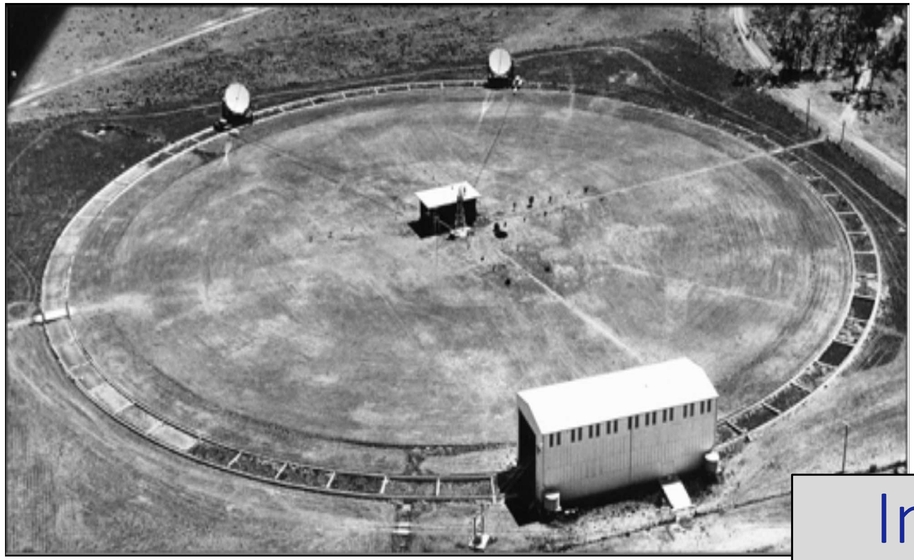
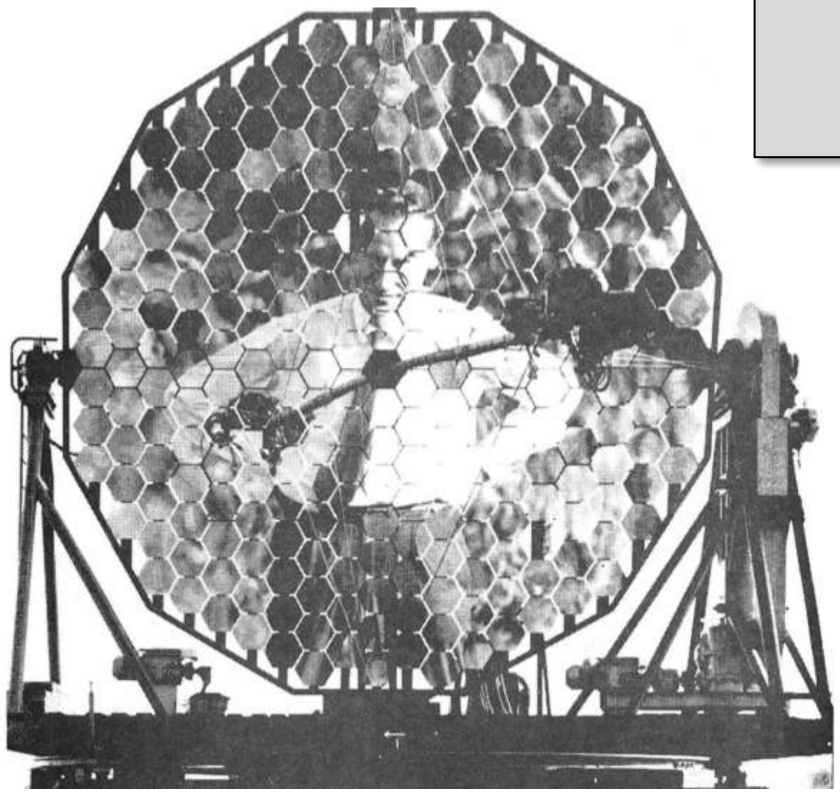


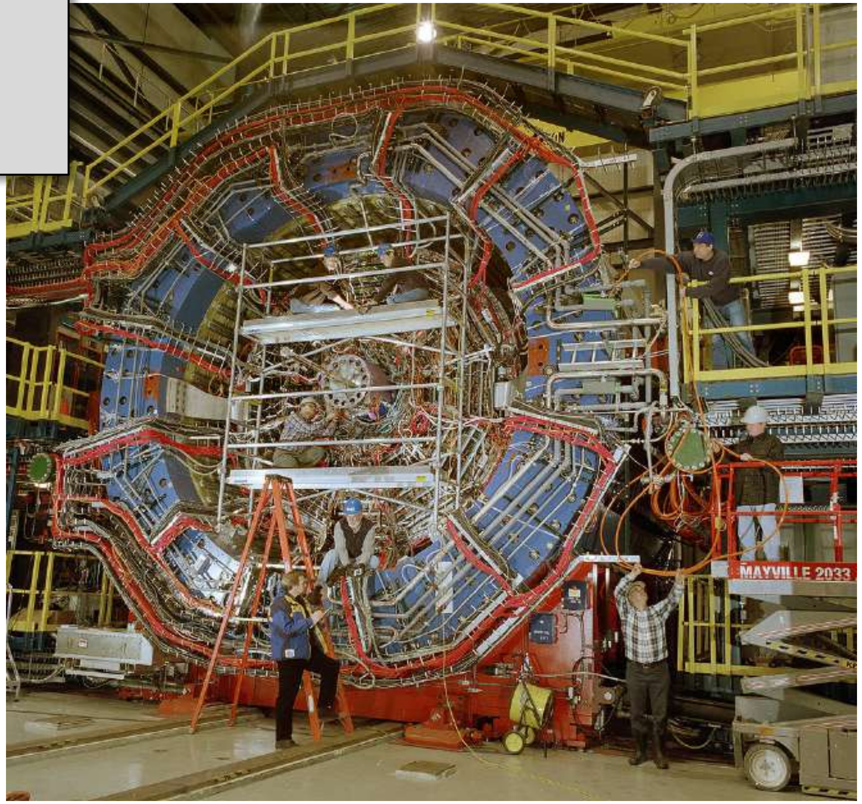
Intensity interferometry: From stars to STAR

(… and back)



Mike Lisa

Ohio State University



Outline

- Hanbury Brown-Twiss stellar interferometry (1954~1970)
  - History, physics, promise

Part I

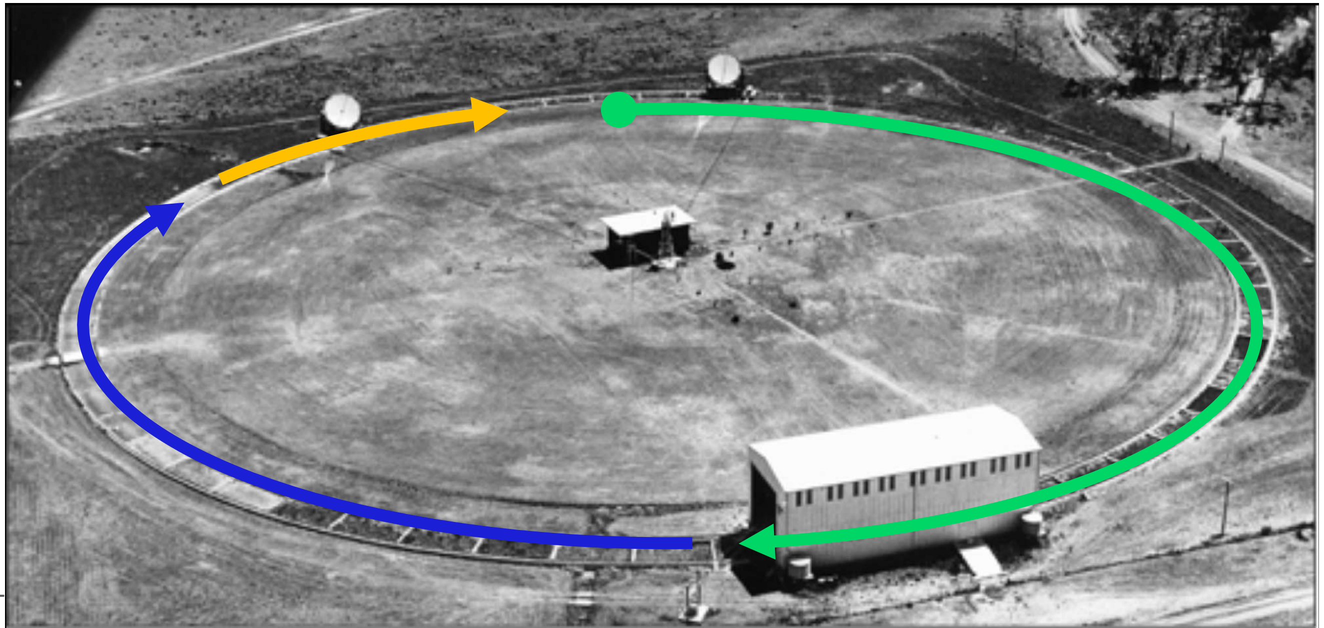
- The GGLP effect in subatomic collisions (1960-)
- Femtoscopy: in heavy ion physics (1976-)
  - the importance of space-time & results

Part II

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

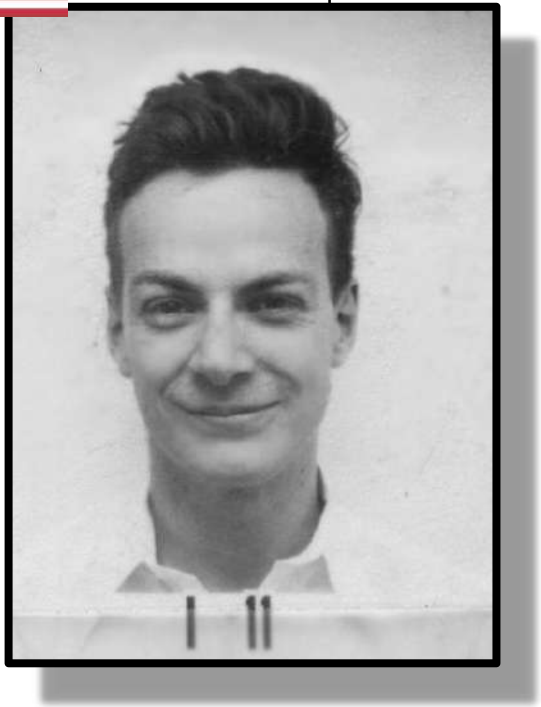
Part III

- Summary



Scientific careers interrupted/shaped by WWII

Los Alamos ID photo



Richard Feynman (1918-1988)

PhD (Princeton) 1942

Joined Manhattan Project (Los Alamos), 1942

- secret emergency development of A-bomb

Robert Hanbury Brown (1916-2002)

“B.S.” Elec. Eng. 1935, Univ London *

Joined R.D.F. project (Suffolk) 1936

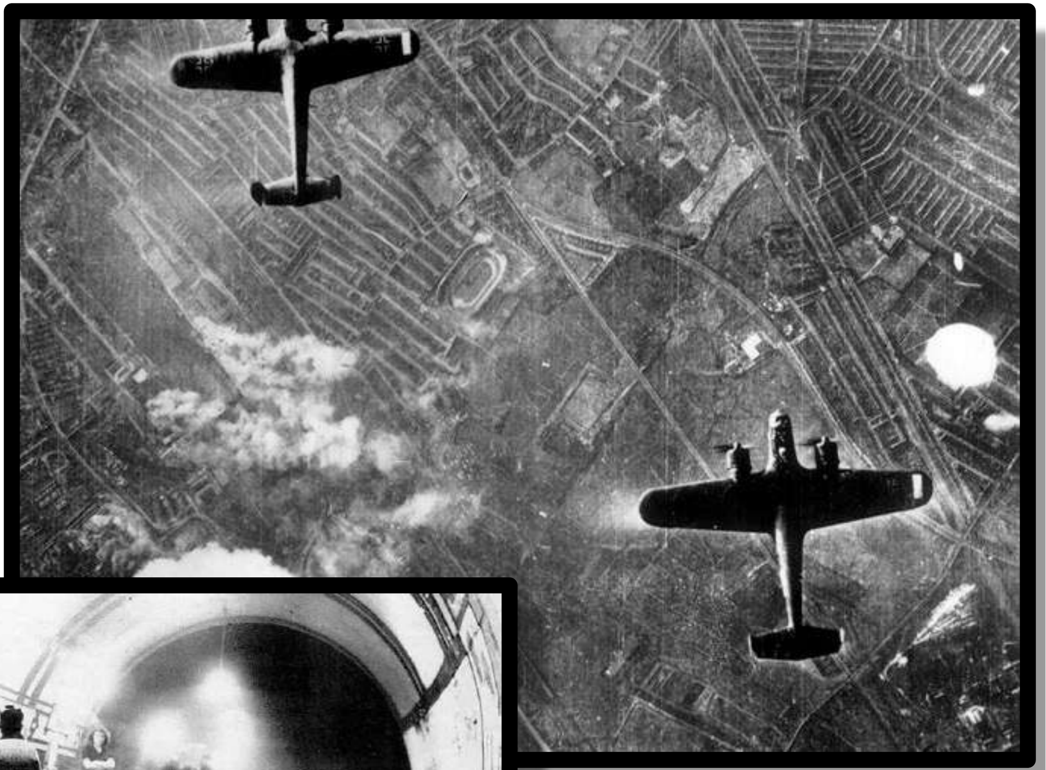
- secret emergency development of radar

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

The problem

- Warning
- ground-to-air defense

German Dornier 217 bombers over London (Getty images)



Almshouse bombed Feb. 10, Newbury, Berks., England.

Taking shelter in the London Underground

Tools at hand

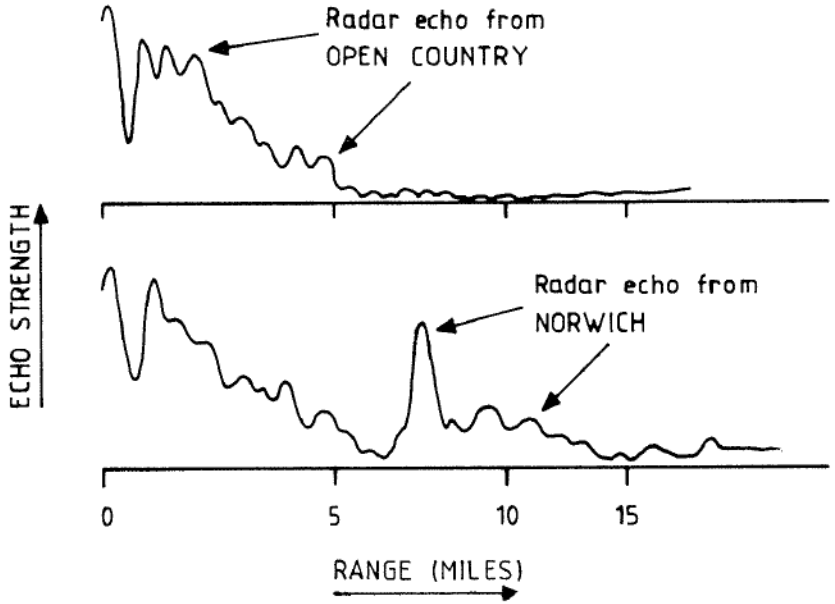
Aircraft spotter on the roof of a building in London.

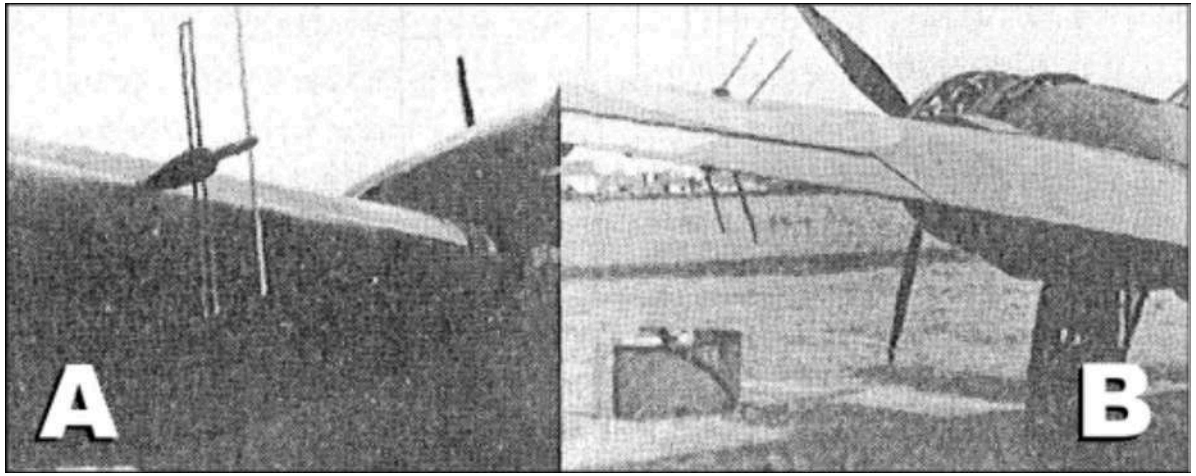
Barrage balloons over London during World War II.
Buckingham Palace & the Victoria in middle ground.

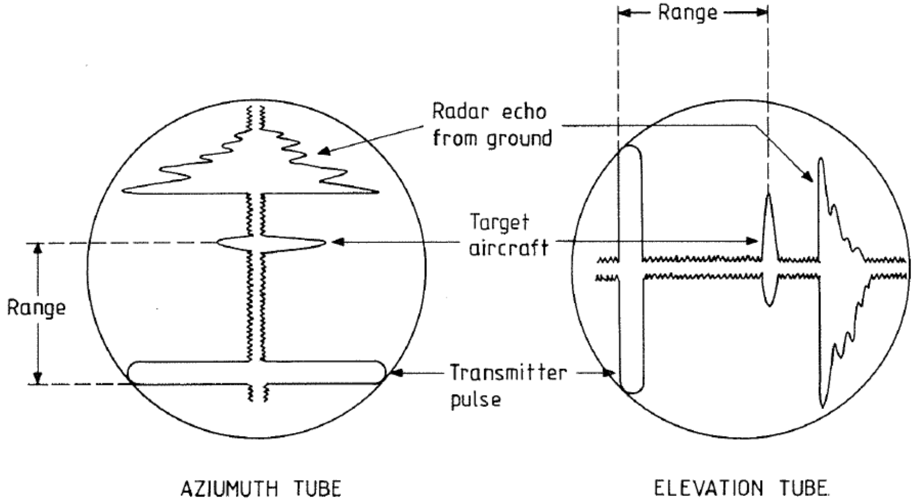
Right: Concrete acoustic mirrors at Denge near Kent

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 (!)







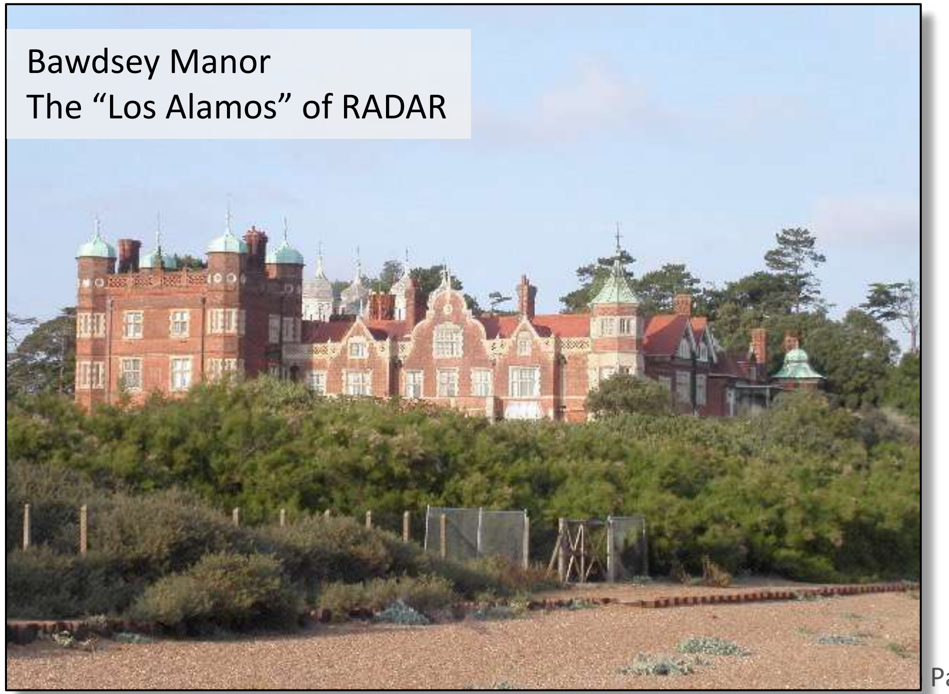
Swords to ploughshares

Engineers after WW II

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

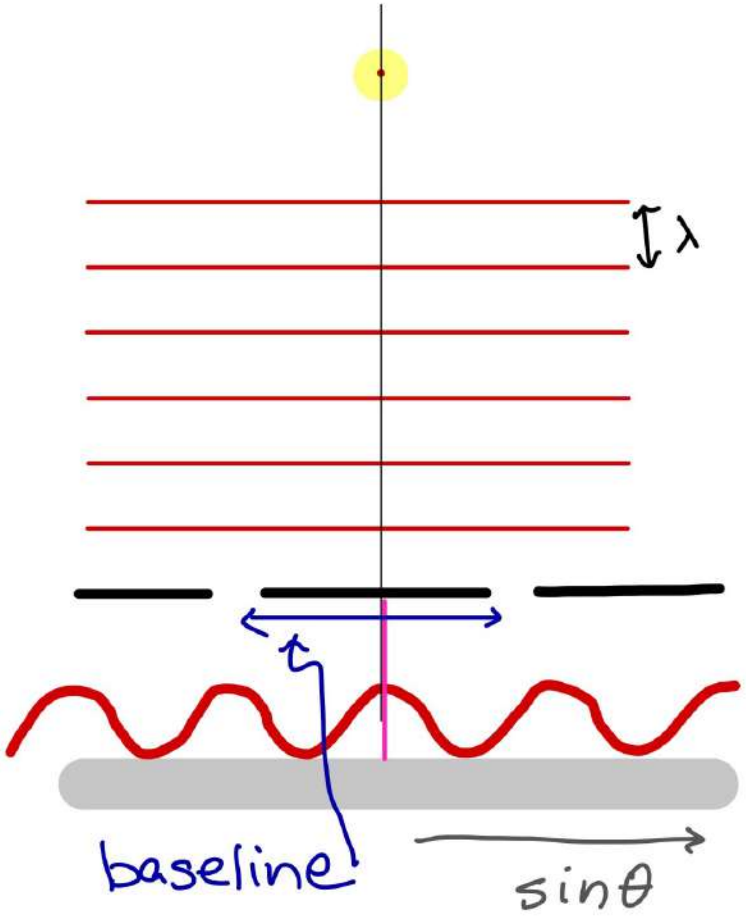
Hanbury Brown turned to emerging field of radioastronomy

- “radio stars” were being measured with Michelson (amplitude) interferometry



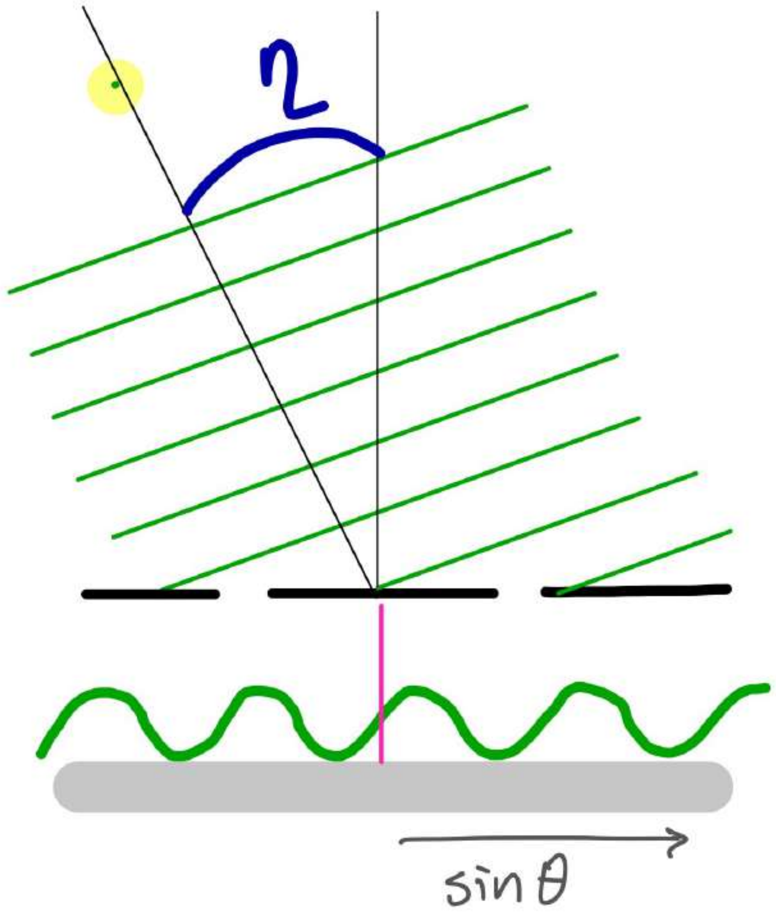
Bawdsey Manor
The “Los Alamos” of RADAR

Michelson Interferometry 101



“Overhead” point source through 2 slits:
Dark fringes on the viewing screen

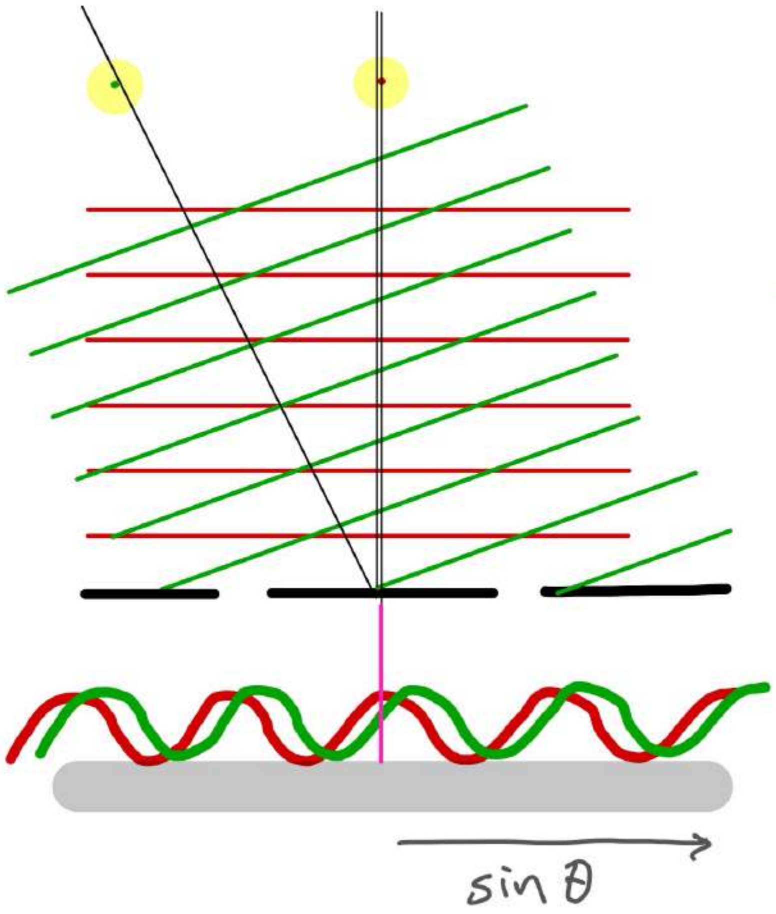
$$\sin\theta_n = \frac{n\lambda}{b}$$



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



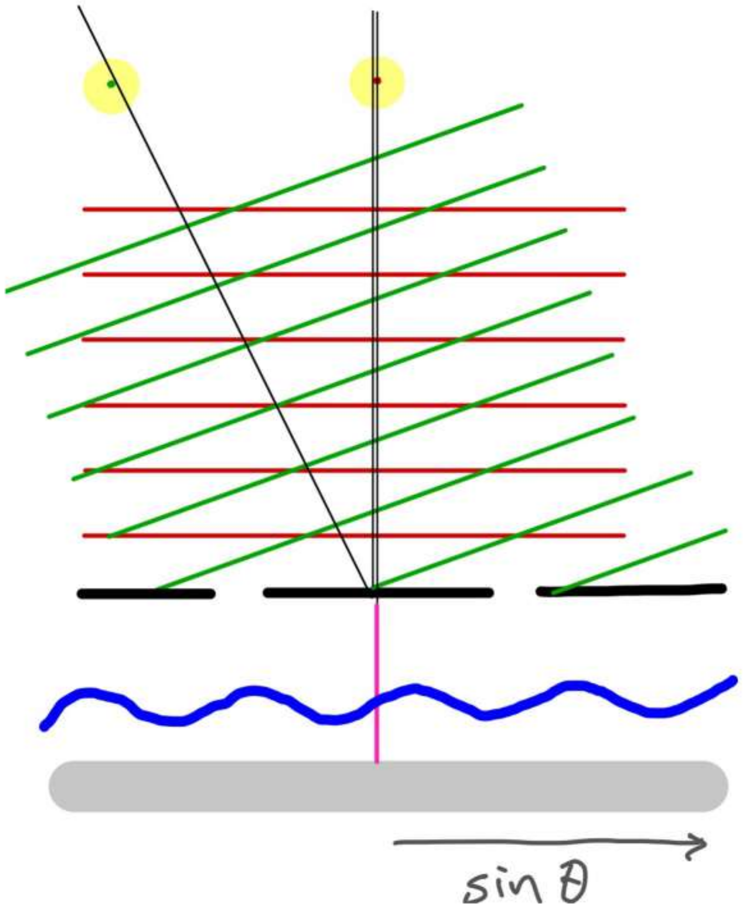
Two **incoherent** sources...

....**Intensities** add

$$I(\theta) = I_1(\theta) + I_2(\theta)$$

(assumes equal brightness)

Michelson Interferometry 101



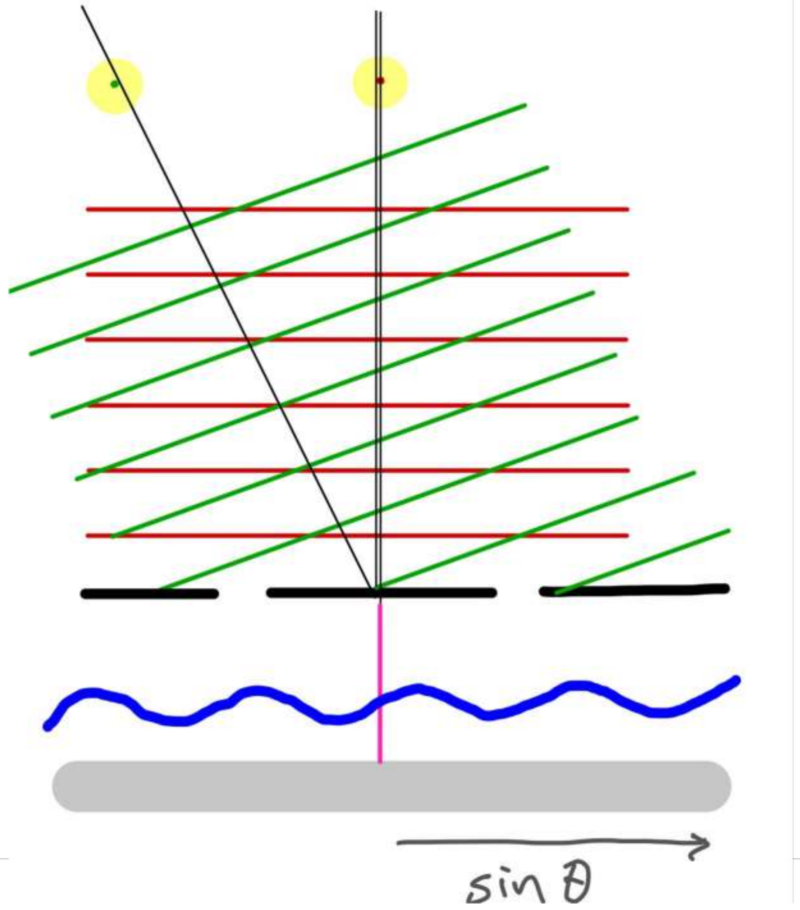
Two **incoherent** sources...

....**Intensities** add

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

(assumes equal brightness)

Michelson Interferometry 101



Two **incoherent** sources...

....**Intensities** add

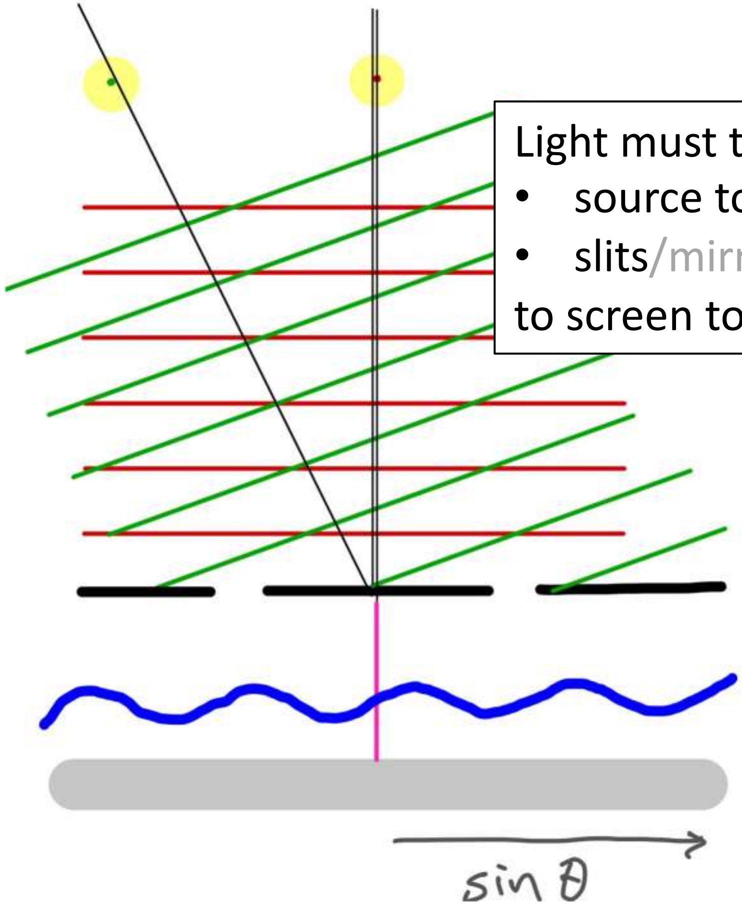
VISIBILITY

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

(assumes equal brightness)

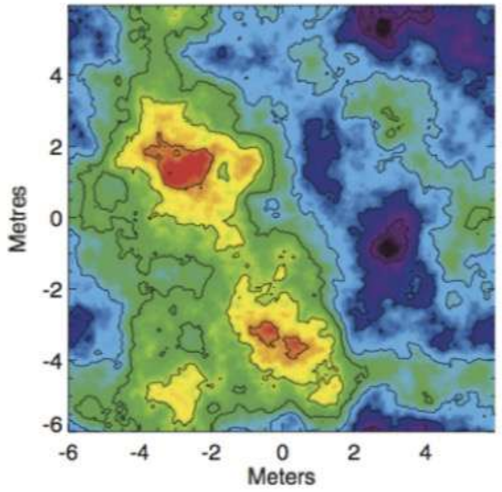
ca Teórica (IFT), Universidade Estadual Paulista (UNESP), São Paulo, Brasil

Michelson Interferometry 101



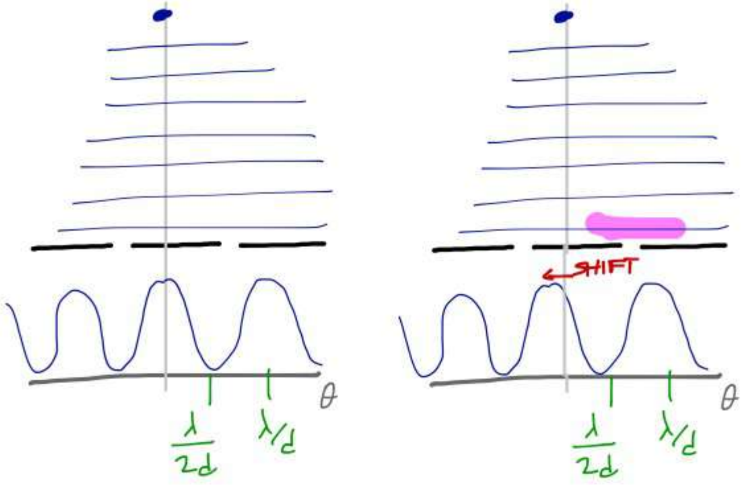
Light must travel undisturbed from:
- source to slits/mirrors/telescopes
- slits/mirrors/telescopes to screen

to screen to preserve E(t) phase



Challenge #1

Kolmogorov turbulence calculation. Each contour represents $\lambda/2$ of wavefront distortion. (Here, $\lambda = 2.2\,\mu m$)



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

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

Challenge #2
measuring small stars requires large baseline

Measurement of Betelgeuse (α Orionis)

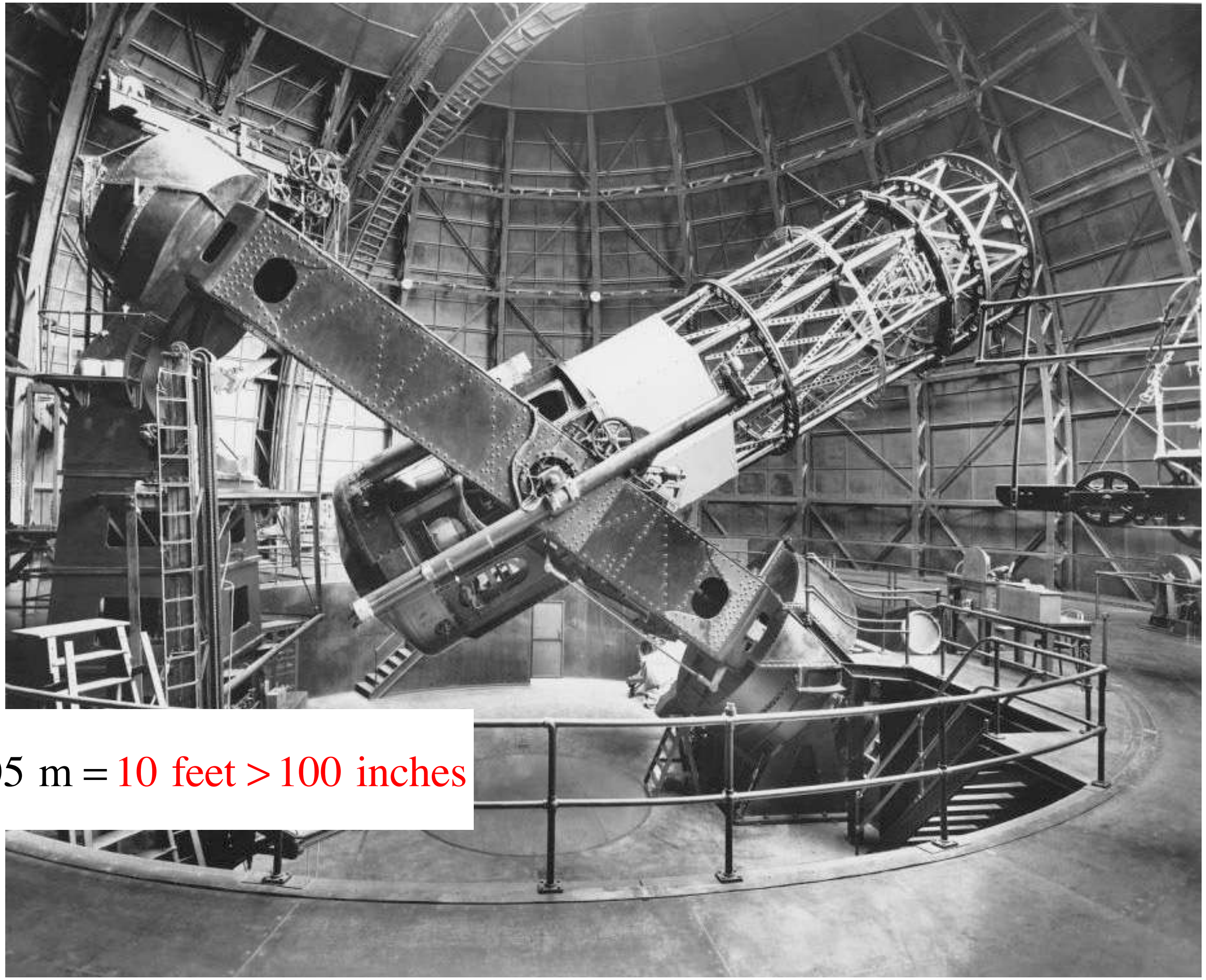
$$\text{round star: } \alpha = 1.22 \times \frac{\lambda}{2d} \quad \rightarrow \quad \text{correlation vanishes}$$

$$\text{to measure small } \alpha : \begin{cases} \text{small } \lambda \text{ (visible)} \\ \text{large baseline } d \end{cases}$$

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

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

using yellow-green (575 nm) light

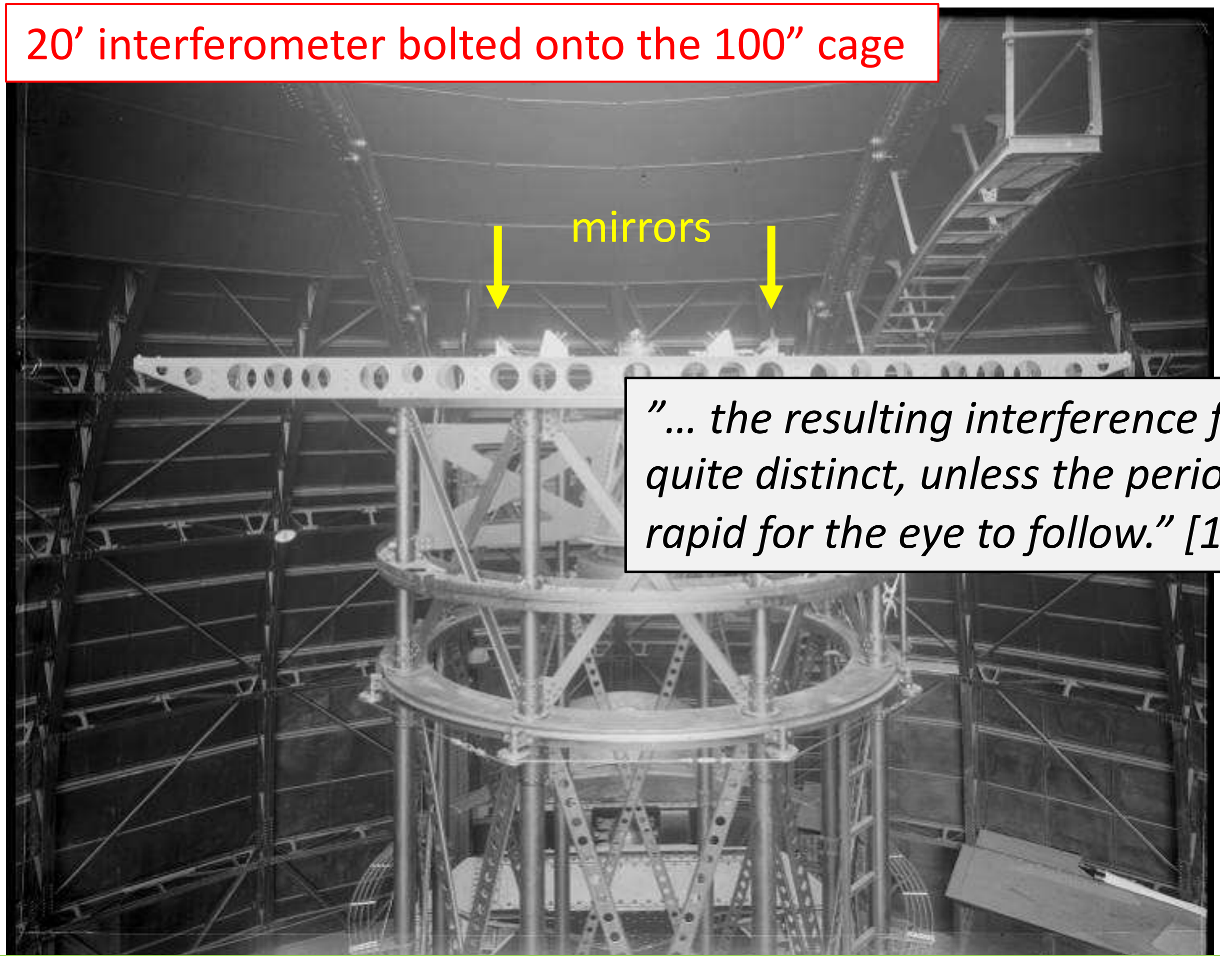


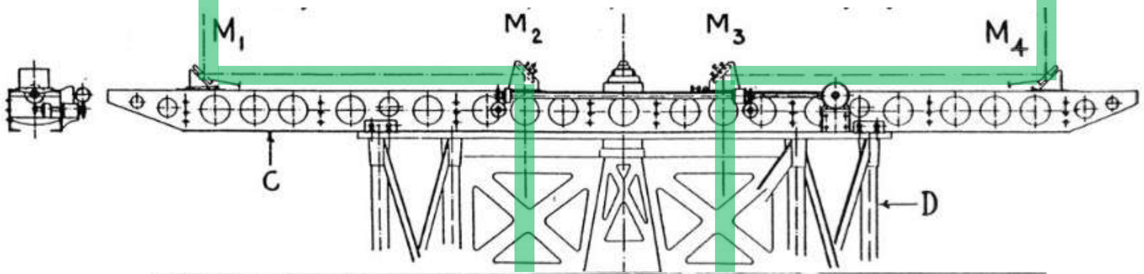
$$\rightarrow \text{ need baseline: } d = 1.22\frac{\lambda}{\alpha} = 1.22\frac{575 \cdot 10^{-9}\text{ m}}{2.3 \cdot 10^{-7}} = 3.05\text{ m} = 10\text{ feet} > 100\text{ inches}$$

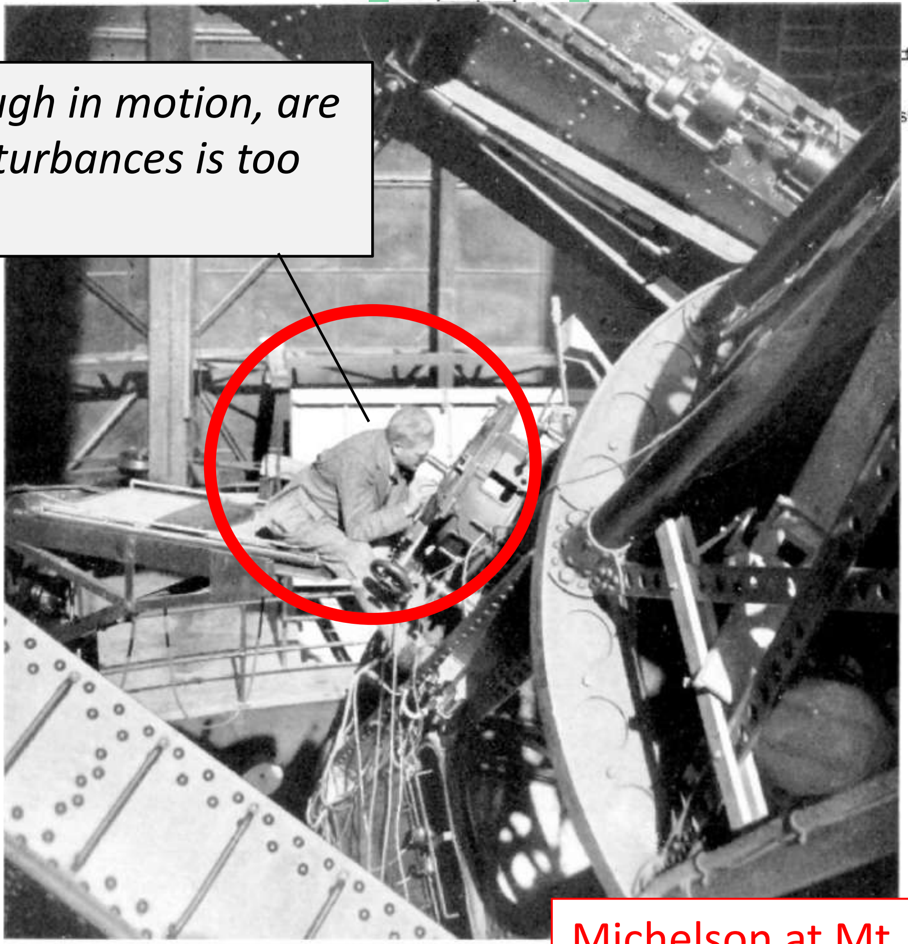
[1] Michelson & Pease, ApJ 53 (1921) 249

The 20’ (Michelson) Interferometer

20’ interferometer bolted onto the 100” cage







”… 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]

steel plate;

Abb. 3. Showing observer at eyepiece of

Michelson at Mt. Wilson

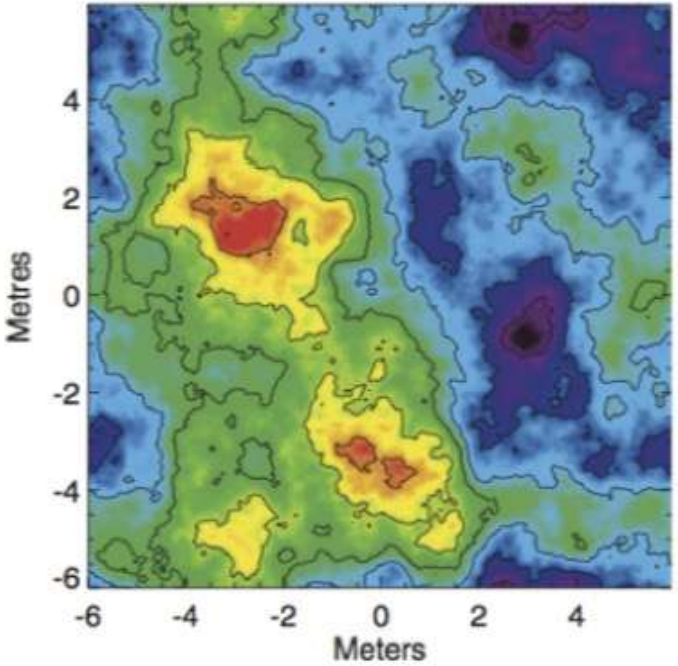
Encouraged by this success, attempt in 1931 at larger (50’) design....

... but failed:

- technique requires phase stability to within λ
- steel flexed too much, turbulence effects too great

The end of optical-spectrum Michelson interferometry for decades

Long baseline challenges

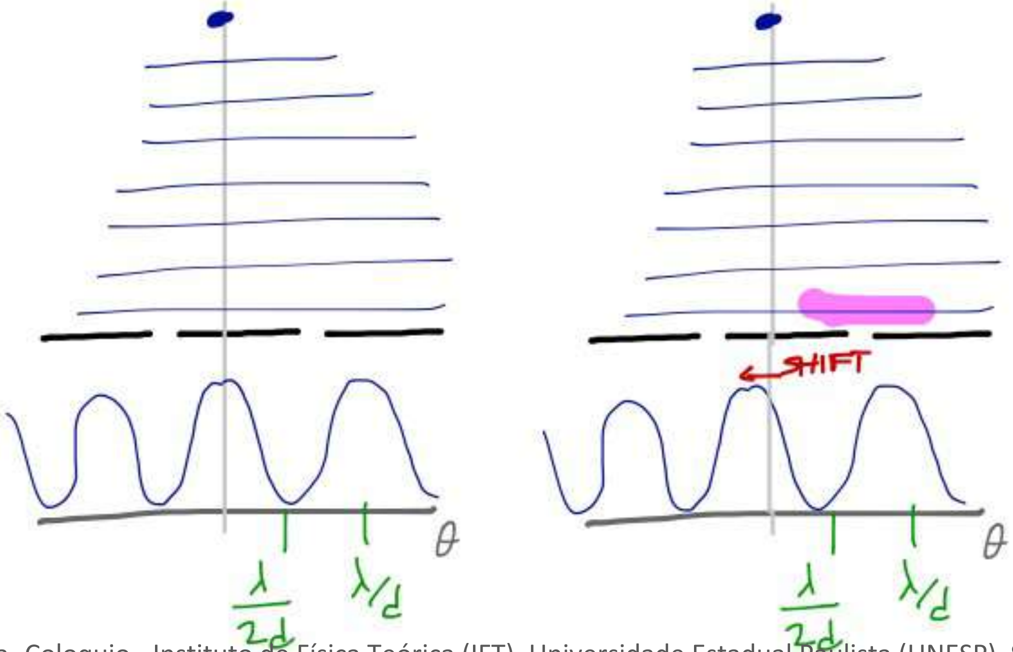


Kolmogorov turbulence calculation. Each contour represents $\lambda/2$ of wavefront distortion. (Here, $\lambda = 2.2\,\mu m$)

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: $$\Delta\eta_{\text{interferometer}} = \frac{\lambda}{2b}$$

- 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

Radiation: $\lambda \simeq 1.5$ m (200 MHz)

Observed $\Delta\theta \simeq 5' \simeq 1.5 \cdot 10^{-3}$ rad.

nature
International weekly journal of science

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

$$\Delta\theta_{\text{vanish}} = \frac{\lambda}{2b} \quad \rightarrow \quad b_{\text{required}} \approx \frac{\lambda}{2\Delta\theta} = \frac{1.5\ \text{m}}{3\cdot 10^{-3}} = 500\ \text{m}$$

Apparent Angular Sizes of Discrete Radio Sources: Observations at Jodrell Bank, Manchester

R. Hanbury Brown, *et al*, Nature (1952)

A friendly referee!

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.

	Base-line	
	Length* (km.)	Bea
A	0·30	34
B	2·16	11
C	2·16	23
D	3·99	17

* The value given of the base-line is ca base-line.

† The bearing is n from the fixed stati

** This value is n the point may lie on base-line.

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

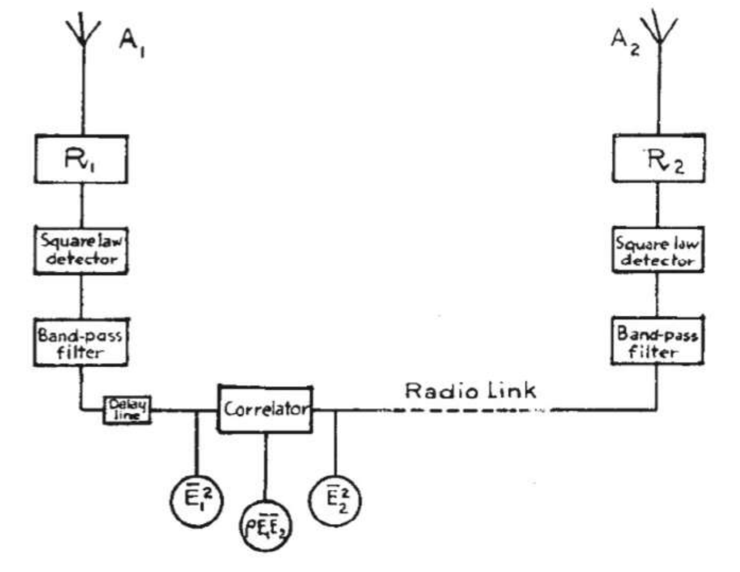


Fig. 1. Schematic diagram of the equipment

The theory of the instrument is involved, and it will be given in detail elsewhere[7]. It can be shown that the value of the cross-correlation coefficient (ρ) is given by an expression similar to that for the visibility of the fringes in a Michelson stellar interferometer:

$$\rho = \frac{\sin^2(\pi\alpha b/\lambda)}{(\pi\alpha b/\lambda)^2}, \qquad (1)$$

where α is the angular width of an equivalent rect-

The theory of the instrument is involved, and it will be given in detail elsewhere....

... 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.

Philosophical Magazine **45** (1954) 663

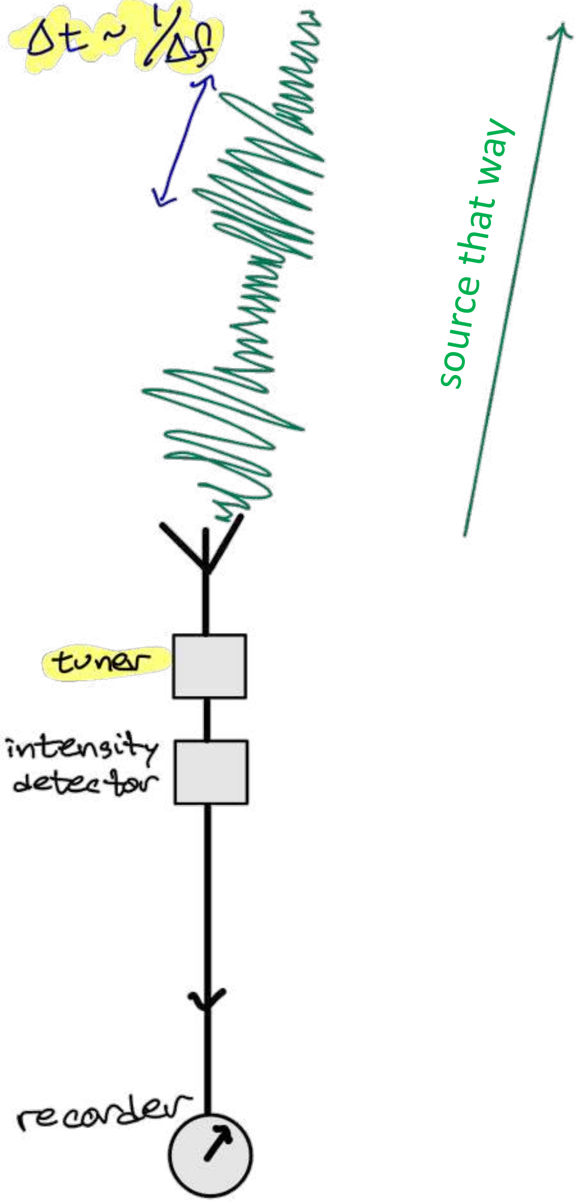
The Intensity Interferometer

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)



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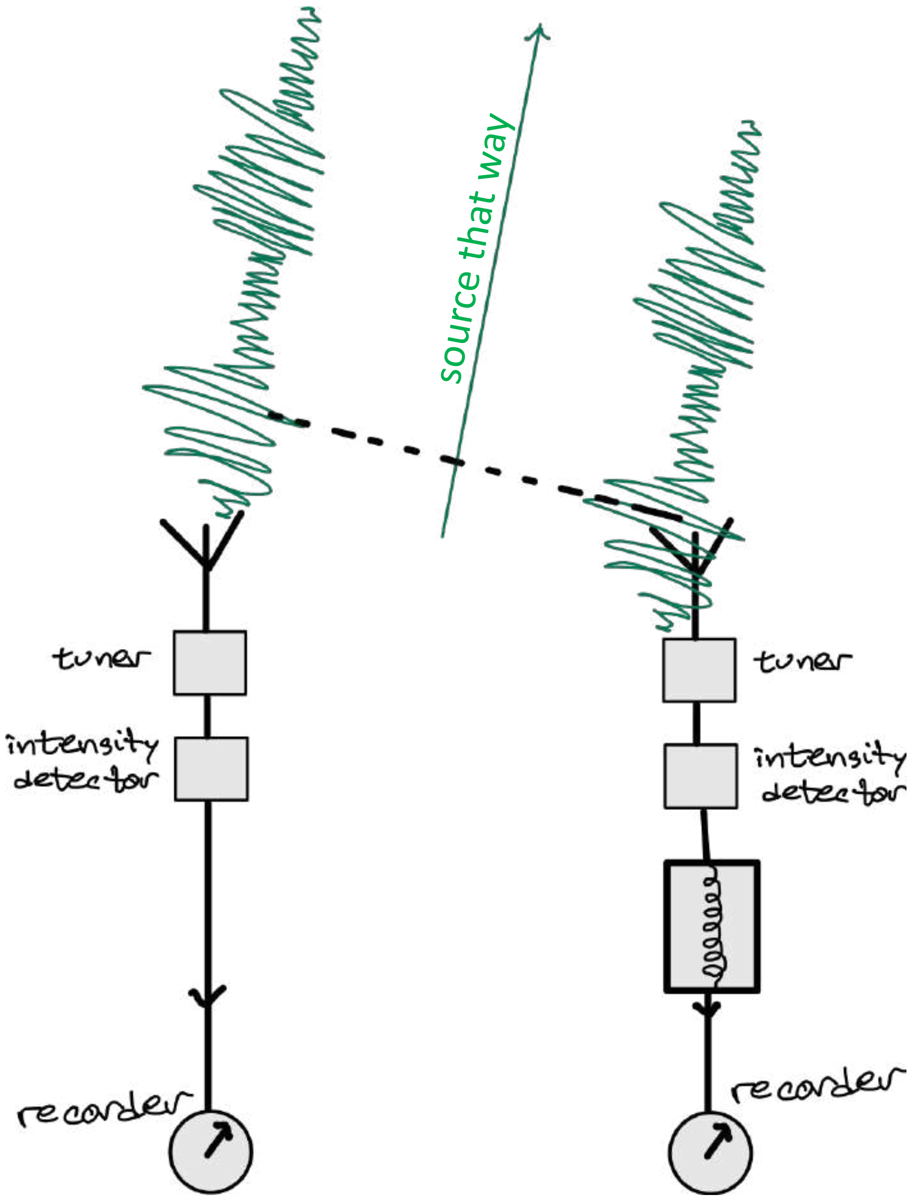

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A narrow range of frequencies from a point source
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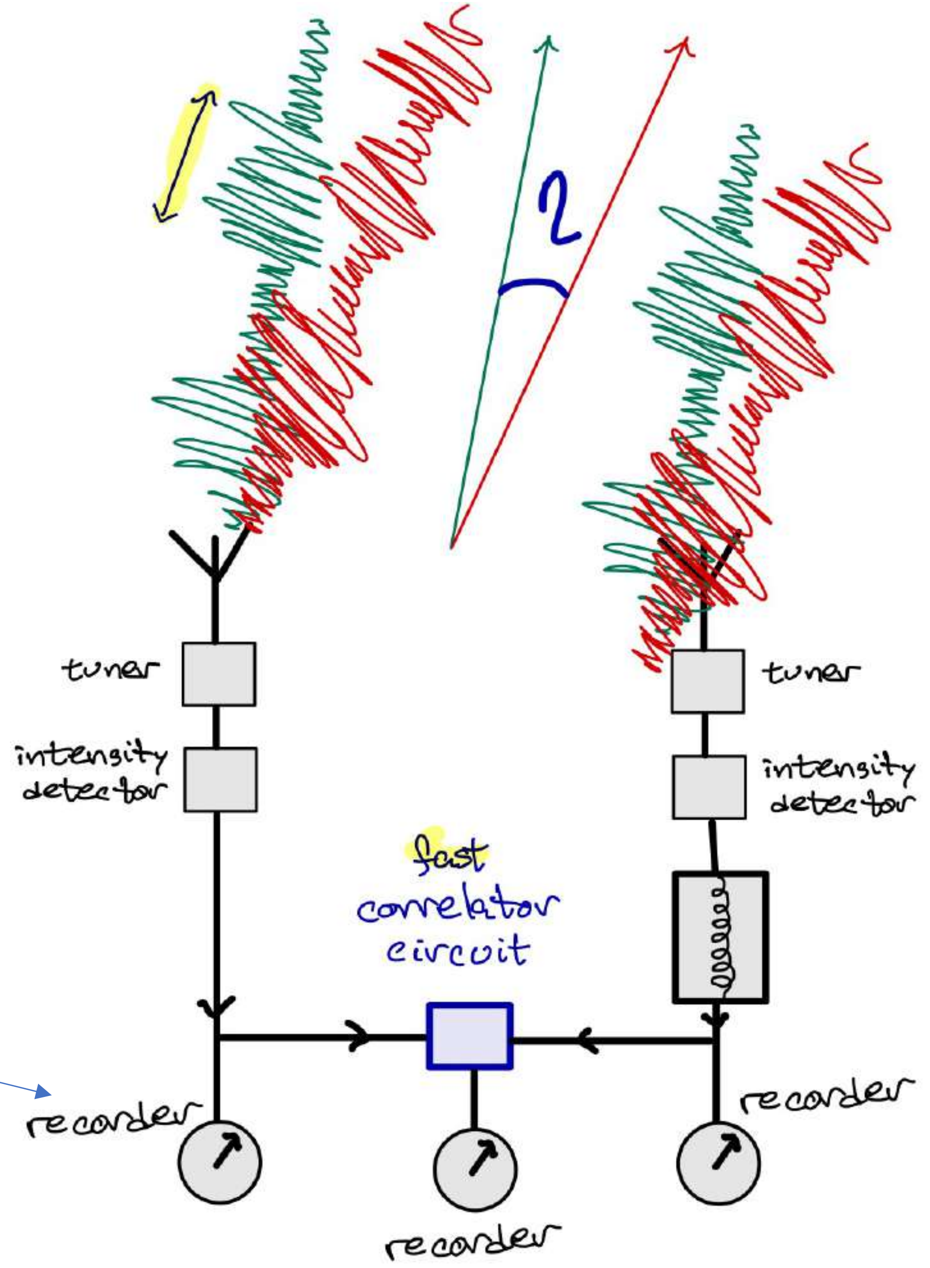
Incoherent second source, with its own random beats…
→ a *time* correlation measured by correlator circuit
→ "Visibility" (in time) patterns similar to Michelson interferometer

Data recorded on paper strip charts (☺!).
- (too slow to capture fast beats)



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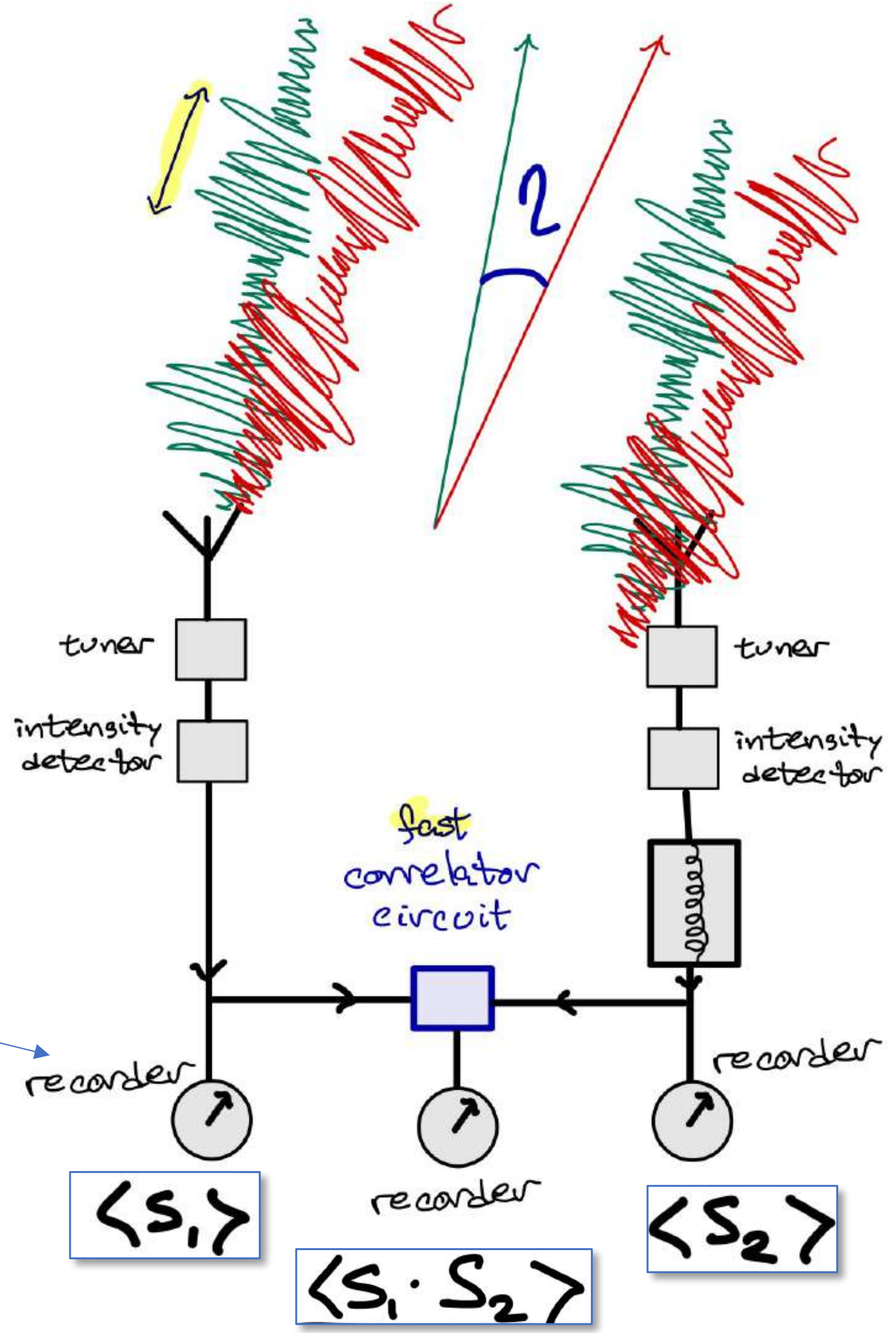
Normalized correlation:

$$C = \frac{\langle S_1 \cdot S_2 \rangle}{\langle S_1 \rangle \langle S_2 \rangle}$$



The Intensity Interferometer

Jennison & Das Gupta, Nature 172 (1953) 996

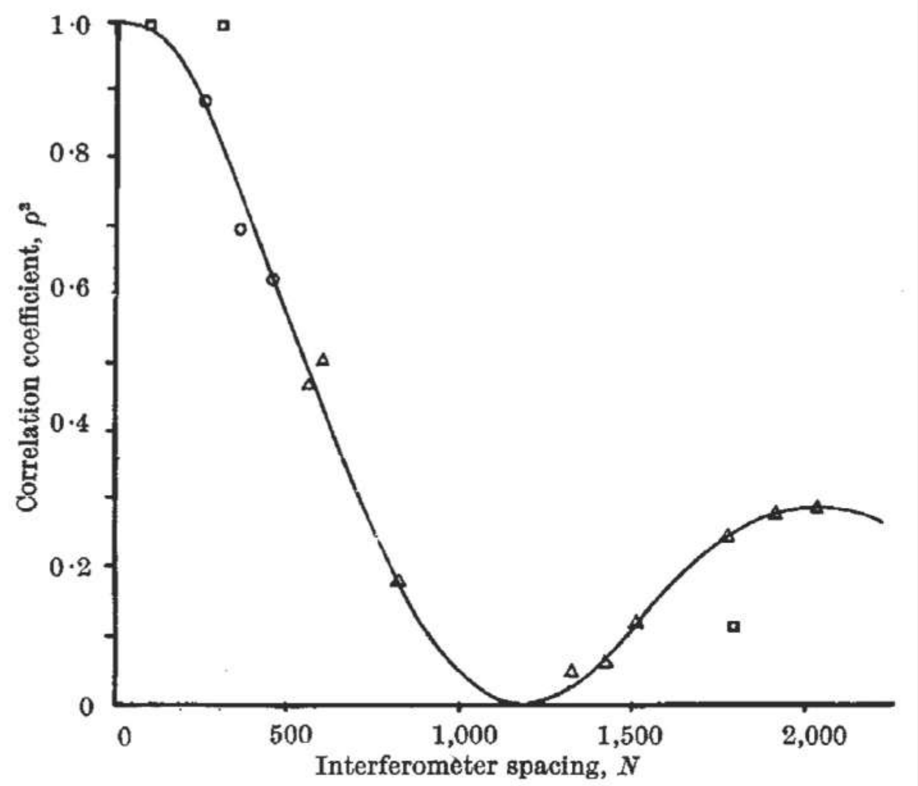
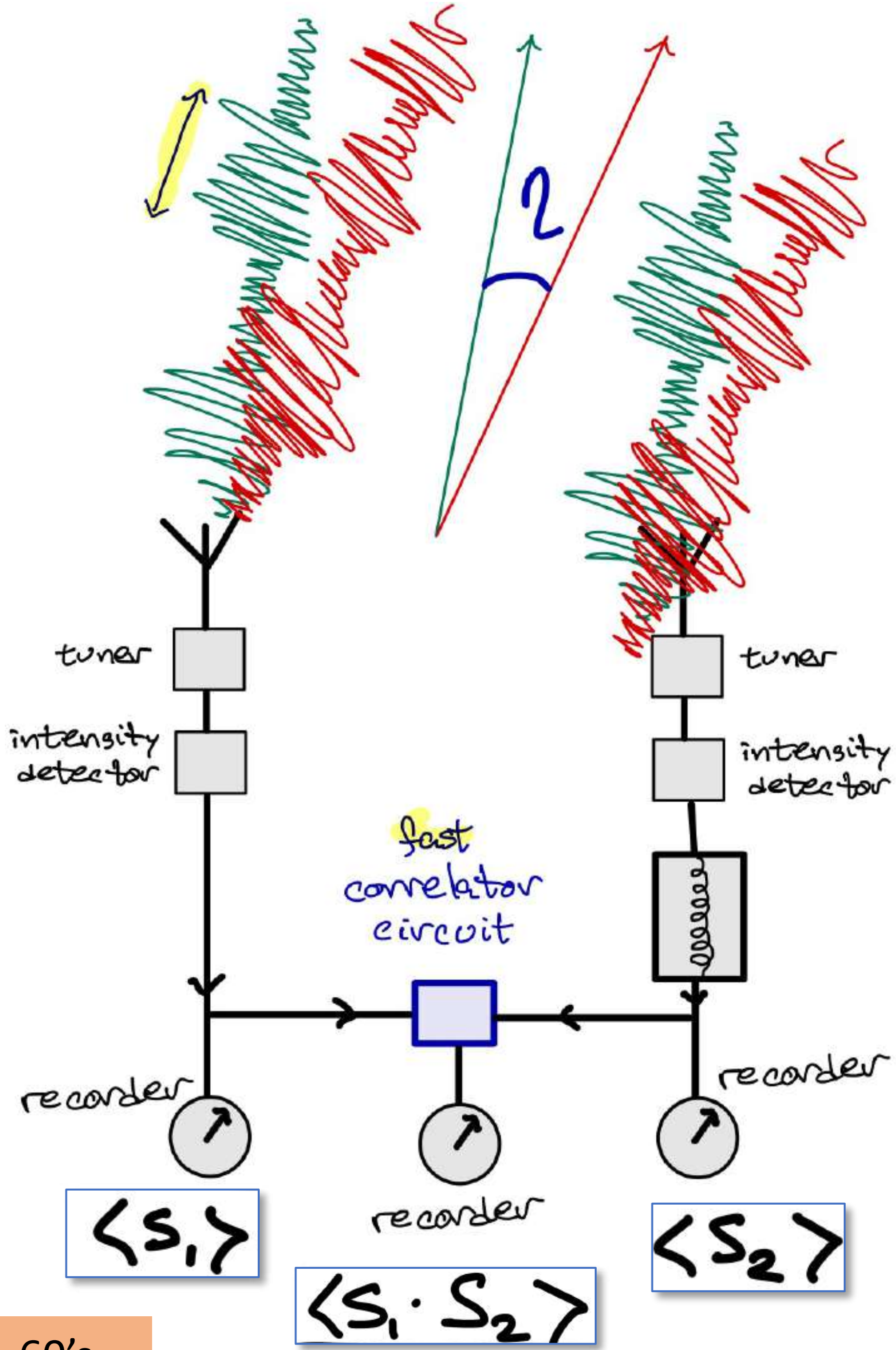


Fig. 1. Correlation coefficients ρ^2 measured at various interferometer spacings, N, for the radio source in Cygnus. Observations by Smith, ○ ; observations by Mills, □ ; observations by Jennison and Das Gupta, △. The continuous curve denotes the theoretical transform of the distribution shown in Fig. 2

Normalized correlation:

- dependance on separation (baseline) reveals source size

$$C = \frac{\langle S_1 \cdot S_2 \rangle}{\langle S_1 \rangle \langle S_2 \rangle}$$

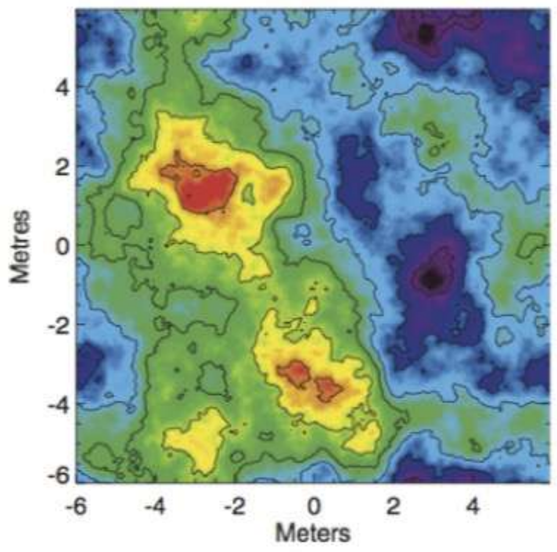


HBT interferometer contributed to growing catalog of radio sources in 50's & 60's

An innocent suggestion

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.



Nature **177** (1956) 27

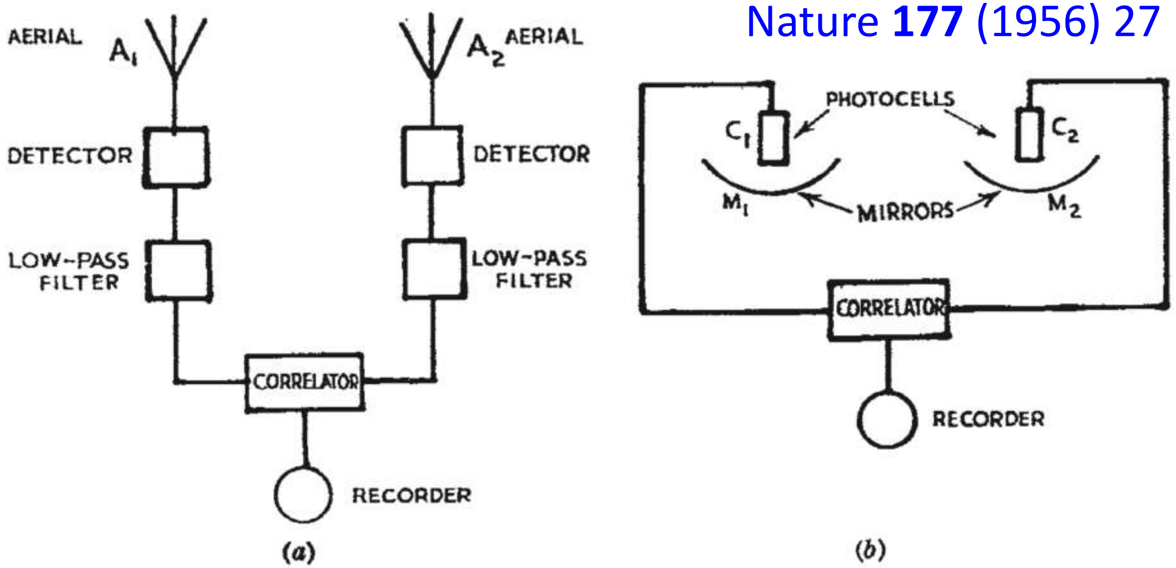


Fig. 1. A new type of radio interferometer (a), together with its analogue (b) at optical wave-lengths

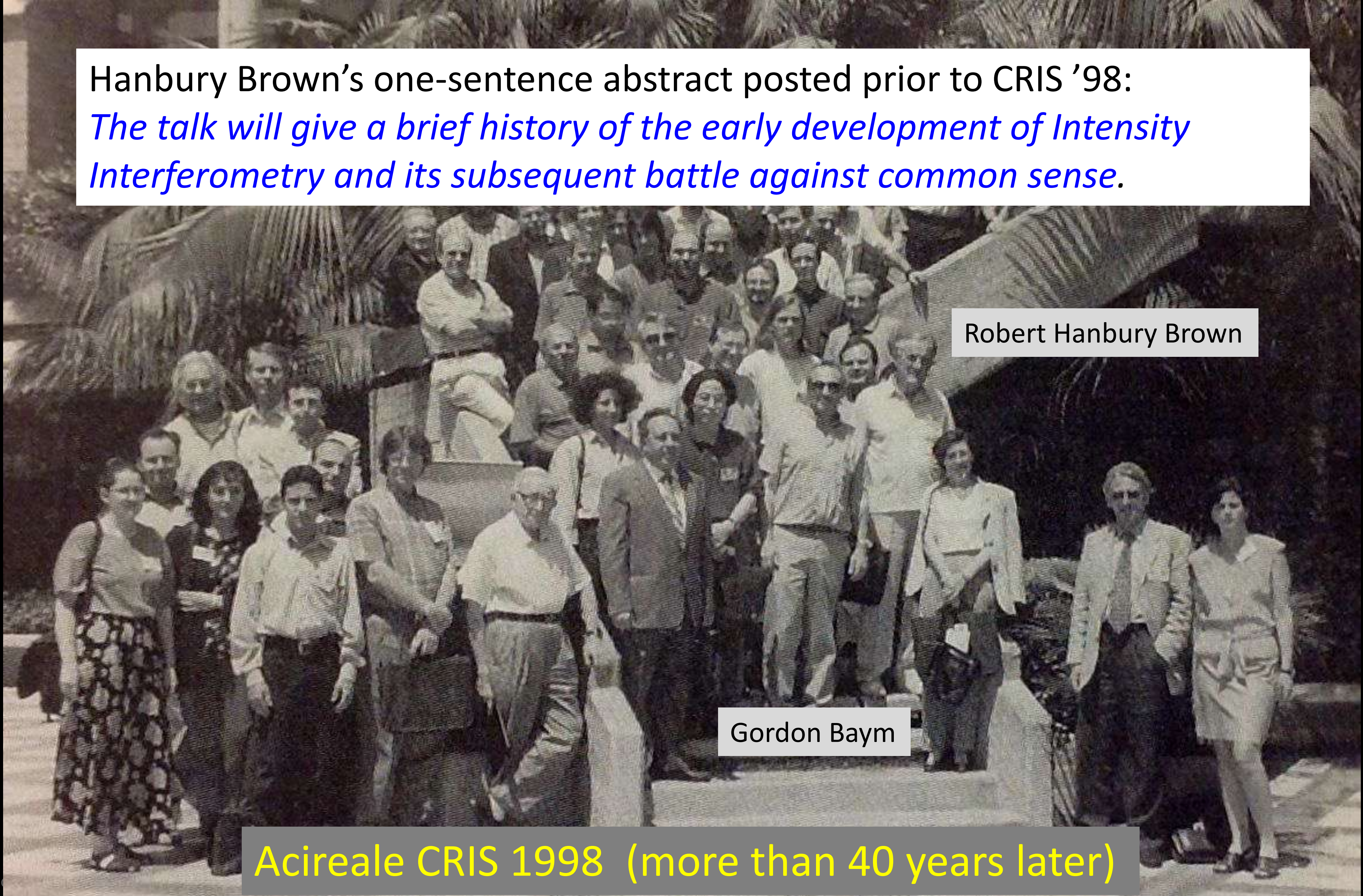
$$\Delta\theta \approx \frac{\lambda}{2b} \sim \frac{1}{\#\lambda's}$$

Cygnus measurement: $\#\lambda's \approx \dfrac{10\text{ km}}{1\text{ m}} = 10^4$

optical: $\lambda \sim 5 \cdot 10^{-7}$ m $\rightarrow$ 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.



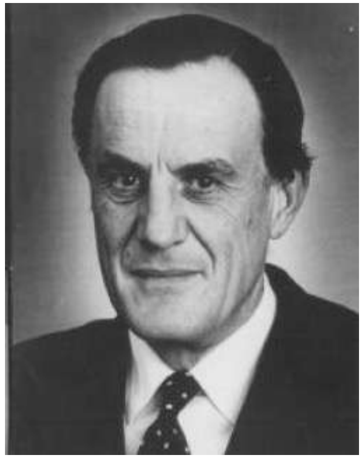
Acireale CRIS 1998 (more than 40 years later)

Immediate and prolonged controversy

P.A.M. Dirac
Nobel Prize 1933

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."



B.S. Radio engineering

"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."
-- (Proc. Roy. Soc. London (1957))

Edward Purcell
1952 Nobel Prize

"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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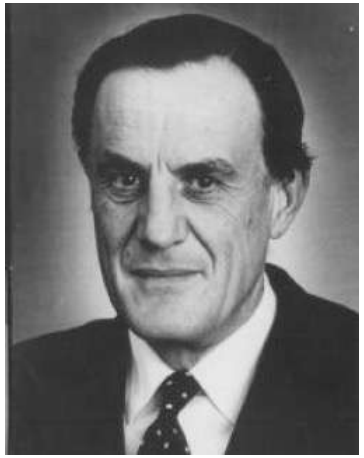


B.S. Radio engineering

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

Edward Purcell
1952 Nobel Prize

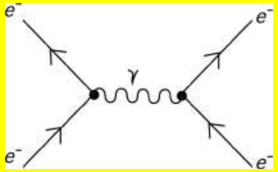
“The Brown-Twiss effect, far from requiring a revision of quantum mechanics, is an instructive illustration of its elementary principles.”
-- Nature 178 (1956)

Immediate and prolonged controversy

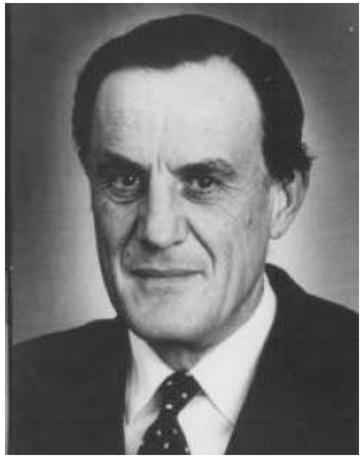
While HBT interferometry was not controversial when applied to radio wavelengths, light in the optical spectrum was considered in terms of photons, and it seemed that "photons were interfering"

P.A
No

"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!



B.S. Radio engineering

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

Edward Purcell
1952 Nobel Prize

"The Brown-Twiss effect, far from requiring a revision of quantum mechanics, is an instructive illustration of its elementary principles."
-- Nature 178 (1956)

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
No

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 billi ***ot as a thing,***
as something which
-- proceedings of CRIS

Photons do not travel
... Particles do not tr

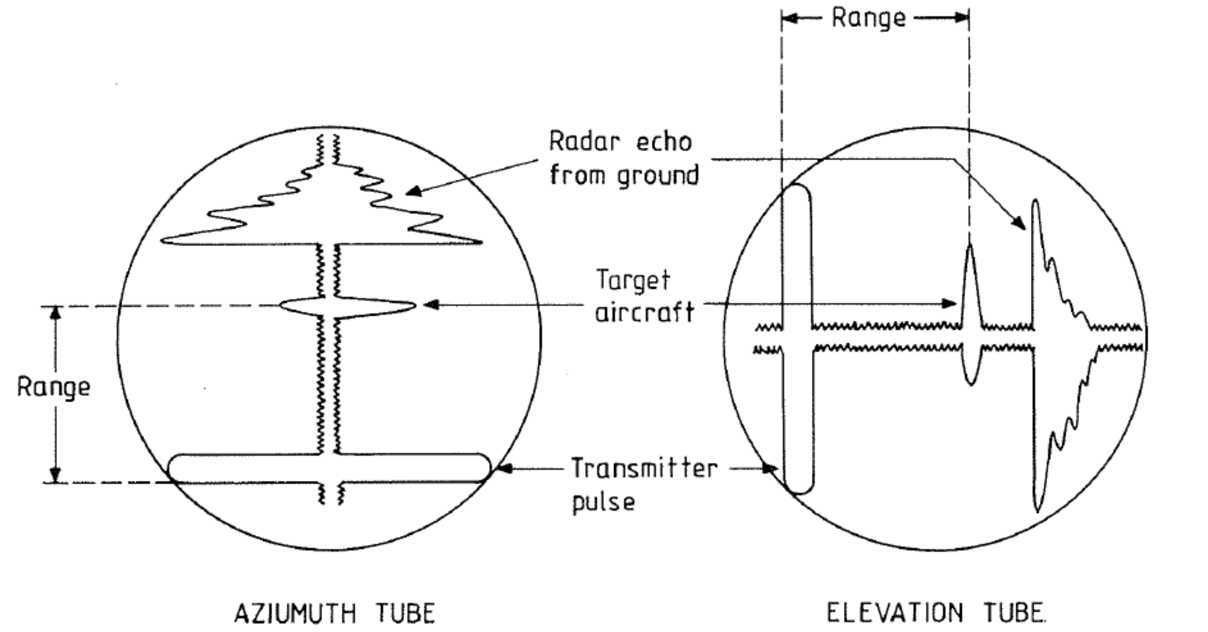
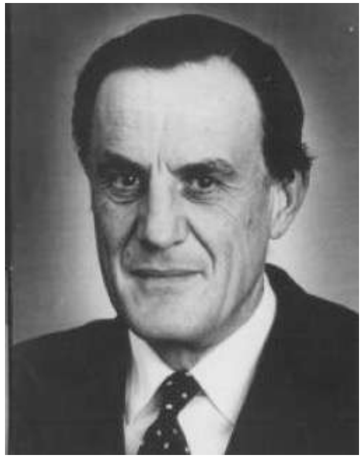


Figure 2.3 The display used for metre-wave AI (air-interception) radar). The left-hand (azimuth) cathode-ray tube shows that the target aircraft is off to the right of the fighter; the right-hand (elevation) tube shows that



B.S. Radio engineering

on a classical
erlooked."

"The Brov ... nics,
is an instr
-- Nature 1

Edward Purcell
1952 Nob

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 →

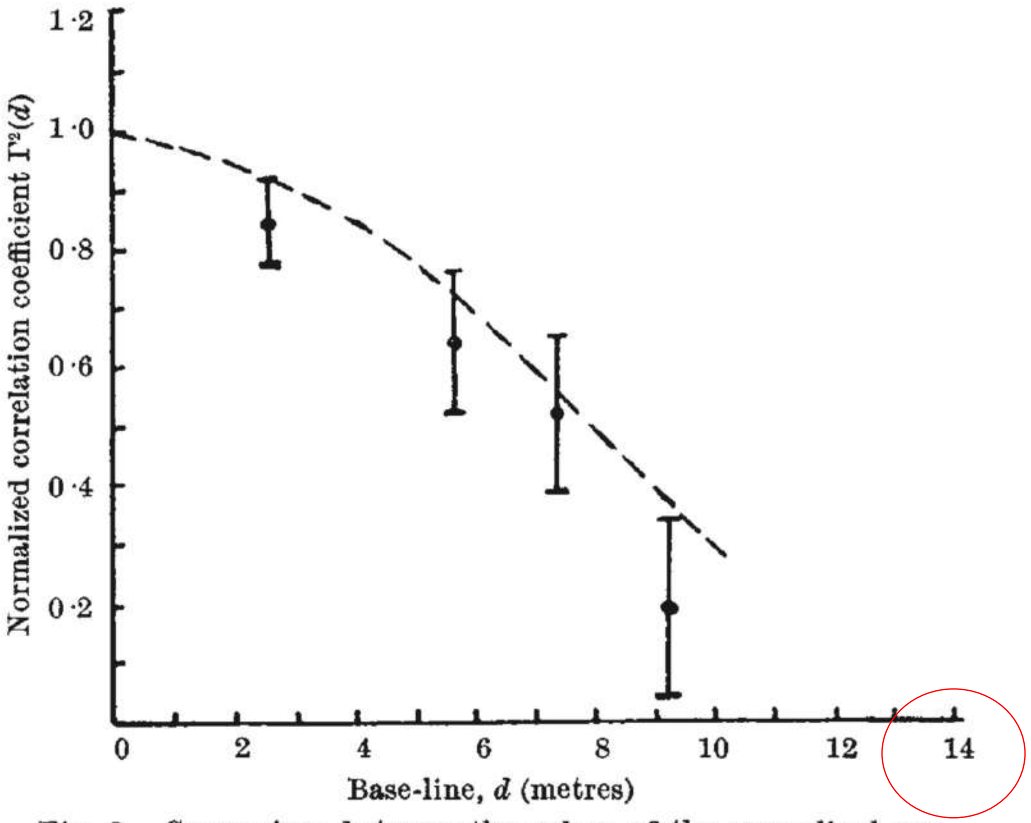


Fig. 2. Comparison between the values of the normalized correlation coefficient $\Gamma^2(d)$ observed from Sirius and the theoretical values for a star of angular diameter 0·0063″. The errors shown are the probable errors of the observations

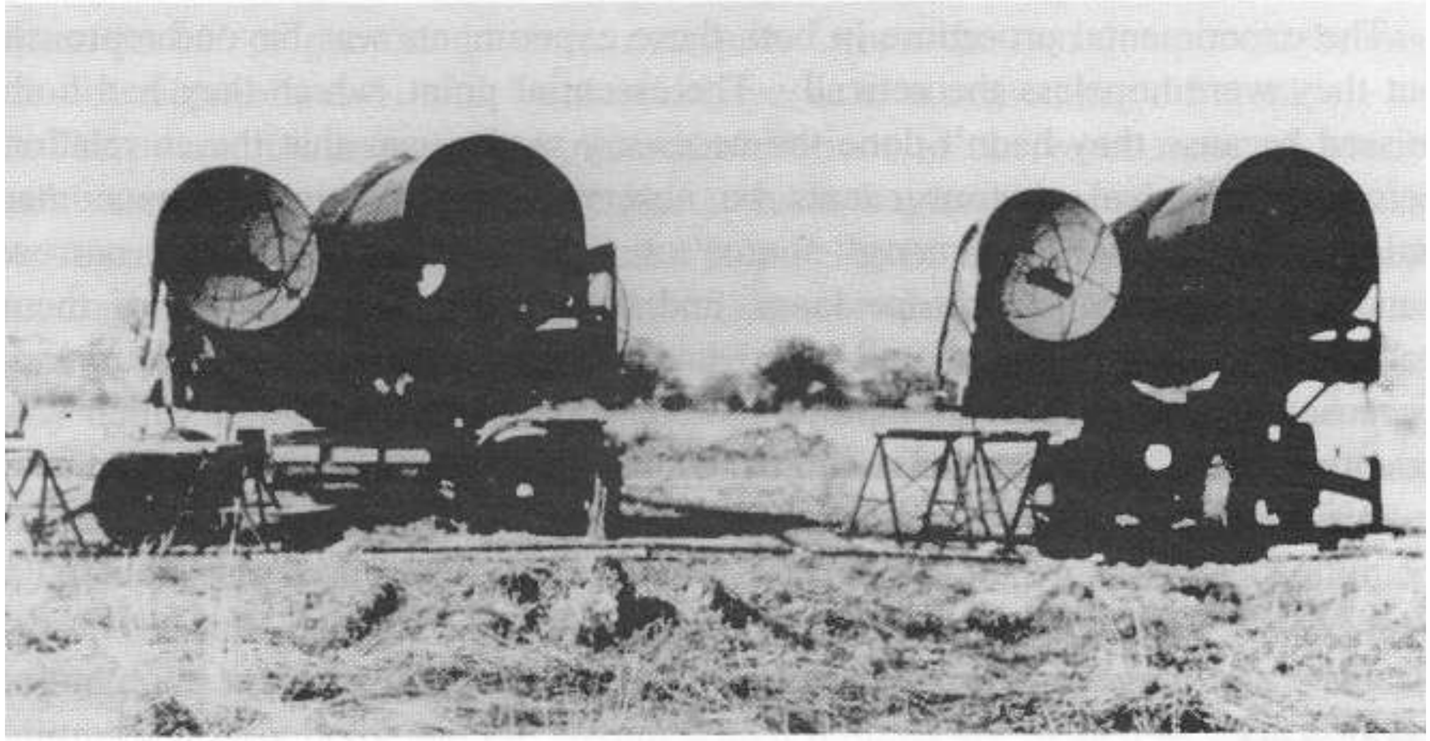


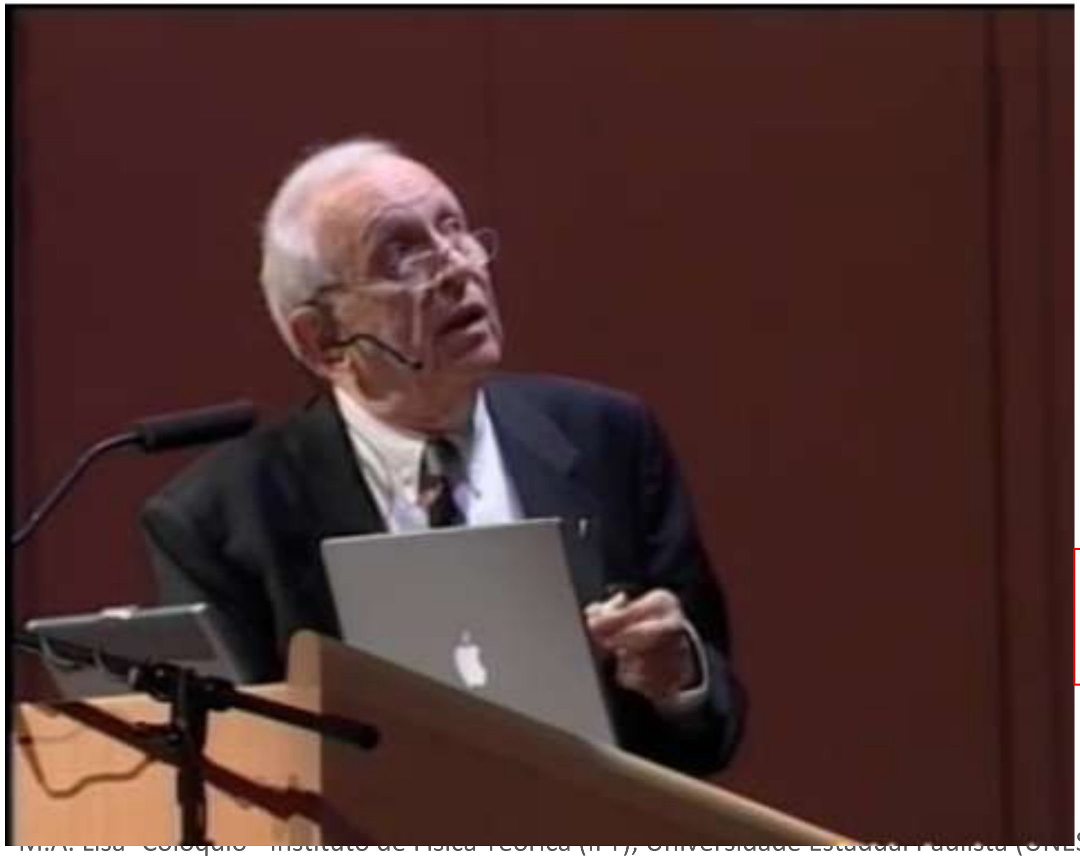
Figure 10.1 The first stellar intensity interferometer; the pilot model of the stella intensity interferometer at Jodrell Bank in 1955. Two Army searchlights were used to make the first measurement of the angular diameter of a main sequence star (Sirius)

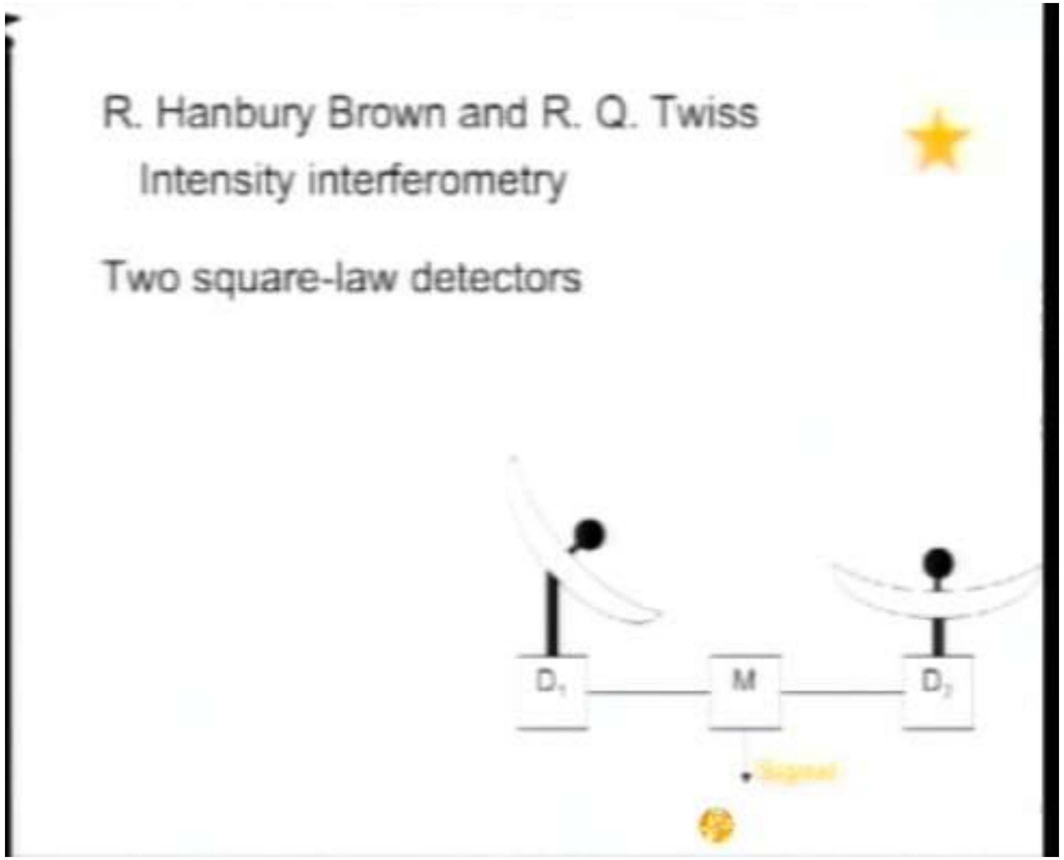
The humble beginnings of Quantum Optics

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." *



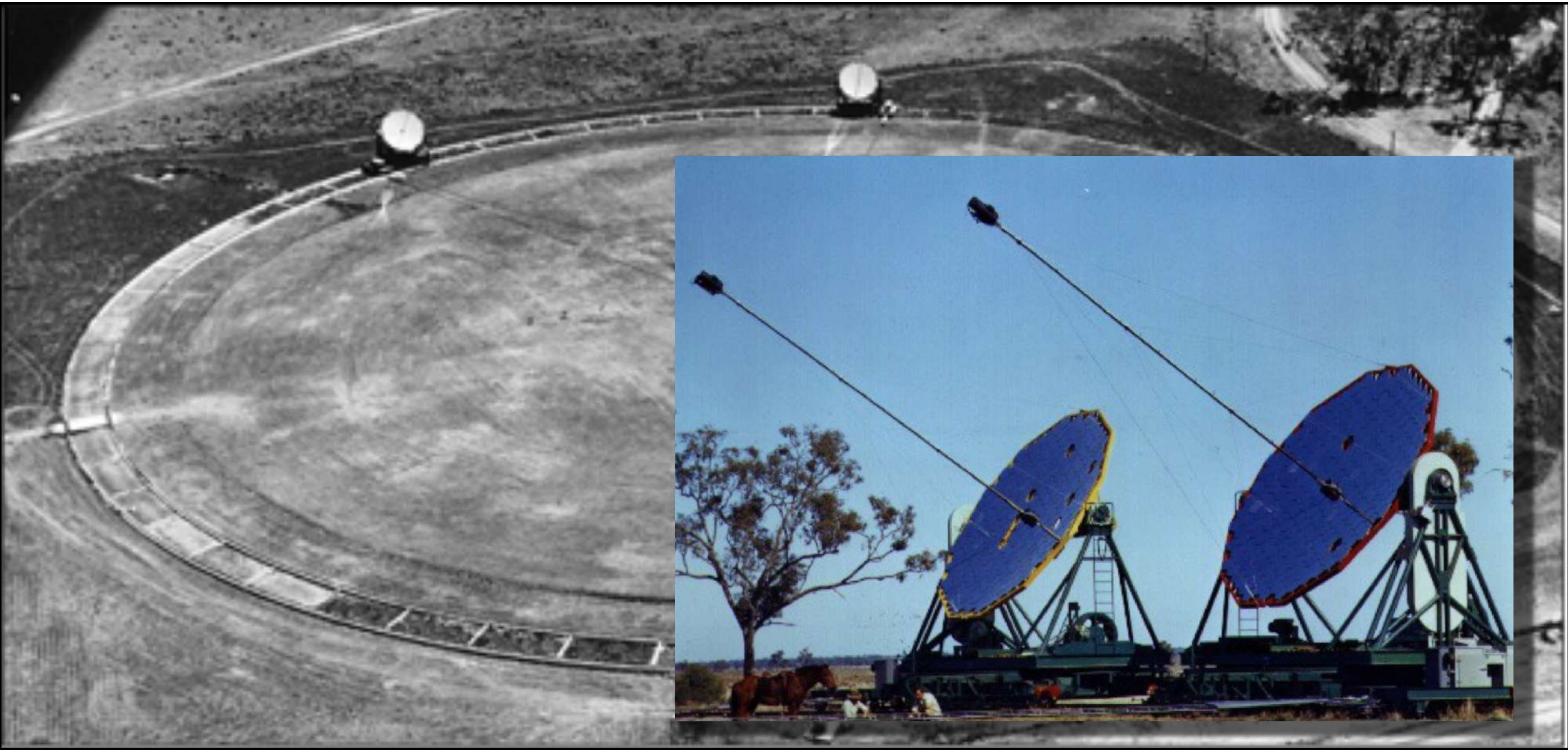


slide from Glauber's Lecture

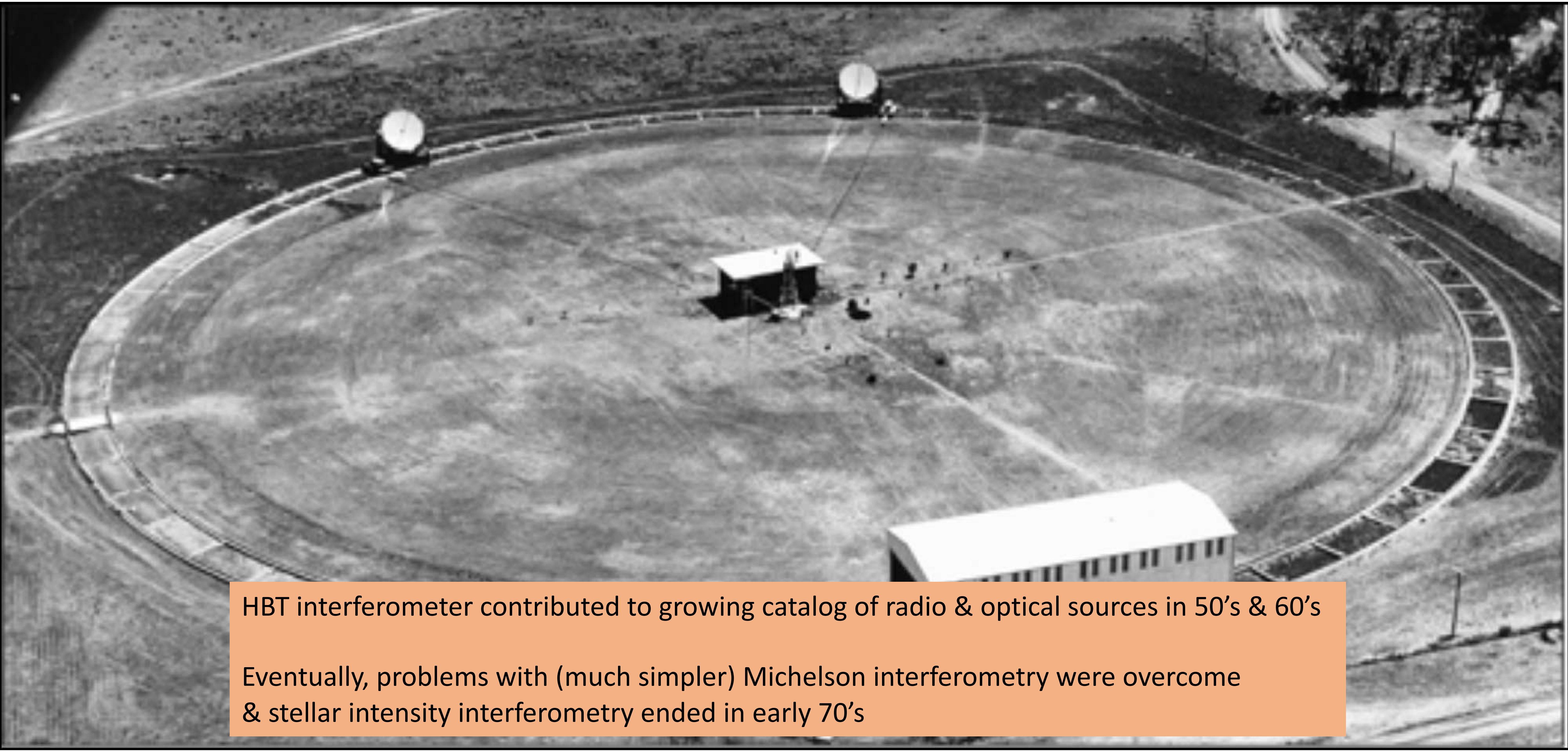
An appropriate subtitle for the Lecture:
"Why Robert Hanbury-Brown also should have gotten the Nobel Prize"

* This statement is in his talk, but not the later write-up

Intensity Interferometry in 1963 Narrabri, Australia



Intensity Interferometry in 1963 Narrabri, Australia

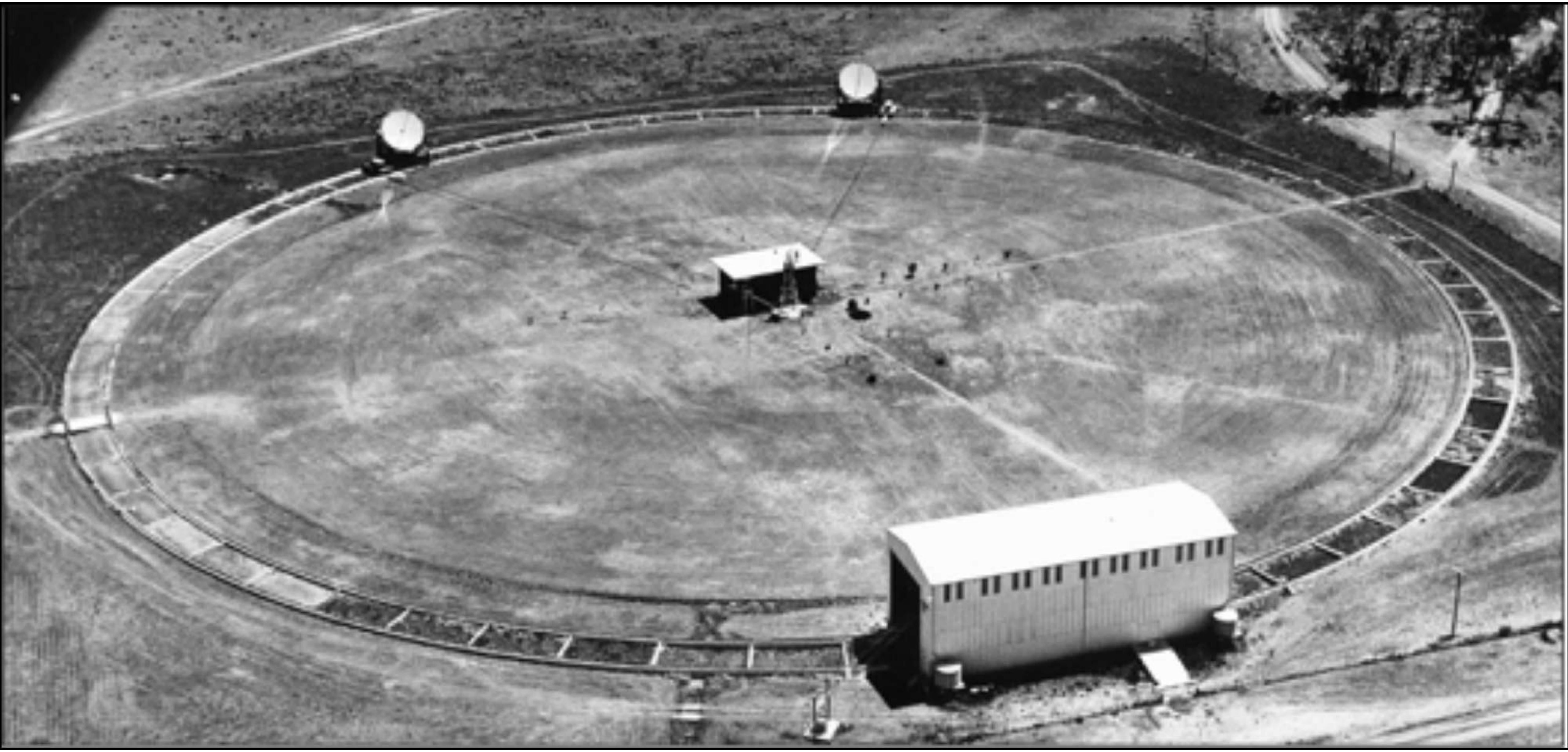


HBT interferometer contributed to growing catalog of radio & optical sources in 50’s & 60’s

Eventually, problems with (much simpler) Michelson interferometry were overcome
& stellar intensity interferometry ended in early 70’s

Intensity Interferometry in 2000, Long Island, NY

Intensity Interferometry in 1963 Narrabri, Australia



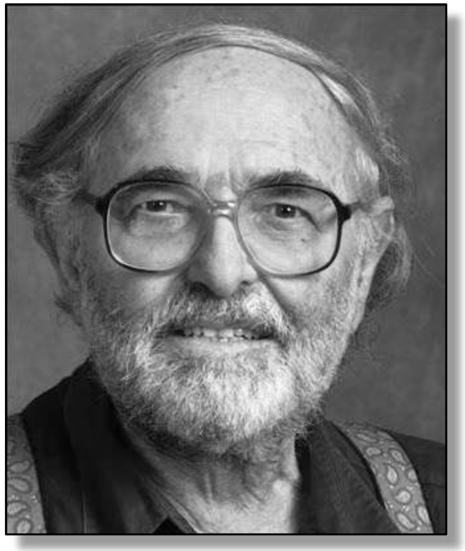
Meanwhile, in particle physics (1960)

PHYSICAL REVIEW VOLUME 120, NUMBER 1 OCTOBER 1, 1960

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

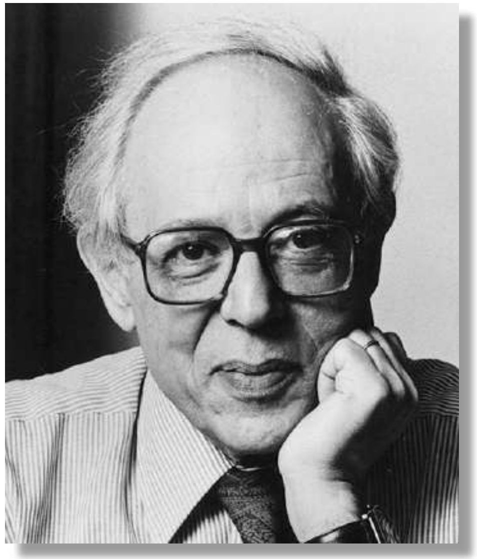
(Received May 16. 1960)



Gershon Goldhaber

Sulamith Goldhaber

Wonyong Lee



Abraham Pais

PHYSICAL REVIEW VOLUME 120, NUMBER 1 OCTOBER 1, 1960

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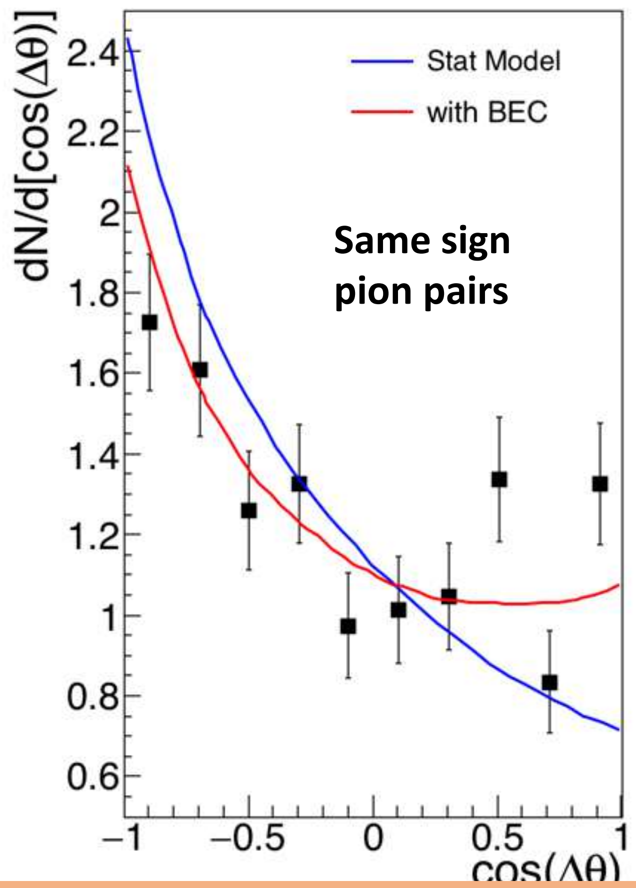
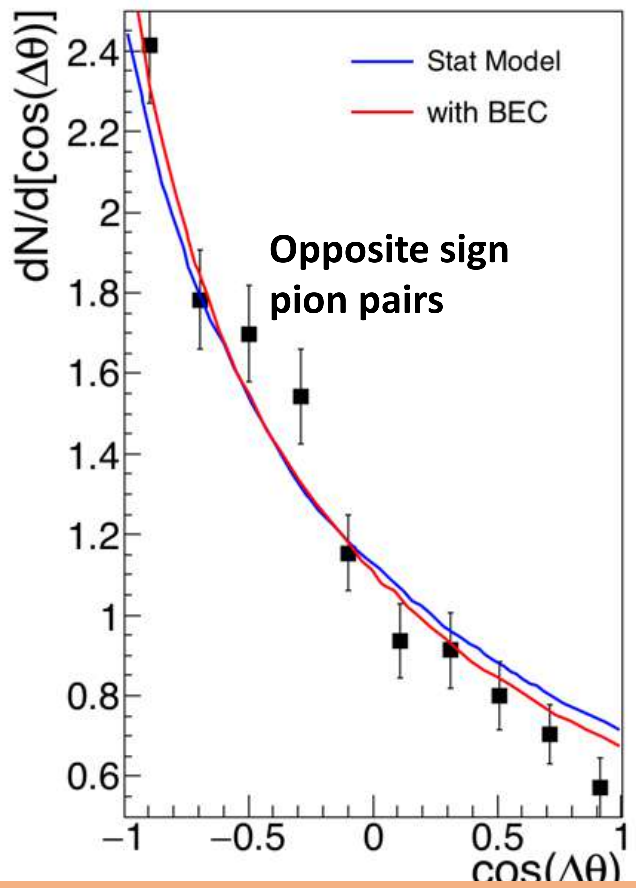
Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California
(Received May 16. 1960)

- 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]

$\pi^-\pi^-$ and $\pi^+\pi^+$ pairs

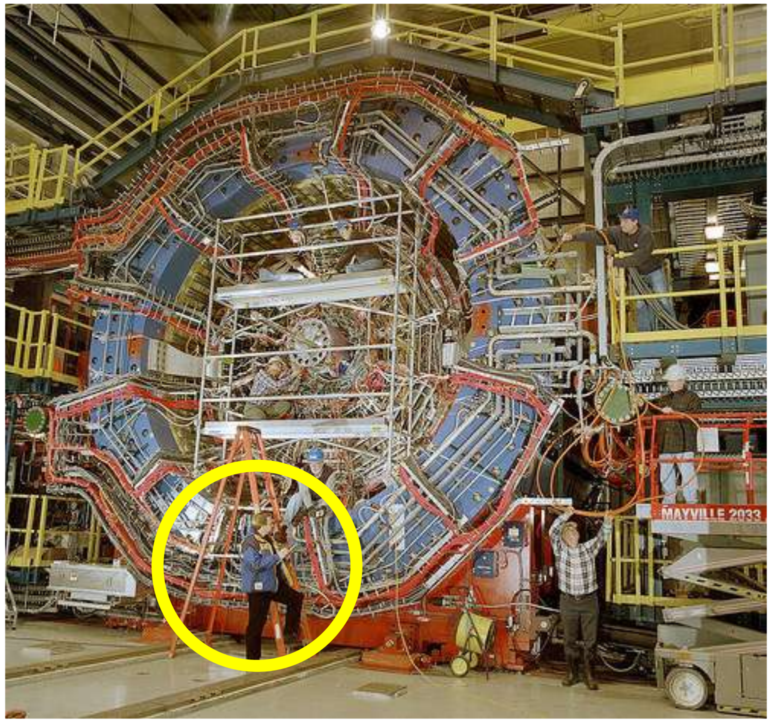


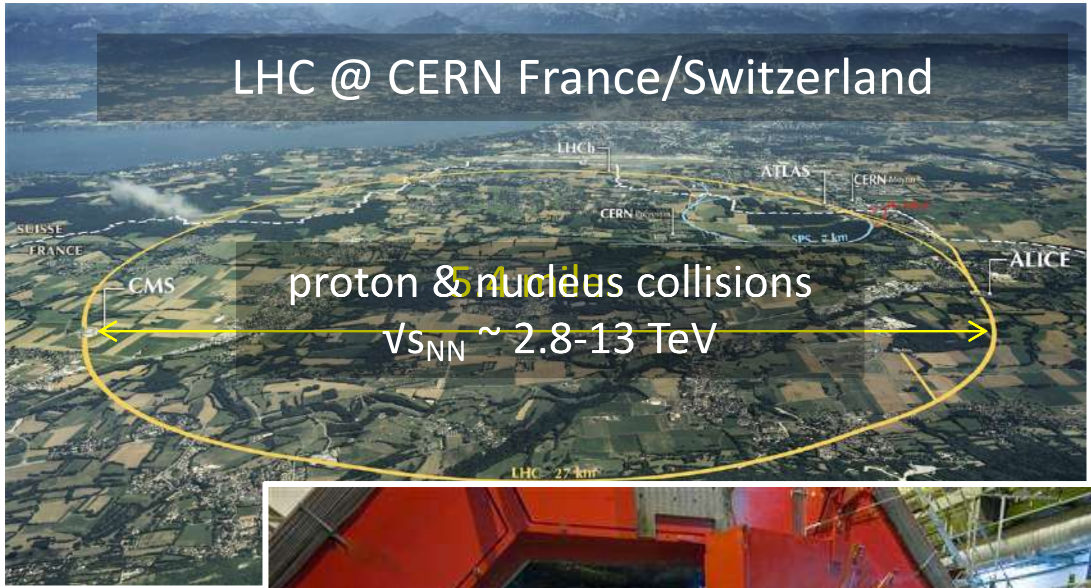
$\pi^-\pi^+$ pairs

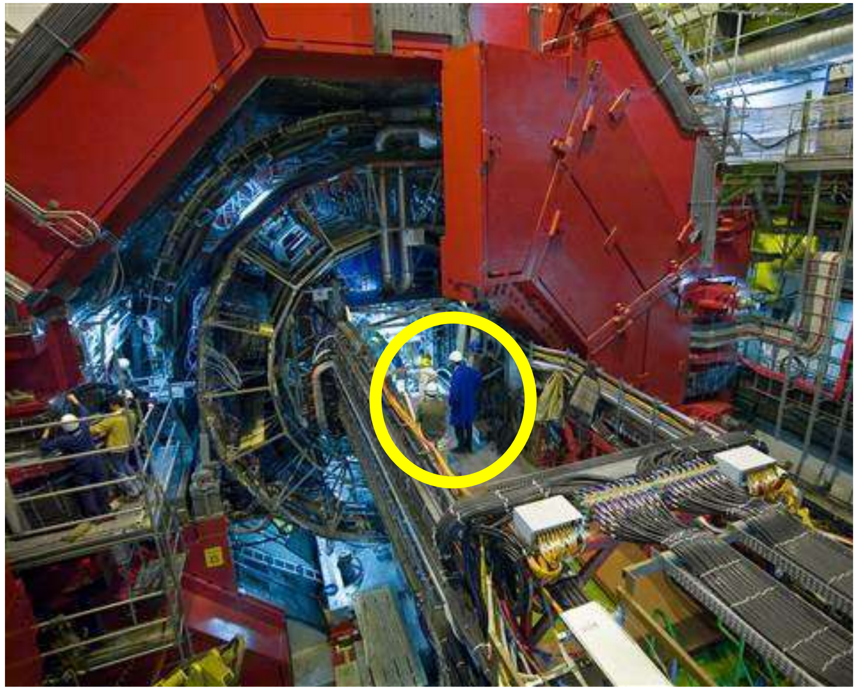


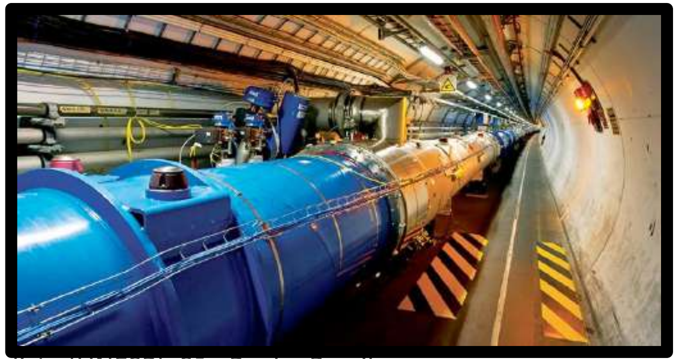
- until recently, in particle physics the GGLP effect is relevant mostly inasmuch as it distorts the W mass (e.g. arXiv:hep-ph/9805223)
- in heavy ion physics, however, it plays a prominent role


RHIC @ Brookhaven Lab, NY
proton & nucleus collisions
0.76 miles
$\sqrt{s_{NN}}$ ~ 7-550 GeV


MAYVILLE 2033


LHC @ CERN France/Switzerland
LHCb
ATLAS
CERN
ALICE
CMS
SUISSE
FRANCE
proton & nucleus collisions
5.4 miles
$\sqrt{s_{NN}}$ ~ 2.8-13 TeV
LHC 27 km





* proton

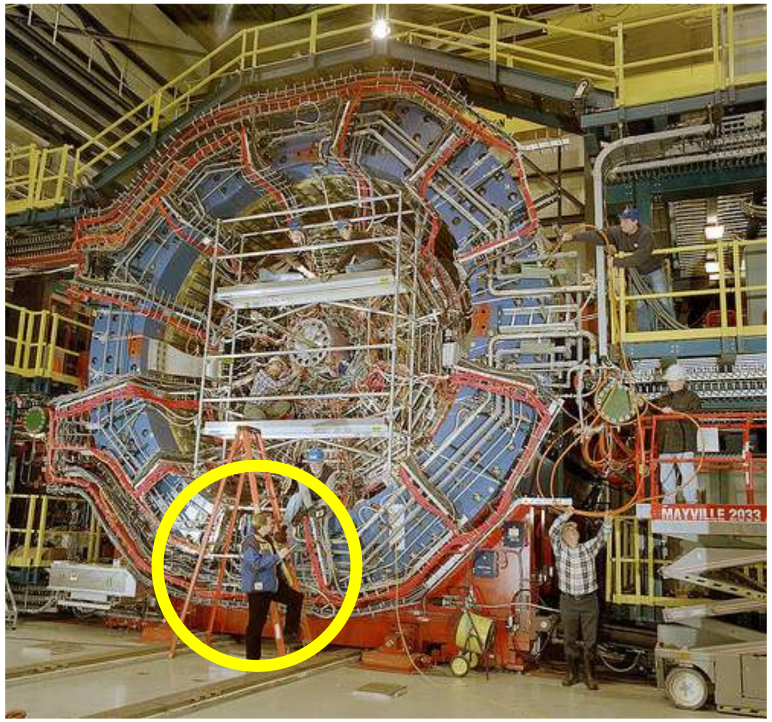
Relativistic Heavy Ion Collider

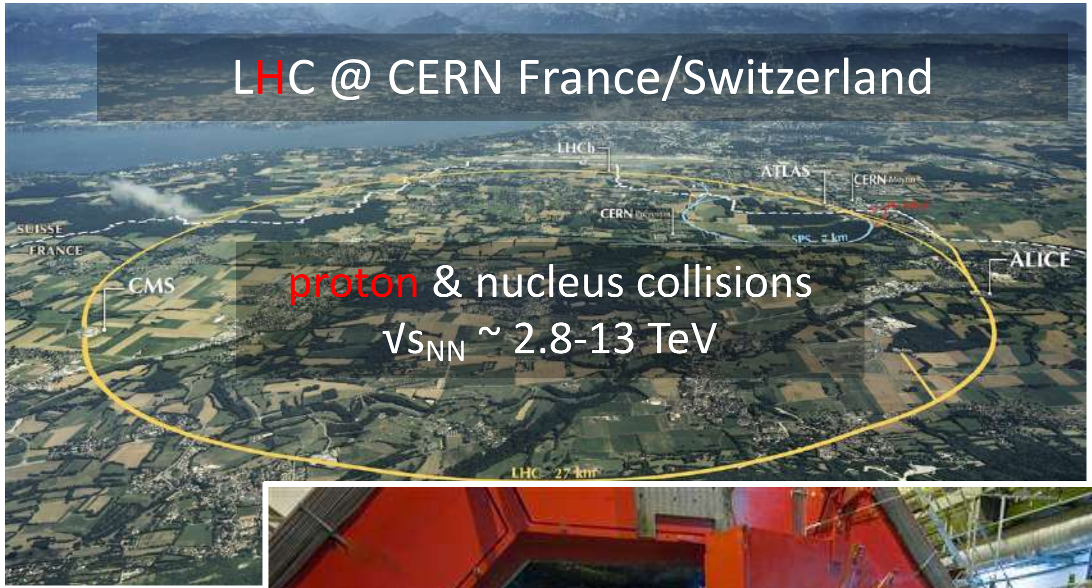
Large Hadron* Collider

RHIC @ Brookhaven Lab, NY

proton & nucleus collisions

$\sqrt{s_{NN}}$ ~ 7-550 GeV

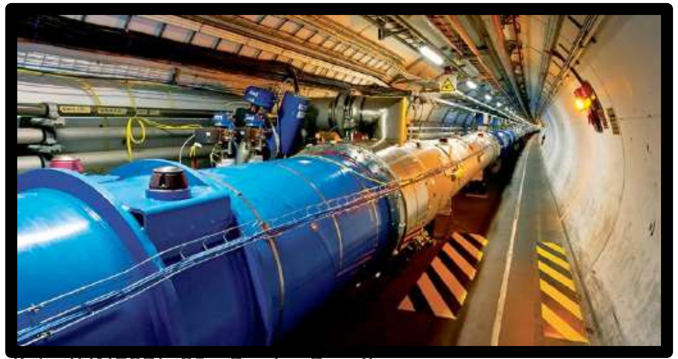


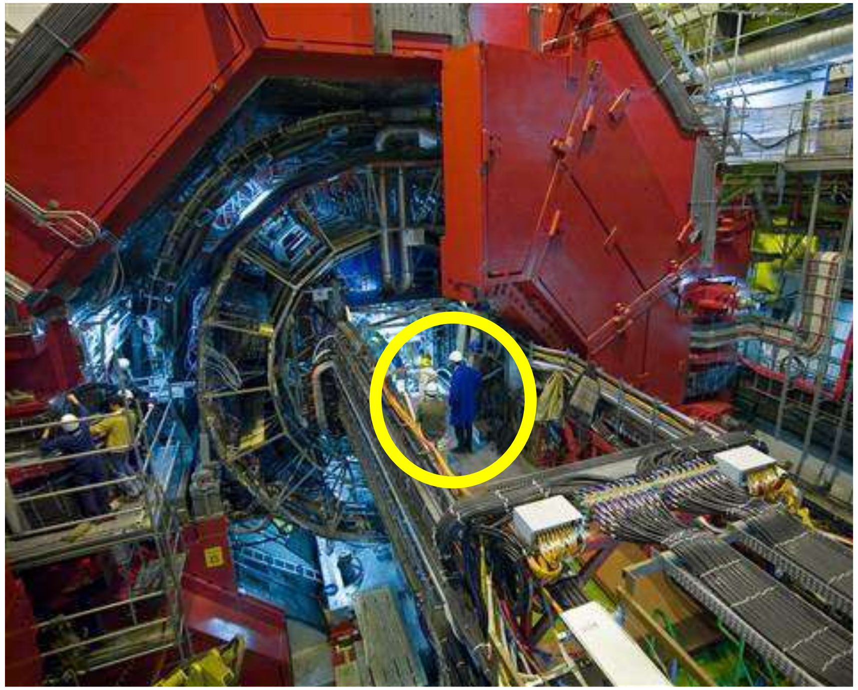


LHC @ CERN France/Switzerland

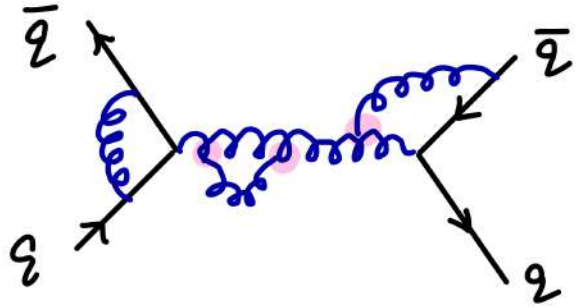
proton & nucleus collisions

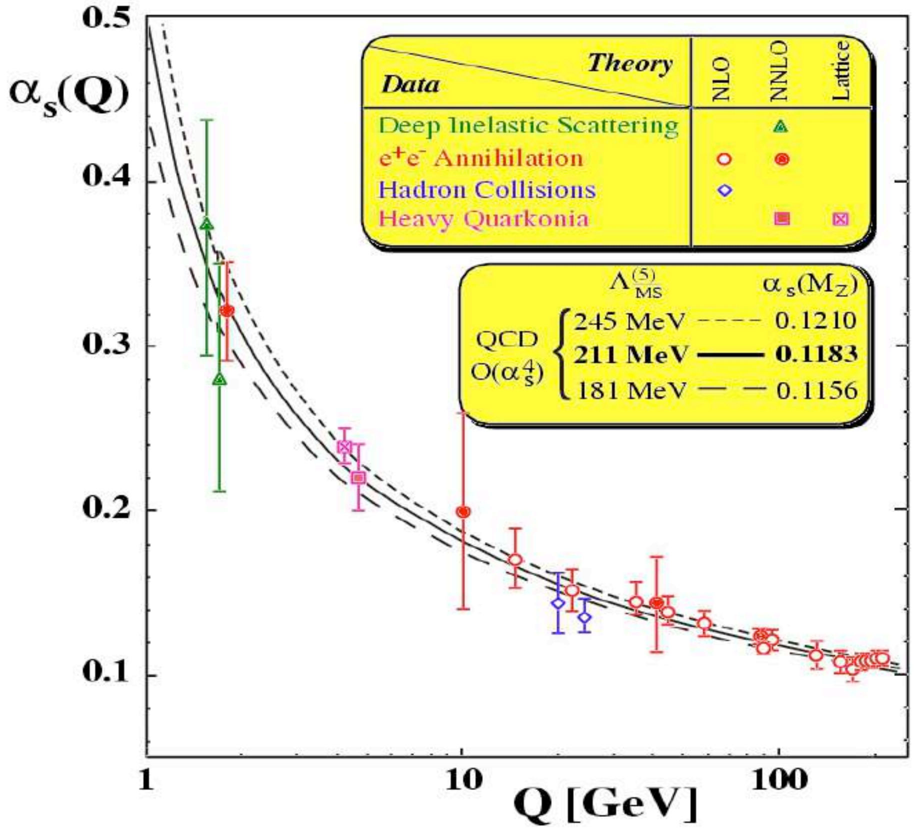
$\sqrt{s_{NN}}$ ~ 2.8-13 TeV

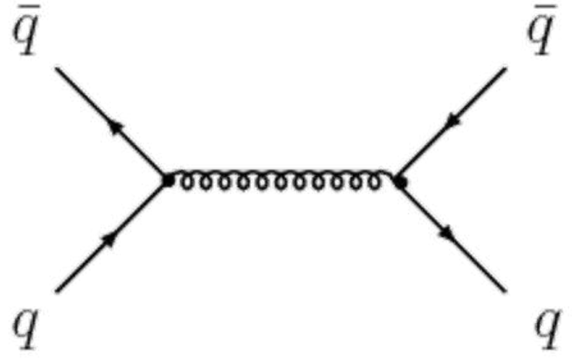




- Theory of Strong Force between quarks: Quantum Chromodynamics (QCD)
- Strength of the Strong Force depends on momentum transfer (spatial scale)
- Complicated & least-well-understood interaction



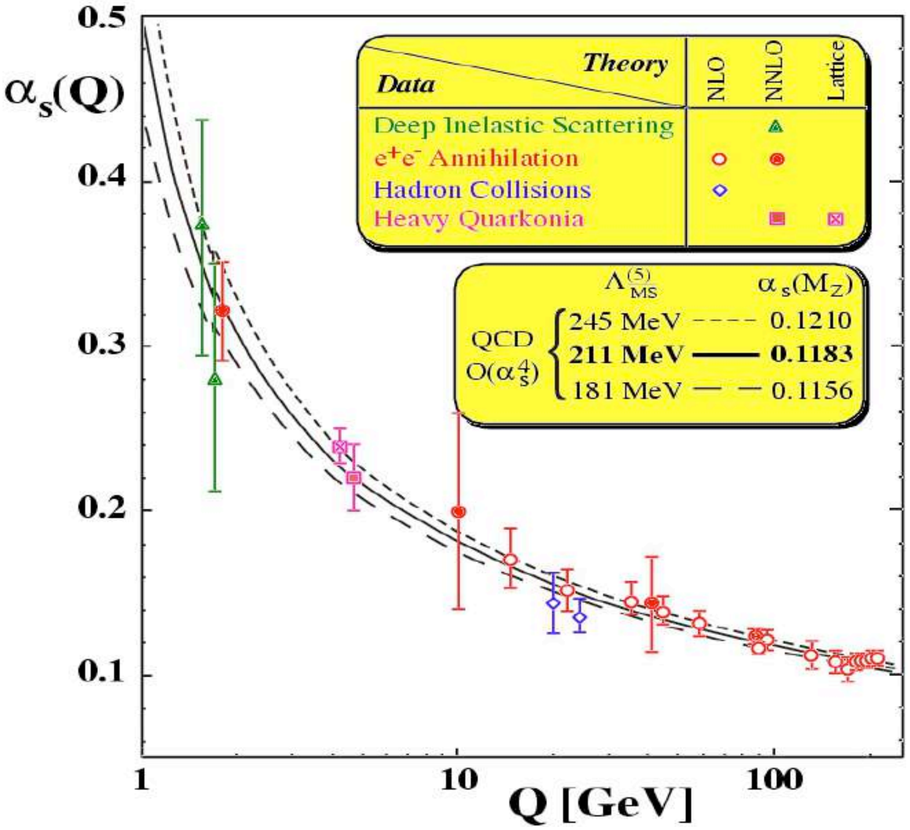




"Running" of the QCD coupling constant

e.g. **Higgs**

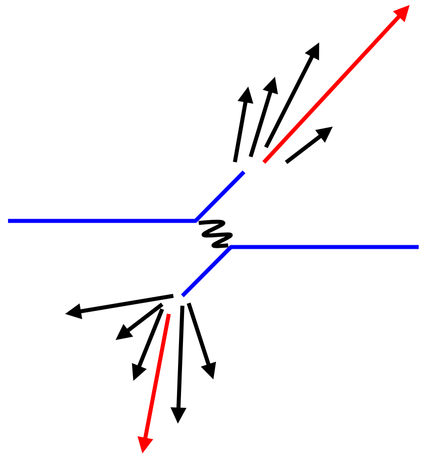
Particle ^ Physics



focus on fundamental particles

Large Q : **Asymptotic Freedom**

- reduce "messy" QCD effects



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

Heavy Ion Physics

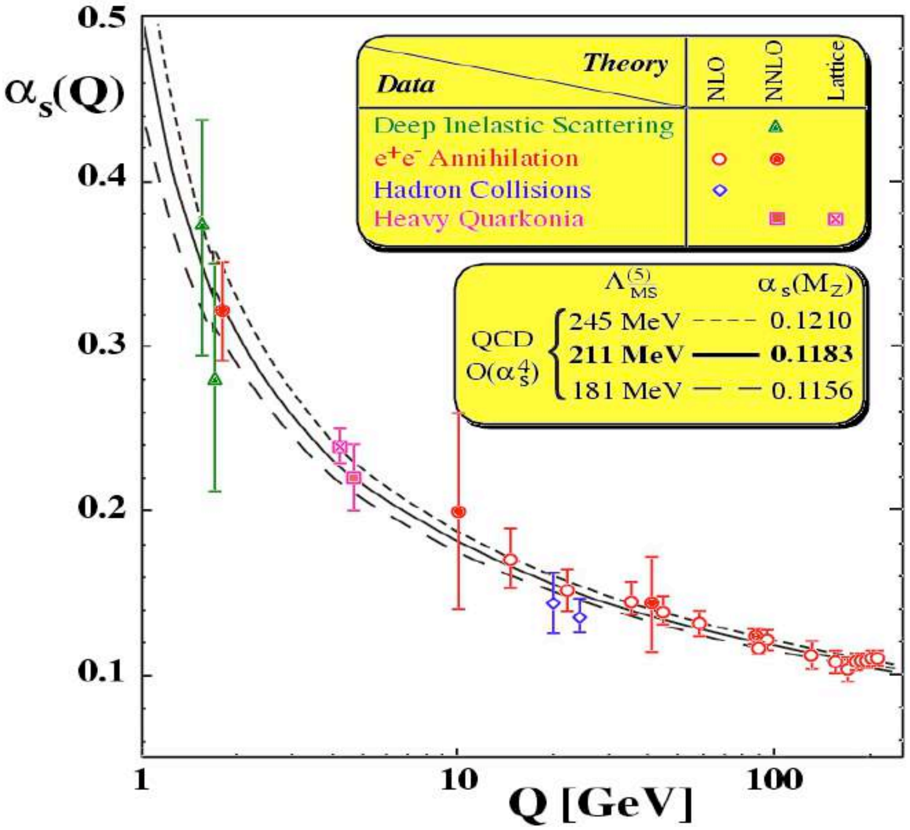
Low Q: **Confinement**
- dominates mass in universe
- theoretical insight limited

intrinsic scales of QCD→

✓ optimum energy range

✓ bigger is better (>> 1 fm)

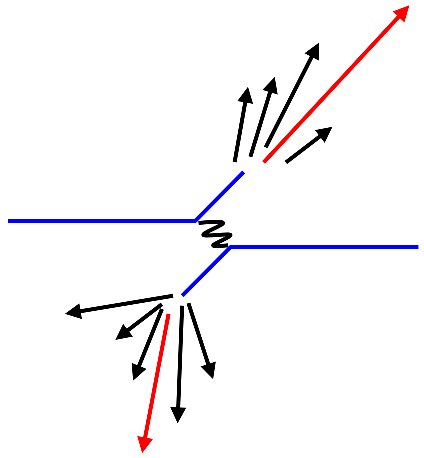
focus on fundamental interaction



focus on fundamental particles

e.g. Higgs Particle ^ Physics

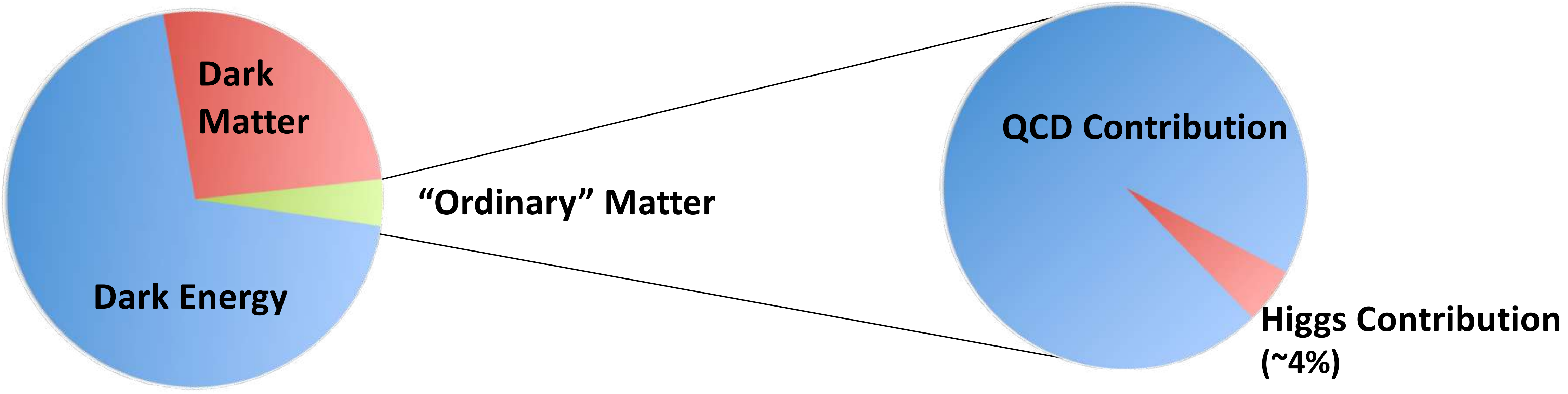
Large Q : **Asymptotic Freedom**
- reduce "messy" QCD effects

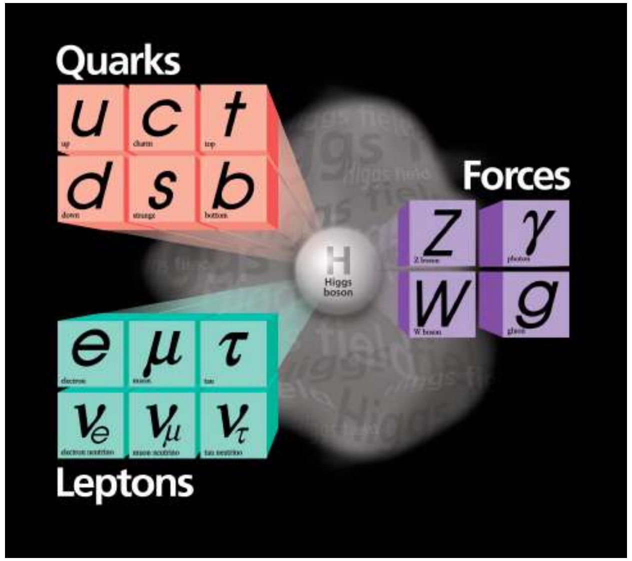


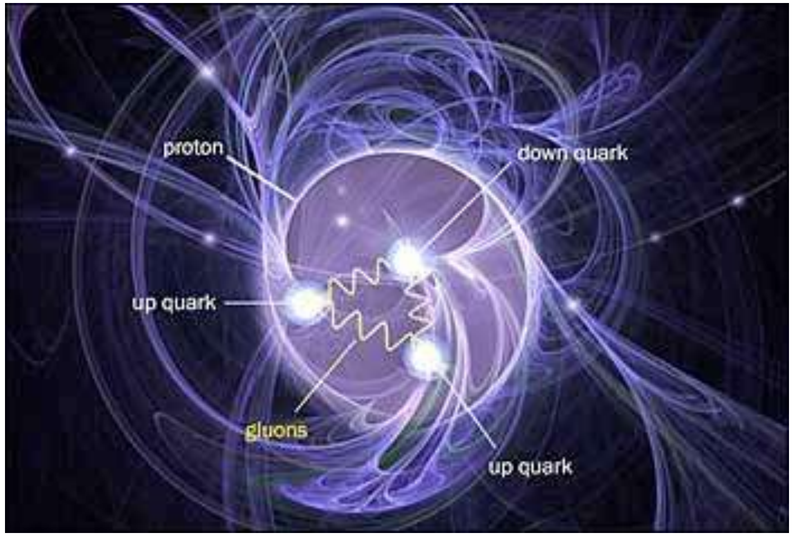
✓ Smaller/simpler is better

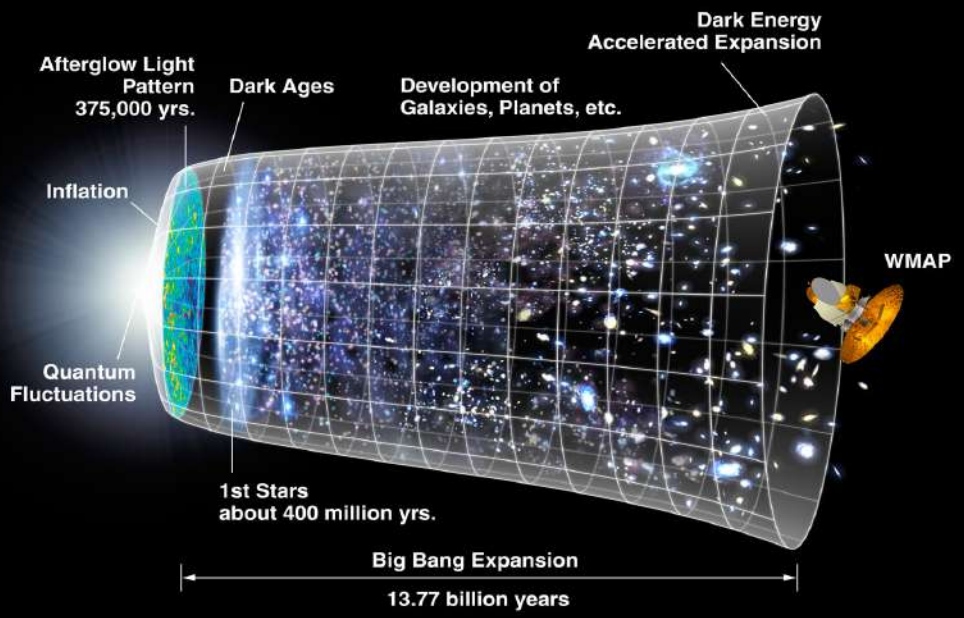
✓ More energy is better

Confinement generates most (visible) mass

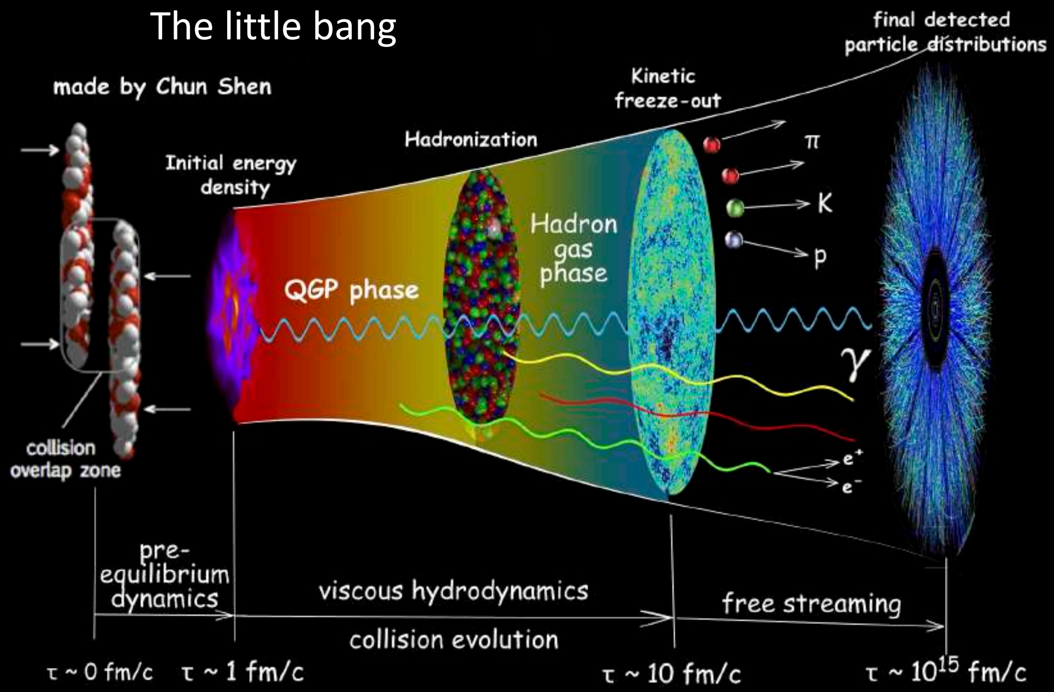








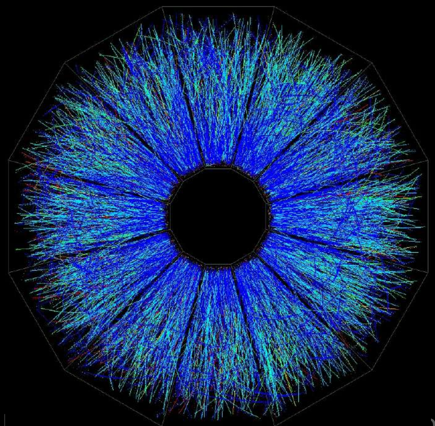
The little bang

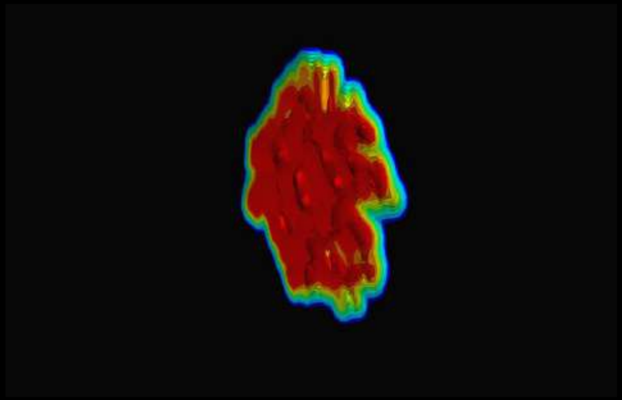


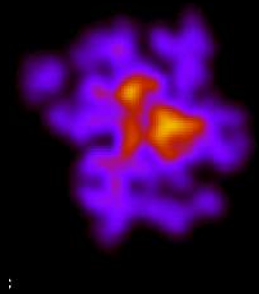
Heavy ion collisions form a geometrically nontrivial *system* that experiences bulk evolution

- space-time plays a huge role

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







hydro simulations by Bjorn Schenke

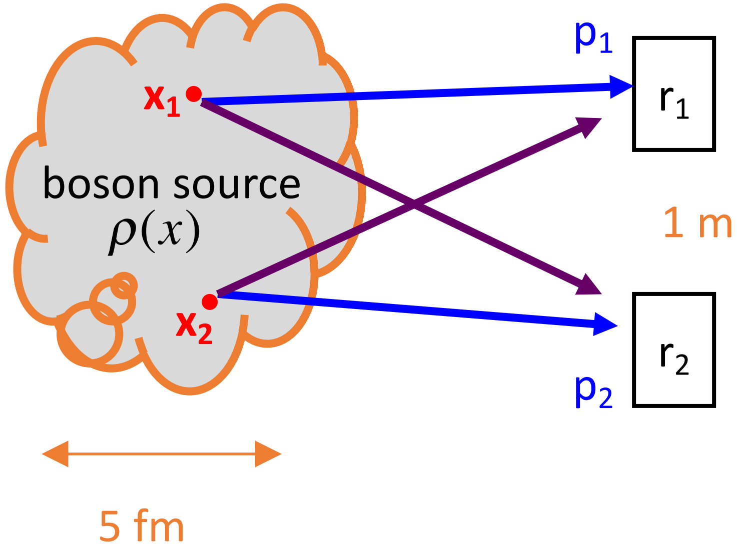
Evolution to heavy ion collisions

Phys. Lett. 44B (1973) 387

Edward Shuryak

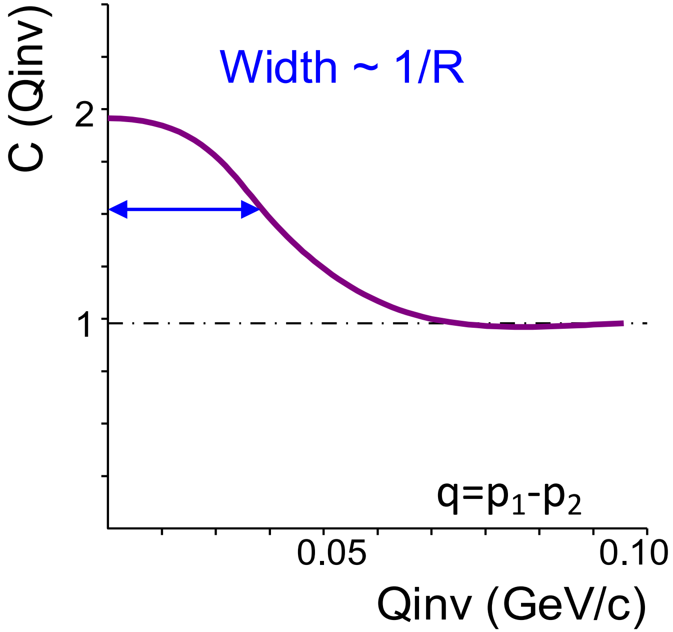
- early 1970’s: connection between GGLP and HBT [Shuryak. Kopylov, Podgiretsky...]

Identical non-interacting bosons



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

$$\Psi^*\Psi = \underbrace{U_1^*U_1}_{\text{Prob. for particle 1}} \cdot \underbrace{U_2^*U_2}_{\text{Prob. for particle 2}} \cdot \left(1 + e^{i(\vec{p}_2-\vec{p}_1)\cdot(\vec{x}_2-\vec{x}_1)}\right)$$



$$C(\vec{p}_1,\vec{p}_2) \equiv \frac{P(\vec{p}_1,\vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)} = 1 + \left|\tilde{\rho}(\vec{q})\right|^2$$

Measurable

F.T. of pion source

Evolution to heavy ion collisions

Edward Shuryak

- 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

Miklos Gyulassy

Steve Koonin

Scott Pratt

Richard Lednicky

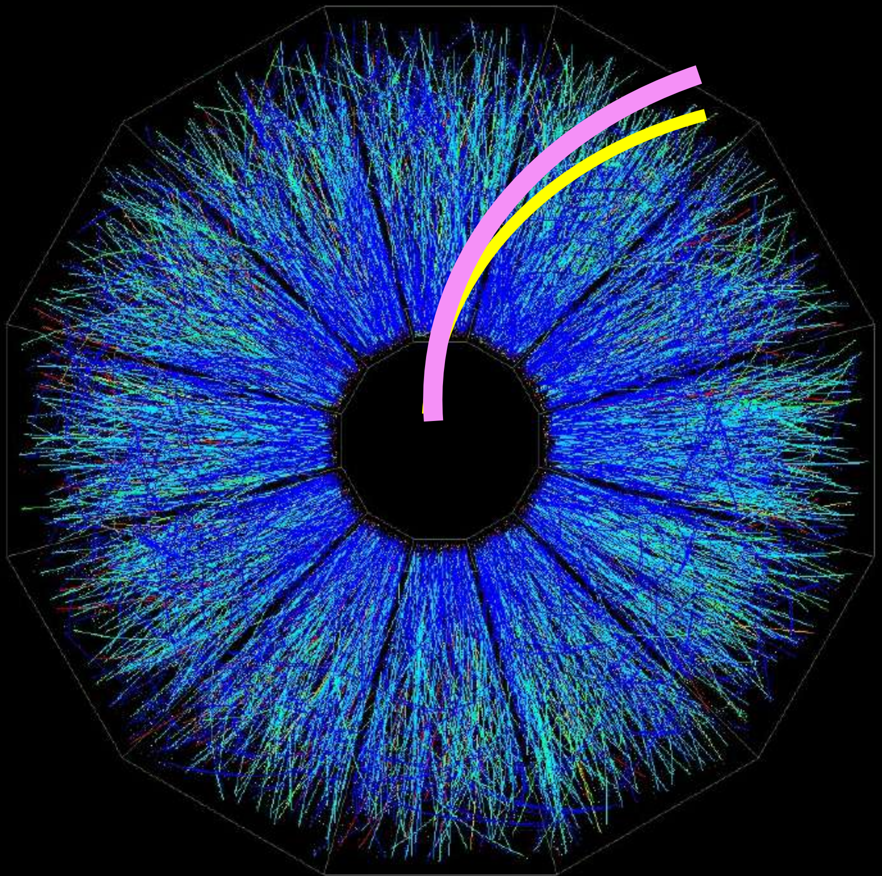
Bill Zajc

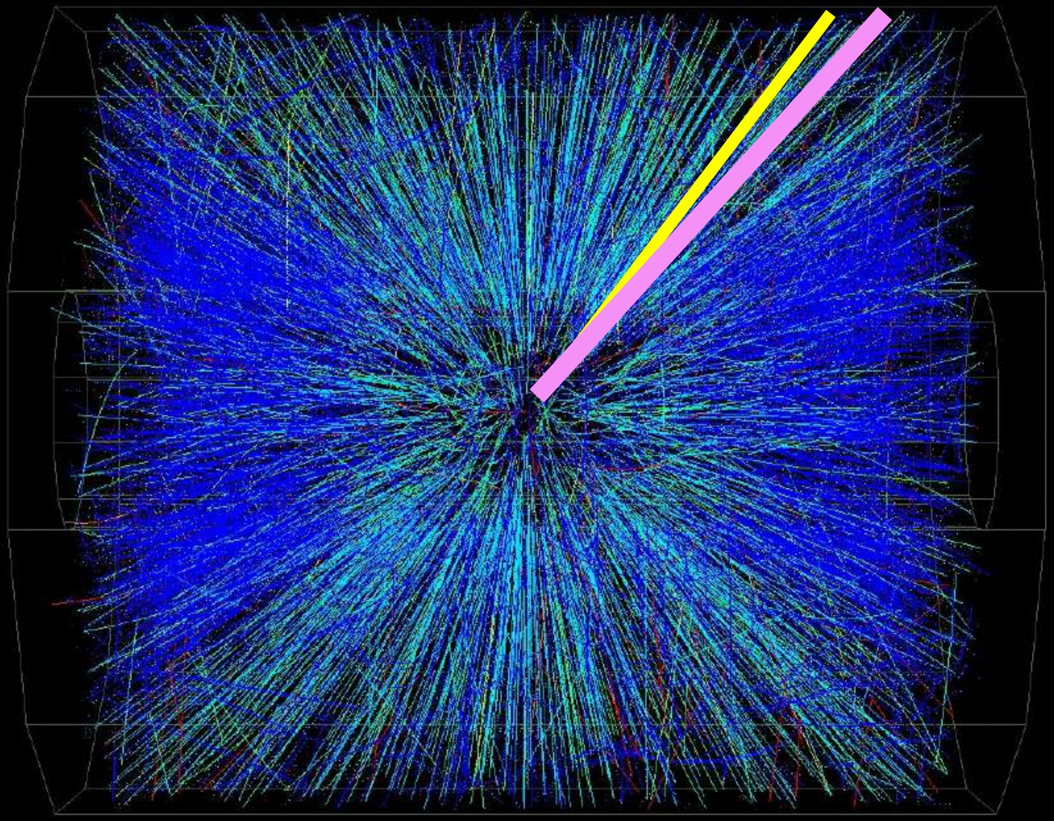
$$C(\vec{q}) = 1 + \int d^3r\, S(\vec{r}) \cos(\vec{q}\cdot\vec{r}) \quad = \frac{N(\vec{p}_1, \vec{p}_2)}{N_{\mathrm{mix}}(\vec{p}_1, \vec{p}_2)}$$

still dominated by phasespace

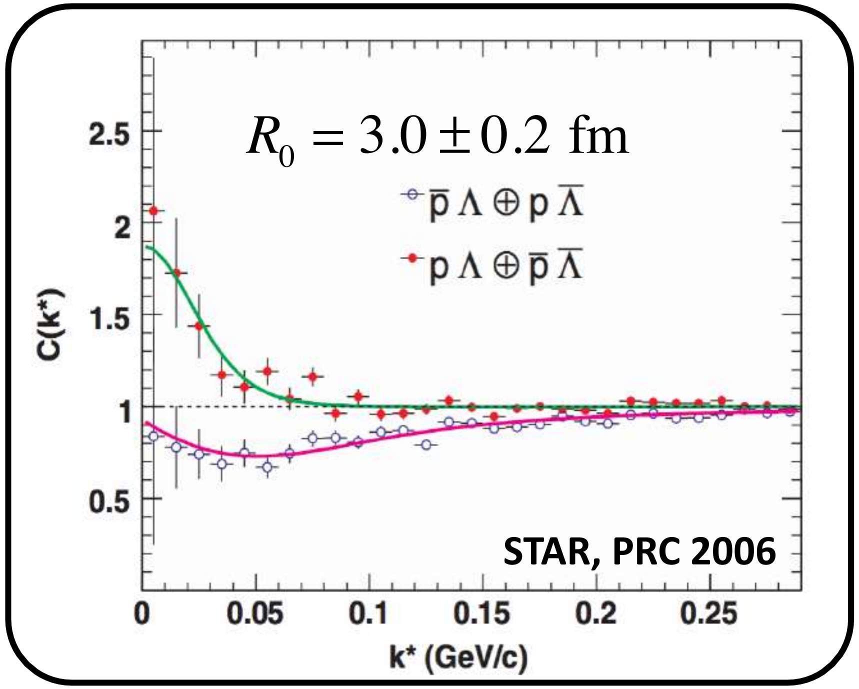
separation distribution: $S(\vec{r}) \equiv \dfrac{\int d^4x_1 \int d^4x_2 \rho_1(x_1)\rho_2(x_2)\delta(\vec{r} - \vec{x}_1 + \vec{x}_2)}{\int d^4x_1 \rho_1(x_1) \int d^4x_2 \rho_2(x_2)}$

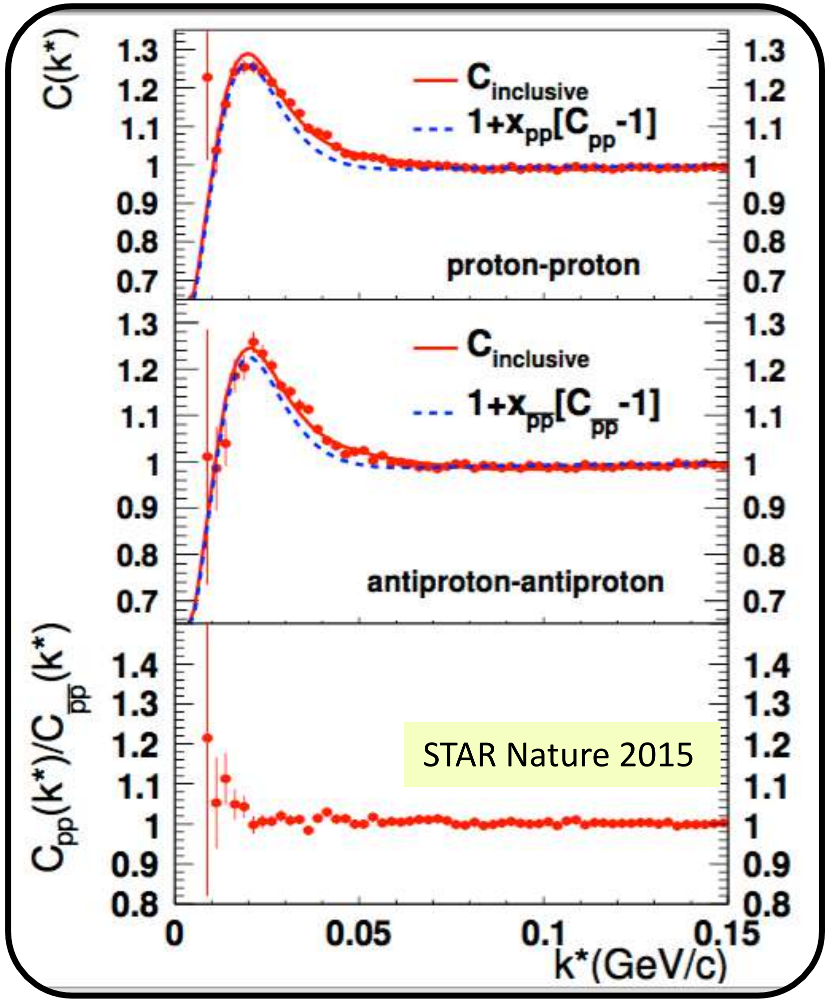
Correlation expresses a conditional probability (~stellar HBT)

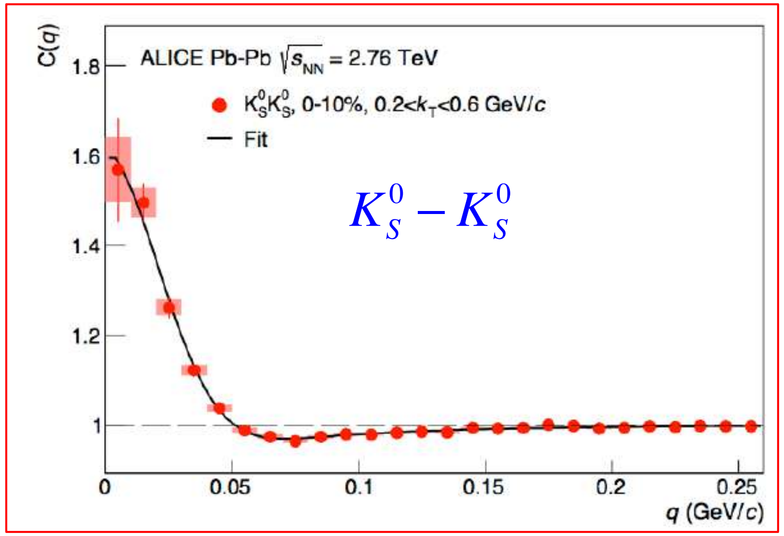




$$\pi^{\pm}-\pi^{\pm},K^{\pm}-K^{\pm},K_S^0-K_S^0,p-p,\bar{p}-\bar{p},\Lambda-\Lambda,K^{\pm}-\pi^{\pm},p-\Lambda,\Xi-\pi...$$



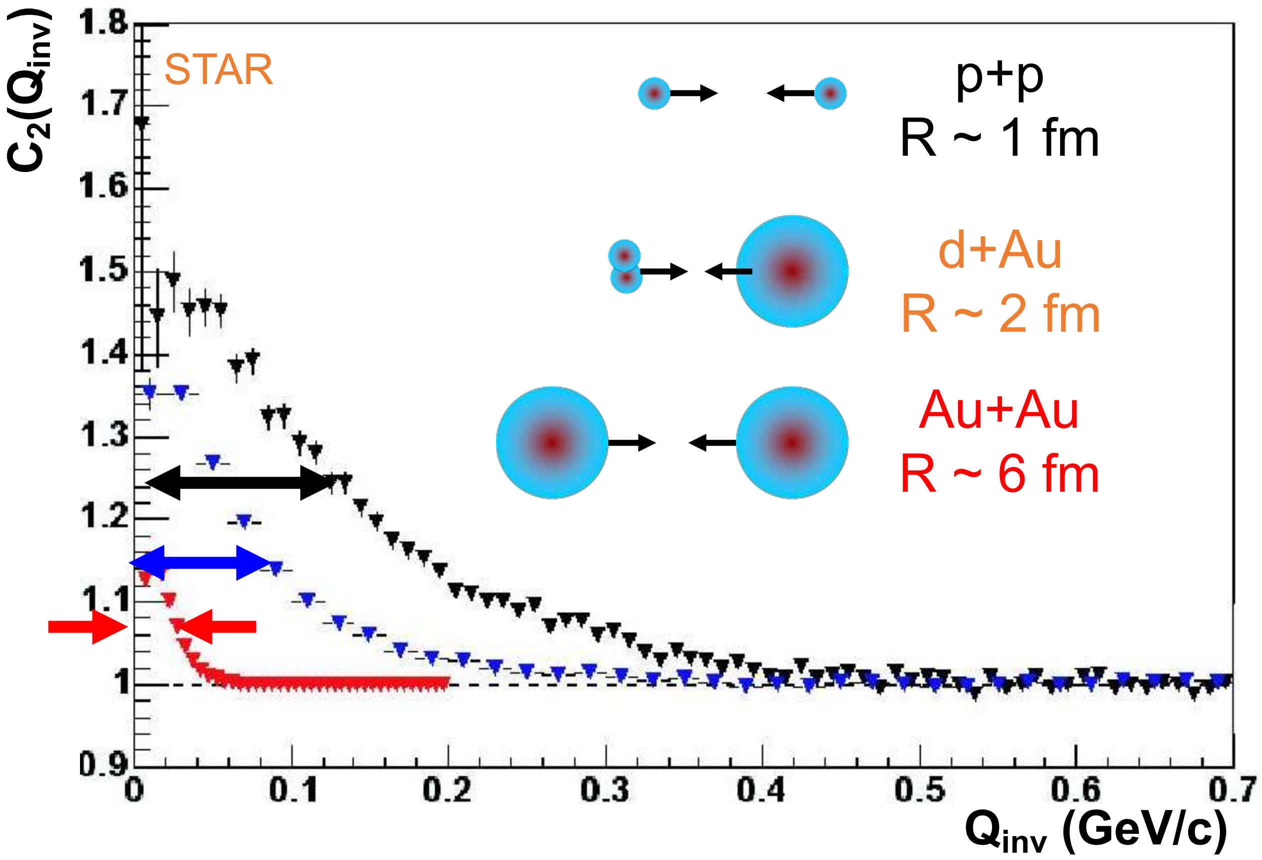




Geometry – the hallmark of heavy ion physics

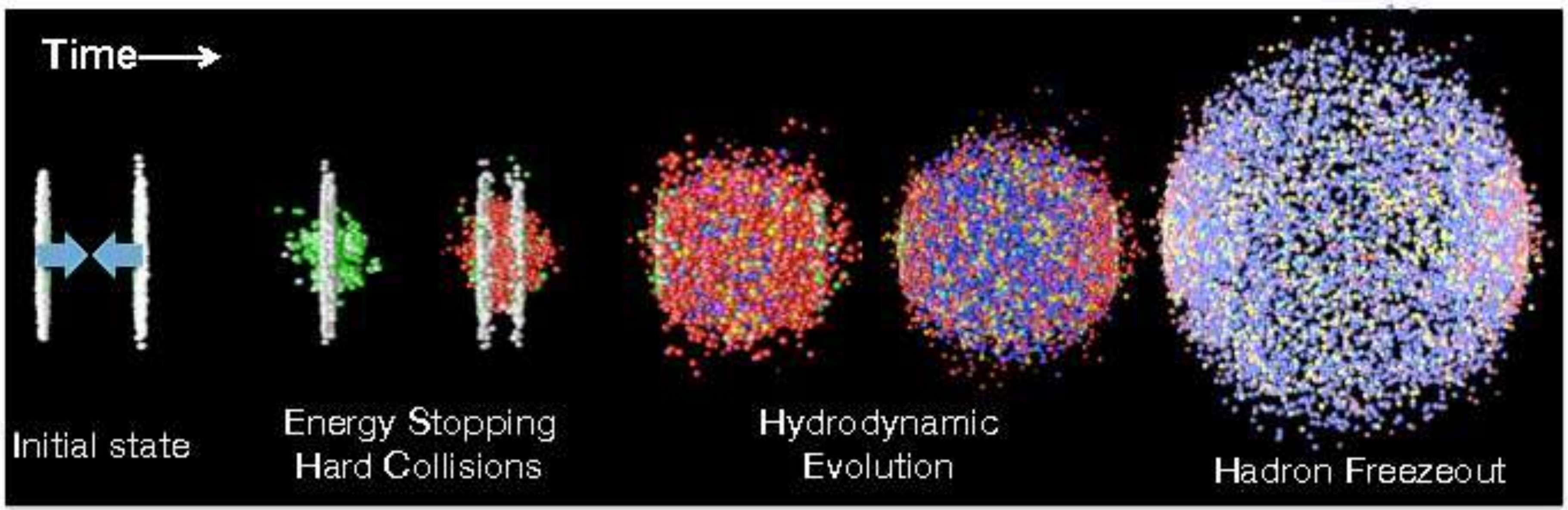
- Size matters – need a *bulk* system

Sanity check: intensity interferometry for 3 colliding systems



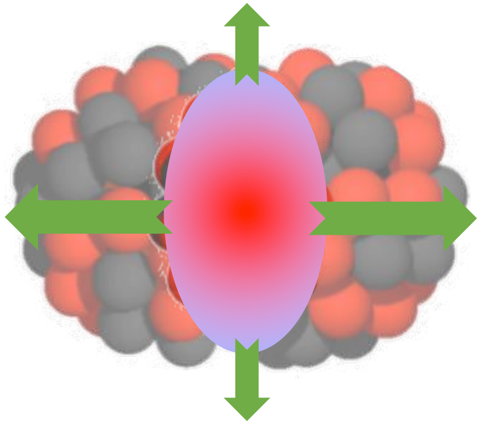
Geometry – the hallmark of heavy ion physics

- Size matters – need a *bulk* system
- Timescale matters – highly dynamic system

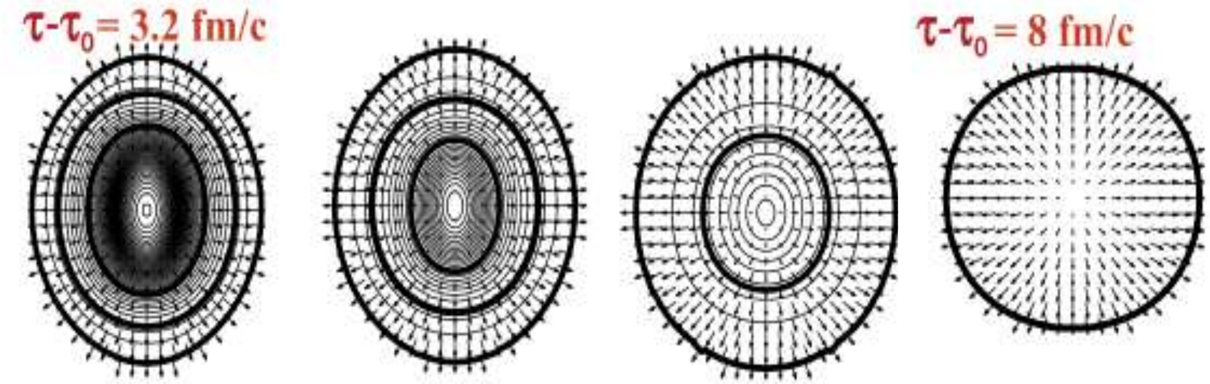


Geometry – the hallmark of heavy ion physics

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

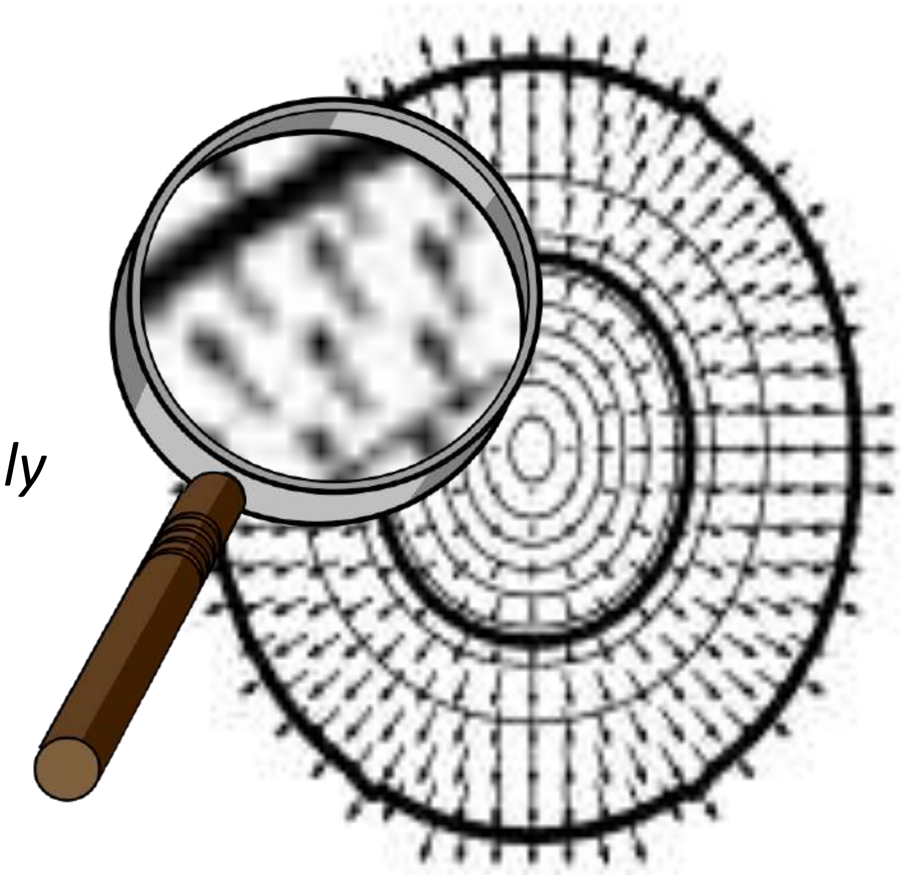


hydro calculations: Kolb & Heinz



Geometry – the hallmark of heavy ion physics

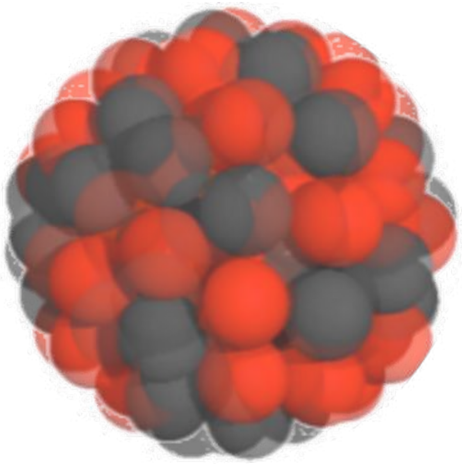
- Size matters – need a *bulk* system
- Timescale matters – highly dynamic system
- Shape matters – anisotropic geometry key
- Substructure matters



Intensity interferometry is the *only* direct probe of spacetime in subatomic collisions

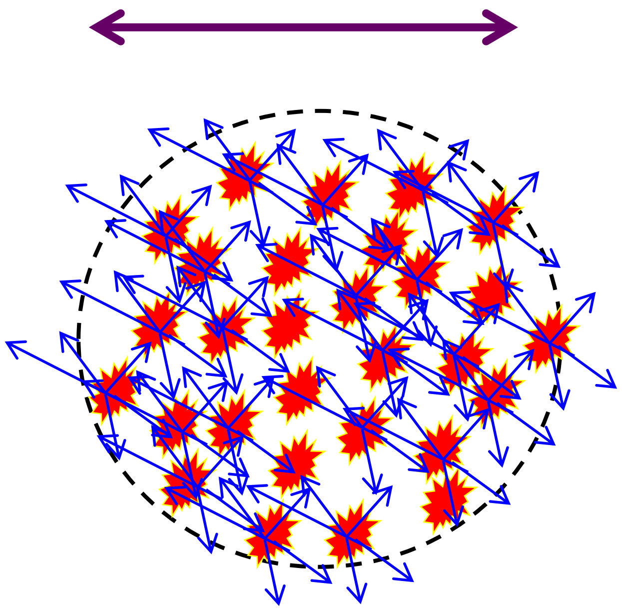
Geometric substructure

What type of system is formed?
Indeed, *is* it a system?



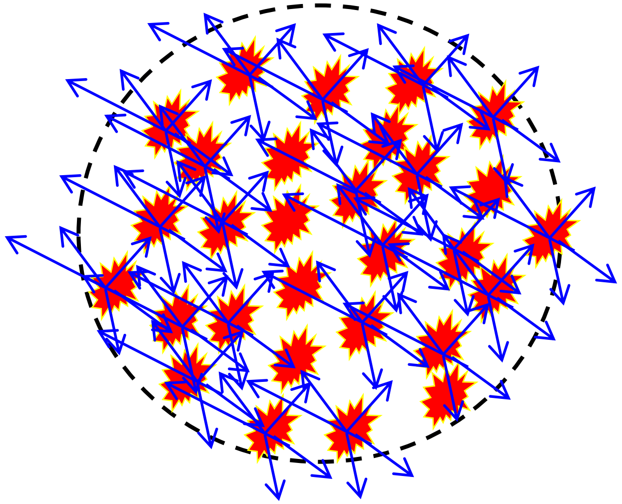
Geometric substructure

Independent of momentum



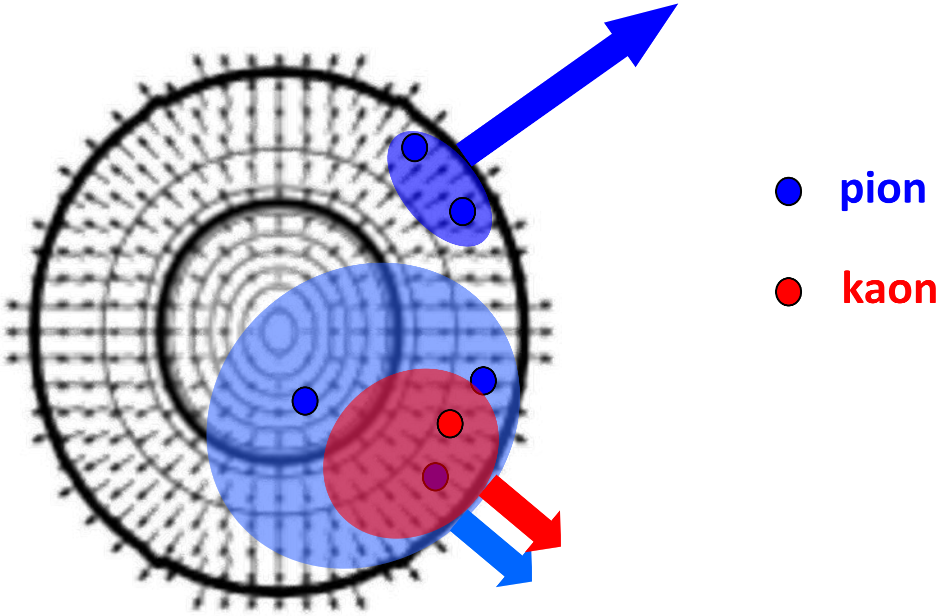
A collection of nearby, independent p+p collisions. **Not "matter"**

Geometric substructure



A collection of nearby, independent p+p collisions. **Not “matter”**

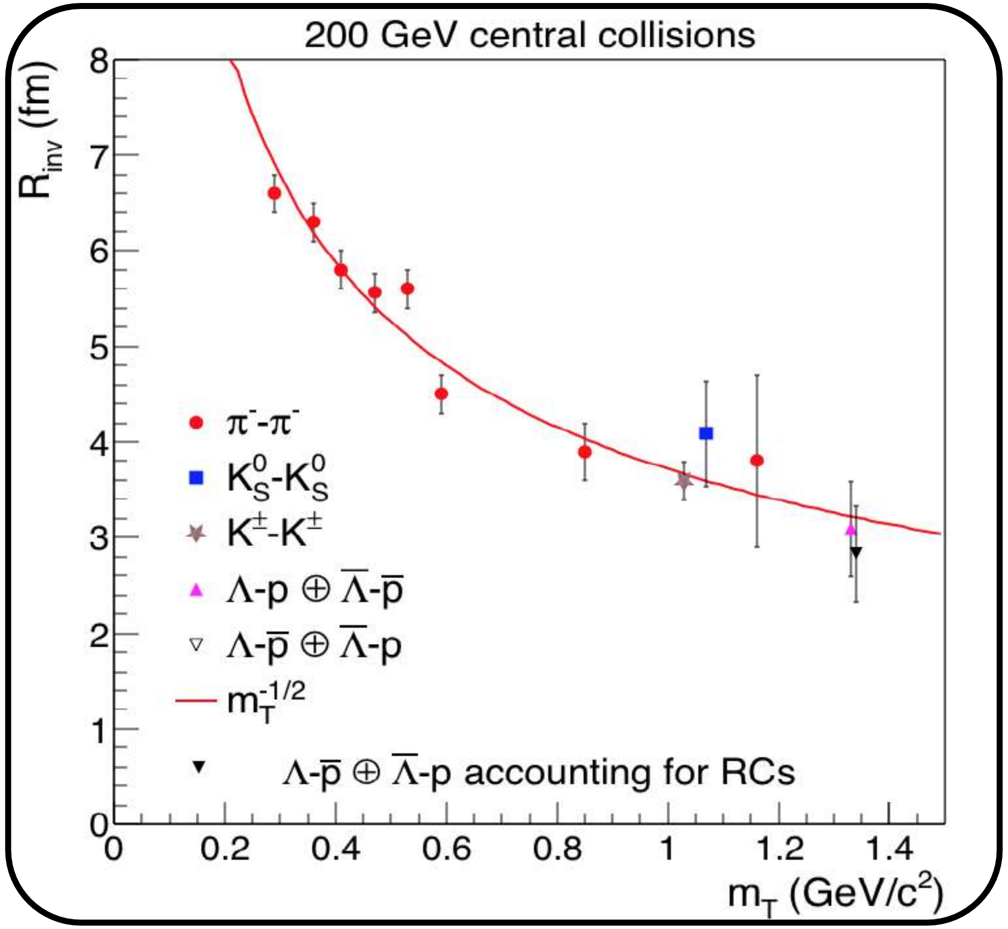
Hydrodynamic expectation:



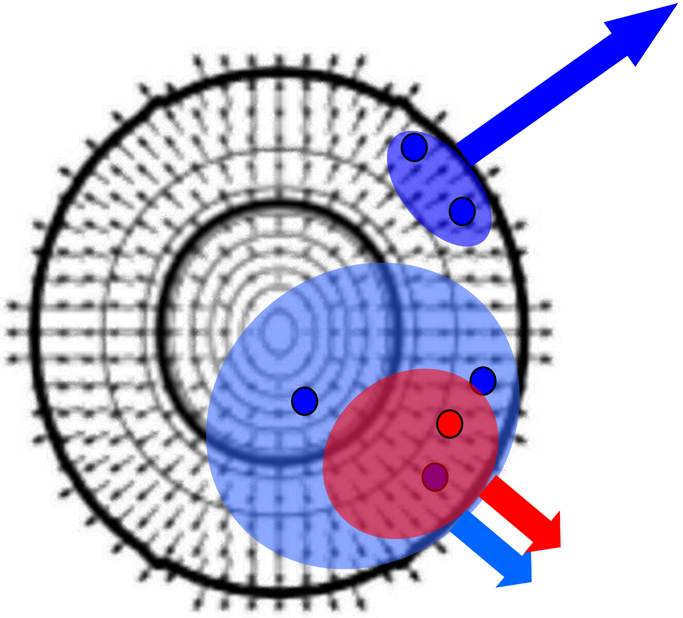
Matter is characterized by fields of **bulk** properties

Geometric substructure

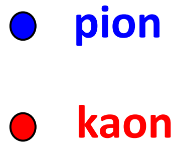
Sizes for particles of different momentum & mass



Hydrodynamic expectation:

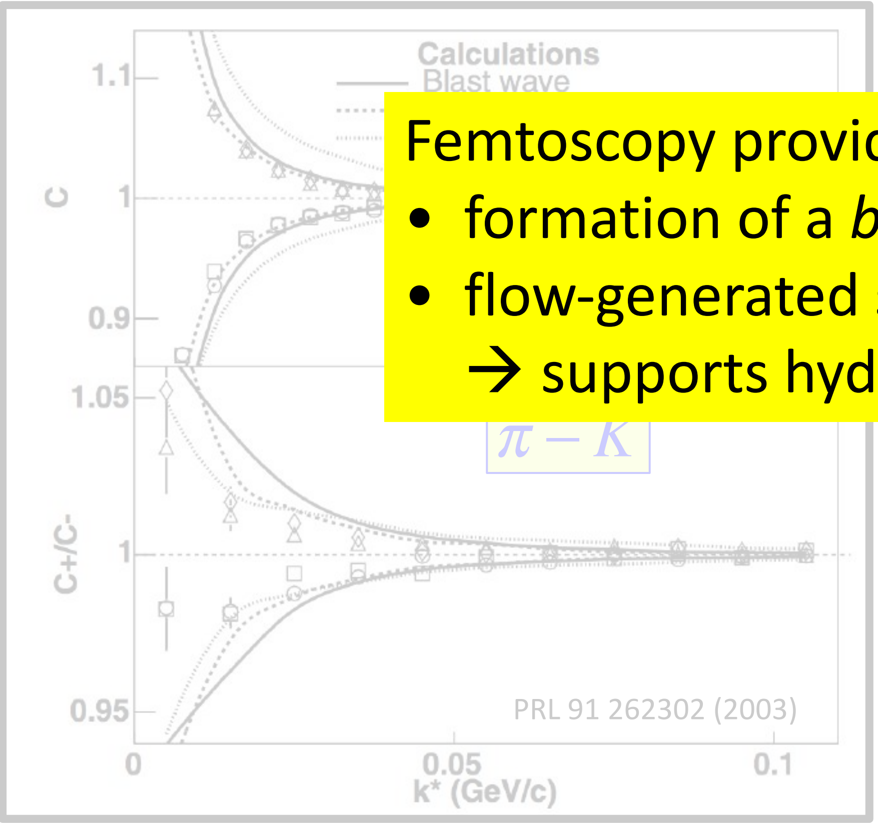


Matter is characterized by fields of **bulk** properties



Geometric substructure

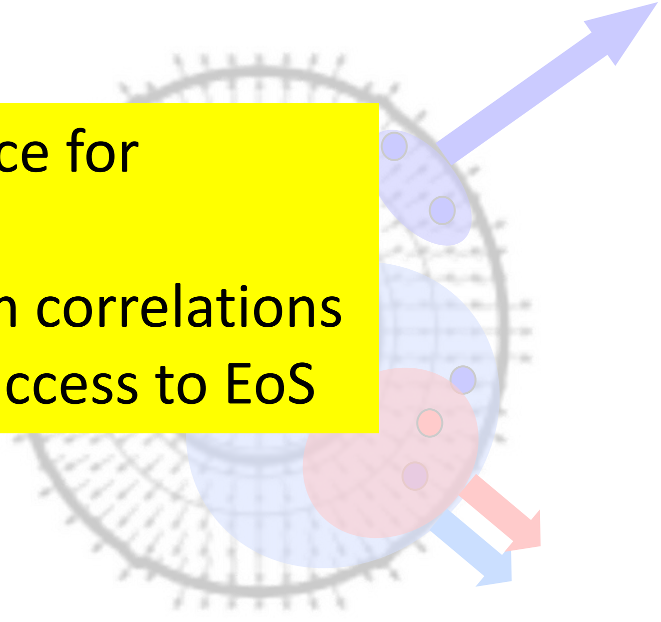
$\pi^{\pm} - K^{\pm}$ correlations reveal mass-ordered separation



Femtoscopy provides strong evidence for

- formation of a *bulk system*
- flow-generated space-momentum correlations
  → supports hydro treatment → access to EoS

Hydrodynamic expectation:

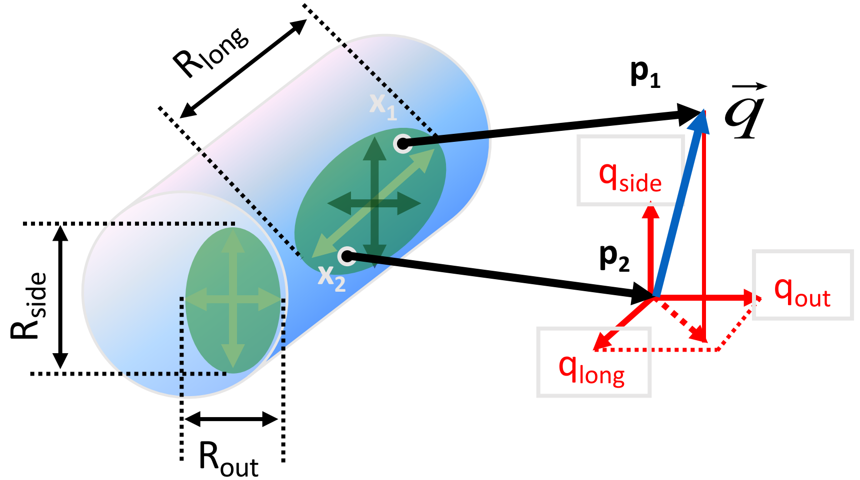


Matter is characterized by fields of **bulk** properties

- pion
- kaon

3D info and timescale

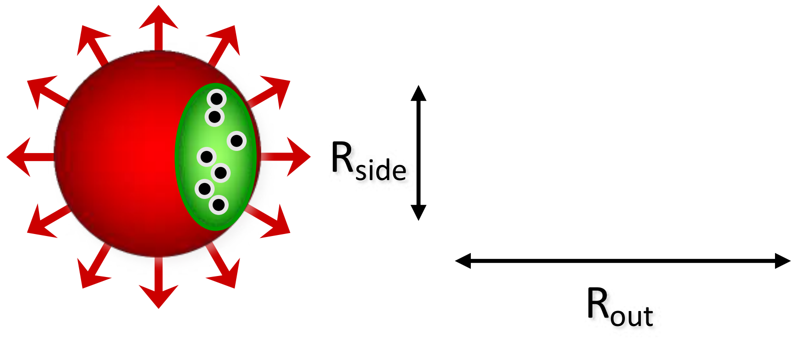
Bertsch-Pratt decomposition: R_{out}, R_{side}, R_{long}



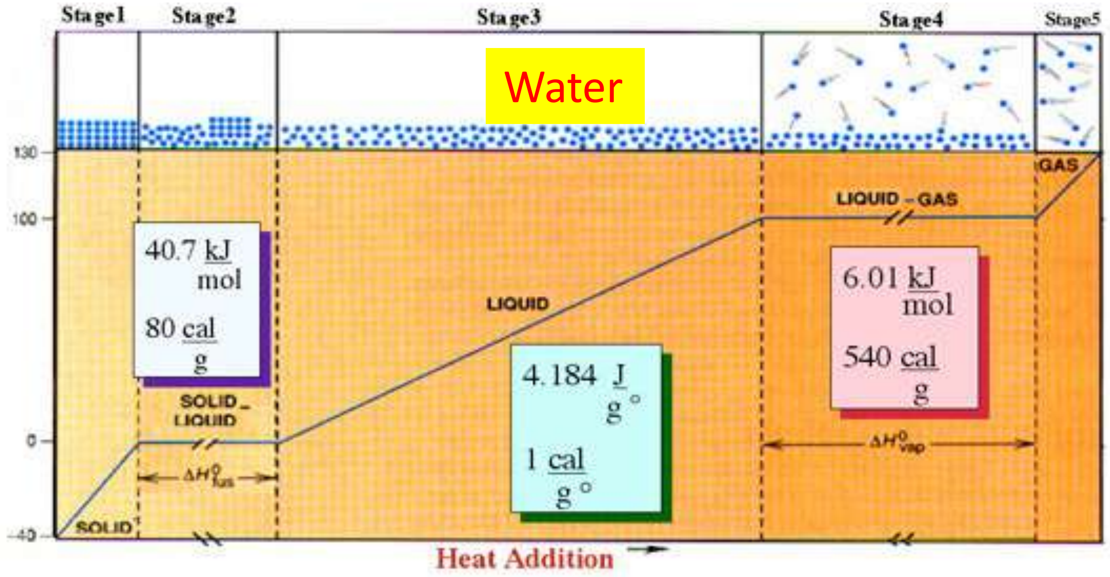
$$\vec{q} = \vec{p}_2 - \vec{p}_1$$

$$\vec{k} = \frac{1}{2}\left(\vec{p}_2 + \vec{p}_1\right)$$

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



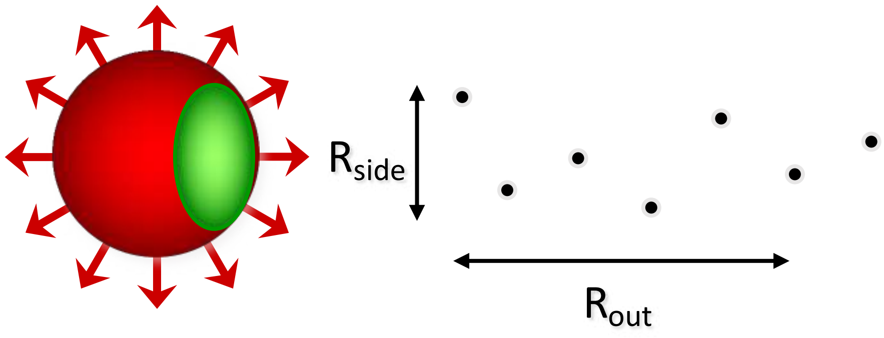
Phase transition? Order?



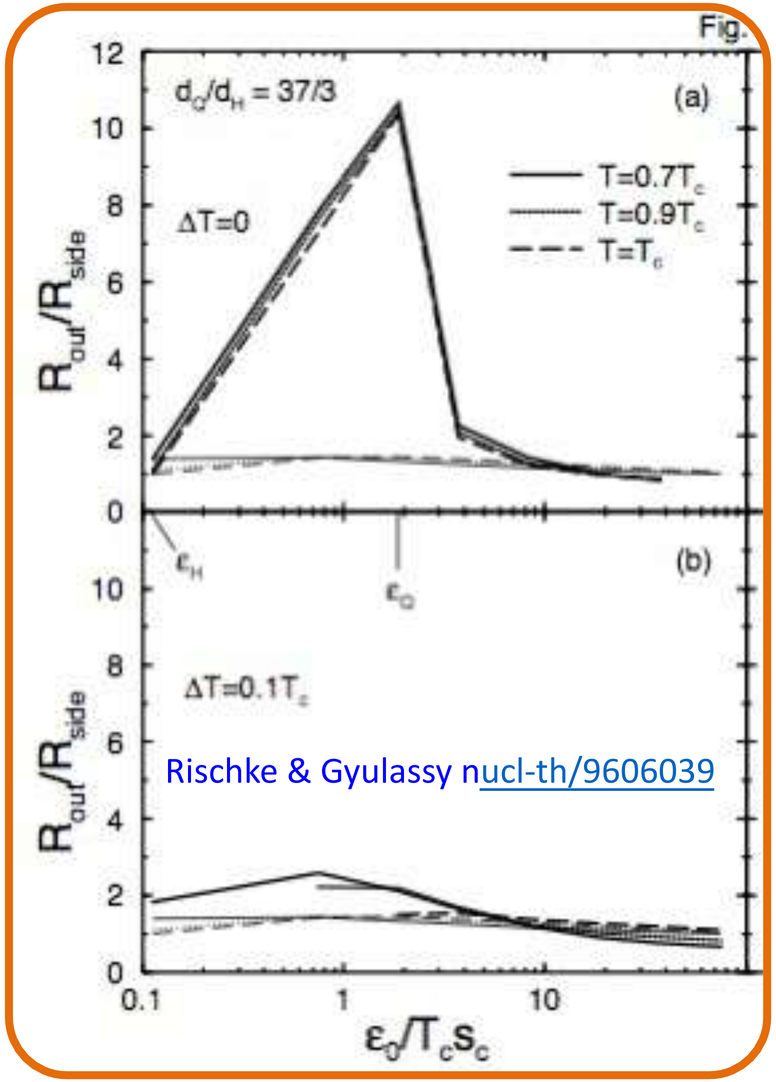
Probe for phase transition → vary conditions

RHIC Beam Energy Scan

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



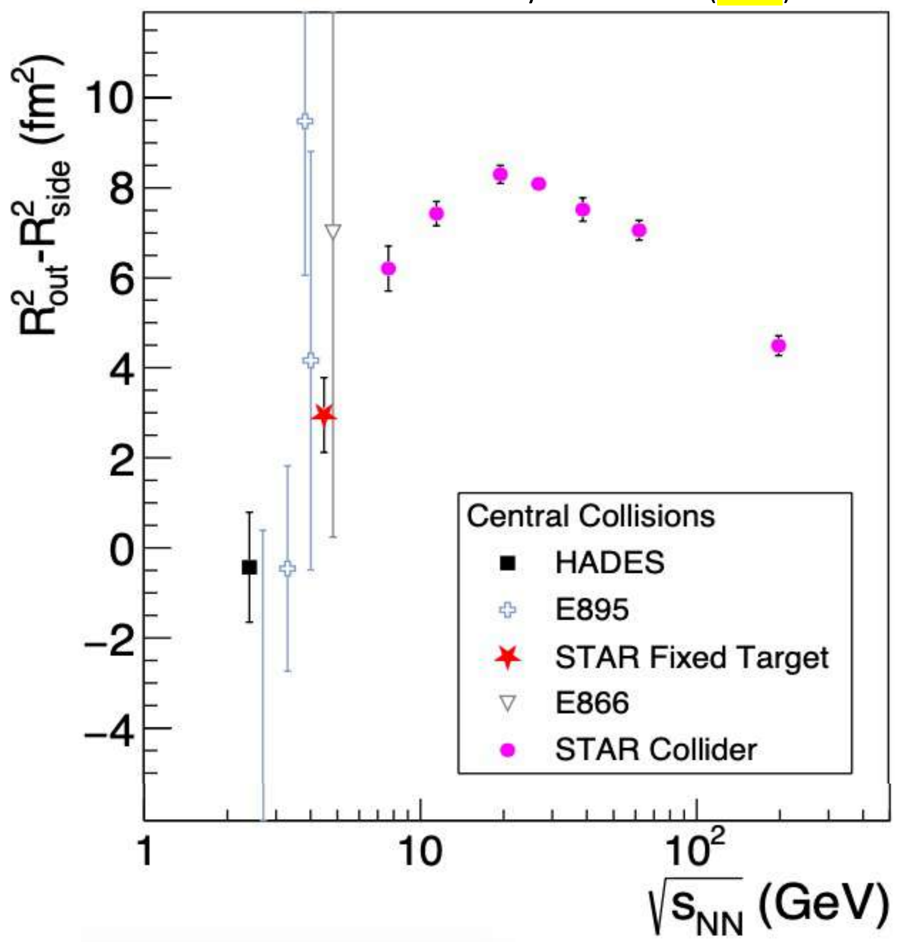
Early expectations at RHIC 200 GeV



Rischke & Gyulassy nucl-th/9606039

Phase transition? Order?

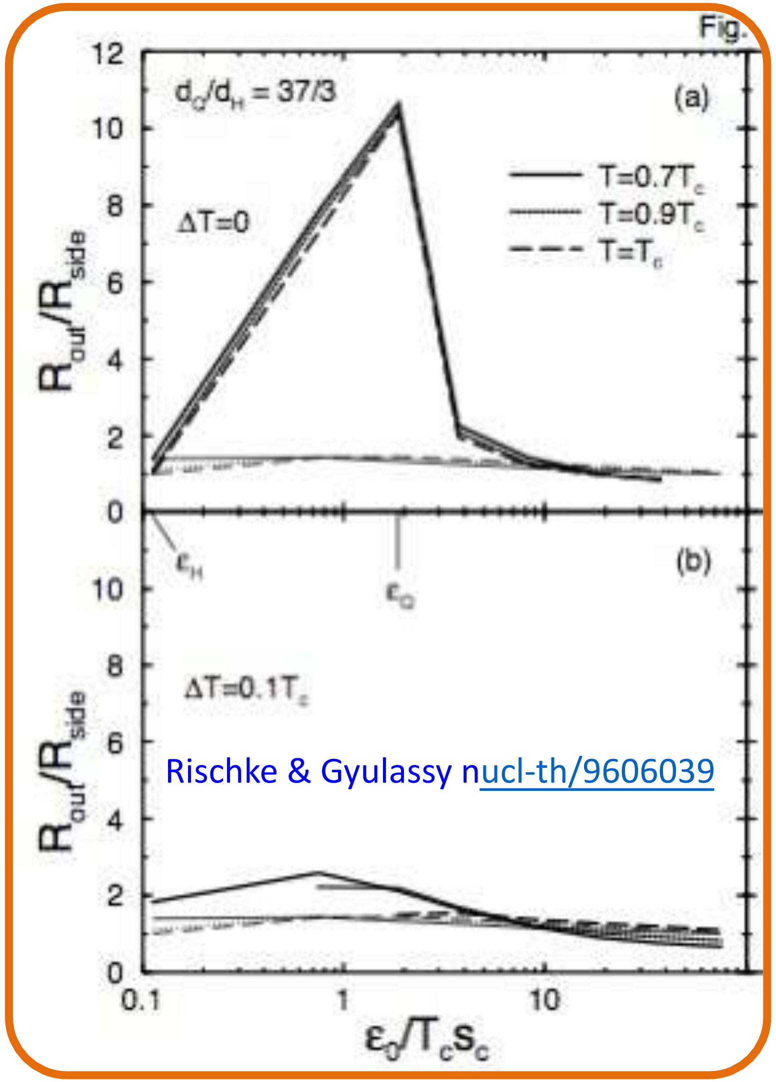
STAR Phys. Rev. C **103** (2021) 34908



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

Early expectations at RHIC 200 GeV

NOT OBSERVED



Phase transition? Order?

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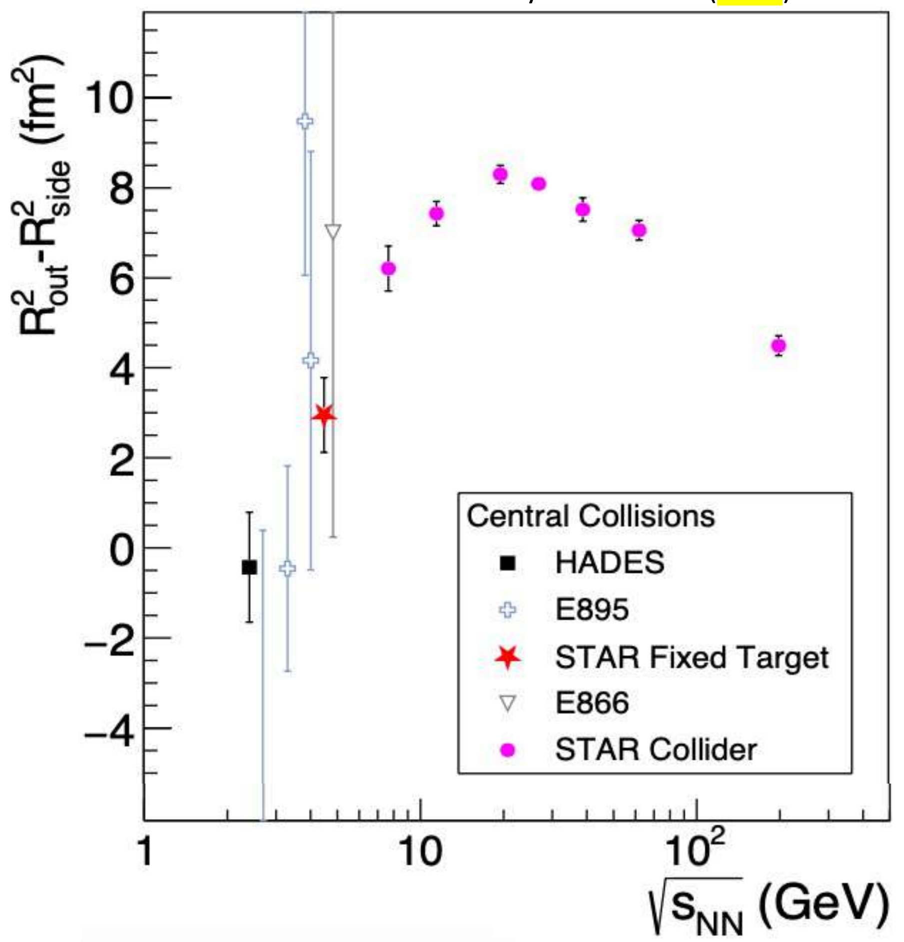
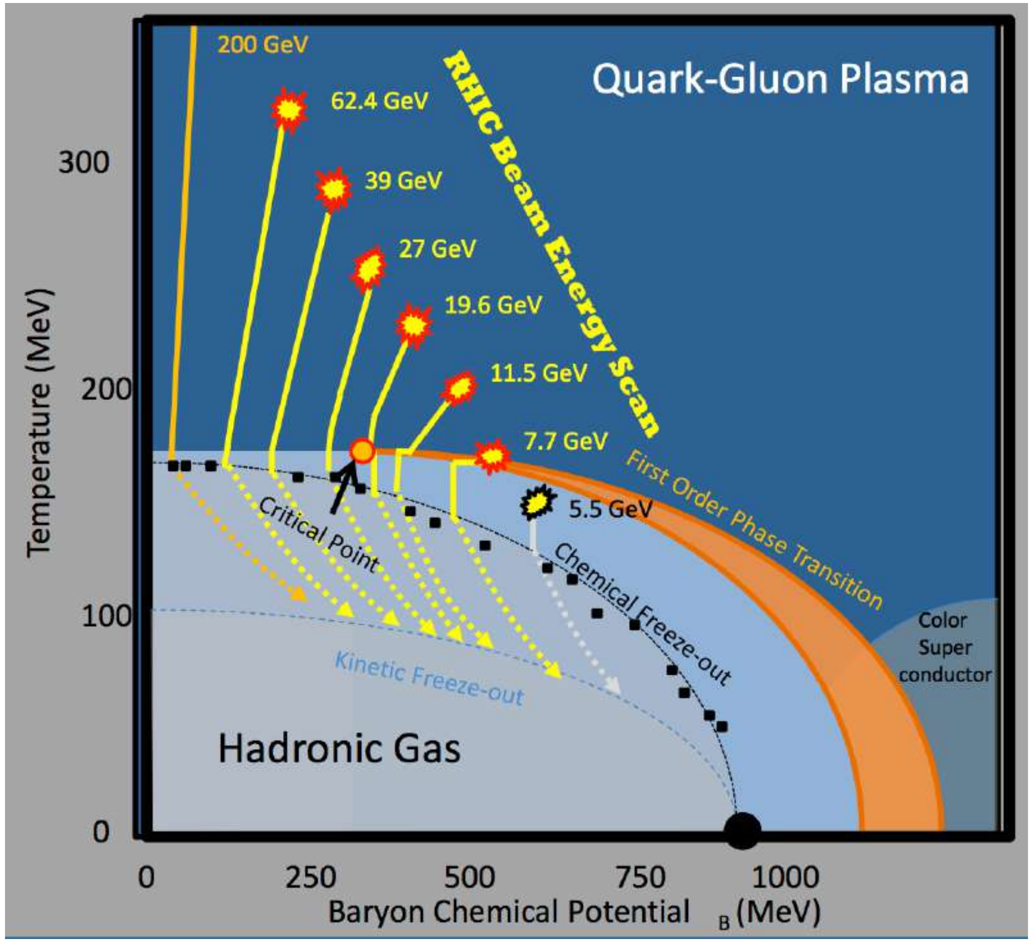


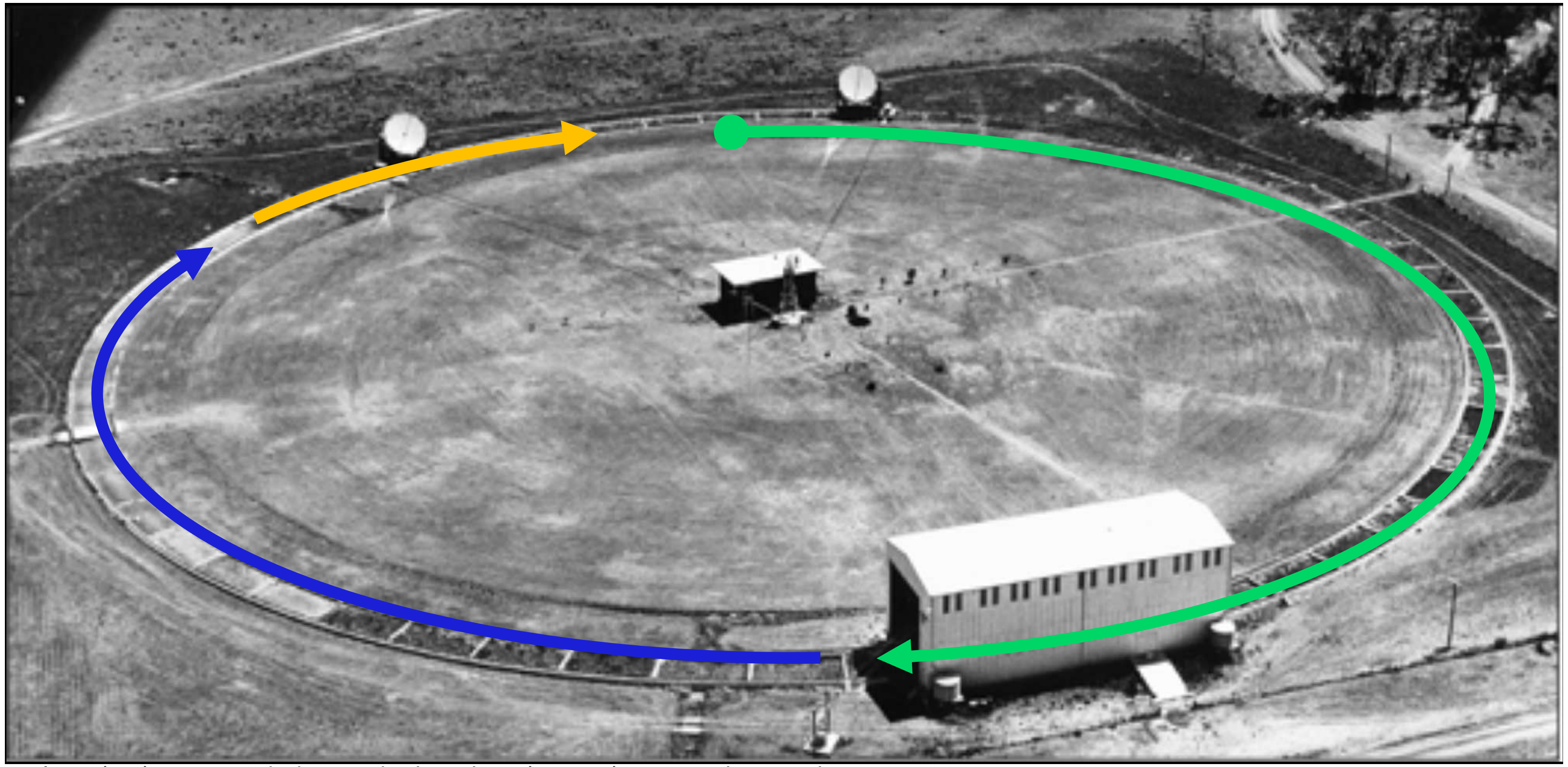


Evidence for
- cross-over at high energy (low chemical potential)
- first-order phase transition ~ 15 GeV

Reminder: stellar HBT "died" in the early 1970's

Coming full circle…
Stellar Intensity Interferometry

…in the modern age



Stellar Intensity Interferometry in the 21st century

$$C(\tau) = \frac{\langle S_1(t)\, S_2(t-\tau)\rangle}{\langle S_1(t)\rangle \cdot \langle S_2(t)\rangle}$$

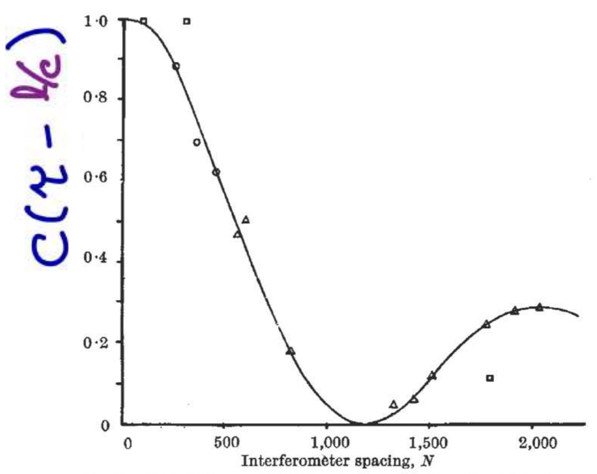
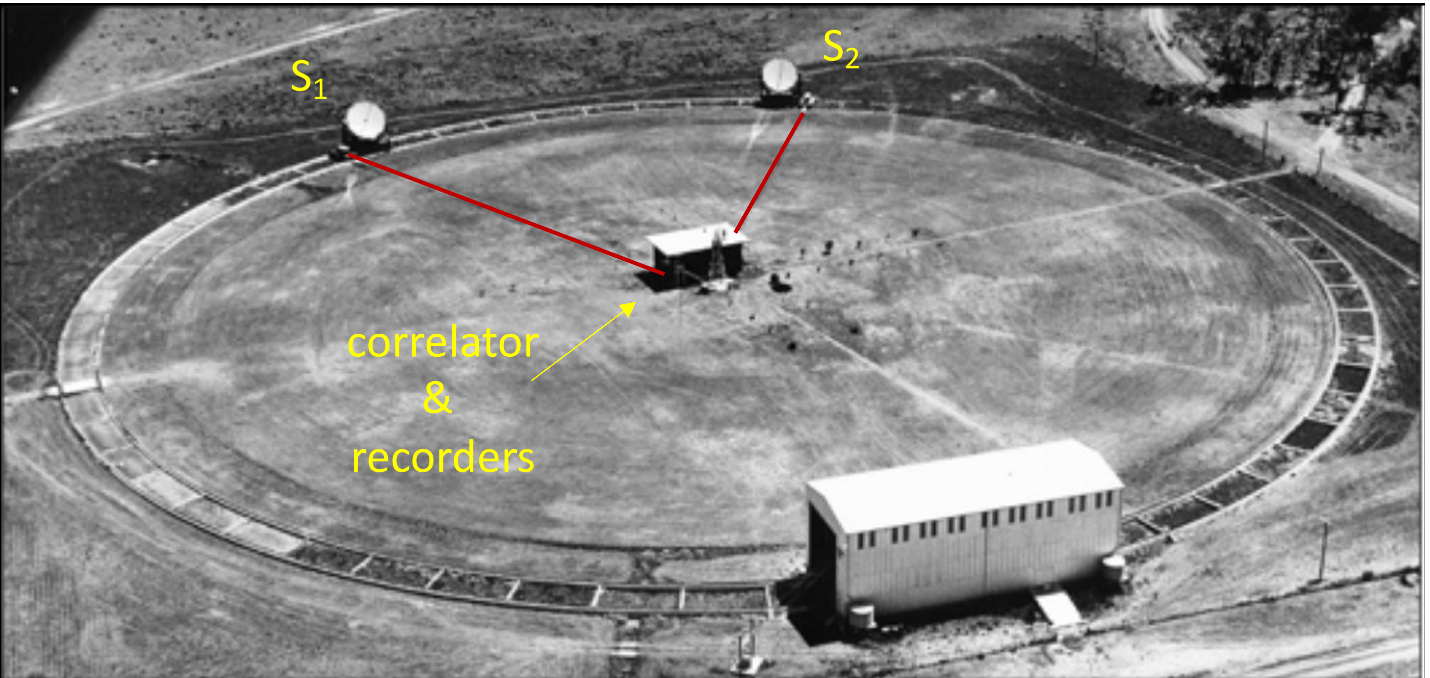
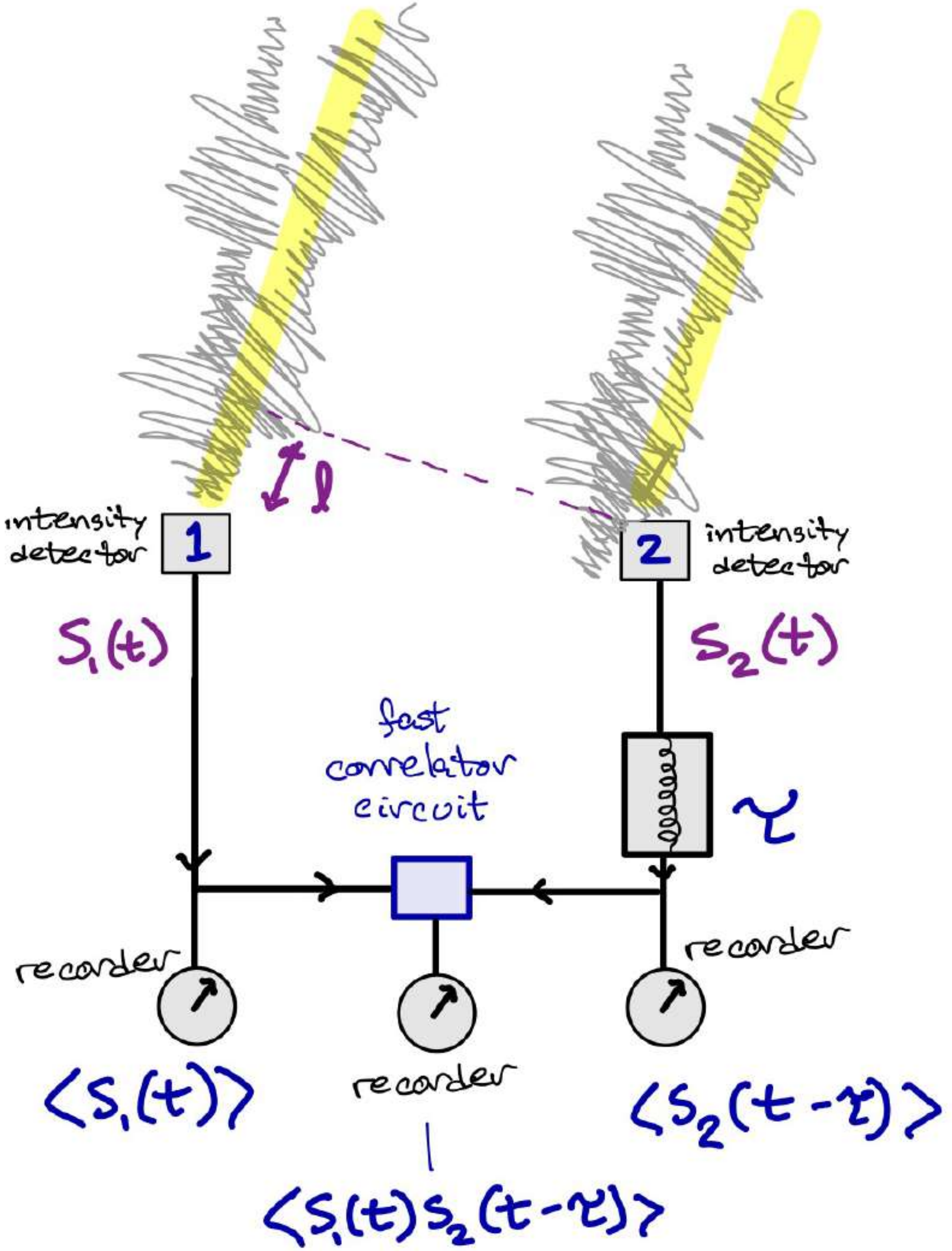


Fig. 1. Correlation coefficients ρ^2 measured at various interferometer spacings, N, for the radio source in Cygnus. Observations by Smith, ○; observations by Mills, □; observations by Jennison and Das Gupta, △. The continuous curve denotes the theoretical transform of the distribution shown in Fig. 2





Stellar Intensity Interferometry in the 21st century

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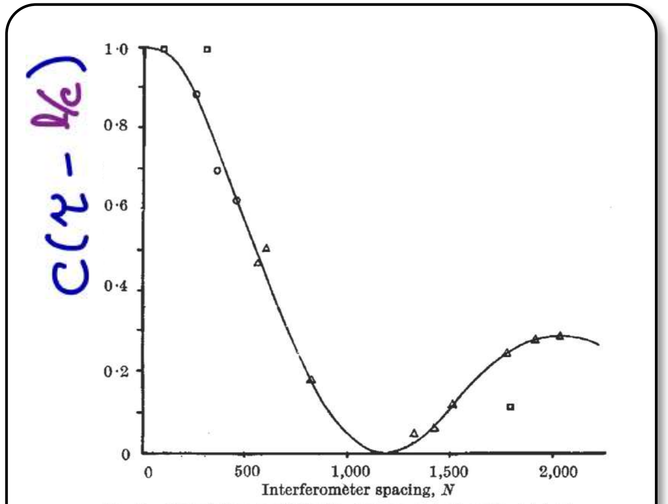

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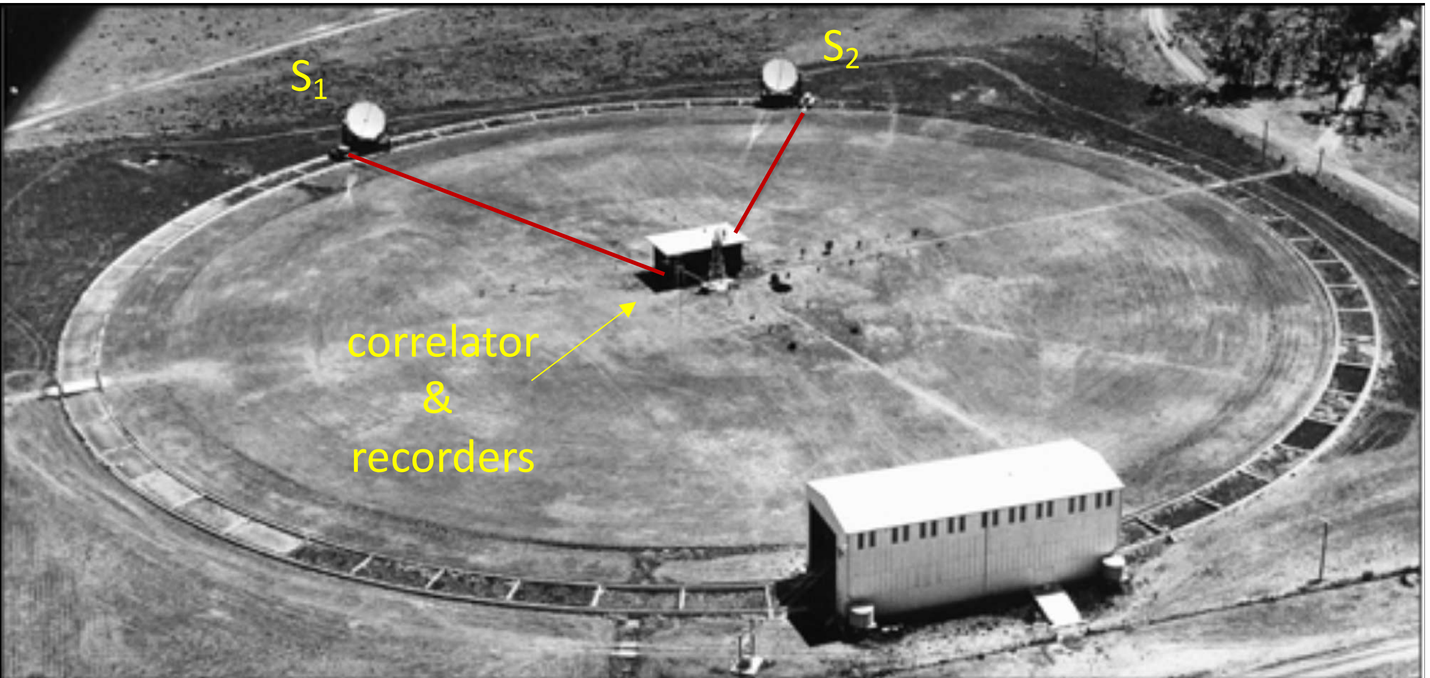
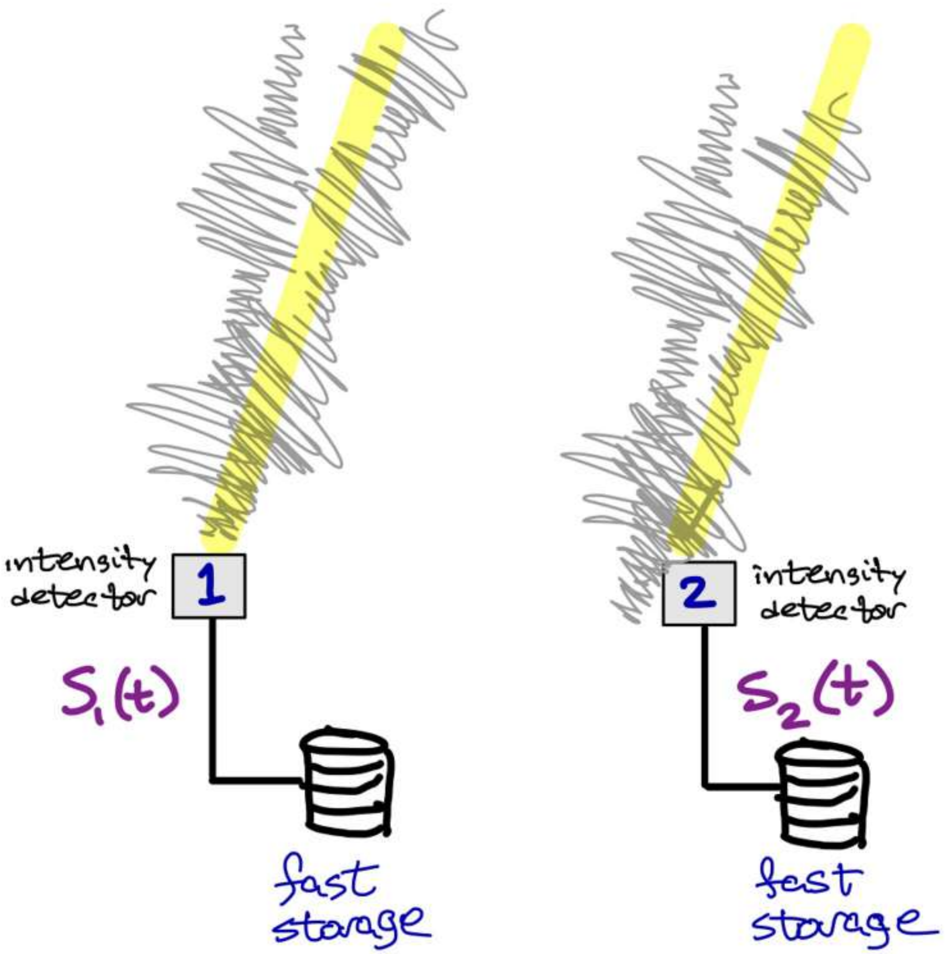


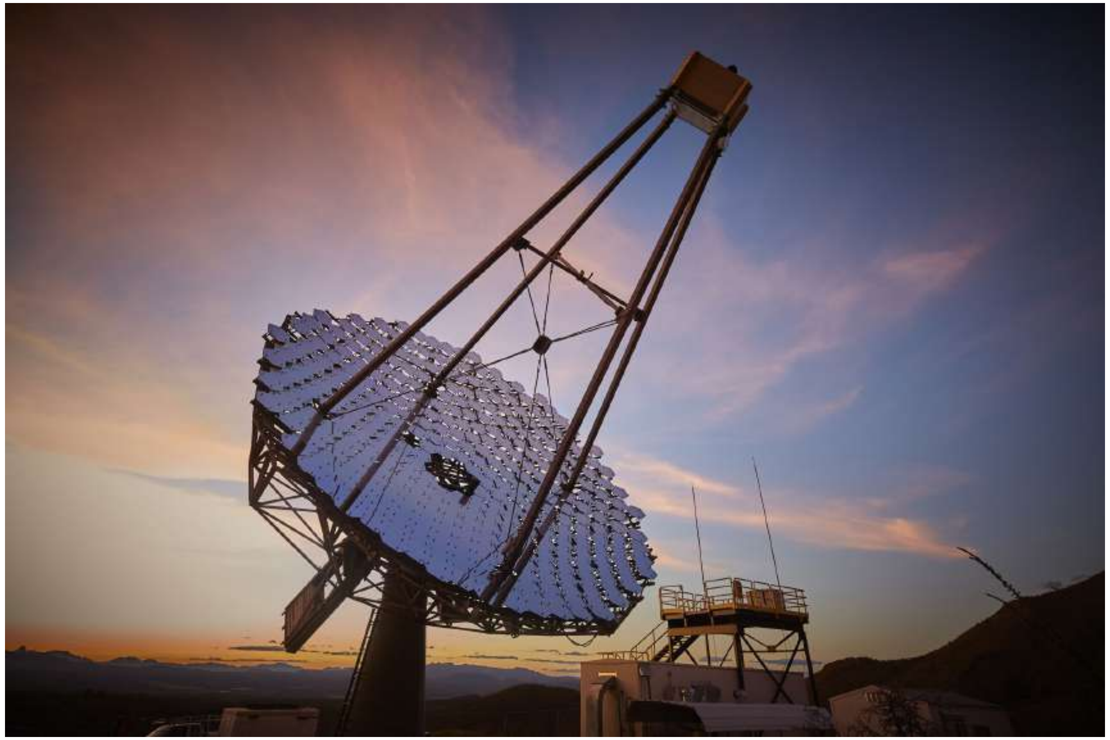


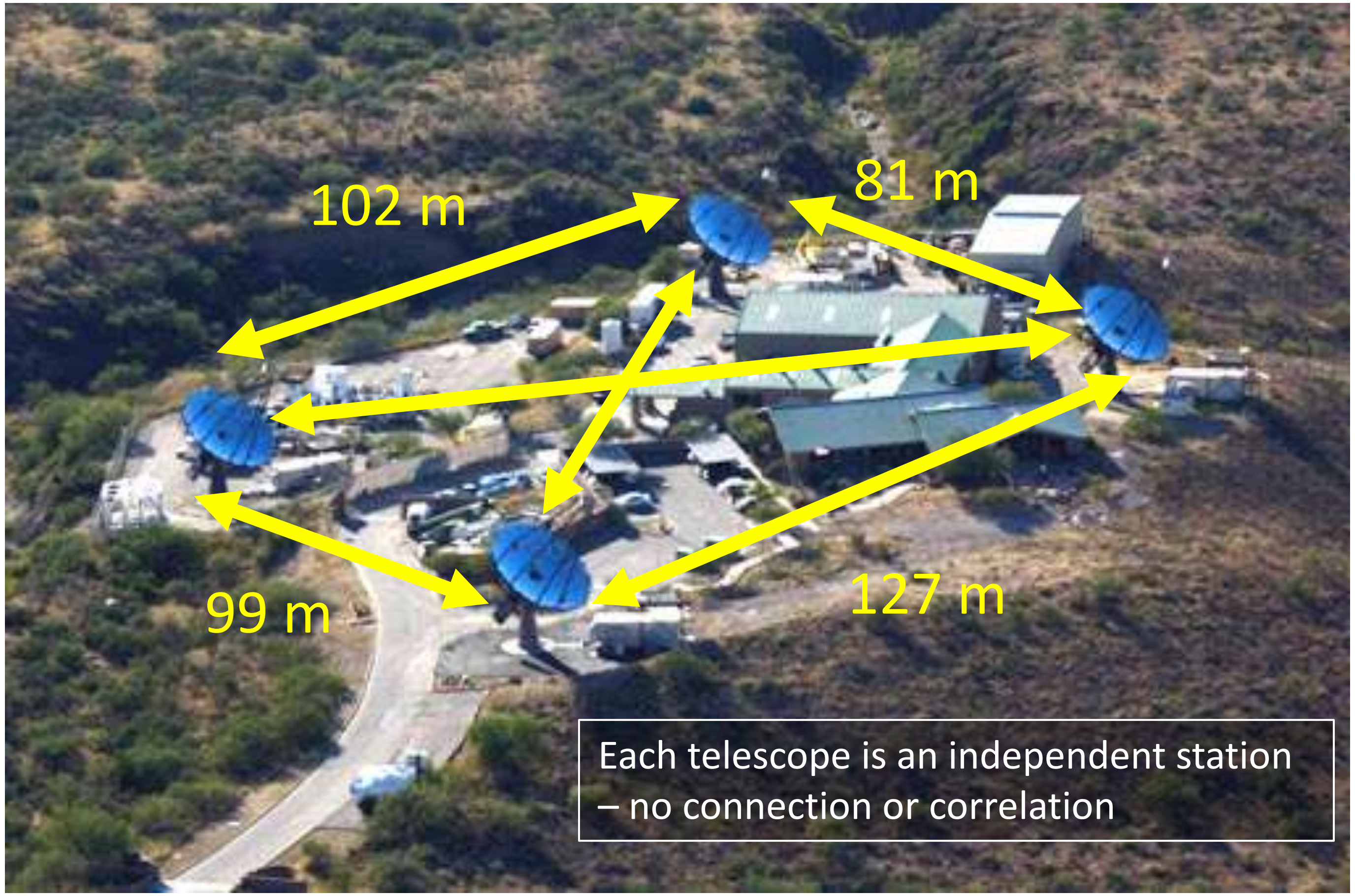
With modern electronics, we can cut the cord!

- arbitrarily long baseline, even for optical
- offline DSP for signal clean-up of noise, afterpulsing, etc

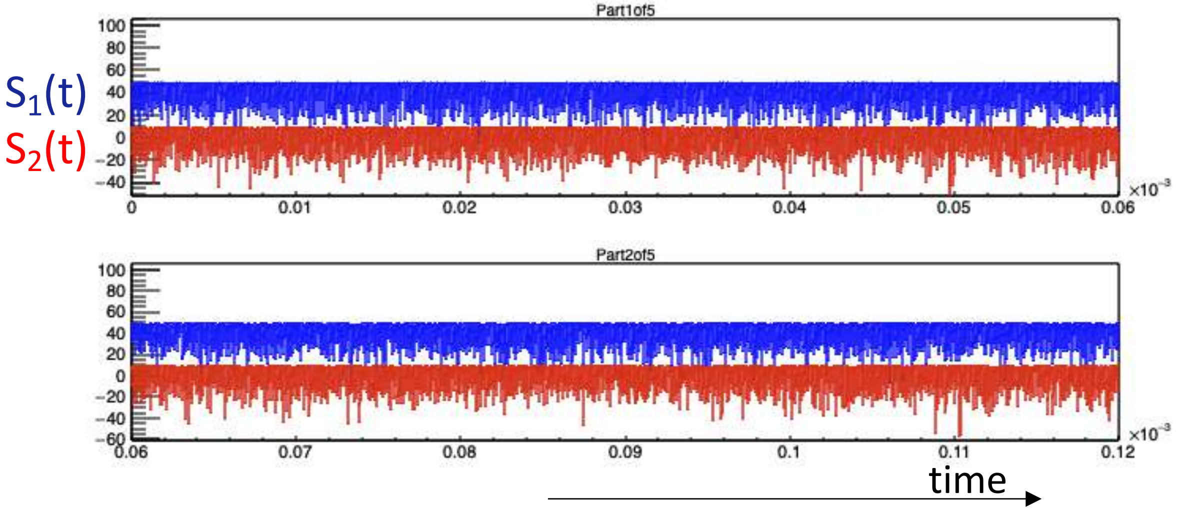
VERITAS Collaboration Array

- 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!



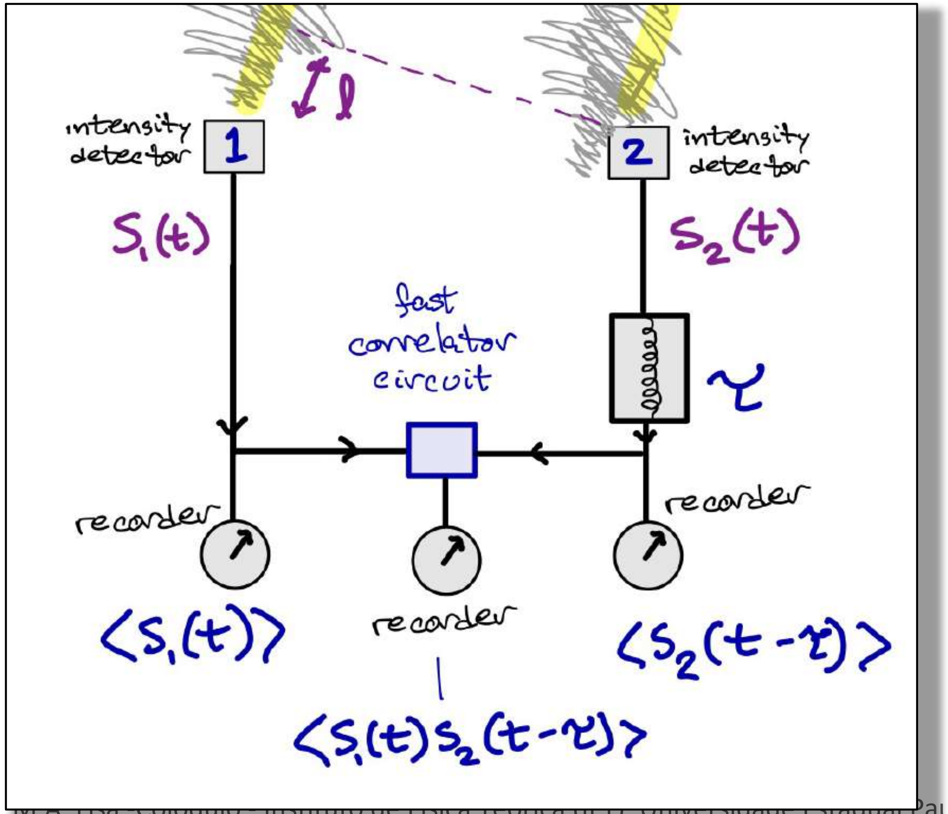


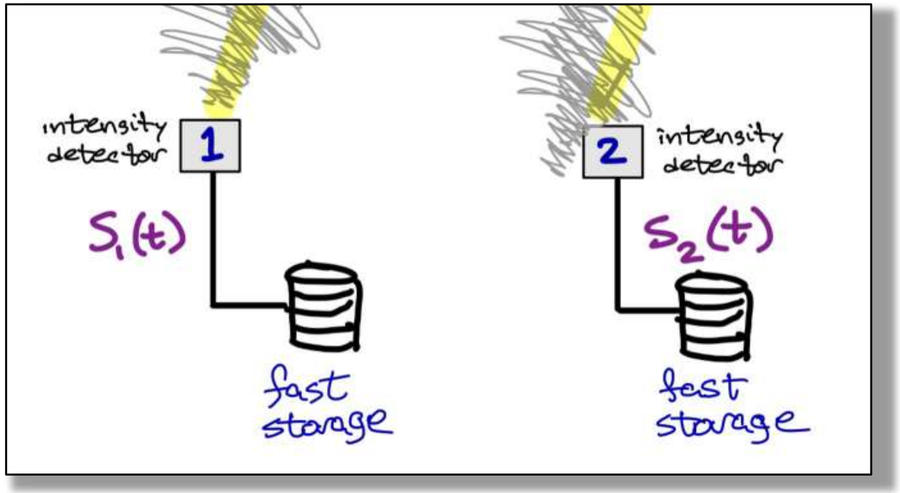
Each telescope is an independent station – no connection or correlation

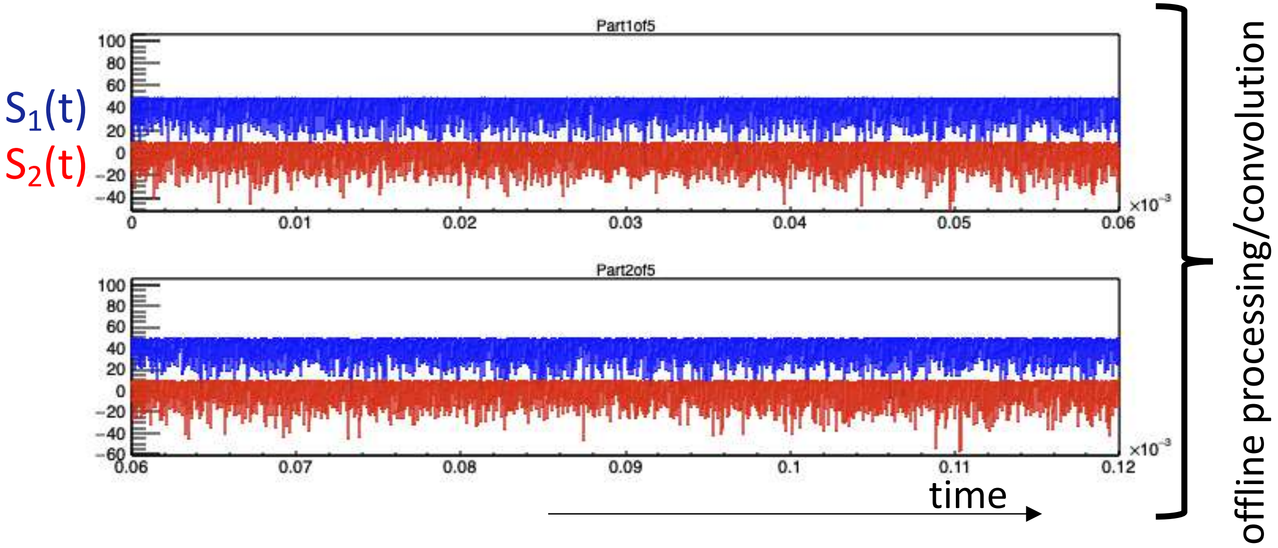


Waveforms sampled @ 250 MHz, digitized to 8 bits, streamed to disk *independently and separately*

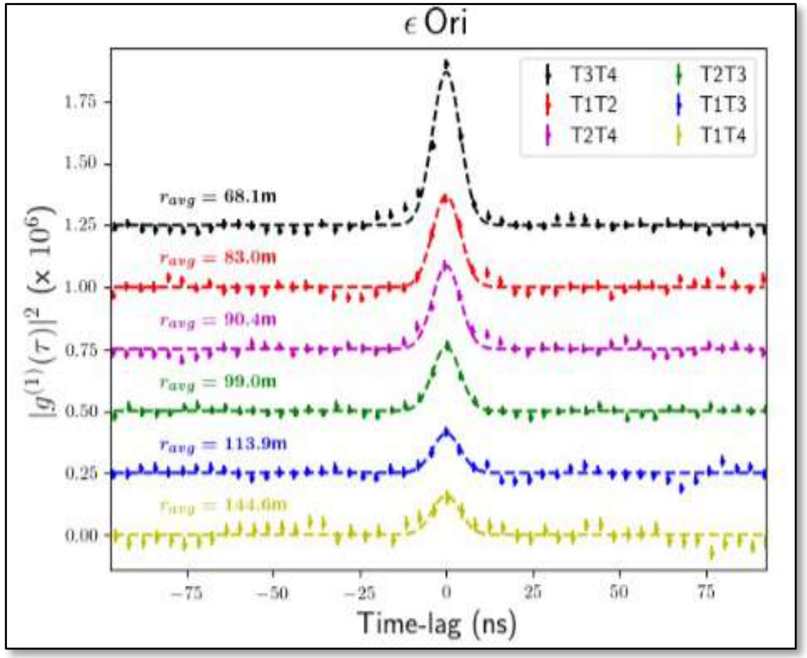
3.5 TB per 1-hour run

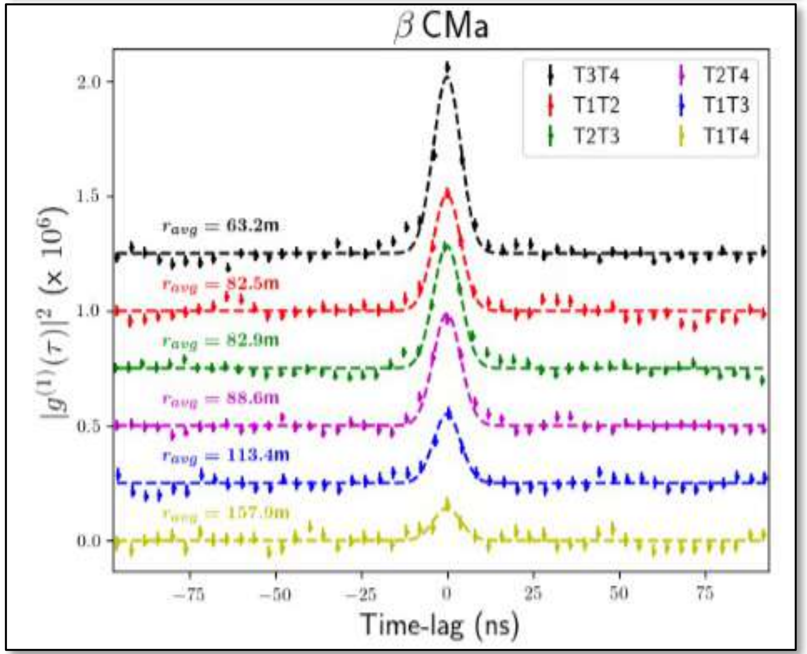






Abeysekara et al, Nature Astronomy 4 (2020) 1164





After correcting for optical path delay & integrating over run

First VERITAS results

Abeysekara et al, Nature Astronomy 4 (2020) 1164

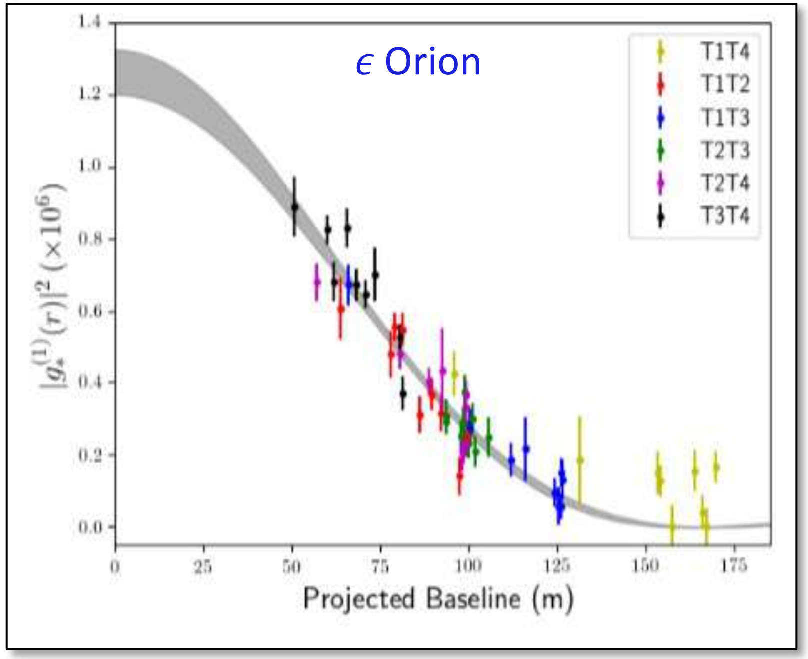
- first SII in 30+ years (!)
- first digital SII ever (!!)

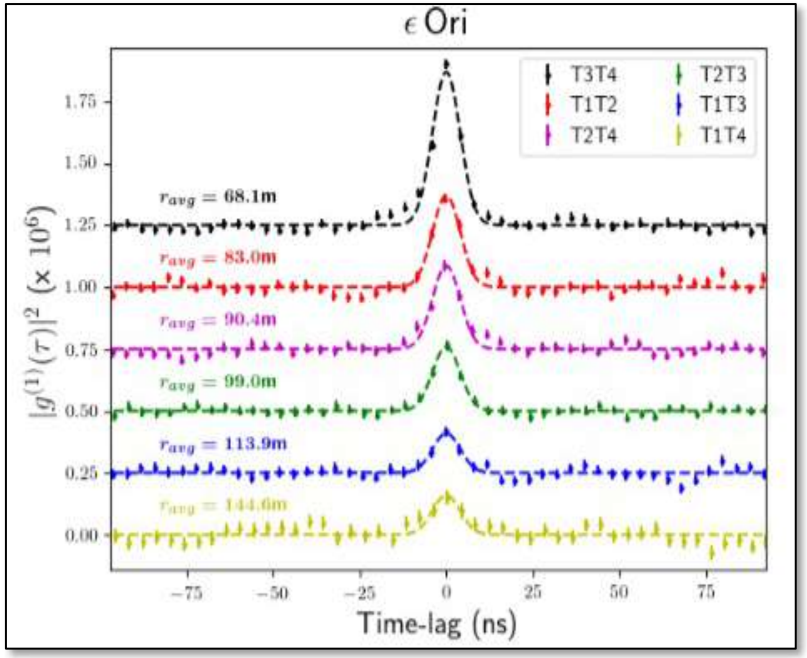
Uniform Disk (UD) radii

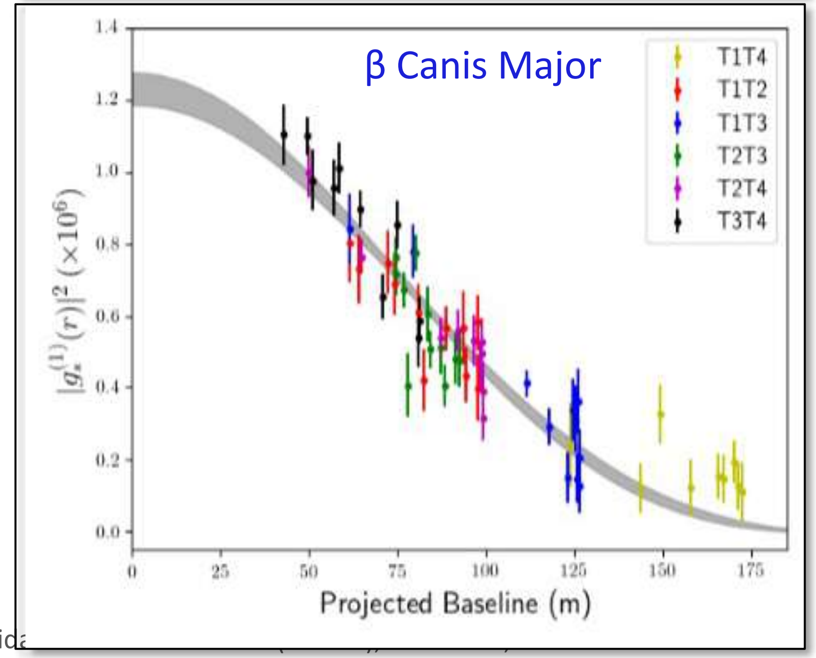
- ϵ Ori θ_{UD}= 0.631 ± 0.017 mas
- β Cma θ_{UD}= 0.523 ± 0.017 mas

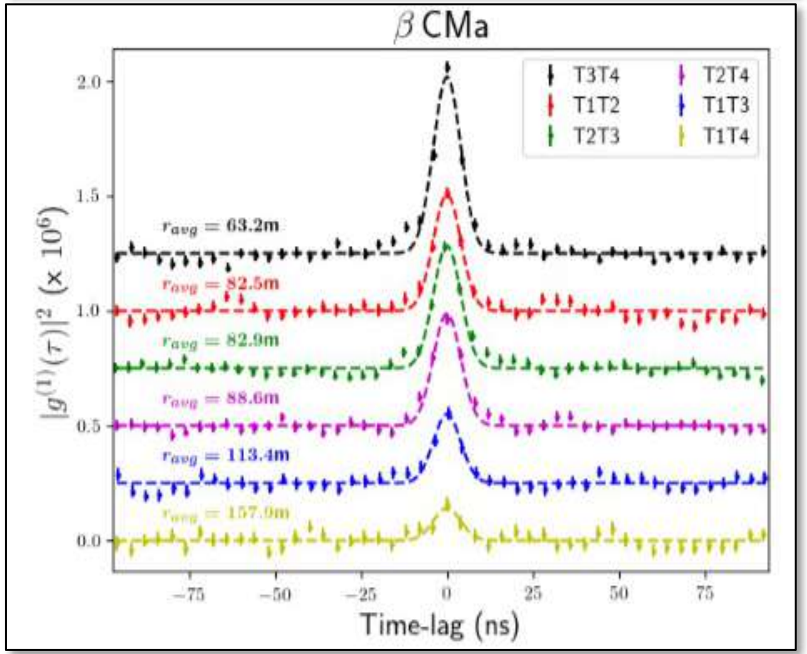
Both in agreement with original NSII

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



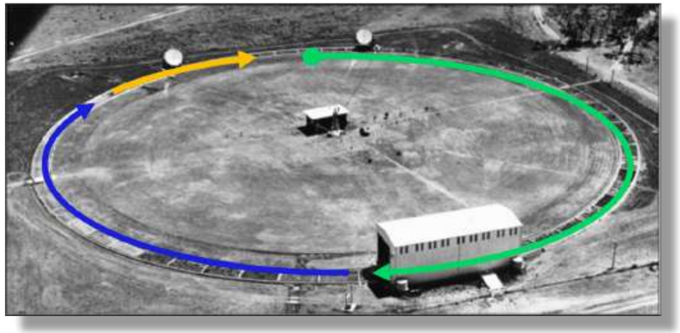




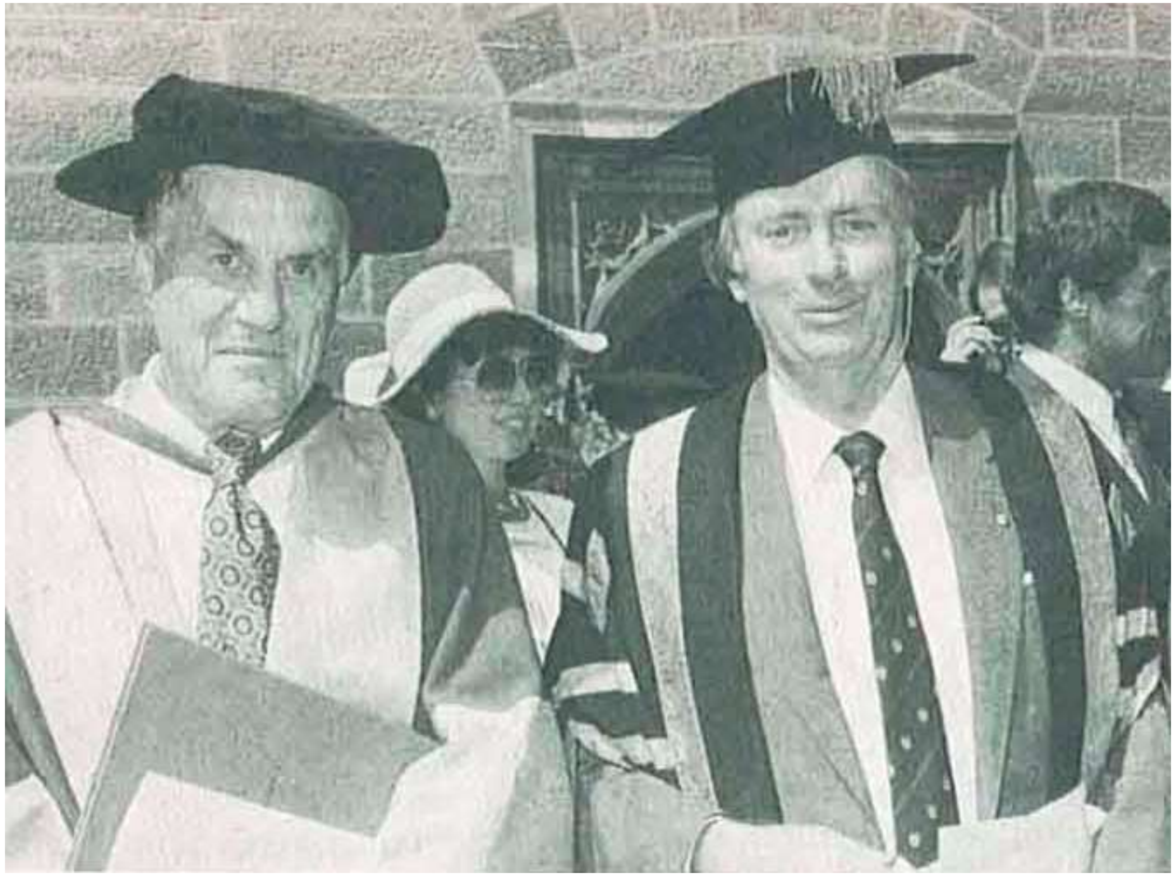


Summary

- 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