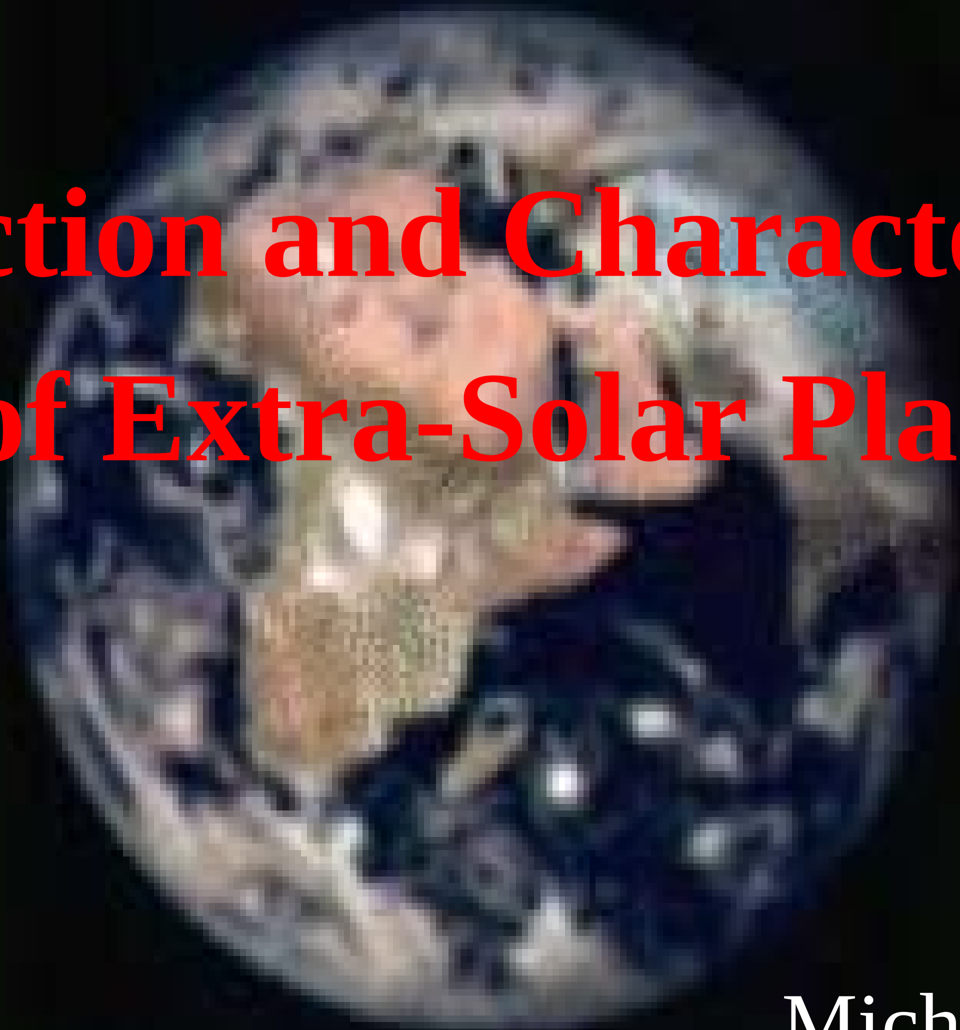
Detection and Characterization of Extra-Solar Planets



Michael Perryman

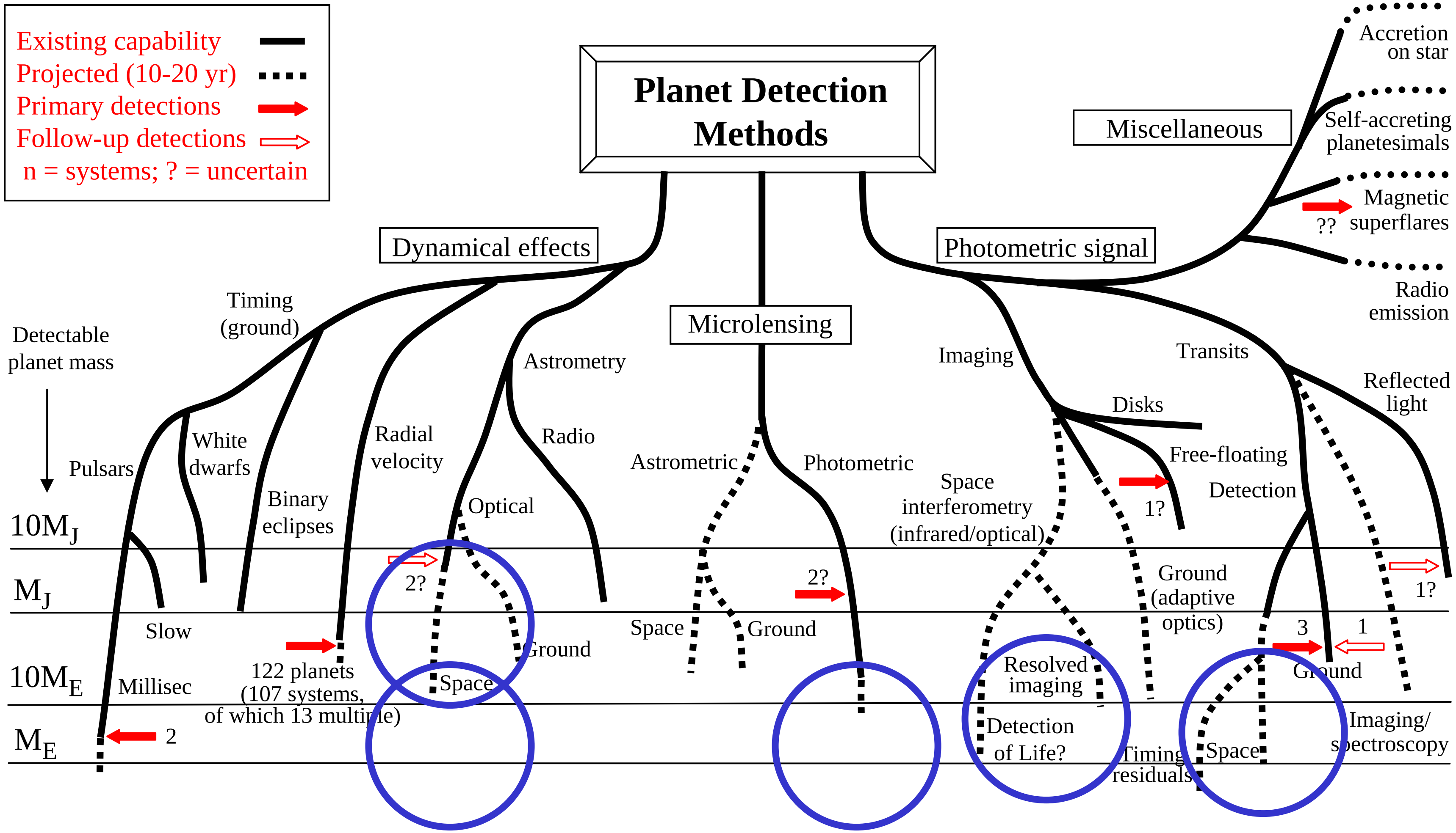
European Space Agency

Exploring the Cosmic Frontiers

Planet Detection Methods

Michael Perryman, Rep. Prog. Phys., 2000, 63, 1209 (updated May 2004)

[corrections or suggestions please to michael.perryman@esa.int]



* OGLE P<2 days

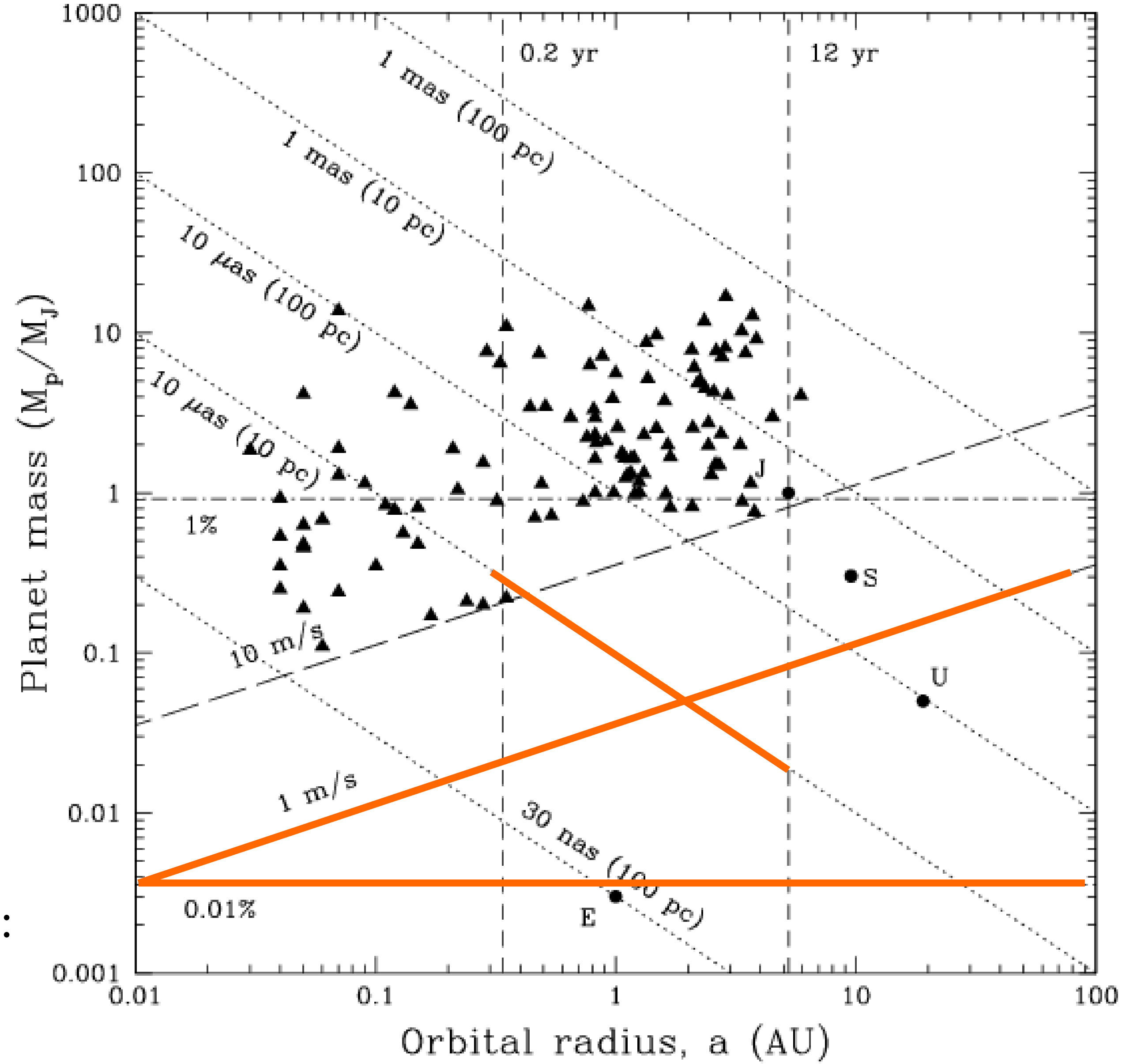
What will not be covered…

- Observations of protostellar disks, formation, evolution, migration, stability, etc
- Review of ground-based surveys:
  - radial velocity: 15 ongoing 3 planned
  - transit: 13 2
  - micro-lensing: 5 -
  - imaging (detection): 2 8
  - radio: 2 (+ pulsar) -
  - astrometry: 1 2
- Space observations by HST, Spitzer, JWST
- Capabilities of OWL/ELT (see talk by Hainaut)

Detection domains:

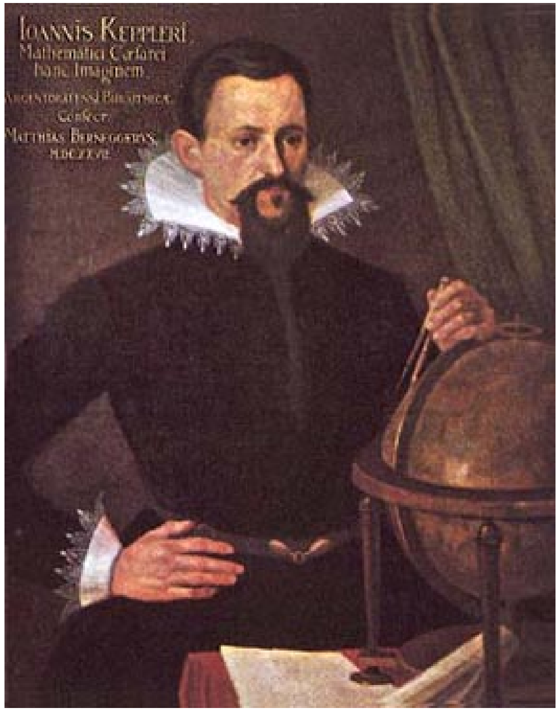
- radial velocities
- astrometry
- transits

- Not shown:
  - imaging/detection
  - lensing



These address different types of objects, with at least two different goals: **formation; habitability**

MOST: launched June 2003, 15cm
('working beautifully', results soon…)
COROT: launch planned June 2006
HST bulge: Sahu 100-200 expected



Launch: Oct 2007

http://www.kepler.arc.nasa.gov/

Kepler (NASA)

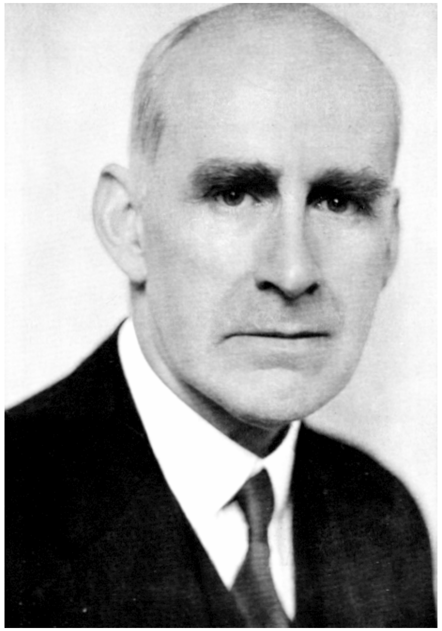
Method:
- high precision, long-duration photometry
- 1 m telescope, 12° field
- 10^5 main sequence stars, V<14 mag

Objectives:
- photometric transits for Earth-like objects

Results:
- **terrestrial inner-orbit transits:**
  - **50/185/640 with R ~ 1.0/1.3/2.2 R_{Earth}**
- **giant inner planets from reflected light:**
  - **~ 870 planets with P < 1 week**
- **giant planet transits:**
  - **135 inner-orbit planets + 30 outer orbit**

To note:
- sensitive to acceptable S/N
- monochromatic observations

Eddington (ESA)



Launch: TBC

http://www.rssd.esa.int/Eddington

Method:

- high precision, long-duration photometry
- 1.2 m telescope, 3° field
- 5×10^5 stars, V<18 mag

Objectives:

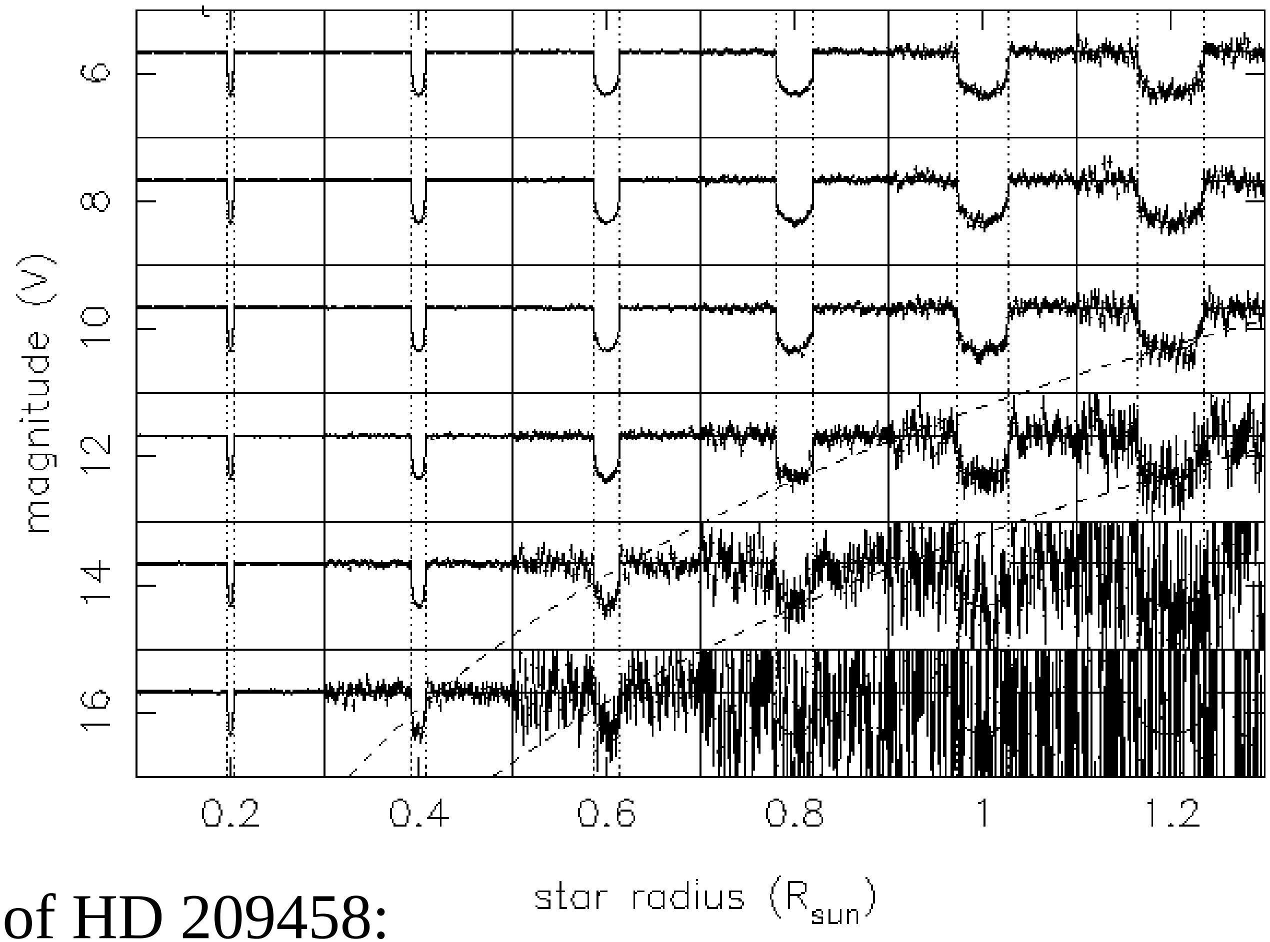
- asteroseismology + photometric transits

Results:

- **20,000 planets with $R < 15\ R_{Earth}$**
- **2000 terrestrial planets**
- **dozens of Earth-like planets**

- Approved: 2002
- Cancelled: Nov 2003
- Studies continue in context of future options

Transits of habitable Earths



Physical diagnostics of HD 209458:

- detection of sodium (Charbonneau et al 2003)
- extended hydrogen exosphere (Vidal-Madjar et al 2003)
- detection of O and C (Vidal-Madjar et al 2004)
- search for CO (Brown et al 2002, Deming et al); water (Rojo et al)

Gaia (ESA)

Launch: 2010

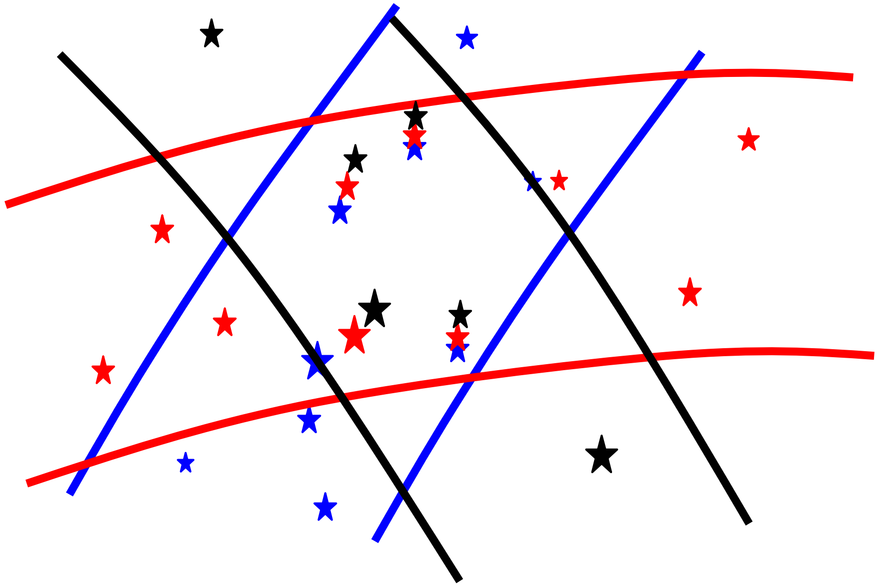
http://www.rssd.esa.int/GAIA

Method:

- astrometry, Hipparcos principles
- two 1.4×0.5 m^2 mirrors + CCDs
- continuous 'revolving' sky scanning
- 5-year observations: 100 epochs per star

Objectives:

- distances + motions for 10^9 stars
- 10-20 microarcsec at 15 mag
- structure and evolution of Galaxy

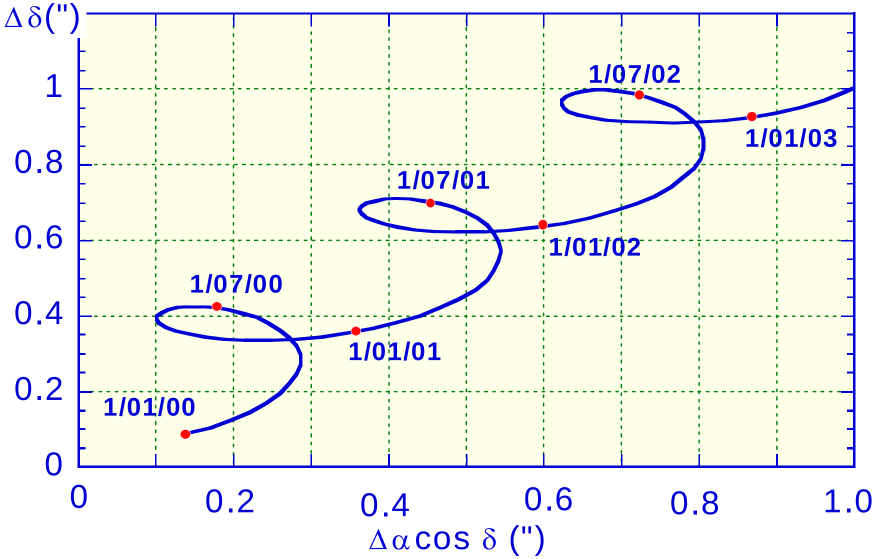


Gaia: Planet motions

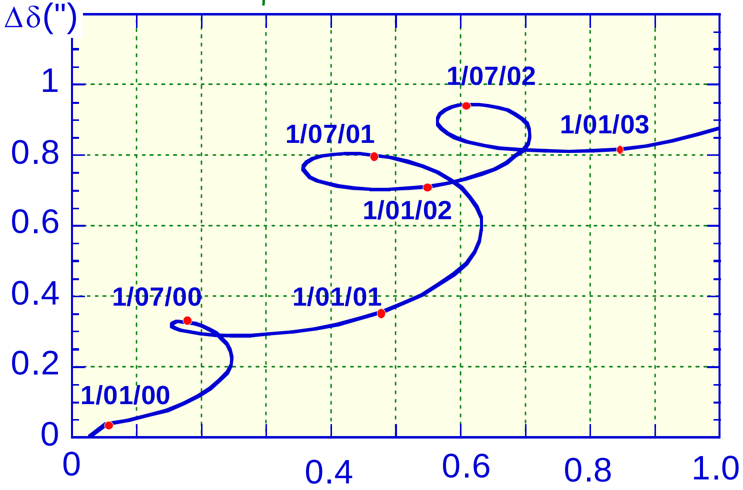
μ ~ 250 milliarcsec/year

π ~ 100 milliarcsec

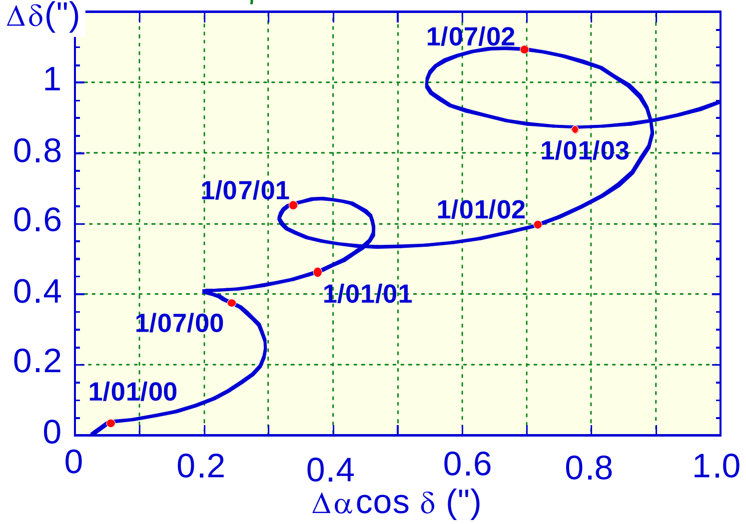
Single star



Planète : ρ = 100 mas P = 2.5 ans



Planète : ρ = 100 mas P = 18 mois



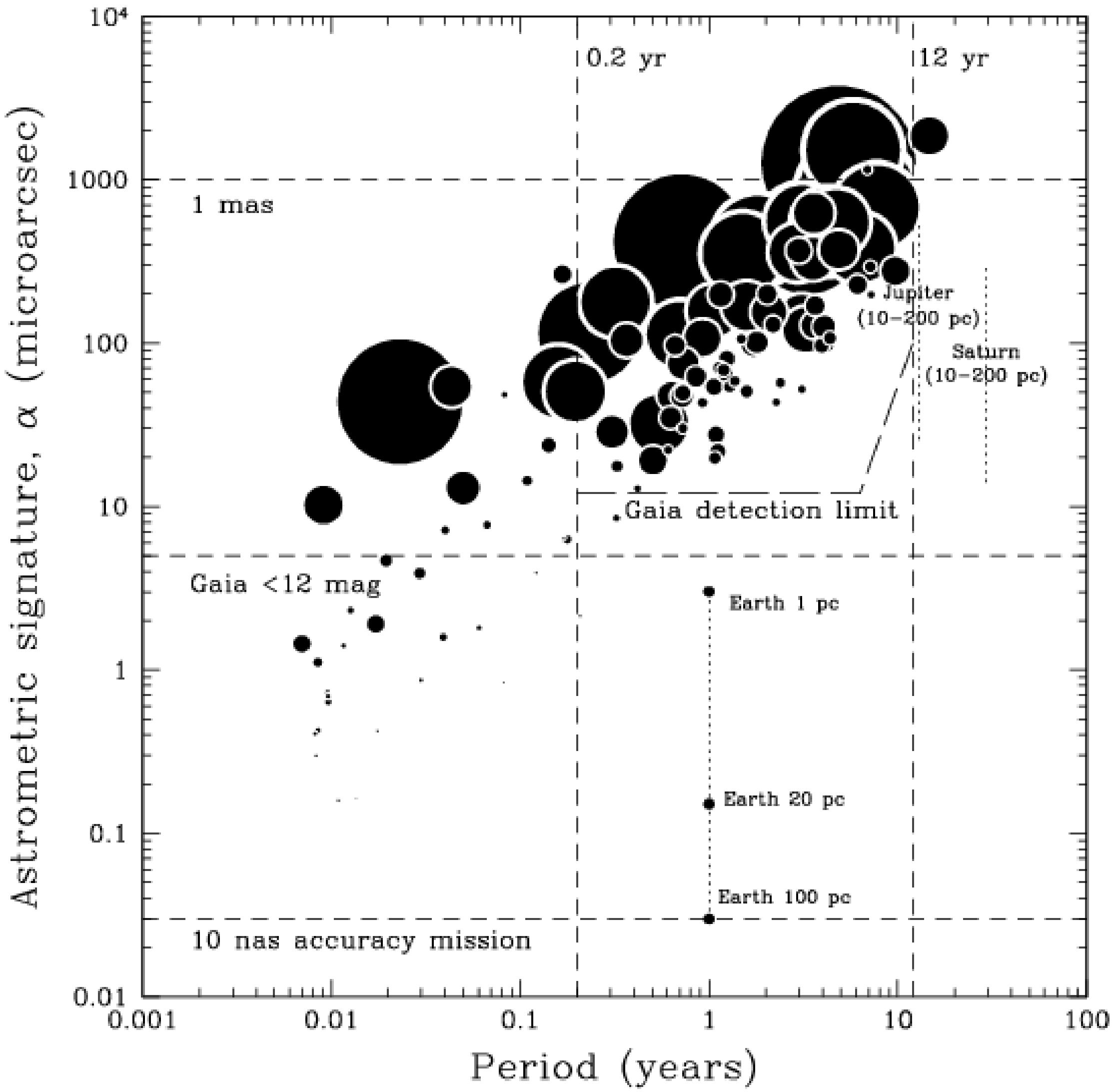
… and their resulting astrometric signatures

$$\alpha = \left(\frac{M_p}{M_s}\right)\left(\frac{a_p}{d}\right)$$

...α in arcsec if *a* in AU
and *d* in pc

At 10 pc:

Jupiter: 500 μarcsec
10 Earth: 3 μarcsec
Earth: 0.3 μarcsec



Gaia: Expected Astrometric Discoveries

- Survey to 150–200 pc:
  - complete census of all stellar types; periods in range 2–9 years
  - primarily sensitive to Jupiter-type systems
- Large-scale detection and physical characterisation:
  - detection of 20–30,000 planetary systems
  - masses, rather than lower limits ($M \times \sin i$)
  - orbits for ≈5000 systems + multiple systems: relative inclinations
  - mass down to 10 M_{Earth} to 10 pc
- Photometric events:
  - transits: ~4000 'hot-Jupiters' possible
  - planetary collisions: Zhang, ApJ2003, 596, L95: 2×10^9* for 1 year

SIM (NASA)

Launch: 2009

Mission:

- pointed interferometer
- baseline: 10 m

Objectives:

- astrometric detection
- 1-4 microarcsec to 20 mag
- survey: thousands of stars
- detailed orbits
- **planet programmes:**
  - **50 epochs × 1 hour each**
  - **250 stars at 1 microarcsec**
  - **2000 stars at 4 microarcsec**

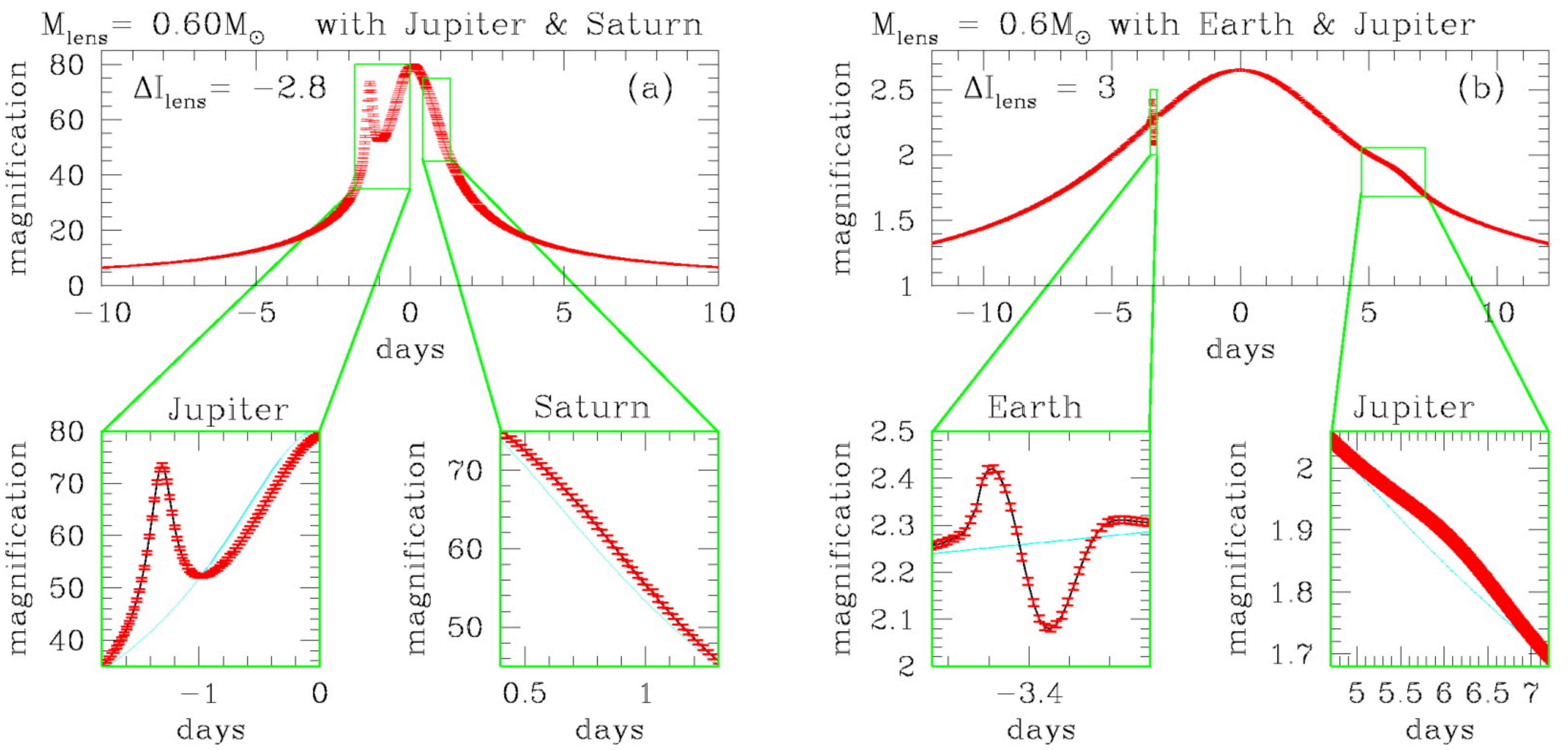
GEST

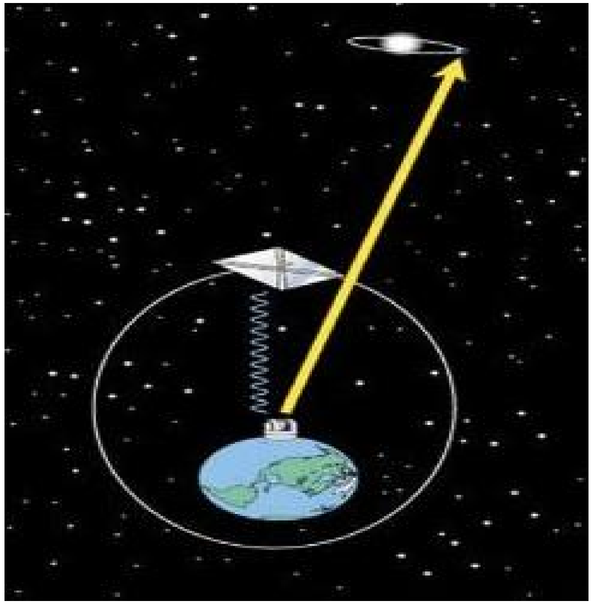
- microlensing
- 1.5 m aperture
- 1.25° field
- targets: 10^8 distant, bulge main-sequence stars

Objectives:

- ~100 Mars-Earth mass between 0.7-10 AU
- free-floaters (if by-products of formation)
- 50,000 giant planets via transits

Status: not selected in 2002 Discovery, but re-proposal expected in 2004





BOSS (and UMBRAS, CORVET, NOME)

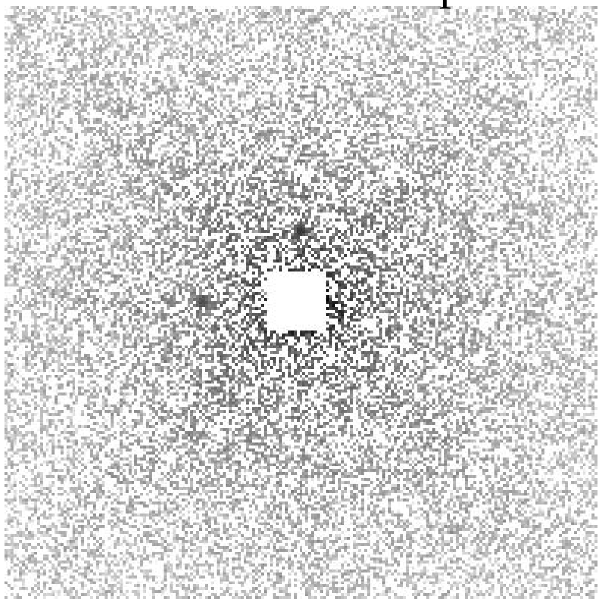
Concept: Big Occulting Steerable Satellite

- e.g. 70×70 m^2 occulting screen
- solar sailing + ion/chemical propulsion
- e.g. used in conjunction with JWST at L2
- Copi & Starkman 2000, ApJ 532, 581
- but: TPF focusing on interferometry/coronography

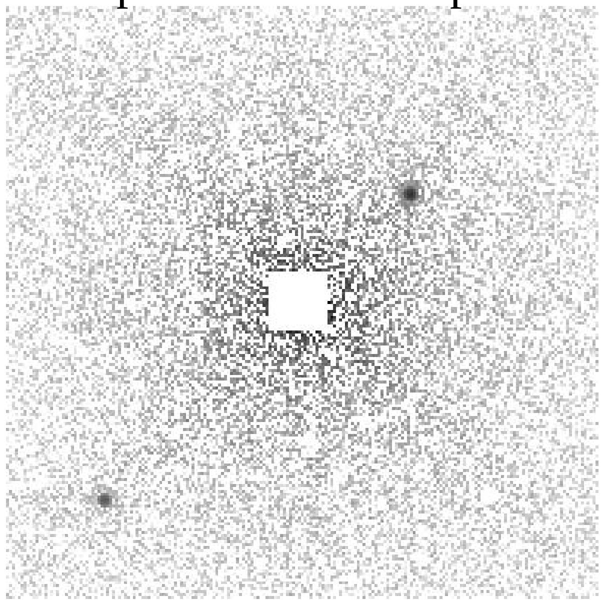
Results (C&S 2000):

- 2×2 $arcsec^2$ 'solar systems'
- λ = 1μm
- 8m telescope, t = 3000s
- separations of 0.1–0.2 arcsec
- 10^{-9} at 8 mag

Venus/Earth at 3 pc



Jupiter/Saturn at 10pc



Biomarkers: a synposis

- terrestrial atmospheres: degassing
- transition to life: ~ 4 billion years ago
- photosynthetic cyanobacteria: ~ 2 by

from photodissociation of H_2O

$$CO_2 + H^+ \rightarrow \text{organics} + O_2$$

photosynthesis

Biological activity

760 nm tracer (but Earth O_2-free until -2 Gyr)

anaerobic decomposition of organics; combines with O_2

O_3 (O_2 tracer): 9.6 μm

H_2O: 6-8 μm

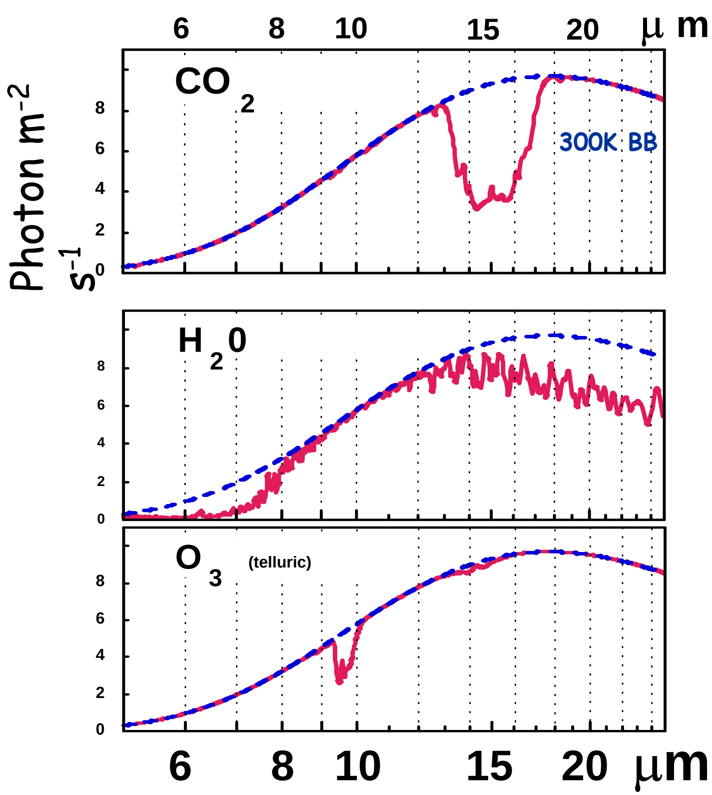
CH_4: 7.7 μm (or shorter)

CO_2: 15 μm

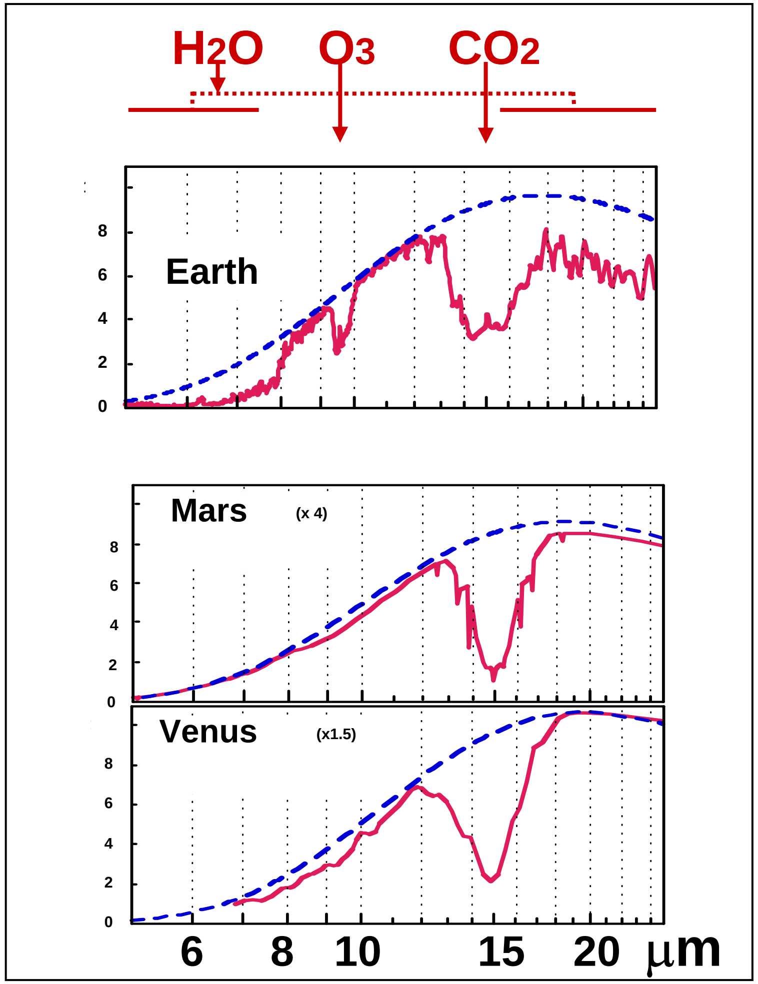
- Absence of $O_2 \neq$ absence of life
- Simultaneous detection of $CH_4 + O_2 \Rightarrow$ life?
- Simultaneous detection of $H_2O + O_3 \Rightarrow$ photosynthesis?
- Detection of vegetation signature?

Characterizing Earths

Calculated atmospheric spectra ($\lambda/\Delta\lambda = 200$)



Observed spectra



Darwin Study Report (2000)

TPF (NASA)

Launch:

- precursor (TPF-C): 2014
- free-flying interferometer: <2020

Mission (pre-March 2004):

- instrument choice:
  - IR interferometer (40m^2), or…
  - optical coronograph
- scientific choice: reflected or thermal

Objectives:

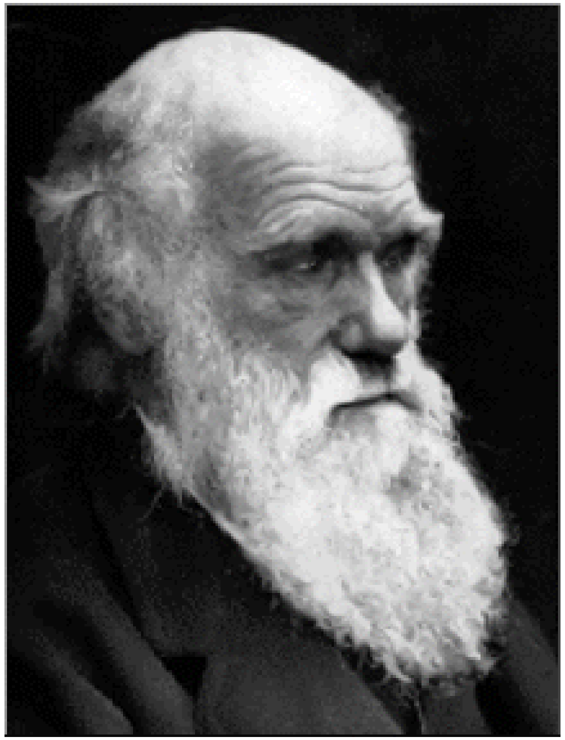
- direct detection of planetary systems
- spectroscopy indicating life
- ozone at 25pc: 2-8 weeks/object

April 2004: NASA announcement:

- 6×3.5m visual coronograph in 2014:
  - 32 nearby stars full search
  - 130 stars incomplete search

  (low p(Earth), but good for Jupiters)
- ESA collaboration for full mission

Darwin (ESA)



Launch: 2015?

Method:

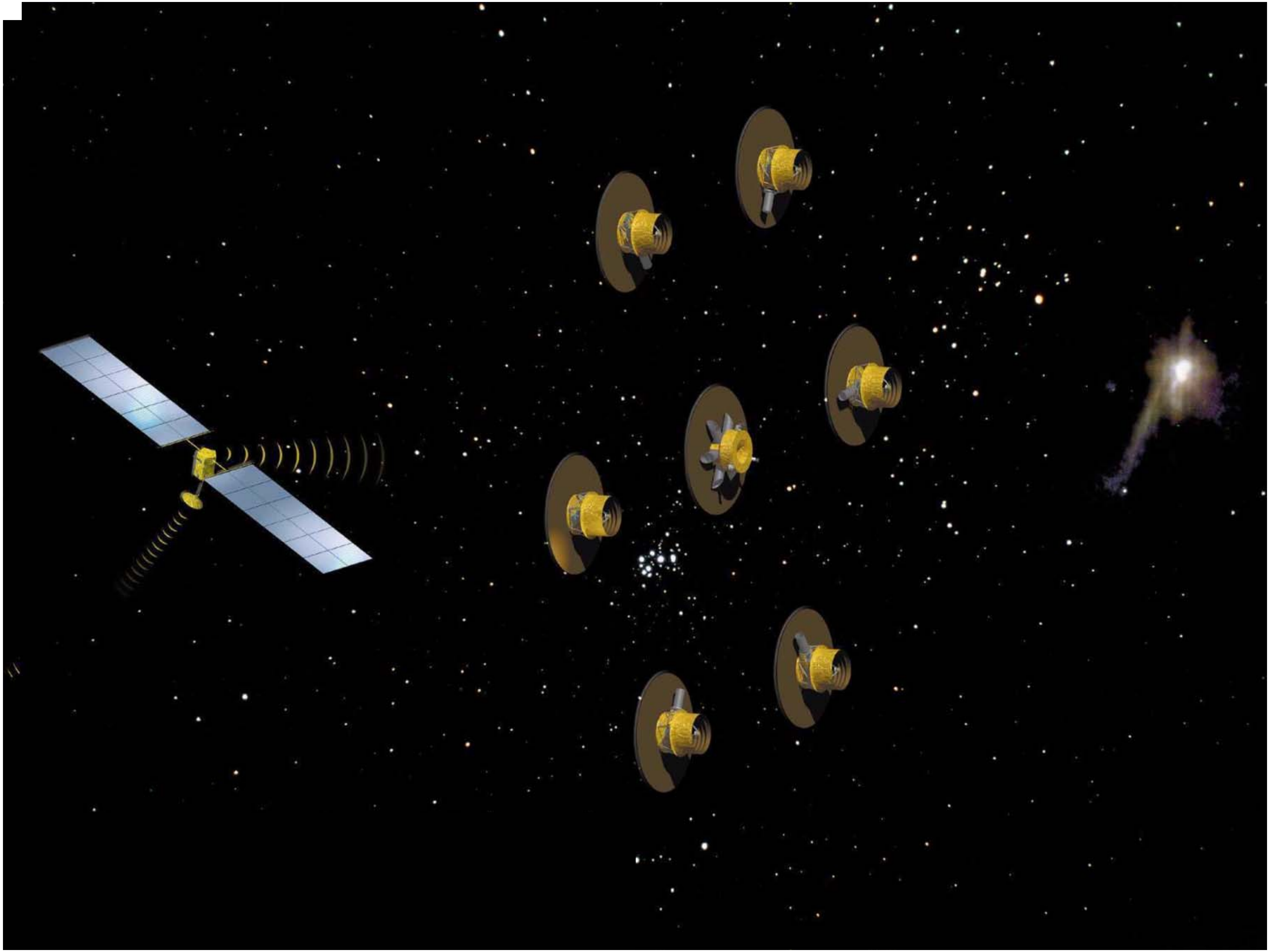
- 20–80 m baseline mid-IR interferometer
- 4 × 2.5 m (was 6 × 1.5) telescopes
- star/planet intensity: 10^6–10^9

Objectives:

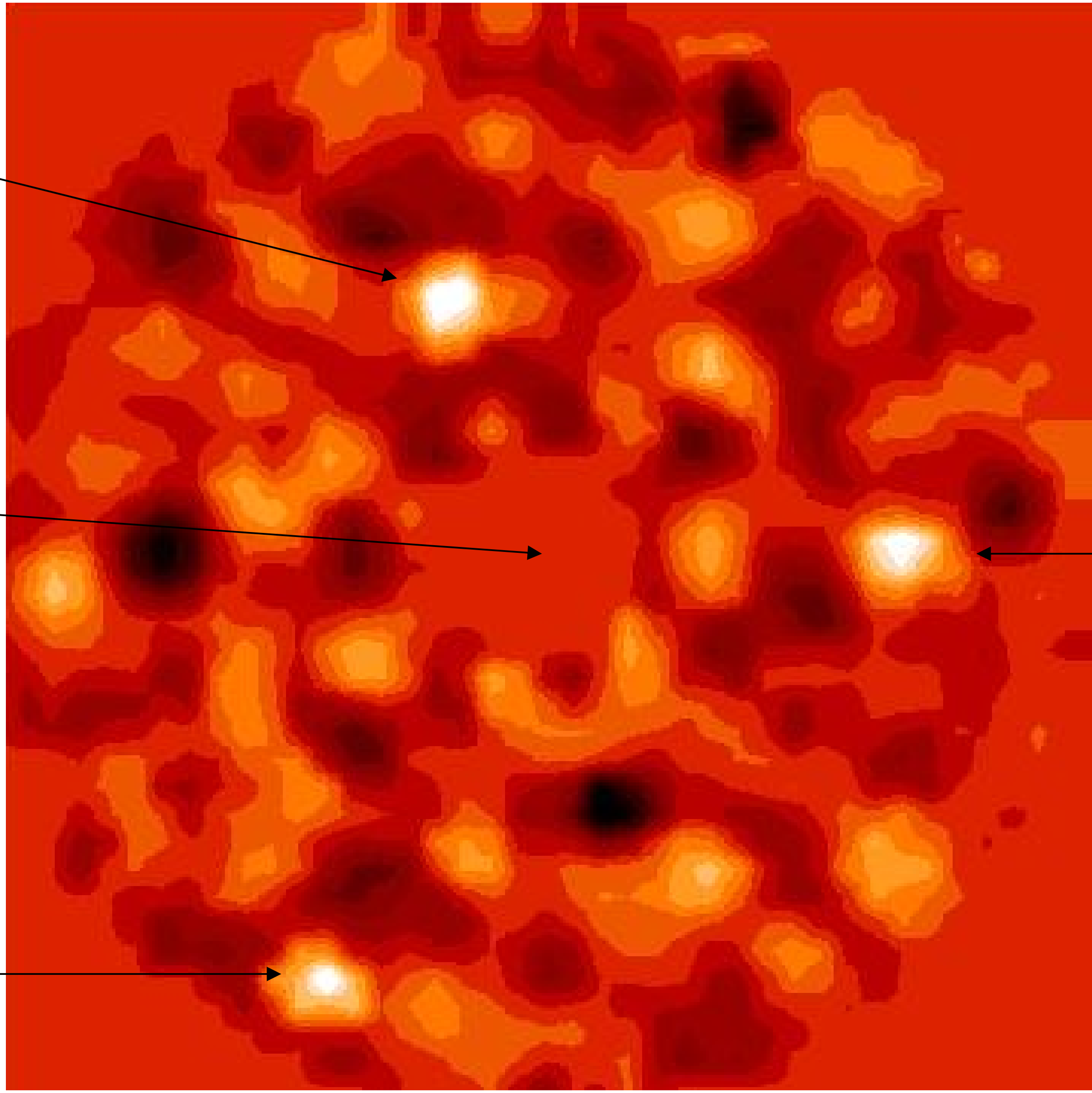
- direct detection
- are Earth-like planets common?
- how do they form?
- detect tracers of life in mid-infrared

Precursors:

- GENIE (ongoing): VLTI nulling interferometer
  - technical precursor, using UTs or ATs, L=3.6μm
  - required for pre-launch study of Darwin targets
  - to ESA/ESO 5-7 May, ESO Council late 2004
- SMART-3 (not yet approved): demonstration of formation flying for 2 spacecraft (Darwin/XEUS)



Darwin/TPF detection (Mennesson & Marrioti 1997)



Interferometry vs Coronography

- Science aspect:
  - is reflected (optical or near IR) or thermal (mid-IR) best to characterise planets (albedo, colour, temperature)?
- Instrumental aspect:
  - is an interferometer or coronagraph the ‘best’?
- NASA technology plan for TPF:
  - “Technology readiness, rather than a scientific preference for any wavelength region, will probably be the determining factor in the selection of a final architecture”
- ESA effort (Darwin) is focused on an interferometer
- Many idea for precursors to TPF, especially in US:
  - which are scientifically driven, decoupled from long-term technology?
  - which are mandatory technology precursors?

Unapproved TPF ‘precursors’: missions/concepts

- **Eclipse**: (Trauger et al. 2003) – 2004 Discovery?
  - 1.8 m + coronograph + wavefront correction – Jupiters to 5 AU for stars to 15 pc
- **JPF**: Jovian planet finder (Clampin et al. 2002) – 2004 Discovery?
  - 1.5 m + coronograph, originally on ISS – Jupiters to 2-20 AU
- **ESPI**: Extrasolar planet imager, Midex, (Lyon et al. 2003)
  - 1.5×1.5 m apodized square aperture – Jupiters around 160 stars to 16 pc

EPIC (JPF + ESPI)

- **ExPO**: Extrasolar planet observatory (Gezari et al. 2003)
  - similar concept to ESPI proposed as Discovery class mission
- **SPF**: Self-luminous planet finder (Woolf et al. 2001)
  - search for younger/more massive Jupiters in Jupiter orbits
- **FKSI**: Fourier-Kelvin stellar interferometer (Danchi et al. 2003)
  - mid-infrared nulling interferometer: detection of 25 EGPs within 10 pc
- **OPD**: Optical planet discoverer (Mennesson et al. 2003)
  - midway between coronography and Bracewell nulling
- **PIAA**: Phase-induced amplitude apodization (Guyon 2003)
  - reflection of an unapodized flat wavefront on two shaped mirrors

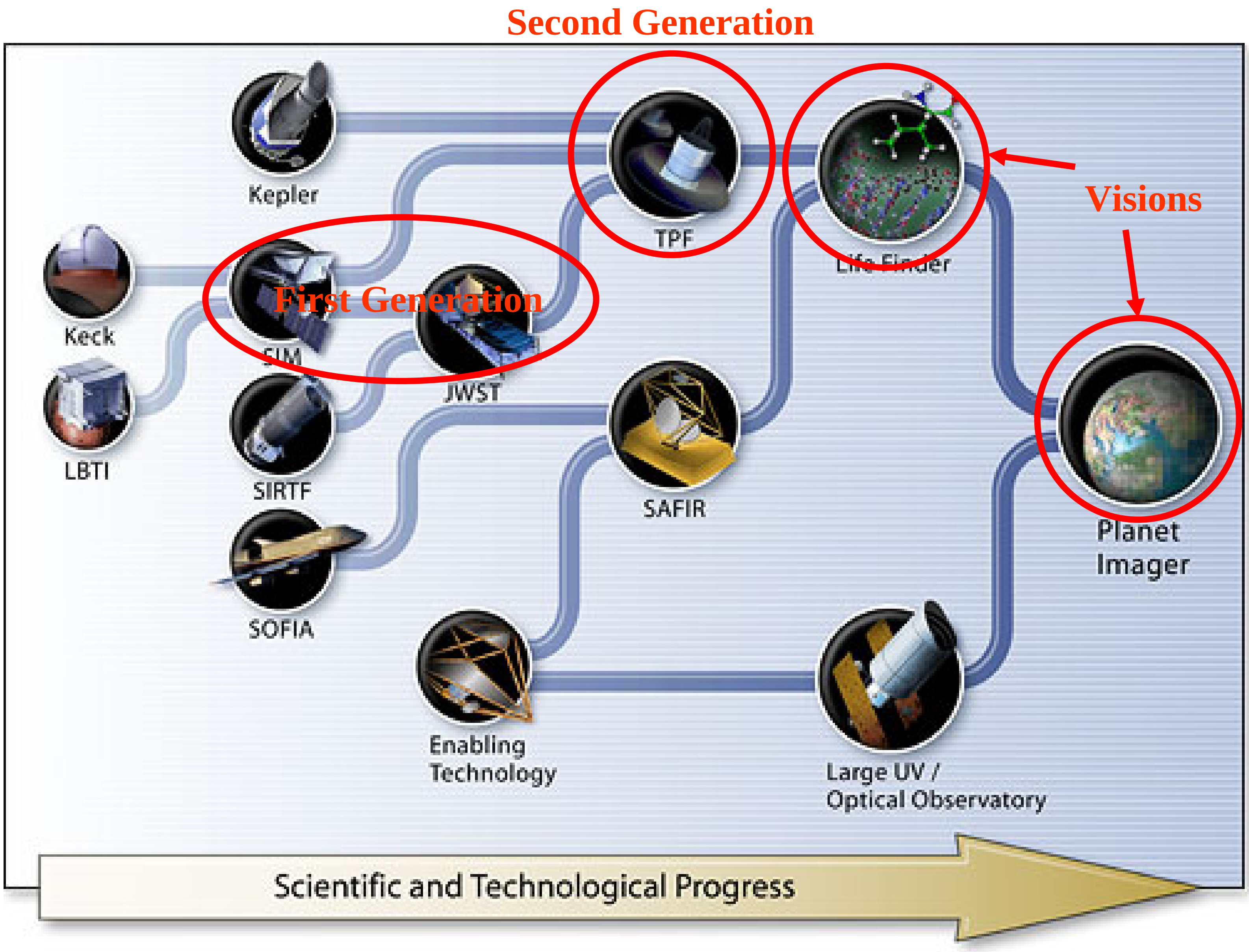
Detection capabilities: Earth at 10pc (Angel 2003)

[$\Delta\theta$=0.1 arcsec, t=24 hr, QE=0.2, $\Delta\lambda/\lambda$=0.2]

Telescope	**Size**	**λ (μm)**	**Mode**	**S/N**	**Comment**
Darwin/TPF-I	4 × 2 m	11	N	8	
TPF-C	3.5 m	**0.5**	**C**	**11**	Typical launcher fairing diameter
"	7 m	**0.8**	**C**	**5–34**	
Antarctic	21 m	11	N	0.5	
		0.8	**C**	**6**	
CELT, GMT	30 m	11	N	0.3	30m too small at 11 μm with coronograph
		0.8	**C**	**4**	
OWL	100 m	11	C	4	Large Φ for IR coronographic suppression
		0.8	**C**	**46**	Optical spectroscopy possible
Antarctic OWL	100 m	11	C	17	Comparable to Darwin/TPF
		0.8	**C**	**90**	Water bands at 1.1 and 1.4 μm feasible

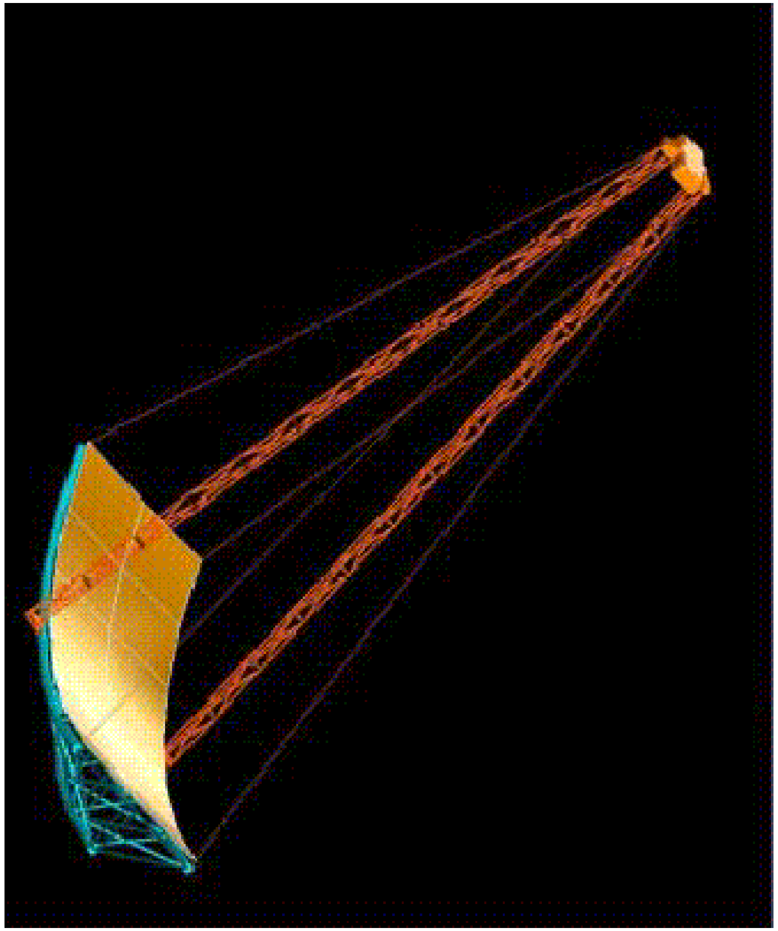
Background = thermal, zodiacal (unknown density), stellar
N = null, C = coronograph
Ground results assume long-term average, fast atmospheric correction

NASA's Origins development



Life Finder

Mini Life Finder (Woolf et al 2001)
50 x 10 m^2, 10 tons (optics+structure)

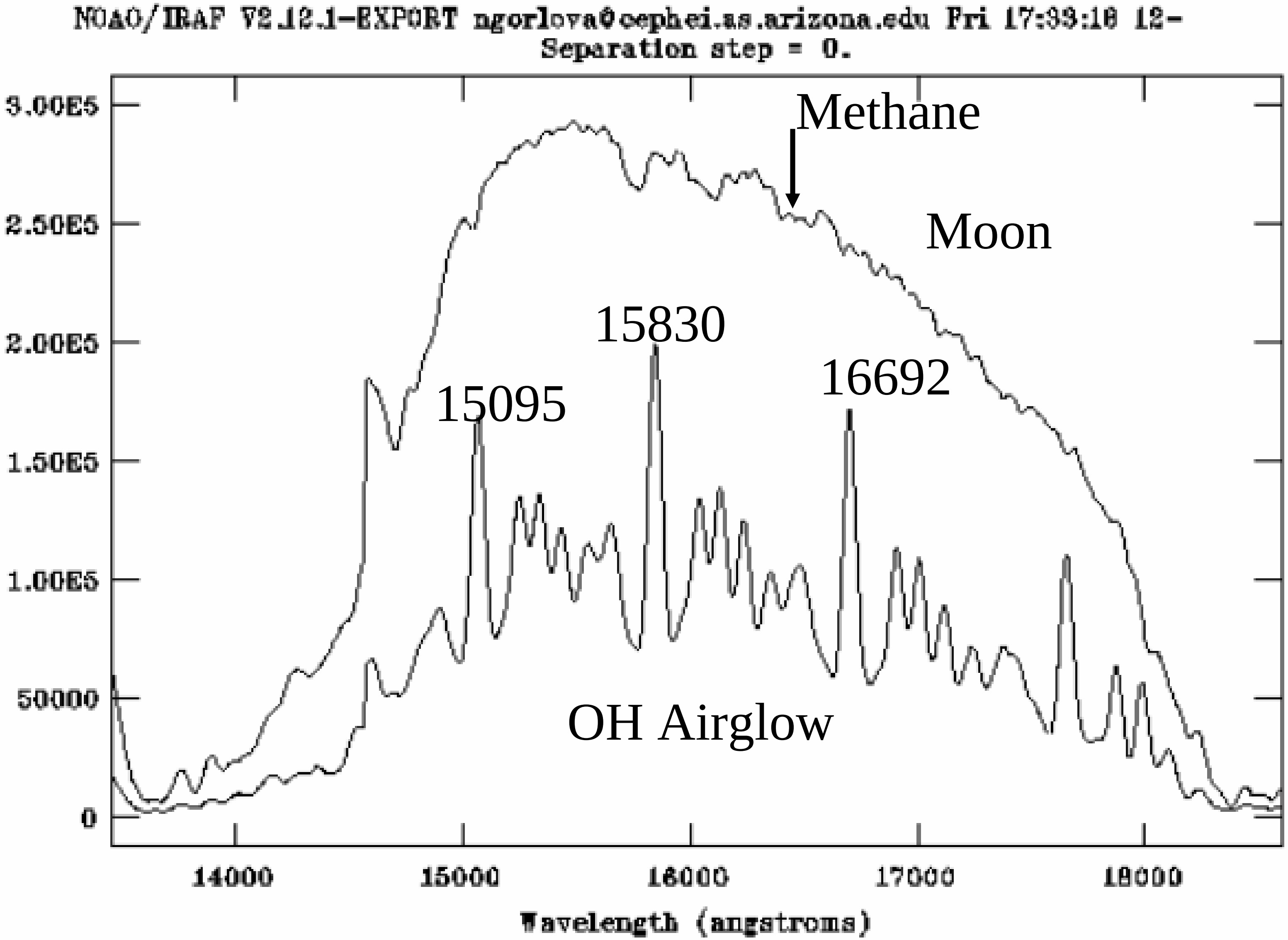


http://www.niac.usra.edu

Objectives: confirm evidence of life revealed by TPF/Darwin (e.g. oxygen/ methane or ‘vegetation signature’). Targets are as faint as HDF galaxies, in star glare at 0.1 arcsec

Developments needed:
- lower mass, better wavefront optics
- pointing/sunshield/vibration damping
- cooling, orbit control
- space assembly: costs $\propto D^3$

Requirements (how big is needed?):
- **for 7.6 μm methane (50m^2 for TPF):**
  - **220 m^2 (5 × 8m) at d = 3.5 pc**
  - **4000 m^2 (80 × 8m) at only d = 15 pc**


NOAO/IRAF V2.12.1-EXPORT ngorlova@cephei.as.arizona.edu Fri 17:33:18 12-
Separation step = 0.
Methane
Moon
15830
16692
15095
OH Airglow
3.00E5
2.50E5
2.00E5
1.50E5
1.00E5
50000
0
14000
15000
16000
17000
18000
Wavelength (angstroms)

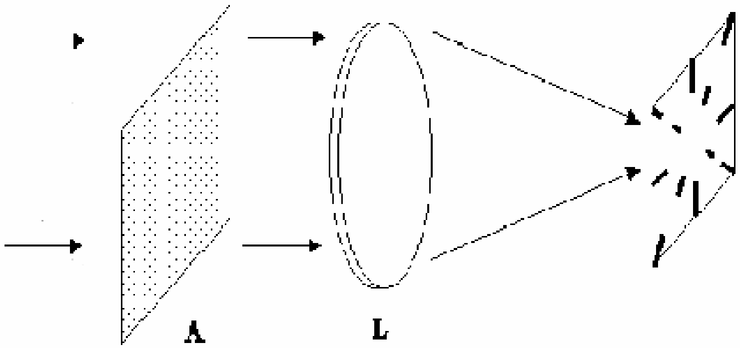
Labeyrie (1999):

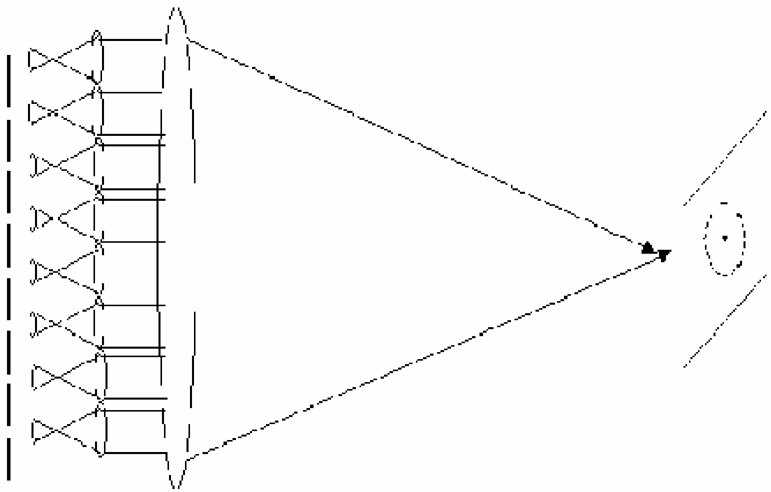
– 150 × 3 m diameter mirrors over 150 km

– densified free-flying ‘hypertelescope’

– detect Amazon ‘green spots’ at 3 pc

Densified exit pupil: exit pupil has sub-pupils with larger relative size than sub-apertures in the entrance pupil





Simulations (Riaud et al 2002):

- 37 × 60 cm infrared telescopes
- baseline = 80 m
- 389 M5-F0 stars < 25 pc
- zodiacal + exo-zodiacal light
- 10-hour ‘snapshots’

Results:

- Earth-like planet detected around 73%

Ground-based imaging:

- Carlina (OVLA-type)
- VIDA: densified pupils on VLTI
- ALIRA: Atacama large IR array
- Antarctic Plateau Interferometer

Earth Imager: imaging of Earth-type planets

- Bender & Stebbins (1996):
  - 10 × 10 resolution elements across ‘Earth’ at 10 pc:
    - 15–25 spacecraft (telescopes) each of 10 m diameter, spread over 200 km
    - image re-constructi on uncertainties (rotation, variable cloud cover, etc)
      (Cho & Seager 2004: large-scale atmospheric flow, coupling of
      land and ocean, and implications for habitability)
  - 100 × 100 resolution elements:
    - 150–200 spacecraft distributed over 2000 km, integration time: 10 years

- Labeyrie et al. (1999)
  - Epicurus: extra-solar earth imager, submitted to ESA F2/F3 AO

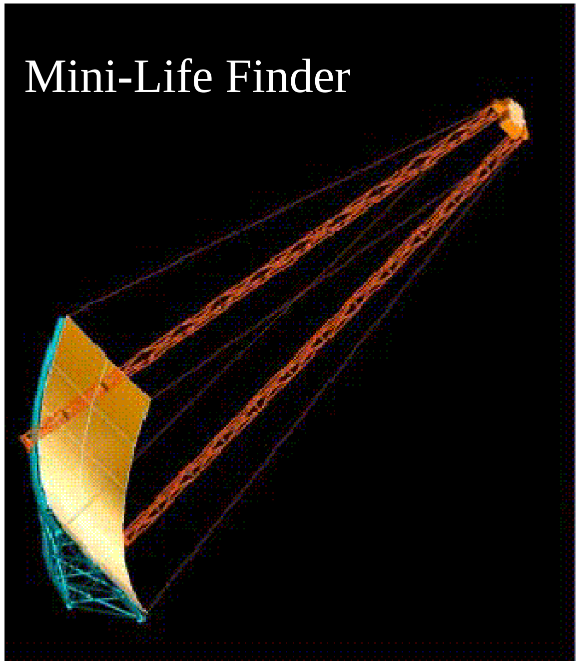
- Woolf et al (2001):
  - ~50-100 Life Finders, operating in an interferometric array

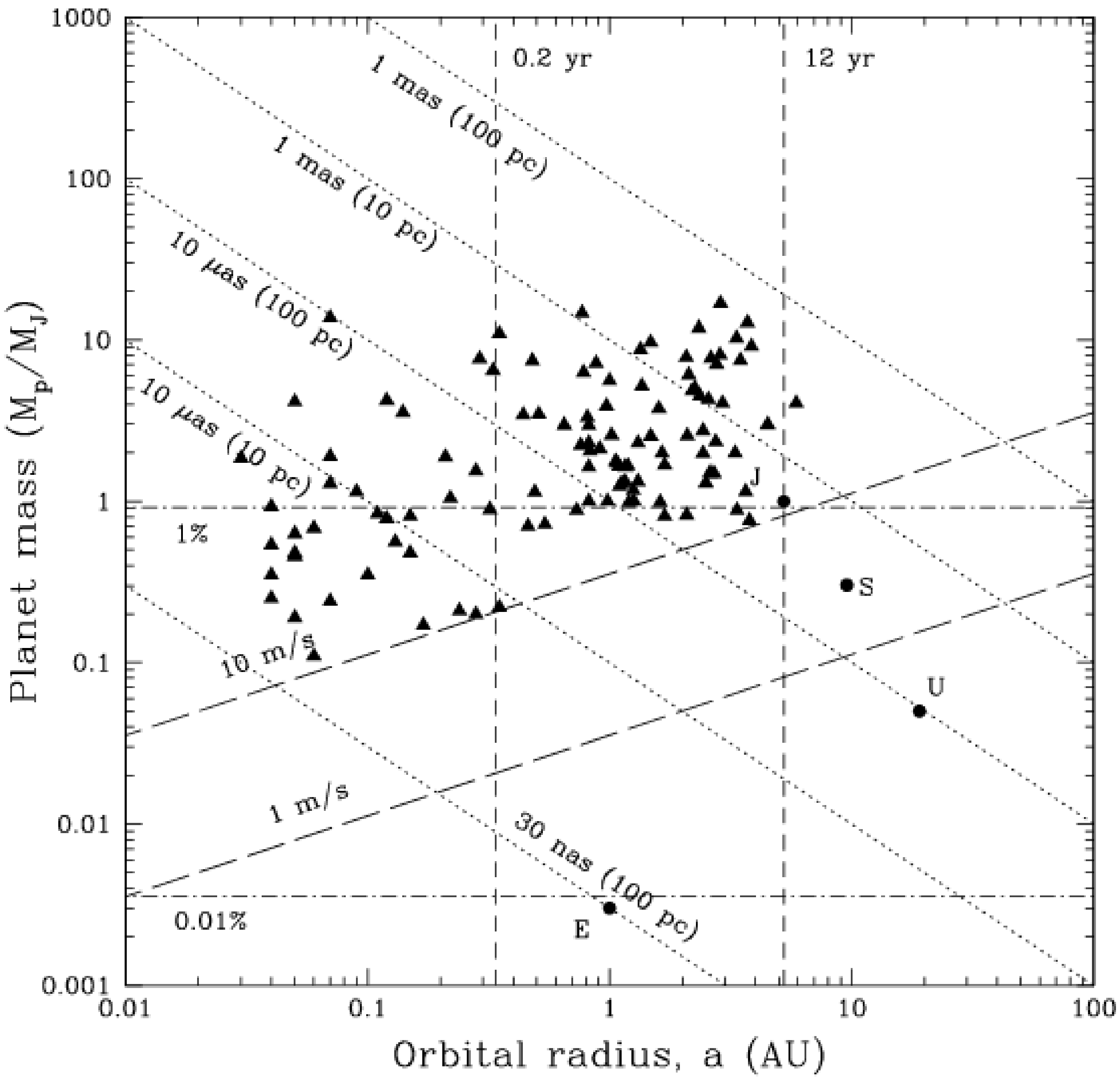
- The consensus:
  - ‘daunting’, ‘monstrously difficult’, ‘unjustifiable’
  - costs: 50-100 × (>> $2 billion), ‘dwarfing Apollo’

Nanoarcsec Astrometry

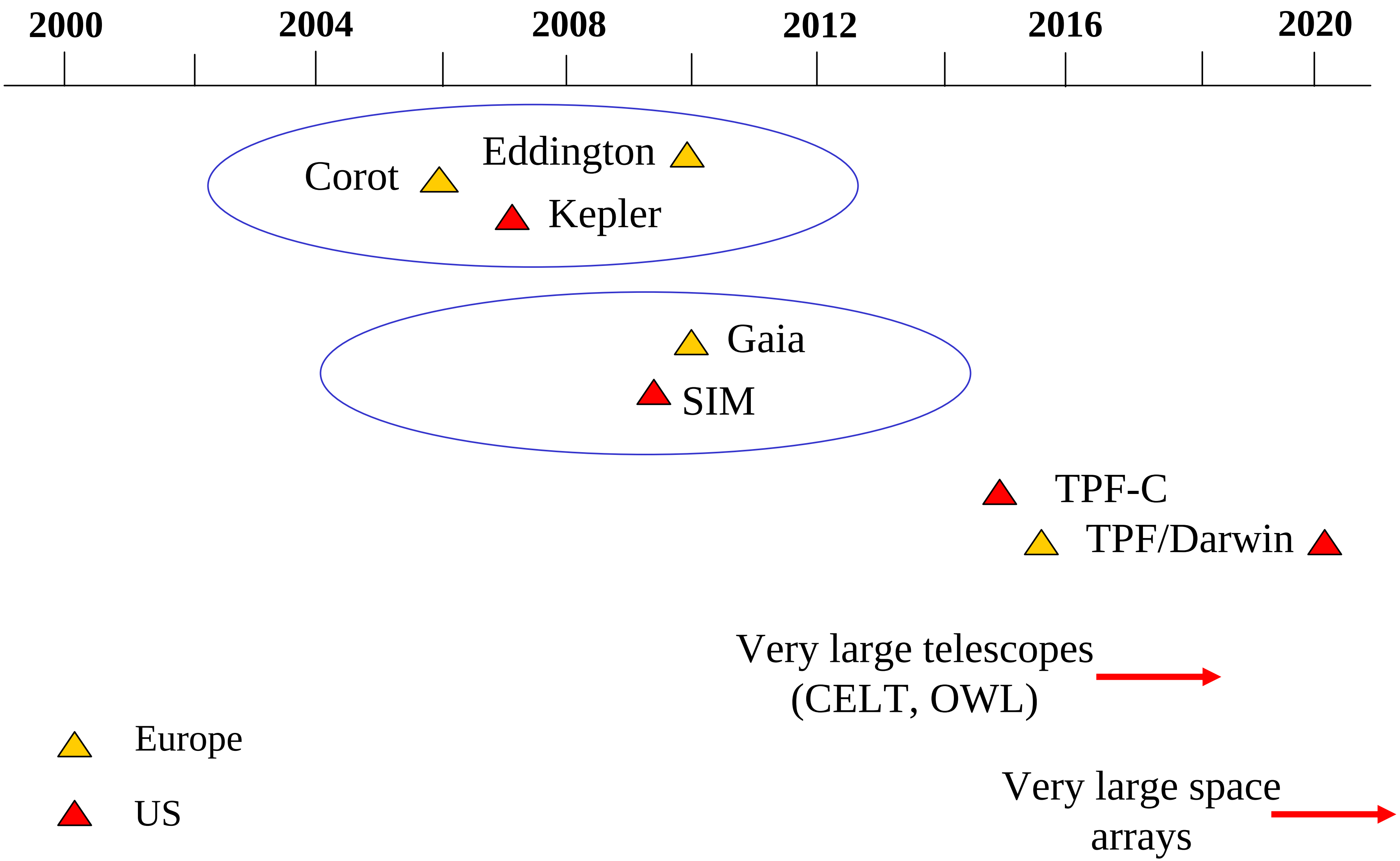
Earth at 100pc: 30 nas
Mission: 10 nas

$\sigma \propto D^{-3/2} \times H^{-1/2}$
$\Rightarrow$ 50m × 10m aperture
$\Rightarrow$ focal length: 1600m





Schedule


2000
2004
2008
2012
2016
2020
Corot
Eddington
Kepler
Gaia
SIM
TPF-C
TPF/Darwin
Very large telescopes
(CELT, OWL)
Very large space
arrays
Europe
US

Summary

- Statistics – formation & habitability (2008-2012):
  - Kepler/[Eddington]: several thousand, several hundred habitable zone
  - Gaia: astrometry: ~ 20,000 Jupiters (P~years) + 5000 photometric
  - [GEST]: lensing + transits, including free-floating planets
- Detection ('imaging') of specific systems (2015-20):
  - TPF/Darwin: few Earths in habitable zone to 20–30 pc
- Distant Visions:
  - Life Finder (confirmation of life): 'very challenging'
  - Planet Imager (resolving surface): 'monstrously difficult'

END