Simulations of Planet Formation and Extrasolar Planets

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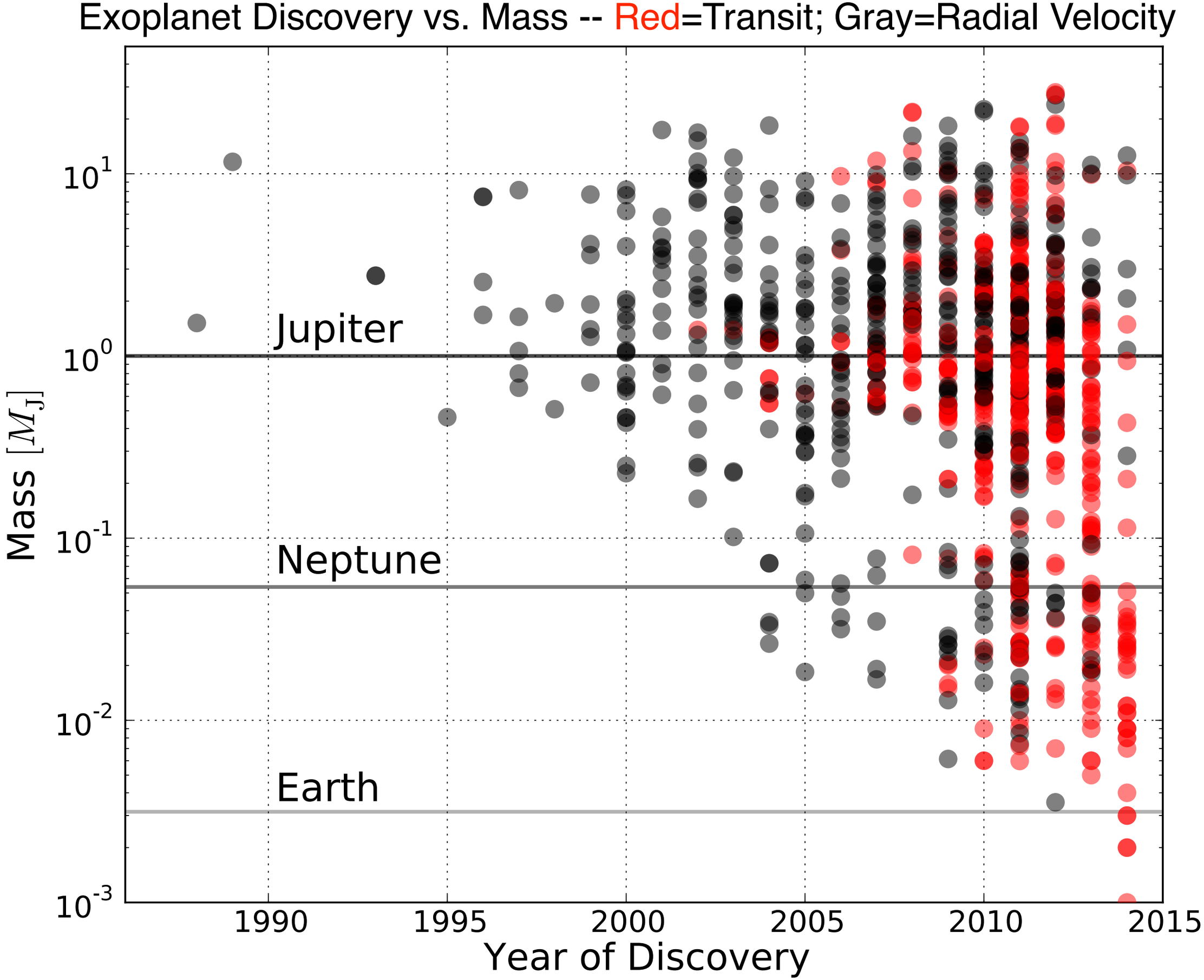
Computational Astrophysics 2014–2020: Approaching Exascale

13 slides


Exoplanet Discovery vs. Mass -- Red=Transit; Gray=Radial Velocity
Jupiter
Neptune
Earth
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
Mass $[M_J]$
1990
1995
2000
2005
2010
2015
Year of Discovery

Mass Ratio -- Period Diagram for Satellites and Planets

Mass Ratio $[M/M_{Sun}]$

Period $[Days]$

10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}

10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

Hot Jupiters

Eccentric Giants

Earth's Moon

Solar System Satellites

Microlensed Planets

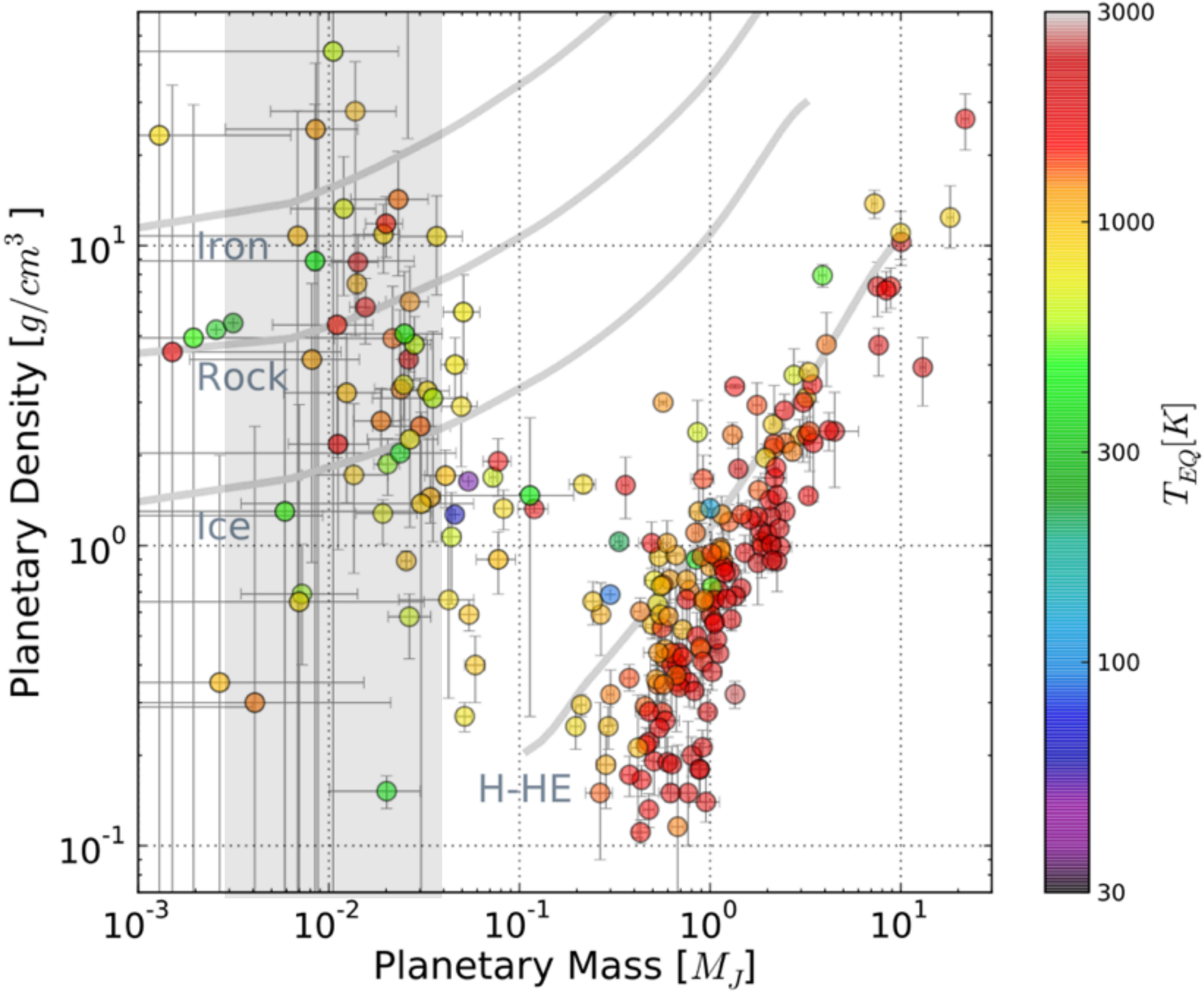
Ungiants

Pulsar Planets

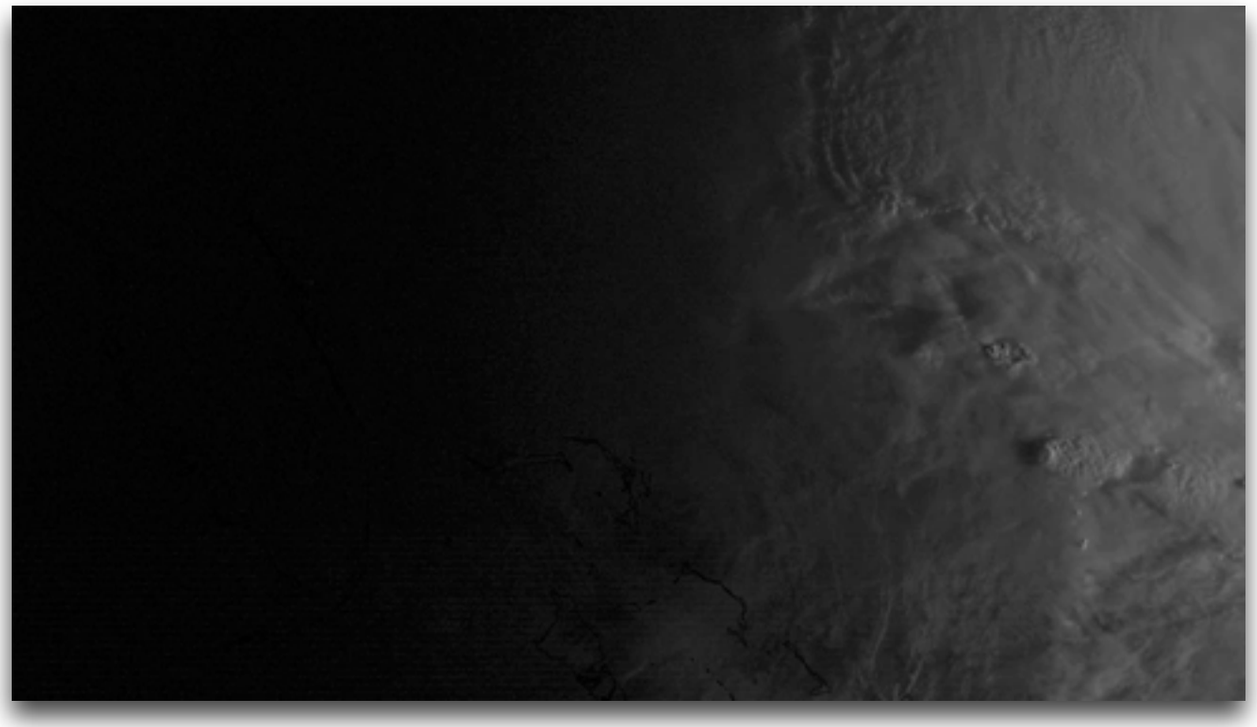
J

V

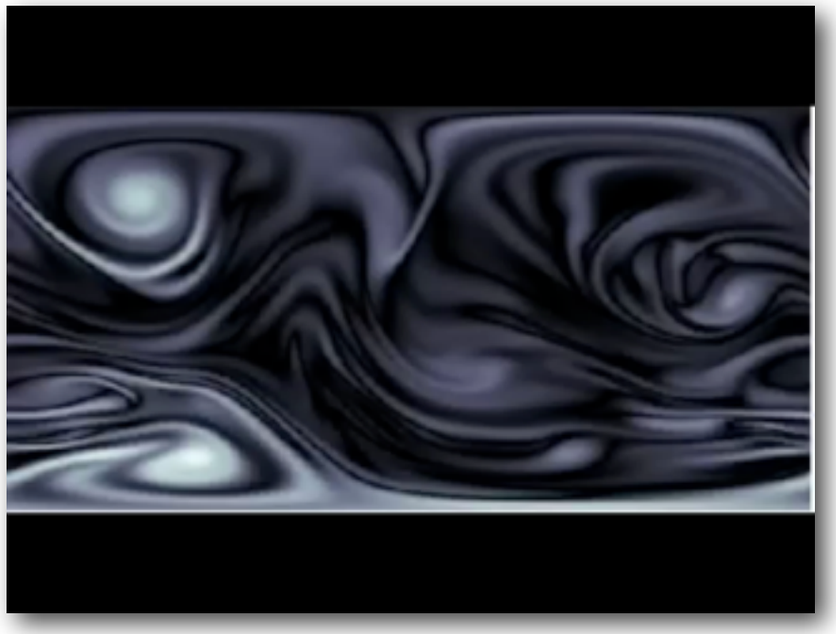
E

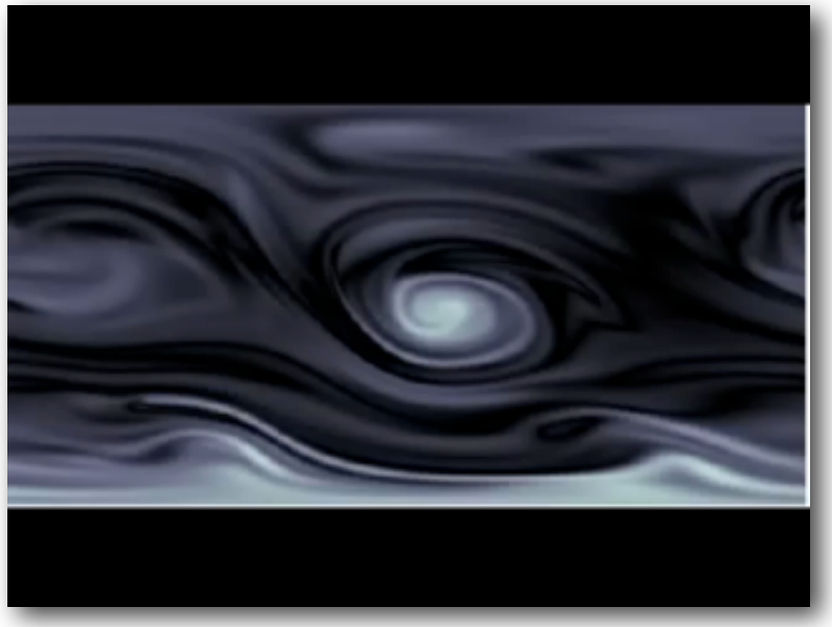


The Computational Challenge: How do planets work and how did they form?

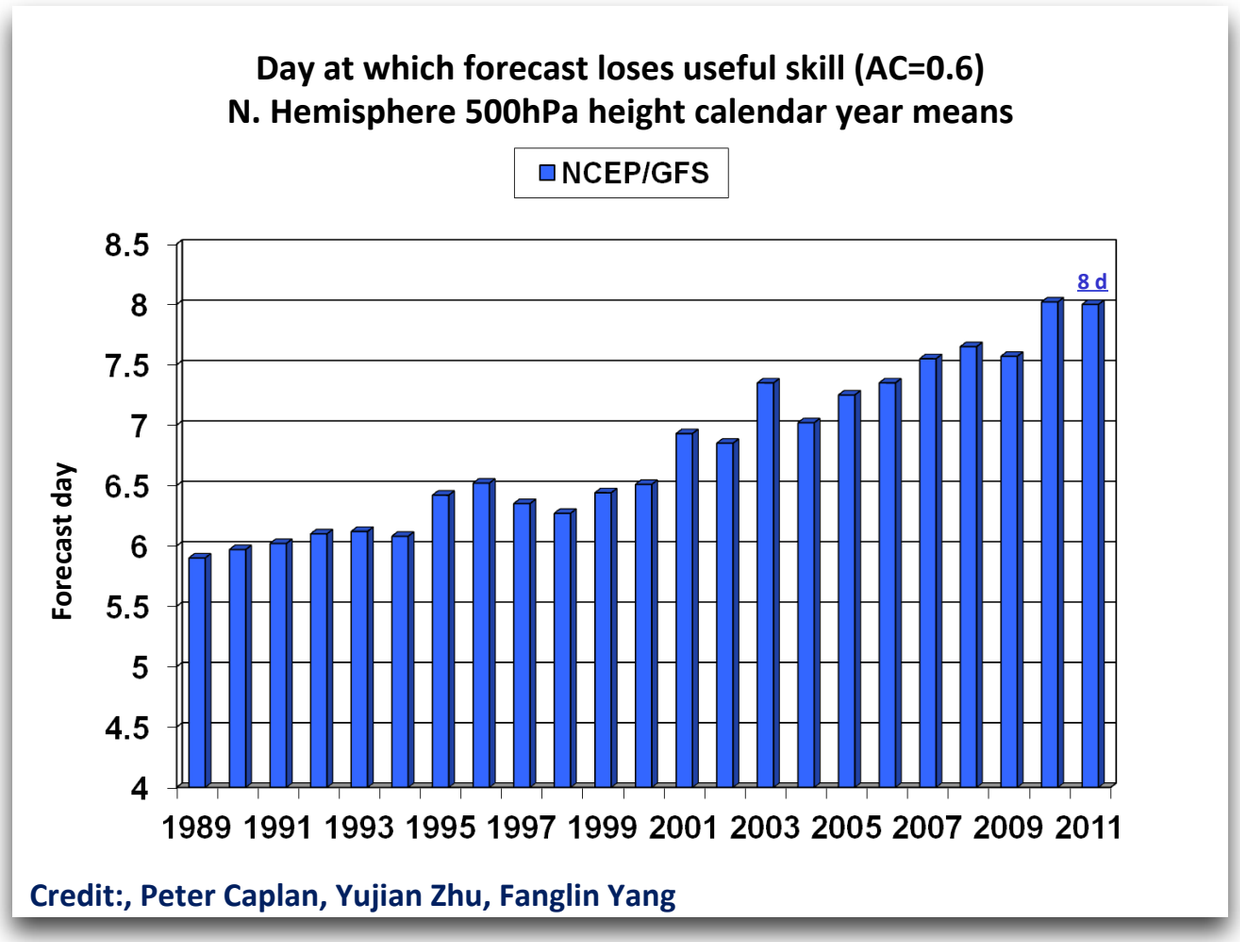


Hurricane Sandy on Earth





Langton & Laughlin 2009



20 year improvement from better supercomputing, but also better ICs.

Exoplanetary Atmospheric simulations need:

- Fully 3D MHD, w/ chemical disequilbrium
- Frequency Dependent Radiative Transfer
- Time dependent insolation

+

A Dozen Years of Exoplanetary Weather Reports

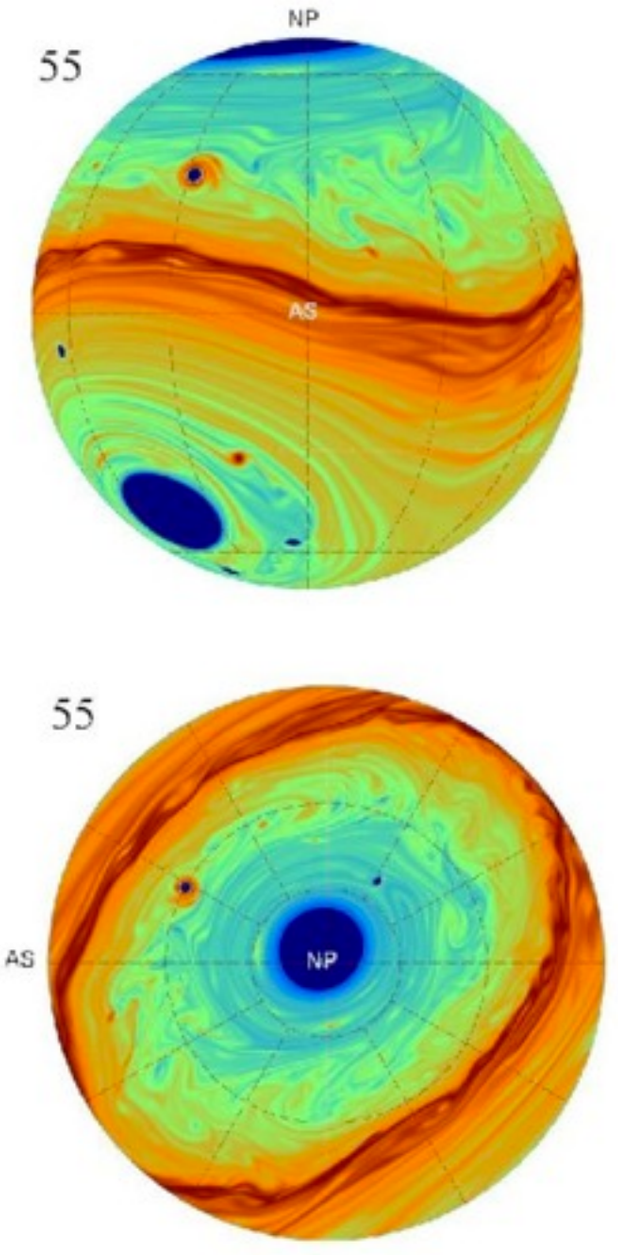
arXiv.org > astro-ph > arXiv:astro-ph/0209227

Astrophysics

Changing Face of the Extrasolar Giant Planet, HD 209458b

James Y-K. Cho, Kristen Menou, Brad Hansen, Sara Seager

(Submitted on 11 Sep 2002 (v1), last revised 12 Mar 2003 (this version, v2))



2002

arXiv.org > astro-ph > arXiv:1401.5815

Astrophysics > Earth and Planetary Astrophysics

Magnetohydrodynamic Simulations of the Atmosphere of HD 209458b

T.M. Rogers, A.P. Showman

(Submitted on 22 Jan 2014)

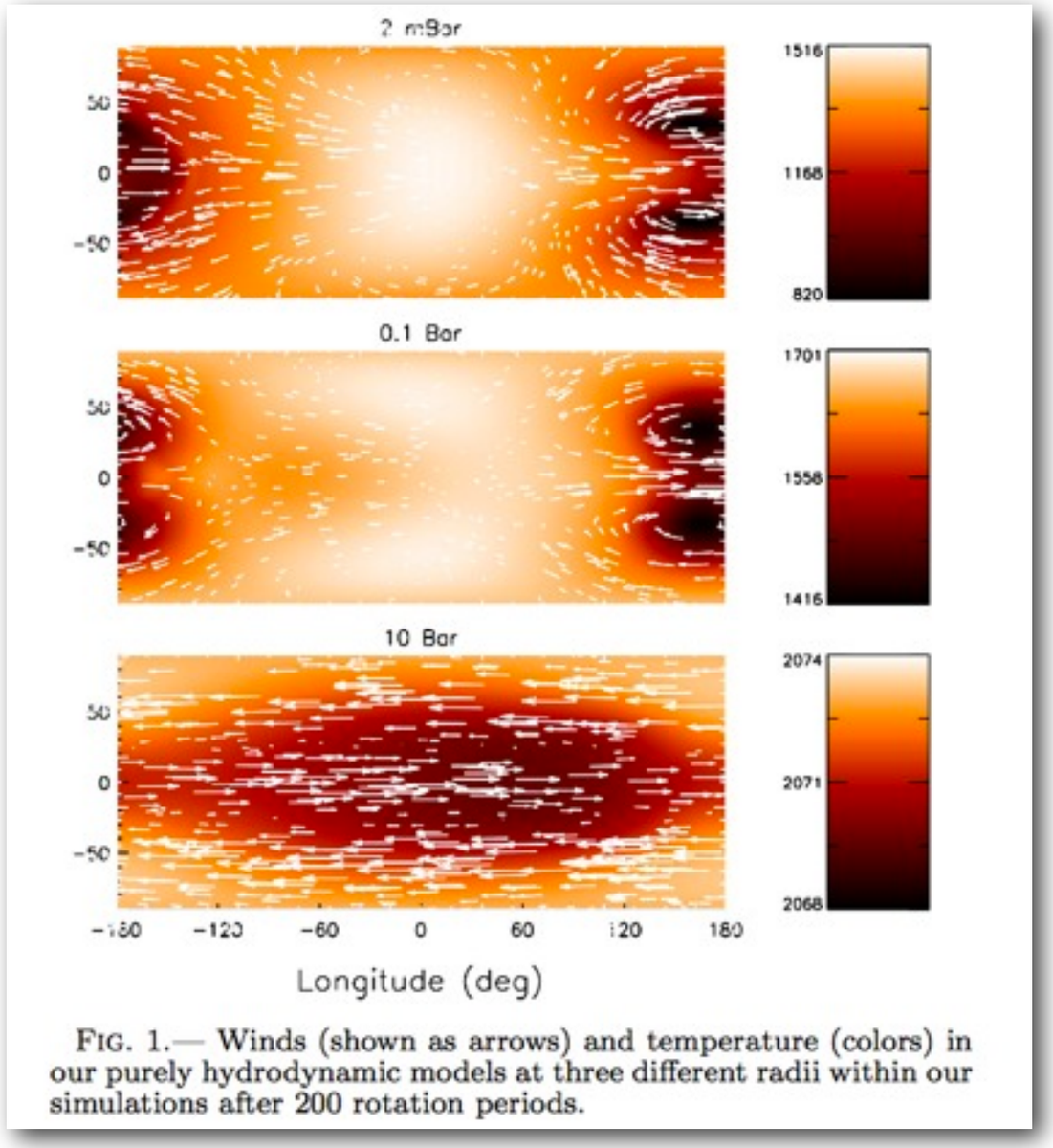


FIG. 1.— Winds (shown as arrows) and temperature (colors) in our purely hydrodynamic models at three different radii within our simulations after 200 rotation periods.

2014

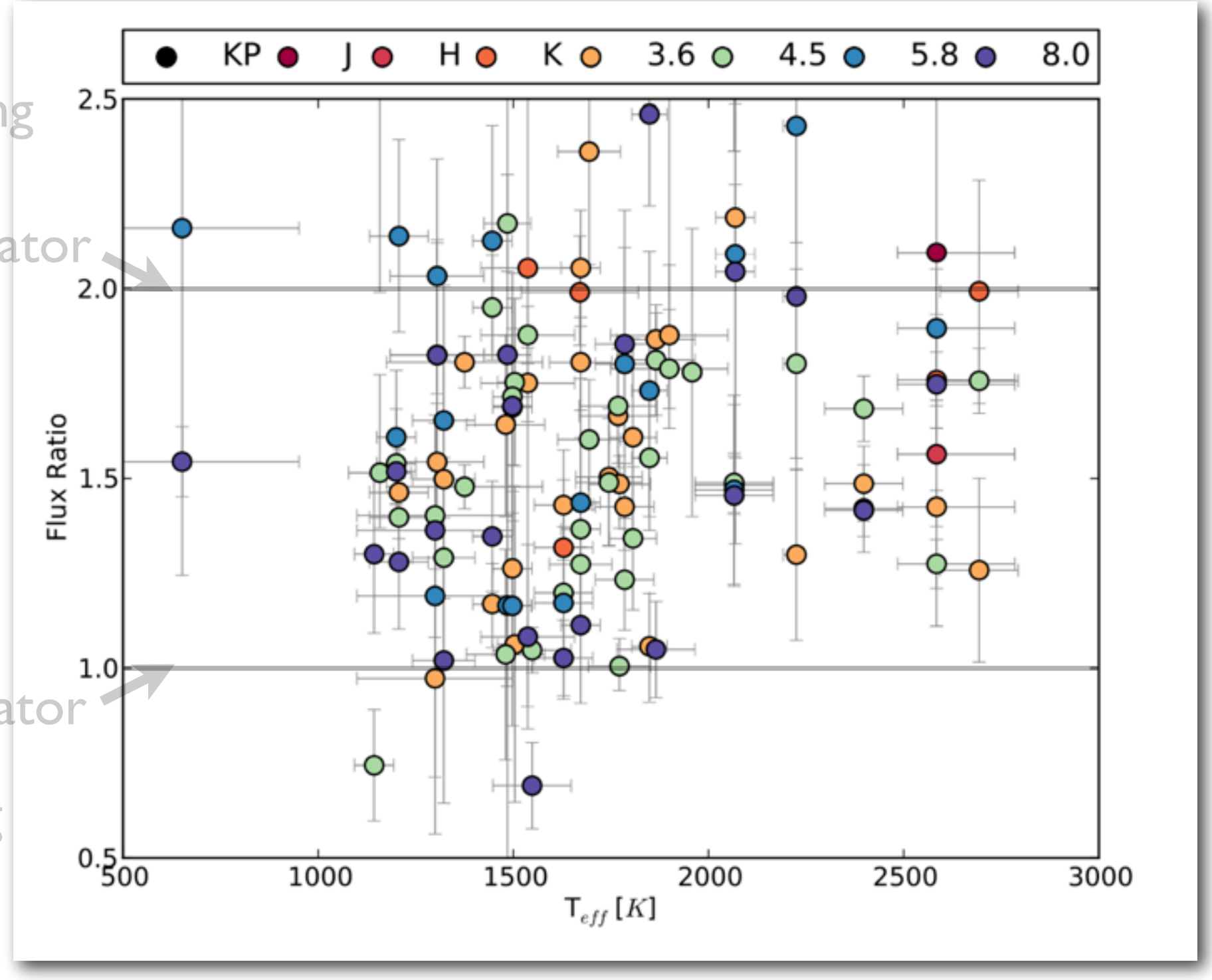
Iron
Rock
Ice
H-HE
Planetary Density [g/cm^3]
Planetary Mass [M_J]
$T_{EQ}[K]$
3000
1000
300
κ_e=0.0, P_n=0.1
κ_e=0.1, P_n=0.3
κ_e=0.2, P_n=0.1
Occultation depth [ppm]
λ [μm]
C/O Ratios
non-Equilibrium chemistry
stratospheric inversions
inefficient redistribution

Flourescing

2pi re-radiator

4pi re-radiator

Absorbing

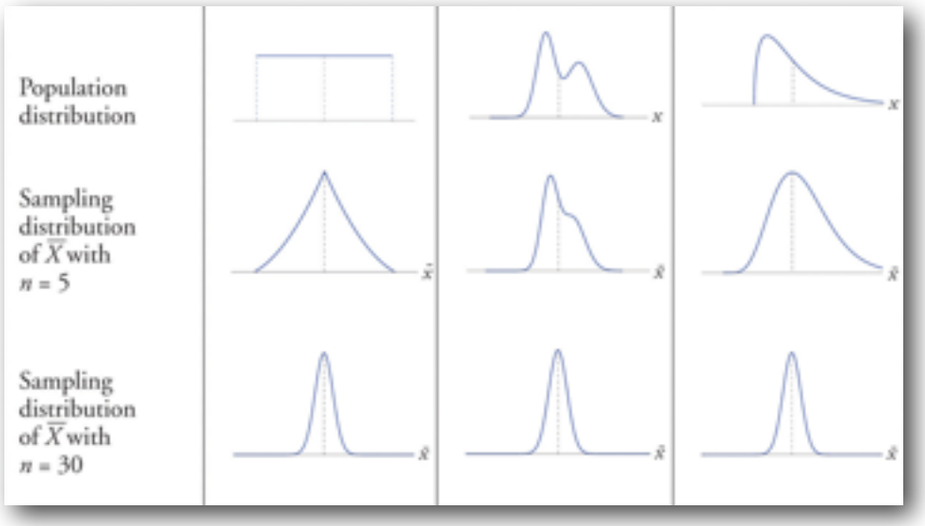


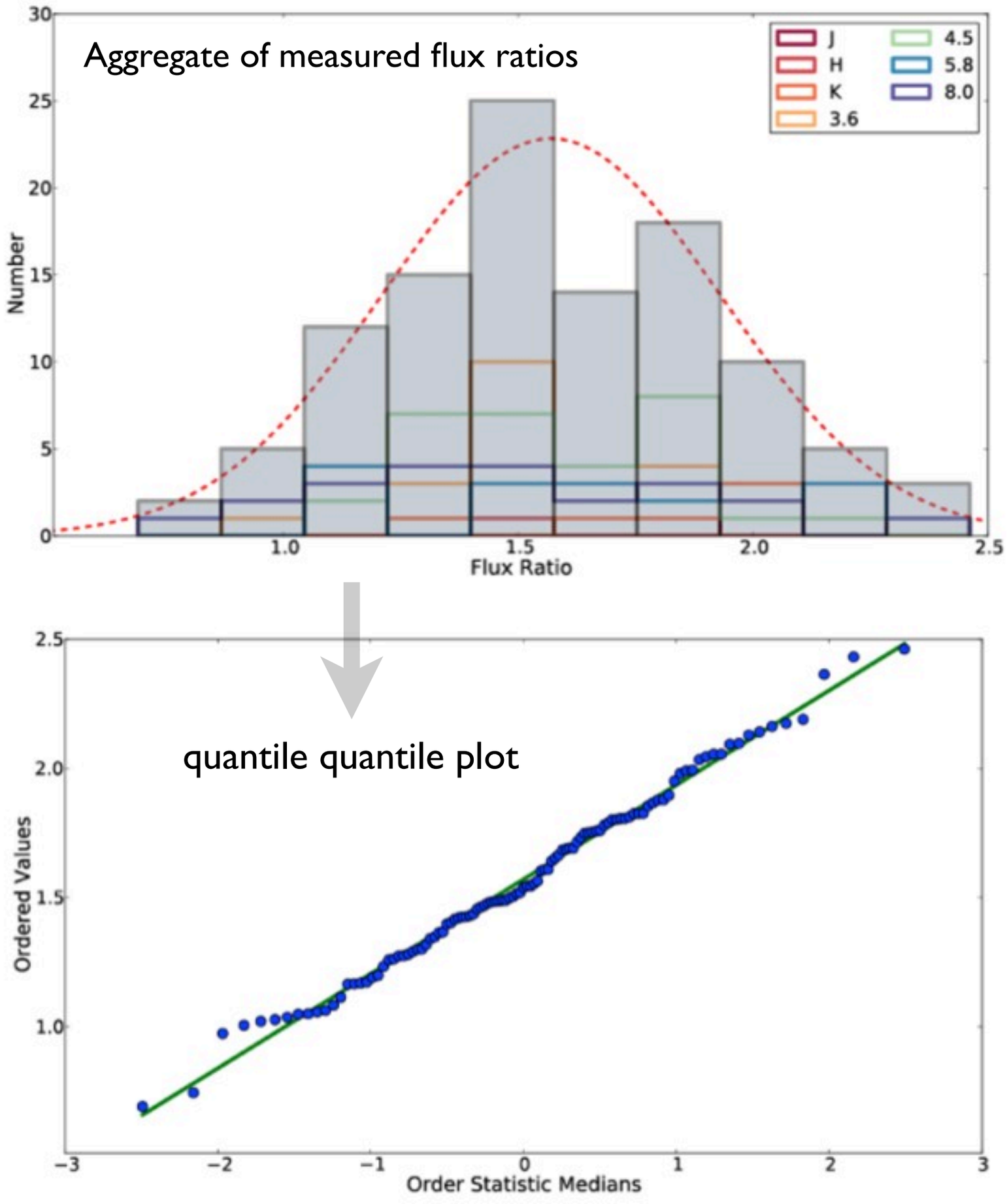
Planets are ordered on the *x*-axis by the equilibrium temperature, T_{eq}, computed with the assumption that they are A=0 blackbodies that re-radiate from the full planetary surface. Measured secondary eclipse depths (in bands ranging from Kepler's optical bandpass to 8μm) are expressed as ratios of the observed eclipse depth in the band relative to the expected depth in the band under the assumption that the planet is a uniformly re-radiating A=0 blackbody.

$$T_{\rm eq} = (R_\star^{1/2} T_\star)/((2a)^{1/2}(1-e^2)^{1/8})$$

Central Limit Theorem

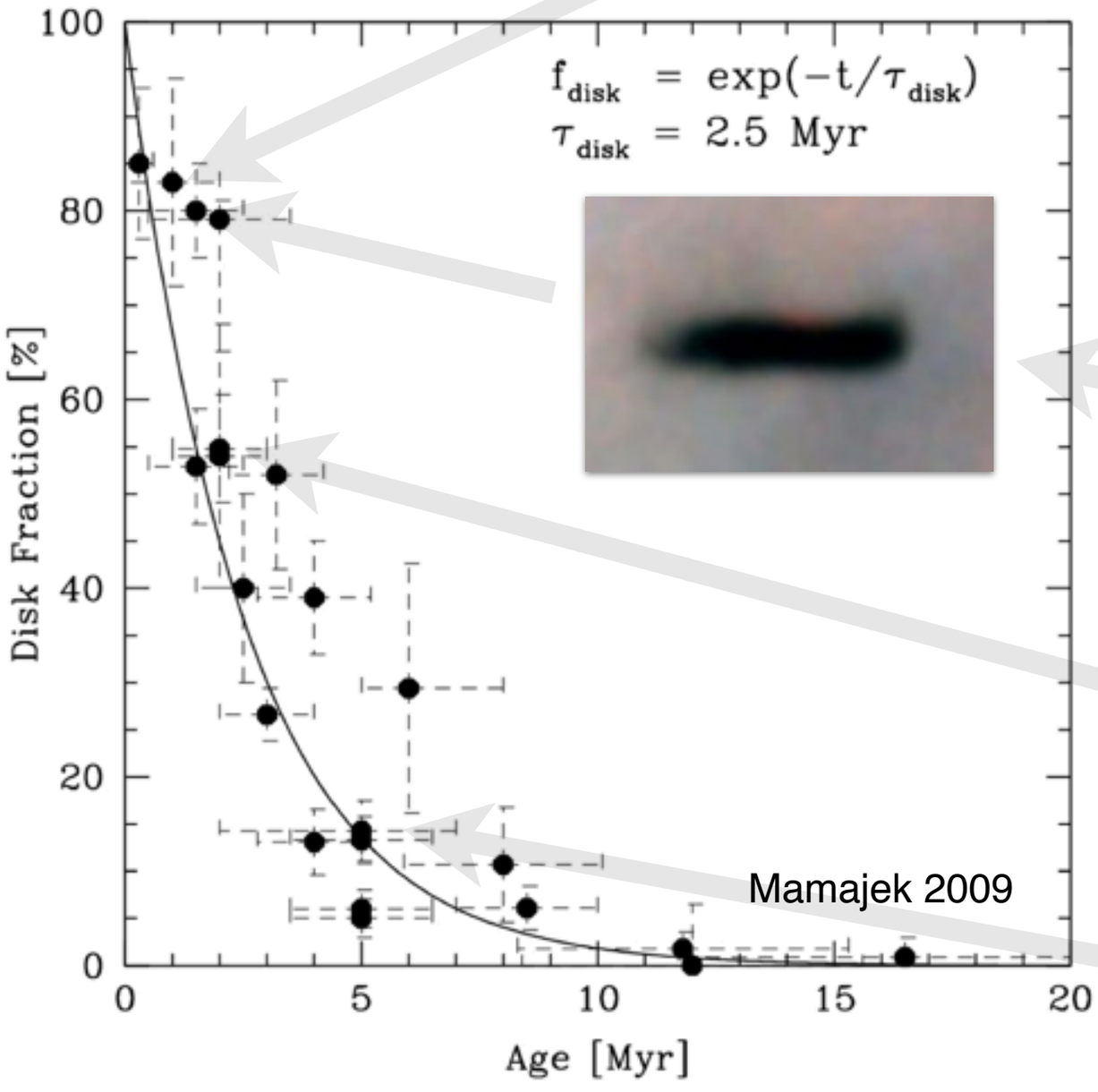
The central limit theorem states that a sufficiently large number of iterates of independent random variables, each with a well-defined expected value and well defined variance, will be approximately normally distributed.



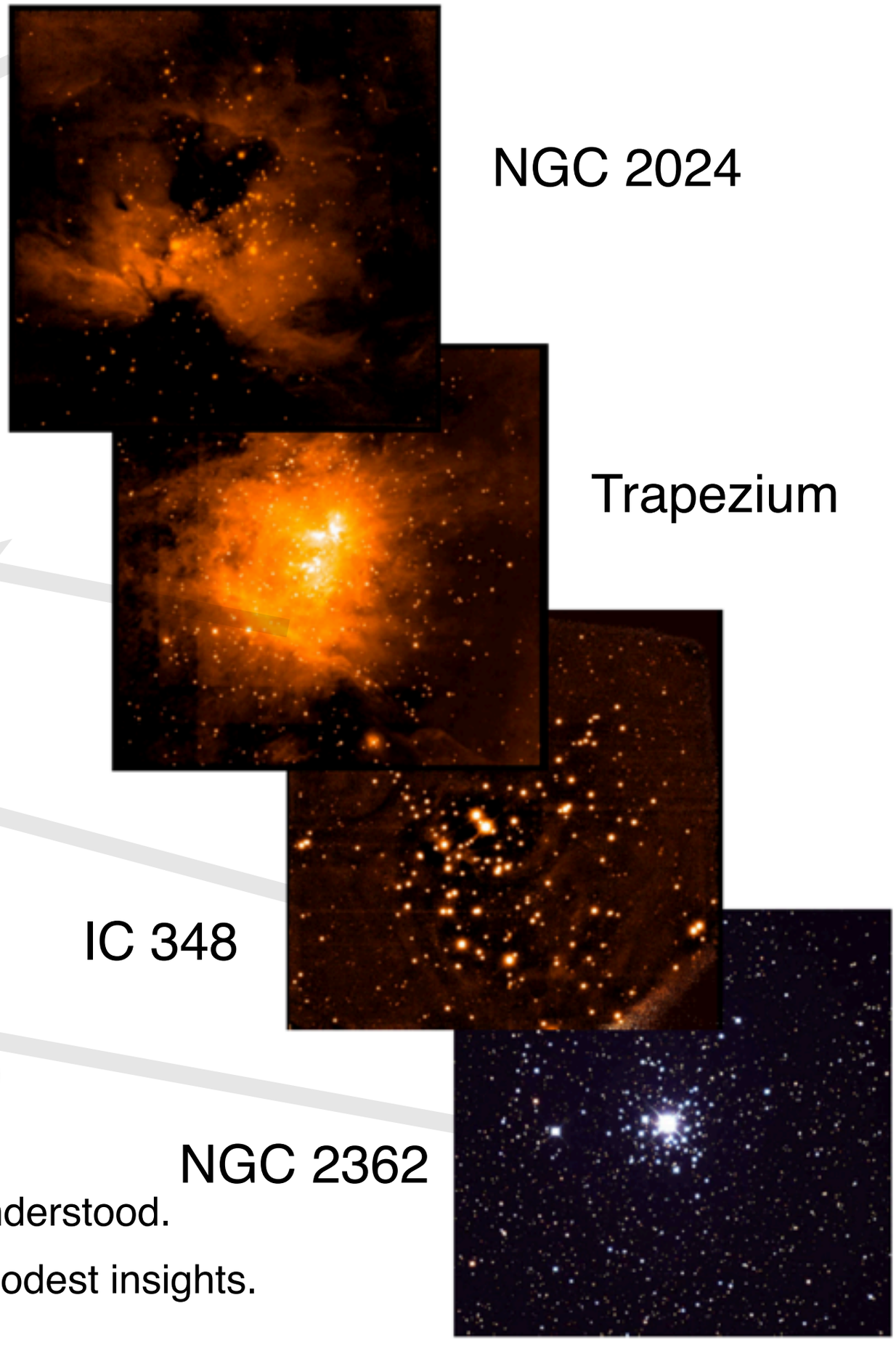


Fact: Protoplanetary Disks disperse in a few million years, and **more often than not, they leave planets behind.**

This part is new



Mamajek 2009



NGC 2024

Trapezium

IC 348

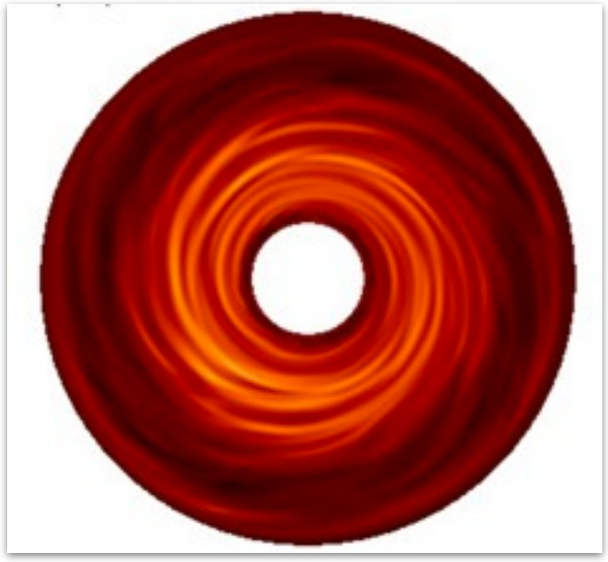
NGC 2362

Fact: Planet formation is not particularly well understood.

Opinion: Large scale computations can offer modest insights.

Disk Galaxy: 10^1-10^2 orbits

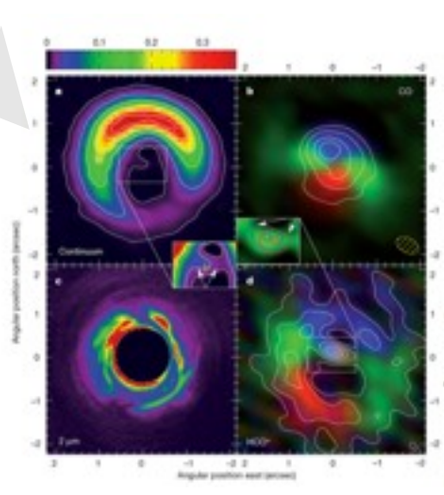
Very Detailed observations



MHD Simulation by Lyra (2011), **Not** a photograph.

Protostellar Disk: 10^5-10^7 orbits

Even ALMA observations are *not at all* detailed by comparison



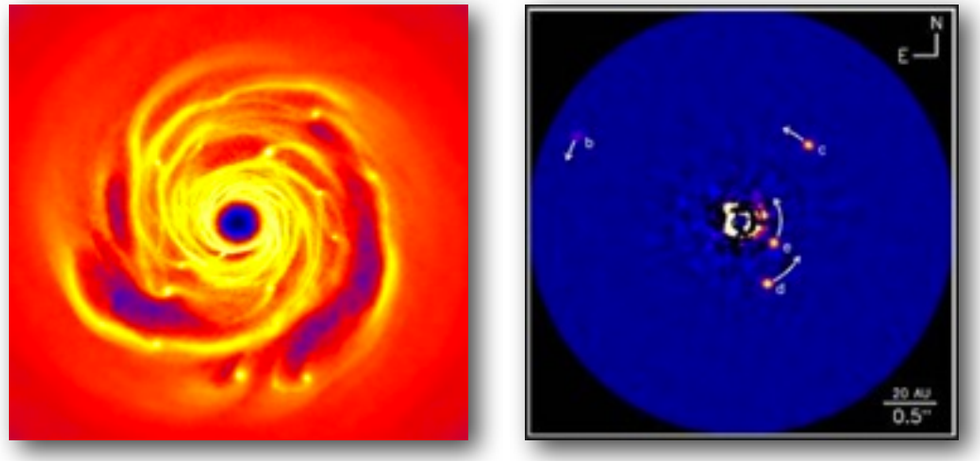
Cassasas et al. 2013 Nature

Planetary Rings: 10^{11}-10^{12} orbits

Extraordinarily Detailed observations

Challenges

Details of Disk Gravitational Instability



Left image from Rice et al.

Meter-size barrier

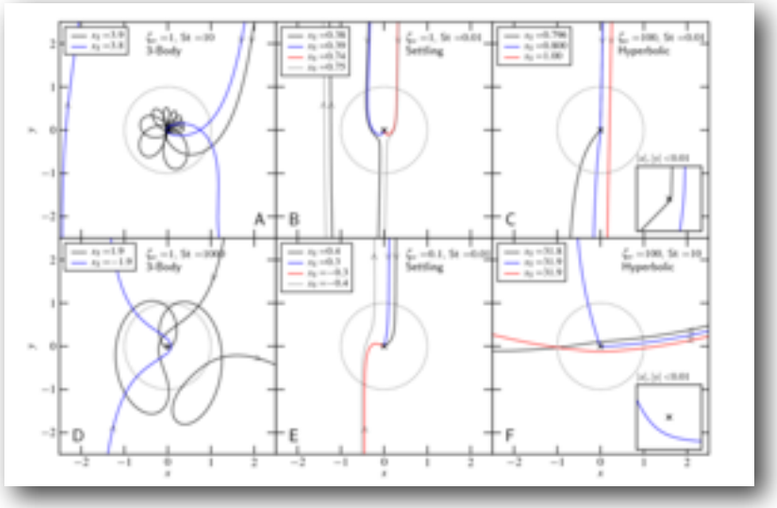
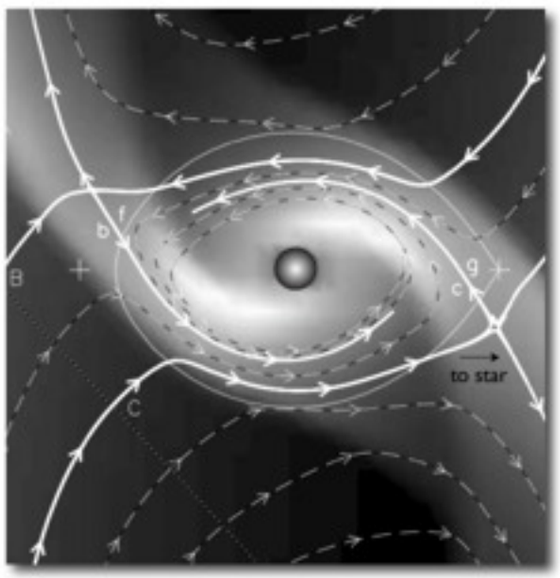
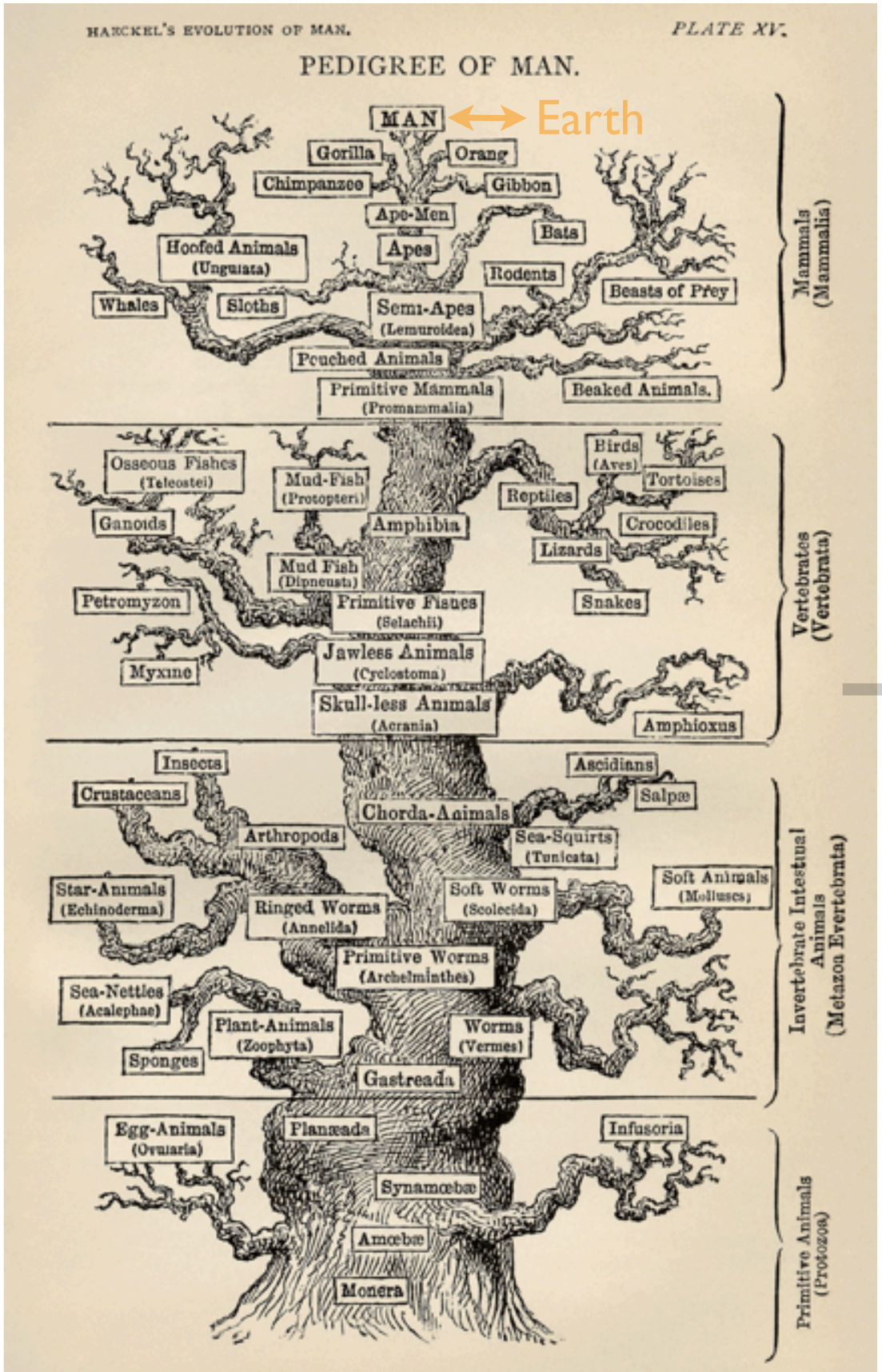


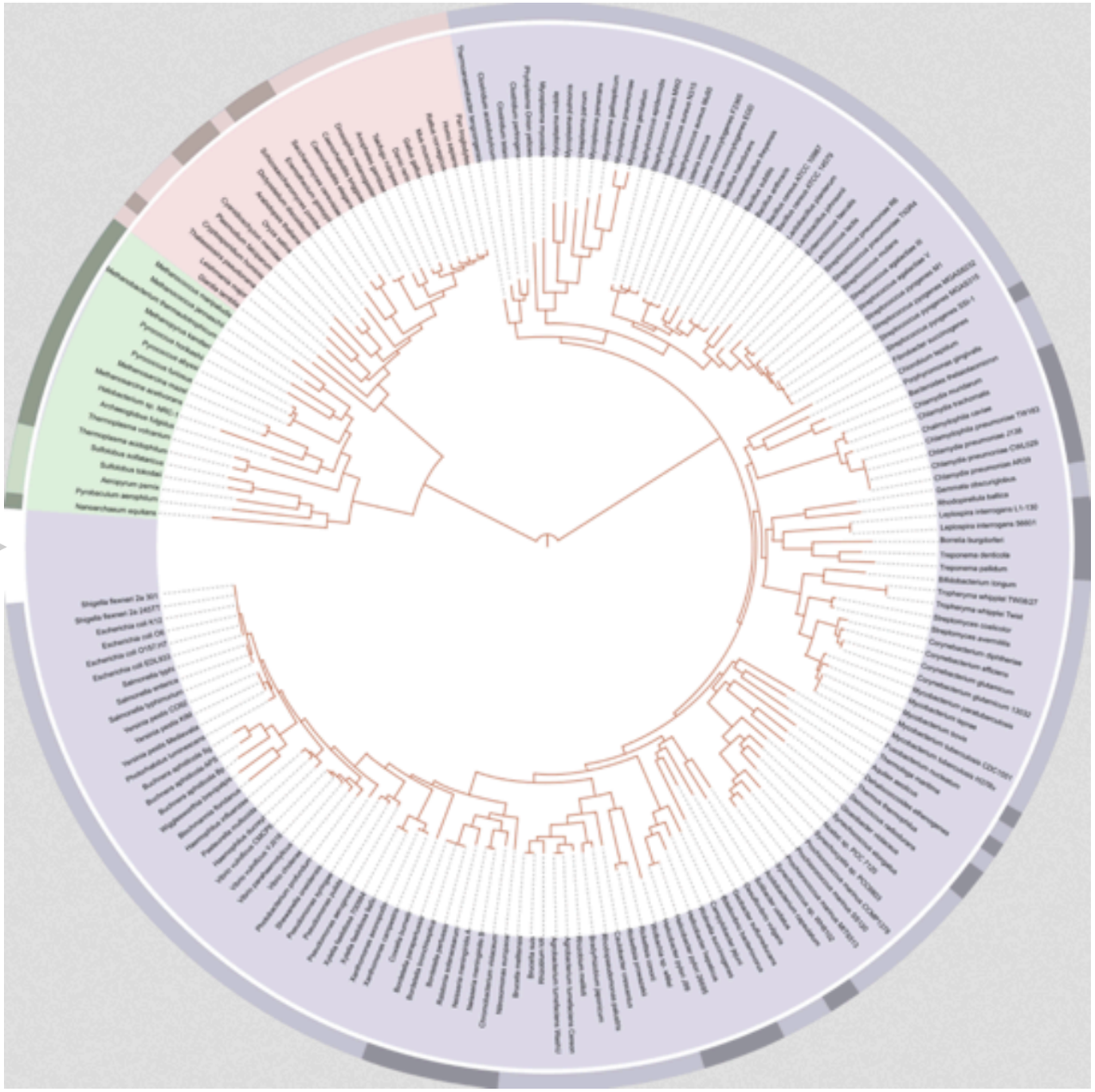
Image from Ormel

Migration or *in-situ*



Images adapted from Lubow et al.


HAECKEL'S EVOLUTION OF MAN.
PLATE XV.
PEDIGREE OF MAN.
MAN
Earth
Gorilla
Orang
Chimpanzee
Gibbon
Ape-Men
Apes
Bats
Hoofed Animals (Ungulata)
Rodents
Beasts of Prey
Whales
Sloths
Semi-Apes (Lemuroidea)
Pouched Animals
Primitive Mammals (Promammalia)
Beaked Animals.
Mammals (Mammalia)
Osseous Fishes (Teleostei)
Mud-Fish (Protopteri)
Birds (Aves)
Tortoises
Reptiles
Ganoids
Amphibia
Crocodiles
Lizards
Mud Fish (Dipneusta)
Petromyzon
Primitive Fishes (Selachii)
Snakes
Jawless Animals (Cyclostoma)
Myxine
Skull-less Animals (Acrania)
Amphioxus
Vertebrates (Vertebrata)
Insects
Ascidians
Crustaceans
Salpæ
Chorda-Animals
Arthropods
Sea-Squirts (Tunicata)
Star-Animals (Echinoderma)
Soft Worms (Scolecida)
Soft Animals (Molluscs)
Ringed Worms (Annelida)
Primitive Worms (Archelminthes)
Sea-Nettles (Acalephae)
Plant-Animals (Zoophyta)
Worms (Vermes)
Sponges
Gastreada
Invertebrate Intestinal Animals (Metazoa Evertebrata)
Egg-Animals (Ovularia)
Planæada
Infusoria
Synamœbæ
Amœbæ
Monera
Primitive Animals (Protozoa)



NIH.GOV