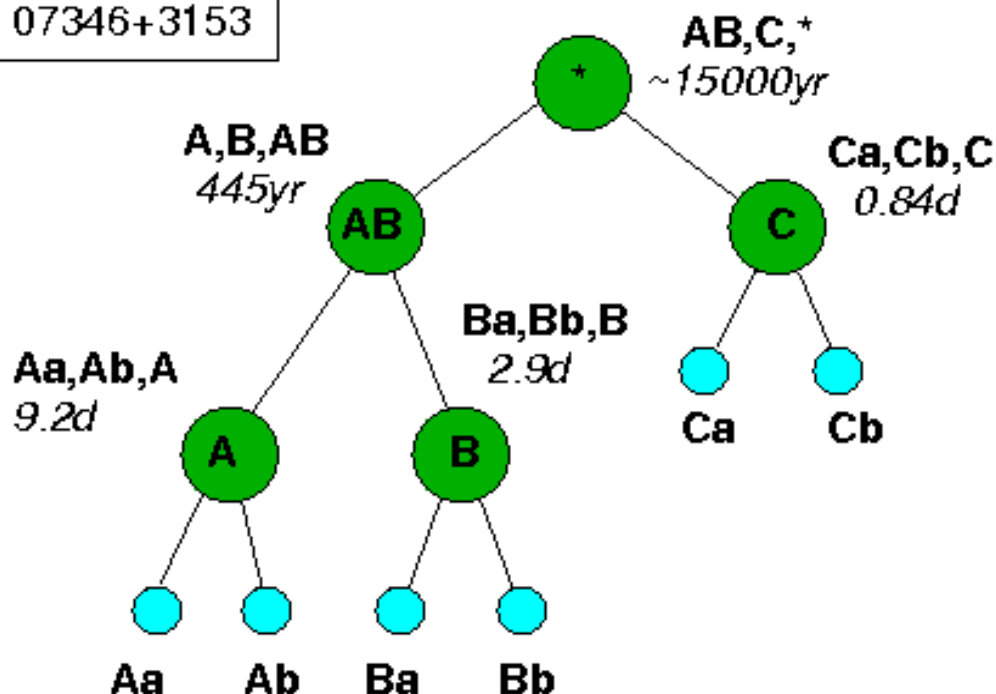


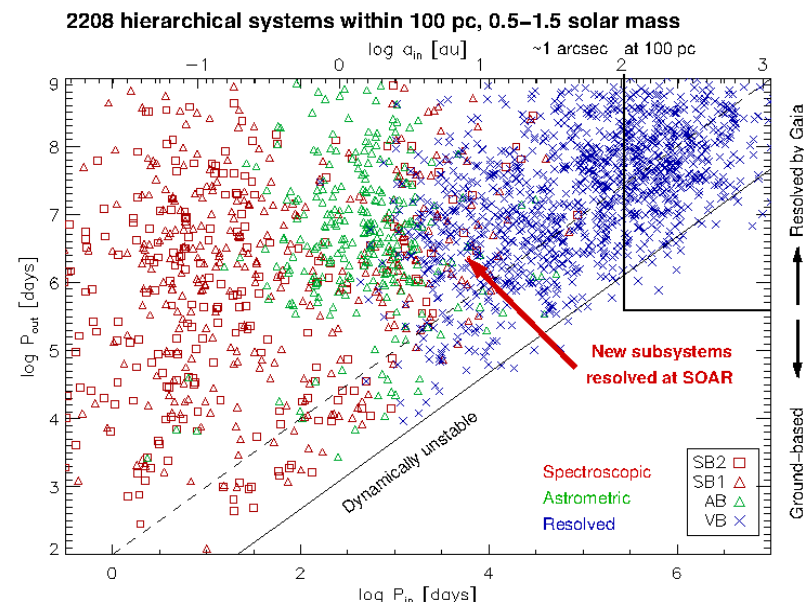
Statistics of Hierarchical Systems

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Castor (Torres et al. 2022)



Utility of multiplicity statistics

- Estimate number of systems of interest for evolution (e.g. SN progenitors)
- Understand formation of stars & binaries
- Detect and study populations?

Galactic populations – well developed

Binary populations – first steps (close bin. vs. metallicity, dependence on density)

Hierarchical populations – uncharted territory

Parameters of hierarchies

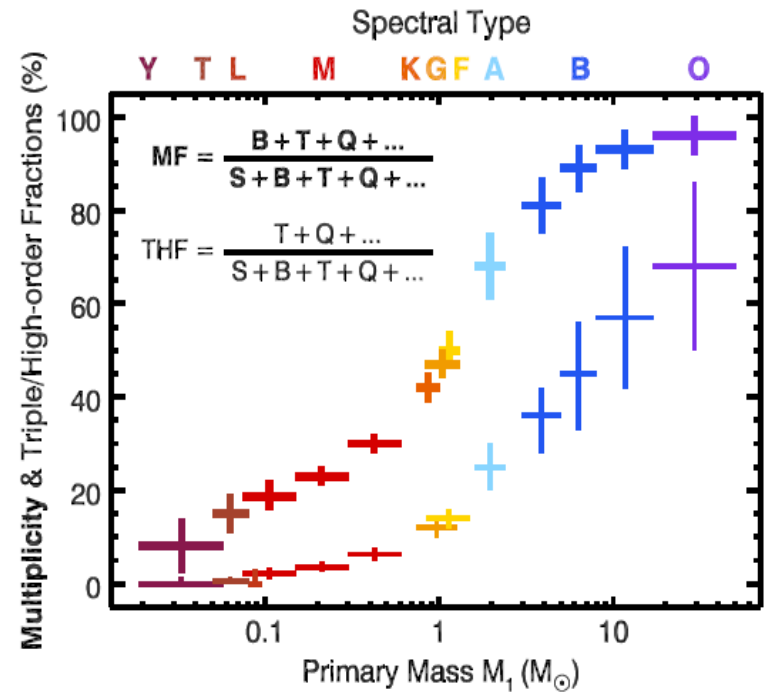
- Number of components N_c
- Periods, mass ratios, eccentricities $(P, q, e) * N_c$
- Period ratios, mutual incl.

$$MF = (B + T + Q + \dots) / N_{\text{sys}} = \epsilon$$

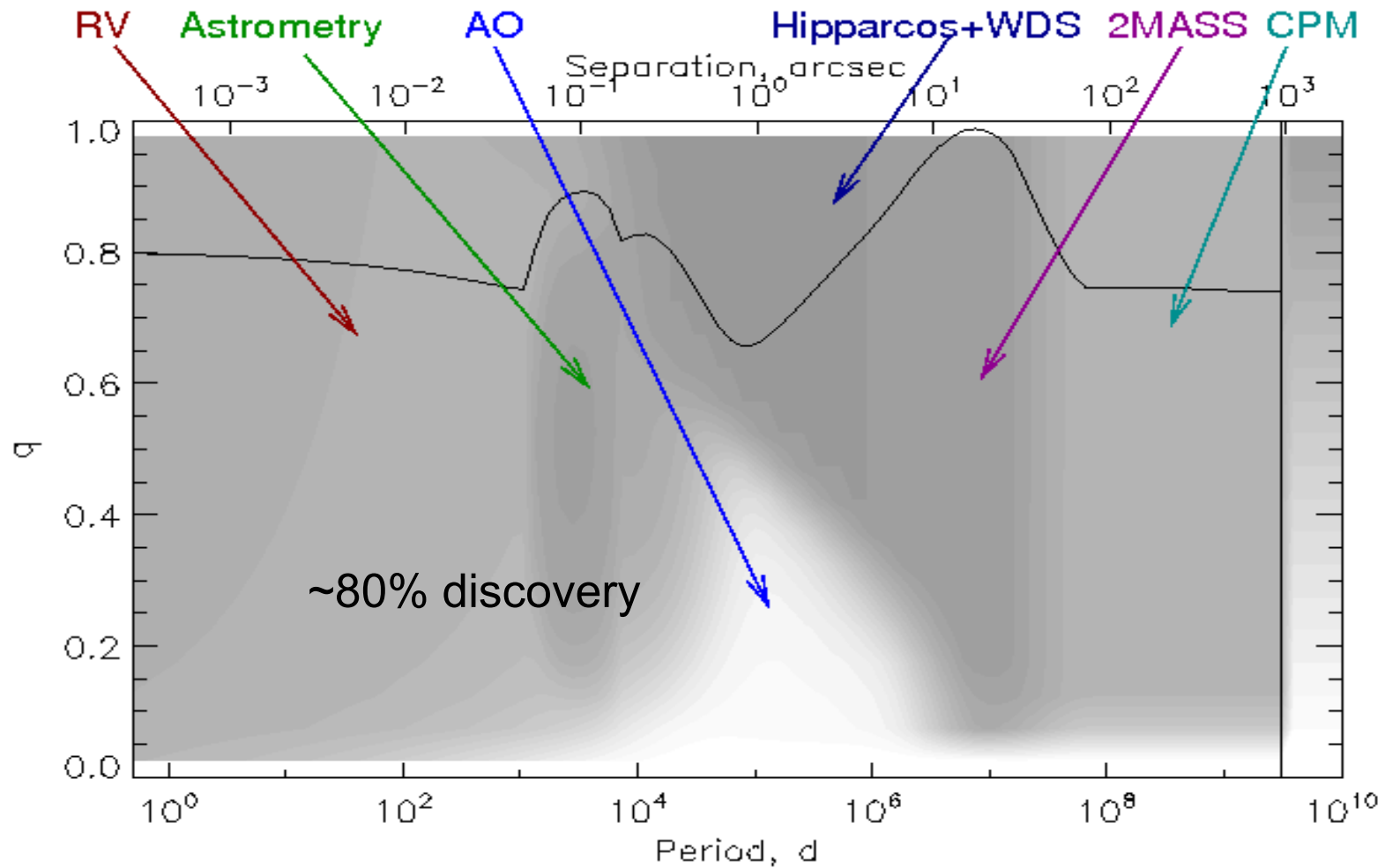
$$CF = (B + 2 * T + 3 * Q + \dots) / N_{\text{sys}}$$

$$HF = (T + Q + \dots) / N_{\text{sys}}$$

HF=0.14 for solar-type stars
 α Cen is triple!



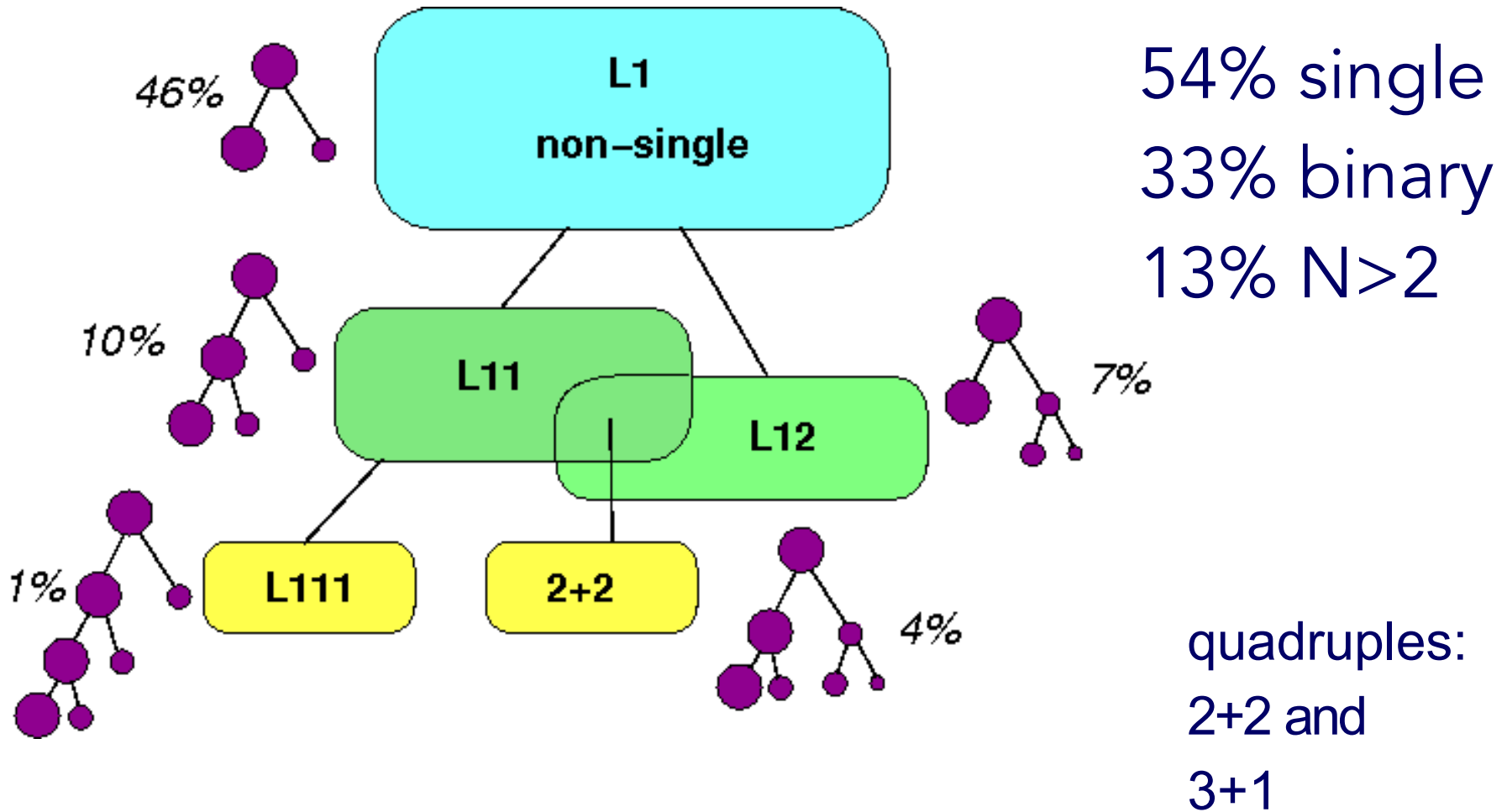
Combination of observing techniques



Solar-type stars within 67pc (2014 AJ 147, 87)

Aug 30, 2017

Fraction of hierarchies in the 67-pc sample



One star in 8 has 3+ components, one star in 25 is 2+2 quadruple

Triple = two binaries? Yes, maybe, no...

- “Independent multiplicity”: select inner and outer pairs from generic $f(P)$, keep dynamically stable combinations
- A reasonable first-order guess, but many caveats:
 - Frequencies do not match (ϵ , ϵ^2 , ϵ^3 , ... ?)
 - Quadruples are under-predicted
 - Close subsystems are enhanced by 2x

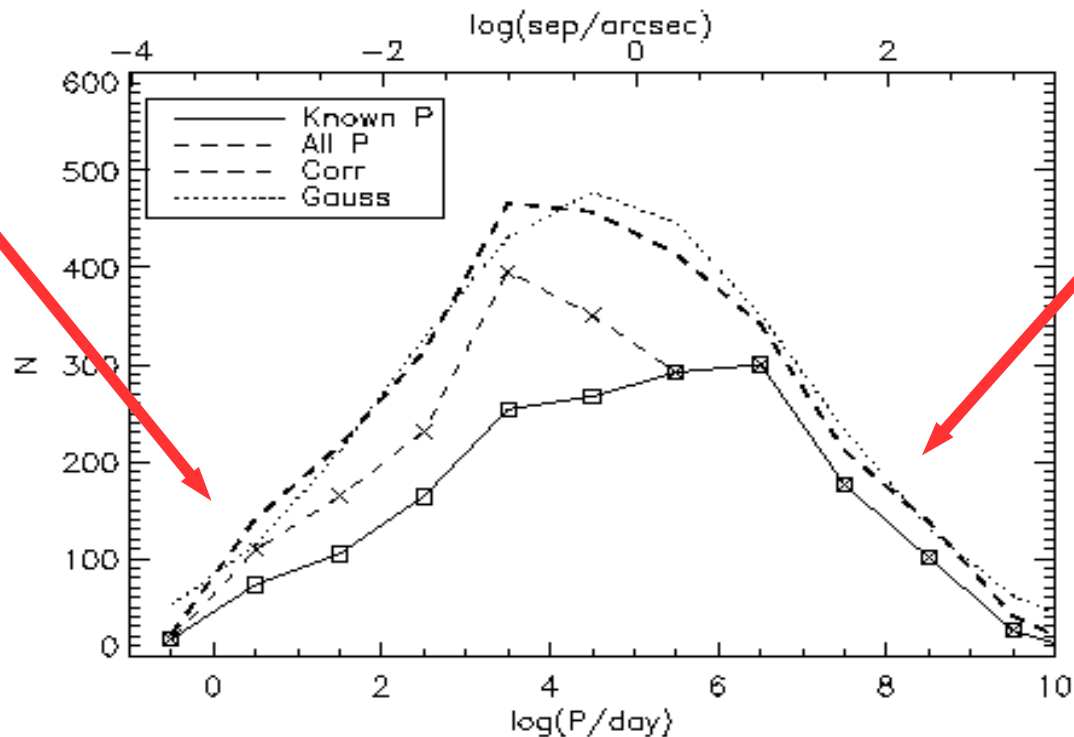
Frequency of hierarchies

- Independent multiplicity implies a geometric progression: $f(N) \sim \epsilon^N$; ϵ strongly depends on mass
- A constant ϵ under-predicts triples
- Assume variable ϵ (mix of binary-rich and binary-poor environments) to match the numbers
- Still under-predicts 2+2 quadruples: presence of subsystems in both components is correlated

Is $f(P)$ **really** log-normal?

- Popular (G.Kuiper, Duquennoy & Mayor, Raghavan...)
- A simple but not physically justified model, $f(P)$ can be asymmetric

Migration

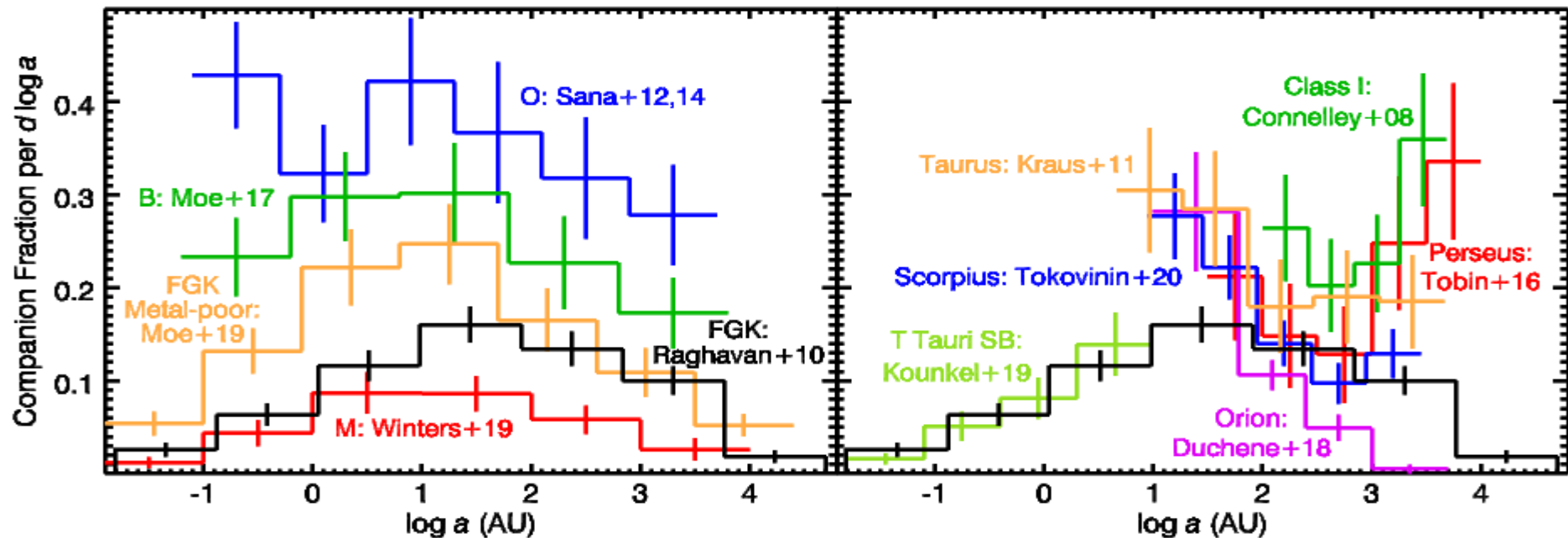


Dynamics

67-pc sample

Young populations vs. field

- The field is a mixture coming from different environments



Old stars (field)

Young stars

Relation between close binaries and triples

- Suspected for a long time (A.Batten, S.Rucinsky,...)
- Hints on close-binary formation by Kozai-Lidov cycles with tidal friction (KCTF) – Eggleton, Kiseleva.
- Statistics proves that CBs are related to hierarchies; increased fraction of tertiaries for closest binaries.
- Yet, close pairs without tertiary companions do exist!

KCTF: Kozai-Lidov cycles with tidal friction

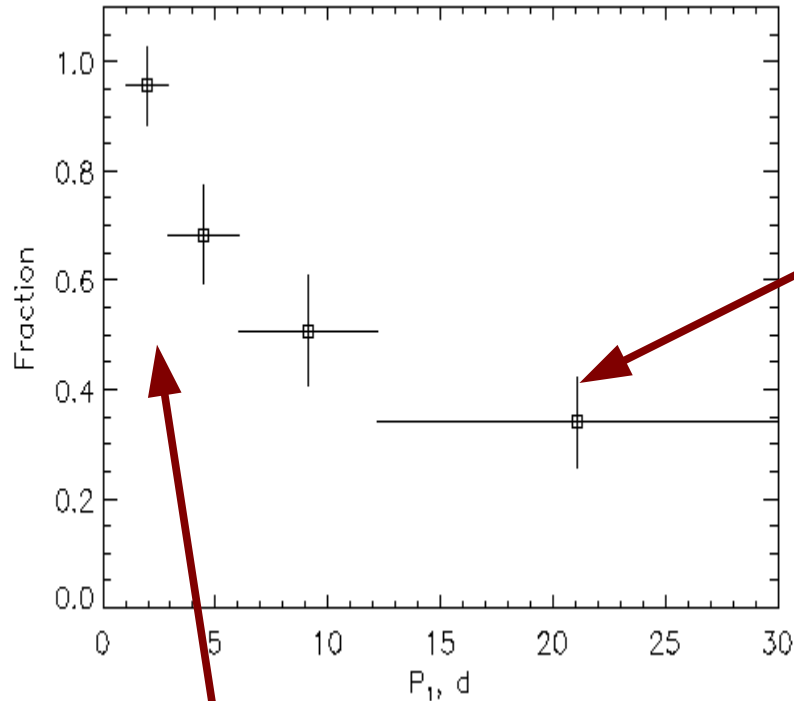
- Mis-aligned triple ($i > 39^\circ$) with K-L cycles
- Inner eccentricity grows, causing tidal interaction
- Result: $P_{\text{in}} < 10\text{d}$, circular orbit, mis-aligned
- Various modifications to basic KCTF

Fabrycky & Tremaine (2007): preference of $P \sim 10\text{d}$, $i \sim 39^\circ$

Moe & Kratter (2018 ApJ 854, 44): KCTF works at PMS.
~30% can be KCTF products, but most CBs are not.

KCTF can work (slowly) in 3+1 quadruples (cascade)

Tertiary companions to close binaries



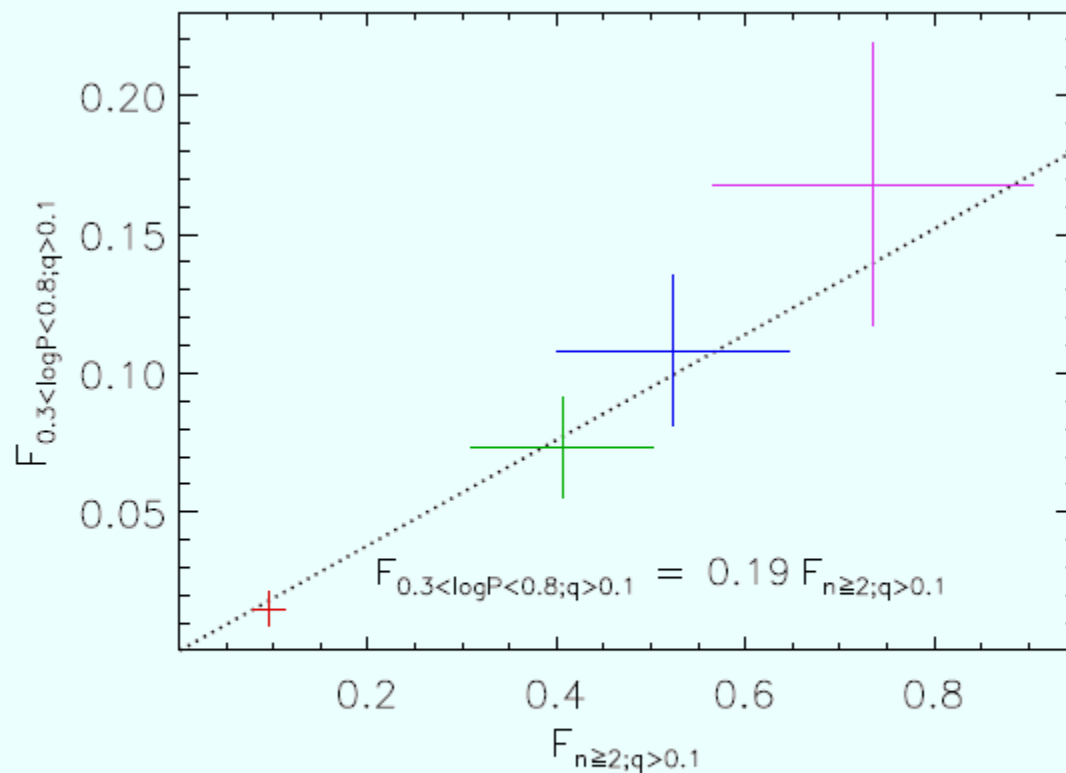
Many tertiaries are very wide!?

- Frequency of tertiaries depends on P_{in}
- $P > 10$ d binaries exist without tertiary companions, formed via migration.

2006, A&A, 450, 681
NACO + 2MASS

CB fraction is proportional to multiplicity

Fraction of $P=2\dots 6d$

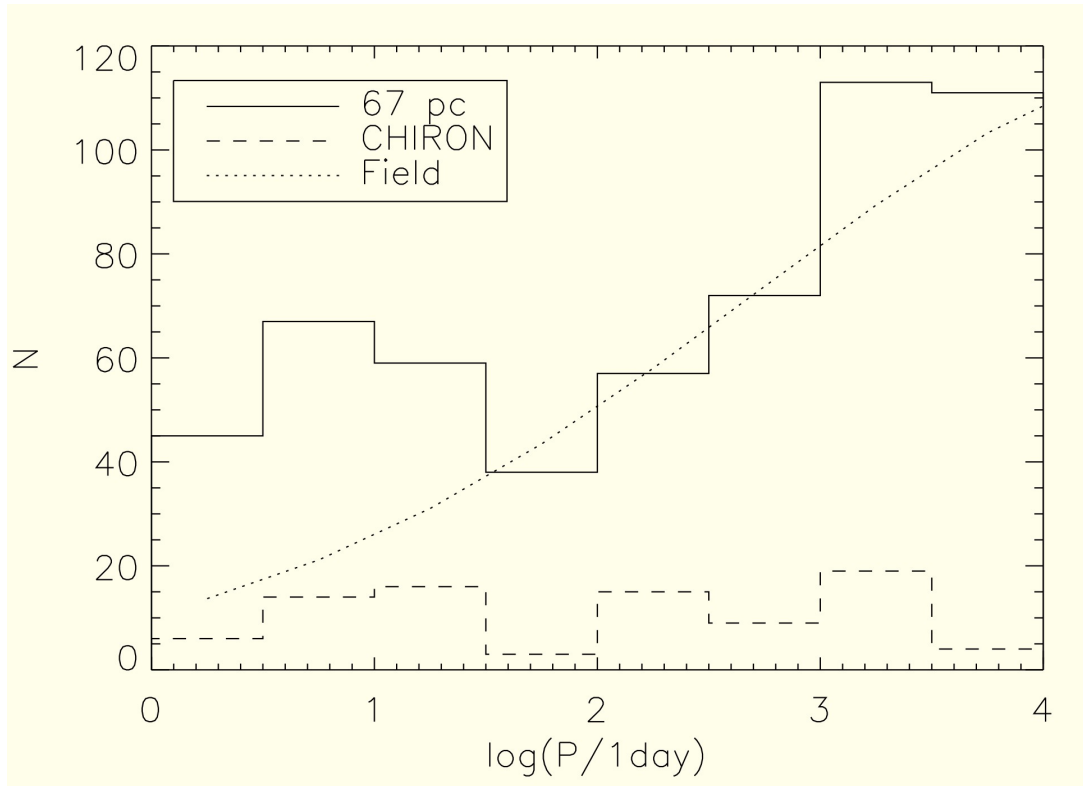


One pair
out of 5 hosts a
close binary

Moe & Di Stefano
2017 ApJS, 230, 15

FIG. 39.— The close companion fraction $F_{0.3 < \log P < 0.8; q > 0.1}$ as a function of overall triple plus quadruple star fraction $F_{n \geq 2; q > 0.1}$ colored according to primary spectral type. For

Close binaries “like” to be in triples



What fraction of solar-type binaries with $P < 10\text{d}$ are inner subsystems in triples?

Independent mult.: 35%

Reality: 57%

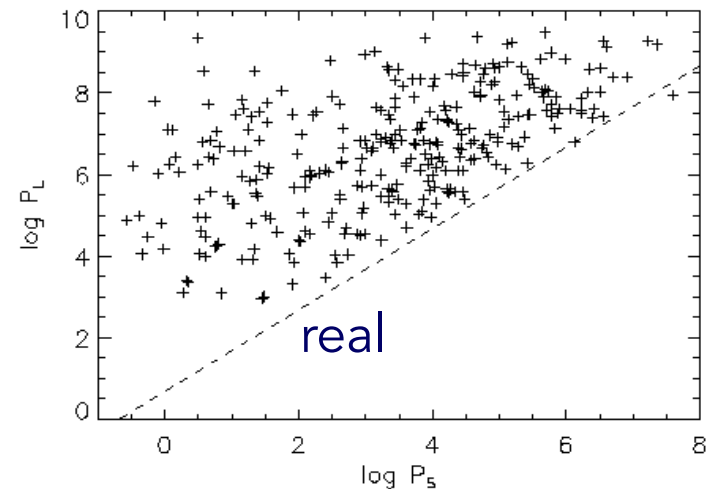
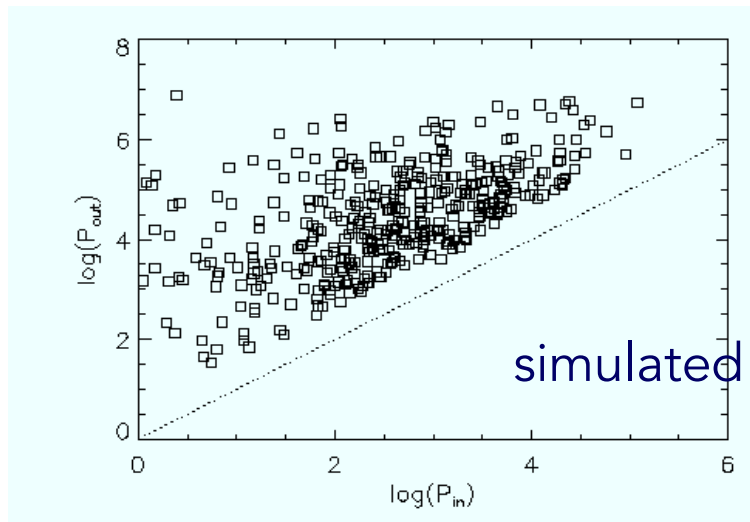
$P < 10^4\text{d}$: 279 inner,
439 solitary

Independent-multiplicity
model fails for $P < 30\text{d}$

Solar-type stars within 67pc
(updated: 2023, DR3 and 10 years of CHIRON)

Why many CBs are triple?

- Close binary = strong migration = large accretion
- Large accretion = more companions = more triples = more massive stars (a cascade)
- Dissipative capture and accretion burst?



Recent updates on CBs in hierarchies

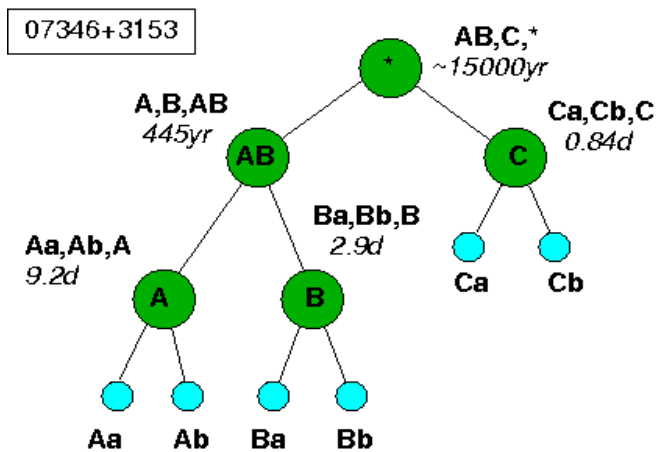
- H.-C. Hwang (2023 MNRAS 518, 1750): frequency of tertiary companions to Gaia EBs is enhanced by 2.28x, less for SBs, and not enhanced for astrometric. These tertiaries are wide (1-10 kau).
- EBs with close tertiary companions from Kepler (Borkovits et al. 2016) and TESS (ongoing).
- Doubly and triply eclipsing planar hierarchies

Doubly eclipsing (2+2) quadruples

- Catalogs based on OGLE (Zache et al.) and TESS (Kostov et al. 2022)
- Some 2+2 systems are compact and planar:
 - VW LMi ($P_{\text{out}} \sim 1$ yr) Pribulla et al. 2020
 - TIC 219006971 ($P_{\text{out}} = 168\text{d}$) Kostov et al. 2023, MNRAS, 522, 90
 - BU CMi (Zasche, submitted) $P_{\text{out}} = 120\text{d}$
- Comparable masses of all 4 stars ($q \sim 1$)
- Resonances between inner periods?

Triply eclipsing sextuple systems

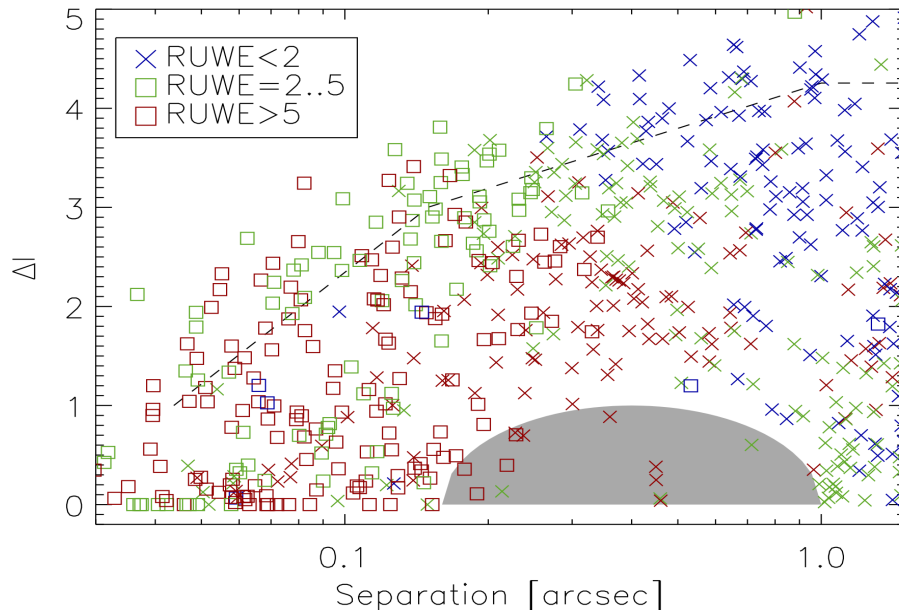
- TIC 168789840 (Powell et al. 2021 AJ 161, 162): periods of A,B,C: 1.6, 1.3, 8.2 days, similar masses, $q \sim 0.6$.
- V994 Her (Zasche et al. 2023 MNRAS 520, 3127): periods 2.08, 1.42, 1.96 days, AB: $P \sim 3$ yr, planar
- All mass ratios above 0.5, all primaries between 1 and $2.8 M_{\text{sun}}$, outer separations > 100 au.



Challenge to theory!

Better multiplicity statistics within 100 pc

- Gaia DR3: resolved companions >100 au, astrometric and spectroscopic orbits, accelerations, var. RV, semi-resolved
- Complemented by speckle survey (2023 AJ 165, 180): 1200 candidate triples observed, ~500 subsystems resolved
- Visual binaries are still missing from Gaia

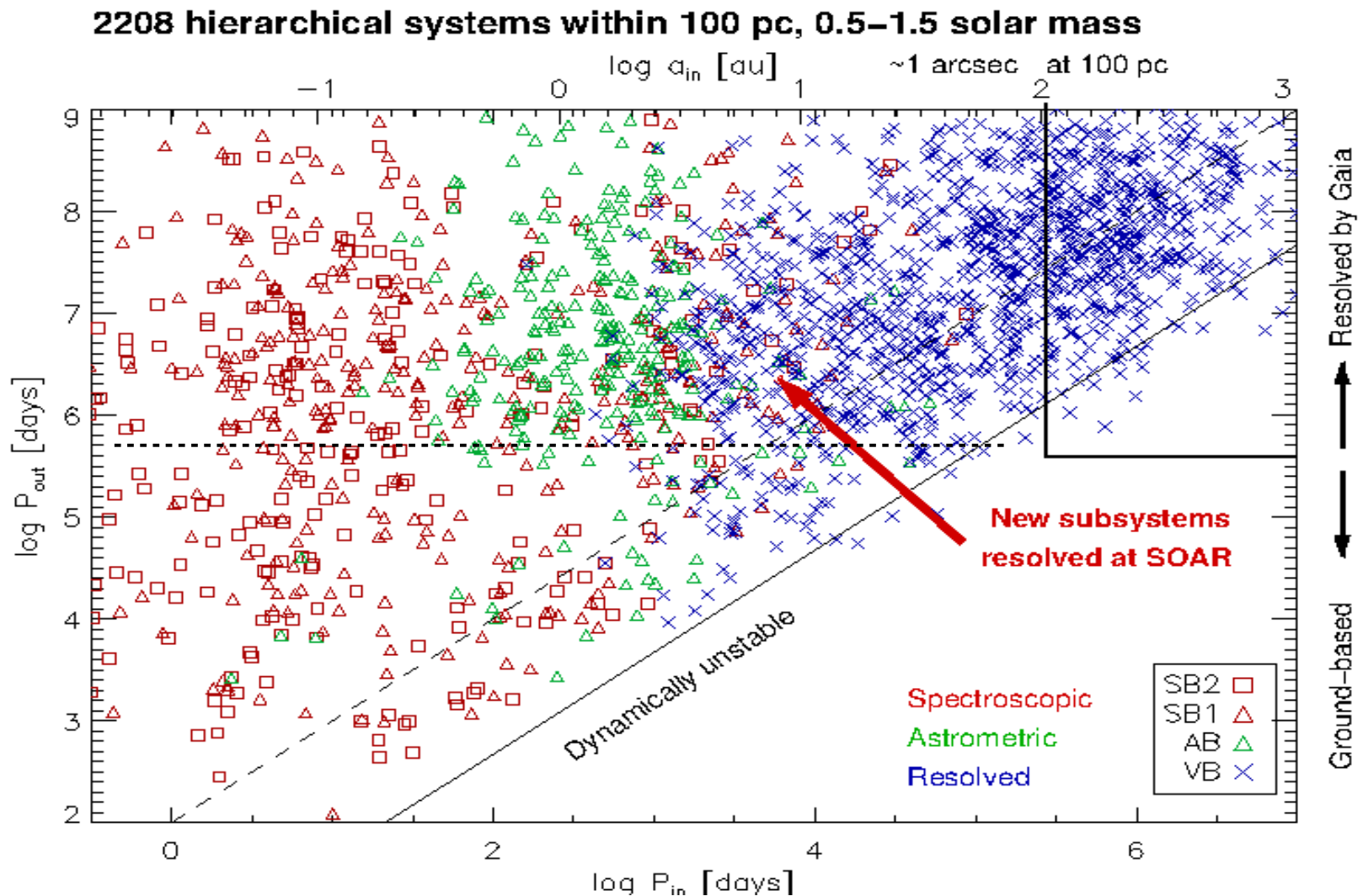


RUWE > 2: astrometric

FDBL > 2: resolved

Periods and mass ratios
remain unknown

Period-period plot



Selection-dominated, $\sim 25\%$ complete

Aug 3, 2023

20

Are triples co-planar?

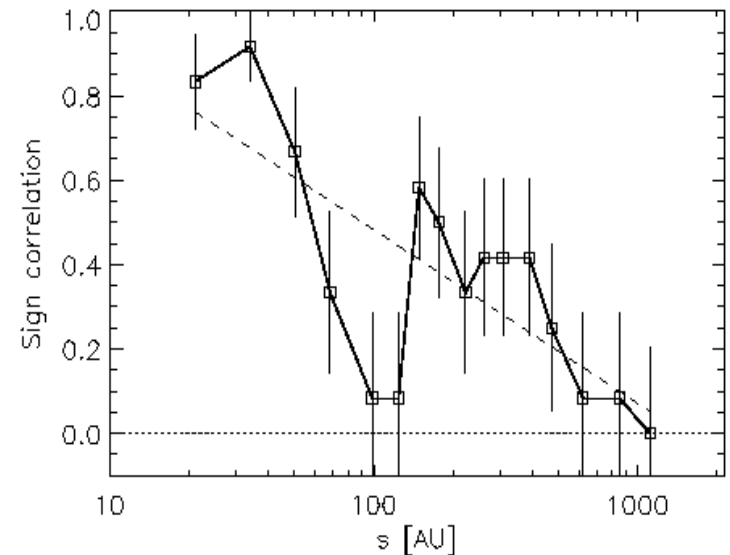
- Generally, not. Misaligned orbits → KCTF!
- Strong alignment for $a_{\text{out}} < 50$ AU. Average mutual inclination $i \sim 30^\circ$.
- No alignment for $a_{\text{out}} > 1000$ AU.

Borkovits+ 2016 MNRAS, 455, 4136:
close triples are aligned

Not enough misaligned triples for KCTF

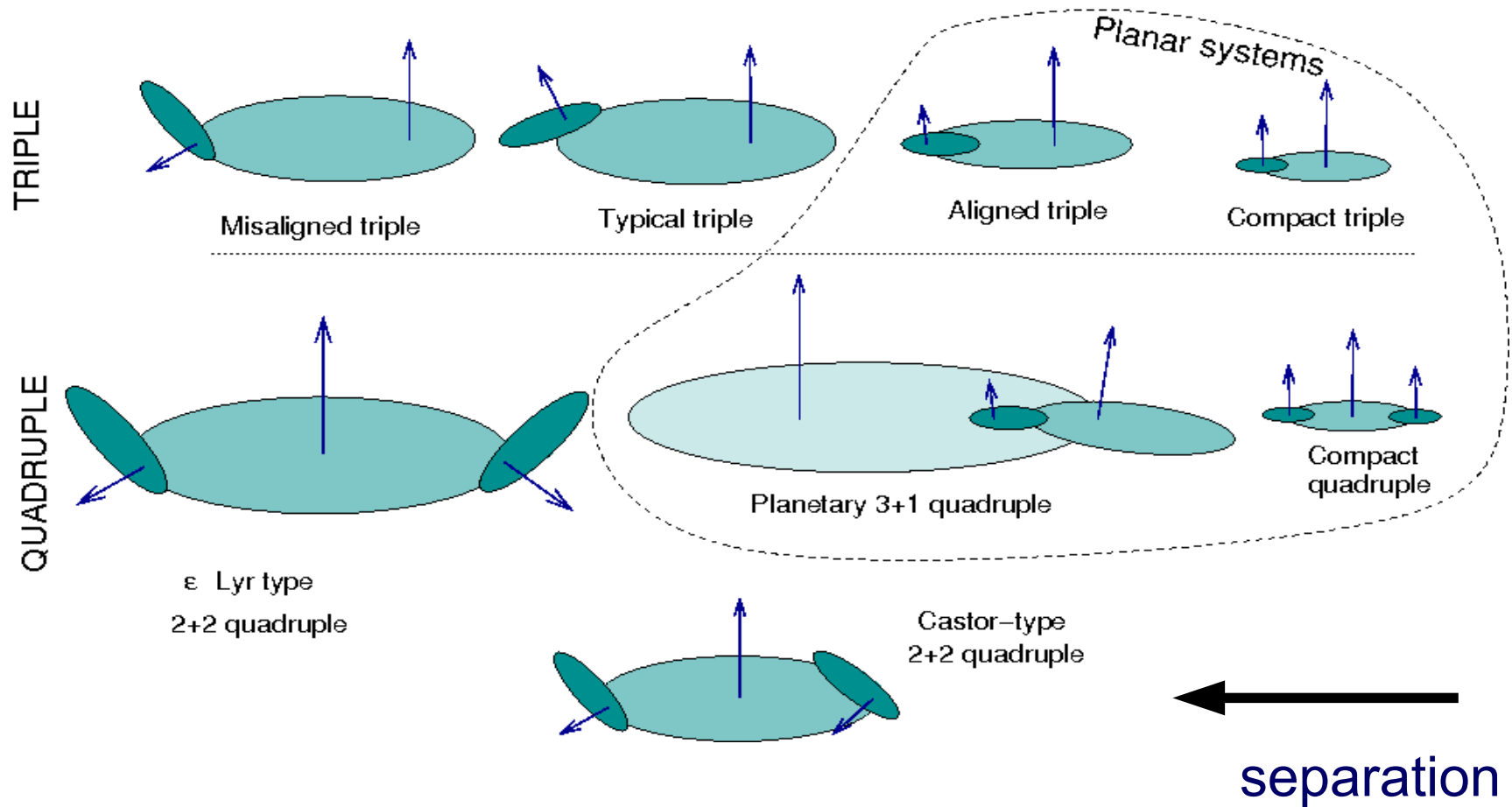
Less alignment in massive triples?

Aligned triples:
less eccentric
inner orbits



2017, ApJ, 844, 103

Classification of hierarchical systems (welcome to the Zoo)



Review: 2021, Universe, 7, 352

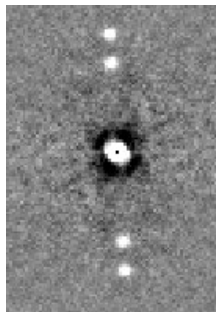
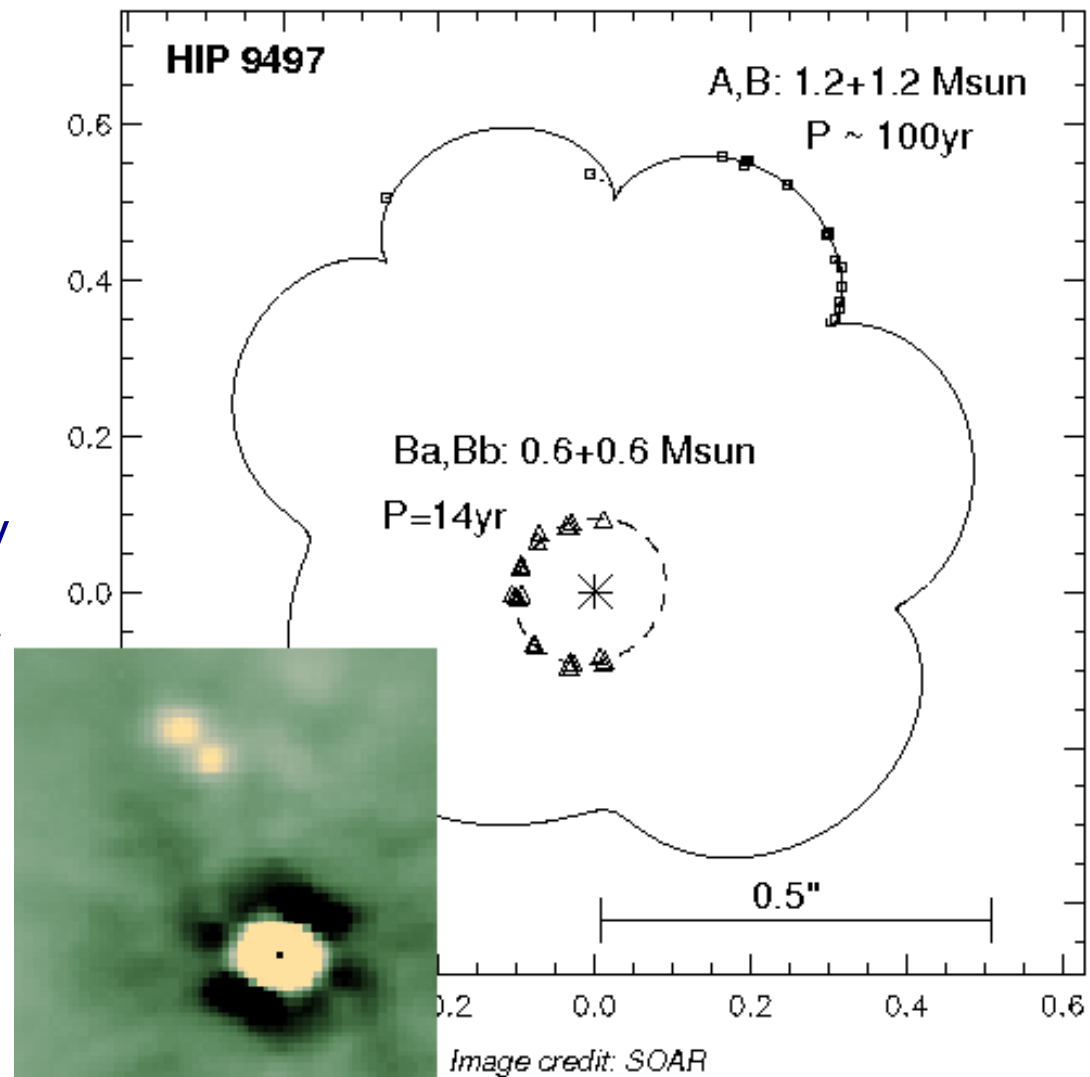
Aug 3, 2023

Dancing twins

Low-mass triples where an inner pair of equal-mass stars is paired to the tertiary as massive as the inner pair.

A-(BC), with a moderate period/separation ratio, near-circular orbits.

Resonance?



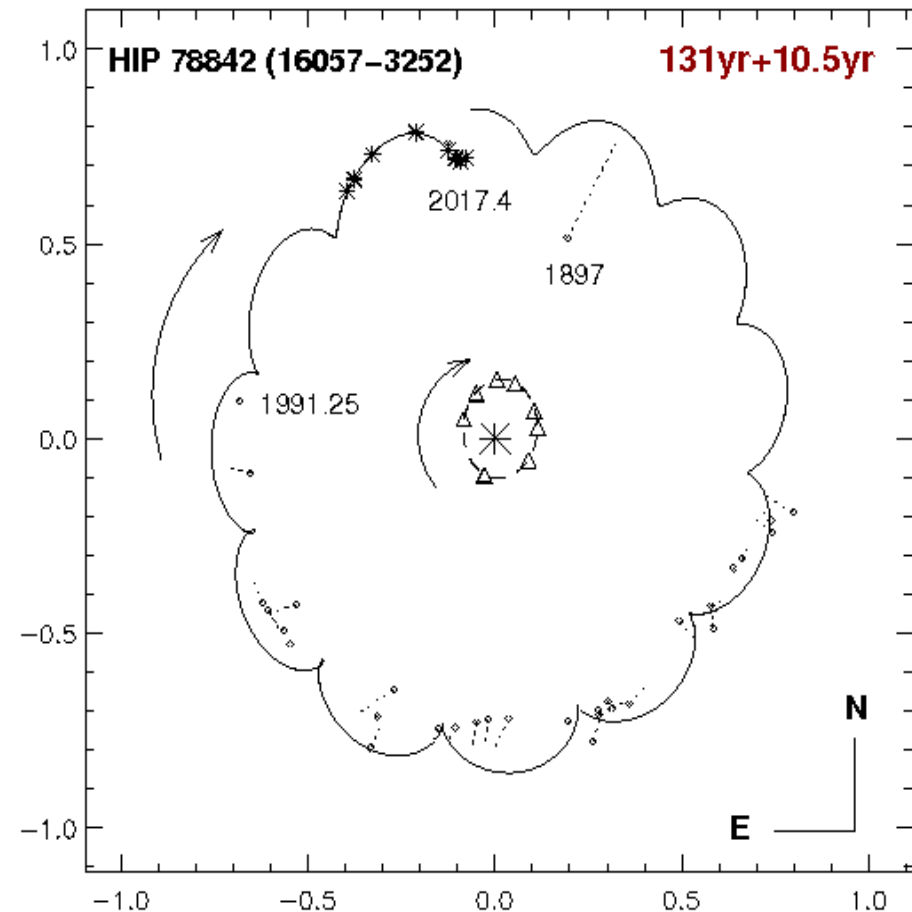
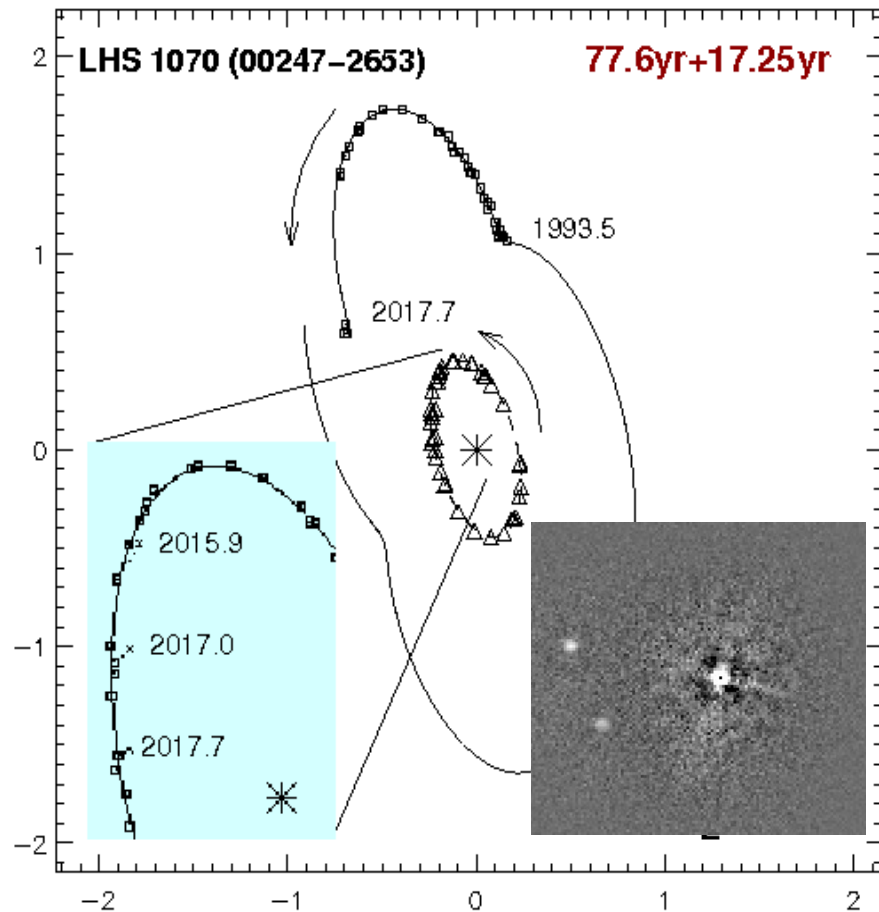
Several more candidates,
but life is short...

2018 AJ, 155, 160

23

Apr 2020

More dancing twins...

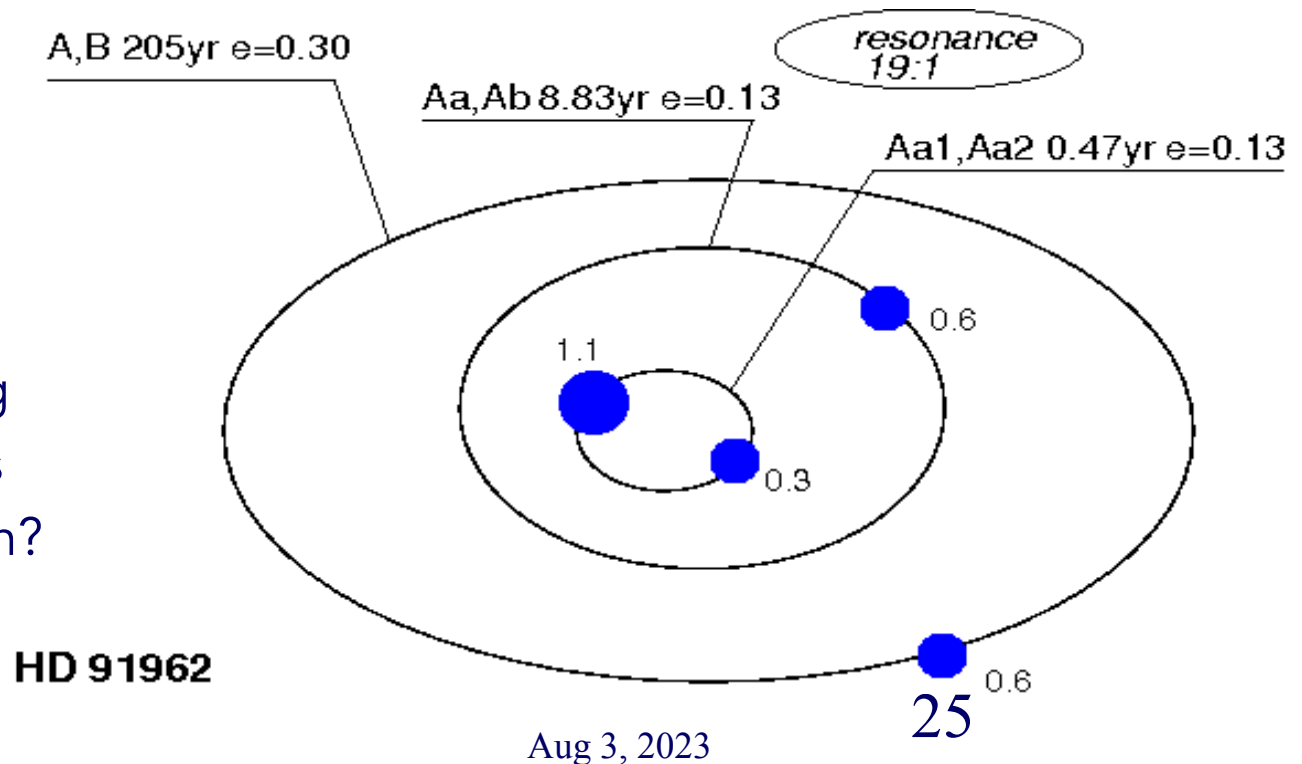


B,C: 0.07 solar mass each
9:2 resonance?

"Planetary" 3+1 hierarchies: product of migration?

- Resemble solar system
- Co-planar to within 30° , mildly eccentric orbits
- Moderate period ratios (~ 20), resonances?

Companions formed too soon, preventing growth of inner pairs and further migration?

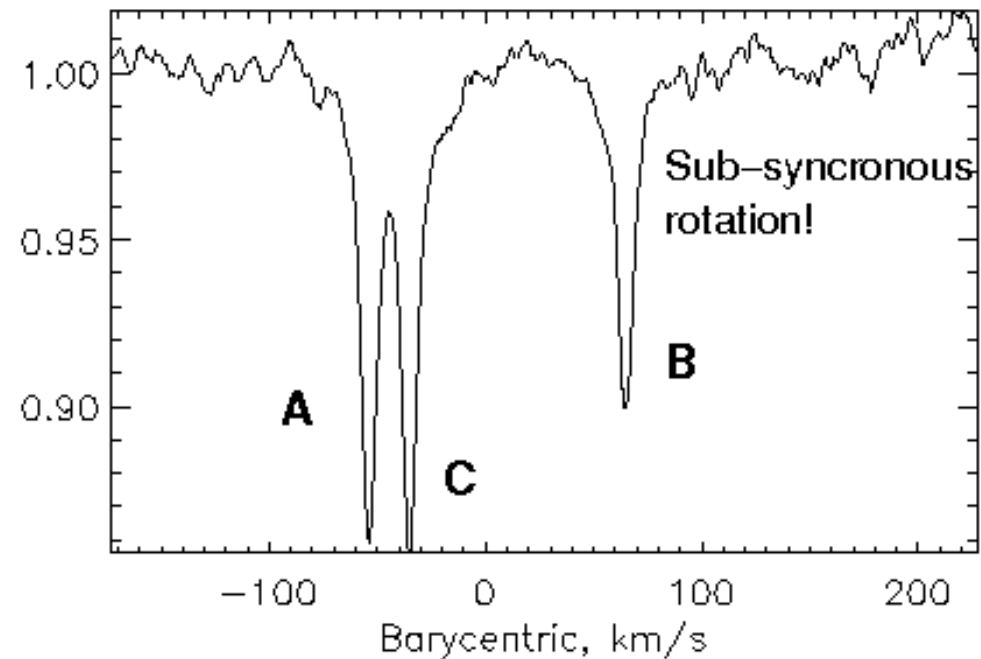
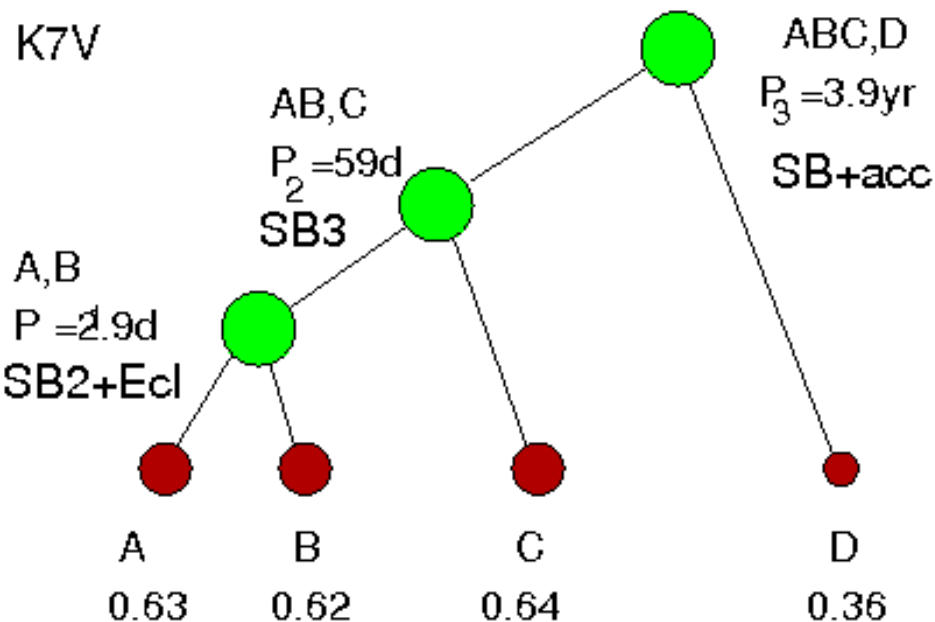


HIP 41431 (Borkovits et al., 2019, MNRAS, 487, 4631)

HIP 41431 (GJ 307)

plx 20.06 mas (DR2)

K7V

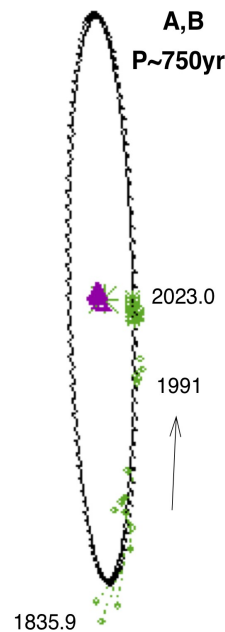
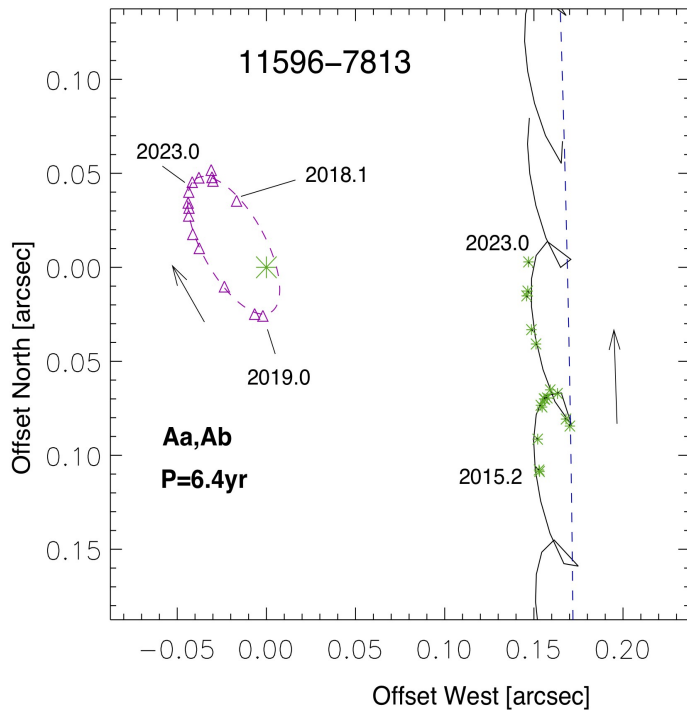


Strong dynamical interaction between orbits
All nearly co-planar!

Tight “planetary” 3+1 quadruple and a “triplet”

Triplets

- Three stars of similar masses
- Misaligned, eccentric orbits, often comparable separations



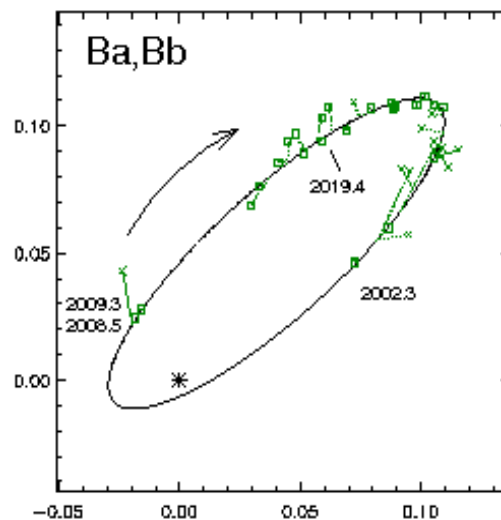
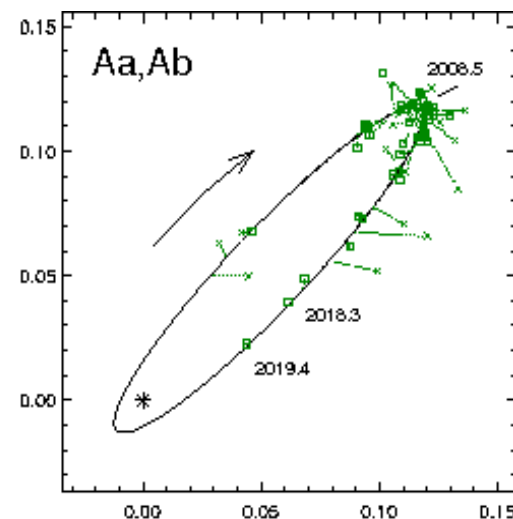
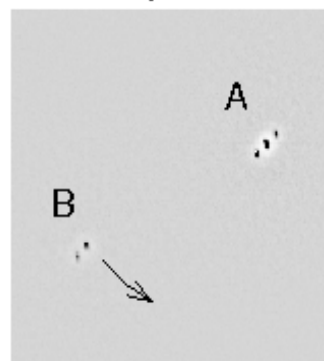
ϵ Cha: three B-type stars, 6.4yr+~750yr
5 Myr old

A decayed 2+2 quadruple?

The tweedles (FIN 332)

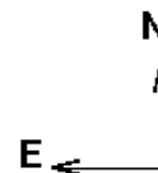
- 2+2 quadruple of “ ϵ Lyr” type
- 4 x A1V at 213pc
- 27.6 + 40 yr, $e=0.8$
- Remarkable alignment of inner orbits
- Outer orbit is mis-aligned

AB: PA=120deg
Sep.=2.5"



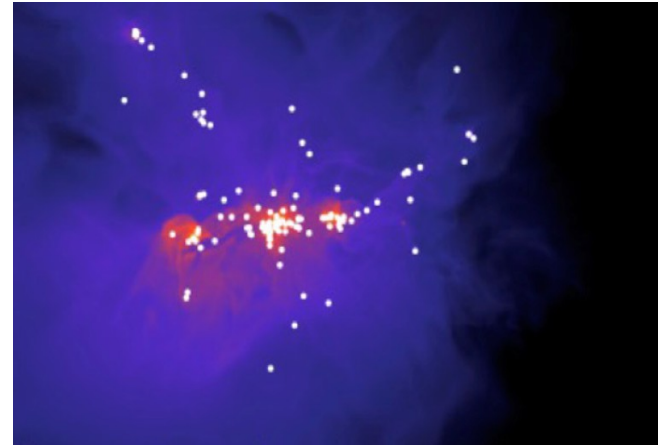
$P=27.62\text{yr}$
 $e=0.82$
 $W=136.1$
 $i=107.9$

$P=39.77\text{yr}$
 $e=0.84$
 $W=119.3$
 $i=106.9$



Formation mechanisms and evolution

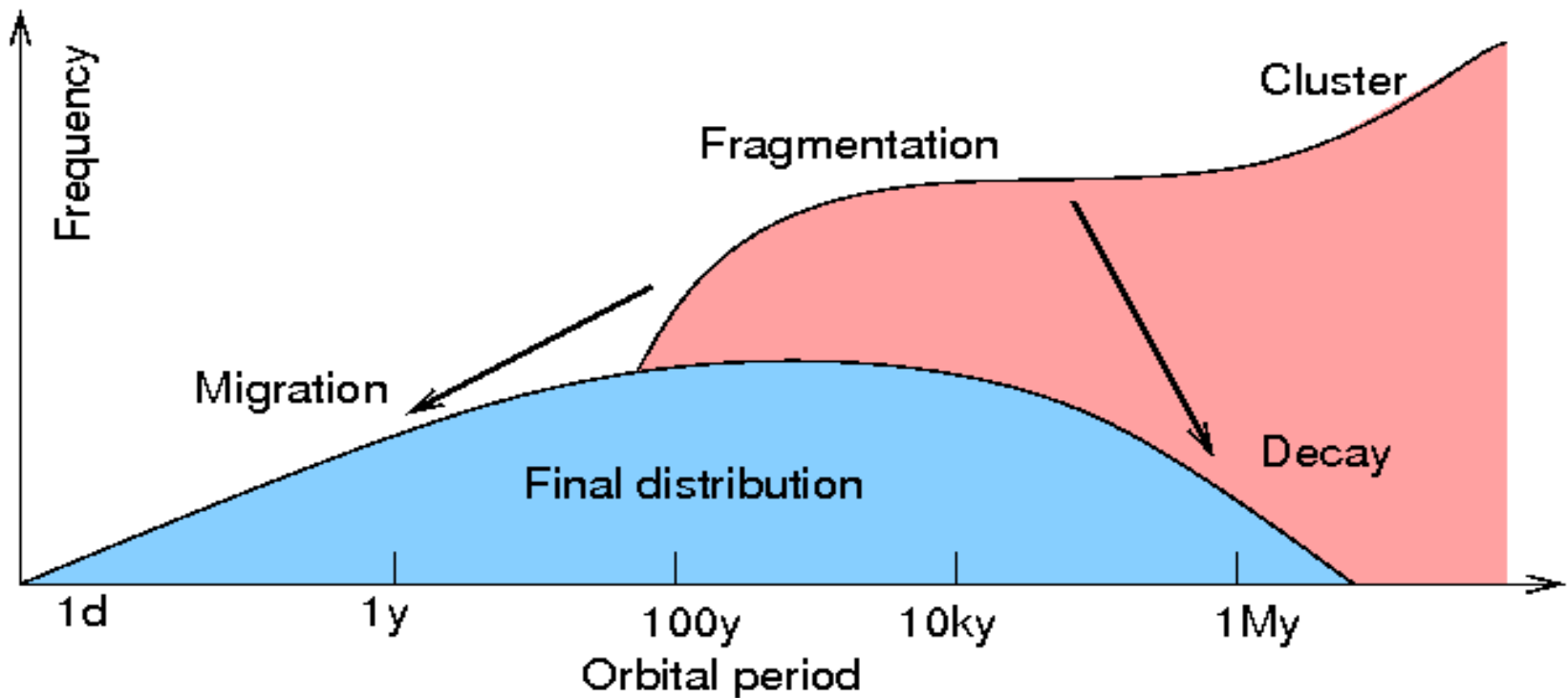
- Disk fragmentation
- Core fragmentation
- Dissipative capture



- Migration & accretion
- Small-N dynamics
- Cluster dynamics

Populations of
binaries & multiples

Formation: the big picture



Summary

- Statistics of hierarchical systems are incomplete, dominated by selection even in our neighborhood
- Architecture is very diverse, suggesting several formation channels or scenarios
- Emerging classification into “families”; the combined statistics may be misleading
- A rapidly developing field, stimulated by space missions (Gaia, TESS). Ground-based observations are essential
- Expected contribution to star formation

Thank you!