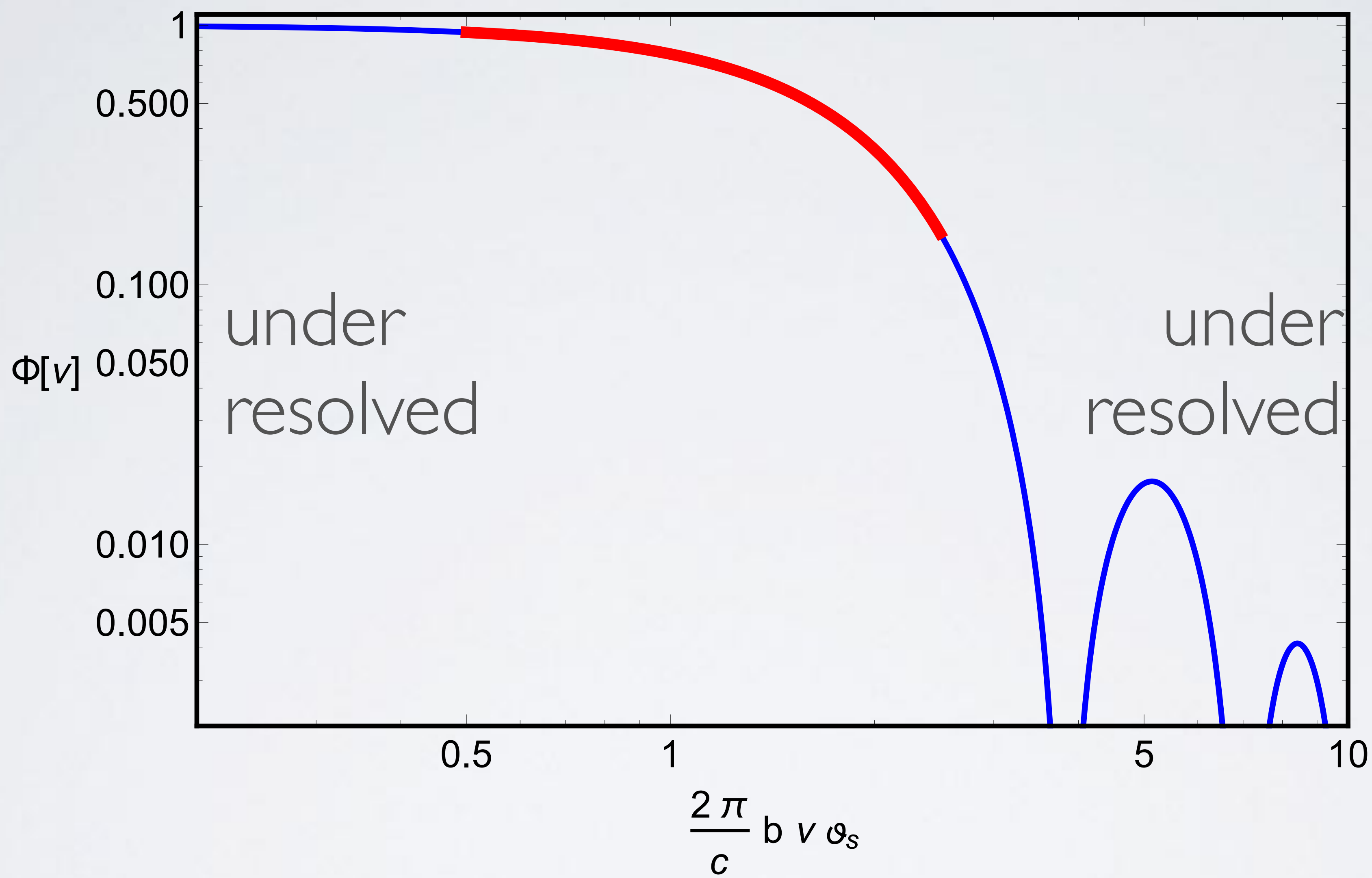
$\tilde{I}_\nu[\vec{\ell}] \equiv \int d^2\hat{n}\, e^{-i\,2\pi\,\vec{\ell}\cdot\hat{n}}\; I_\nu[\hat{n}]$ Fourier transform of intensity pattern

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

$\boldsymbol{b} = \boldsymbol{x}_1 - \boldsymbol{x}_2$ telescope baseline

COHERENCE FUNCTION

(UNIFORM BRIGHTNESS DISK E.G. STAR)



- **b** transverse baseline
- $\boldsymbol{\nu}$ frequency
- $\boldsymbol{\vartheta_s}$ angular radius of disk
- $\boldsymbol{\Phi[\nu]}$ coherence function $\in[0,1]$

SIGNAL-TO-NOISE

$$\frac{S}{N} \cong \sqrt{4\,T \int_{\nu_-}^{\nu_+} d\nu \, \frac{q[\nu]}{1 + 2\, q[\nu]\, \Phi[\nu]} \left(\frac{\overline{A}[\nu]\, f_\nu\, \Phi[\nu]}{h\,\nu} \right)^2} \propto Q \sqrt{\frac{\#_{\text{pixels}}}{\delta t}}$$

$$\leq \frac{S}{N_{ql}} \equiv \sqrt{4\,T \int_{\nu_-}^{\nu_+} \frac{d\nu}{1 + 2\,\Phi[\nu]} \left(\frac{\overline{A}[\nu]\, f_\nu\, \Phi[\nu]}{h\,\nu} \right)^2} \propto D^2$$

(no background)

$$\overline{A}[\nu] \equiv \sqrt{A_1\, A_2}\; Q[\nu] \qquad q[\nu] \equiv \frac{1}{2\,\delta\nu\,\delta t}$$

$\propto D^4$

(dominant background)

- **T** observation time (hours)
- **A_i** telescope aperture
- **f_ν** flux density energy/time/area/frequency
- **Q** quantum throughput $\in[0,1]$
- **q[ν]** spectroscopic efficiency $\in[0,1]$
- **Φ[ν]** coherence function $\in[0,1]$

FLUX SENSITIVITY

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{\overline{f_{\mathrm{II}}}}{f_\sigma} \sqrt{3}\, \Phi \qquad f_\sigma \equiv \frac{1}{2} \frac{h}{\overline{A}\,\overline{Q}} \sqrt{\frac{3\,c}{\overline{q}\,\Delta\lambda\, T}} = \frac{23\,\mu\mathrm{Jy}}{\overline{Q}} \left(\frac{30\,\mathrm{m}}{D}\right)^2 \sqrt{\frac{1}{\overline{q}} \frac{\mu\mathrm{m}}{\Delta\lambda} \frac{\mathrm{hr}}{T}}$$

N.B. 23μJy ~ 20.5 AB magnitude

$$\Phi \equiv \sqrt{\frac{\int_{\nu_-}^{\nu_+} \frac{d\nu}{\nu^2} \frac{Q_1[\nu]\, Q_2[\nu]\, q[\nu]}{1+2\, q[\nu]\, \Phi[\nu]} (f_\nu\, \Phi[\nu])^2}{\int_{\nu_-}^{\nu_+} \frac{d\nu}{\nu^2} Q_1[\nu]\, Q_2[\nu]\, q[\nu]\, f_\nu^2}} \in [0,\, 1] \quad \overline{q} \equiv \frac{\int_{\nu_-}^{\nu_+} \frac{d\nu}{\nu^2} Q_1[\nu]\, Q_2[\nu]\, q[\nu]}{\int_{\nu_-}^{\nu_+} \frac{d\nu}{\nu^2} Q_1[\nu]\, Q_2[\nu]} \in [0,\, 1] \quad \overline{A} \equiv \sqrt{A_1\, A_2} = \pi \left(\frac{D}{2}\right)^2$$

$$\overline{f_{\mathrm{II}}} \equiv \sqrt{\frac{\int_{\nu_-}^{\nu_+} \frac{d\nu}{\nu^2} Q_1[\nu]\, Q_2[\nu]\, q[\nu]\, f_\nu^2}{\int_{\nu_-}^{\nu_+} \frac{d\nu}{\nu^2} Q_1[\nu]\, Q_2[\nu]\, q[\nu]}} \in \mathrm{Range}[f_\nu] \quad \overline{Q} \equiv \sqrt{\frac{\int_{\nu_-}^{\nu_+} \frac{d\nu}{\nu^2} Q_1[\nu]\, Q_2[\nu]}{\int_{\nu_-}^{\nu_+} \frac{d\nu}{\nu^2}}} \in [0,\, 1] \quad \Delta\lambda \equiv \frac{c}{\nu_-} - \frac{c}{\nu_+} = c \int_{\nu_-}^{\nu_+} \frac{d\nu}{\nu^2}$$

ENABLING TECHNOLOGY

Intensity interferometry measures the excess rate of "coincident" photon counts from a single source at two (or more) widely separated locations. Requires recording of vast numbers of photon arrival times. Ideally each photon should also have an accurate wavelength determination, i.e. a separate counter for each wavelength bin.

- large collecting area telescopes
- S/N increases proportional to number of photons counts (rate x observation time)
- "giant" 30m diameter telescopes **or** less expensive light buckets (w/ poorer optical characteristics)
- benefits of an expensive telescope is that one can greatly reduce contamination by photons unrelated to target

- precise times of arrival
- S/N increases with better timing resolution $\propto 1/\sqrt{\delta t}$

- accurate times of arrival
- need precise and stable clocks at each location synchronized to each other
- radio VLBI does this but optical observatories have not needed this.

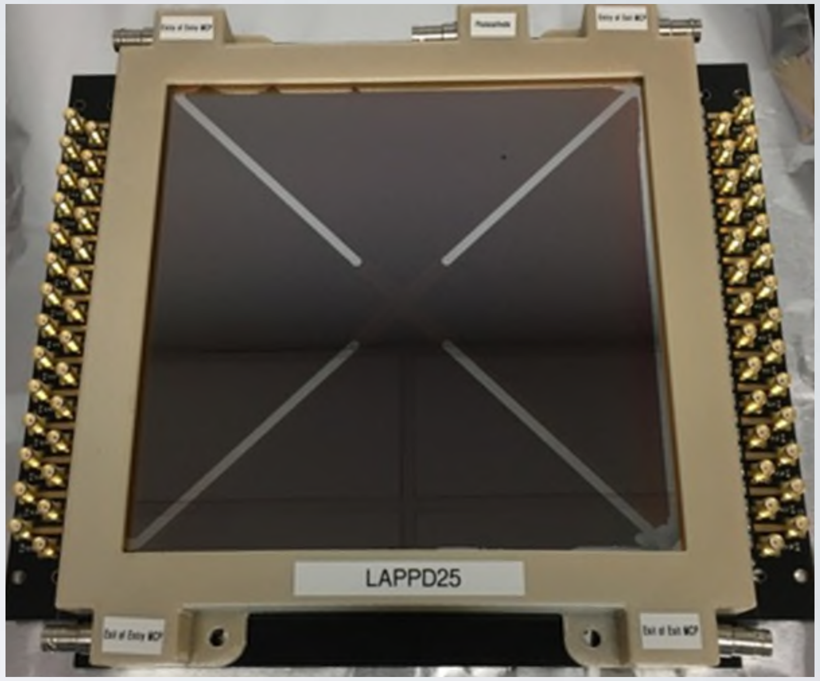
- detectors with large numbers of independent counters (i.e. pixels)
- S/N increases with number of independent frequency bins $\propto \sqrt{\#_{pixels}}$ ($\#_{pixels} \sim$ bandwidth/$\delta\nu$)
- for large numbers of photons one wants a large bandwidth but also high frequency resolution for increase S/N.
- S/N increases with decreasing $\delta\nu$ down to "quantum limit" $\delta\nu\delta t \gtrsim 1$: only require $\#_{pixels} \sim$ bandwidth $\delta t \sim 10^4$.

QUANTUM LIMITED DETECTOR: LAPPD?

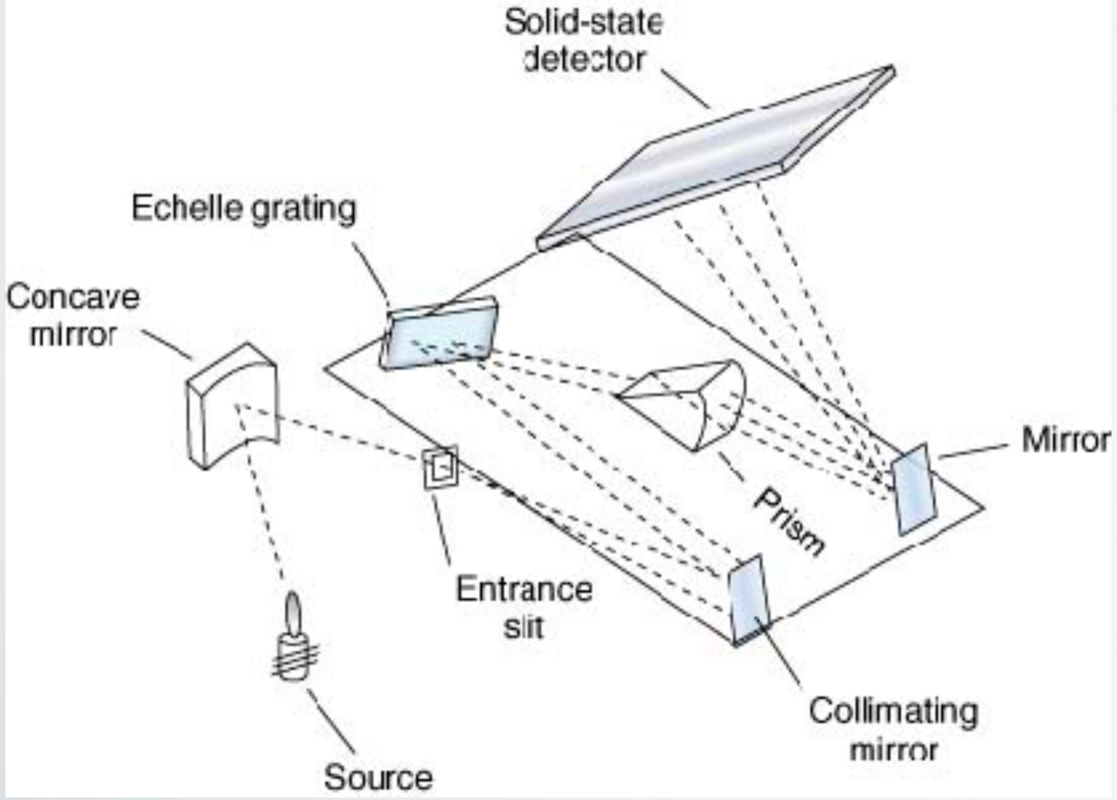
Large Area Picosecond Photon Detector

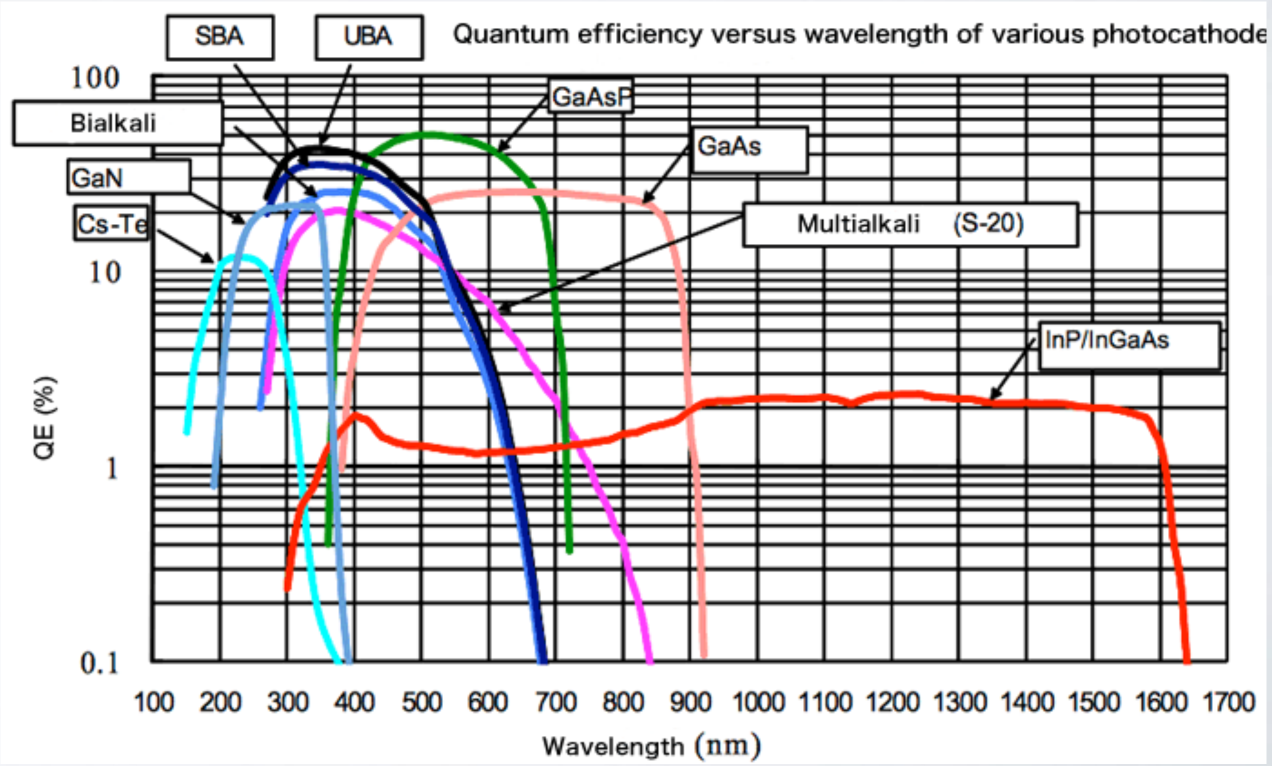
LAPPD could be centerpiece of fast spectroscopic counters

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

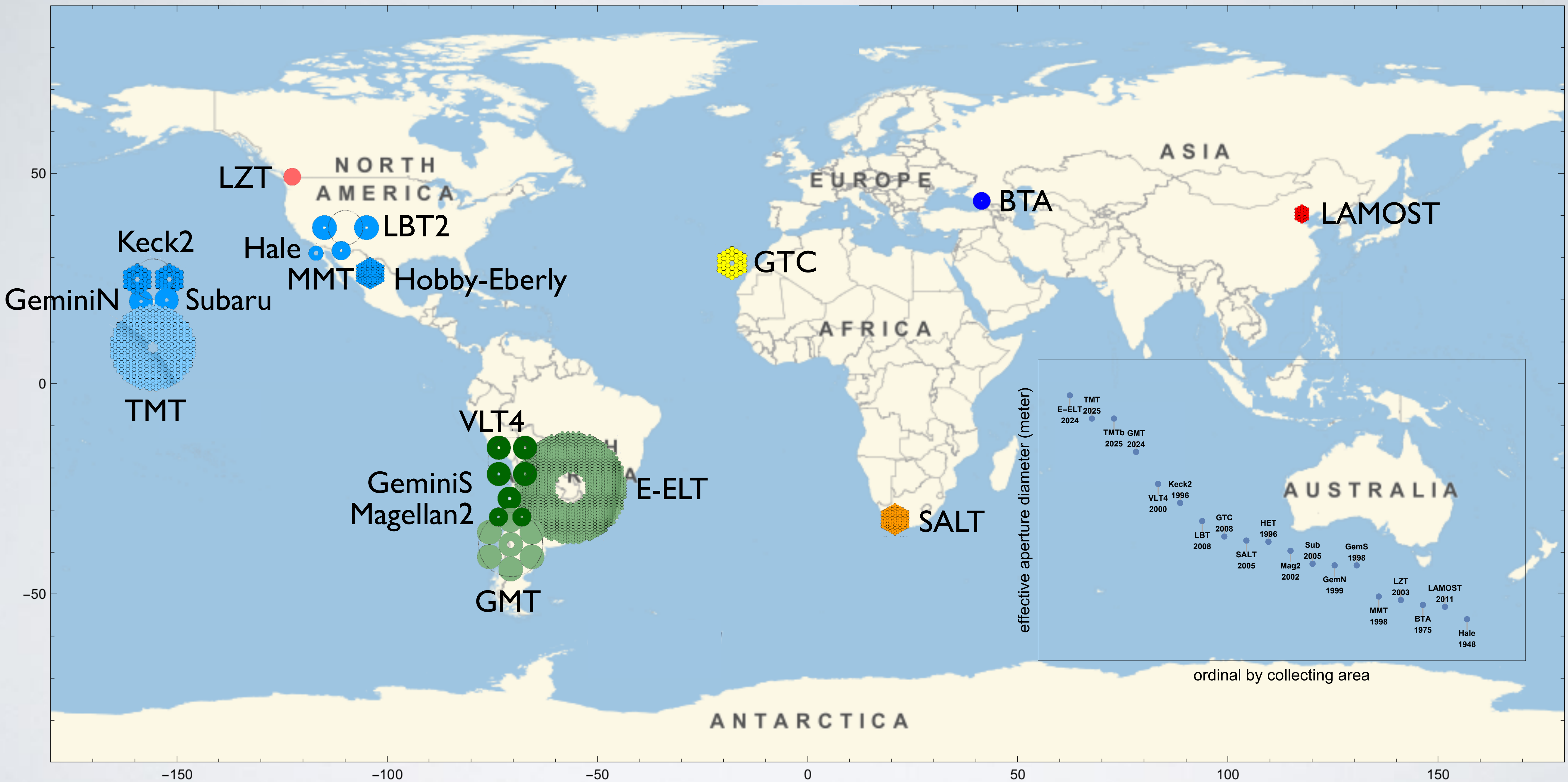


alternately, SiPM, SPAD, nanowire, …



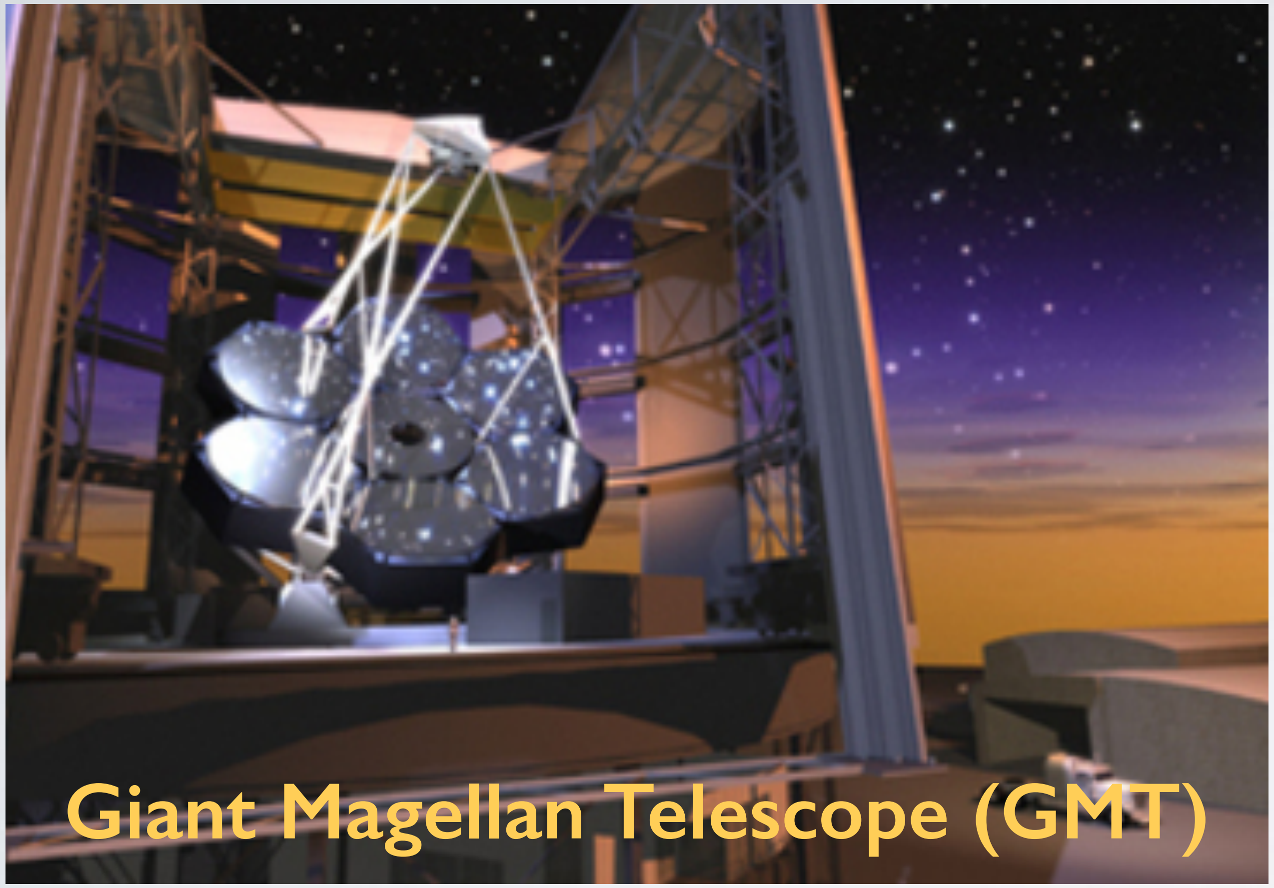


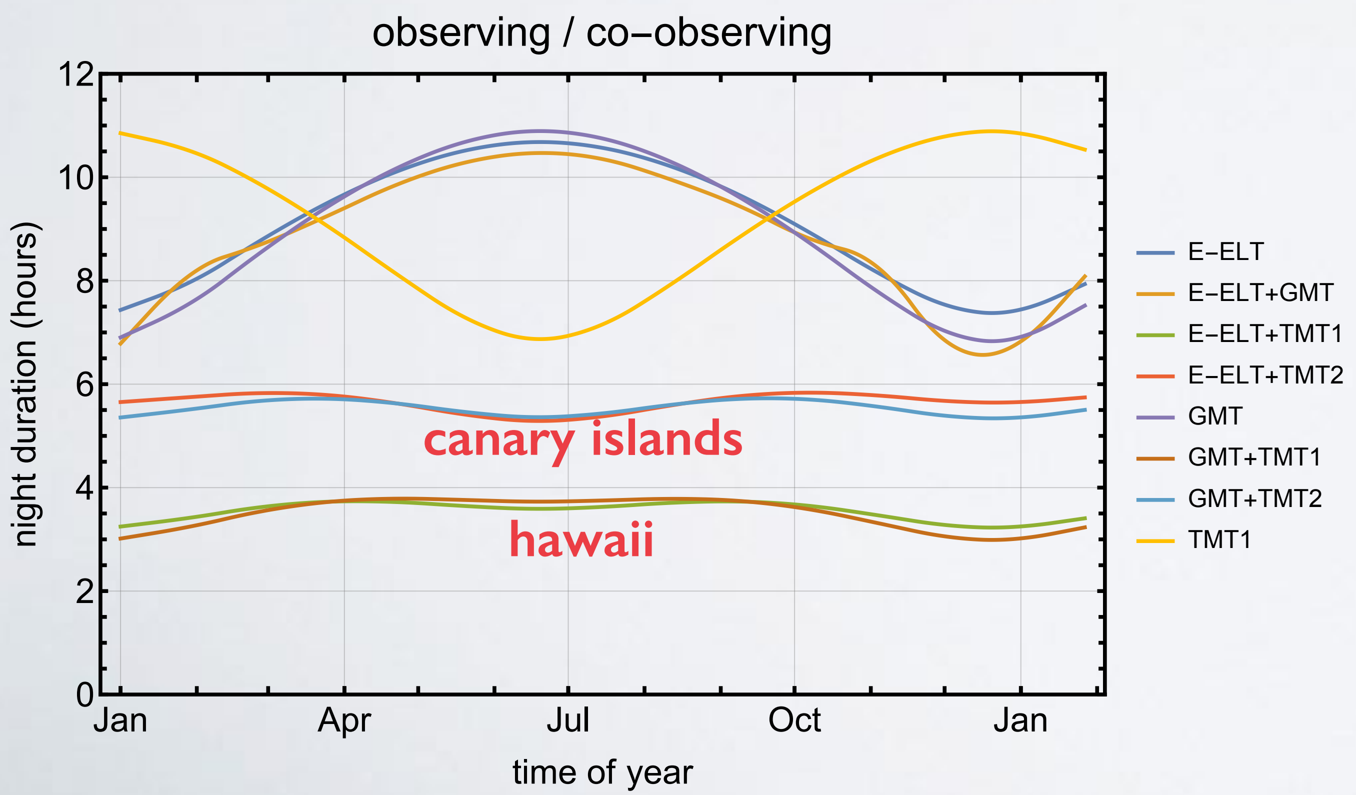
LARGE TELESCOPES WORLDWIDE

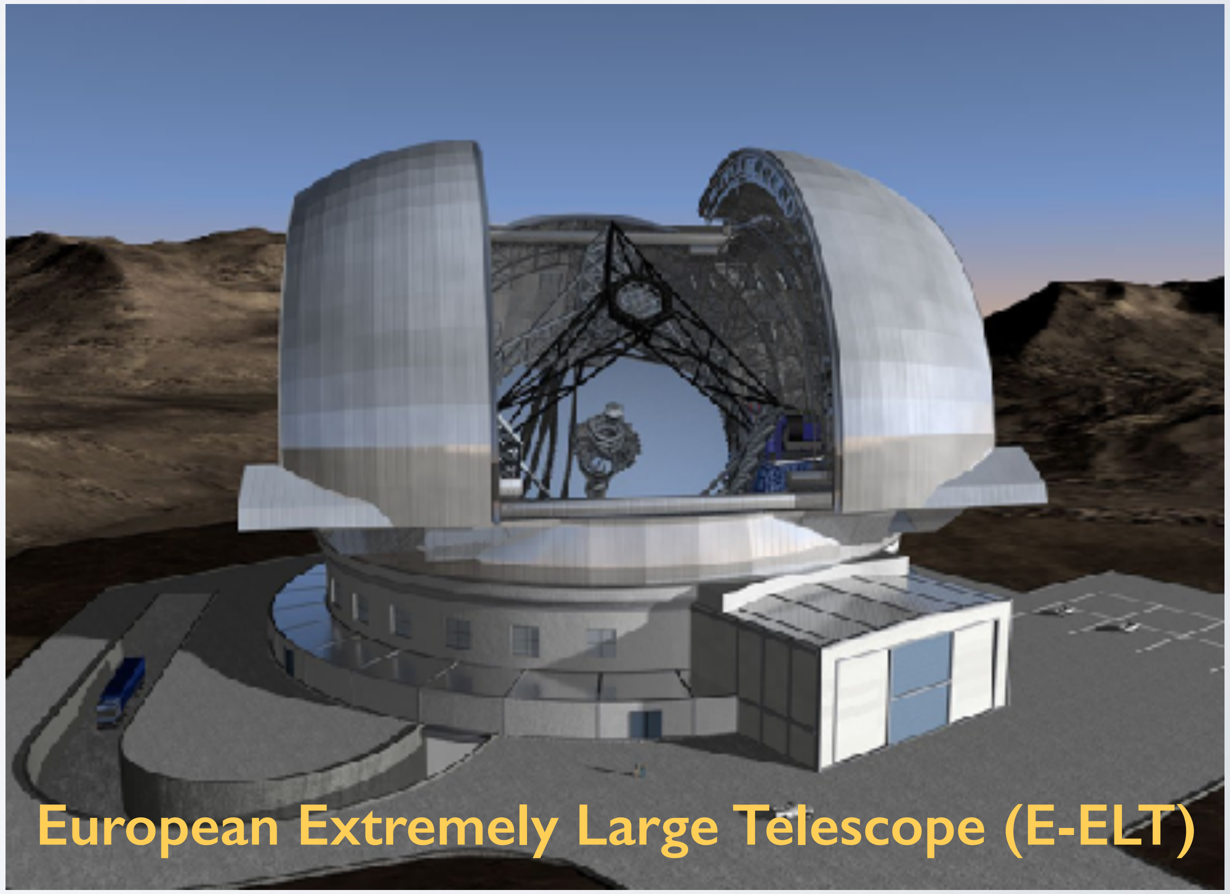


APERTURE “DIAMETER” ≥ 200”

EXTREMELY LARGE TELESCOPES





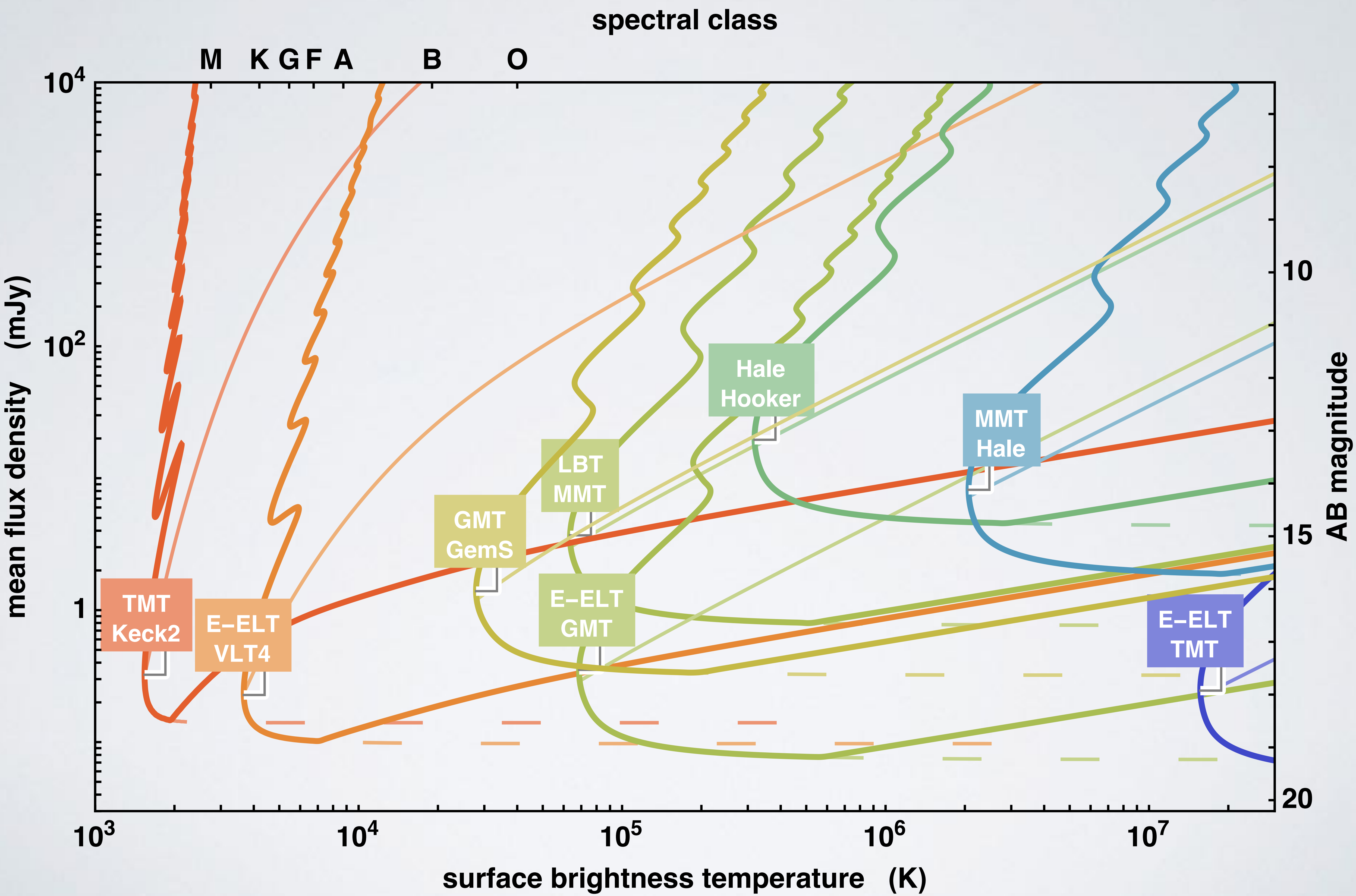


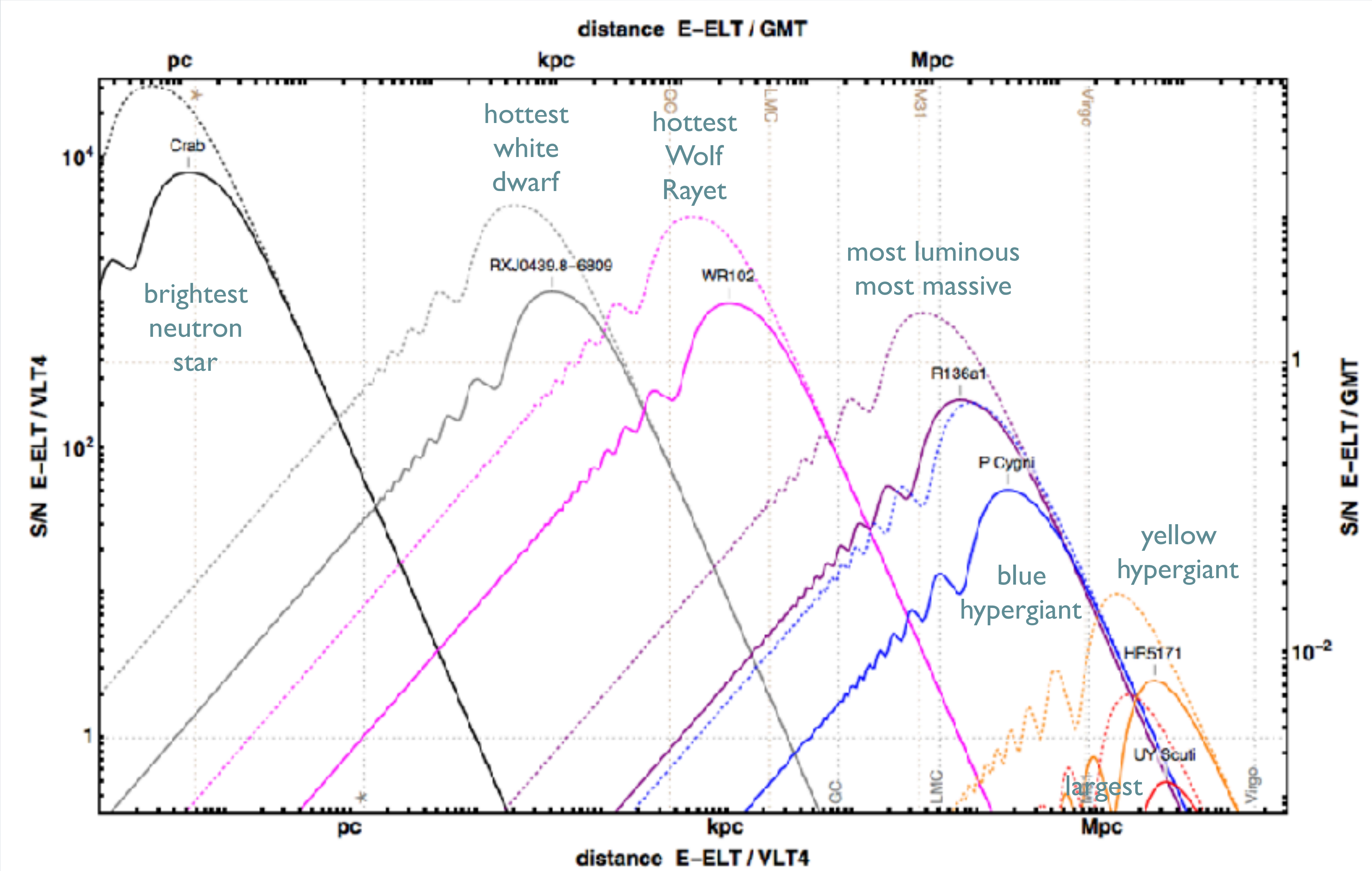
	GMT	E – ELT	TMTa	TMTb
GMT		$600\ m^2$ 495 km	$491\ m^2$ 9435 km	$491\ m^2$ 9925 km
E – ELT	≥ 125 nasec ≥ 18.7 km / pc		$800\ m^2$ 9334 km	$800\ m^2$ 9772 km
TMTa	≥ 7 nasec ≥ 1.0 km / pc	≥ 7 nasec ≥ 1.0 km / pc		
TMTb	≥ 6 nasec ≥ 0.9 km / pc	≥ 6 nasec ≥ 0.9 km / pc		

GIANT TELESCOPES

SURFACE BRIGHTNESS REQUIREMENTS

TEMPERATURE SENSITIVITY



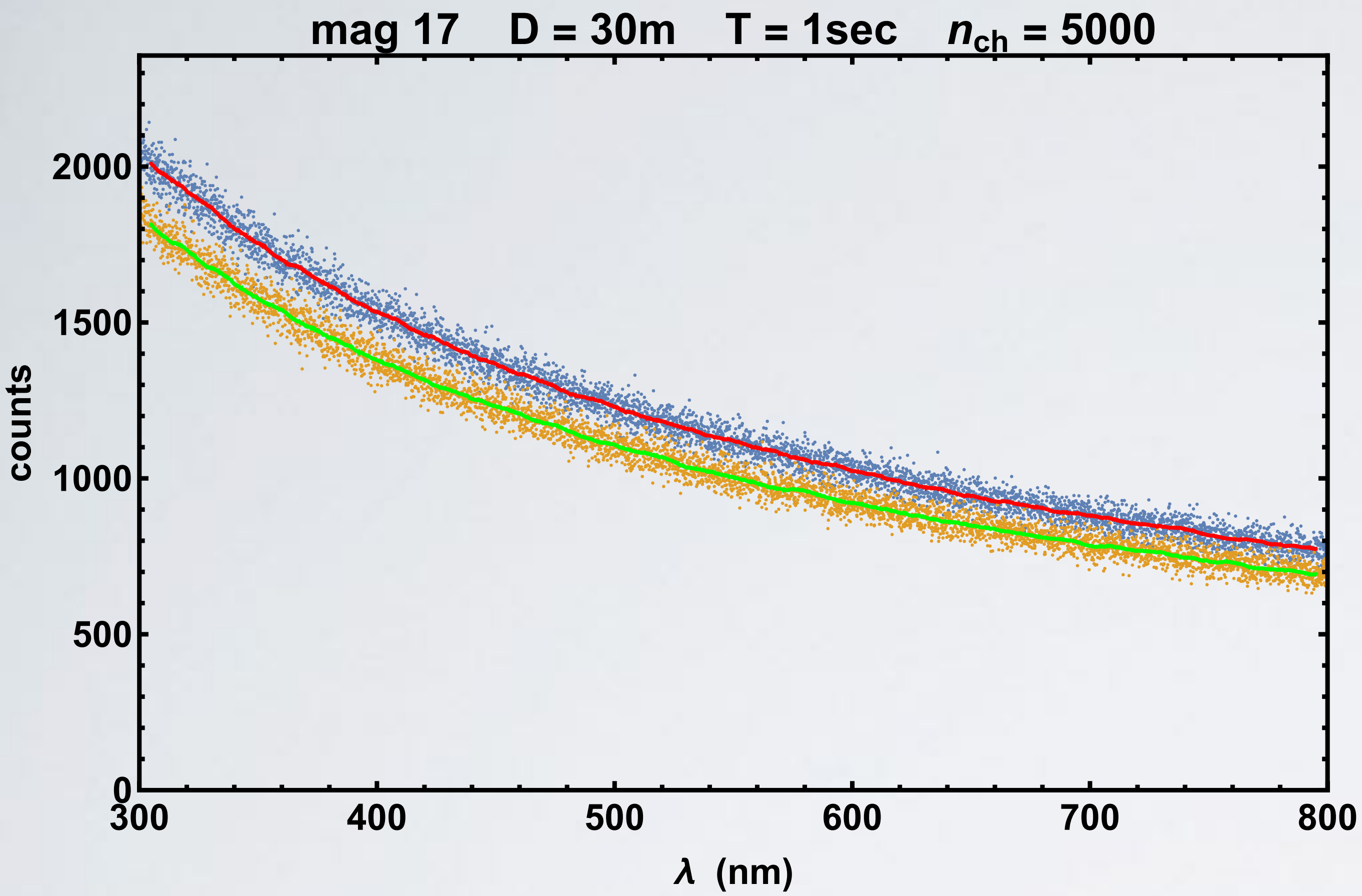


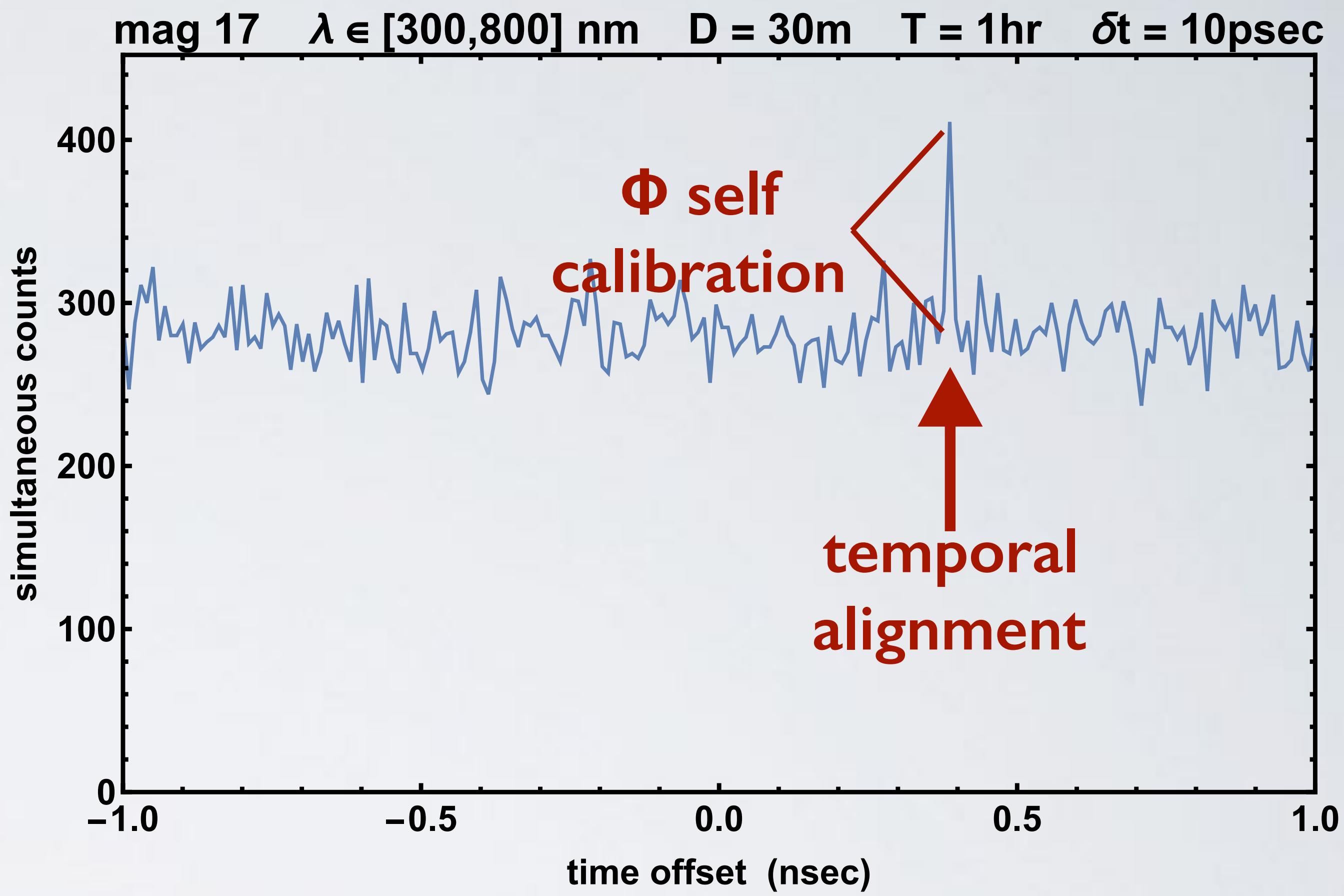
TARGETS: EXTREME STARS

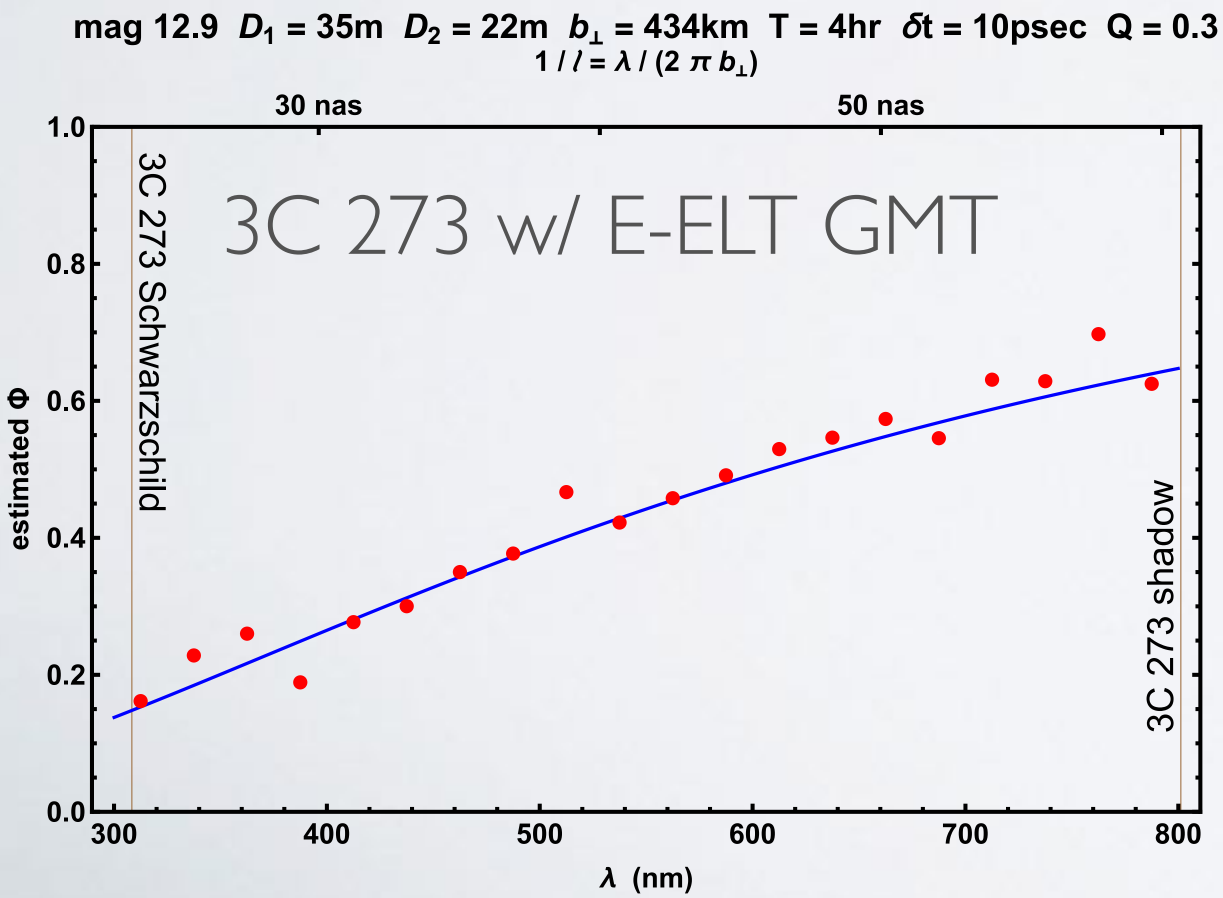
brightest / hottest / biggest / most massive / …

limited by assumed optical only (no IR) coverage [0.3,1]**µm**

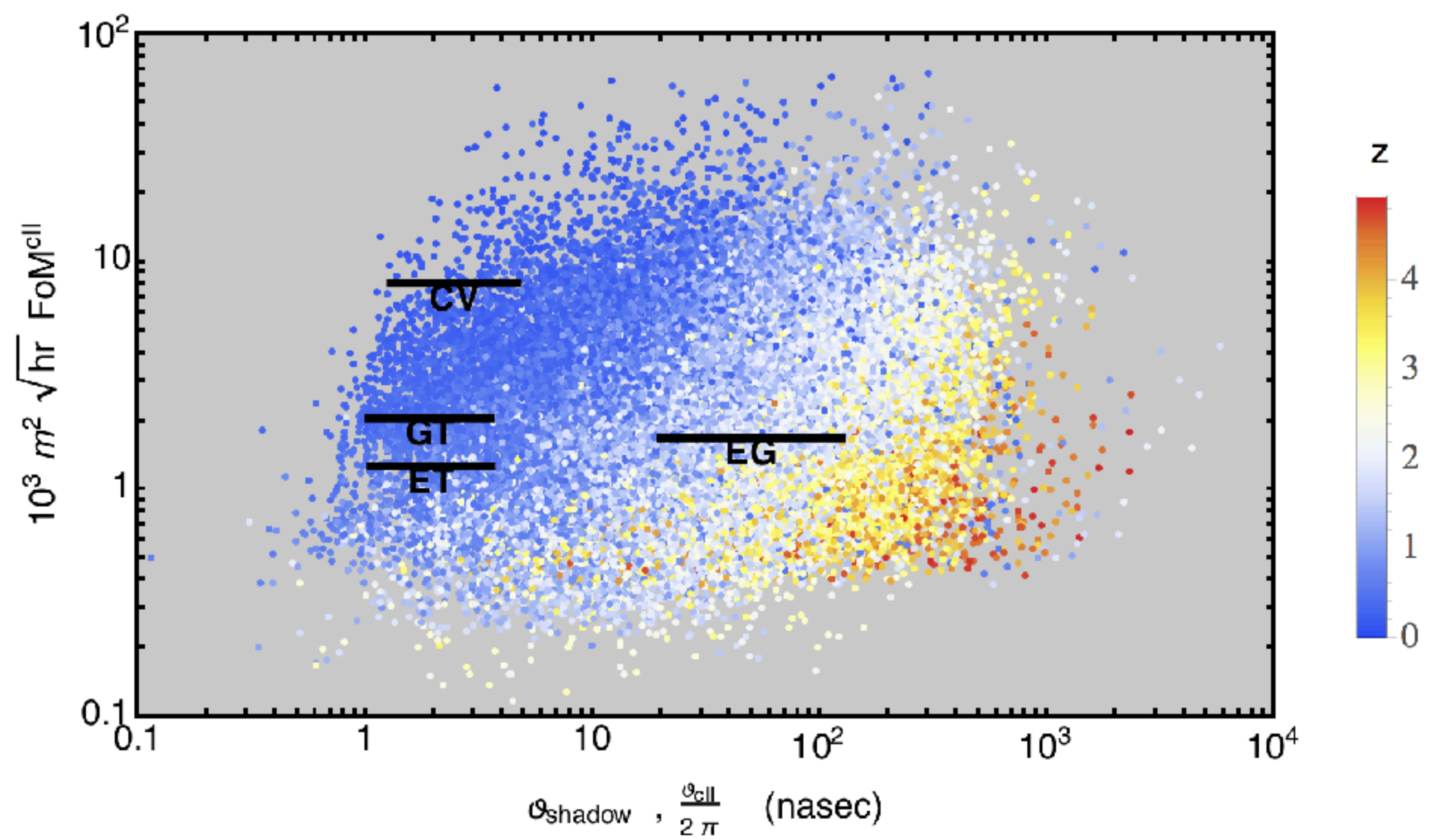
SIMULATED DATA







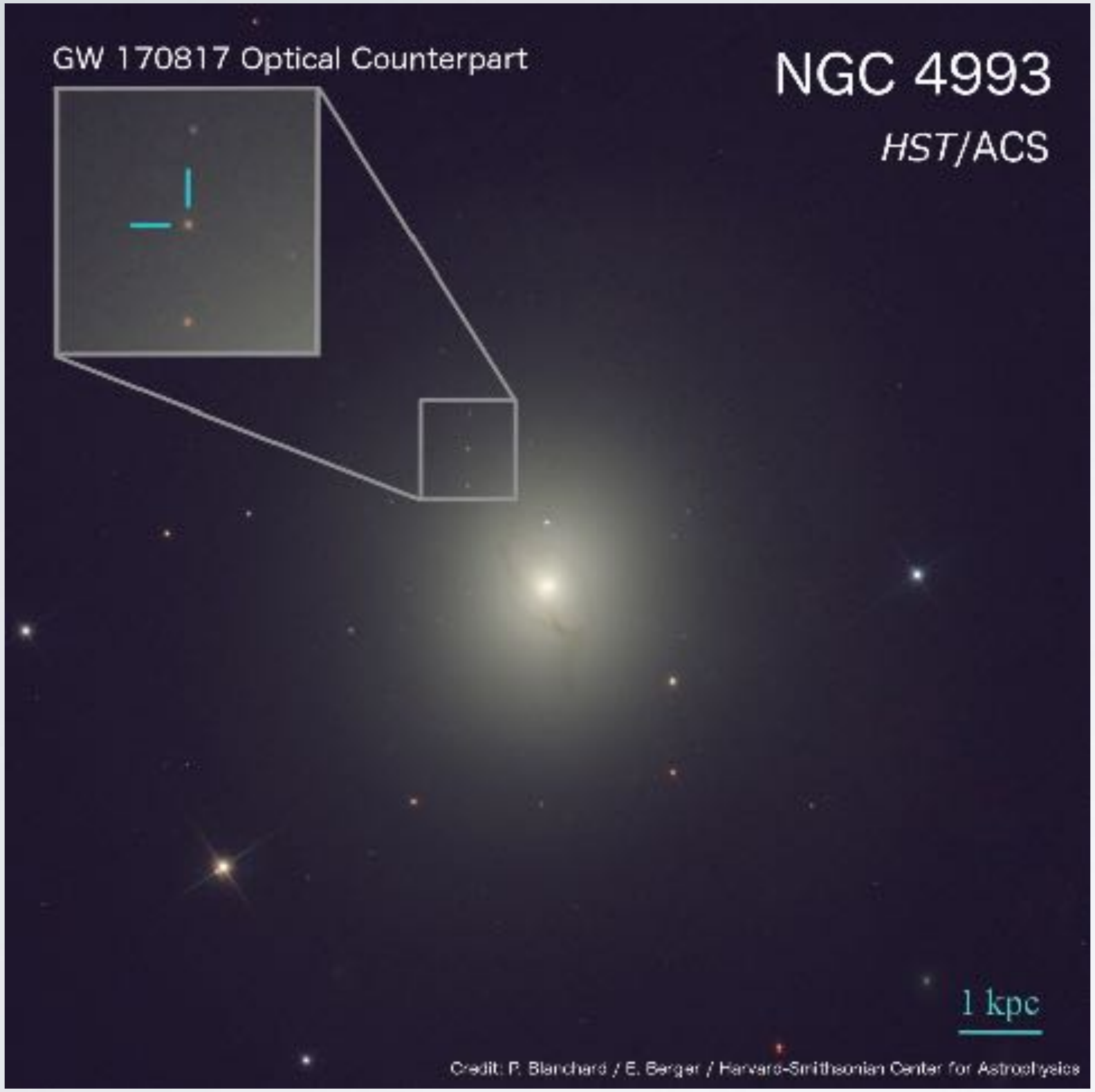
- each camera is a moderate spectral resolution / high very high time resolution spectro-photometer
- temporal alignments removes
  - tides / astrometric uncertainties / atmospheric refraction
- coherence function is self-calibrated by counts
-

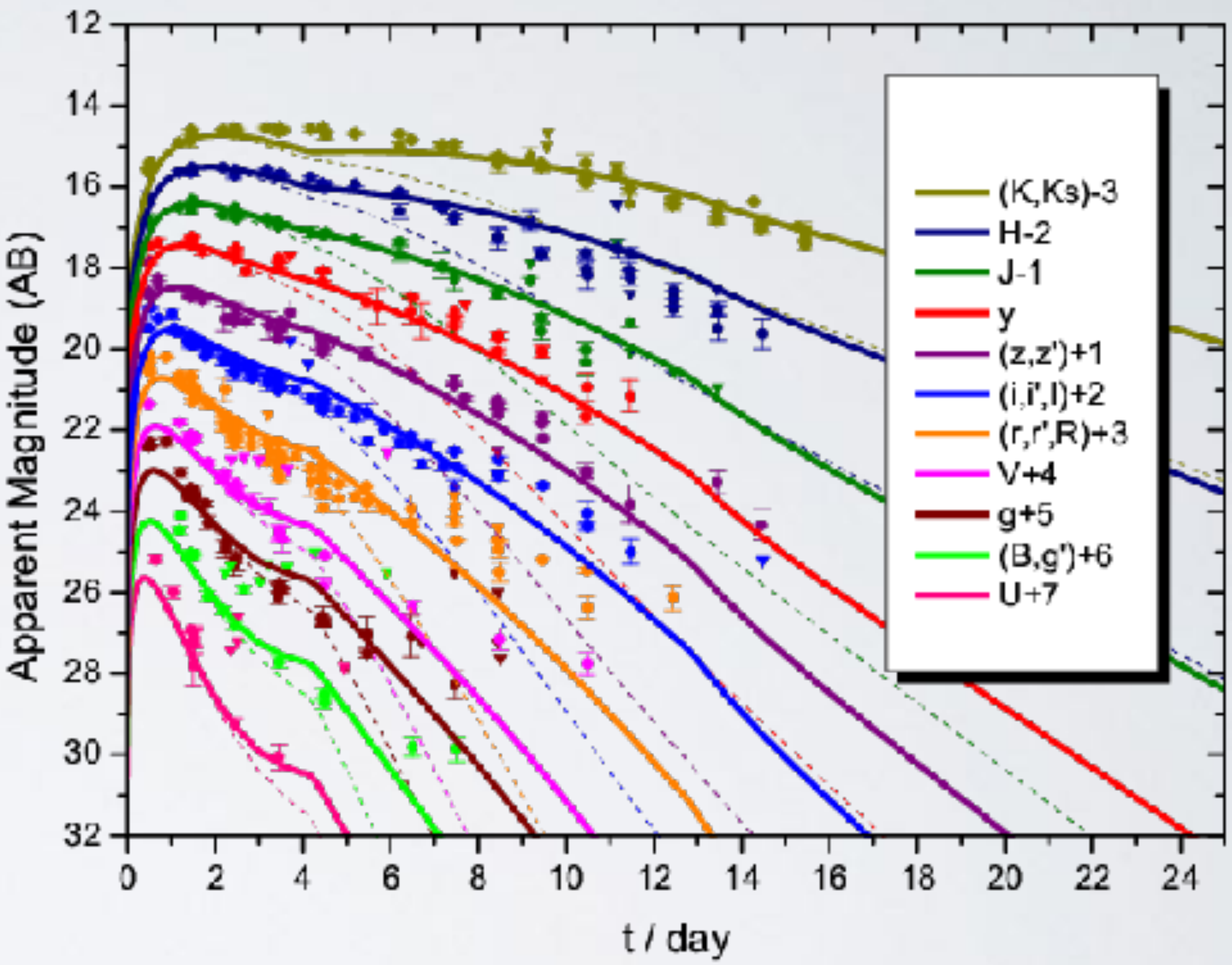


$10^3\ m^2\ \sqrt{hr}\ FoM^{cll}$
CV
GT
ET
EG
$\vartheta_{shadow}\ ,\ \frac{\vartheta_{cll}}{2\pi}$ (nasec)
z

TARGETS: QSO

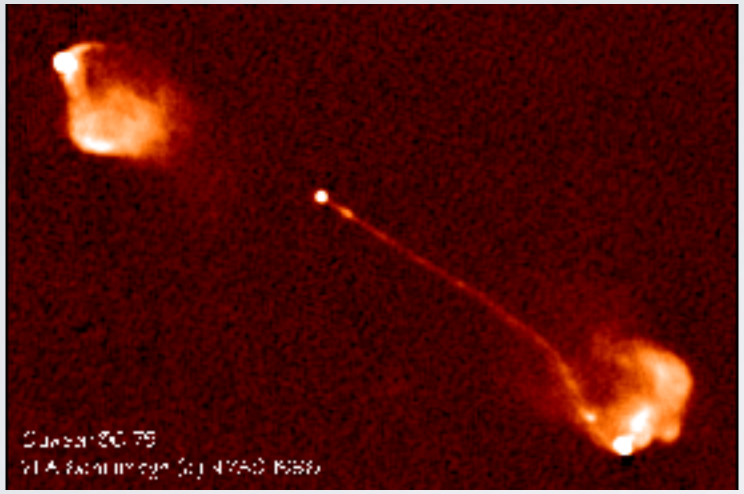
GW 170817

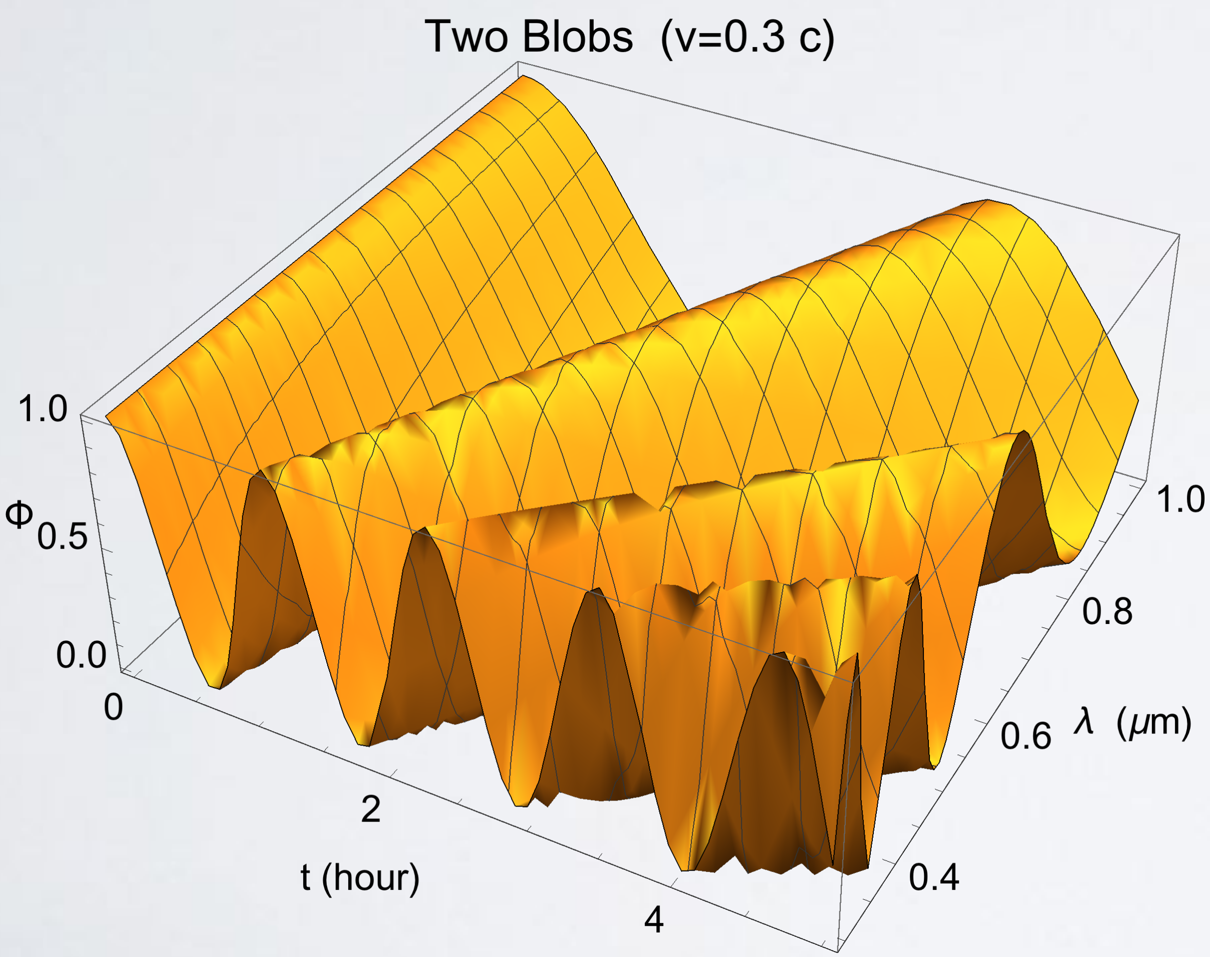


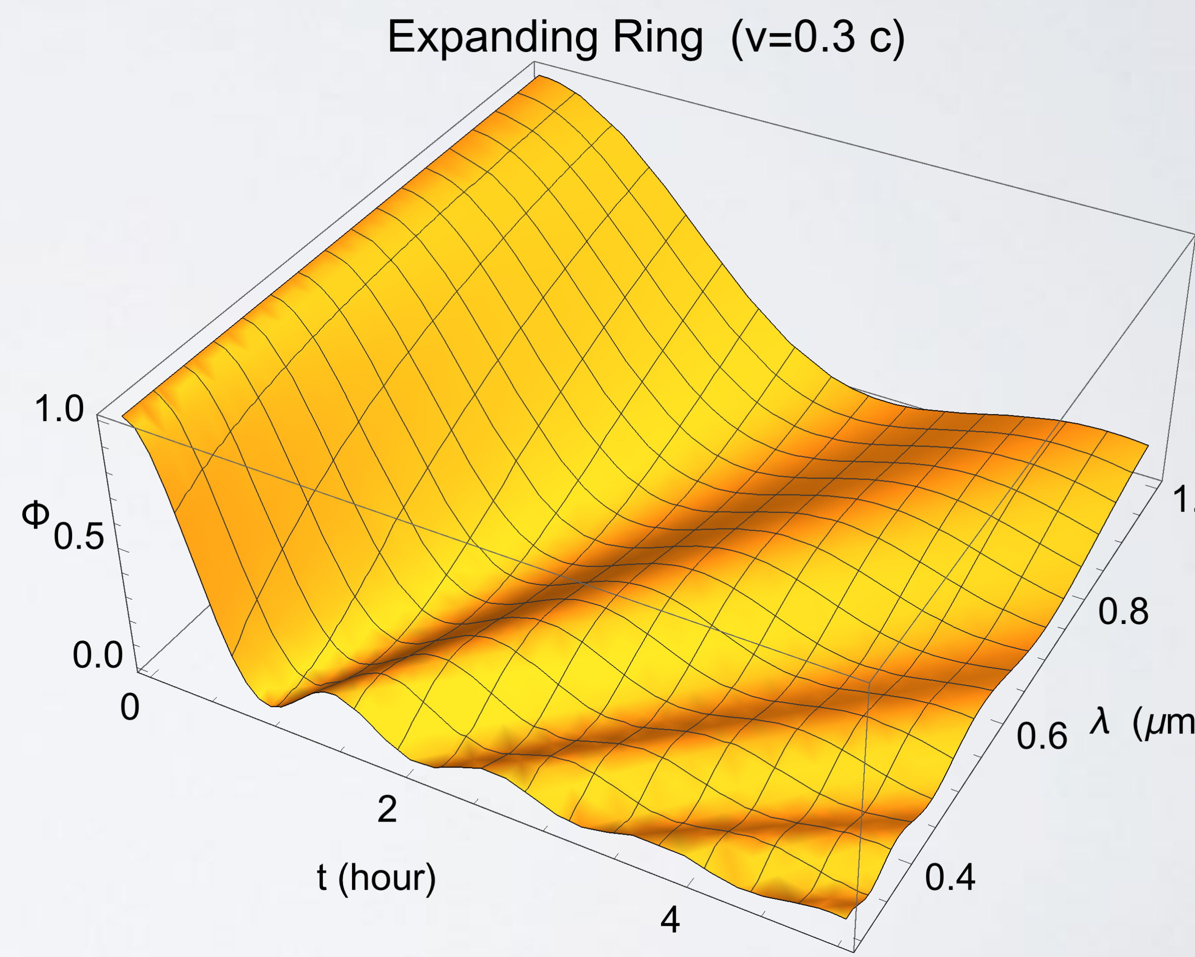


TARGETS: NEUTRON STAR MERGERS

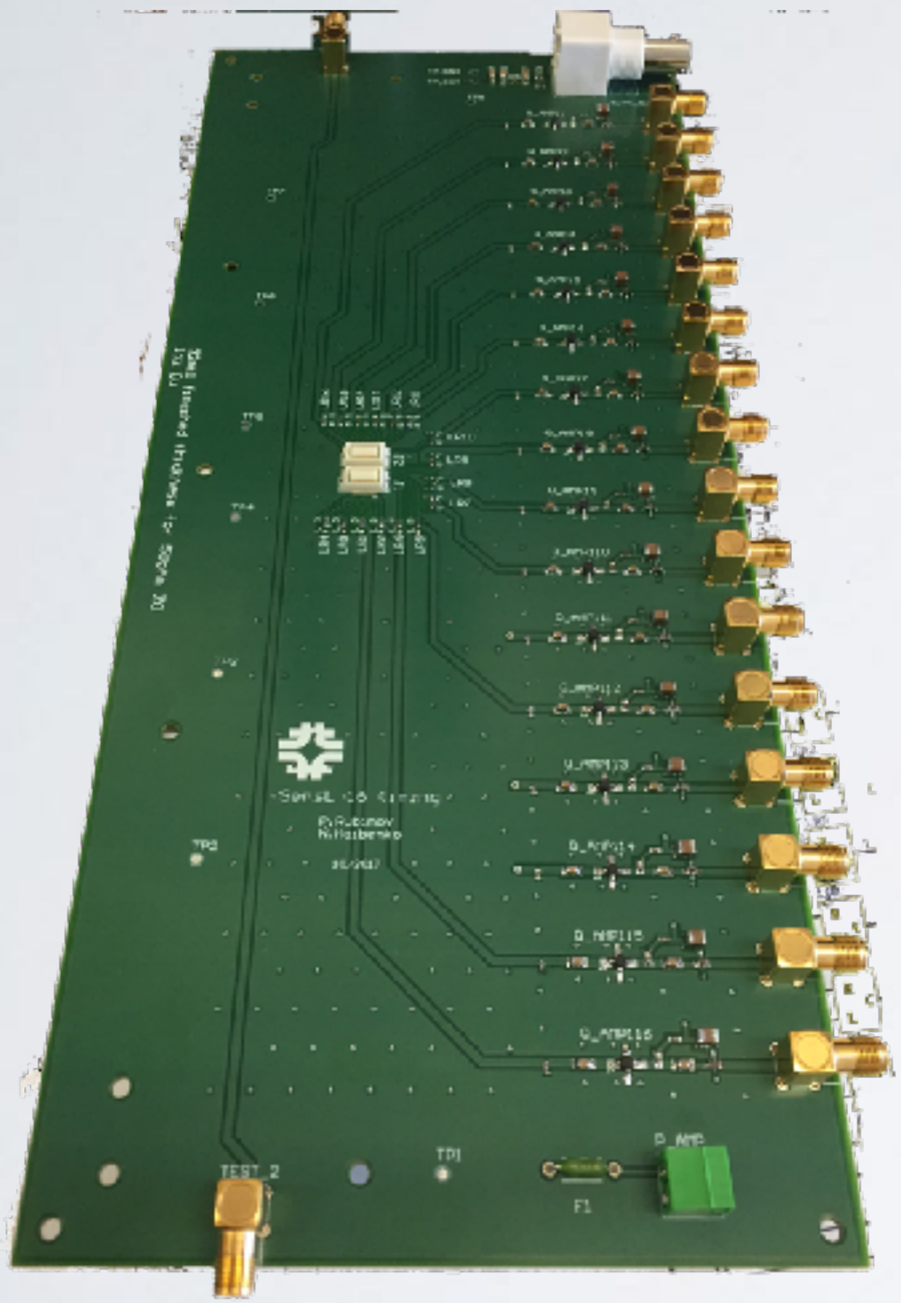
GW 170817 W/ GMT/E-ELT

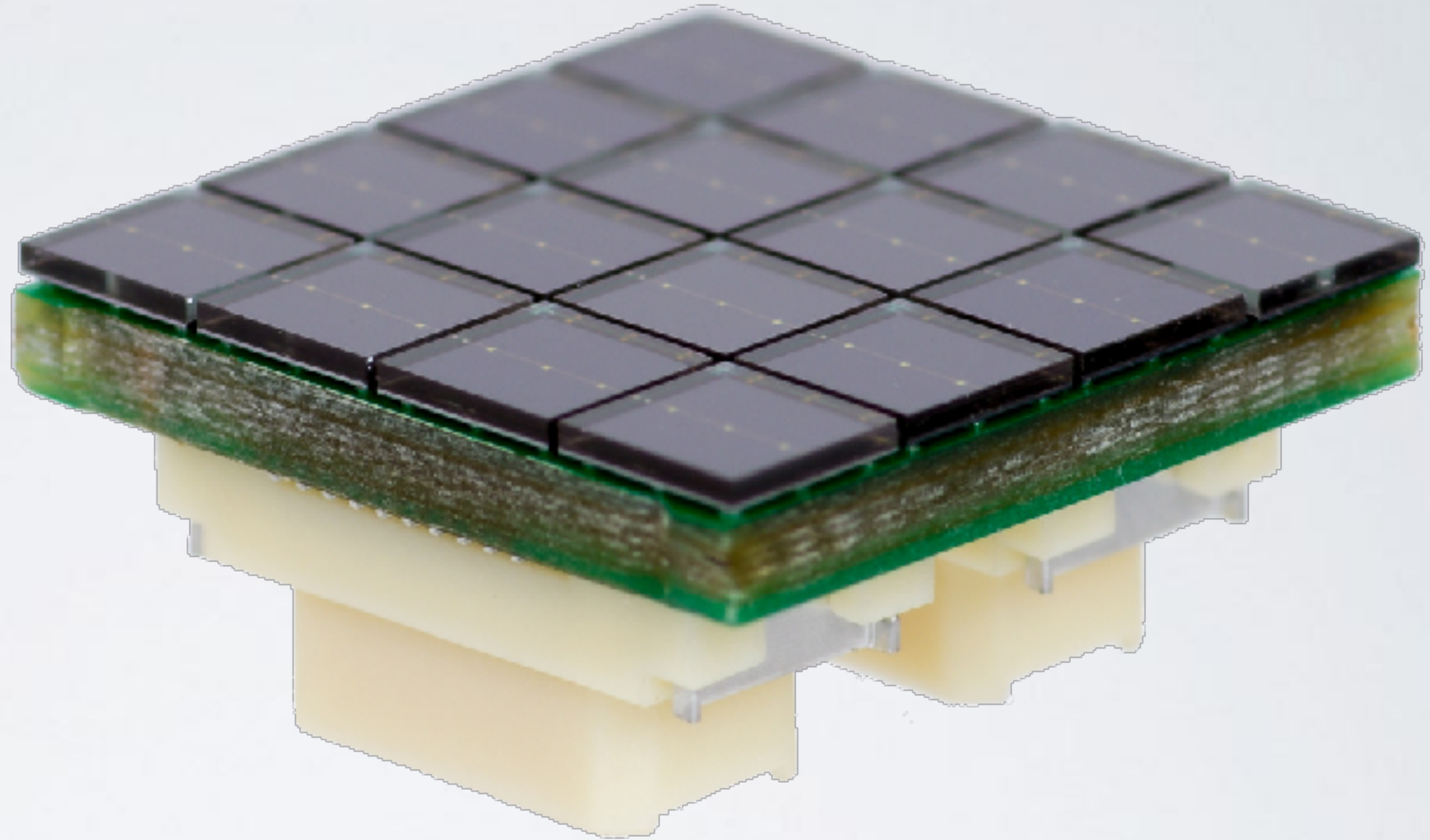






NANOCAM 2A





SUMMARY

- with technology that exists or will be available in next decade one is capable of decreasing best astronomical angular resolution to the nano-arc-second scale.

- this can be done in the optical!

- while most sources do not emit enough radiation on this angular scale to be observed there are many that do: e.g. supermassive black holes.

- detector technology is what is already used in HEP.