Detection of Extrasolar Planets

With contributions from:
Geoff Marcy, Eric Ford UC Berkeley
Paul Butler, Carnegie Institution, D.C.
Steve Vogt, Greg Laughlin UC Santa Cruz
Jeff Valenti, STScI
Chris McCarthy, Peter Driscoll SFSU

Uniform Doppler Precision: 3 m s^{-1}

➔ Uniform Detectability of Planets

1988 – Present (5 AU)

1997 – Present (3.1 AU)

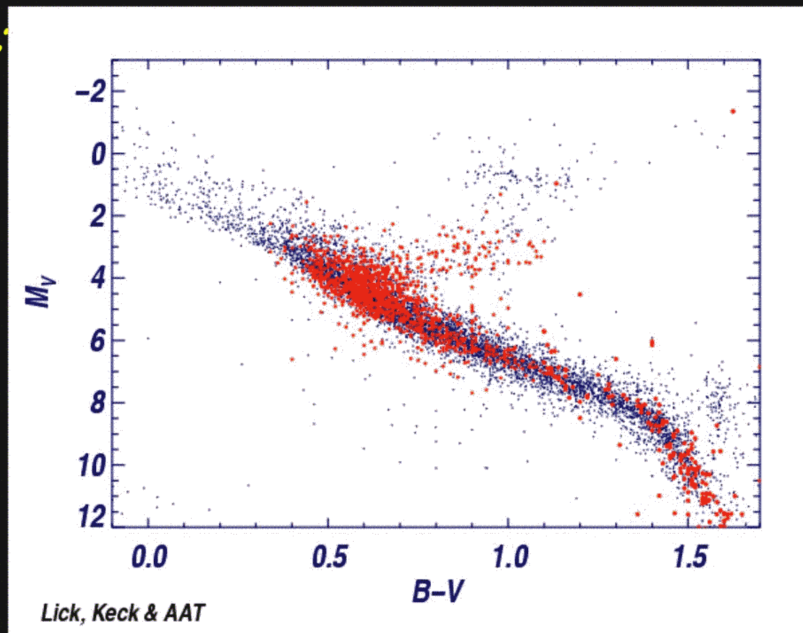
1998 – Present (2.9 AU)

- Stellar Sample -
1330 FGKM Main-Sequence

Selection Criteria:

Hipparcos Cat.
& Gliese Cat.

- $V_{mag} < 10$ mag
- B-V > 0.55 (F8V)
- Sep > 2 arcsec
- Age > 2 Gyr
- No Giants



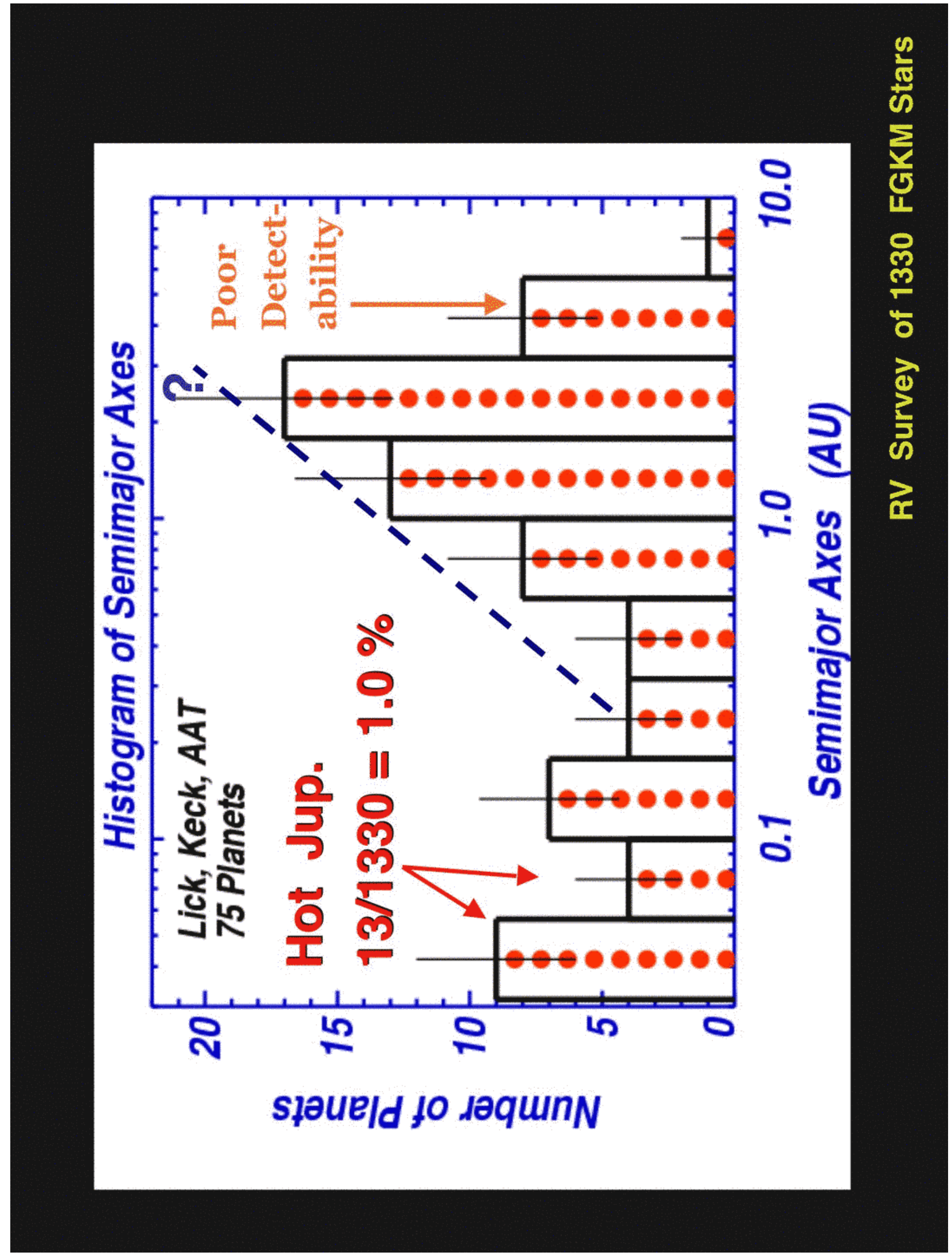
RV Survey 1330 FGKM
Results:

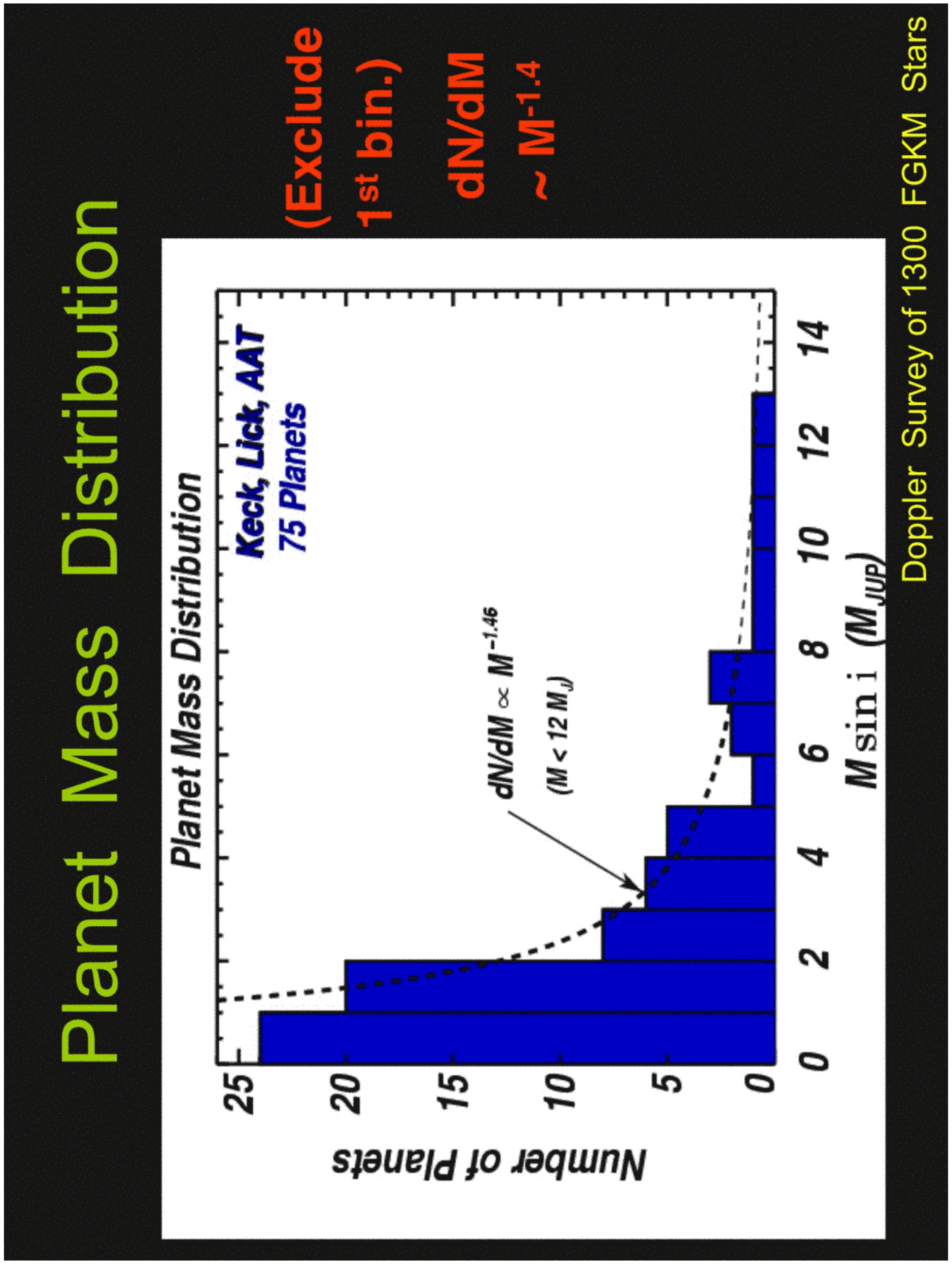
- Yield: 75 Planets
- 8 Multiple-Planet Systems
- 65 Stars have known planets

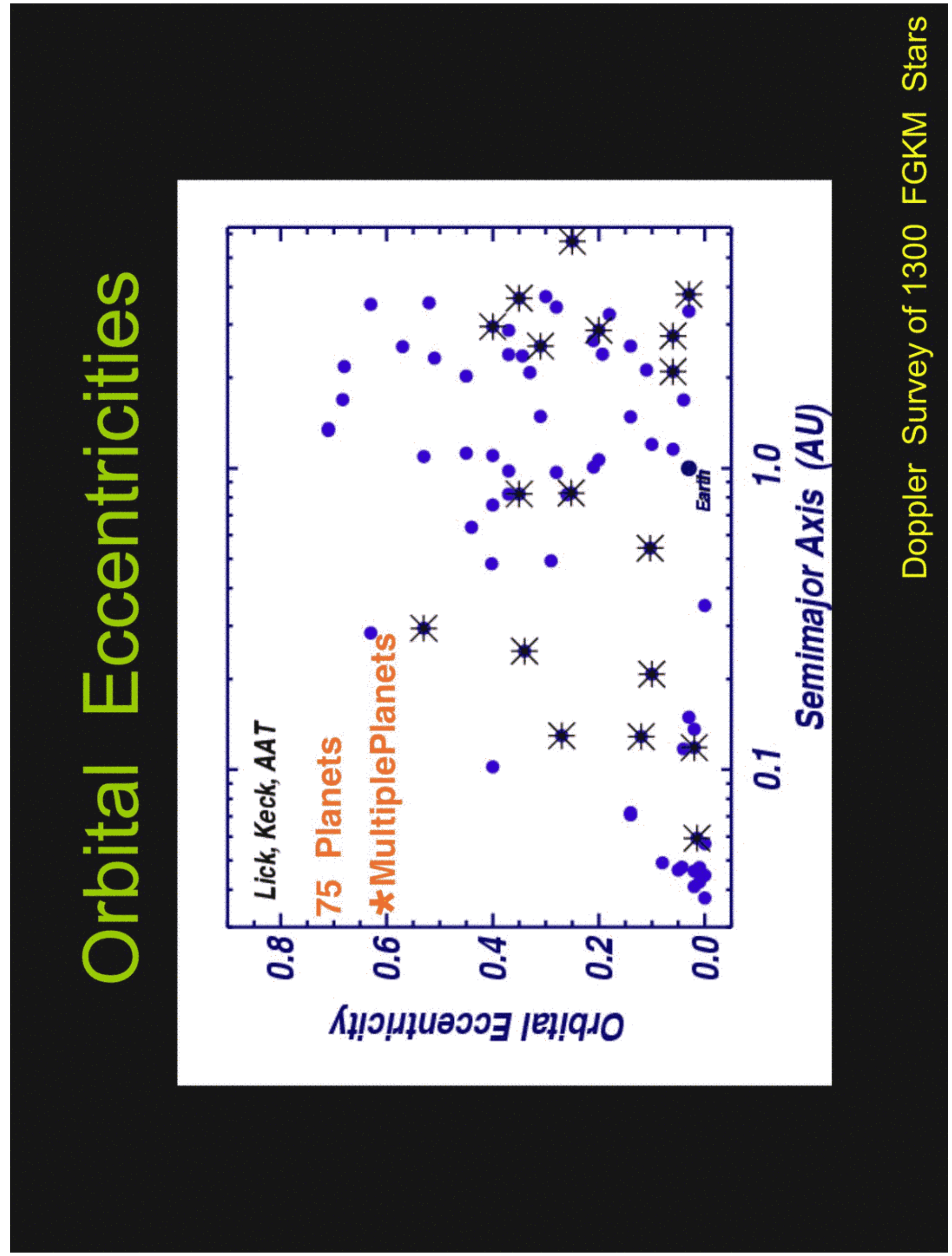
- Occurrence: 65 / 1330 = 5 %

➢ 5 % of stars have giant planet within 3 AU.


Formation and Evolution
What observations serve as boundary conditions for theory?
How do we get to the end-state systems that we observe now?


RV Survey of 1330 FGKM Stars
Histogram of Semimajor Axes
Lick, Keck, AAT
75 Planets
Hot Jup.
13/1330 = 1.0 %
Poor
Detect-
ability
?
Number of Planets
0
5
10
15
20
0.1
1.0
10.0
Semimajor Axes (AU)


Planet Mass Distribution
(Exclude 1st bin.)
dN/dM ~ M-1.4
Planet Mass Distribution
Keck, Lick, AAT
75 Planets
dN/dM ∝ M-1.46
(M < 12 MJ)
Number of Planets
0 5 10 15 20 25
0 2 4 6 8 10 12 14
M sin i (MJUP)
Doppler Survey of 1300 FGKM Stars


Orbital Eccentricities
Lick, Keck, AAT
75 Planets
*MultiplePlanets
Orbital Eccentricity
0.0 0.2 0.4 0.6 0.8
Earth
0.1 1.0
Semimajor Axis (AU)
Doppler Survey of 1300 FGKM Stars


In the beginning, there was 51 Peg
Tidally circularized, short-period gas giant planets, or “hot Jupiters
Lower Msini
Higher stellar masses
Pile-up in orbital periods at 3d
OGLE transit: exception

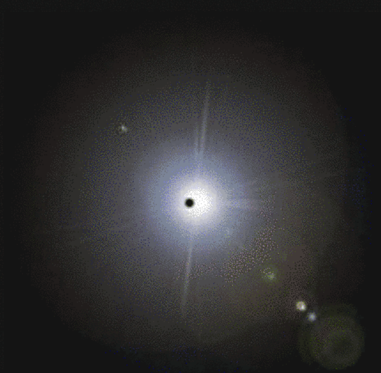

Hot Jupiters
Hundreds of citations in literature
Boundary conditions for theories of orbital migration, planet-planet and planet-disk (tidal) interactions and disk evolution
High probability transit candidates (HD 209458)
Offer constraints on tidal dissipation indicating the presence or absence of solid cores
Serve as tracers of multiple planet systems with orbital periods short enough to exhibit non-Keplerian interactions

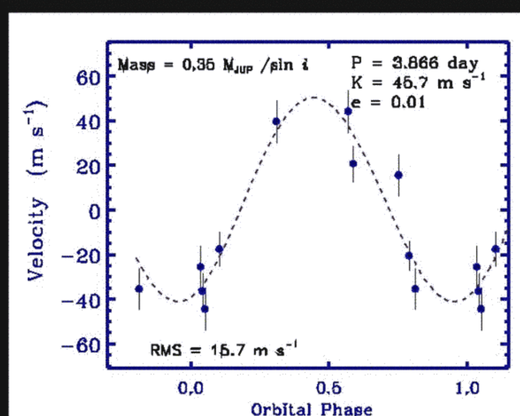
Hot Jupiters

Current sample of hot Jupiters is a stagnant set - virtually all of these short period planets have been detected in current Doppler samples.

Only way to detect more of these important objects is to survey a fresh sample of stars.

Hot Jupiter Search: "N2K"





International Consortium

Fischer, Laughlin (NASA / NOAO Keck)

Ida, Sato (Japan: Subaru)

Minniti (Chile: Magellan)

Quirrenbach, Frink (ESA TAC declined)

Massive Eccentric Planets

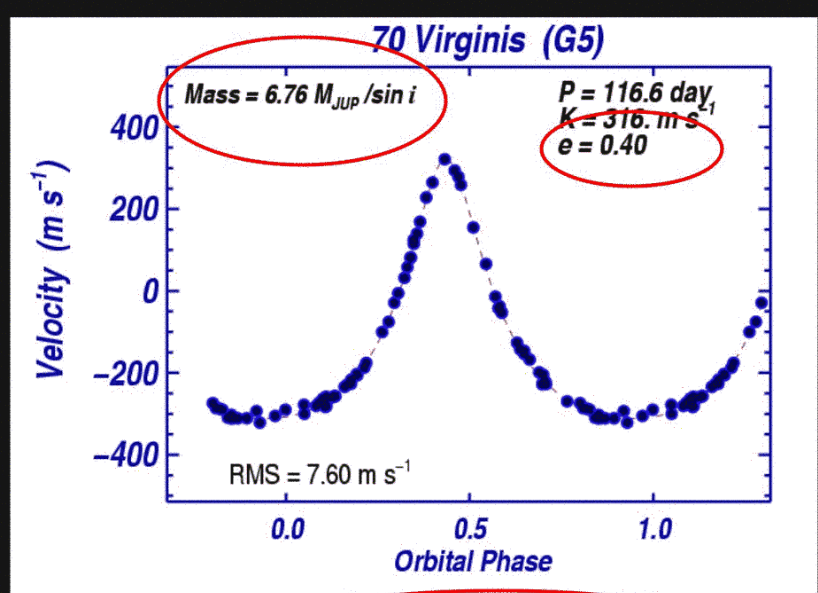
- Msini > 1 M_{JUP}
- Ecc > 0.2

Most have:

No other giant planet

No stellar companion

Massive Eccentric Planets

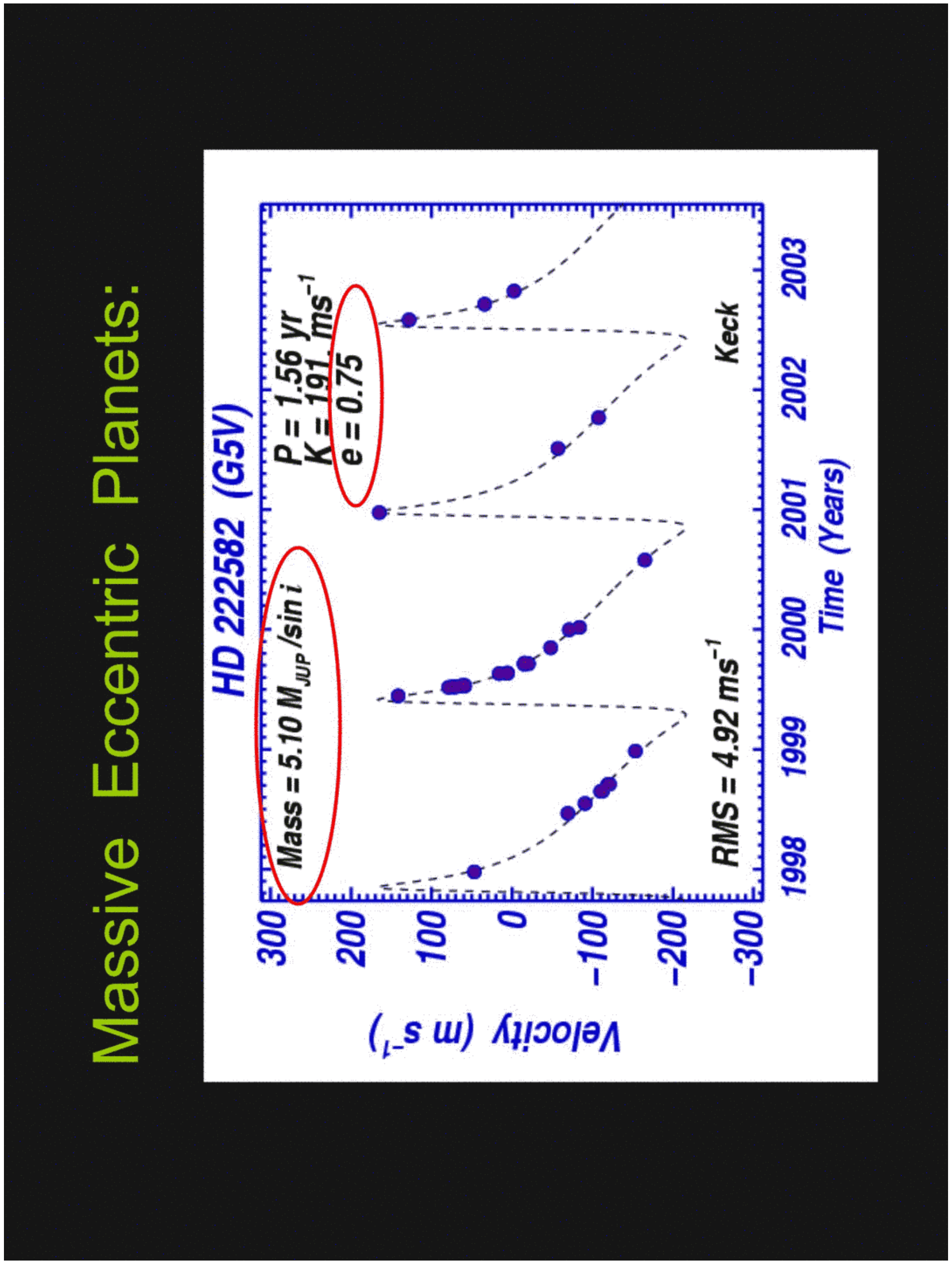


15 Years of RV from Lick Obs.

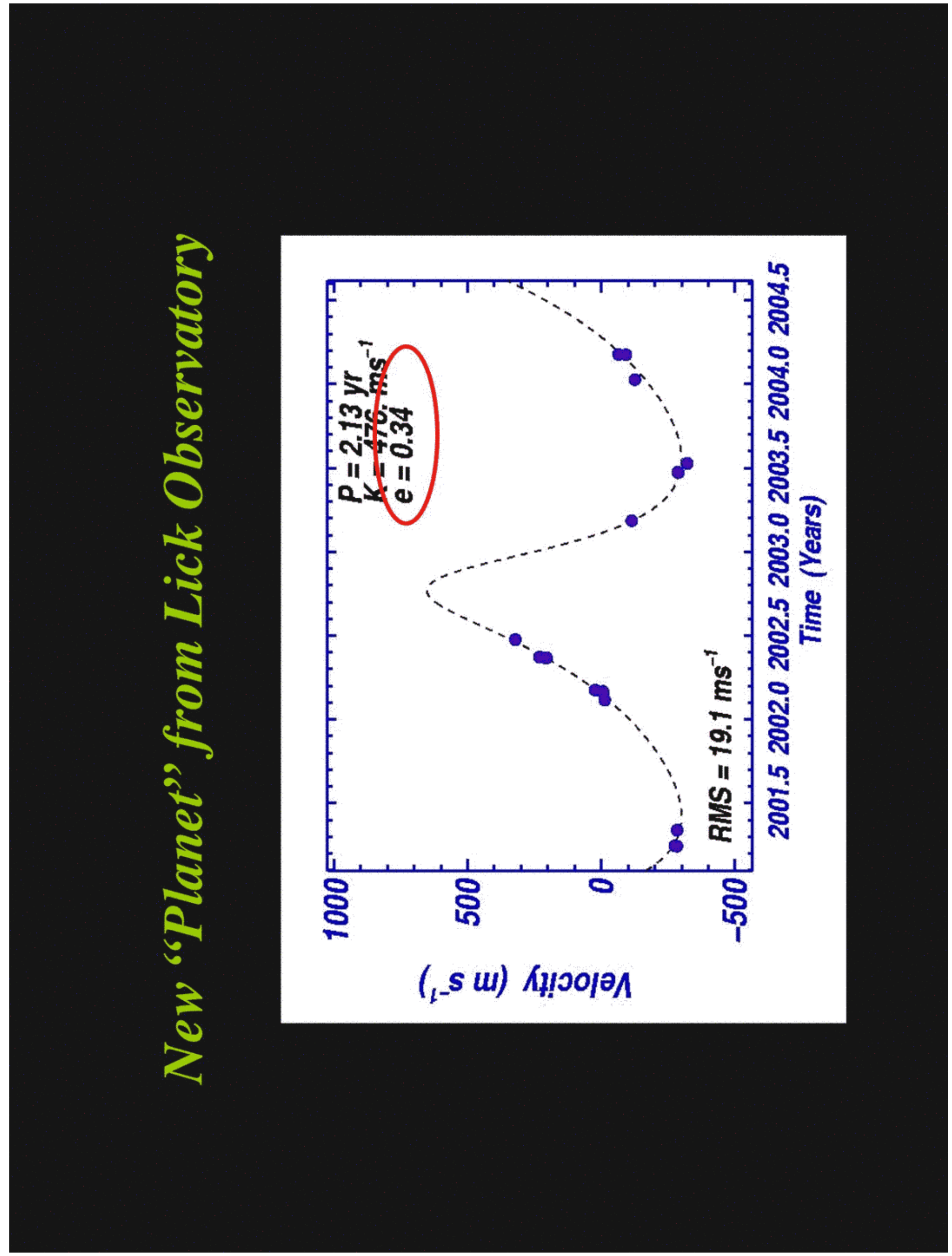
No Other Massive Planets

No Stellar Companion

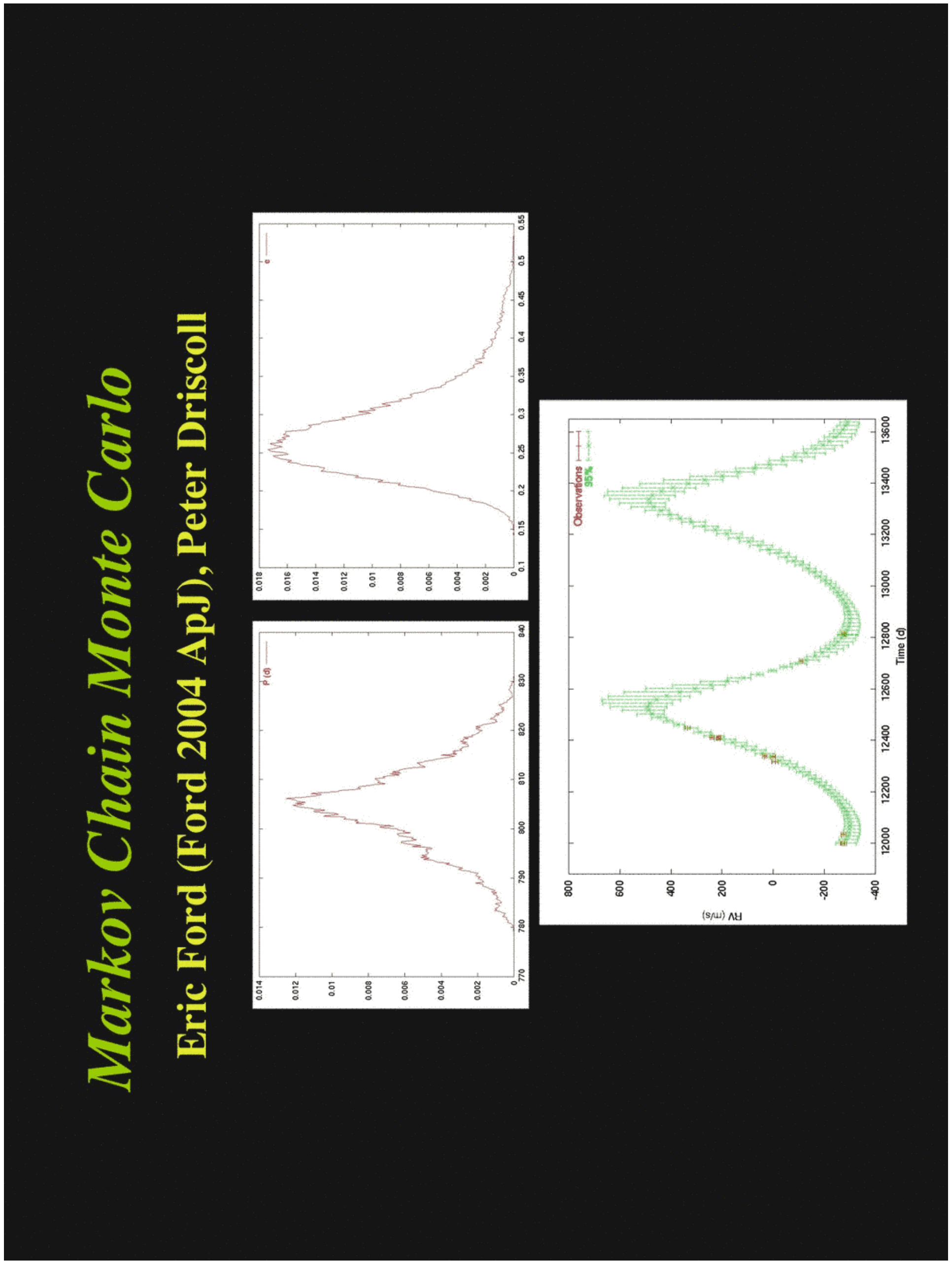
Origin of Eccentricity ?

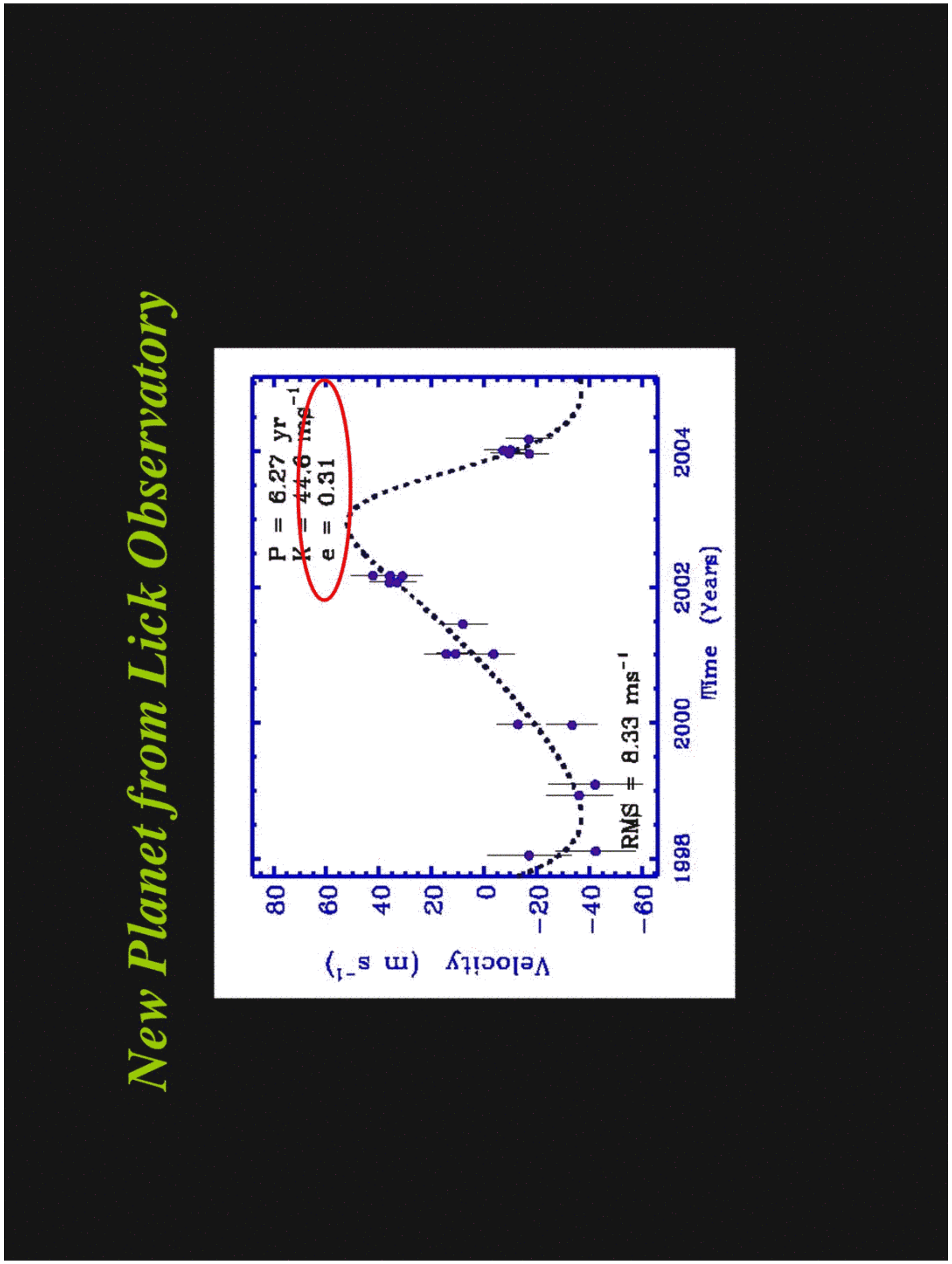


Massive Eccentric Planets:
HD 222582 (G5V)
Mass = 5.10 M_{JUP}/sin i
P = 1.56 yr
K = 191. ms^{-1}
e = 0.75
Keck
RMS = 4.92 ms^{-1}
Velocity (m s^{-1})
300 200 100 0 −100 −200 −300
1998 1999 2000 2001 2002 2003
Time (Years)



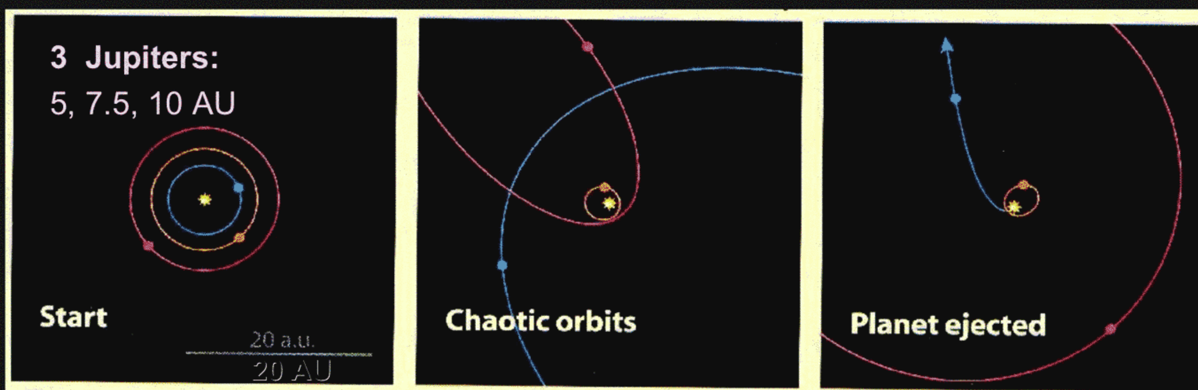
New “Planet” from Lick Observatory
P = 2.13 yr
K = 476. ms^{-1}
e = 0.34
RMS = 19.1 ms^{-1}
Velocity (m s^{-1})
1000 500 0 −500
2001.5 2002.0 2002.5 2003.0 2003.5 2004.0 2004.5
Time (Years)


Markov Chain Monte Carlo
Eric Ford (Ford 2004 ApJ), Peter Driscoll
Observations
95%
Time (d)
RV (m/s)


New Planet from Lick Observatory
P = 6.27 yr
K = 44.6 ms^-1
e = 0.31
RMS = 8.33 ms^-1
Velocity (m s^-1)
Time (Years)

Origin of Eccentricities: Planet - Planet Interactions ?

Problems:
- No Other Planet Detected
- Initial Conditions Unstable
- Few Final Orbits a < 1 AU

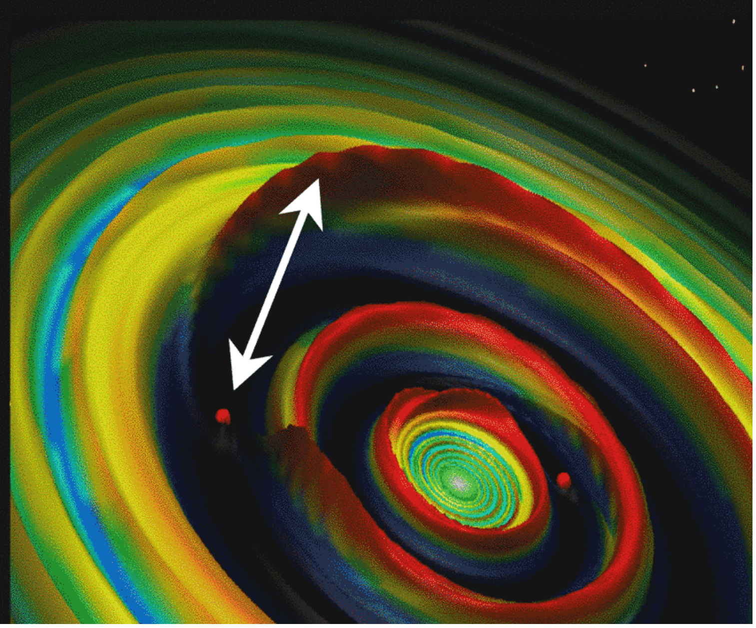


Rasio & Ford; Lin & Ida; Murray et al. Weidenschilling & Marzari

Origin of Eccentricities: Planet – Disk Interactions

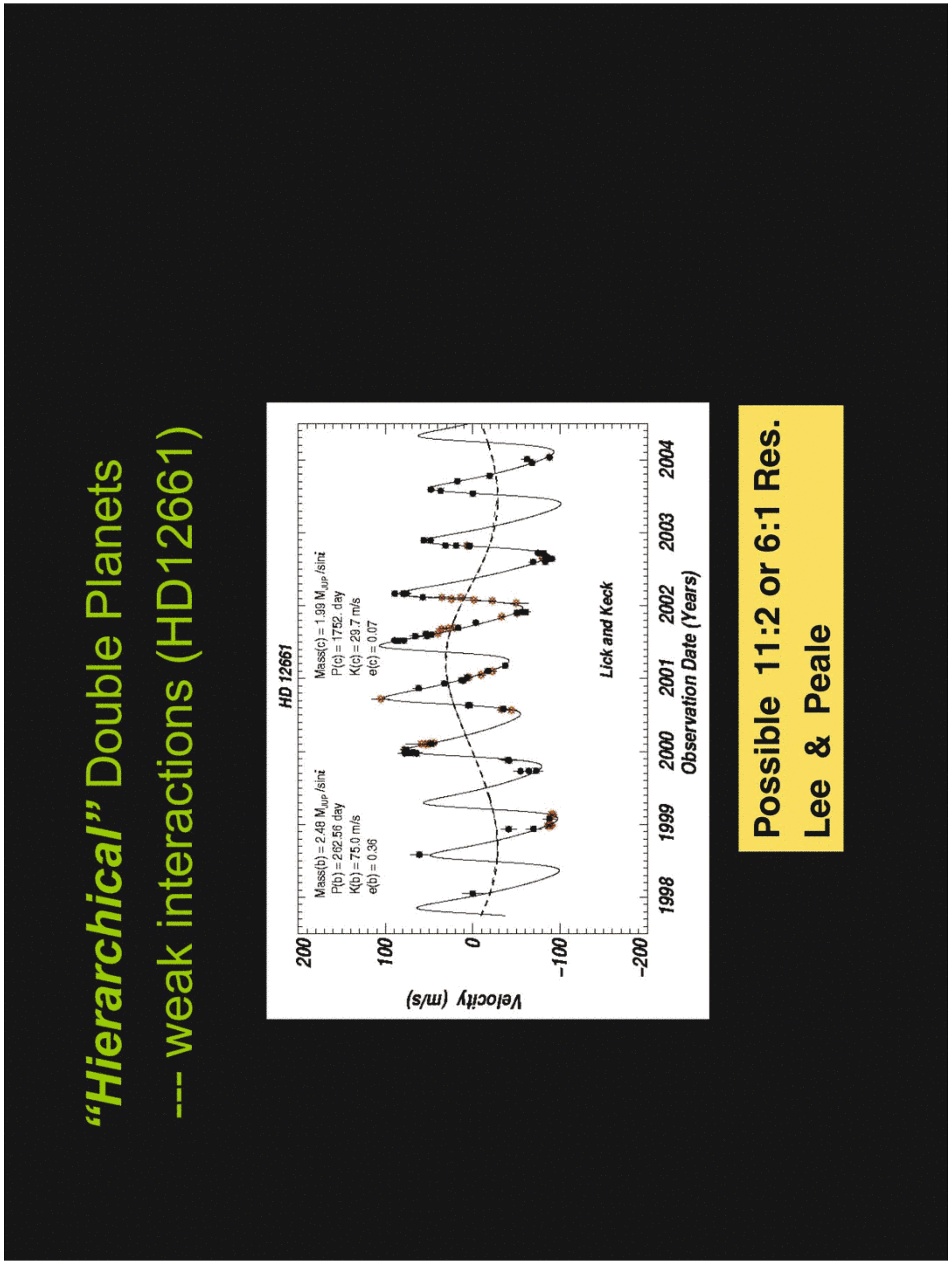
(Sari & Goldreich, 2003)

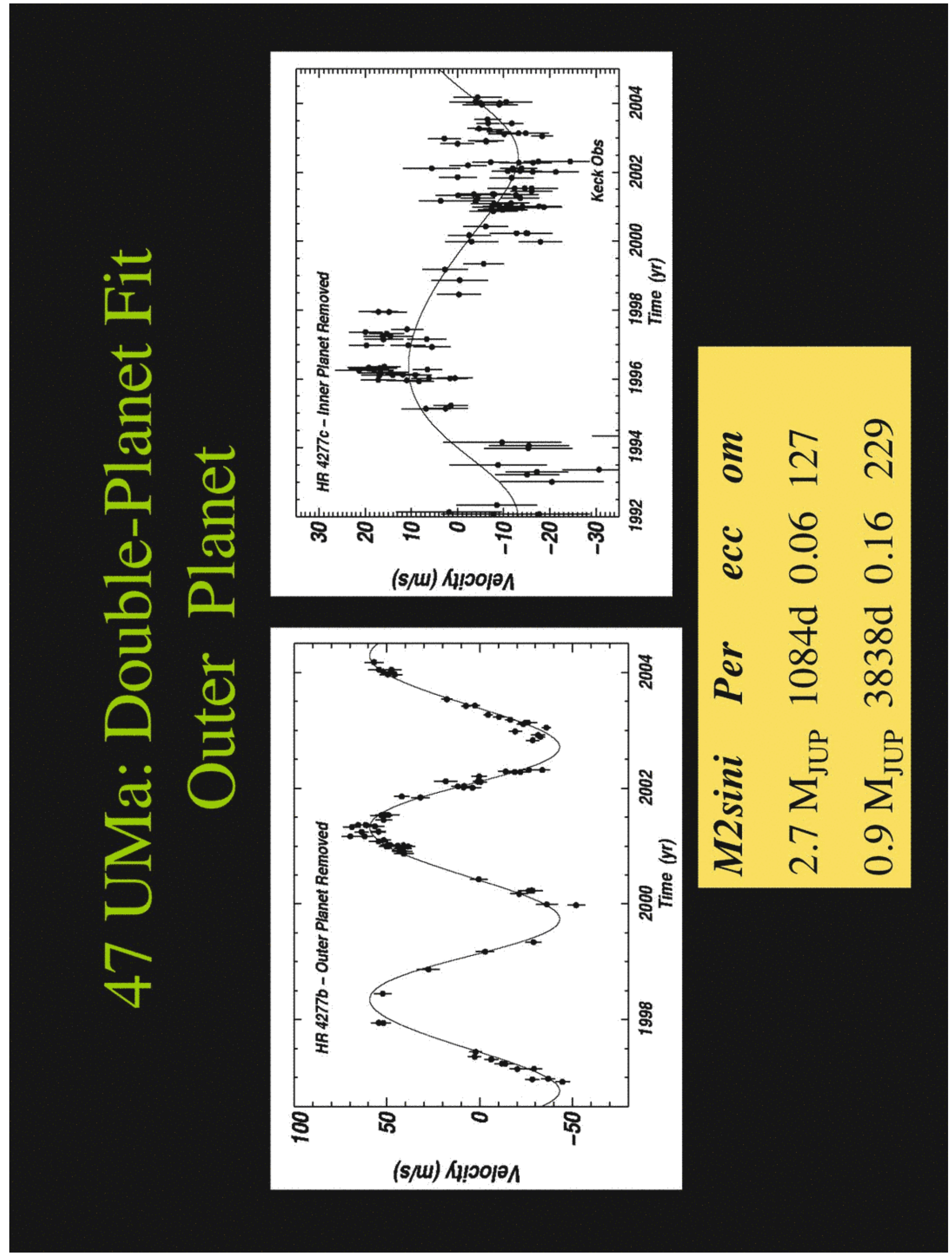
Gas Disk
Pumps
Eccentricity



Require:

$M_{DISK} > M_{Planet}$


“Hierarchical” Double Planets
--- weak interactions (HD12661)
HD 12661
Mass(b) = 2.48 M_JUP /sini
P(b) = 262.56 day
K(b) = 75.0 m/s
e(b) = 0.36
Mass(c) = 1.99 M_JUP /sini
P(c) = 1752. day
K(c) = 29.7 m/s
e(c) = 0.07
Lick and Keck
Velocity (m/s)
Observation Date (Years)
Possible 11:2 or 6:1 Res.
Lee & Peale


47 UMa: Double-Planet Fit
Outer Planet
HR 4277b – Outer Planet Removed
Velocity (m/s)
Time (yr)
HR 4277c – Inner Planet Removed
Keck Obs
Velocity (m/s)
Time (yr)
M2sini Per ecc om
2.7 M_JUP 1084d 0.06 127
0.9 M_JUP 3838d 0.16 229

"Resonance" Systems

--- Resonant interactions

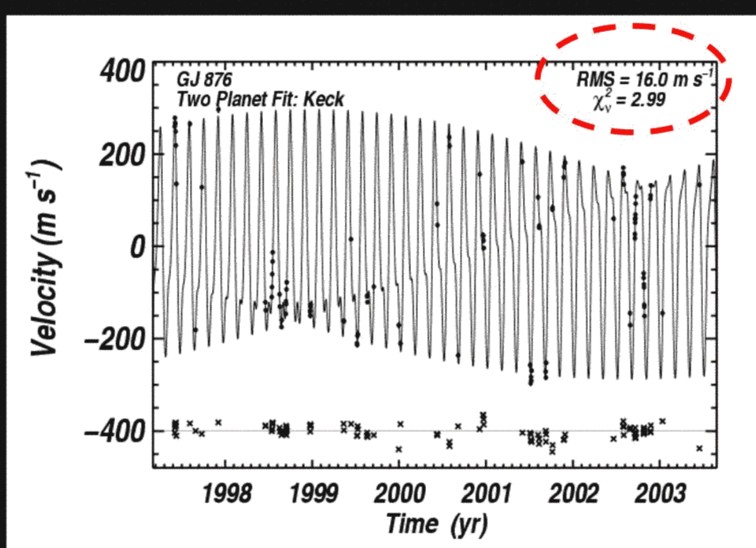
GJ 876

55 Cnc

Upsilon Andromedae

GL 876 (M4V)

2:1 Resonance

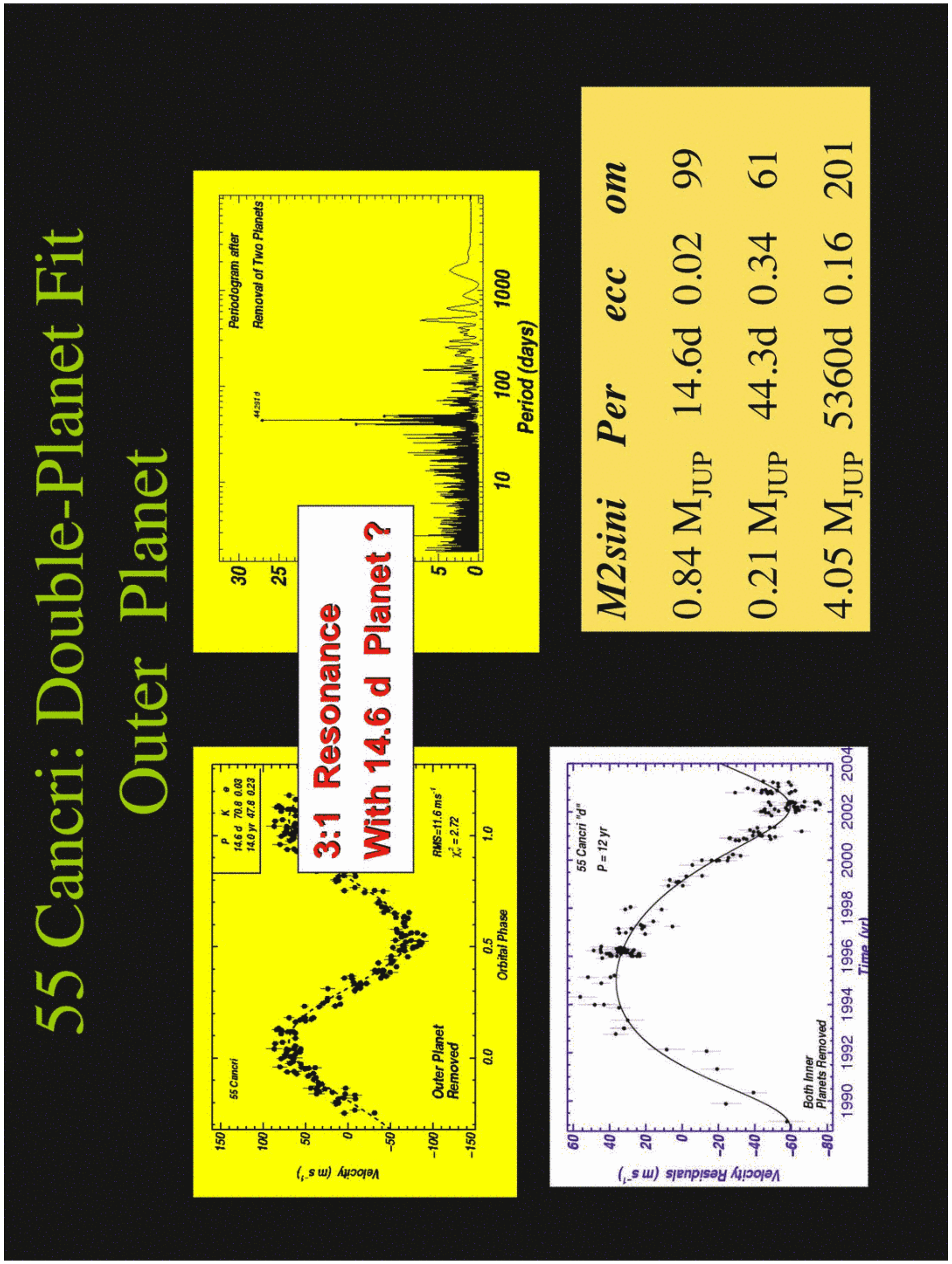


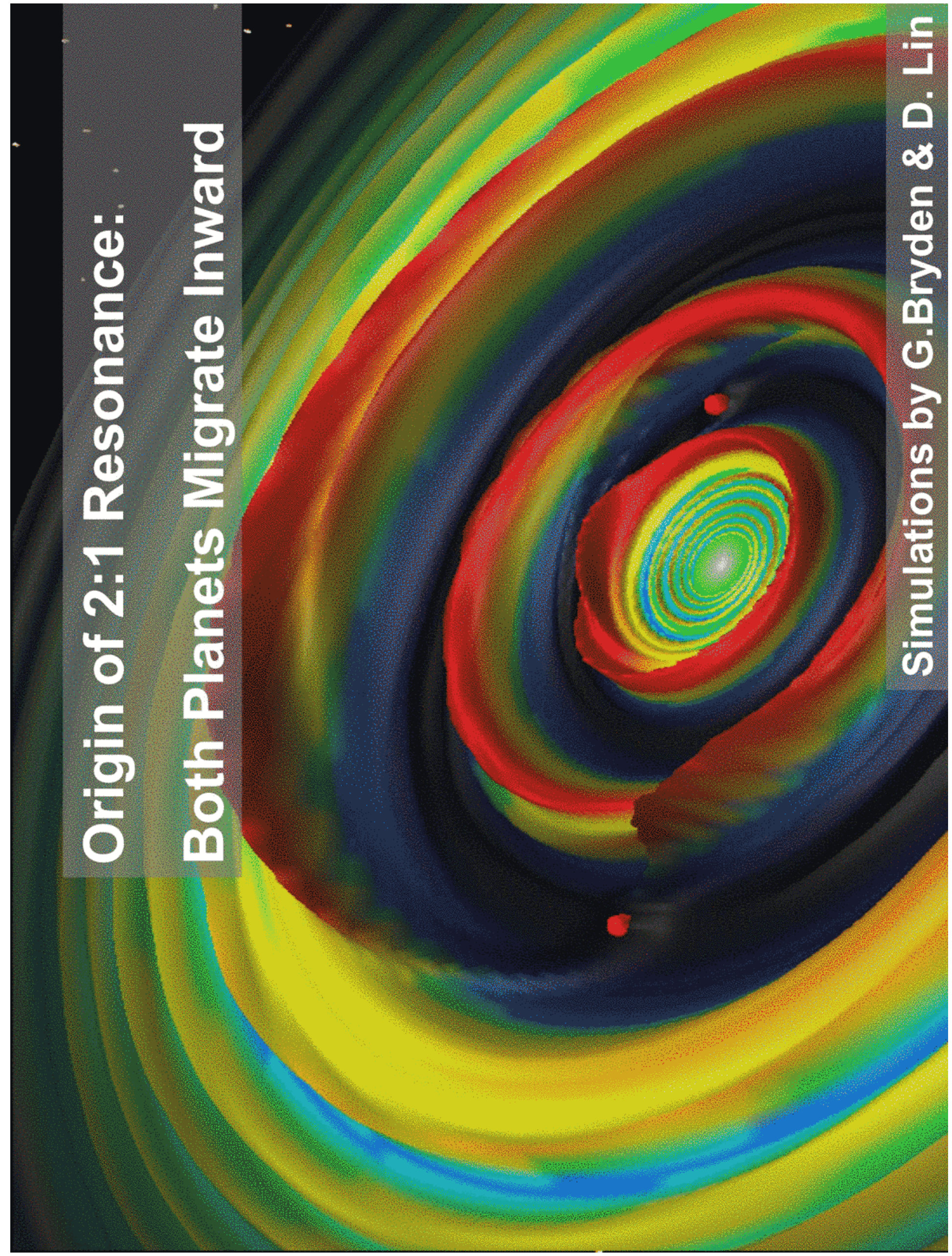
P = 61.0 d

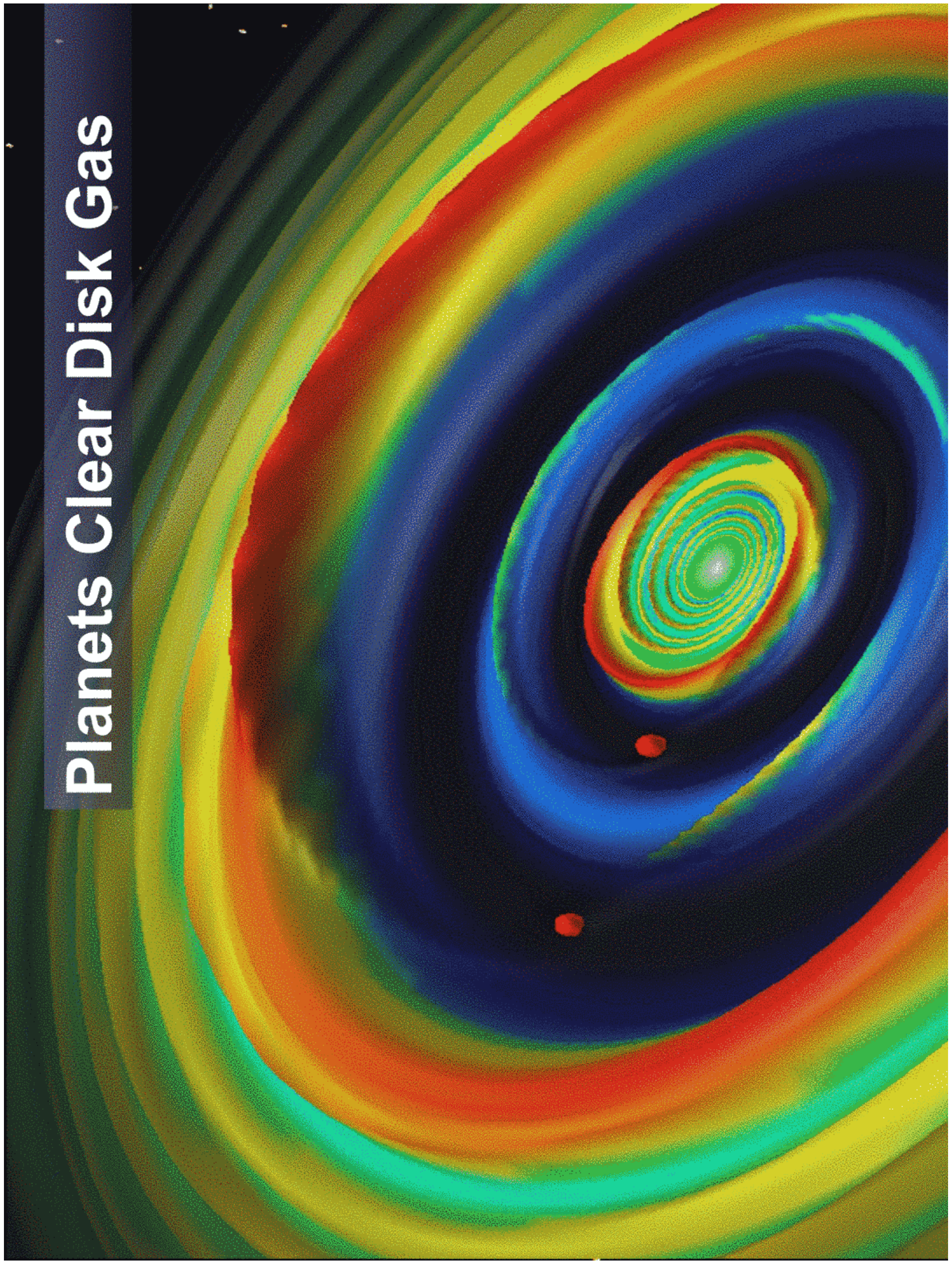
P = 30.1 d

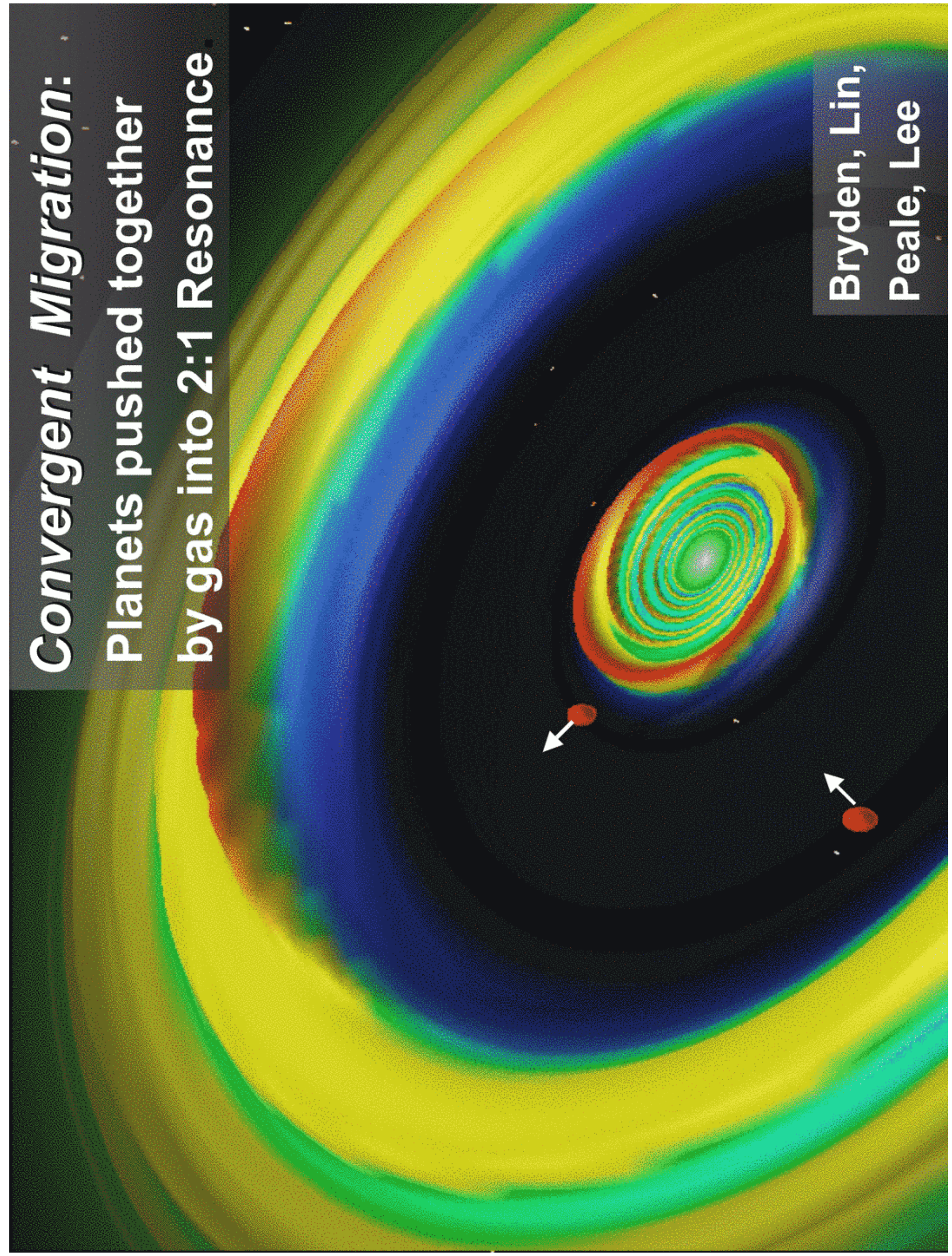
M sin*i* = 1.9 M_J

M sin*i* = 0.56 M_J

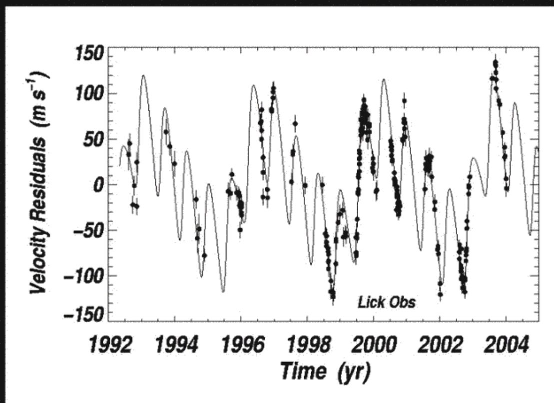

55 Cancri: Double-Planet Fit
Outer Planet
3:1 Resonance
With 14.6 d Planet ?
Periodogram after
Removal of Two Planets
Period (days)
Velocity (m s⁻¹)
Orbital Phase
55 Cancri
Outer Planet
Removed
RMS=11.6 ms⁻¹
55 Cancri "d"
P = 12 yr
Both Inner
Planets Removed
Time (yr)
Velocity Residuals (m s⁻¹)
M2sini Per ecc om
0.84 M_JUP 14.6d 0.02 99
0.21 M_JUP 44.3d 0.34 61
4.05 M_JUP 5360d 0.16 201


Origin of 2:1 Resonance:
Both Planets Migrate Inward
Simulations by G.Bryden & D. Lin


Planets Clear Disk Gas


Convergent Migration:
Planets pushed together
by gas into 2:1 Resonance
Bryden, Lin,
Peale, Lee

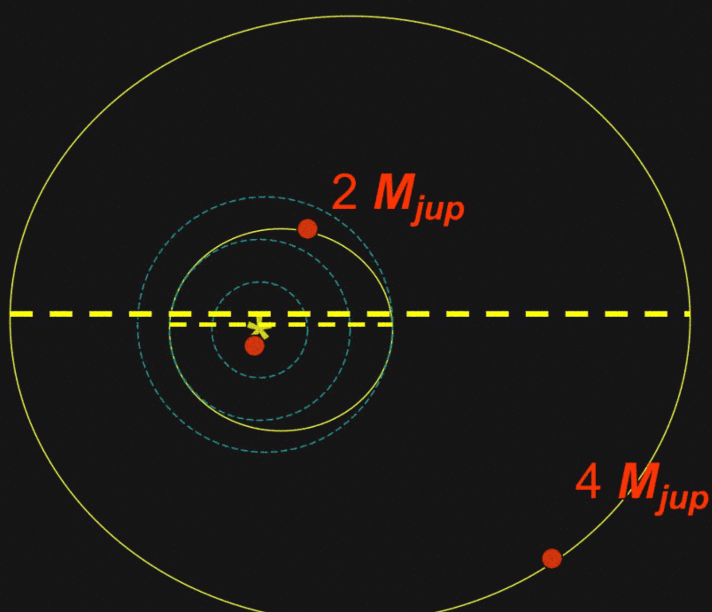
Ups And Fit: Two Outer Planets



M2sini	*Per*	*ecc*	*om*
0.71 M_{JUP}	4.617d	0.02	67
2.05 M_{JUP}	241.3d	0.26	251
4.08 M_{JUP}	1291.7d	0.26	288

Upsilon Andromedae Orbits

4 M_{jup}, P = 4 yr
2 M_{jup}, P = 0.7 yr



Laughlin & Adams
Lin et al.

Eugene Chiang:
Capture into
Secular Resonance

ω1 = 246 °
ω2 = 259 °

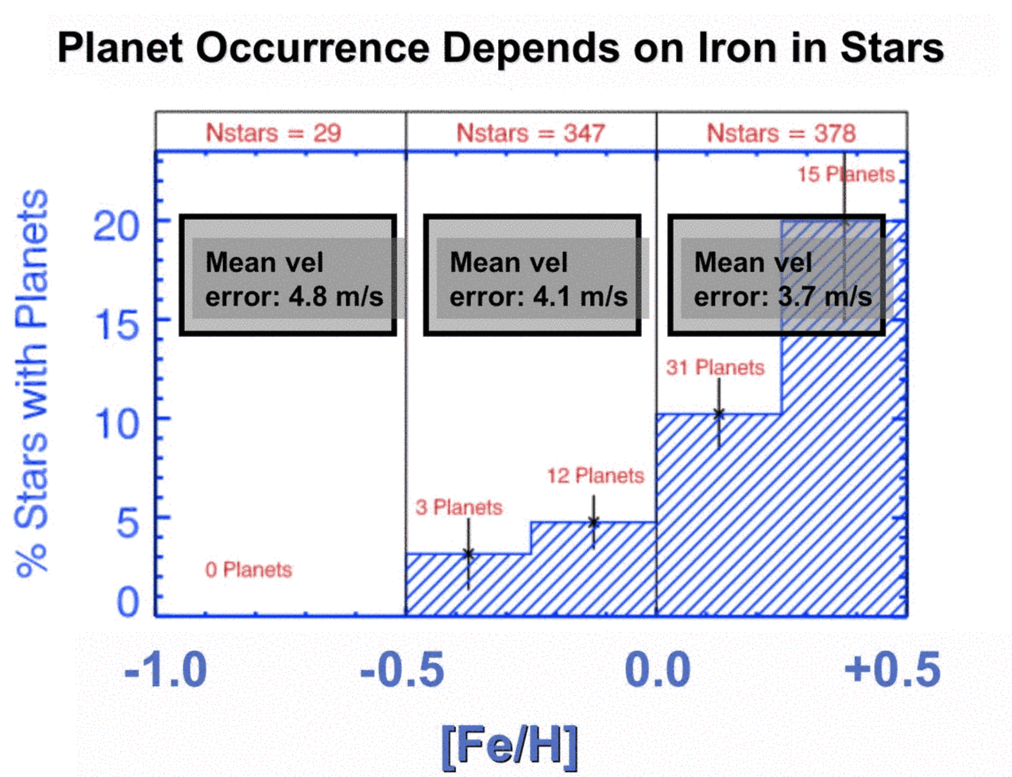
Orbital Dynamics tell us about conditions for formation and evolution of these systems.

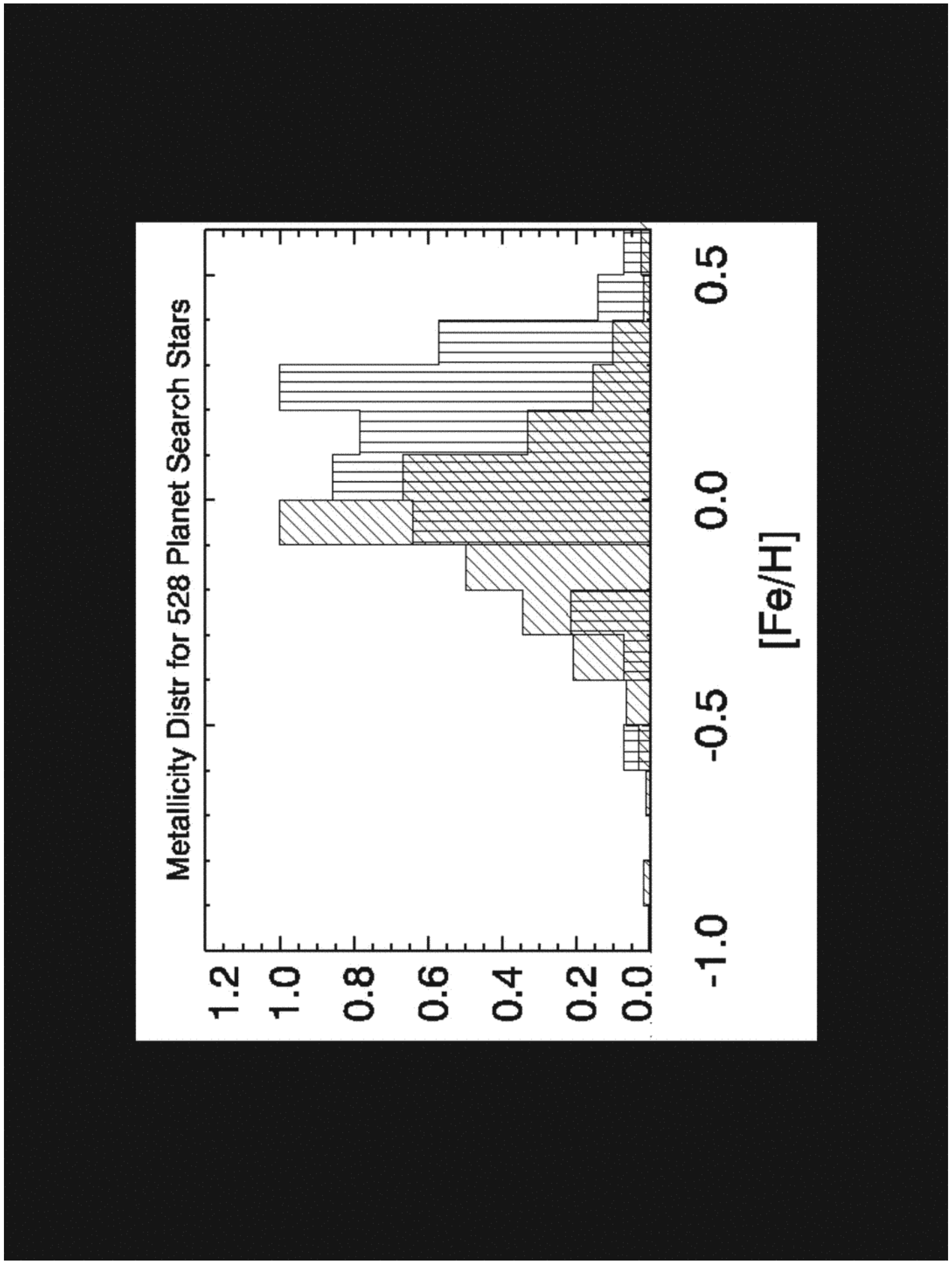
Characteristics of the host stars also reveal some clues.

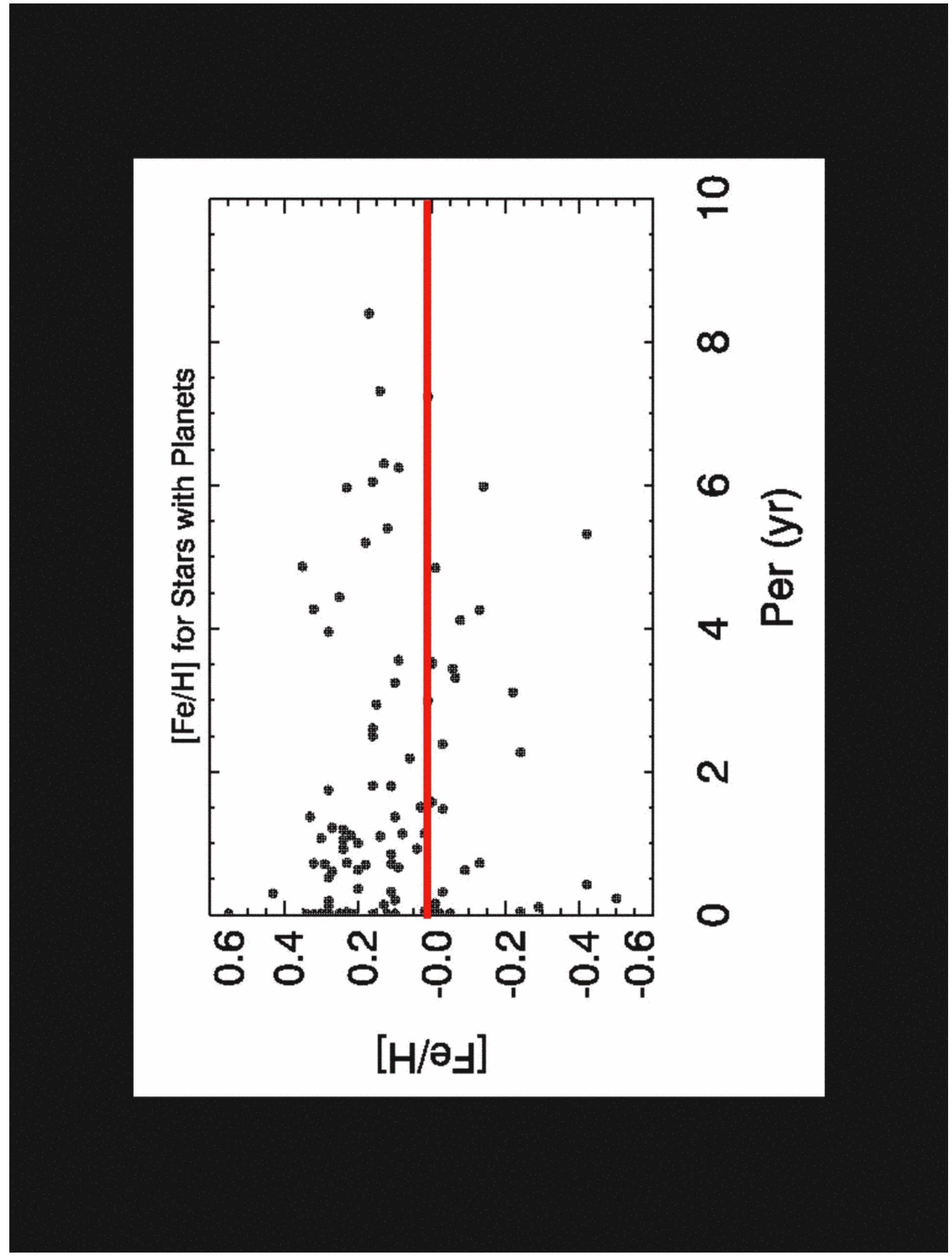
Metallicity Analysis of Keck, Lick, AAT Stars (Fischer & Valenti 2003)

Divide stars into 0.25 dex metallicity bins

Asked: what fraction of stars in each metallicity bin have detected planets?




Metallicity Distr for 528 Planet Search Stars
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-1.0
-0.5
0.0
0.5
[Fe/H]


[Fe/H] for Stars with Planets
0.6
0.4
0.2
-0.0
-0.2
-0.4
-0.6
[Fe/H]
0
2
4
6
8
10
Per (yr)

If accretion, then…

Might expect stars with planets in closer orbits to show higher metallicity than stars with planets in more distant orbits.

However, ESP's at large separations orbit some of the most metal-rich stars on our surveys:

14 Her, 55 Cnc plus new detections at wide separations orbit metal-rich stars

No accretion signature observed

No trend in max metallicity with CZ depth

Subgiants with ESP's are as metal-rich as main sequence stars.

No tendency for planets at large semi-major axes to exhibit lower metallicity

While accretion certainly takes place, these findings imply high metallicity throughout star and point to initial conditions as most important factor in observed correlation.

Supports core accretion scenario.

Conclude:

1) Planet occurrence depends on the metal content of the host star.

Only for gas giant planets?

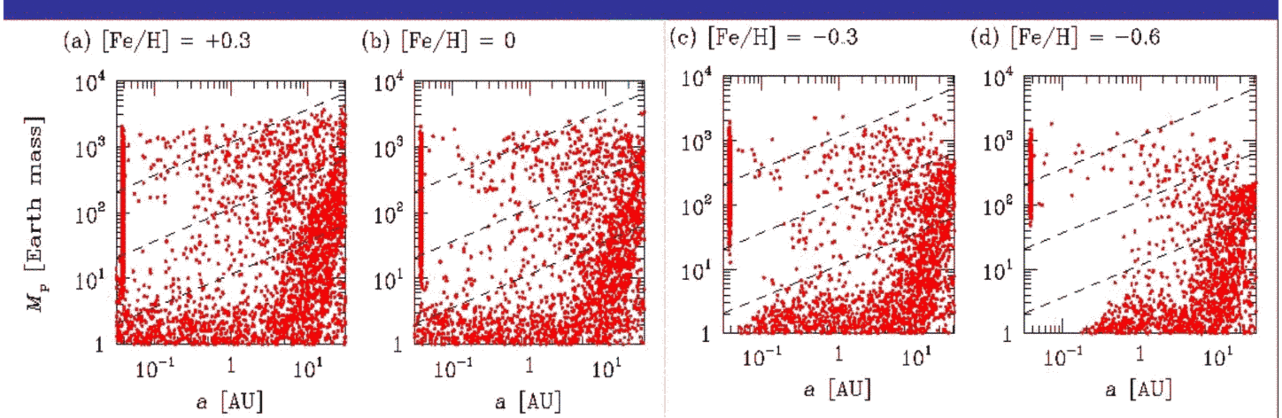
2) No evidence for accretion as the underlying mechanism for metal enrichment in stars with gas giant planets.

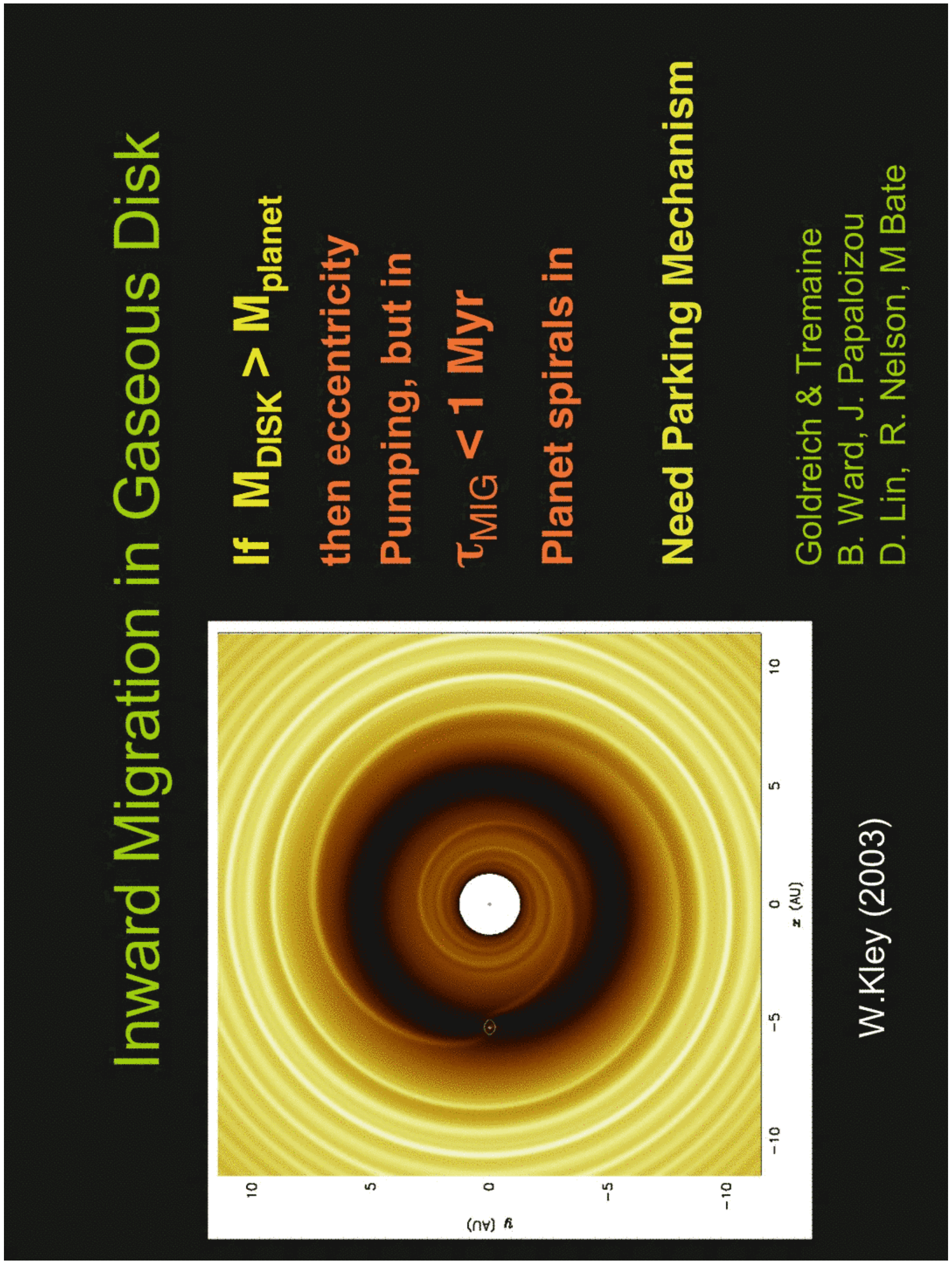
Initial high metallicity is key factor for formation in Doppler-detected systems

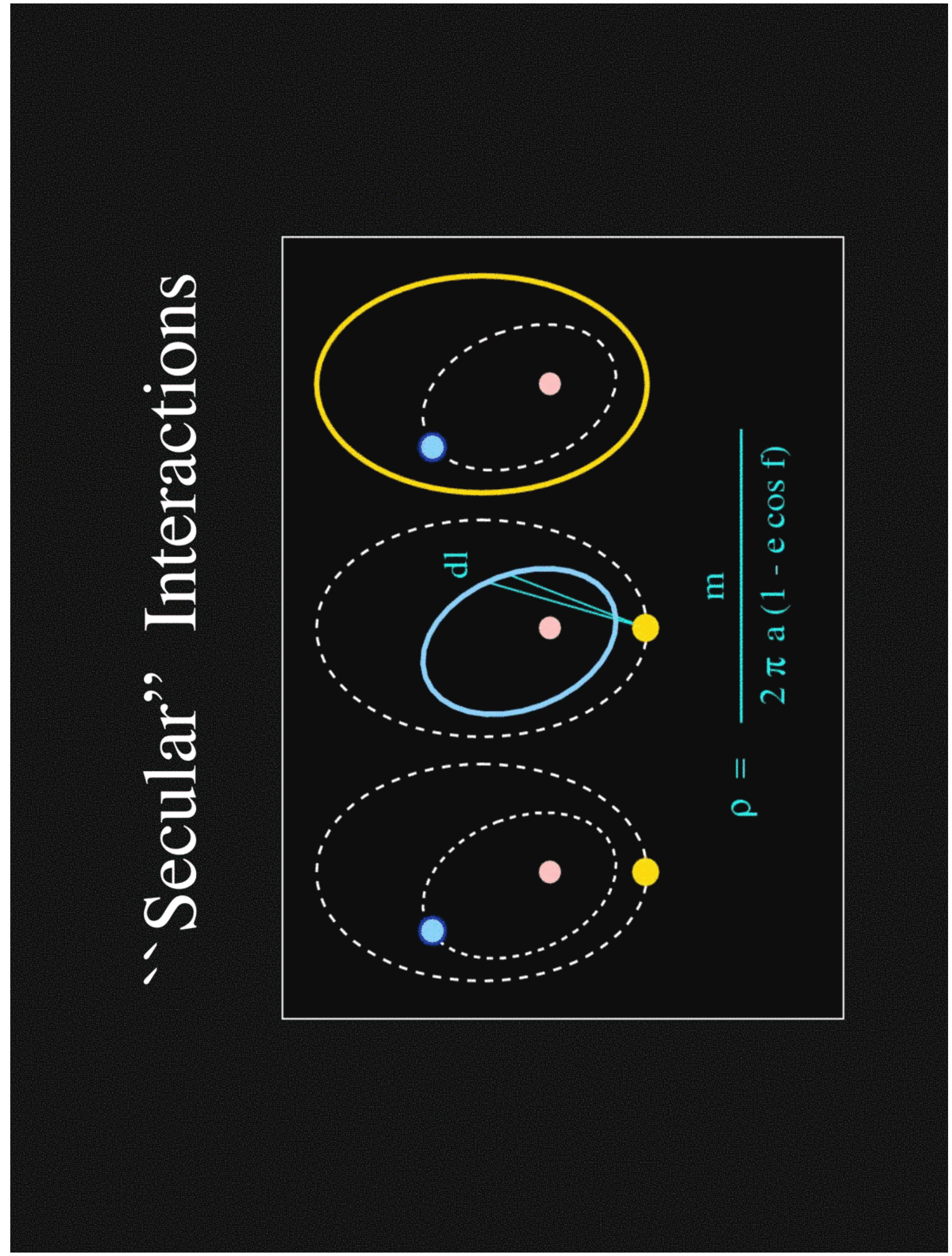
Theoretical Connections

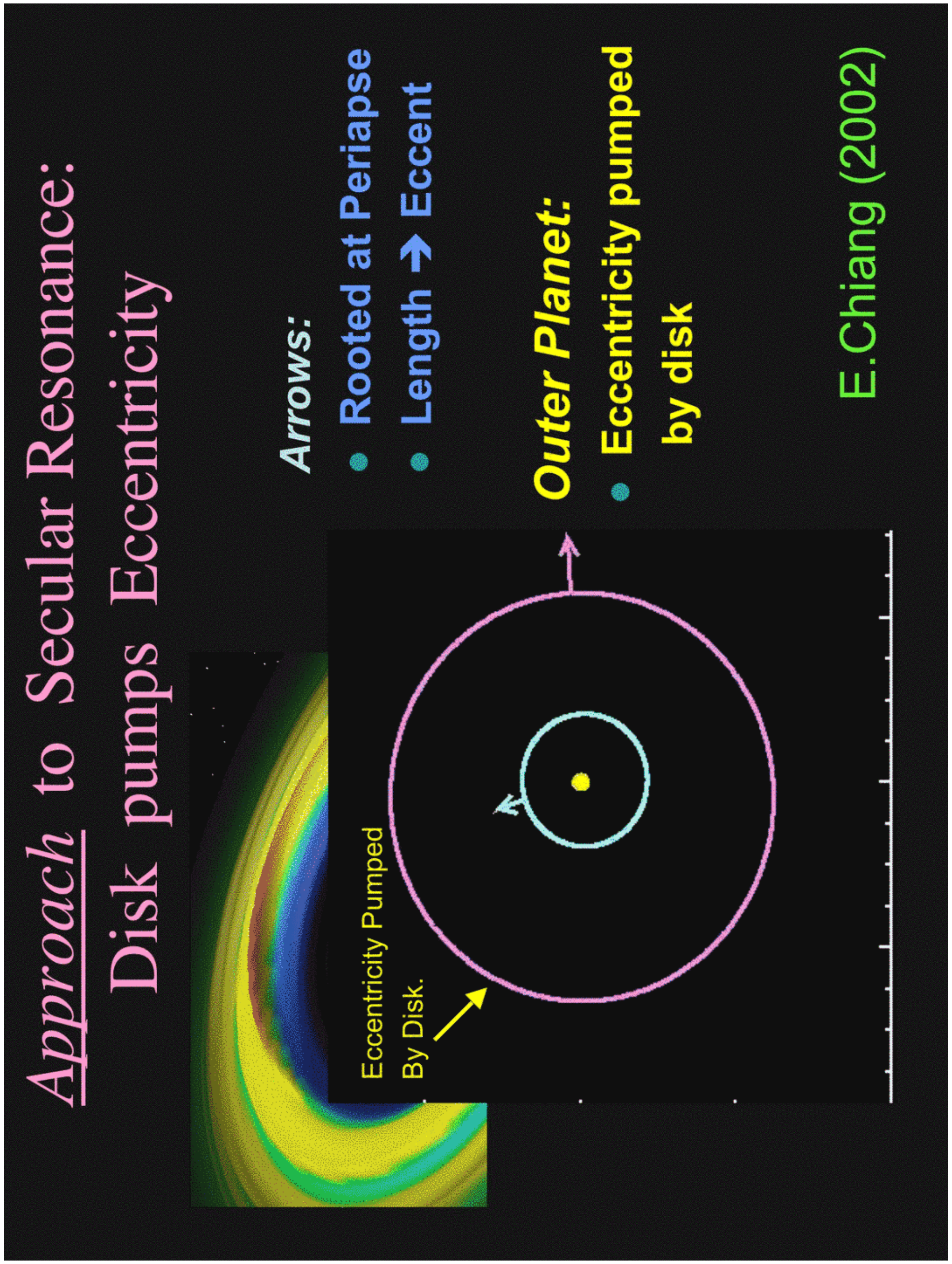
Lin & Ida (2003)

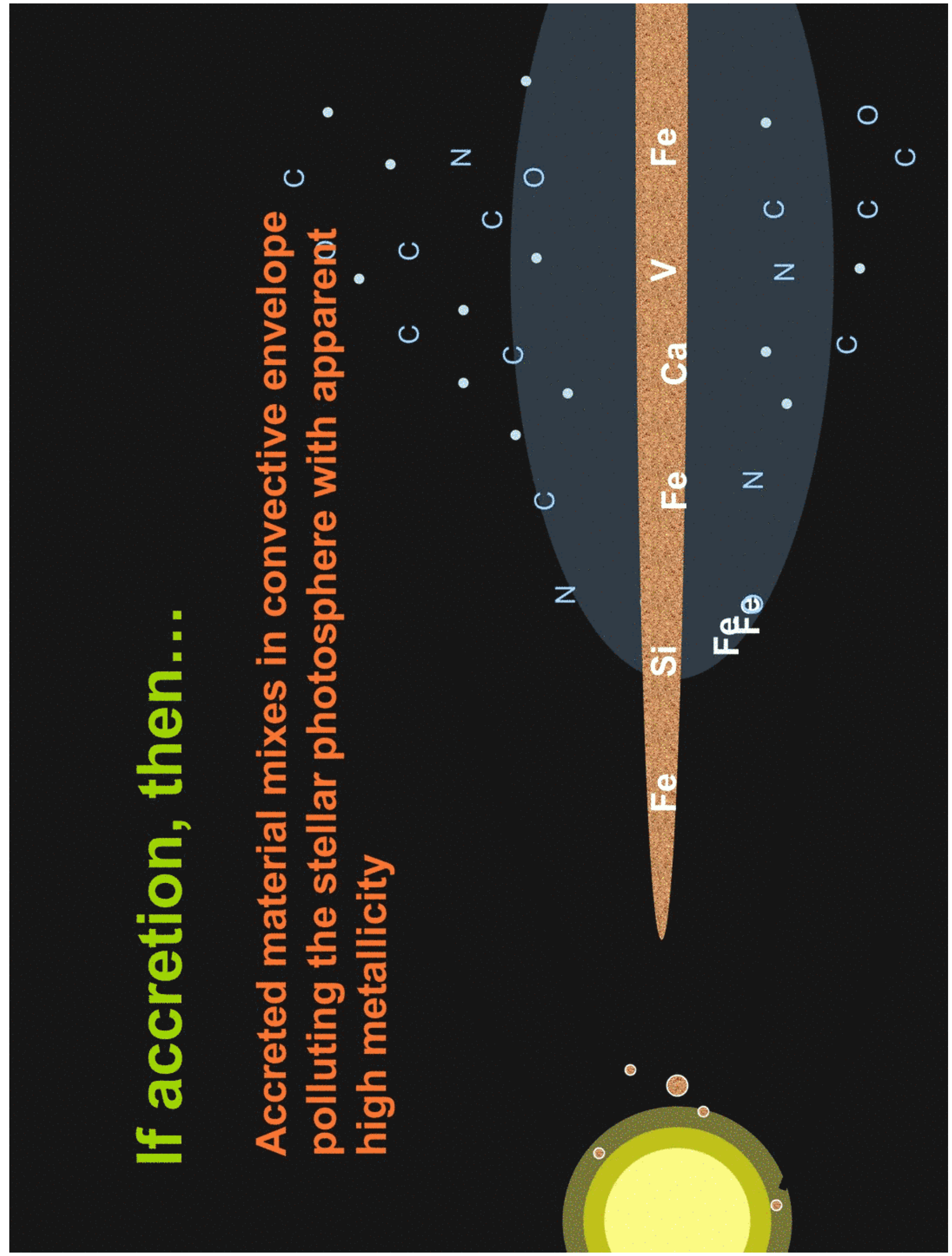
- quantify planet-formation dependence on metallicity

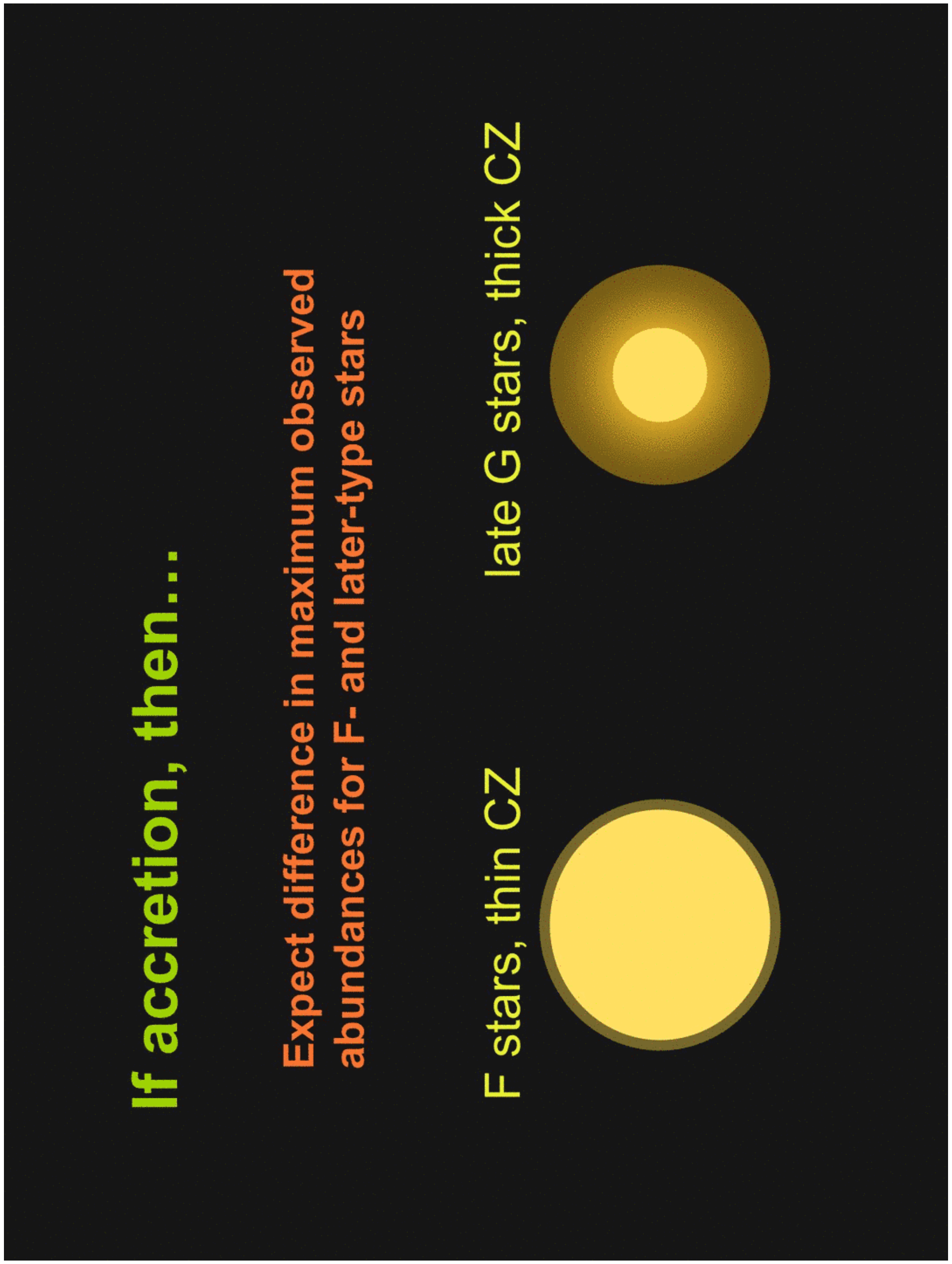


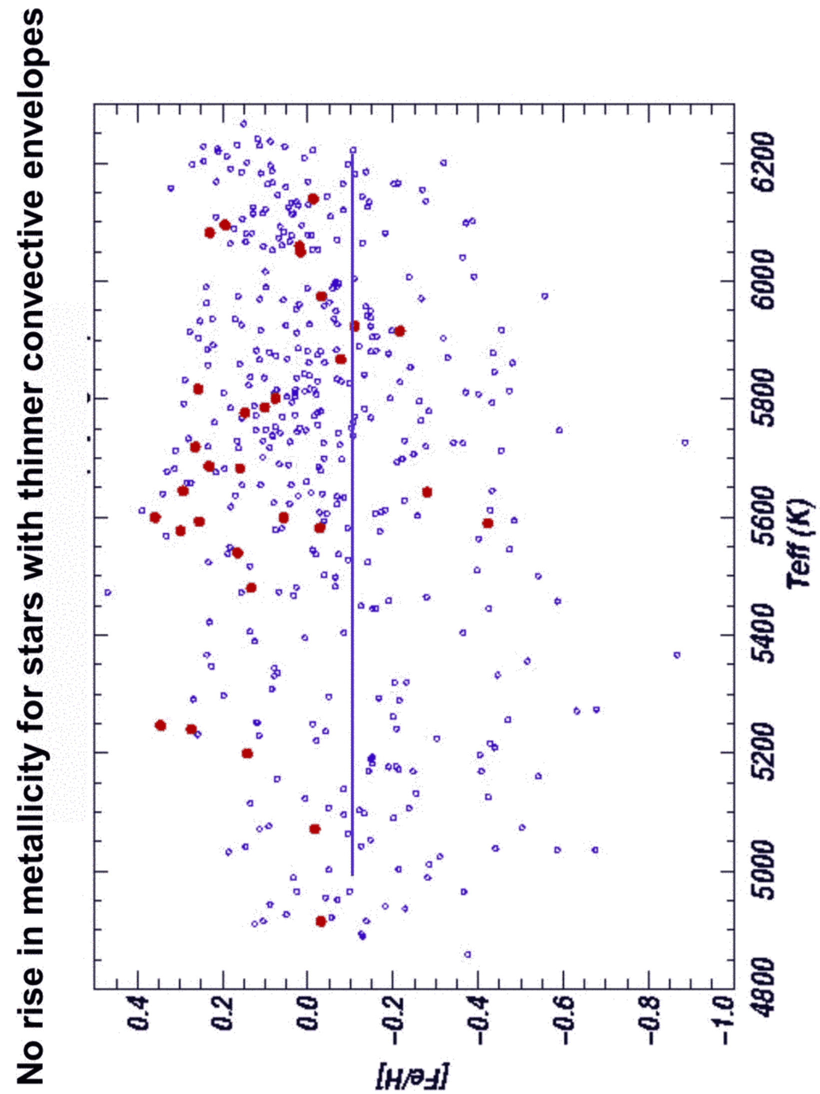

Inward Migration in Gaseous Disk
If $M_{DISK} > M_{planet}$
then eccentricity
Pumping, but in
$\tau_{MIG} < 1$ Myr
Planet spirals in
Need Parking Mechanism
Goldreich & Tremaine
B. Ward, J. Papaloizou
D. Lin, R. Nelson, M Bate
W.Kley (2003)
x (AU)
y (AU)

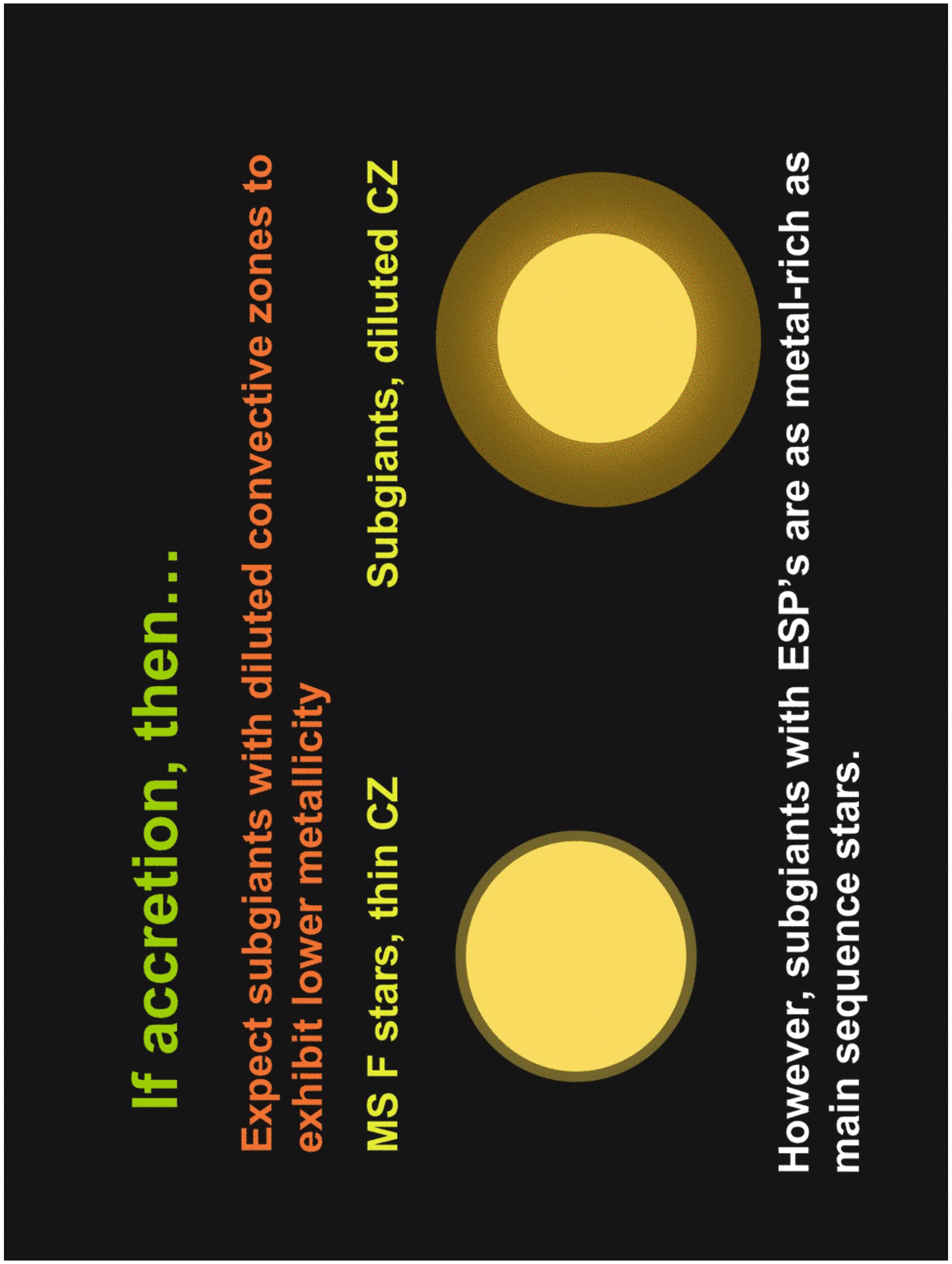

``Secular'' Interactions
dl
$\rho = \frac{m}{2 \pi a (1 - e \cos f)}$


Approach to Secular Resonance:
Disk pumps Eccentricity
Arrows:
Rooted at Periapse
Length → Eccent
Outer Planet:
Eccentricity pumped by disk
E.Chiang (2002)
Eccentricity Pumped By Disk.


If accretion, then…
Accreted material mixes in convective envelope polluting the stellar photosphere with apparent high metallicity
Fe
V
Ca
Fe
Si
Fe


If accretion, then…
Expect difference in maximum observed
abundances for F- and later-type stars
F stars, thin CZ
late G stars, thick CZ


No rise in metallicity for stars with thinner convective envelopes
[Fe/H]
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
Teff (K)
4800
5000
5200
5400
5600
5800
6000
6200


If accretion, then…
Expect subgiants with diluted convective zones to exhibit lower metallicity
MS F stars, thin CZ
Subgiants, diluted CZ
However, subgiants with ESP's are as metal-rich as main sequence stars.