Astronomy on the Cusp (Driven by Technology)

S. R. Kulkarni
Director, Caltech Optical Observatories

Astronomy: The Golden Age

- 1930-1970: Stars understood
- 1950-1980: Elements understood
- 1960-2000: Neutron Stars, Black Holes
- 1990-2010: Cosmology Understood
- 1990-2010: Growth of galaxies mapped

What next?

[redacted]

[redacted]

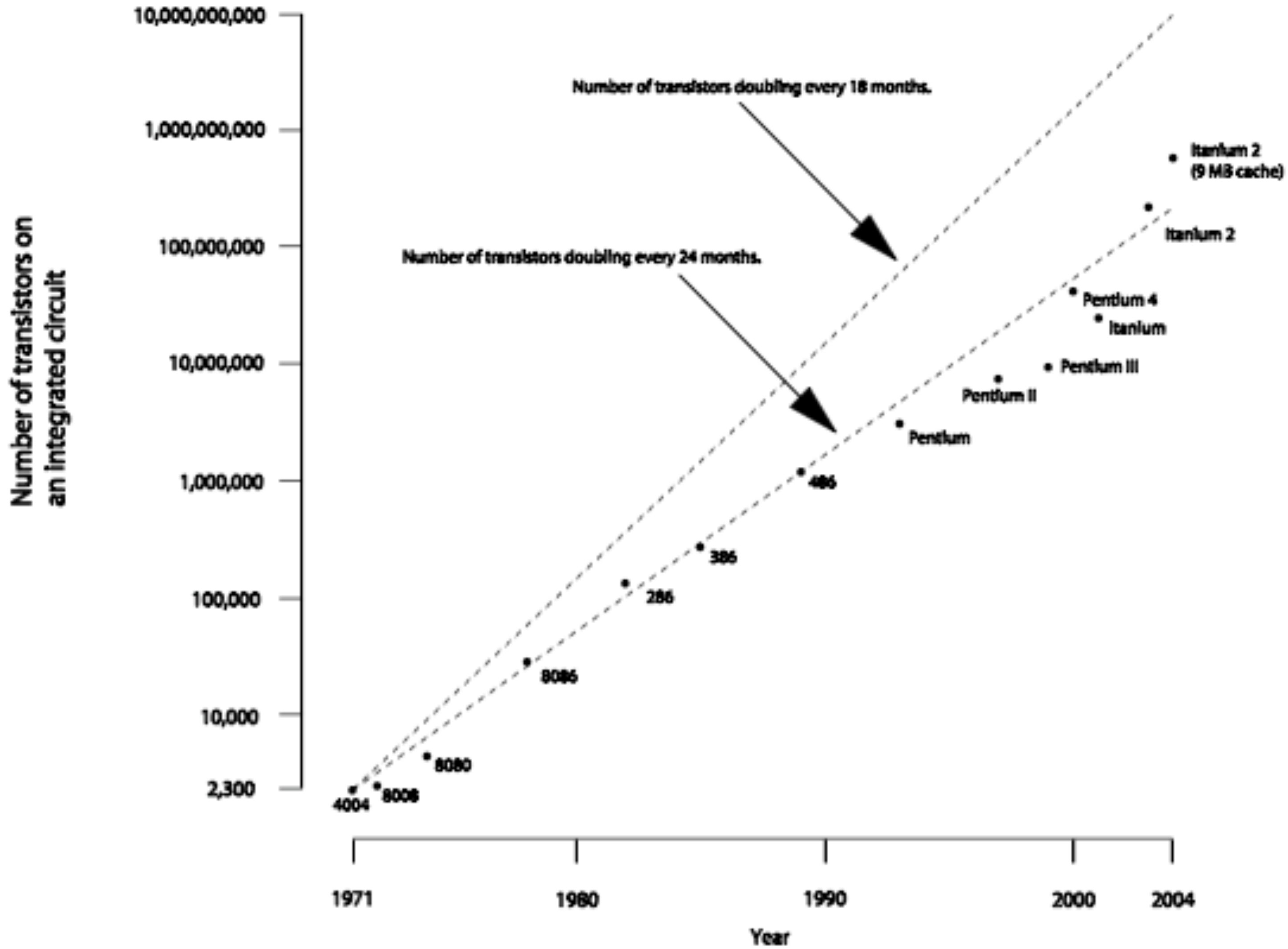
New Growth Areas

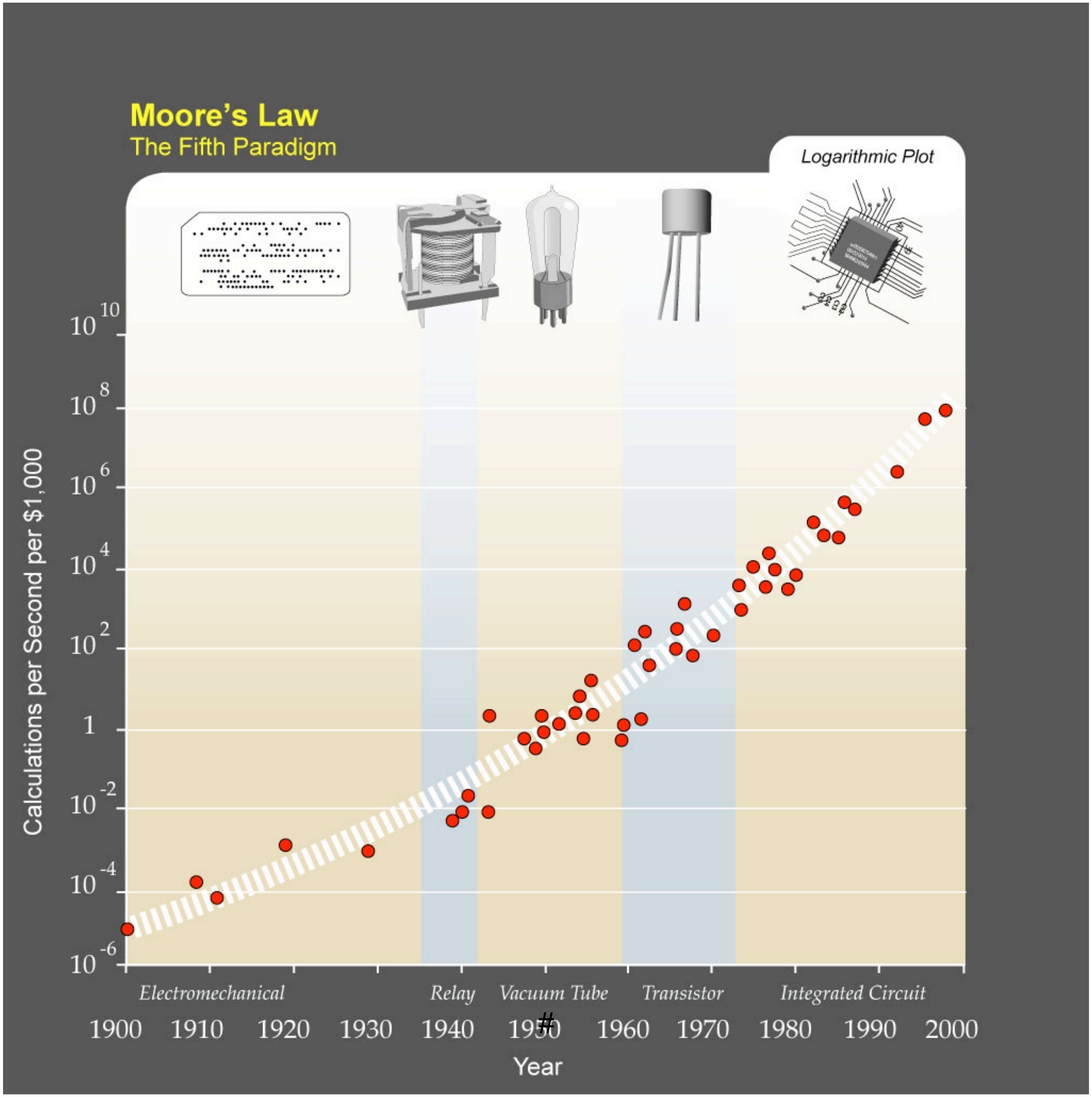
- Dark Matter and Dark Energy
- Search for & Characterization of Extra-solar planets
- Synoptic Imaging at Radio and Optical Wavelengths
- New Bands (Sub-mm, Decameter, Very High Energy)
- Strong Gravity
- The Early Universe

Exponential Growth

- Moore's law (Exponential Growth):
  - Semiconductor gains grow exponentially
- Kurzweil's observations (Accelerating Returns):
  - The exponential timescales can, in many cases, become, successively shorter

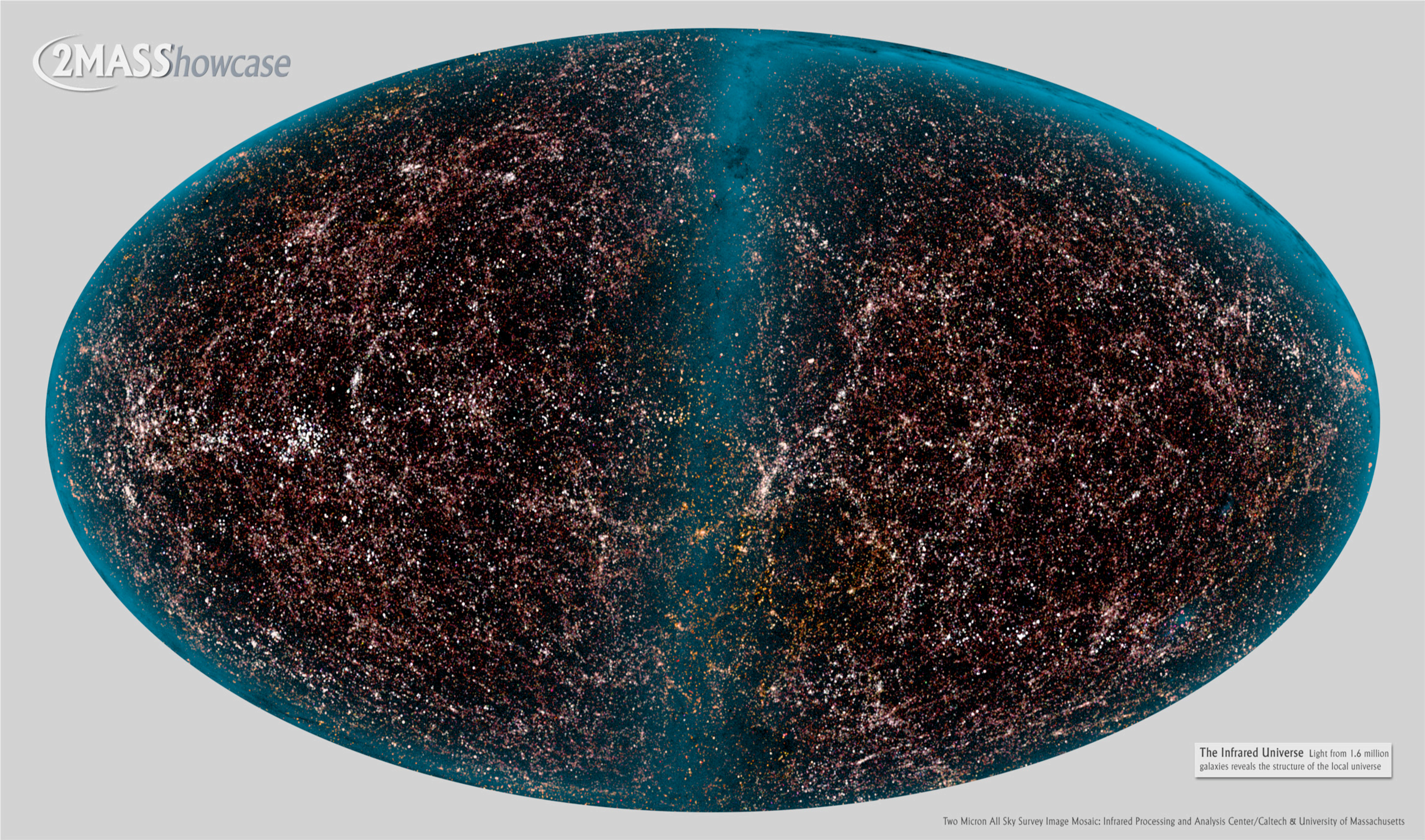
Moore's Law


10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
2,300
Number of transistors on an integrated circuit
Number of transistors doubling every 18 months.
Number of transistors doubling every 24 months.
Itanium 2 (9 MB cache)
Itanium 2
Pentium 4
Itanium
Pentium III
Pentium II
Pentium
486
386
286
8086
8080
8008
4004
1971
1980
1990
2000
2004
Year



Moore's Law
The Fifth Paradigm
Logarithmic Plot
Calculations per Second per $1,000
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
10^{-2}
10^{-4}
10^{-6}
Electromechanical
Relay
Vacuum Tube
Transistor
Integrated Circuit
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000
Year

The Palomar Sky Survey


2MASS Showcase
The Infrared Universe Light from 1.6 million galaxies reveals the structure of the local universe
Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

Accelerating Returns

- When different technologies can be combined the returns are faster than that provided by either technology
  - Such convergences can provide periods of exponential growth (even in absence of a Moore's law regime)

New Growth Areas

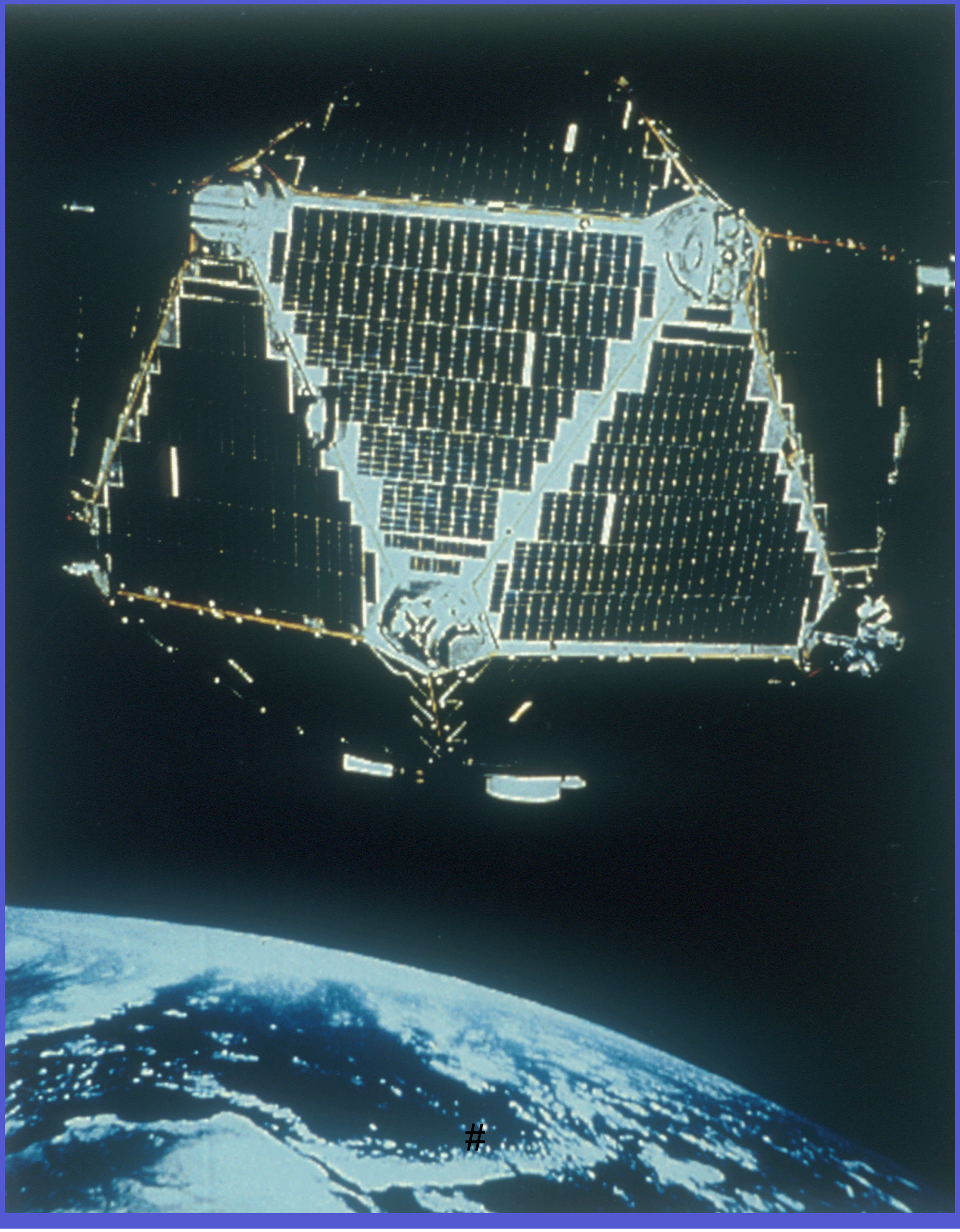
- Dark Matter and Dark Energy
  – Massive Multiplexing
- Search & Characterization of Extra-solar planets
  – Many technologies
- Synoptic Imaging at Radio and Optical Wavelengths
  – Moore's law
- New Bands (Sub-mm, Decameter, Very High Energy)
  – Accelerating Returns
- Strong Gravity
  – Accelerating Returns
- The Very Early Universe

Outline

- I. Gamma-ray bursts: An exemplar of technological convergence
- II. Synoptic Imaging at Optical Wavelengths
  - Palomar Transient Factory
- III. Synoptic Imaging at Radio Wavelengths
  - Radio band
  - Sub-millimeter: The Lush Frontier

I. Gamma-ray bursts

Vela Satellite (circa 60’s)



The Great Debate

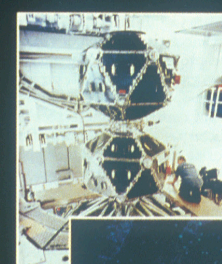
I gamma-*burst* furono scoperti negli anni '70 dai satelliti della serie Vela (pagina a fronte), posti in orbita per monitorare gli esperimenti nucleari sovietici. Al loro studio hanno contribuito numerosi altri satelliti e in particolare il Gamma Ray Observatory (GRO) che ne ha catalogati più di 2000. Solo di recente però si comincia a far luce sulla natura di questi lampi di alta energia, grazie al satellite italo-olandese BeppoSAX (qui sopra) che per primo ha permesso di misurare la loro posizione con una precisione e una rapidità sufficienti a individuarne le controparti ottiche. Il nome di questo satellite vuole ricordare Giuseppe Occhialini, "Beppo" per gli amici, pioniere dello studio della radiazione cosmica (nella foto in alto). Sullo sfondo Il gamma-*burst* registrato il 3 settembre 1996.
Qui a lato, il lancio del satellite avvenuto il 30 aprile 1996 da Cape Canaveral con un vettore Atlas-Centaur.

I lampi gamma nell'Era di Beppo

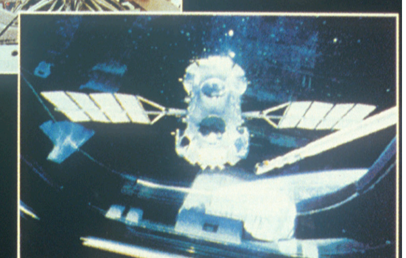
LUIGI PIRO

Il satellite italiano ha consentito risultati decisivi, quali l'identificazione della natura extragalattica di questi grandiosi eventi cosmici. Ma qual è il meccanismo astrofisico che li innesca?

DA PIÙ DI UN QUARTO DI SECOLO un fascinoso mistero accompagna l'astrofisica. In media, una volta al giorno nel cielo si accende un lampo abbagliante; ovviamente non ci riferiamo ai fenomeni di origine atmosferica, bensì a un evento astronomico che caratterizza il cielo nella regione dei raggi gamma. Stiamo parlando dei gamma-*burst*.
La storia curiosa della loro scoperta inizia negli anni '70, in piena guerra fredda. Gli Stati Uniti lanciano una serie di satelliti, denominati Vela, dedicati a monitorare gli esperimenti nucleari sovietici. Durante un'esplosione nucleare si ha una copiosa emissione di raggi gamma: i satelliti Vela trasportano rivelatori atti a scoprire *flash* di tali radiazioni. E' così che, fra lo stupore degli astronomi, si scopre che diversi *flash* gamma non provengono dalla Terra, ma dal cielo. La notizia era rimasta segreta per alcuni anni finché, aperti gli archivi agli scienziati, la scoperta fu annunciata nel 1973.
Da allora, numerosi strumenti a bordo di satelliti (l'atmosfera terrestre è opaca alla radiazione di alta energia) sono stati dedicati allo studio di questi strani fenomeni astrofisici. Tra quelli ancora in funzione è da ricordare il BATSE (acronimo di *Burst and*

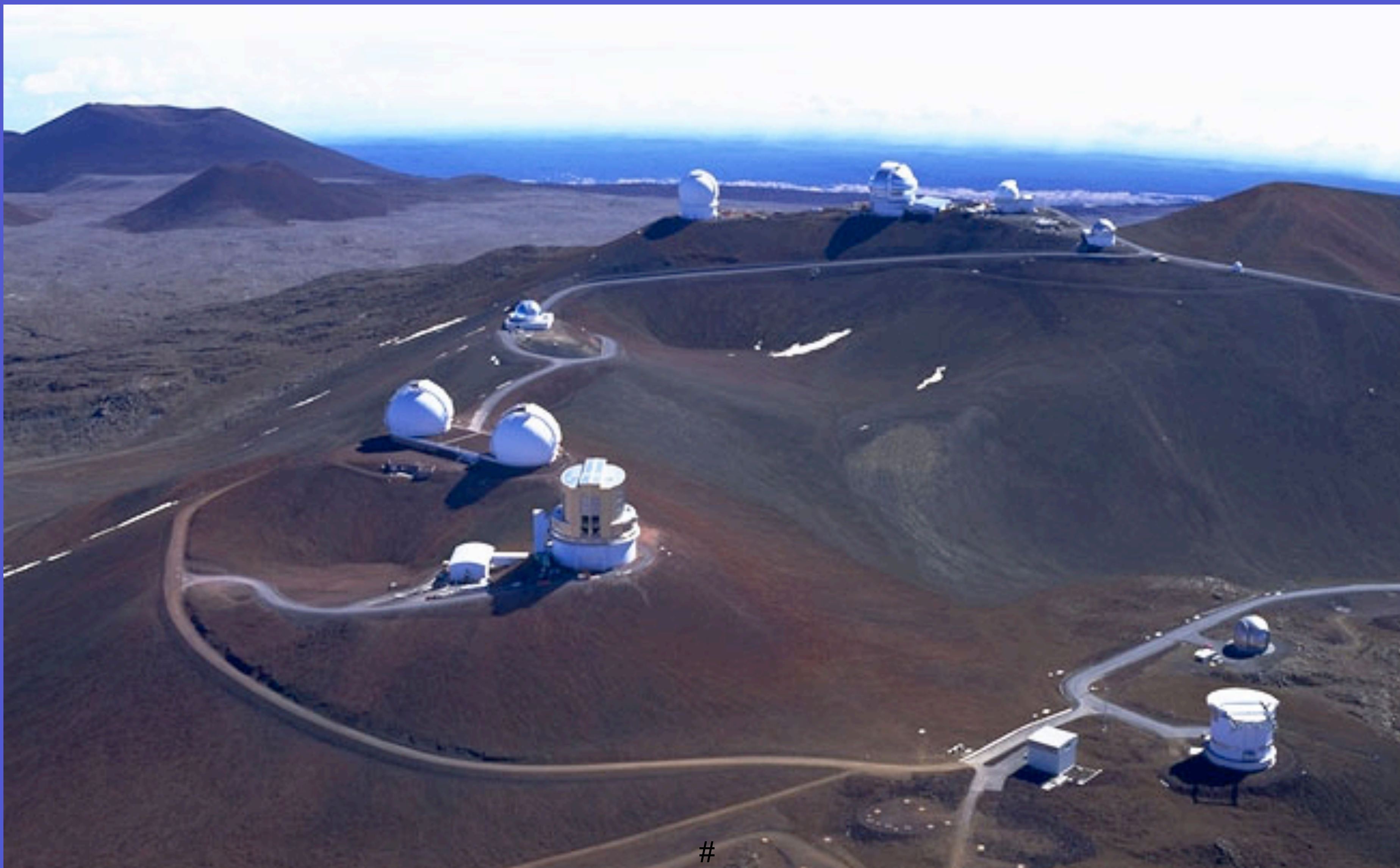


◁ Satellite Vela

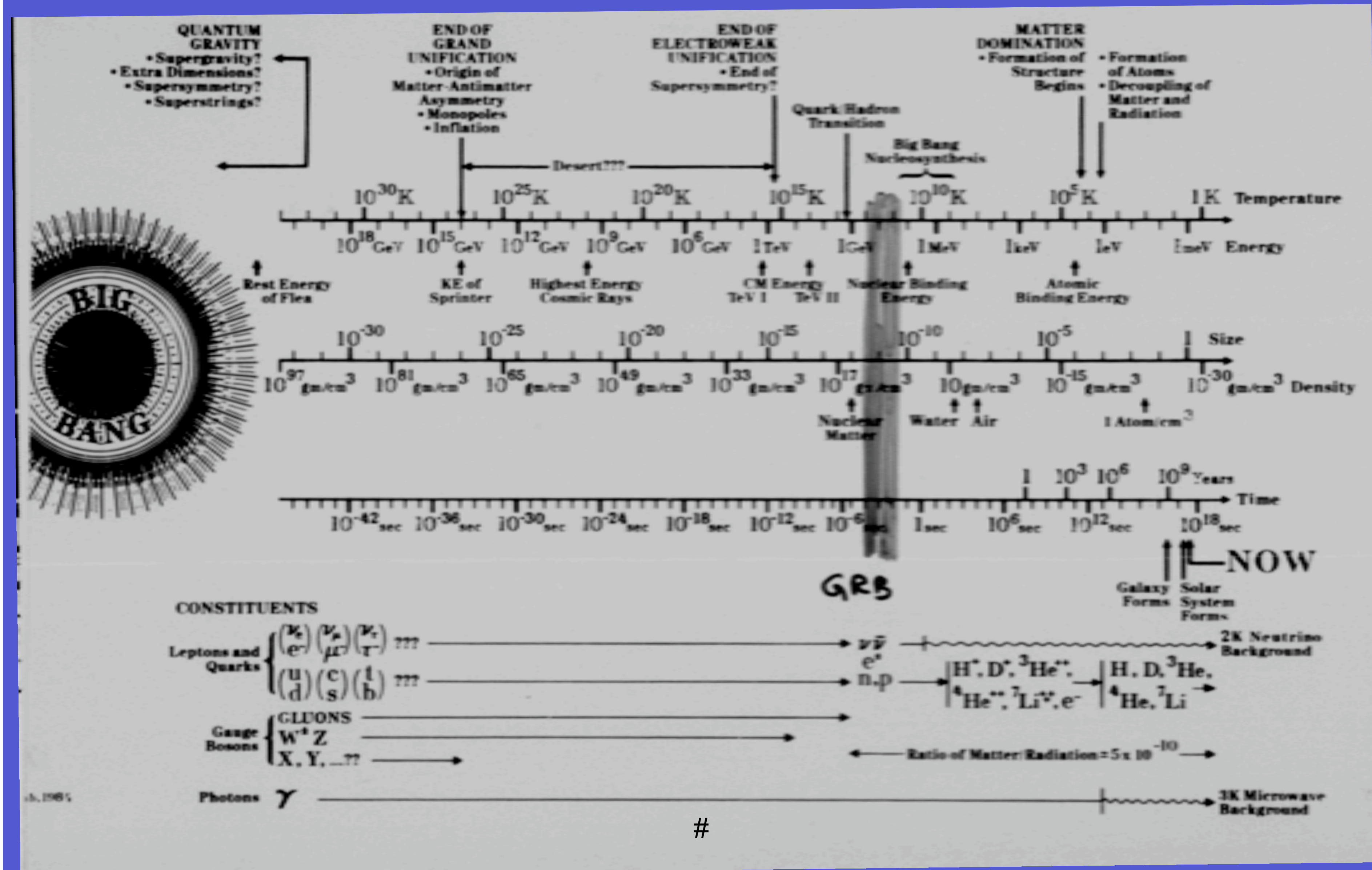


▽ Gamma Ray Observatory (GRO)

GRB 970508: THE GOLDEN BURST



Big Bang II


QUANTUM GRAVITY
• Supergravity?
• Extra Dimensions?
• Supersymmetry?
• Superstrings?
END OF GRAND UNIFICATION
• Origin of Matter-Antimatter Asymmetry
• Monopoles
• Inflation
END OF ELECTROWEAK UNIFICATION
• End of Supersymmetry?
Quark/Hadron Transition
Big Bang Nucleosynthesis
MATTER DOMINATION
• Formation of Structure Begins
• Formation of Atoms
• Decoupling of Matter and Radiation
Desert???
Temperature
Energy
Rest Energy of Flea
KE of Sprinter
Highest Energy Cosmic Rays
CM Energy TeV I TeV II
Nuclear Binding Energy
Atomic Binding Energy
Size
Density
Nuclear Matter
Water
Air
1 Atom/cm^3
Time
Years
NOW
Galaxy Forms
Solar System Forms
GRB
BIG BANG
CONSTITUENTS
Leptons and Quarks
Gauge Bosons
GLUONS
$W^{\pm}$ Z
X, Y, ...??
Photons γ
2K Neutrino Background
3K Microwave Background
Ratio of Matter/Radiation = 5 x 10^{-10}

Shrinivas Kulkarni from Kolhapur, IIT alumnus, led Caltech team which discovered the biggest cosmic explosion after Big Bang

Indian detects Big Bang II which happened 12 billion years ago

CHIDANAND RAJGHATTA
WASHINGTON, MAY 8

THE Kolhapur village of Kurundwad in Maharashtra is a long, long way from galaxy GRB 971214 somewhere out there in the universe. But Dr Shrinivas Kulkarni has traversed the distance with great distinction.

Earlier this week, the Indian astrophysicist from Caltech — and an IIT Delhi alumnus — threw the astronomical world into a tizzy by detecting and measuring what is being acknowledged as the biggest cosmic explosion since the Big Bang which created the universe.

So bright and violent was the explosion that scientists say that for about 40 seconds, it appeared to outshine all the rest of the universe. It was so powerful and luminous that in one second it released almost as much energy as all the rest of the universe.

SPECIAL REPORT

"The energy burst staggers the imagination," Kulkarni said at a NASA briefing in Washington on Wednesday, as other awed astrophysicists struggled to come to terms with arguably the biggest cosmic event ever detected. "This is the greatest documented explosion since the dawn of man," added Stan Woosley, a University of California theorist specialising in astronomical explosions. Of course, it requires a staggering feat of imagination to comprehend the staggering events that only astrophysicists are capable of relating as if it happened in our backyard.

The cataclysm involving GRB 971214 is described as a gamma ray burster which occurred some 12 billion years ago in the young universe. Essentially it was a primal explosion of an incredibly dense matter that reached temperatures of billions of degrees, somewhat like in the run-up to the Big Bang which created the universe.

Assuming the universe itself is 14 billions years old, the Caltech team estimates that the GRB 971214 radiation has been travelling for 90 per cent of the age of the universe. This means the light must have left its source some 8 billion years before the earth formed.

Even accounting for the speed at which light travels (186,000 miles per second or 5.9 trillion miles per year), the event was only detected on December 14 last year and measured soon after by an international groups of scientists led by Kulkarni.

The team is publishing its findings in the latest issue of *Nature* magazine. As for the energy released, scientists say it would be equal to 5 billion supernovae, the explosion of dying stars that was hitherto the best documented burst of energy in the universe. If all the nuclear weapons made were exploded in one go, it wouldn't match the fizz and pop of a single supernova. Ten billion years of our Sun's existence has not produced one hundredths of the energy that GRB 971214 released.

As slackjawed mortals listened in wonderment to the mindbending numbers and theorising, astrophysicists grappled with the meaning of this 12-billion-year old event. "Most of the theoretical models proposed to explain these bursts cannot explain this much energy. However, there are recent models involving rotating black holes which can work," Dr Kulkarni explained, adding, "On the other hand, this is such an extreme phenomenon that it is possible we are dealing with something completely unanticipated and even more exotic."

Kulkarni, who is rated among the top astrophysicists in the world today, is among the pioneers who have detected the brilliant flashes of cosmic explosions called gamma ray bursters. An expert on neutron stars and galactic and extragalactic interstellar medium, he is also credited with discovering what are known as Brown Dwarfs, dim brown objects bigger and hotter than planets but which failed to become stars.

Kulkarni, 42, who was born in the Maharashtra village of Kurundwad, is called "Shri" by his colleagues. He came to the US after doing his in Physics from IIT Delhi (1978) and earned a Ph.D in Astronomy from the University of California in Berkeley. "He's one of the most brilliant minds in the field," said Caltech chronicler Robert Tindol.

Indian Express – Sunday May – 18

Riesen-Knall im All

Vor 12 Milliarden Jahren hat es gerummst – jetzt haben wir es gehört

Donnerstag, 7. Mai 1998, 70 Pf

Bild

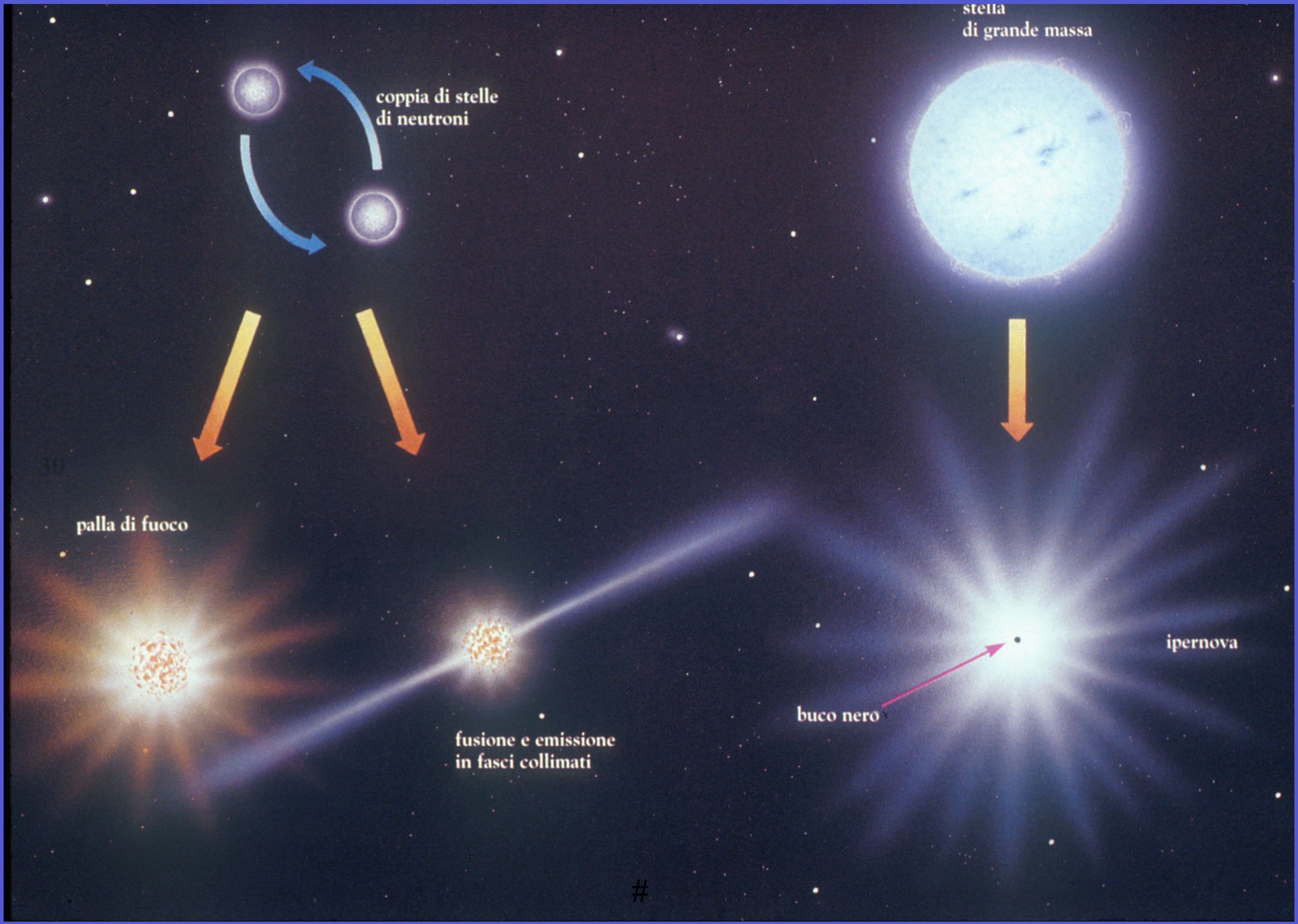
UNABHÄNGIG · ÜBERPARTEILICH

RHEIN-NECKAR

Doch sexuelle Motive?

#

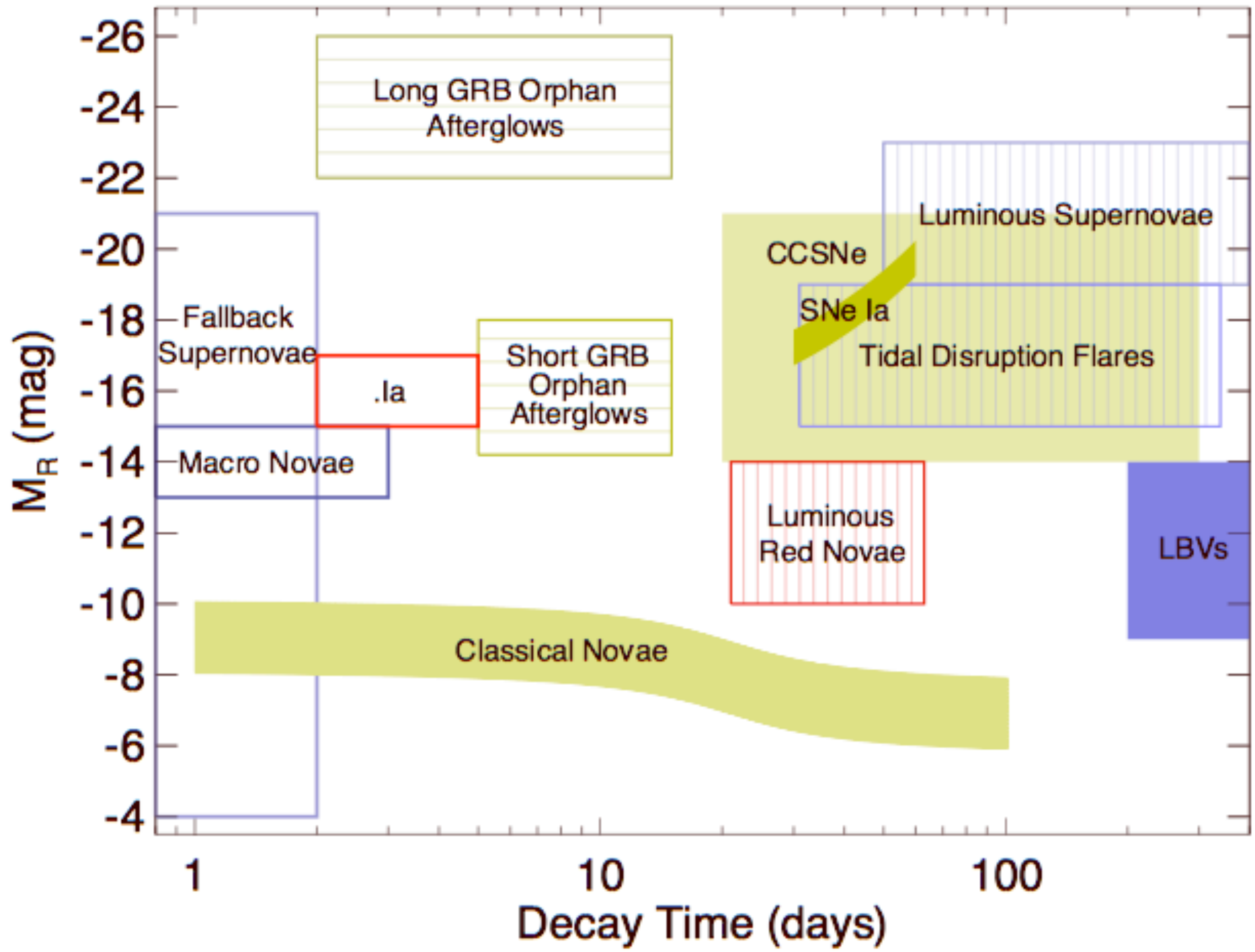
Popular Models



What led to this breakthrough?

- The X-ray and gamma-ray detectors on BeppoSAX have been around for decades
- Availability of
  - Large format detectors
  - Rapid information dissemination (Internet)
  - Rapid Data Reduction (Fast Computing)

II. Synoptic Optical Imaging



-26
-24
-22
-20
-18
-16
-14
-12
-10
-8
-6
-4
M_R (mag)
1
10
100
Decay Time (days)
Long GRB Orphan Afterglows
Luminous Supernovae
CCSNe
SNe Ia
Tidal Disruption Flares
Fallback Supernovae
.Ia
Short GRB Orphan Afterglows
Macro Novae
Luminous Red Novae
LBVs
Classical Novae

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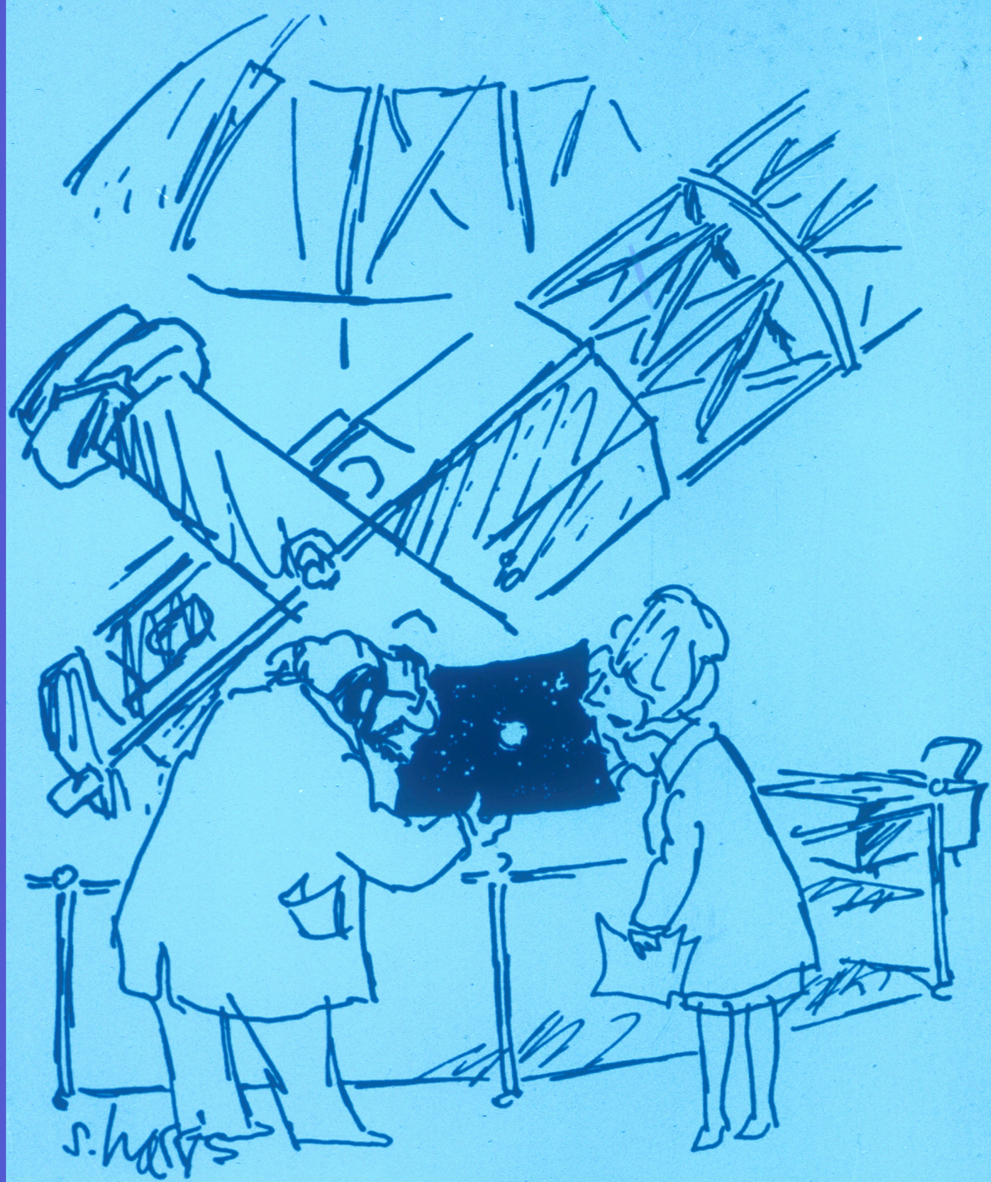
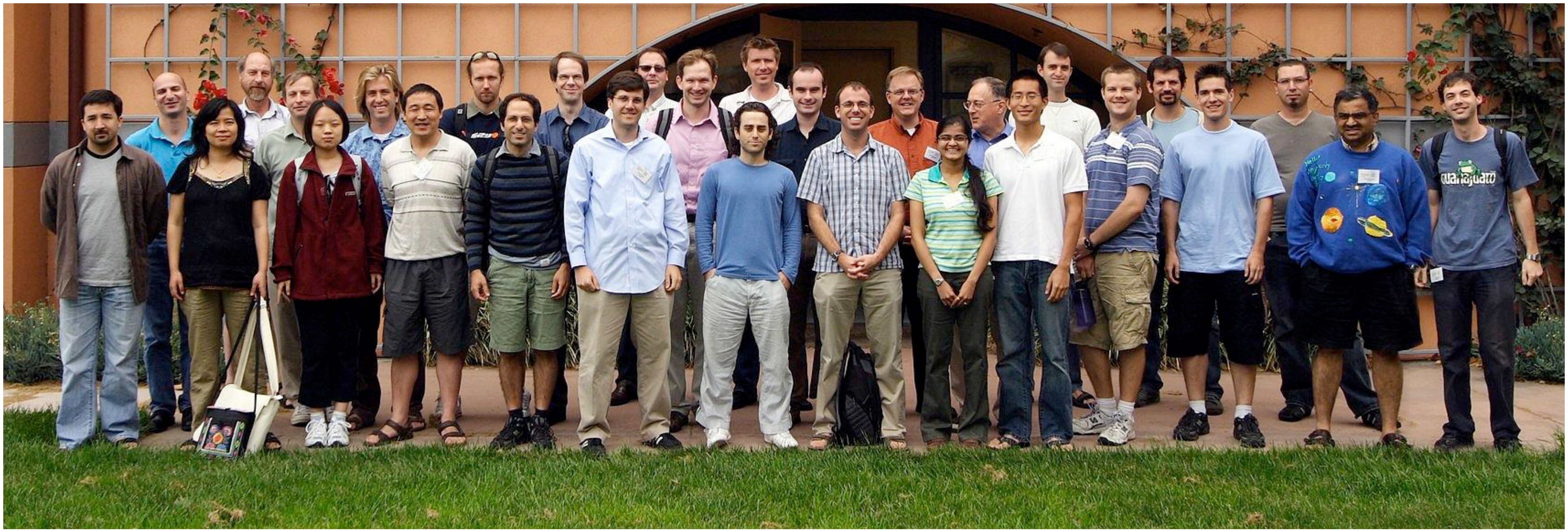


"It's somewhere between a nova and a supernova ... probably a pretty good nova."

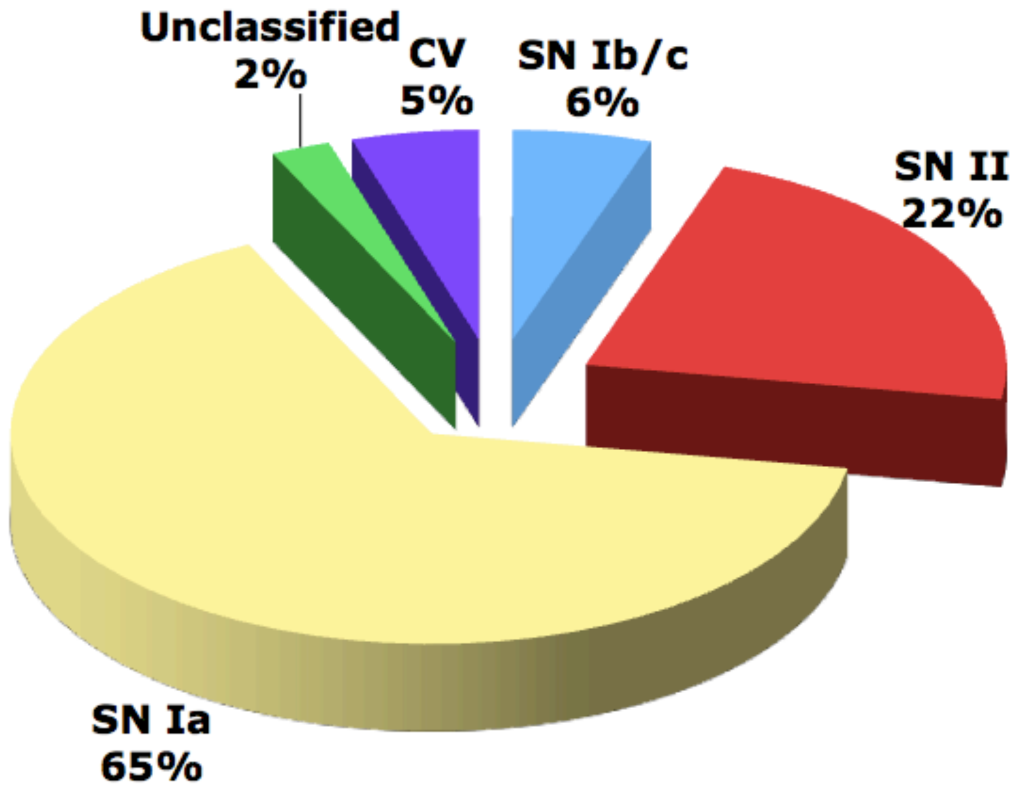
Palomar Transient Factory

PTF collaboration



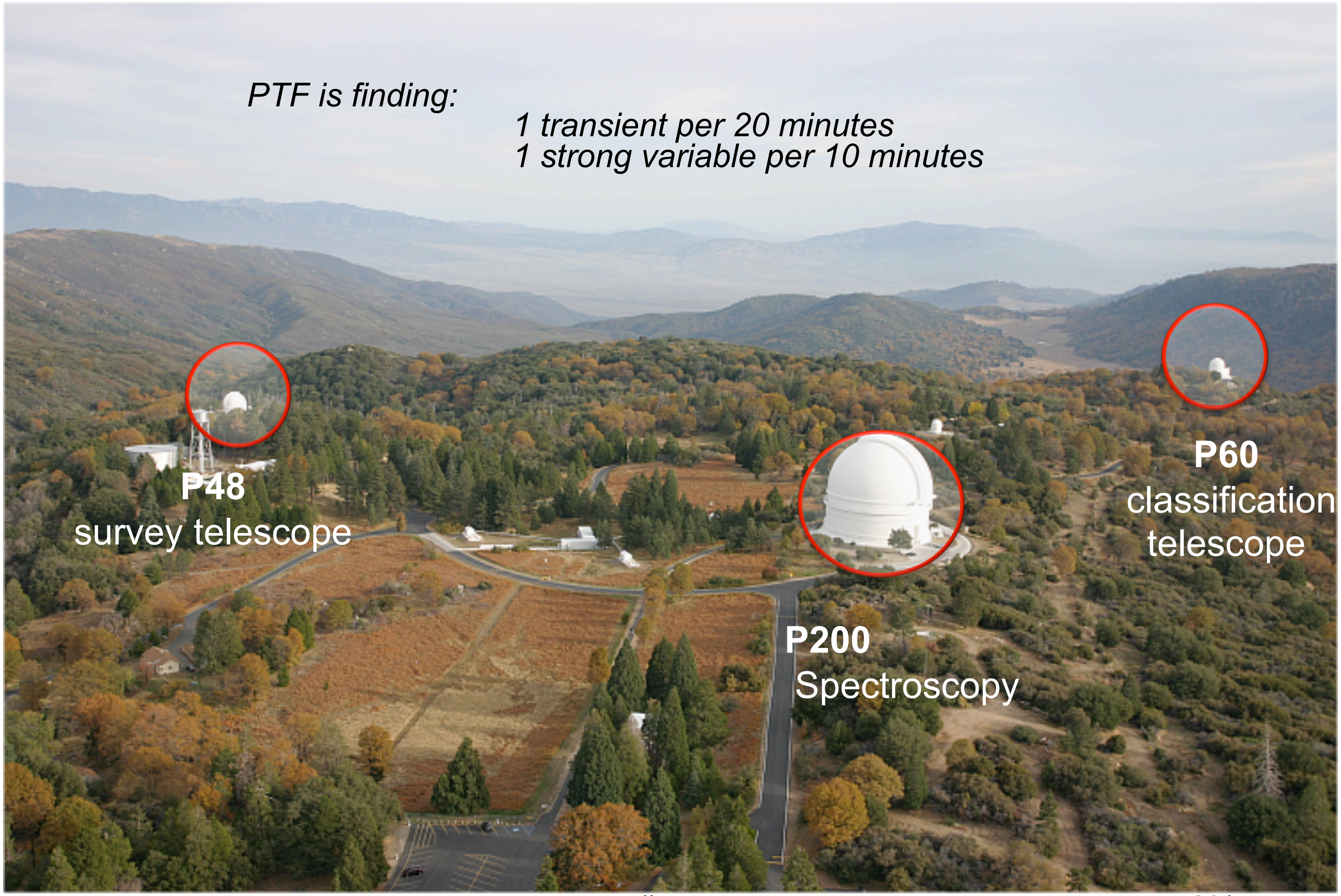
Caltech, LCOGT, Berkeley, LBL, IPAC, Columbia, Oxford, Weizmann

PTF haul (to date)



655 Spectroscopically Confirmed PTF Transients To Date

953


PTF is finding:
1 transient per 20 minutes
1 strong variable per 10 minutes
P48
survey telescope
P60
classification
telescope
P200
Spectroscopy

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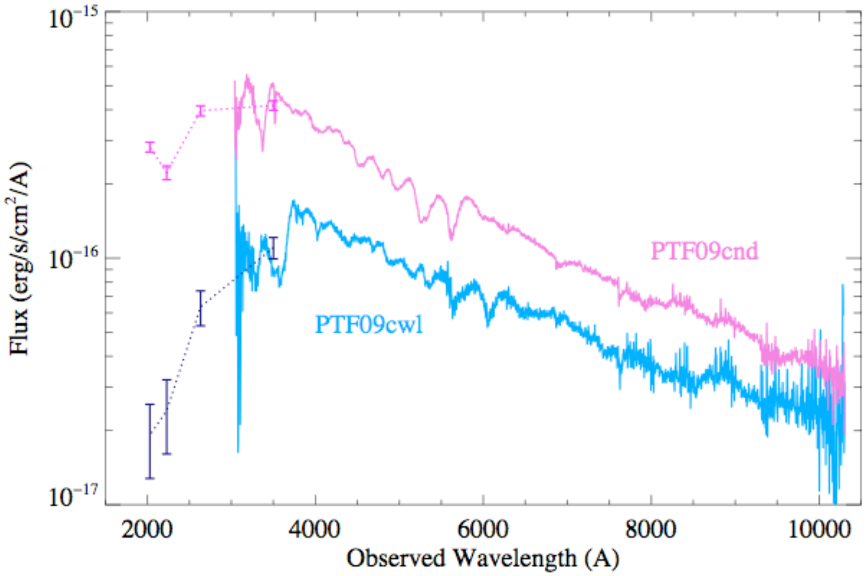
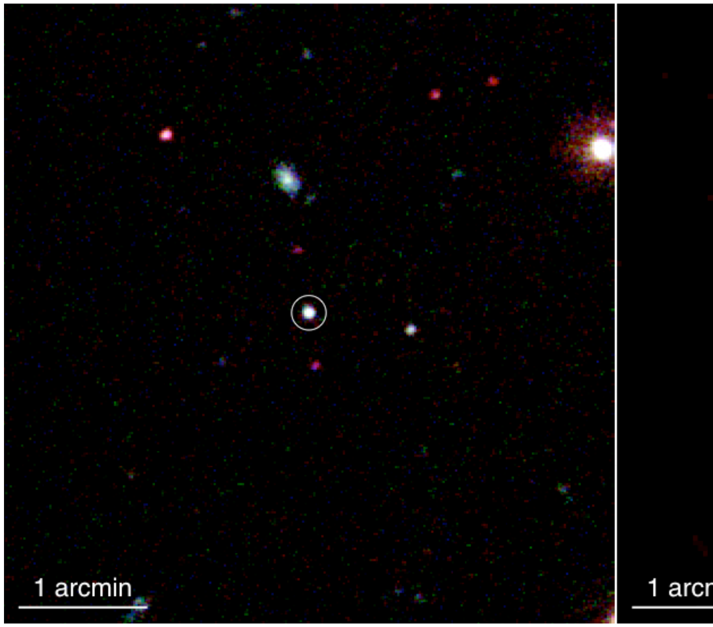
Swift Observations

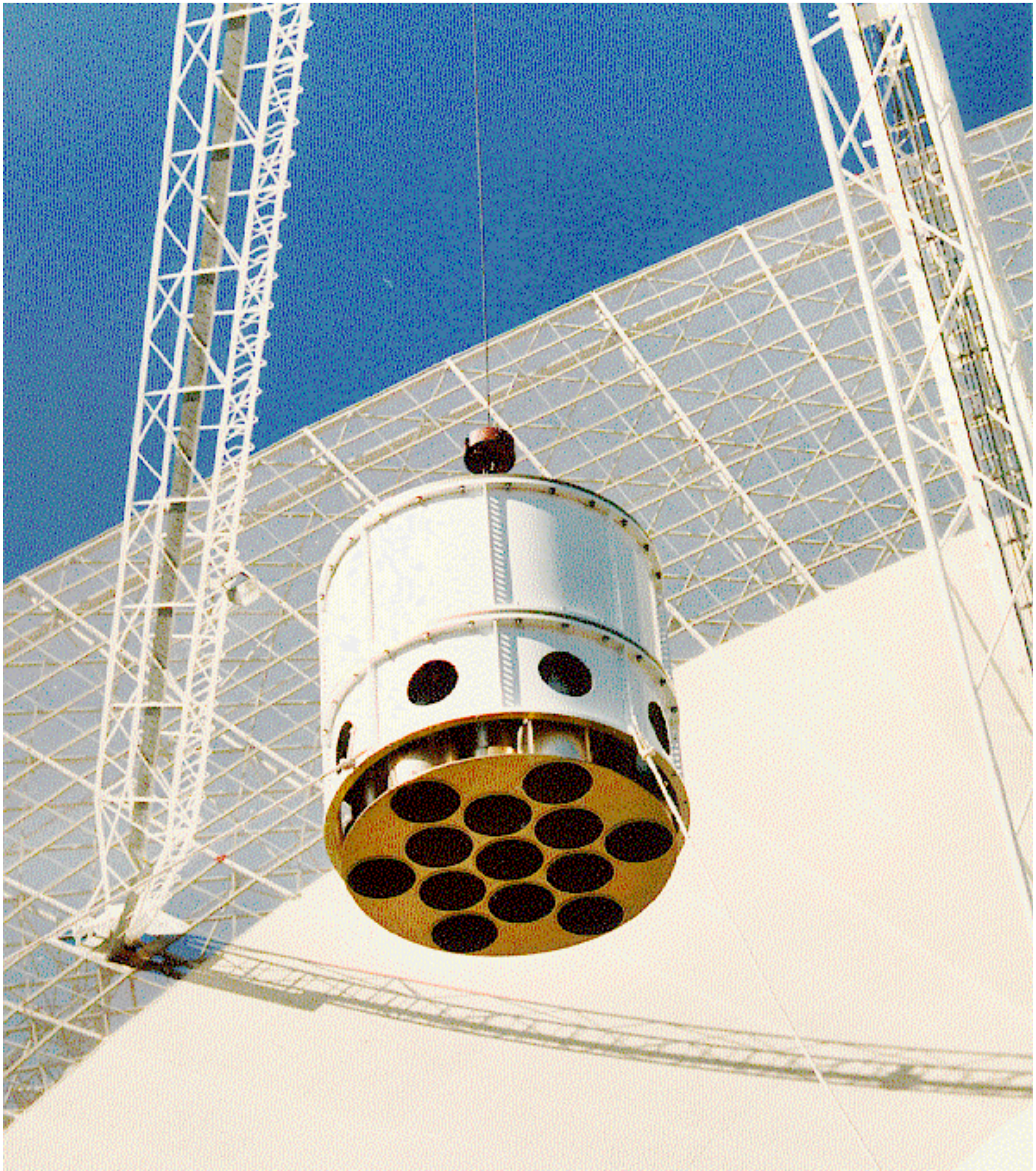
Kiran (2008-08-18)

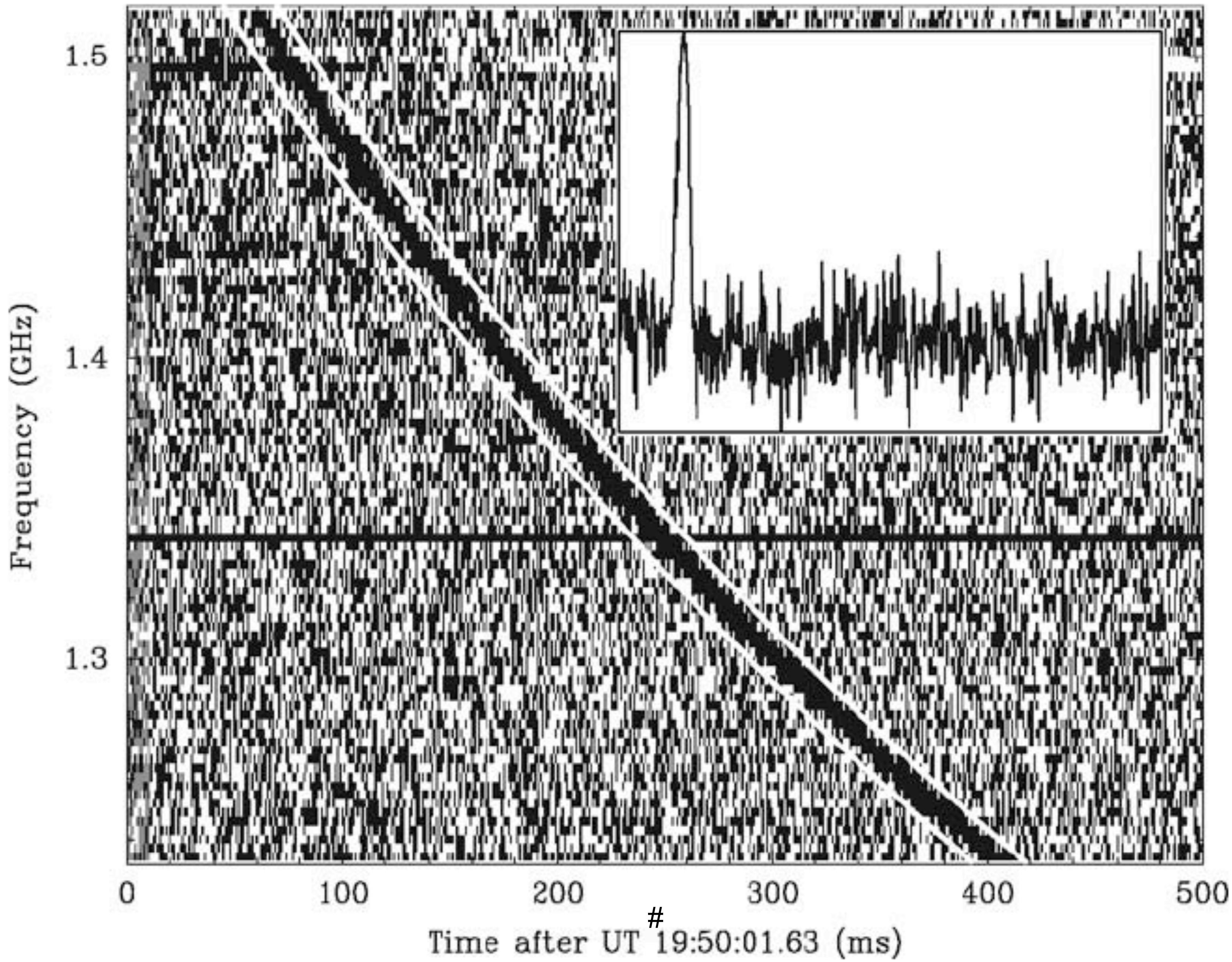
$\boldsymbol{M_{uv}}$ **= −23.5 (!)** for z = 0.29





IIIa. Synoptic Imaging at Radio Wavelengths





1.5
1.4
1.3
Frequency (GHz)
0
100
200
300
400
500
Time after UT 19:50:01.63 (ms)

Low Frequency Arrays

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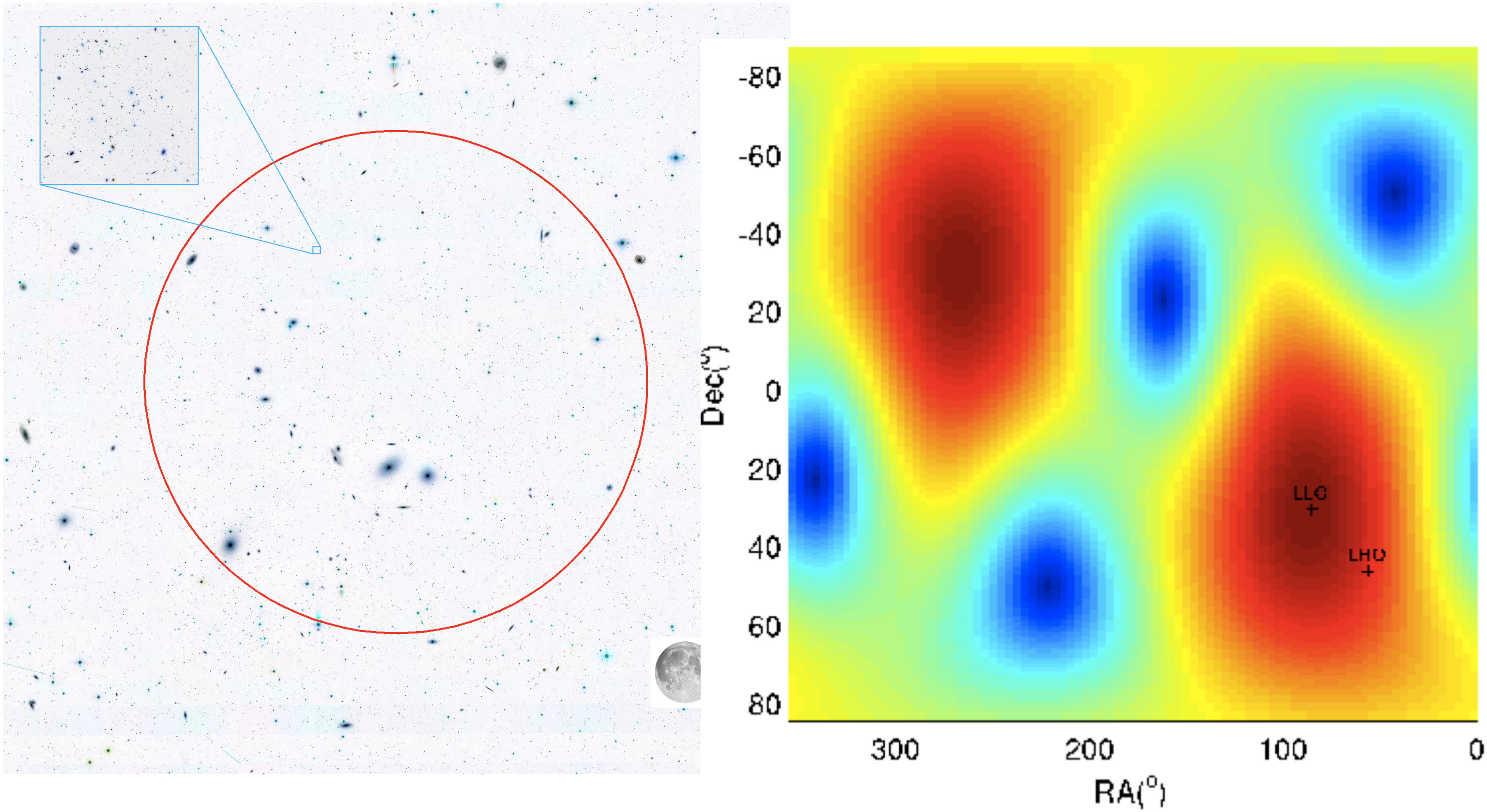
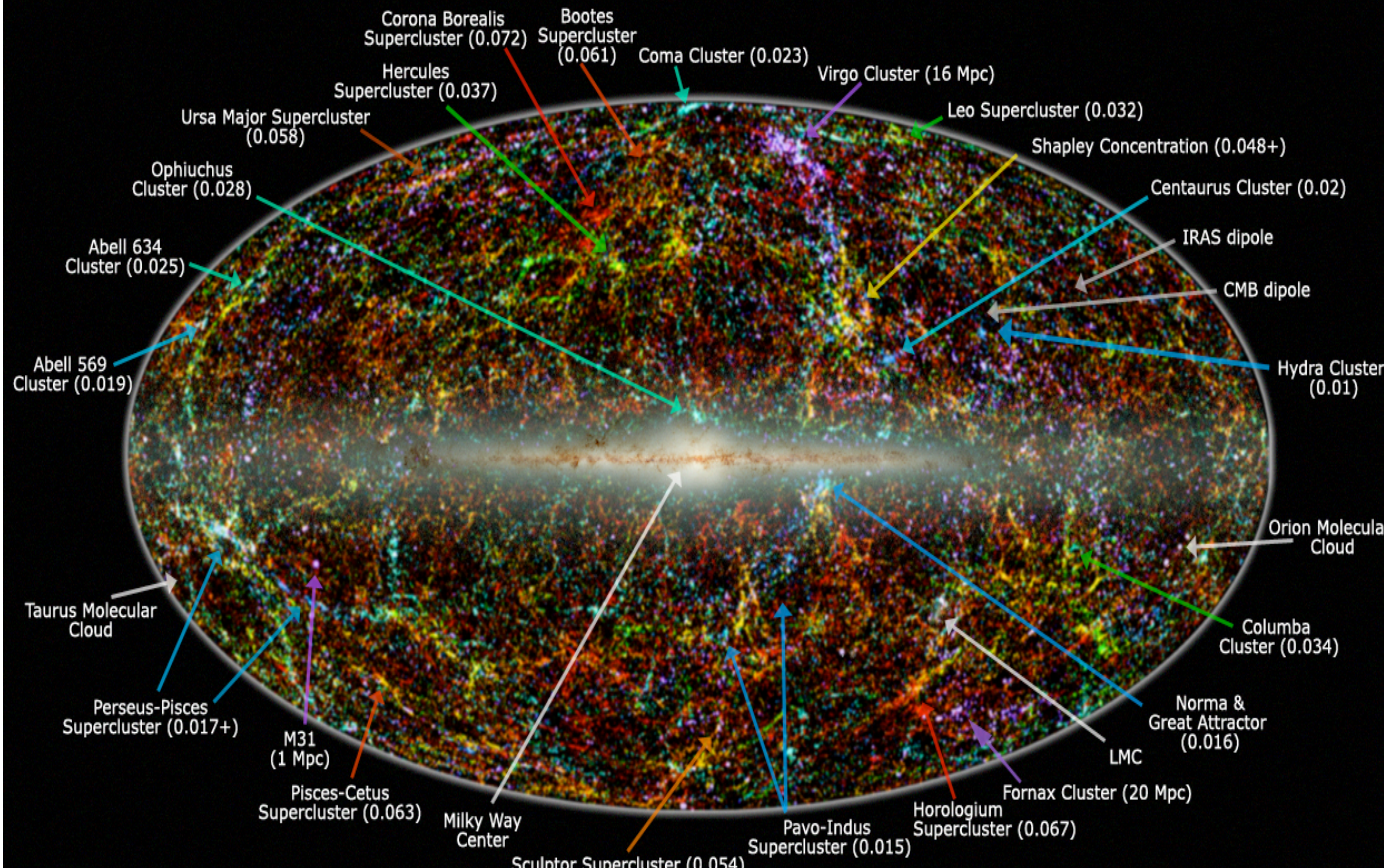
Strong Gravity (LIGO)

Gravitational Wave Observatories


Dec(°)
-80
-60
-40
20
0
20
40
60
80
RA(°)
300
200
100
0
LLO
LHO

Large Scale Structure in the Local Universe



Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004); familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift). Graphic created by T. Jarrett (IPAC/Caltech)

IIIb. The Lush Sub-mm Frontier

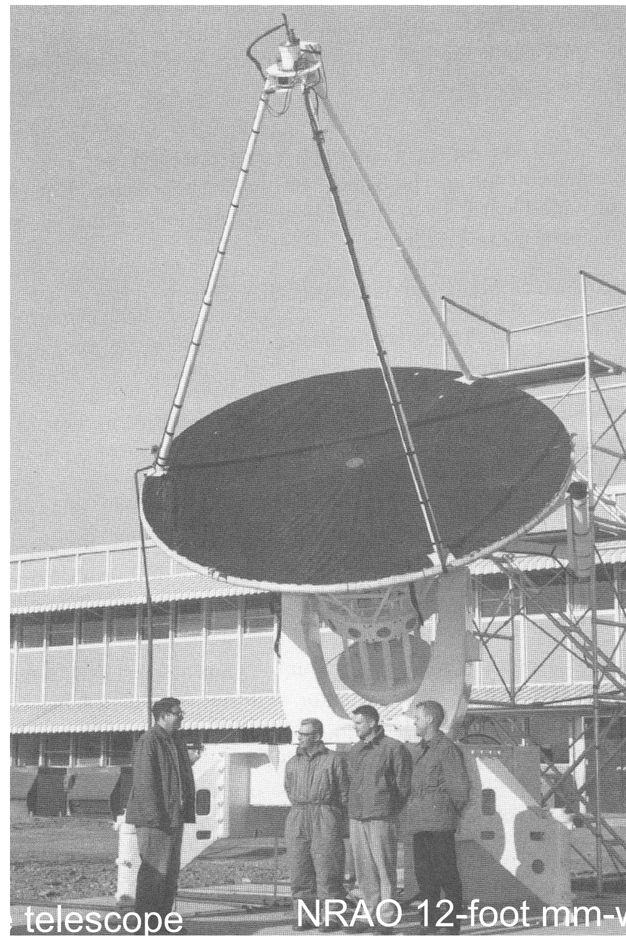
Early mm-wave astronomy

- 1961: Frank Low invents the Ge bolometer
- 1963: Sun, Moon, bright planets

TABLE

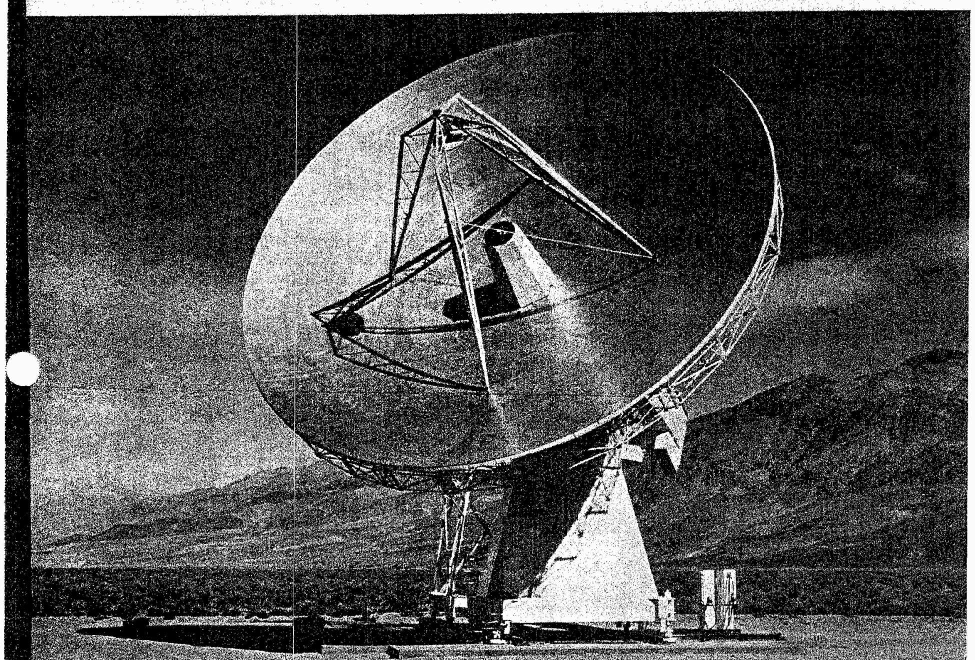
N.R.A.O. MICROWAVE THERMAL-DETECTION RADIOMETER

Center frequency = 250 GC (λ = 1.2 mm)
Bandwidth = ~35 per cent
ΔT_{min} = 0.015 °K, rms for τ = 10 seconds
1.2 mm Efficiency = 25 per cent
dc Bolometer Characteristics:
T_0 = 2.0 °K
R_0 = 7 by 10^6 Ω
G = 0.85 μ watt/°K
τ_B = 12 ms
f_0 = 10 c/s
Volume = 1.2 by 1.0 by 0.36 mm³
S = 1.3 by 10^6 volts/watt
Noise = 5 by 10^{-8} volt/cs, rms
N.E.P. = 4 by 10^{-14} watt



1973-78: 10-m telescope

A 10-METER TELESCOPE
for
MILLIMETER AND SUB-MILLIMETER ASTRONOMY

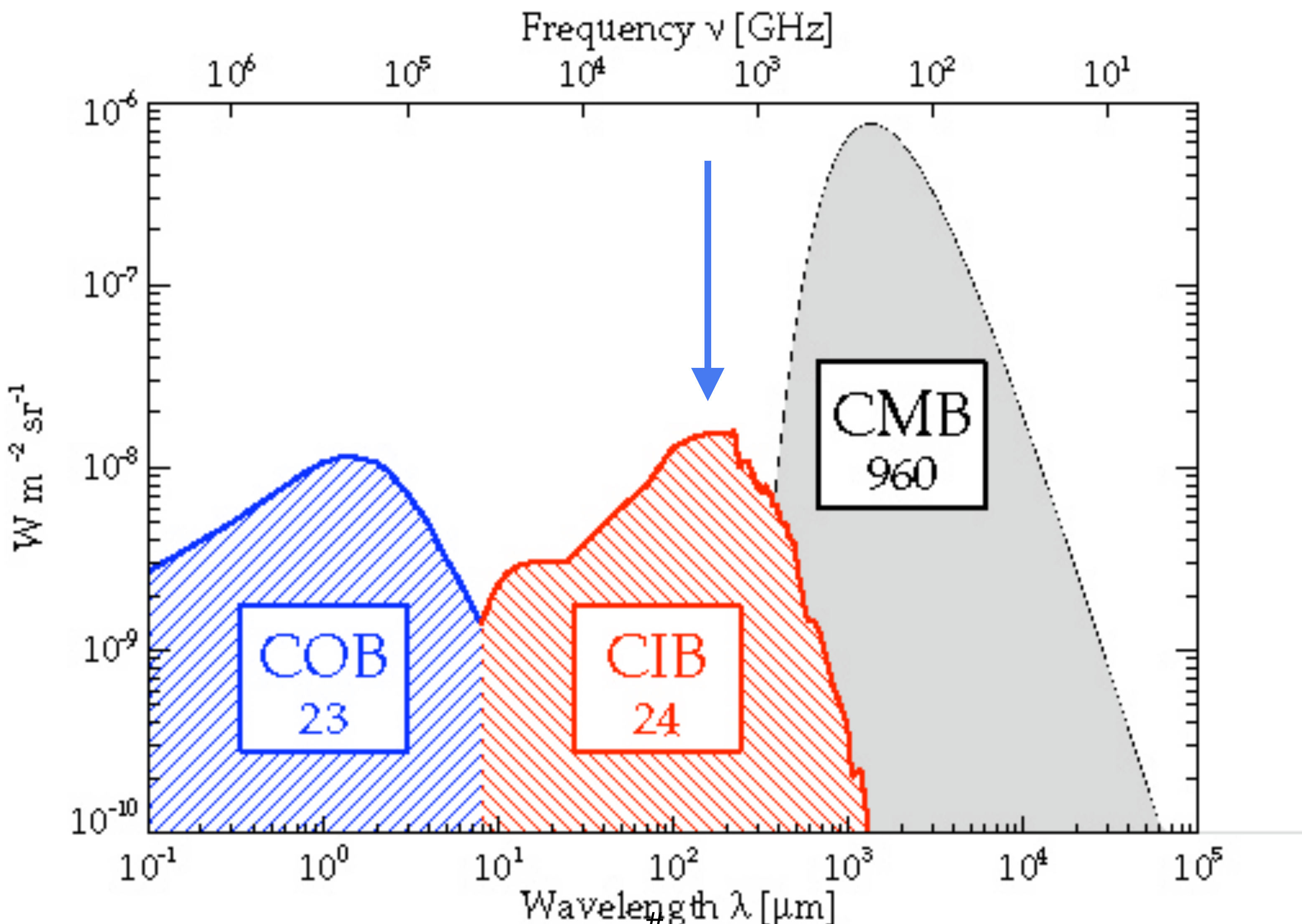


Robert B. Leighton
California Institute of Technology

May, 1978

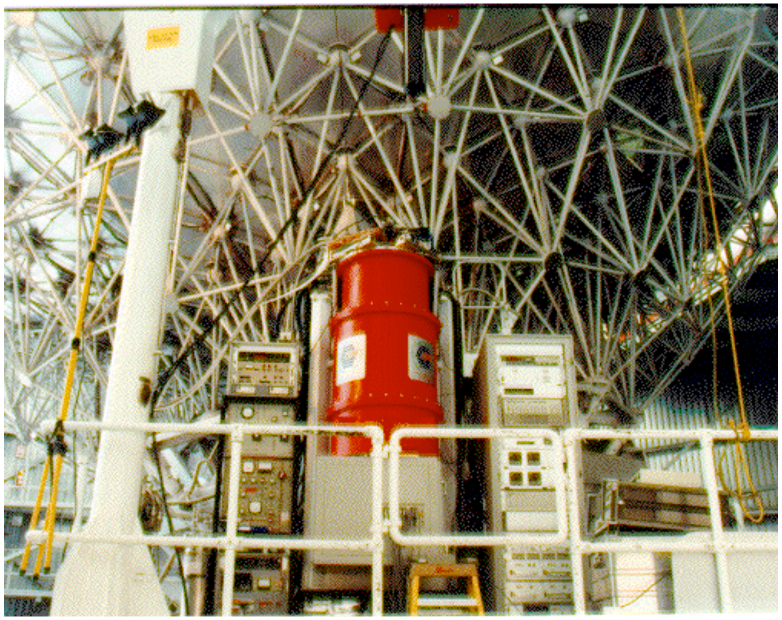
Final technical report for
NSF Grant AST 73#4908

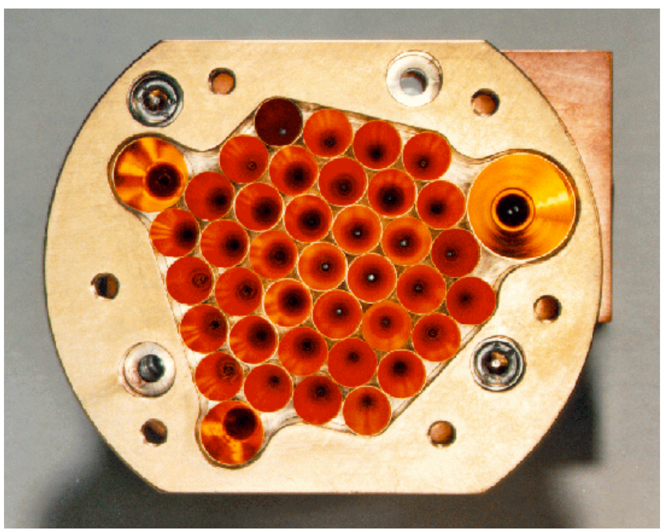
COBE: Sub-mm Background

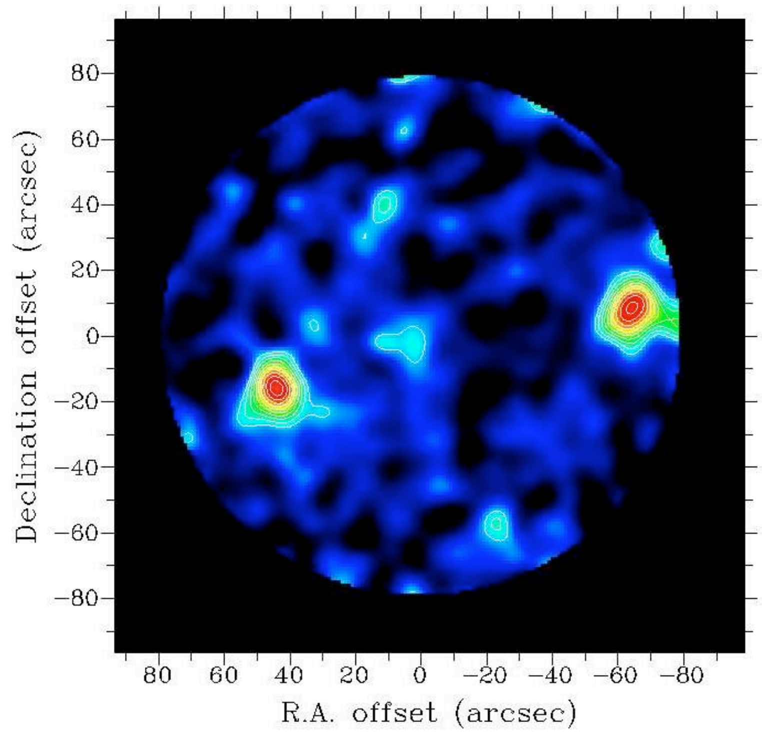


Dole et al. 2006

1997: SCUBA







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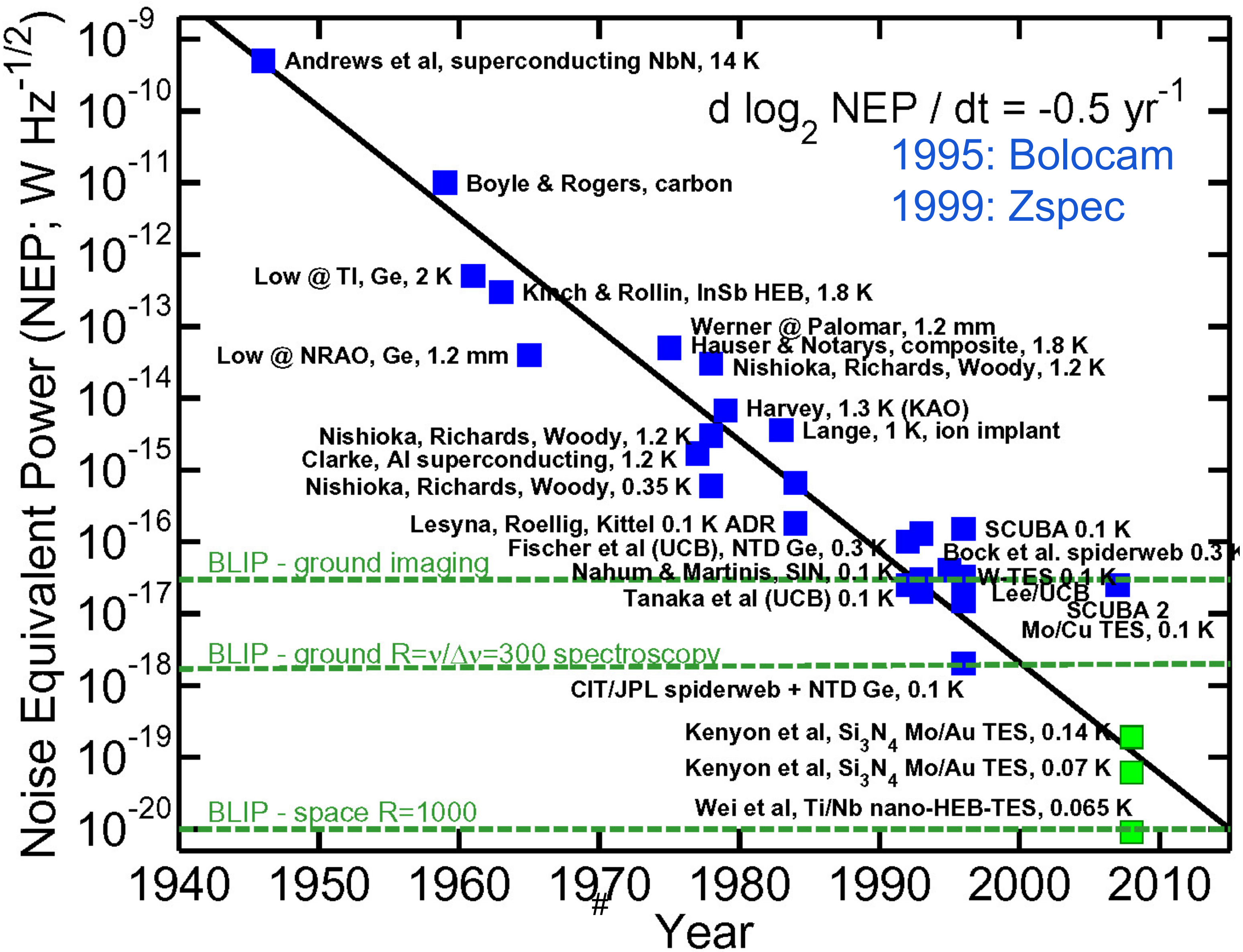
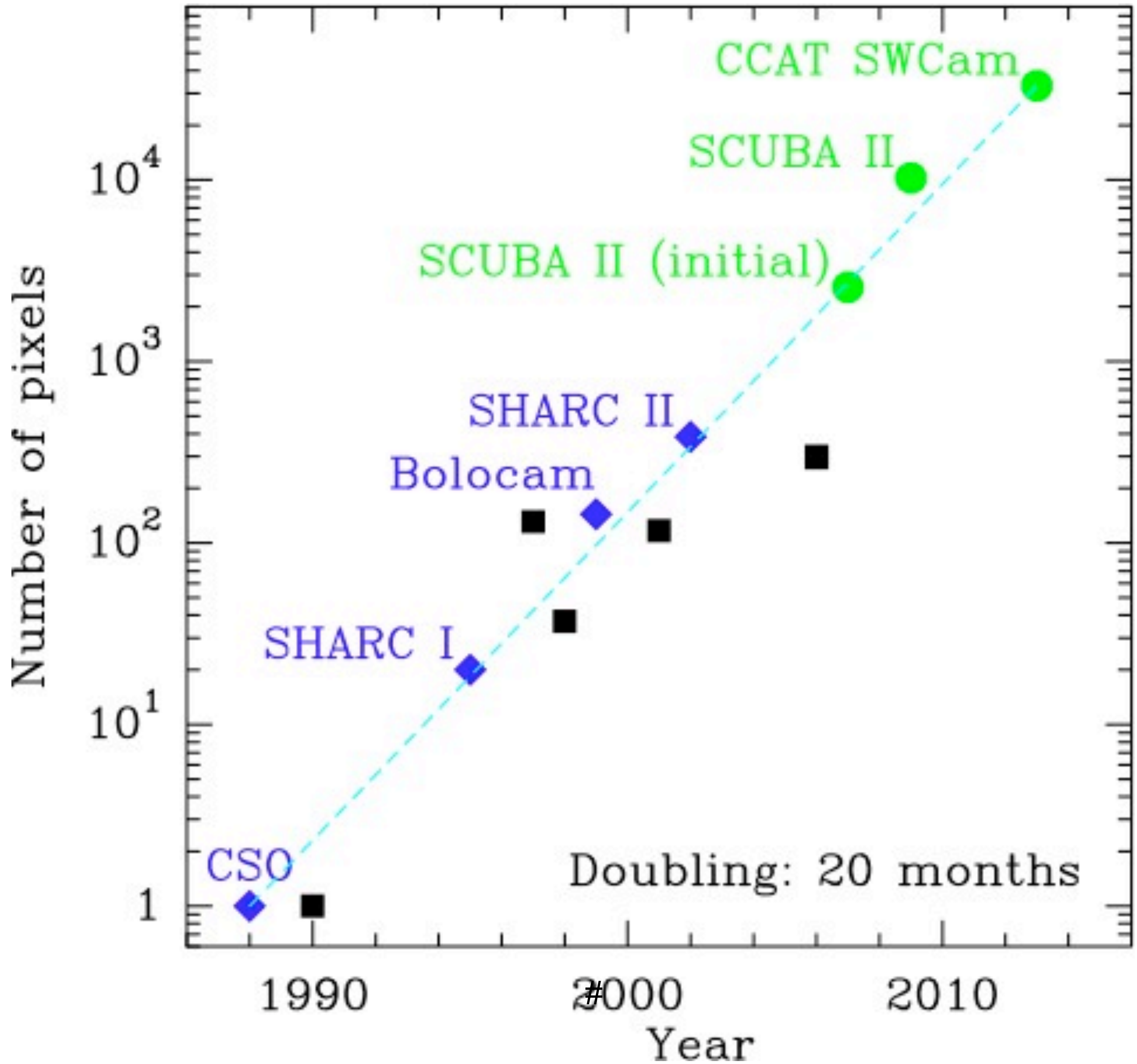
Smail, Chapman, Blain

Bolometer Performance

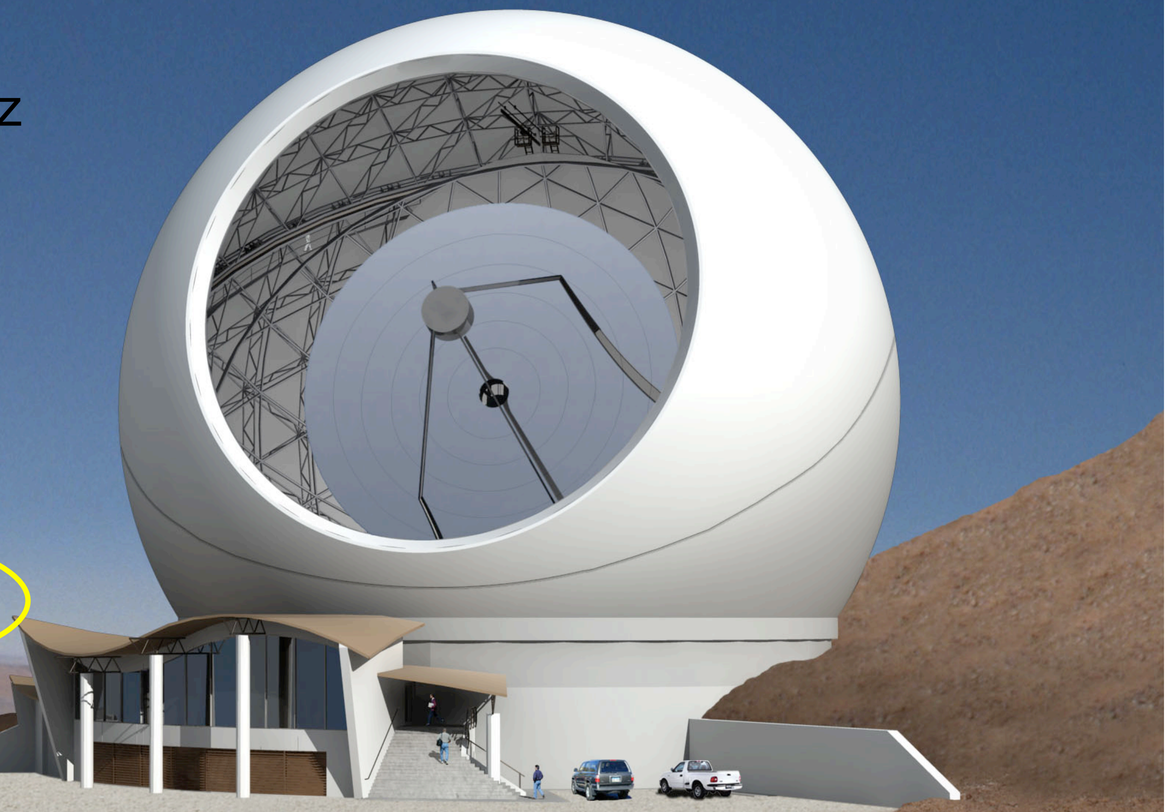


Moore's Law Again



CCAT: a 25-m submillimeter telesope

- Cerro Chajnantor, Atacama, Chile, 5600m
- Wavelengths 2 - 0.2 mm
- Frequencies 150-1500 GHz
- Surface accuracy 10 μm
  - Active surface !
- Angular resolution 2-20”
- Survey instrument:
  - Wide field of view
  - *Large submm cameras*
  - *Spectrometers*



"Vacuums, black holes, anti-matter — it's the elusive and intangible which appeals to me."

Now for something of real use in life