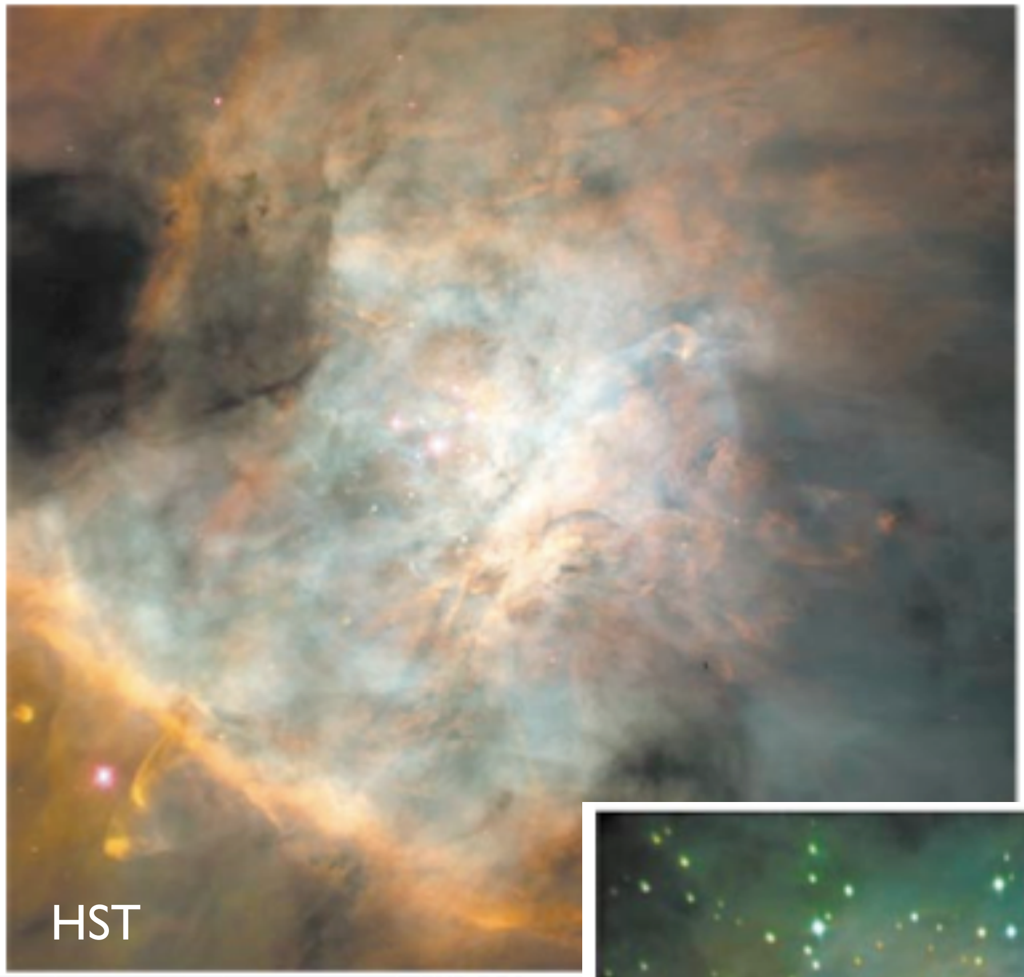
Star Cluster Formation



Trapezium

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Outline

- Star Clusters: Background + Observations
- The Life of a Cluster
  - Fragmentation
  - Feedback Effects
  - Mass Segregation + Stellar Dynamics
  - Gas Expulsion + Relaxation
- Outlook

Background

- ~70-90% of stars form in clusters: understanding star formation requires understanding cluster formation

- Key information from clusters:
  - color-magnitude diagram tests stellar evolution theory
  - IMF determination
  - stellar dynamics testbed

Lada & Lada (2003)

Background

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- Two environmental classes:
  - Exposed clusters
  - Embedded clusters (ECs)

- Two dynamical classes:
  - Bound clusters: $K+V < 0$
  - Unbound clusters: $K+V > 0$

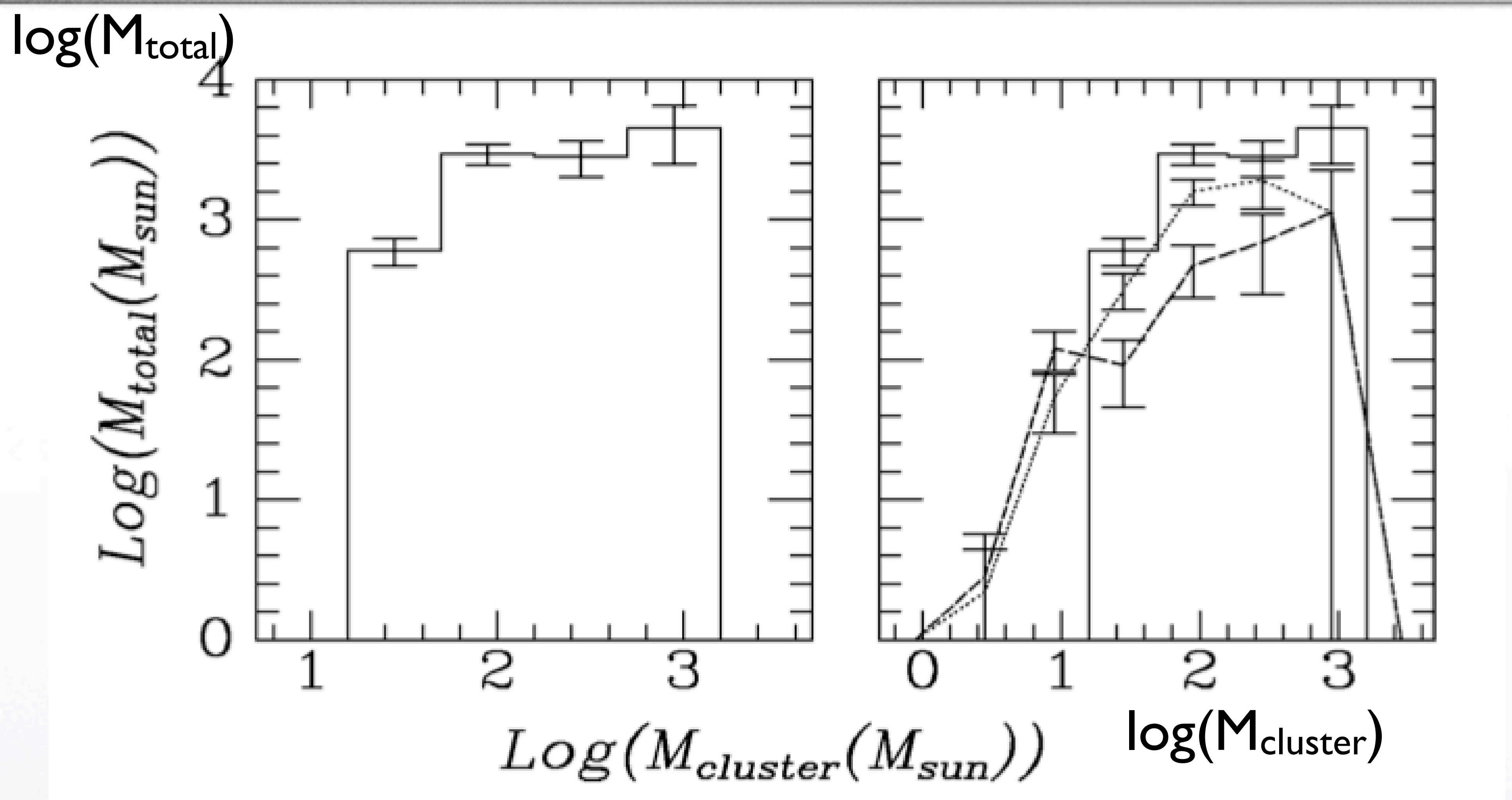
Lada & Lada (2003)

Background

- Criteria for a star cluster:
  $\rho_* > 1\ M_{sun}/pc^3$ (to resist tidal disruption by Galaxy and passing clouds)
  $N > 35$ stars (so that $t_{evap} > 10$ Myr)
- Masses ~ O(10-100s) M_{sun}
  Sizes ~ O(pc)
- Typical timescale of embedded phase: 2-3 Myr
  Clusters older than ~5 Myr typically have no molecular gas
- Identified in IR, e.g. 2.2 µm or K band (often ~invisible in optical)
- First deeply embedded cluster found in MC: Ophiuchi (1974)
  Now >100 known, but far from complete sample

Lada & Lada (2003)

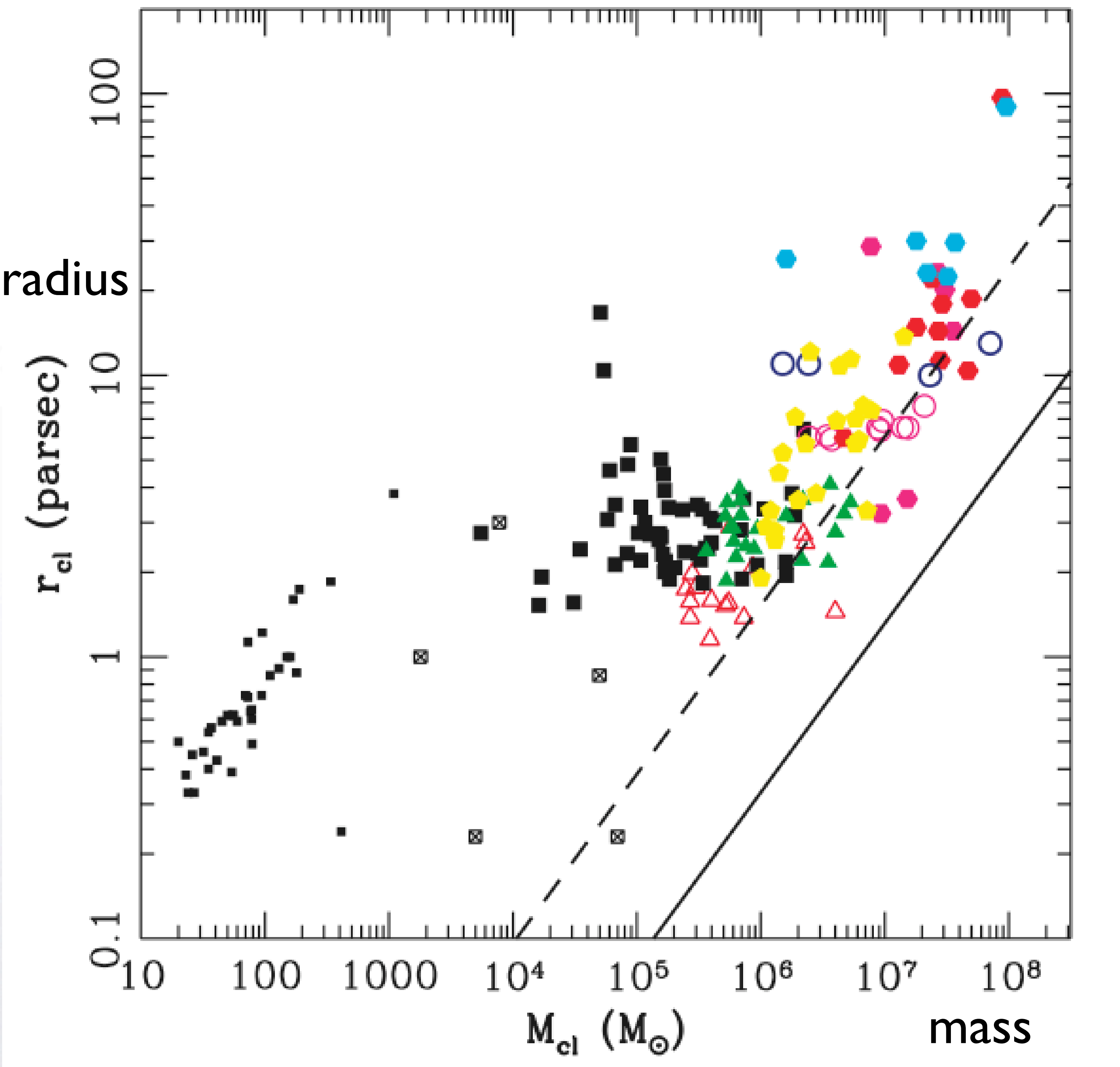
Observations



- Embedded cluster mass function: dn/dM ~ M^{-2}

- M dn/dlogM is flat over wide range in mass (~50-1000 Msun)
  Steep decline below ~50 Msun
- Masses + EC ages imply they host much (most?) of local SF

Observations

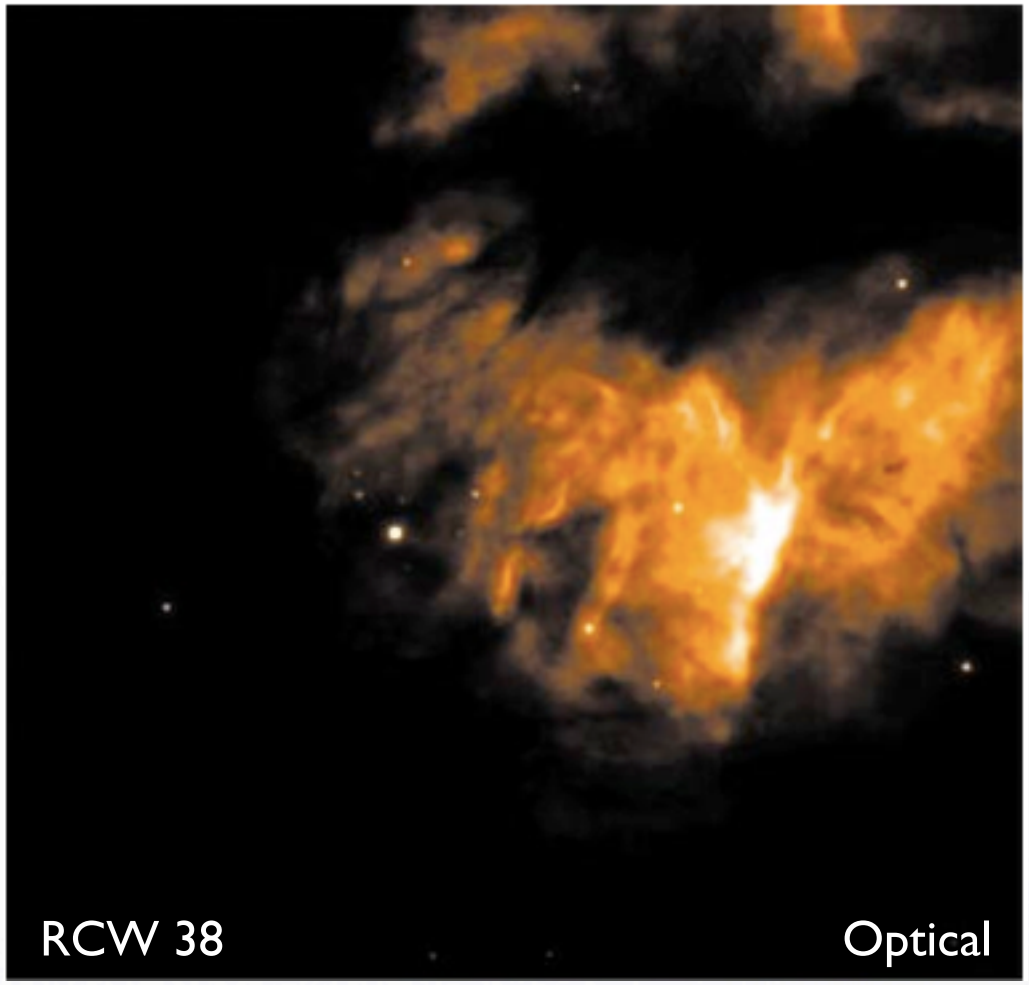


- Little variation in cluster size over wide range in mass (at least ~10^4-10^6 M_{sun})
- Higher masses: radiation pressure becomes important
- Lower masses: something else must provide support during formation

Murray (2009)
Allen et al. (2007)

Observations

- EC birthrate: ~8-16 times higher than that of classical open clusters
- Vast majority of ECs do not survive emergence from MCs beyond few Myr
- But it appears most stars are formed in ECs -- overall SFE ~ O(1-10%)
- The process:
  Initial collapse/fragmentation
  Role of turbulence?
  Feedback processes?
  Dynamical evolution - mass segregation
  Relaxation/gas expulsion



Lada & Lada (2003)

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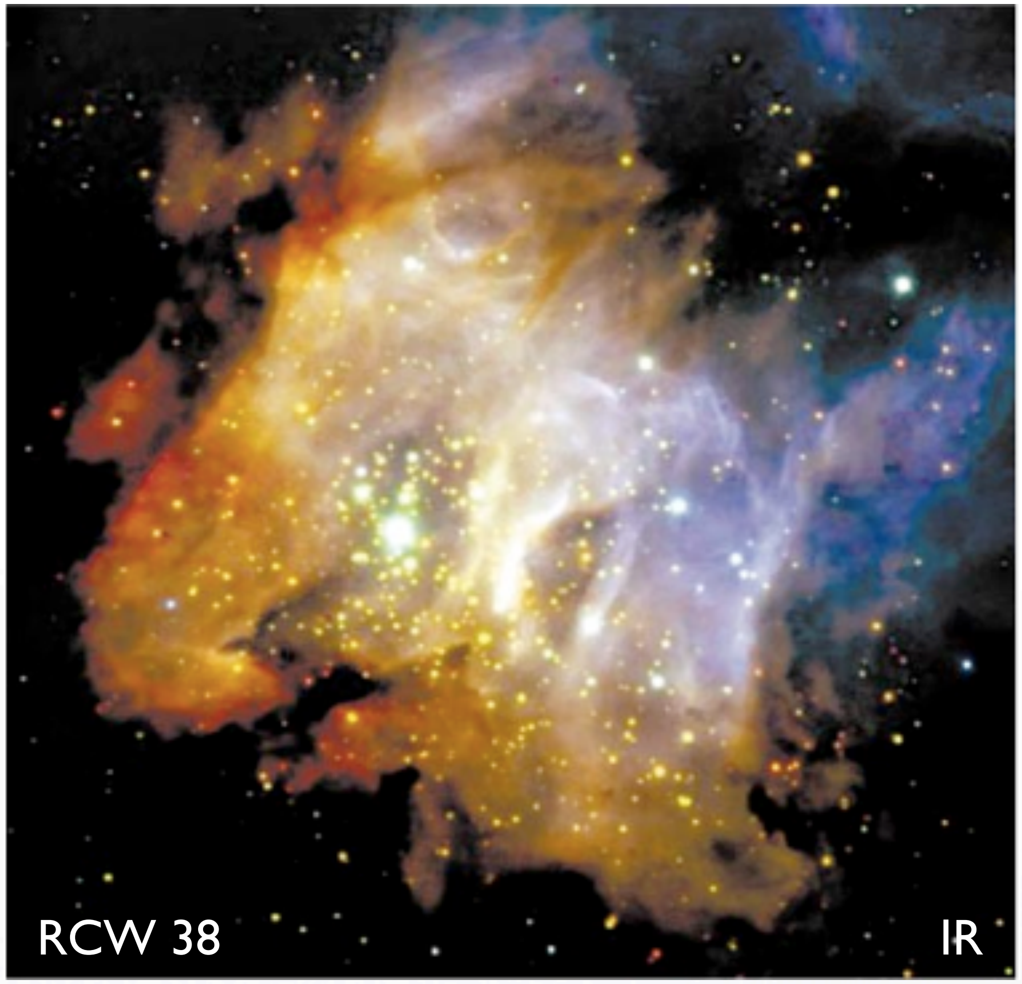


Lada & Lada (2003)

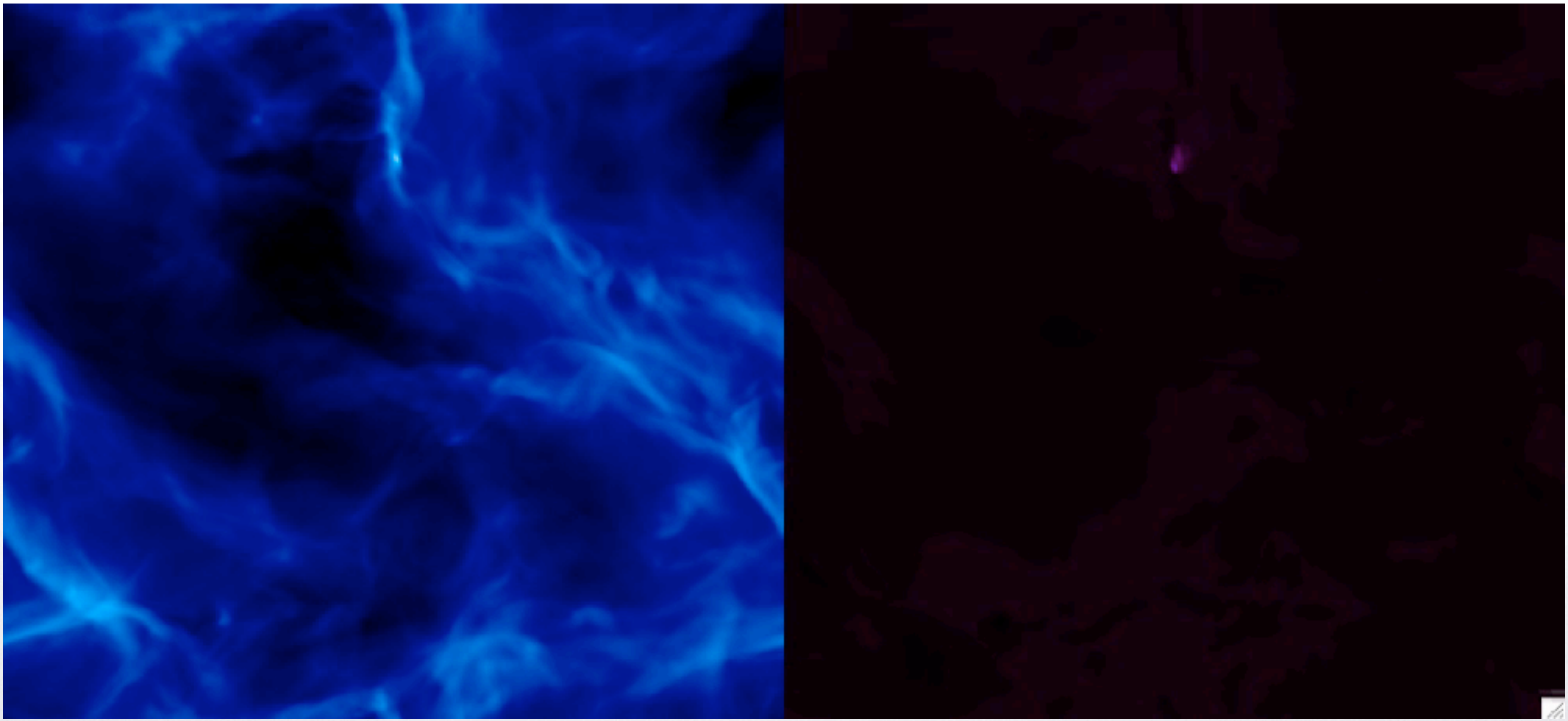
Fragmentation

- Recall: Jeans scale
  λ_J = 0.6 pc (T/20 K)$^{1/2}$ (ρ/10^{-20} g/cm^3)$^{-1/2}$
  M_J = 130 M_{sun} (T/20 K)$^{3/2}$ (ρ/10^{-20} g/cm^3)$^{-1/2}$
  t_J = 2.2 Myr (ρ/10^{-20} g/cm^3)$^{-1/2}$
- Limited T variation due to highly efficient radiative cooling in MCs
- Large ρ variation (log-normal) ~10^{-20} g/cm^3 to stellar densities
- What about T variation on small scales?
  - Gas becomes optically thick at densities far above MC mean
  - Transition regime is complicated
  - If too cold, leads to increased fragmentation, overproduction of low-mass objects or brown dwarfs
  - Simulate via 3D AMR code including radiative feedback

Murray (2009)
Offner et al. (2009)

Fragmentation

Full radiative transfer sim: protostellar feedback, viscous dissipation, gas compression



log(gas column density) log(density-weighted gas temp.)

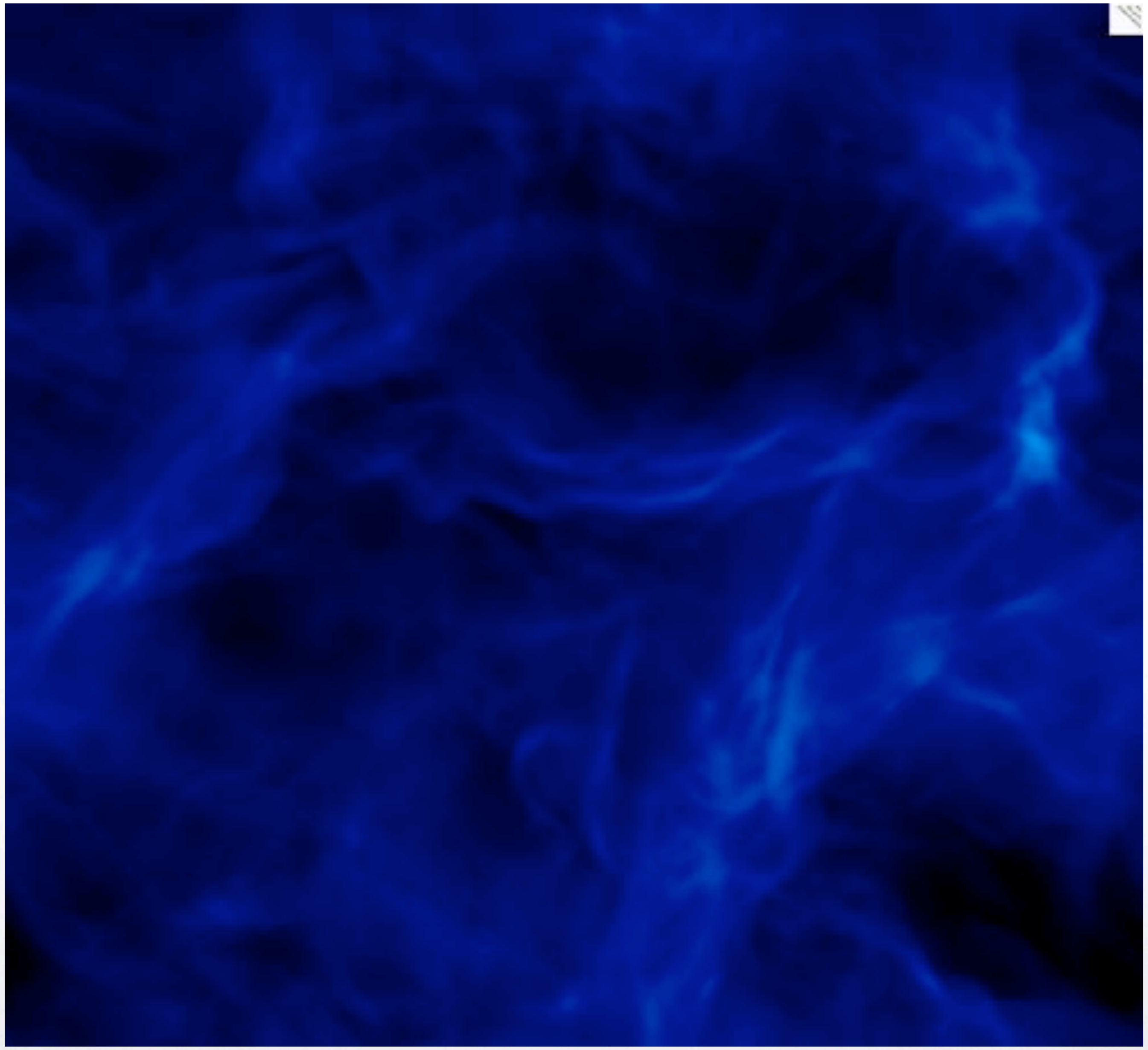
IC: T = 10 K, L = 0.65 pc, M = 185 M_{sun}

Offner et al. (2009)

No B field

Fragmentation

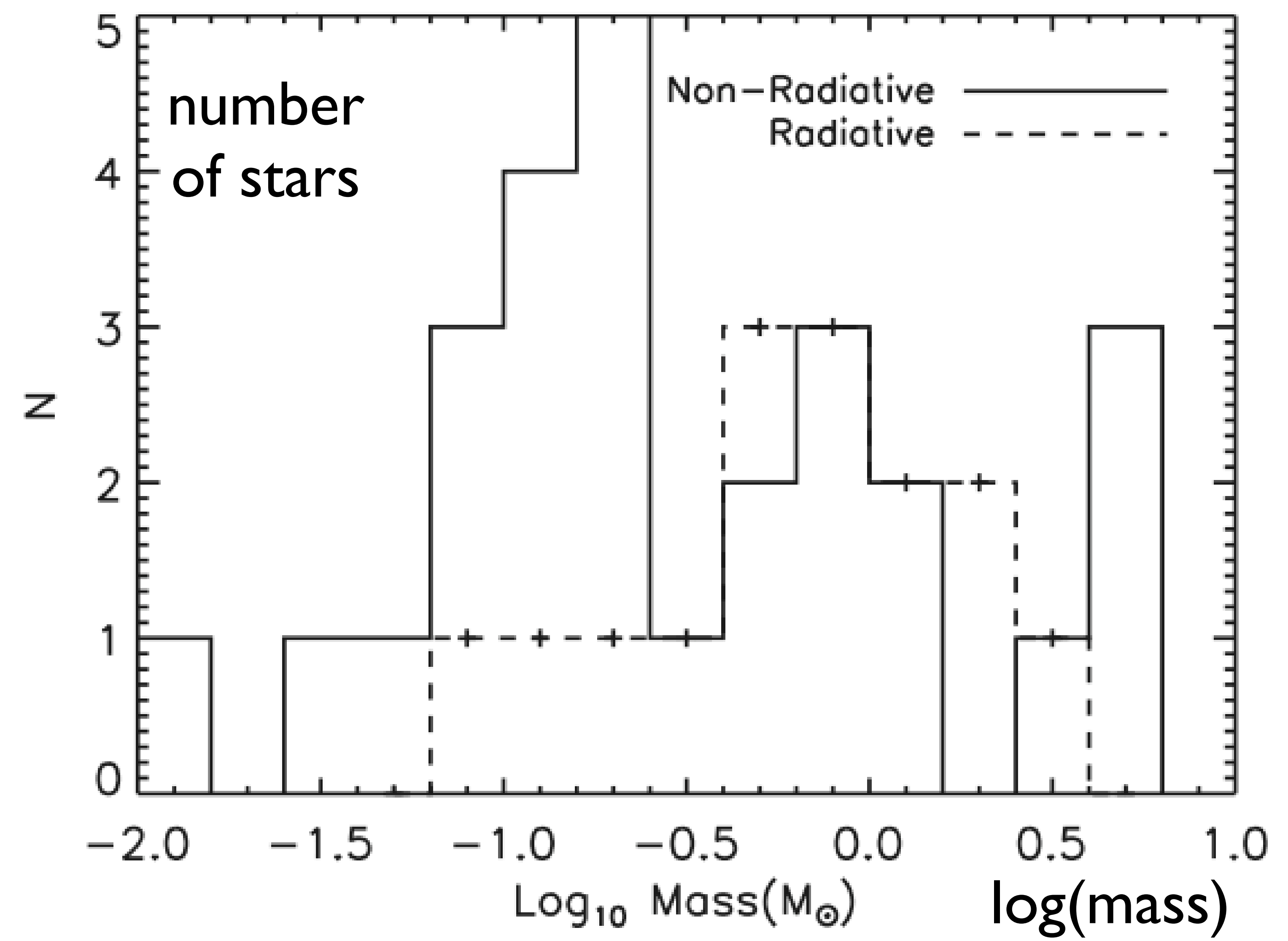
EOS-only sim



log(gas column density)

Offner et al. (2009)

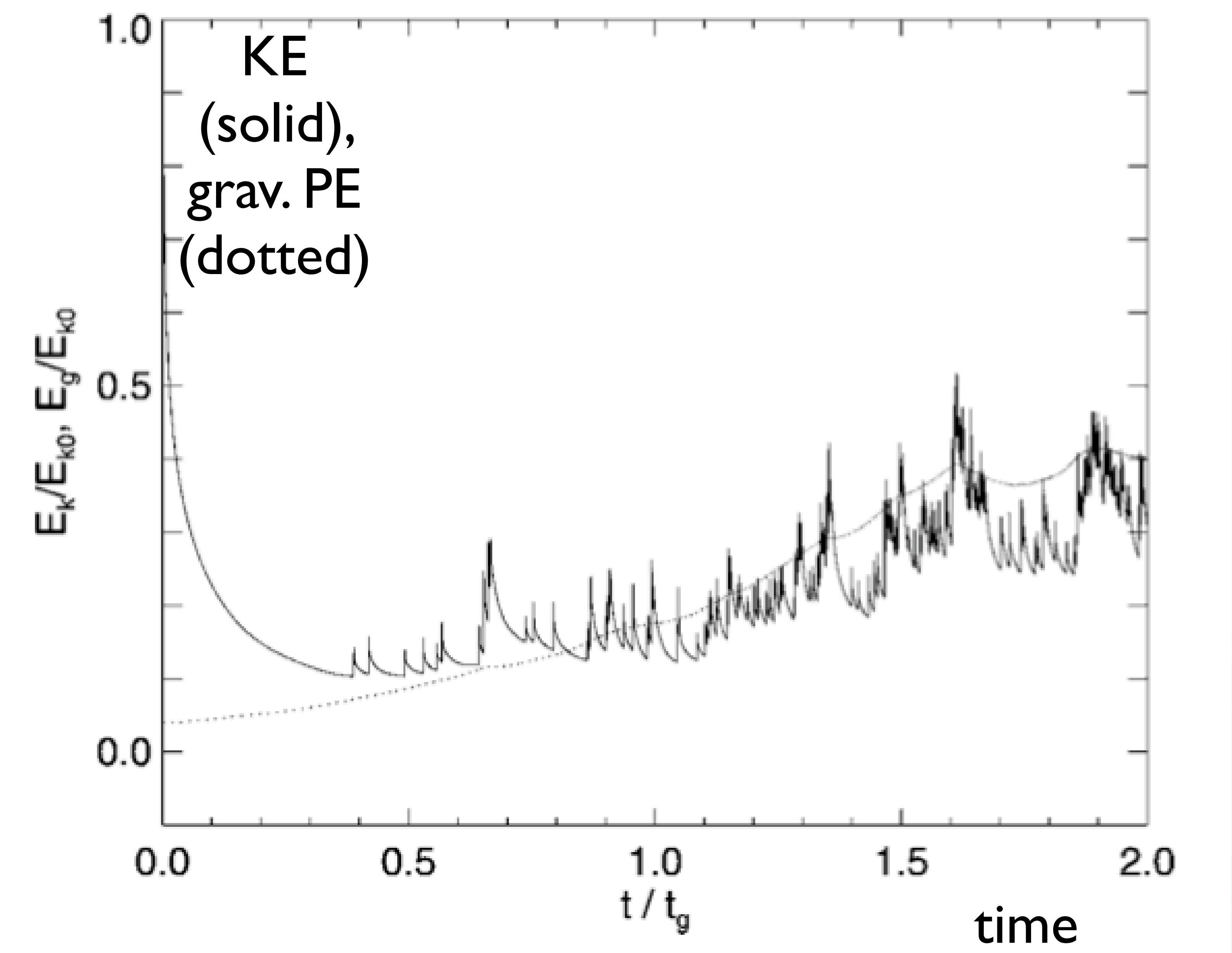
Fragmentation/Feedback



- RT suppresses small-scale fragmentation
- Protostellar radiation is dominant heating source
- RT leads to smoother and less variable accretion
- Mean accretion rate increases with final stellar mass - SF time thus quasi-ind. of mass

Offner et al. (2009)

More Feedback

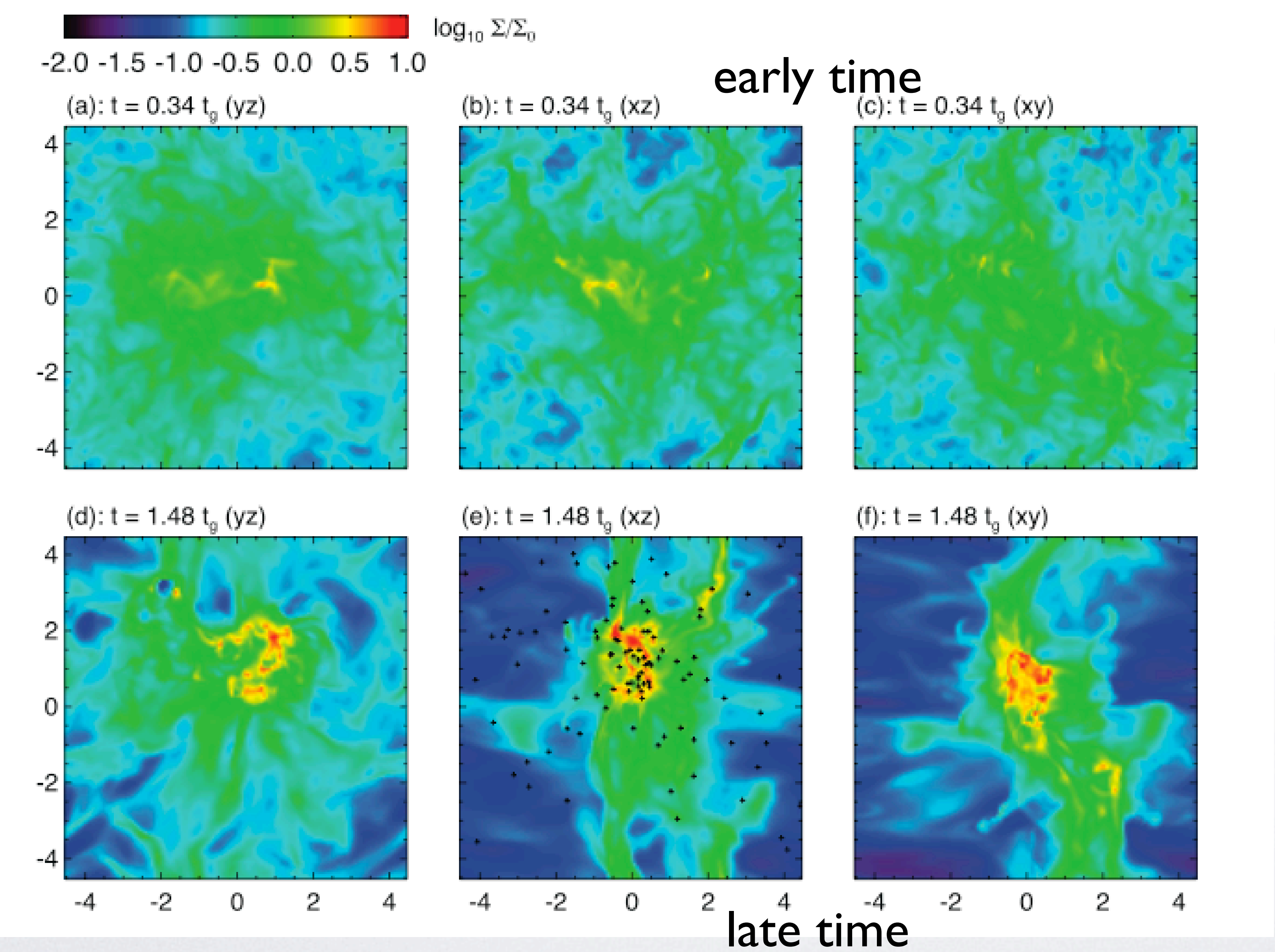


- What about turbulence?
- Initial turbulence inherited from ISM decays away very quickly
- Replaced by protostellar outflow-driven turbulence
- Limits mass accretion onto forming stars
- May lead to evolution of cluster-forming clumps toward centrally-condensed state

IC: T = 20 K, L = 1.5 pc, M = 939 M_{sun}
3D MHD w/ B field

Li & Nakamura (2006)

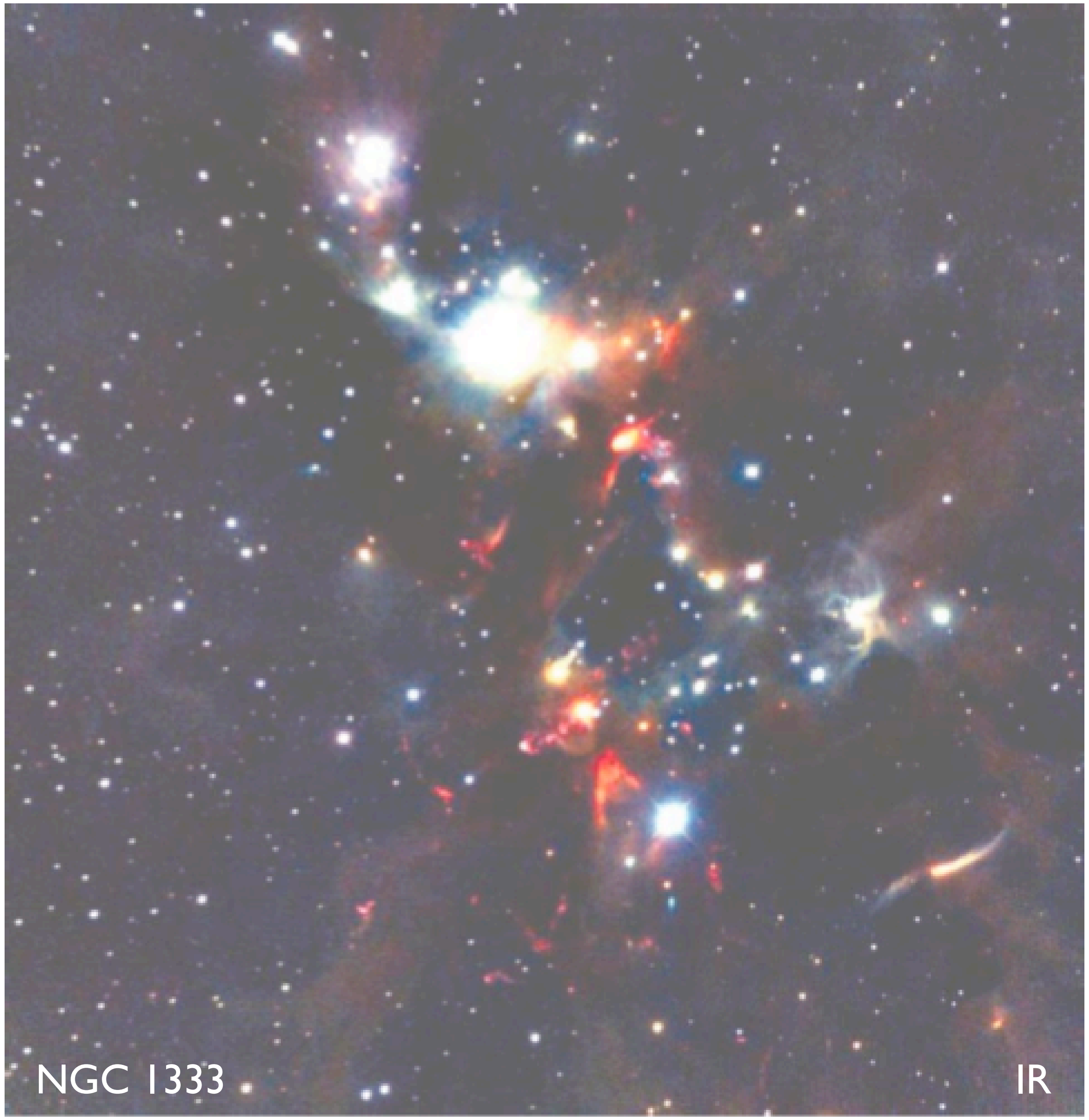
More Feedback



- Morphology of cloud is altered by outflows following SF
- Settling and accretion at center of clump may lead to formation of massive stars

Li & Nakamura (2006)

More Feedback



Lada & Lada (2003)

Dynamics

- Precise origin of embedded clusters is still unknown, but subsequent dynamical evolution and emergence from MCs is well-studied
- Interplay between SF efficiency and gas removal process
- Major question: origin of mass segregation in embedded clusters

  e.g., Orion nebula cluster (age ~ 2-3 Myr)

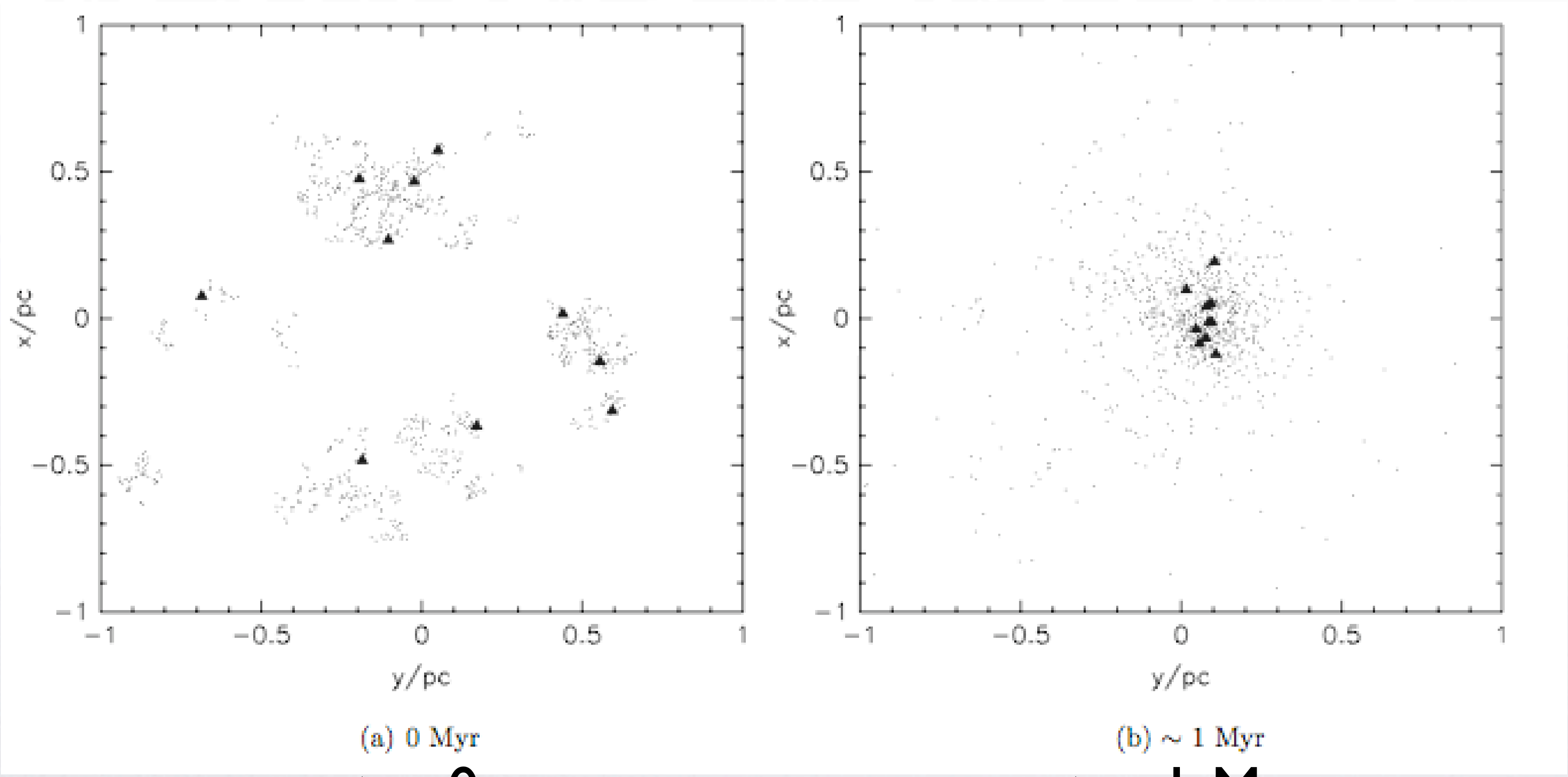
  Primordial or the result of dynamical evolution?

  Are the masses of the most massive stars set by the mass of the core in which they form or by competitive accretion due to favorable location?
- Observations indicate massive stars often found near cluster centers, but overall evidence inconclusive

Lada & Lada (2003)
Allison et al. (2009, 2010)

Dynamics/Mass Segregation

- Allison et al.: rapid and violent early dynamical evolution can drive significant mass segregation
- Claim: clusters form cool (subvirial) and with substructure



t = 0   t = 1 Myr

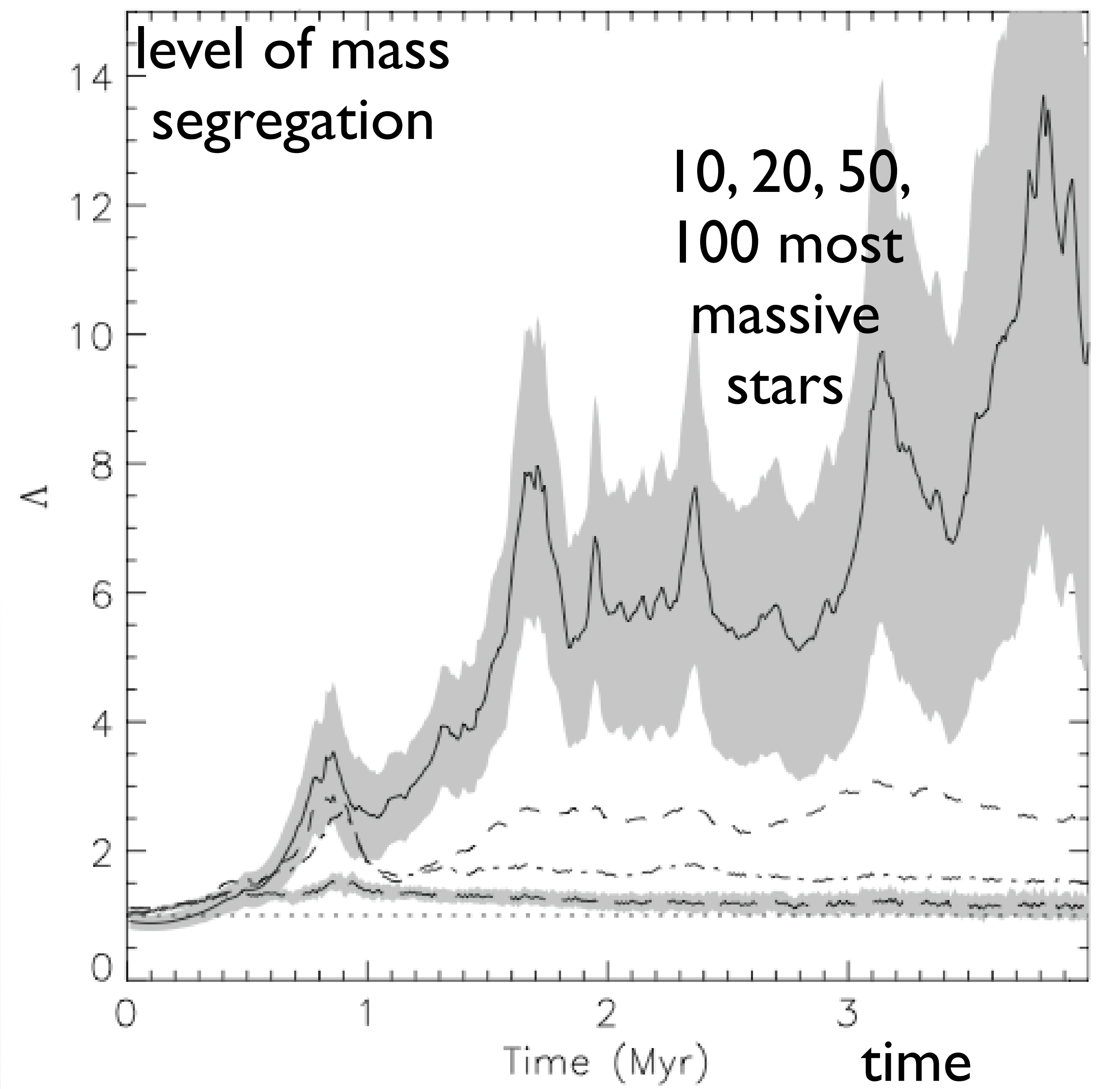
- Simulate very clumpy initial stellar distributions with K = 0.3U (subvirial)

Allison et al. (2009, 2010)

IC: N = 1000 stars, r = 1 pc, M = 500 M_{sun}

N-body only, no gas, no binaries

Dynamics/Mass Segregation



- Mass segregation scale Λ (related to typical distances between avg randomly selected stars and most massive stars)
- Mass segregation caused by production of a short-lived, very dense core

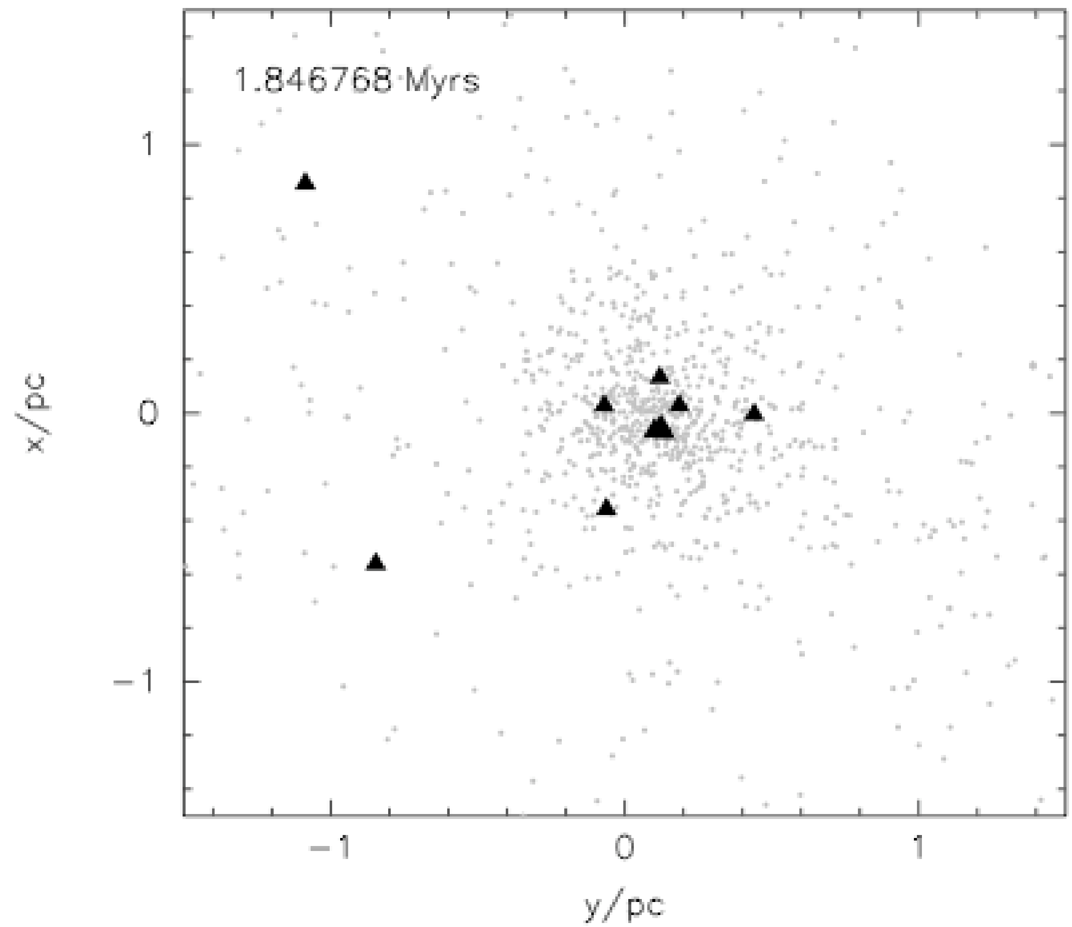
$$t_{seg} \approx \frac{m}{M} \frac{N}{8 \ln N} \frac{R}{\sigma}$$

- Rapid segregation possible for $M_* > 4\ M_{sun}$

Allison et al. (2009, 2010)

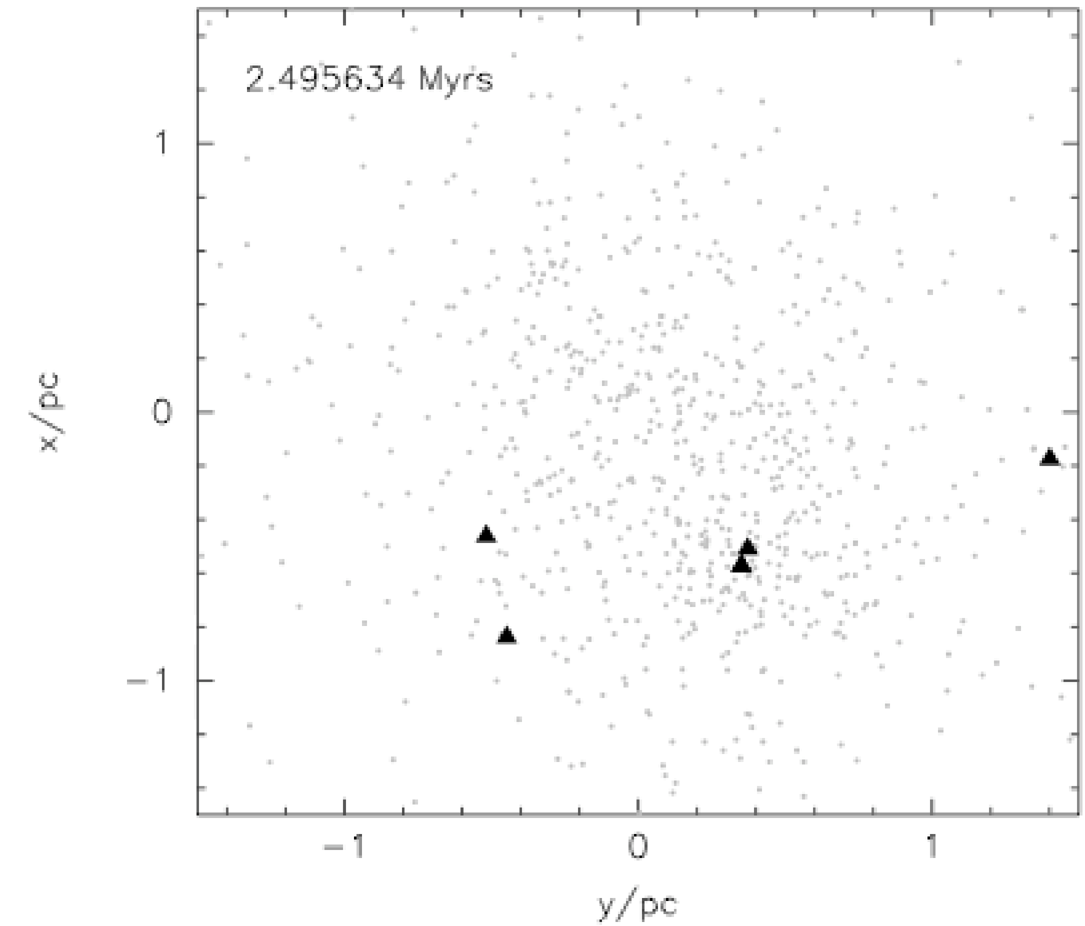
Dynamics/Mass Segregation

t = 1.85 Myr



(a)

t = 2.5 Myr



(b)

- Trapezium-like systems form during dense core phase
- Can be followed by core collapse and disruption of the cluster, including ejection of massive stars

Allison et al. (2009, 2010)

Gas Expulsion

- ECs are fairly short-lived -- limits overall SFE (fraction of total mass that is converted to stars)
  - SFE for ECs seems to increase with time from ~10% to ~30%
  - Global SFE for GMCs ~1-5%

- How is gas removed?
  - Explosive gas removal -- $t_{removal} << t_{cross}$ (e.g., due to O stars)
  - Adiabatic gas removal -- $t_{removal} >> t_{cross}$ (allowing evolution into OCs)

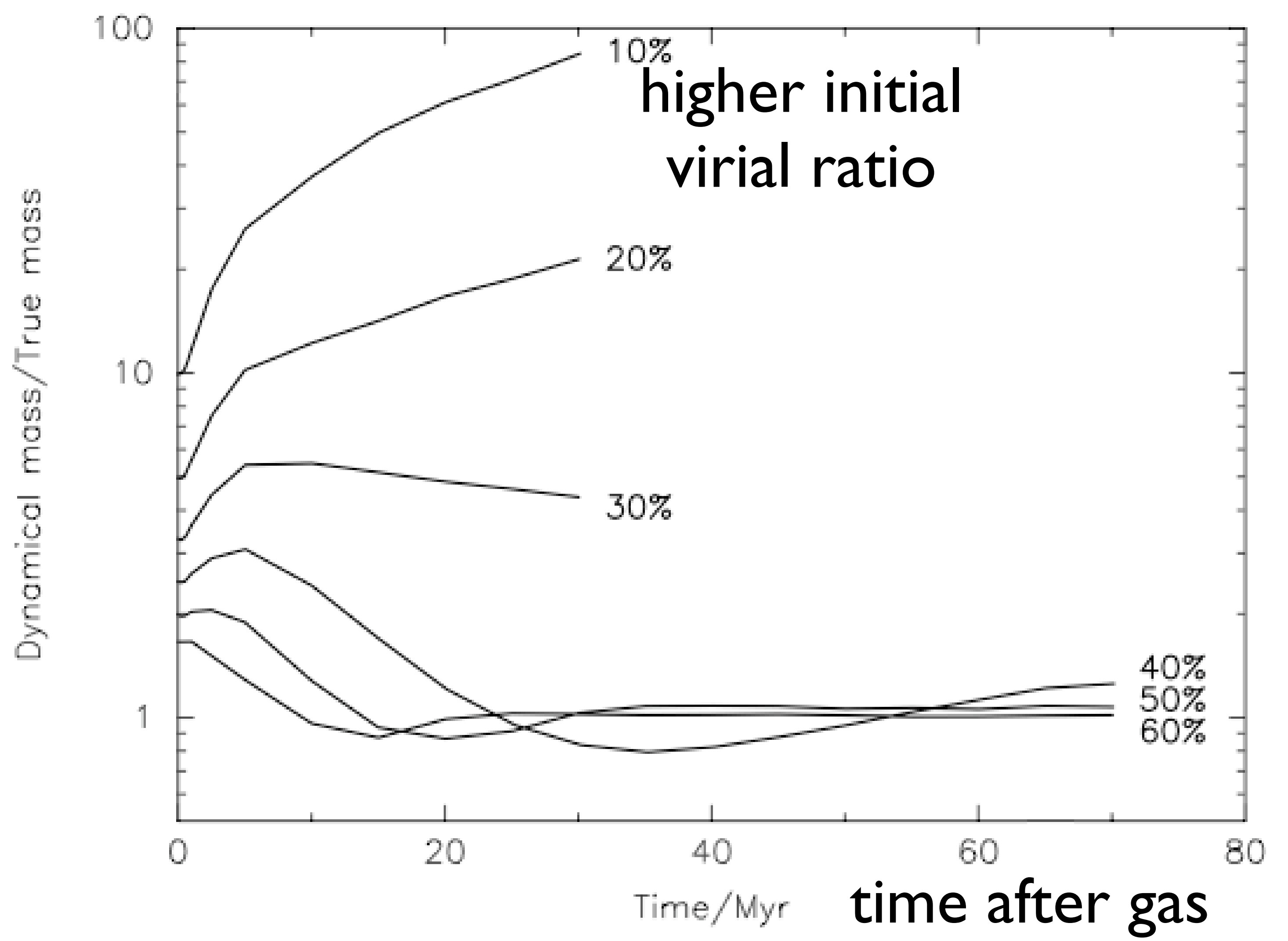
- Clusters will typically expand and lose members in this process

- Production of a bound cluster from dense cloud core requires special conditions ($M > 500\ M_{sun}$ to obtain stable open cluster)

- Most ECs (~90%) emerge from MCs as unbound systems

Lada & Lada (2003)
Goodwin & Bastian (2006)

Gas Expulsion



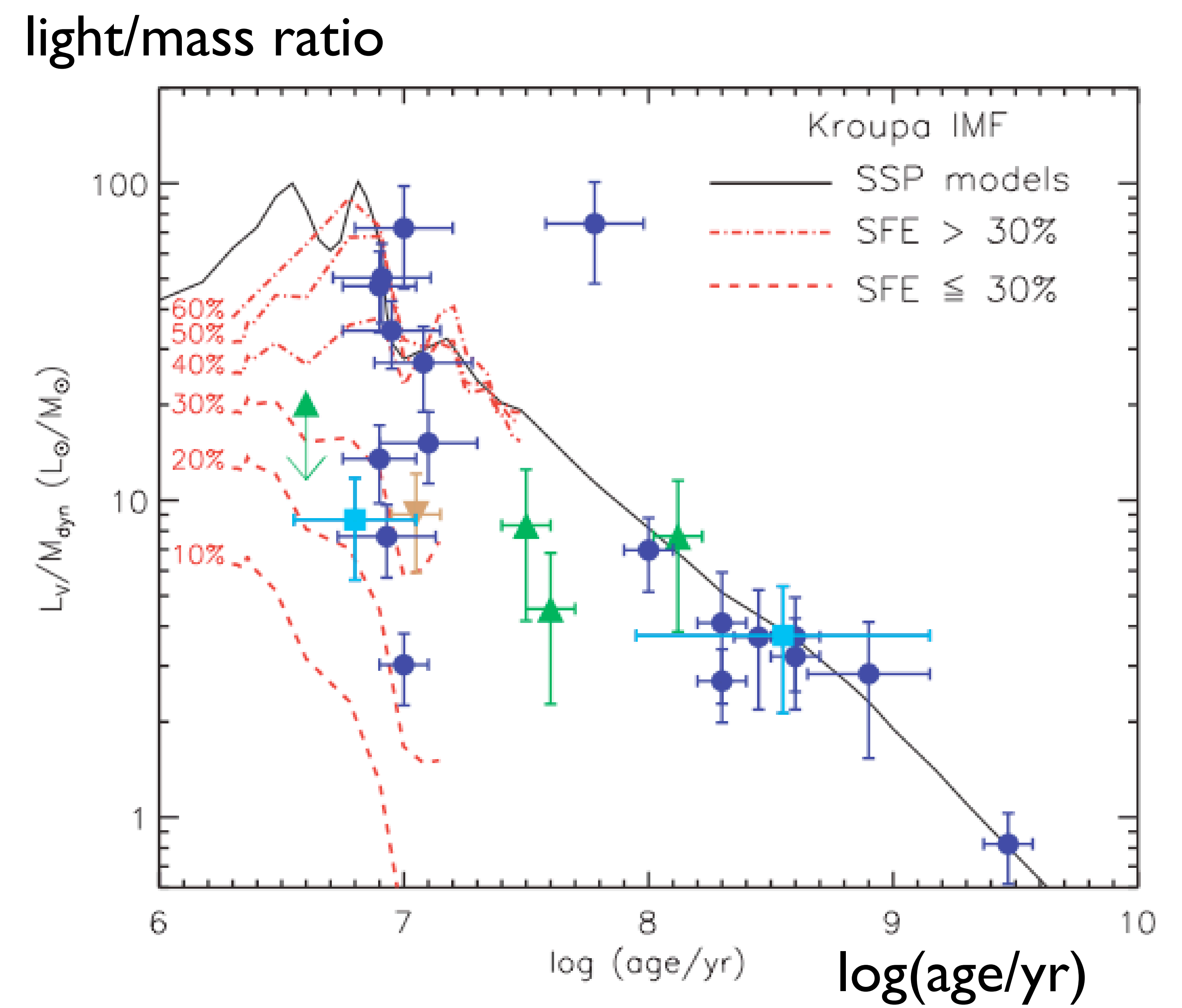
- Goodwin & Bastian: luminosity and dynamical mass estimates for young massive clusters differ significantly
- Likely out of virial equil. due to violent relaxation after expelling unused gas (~50% initial cluster mass)
- Simulate this by setting up out-of-VE N-body systems

IC: N = 30000 stars, r = 3.5 pc, M = 50000 M_{sun}

Goodwin & Bastian (2006)

N-body only, no gas, no binaries

Gas Expulsion



“infant mortality”
“infant weight loss”

- Compare to obs.:
  - Older clusters: luminosity and dynamical masses tend to agree
  - Younger clusters: lie below canonical expectation
- Explanation: dyn. mass overestimates true mass; younger clusters are out of VE after gas expulsion
- Some will be destroyed (>~50%), some will relax to new virial equilibrium

Goodwin & Bastian (2006)

Outlook

- ECs -- site of much, if not most, of SF in the galaxy
- Origin of ECs remains mysterious
  - Source of turbulence in cluster-forming regions?
  - Formation of massive stars?
- Mass segregation to get massive stars in center now tractable
- Dynamical evolution and disruption of clusters now well-studied

References

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