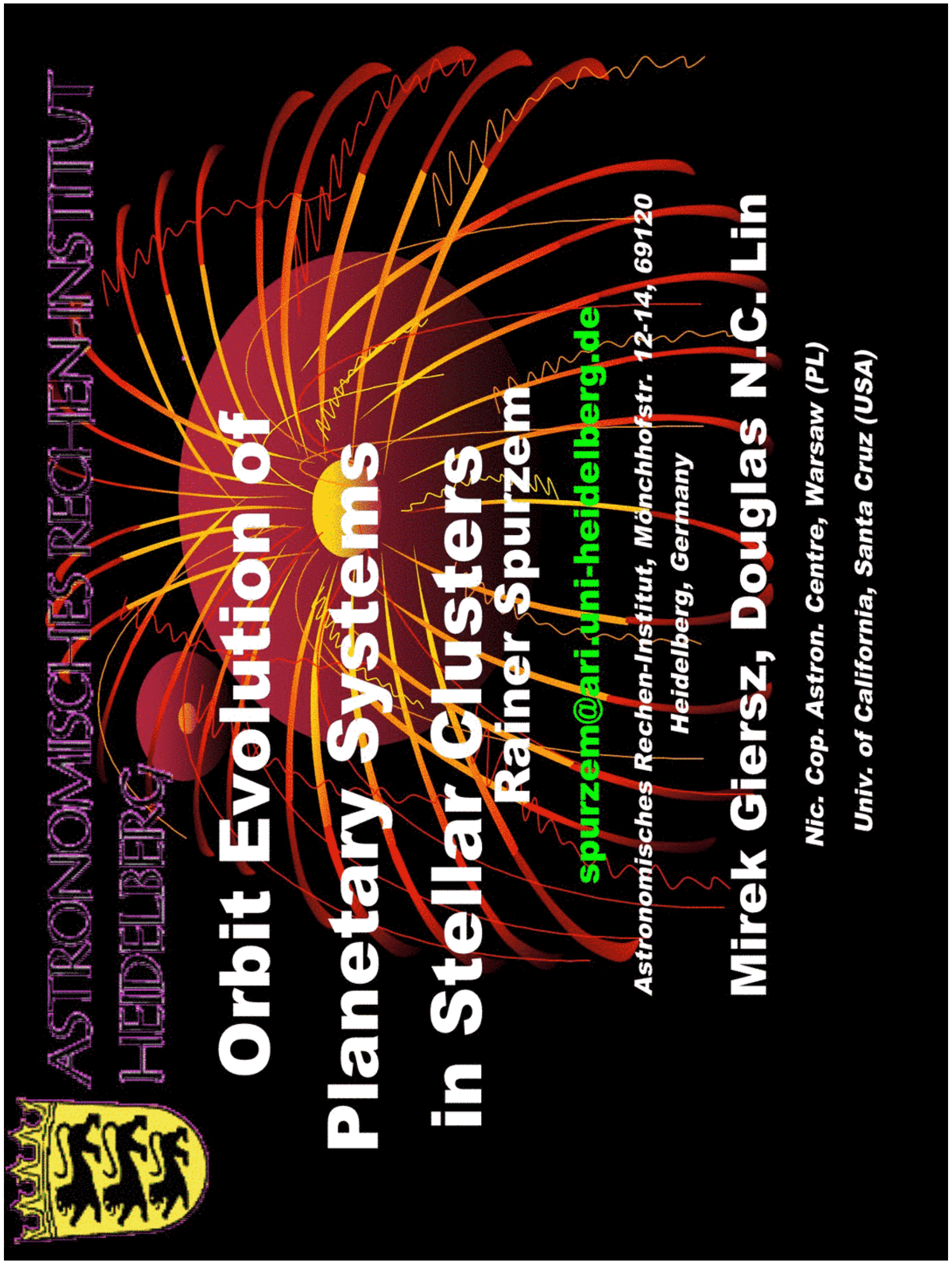
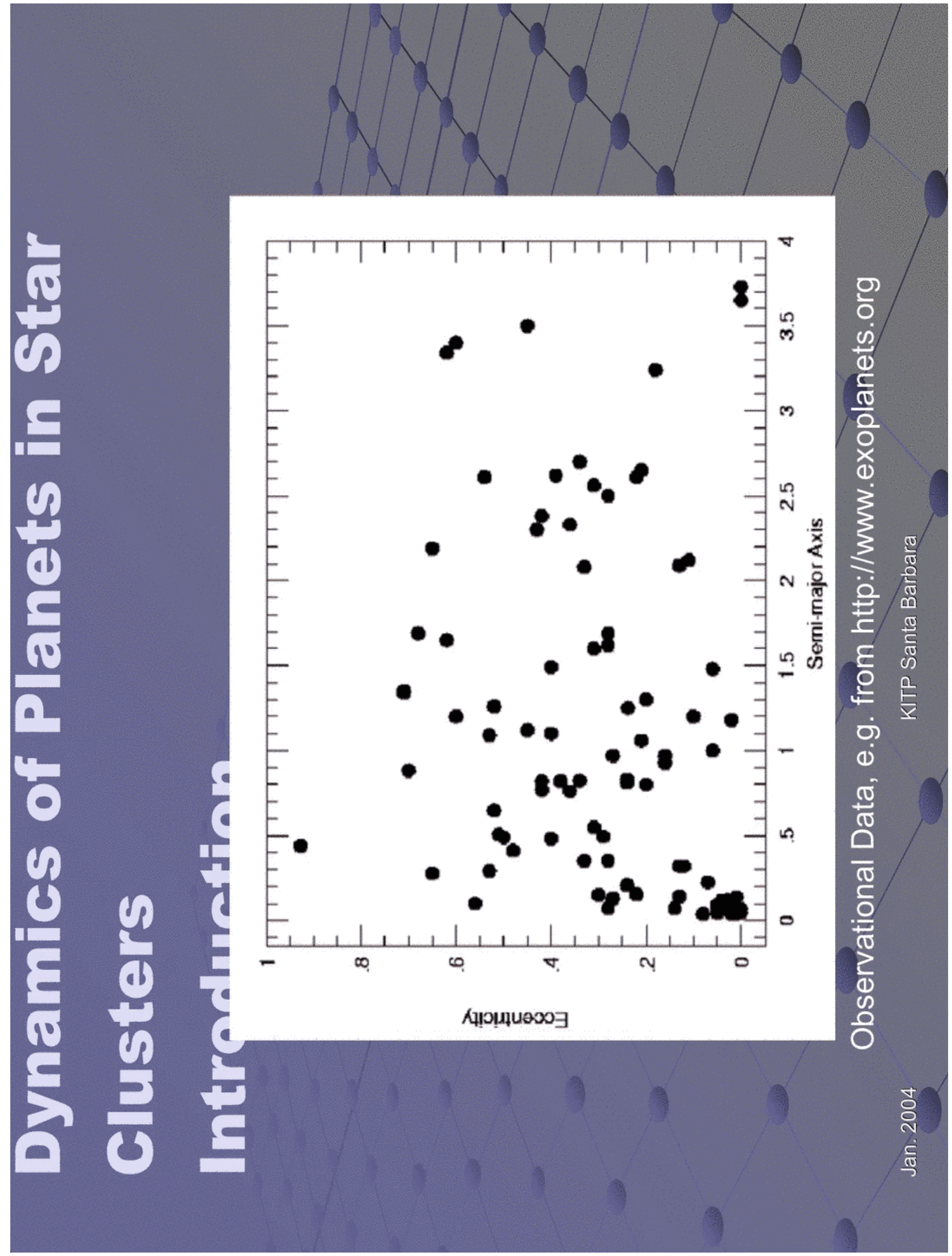

ASTRONOMISCHES RECHEN-INSTITUT
HEIDELBERG
Orbit Evolution of
Planetary Systems
in Stellar Clusters
Rainer Spurzem
spurzem@ari.uni-heidelberg.de
Astronomisches Rechen-Institut, Mönchhofstr. 12-14, 69120
Heidelberg, Germany
Mirek Giersz, Douglas N.C. Lin
Nic. Cop. Astron. Centre, Warsaw (PL)
Univ. of California, Santa Cruz (USA)


Dynamics of Planets in Star
Clusters
Eccentricity
0
.2
.4
.6
.8
1
Semi-major Axis
0
.5
1
1.5
2
2.5
3
3.5
4
Observational Data, e.g. from http://www.exoplanets.org
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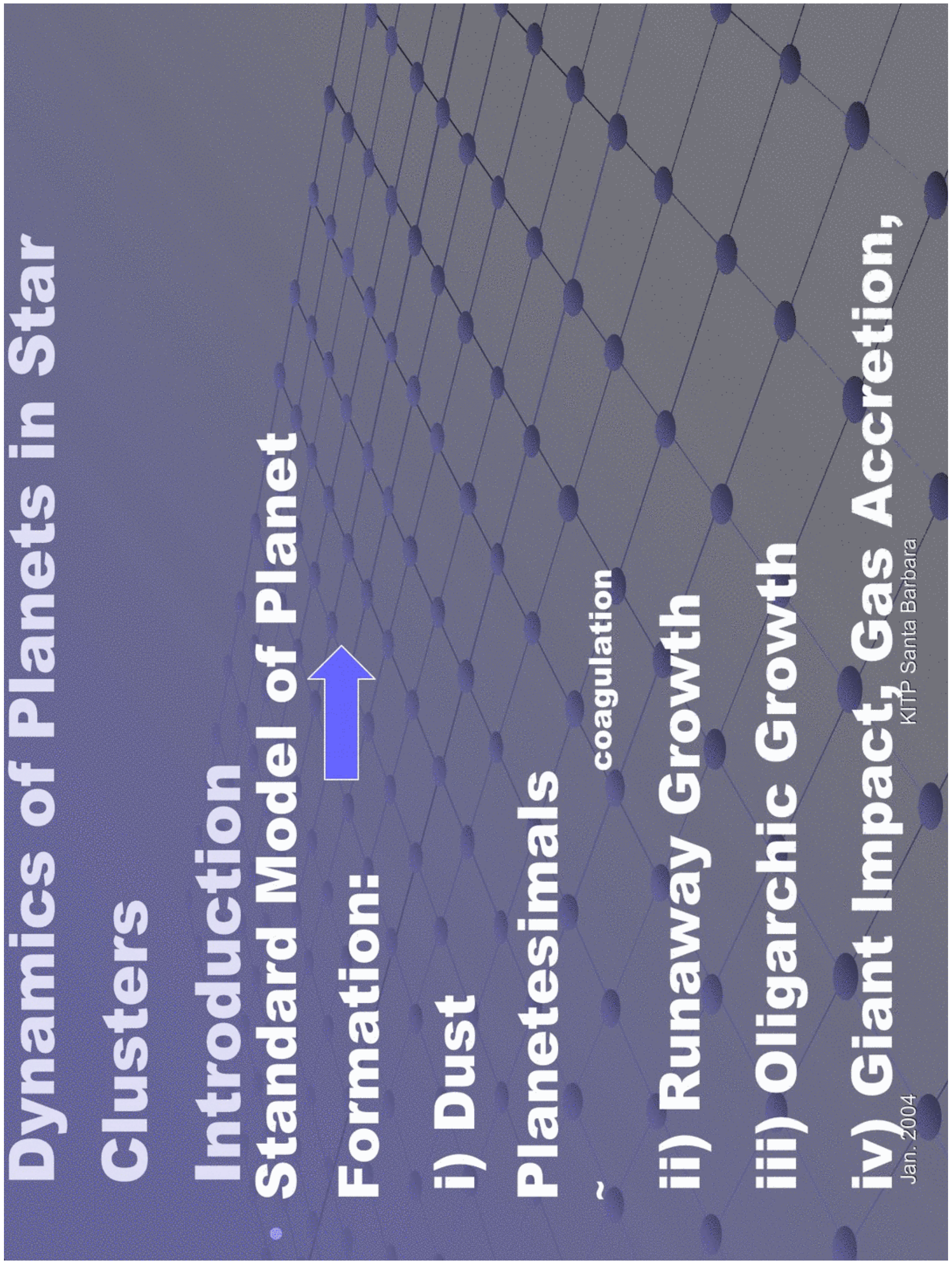
Dynamics of Planets in Star Clusters
Introduction
Standard Model of Planet Formation:
i) Dust
Planetesimals
~ coagulation
ii) Runaway Growth
iii) Oligarchic Growth
iv) Giant Impact, Gas Accretion,
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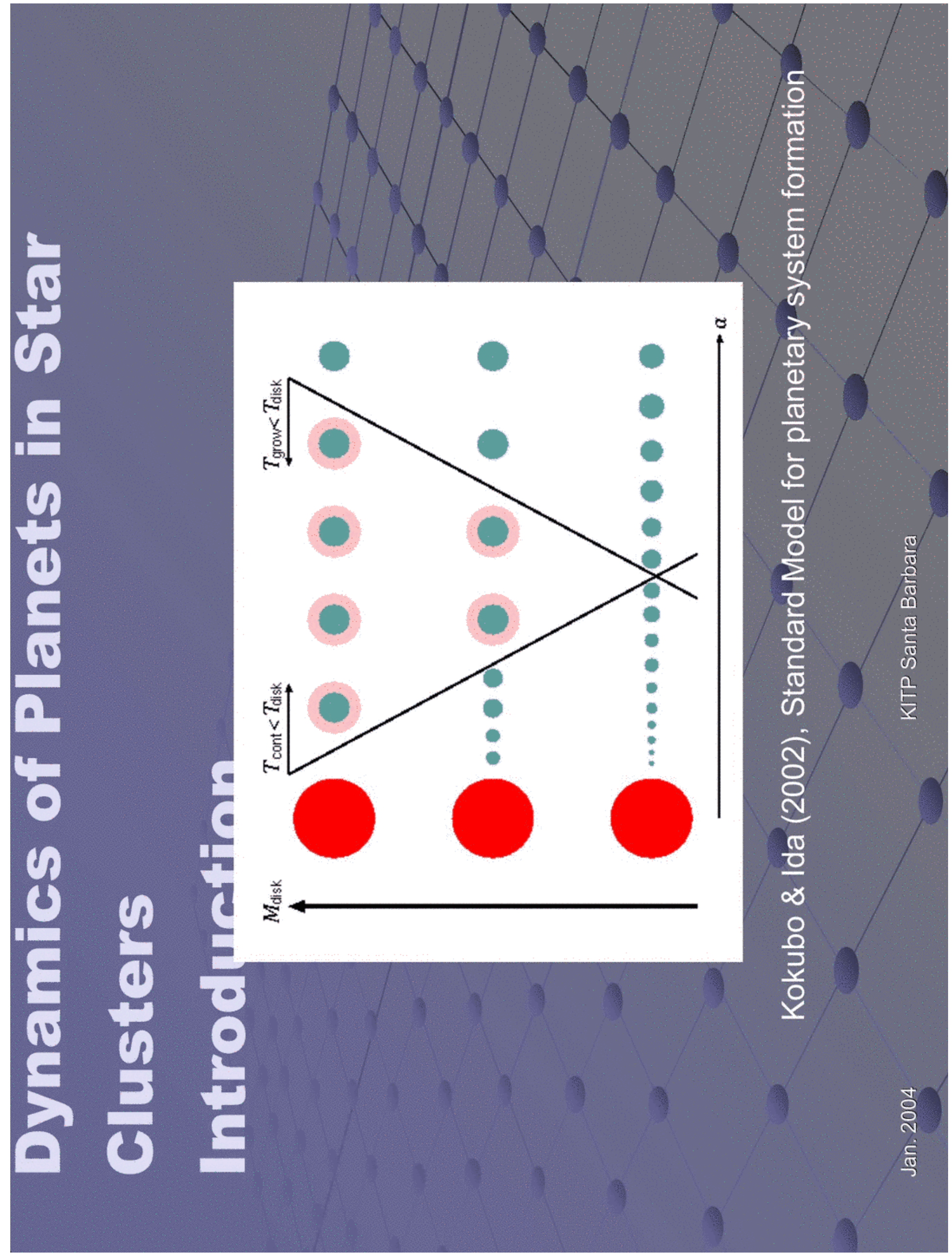
Dynamics of Planets in Star Clusters
Introduction
M_{disk}
$T_{cont} < T_{disk}$
$T_{grow} < T_{disk}$
α
Kokubo & Ida (2002), Standard Model for planetary system formation
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Dynamics of Planets in Star Clusters

Introduction

- M, R, N of Planets ok

$t_{grow} < t_{gas\text{-}disk}$: Gasplanets

- Variety: disk density profile

  (Kokubo und Ida 2002)

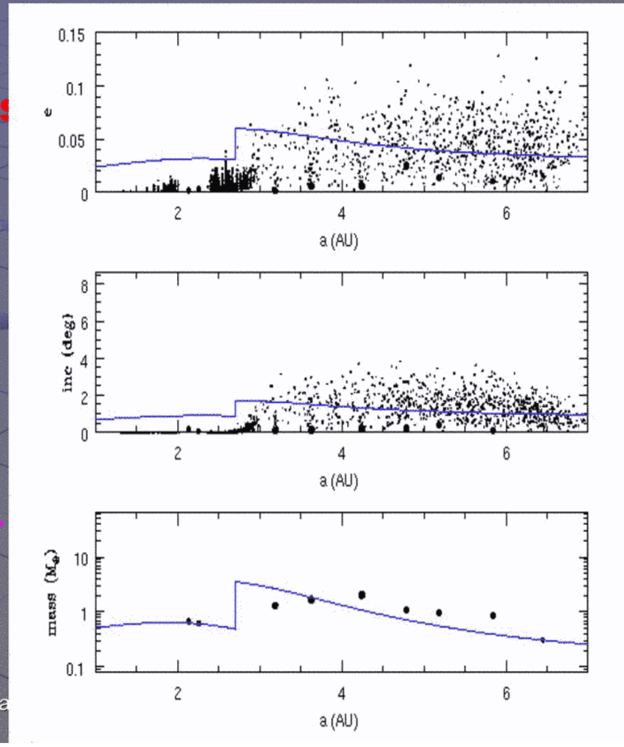
- high e, small R of extrasolar Jupiters?

  Strong Diversity of extrasolar planets!

Possible Mechanisms to excite high e?

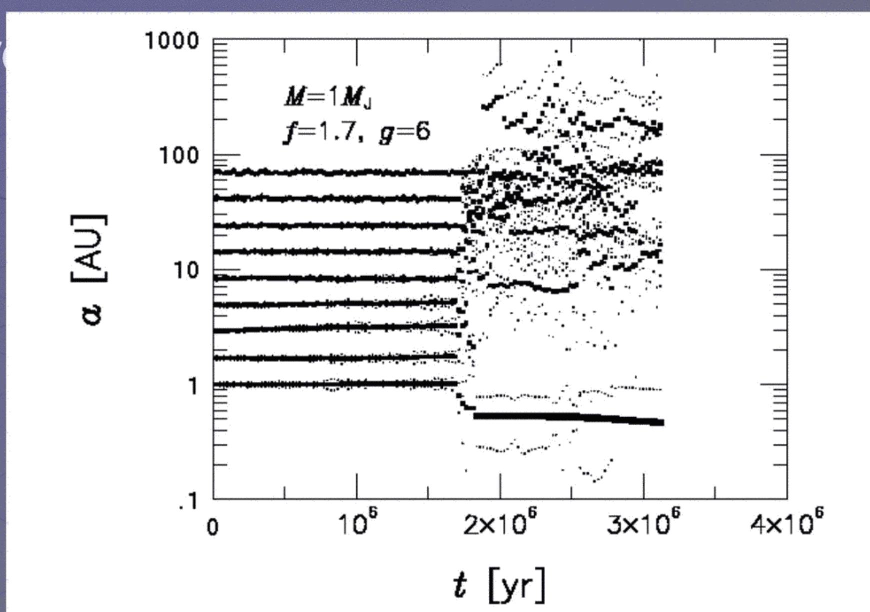
Interaction with gas

(Thommes et al. 2002)



Dynamics of Planets in Star Clusters

Intr



—Time evolution of the semimajor axes and eccentricities of nine $1M_J$ planets with initial conditions $e_{max} = 0.05$, $f = 1.7$, and g

Lin & Ida 1997, Resonance crossings by grav. Interactions of protopl.

Dynamics of Planets in Star Clusters

Introduction

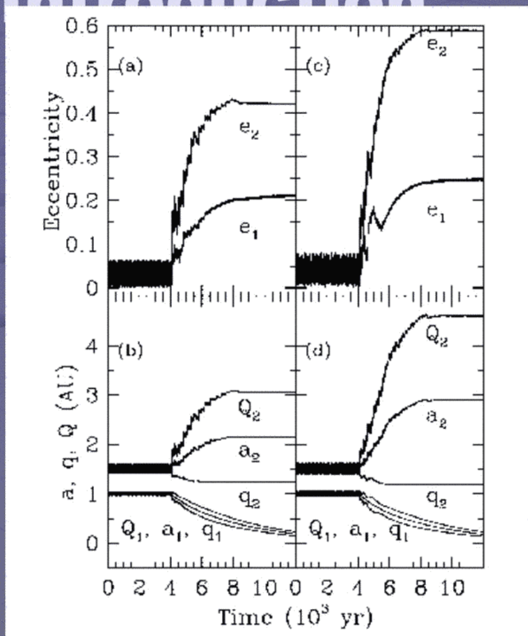


FIG. 3.—Resonance passages involving two massive planets. Masses of the inner and outer planets are $M_1/M_* = 2 \times 10^{-3}$ and $M_2/M_* = 1 \times 10^{-3}$, respectively. The drag force is applied to the inner planet over $t_{drag} = 1 \times 10^4$ yr starting at $t_{start} = 4 \times 10^3$ yr. At $t = 0$, the ratio of semimajor axes is $a_2/a_1 = 1.5$, the osculating eccentricities are both 0.005 (panels *a* and *b*) or 0.03 (panels *c* and *d*), and the planets are separated by an angle $\Delta = 180°$. At $t < t_{start}$, the planets mutually excite eccentricities of less than 0.075. Only after $t > t_{start}$ is differential migration introduced; the eccentricities of both objects become substantially excited through repeated resonance crossings. Panels *b* and *d* also plot apastron distances $Q = a(1 + e)$ and periastron distances $q = a(1 - e)$.

Chiang, Fischer & Thommes (2002)

Resonances induced by protoplanet-disk interactions

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Dynamics of Planets in Star Clusters

Introduction

Perturbations in (young) star clusters, previous work

- de la Fuente Marcos & de la Fuente Marcos 1997 (semi-analytic, eccentric giant planets in open clusters)
- de la Fuente Marcos & de la Fuente Marcos 1999 (N-Body N < 2500, 3% of runaway planets)
- Davies & Sigurdsson 2001 Monte-Carlo cross sections, no cluster evolution, small rates
- Smith & Bonnell 2001, Bonnell et al. 2001 with (somewhat strange) semianalytic cluster evolution

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Dynamics of Planets in Star Clusters

Introduction

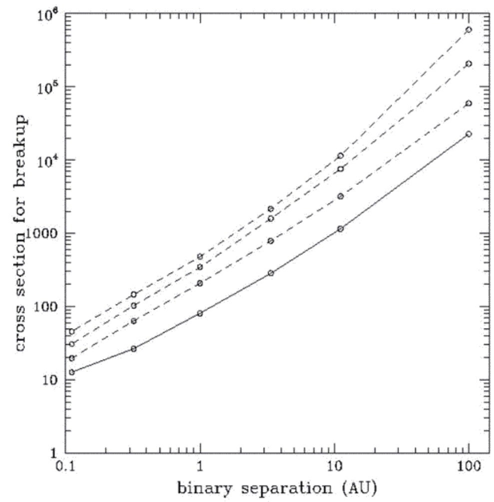

Figure 3. The cross-section for breakup of the planet–star system from encounters with single stars as a function of separation in au (full line), and for the planet to be left in an eccentric orbit with eccentricity, $e > 0.03$, 0.1, 0.3 (broken lines, from top to bottom).

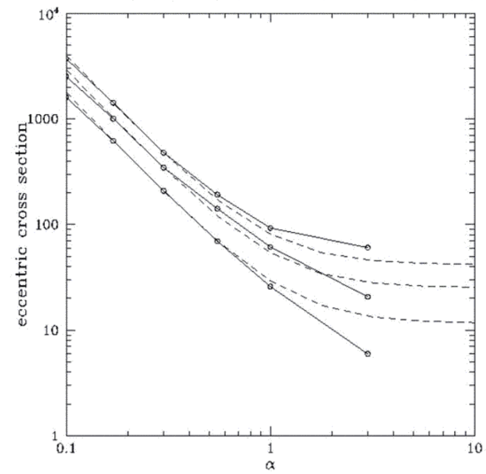

Figure 2. The cross-section for the planet to be left in an eccentric orbit as a function of $\alpha = V_\infty / V_{orb}$. Cross-sections are for systems with eccentricity $e > 0.03$, 0.1 and 0.3 (top to bottom). All cross-sections are given in units of the binary separation as in Fig. 1. The broken curve is the breakup cross-section for $\alpha = 0.3$ rescaled assuming that the change in cross-section is purely an effect of the differing degree of gravitational focusing ocurring for different values of α.

Davies & Sigurdsson 2001

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Dynamics of Planets in Star Clusters

Introduction

Table 3. Time-scales (in years) for systems to be broken up or left in eccentric orbits for both binary–single and binary–binary encounters, assuming a number density, $n = 10^5$ stars pc^{-3}, and $V_\infty = 9$ km s^{-1}.

d (au)	$\tau_{breakup}$	$e > 0.3$	$e > 0.1$	$e > 0.03$
Binary–single encounters				
1.0000	5.2E+08	2.0E+08	1.2E+08	8.7E+07
0.1000	5.2E+09	2.0E+09	1.2E+09	8.7E+08
0.0500	1.0E+10	4.0E+09	2.4E+09	1.7E+09
0.0300	1.7E+10	6.7E+09	4.0E+09	2.9E+09
Binary–binary encounters				
1.0000	3.0E+08	1.1E+08	5.6E+07	3.7E+07
0.1000	3.0E+09	1.1E+09	5.6E+08	3.7E+08
0.0500	6.0E+09	2.7E+09	1.1E+09	7.4E+08
0.0300	1.0E+10	3.8E+09	1.9E+09	1.2E+09

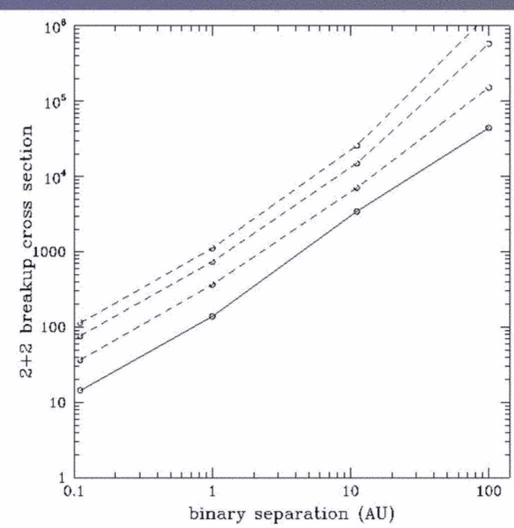

Figure 4. The cross-section for breakup of the planet–star system from encounters with binary stars as a function of separation in au (full line), and for the planet to be left in an eccentric orbit with eccentricity, $e > 0.03$, 0.1, 0.3 (broken lines, from top to bottom).

Davies & Sigurdsson 2001

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Dynamics of Planets in Star Clusters

Introduction

Smith & Bonnell 2001

Table 1. The properties of the types of clusters studied. The minimum and maximum impact parameters, b, are also shown. These correspond to roughly 10 and 99 per cent encounter probabilities for each cluster.

Cluster	Density pc^{-3}	V_{disp} $km\,s^{-1}$	Lifetime yr	b (au) Min	b (au) Max
Globular	10^3	10	10^9	3.43	24.26
Open	10^2	1	10^9	33.32	221.22
Young	5×10^3	2	5×10^6	47.27	328.09

Table 2. The fate of planets in different cluster environments. In the case of ionization, three fractions are shown: the total percentage of systems ionized, the percentage that are retained in the cluster, and the percentage that escape within a crossing time.

Cluster	Ionized (per cent) Total	Kept	Lost	Survived (per cent)	Exchanged (per cent)
Globular	47.3	30.1	17.2	51.5	1.3
Open	26.6	0.5	26.1	61.1	12.3
Young	7.8	0.5	7.3	90.1	2.1

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Dynamics of Planets in Star Clusters

Introduction

Some interesting work:

- **Heggie & Rasio (1996)** analytic estimates
- **Hurley & Shara (2002)**

$$\delta e = -\frac{15\pi}{16}\left(\frac{2m_3^2 a^3}{M_{123}M_{12}r_p^3}\right)^{1/2} e\sqrt{1-e^2}\sin 2\Omega \sin^2 i.$$

full N-Body using GRAPE-6, N=22.000

TABLE 2

AVERAGED RESULTS FOR THE PLANET POPULATION AT 1.0 Gyr INTERVALS

TIME (Myr)	LIBERATED Total (%)	Kept (%)	Current (%)	ESCAPED (%)	SWALLOWED (%)	EXCHANGED (%)
1000.0	5.6	69.8	48.4	11.7	0.4	1.0
2000.0	7.7	66.8	33.1	31.4	0.8	1.7
3000.0	9.1	66.5	22.4	51.1	0.9	2.3
4000.0	10.4	64.0	12.7	65.8	1.0	3.6

NOTES.—The percentage of all planets liberated from their parent star, the percentage of these that remain in the cluster for more than a crossing-time, and the percentage in the cluster at that time, are given in columns 2-4. The percentage that have escaped attached to their parent star is given in column 5. Columns 6 and 7 give the percentages of planets that have been engulfed by their parent star, and those that have been exchanged into orbit about another parent star, respectively.

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Dynamics of Planets in Star Clusters
Numerical Experiments

Numerical Experiments 1

- Direct N-body modelling of star cluster with massless planets, evolving cluster, same e!
- Using NBODY6++ with Ahmad-Cohen scheme Regularization of planetary orbits, CRAY T3E

(Spurzem und Aarseth 1996, Spurzem 1999, Spurzem et al. 2002)

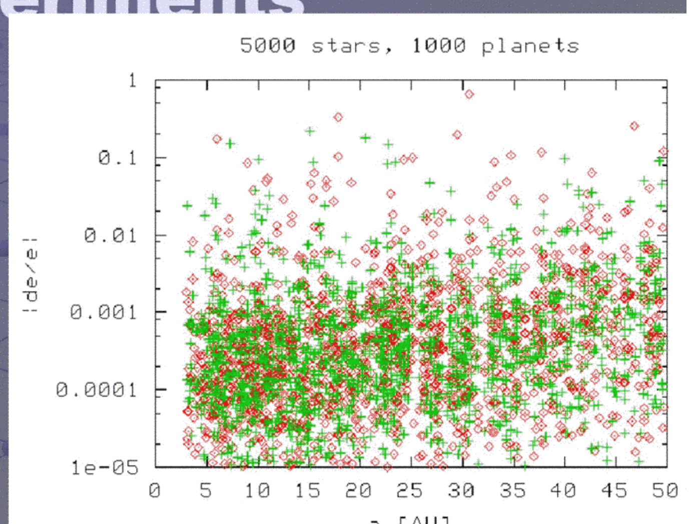
Here (work in progress ongoing):
5000 stars, 1000 planets,
3-50 AU, fixed e (0.1,0.3,0.6,0.9) or thermal

Dynamics of Planets in Star Clusters
Numerical Experiments

Table 1. Model Parameters

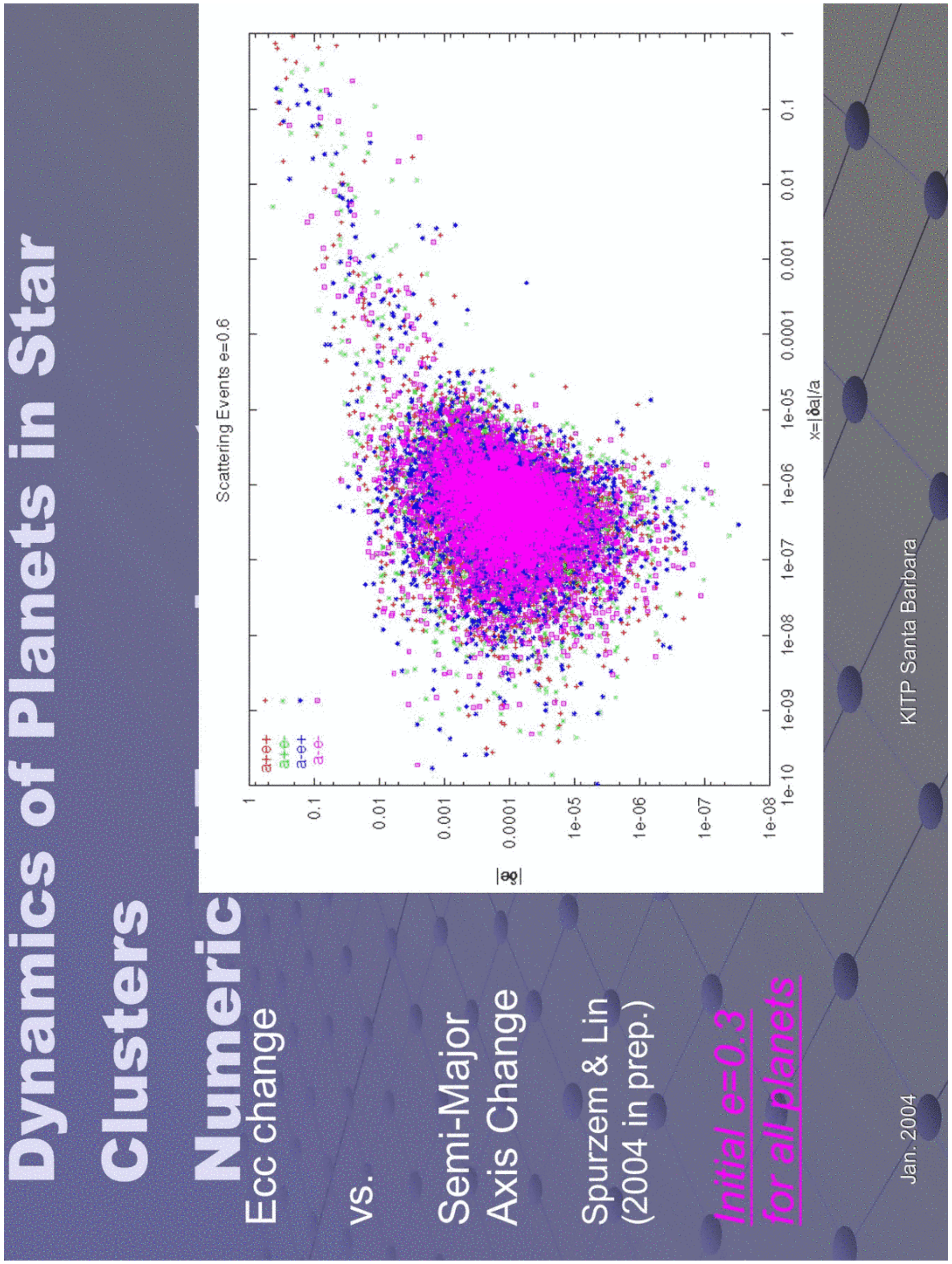
Model	N_*	$M_*(M_\odot)$	N_p	a_p(AU)	e_p
1	10^3	1	10^3	3-50	0.1
2	10^3	1	10^3	3-50	0.3
3	10^3	1	10^3	3-50	0.6
4	10^3	1	10^3	3-50	0.9
5	10^3	1	10^3	3-50	thermal
6	10^3 (ktg)	1	10^3	3-50	thermal

Models 1-4 are the most idealized ones, having equal stellar masses an
equal initial planetary eccentricities. Model 6 is yet the only one utilising



Spurzem & Lin (2003)
(Washington Conf. Paper)

Spurzem & Lin (2004) in prep.


Dynamics of Planets in Star Clusters
Numeric
Ecc change
vs.
Semi-Major Axis Change
Spurzem & Lin (2004 in prep.)
Initial e=0.3 for all planets
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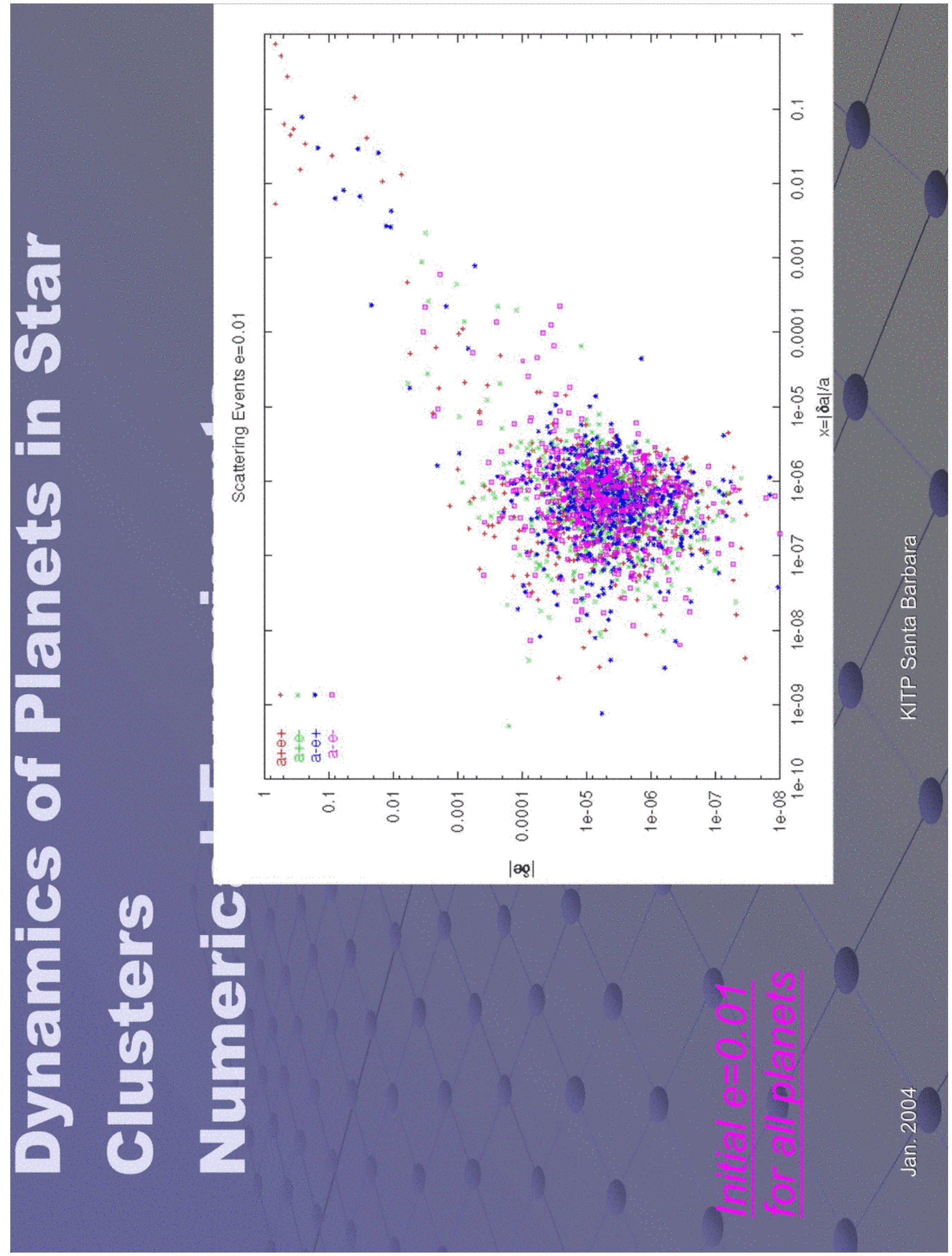
Scattering Events e=0.6
a+e+
a+e-
a-e+
a-e-
|δe|
x=|δa|/a


Dynamics of Planets in Star Clusters
Numeric
Initial e=0.01 for all planets
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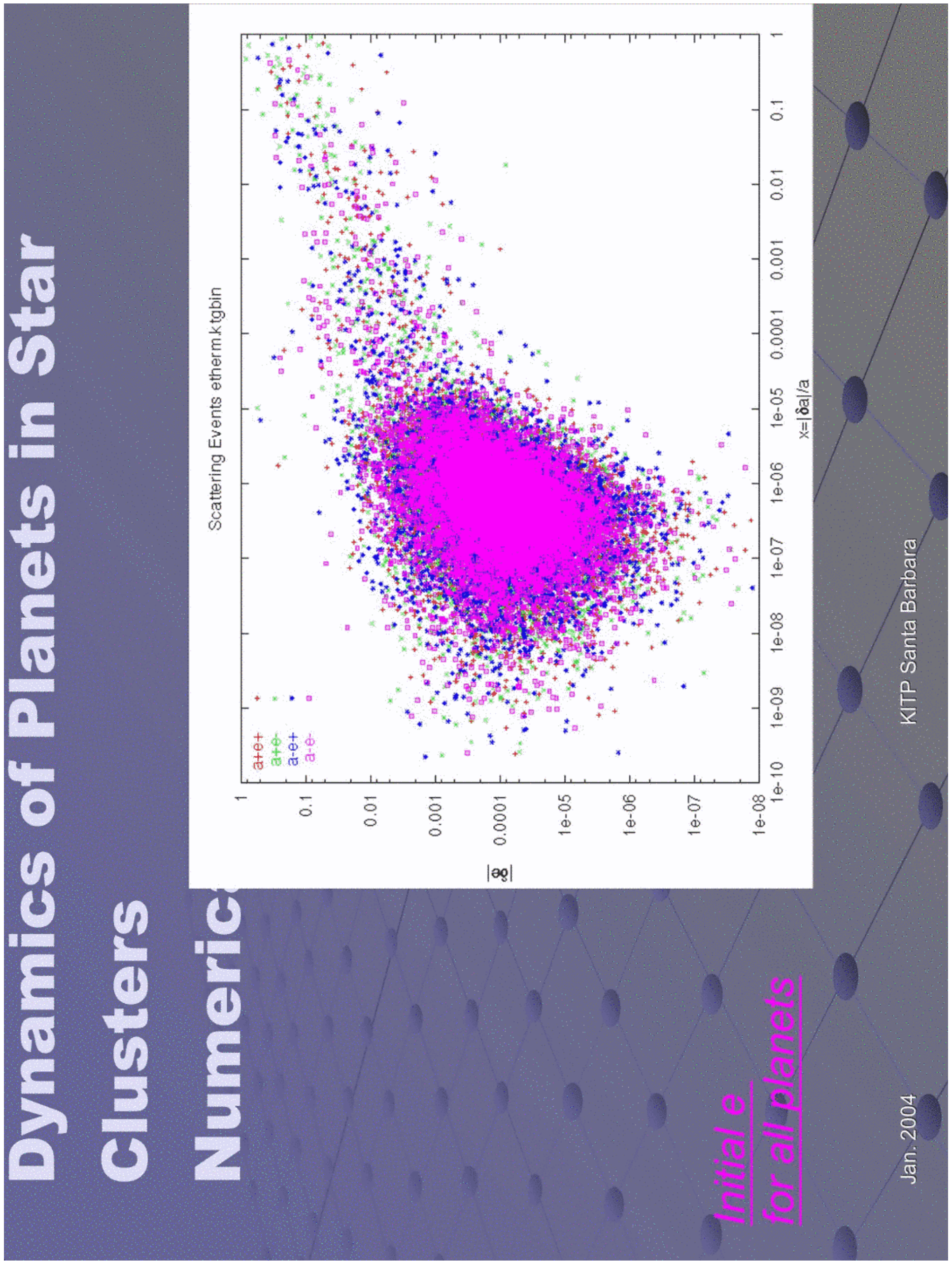
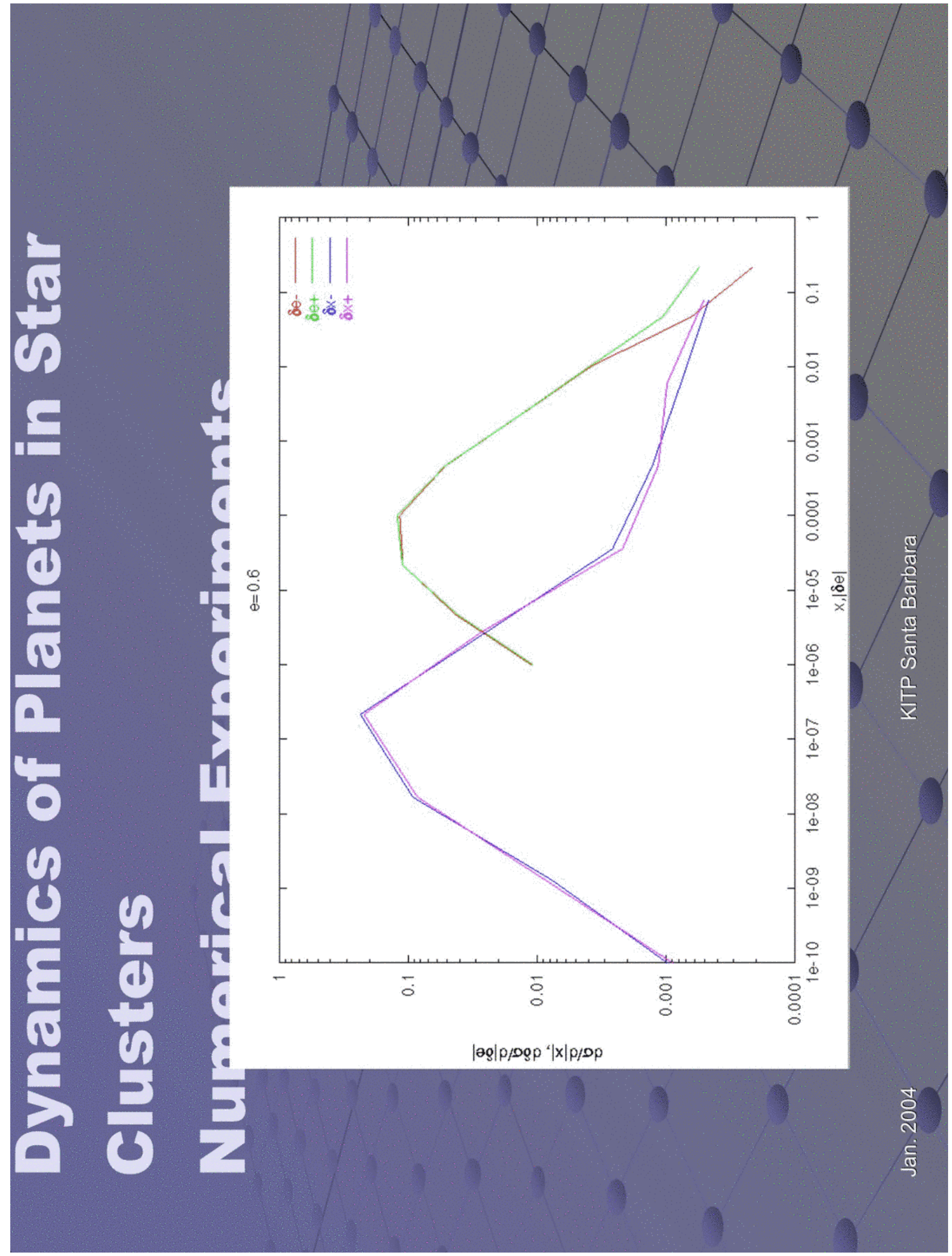
Scattering Events e=0.01
a+e+
a+e-
a-e+
a-e-
|δe|
x=|δa|/a


Dynamics of Planets in Star
Clusters
Numeric
Scattering Events etherm.ktgbin
a+e+
a+e-
a-e+
a-e-
|δe|
x=|δa|/a
Initial e
for all planets
Jan. 2004
KITP Santa Barbara


Dynamics of Planets in Star
Clusters
Numerical Experiments
e=0.6
δe-
δe+
δx-
δx+
dσ/d|x|, dσ/d|δe|
x,|δe|
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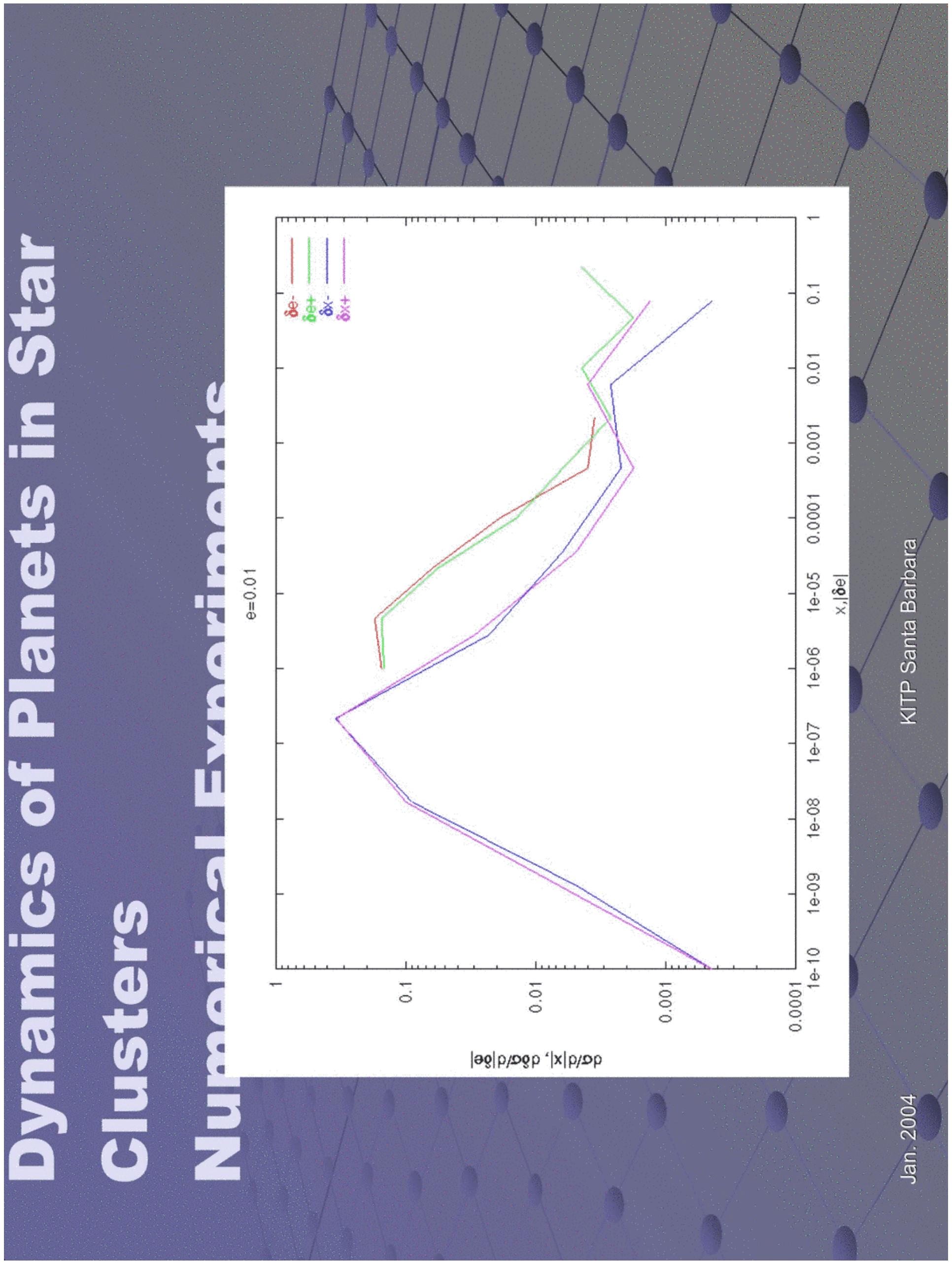
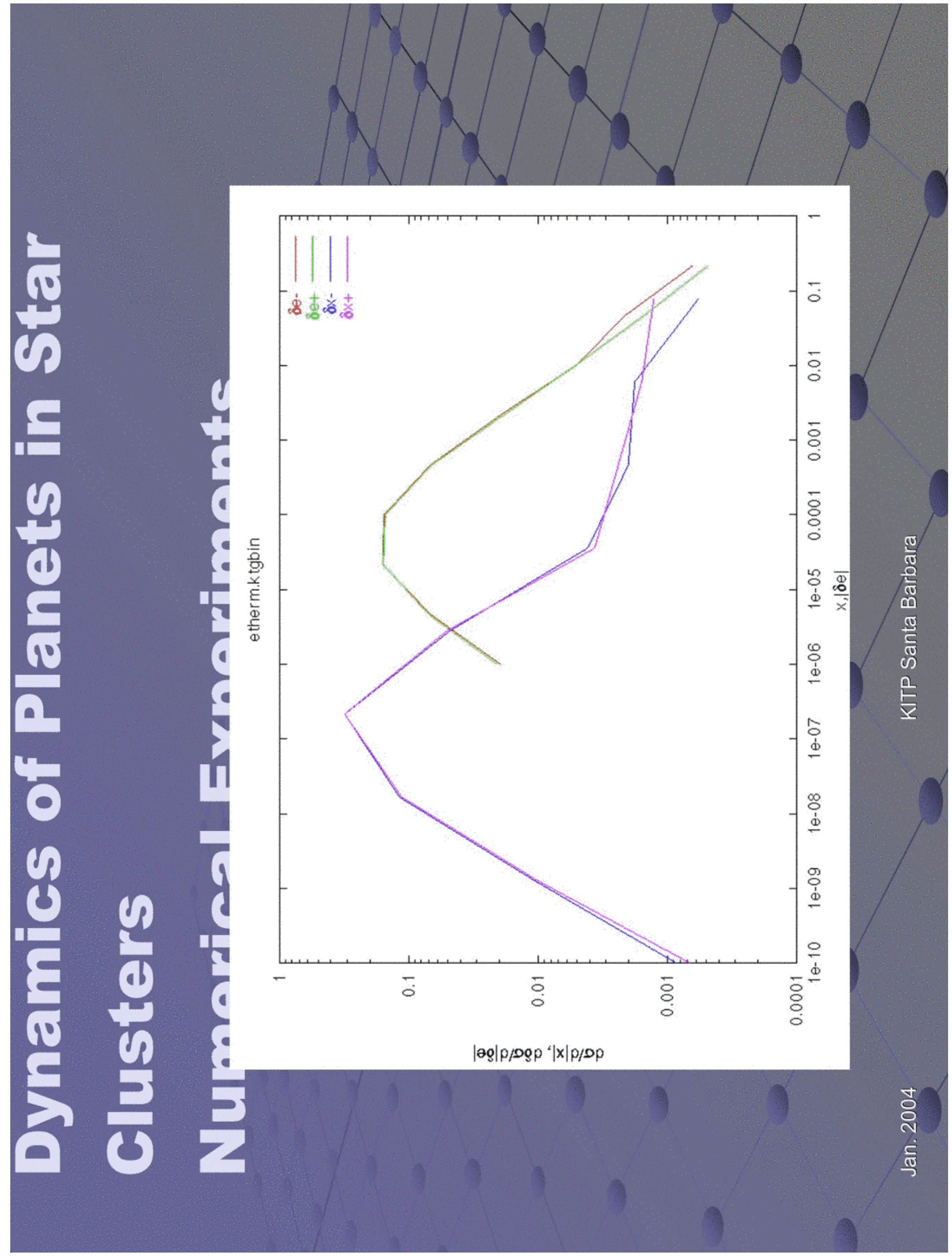
KITP Santa Barbara


Dynamics of Planets in Star Clusters
e=0.01
KITP Santa Barbara
Jan. 2004


Dynamics of Planets in Star Clusters
etherm.ktgbin
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Dynamics of Planets in Star Clusters

Numerical Experiments

Statistics of free floater creation

e-Distrib.	dN/dt_{cross}
0.1	0.4
0.3	0.4
0.6	0.7
0.9	1.4
f(e)=2e	1.4
0.1 (high)	35
0.3 (high)	25
0.9 (high)	45

Conclusions:

- 1% of planets change e,a significantly for low density (e.g. Orion)
- 10% in case of high density (47 Tuc, Quintuplet)

Future Work:

Large N! Binaries!
Longer Cluster Evolution!
(Spurzem+Lin 2004, in prep.)

Dynamics of Planets in Star Clusters

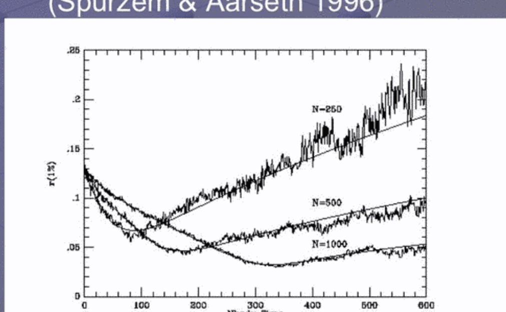
A stochastic Monte Carlo approach to model real star cluster evolution, III. Direct integrations of three- and four-body interactions.

R. Spurzem[1] and M. Giersz[2]

[1] Astronomisches Rechen-Institut, Mönchhofstraße 12-14, D-69120 Heidelberg, Germany
[2] Nicolaus Copernicus Astronomical Centre, Polish Academy of Science, ul. Bartycka 18, 00-716 Warsaw, Poland

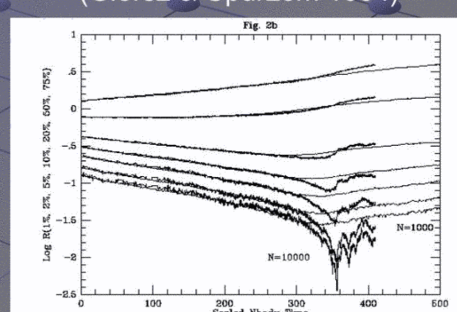
Giersz & Spurzem 1996, Paper I
Giersz & Spurzem 2001, Paper II

(Spurzem & Aarseth 1996)

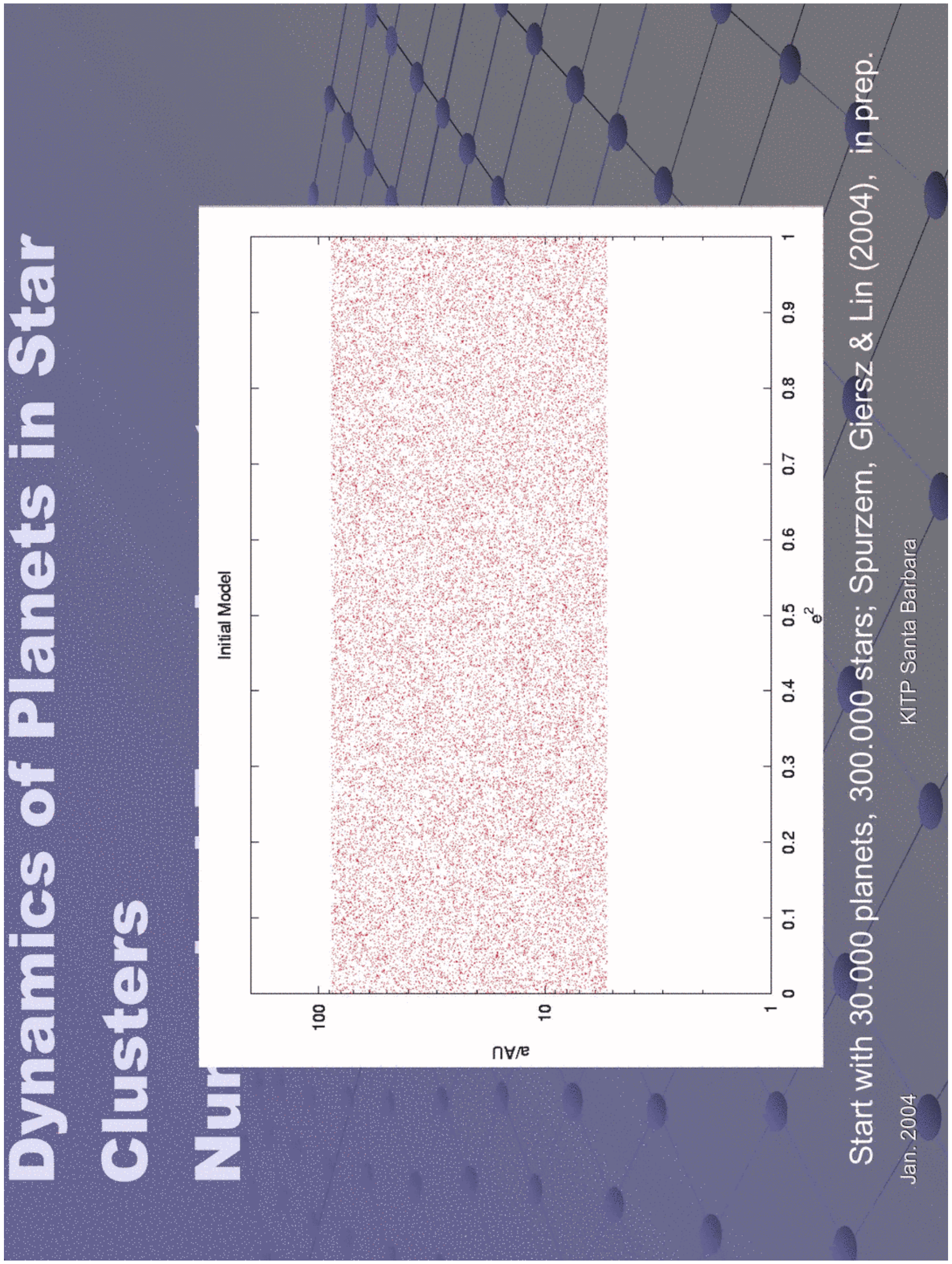


N-Body / N-Body

(Giersz & Spurzem 1994)



N-Body / Fokker-Planck


Dynamics of Planets in Star
Clusters
Nu
Initial Model
a/AU
e2
Start with 30.000 planets, 300.000 stars; Spurzem, Giersz & Lin (2004), in prep.
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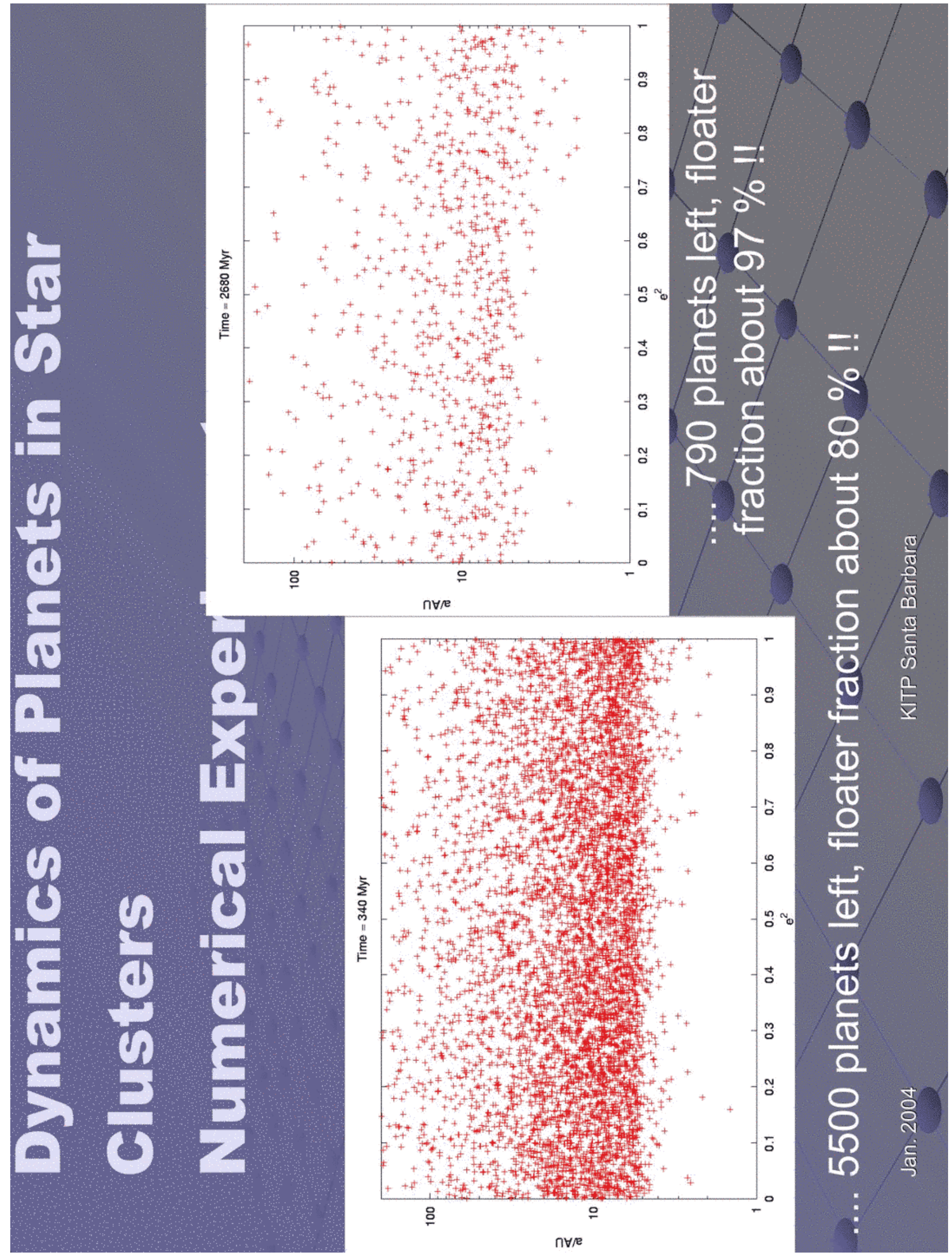
Dynamics of Planets in Star
Clusters
Numerical Exper
Time = 2680 Myr
Time = 340 Myr
a/AU
e2
… 790 planets left, floater fraction about 97 % !!
… 5500 planets left, floater fraction about 80 % !!
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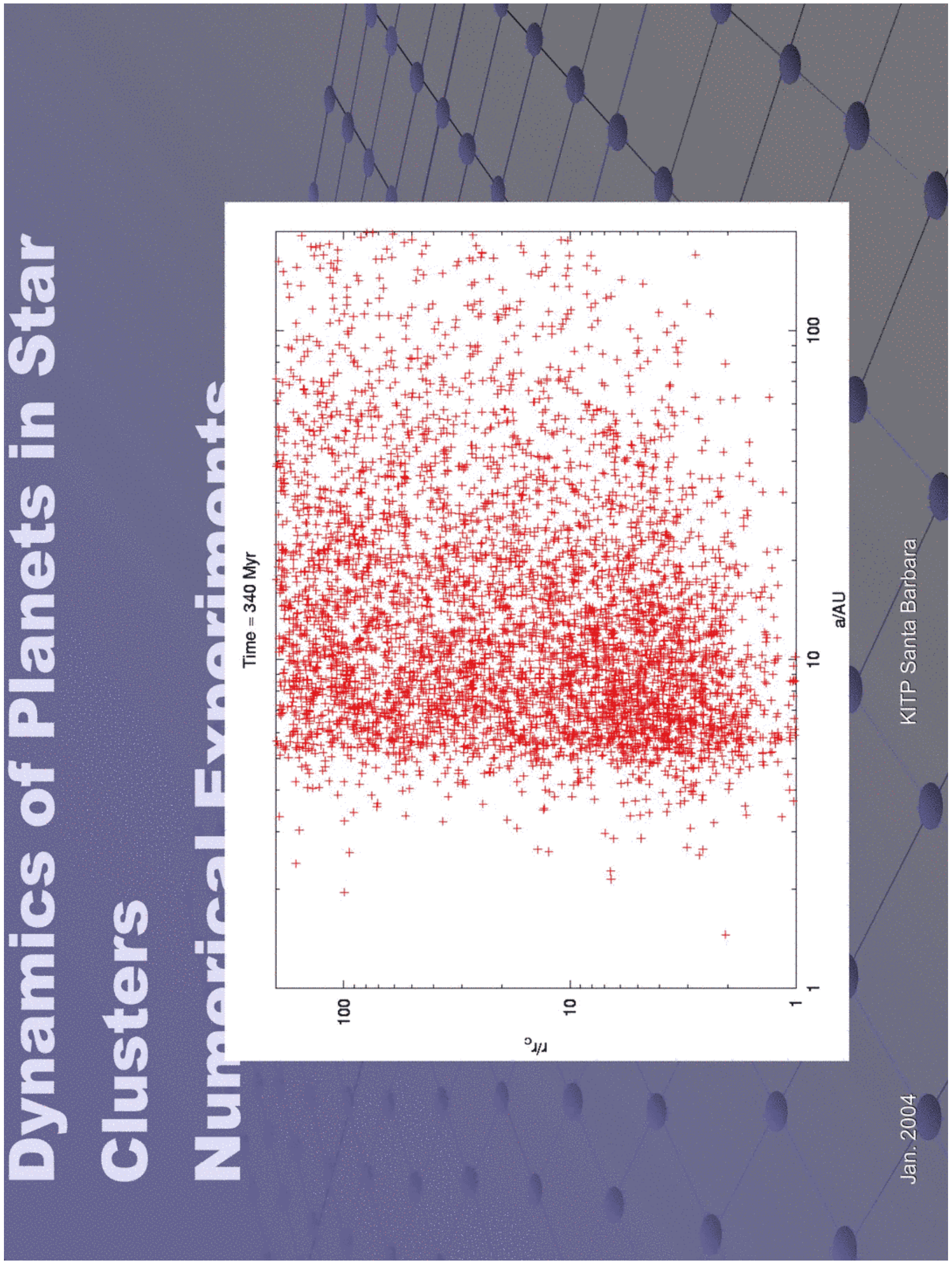
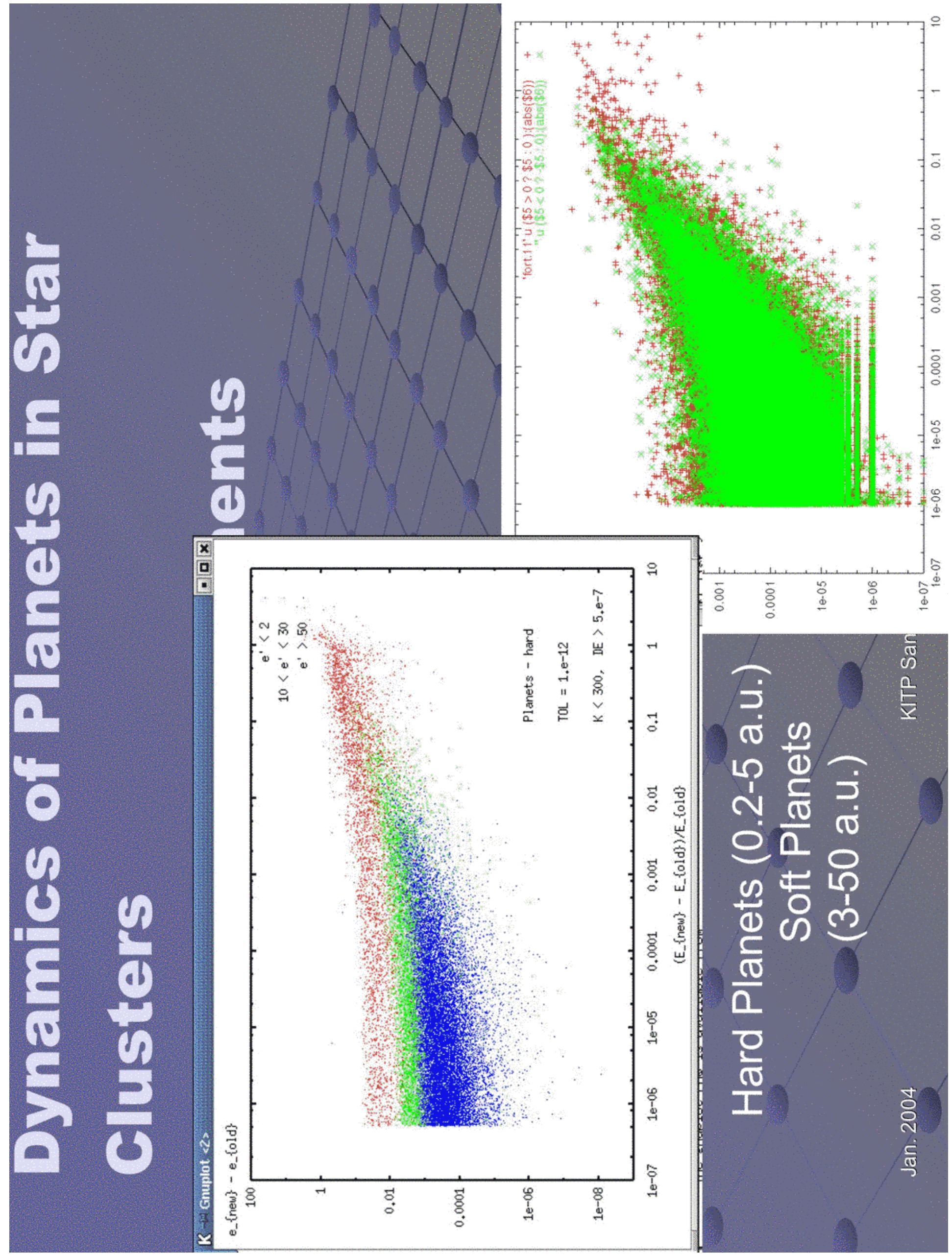

Dynamics of Planets in Star Clusters
Time = 340 Myr
a/AU
r/r_c
KITP Santa Barbara
Jan. 2004


Dynamics of Planets in Star Clusters
e_{new} - e_{old}
(E_{new} - E_{old})/E_{old}
e' < 2
10 < e' < 30
e' > 50
Planets - hard
TOL = 1.e-12
K < 300, DE > 5.e-7
Hard Planets (0.2-5 a.u.)
Soft Planets
(3-50 a.u.)
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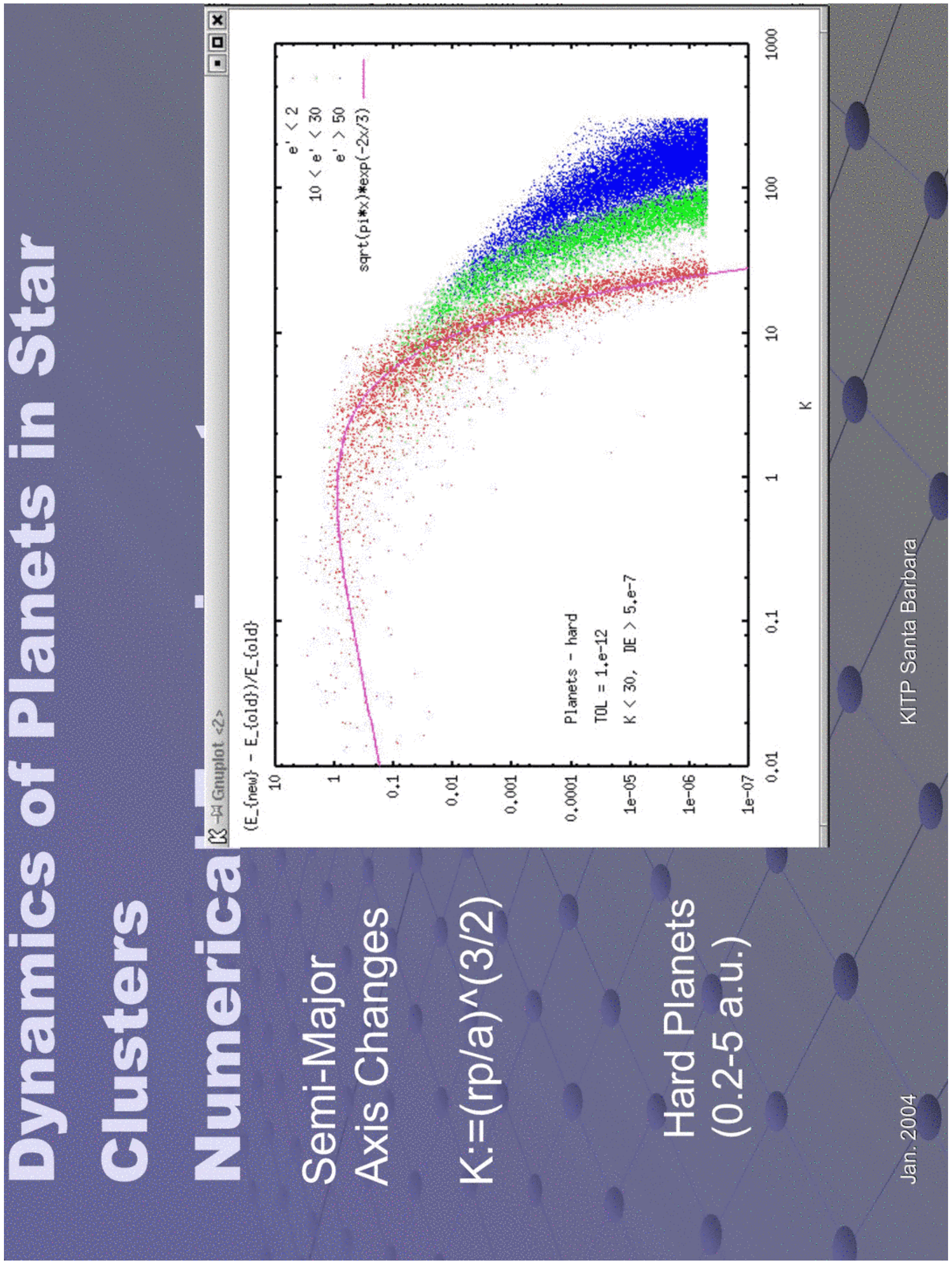
Dynamics of Planets in Star Clusters
Semi-Major Axis Changes
K:=(rp/a)^(3/2)
Hard Planets (0.2-5 a.u.)
Gnuplot <2>
(E_{new} - E_{old})/E_{old}
e' < 2
10 < e' < 30
e' > 50
sqrt(pi*x)*exp(-2x/3)
Planets - hard
TOL = 1.e-12
K < 30, DE > 5.e-7
K
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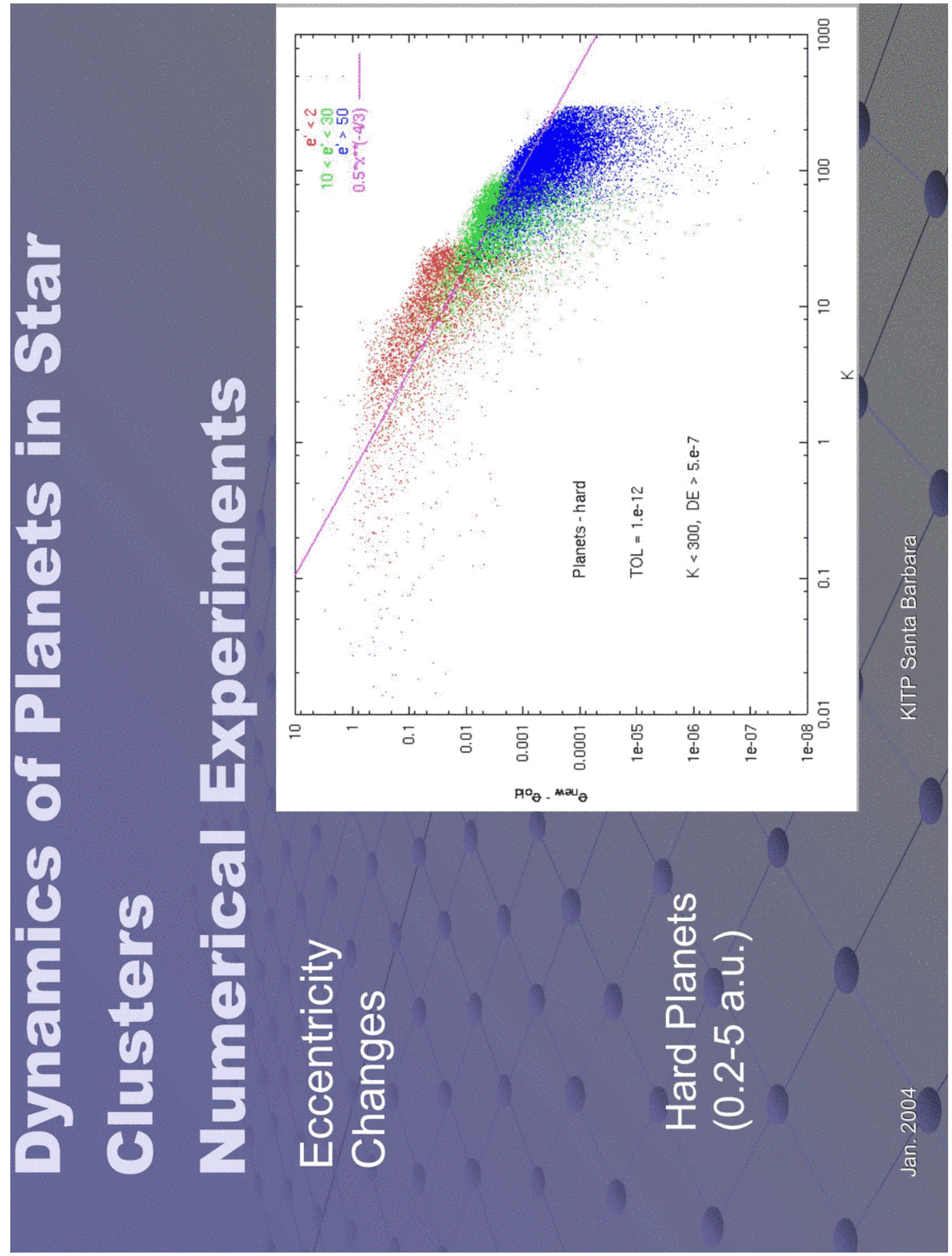
Dynamics of Planets in Star Clusters
Numerical Experiments
Eccentricity Changes
Hard Planets (0.2-5 a.u.)
e' < 2
10 < e' < 30
e' > 50
0.5*x**(-4/3)
Planets - hard
TOL = 1.e-12
K < 300, DE > 5.e-7
K
e_new - e_old
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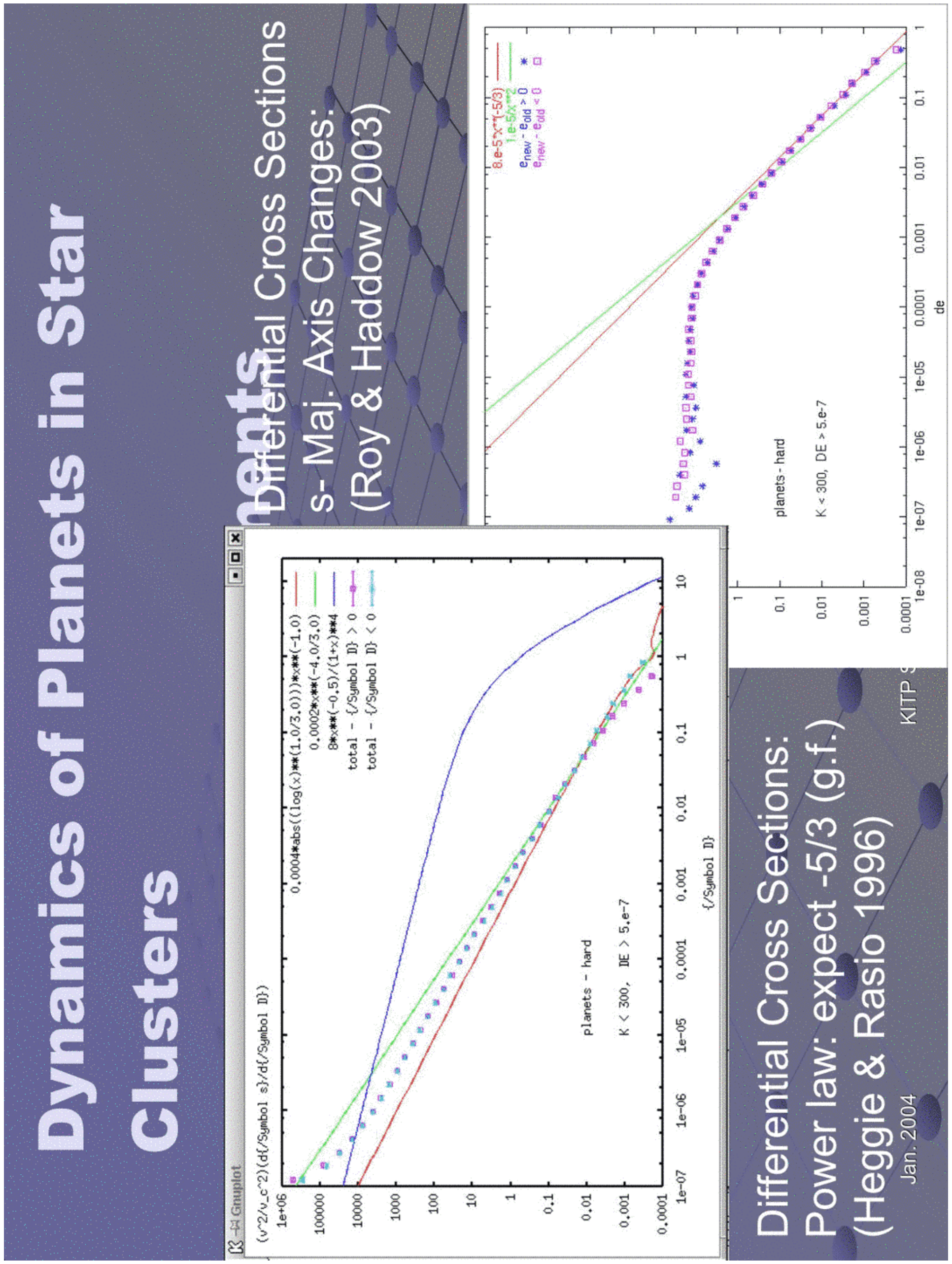
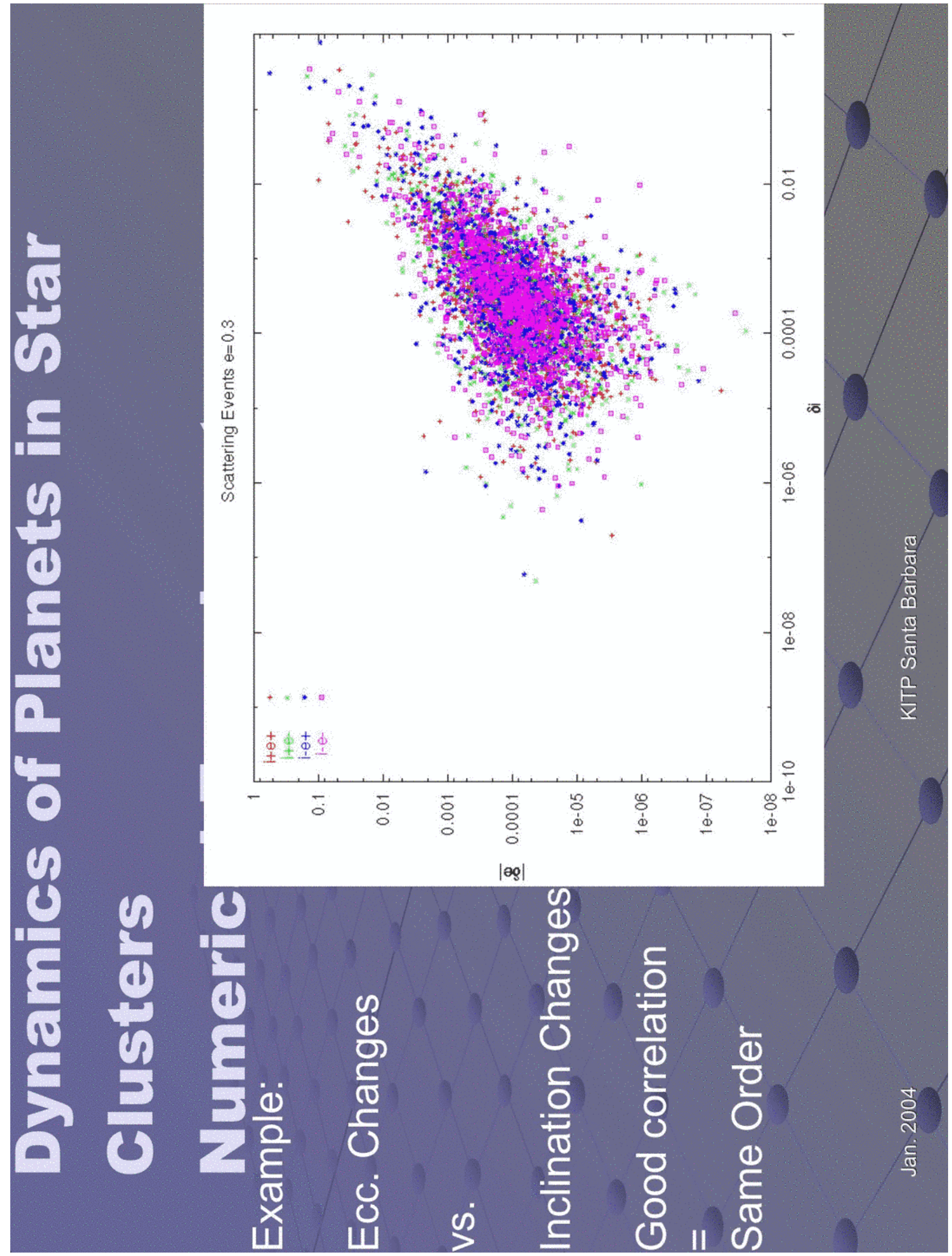

Dynamics of Planets in Star Clusters
Differential Cross Sections
s- Maj. Axis Changes:
(Roy & Haddow 2003)
planets - hard
K < 300, DE > 5.e-7
de
Gnuplot
planets - hard
K < 300, DE > 5.e-7
Differential Cross Sections:
Power law: expect -5/3 (g.f.)
(Heggie & Rasio 1996)
Jan. 2004


Dynamics of Planets in Star Clusters
Numeric
Example:
Ecc. Changes
vs.
Inclination Changes
Good correlation
=
Same Order
Scattering Events e=0.3
δi
|δe|
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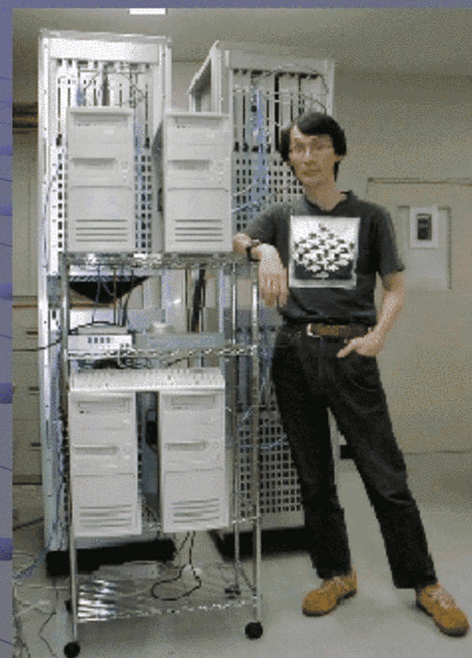
Parallelization and Hardware: Hardware

GRAPE-6 Gravity/Coulomb Part

- G6 Chip: 0.25μ 2MGate ASIC, 6 Pipelines
- at 90MHz, 31Gflops/chip
- 48Tflops full system (March 2002)
- Plan up to 72Tflops full system (in 2002)
- Installed in Cambridge, Marseille, Drexel, Amsterdam, New York (AMNH), Mitaka (NAO), Tokyo, etc..
  New Jersey, Indiana, Heidelberg



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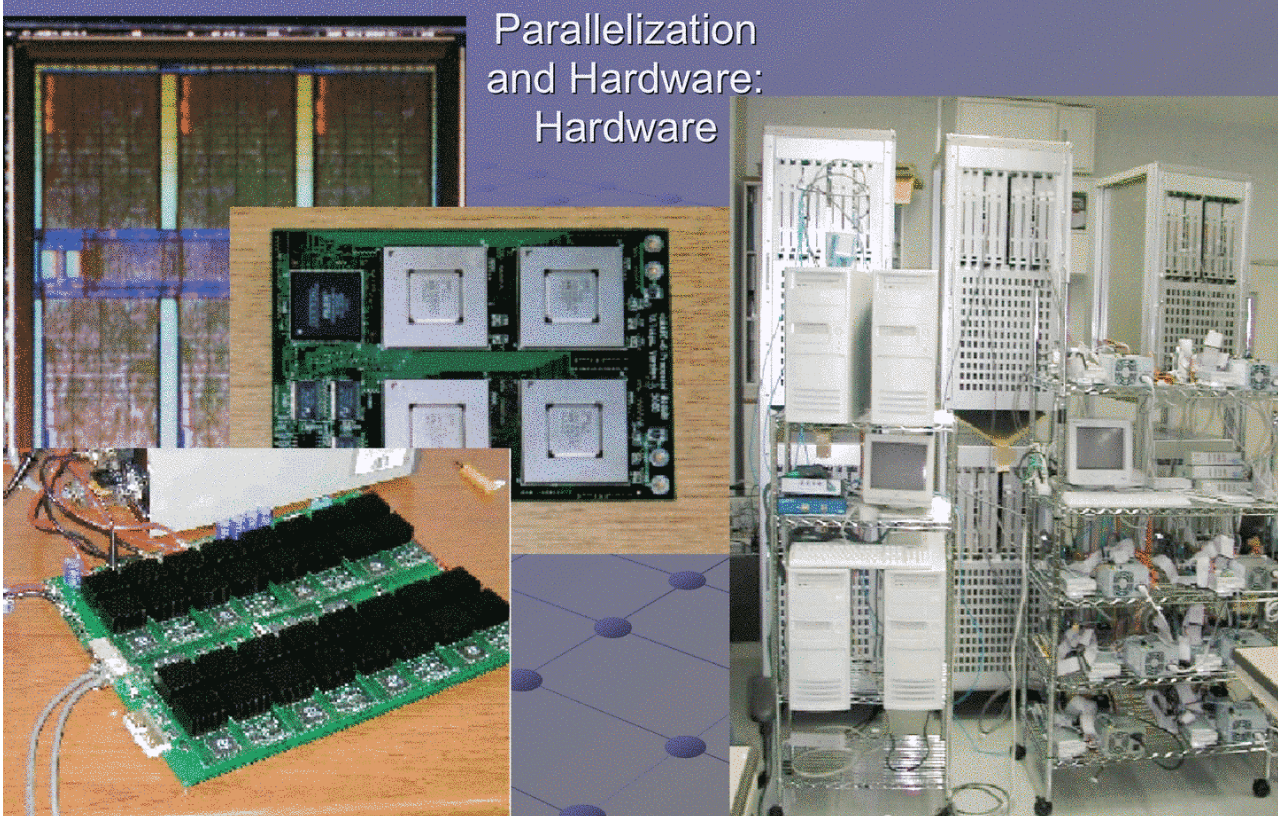
Parallelization and Hardware: Hardware



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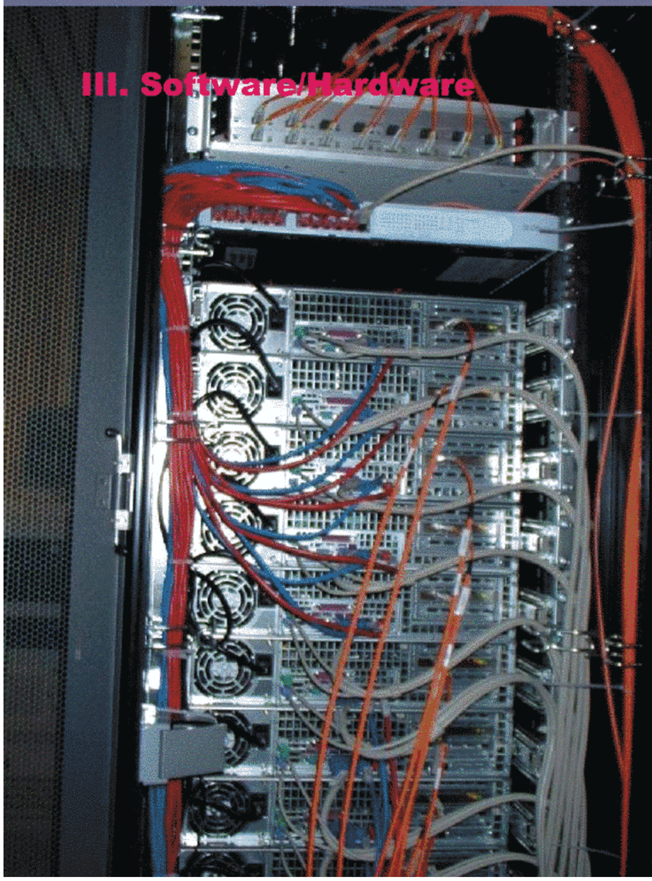
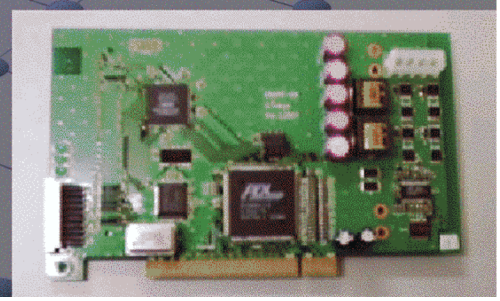
III. Software/Hardware



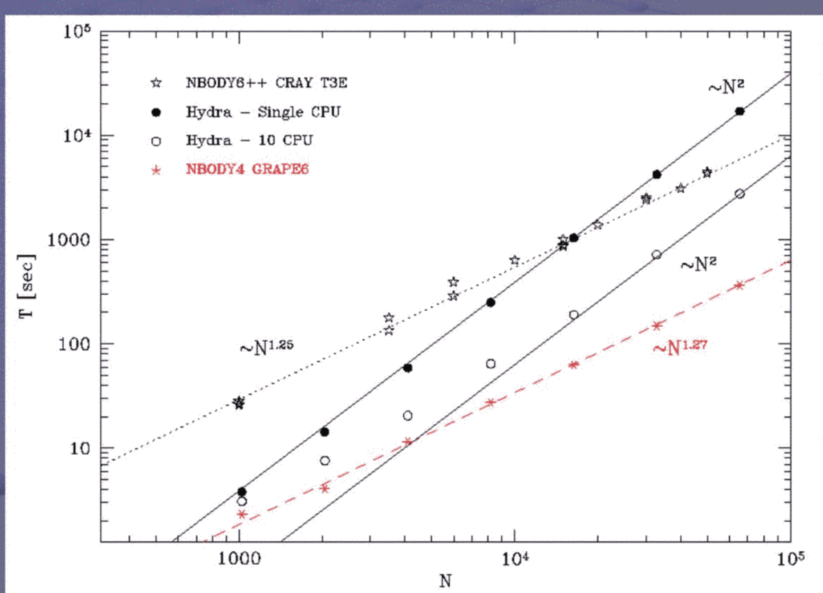
- Galactic Nuclei/Gal. Dynamics
- Radiative Transfer
- Star Cluster Dynamics
- Planetary Dynamics
- Parallel Data Bank Testbed for DIVA Satellite Data

To be extended by further nodes
Plus GRAPE-6 PCI cards (150 Gflop)
0.05-0.1 US-$ per Mflop!!!



Barbara

III. Software/Hardware



Methods used (T3E):

- **Parallel (MPI) Work Distribution**
- **No (yet) domain decomposition**
- **Systolic blocking communication (need sustained 200-400 MB/s)**

GRAPE-6 data by Holger Baumgardt, JSPS/U Tokyo

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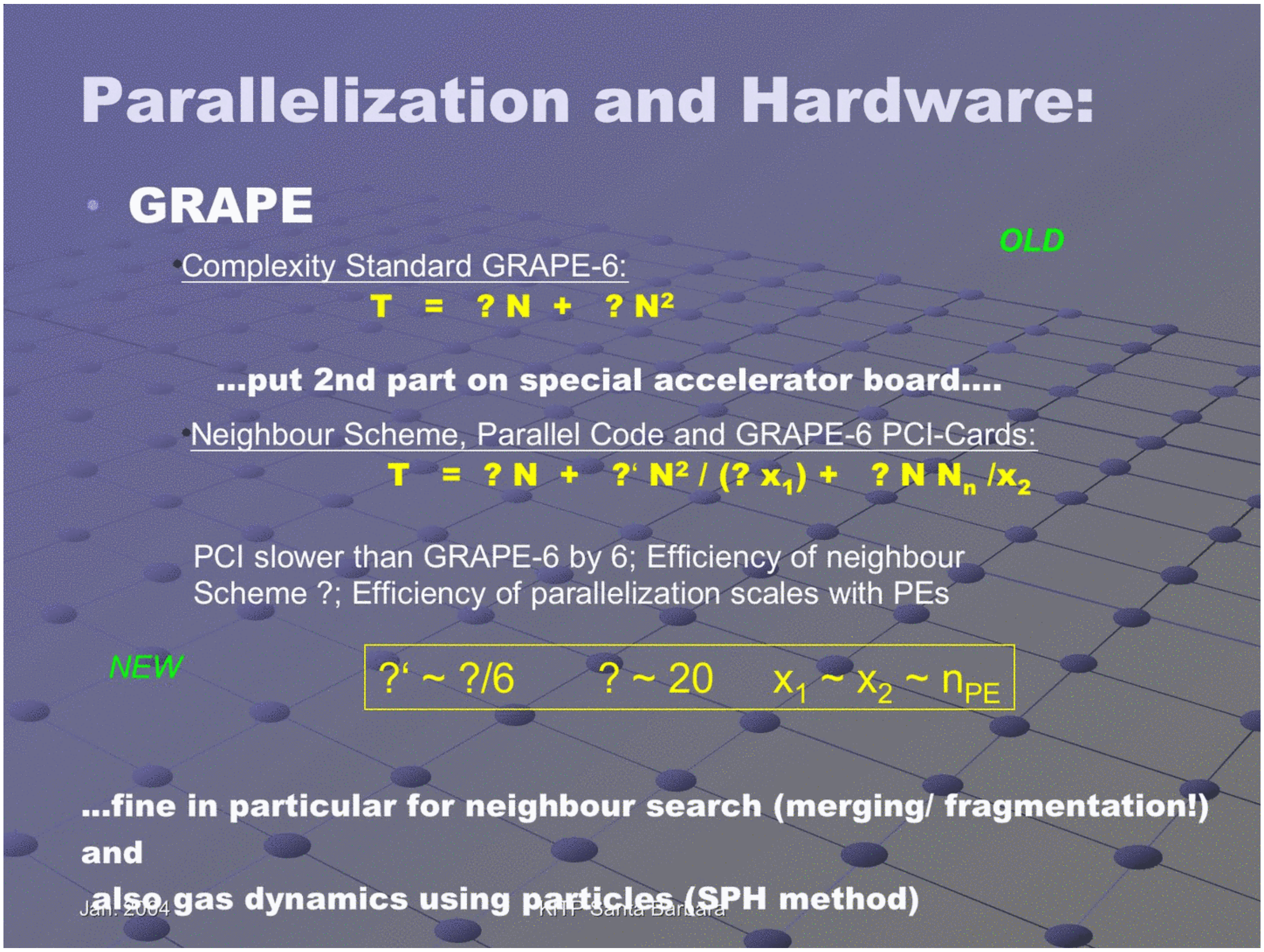
Parallelization and Hardware:
GRAPE
Complexity Standard GRAPE-6:
T = ? N + ? N²
OLD
...put 2nd part on special accelerator board....
Neighbour Scheme, Parallel Code and GRAPE-6 PCI-Cards:
T = ? N + ?' N² / (? x1) + ? N Nn /x2
PCI slower than GRAPE-6 by 6; Efficiency of neighbour Scheme ?; Efficiency of parallelization scales with PEs
NEW
?' ~ ?/6 ? ~ 20 x1 ~ x2 ~ nPE
...fine in particular for neighbour search (merging/ fragmentation!)
and
also gas dynamics using particles (SPH method)
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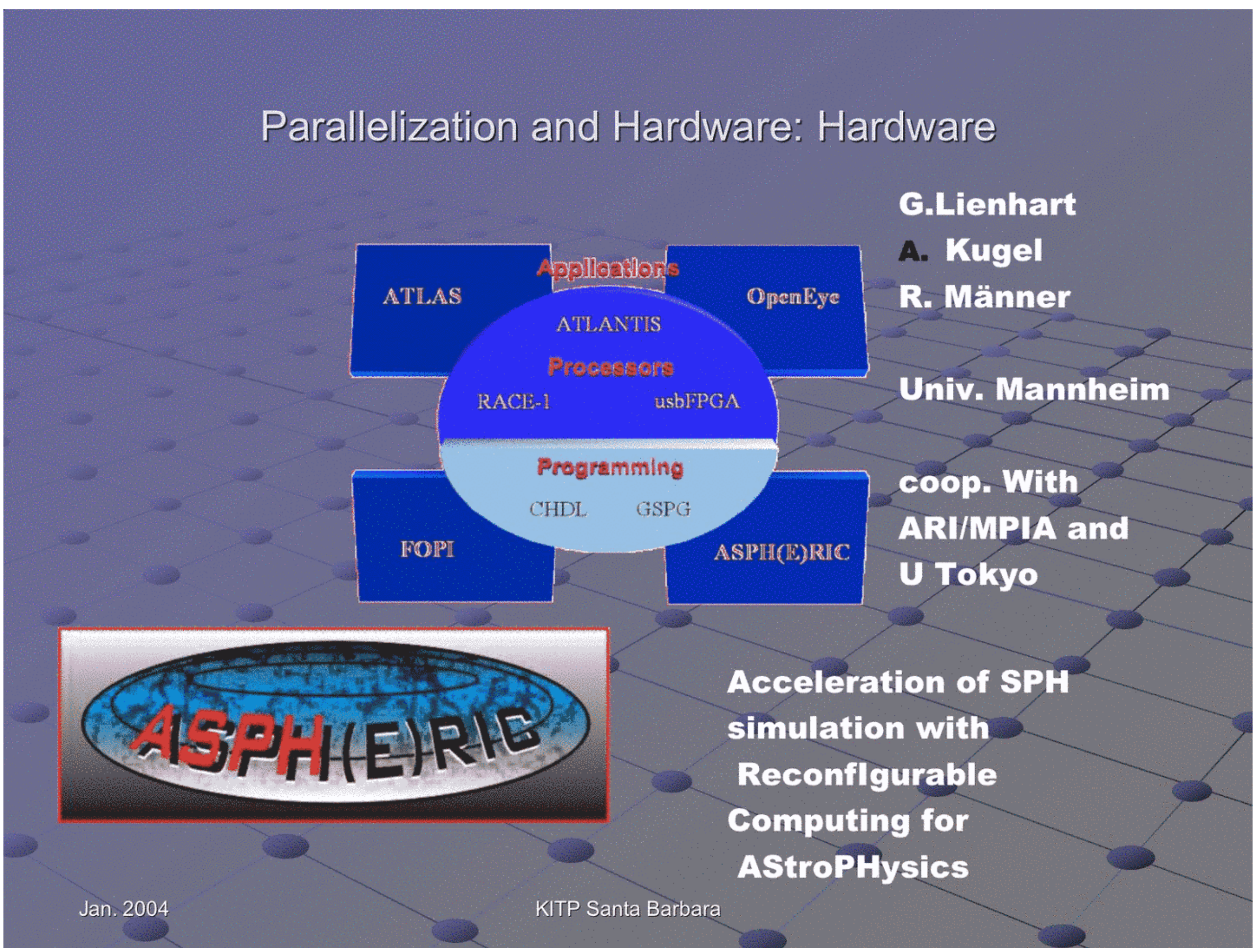
Parallelization and Hardware: Hardware
Applications
ATLAS
OpenEye
ATLANTIS
Processors
RACE-1
usbFPGA
Programming
CHDL
GSPG
FOPI
ASPH(E)RIC
G.Lienhart
A. Kugel
R. Männer
Univ. Mannheim
coop. With
ARI/MPIA and
U Tokyo
ASPH(E)RIC
Acceleration of SPH
simulation with
Reconfigurable
Computing for
AStroPHysics
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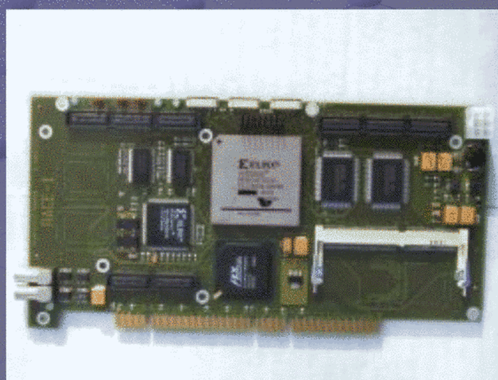
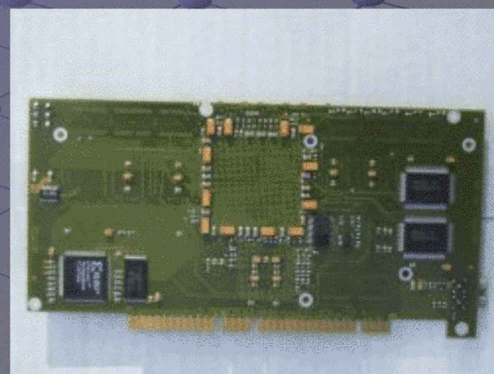
Parallelization and Hardware: Hardware

- RACE-Boards
  usable as 64bit PCI-Interface for GRAPE (200 MB/s)
  and device for SPH simulation (up to 5 Gflop on one card now)
- GRACE = GRAPE + RACE





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Dynamics of Planets in Star Clusters

Numerical Experiments

CONCLUSIONS:

- Changes of e and a are diffusive process – no preferred sign for most semi-major axes – get free floaters as well as inward migrants... Are 2b encounters dominant?
- In evolving dense environments about ten times more free floaters than previously expected (Hurley & Shara 2001 ok)
- Perturbation theory (Heggie & Rasio 1996, Roy & Haddow 2003
- but there is more to understand
- Note that ALL orbital elements will „diffuse“ due to cluster environment – difference to resonances etc... study diffusion of inclination, node, perihelion...

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