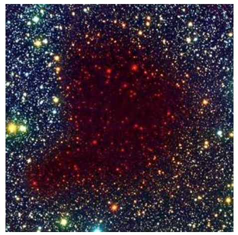
Challenges in star and planet formation

Ralf S. Klessen Zentrum für Astronomie Heidelberg

Mordecai-Mark Mac Low American Museum of Natural History
ZAH/ITA & MPIA Heidelberg

challenges in star and planet formation

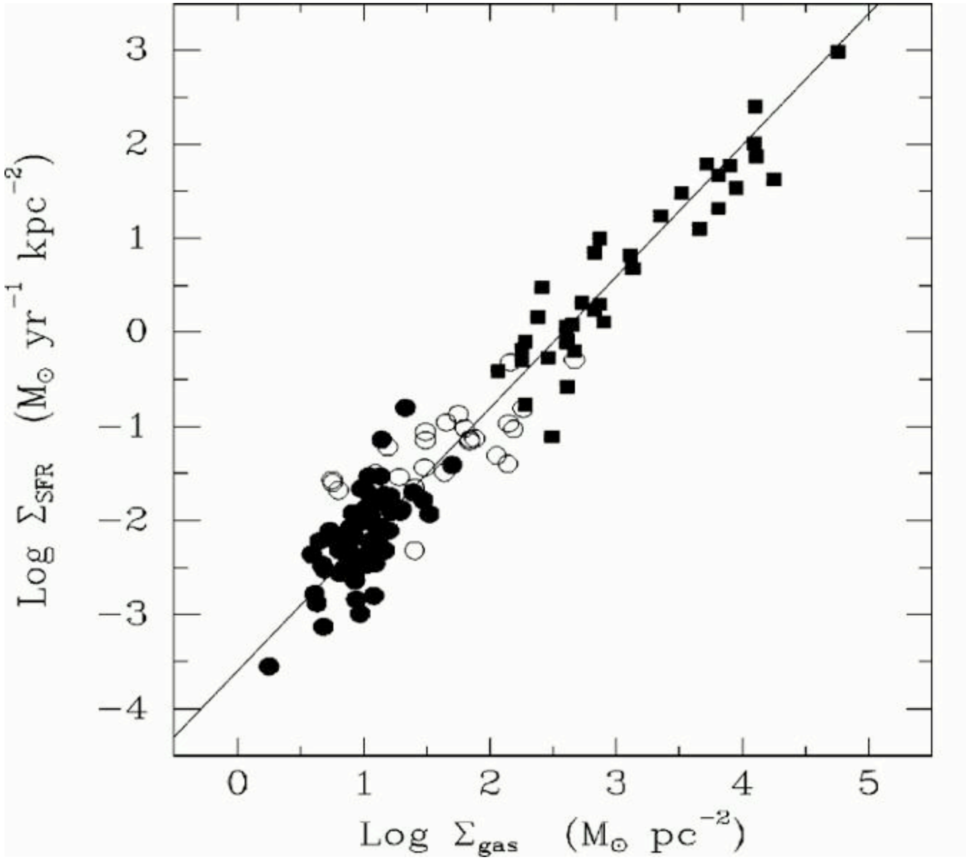
- challenges in galactic-scale star formation and build-up of stellar clusters
- challenges in star and planet formation
- structure formation through the universe?
  - universal aspects of structure formation
  - scale-specific differences



galaxies and star clusters

- why does the Schmidt law work?
- how do molecular clouds form?
- what is the structure of star-forming clouds?
- what drives interstellar turbulence?
- how do star clusters build up?
  (monolithic collapse vs. dynamic interactions)
- what determines the IMF?
- how do massive stars form?
- how did stars form in the early universe?

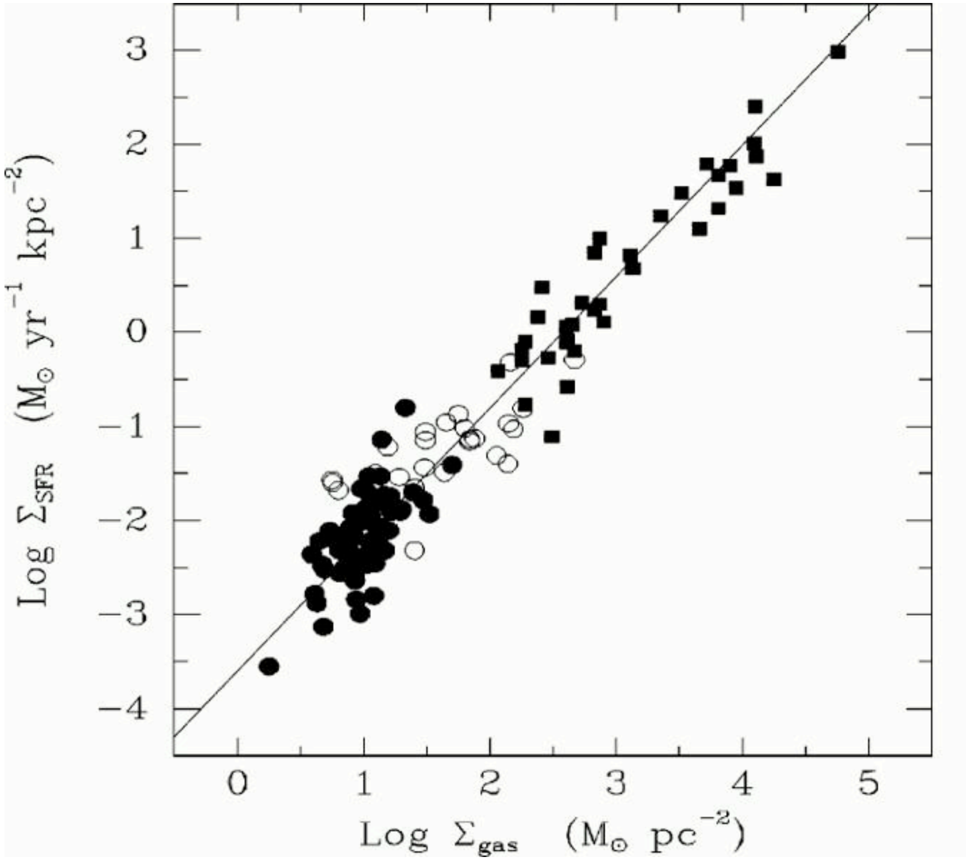
Schmidt law



- gravitational instability in the disk (Toomre Q)
- regulated by turbulence in the disk
- coagulation of quasi-equilibrium clouds in disk
- regulated by pressure in the disk (or porosity)

(from Kennicutt 1998)

Schmidt law



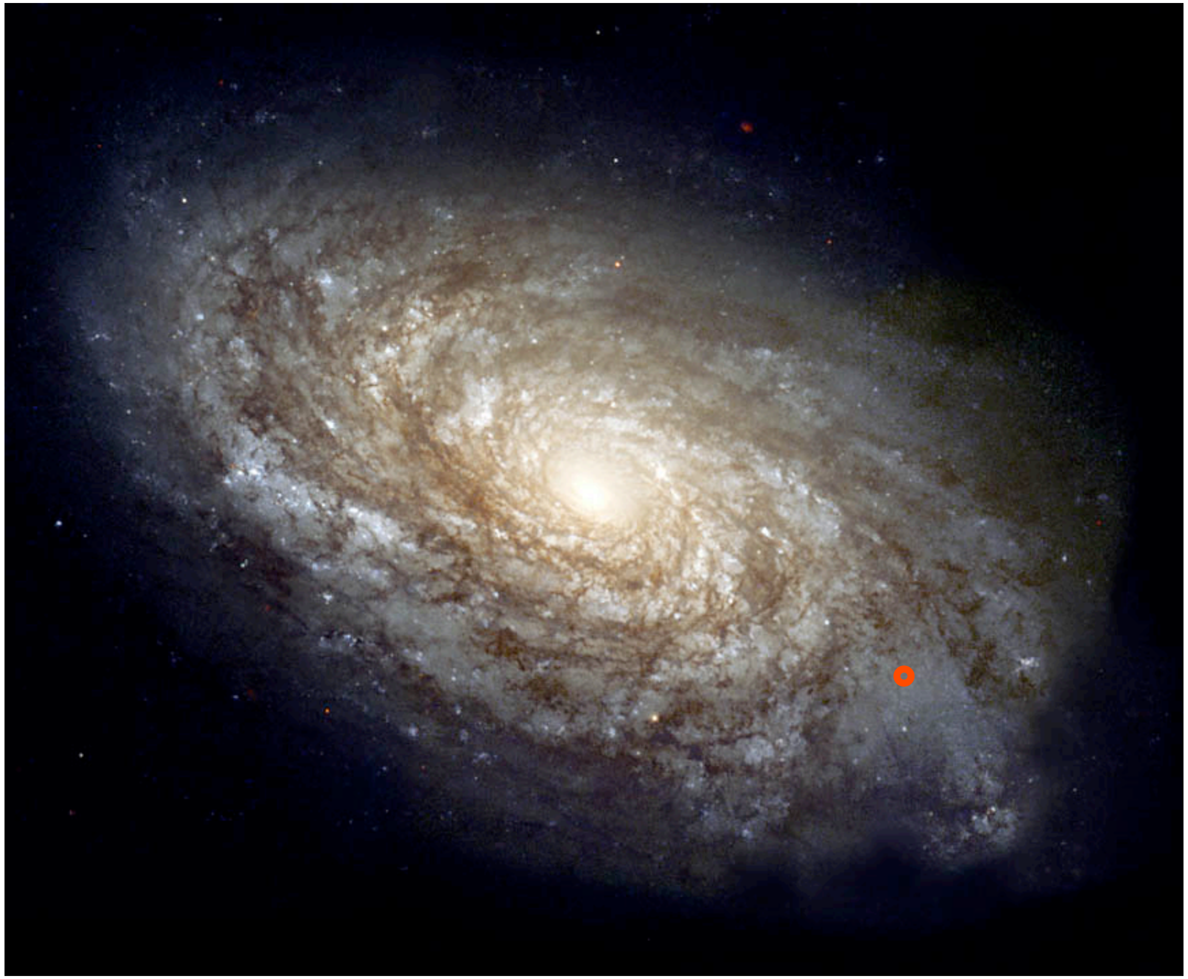
(from Kennicutt 1998)

rate limited by strength of gravitational collapse and timescale of MC formation

rate limited by star formation processes within molecular clouds

how can we distinguish between different models?

star formation on galactic scales

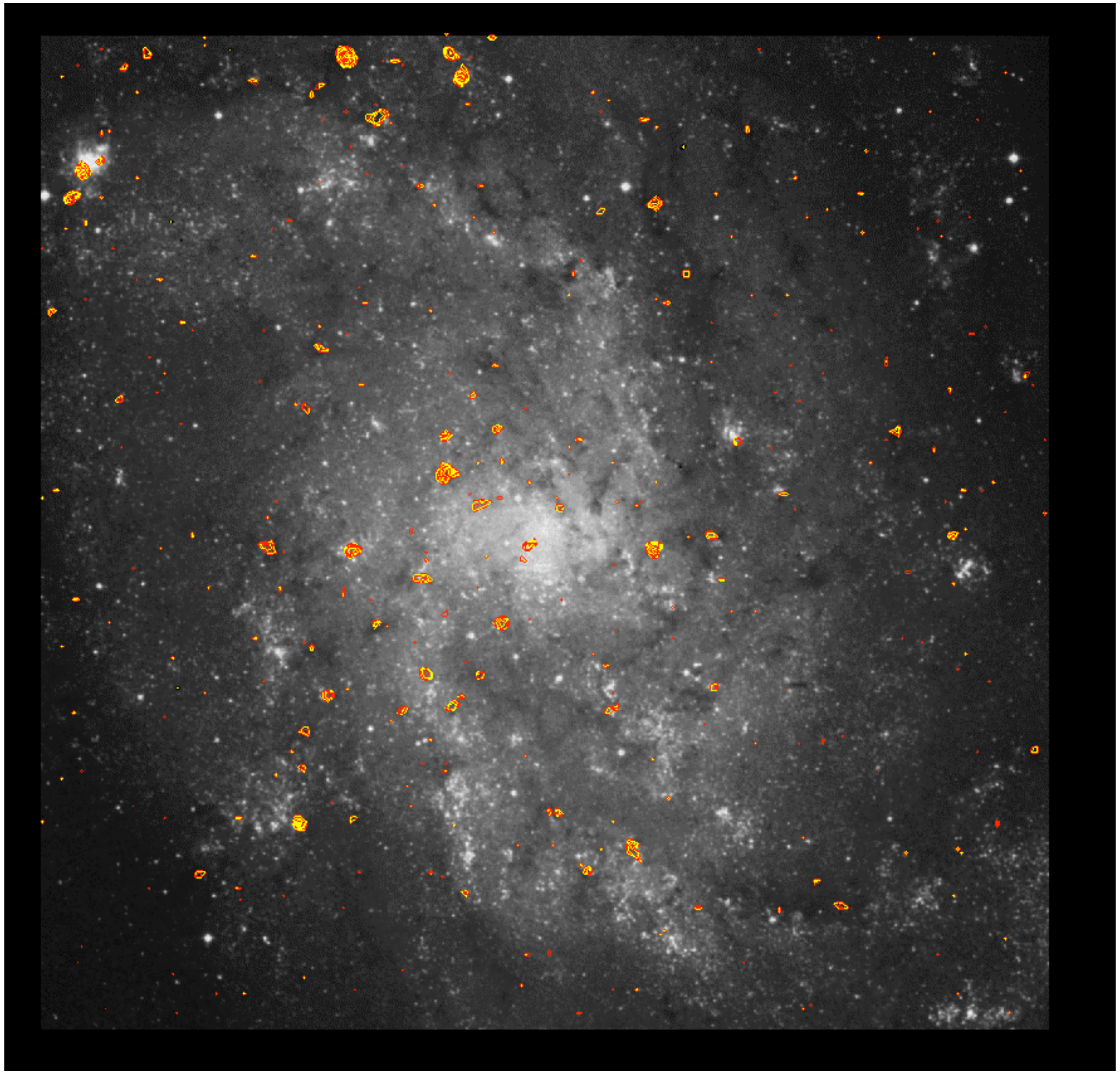


NGC4414 observed with HST

size of galaxy:
several 10 kpc

size of star-forming regions:
~ 1pc

what is the relation between global dynamics and the local process of star formation?

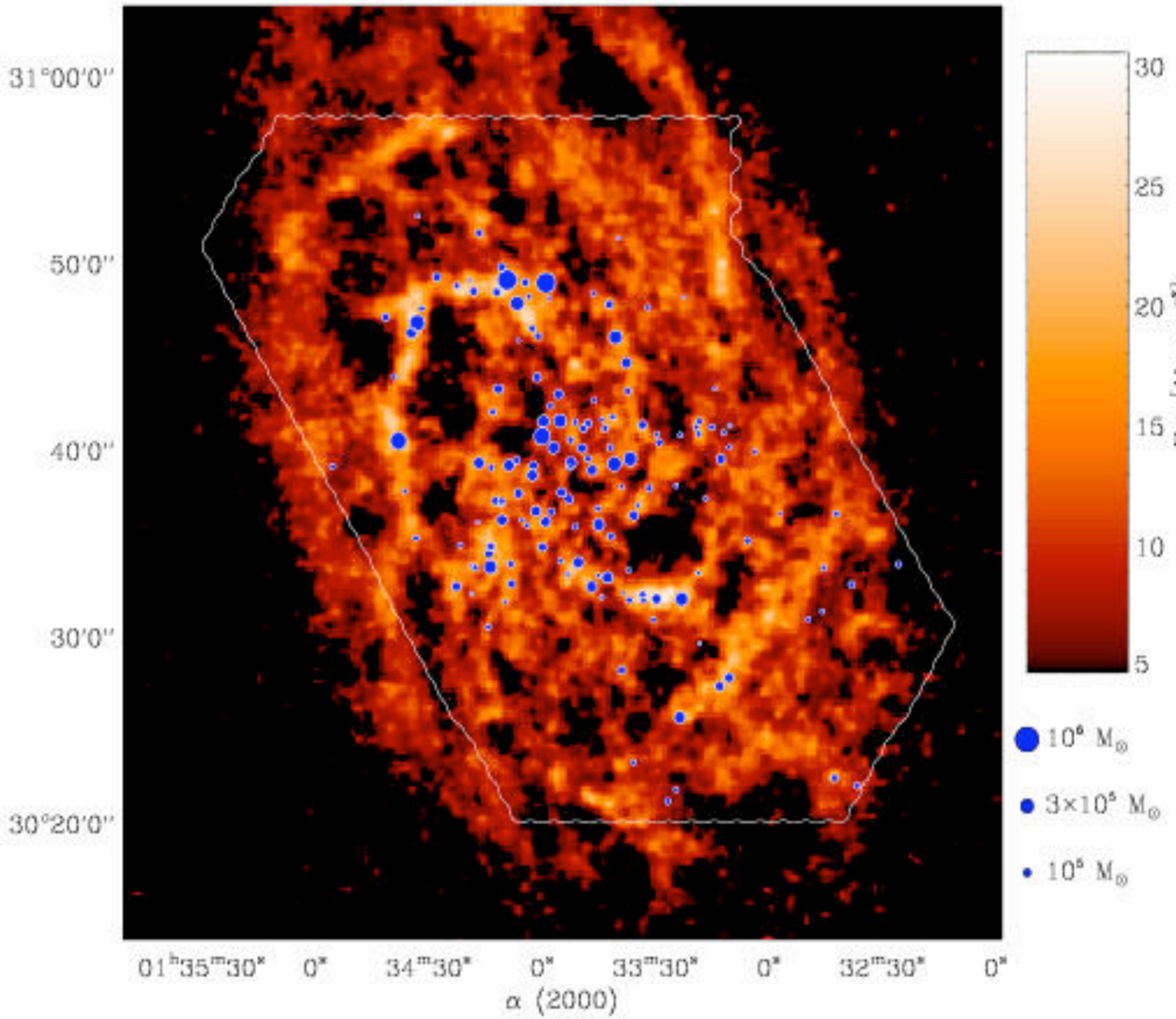


(M33 with BIMA: Blitz, Rosolowsky, Engargiola, & Plambeck)

all stars form in molecular cloud complexes

KEY ISSUE: understand formation of molecular clouds in galactic disks

correlation between H_2 and HI



Compare H_2 - HI in M33:

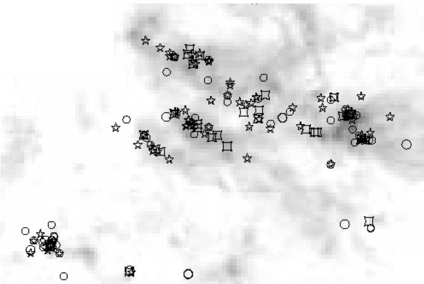
- H_2: BIMA-SONG Survey, see Blitz et al.
- HI: Observations with Westerbork Radio T.

H_2 clouds are seen in regions of high HI density
(in spiral arms and filaments)

(Deul & van der Hulst 1987, Blitz et al. 2004)

formation and evolution of MCs

- how do molecular clouds (MC) form from atomic hydrogen?
  (thermal instab. / grav. instab. / turb. compression / coagulation?)
- what are the properties of MCs?
  (density / velocity structure, chemical composition)
- how do they evolve?
  (dynamically or quasi-statically?)
- what fraction does form stars?
- how quickly?



(Taurus: Hartmann 2002)

interstellar turbulence

- determines structure of ISM (atomic & molecular gas)
- KEY ISSUE: what drives turbulence?
  - *GLOBALLY*
    - multiple supernovae (what about outer regions?)
    - gravitational instability in disk (spiral waves?)
    - gas accretion from outside (high velocity clouds?)
  - LOCALLY (on scales of MCs and SF regions)
    - process of formation (convergent flows?)
    - stellar feedback (outflows and winds?)

star cluster formation

- most stars form in clusters
- **KEY ISSUE:** how do star clusters form?
  - what triggers the process?
    (grav. instability / external compression / amb. diffusion)
  - what regulates star cluster formation?
    (turbulence / feedback / magnetic fields)
  - what is the timescale of star cluster formation?
    (slow versus fast star formation)
  - what determines the efficiency of star formation?
    (external flows / internal feedback / magnetic fields)
  - how does this vary with environment?
    (galactic center / solar neighborhood / halo)

initial mass function

- stellar properties are determined by stellar mass
- **KEY ISSUE:** what determines the IMF?
- **KEY ISSUE:** is the IMF universal?
    - IMF from turbulence / clump mass spectrum
    - IMF from gravitational interaction in dense enviroment (competitive accretion)
    - IMF set by thermodynamic properties of gas
    - IMF as purely statistical feature (central limit theorem) (random sampling of fractal cloud / closest packing problem)
    - IMF from stellar feedback

initial mass function

- IMF from thermodynamic properties of gas

Richard Larson in MNRAS, 359, 211 - 222 (2005)

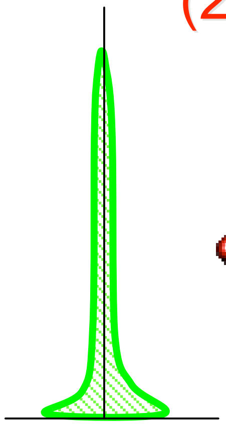
The thermal properties of star-forming clouds have an important influence on how they fragment into stars, and it is suggested in this paper that the low-mass stellar initial mass function (IMF), which appears to be almost universal, is determined largely by the thermal physics of these clouds. In particular, it is suggested that the characteristic stellar mass, a little below one solar mass, is determined by the transition from an initial cooling phase of collapse to a later phase of slowly rising temperature that occurs when the gas becomes thermally coupled to the dust. Numerical simulations support the hypothesis that the Jeans mass at this transition point plays an important role in determining the peak mass of the IMF.

(see also Y. Li et al. 2003, Jappsen et al. 2005, Bonnell et al. 2006)

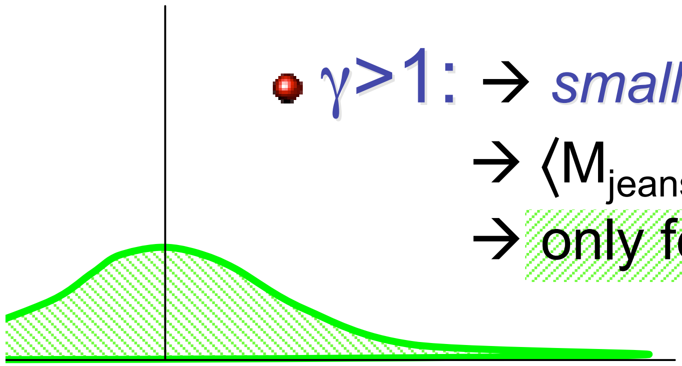
fragmentation depends on EOS

(1) $p \propto \rho^{\gamma} \rightarrow \rho \propto p^{1/\gamma}$

(2) $M_{jeans} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2}$

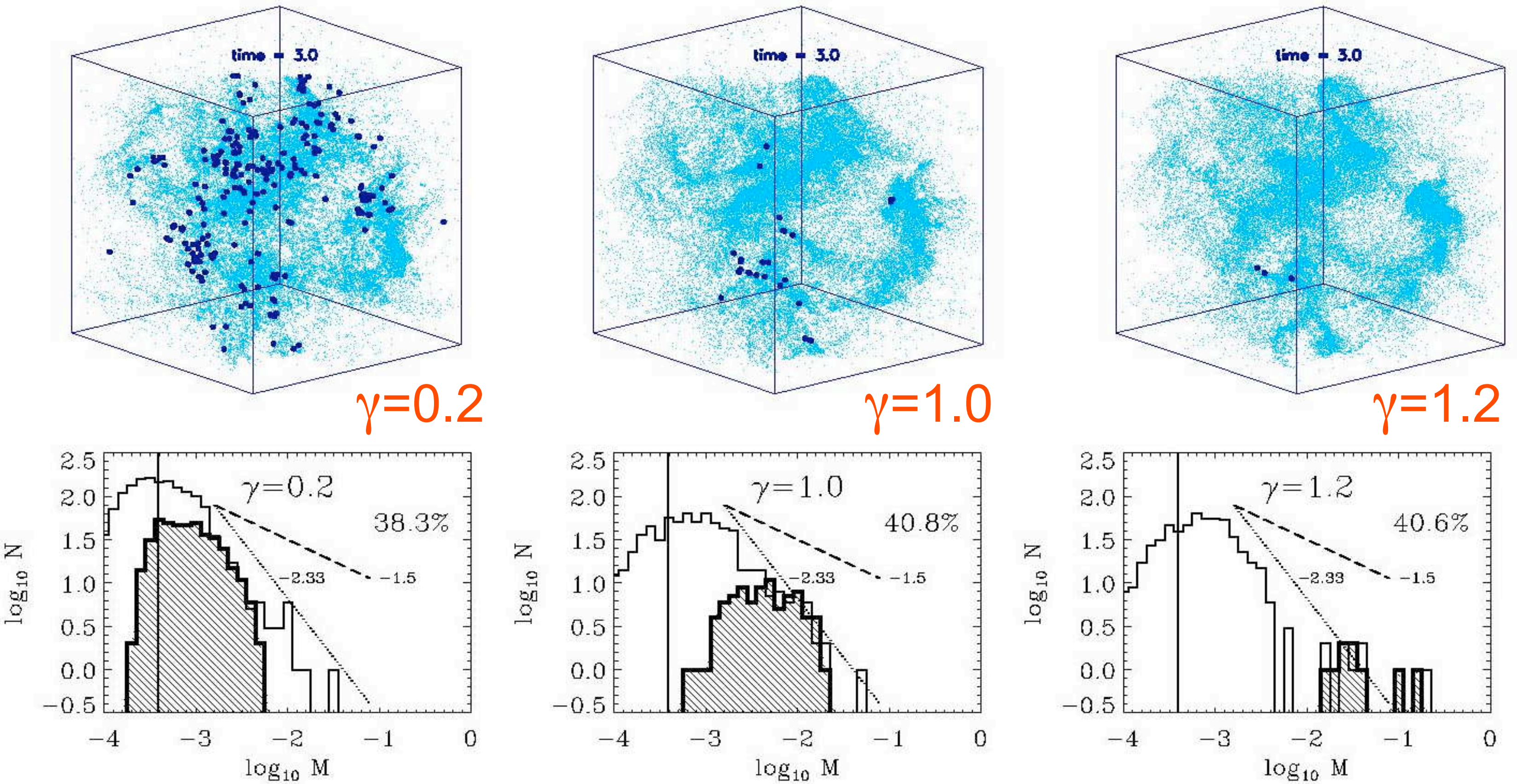


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

fragmentation depends on EOS

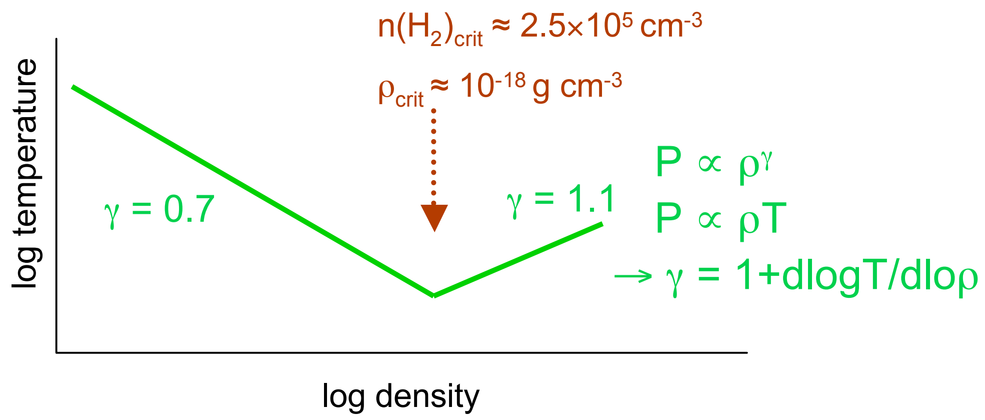


for $\gamma<1$ fragmentation is enhanced → *cluster of low-mass stars*

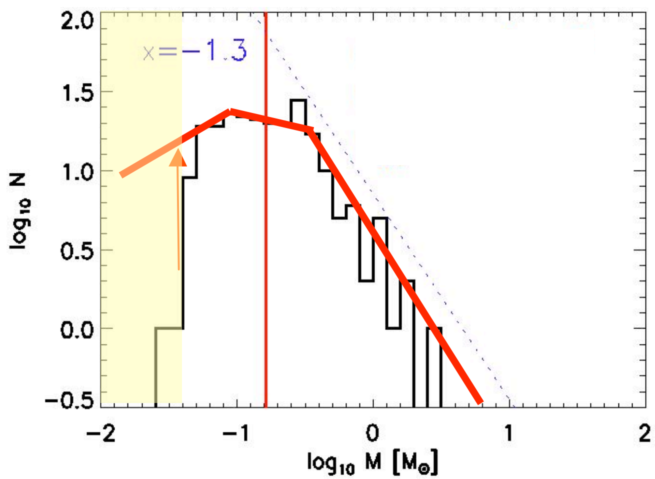
for $\gamma>1$ it is suppressed → formation of *isolated massive stars*

(from Li, Klessen, & Mac Low 2003, ApJ, 592, 975)

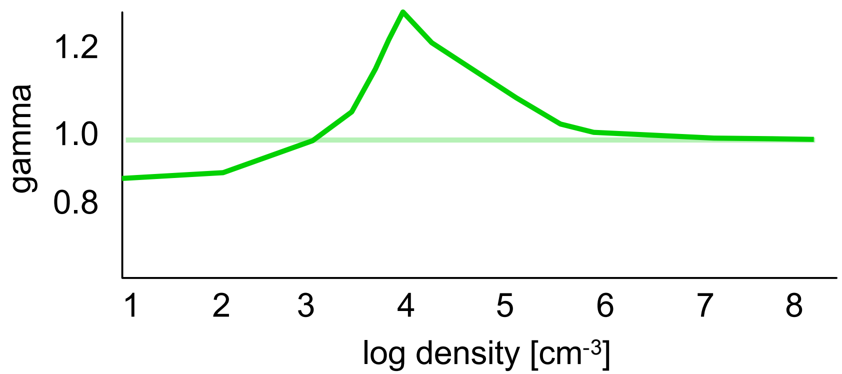
fragmentation depends on EOS



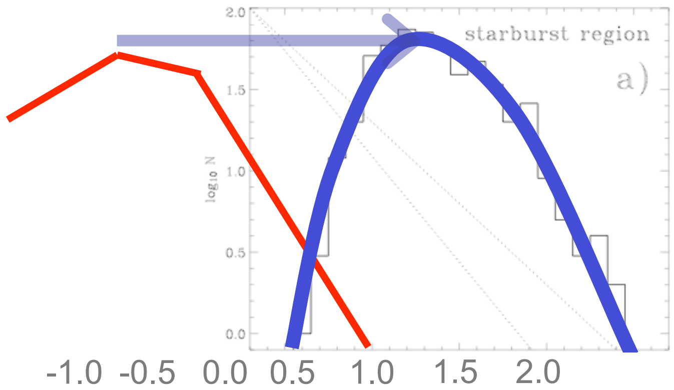
(Larson 2005)



(Jappsen et al. 2005)

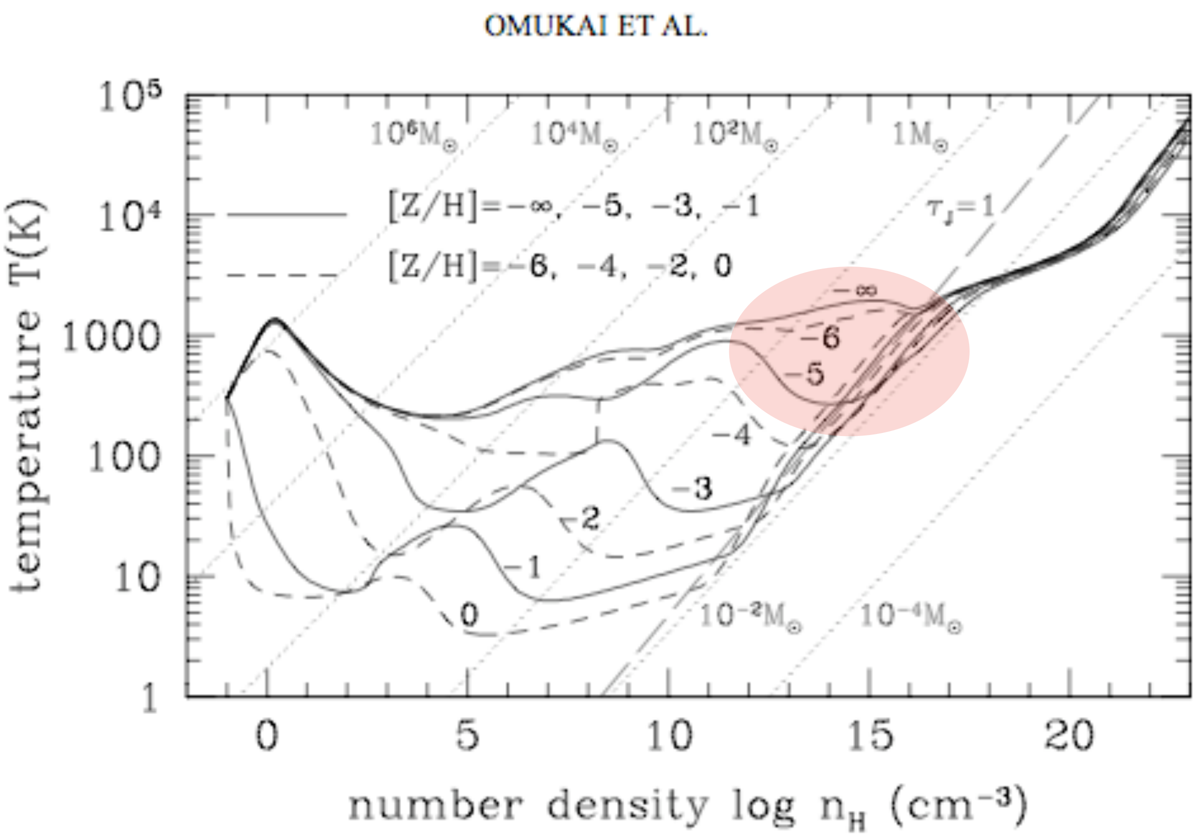


(Spaans & Silk 2005)



(Klessen et al. 2007)

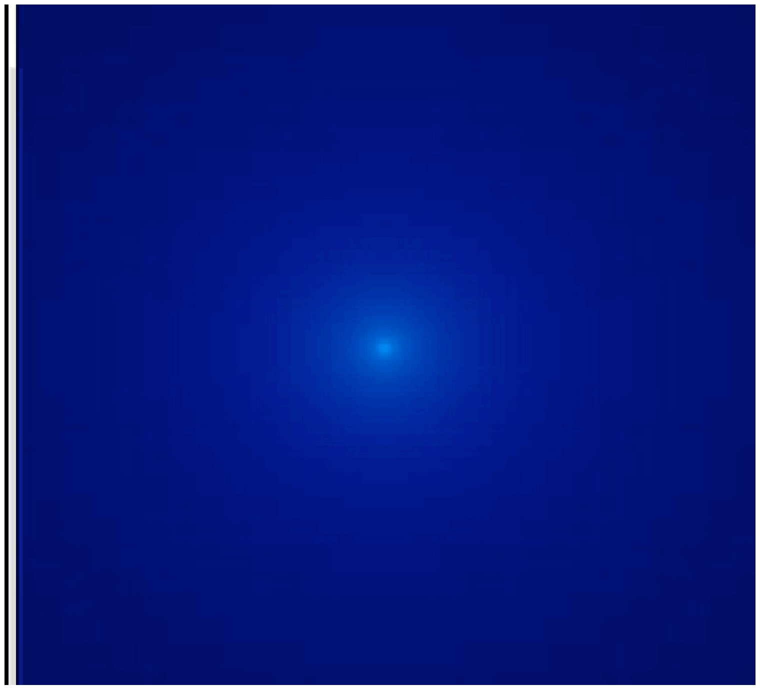
fragmentation depends on EOS



(Omukai et al. 2005, poster by P. Clark)

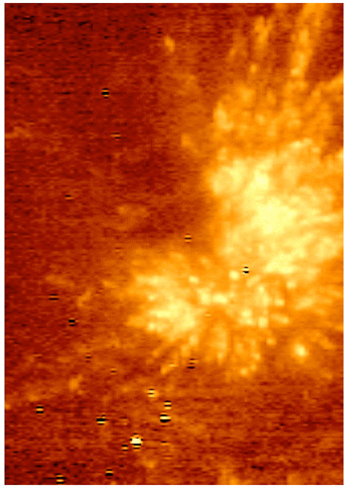
star cluster formation

- **QUESTION:**
  do stars in a cluster form from simple gravitational collapse of prestellar cores or do protostars interact and / or fragment during collapse?



massive star formation

- do massive stars form like „normal“ stars?
  or do we need to invoke „more“ physics?
  - strong effects of radiation (Eddington limit)
  - mostly in clusters: mutual interaction?
  - more complex chemistry



(BNKL: McCaughrean)

- observational questions:
  - are the disks around high-mass stars?
  - characterize feedback from winds and radiation

SF in early universe

- transition Population III to Population II.5
  (atomic fine structure lines / dust cooling)
- distribution of metals from first SN
- feedback from Pop III stars
  (positive or negative)
- initial conditions for Pop II.5 stars?
  (ionized halos stayed warm or cooled down)

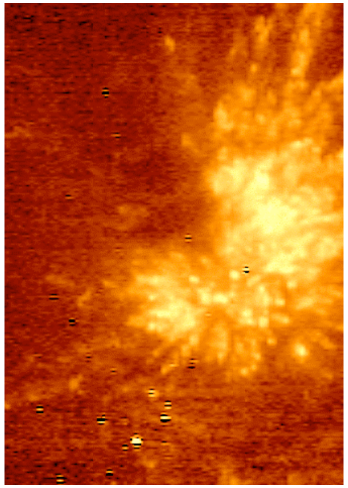
Mordecai

- Aggregation and destruction of solid objects
  - can it overcome meter-size barrier alone?
  - or at least produce enough cm-meter size objects for gravitational instability?
  - what does rapid dust coagulation imply about properties of dust in protostellar cores, disks?

- Formation of planets with migration.
  - migration of planetesimals
  - modeling with advection-diffusion equation,
  - trapping in disk transitions, resonances
  - simultaneous production of terrestrial, giant planets

- Brown dwarf formation
  - gravitational instability in disks?
  - truncated competitive accretion?
  - direct collapse from low mass end of turbulent core spectrum?

- Massive star formation
  - the high-mass end of the turbulent cloud core mass spectrum?
  - the centers of collapsing fragmenting cores winning the competition for accretion?
  - Is currently included physics (RT + HD) full story?



(BNKL: McCaughrean)

- Origin of core mass spectrum
  - (M)HD supersonic/super-Alfvénic turbulence
  - gravitational fragmentation
  - thermal instability
  - combination of all three

- Effect of metal propagation on early star formation
  - how do metals get incorporated into later generations of star formation?
  - is there a distinct primordial IMF?
  - what determines transition from primordial to modern IMF?

structure formation in the universe

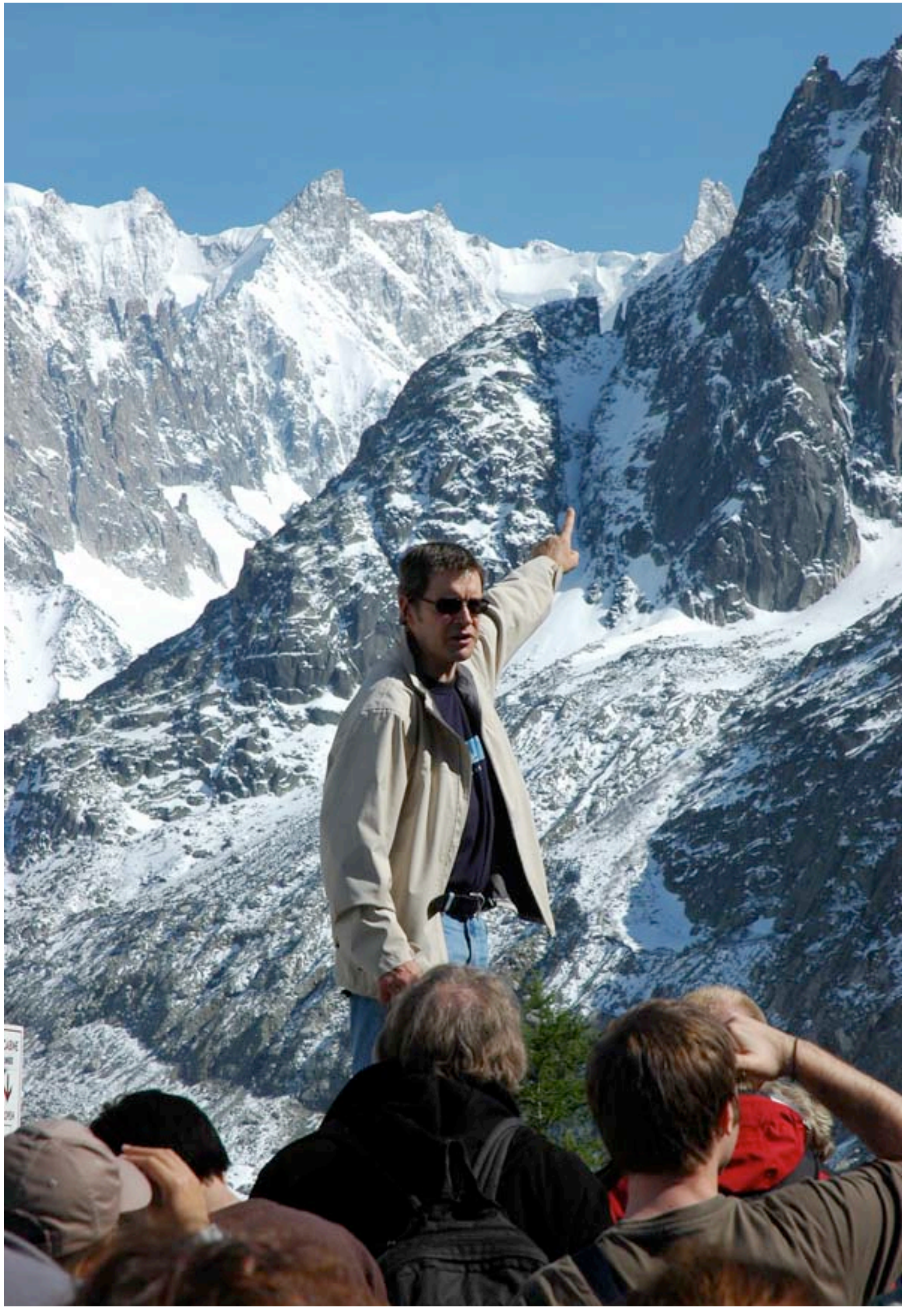
- are the problems mentioned here really all so similar?
- dosn‘t each problem require to think anew about relevant physical processes and scales?

current

- so far, most studies focus on few phys. phenomena
  - gravity
  - turbulence
  - thermal instability
  - magnetic fields
  - radiation
  - chemistry

future

- we need to integrate more physics into our numerical schemes
  (the new massively parallel computers make complex, multi-scale and multi-physics models feasible)
- yet, there will always be need for highly specialized and focused approaches
  (test of individual processes and scales)
- wealth of observational data on horizon
  (ALMA, JWST, LOFAR, panSTARRS, GAIA)



Thanks Gilles!