Future Ground-based Interferometry

Peter Lawson
Jet Propulsion Laboratory

Introduction and Overview

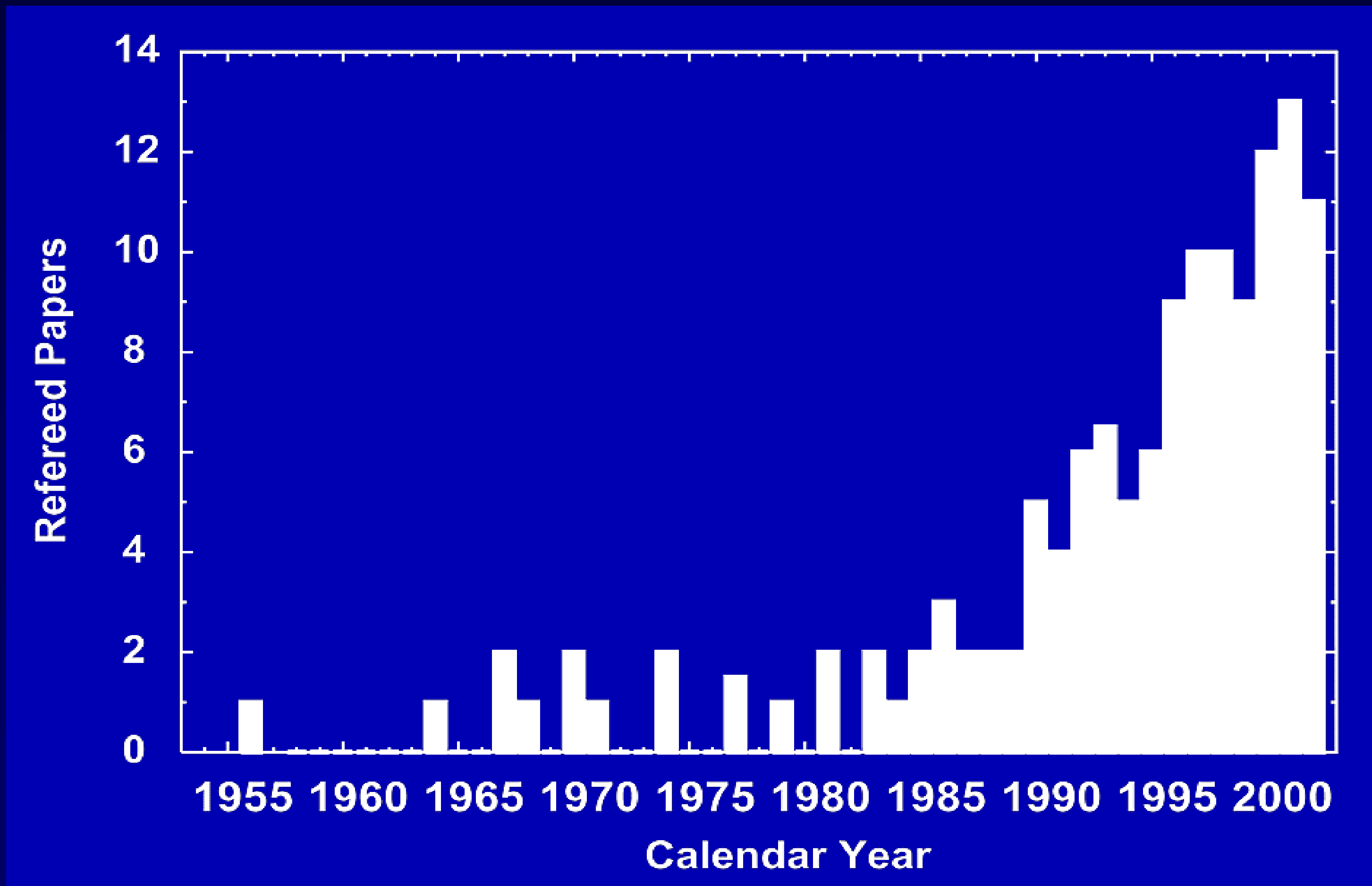
On roadmaps, decadal surveys, and the future of science with ground-based interferometry.

- State of the art
- Near future science programs
- On the design of future facilities

Part I

State of the Art

Refereed Papers in Astrophysics (1955-2002)



Astronomy Papers by Facility

I2T	Mark II	Mark III	GI2T	IRMA	ISI	COAST	NPOI	PTI	IOTA
16.5	1	23	10	4.5	16	5	12	19	15

Totals up until end of 2002 Calendar Year

Refereed Papers by Subject

Stellar Diameter Measurements

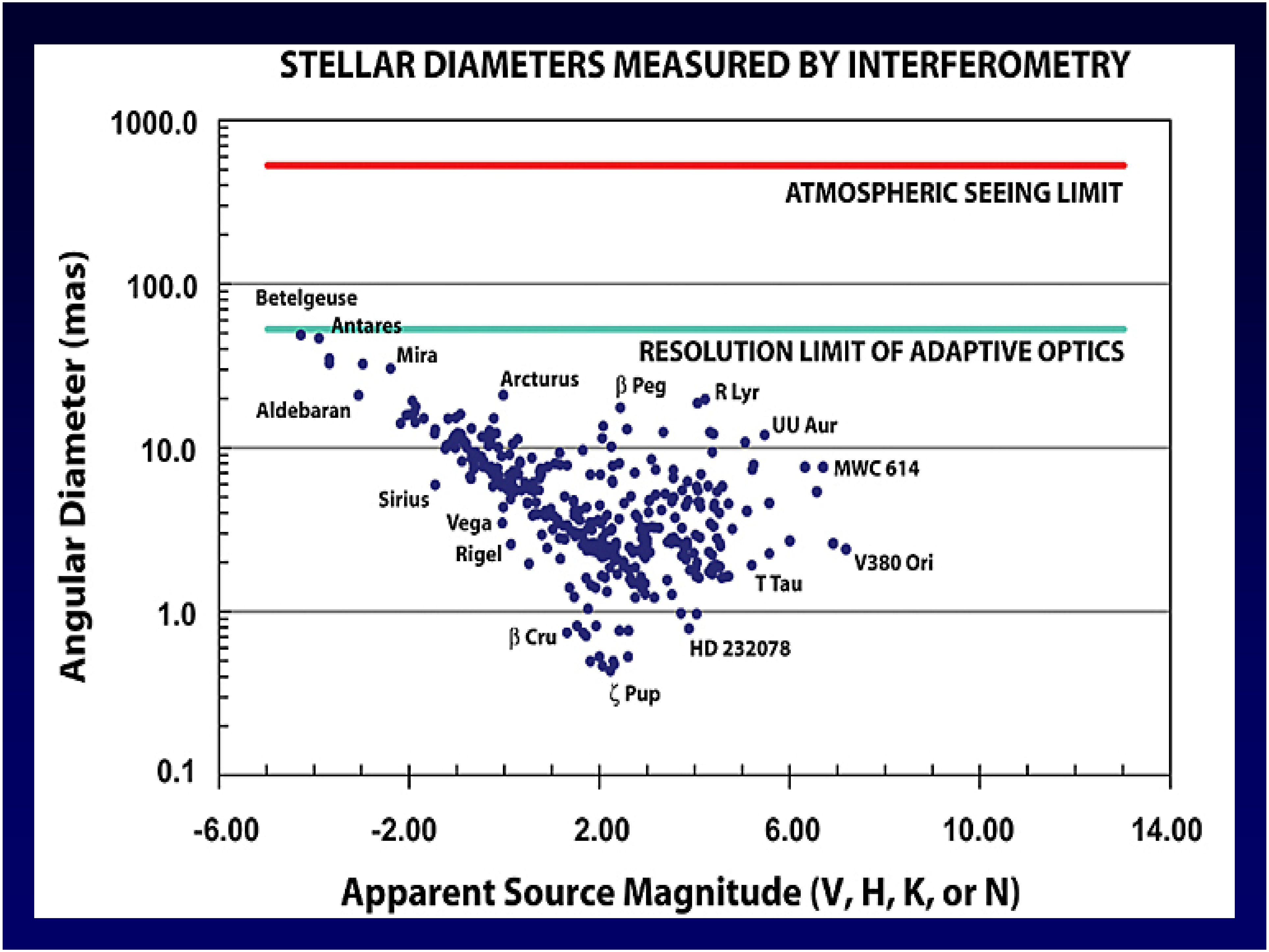
Early Type Stars (O-F)	
Main Sequence	5
Other	7
Late-Type Stars (G-M)	
Main Sequence	1
Giants & Supergiants	23
Carbon and S Stars	3
Various Diameters	6
Dust Shells of Late Type Stars	12
Other Shells	2
Variable Stars: Pulsating	
Cepheid Variables	7
Mira Variables	13
Variable Stars: Rotating	
Wolf-Rayet Stars	1
Be Stars (Envelopes)	12
Variable Stars: Eruptive	
P Cygni	1
Young Stellar Objects	
Herbig Ae/Be Stars	3
T Tauri Stars	2
FU Orionis Stars	1
Stellar Limb darkening	4
Stellar Surface Structure	1
Binary Star Orbits	
Double-lined Spect.	16
Single-lined Spect.	3
Eclipsing Binaries	4
Other Binaries	3
Astrometry	4
Faint Companion Search	1
Nova	1

Stars Measured

Most diameter measurements have been of cool late-type giant stars.

Stellar Diameters Measured

Spectral type	Luminosity class I Supergiants	II	III Giants	IV	V Main Seq.
O	3				1
B	5	1	6	6	6
A	2		1	2	5
F	8	2		2	1
G	5	3	35	4	1
K	10	17	49	2	3
M	13	15	101		8
Totals	**46**	**38**	**192**	**16**	**25**



STELLAR DIAMETERS MEASURED BY INTERFEROMETRY
ATMOSPHERIC SEEING LIMIT
RESOLUTION LIMIT OF ADAPTIVE OPTICS
Angular Diameter (mas)
1000.0
100.0
10.0
1.0
0.1
Betelgeuse
Antares
Mira
Aldebaran
Arcturus
β Peg
R Lyr
UU Aur
MWC 614
Sirius
Vega
Rigel
V380 Ori
T Tau
β Cru
HD 232078
ζ Pup
-6.00
-2.00
2.00
6.00
10.00
14.00
Apparent Source Magnitude (V, H, K, or N)

Current Trends

- Longer baselines (~1 mas resolution)
- Multiple telescopes used simultaneously
- Increased emphasis on imaging
- Observing in the infrared: J, H, K, L’, N
- Larger apertures and adaptive optics
- Better quality sites (shared facilities)

Part II

Near Future Science Programs

Future Science: Stars

- Cepheid variables
- Stellar rotation across the H-R diagram
- Envelopes of Be stars
- Winds from hot stars
- Evolved stars
  - AGB dust shells
  - Miras
  - Symbiotic stars
  - Envelopes of S stars
  - Survey of Wolf-Rayets
- Post AGB stars
  - R Corona Borealis stars

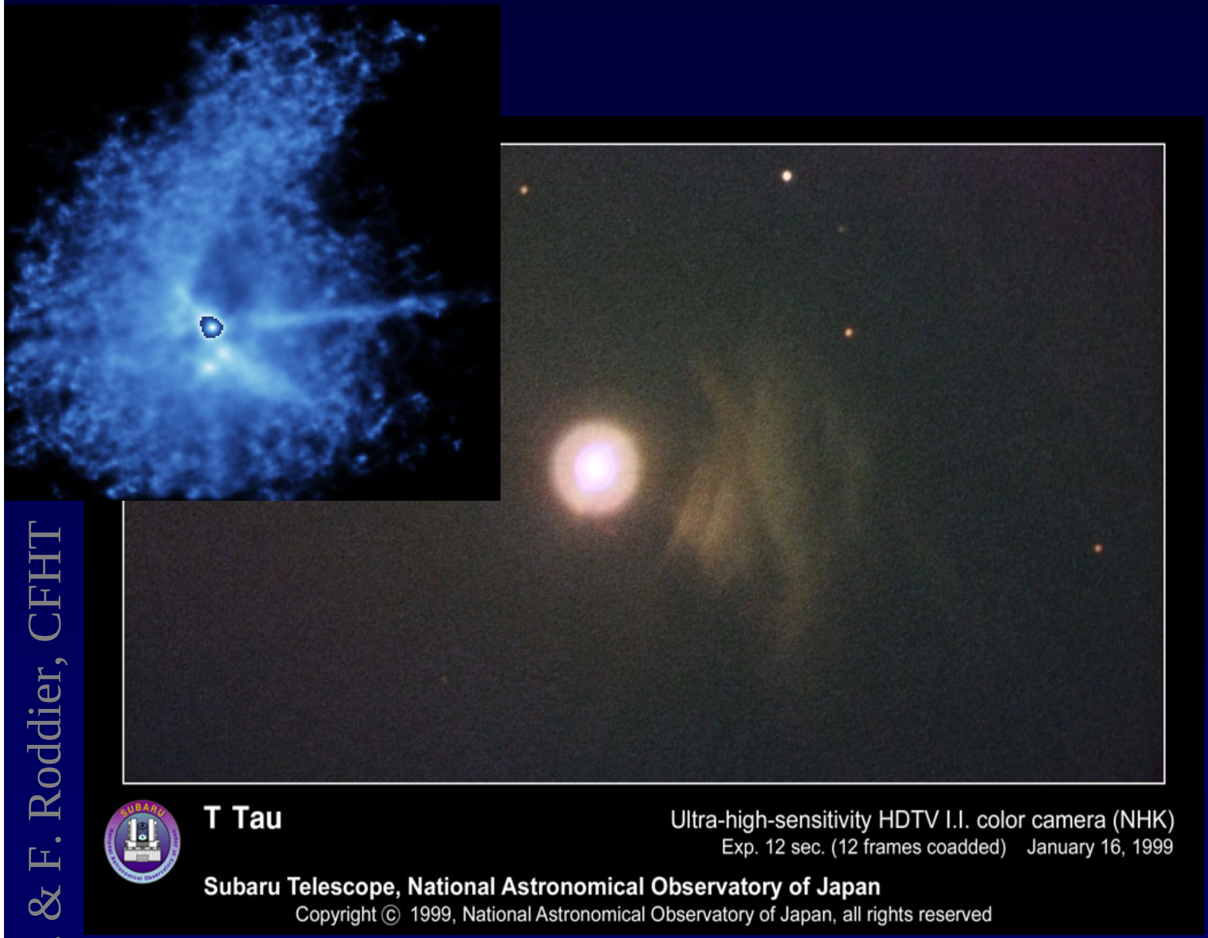
Spectroscopic Binaries

Resolvable SB2s

Separation (mas)	All Magnitudes	$m_V < 11$	$m_V < 9$	$m_V < 7$	$m_V < 5$
0	505	441	351	232	58
0.050	443	419	342	228	58
0.1	408	390	329	222	58
0.2	359	345	292	210	57
1.0	185	175	149	122	41
10	55	53	47	37	21

"The CHARA Catalog of Orbital Elements of Spectroscopic Binary Stars," S.F. Taylor, J.A. Harvin, and H.A. McAlister, *PASP* **115**, 609-617 (2003)

Young Stellar Objects



C. & F. Roddier, CFHT

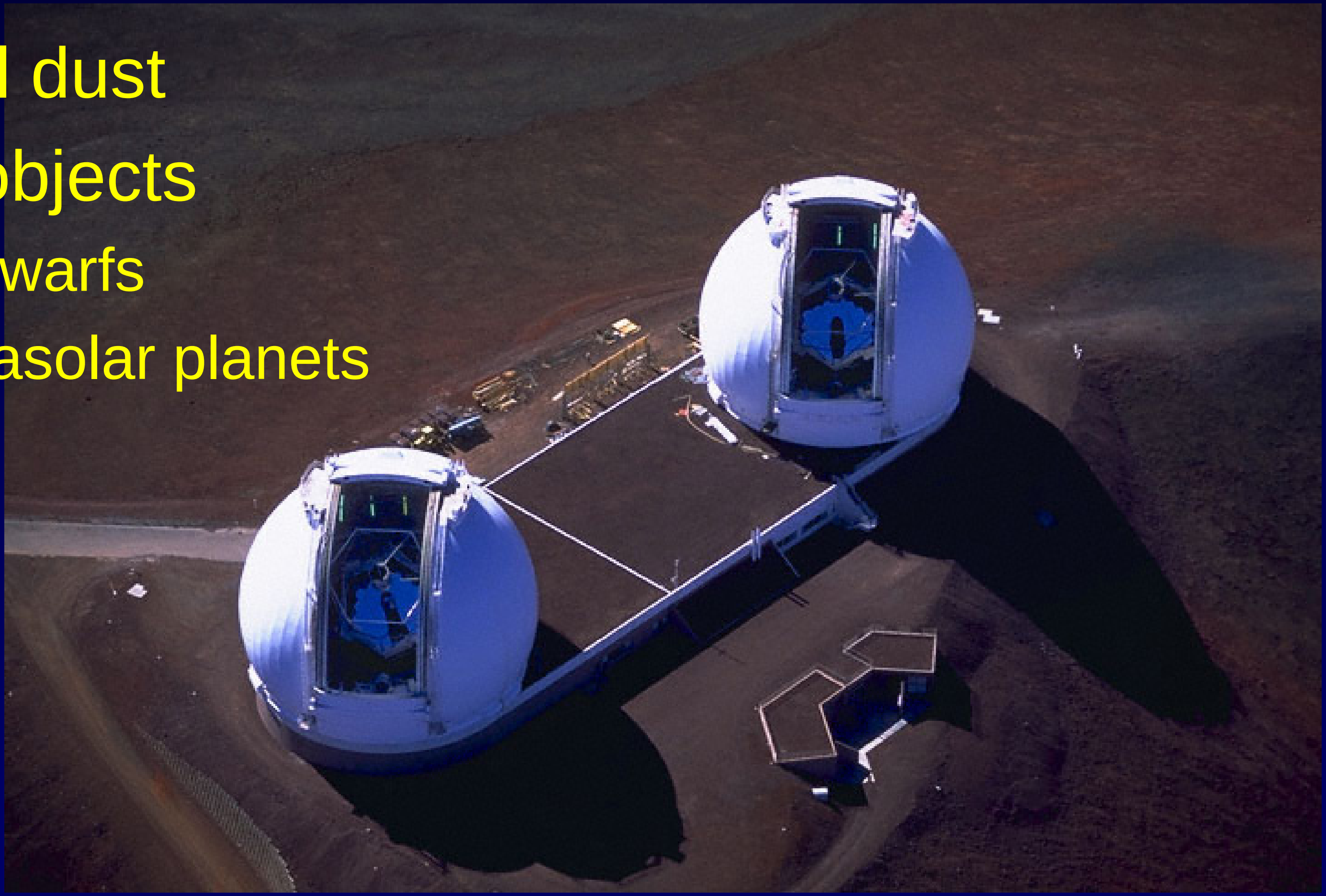
Intermediate mass
- Herbig Ae/Be Stars

Low mass
- T Tauri, FU Ori, GG Tau, HL Tau

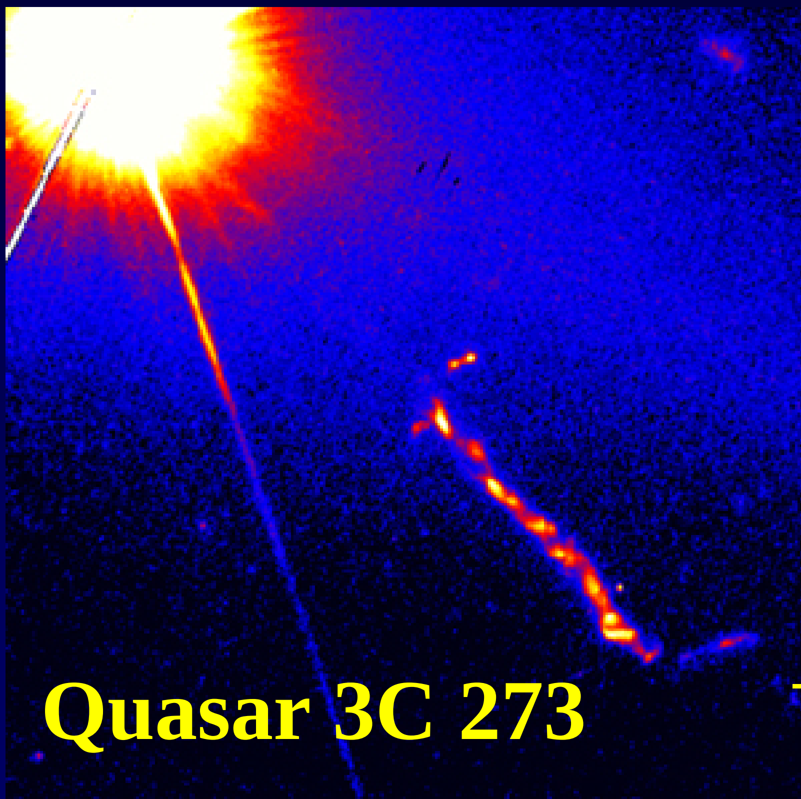
Jets around YSOs

Planet Finding

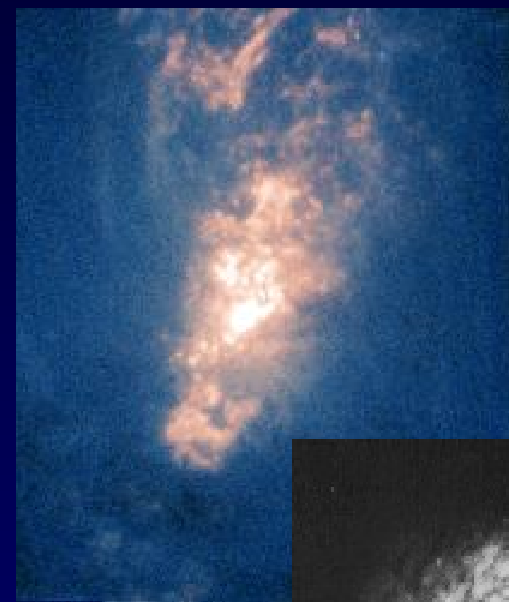
- Exozodiacal dust
- Low-mass objects
  - Brown dwarfs
  - Hot extrasolar planets



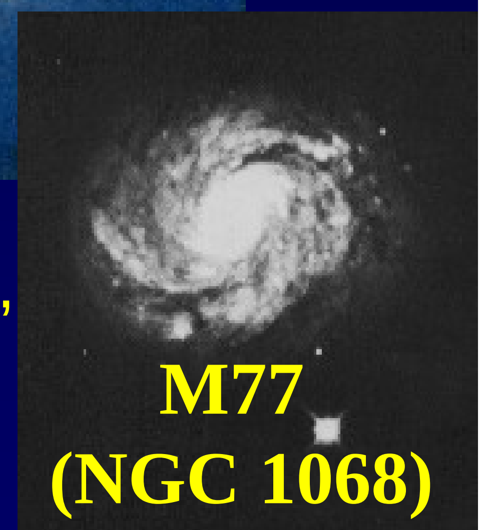
Galaxies and AGNs



NASA/STScI

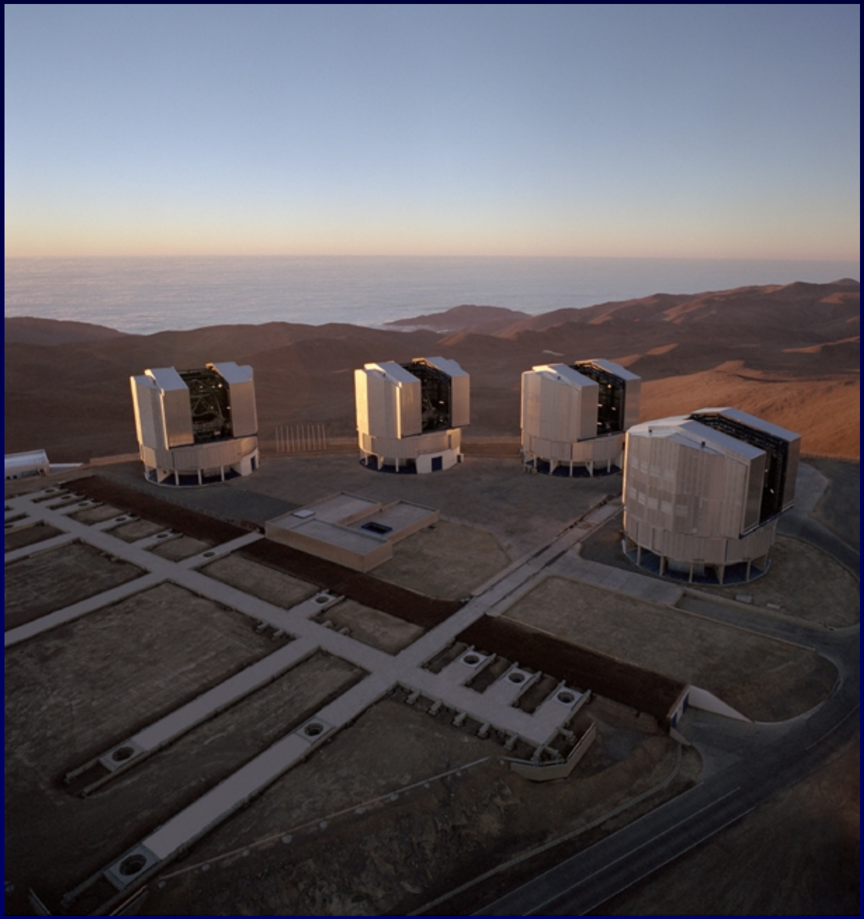


HST/COSTAR



– NGC 1068, 3C 273, M87. Dust disks…

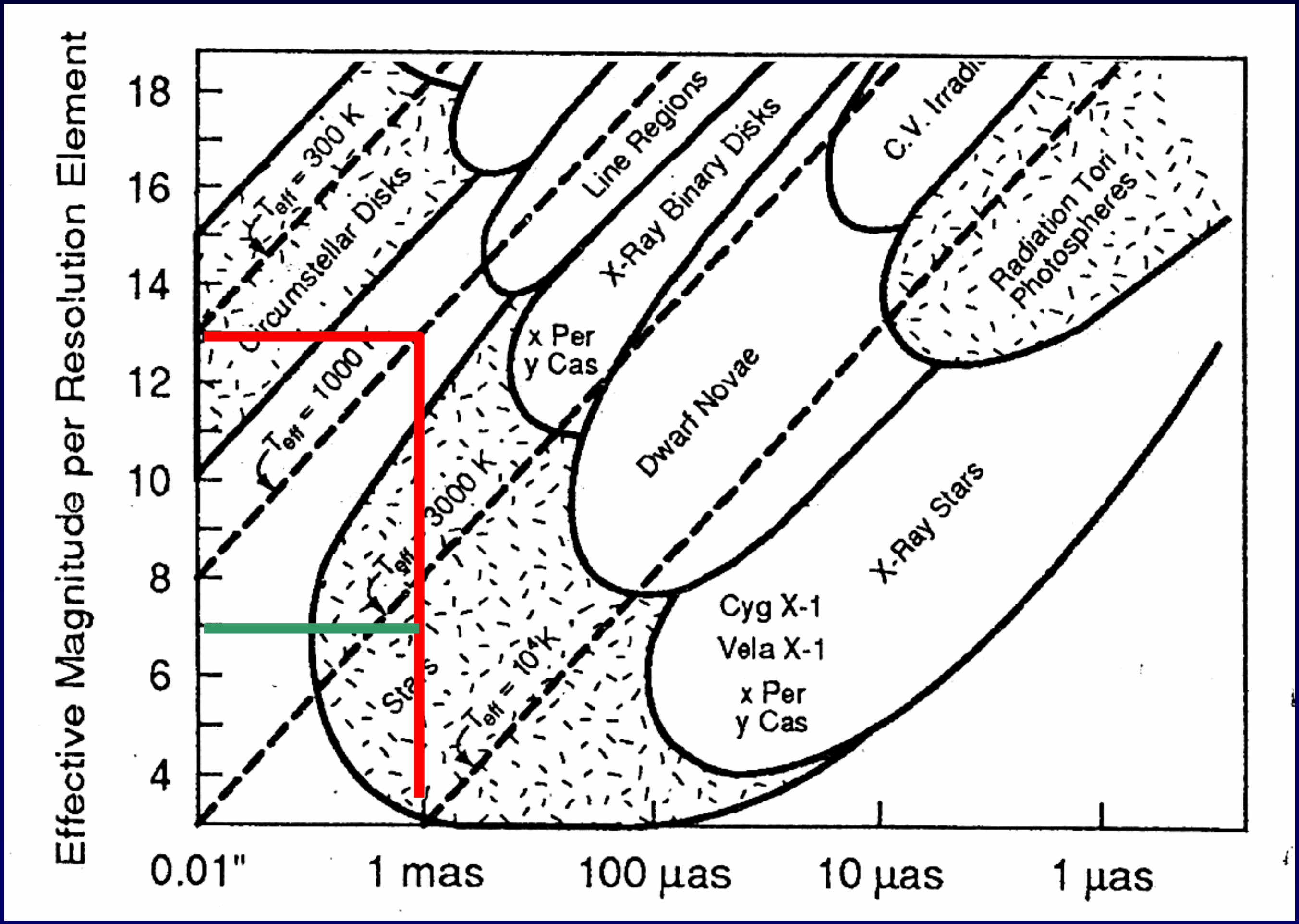
Extragalactic Science



- Circumstellar environment of the white dwarf AE Aqu
- Planetary nebulae
- Galactic X-Ray binaries

Resolution and Sensitivity

From Begelman & Krolik 1991, reproduced in "Kilometric Baseline Space Interferometry" ESA SCI (96) 7.

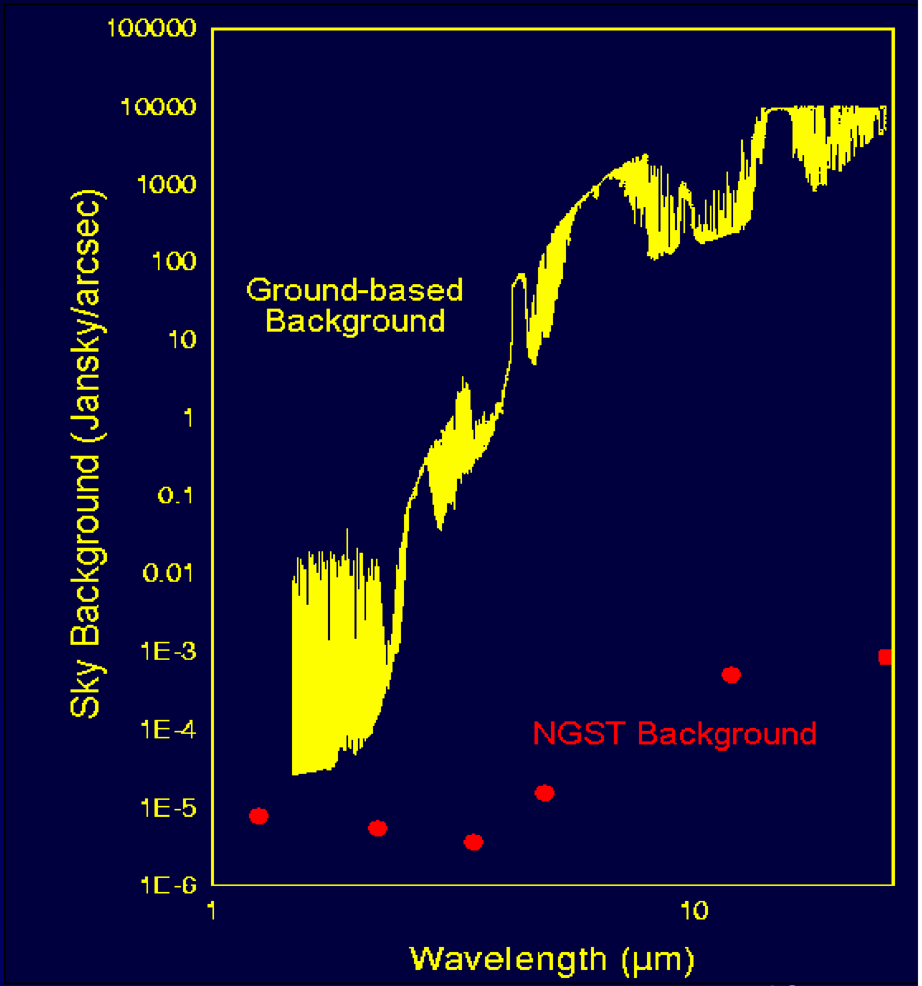


Part III

On the Design of Future Facilities and Science Programs

Ground vs Space

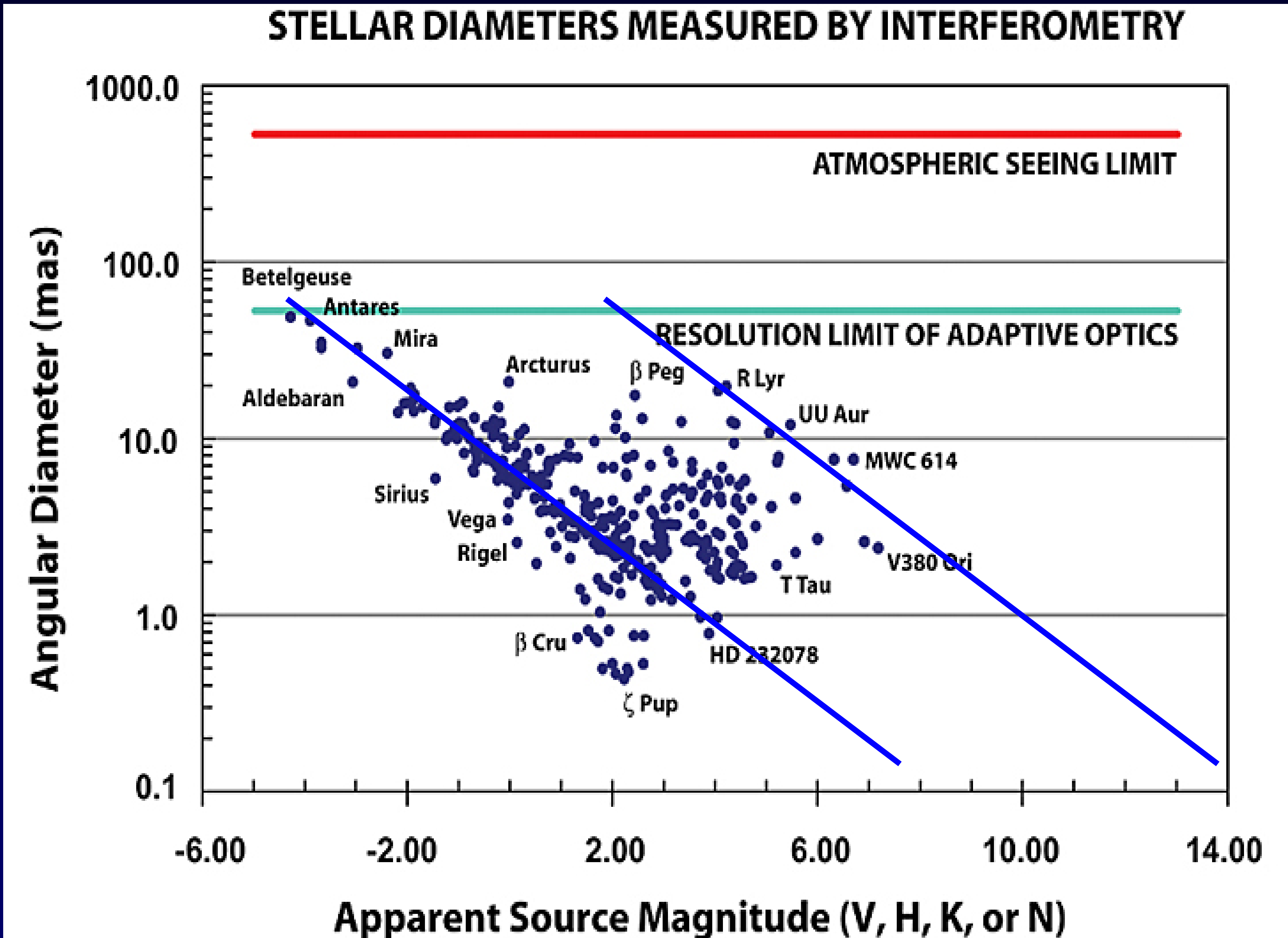
– Above-atmosphere, access to the whole IR spectrum
– Cooled telescopes give low backgrounds, limited by zodiacal emission
– Telescope apertures restricted by rocket payloads



Slide Courtesy of Pat Roche (Oxford Univ.)

Is There a Limiting Magnitude?

- Tip-tilt performance
- Adaptive optics
- Phase referencing


STELLAR DIAMETERS MEASURED BY INTERFEROMETRY
ATMOSPHERIC SEEING LIMIT
RESOLUTION LIMIT OF ADAPTIVE OPTICS
Angular Diameter (mas)
1000.0
100.0
10.0
1.0
0.1
Betelgeuse
Antares
Mira
Aldebaran
Arcturus
β Peg
R Lyr
UU Aur
MWC 614
Sirius
Vega
Rigel
V380 Ori
T Tau
β Cru
HD 232078
ζ Pup
-6.00
-2.00
2.00
6.00
10.00
14.00
Apparent Source Magnitude (V, H, K, or N)

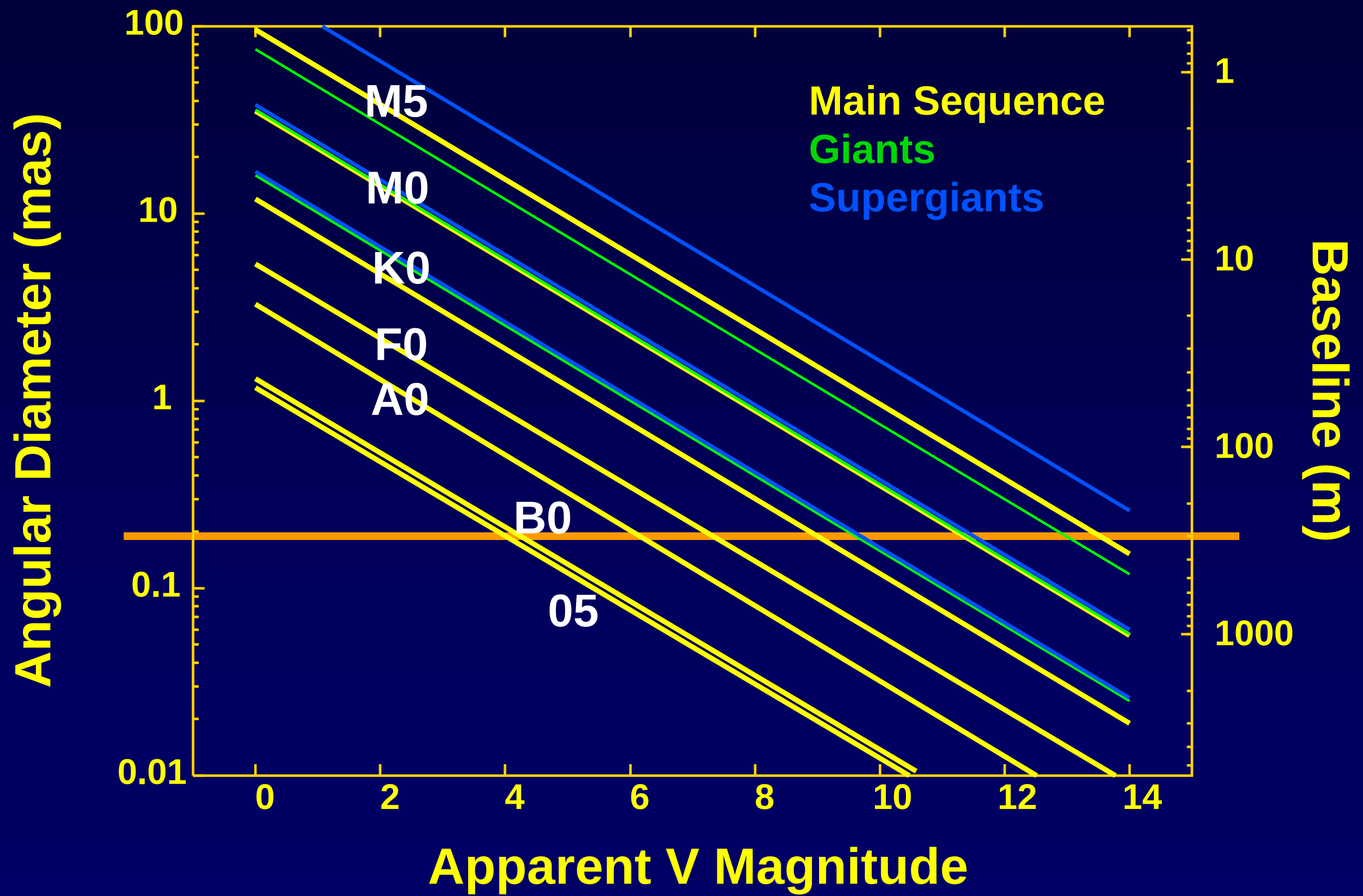
Future Facility Described

- International or national facility
- Dedicated (not multi-purpose)
- Snap-shot imaging capability (48 hrs)
- Infrared wavebands (J, H, K)
- Tip/tilt and low-order adaptive optics
- Limiting magnitude of about 14
- Baselines of 1000 to 2000 m
- Comparable in cost to a space mission

A Future Facility for your Science Program

- Choose your science program
- Pick a number, any number… 150 targets?
- How small and how faint is the 150th object?
- Design your interferometer!
- Is your program science or science fiction?

Angular Resolution



Sensitivity
How much glass do you need?

- Atmospheric windows
- Aperture Size
- Seeing Conditions
  - Coherence time

- Thermal Background fluctuations
- See talk by Millan-Gabet (2002).

Potential Targets for Infrared Interferometry

Source Type	Typical Distance	Resolved	Partially Resolved
Asteroid	2 AU	200 m	20 m
M dwarf	5 pc	0.5 R	0.05 R
Evolved star	100 pc	0.02 R	0.002 R
YSO	400 pc	0.04 AU	0.004 R
Recurrent Nova	2 kpc	0.4 AU	0.04 AU
Relativistic disk	5 kpc	1 AU	0.1 AU
Local group galaxy	16 kpc	3.2 AU	0.3 AU
M81 group	3.4 Mpc	0.003 pc	6 AU
Seyfert, BL Lac	10 Mpc	0.01 pc	18 AU
Virgo cluster	19 Mpc	0.02 pc	0.002 pc
Quasar	1500 Mpc	1.4 pc	0.14 pc

Going Forward

- How much will it cost?
- Who will pay for it?
- Where would it be built?

What makes a good infrared observing site?

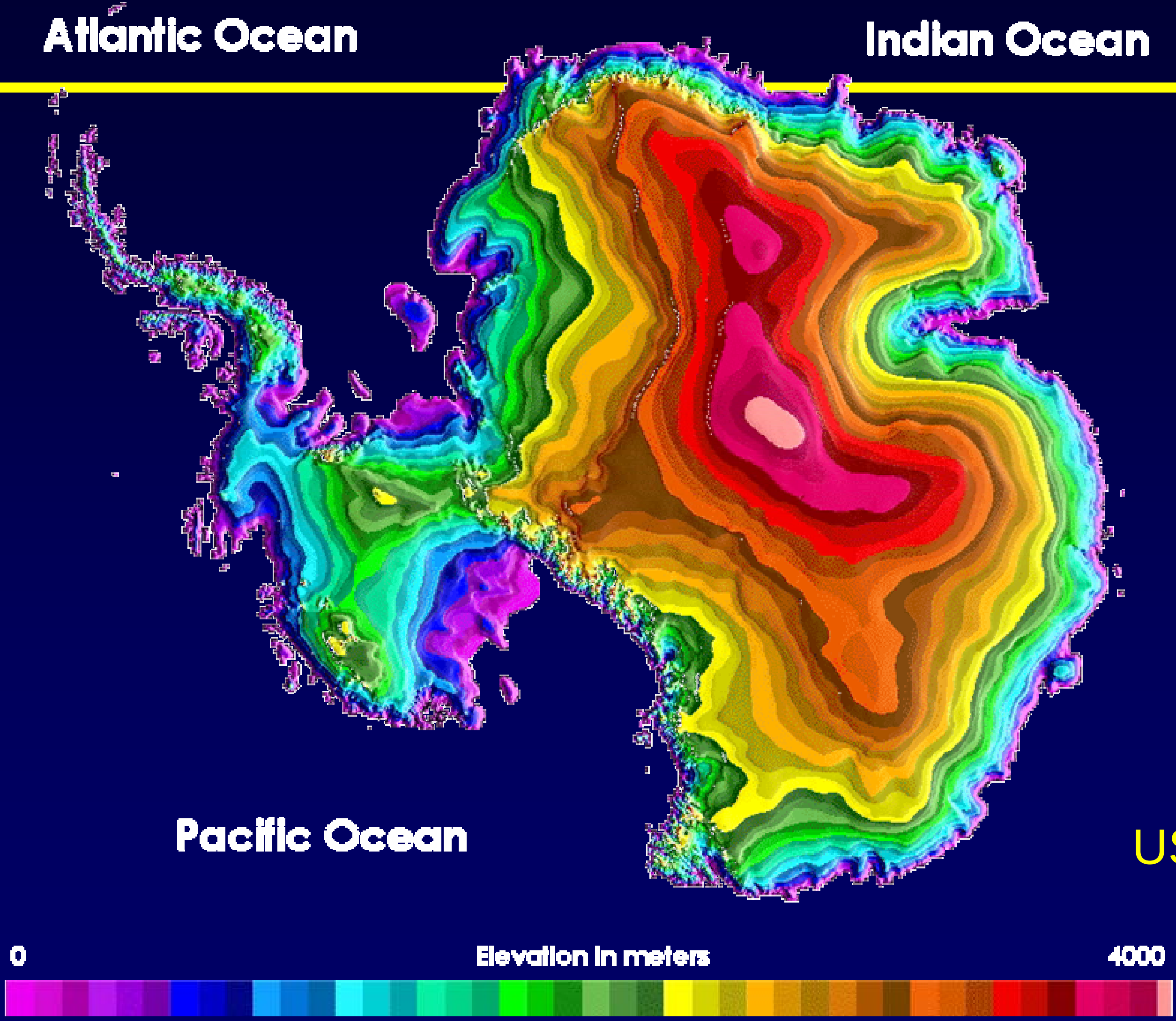
- Cloud-free
- High
- Dry
- Cold
- Dark
- Low integrated turbulence
- Low high-altitude turbulence
- Low wind
- Accessible

Slide Courtesy of John Storey (Univ. New South Wales)

Cerro Chajnantor, Chile

Antarctic Plateau

Dome A



USGS image

Further Reading

- S.T. Ridgway, “Future Ground-based interferometry,” Chapter 18 in *Principles of Long Baseline Stellar Interferometry*, JPL Publication 00-009 (2000).
- J.E. Baldwin, “Ground-based interferometry: the past decade and the one to come,” in *Interferometry for Optical Astronomy II*, Proc. SPIE 4838, 1-8 (2002).
- J. Davis, “Measuring stars with high angular resolution: current status and future prospects,” in *Calibration of Fundamental Stellar Quantities*, D.S. Hayes et al. eds., 193-208 (1985).

Further Reading (cont.)

- G.W. van Citters, "The Future of Optical/IR Interferometry: The View from NSF," in *Working on the Fringe: Optical and IR Interferometry from Ground and Space* , S. Unwin and R. Stachnik eds., ASP Conf. Series **194,** 448-459 (1999).
- D.F. Buscher, "Interferometric fitness and the Large Optical Array," in *Interferometry for Optical Astronomy II*, Proc. SPIE 4838, 119-125 (2002).
- *Report of the Workshop on Imaging with Ground-based Optical Interferometers,* June 13/14, 2000. T. Cornwell and H.A. McAlister, eds. http://olbin.jpl.nasa.gov/papers/Report1.0.PDF

Acknowledgments

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Backup Slides

Towards the 2010 Decadal Survey

Draft a detailed list of tasks and identify individuals or groups willing to undertake the work.

Work towards having all necessary tasks completed in time to influence the next Decadal Survey - well before 2008 or 2009.

Towards the 2010 Decadal Survey (continued)

- Detail the science case for the facility
  - Beyond VLTI, Keck, CHARA, and NPOI.
  - For each class of science target
    - Specify the number of objects attainable
    - Catalog the list of the targets and their known properties
- Identify suitable sites.

Towards the 2010 Decadal Survey (continued)

- Begin the dialog with funding agencies, partners, and developers of potential sites.
- Identify the funding wedge - after OWL or CELT?
- Fund a preliminary design and cost study.
- Fund optical/infrared site testing.
- Publish in refereed literature all material related to this work.

Large Binocular Telescope Interferometer

Magdalena Ridge Observatory