Intensity interferometry:
From stars to STAR
(... and back)

Mike Lisa
Ohio State University
# Outline

**Part I**
  - History, physics, promise

**Part II**
- The GGLP effect in subatomic collisions (1960-)
- Femtoscopy: in heavy ion physics (1976-)
  - the importance of space-time & results

**Part III**
- Back to the stars – VERITAS (2020-)
  - a high-energy-physics approach to stellar HBT interferometry

• Summary
Scientific careers interrupted/shaped by WWII

Richard Feynman (1918-1988)
PhD (Princeton) 1942
Joined Manhattan Project (Los Alamos), 1942
• secret emergency development of A-bomb

Joined R.D.F. project (Suffolk) 1936
• secret emergency development of radar

* Ph.D. plans “temporarily” interrupted...
The problem

- Warning
- ground-to-air defense
Tools at hand

Barrage balloons over London during World War II. Buckingham Palace & the Victoria in middle ground.

Right: Concrete acoustic mirrors at Denge near Kent

Aircraft spotter on the roof of a building in London.
An heroic story

- early warning
- ground-to-air targeting
- air-to-ground: bombing at night
- air-to-air: oscilloscopes in the belly of bombers and dogfighters (!)
Swords to ploughshares

Engineers after WW II
- highly trained in areas invented/developed **covertly & hurriedly**
- **arcane, confusing** formalism
- new perspectives brought to science and industry

Hanbury Brown turned to emerging field of radioastronomy
- “radio stars” were being measured with Michelson (amplitude) interferometry

Bawdsey Manor
The “Los Alamos” of RADAR
Michelson Interferometry 101

“Overhead” point source through 2 slits:

Dark fringes on the viewing screen

\[ \sin \theta_n = \frac{n \lambda}{b} \]

Point source “at an angle” through 2 slits:

Dark fringes on the viewing screen (shifted over)

\[ \sin \theta_n = \frac{n \lambda}{b} - \sin \eta \]
Michelson Interferometry 101

Two incoherent sources...

....Intensities add

\[ I(\theta) = I_1(\theta) + I_2(\theta) \]

(assumes equal brightness)
Michelson Interferometry 101

Two incoherent sources...

....Intensities add

\[ I(\theta) = I_1(\theta) + I_2(\theta) = 2I_0 \left( 1 + \cos \frac{\pi b \sin \eta}{\lambda} \cdot \cos \left[ \frac{2\pi b}{\lambda} (\sin \theta + \frac{1}{2} \sin \eta) \right] \right) \]

(assumes equal brightness)
Michelson Interferometry 101

Two incoherent sources...

....Intensities add

\[ I(\theta) = I_1(\theta) + I_2(\theta) = 2I_0 \left\{ 1 + \cos \frac{4\pi b \sin \eta}{\lambda} \cos \left[ \frac{2\pi I}{\lambda} (\sin \theta + \frac{1}{2} \sin \eta) \right] \right\} \]

(assumes equal brightness)

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Michelson Interferometry 101

"visibility": \( V \equiv \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{\text{Fringe amplitude}}{\text{Average intensity}} \)

resolution: \( \Delta \eta_{\text{interferometer}} = \frac{\lambda}{2b} \)

Light must travel undisturbed from:
- source to slits/mirrors/telescopes
- slits/mirrors/telescopes to screen to screen to preserve \( E(t) \) phase

Challenge #1
Kolmogorov turbulence calculation. Each contour represents \( \frac{\sqrt{2}}{2} \) of wavefront distortion (here, \( \lambda = 2.2 \mu \text{m} \))

Challenge #2
measuring small stars requires large baseline
Measurement of Betelgeuse (α Orionis)

Betelgeuse angular size: $2.3 \times 10^{-7}$ rad ($= 4.8$ mas)

First measured by Michelson at Mt. Wilson Observatory, home of the 100-inch telescope

using yellow-green (575 nm) light

→ need baseline: $d = 1.22 \frac{\lambda}{\alpha} = 1.22 \frac{575 \cdot 10^{-9}}{2.3 \cdot 10^{-7}} m = 3.05 m = 10$ feet $> 100$ inches

round star: $\alpha = 1.22 \times \frac{\lambda}{2d} \rightarrow$ correlation vanishes
to measure small $\alpha$:

\[
\begin{aligned}
\text{small } \lambda \text{ (visible)} \\
\text{large baseline } d 
\end{aligned}
\]

Encouraged by this success, attempt in 1931 at larger (50') design....

... but failed:
- technique requires phase stability to within $\lambda$
- steel flexed too much, turbulence effects too great

The end of optical-spectrum Michelson interferometry for decades

"... the resulting interference fringes, though in motion, are quite distinct, unless the period of the disturbances is too rapid for the eye to follow." [1]
Michelson discussed “rapidly-shifting fringe patterns” on stormy nights, with optical frequencies.

- (Today, effect can be reduced through “closure phases”– redundancy with large arrays)

Much less of a problem with radio.

resolution: \( \Delta n_{\text{interferometer}} = \frac{\lambda}{2b} \)

- much longer baselines required...
- ... but transmitting radio signals with fidelity over cables is easier

+ advances in RADAR & electronics during the war

→ 1950’s – radioastronomy & radiointerferometry boom
Three simultaneous publications

Size determination of radio sources Casseopia A & Cygnus A

Apparent Angular Sizes of Discrete Radio Sources: Observations at Jodrell Bank, Manchester
R. Hanbury Brown, R.C. Jennison, M.K. Das Gupta
Nature 170 (1952) 1061

Apparent Angular Sizes of Discrete Radio Sources: Observations at Sydney
B.Y. Mills
Nature 170 (1952) 1063

Apparent Angular Sizes of Discrete Radio Sources: Observations at Cambridge
F.G. Smith
Nature 170 (1952) 1065

Michelson interferometers with baselines ~ km

\[ \Delta \theta_{\text{vanish}} = \frac{\lambda}{2b} \quad \rightarrow \quad b_{\text{required}} \approx \frac{\lambda}{2\Delta \theta} = \frac{1.5 \text{ m}}{3 \cdot 10^{-3}} = 500 \text{ m} \]
The resolving power of an interferometer depends primarily on the ratio of the wave-length to the base-line, and the limits quoted above represented the best performance obtained with the instruments. These limits cannot be reduced significantly without a corresponding extension of the base-line.

In 1950 it was decided at Jodrell Bank to attempt to measure the angular size of the two sources shown in Table 1, or at least to reduce the upper limits given for their size. It was assumed that this angular size might lie anywhere between the limit of a few minutes of arc and the diameter of the visible stars, and an instrument of the highest possible resolving power was therefore sought. While it appeared to be possible to extend the base-lines of existing interferometers to lengths of the order of 10–50 km, it was considered that for much longer base-lines the problem of maintaining an adequate stability of phase in the transmission of signals along the base-line would prove to be difficult. For this reason an interferometer of completely new design was developed.

For this reason [difficulty of phase stabilization over long distances], an interferometer of completely new design was developed.

The theory of the instrument is involved, and it will be given in detail elsewhere. It can be shown that the value of the cross-correlation coefficient ($\rho$) is given by an expression similar to that for the visibility of the fringes in a Michelson stellar interferometer:

$$\rho = \frac{\sin^2 (\pi x b \lambda)}{(\pi x a \lambda)^2},$$

where $\lambda$ is the angular width of an equivalent point source.

... more than 2 years later!
LXXIV. A New Type of Interferometer for Use in Radio Astronomy

By R. Hanbury Brown
Jodrell Bank Experimental Station, Cheshire

and

R. Q. Twiss
Services Electronics Research Laboratory, Baldock, Herts.*

[Received March 20, 1954]

Summary

A new type of interferometer for measuring the diameter of discrete radio sources is described and its mathematical theory is given. The principle of the instrument is based upon the correlation between the rectified outputs of two independent receivers at each end of a baseline, and it is shown that the cross-correlation coefficient between these outputs is proportional to the square of the amplitude of the Fourier transform of the intensity distribution across the source. The analysis shows that it should be possible to operate the new instrument with extremely long baselines and that it should be almost unaffected by ionospheric irregularities.
The Intensity Interferometer

HB & T Phil. 45 (1954) 663

More complicated, in principle and in practice and in formalism!

E(t) phase information is discarded – intensities are analyzed

A narrow range of frequencies from a point source → noise (with random beats)
The Intensity Interferometer

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Incoherent second source, with its own random beats...
→ a time correlation measured by correlator circuit
→ “Visibility” (in time) patterns similar to Michelson interferometer

Data recorded on paper strip charts (😊!).
• (too slow to capture fast beats)
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Normalized correlation:

\[ C = \frac{\langle S_1 \cdot S_2 \rangle}{\langle S_1 \rangle \langle S_2 \rangle} \]
The Intensity Interferometer

Normalized correlation:
- dependence on separation (baseline) reveals source size

\[ C = \frac{\langle s_1 \cdot s_2 \rangle}{\langle s_1 \rangle \langle s_2 \rangle} \]

HBT interferometer contributed to growing catalog of radio sources in 50’s & 60’s
In the final paragraph of Phil Mag 45 (1954) 663, almost as an afterthought...

The use of the 'Michelson' interferometer at radio wavelengths is a logical extension of optical practice and it is interesting to enquire whether the principle of the new type of interferometer can in turn be applied to visual [optical] astronomy, since in this way it might be possible to increase the resolving power and mitigate the effects of atmospheric turbulence.

\[
\Delta \theta \approx \frac{\lambda}{2b} \sim \frac{1}{\# \lambda'}
\]

Cygnus measurement: \( \# \lambda' \approx \frac{10 \text{ km}}{1 \text{ m}} = 10^4 \)

optical: \( \lambda \sim 5 \cdot 10^{-7} \text{ m} \) → potential to measure even smaller stars (in principle)
Hanbury Brown’s one-sentence abstract posted prior to CRIS ’98: 
The talk will give a brief history of the early development of Intensity Interferometry and its subsequent battle against common sense.
Immediate and prolonged controversy

While HBT interferometry was not controversial when applied to radio wavelengths, light in the optical spectrum was considered in terms of photons, and it seemed that “photons were interfering”

P.A.M. Dirac, in his 1930 textbook: “Each photon interferes only with itself. An interference between two different photons never occurs.”

“The existence of a correlation between photons has been denied by some authors... who have stated... that it is contrary to the laws of quantum mechanics. The error appears to have arisen because of a too literal reliance on the corpuscular picture of light.... In practice, the corpuscular picture is more of a hindrance than a help.”


“The Brown-Twiss effect, far from requiring a revision of quantum mechanics, is an instructive illustration of its elementary principles.”

-- Nature 178 (1956)
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-- Edward Purcell, 1952 Nobel Prize
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“The difficulty which many physicists had in accepting that the arrival of photons can be correlated was that most of them were particle physicists who thought of a photon as a real thing with its own properties, like a billiard ball, whereas it is better to think of a photon as an event, not as a thing, as something which happens when light is generated or detected.”
-- R.HB. proceedings of CRIS ‘98

Photons do not travel. Waves propagate and photons are quantum events
... Particles do not travel!

“The fact that this correlation is equally to be expected, on a classical theory, at optical wavelengths, appears to have been overlooked.”

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Edward Purcell 1952 Nobel Prize

Meanwhile, HB’s experience led naturally to extracting geometric information from the detection time of radiation.
All one needs are "photon buckets"

Two army searchlights used to measure Sirius

Figure 10.1 The first stellar intensity interferometer: the pilot model of the stellar intensity interferometer at Jodrell Bank in 1955. Two Army searchlights were used to make the first measurement of the angular diameter of a main sequence star (Sirius)

The humble beginnings of Quantum Optics
Roy Glauber – 2005 Nobel Prize for work on Quantum Optics

P.A.M. Dirac, in his 1930 textbook: “Each photon interferes only with itself. An interference between two different photons never occurs.”

In Glauber’s Nobel Lecture: “Forgive me. This is QM scripture, but it is also nonsense.”

An appropriate subtitle for the Lecture: “Why Robert Hanbury-Brown also should have gotten the Nobel Prize”

* This statement is in his talk, but not the later write-up
Intensity Interferometry in 1963 Narrabri, Australia
HBT interferometer contributed to growing catalog of radio & optical sources in 50’s & 60’s

Eventually, problems with (much simpler) Michelson interferometry were overcome & stellar intensity interferometry ended in early 70’s
Intensity Interferometry in 2000, Long Island, NY

How did we get here?

Relativistic Heavy Ion Collider (RHIC) ring – 2.4-mile circumference
Intensity Interferometry in 1963 Narrabri, Australia

M.A. Lisa - Coloquio - Instituto de Física Teórica (IFT), Universidade Estadual Paulista (UNESP), São Paulo, Brasil
Influence of Bose-Einstein Statistics on the Antiproton-Proton Annihilation Process*

Gerson Goldhaber, Sulamith Goldhaber, Wonyong Lee, and Abraham Pais†

Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California
(Received May 16, 1960)
• low statistics!
• back-to-back preference lower for like-sign pairs
• Statistical Model (SM) captures main features (phasespace dominates)
• Agreement improves when Bose-Einstein correlations modify phasespace
  • R=0.75 fm used [reasonable enough]

until recently, in particle physics the GGLP effect is relevant mostly inasmuch as it distorts the W mass (e.g. arXiv:hep-ph/9805223)
• in heavy ion physics, however, it plays a prominent role
LHC @ CERN France/Switzerland

proton & nucleus collisions
$\sqrt{s_{\text{NN}}} \sim 2.8\text{-}13 \text{ TeV}$

RHIC @ Brookhaven Lab, NY

proton & nucleus collisions
$\sqrt{s_{\text{NN}}} \sim 7\text{-}550 \text{ GeV}$
Relativistic **Heavy Ion Collider**

**RHIC @ Brookhaven Lab, NY**

Proton & **nucleus** collisions
\[ \sqrt{s_{NN}} \approx 7-550 \text{ GeV} \]

**Large Hadron* Collider**

**LHC @ CERN France/Switzerland**

Proton & nucleus collisions
\[ \sqrt{s_{NN}} \approx 2.8-13 \text{ TeV} \]
• Theory of Strong Force between quarks: Quantum Chromodynamics (QCD)
• Strength of the Strong Force depends on momentum transfer (spatial scale)
• Complicated & least-well-understood interaction

"Running" of the QCD coupling constant
Particle Physics

- Asymptotic Freedom
  - reduce “messy” QCD effects

Focus on fundamental particles

- Smaller/simpler is better
- More energy is better

Large Q:

- QED vs QCD
  - \( e^+ e^- \) vs Gluon

Vacuum fluctuations (e.g. \( e^+ e^- \) pairs) screen electric charge

Electric charge appears stronger at smaller distance (e.g. \( \alpha \approx 1/128 \) at 90 GeV)

Gluons (unlike photons) carry (color-) charge

Contribution of Gluons (Spin 1) to vacuum fluctuations leads to anti-screening

Color charge appears smaller at smaller distance (higher momentum interactions)

Polarization of the Vacuum

Asymptotic Freedom

- QED
- QCD

Large Q:

- reduce “messy” QCD effects

Smaller/simpler is better

More energy is better
**Heavy Ion Physics**

**Low Q: Confinement**
- dominates mass in universe
- theoretical insight limited

**intrinsic scales of QCD**
- optimum energy range
- bigger is better (>> 1 fm)

**Large Q: Asymptotic Freedom**
- reduce “messy” QCD effects

**fundamental interaction**

**fundamental particles**

**Asymptotic Freedom**
- reduce “messy” QCD effects

**Smaller/simpler is better**
- More energy is better

**QED vs QCD**

- **e^+ e^-**
- **γ**
- **q q**
- **Vacuum fluctuations (e.g. e^+ e^- pairs) screen electric charge**
  - Electric charge appears stronger at smaller distance (e.g. \( \alpha \approx 1/128 \) at 90 GeV)

- **Gluons (unlike photons) carry (color-) charge**
  - Contribution of Gluons (Spin 1) to vacuum fluctuations leads to anti-screening
  - Color charge appears smaller at smaller distance (higher momentum interactions)

**Polarization of the Vacuum**

**Optimum Energy Range**
- **bigger is better** (>> 1 fm)

**Intrinsic Scales of QCD**
- **focus on fundamental particles**

**Confinement**
- **focus on fundamental interaction**

**Heavy Ion Physics**
- **e.g. Higgs**

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Confinement generates most (visible) mass

- **Dark Energy**
- **Dark Matter**
- **“Ordinary” Matter**
- **QCD Contribution** (~4%)
- **Higgs Contribution** (~4%)
Heavy ion collisions form a geometrically nontrivial *system* that experiences bulk evolution

- space-time plays a huge role

but... we detect only particle *momenta*, not spacetime information

hydro simulations by Bjorn Schenke
Evolution to heavy ion collisions

- early 1970’s: connection between GGLP and HBT [Shuryak. Kopylov, Podgiretsky...]

\[ \Psi = \frac{1}{\sqrt{2}} \left[ U(\vec{x}_1, \vec{p}_1) e^{i(\vec{r}_1 - \vec{x}_1) \cdot \vec{p}_1} \times U(\vec{x}_2, \vec{p}_2) e^{i(\vec{r}_2 - \vec{x}_2) \cdot \vec{p}_2} \right. 
\[ \quad + U(\vec{x}_2, \vec{p}_1) e^{i(\vec{r}_1 - \vec{x}_2) \cdot \vec{p}_1} \times U(\vec{x}_1, \vec{p}_2) e^{i(\vec{r}_2 - \vec{x}_1) \cdot \vec{p}_2} \left. \right] 
\]

\[ \Psi^* \Psi = U^*_1 U_1 \cdot U^*_2 U_2 \cdot \left( 1 + e^{i(\vec{p}_2 - \vec{p}_1) \cdot (\vec{x}_2 - \vec{x}_1)} \right) \]

Width ~ $1/R$

\[ C(\vec{p}_1, \vec{p}_2) \equiv \frac{P(\vec{p}_1, \vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)} = 1 + |\hat{\rho}(\vec{q})|^2 \]

<table>
<thead>
<tr>
<th>C (Q⁻)</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>q=p₁-p₂</td>
<td>0.05</td>
<td>0.10</td>
</tr>
</tbody>
</table>

| Width ~ 1/R | Measurable | F.T. of pion source | Phys. Lett. 44B (1973) 387 | Edward Shuryak | M.A. Lisa - Coloquio - Instituto de Física Teórica (IFT), Universidade Estadual Paulista (UNESP), São Paulo, Brasil |
Evolution to heavy ion collisions

- early 1970’s: connection between GGLP and HBT [Shuryak, Kopylov, Podgiretsky...]

- late 1970’s – early 1980’s: explosive development in new field of heavy ion collisions
Correlation expresses a conditional probability ($\sim$stellar HBT)

\[
C(\vec{q}) = 1 + \int d^3r S(\vec{r}) \cos(\vec{q} \cdot \vec{r}) = \frac{N(\vec{p}_1, \vec{p}_2)}{N_{\text{mix}}(\vec{p}_1, \vec{p}_2)}
\]

separation distribution:

\[
S(\vec{r}) \equiv \frac{\int d^4x_1 \int d^4x_2 \rho_1(x_1) \rho_2(x_2) \delta(\vec{r} - \vec{x}_1 + \vec{x}_2)}{\int d^4x_1 \rho_1(x_1) \int d^4x_2 \rho_2(x_2)}
\]

still dominated by phasespace
\[ \pi^\pm - \pi^\pm, K^\pm - K^\pm, K_S^0 - K_S^0, p - p, \bar{p} - \bar{p}, \Lambda - \Lambda, K^\pm - \pi^\pm, p - \Lambda, \Xi - \pi... \]

\[ R_0 = 3.0 \pm 0.2 \text{ fm} \]

\[ C(k^*) \]

\[ C_{pp}(k^*)/C_{pp}(k^*) \]

\[ K_S^0 - K_S^0 \]
Geometry – the hallmark of heavy ion physics

- Size matters – need a *bulk* system

Sanity check: intensity interferometry for 3 colliding systems

- STAR
  - p+p
  - \( R \sim 1 \text{ fm} \)
- d+Au
  - \( R \sim 2 \text{ fm} \)
- Au+Au
  - \( R \sim 6 \text{ fm} \)
Geometry – the hallmark of heavy ion physics

- Size matters – need a *bulk* system
- Timescale matters – highly dynamic system
Geometry – the hallmark of heavy ion physics

• Size matters – need a *bulk* system
• Timescale matters – highly dynamic system
• Shape matters – anisotropic geometry key

hydro calculations: Kolb & Heinz
Geometry – the hallmark of heavy ion physics

- Size matters – need a *bulk* system
- Timescale matters – highly dynamic system
- Shape matters – anisotropic geometry key
- Substructure matters

Intensity interferometry is the *only* direct probe of spacetime in subatomic collisions
What type of system is formed?

Indeed, is it a system?
Geometric substructure

Independent of momentum

A collection of nearby, independent p+p collisions. Not “matter”
Matter is characterized by fields of bulk properties.
Geometric substructure

Sizes for particles of different momentum & mass

Hydrodynamic expectation:

Matter is characterized by fields of bulk properties

- pion
- kaon
Geometric substructure

\( \pi^{\pm} - K^{\pm} \) correlations reveal mass-ordered separation

Femtoscopy provides strong evidence for
- formation of a *bulk system*
- flow-generated space-momentum correlations ➔ supports hydro treatment ➔ access to EoS

Matter is characterized by fields of *bulk* properties

- pion
- kaon

Hydrodynamic expectation:

*Calculations*
*Blast wave*

*PRL 91 262302 (2003)*
3D info and timescale

Bertsch-Pratt decomposition: $R_{\text{out}}$, $R_{\text{side}}$, $R_{\text{long}}$

A long emission duration results in $R_{\text{out}} > R_{\text{side}}$

$\vec{q} = \vec{p}_2 - \vec{p}_1$

$\vec{k} = \frac{1}{2} (\vec{p}_2 + \vec{p}_1)$
Phase transition? Order?

Early expectations at RHIC 200 GeV

Probe for phase transition $\rightarrow$ vary conditions

RHIC Beam Energy Scan

A long emission duration results in $R_{\text{out}} > R_{\text{side}}$

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Phase transition? Order?

Multi-year program (BES) to vary the collision energy

Early expectations at RHIC 200 GeV
NOT OBSERVED

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Evidence for
- cross-over at high energy (low chemical potential)
- first-order phase transition ~ 15 GeV

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Coming full circle...

Stellar Intensity Interferometry

...in the modern age

Reminder: stellar HBT “died” in the early 1970’s
Stellar Intensity Interferometry in the 21st century

\[ C(\gamma) = \frac{\langle S_1(t)S_2(t-\gamma) \rangle}{\langle S_1(t) \rangle \langle S_2(t) \rangle} \]

Fig. 1. Correlation coefficients \( \rho \) measured at various interferometer spacings, \( \lambda \), for the radio source in Cygnus. Observations by Smith, \( S \); observations by Mills, \( M \); observations by Jennings and Bieroga, \( J \). The continuous curve denotes the theoretical transform of the distribution shown in Fig. 2.
Stellar Intensity Interferometry in the 21st century

\[ C(t) = \frac{\langle S_1(t) S_2(t-\tau) \rangle}{\langle S_1(t) \rangle \langle S_2(t) \rangle} \]

With modern electronics, we can cut the cord!
- arbitrarily long baseline, even for optical
- offline DSP for signal clean-up of noise, afterpulsing, etc
VERITAS Collaboration Array

- 12-m mirrors with good optical reflectivity
- primary focus: Cherenkov flashes from ultra-high-energy cosmic rays
- Cherenkov observations impossible during moonlight
  - ... but intensity interferometry can be done!

Each telescope is an independent station – no connection or correlation
Waveforms sampled @ 250 MHz, digitized to 8 bits, streamed to disk independently and separately

3.5 TB per 1-hour run
After correcting for optical path delay & integrating over run
First VERITAS results

- first SII in 30+ years (!)
- first digital SII ever (!!!)

Uniform Disk (UD) radii

- $\epsilon$ Ori: $\theta_{UD} = 0.631 \pm 0.017$ mas
- $\beta$ Cma: $\theta_{UD} = 0.523 \pm 0.017$ mas

Both in agreement with original NSII

Non-isotropic sources, mag-3 targets are under study
Summary

• Insight from radar development during WWII → unconventional techniques to radioastronomy – HBT effect
  • A newcomer often brings new approach to a field!

• Application to optical spectrum brought new insights and gave birth to quantum optics
  • Important discussions in quantum mechanics

• A “curious” effect (GGLP) in early particle physics turned out to be closely connected to HBT
  • pay attention to even small effects

• Femtoscopy plays a major role to understand bulk dynamics of heavy ion collisions
  • probing substructure of the “perfect fluid” of the quark-gluon plasma
  • bulk system, hydro evolution, size, shape, orientation, substructure, phase transition

• Modern advances in technology (high-speed sampling/digitization/storage/CPU) & “big data” analysis
  • revive Hanbury Brown’s “dream” and enable much larger baseline measurement
  • even a nuclear physics professor branch into new directions
  • A newcomer often brings new approach to a field
Students – Don’t lose heart!

While he served as supervisor for PhD students, and held the Chair of Physics (Astronomy) for nearly 20 years, Hanbury Brown never received a PhD!

Above, Emeritus Professor Hanbury-Brown receives an honorary Ph.D. from Univ. Sydney