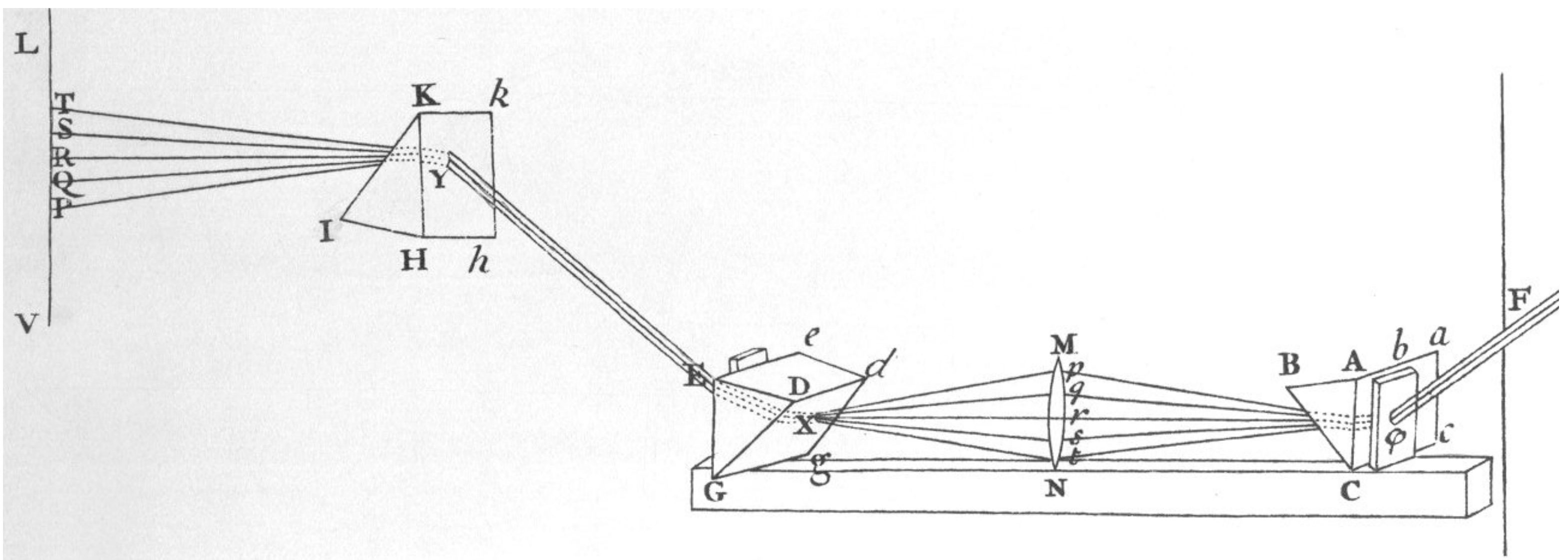
Some exceptional Physics experiments of twentieth century

U A Yajnik
Physics Department, IIT Bombay and IIT Gandhinagar

Outline

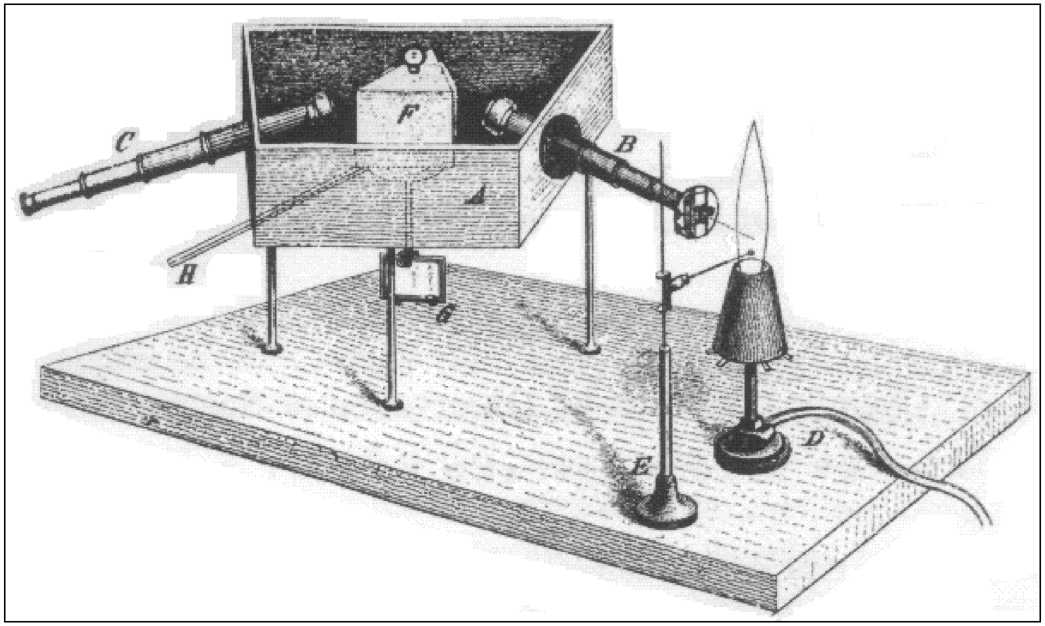
- Precursor : Kirchhoff's challenge and the Black Body radiation
- Mass of the moving electron – confirming Special Relativity
- A noisy microwave antenna – Cosmic Microwave Background Radiation
- Rescheduling an accelerator experiment – unification of electromagnetism and Weak force
- Ancient explosion of a supernova online – the new cosmography
- Picturing the elusive neutrino – superKamiokande

Prehistory : Newton's "spectrum"



... what is dispersed is gathered back to the original ...

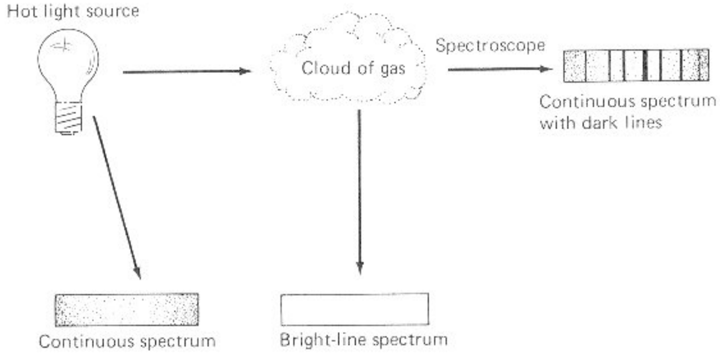
A precursor : Glowing metals



Spectroscope (1860)

Robert Bunsen

Complementarity of emission and absorption



Gustav Kirchoff

Kirchoff's challenge (1859)

To prove that the Emissivity of a glowing substance was a universal function only of its temperature.

More precisely,

$$\frac{\mathcal{E}(\nu)}{A_\nu} = J(\nu, T)$$

It is necessary to factor out the absorptivity A_ν. Ideal substance for which $A_\nu = 1$ is called Black Body. An enclosure with perfectly reflecting walls (and a small exit hole) is Black Body and is well approximated by a cavity made in a metalic block.

'An act of desperation ...

I had to obtain a positive result, under any circumstances and at whatever cost'

Planck, in 1931, recalling his situation in 1900

- Wien had already recognised the high frequency behaviour to be exponential

$$\rho(\nu, T) \; = \; \alpha \nu^3 e^{-\nu/\beta T}$$

- This high frequency behaviour conflicted with classical expectation of continuum waves

- This high frequency behaviour conflicted with classical expectation of continuum waves

- However, the hint came from the infrared

On a Sunday afternoon family visit Lummer and Prigsheim tell Planck that they see a linear dependence on temperature at low frequencies.

This was sufficient hint to Planck to see that

$$\alpha\nu^3 \frac{1}{e^{\nu/\beta T} - 1} \longrightarrow \alpha\nu^2\beta T$$

The rest as they is history ... We may conjecture that after this Planck could see this to be ageometric series

$$\sum_{0}^{\infty}(e^{\frac{\nu}{\beta T}})^{n}$$

Theories of electron mass

- H. A. Lorentz
  - Charge uniformly distributed through out the volume of the sphere
  - Length contraction
  - Speed of light same relative to aether, hence if aether carried with the frame, so is the speed of light

Theories of electron mass

- H. A. Lorentz
  - Charge uniformly distributed through out the volume of the sphere
  - Length contraction
  - Speed of light same relative to aether, hence if aether carried with the frame, so is the speed of light

- Max Abraham – charge unifromly distributed over the sphere; longitudianl and transverse mass, with volume constant

Theories of electron mass

- H. A. Lorentz
  - Charge uniformly distributed through out the volume of the sphere
  - Length contraction
  - Speed of light same relative to aether, hence if aether carried with the frame, so is the speed of light
- Max Abraham – charge unifromly distributed over the sphere; longitudianl and transverse mass, with volume constant
- Henri Poincaré
  - Group structure of Lorentz transformations and the possibility that the speed of light had to be constant

Theories of electron mass

- H. A. Lorentz
  - Charge uniformly distributed through out the volume of the sphere
  - Length contraction
  - Speed of light same relative to aether, hence if aether carried with the frame, so is the speed of light

- Max Abraham – charge unifromly distributed over the sphere; longitudianl and transverse mass, with volume constant

- Henri Poincaré
  - Group structure of Lorentz transformations and the possibility that the speed of light had to be constant

The key conceptual issue being debated was whether none / a part of / all of electron mass was of electromagnetic rather than "mechanical" origin

Walter Kaufmann's experiments

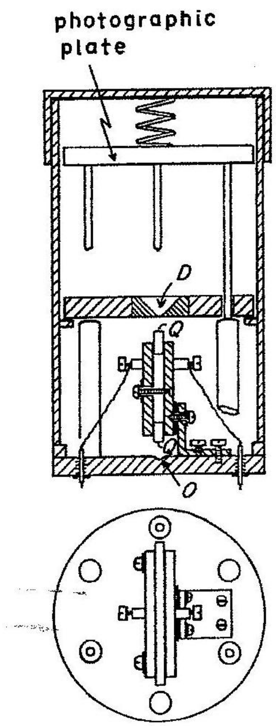


FIGURE 15.3 A sketch of Kaufmann's actual apparatus

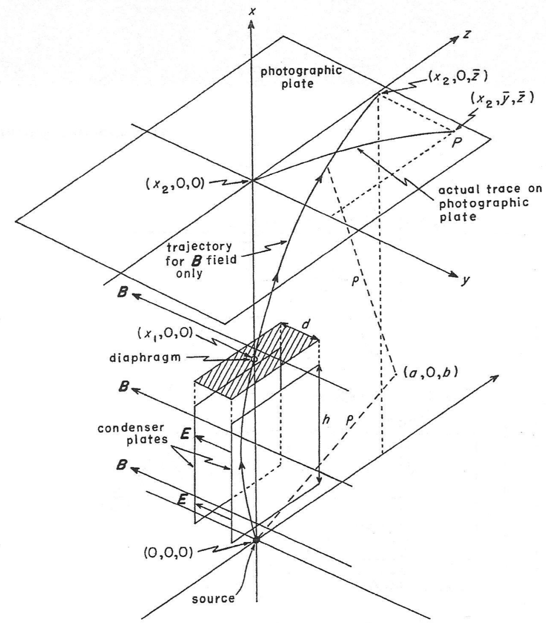


FIGURE 15.4 A diagram of Kaufmann's apparatus

Kaufmann's 1901 analysis

- Kaufmann analysed the data in terms of the mechanical mass ("true" mass) and electromagnetic mass ("apparent" mass) of an electron.

Kaufmann's 1901 analysis

- Kaufmann analysed the data in terms of the mechanical mass ("true" mass) and electromagnetic mass ("apparent" mass) of an electron.

- Kaufmann used Searle's equation for total energy of a moving spherical electron, which used longitudinal mass.

Kaufmann's 1901 analysis

- Kaufmann analysed the data in terms of the mechanical mass ("true" mass) and electromagnetic mass ("apparent" mass) of an electron.

- Kaufmann used Searle's equation for total energy of a moving spherical electron, which used longitudinal mass.

- Kaufmann deduced that the "true" mass is about 3 times larger than the apparent mass. It contradicted Lorentz's theory.

Kaufmann's 1901 analysis

- Kaufmann analysed the data in terms of the mechanical mass ("true" mass) and electromagnetic mass ("apparent" mass) of an electron.

- Kaufmann used Searle's equation for total energy of a moving spherical electron, which used longitudinal mass.

- Kaufmann deduced that the "true" mass is about 3 times larger than the apparent mass. It contradicted Lorentz's theory.

Table I. Kaufmann's original (1901) data.[41]

Data point(i)	$\bar{z}$	$\bar{y}$	$\beta = v/c$	$\frac{e}{m_{total}} \times 10^{-7}$(exp.)	$\frac{(e/m)i}{(e/m)5}$ (exp.)	$\frac{e}{m_{total}} \times 10^{-7}$(calc)	$\frac{(e/m)i}{(e/m)5}$ (calc)	$[(1-\beta_i^2)/(1-\beta_5^2)]^{1/2}$
1	0.271	0.0621	0.945	0.63	0.481	0.524	0.403	0.539
2	0.348	0.0839	0.907	0.77	0.588	0.775	0.597	0.683
3	0.461	0.1175	0.864	0.975	0.744	1.010	0.778	0.819
4	0.576	0.1565	0.827	1.17	0.893	1.163	0.895	0.911
5	0.688	0.198	0.787	1.31	1.000	1.299	1.000	1.000

Kaufmann’s 1902 Experiments

- Kaufmann’s 1901 analysis was incorrect because he used longitudinal mass rather than transverse mass.

Kaufmann's 1902 Experiments

- Kaufmann's 1901 analysis was incorrect because he used longitudinal mass rather than transverse mass.
- In 1902, Kaufmann published more data and analyzed in term of Abraham's transverse mass. Kaufmann corrected an algebraic error in his formula, and made some geometric change in the dimensions of his apparatus.

Kaufmann's 1902 Experiments

- Kaufmann's 1901 analysis was incorrect because he used longitudinal mass rather than transverse mass.

- In 1902, Kaufmann published more data and analyzed in term of Abraham's transverse mass. Kaufmann corrected an algebraic error in his formula, and made some geometric change in the dimensions of his apparatus.

- The boost factor Kaufmann was trying to deduce had huge error from error in determination of velocity :

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \Longrightarrow \delta\gamma = \beta\gamma^3\delta\beta$$

Kaufmann declared that

"The mass of the electrons that constitute the Becquerel rays is dependent on velocity. The dependency can be demonstrated exactly by the formula of Abraham. Therefore the mass of electron is purely of an electromagnetic nature."

Kaufmann's 1905 results

Table 15.2. *Kaufmann's 1905 data*

$\bar{z}$	$\bar{y}_{\mathrm{exp}}$	$\bar{y}_{\mathrm{theo}}$ Abraham	Lorentz	$\delta = (\bar{y} - y_t) \times 10^4$ Abraham	Lorentz	β Abraham	Lorentz
0.1350	0.0246	0.0251	0.0246	-5	0	0.974	0.924
0.1919	0.0376	0.0377	0.0375	-1	$+1$	0.922	0.875
0.2400	0.0502	0.0502	0.0502	0	0	0.867	0.823
0.2890	0.0545	0.0649	0.0651	-4	-6	0.807	0.765
0.3359	0.0811	0.0811	0.0813	0	-2	0.752	0.713
0.3832	0.1001	0.0995	0.0997	$+6$	$+4$	0.697	0.661
0.4305	0.1205	0.1201	0.1202	$+4$	$+3$	0.649	0.616
0.4735	0.1404	0.1408	0.1405	-4	-1	0.610	0.579
0.5252	0.1666	0.1682	0.1678	-16	-12	0.566	0.527

"The prevalent results decidedly speak against the correctness of Lorentz's assumption as well as Einstein's. If on account of that one considers this basic assumption refuted, then one would be forced to consider it a failure to attempt to base the entire field of physics, including electrodynamics and optics, upon the principle of relative movement. A choice between the theory of Abraham and Bucherer for the time being is impossible and does not seem to be attainable by observations of the type described above due to the largely numerical identity of the values of $\Phi(\beta)$. Whether Bucherer's formula for the optics of movie bodies in the realm of possible observation can yield the same results as Lorentz's, still has yet to be proven."

Planck reinstates Lorentz-Einstein

- Lorentz was keenly following Kaufmann's experiments was clearly dicouraged by his pronouncements

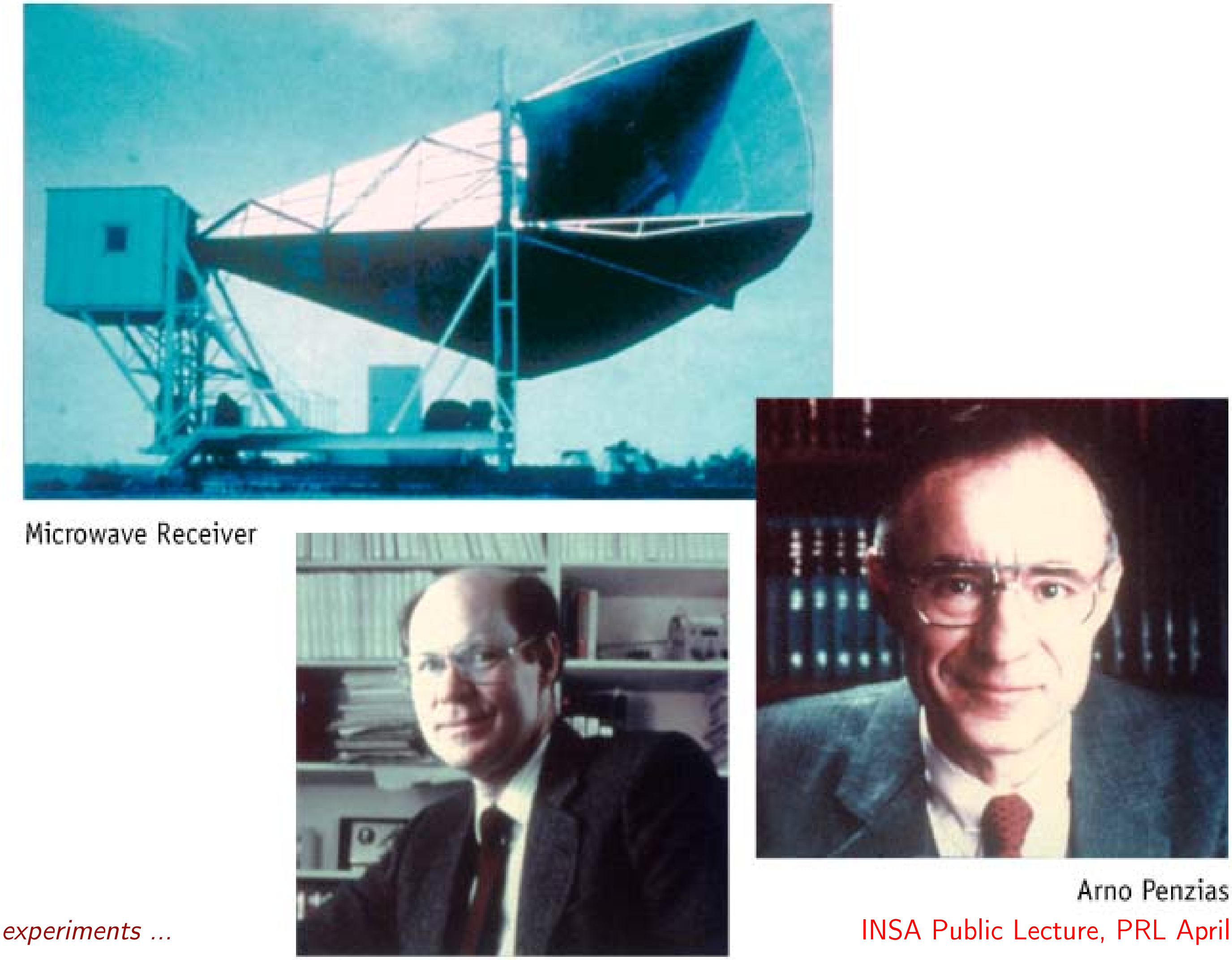
- Poincaré seems to have arrived at correct conclusions but did not opine decisively, also perhaps guided by these experiments.

- The measurements could be satisfactorily carried out only much later, 1940's.

"To be sure, this question [of the acceptability of the relativity principle] appears to be already answered through the recent and important measurements of W. Kaufmann, that is, however in the negative sense so that every further investigation seems to be unnecessary. In the meantime I would still like to consider it possible, in view of the extremely complex theory of these experiments, that the principle of relativity could be reconciled with these observations if one would more carefully elaborate them." - Planck (1906)

A noisy antenna

Discovery of Cosmic Background



Microwave Receiver

Arno Penzias

Robert Wilson

MAP990045

Excess temperature!

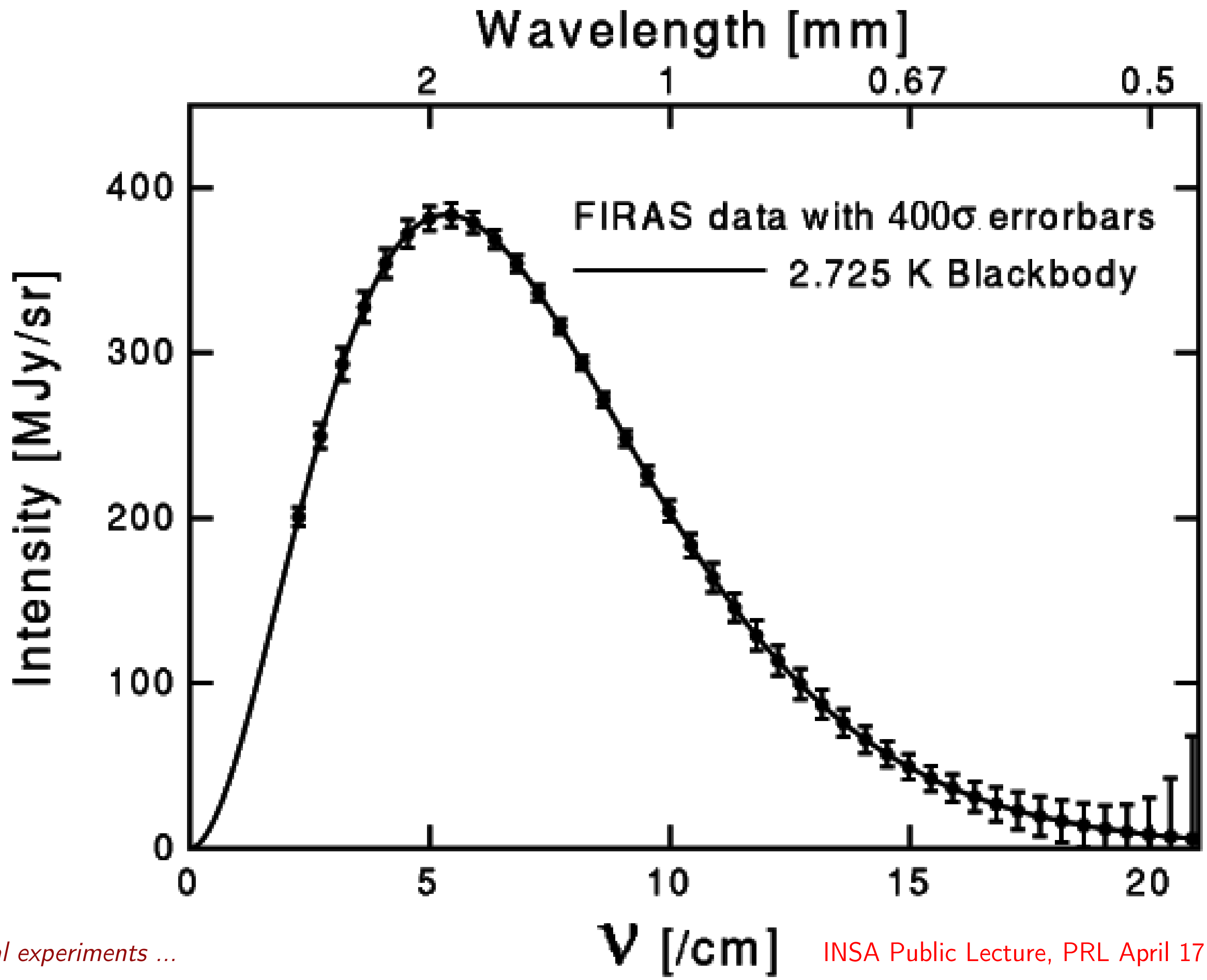
- After all attempts at removing the "backgorund noise" Penzias and Wilson concluded that there was "excess background temprature" in the frequency range they were scanning

- Almost twenty years earlier, Alpher [Bethe] and Gamow, "alpha-beta-gamma" paper had concluded that there must be residual radiation at temprature somewhere between 10 and 40 Kelvin.

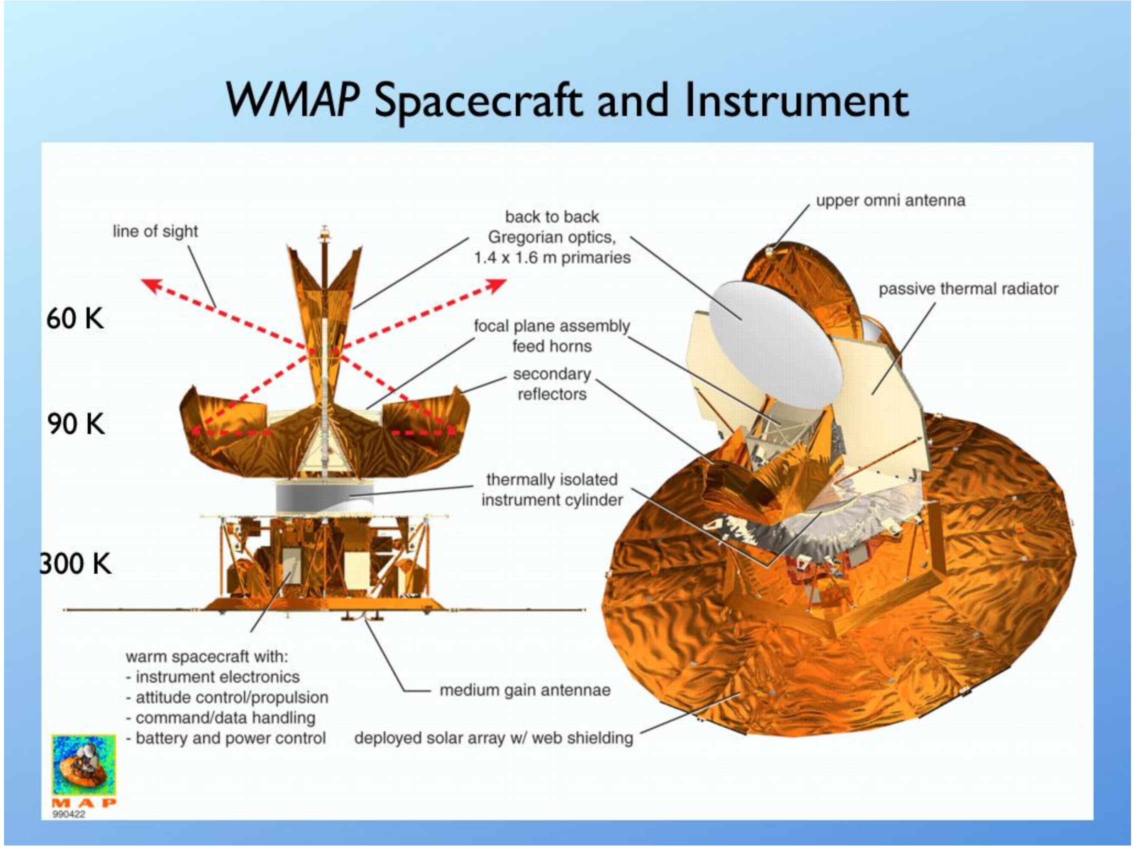
- Robert Dicke and others at Princeton immediately concluded that the 3 K excess teperature was precisely this.

COBE 1992

Satellite based Cosmic Background Explorer determined the exact spectrum and also saw the required anisotropies at parts per milllion.


Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
0
FIRAS data with 400σ errorbars
2.725 K Blackbody
Intensity [MJy/sr]
0
5
10
15
20
ν [/cm]

WMAP project circa 2000



A sensitive neutrino experiment and new unified theory

- In 1968 neutrino research is sought to be expanded
  - Gargamelle at CERN
  - Harvard, Penn, Wisconsin, Fermilab (HPWF) in the USA

A sensitive neutrino experiment and new unified theory

- In 1968 neutrino research is sought to be expanded
  - Gargamelle at CERN
  - Harvard, Penn, Wisconsin, Fermilab (HPWF) in the USA
- In 1967 and 1968 Weinberg and Salam have independently advanced a renormalizable theory of Weak interactions.
- Upto then Weak interaction necessarily change charge.
- The new theory, a concrete realisation of Schwinger's hypothesis, predicts new neutral mediators of Weak force

A sensitive neutrino experiment and new unified theory

- In 1968 neutrino research is sought to be expanded
  - Gargamelle at CERN
  - Harvard, Penn, Wisconsin, Fermilab (HPWF) in the USA
- In 1967 and 1968 Weinberg and Salam have independently advanced a renormalizable theory of Weak interactions.
- Upto then Weak interaction necessarily change charge.
- The new theory, a concrete realisation of Schwinger's hypothesis, predicts new neutral mediators of Weak force

- All experimental attempts till that date have turned up negative results for neutral weak current and it is very discouraging to look for them again.

- The proof of renormalizability is a gargantulan task. [Weinberg in private communication has said he was preoccupied with the SALT II Committee]

- All experimental attempts till that date have turned up negative results for neutral weak current and it is very discouraging to look for them again.
- The proof of renormalizability is a gargantulan task. [Weinberg in private communication has said he was preoccupied with the SALT II Committee]
- During 1970-72 Gerard 'tHooft and M. Veltman prove this. [It is 'tHooft's PhD thesis].

Change of strategy

- After extensive debate the researchers change their analysis strategy
- Experiment remians the same, an extensive revamp of search strategy is required
- They (Fry and Heidt at CERN) write new simulation programs and calibrate them
- In a 1974 conference both CERN and HPWF make a preliminary announcement; C N Yang lauds it as an important new result in his summary talk

Change of strategy

- After extensive debate the researchers change their analysis strategy
- Experiment remians the same, an extensive revamp of search strategy is required
- They (Fry and Heidt at CERN) write new simulation programs and calibrate them
- In a 1974 conference both CERN and HPWF make a preliminary announcement; C N Yang lauds it as an important new result in his summary talk
- Soon afterwards, under further scrutiny, HPWF's signal proves to be noise

Change of strategy

- After extensive debate the researchers change their analysis strategy
- Experiment remians the same, an extensive revamp of search strategy is required
- They (Fry and Heidt at CERN) write new simulation programs and calibrate them
- In a 1974 conference both CERN and HPWF make a preliminary announcement; C N Yang lauds it as an important new result in his summary talk
- Soon afterwards, under further scrutiny, HPWF's signal proves to be noise

- CERN continues to gather data, and through fortunate circumstances double the precision of their analysis
- By 1974 summer CERN is confident of the results

- CERN continues to gather data, and through fortunate circumstances double the precision of their analysis
- By 1974 summer CERN is confident of the results
- HPWF now identifies their error and approves the existence

- CERN continues to gather data, and through fortunate circumstances double the precision of their analysis
- By 1974 summer CERN is confident of the results
- HPWF now identifies their error and approves the existence

Paving the way to a unified theory

Discovering neutral weak currents at exactly the energy expected by Weinberg-Salam theory causes great spur to theoreticla as well as experimental activity.

Paving the way to a unified theory

Discovering neutral weak currents at exactly the energy expected by Weinberg-Salam theory causes great spur to theoreticla as well as experimental activity.

It then spurs the discovery of $W^+, W^-$and Z^0 particles in 1983

Paving the way to a unified theory

Discovering neutral weak currents at exactly the energy expected by Weinberg-Salam theory causes great spur to theoreticla as well as experimental activity.

It then spurs the discovery of $W^+, W^-$and Z^0 particles in 1983

Which in turn leads to setting up of the 27 km long tunnel for e^+e^-"LEP" collider machine operated during 1990's

Paving the way to a unified theory

Discovering neutral weak currents at exactly the energy expected by Weinberg-Salam theory causes great spur to theoreticla as well as experimental activity.

It then spurs the discovery of $W^+, W^-$and Z^0 particles in 1983

Which in turn leads to setting up of the 27 km long tunnel for e^+e^-"LEP" collider machine operated during 1990's

In turn leading to planning of the Large Hadronic Collider becoming operational now

Paving the way to a unified theory

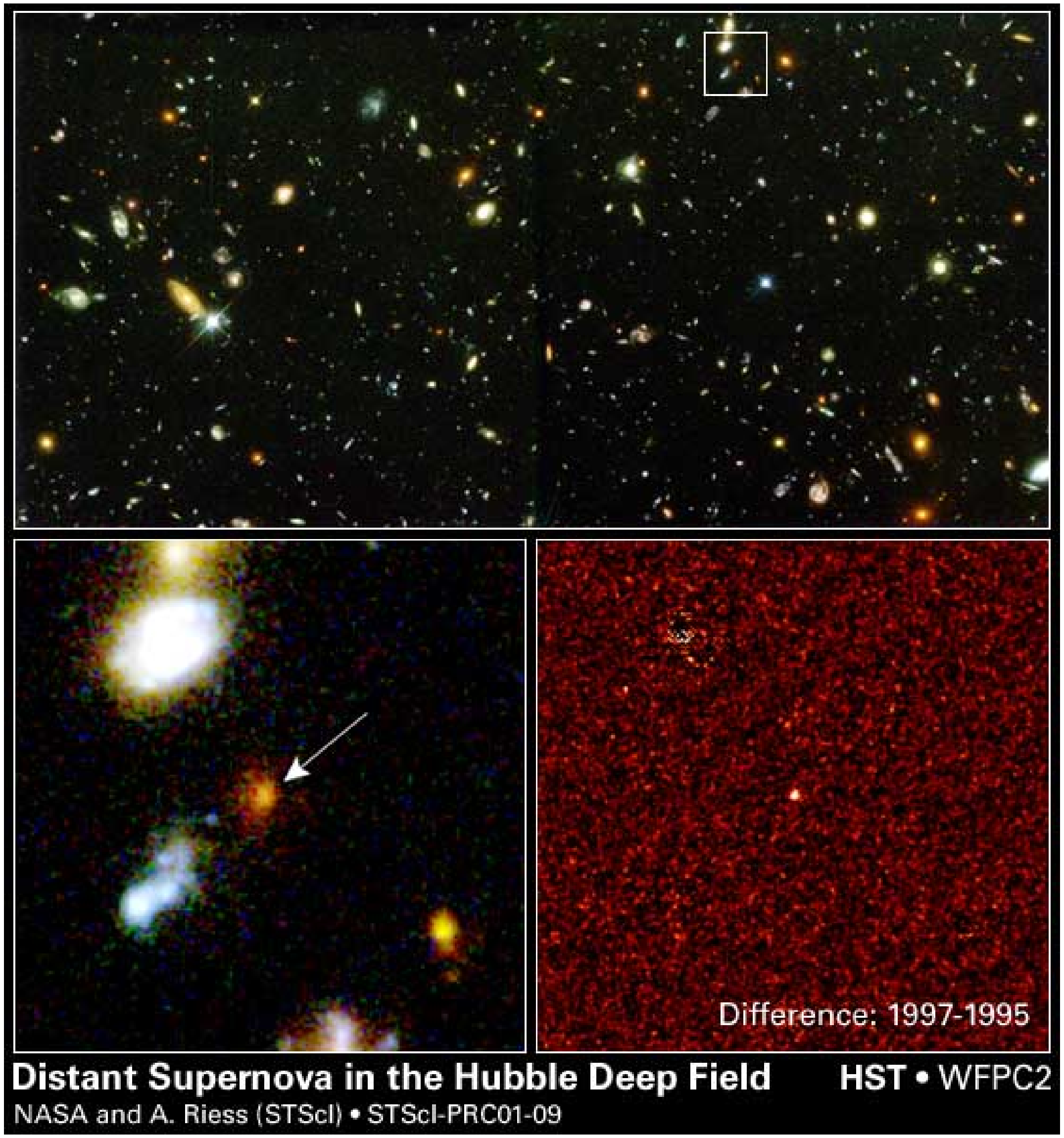
Discovering neutral weak currents at exactly the energy expected by Weinberg-Salam theory causes great spur to theoreticla as well as experimental activity.

It then spurs the discovery of $W^+, W^-$and Z^0 particles in 1983

Which in turn leads to setting up of the 27 km long tunnel for e^+e^-"LEP" collider machine operated during 1990's

In turn leading to planning of the Large Hadronic Collider becoming operational now

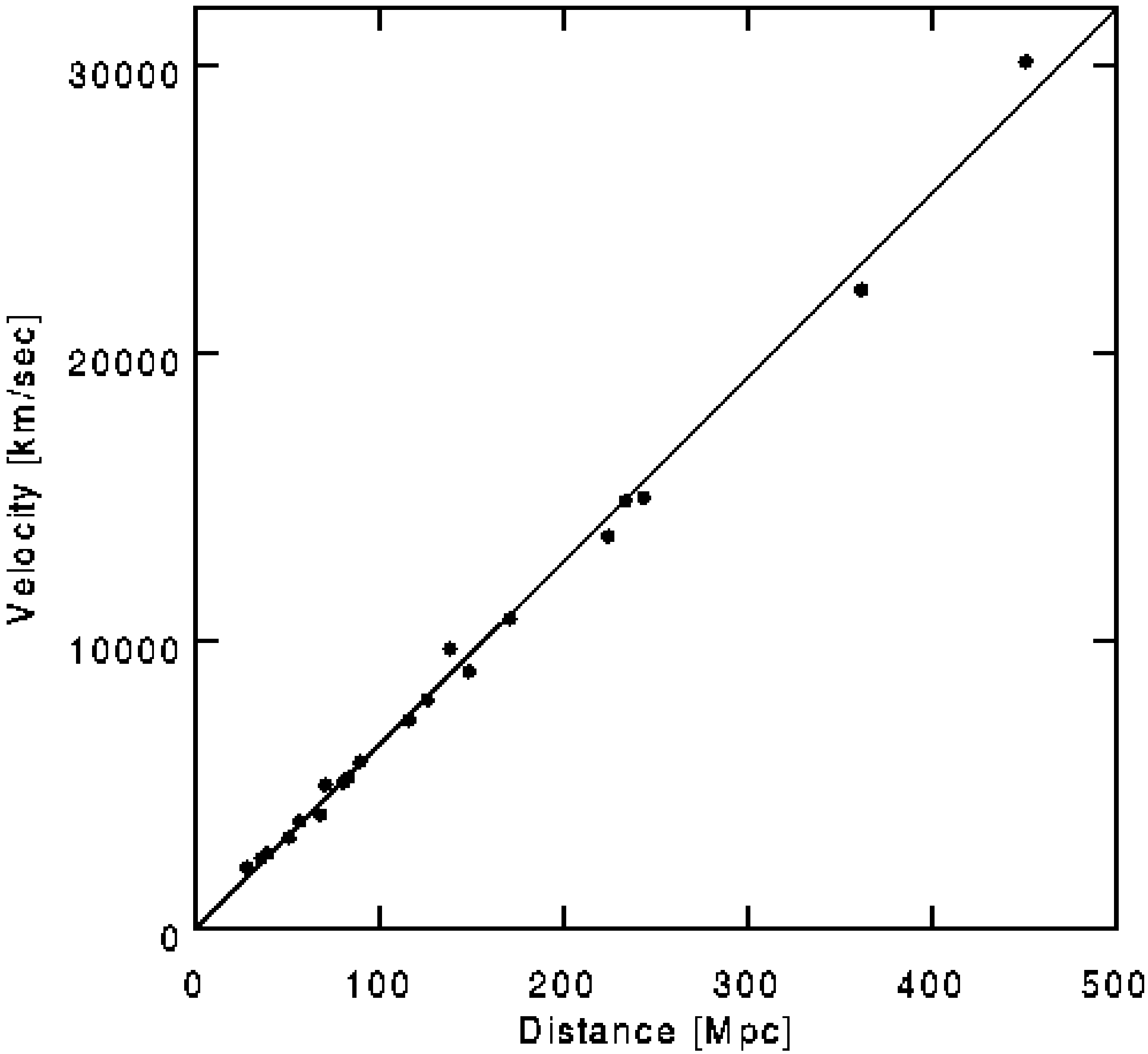
A distant supernova


Difference: 1997-1995
Distant Supernova in the Hubble Deep Field
HST • WFPC2
NASA and A. Riess (STScI) • STScI-PRC01-09

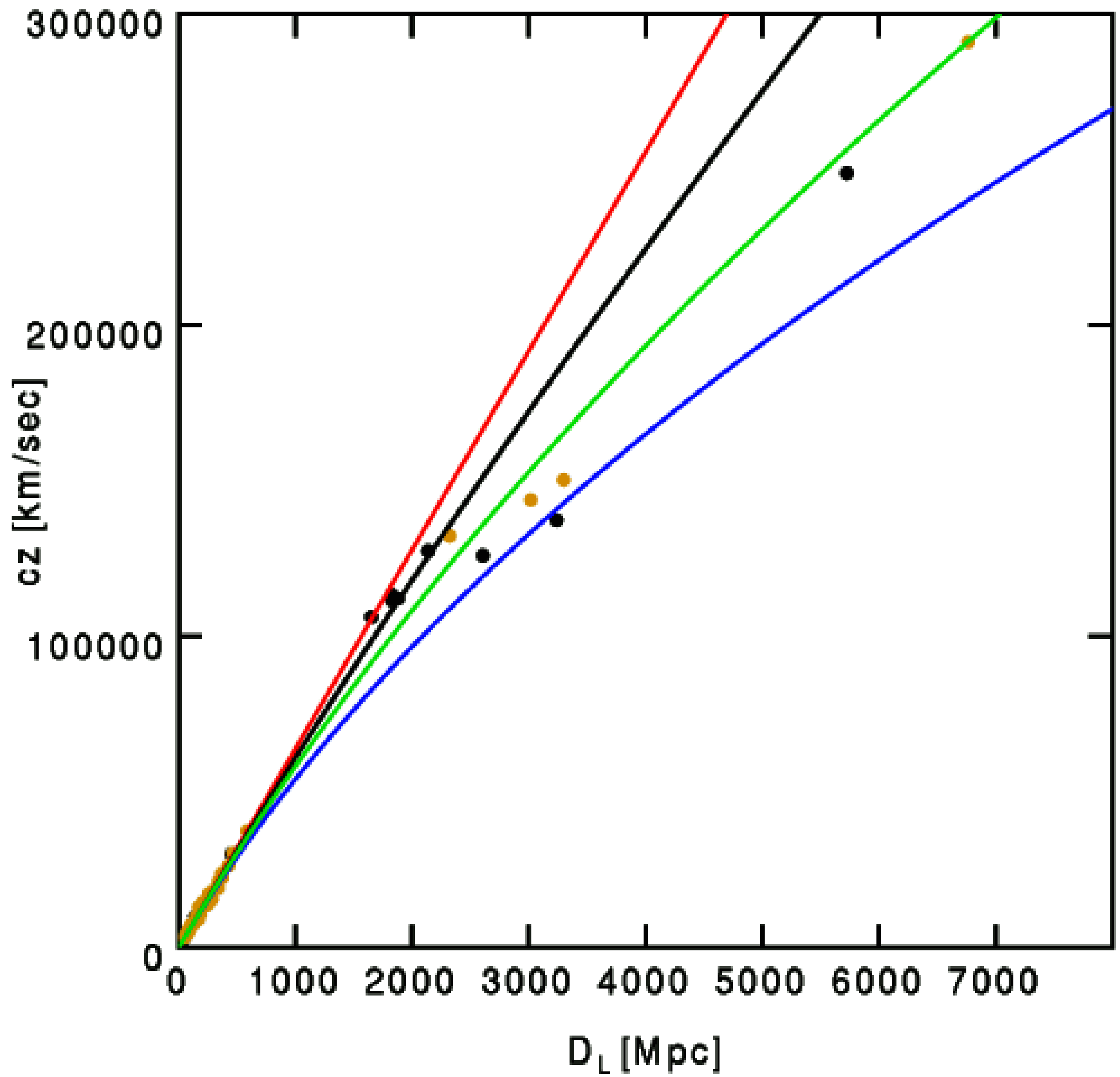
- NASA's Hubble space telescope seeks galactic redshifts
- Permutter group find, in their piece of sky an unkown object
- They request other groups to provide data of the same location at other times
- The object seen was only transitory
- The whole light curve is then constructed digitally
- It is a type Ia supernova that had exploded 7 billion years ago, and its light was reaching us in 1990's

[Show movie]

A revision in the Hubble plot



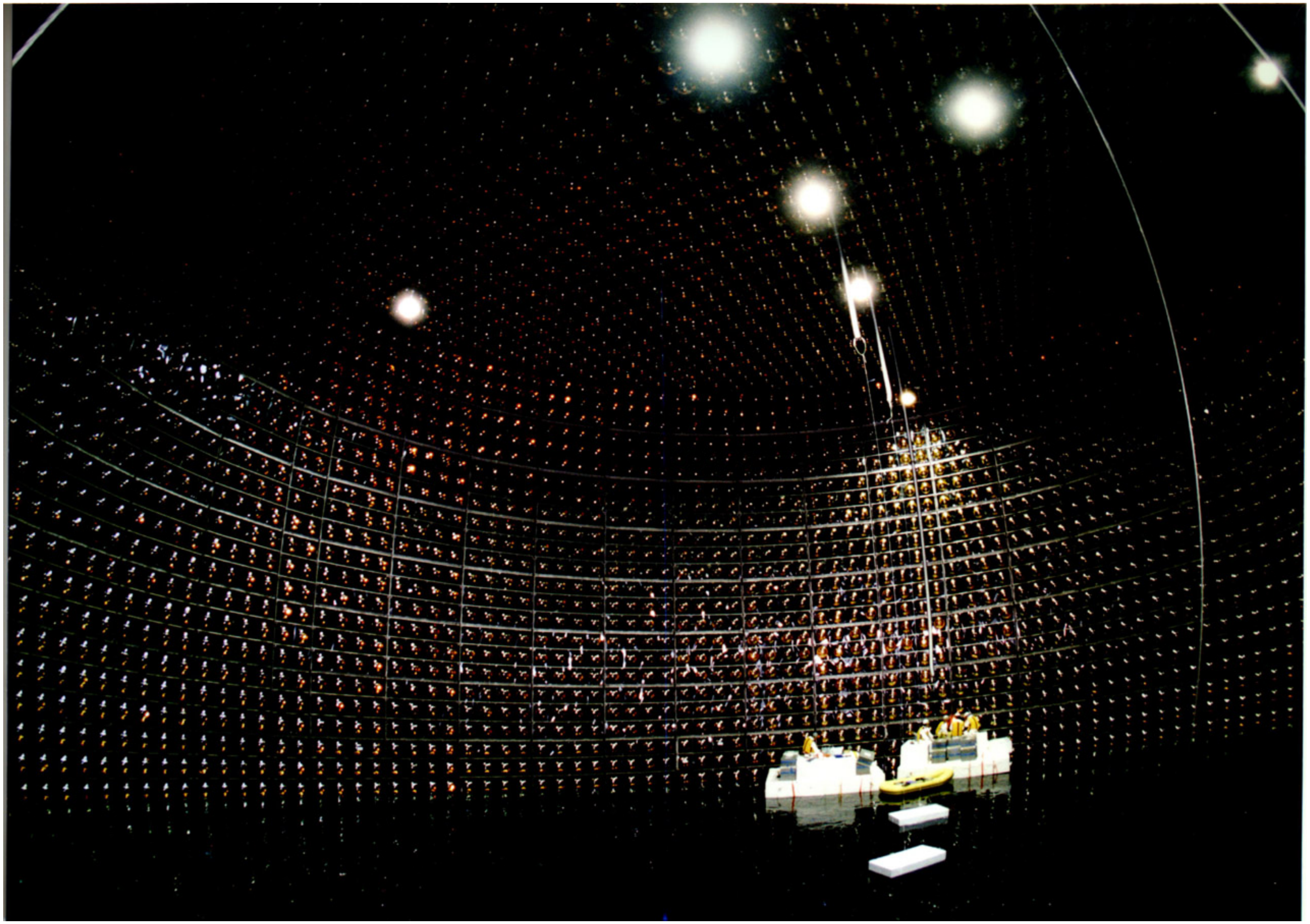
30000
20000
10000
0
Velocity [km/sec]
0
100
200
300
400
500
Distance [Mpc]


300000
200000
100000
0
0
1000
2000
3000
4000
5000
6000
7000
cz [km/sec]
D_L [Mpc]

A new cosmography and a new "substance" in the sky

- Cosmological constant?
- A cosmological constant tens of orders of magnitude smaller than Particle Physics scale
- "Dark Energy"

superKamiokande



superKamiokande

- Originally started as a search for proton decay laboratory in 1982
- 3000 tonnes of distilled water tank fitted with 1000 photomultiplier tubes in abandoned mine
- Protons don't decay decay (not till date)

superKamiokande

- Originally started as a search for proton decay laboratory in 1982
- 3000 tonnes of distilled water tank fitted with 1000 photomultiplier tubes in abandoned mine
- Protons don't decay decay (not till date)
- In 1987 it captures neutrinos from an exploding supernova
- An extensive upgradation in planned, 50,000 tonnes of distilled water and 11000 photomultiplier tubes

- Observes atmospheric neutrinos rather than solar neutrinos in 1998

- This establishes the mixing of neutrino species and that at least one of hte neutrinos is massive

- Koshiba gets Nobel prize in 2002 for the discovery

Postscript : An accident and a recovery

- In November 2001, a photomultiplier tube crahses, sending shockwaves thorugh the tank
- Almost one third of the tubes explode
- Detector returned to normal by 2005

Conclusion

- Theorists should be opportunists and pounce on the first available evidence

Conclusion

- Theorists should be opportunists and pounce on the first available evidence
- Theorists should completely ignore exprimentalists

Conclusion

- Theorists should be opportunists and pounce on the first available evidence
- Theorists should completely ignore exprimentalists
- Experimentalists should expect to find the unexpected

Conclusion

- Theorists should be opportunists and pounce on the first available evidence
- Theorists should completely ignore exprimentalists
- Experimentalists should expect to find the unexpected
- Experimentalists should take theorists seriously and diligently search what they predicted

Conclusion

- Theorists should be opportunists and pounce on the first available evidence
- Theorists should completely ignore exprimentalists
- Experimentalists should expect to find the unexpected
- Experimentalists should take theorists seriously and diligently search what they predicted
- Experimentalists can ignore theorists fantasies like porton decay

Conclusion

- Theorists should be opportunists and pounce on the first available evidence
- Theorists should completely ignore exprimentalists
- Experimentalists should expect to find the unexpected
- Experimentalists should take theorists seriously and diligently search what they predicted
- Experimentalists can ignore theorists fantasies like porton decay
- Experimentalists need not be disheartened if the apparatus doesn't find what was hypothesisesd – may be something else will show up

Conclusion

- Theorists should be opportunists and pounce on the first available evidence
- Theorists should completely ignore exprimentalists
- Experimentalists should expect to find the unexpected
- Experimentalists should take theorists seriously and diligently search what they predicted
- Experimentalists can ignore theorists fantasies like porton decay
- Experimentalists need not be disheartened if the apparatus doesn't find what was hypothesisesd – may be something else will show up

- Experimentalists should gather robust data and present a model that throws all theories off

- Experimentalists should gather robust data and present a model that throws all theories off