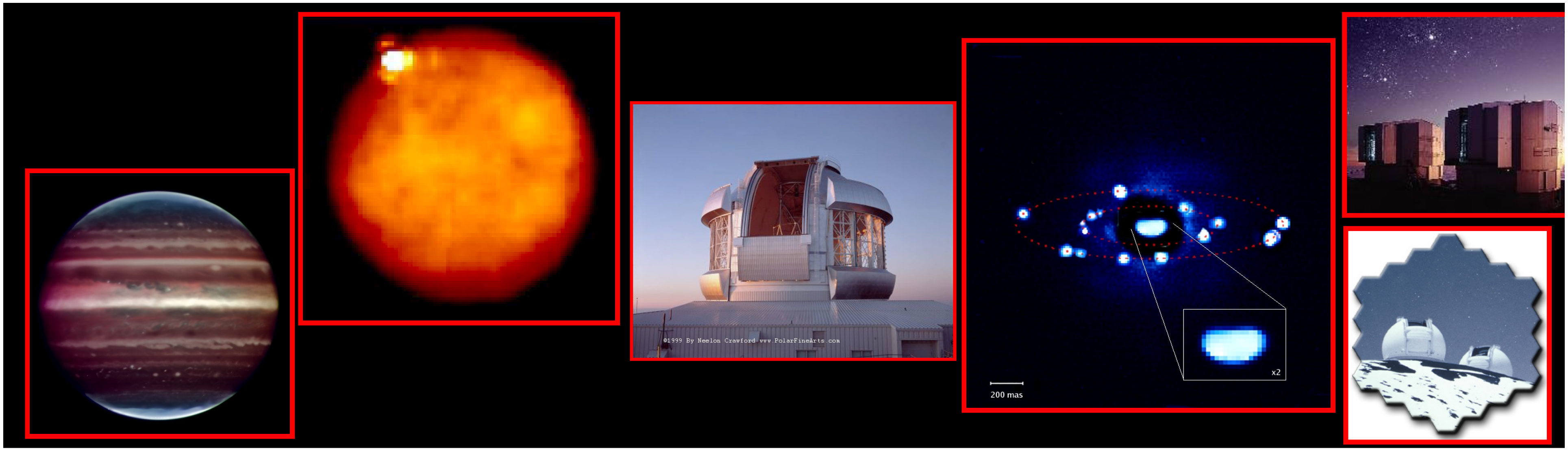
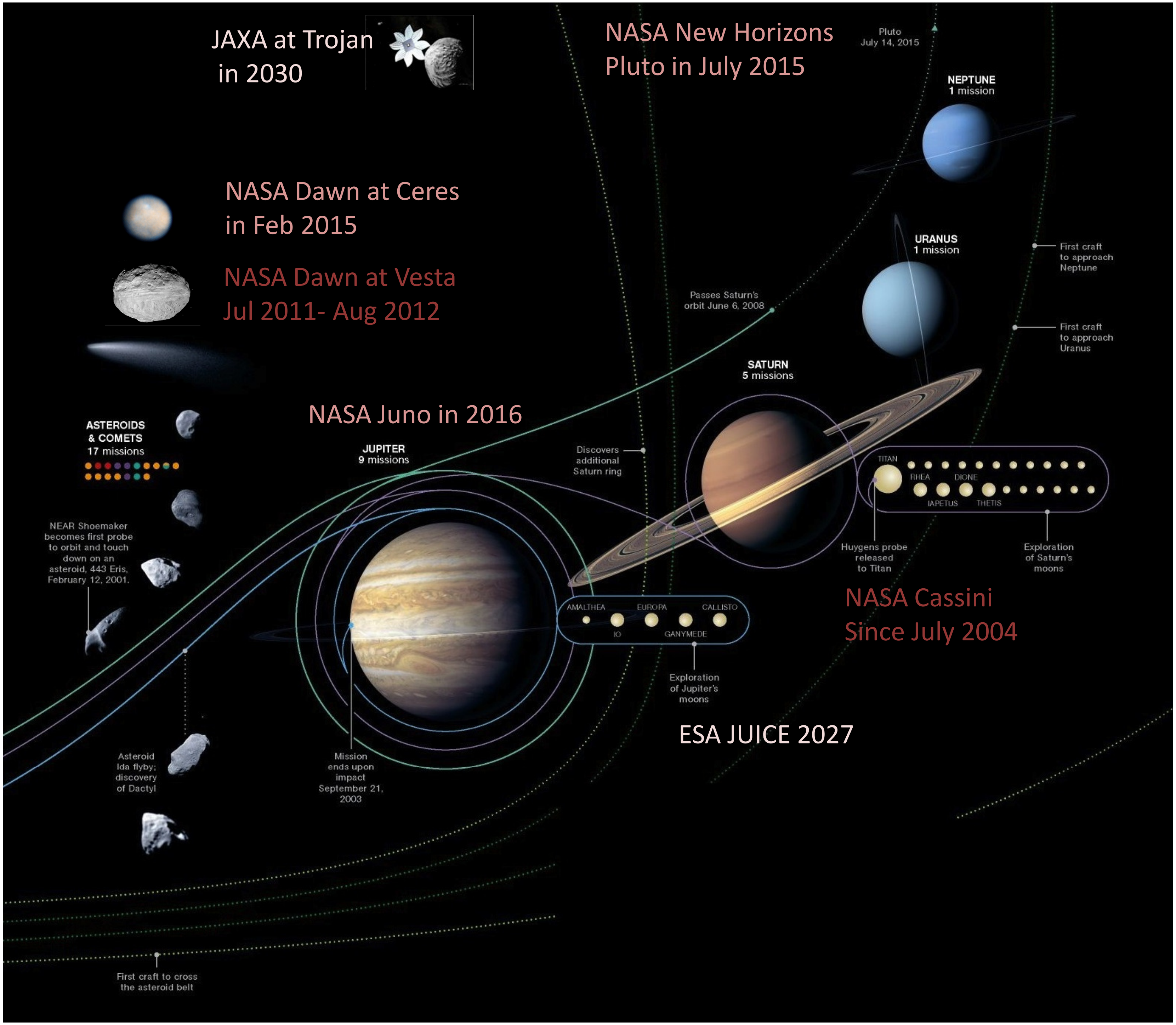


Potential of Present & Future AO Systems for Planetary Sciences

F. Marchis (SETI Institute)

June 20 2012, GNAO Science Workshop, Victoria, BC

52 Years of Space Missions
Outer Solar System



JAXA at Trojan in 2030

NASA New Horizons Pluto in July 2015

NASA Dawn at Ceres in Feb 2015

NASA Dawn at Vesta Jul 2011- Aug 2012

NASA Juno in 2016

NASA Cassini Since July 2004

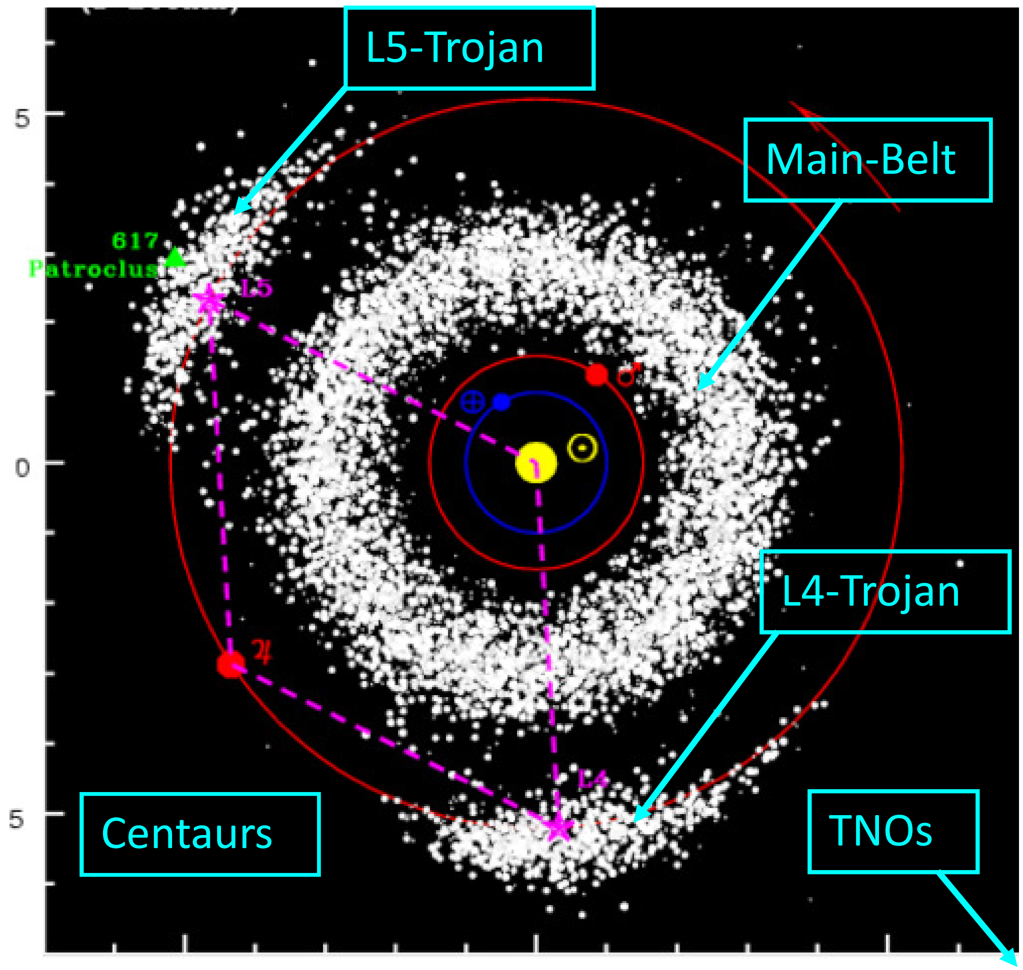
ESA JUICE 2027

Outline

- 3 science cases
  - Small Solar System Bodies, Observability, Size & Shape, Comparative Spectroscopy
  - Satellites of Giant Planets, e.g. Io
  - Jupiter Atmosphere, challenging observation, MAD
- Future Gemini North AO
  - Instruments
  - AO requirements

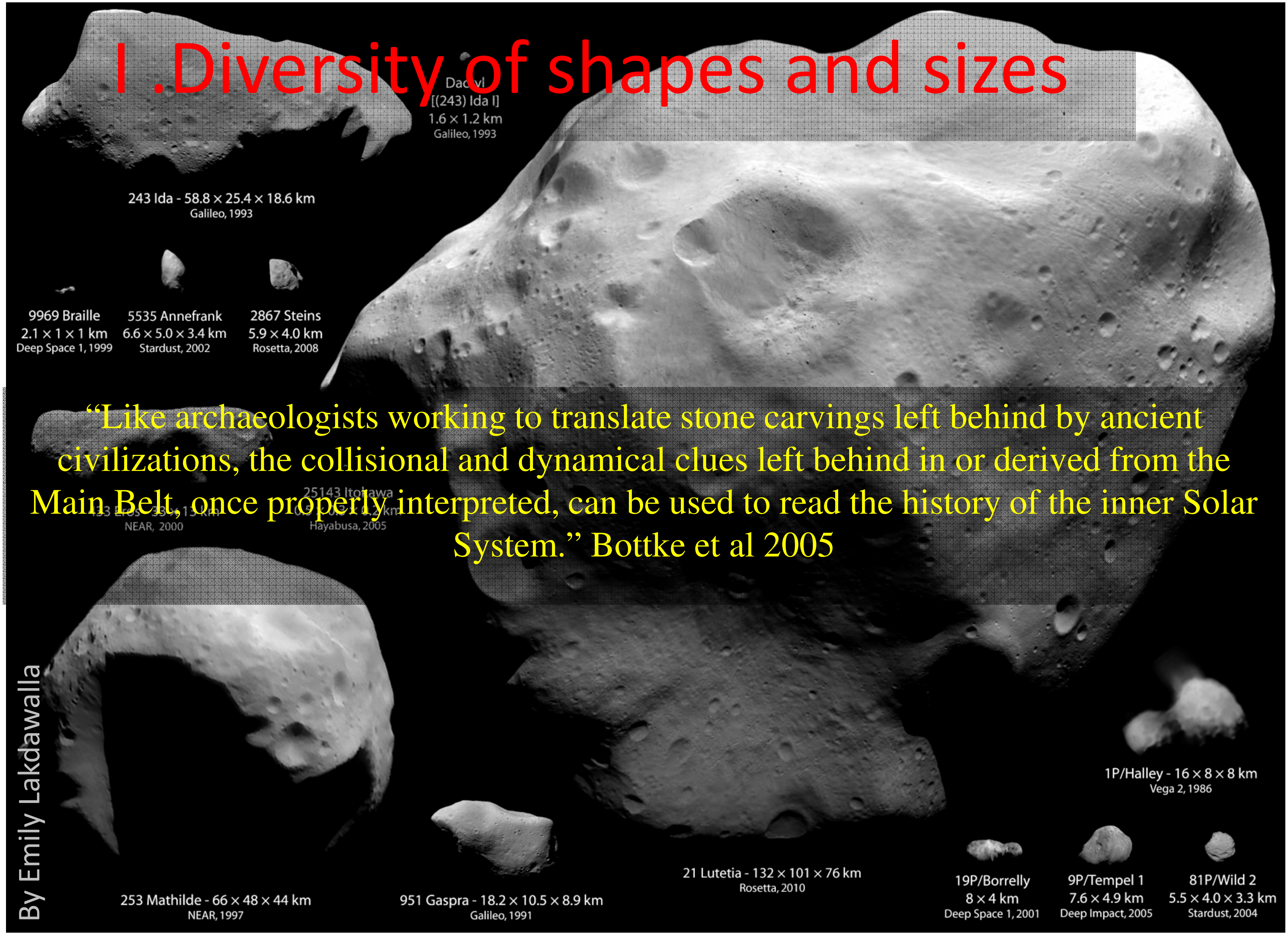
Case I - Small Solar System Bodies

- Building blocks of the Solar System linked to its formation
- 586,571 known minor planets (a.k.a. with a characterized orbit) on June 19 2012
- Small apparent size (largest is 1 Ceres, D_{app}=0.7arcsec -> “seeing” limit)

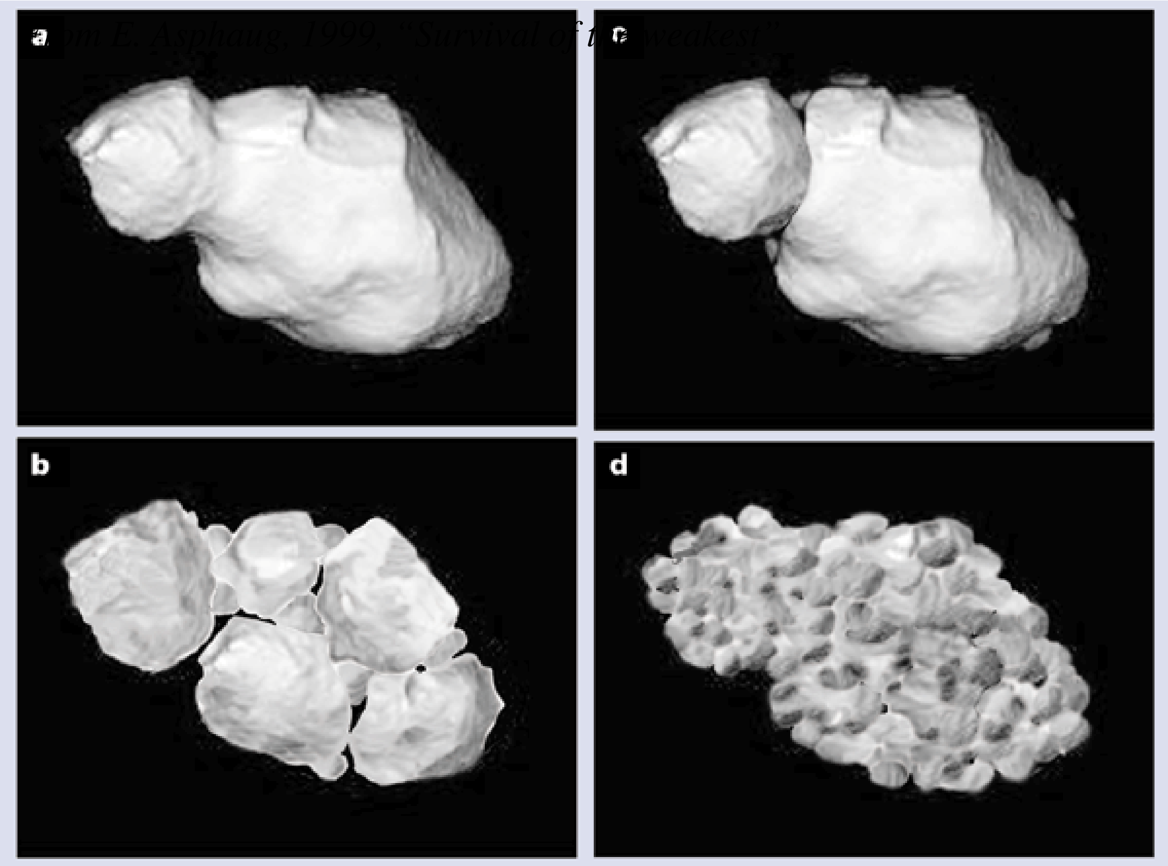


I .Diversity of shapes and sizes

"Like archaeologists working to translate stone carvings left behind by ancient civilizations, the collisional and dynamical clues left behind in or derived from the Main Belt, once properly interpreted, can be used to read the history of the inner Solar System." Bottke et al 2005



I. Internal Structure & Composition



From E. Asphaug, 1999, "Survival of the weakest"

(a) Shape of NEA called Toutatis observed with radar

Internal structure?

(b) Monolith
(c) Contact Binary
(d) Rubble Pile

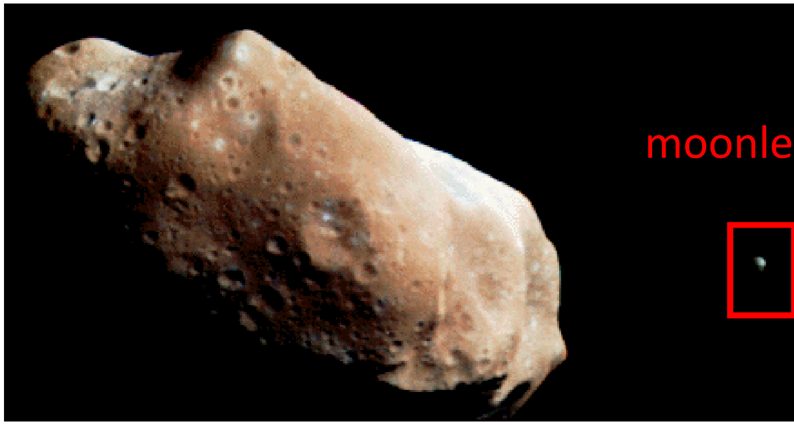
(e) Differentiated (Vesta, Lutetia)

(not shown here) D>50-100 km

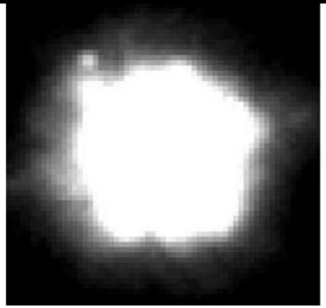
- **Internal structure** & **density** (thus composition) of asteroids is <u>unknown</u>
- They influence:
  - The evolution of an asteroid (orbit, spin, shape, multiplicity)
  - The result of an impact (fragmentation, crater shape, size distribution)
  - The alteration of the surface due to space environment

I. Multiple Asteroids
A Family Portrait

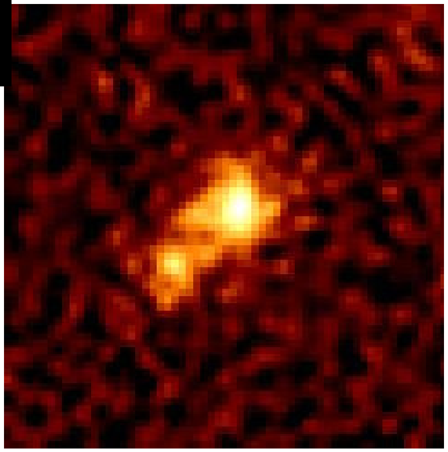
MB Ida and Dactyl (Galileo 1993)

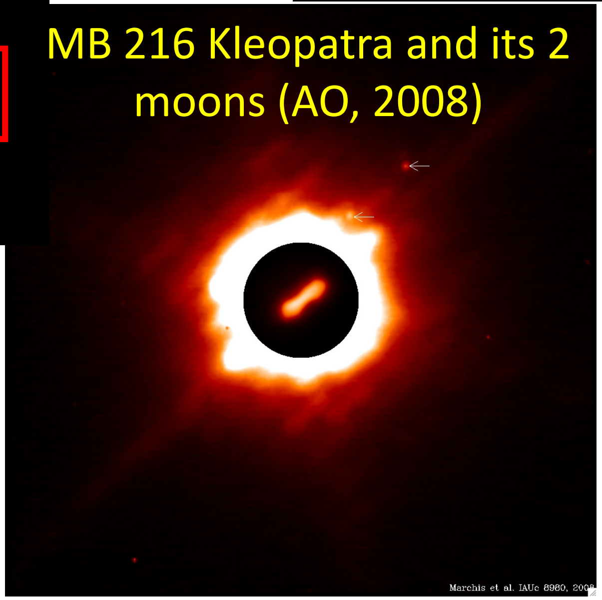


MB 45 Eugenia &
Petit-Prince
(AO, 1998)



TNO 1998WW31
(Classical, 2000)

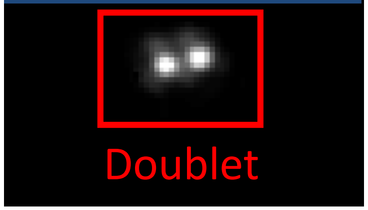




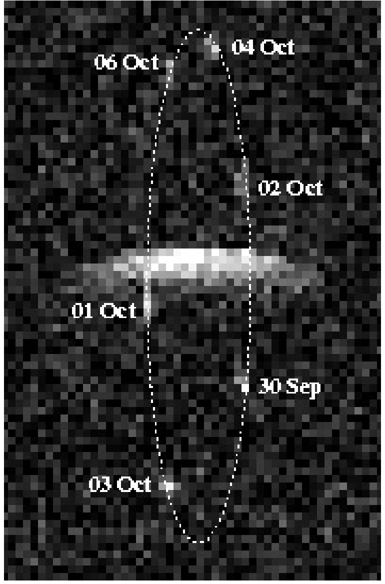
MB 216 Kleopatra and its 2 moons (AO, 2008)

Marchis et al. IAUc 8980, 2008

MB 90 Antiope
(AO, 2001)



NEA 2000DP107
(2002, radar)



~200 are known (all populations of SSSBs: MBAs, NEA, Trojans, TNOs)

~80 can be visualized with AO , HST, or Radar

~25 observable with current NGS (d>0.3", Dm<5 mag), ~20 with LGS on 8-10m class telescopes (d>0.3", Dm<4 mag)

➔ Mass, Density➔Collisional History ➔Formation of Solar System

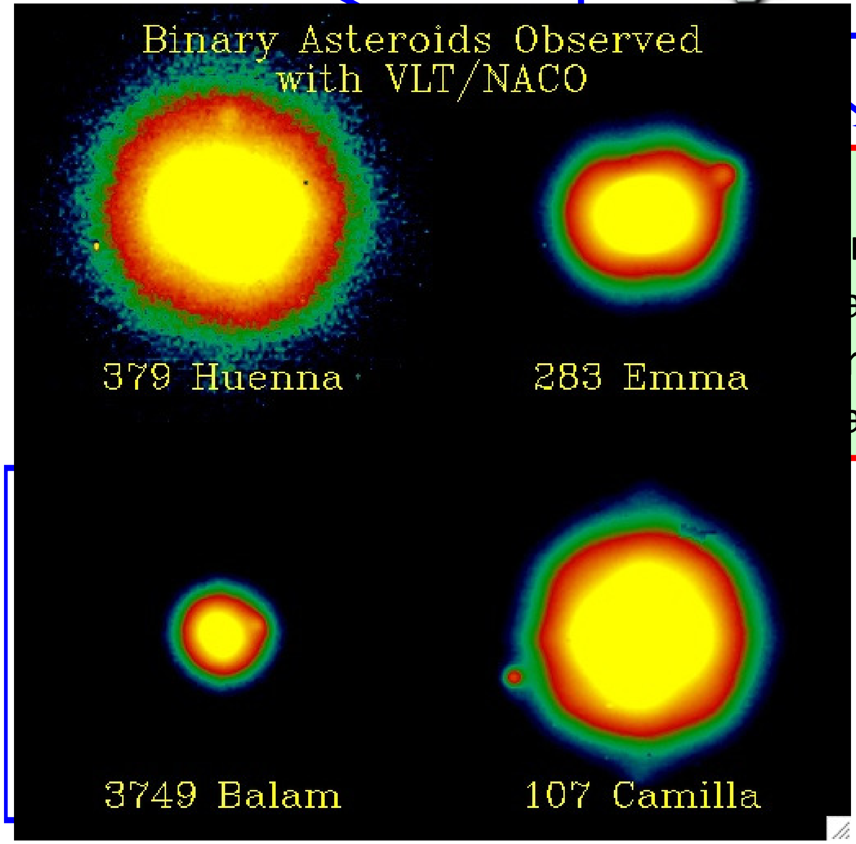
I. Virtual Observatory Binary Asteroid Database (VOBAD)

VLT 8m-ESO
Paranal (Chile)
2003-2012

Keck II 10-m
Mauna Kea (Hawaii)
2002-2011

Gemini-North 8m
Mauna Kea (Hawaii)
2005-2011

HST 2m
2000-2008

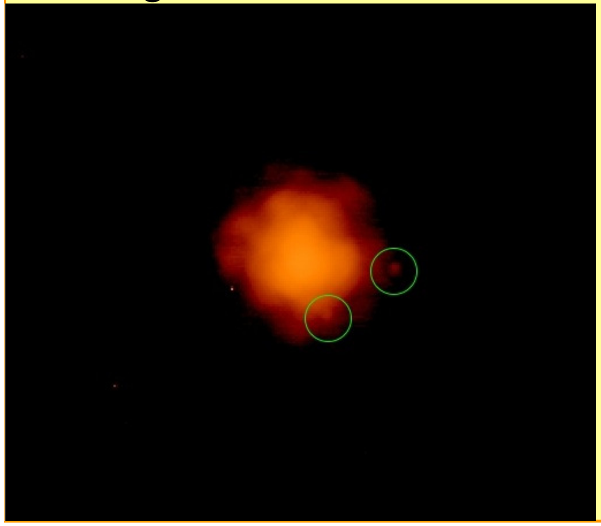


VOBAD
rvations of 501 SSSBs: 44 NEAs, 402
an, 1 Centaur, 2 TNOs
rvations of 500 SSSBs: 60 NEAs, 150
an, 20 Centaurs, ~240 KBOs

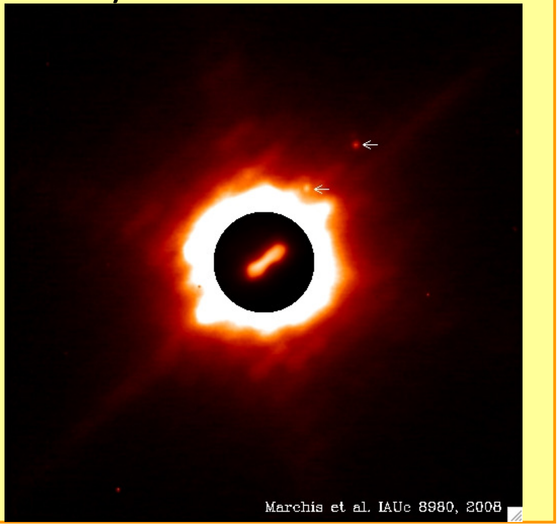
CFHT 4m
Mauna Kea (HI)
1999-2000

I. Triple Main-Belt Asteroid Systems
A Family Portrait

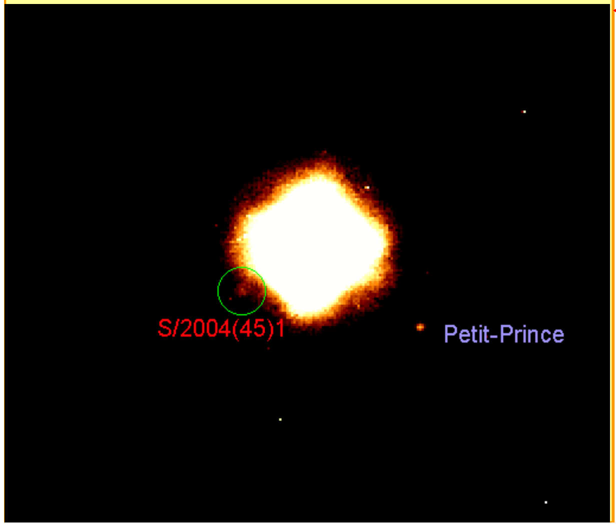
(93) Minerva
Aug 2009 with Keck AO



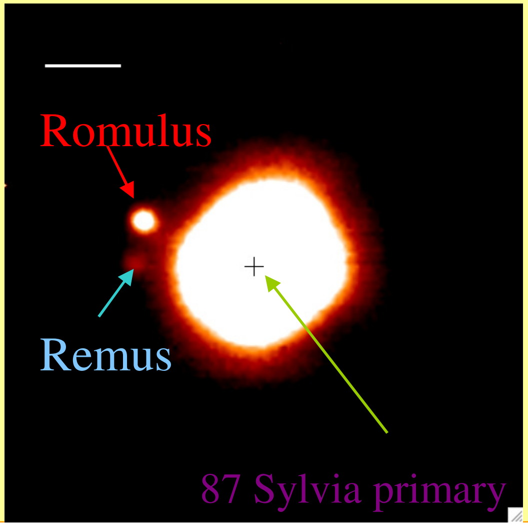
(216) Kleopatra
July 2008 with Keck AO



(45) Eugenia
Mar 2007 with VLT/NACO



(87) Sylvia
Aug 2005 with VLT/NACO



- D_p~100-300km, D_s~3-20 km
- Orbit analysis a~2/100 x R_{Hill}
- Use of Dynamical Models

-> Evolution & Stability (J2>0.1)

- Physical Properties (porosity>30%)
- Formation scenario (see next)

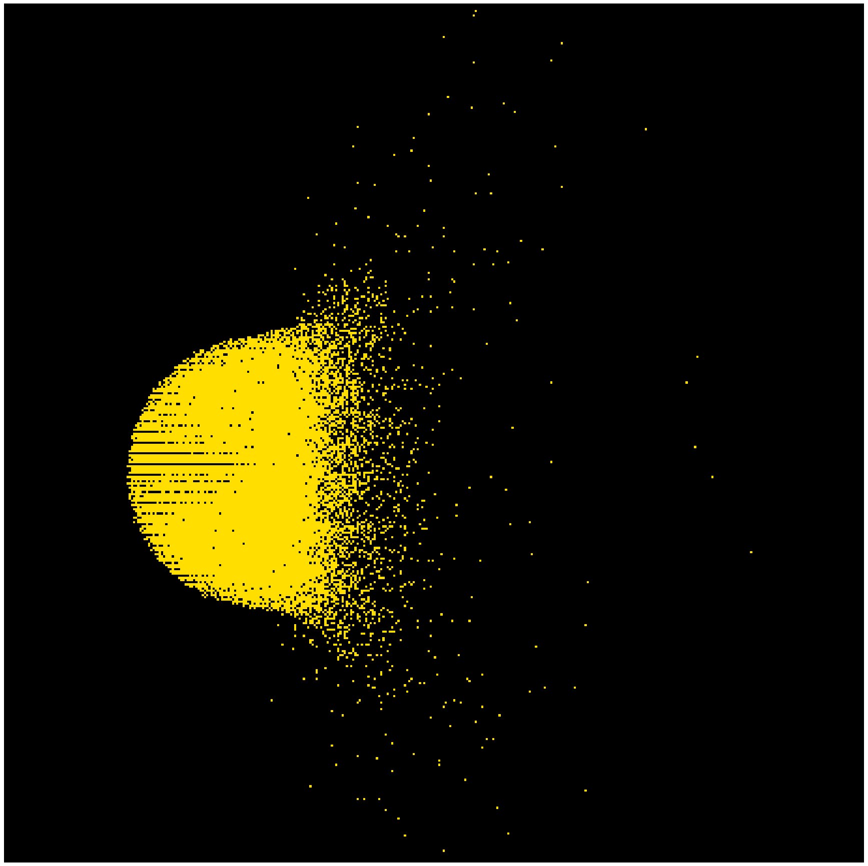
Formation of MBA triple systems

A catastrophic impact produced the disruption of a parent asteroid, follow by gravitational reaccumulation

->Simulation by 3D particle hydrodynamics, then N-body code

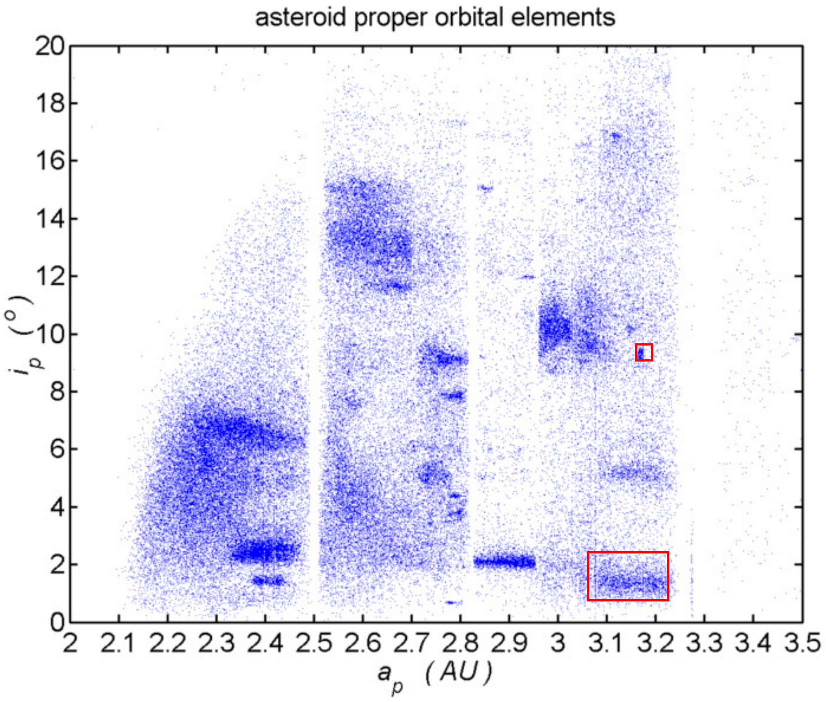
•Outcome of the simulation:

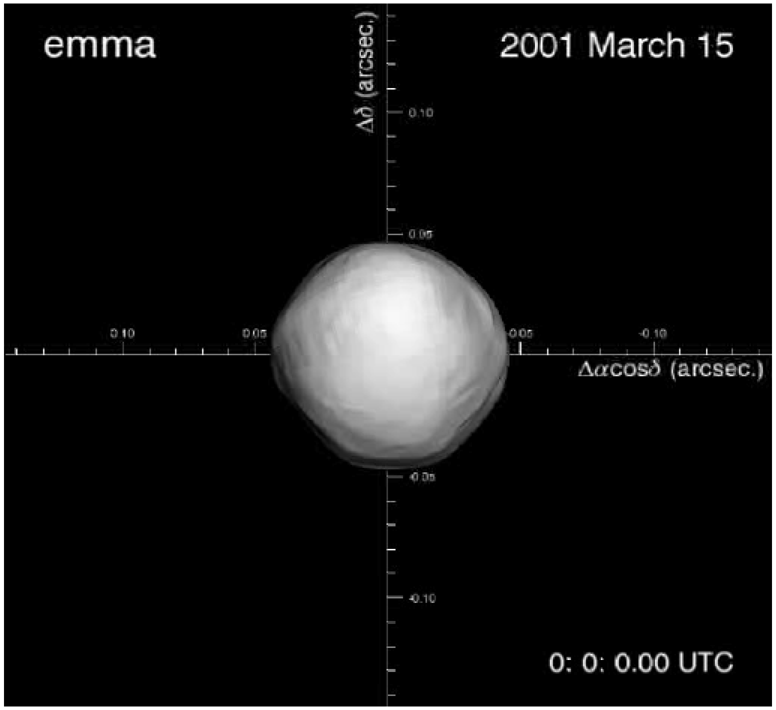
- ✓Irregular primary with rubble-pile structure R_p ~ 100 km
- ✓Small moonlet R_s~ a few km close to the primary (3-6x R_p) describing a circular and equatorial orbit (due to damping by tidal effect)
- ✓Multiple systems (less than 5%)



I. Argot in the Asteroid field

- **Size, Albedo** combining *radiometric* data (Far IR with IRAS or SPITZER) + visible
- **Pole solution** (orientation of spinning pole) and **shape** by *lightcurve* observations (Kaasalainen et al.)
- **Surface composition** by *taxonomic classes* C-type (carbonaceous), S-type (Silicate), M-type (Metallic), …
- **Age** estimated in a few cases (if member of a *collisional families*)

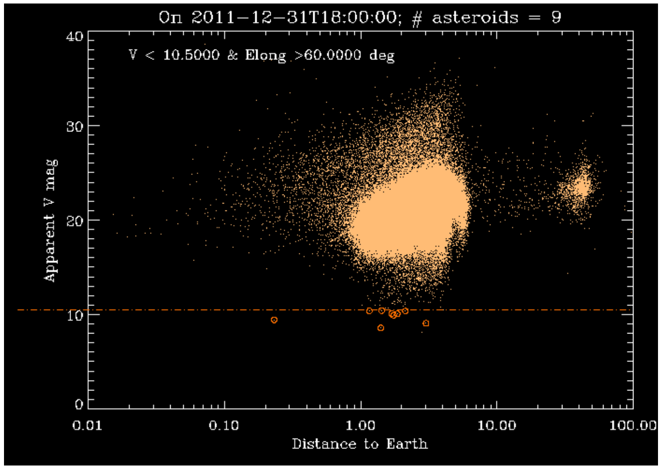




I. Small Solar System Bodies “Observability”

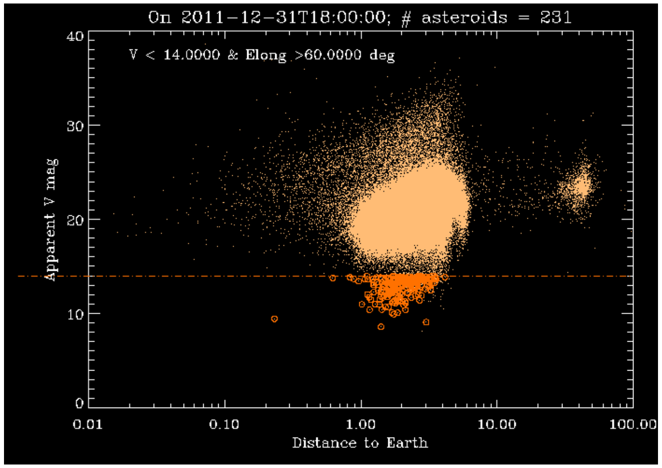
- **What is this?**
  - When the brightness of an asteroid is sufficient to be used as a guiding for the Tip-tilt or AO wavefront sensing.
  - How many and which asteroids will be observable with future AO systems per population
- **Why?**
  - Direct imaging of an asteroid to estimate its size/shape/multiplicity/composition
  - Use of asteroids to increase the sky coverage
- **Simulations**
  - Calculation of apparent magnitudes of all SSSBs from the ASTORB table (586571 on June 18 2012) between Jan 2012 and Sep 2021 (step of 7 days)
  - 5 types of AO were considered:
    - **V_{lim} < 10.5, d<6”**, solar elongation>60, airmass<2.0 (eq. to GPI at Gemini South)
    - **V_{lim} < 14.0, d<20”**, solar elongation>60, airmass<2.0 (eq. to ALTAIR Gemini North NGS)
    - **V_{lim} < 15.0 d<20”**, solar elongation>60, airmass<2.0 (eq. to Keck II AO & VLT-NACO)
    - **V_{lim} < 18.5 d<25**”, solar elongation>60, airmass<1.6 (eq. to ALTAIR Gemini North LGS)
    - **V_{lim} < 19.0 d<72”**, solar elongation>60, airmass<1.8 ((eq. to Keck II AO LGS)

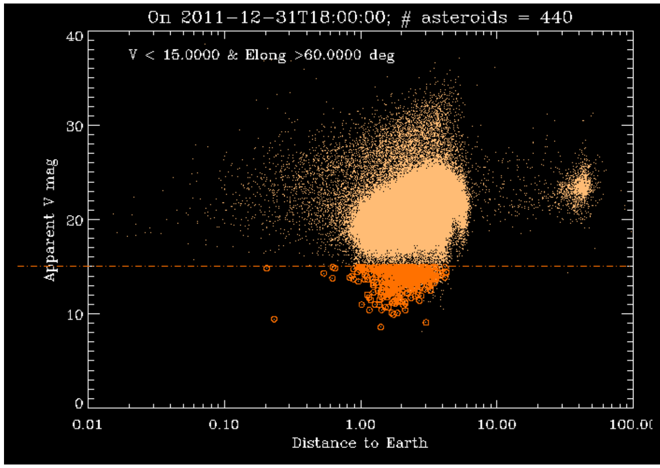
I. Small Solar System Bodies “Observability”

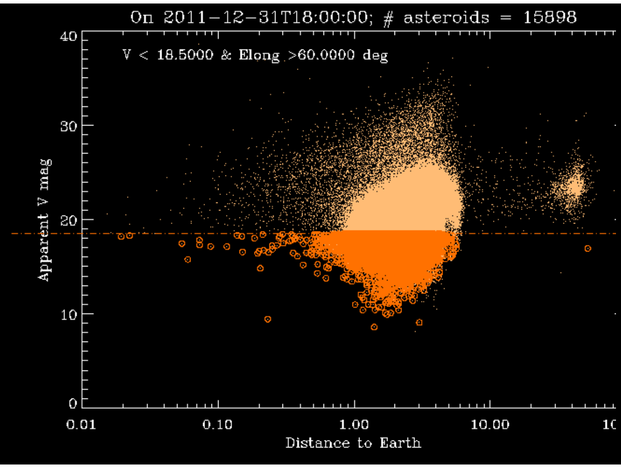


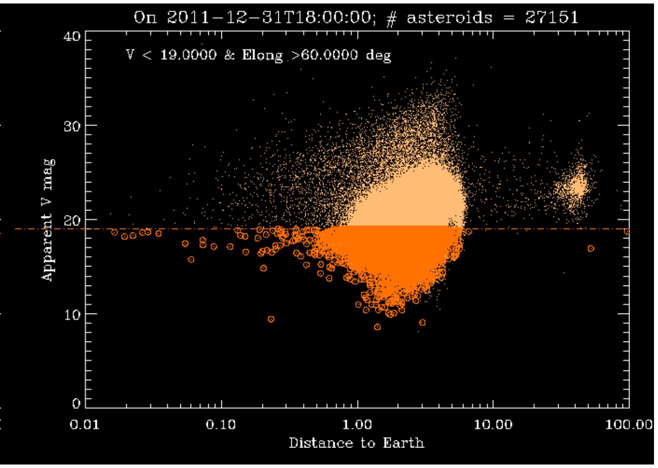
Number of SSSBs observable per night

- GPI ~8 (MBAs)
-ALTAIR NGS ~ 210 (MBAs)
-Keck/VLT NGS ~ 450 (+ 1-3 Trojans)
-ALTAIR LGS ~15,000
-KECK LGS ~27,000









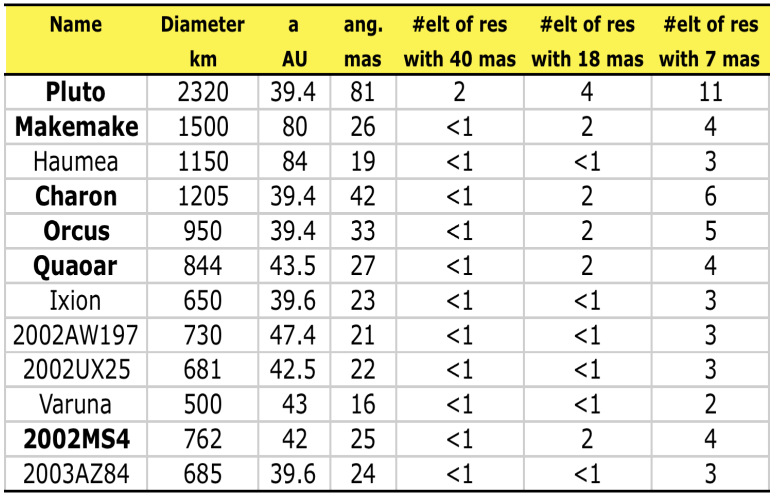
Small Solar System Bodies "Observability"

Jan 2012-Sep 2021	NEAs	MBAs	Trojan	Outer	Total per AOs
Total per population	18748	555,956	5245	1774	586,571
GPI $V_{lim}<10.5$	2/0.01%	84/0.02%	0/0%	0/0%	86/0.01%
ALTAIR NGS $V_{lim}<14.$	60/0.32%	1259/0.23%	1/0.02%	0/0%	1337/0.22%
Keck/VLT NGS $V_{lim}<15.$	223/1.19%	3413/0.61%	7/0.13%	2/0.11%	3690/0.63%
ALTAIR LGS $V_{lim}<18.5$	5874/31.3%	167,398/30.1%	596/11.4%	16/0.9%	174,953/29.8%
Keck/VLT NGS $V_{lim}<19.0$	8504/44.5%	250,197/45.0%	965/18.4%	27/1.5%	261,139/44.5%

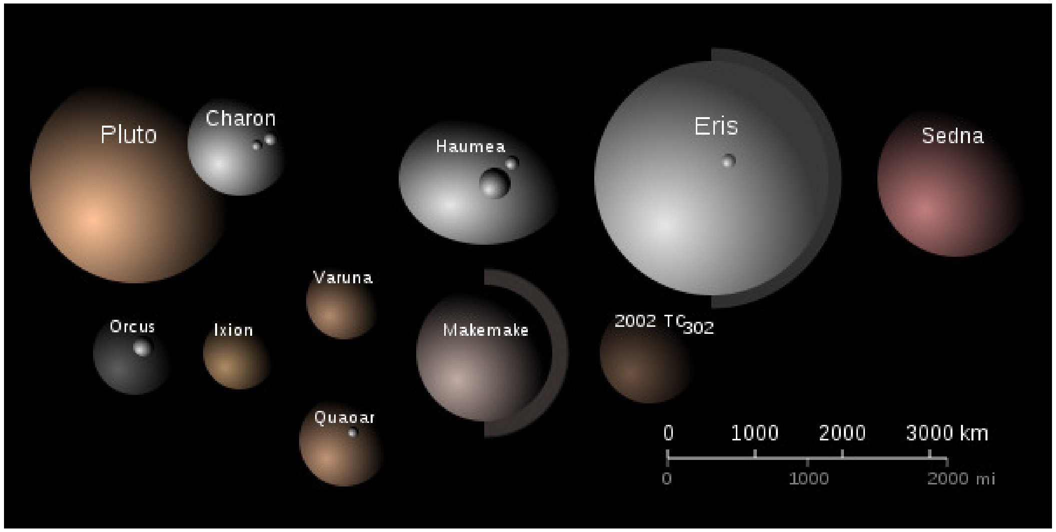
- Already observed based on our survey (VOBAD database)
  - With AO ~1340 observations of 501 SSSBs: 44 NEAs, 402 MBAs, 62 Jupiter-Trojan, 1 Centaur, 2 TNOs
  - With HST ~600 observations of 500 SSSBs: 60 NEAs, 150 MBAs, 30 Jupiter-Trojan, 20 Centaurs, ~240 KBOs
  - AO with $V_{lim}>18.5$ -> ~1/3 of the MBAs & NEAs are observable
- Number of TNOs, the more distant population, remains low (less than 2%, 27 targets)

Size, Shape, Surface Mapping, Atmosphere of TNOs

Population of 1,774 Minor planets orbiting at 30+ AU made of mixture of ices and rock.
vis/NIR spectra of the surface -> water ice, amorphous carbon, organic, and silicates.



Name	Diameter km	a AU	ang. mas	#elt of res with 40 mas	#elt of res with 18 mas	#elt of res with 7 mas
Pluto	2320	39.4	81	2	4	11
Makemake	1500	80	26	<1	2	4
Haumea	1150	84	19	<1	<1	3
Charon	1205	39.4	42	<1	2	6
Orcus	950	39.4	33	<1	2	5
Quaoar	844	43.5	27	<1	2	4
Ixion	650	39.6	23	<1	<1	3
2002AW197	730	47.4	21	<1	<1	3
2002UX25	681	42.5	22	<1	<1	3
Varuna	500	43	16	<1	<1	2
2002MS4	762	42	25	<1	2	4
2003AZ84	685	39.6	24	<1	<1	3



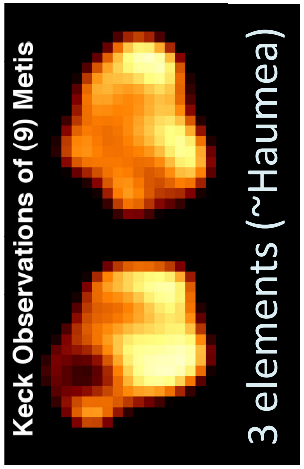
Scientific Objectives with a 8m-telescope:

-Detect small satellites and follow up their orbits

-Determine their size and shape (6 of them)

Outstanding Questions (Pre-New Horizons):

- Cryovolcanism on TNOs
- Bulk density and interior structure of the most primitive planetesimals

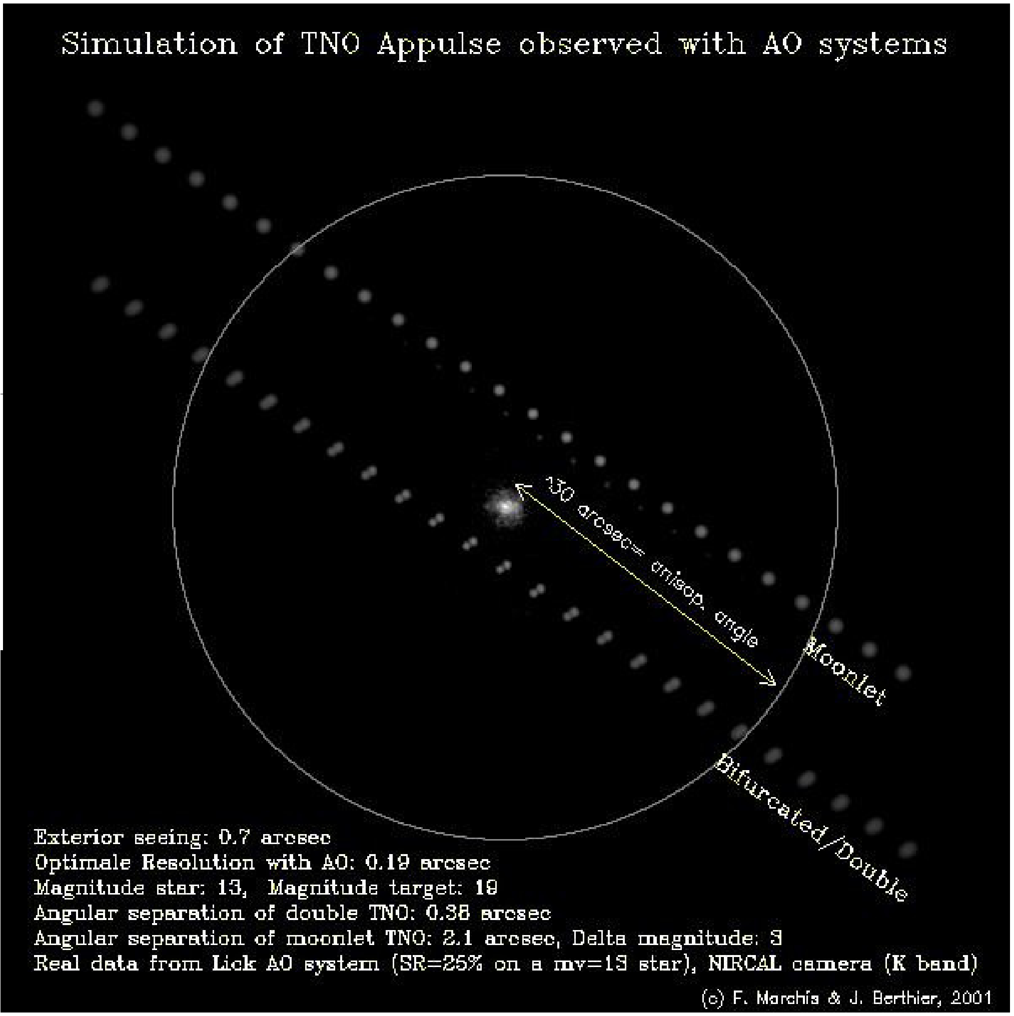


SSSBs
expanding the “Observability” of TNOs

Jan 2012-Sep 2021	Outer	Outer By Appulse
Total per population	1774	1774
GPI V_{lim}<10.5	0/0%	98/6%
ALTAIR NGS V_{lim}<14.	0/0%	652/37%
Keck/VLT NGS V_{lim}<15.	2/0.11%	653/37%
ALTAIR LGS V_{lim}<18.5	16/0.9%	>662/37%
Keck/VLT NGS V_{lim}<19.	27/1.5%	>692/39%

>1/3 of TNOs can be observed (V_{TNOs} ~22.9 & V_{star} <15)

Appulse calculated using USNO-A2.0 catalog
-Incomplete for V>16
-Need for a model of galaxy for proper comparison


Simulation of TNO Appulse observed with AO systems

Exterior seeing: 0.7 arcsec
Optimale Resolution with AO: 0.19 arcsec
Magnitude star: 13, Magnitude target: 19
Angular separation of double TNO: 0.38 arcsec
Angular separation of moonlet TNO: 2.1 arcsec, Delta magnitude: 3
Real data from Lick AO system (SR=25% on a mv=13 star), NIRCAL camera (K band)

(c) F. Marchis & J. Berthier, 2001

I. Shape & Size of Asteroids
The Case of 624 Hektor

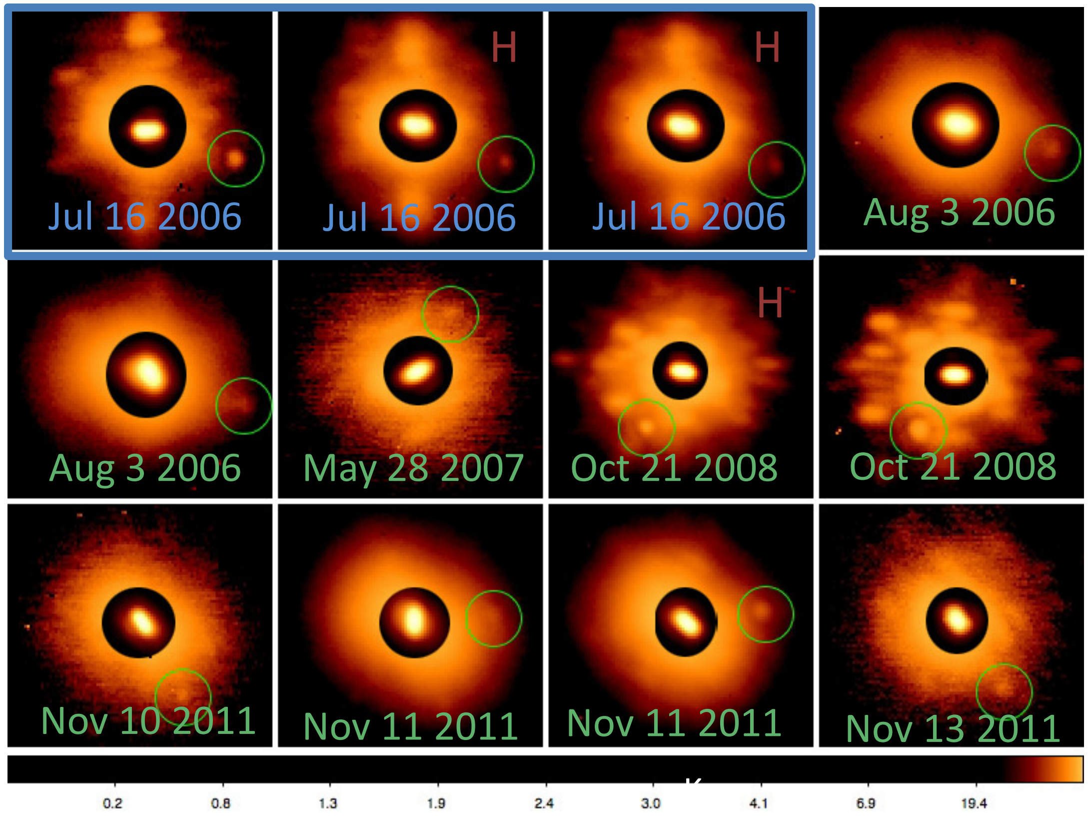
The case of (624) Hektor:
- Largest Trojan Asteroids D~220 km, V=14.5-15.5
- Moon discovered with Keck LGS, and follow up with Keck NGS

Hektor I (moon)
- 12 astrometric positions
- angular separation ~0.22-0.36"
- D_{sat} ~ 12 ± 3 km (assum. same p_V)

Hektor primary
- Resolved (D_{max}=111-177 mas)
- distance 4.34-5.50 AU

Satellite (0.3", Dm~4) is barely detectable -> astrometric error ~12 mas

What is the real shape of (624) Hektor Primary?



I. Shape & Size of Asteroids Simulations

- Library of PSFs

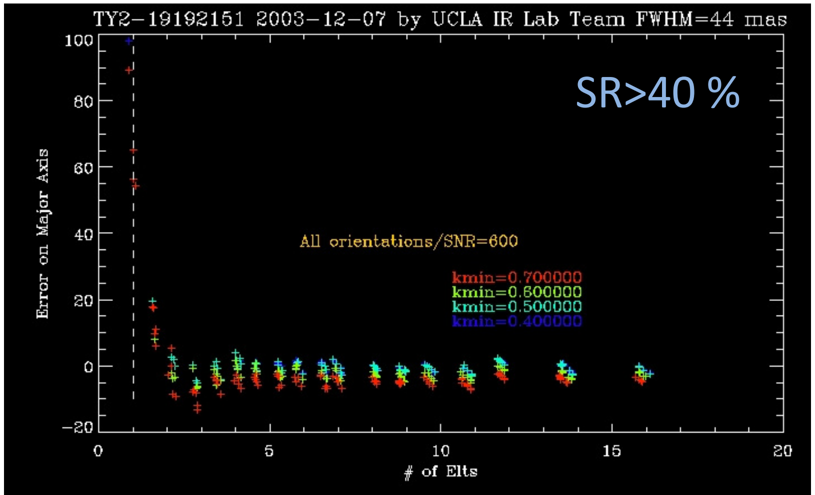
(1) TY2-19192151 2003-12-07 by UCLA IR Lab Team FWHM=44 mas
(2) (2) PSF_FeII 2009-08-16 by F. Marchis FWHM=41 mas
(3) PSF_Frede FeII 2011-11-10 by F. Marchis FWHM=41 mas
(4) PSF_FeII 2011-11-11 by F. Marchis FWHM=41 mas
(5) PSF_Hektor2 2006-08-03 by F. Marchis FWHM = 99 mas
(6) PSF_Hektor 2006-08-03 by F. Marchis FWHM = 112 mas
(7) PSF_Leontheus2 2006-08-03 by F. Marchis FWHM = 87 mas
(8) PSF_Leontheus 2006-08-03 by F. Marchis FWHM = 69 mas

- MC simulations of an ellipsoidal asteroid (2a=1.2, 2b=1.1, 2c=0.8)
  - SNR from 100 to 2100
  - Angular size from 20 mas to 420 mas
  - Orientation from 0 deg to 80 deg
  - Scattering by Minnaert law with k_{min} from 0.4 to 0.8

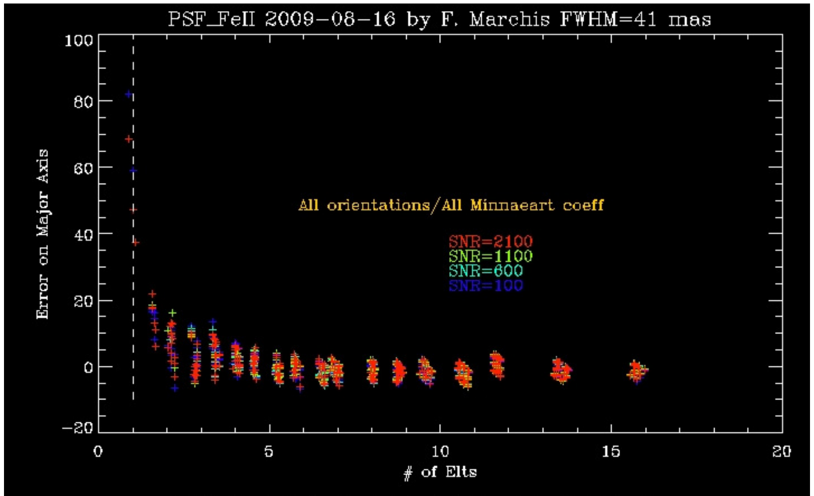
VIDEO?

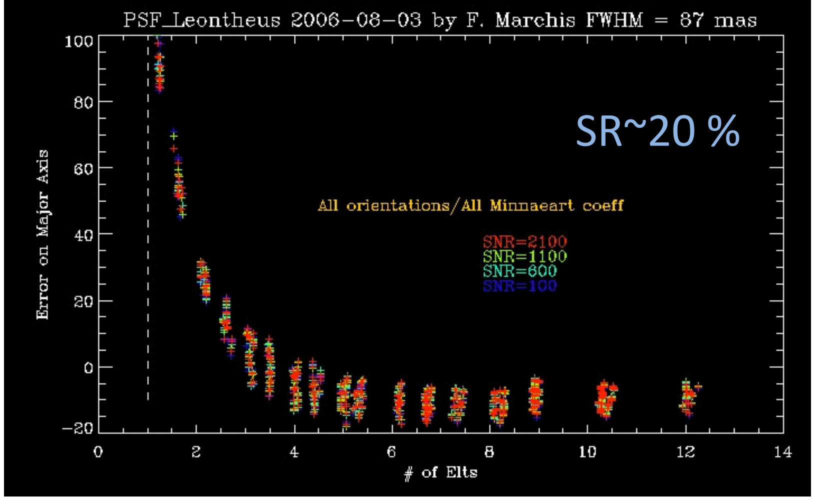
I. Shape & Size of Asteroids Simulations

- Errors on size varies with the quality of the AO systems
  - low SR<20% -> error(2 elts of res) = 28% with 1-sigma = 10%
  - High SR>40% -> error(2 elts of res) = 0% with 1-sigma = 5%
  - Error(3 elts of res) is ALWAYS less than 10%

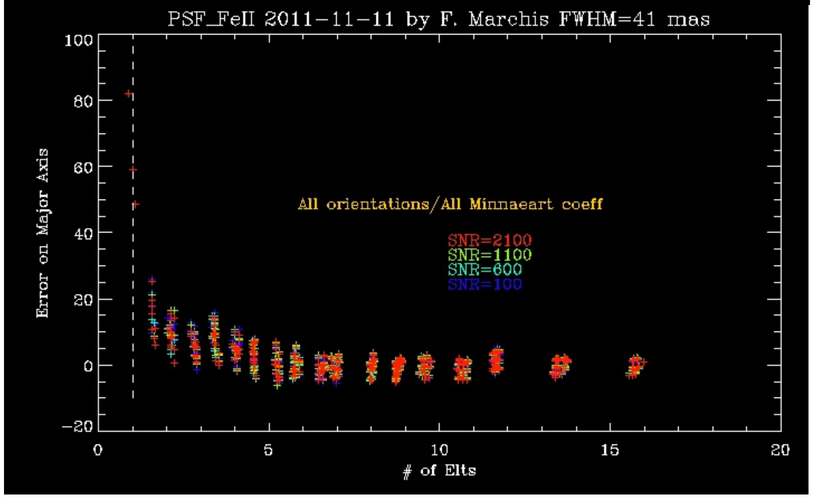

TY2−19192151 2003−12−07 by UCLA IR Lab Team FWHM=44 mas

SR>40 %


PSF_FeII 2009−08−16 by F. Marchis FWHM=41 mas

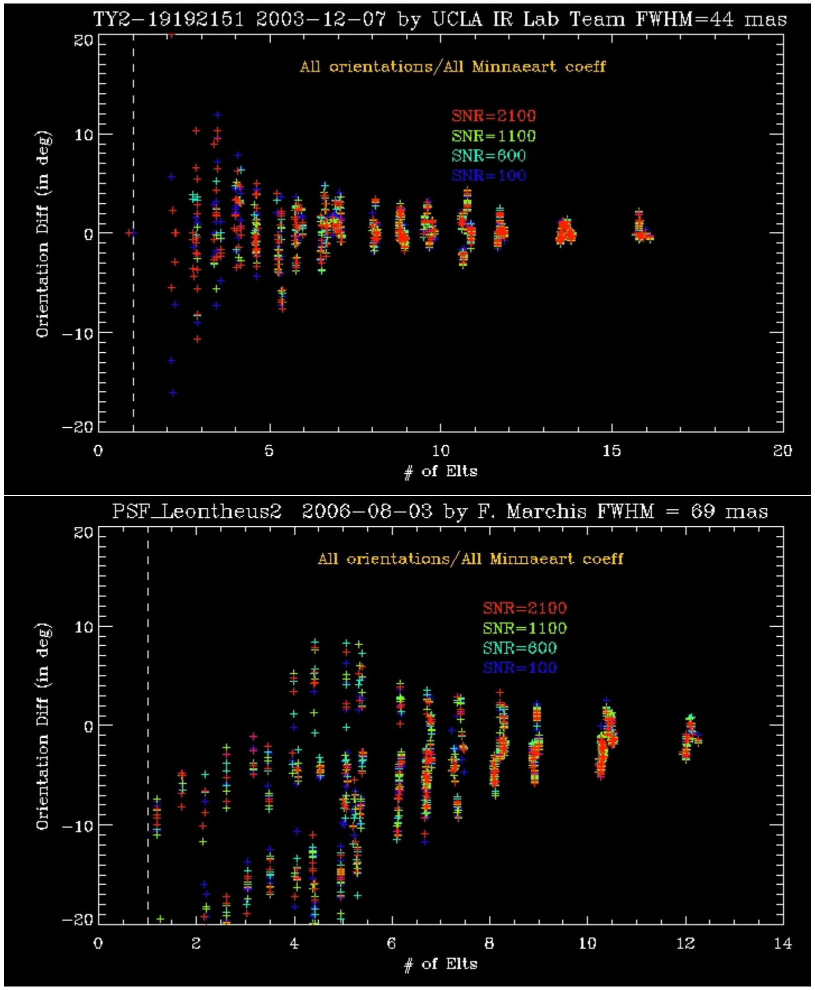

PSF_Leontheus 2006−08−03 by F. Marchis FWHM = 87 mas

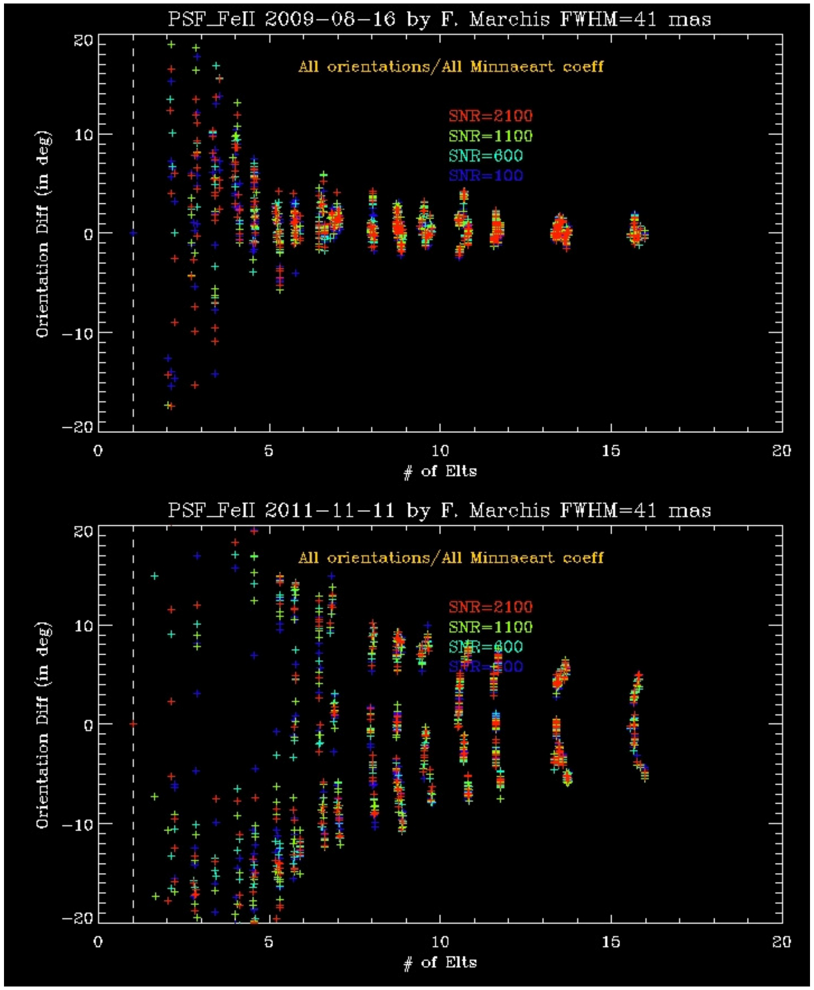
SR~20 %


PSF_FeII 2011−11−11 by F. Marchis FWHM=41 mas

I. Shape & Size of Asteroids Simulations

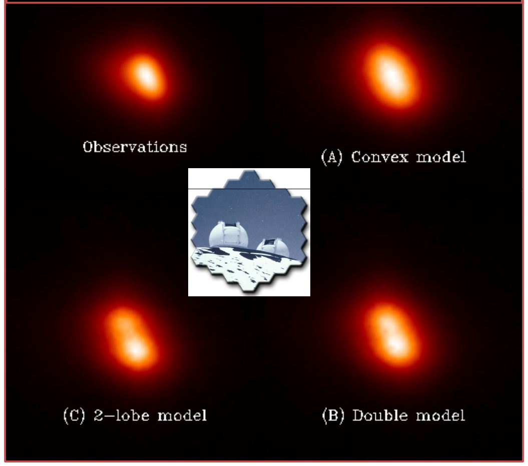
- Errors on Orientation varies with the quality of the AO systems –
  - low SR<20% -> error(<6 elts of res) = 20 deg with 1-sigma uncertainty = 15 deg
  - High SR>50% -> error(3+ elts of res) ~0 deg with 1-sigma uncertainty = 8 deg



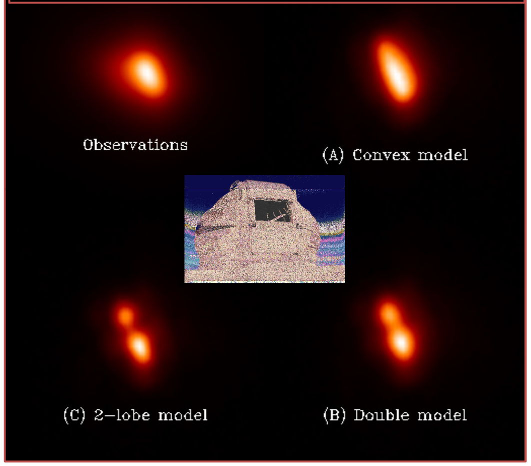


I.Shape & Size of Asteroids
Hektor Primary

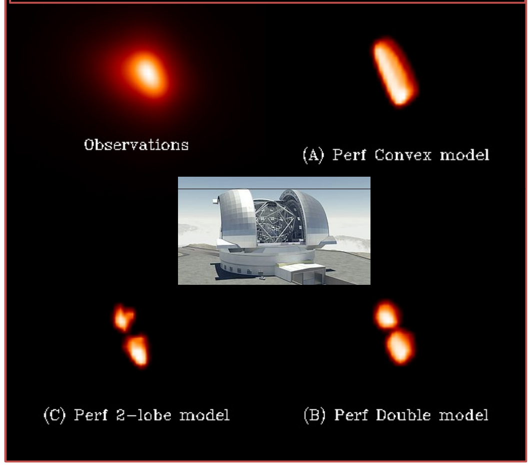
Current Keck AO quality
FWHM = 70 mas



New Gemini AO
FWHM = 45 mas



AO on ELTs
FWHM = 10 mas

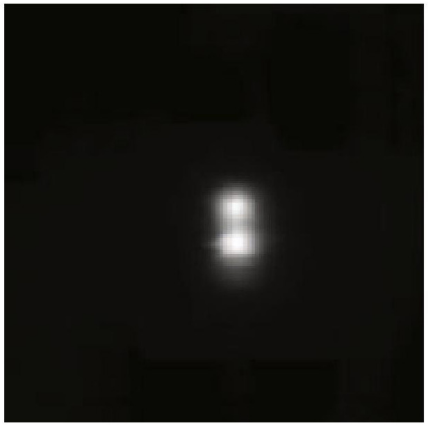


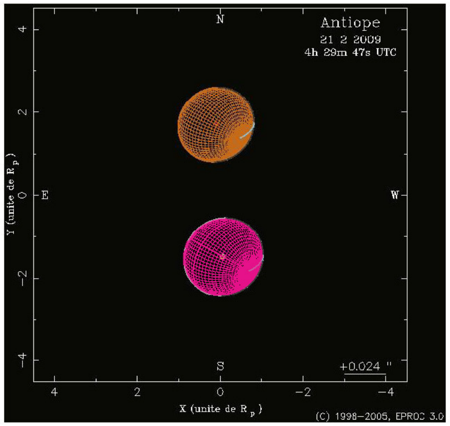
D_{eq} = 250 ± 30 km => density = 1.0 ± 0.4 g/cm^3

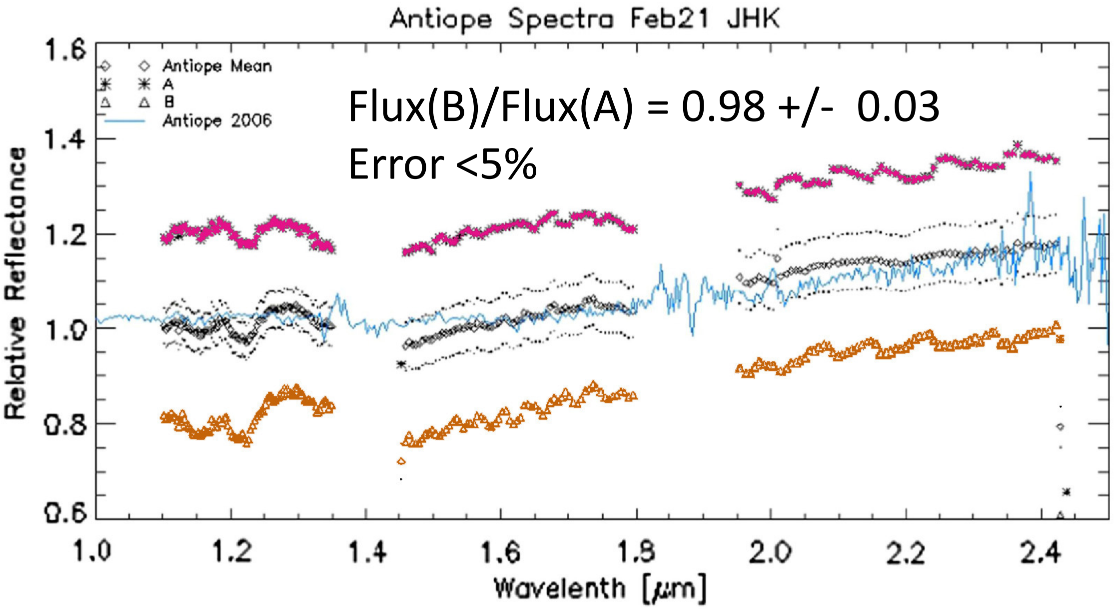
High performance (SR>50%) on faint target (V>15 mag) to estimate the real shape & size of 624 Hektor, hence reduce the error on the density.

I. Spectroscopic Comparative Study Binary Asteroids

- SINFONI@ VLT NACO (Antiope, Marchis et al. 2011)
- OSIRIS@ Keck AO (Kalliope, Laver et al. 2009)







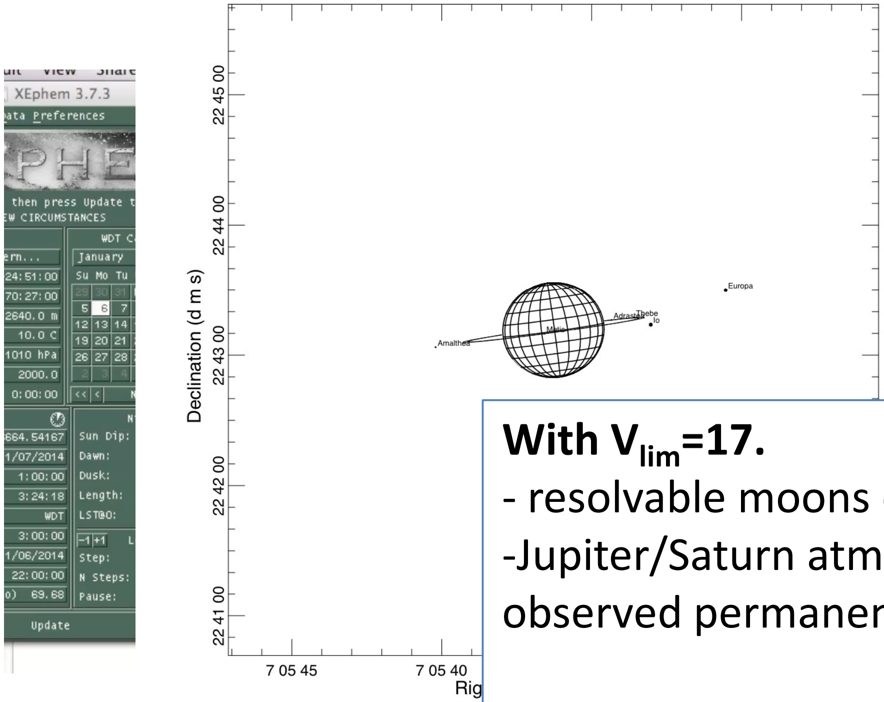
Flux(B)/Flux(A) = 0.98 +/- 0.03

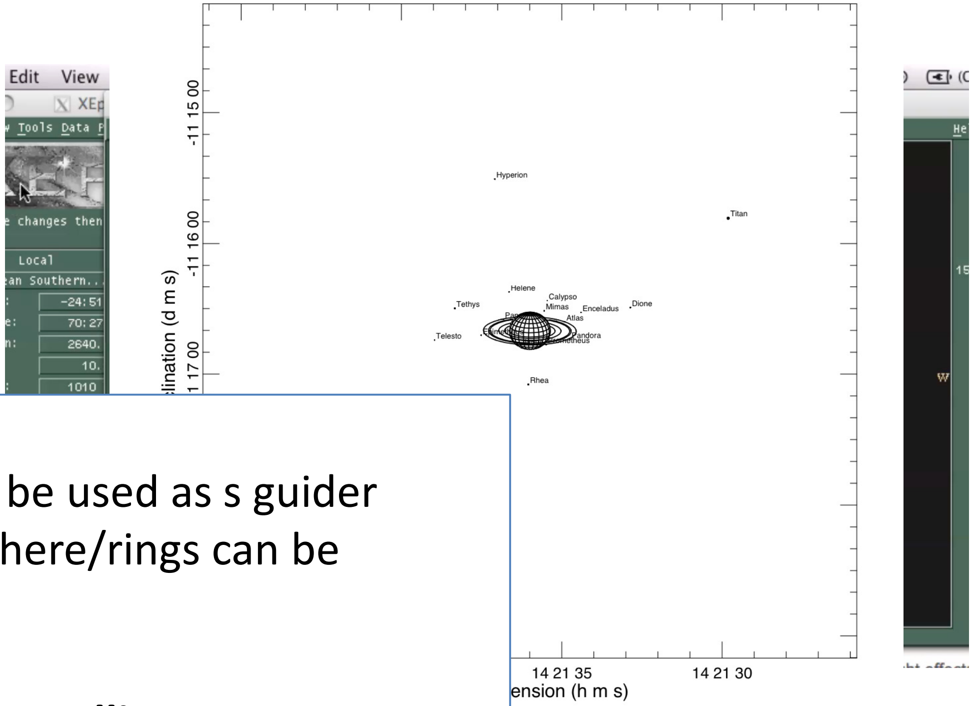
Error <5%

90 Antiope, double asteroid:
- Two components D~86km
- low density ~1.3 g/cc, porosity>50%
- puzzling binary system, formation scenario still unknown
-Orbit known -> scheduled obs at maximum elongation

same NIR spectra
=> formed at the same time from the same material.
=> mutual capture scenario can be rejected

II & III. Giant Planet Systems





With V_{lim}=17.

- resolvable moons can be used as s guider

-Jupiter/Saturn atmosphere/rings can be observed permanently

-**Science Objectives for Satellites**

- Shape & Size
- Surface composition
- Activity monitoring (weather, volcanism, geyser)
- -Orbit determination (Uranus, Neptune satellites)

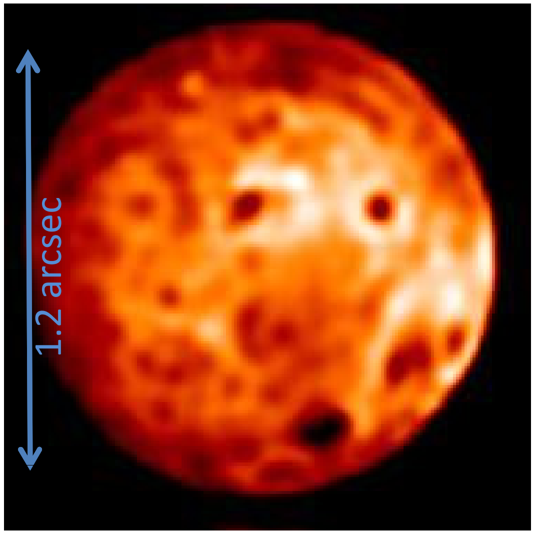
Moons	Vmag	Dmax
Metis	17.5	60
Adrastea	19.1	20
Amalthea	14.1	250
Thebe	15.7	116
Io	5.0	3660
Europa	5.3	3122
Ganymede	5.5	5262
Callisto	5.7	4820
Leda	20.2	16
Himalia	14.8	170
Lysithea	18.3	36
Elara	16.8	86
Ananke	18.9	28
Carme	17.8	46
Pasiphae	16.9	60
Sinope	18.3	38
% of	resolved moons	
With	total known	moons = 66
%	of	Guiding-Moons
With	Vlim=10.5	6%
With	Vlim=14.0	6%
With	Vlim=15.0	9%
With	Vlim=17.0	14%
With	Vlim=18.5	20%

#_of_elts (res=40mas)	#_of_elts (res=18mas)	#_of_elts (res=7mas)
<1	<1	~2
<1	<1	1
<1	1	3
<1	<1	2
<1	1	3
<1	1	4
2	4	9
2	4	11
4	9	24
<1	<1	~1
<1	<1	~1
4	10	25
<1	<1	~1
6	13	34
20	44	114
1	3	8
6	13	33
<1	2	5
<1	<1	~1
13%	20%	31%

%	of	Guiding-Moons
With	Vlim=10.5	3%
With	Vlim=14.0	11%
With	Vlim=15.0	13%
With	Vlim=17.0	20%
With	Vlim=18.5	20%

Case II. Satellites of Giant Planets
Study of Io Volcanism

Feb 2001 Keck AO obs



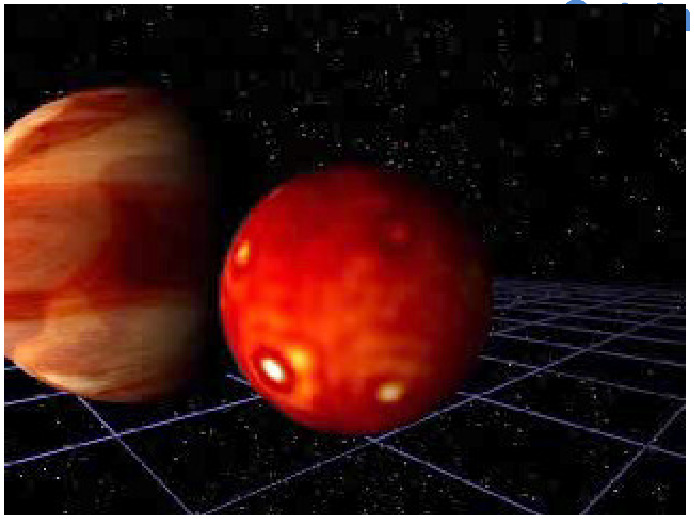
Io in a nutshell: V~5, ang size=1.2”, innermost Galilean satellite, most volcanic place due to resonance with other Galilean satellites

->Spatial resolution 125 -250 km with Keck AO at 1.6 um

Scientific Objectives:

- Monitoring of individual volcanoes
- Temperature and type of volcanic activities (fire fountaining, lava lake, lava field)
- Thermal Output of Io and its evolution

Snapshot of Io in Lp with Keck (Dec 2001)



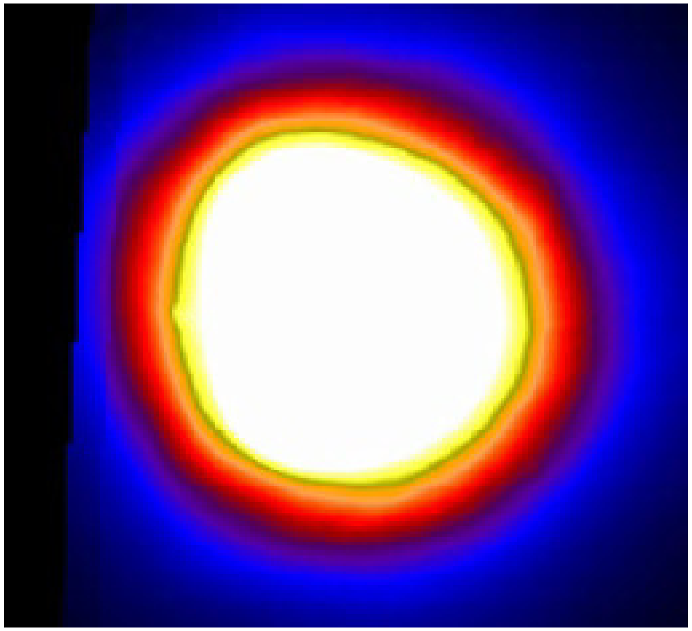
Outstanding Questions:

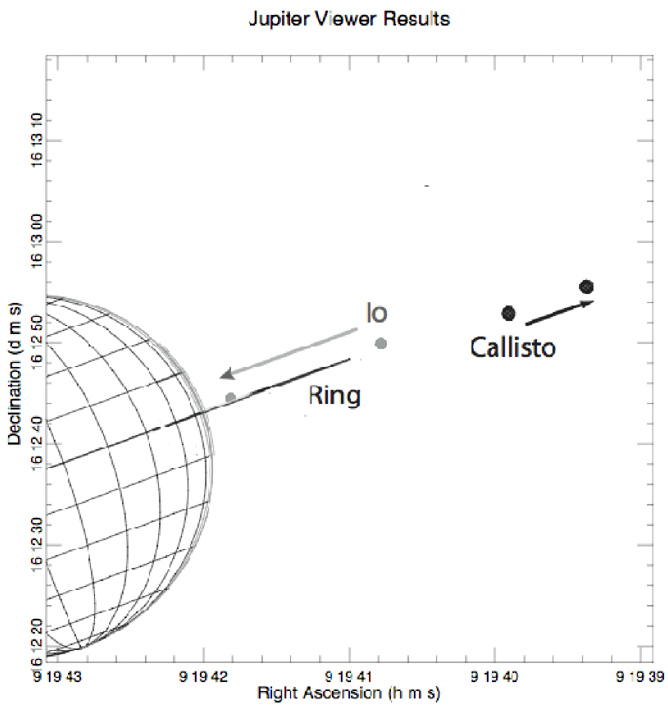
- Highest temperature of lava (sulfuric T<1000K, mafic T<1450K, ultra-mafic T>1500 K?) & Interior of Io (Ocean of magma, partially differentiated?)
- Understanding the evolution of Io into the Laplace resonance
- Potential for life in Europa and around exomoons (Exovolcanism)

II. Observing Io in Eclipse

A challenging and exciting observation!

- Io mv >21 (no sunlight reflection)
- NGS source? a close and moving galilean satellite -> integration time is limited , ~2 opportunities per year





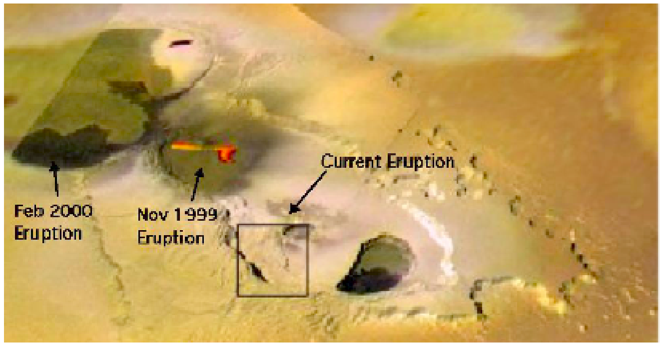
Observed at 2.2 υm, with Keck II + NIRSPAO on Nov. 12 2002

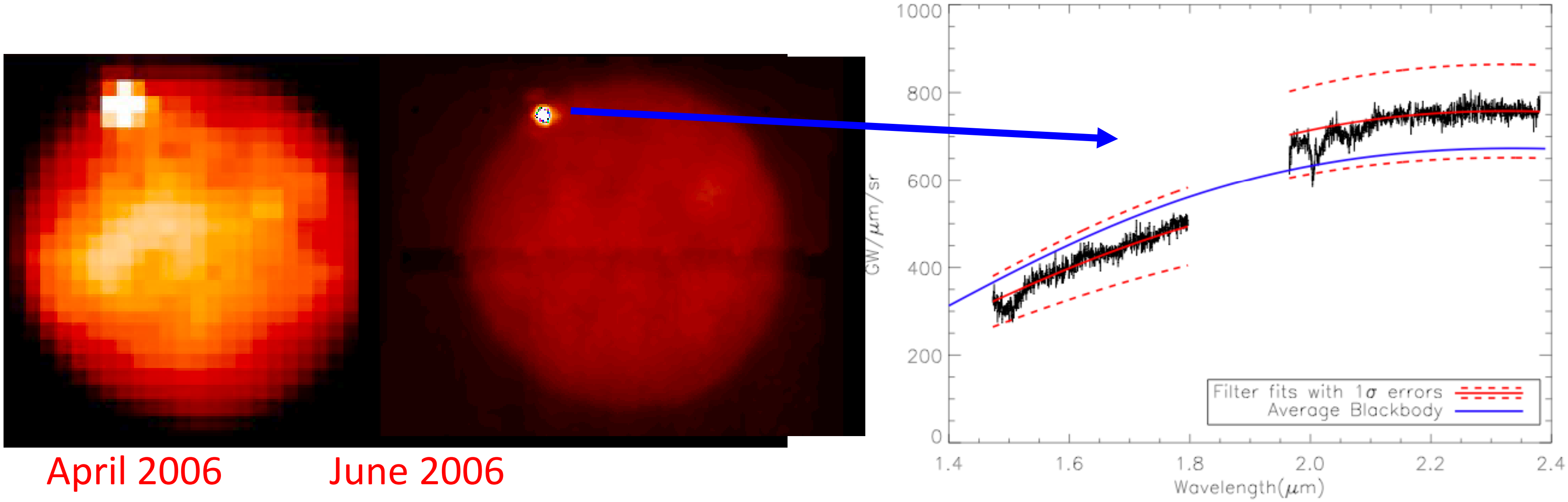
- 19 active centers were detected in H, K, L, and M bands
- Small thermal total output

(de Pater et al., Icarus, 2007)

II. Awakening of Tvashtar

- Tvashtar eruption was observed by Galileo spacecraft in Nov 1999
- No detection from Keck in 2001-2004
- Awakening in April 2006 observed with Keck/OSIRIS

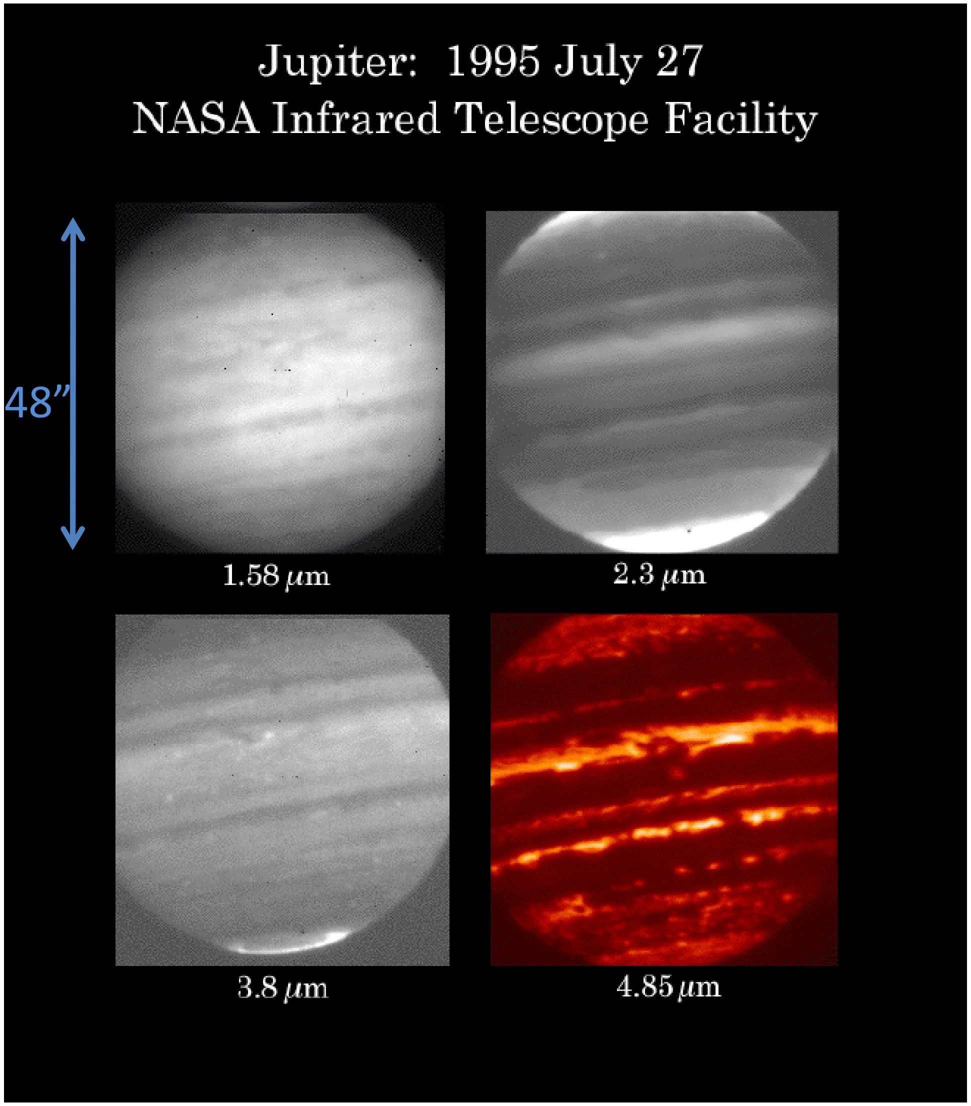




April 2006 June 2006

T_{color} = 1240 ± 4 K over 60 km^2 -> Basaltic lava
No emission/absorption features visible. (Laver et al. 2008)

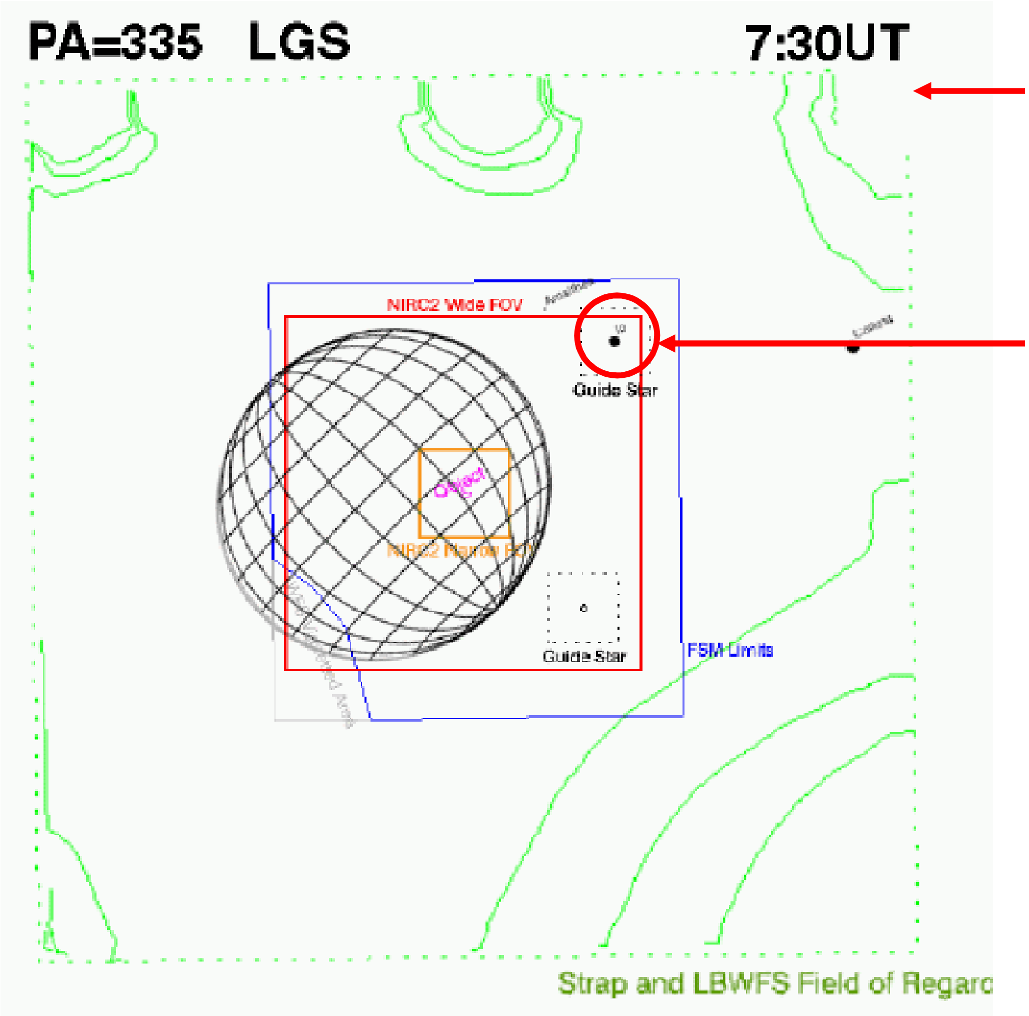
Case III: Jupiter in the near infrared



H band (1.6 υm): cloud features
K band (2.2 υm): haze
L band (3.7 υm): Aurora emissions
M band (4.6 υm): hot region

III. AO Observations of Jupiter atmosphere

D_{ang}(Jupiter)~45”
-> need for guide star reference (satellite or LGS)
-> Tip-tilt reference (one Galilean satellite mv=5-6)

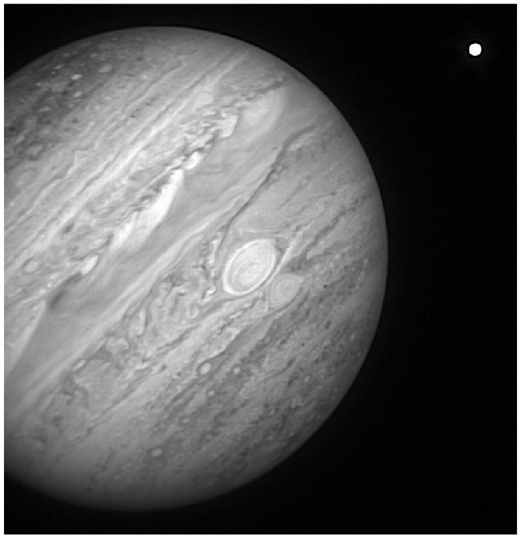


An hour and half into the observation (LGS)

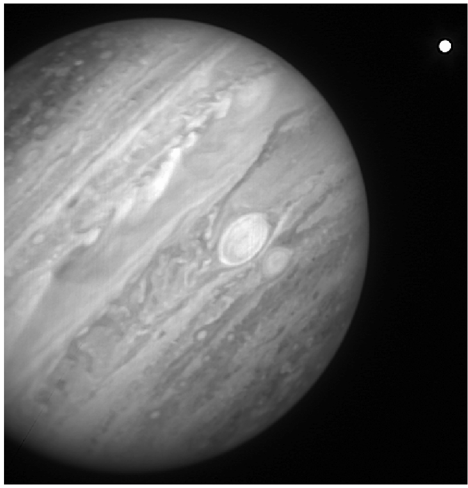
after Io had moved close enough to our field of interest, the laser off and Io used as our reference (NGS).

Limits:
-LGS spot cannot be at less than 10-20” from the limb
-Variable correction across image

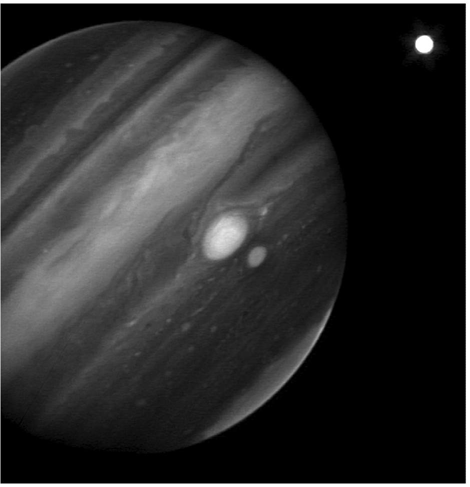
III. Red spot Jr. observed by Keck AO



1.58 υm



1.29 υm



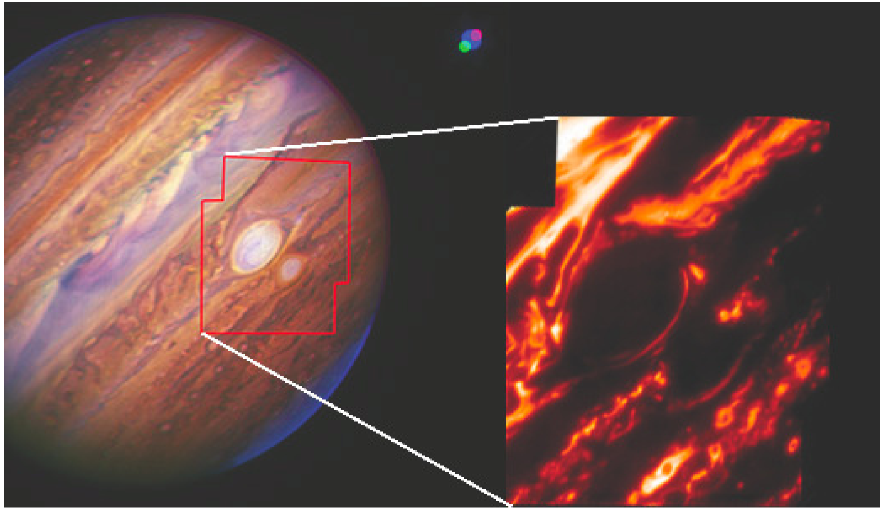
1.65 υm

Obs. on July 20 2006

Not the same color in NIR

-> different altitude, T and composition

de Pater *et al.*, 2010



5 υm

Limited period of obs (less than 1h) -> No velocity fields recorded

Could we use an MCAO?

III. Jupiter observations

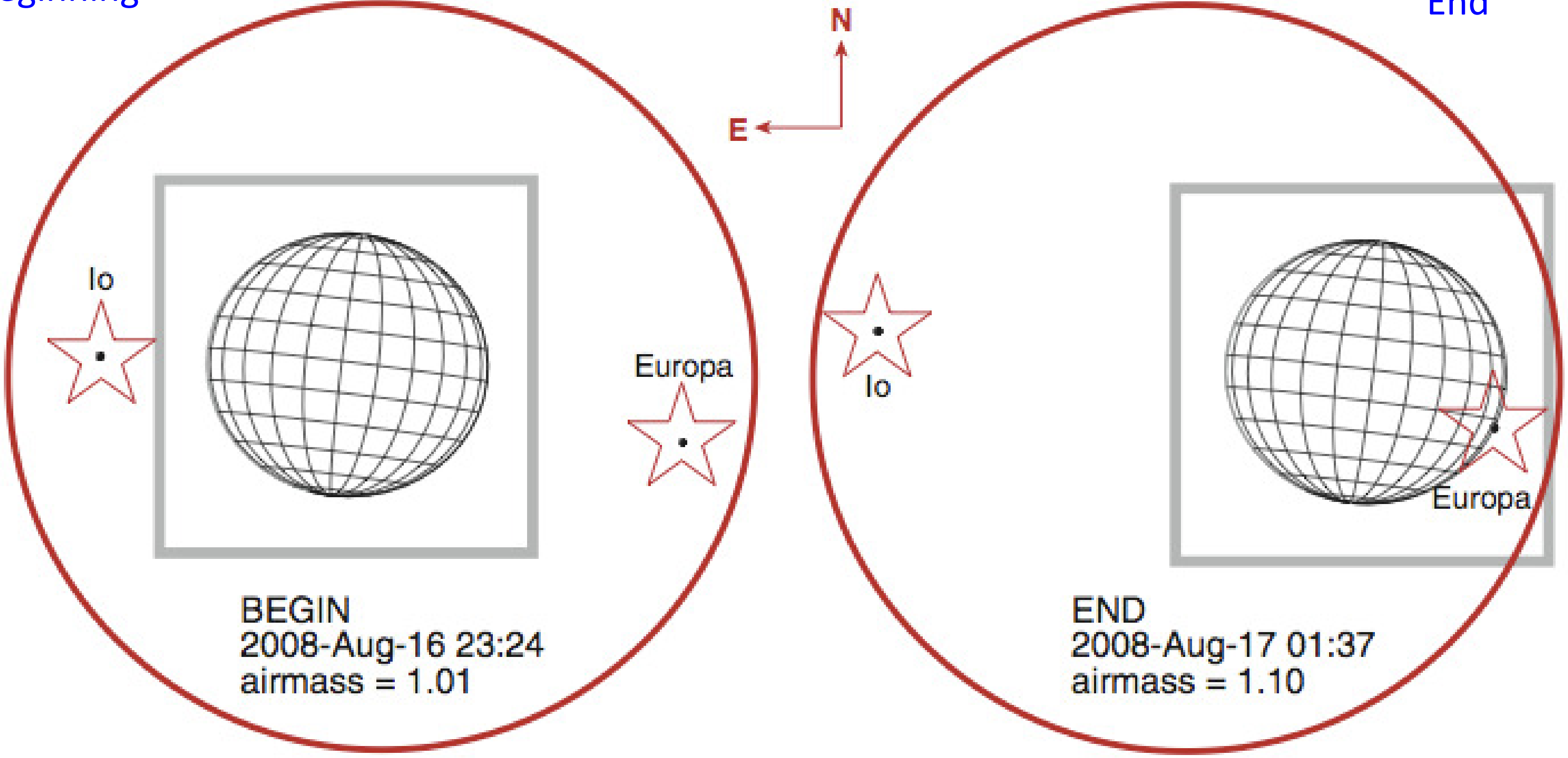
- Observations proposed for the 3rd Science demonstration run for MAD (PI: F. Marchis)
- Io and Europa used as Natural Guide “Star” on each side of Jupiter. No red Spots unfortunately.

- 265 frames recorded from 23:41 to 01:32 UT (2008 Aug 16/17)
- Observations at 2.02, 2.14. And 2.16 υm into the CH_4 absorption band

III. Geometry of the observations

Beginning

End



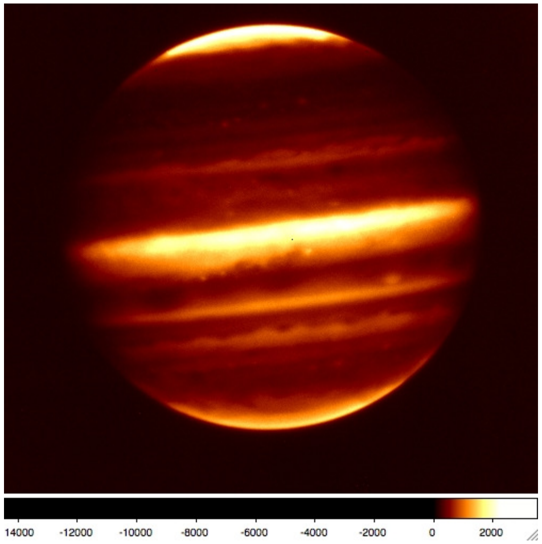
Io emerged from eclipse at 23:24 UT
m_v(io)=5.2
m_v(Europa)=5.4

Europa closed to Jupiter limb at 01:32 UT

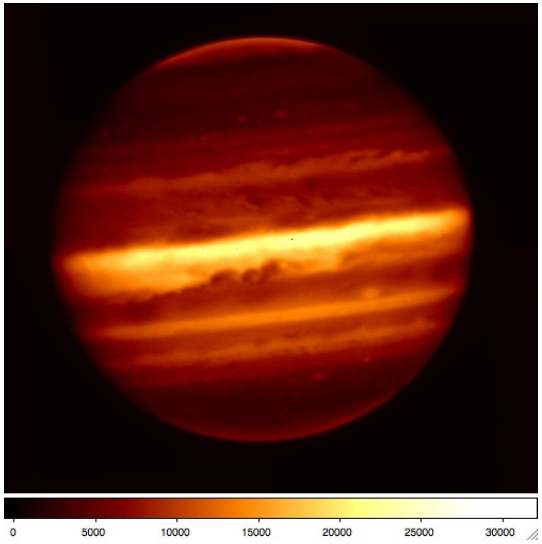
III. Multi-filter observations

Basic-processed images (FF,badpix, sky) in three narrow filters

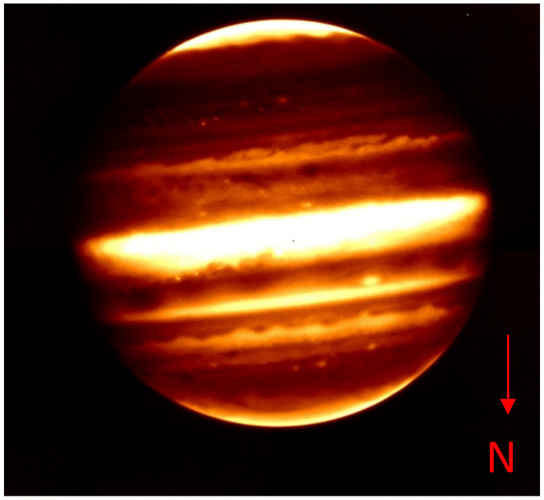
Filter BrG (10s)
2.158 (+0.013, -0.005)



Filter K (2s)
2.024 (+0.024, -0.054)

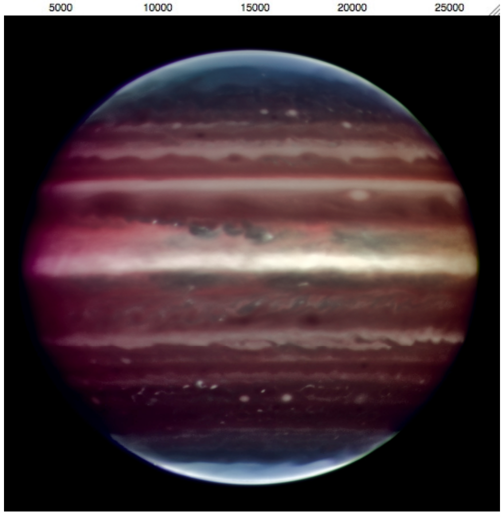


Filter Kc (10s)
2.142 (+0.011, -0.009)

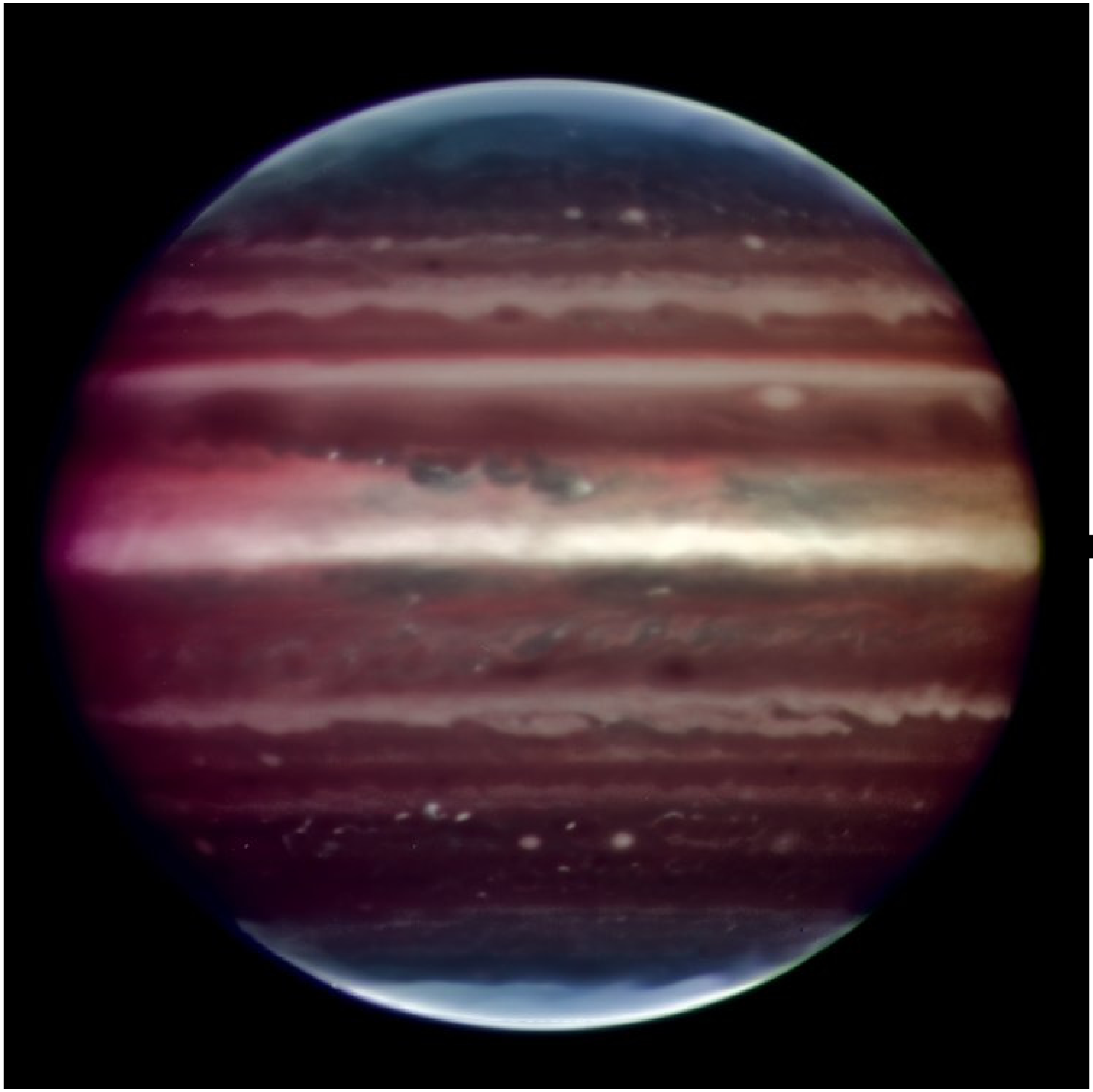


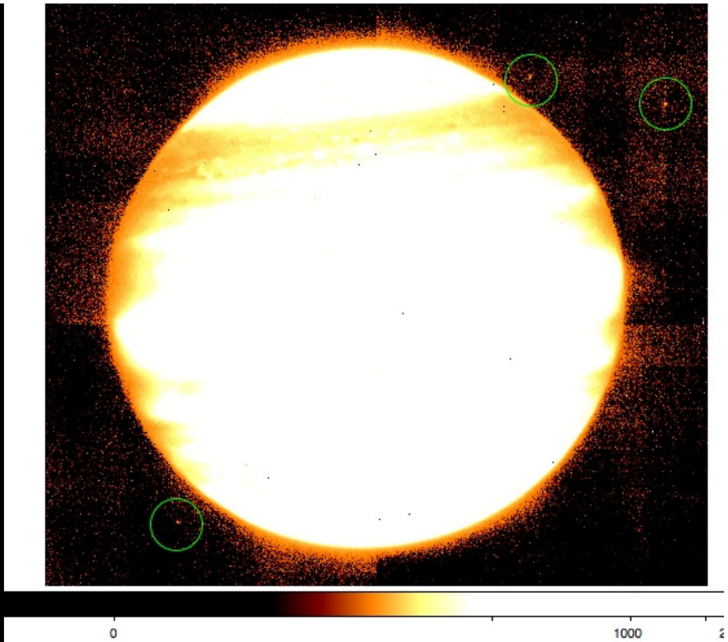
Deprojection, normalization

3-color composite image



III. 3-color Composite Color Image of Jupiter



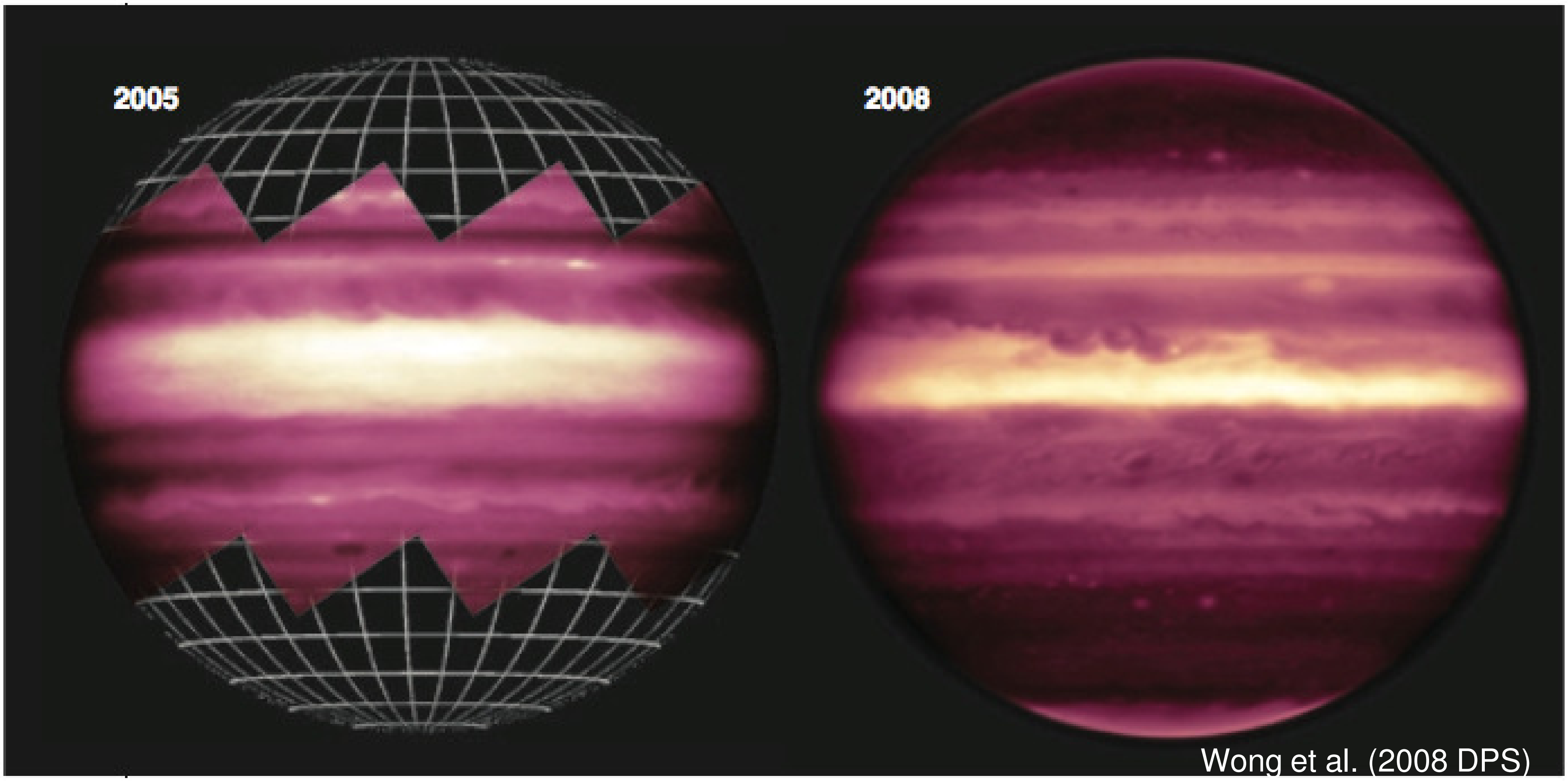


Background stars seen on individual frames ->

Angular resolution ~90 milli-arscec

(+/-4 mas)

III. Comparison with HST



Wong et al. (2008 DPS)

Mosaic of 4 HST/NICMOS at 2.12 um
2005-03-25 at 15:00 UT
Angular resolution ~ 0.21 arcsec
Uniform across the FOV and stable in time

One MAD image at 2.02 um
2008-08-17 at 00:30 UT
Angular resolution ~0.09 arcsec
SR~0.15 variable with time

Changes of the appearance of Jupiter: haze source mechanism?

III. Showing the capabilities of MCAO

Physics Today (Dec 2009)

back scatter

Adapting adaptive optics

For the past 20 years, adaptive optics techniques have provided ground-based astronomers with space-quality images. With rapid, real-time analysis of the time-varying spread of light from a star or other point source (termed a guide star), a computer-controlled deformable mirror corrects for the distortion introduced by atmospheric turbulence and restores crisp detail to images. But the corrections are effective only for light arriving from essentially the same direction, and that limits the field of view to only about 15 arcseconds. An international team led by Franck Marchis of the University of California, Berkeley, **[OK?]** has recently demonstrated one technique to overcome that limitation: the Multi-Conjugate Adaptive Optics Demonstrator, or MAD.

MAD uses multiple guide stars and two deformable mirrors to correct for phase distortions over a broader range of angles; the resulting field of view is 30 times larger. Shown here is a false-color IR image of Jupiter obtained with MAD at the European Southern Observatory's Very Large Telescope in August. The moons Io and Europa, on either side of Jupiter at the time, served as guide stars. The corrected angular resolution was less than a tenth of an arcsecond—details about 300 km across could be resolved. In the observed region of the IR, absorption by hydrogen and methane is strong. The image thus maps the distribution of the planet's high-altitude haze. A comparison with images taken three years ago by the *Hubble Space Telescope* reveals significant changes in the haze distribution; the researchers attribute those changes to a planet-wide upheaval last year. Michael Wong presented the team's results at the October meeting of the American Astronomical Society's Division for Planetary Science in Ithaca, New York. (Image courtesy of ESO/F. Marchis, M. Wong, E. Marchetti, O. Amico, and S. Tordo.)

To submit candidate images for Back Scatter, visit http://www.physicstoday.org/backscatter.html.

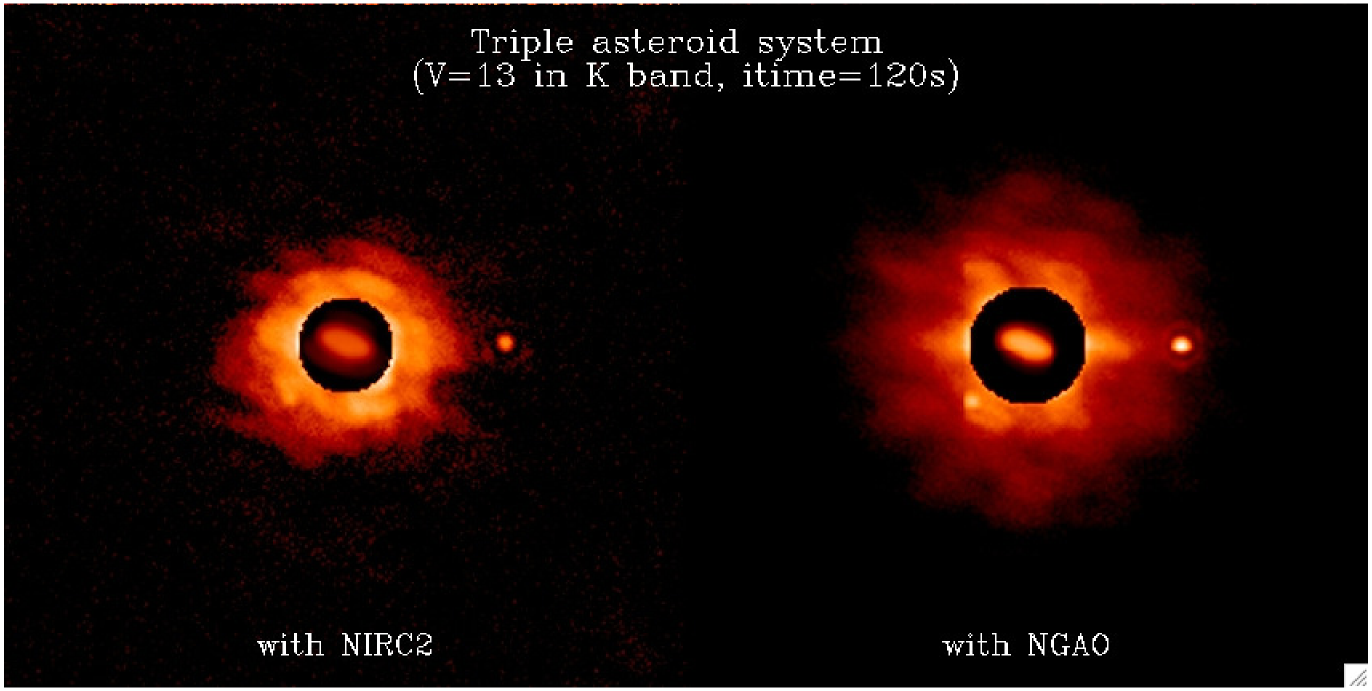
104 December 2008 Physics Today www.physicstoday.org

Simultaneous PRs ESO & UC-Berkeley published on Oct 2 2008

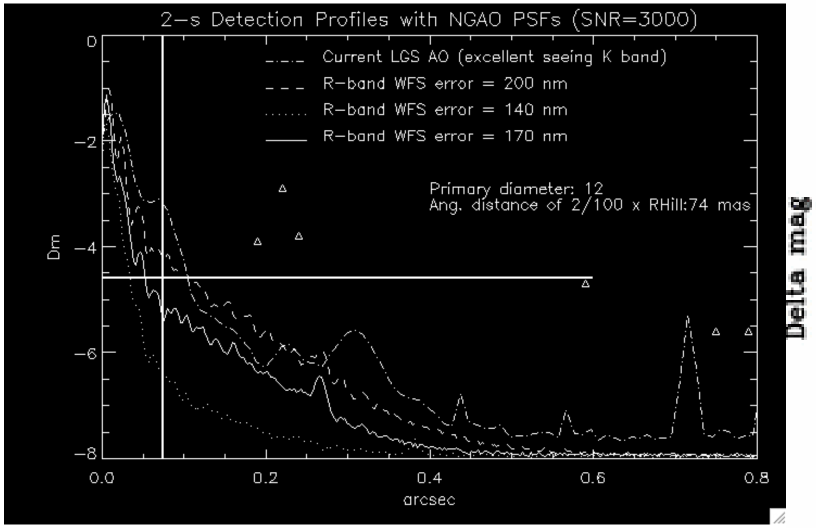
- APOD
- National Geographic
- Space.com
- Major Newspapers
- scientific journals (WIRED)
- Physics Today
- and so on…

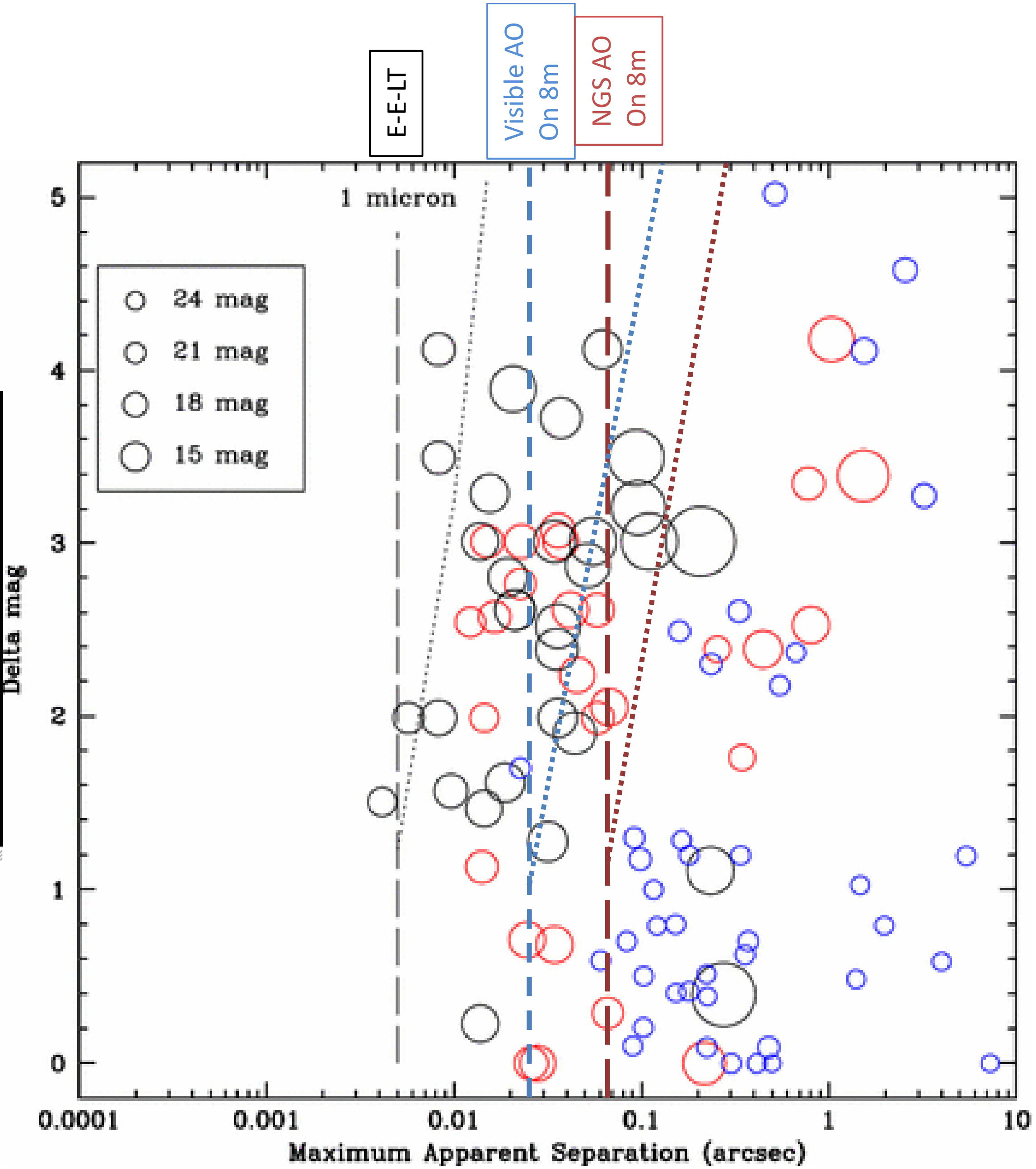
Future AOs for Planetary Science

- Future AO instruments. My wish list…
  - Better angular resolution (Visible AO)
  - Better sensitivity (high SR ~70-80%)
  - Enhance "observability" V_{lim} ~ 17
  - Imaging & spectroscopy observations



Simulated Observation: 17th-mag asteroid with 2 moons Dm~6.5 & 7.5 Simulated with 170 nm rms error Keck-NGAO

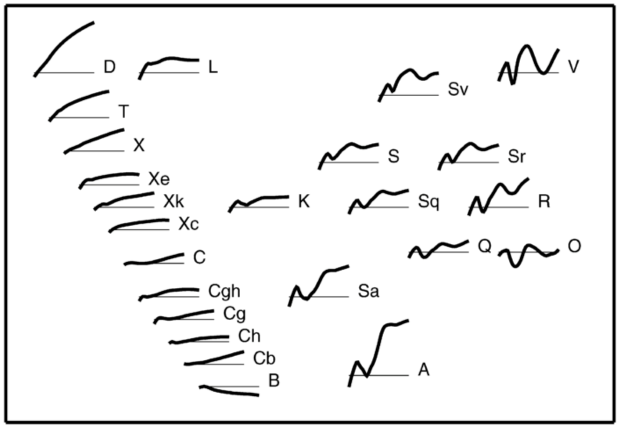


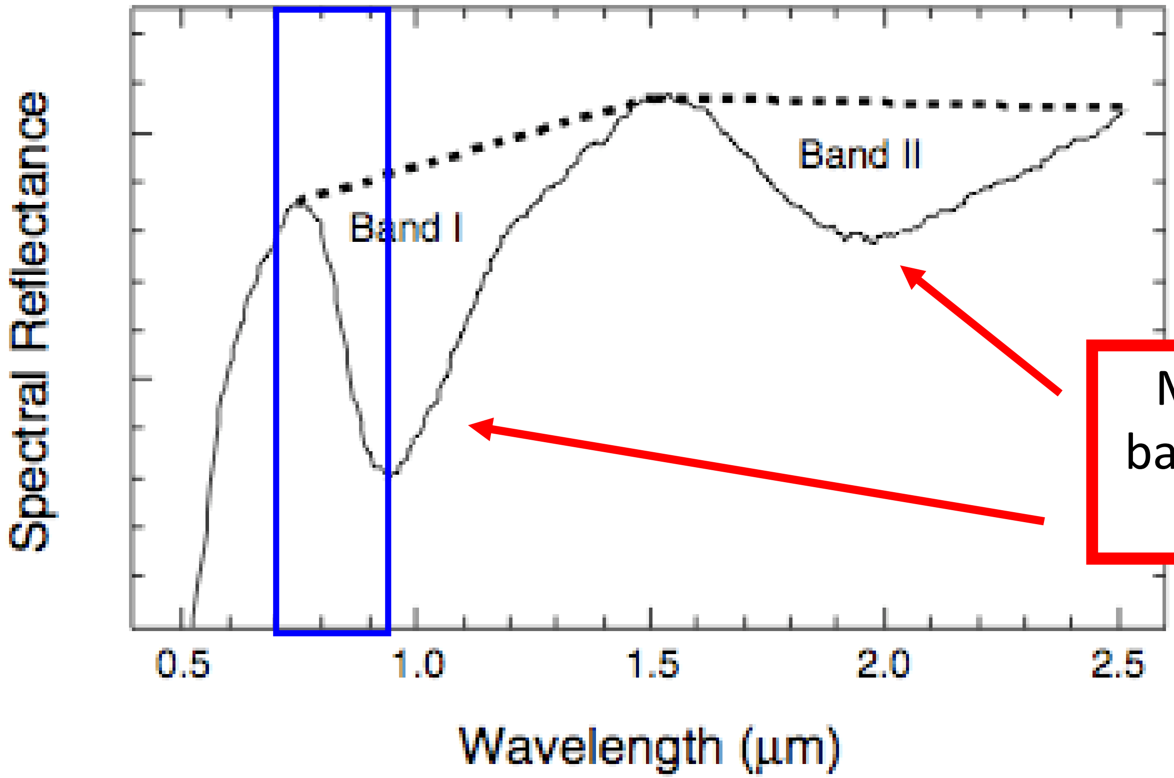


Estimates for the difference in binary component magnitude as function of maximum separation for known binary NEA, MBA, TNO (from Walsh, 2009)

Low resolution spectroscopy

- Pyroxene/Olivine Band I and Pyroxene Band II
- Visible wavelength range -> characterize the surface composition



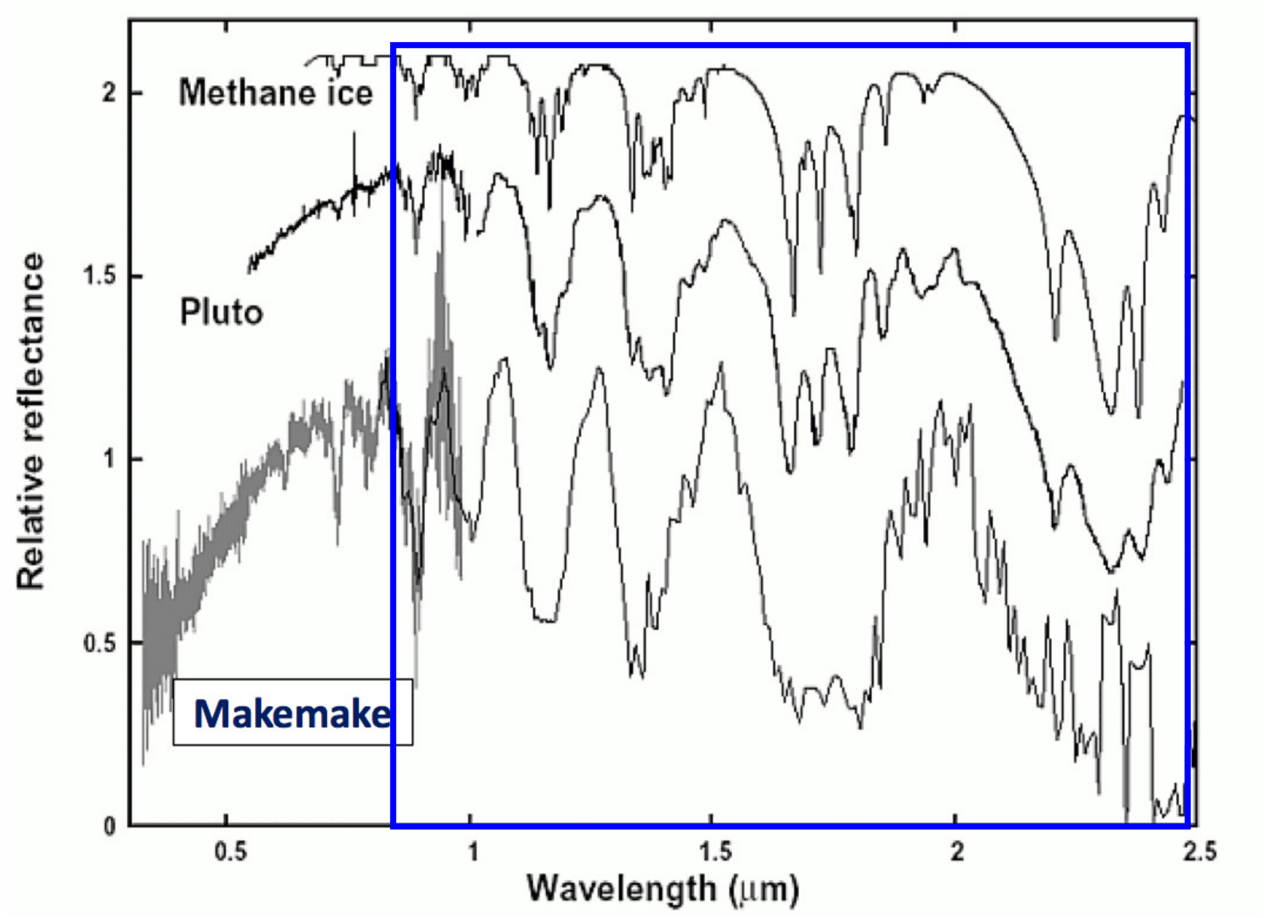


R~100 spectrum

Mafic absorption bands centered at 1 and 2 υm

Medium resolution spectroscopy

- Numerous bands of ices (CH_4, H_2O, NH_3)
- Visible wavelength range -> characterize the surface composition

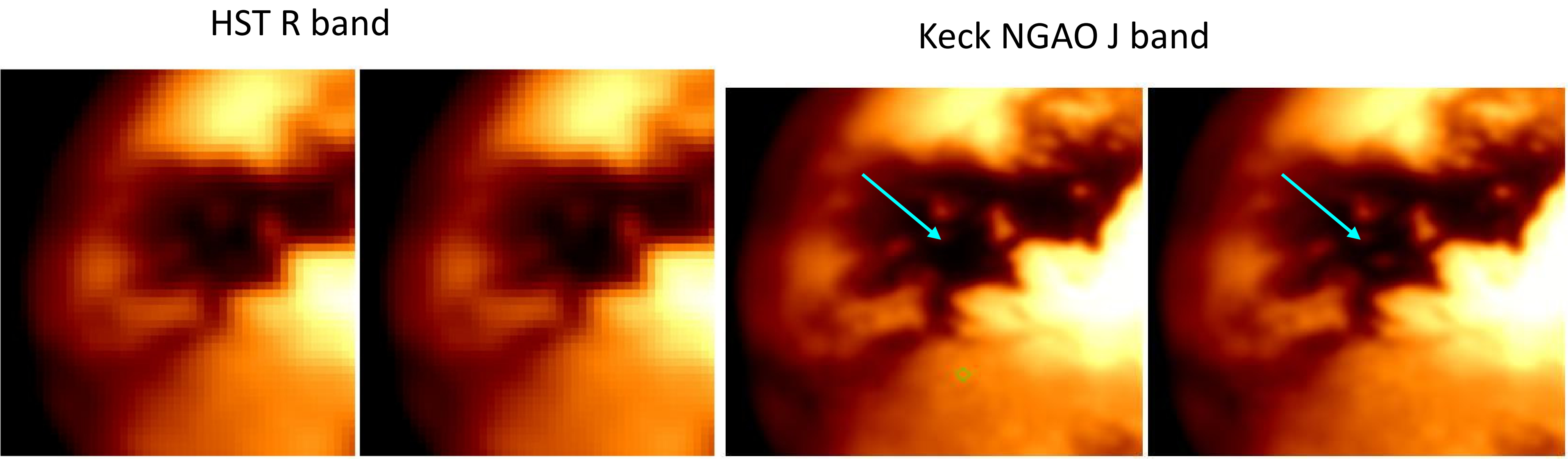


R~1000 spectrum

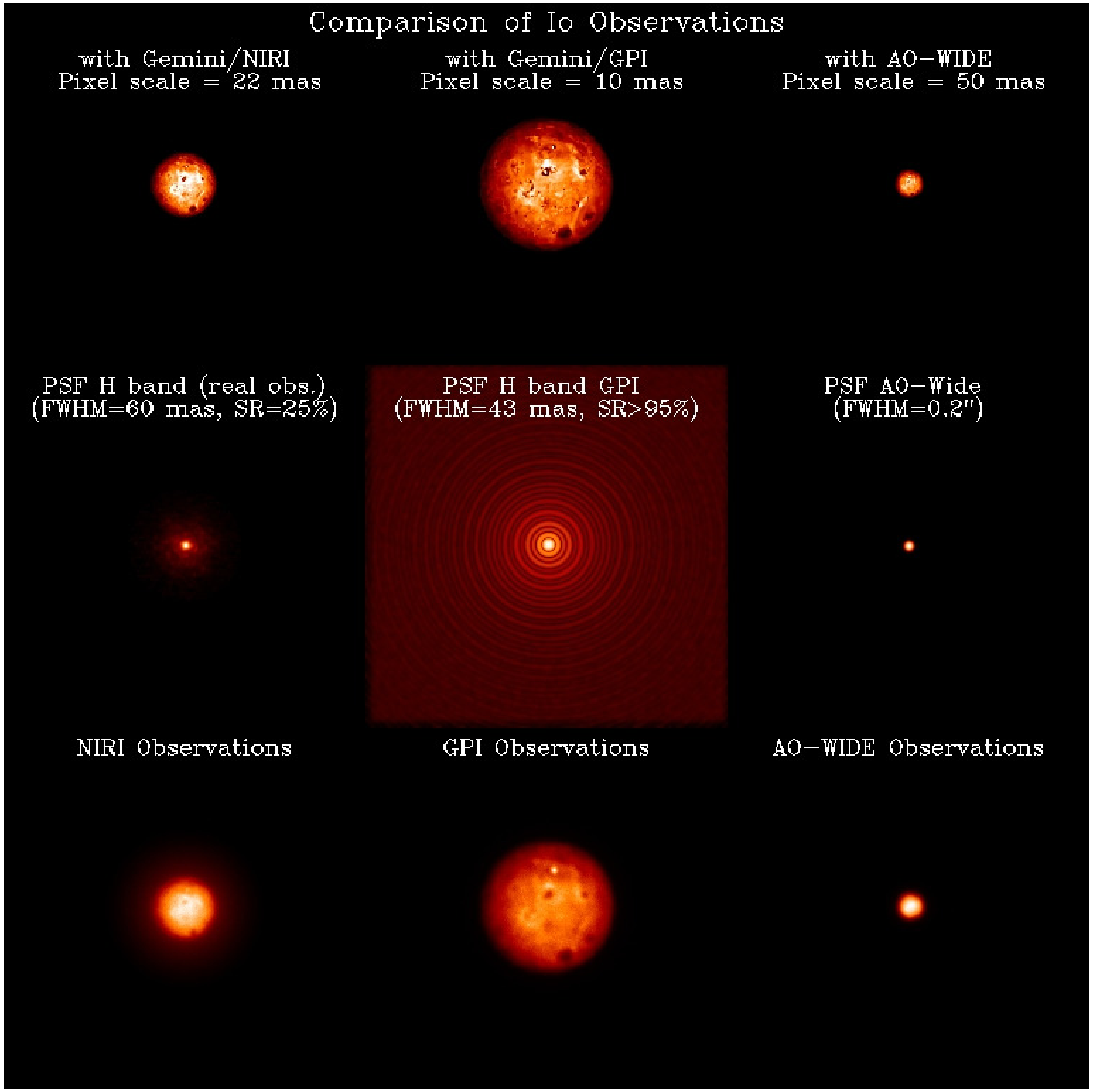
Next Generation of AOs for Planetary Science

- Satellites of Giant Planets
  - Better stability (->more efficient deconvolution) to characterize atmospheric and volcanic surface changes
  - Medium spectra resolution (R~1000) between 0.8-2.5 υm with IFS to characterize the surfaces and atmosphere (Titan)

Simulation a cryovolcanic surface change on Titan



Future AOs for Planetary Science



Future Gemini AO

I have a dream…

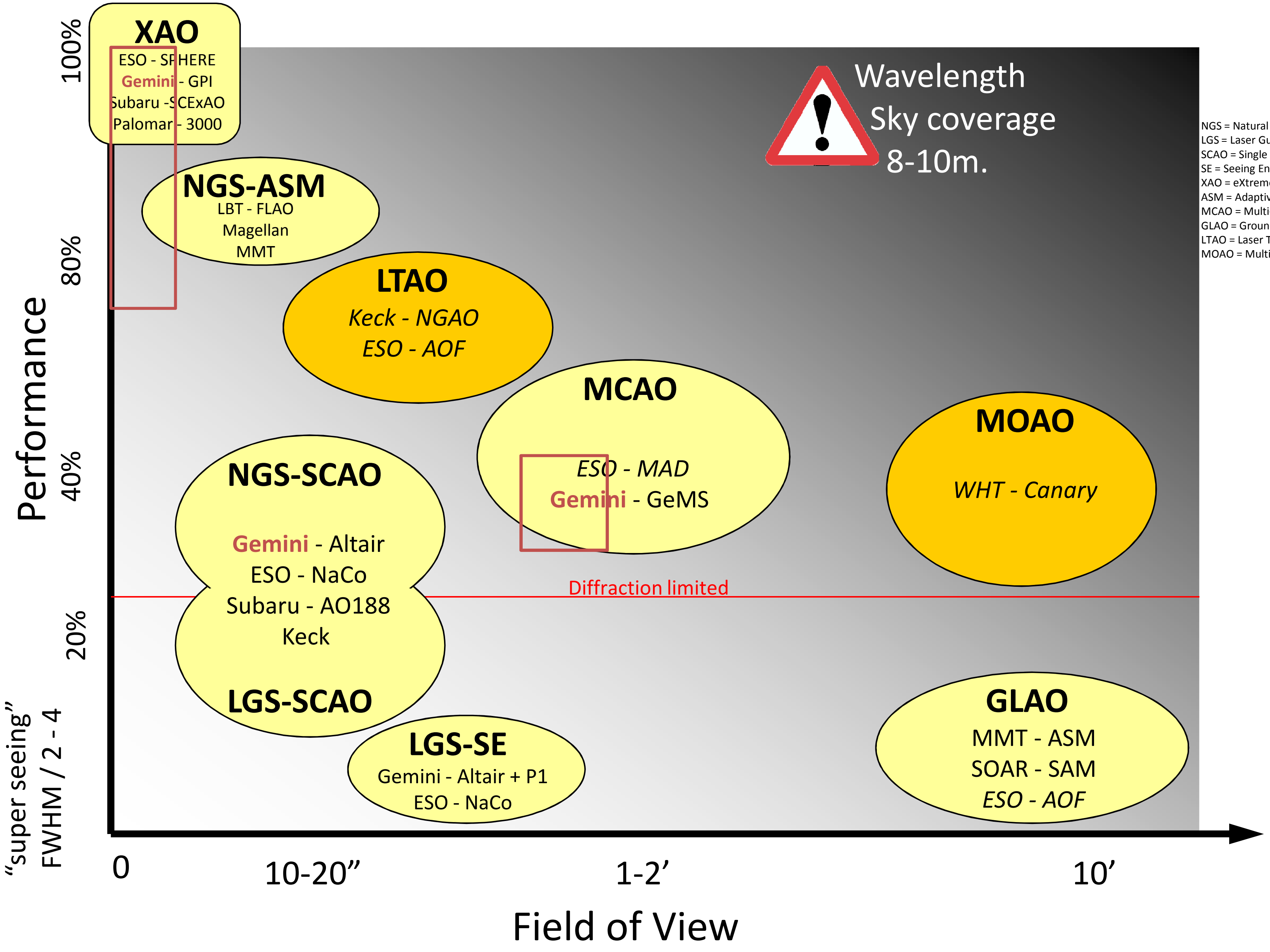
- **Asteroids, Shape & Multiplicity**
  - Corrected FOV < 2”, V_{lim} < 17, SR>70% in K, SR>20% in R band
  - Vis/NIR (0.7-2.5 um) imager at Nyquist sample
  - IFU low Res~100 (complete 1-cube coverage?)

- **Satellites of Giant Planets**
  - Corrected FOV < 3”, V_{lim} < 17, SR>70% in K, SR>20% in R
  - IR WFS (to minimize the glare contamination from the planets)
  - Vis/NIR/Thermal IR (0.7 – 5 um) imager at Nyquist sample
  - IFU (0.8-2.2 um) Res ~1000

- **Atmosphere & Rings of Giant Planets**
  - Large corrected FOV (>50”), V_{lim} <17, SR=30% in H band
  - IR WFS (to minimize the glare contamination from the planets)
  - Vis/Thermal (1 – 5 um) imager at Nyquist sample
  - IFU (0.8-2.2 um) Res ~1000

We have the tools to refine the characteristics of your AO system. Ask us…

What's your favorite AO flavor ?



XAO
ESO - SPHERE
Gemini - GPI
Subaru - SCExAO
Palomar - 3000

NGS-ASM
LBT - FLAO
Magellan
MMT

LTAO
Keck - NGAO
ESO - AOF

MCAO
ESO - MAD
Gemini - GeMS

MOAO
WHT - Canary

NGS-SCAO
Gemini - Altair
ESO - NaCo
Subaru - AO188
Keck
LGS-SCAO

LGS-SE
Gemini - Altair + P1
ESO - NaCo

GLAO
MMT - ASM
SOAR - SAM
ESO - AOF

Wavelength
Sky coverage
8-10m.

Diffraction limited

Performance
100%
80%
40%
20%
"super seeing"
FWHM / 2 - 4

0
10-20"
1-2'
10'
Field of View

NGS = Natural Guide Star
LGS = Laser Guide Star
SCAO = Single Conjugate AO
SE = Seeing Enhancer
XAO = eXtreme AO
ASM = Adaptive Secondary Mirror
MCAO = Multi-conjugate AO
GLAO = Ground Layer AO
LTAO = Laser Tomography AO
MOAO = Multi-Object AO

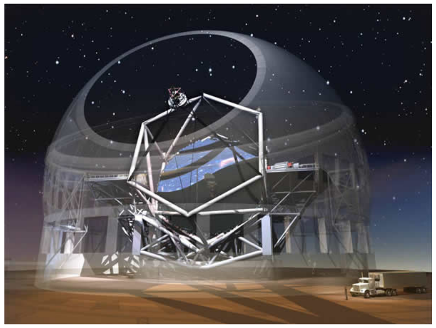
Future Gemini AO

- Take advantage VG seeing to schedule the visible AO obs in the Gemini Queue
- Slit spectroscopy for low R is possible
- Polarimetry? Still unclear. GPI/SPHERE?

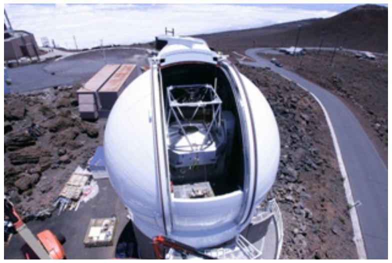
"Prediction is very difficult, especially if it's about the future. " *Niels Bohr*

X12 more SSSBs in 10 years? New populations? The unexpected? (interstellar interlopers?)

ELTs



Pan-STARRS



LSST

NGCFHT