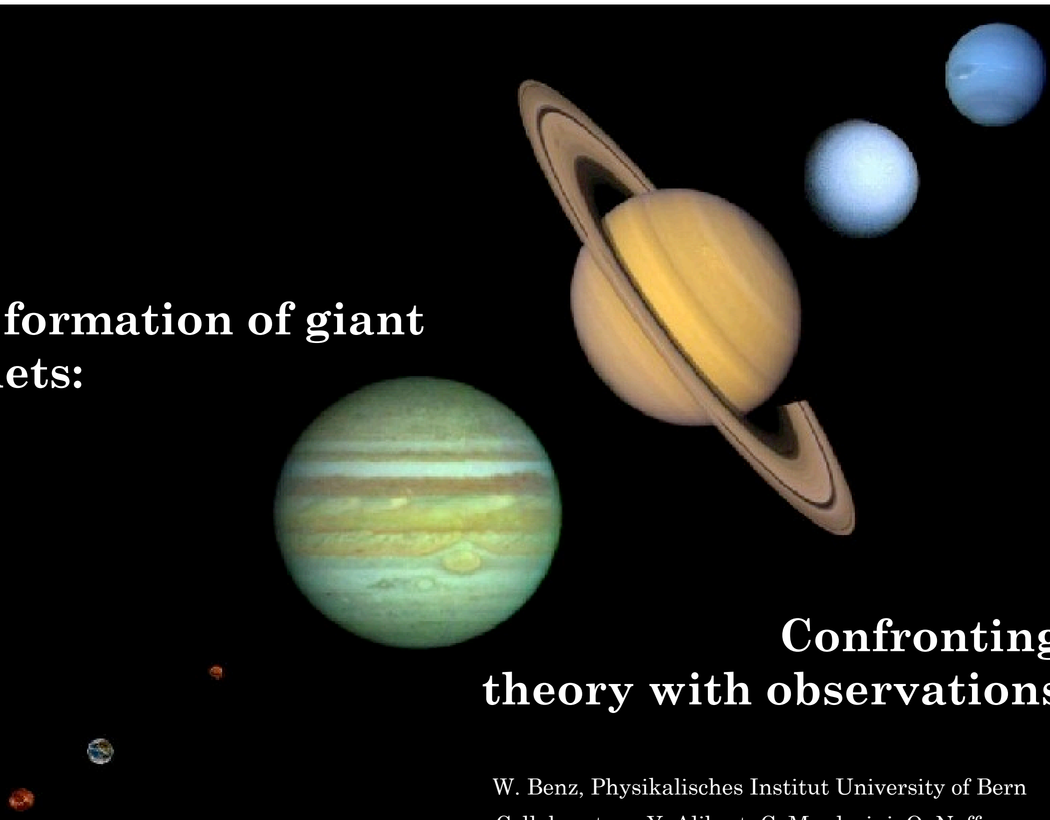
The formation of giant planets:



Confronting theory with observations

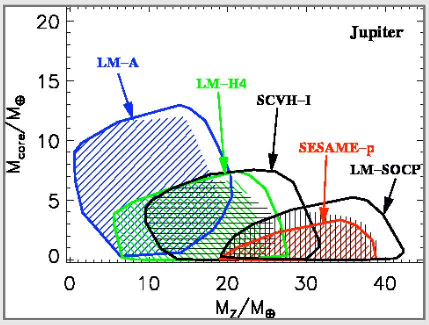
W. Benz, Physikalisches Institut University of Bern
Collaborators: Y. Alibert, C. Mordasini, O. Nyffenegger

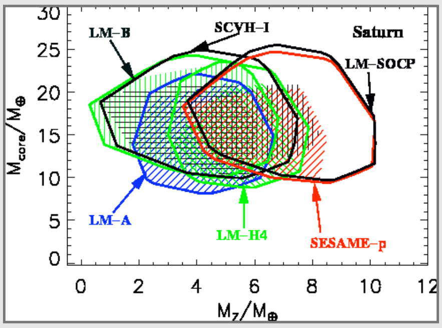
Solar system: Jupiter and Saturn

- provide detailed tests for formation models
→necessary vs. accidental

- interiors models

(Saumon & Guillot 2004)





- surface abundance compared to solar:

C	3.7 ± 0.9	Ar	1.8 ± 0.4
N	3.1 ± 1.2	Kr	2.4 ± 0.4
S	2.7 ± 0.6	Xe	2.1 ± 0.4

Mahaffy et al. 2000; Wong et al. 2004

C	3.2 ± 0.8	C	8.1 ± 1.6
N	2.4 ± 0.5		
S	12 ??		

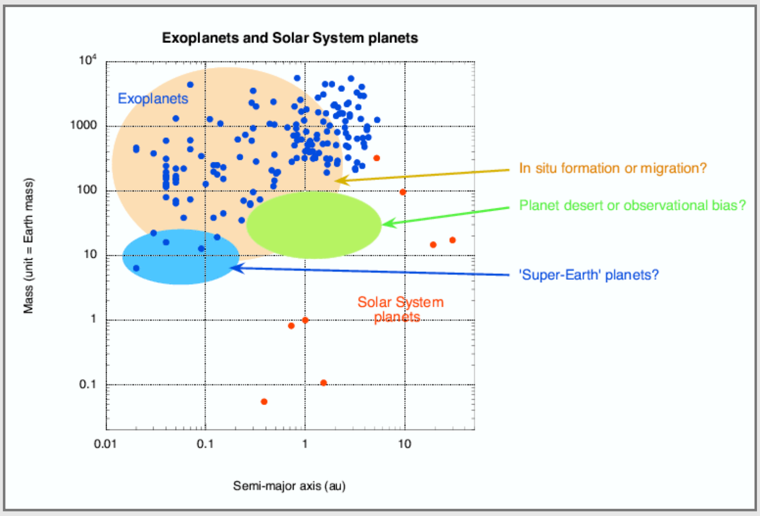
Brigg & Sackett 1989; Kerola et al. 1997
Flasar et al. 2005

Extra-solar planets:
Over ten years already

Global statistics:
- 146 planetary systems
- 169 planets
- 17 multiple planet systems

Extra-solar planet encyclopedia
10 January 2006

New field:
- started in Europe
- ~50% discoveries ∈ Europe



Diversity
- *close-in giant planets*
- *evaporating planets*
- *eccentric planets*

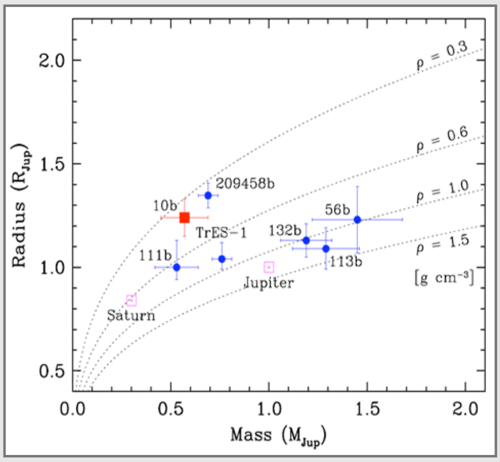
For the most part, little physical information about the planets themselves

Transiting planets: Exoplanetology

9 transiting planet detected so far...

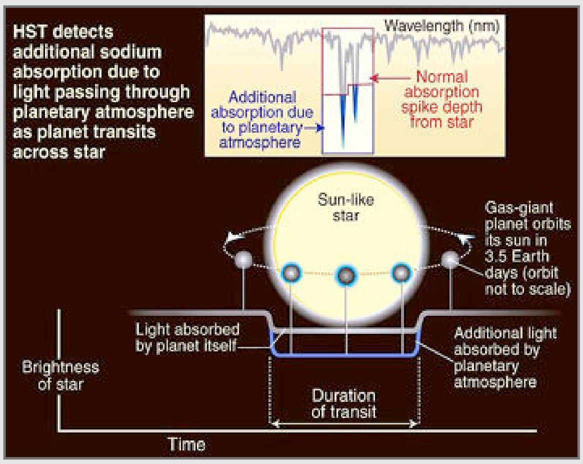
Mass-radius relation

Konacki et al 2004



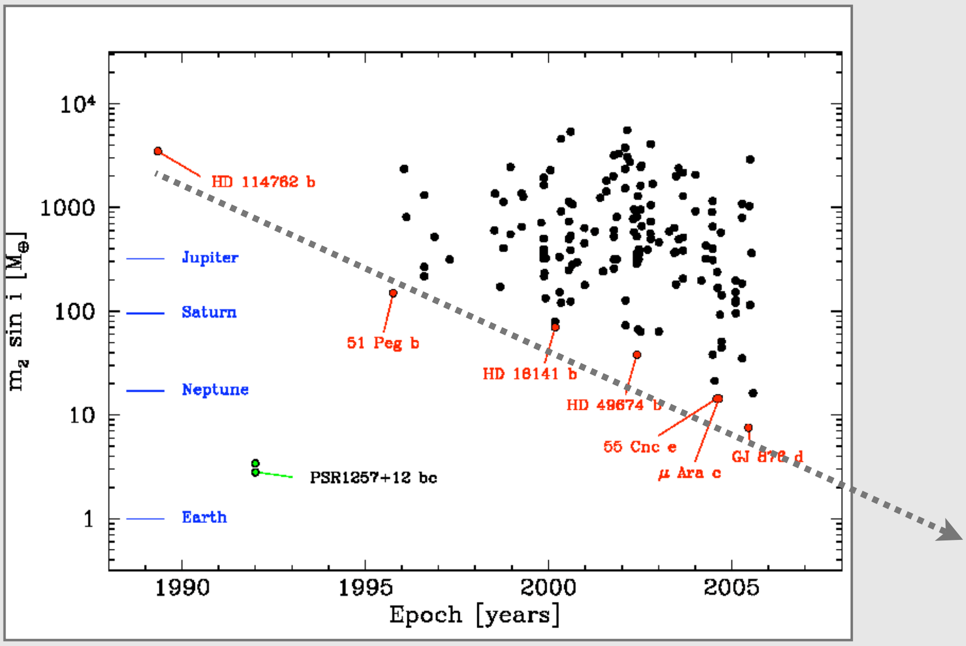
Some atmospheric composition

Charbonneau et al 2004



Determination of some important physical characteristics
→ only giant planets close-by
→ no real spectroscopy yet!

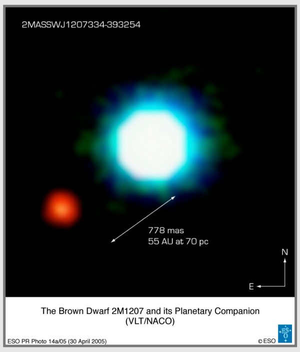
Progress in ground-based RV detections



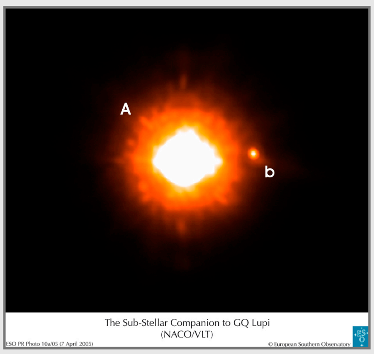
Earth-like planet detection from the ground by 2010?
→ still indirect observations
→ only close-by planets

Direct imaging: 3 candidates

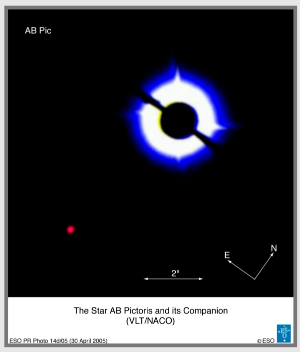
2M1207 b:
M≈ 5 M_J
d= 41 AU



GQ Lup b:
M≈ 21.5 M_J
d= 103 AU

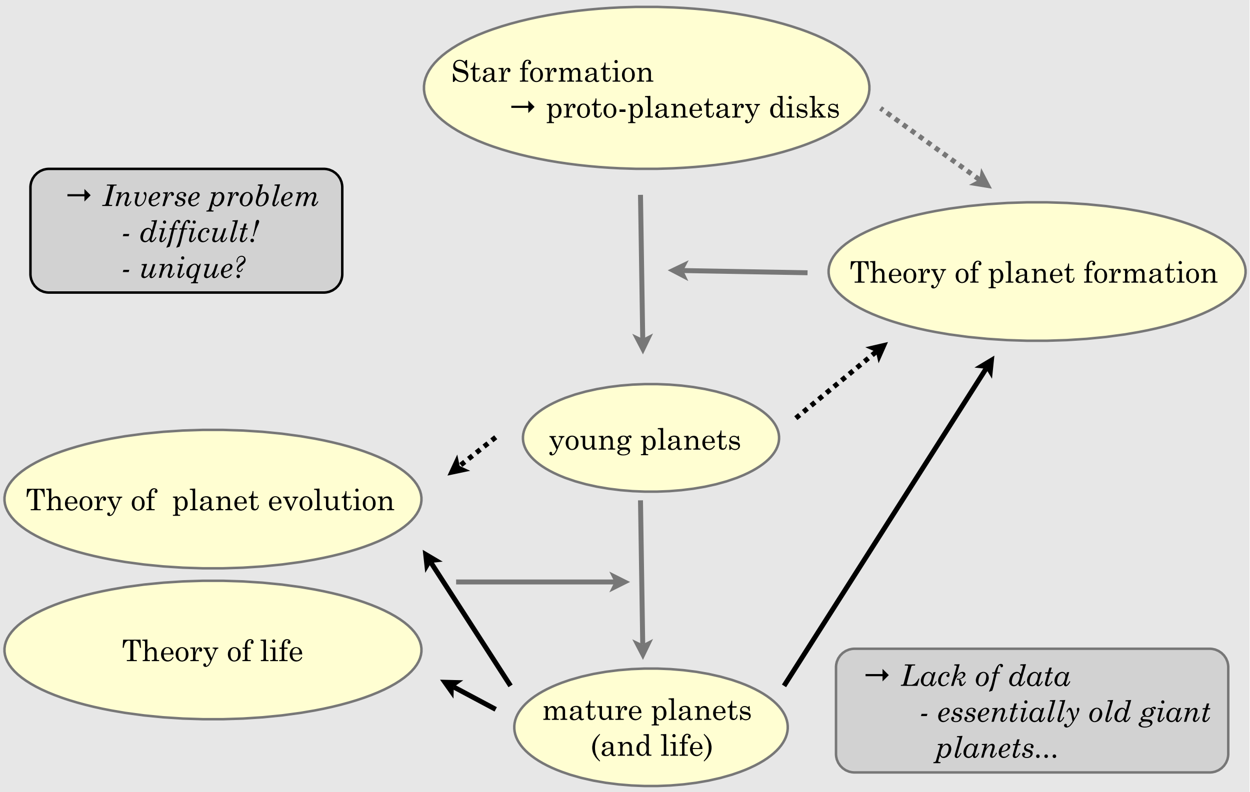


AB Pic b:
M≈ 13.5 M_J
d= 275 AU

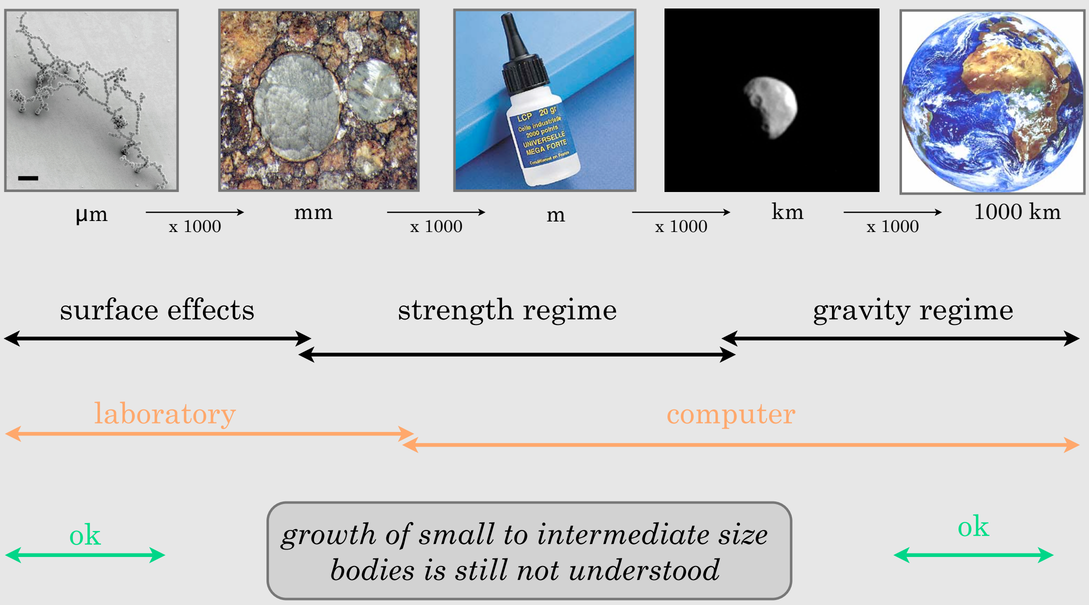


Very special systems can be imaged from the ground today...
far from terrestrial planets in the habitable zone!

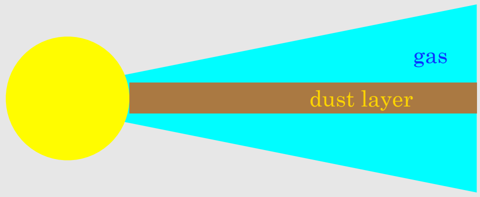
The problem:



Formation of cores and terrestrial planets: Sticking and survival



Small bodies:
Size dependent gas drag



- solids $\frac{v_k^2}{r} = \frac{GM}{r^2}$

- gas $\frac{v_g^2}{r} = \frac{GM}{r^2} + \frac{1}{\rho}\frac{dP}{dr} \leq \frac{v_k^2}{r}$

→ velocity difference:
$(v_k - v_g) = few\ 10^{-3}\ v_k \approx 100\ m/s\ @\ 1AU$

↓

size dependent gas drag
determines collision velocity

↓

- escape velocity:

$$v_{esc} = \sqrt{\frac{2GM}{R}} = \sqrt{\frac{8\pi G\rho}{3}}R = 1.3\left(\frac{R}{1km}\right)\ \mathrm{m/s} \longrightarrow v_{coll} >> v_{esc}$$

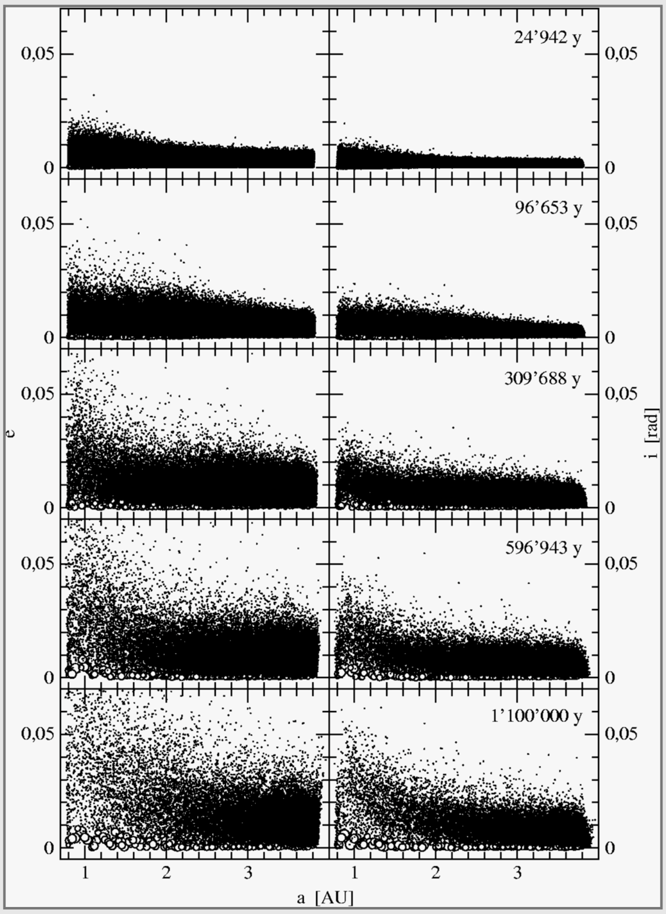
disruptions rather than growth!

Possible solutions:

1) gravitational instabilities in dust layer

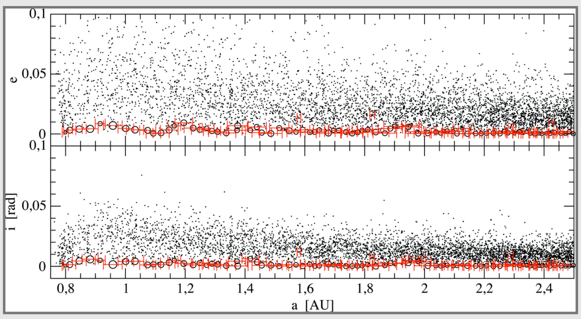
2) vortex formation in gaseous disk

3) mechanical properties of planetesimals

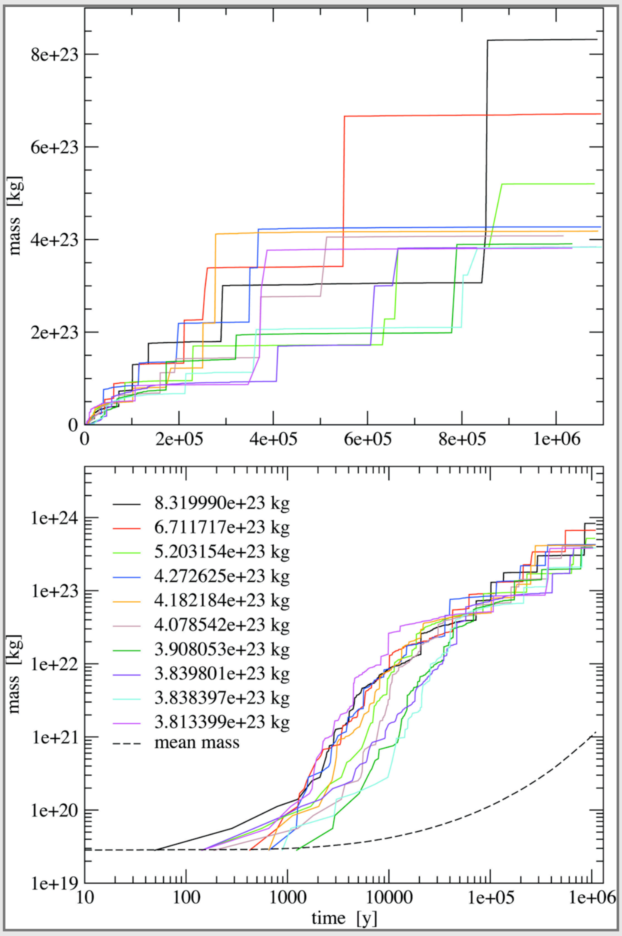


Collisional growth: Gravitational encounters

simulation of the collisional evolution of 1 million bodies using an orbit averaged Monte Carlo scheme



Gravitational encounters lead to equipartition of random kinetic energy
⇒ small bodies have larger random velocities



Runaway and oligarchic growth

Gravitational focusing enhances collisional cross section:

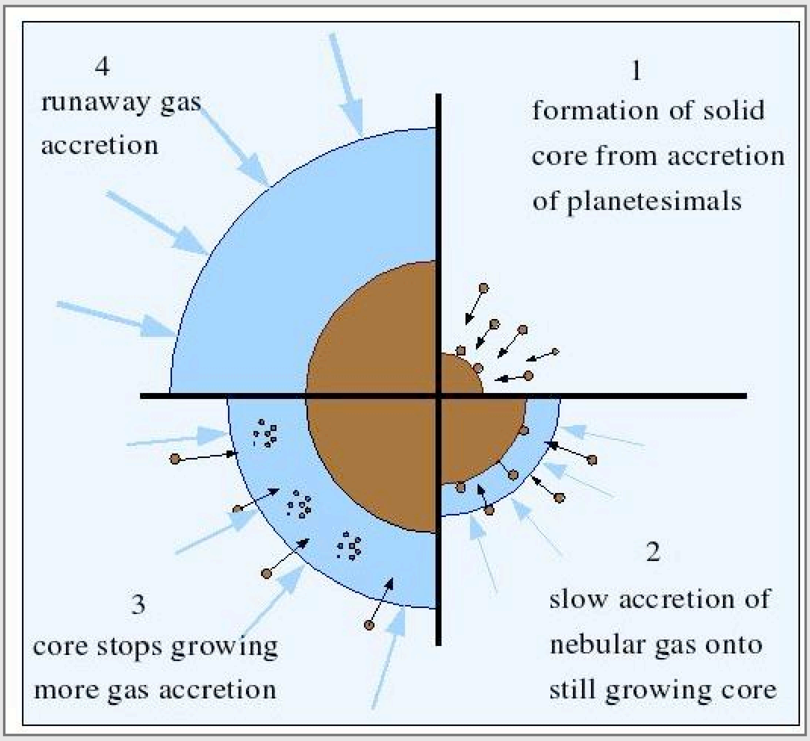
$$\sigma = \sigma_0 \left(1 + \frac{v_{esc}^2}{v_{rel}^2}\right)$$

Bodies grow by colliding with bodies nearly as big as themselves

↓

giant collisions must have been frequent occurences

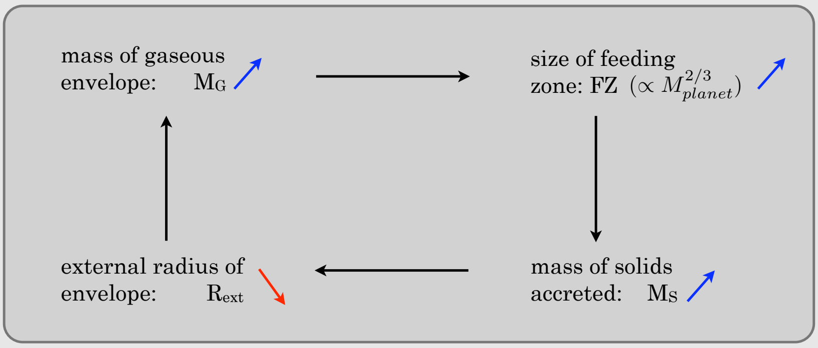
The core accretion: scenario



The core accretion: basics

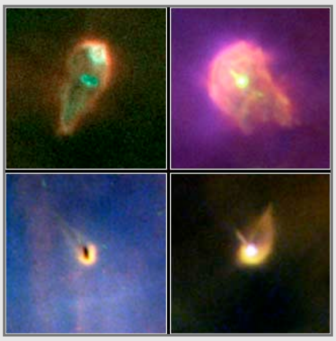
1) rapid accretion of planetesimals until feeding zone is depleted: Phase I

2) slow accretion of gas and planets: Phase II



3) cooling instability: Runaway gas accretion: Phase III

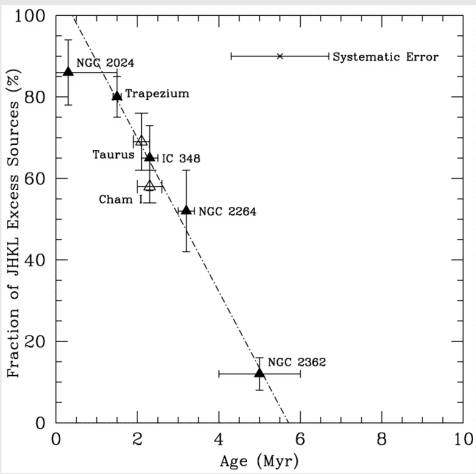
Circumstellar disks



1) Lifetime

L-band (3.4 μm) photometry:
- excess caused by μ-sized dust @ ~900K
→ inner disk only?

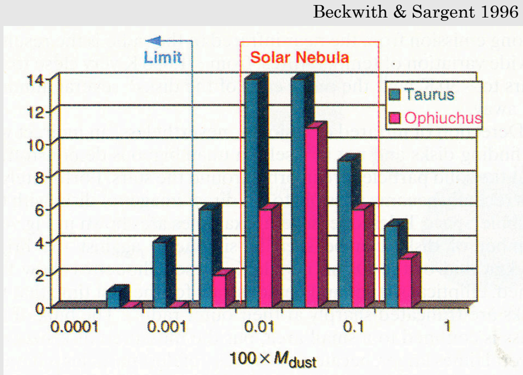
Haisch et al. 2001



Giant planets must form within 4-8 Myr

2) Masses

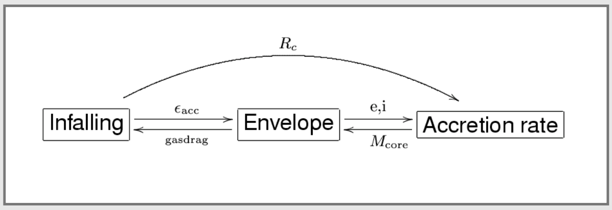
Beckwith & Sargent 1996

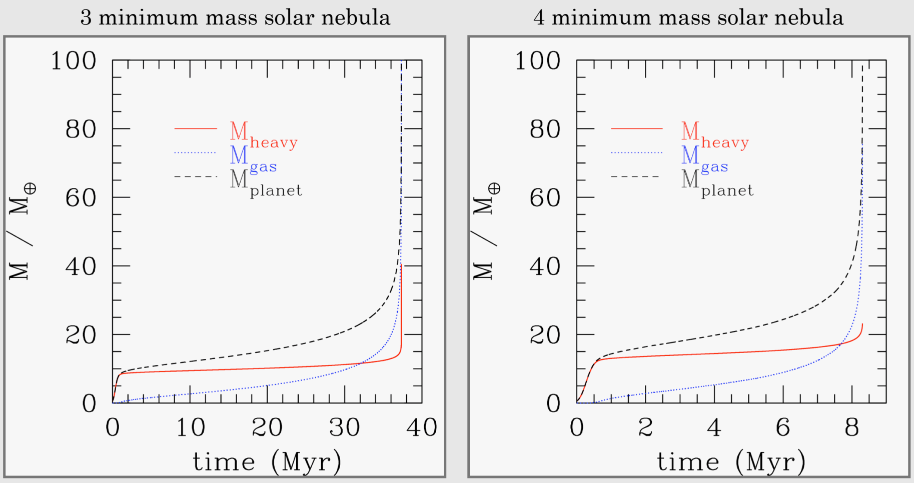


typical masses: 0.01-0.1 M_{sun}

The core accretion: Pollack et al. 1996

- constant T and P (no disk evolution)
- fixed embryo location (no migration)

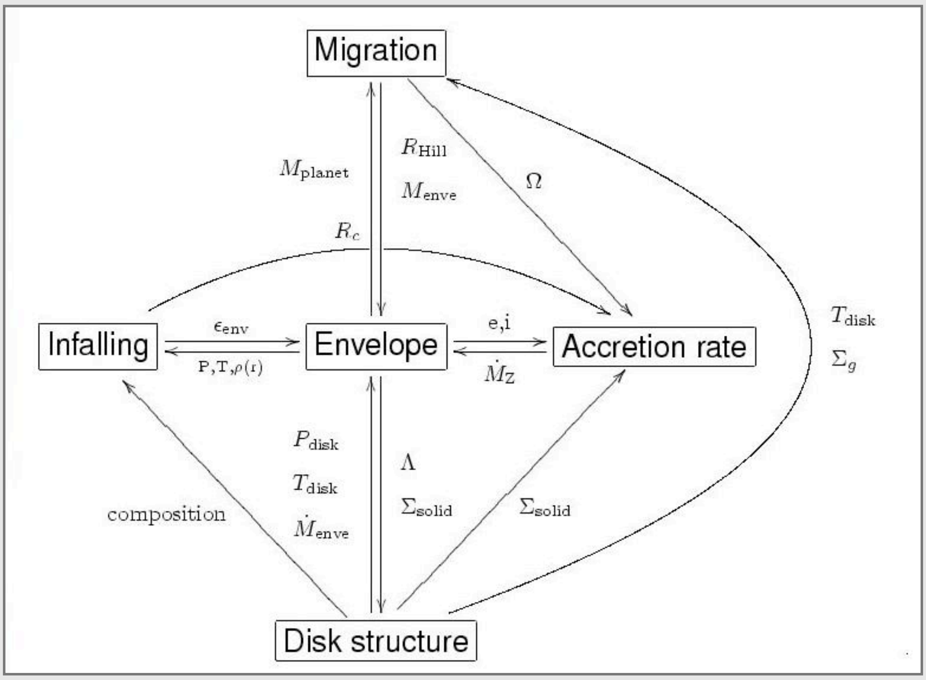




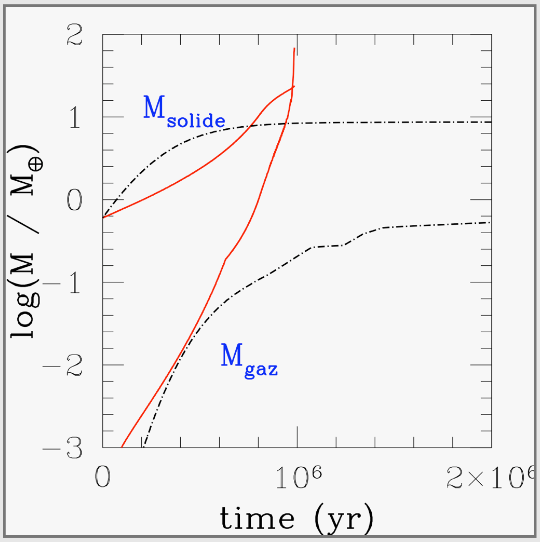
- formation timescale very sensitive to disk mass
- need relatively massive nebula to form planets within disk lifetime

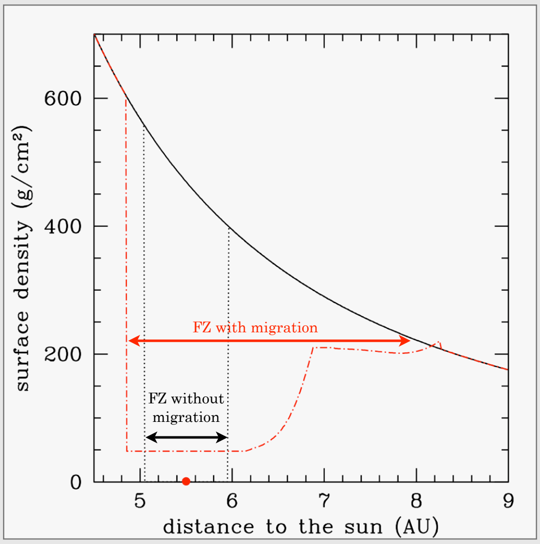
The core accretion: Extended models

- disk is evolving: P & T at planet boundary are evolving
- growing planets are migrating
- better treatment of planetesimal infall



Extended models: Formation time scale



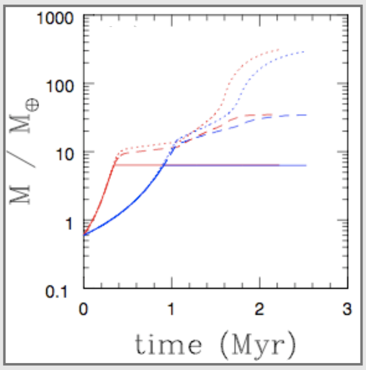


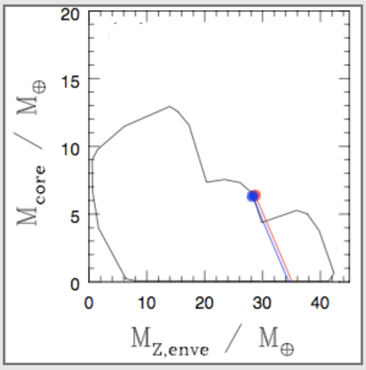
formation speed-up of ≈ 30!
→ planets form well within disk lifetime!

migration prevents the depletion of feeding zone

Formation of Jupiter and Saturn

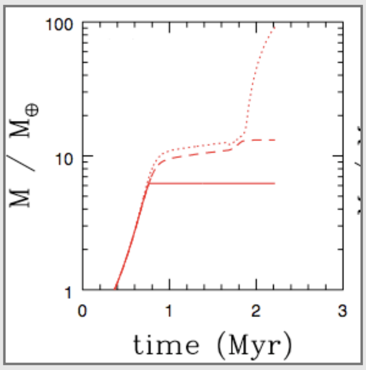
Jupiter

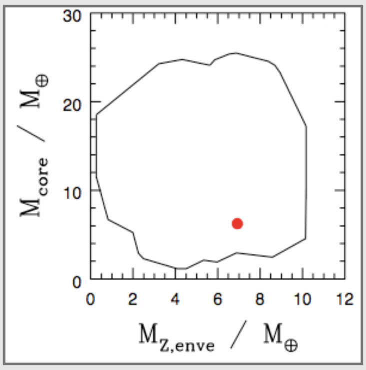




species	measured	computed
Ar	1.8 ± 0.4	2.
Kr	2.4 ± 0.4	2.1
Xe	2.1 ± 0.4	2.6
C	3.7 ± 0.9	2.8
N	3.2 ± 1.2	2.5
S	2.7 ± 0.6	2.1

Saturn





species	measured	computed
Ar		1.7
Kr		1.9
Xe		2.3
C	3.2 ± 0.8	2.4
N	2.4 ± 0.5	2.2
S		1.9

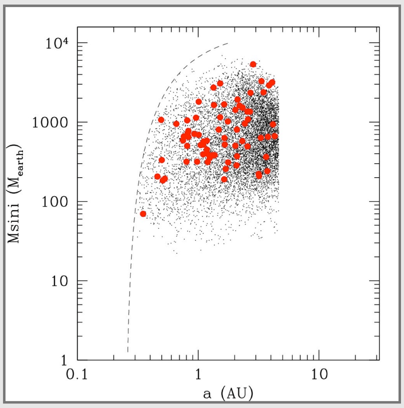
formation models can account for the bulk properties of Jupiter and Saturn

Monte Carlo models of giant planet formation

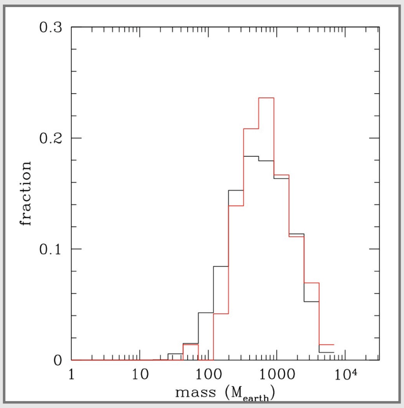
Giant planet formation models following the core-accretion scenario

- 0.6 M⊕ seed cores
- initial conditions from
  1) observations
  2) theory (Alibert et al 2005)

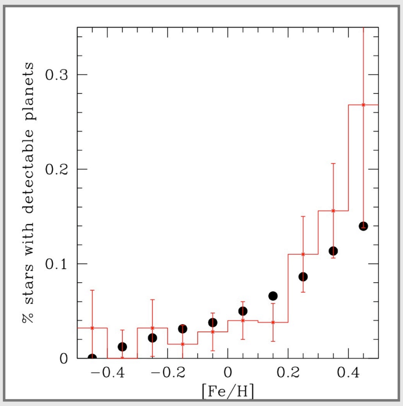
mass vs semi-major axis



mass distribution



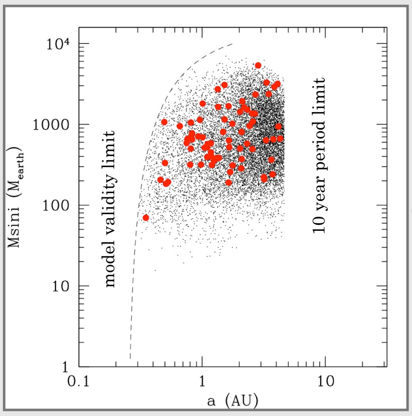
metallicity correlation



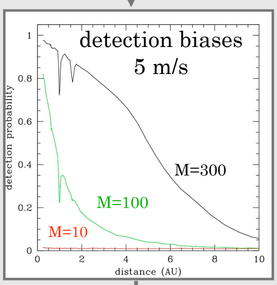
Models are getting better at explaining the characteristics of the currently observed population of extra-solar planets

The tip of the iceberg

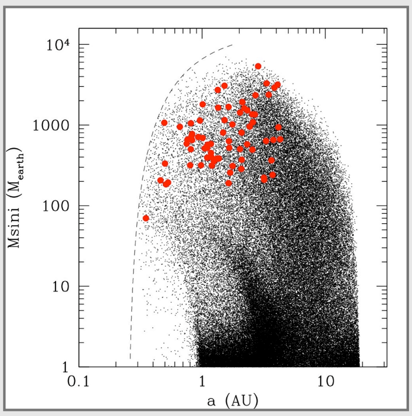
potentially detectable planets
RV 5 m/s precision



Radial velocity technique is most sensitive to large masses close-by....



underlying planet population

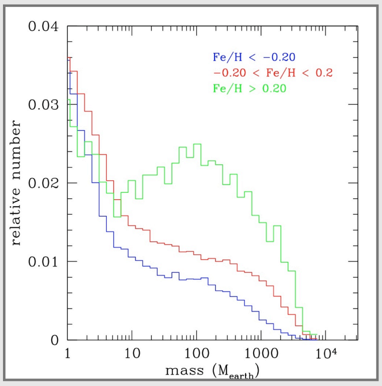


Models predict many more planets with small masses!

We dont know anything about ≥ 90% of the planets that are out there

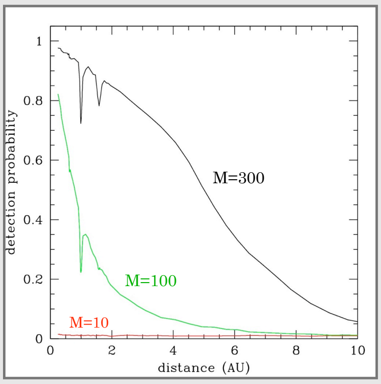
Understanding data is key to further progress

Metal rich systems favor the formation of massive planets



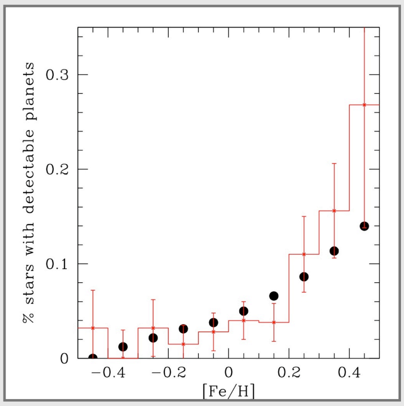
+

Massive systems are more easy to detect



=

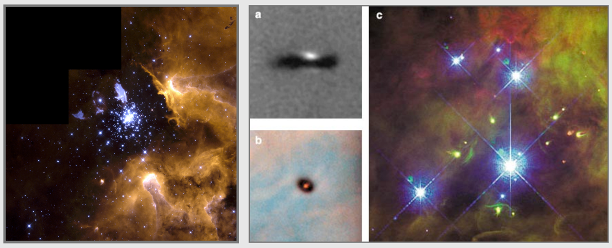
Metallicity correlation



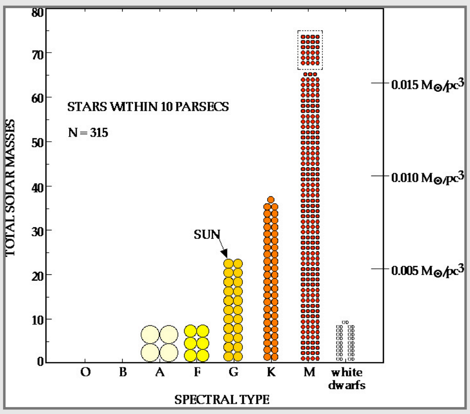
To find small mass planets metal rich stars may not necessarily be better targets!

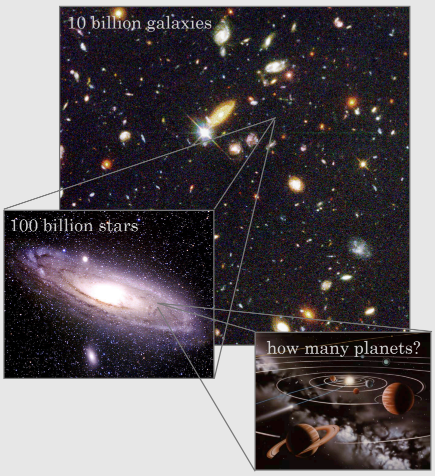
Future progress

- *Star formation: initial conditions*
  method: long wavelength imaging and spectroscopy



- *A complete census of the solar neighborhood*
  method: direct + indirect detections
  ... the collector's approach





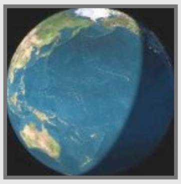
Future progress

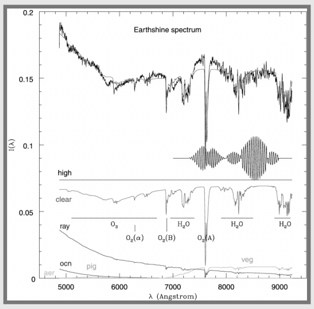
earth-shine spectrum

Woolf et al 2002

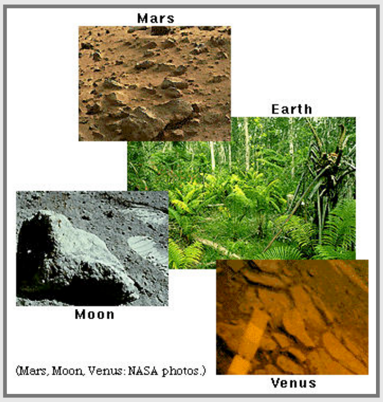
- *Physical studies of existing planets*
  method: imaging + spectroscopy

... the astronomer's approach





why such large differences

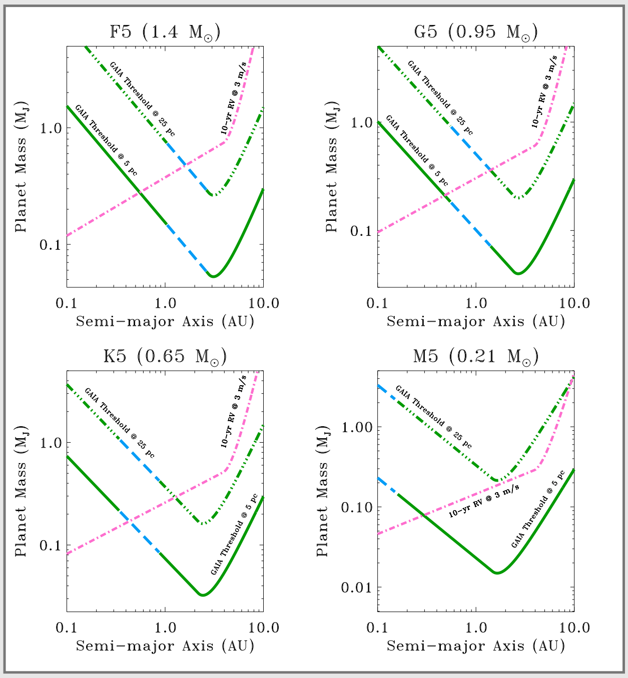


- *Ground truth: Key characteristics of solar system*
  method: In situ measurements and sample return
  → accidental vs. necessary
  - *mixing and timescales (cosmochemistry)*
  - *collisional evolution*
  - *migration*
  - *interiors and atmospheres*

extra-solar planets provide diversity
solar system provides details
→ both are required

Gaia (planets)

precision:
- *few μ-as astrometry*
- *millimagnitude photometry*



Expected number of discoveries as a function of distance

Δd (pc)	N_*	Δa (AU)	N_d (1)	N_m (2)
0-100	~61 000	1.3 - 5.3	≥ 1600	≥ 640
100-150	~114 000	1.8 - 3.9	≥ 1600	≥ 750
150-200	~295 000	2.5 - 3.3	≥ 1500	≥ 750

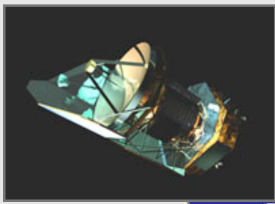
Expected number of transits as a function of stellar type and orbital separation

	F	G	K	M	Sum
0 < a < 2AU:	3000	2000	1500	15	6500
a > 2AU:	50	30	20	0	100

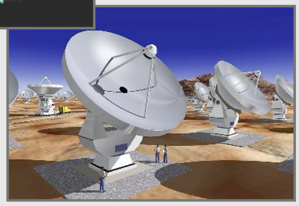
- giant planets out to ≈ 200 pc
- mass-radius relation
- target definition
→ still indirect observations

Initial conditions: The physics of cold gas...

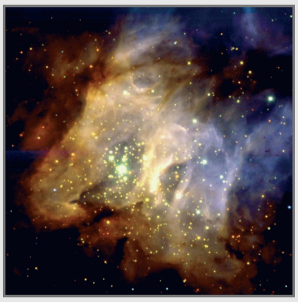
Herschel + JWST



Alma

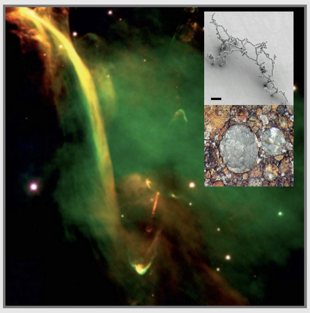


star formation



environment: Galactic, stellar

Gas & dust



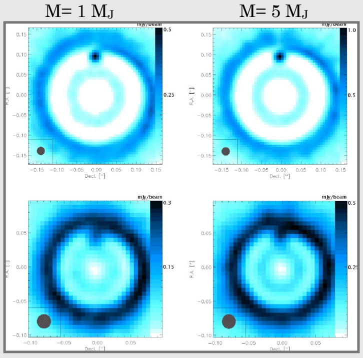
coagulation, composition/size
water, biogenic molecules

Planets & disks

M= 1 M_J M= 5 M_J

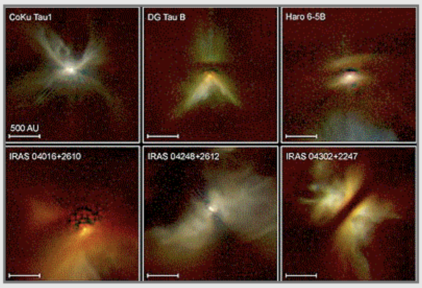
50 pc

100 pc



Wolf & D'Angelo 2005

protostars, protoplanetary disks



Transit: Earth-like planets

Expected detections

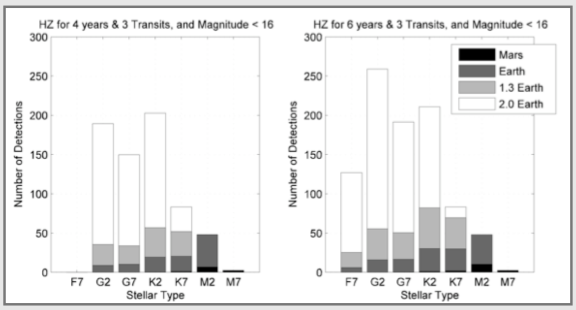
Bordé et al. 2003

a_t (AU)	T_P (K)	1 $R_⊕$	1.5 $R_⊕$	2 $R_⊕$	3 $R_⊕$	5 $R_⊕$
0.05	1200	120	570	1320	2800	3800
0.14	750	17	90	260	750	1300
0.30	500	2	17	55	160	240
0.86	300	0	1	3	3	3
1.00	278	0	1	2	2	2

Launch: 2006

mostly "hot planets"
→no Earth in the HZ

Borucki et al. 2005



Launch: 2008

a number of planets in HZ
→a few 10 Earths in HZ

ESA's Cosmic Vision: 2015-2025

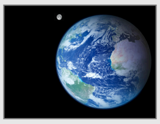
Theme 1:

What are the conditions for planet formation and the emergence of life?

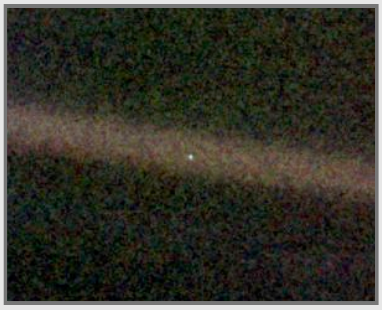
1.1 From gas and dust to stars and planets
1.2 From exo-planets to biomarkers
1.3 Life and habitability in the solar system

Direct imaging: Spectroscopy

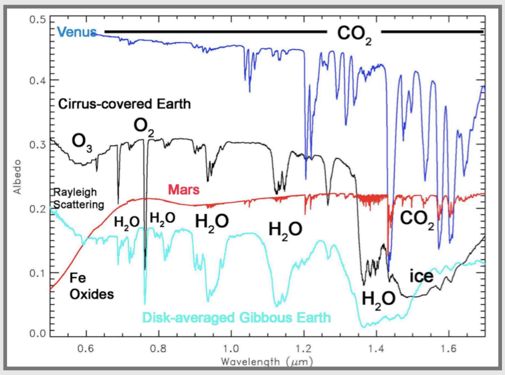
Resolved imaging



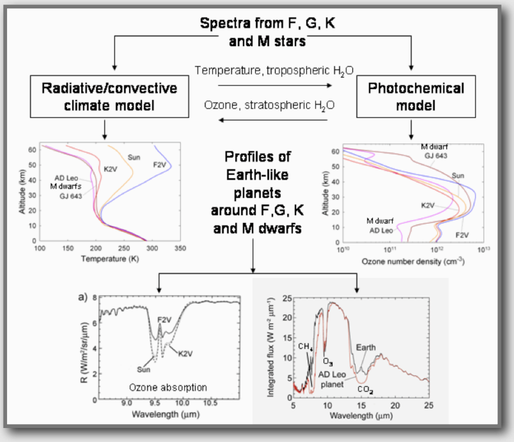
Earth from Voyager 1 on 14.2.90, 42.6 AU away



Meadows. 2005



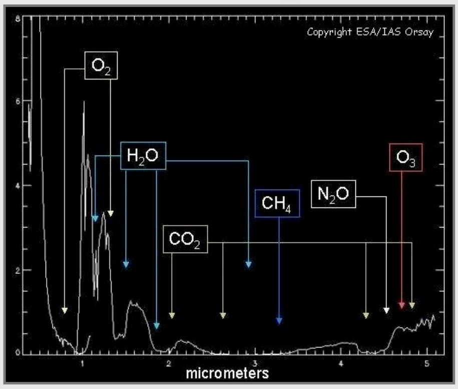
Segura et al. 2005



Comparative exo-planetology
- composition and climate
- formation
- evolution

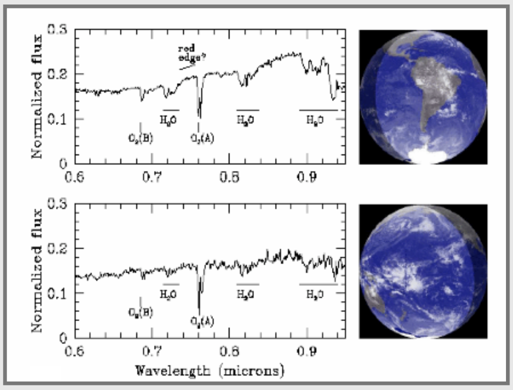
Direct imaging: The search for life

- atmospheric bio-signatures
  O_2, O_3, H_2O, CH_4, ...



Earth spectrum from Mars Express

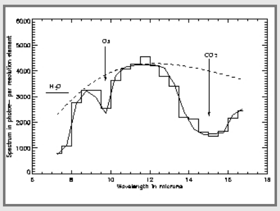
- surface bio-signatures
  vegetation red-edge, seasons, ...



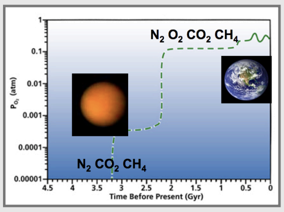
Woolf et al 2002

- difficulties:

low resolution

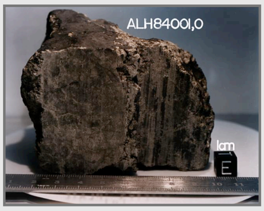

simulated Darwin spectrum

time dependence



Meadows 2005

difficult to recognize



MacKay et al 1997

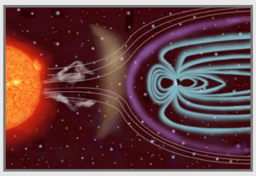
Extraordinary claims require extraordinary evidences!

Habitability, evolution and survival

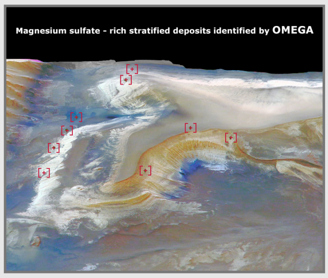
(life as we know it...)

- Habitability
  - liquid water
    → requires energy source
  - nutrients: N, Mg, P, S, K, Ca, ...

sun-planet interactions

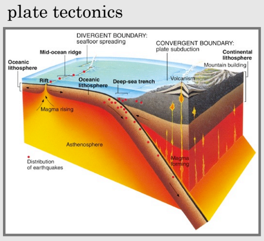


Mars Express

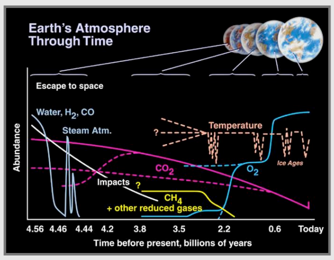


- Evolution
  - renewal of nutrients
    → geological activity
  - interactions life processes - planet
    → changing environment

plate tectonics



interactions



- Survival
  - natural hazards
    → extinctions
  - other hazards

Don Davis

Solar system only place where these processes can be studied in enough details

Conclusions

- Field is observationally driven, theory has not kept pace...

- Theory is making progress but there are still major aspects that are not yet understood

- Core-instability scenario allows quantitative comparisons with observations. Extended models have been confronted with:
  - solar system giant planets
    - internal structure
    - surface abundances
  - extra-solar planets
    - lifetime of proto-planetary disks
    - Monte Carlo calculations required to extract statistical information
      - mass and orbital distributions not yet satisfactory
      - explains correlation with metallicity

- The future looks bright (solar system + extra-solar planets)

Much of astronomy is phenomenological (descriptive) but, ultimately, the goal is to conceive and verify universal theoretical constructs that explain the observed behavior of astronomical objects across the vast scales of the Universe. Accordingly, support for theoretical investigations must be proportional and synchronized with the great data-gathering projects undertaken in laboratories and observatories.

OECD report on large scale project in astronomy