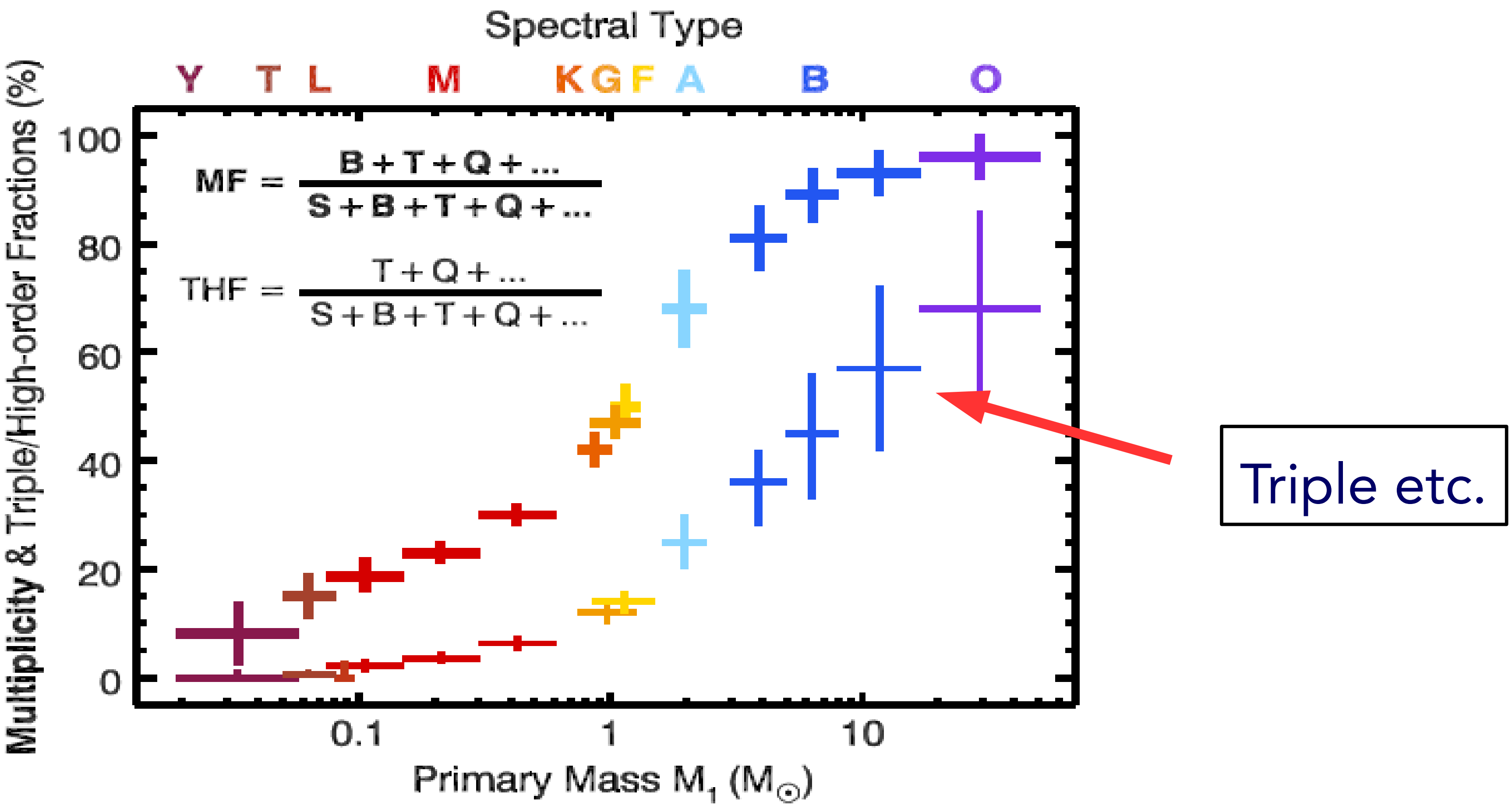
# Populations of Hierarchical Systems

**Andrei Tokovinin,** ***CTIO/NOIRLab***

- Context: single, binary, triple, etc.
- The concept of populations
- Formation processes and scenarios illustrated by examples
- Role of large surveys

**Multiple Star Catalog** (last: Jan 1, 2024)
https://www.ctio.noirlab.edu/~atokovin/stars

# Hierarchical stellar systems are frequent products of star formation

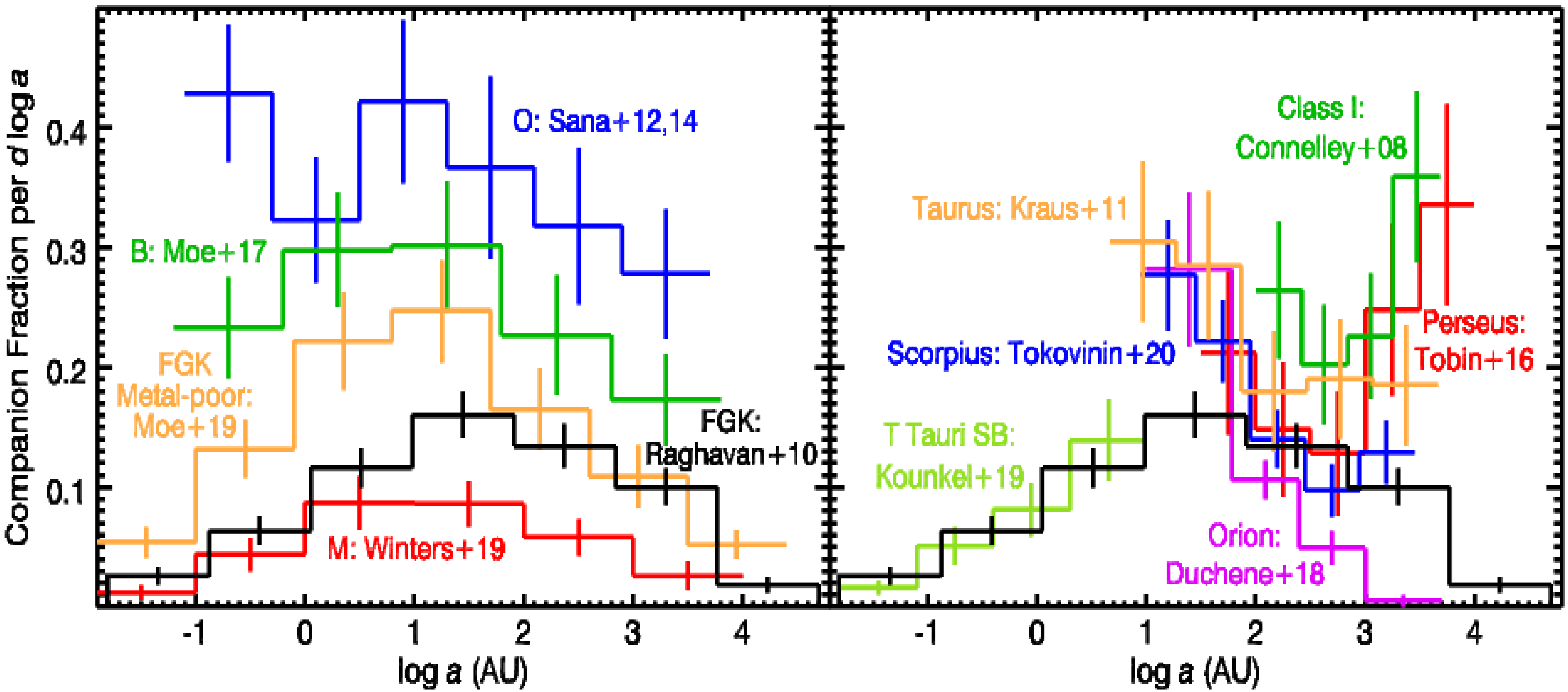



*Offner et al.2023, PPVII*

# Populations of binaries

- Field, solar-type (e.g. Raghavan et al. 2010): a well known population? No!
- Fraction of close binaries anti-correlates with metallicity (Badenes et al. 2019)
- Fraction of wide binaries depends on both metallicity and density of environment (Hwang, Deacon & Kraus)
- Binaries and hierarchies form via several channels (disk fragmentation, core fragmentation, capture), but the statistics is shaped by subsequent evolution (mostly by accretion). The field is a mixture of populations!

# Young binary populations vs. field




Old stars (field)

Young stars

*Offner et al. 2023 (PP VII)*

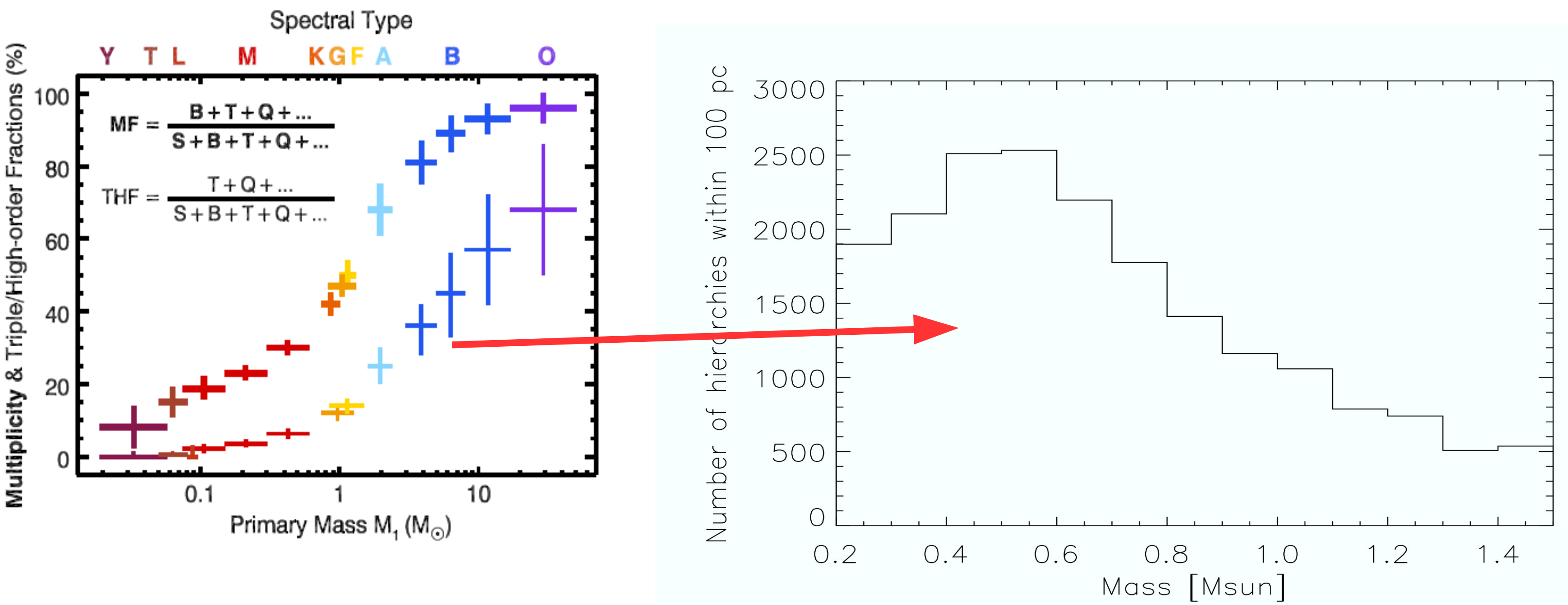
# Populations of hierarchies

- Hierarchies have more parameters, hence are more informative than binaries
- We hope to find a better connection between architecture and formation
- "Zoological" approach: empirically classify into families
- Propose formation scenarios (sequence of events)
- Rare hierarchies (e.g.with 5-7 stars) might give additional insights (find them in large surveys!)

"Families" are defined tentatively and subjectively

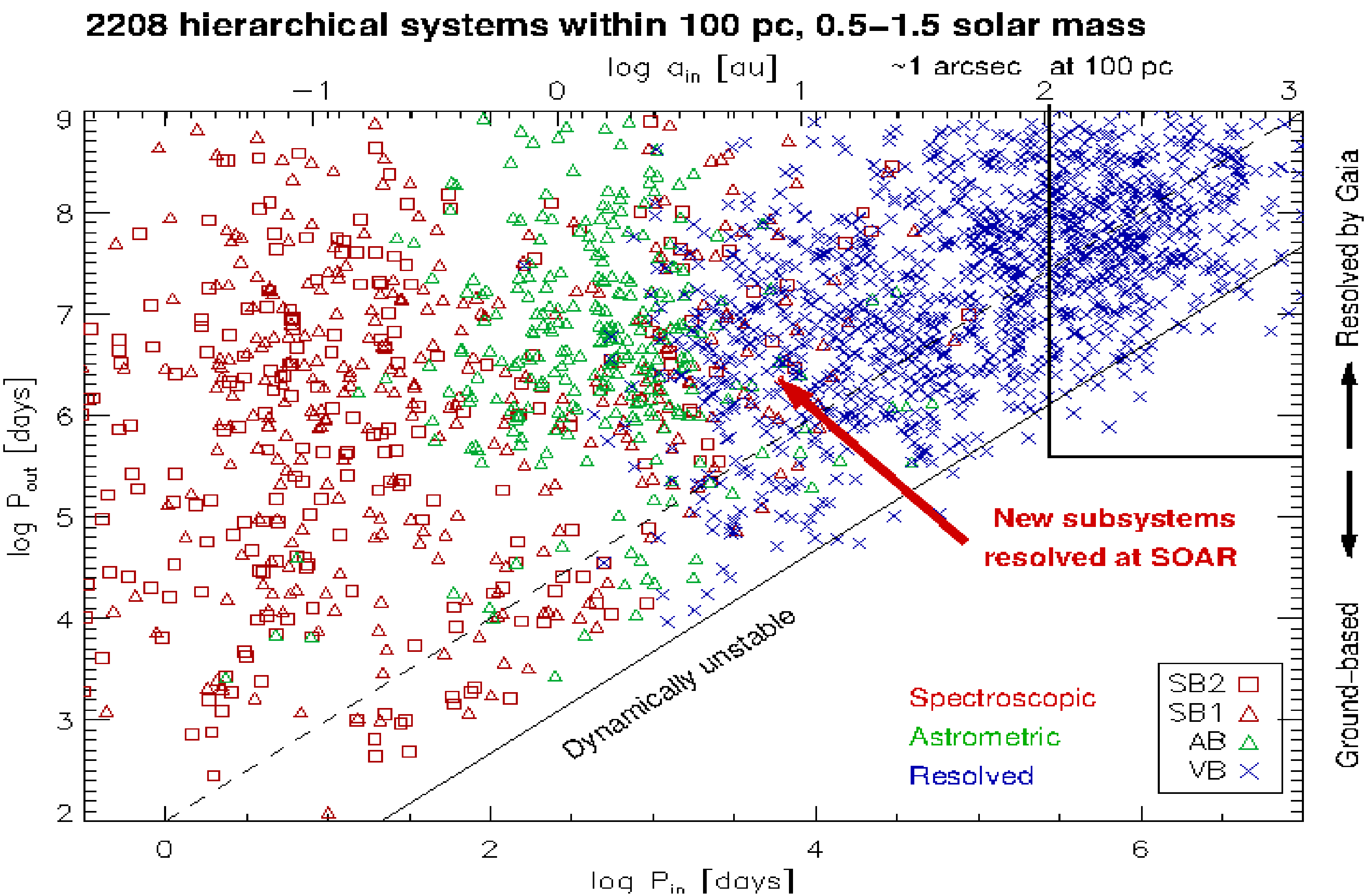
# Completeness

- Expected within 100 pc: ~10000 hierarchies >0.2 Msun, ~8000 >0.5 Msun
- Known (MSC): 2200 (mostly ~1 Msun), completeness ~25%



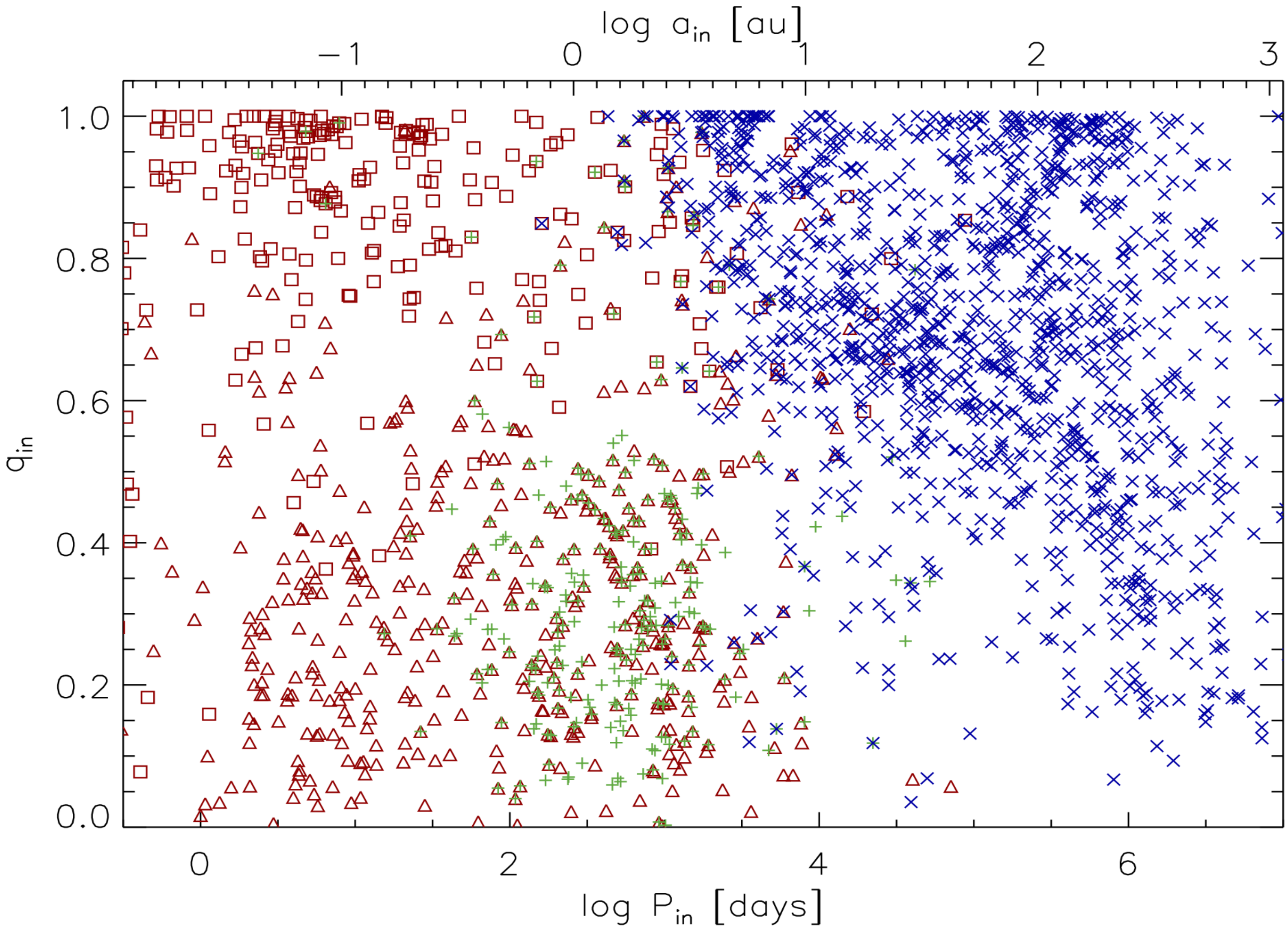

<25pc: 56 solar-mass hierarchies → 100x increase!

# Period-period plot




MSC is selection-dominated, ~25% complete

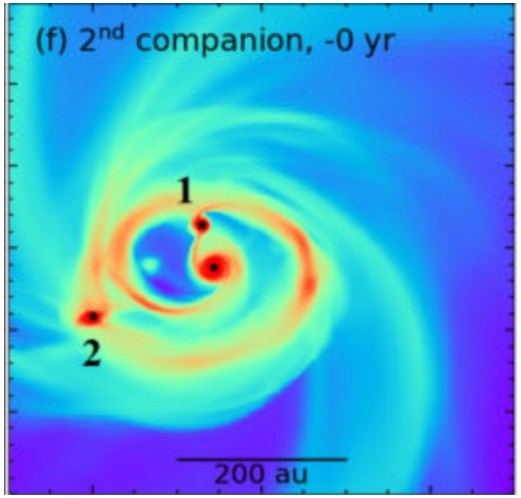
# Discovery techniques: inner pairs



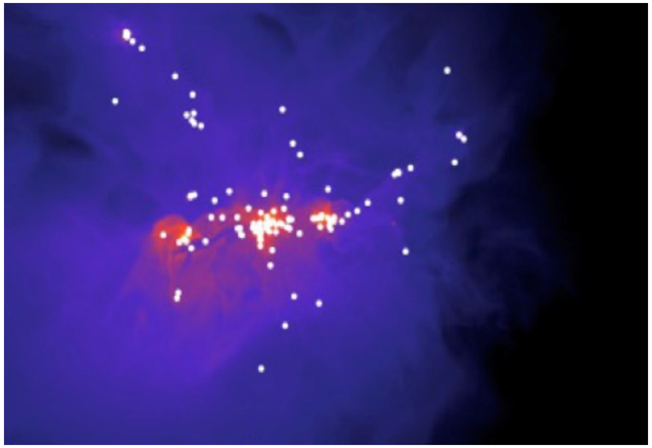
# Formation of hierarchies

- 1. N-body dynamics (cluster-like)
- 2. Dynamics + tides (Kozai-Lidov)
- 3. Disk fragmentation and accretion (inside-out)
- 4. Core fragmentation
- 5. Dissipative capture (outside-in)

**Formation scenario =** sequence of events.
Proposed scenarios are speculative!



# Formation + evolution = statistics



- Disk fragmentation
- Core fragmentation
- Filament fragmentation
- Dissipative capture

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

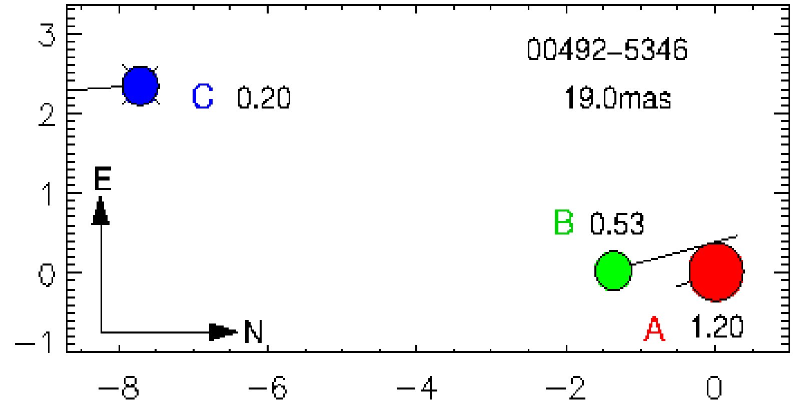
Populations of
binaries & multiples

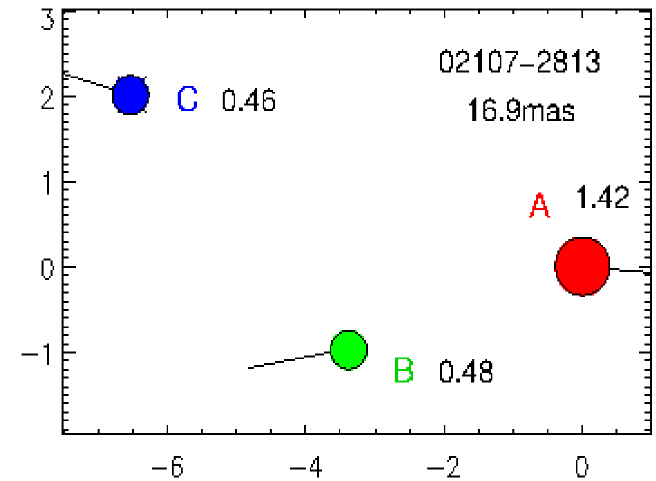
# 1. N-body dynamics

- Encounters in a cluster or between binaries can produce triples. Only gravity matters (stars as point masses)
- Predictions: moderate period ratios, misaligned and eccentric orbits, f(e)=2e (Antognini, Leighton)
- Likely operates on large scales ($10^3$-$10^4$ au), on the order of mean distance between stars

# Gaia: wide triples within 100pc

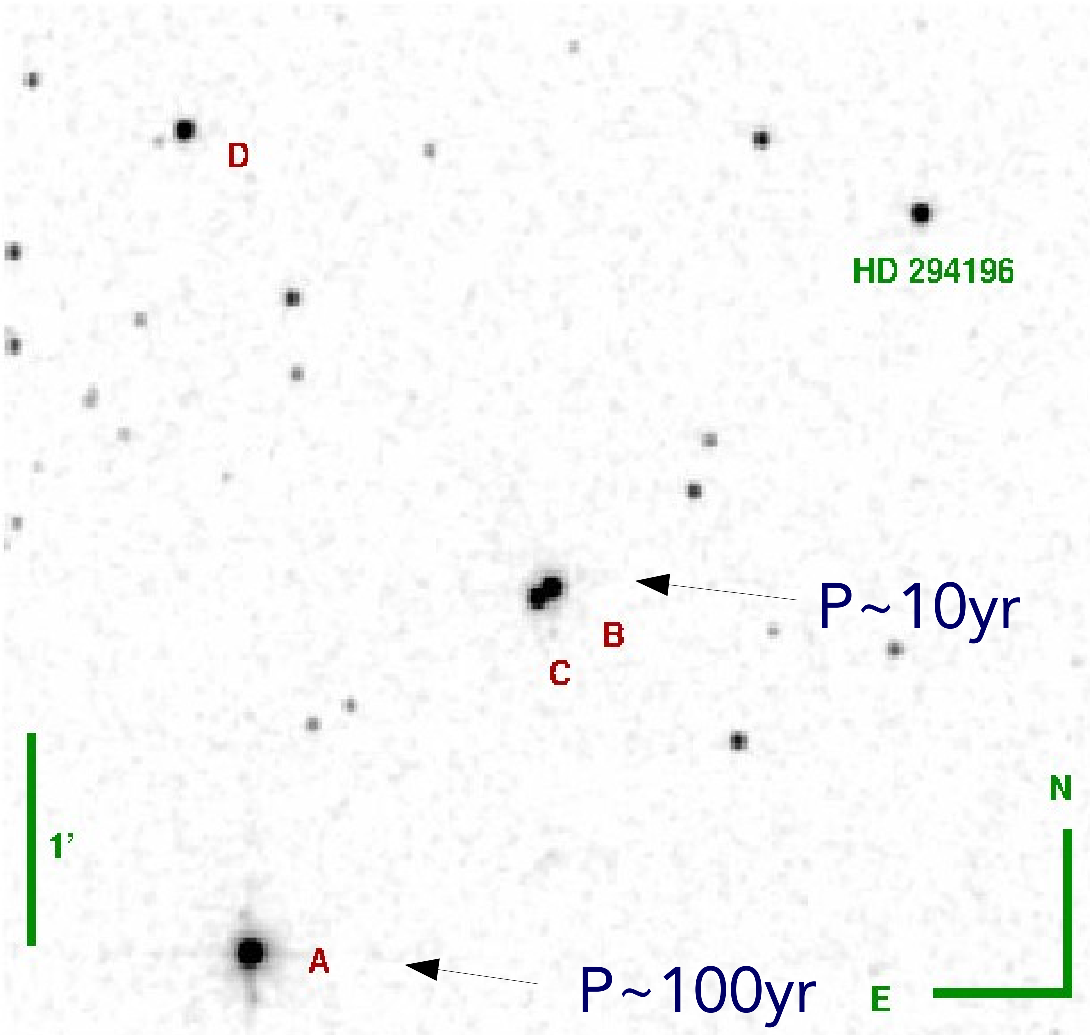
- 392 hierarchies within 100pc
- Separations 100au, ~3kau, known relative motions
- Median separation ratio 14, marginal stability
- No mutual alignment
- f(e): near-thermal inner, e~0.5 outer (as expected)
- More massive than average
- Inner twins:  21%
- Products of core collapse?




2022 ApJ 926, 1

# V1113 Ori: unstable mini-cluster?




ABCD: M dwarfs @39pc

Non-hierarchical

Separations ~10kau

Two close binaries

Age ~24Myr, PMS

2022 AJ 163, 127

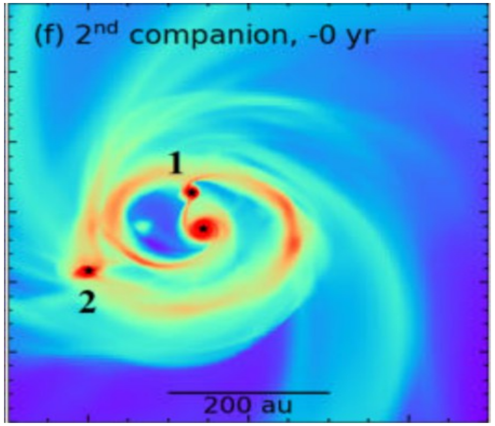
# 2. Dynamics + tides

- Kozai-Lidov cycles in a misaligned triple → increase inner eccentricity → tidal interaction at periastron, formation of a close inner binary
- Tidal interaction is most efficient at PMS stage (stars are bigger)
- Cannot explain the majority of triples (Moe, Kratter 2018), only a fraction. Predictions do not match the statistics (no excess of mutual inclinations near 40 or 140 deg, no pile-up at P~10days).
- Can work slowly in a 3+1 quadruple (cascade K-L).

Eclipsing binary + wide companion → 3+1 triple?
(Powell et al. 2023 MNRAS 524, 4296: TESS+Gaia+speckle)

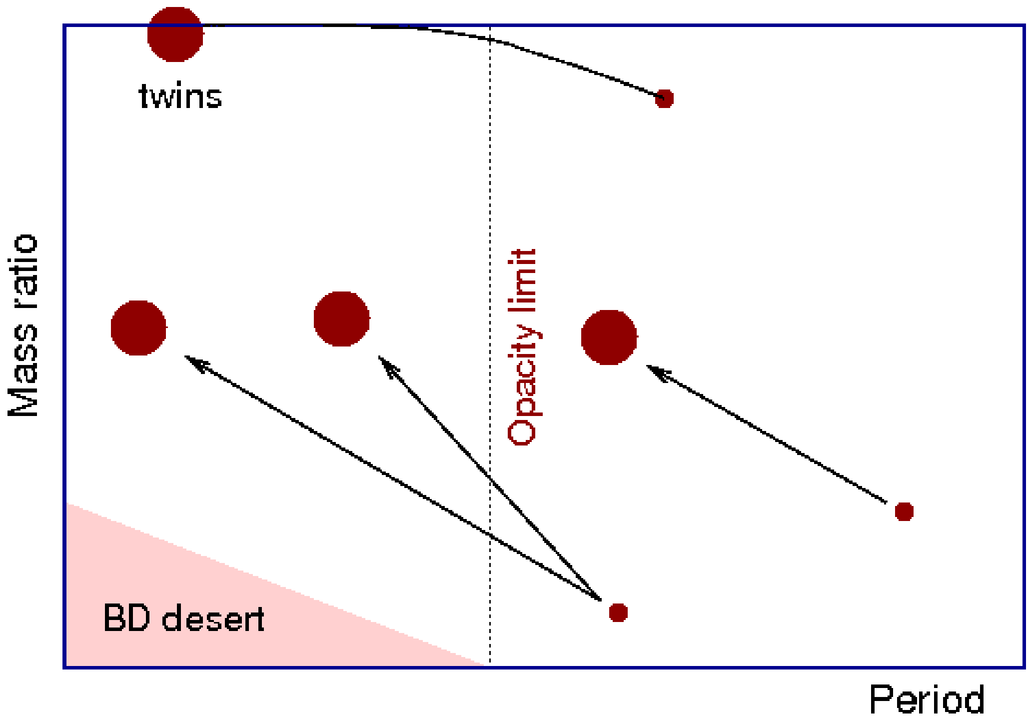
# 3. Disk fragmentation + accretion

- Companions form in accretion disk at random moments (accretion bursts), continue to grow in mass and migrate to shorter periods
- Outer companion forms later (inside-out), likely coplanar with the inner binary. If accretion continues, it becomes the new primary (a double twin).
- Disk fragmentation is more likely for massive stars




Tu el al. 2024, MNRAS 532, 3135: formation of misaligned triples by disk fragmentation

# Accretion-driven migration




1. Pulsed accretion
2. Companions forms at random time
3. Secondary grows faster

Tokovinin, Moe
2020 MNRAS, 491, 5158

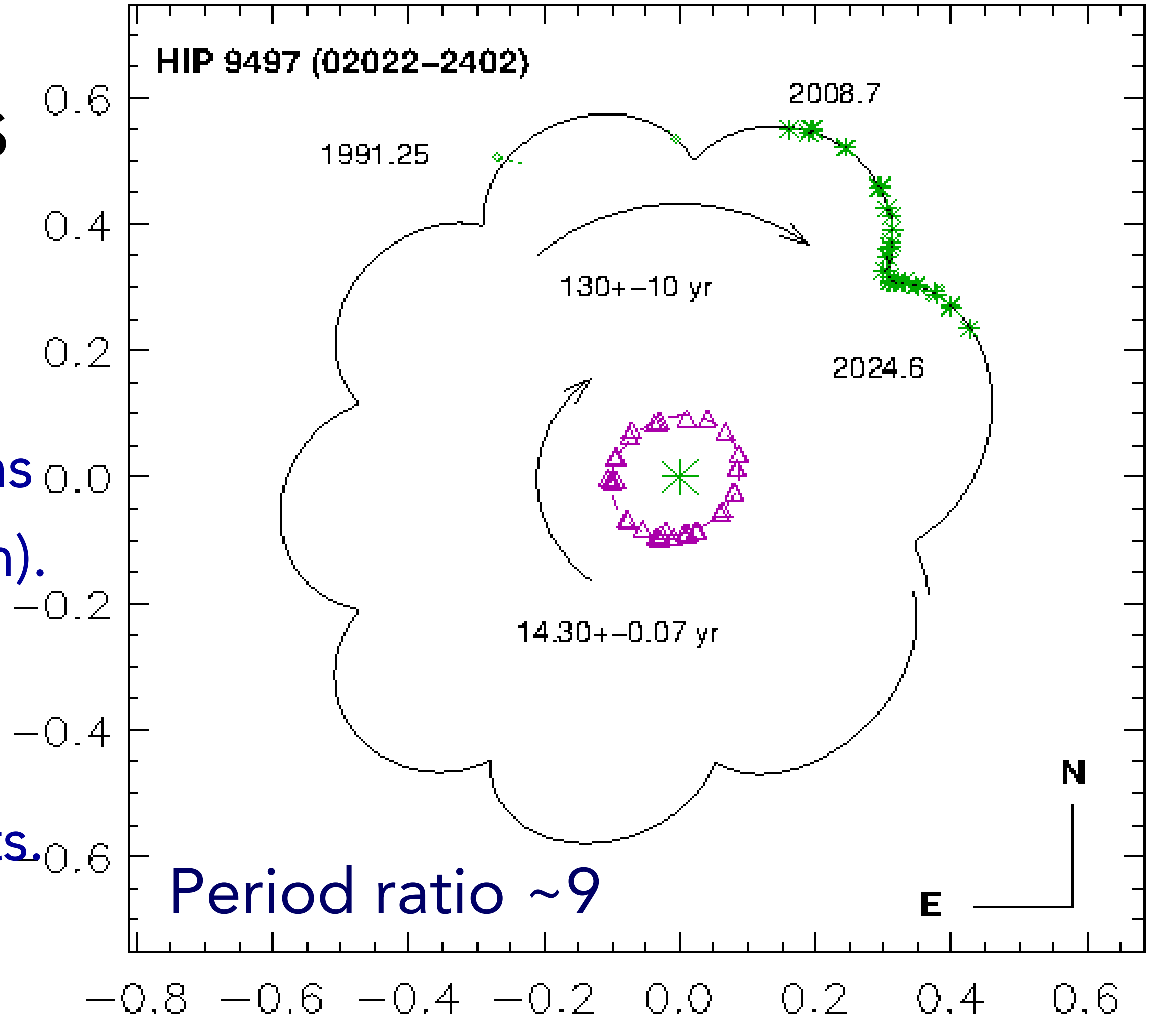
Predictions: approximate coplanarity, moderate eccentricities, inner twins

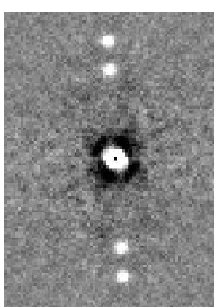
# Dancing twins

Low-mass triples: an inner pair of equal-mass stars and a tertiary as massive as the inner pair (double twin).

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

Resonance?

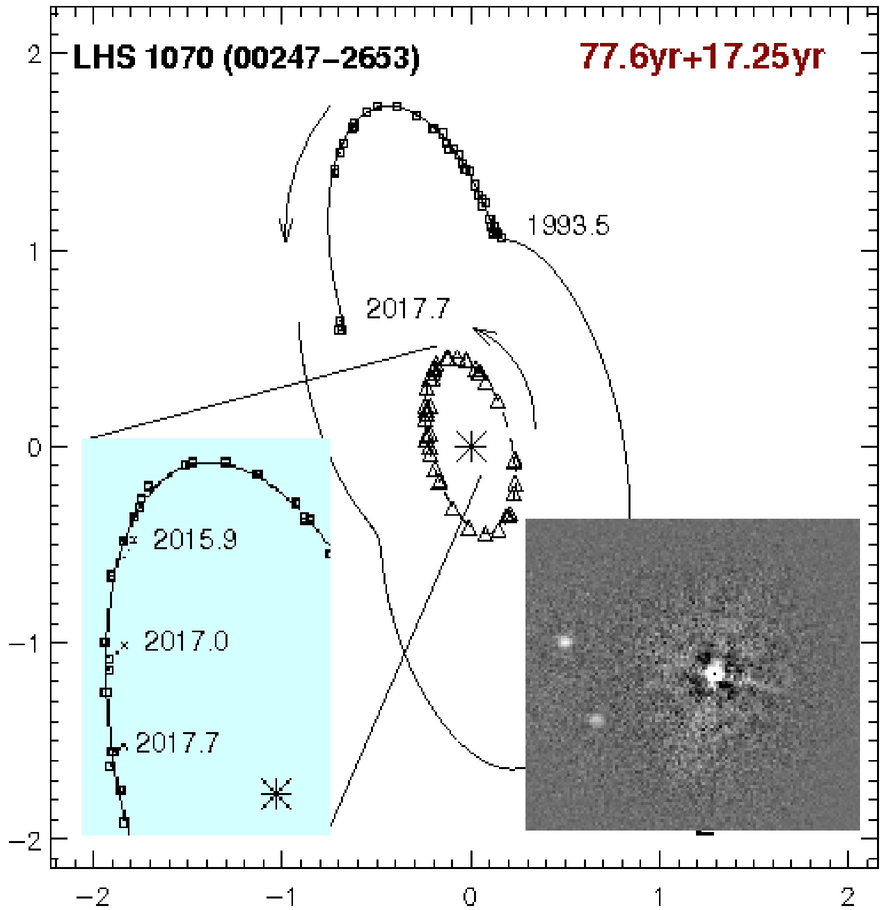


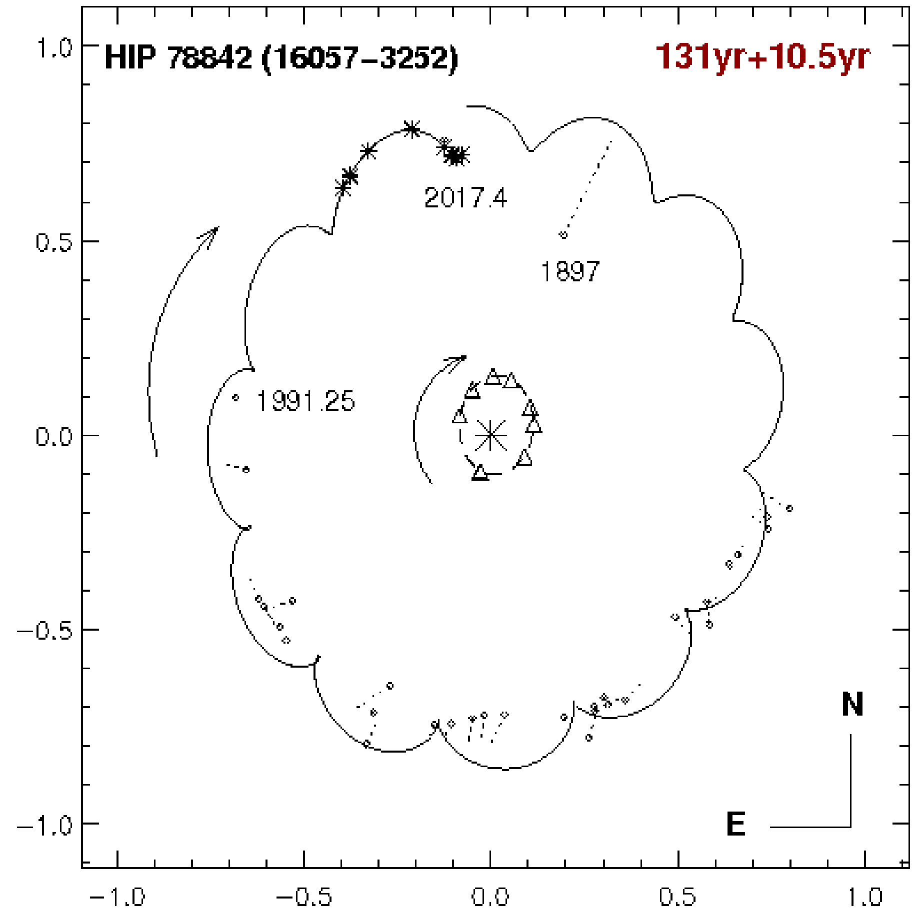



Several candidates, but life is short...

*2018 AJ, 155, 160*

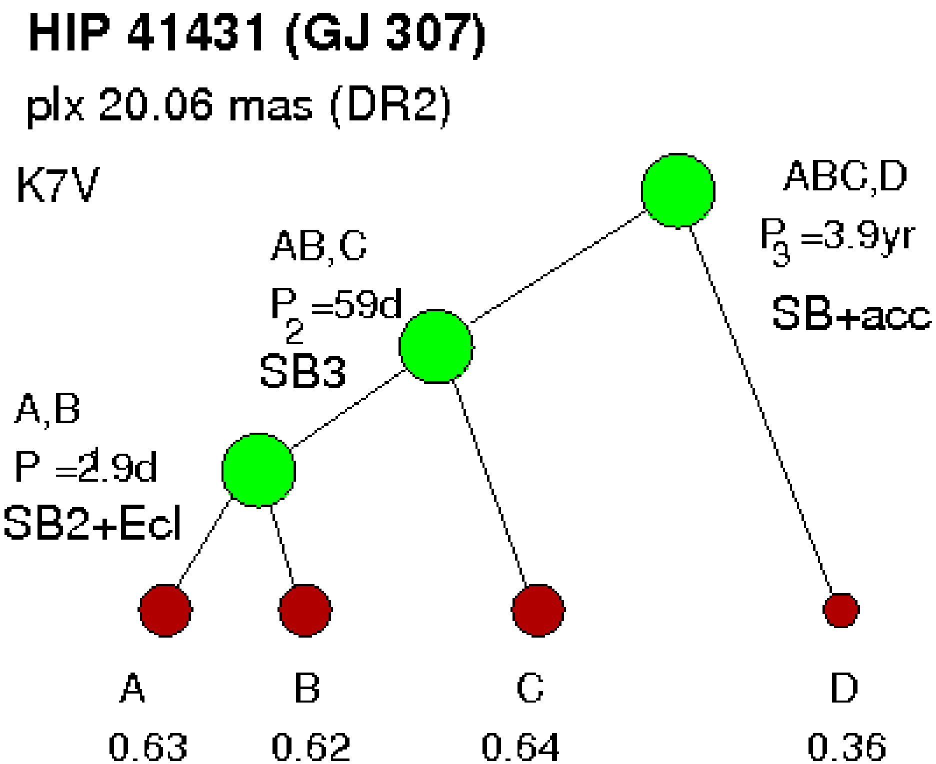
# More dancing twins…

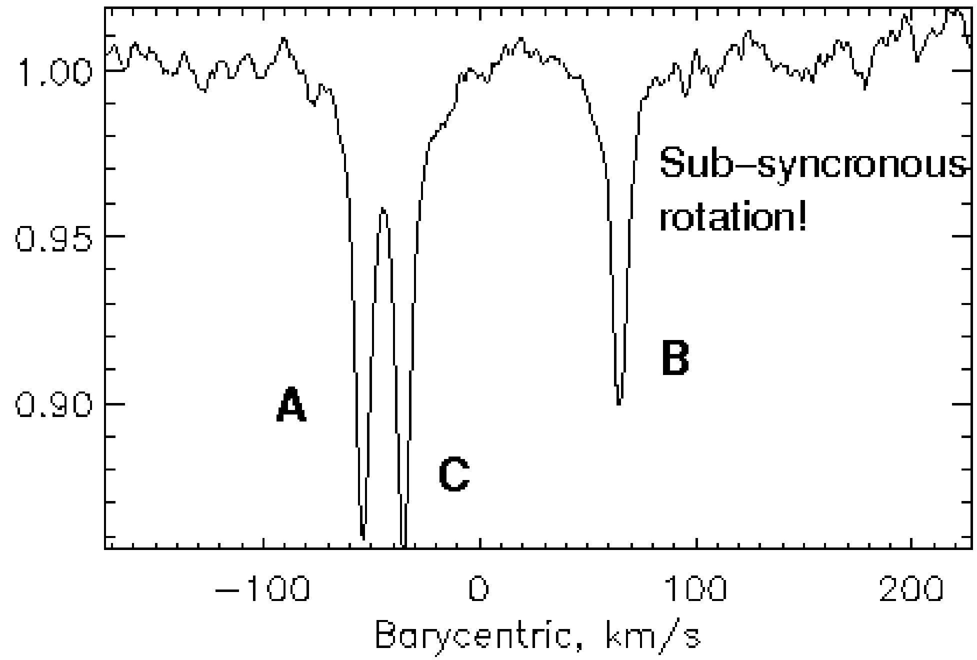



B,C: 0.07 solar mass each
9:2 resonance?

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



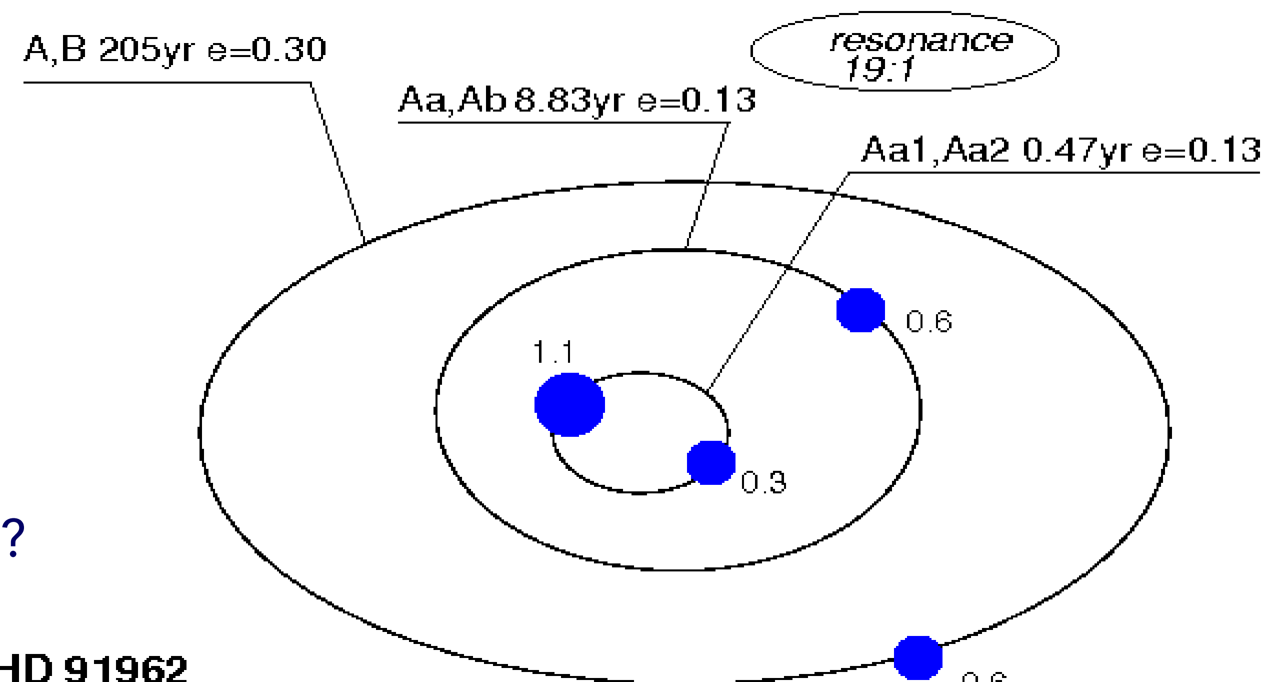

Strong dynamical interaction between orbits
All nearly co−planar!

Compact “planetary” 3+1 quadruple

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

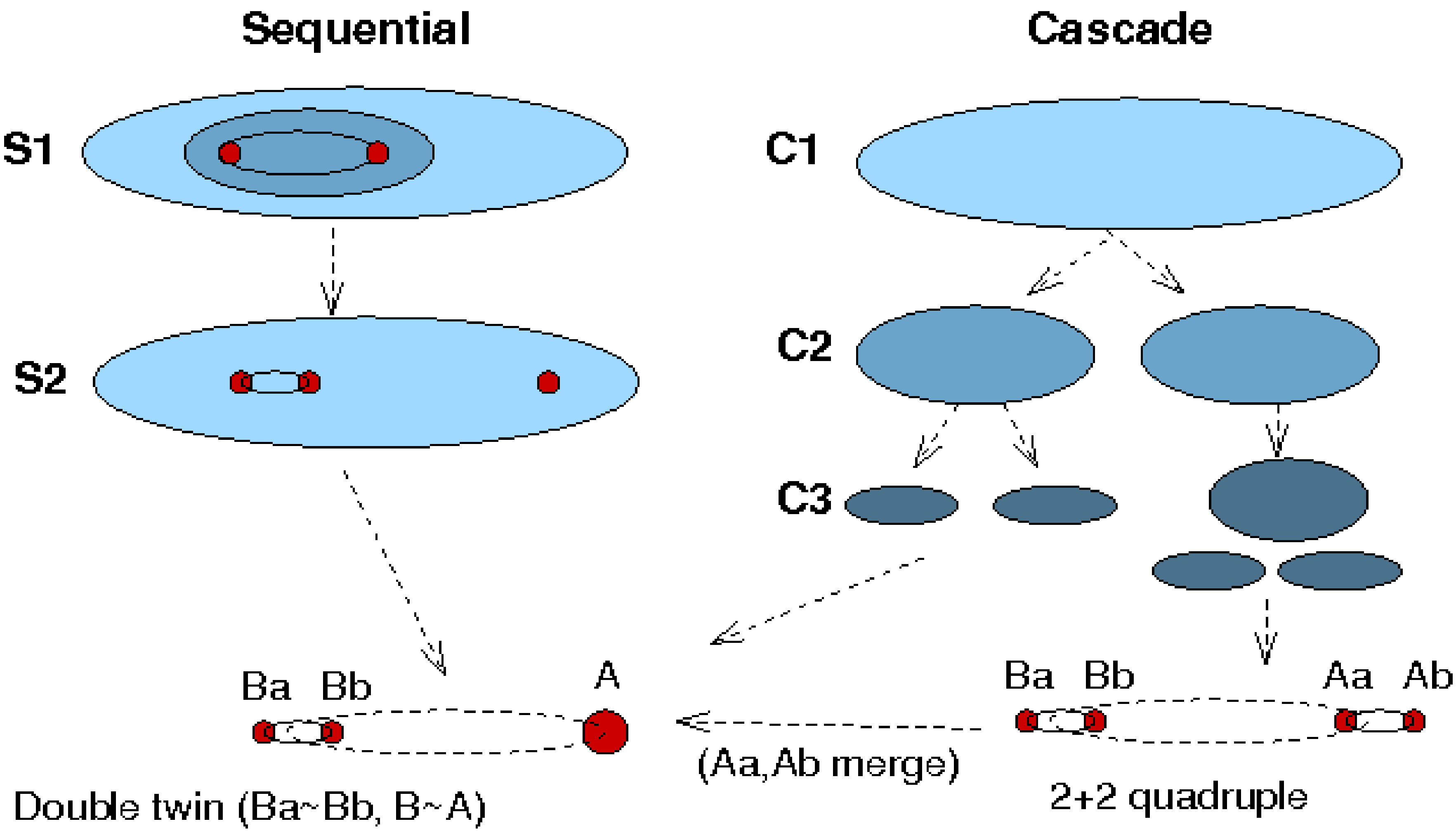
- Resemble solar system
- Co-planar to within 30°, mildly eccentric orbits
- Moderate period ratios (~20), resonances?

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




HD 91962

# Double twins: sequential or cascade?

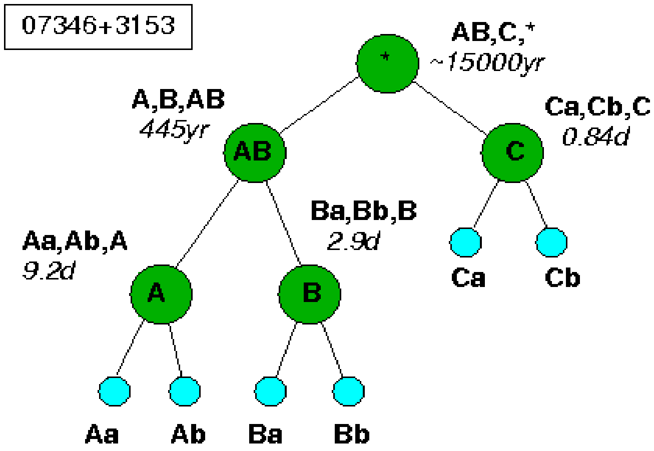


# Doubly eclipsing 2+2 quadruples

- Catalogs based on OGLE (Zache et al. 2022), TESS (Kostov et al. 2022, 2024), ZTF (Vaessen et al. 2023)
- Some 2+2 systems are compact and planar:
  - VW Lmi: $P_{out}$ ~1 yr Pribulla et al. 2020
  - TIC 219006971: $P_{out}$ = 168d (Kostov et al. 2023)
  - BU CMi: $P_{out}$ = 120d (Zasche et al. 2023)
- Comparable masses of all 4 stars (q~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~0.6.
- V994 Her (Zasche et al. 2023 MNRAS 520, 3127): periods 2.08, 1.42, 1.96 days, AB: P~3 yr, planar
- All mass ratios above 0.5, all primaries between 1 and 2.8 $M_{sun}$, outer separations >100 au.

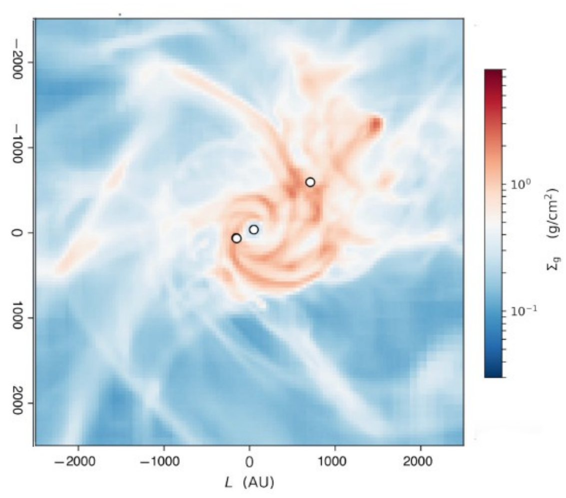


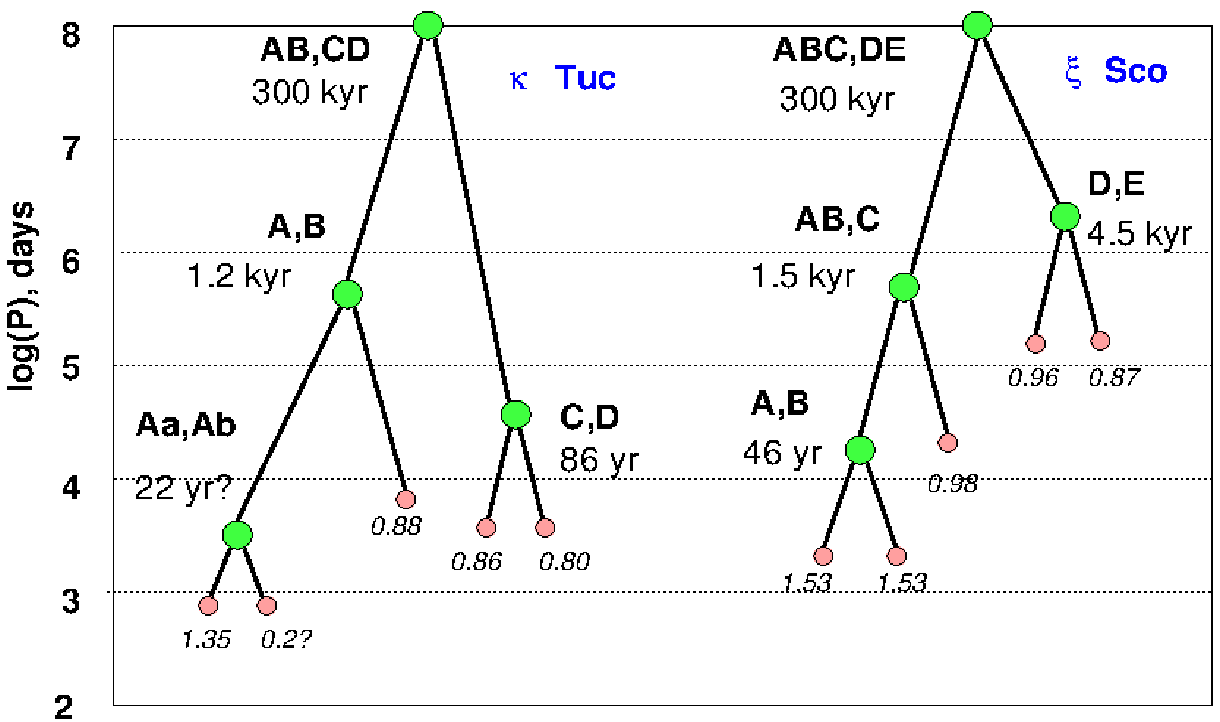

Challenge to the theory!

**Castor**: similar hierarchy but misaligned, small inner mass ratios

# 4. Core or filament fragmentation

- Large-scale N-body system with gas
- Chaotic dynamical interactions between stars and gas
- Continued accretion and migration

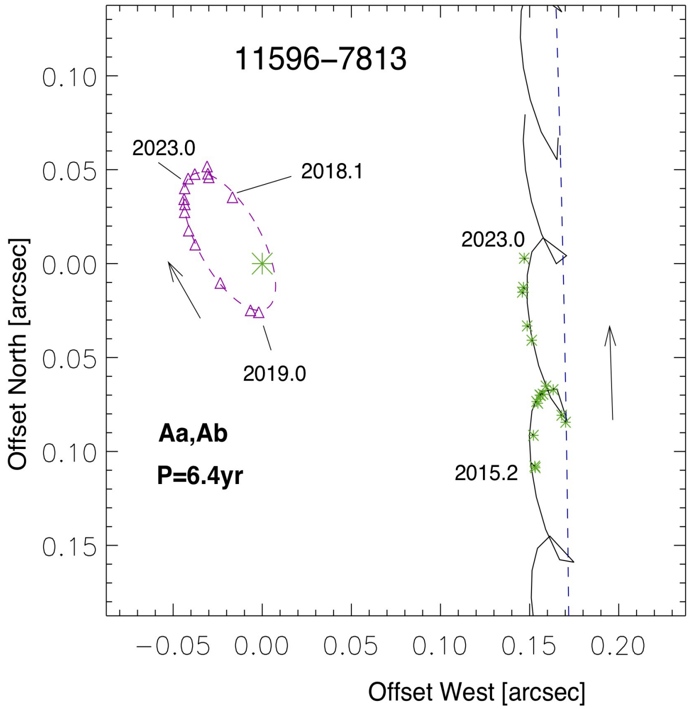


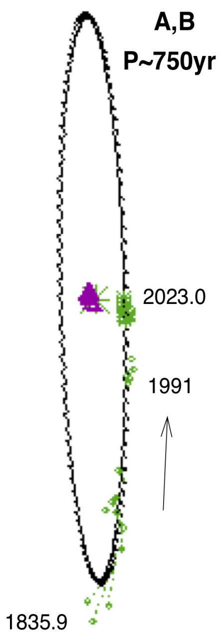




Kopal-2024

# Triplets

- Three stars of similar masses (common accretion?)
- Misaligned, eccentric orbits, often comparable separations



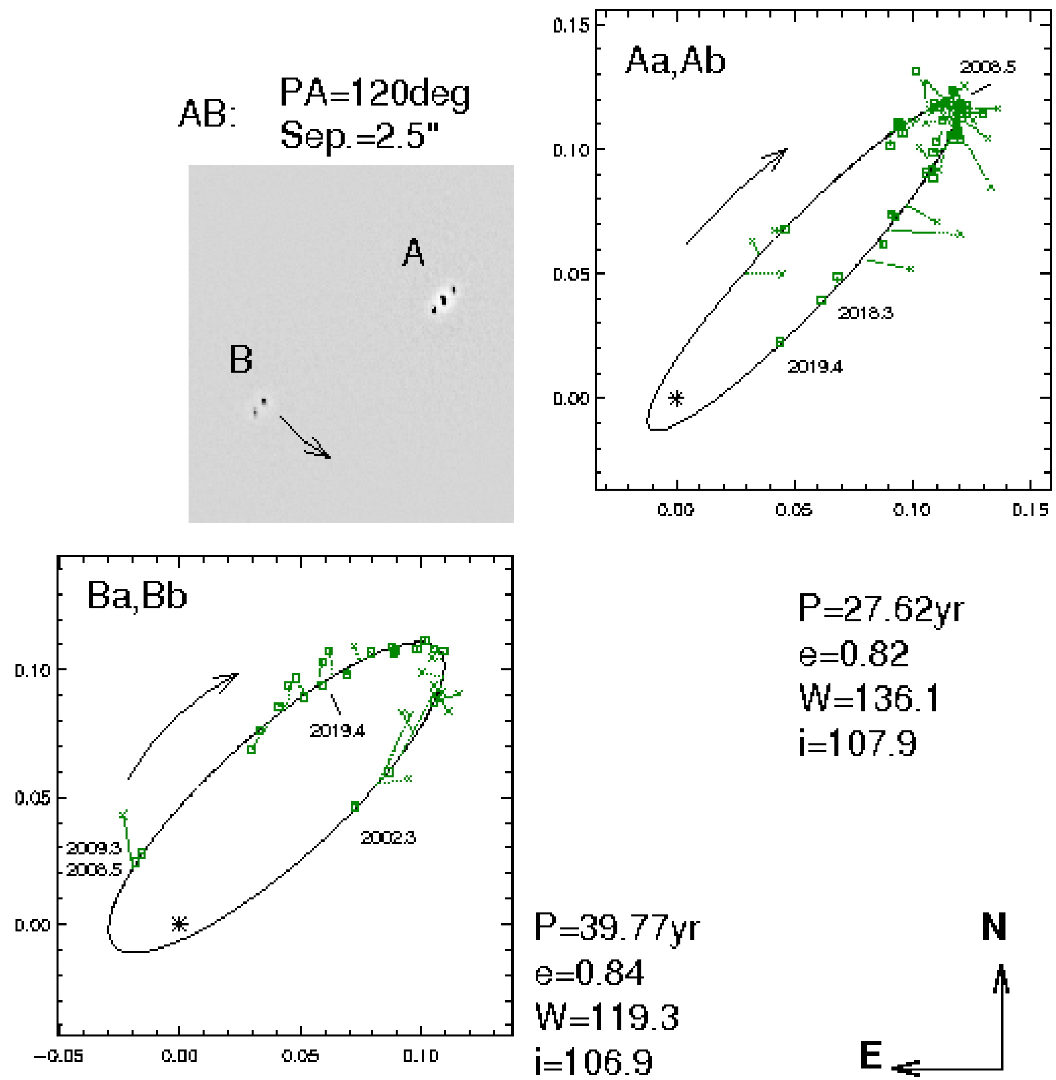




ε Cha: three B-type stars, 6.4yr+~750yr
5 Myr old, PMS

A decayed 2+2 quadruple?
No recoil, moves with gas!

# The tweedles (FIN 332)

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



# 5. Dissipative capture

- Initially unbound fragments (with disks/envelopes) meet, dissipate energy, and get bound.
- Encounter produces accretion burst and can form inner subsystems
- Simulations show that capture is an efficient process
- Subsequent accretion → migration, faster if misaligned → eclipsing binary?

Fly-bys in Taurus (UX Tau: AB triple and C)

# Relation between close binaries and triples

- Suspected for a long time (A.Batten, S.Rucinsky,...)
- CB fraction is proportional to multiplicity (Moe, Di Stefano)
- Statistics: increased fraction of tertiaries for closest binaries (Tokovinin et al. 2006, Hwang 2023).
- Close pairs without tertiary companions also exist!

Close binaries are astrophysically important: supernovae, gravitational waves, etc.

# Recent updates on CBs in hierarchies

- H.-C. Hwang (2023 MNRAS 518, 1750): frequency of **wide** 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, Czavalinga et al. 2023).
- Doubly and triply eclipsing planar hierarchies

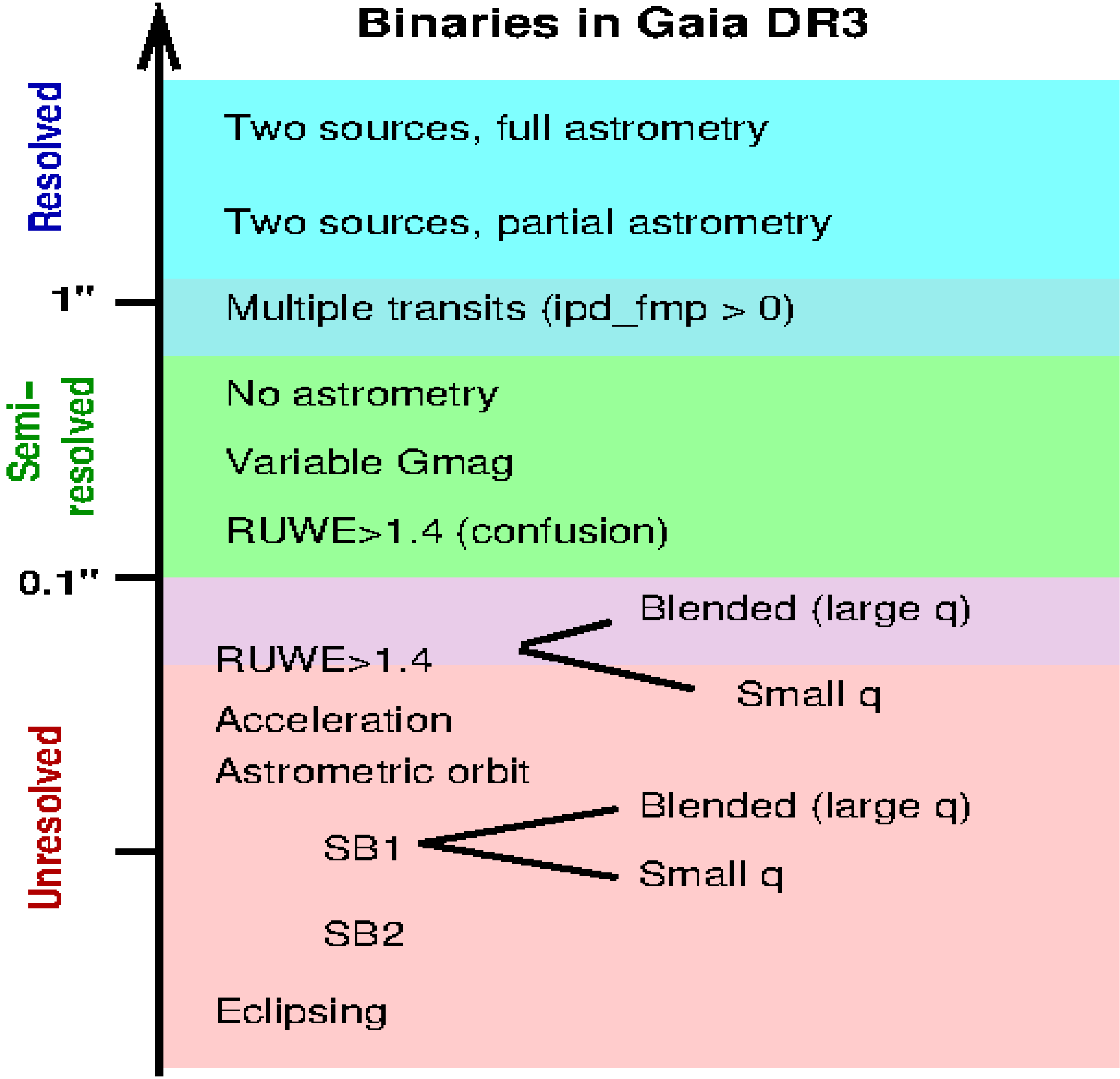
# Why many close binaries are triple?

- Common factor: **accretion**
- Migration and outer companion formation (inside-out)
- Dissipative capture and accretion of misaligned gas (outside-in)?
- "Slow" LK cycles in 3+1 quadruples

# The role of large surveys

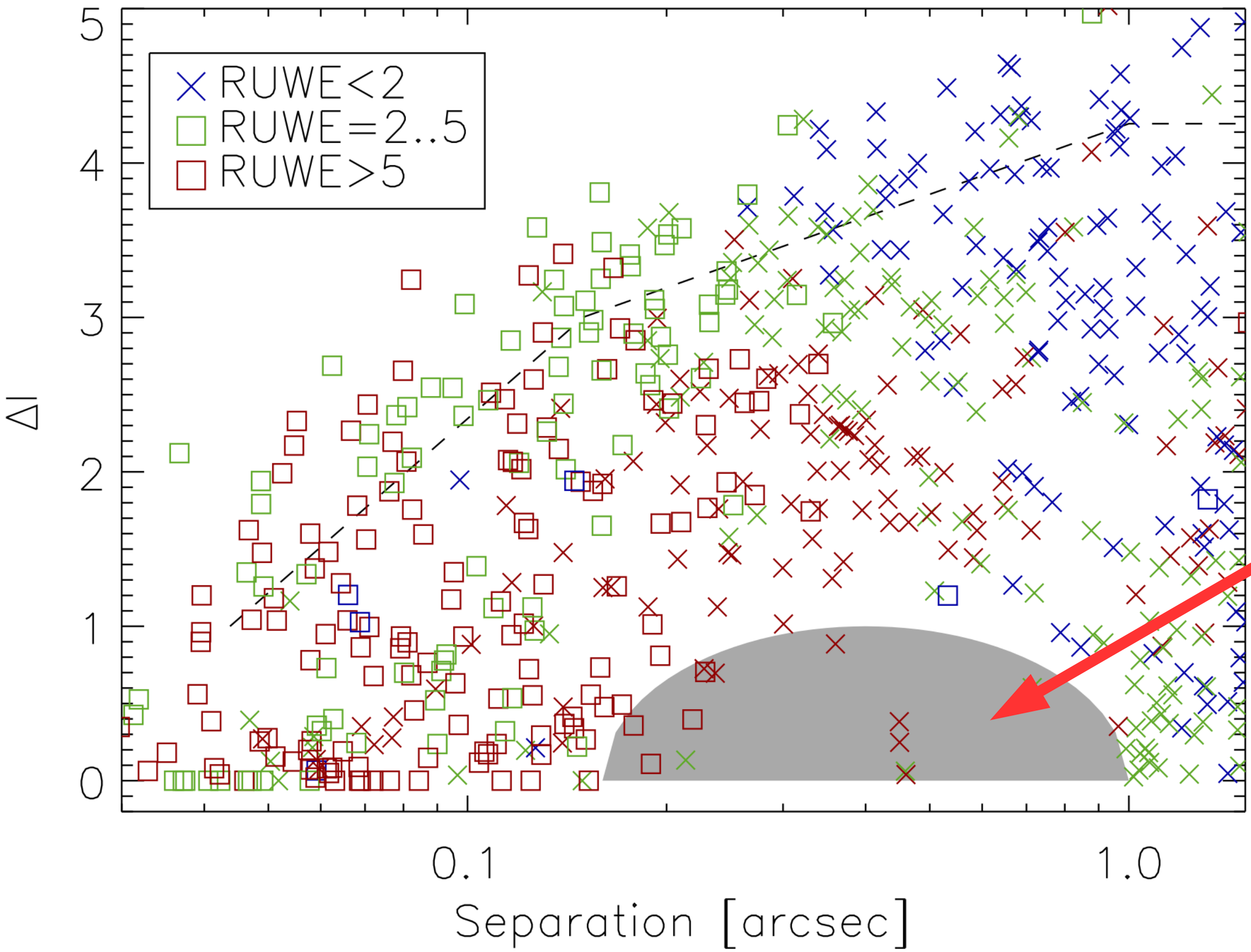
- Surveys have not been designed to detect binaries and triples, these detections are by-products
- Selection effects are always important, sometimes poorly understood (Gaia).
- Statistical inferences from surveys will be the major topic. Methods: forward modeling or deconvolution
- Surveys discover “rare gems” (e.g. eclipsing sextuples, compact triples)
- Surveys require complementary follow-up work

## Binaries in Gaia DR3



# Better multiplicity statistics within 100 pc

Speckle survey: 1200 candidate triples observed, ~500 subsystems resolved

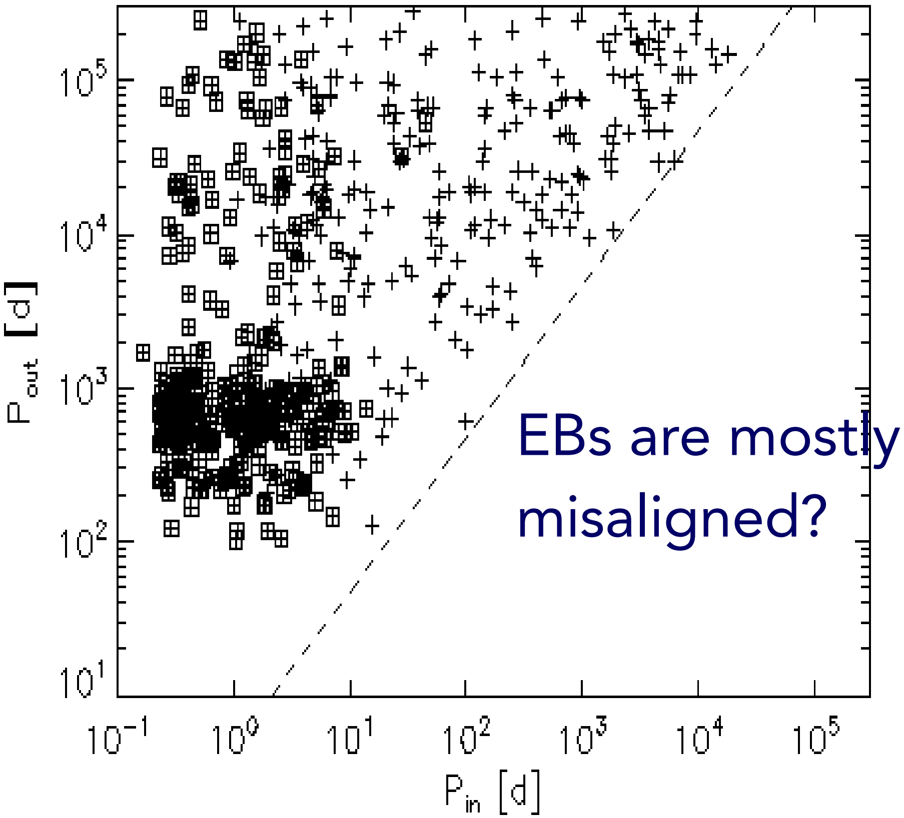


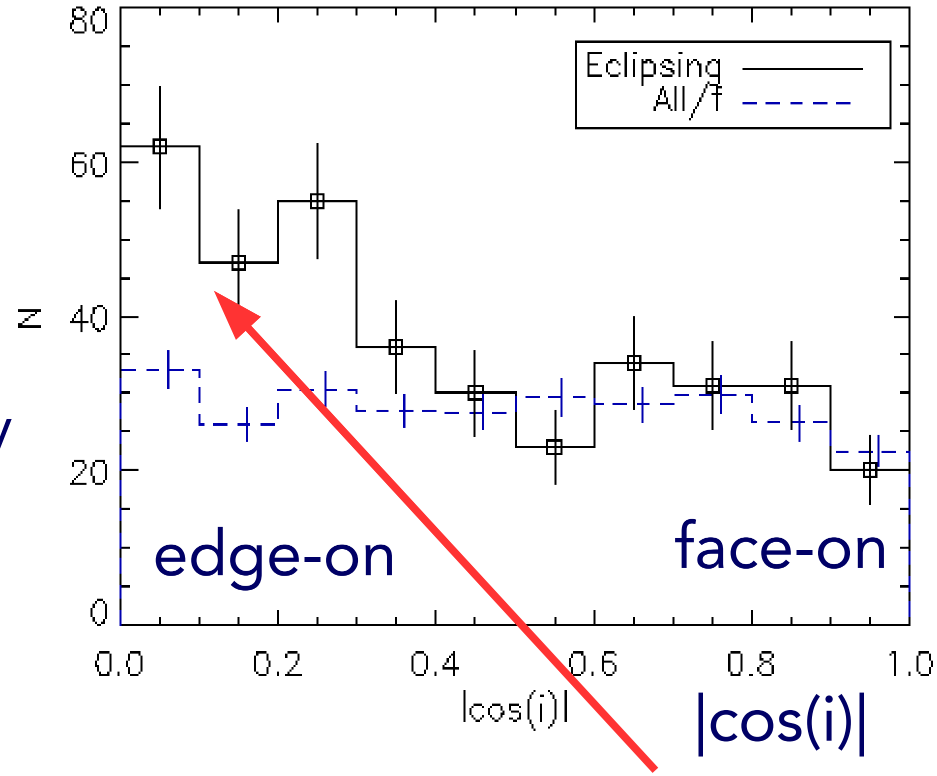

*Gaia was not designed to study multiples*

Gaia hole

2023 AJ 165, 180

# Alignment of eclipsing binaries in triples

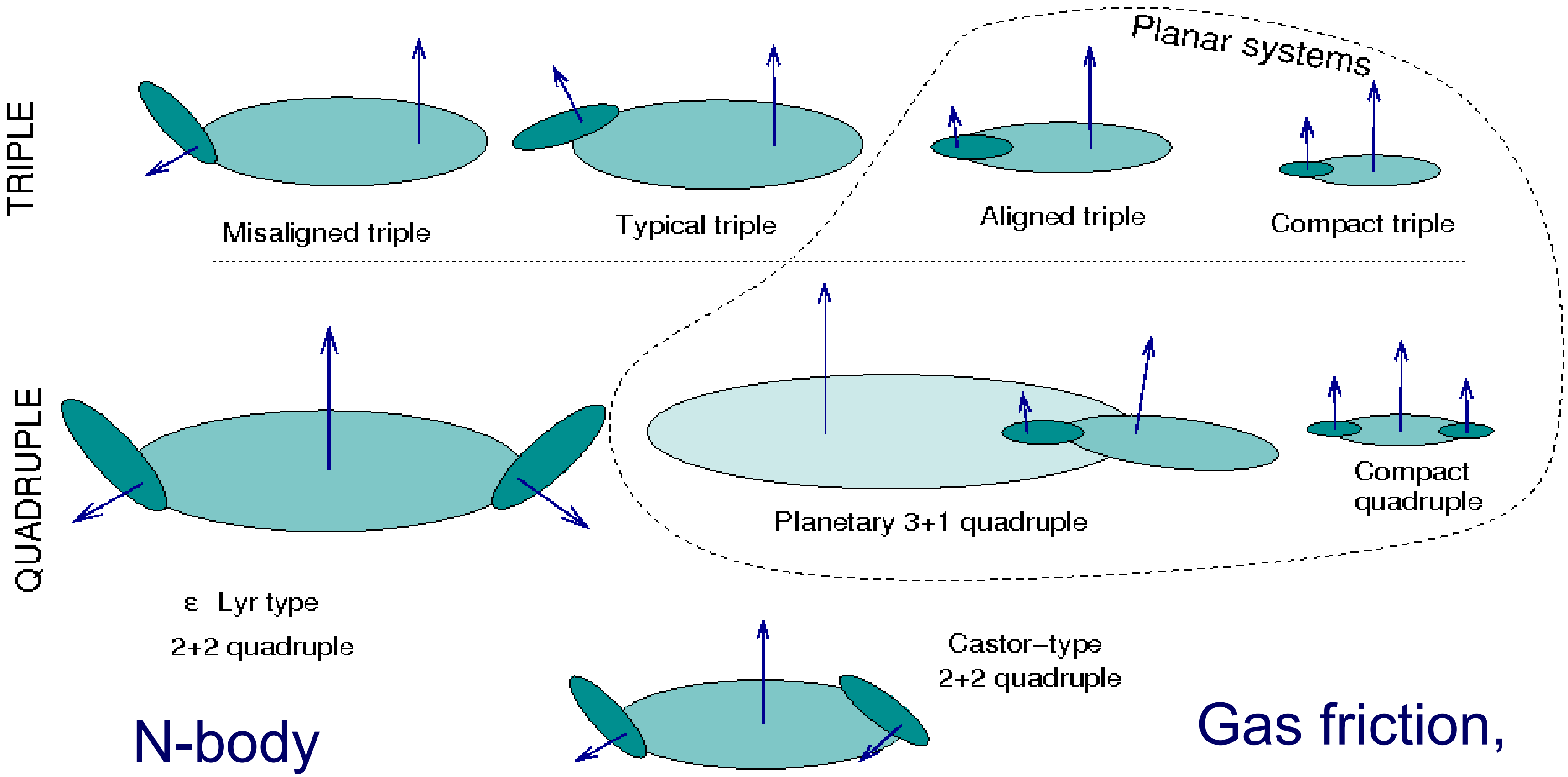



Czavalinga et al. 2023:Gaia astro+ecl.
MSC: known visual/astro outer orbits

Only 23% (81/369) are aligned within ~20deg

# Populations of hierarchical systems




N-body

Gas friction,
accretion

Review: 2021, Universe, 7, 352

# Summary

- Main conclusion: **complicated!**
- Dynamical interaction between stars and gas are key to understanding the architecture of hierarchies.
- Imprints of formation mechanisms are blurred by early evolution
- Emerging classifications into families and their formation scenarios are tentative.
- Large surveys are the future, but they need clever analysis and complementary follow-up observations.
- The research on multiples is very active