Magnetic fields in SPH: A star formation case study

James Wurster

Collaborators: Ian Bonnell, Matthew Bate, Clare Dobbs, Daniel Price

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University of St Andrews

University of Exeter

Monash University

DiRAC

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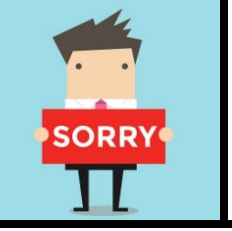
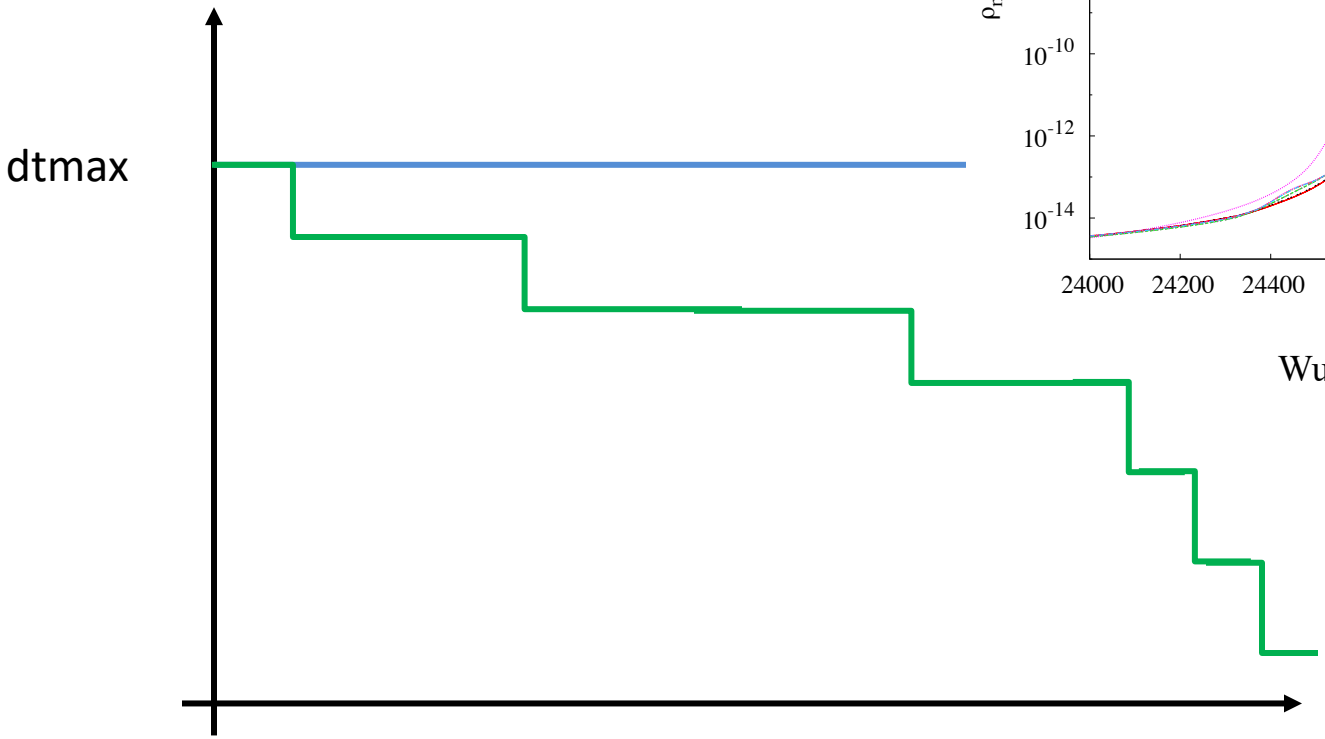
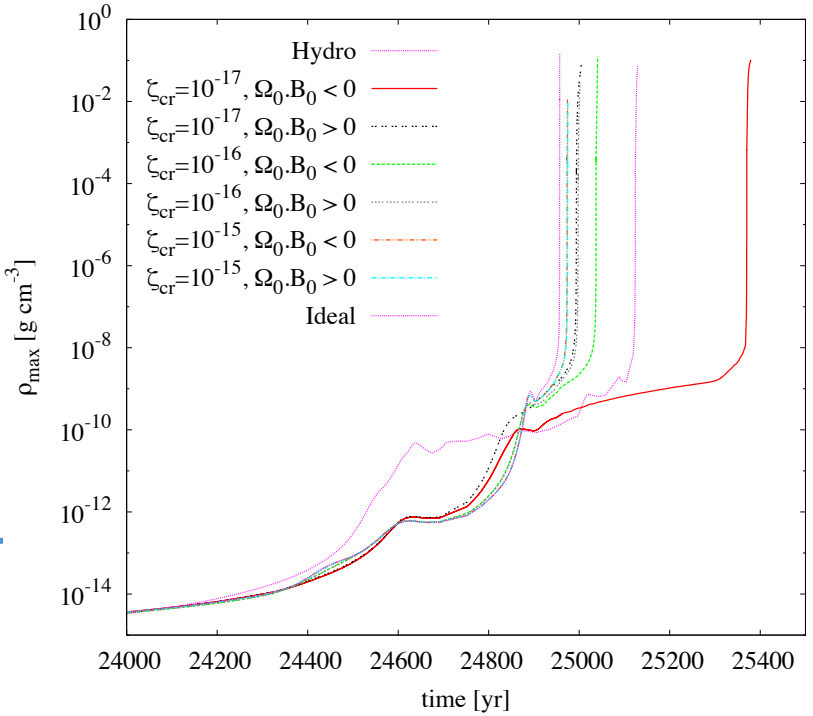


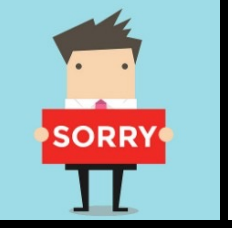
First, an apology...

- *dtmax*:
  - The simulation time between dump files
  - What most people want
  - What star formation simulations require



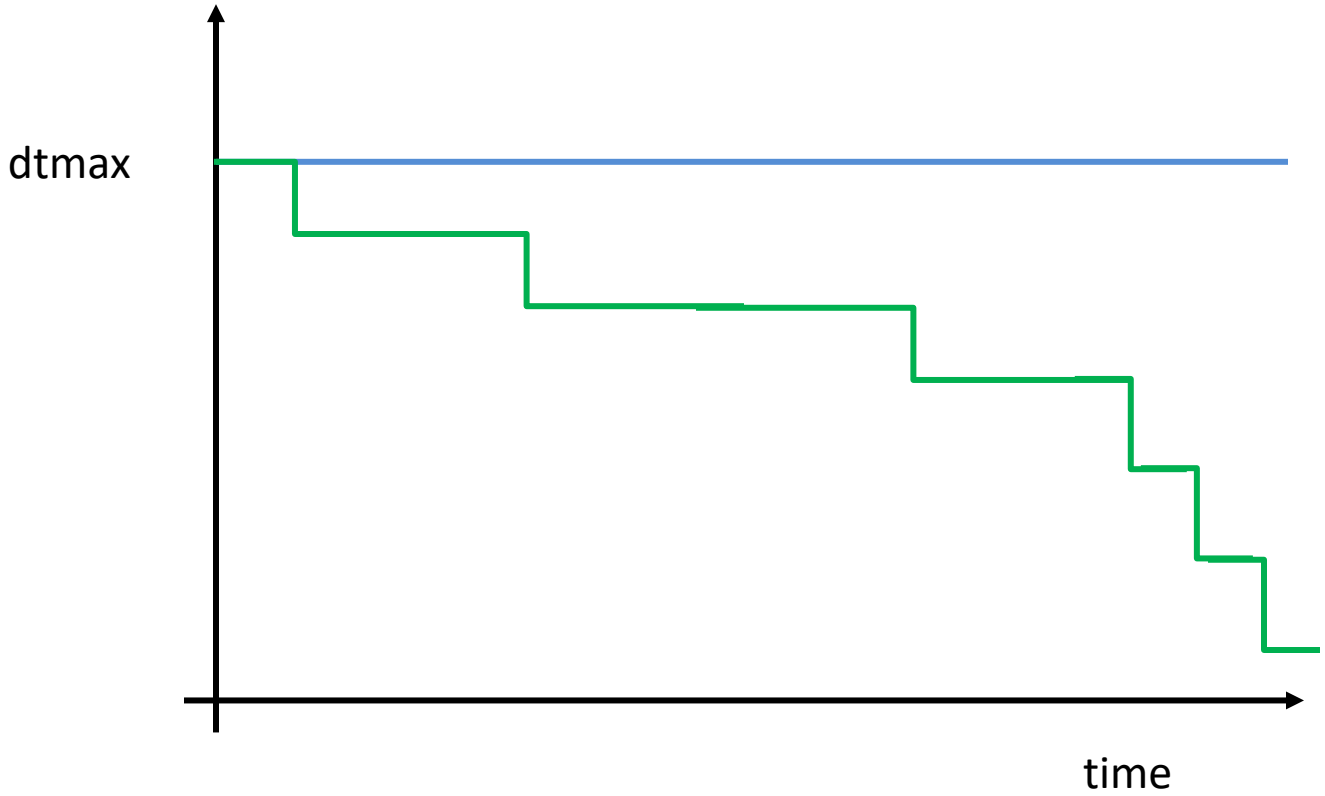


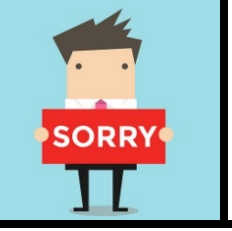
Wurster, Bate & Price (2018a,c)+



First, an apology...

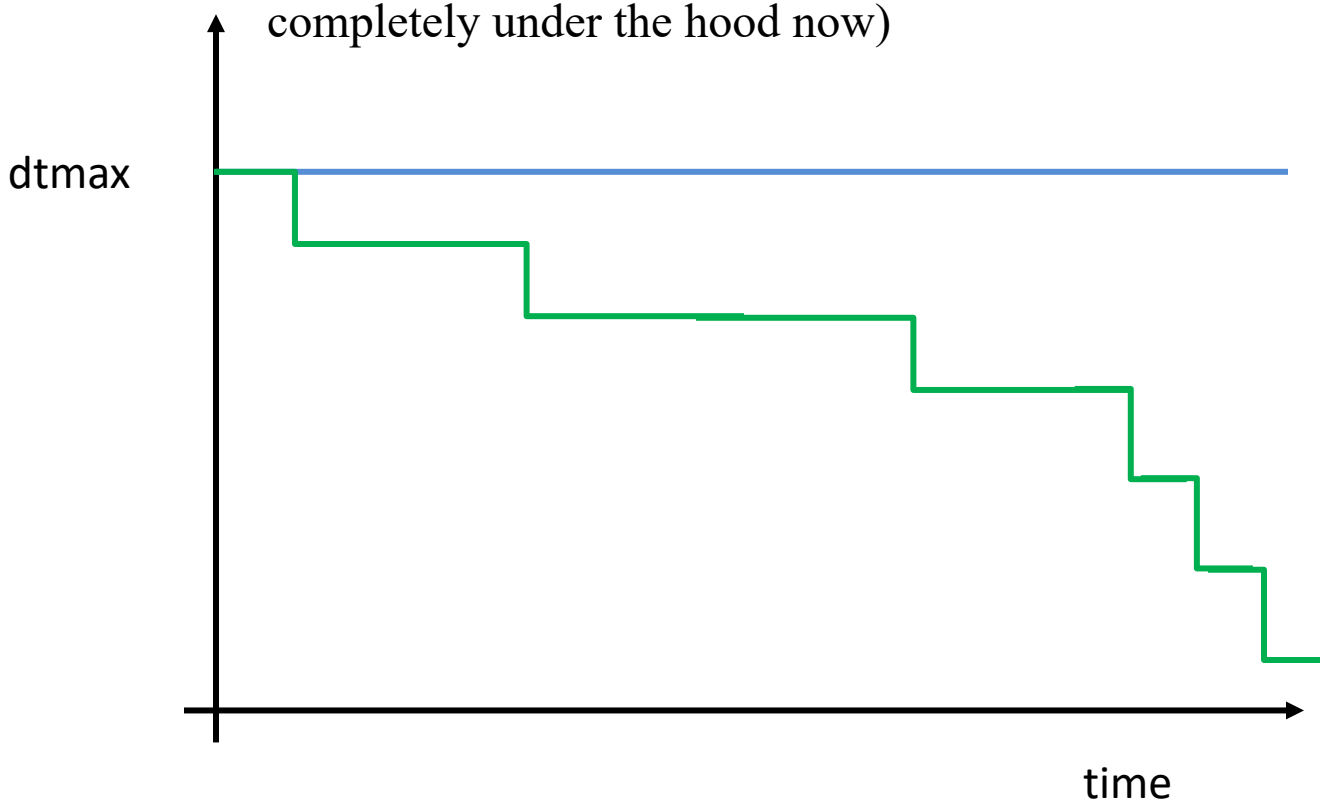
- *dtmax*:
  - The simulation time between dump files
  - What most people want
  - What star formation simulations require
  - This ( ) can also be used for optimal use of HPC clusters & prevent against from lost time due to wall-time limitations, power failures, codes crashes, etc...

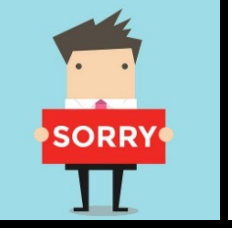




First, an apology...

- *dtmax*:
  - Now introducing the The Best of Both Worlds
  - External value of *dtmax* (i.e., the simulation time between dumps)
  - External value of *dtmax* for rapidly increasing density (optional)
  - Internal value of *dtmax* to optimise computer performance (24h by default)
- i.e., this should protect against failures/crashes while not affecting *dtmax* (and is completely under the hood now)

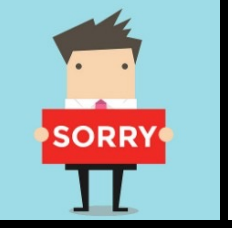




First, an apology...

- *dtmax*:
  - Example:

```
job name
           logfile =  wtimeNoDt01.log   ! file to which output is directed
          dumpfile =  wtimeNoDt_00000.tmp   ! dump file to start from

options controlling run time and input/output
              tmax =  10.7517767    ! end time
             dtmax =  0.0888576587635  ! time between dumps
              nmax =          -1    ! maximum number of timesteps (0=just get derivs and stop)
              nout =          -1    ! write dumpfile every n dtmax (-ve=ignore)
         nmaxdumps =          -1    ! stop after n full dumps (-ve=ignore)
          twallmax =      000:00    ! maximum wall time (hhh:mm, 000:00=ignore)
         dtwallmax =      024:00    ! maximum wall time between dumps (hhh:mm, 000:00=ignore)
         nfulldump =           1    ! full dump every n dumps
          iverbose =           0    ! verboseness of log (-1=quiet 0=default 1=allsteps 2=debug 5=max)

options controlling run time and input/output: supplementary features
      rhofinal_cgs =       0.000    ! maximum allowed density (cgs) (<=0 to ignore)
      dtmax_dratio =       1.258    ! dynamic dtmax: density ratio controlling decrease (<=0 to ignore)
         dtmax_max =  0.0888665445294  ! dynamic dtmax: maximum allowed dtmax (=dtmax if <= 0)
         dtmax_min =  0.0111070685071  ! dynamic dtmax: minimum allowed dtmax
         calc_erot =           T    ! include E_rot in the ev_file

options controlling accuracy
           C_cour =       0.300    ! Courant number
          C_force =       0.250    ! dt_force number
             tolv =   1.000E-02    ! tolerance on v iterations in timestepping
            hfact =       1.200    ! h in units of particle spacing [h = hfact(m/rho)^(1/3)]
             tolh =   1.000E-04    ! tolerance on h-rho iterations
     tree_accuracy =       0.500    ! tree opening criterion (0.0-1.0)

options controlling hydrodynamics, artificial dissipation
            alpha =       0.000    ! MINIMUM shock viscosity parameter
         alphamax =       1.000    ! MAXIMUM shock viscosity parameter
             beta =       2.000    ! beta viscosity

options controlling damping
```



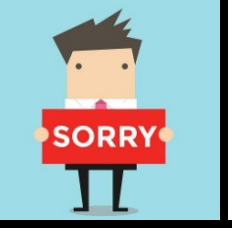
First, an apology...

- *dtmax*:
  - Example:

```
Terminal  Shell  Edit  View  Window  Help
~/rundir/phantom_out/ArroyoJuly — Python                    ~/rundir/phantom

--------->   TIME =    0.000    : full dump written to file wtimeAgain_00000   <---------

 input file wtimeAgain.in written successfully.

 ---> DELETING temporary dump file wtimeAgain_00000.tmp <---

 t =  0.30722E-01 dt =  3.103E-02 (courant), np = 438815
 t =  0.61753E-01 dt =  2.710E-02 (dtprint)
 t =  0.88886E-01 dt =  2.953E-02 (courant)
 modifying dtmax internally due to wall time constraint.  Increasing to    2 sub-dumps

--------->   TIME =   0.8886E-01: full dump written to file wtimeAgain_00001   <---------

 input file wtimeAgain.in written successfully.
 Since code start: 3 timesteps, wall: 19s cpu: 114s cpu/wall: 5.9
 Since last dump : 3 timesteps, wall: 19s cpu: 114s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal      frac
 ├─step             :    19.31s     113.71s      5.89   100.00%    99.04%
 │ ├─tree           :     0.69s       1.86s      2.71   100.00%     3.53%
 │ │ └─balance      :
 │ ├─density        :     6.88s      41.19s      5.99   100.00%    35.26%
 │ │ ├─local        :     6.88s      41.19s      5.99   100.00%    35.26%
 │ │ └─remote       :
 │ ├─force          :    11.75s      70.18s      5.97   100.00%    60.26%
 │ │ ├─local        :    11.69s      69.91s      5.98   100.00%    59.94%
 │ │ └─remote       :
 │ ├─cons2prim      :
 │ └─extf           :
 ├─write_ev         :     0.06s       0.15s      2.36   100.00%     0.32%
 └─write_dump       :     0.12s       0.13s      1.03   100.00%     0.64%
 npart=    438815, n_alive=    438815, n_dead_or_accreted=         0, nptmass=         0
 Etot=-1.729E-01, Ekin= 8.881E-04, Etherm= 5.416E-02, Epot=-2.279E-01
 Linm= 8.446E-06, Angm= 9.830E-02
 Centre of Mass =  4.556E-07, -2.038E-07, -2.472E-08
 density  (max)= 3.836E-03 (mean)= 2.545E-03 (max)= 7.629E-18 g/cm^3
 alpha(max)= 1.000E+00
 RMS Mach #= 1.724E-01

 t =  0.11821     dt =  2.953E-02 (dtmax)
 t =  0.13329     dt =  2.845E-02 (courant)
 modifying dtmax internally due to wall time constraint.  Increasing to    4 sub-dumps

--------->   TIME =   0.1333    : full dump written to file wtimeAgain.restart   <---------
--------->                        Writing sub-dumps:    1 of   2                <---------

 input file wtimeAgain.in written successfully.
 Since code start: 5 timesteps, wall: 33s cpu: 191s cpu/wall: 5.9
 Since last dump : 2 timesteps, wall: 13s cpu: 77s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal      frac
 ├─step             :    13.06s      76.73s      5.87   100.00%    99.05%
 │ ├─tree           :     0.38s       1.28s      3.42   100.00%     2.84%
 │ │ └─balance      :
 │ ├─density        :     4.44s      26.37s      5.94   100.00%    33.65%
 │ │ ├─local        :     4.44s      26.37s      5.94   100.00%    33.65%
 │ │ └─remote       :
 │ ├─force          :     8.19s      48.76s      5.96   100.00%    62.09%
 │ │ ├─local        :     8.12s      48.57s      5.98   100.00%    61.61%
 │ │ └─remote       :
 │ ├─cons2prim      :
 │ └─extf           :
```

```
Terminal  Shell  Edit  View  Window  Help
~/rundir/phantom_out/ArroyoJuly — Python                    ~/rundir/phantom

--------->   TIME =    0.1777    : full dump written to file wtimeAgain_00002   <---------

 input file wtimeAgain.in written successfully.
 Since code start: 7 timesteps, wall: 46s cpu: 266s cpu/wall: 5.8
 Since last dump : 1 timesteps, wall: 6.2s cpu: 37s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal      frac
 ├─step             :     6.25s      36.72s      5.87   100.00%    97.09%
 │ ├─tree           :     0.19s       0.62s      3.28   100.00%     2.91%
 │ │ └─balance      :
 │ ├─density        :     2.12s      12.80s      6.02   100.00%    33.01%
 │ │ ├─local        :     2.12s      12.80s      6.02   100.00%    33.01%
 │ │ └─remote       :
 │ ├─force          :     3.88s      23.15s      5.97   100.00%    60.19%
 │ │ ├─local        :     3.88s      23.06s      5.95   100.00%    60.19%
 │ │ └─remote       :
 │ ├─cons2prim      :
 │ └─extf           :
 ├─write_ev         :     0.06s       0.07s      1.14   100.00%     0.97%
 └─write_dump       :     0.12s       0.12s      0.98   100.00%     1.94%
 npart=    438815, n_alive=    438815, n_dead_or_accreted=         0, nptmass=         0
 Etot=-1.726E-01, Ekin= 1.160E-03, Etherm= 5.416E-02, Epot=-2.279E-01
 Linm= 8.875E-06, Angm= 9.831E-02
 Centre of Mass =  9.305E-07, -4.212E-07, -9.433E-08
 density  (max)= 3.787E-03 (mean)= 2.545E-03 (max)= 7.533E-18 g/cm^3
 alpha(max)= 1.000E+00
 RMS Mach #= 1.803E-01

 t =  0.19993     dt =  2.221E-02 (dtmax)

--------->   TIME =    0.1999    : full dump written to file wtimeAgain.restart   <---------
--------->                        Writing sub-dumps:    1 of   4                <---------

 input file wtimeAgain.in written successfully.
 Since code start: 8 timesteps, wall: 53s cpu: 307s cpu/wall: 5.8
 Since last dump : 1 timesteps, wall: 6.8s cpu: 40s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal      frac
 ├─step             :     6.81s      40.50s      5.94   100.00%    98.20%
 │ ├─tree           :     0.19s       0.59s      3.17   100.00%     2.70%
 │ │ └─balance      :
 │ ├─density        :     2.06s      12.76s      6.19   100.00%    29.73%
 │ │ ├─local        :     2.06s      12.76s      6.19   100.00%    29.73%
 │ │ └─remote       :
 │ ├─force          :     4.56s      26.98s      5.91   100.00%    65.77%
 │ │ ├─local        :     4.50s      26.88s      5.97   100.00%    64.86%
 │ │ └─remote       :
 │ ├─cons2prim      :
 │ └─extf           :
 ├─write_ev         :
 └─write_dump       :     0.12s       0.14s      1.08   100.00%     1.80%
 npart=    438815, n_alive=    438815, n_dead_or_accreted=         0, nptmass=         0
 Etot=-1.726E-01, Ekin= 1.225E-03, Etherm= 5.416E-02, Epot=-2.279E-01
 Linm= 8.974E-06, Angm= 9.831E-02
 Centre of Mass =  1.052E-06, -4.774E-07, -1.181E-07
 density  (max)= 3.799E-03 (mean)= 2.545E-03 (max)= 7.557E-18 g/cm^3
 alpha(max)= 1.000E+00
 RMS Mach #= 1.827E-01

 t =  0.22214     dt =  2.221E-02 (dtmax)
```

```
Terminal  Shell  Edit  View  Window  Help
~/rundir/phantom_out/ArroyoJuly — Python                    ~/rundir/phantom

--------->   TIME =    0.2221    : full dump written to file wtimeAgain.restart   <---------
--------->                        Writing sub-dumps:    2 of   4                <---------

 input file wtimeAgain.in written successfully.
 Since code start: 9 timesteps, wall: 59s cpu: 345s cpu/wall: 5.8
 Since last dump : 1 timesteps, wall: 6.5s cpu: 38s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal      frac
 ├─step             :     6.50s      38.30s      5.89   100.00%    97.20%
 │ ├─tree           :     0.25s       0.66s      2.66   100.00%     3.74%
 │ │ └─balance      :
 │ ├─density        :     2.25s      13.36s      5.94   100.00%    33.64%
 │ │ ├─local        :     2.25s      13.36s      5.94   100.00%    33.64%
 │ │ └─remote       :
 │ ├─force          :     4.00s      24.11s      6.03   100.00%    59.81%
 │ │ ├─local        :     4.00s      24.02s      6.01   100.00%    59.81%
 │ │ └─remote       :
 │ ├─cons2prim      :
 │ └─extf           :
 ├─write_ev         :     0.06s       0.07s      1.18   100.00%     0.93%
 └─write_dump       :     0.12s       0.13s      1.04   100.00%     1.87%
 npart=    438815, n_alive=    438815, n_dead_or_accreted=         0, nptmass=         0
 Etot=-1.725E-01, Ekin= 1.283E-03, Etherm= 5.416E-02, Epot=-2.280E-01
 Linm= 9.035E-06, Angm= 9.831E-02
 Centre of Mass =  1.174E-06, -5.343E-07, -1.437E-07
 density  (max)= 3.816E-03 (mean)= 2.545E-03 (max)= 7.590E-18 g/cm^3
 alpha(max)= 1.000E+00
 RMS Mach #= 1.853E-01

 t =  0.24436     dt =  2.221E-02 (dtmax)

--------->   TIME =    0.2444    : full dump written to file wtimeAgain.restart   <---------
--------->                        Writing sub-dumps:    3 of   4                <---------

 input file wtimeAgain.in written successfully.
 Since code start: 10 timesteps, wall: 66s cpu: 382s cpu/wall: 5.8
 Since last dump : 1 timesteps, wall: 6.2s cpu: 37s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal      frac
 ├─step             :     6.25s      36.66s      5.87   100.00%    98.04%
 │ ├─tree           :     0.19s       0.63s      3.38   100.00%     2.94%
 │ │ └─balance      :
 │ ├─density        :     2.12s      12.72s      5.99   100.00%    33.33%
 │ │ ├─local        :     2.12s      12.72s      5.99   100.00%    33.33%
 │ │ └─remote       :
 │ ├─force          :     3.88s      23.15s      5.97   100.00%    60.78%
 │ │ ├─local        :     3.81s      23.06s      6.05   100.00%    59.80%
 │ │ └─remote       :
 │ ├─cons2prim      :     0.06s       0.05s      0.88   100.00%     0.98%
 │ └─extf           :
 ├─write_ev         :
 └─write_dump       :     0.12s       0.12s      0.96   100.00%     1.96%
 npart=    438815, n_alive=    438815, n_dead_or_accreted=         0, nptmass=         0
 Etot=-1.725E-01, Ekin= 1.333E-03, Etherm= 5.416E-02, Epot=-2.280E-01
 Linm= 9.085E-06, Angm= 9.831E-02
 Centre of Mass =  1.297E-06, -5.921E-07, -1.708E-07
 density  (max)= 3.833E-03 (mean)= 2.545E-03 (max)= 7.625E-18 g/cm^3
 alpha(max)= 1.000E+00
 RMS Mach #= 1.879E-01

 t =  0.26657     dt =  2.221E-02 (dtmax)

--------->   TIME =    0.2666    : full dump written to file wtimeAgain_00003   <---------
```



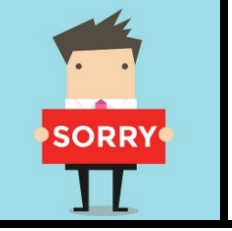
First, an apology...

- *dtmax*:
  - Example:

```
Terminal  Shell  Edit  View  Window  Help
~/rundir/phantom_out/ArroyoJuly — Python                    ~/rundir/phantom

--------->   TIME =    0.000    : full dump written to file wtimeAgain_00000   <---------

 input file wtimeAgain.in written successfully.

 ---> DELETING temporary dump file wtimeAgain_00000.tmp <---

 t =  0.30722E-01 dt =  3.103E-02 (courant), np = 438815
 t =  0.61753E-01 dt =  2.710E-02 (dtprint)
 t =  0.88858E-01 dt =  2.935E-02 (courant)
 modifying dtmax internally due to wall time constraint.  Increasing to    2 sub-dumps

--------->   TIME =    0.8886E-01: full dump written to file wtimeAgain_00001   <---------

 input file wtimeAgain.in written successfully.
 Since code start: 3 timesteps, wall: 19s cpu: 114s cpu/wall: 5.9
 Since last dump : 3 timesteps, wall: 19s cpu: 114s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal      frac
 ├─step             :    19.31s     113.71s      5.89   100.00%    99.04%
 │ ├─tree           :     0.69s       1.86s      2.71   100.00%     3.53%
 │ │ └─balance      :
 │ ├─density        :     6.88s      41.19s      5.99   100.00%    35.26%
 │ │ ├─local        :     6.88s      41.19s      5.99   100.00%    35.26%
 │ │ └─remote       :
 │ ├─force          :    11.75s      70.18s      5.97   100.00%    60.26%
 │ │ ├─local        :    11.69s      69.91s      5.98   100.00%    59.94%
 │ │ └─remote       :
 │ ├─cons2prim      :
 │ └─extf           :
 ├─write_ev         :     0.06s       0.15s      2.36   100.00%     0.32%
 └─write_dump       :     0.12s       0.13s      1.03   100.00%     0.64%
 npart=    438815, n_alive=    438815, n_dead_or_accreted=         0, nptmass=         0
 Etot=-1.729E-01, Ekin= 8.881E-04, Etherm= 5.416E-02, Epot=-2.279E-01
 Linm= 8.446E-06, Angm= 9.830E-02
 Centre of Mass =  4.556E-07, -2.038E-07, -2.472E-08
 density  (max)= 3.836E-03 (mean)= 2.545E-03 (max)= 7.629E-18 g/cm^3
 alpha(max)= 1.000E+00
 RMS Mach #= 1.724E-01


 t =  0.11821     dt =  1.508E-02 (dtprint)
 t =  0.13329     dt =  2.845E-02 (courant)
 modifying dtmax internally due to wall time constraint.  Increasing to    4 sub-dumps

-------->   TIME =    0.1333    : full dump written to file wtimeAgain.restart   <---------
-------->                         Writing sub-dumps:    1 of   2                 <---------

 input file wtimeAgain.in written successfully.
 Since code start: 5 timesteps, wall: 33s cpu: 191s cpu/wall: 5.9
 Since last dump : 2 timesteps, wall: 13s cpu: 77s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal      frac
 ├─step             :    13.06s      76.73s      5.87   100.00%    99.05%
 │ ├─tree           :     0.38s       1.28s      3.42   100.00%     2.84%
 │ │ └─balance      :
 │ ├─density        :     4.44s      26.37s      5.94   100.00%    33.65%
 │ │ ├─local        :     4.44s      26.37s      5.94   100.00%    33.65%
 │ │ └─remote       :
 │ ├─force          :     8.19s      48.76s      5.96   100.00%    62.09%
 │ │ ├─local        :     8.12s      48.57s      5.98   100.00%    61.61%
 │ │ └─remote       :
 │ ├─cons2prim      :
 │ └─extf           :
```

```
Terminal  Shell  Edit  View  Window  Help
~/rundir/phantom_out/ArroyoJuly — Python                    ~/rundir/phantom

-------->   TIME =    0.1777    : full dump written to file wtimeAgain_00002   <---------

 input file wtimeAgain.in written successfully.
 Since code start: 7 timesteps, wall: 46s cpu: 266s cpu/wall: 5.8
 Since last dump : 1 timesteps, wall: 6.2s cpu: 37s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal      frac
 ├─step             :     6.25s      36.72s      5.87   100.00%    97.09%
 │ ├─tree           :     0.19s       0.62s      3.28   100.00%     2.91%
 │ │ └─balance      :
 │ ├─density        :     2.12s      12.80s      6.02   100.00%    33.01%
 │ │ ├─local        :     2.12s      12.80s      6.02   100.00%    33.01%
 │ │ └─remote       :
 │ ├─force          :     3.88s      23.15s      5.97   100.00%    60.19%
 │ │ ├─local        :     3.88s      23.06s      5.95   100.00%    60.19%
 │ │ └─remote       :
 │ ├─cons2prim      :
 │ └─extf           :
 ├─write_ev         :     0.06s       0.07s      1.14   100.00%     0.97%
 └─write_dump       :     0.12s       0.12s      0.98   100.00%     1.94%
 npart=    438815, n_alive=    438815, n_dead_or_accreted=         0, nptmass=         0
 Etot=-1.726E-01, Ekin= 1.160E-03, Etherm= 5.416E-02, Epot=-2.279E-01
 Linm= 8.875E-06, Angm= 9.831E-02
 Centre of Mass =  9.305E-07, -4.212E-07, -9.433E-08
 density  (max)= 3.787E-03 (mean)= 2.545E-03 (max)= 7.533E-18 g/cm^3
 alpha(max)= 1.000E+00
 RMS Mach #= 1.803E-01


 t =  0.19993     dt =  2.221E-02 (dtmax)

-------->   TIME =    0.1999    : full dump written to file wtimeAgain.restart   <---------
-------->                         Writing sub-dumps:    1 of   4                 <---------

 input file wtimeAgain.in written successfully.
 Since code start: 8 timesteps, wall: 53s cpu: 307s cpu/wall: 5.8
 Since last dump : 1 timesteps, wall: 6.8s cpu: 40s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal      frac
 ├─step             :     6.81s      40.50s      5.94   100.00%    98.20%
 │ ├─tree           :     0.19s       0.59s      3.17   100.00%     2.70%
 │ │ └─balance      :
 │ ├─density        :     2.06s      12.76s      6.19   100.00%    29.73%
 │ │ ├─local        :     2.06s      12.76s      6.19   100.00%    29.73%
 │ │ └─remote       :
 │ ├─force          :     4.56s      26.98s      5.91   100.00%    65.77%
 │ │ ├─local        :     4.50s      26.88s      5.97   100.00%    64.86%
 │ │ └─remote       :
 │ ├─cons2prim      :
 │ └─extf           :
 ├─write_ev         :
 └─write_dump       :     0.12s       0.14s      1.08   100.00%     1.80%
 npart=    438815, n_alive=    438815, n_dead_or_accreted=         0, nptmass=         0
 Etot=-1.726E-01, Ekin= 1.225E-03, Etherm= 5.416E-02, Epot=-2.279E-01
 Linm= 8.974E-06, Angm= 9.831E-02
 Centre of Mass =  1.052E-06, -4.774E-07, -1.181E-07
 density  (max)= 3.799E-03 (mean)= 2.545E-03 (max)= 7.557E-18 g/cm^3
 alpha(max)= 1.000E+00
 RMS Mach #= 1.827E-01


 t =  0.22214     dt =  2.221E-02 (dtmax)
```

```
Terminal  Shell  Edit  View  Window  Help
~/rundir/phantom_out/ArroyoJuly — Python                    ~/rundir/phantom

-------->   TIME =    0.2221    : full dump written to file wtimeAgain.restart   <---------
-------->                         Writing sub-dumps:    2 of   4                 <---------

 input file wtimeAgain.in written successfully.
 Since code start: 9 timesteps, wall: 59s cpu: 345s cpu/wall: 5.8
 Since last dump : 1 timesteps, wall: 6.5s cpu: 38s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal      frac
 ├─step             :     6.50s      38.30s      5.89   100.00%    97.20%
 │ ├─tree           :     0.25s       0.66s      2.66   100.00%     3.74%
 │ │ └─balance      :
 │ ├─density        :     2.25s      13.36s      5.94   100.00%    33.64%
 │ │ ├─local        :     2.25s      13.36s      5.94   100.00%    33.64%
 │ │ └─remote       :
 │ ├─force          :     4.00s      24.11s      6.03   100.00%    59.81%
 │ │ ├─local        :     4.00s      24.02s      6.01   100.00%    59.81%
 │ │ └─remote       :
 │ ├─cons2prim      :
 │ └─extf           :
 ├─write_ev         :     0.06s       0.07s      1.18   100.00%     0.93%
 └─write_dump       :     0.12s       0.13s      1.04   100.00%     1.87%
 npart=    438815, n_alive=    438815, n_dead_or_accreted=         0, nptmass=         0
 Etot=-1.725E-01, Ekin= 1.283E-03, Etherm= 5.416E-02, Epot=-2.280E-01
 Linm= 9.035E-06, Angm= 9.831E-02
 Centre of Mass =  1.174E-06, -5.343E-07, -1.437E-07
 density  (max)= 3.816E-03 (mean)= 2.545E-03 (max)= 7.590E-18 g/cm^3
 alpha(max)= 1.000E+00
 RMS Mach #= 1.853E-01


 t =  0.24436     dt =  2.221E-02 (dtmax)

-------->   TIME =    0.2444    : full dump written to file wtimeAgain.restart   <---------
-------->                         Writing sub-dumps:    3 of   4                 <---------

 input file wtimeAgain.in written successfully.
 Since code start: 10 timesteps, wall: 66s cpu: 382s cpu/wall: 5.8
 Since last dump : 1 timesteps, wall: 6.2s cpu: 37s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal      frac
 ├─step             :     6.25s      36.66s      5.87   100.00%    98.04%
 │ ├─tree           :     0.19s       0.63s      3.38   100.00%     2.94%
 │ │ └─balance      :
 │ ├─density        :     2.12s      12.72s      5.99   100.00%    33.33%
 │ │ ├─local        :     2.12s      12.72s      5.99   100.00%    33.33%
 │ │ └─remote       :
 │ ├─force          :     3.88s      23.15s      5.97   100.00%    60.78%
 │ │ ├─local        :     3.81s      23.06s      6.05   100.00%    59.80%
 │ │ └─remote       :
 │ ├─cons2prim      :     0.06s       0.05s      0.88   100.00%     0.98%
 │ └─extf           :
 ├─write_ev         :
 └─write_dump       :     0.12s       0.12s      0.96   100.00%     1.96%
 npart=    438815, n_alive=    438815, n_dead_or_accreted=         0, nptmass=         0
 Etot=-1.725E-01, Ekin= 1.333E-03, Etherm= 5.416E-02, Epot=-2.280E-01
 Linm= 9.085E-06, Angm= 9.831E-02
 Centre of Mass =  1.297E-06, -5.921E-07, -1.708E-07
 density  (max)= 3.833E-03 (mean)= 2.545E-03 (max)= 7.625E-18 g/cm^3
 alpha(max)= 1.000E+00
 RMS Mach #= 1.879E-01


 t =  0.26657     dt =  2.221E-02 (dtmax)

--------->   TIME =    0.2666    : full dump written to file wtimeAgain_00003   <---------
```



First, an apology...

- *dtmax*:
  - Example:

```
Terminal  Shell  Edit  View  Window  Help
~/rundir/phantom_out/ArroyoJuly — Python                    ~/rundir/phantom

--------> TIME =    0.000    : full dump written to file wtimeAgain_00000   <--------

input file wtimeAgain.in written successfully.

 ---> DELETING temporary dump file wtimeAgain_00000.tmp <---

t =  0.30722E-01 dt =  3.103E-02 (courant), np = 438815
t =  0.61753E-01 dt =  2.710E-02 (dtprint)
t =  0.88858E-01 dt =  2.935E-02 (courant)
modifying dtmax internally due to wall time constraint.  Increasing to    2 sub-dumps

--------> TIME =    0.8886E-01: full dump written to file wtimeAgain_00001   <--------

input file wtimeAgain.in written successfully.
Since code start: 3 timesteps, wall: 19s cpu: 114s cpu/wall: 5.9
Since last dump : 3 timesteps, wall: 19s cpu: 114s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal
├─step             :     19.31s     113.71s      5.89   100.00%
│ ├─tree           :      0.69s       1.86s      2.71   100.00%
│ │ └─balance      :
│ ├─density        :      6.88s      41.19s      5.99   100.00%
│ │ ├─local        :      6.88s      41.19s      5.99   100.00%
│ │ └─remote       :
│ ├─force          :     11.75s      70.18s      5.97   100.00%
│ │ ├─local        :     11.69s      69.91s      5.98   100.00%
│ │ └─remote       :
│ ├─cons2prim      :
│ └─extf           :
├─write_ev         :      0.06s       0.15s      2.36   100.00%
└─write_dump       :      0.12s       0.13s      1.03   100.00%
npart=    438815, n_alive=    438815, n_dead_or_accreted=
Etot=-1.729E-01, Ekin= 8.881E-04, Etherm= 5.416E-02, Epot=-2.279E-0
Linm= 8.446E-06, Angm= 9.830E-02
Centre of Mass =  4.556E-07, -2.038E-07, -2.472E-08
density  (max)= 3.836E-03 (mean)= 2.545E-03 (max)= 7.629E-18 g/cm^3
alpha(max)= 1.000E+00
RMS Mach #= 1.724E-01


t =  0.11821     dt =  1.508E-02 (dtprint)
t =  0.13329     dt =  2.845E-02 (courant)
modifying dtmax internally due to wall time constraint.  Increasing to    4 sub-dumps

-------->  TIME =    0.1333    : full dump written to file wtimeAgain.restart  <--------
-------->                       Writing sub-dumps:    1 of   2                <--------

input file wtimeAgain.in written successfully.
Since code start: 5 timesteps, wall: 33s cpu: 191s cpu/wall: 5.9
Since last dump : 2 timesteps, wall: 13s cpu: 77s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal       frac
├─step             :     13.06s      76.73s      5.87   100.00%    99.05%
│ ├─tree           :      0.38s       1.28s      3.42   100.00%     2.84%
│ │ └─balance      :
│ ├─density        :      4.44s      26.37s      5.94   100.00%    33.65%
│ │ ├─local        :      4.44s      26.37s      5.94   100.00%    33.65%
│ │ └─remote       :
│ ├─force          :      8.19s      48.76s      5.96   100.00%    62.09%
│ │ ├─local        :      8.12s      48.57s      5.98   100.00%    61.61%
│ │ └─remote       :
│ ├─cons2prim      :
│ └─extf           :
```

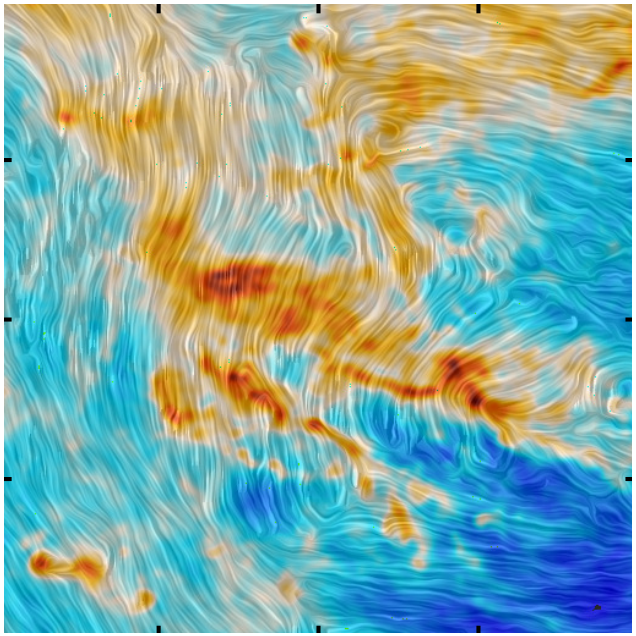
```
Terminal  Shell  Edit  View  Window  Help
~/rundir/phantom_out/ArroyoJuly — Python                    ~/rundir/phantom

--------> TIME =    0.1777    : full dump written to file wtimeAgain_00002   <--------

input file wtimeAgain.in written successfully.
Since code start: 7 timesteps, wall: 46s cpu: 266s cpu/wall: 5.8
Since last dump : 1 timesteps, wall: 6.2s cpu: 37s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal       frac
├─step             :      6.25s      36.72s      5.87   100.00%    97.09%
│ ├─tree           :      0.19s       0.62s      3.28   100.00%     2.91%
│ │ └─balance      :
│ ├─density        :      2.12s      12.80s      6.02   100.00%    33.01%
│ │ ├─local        :      2.12s      12.80s      6.02   100.00%    33.01%
│ │ └─remote       :
│ ├─force          :      3.88s      23.15s      5.97   100.00%    60.19%
│ │ ├─local        :      3.88s      23.06s      5.95   100.00%    60.19%
│ │ └─remote       :
│ ├─cons2prim      :
│ └─extf           :
├─write_ev         :
└─write_dump       :      0.12s       0.14s      1.08   100.00%     1.80%
npart=    438815, n_alive=    438815, n_dead_or_accreted=          0, nptmass=          0
Etot=-1.726E-01, Ekin= 1.225E-03, Etherm= 5.416E-02, Epot=-2.279E-01
Linm= 8.974E-06, Angm= 9.831E-02
Centre of Mass =  1.052E-06, -4.774E-07, -1.181E-07
density  (max)= 3.799E-03 (mean)= 2.545E-03 (max)= 7.557E-18 g/cm^3
alpha(max)= 1.000E+00
RMS Mach #= 1.827E-01


t =  0.22214     dt =  2.221E-02 (dtmax)
```

```
Terminal  Shell  Edit  View  Window  Help
~/rundir/phantom

--------> TIME =    0.2221    : full dump written to file wtimeAgain.restart  <--------
-------->                       Writing sub-dumps:    2 of   4                <--------

input file wtimeAgain.in written successfully.
Since code start: 9 timesteps, wall: 59s cpu: 345s cpu/wall: 5.8
Since last dump : 1 timesteps, wall: 6.5s cpu: 38s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal       frac
├─step             :      6.50s      38.30s      5.89   100.00%    97.20%
│ ├─tree           :      0.25s       0.66s      2.66   100.00%     3.74%
│ │ └─balance      :
│ ├─density        :      2.25s      13.36s      5.94   100.00%    33.64%
│ │ ├─local        :      2.25s      13.36s      5.94   100.00%    33.64%
│ │ └─remote       :
│ ├─force          :      4.00s      24.11s      6.03   100.00%    59.81%
│ │ ├─local        :      4.00s      24.02s      6.01   100.00%    59.81%
│ │ └─remote       :
│ ├─cons2prim      :
│ └─extf           :
├─write_ev         :      0.06s       0.07s      1.18   100.00%     0.93%
└─write_dump       :      0.12s       0.13s      1.04   100.00%     1.87%
                                                                          0
= 1.283E-03, Etherm= 5.416E-02, Epot=-2.280E-01
= 9.831E-02
74E-06, -5.343E-07, -1.437E-07
E-03 (mean)= 2.545E-03 (max)= 7.590E-18 g/cm^3


 2.221E-02 (dtmax)

.2444    : full dump written to file wtimeAgain.restart  <--------
                       Writing sub-dumps:    3 of   4                <--------

in written successfully.
Since code start: 10 timesteps, wall: 66s cpu: 382s cpu/wall: 5.8
Since last dump : 1 timesteps, wall: 6.2s cpu: 37s cpu/wall: 5.9

                          wall         cpu  cpu/wall  load bal       frac
├─step             :      6.25s      36.66s      5.87   100.00%    98.04%
│ ├─tree           :      0.19s       0.63s      3.38   100.00%     2.94%
│ │ └─balance      :
│ ├─density        :      2.12s      12.72s      5.99   100.00%    33.33%
│ │ ├─local        :      2.12s      12.72s      5.99   100.00%    33.33%
│ │ └─remote       :
│ ├─force          :      3.88s      23.15s      5.97   100.00%    60.78%
│ │ ├─local        :      3.81s      23.06s      6.05   100.00%    59.80%
│ │ └─remote       :
│ ├─cons2prim      :      0.06s       0.05s      0.88   100.00%     0.98%
│ └─extf           :
├─write_ev         :
└─write_dump       :      0.12s       0.12s      0.96   100.00%     1.96%
npart=    438815, n_alive=    438815, n_dead_or_accreted=          0, nptmass=          0
Etot=-1.725E-01, Ekin= 1.333E-03, Etherm= 5.416E-02, Epot=-2.280E-01
Linm= 9.085E-06, Angm= 9.831E-02
Centre of Mass =  1.297E-06, -5.921E-07, -1.708E-07
density  (max)= 3.833E-03 (mean)= 2.545E-03 (max)= 7.625E-18 g/cm^3
alpha(max)= 1.000E+00
RMS Mach #= 1.879E-01


t =  0.26657     dt =  2.221E-02 (dtmax)

--------> TIME =    0.2666    : full dump written to file wtimeAgain_00003   <--------
```

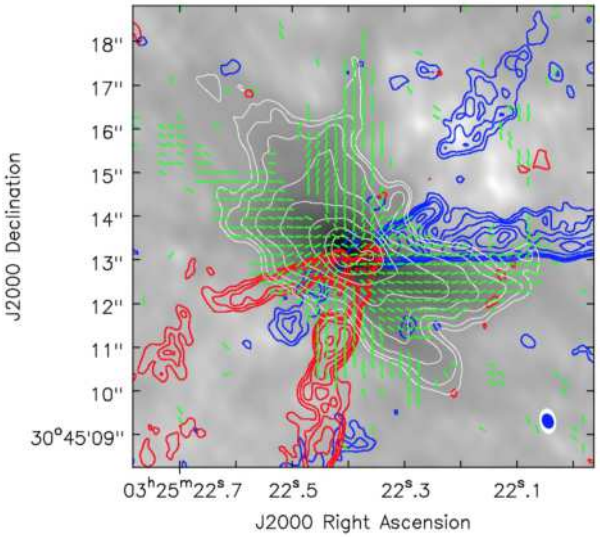
Please discuss & let me know if you would like different defaults, or different / new features

Magnetic fields: Motivation (for me & you!)

- Star forming regions are permeated with magnetic fields!

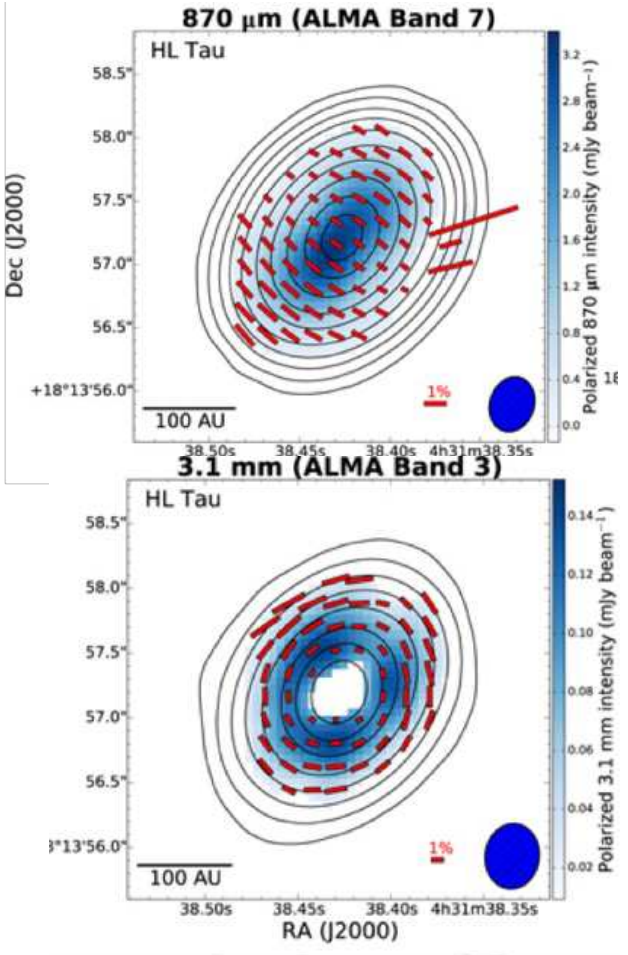


Planck Collaboration (2016)

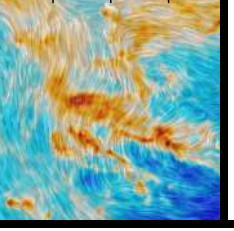


Kwon+ (2019)

- Discs are magnetic!



Stephens+ (2017)



Continuum Magnetohydrodynamic Equations

- Continuum equations:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\rho\nabla\cdot\boldsymbol{v}$$

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{1}{\rho}\nabla\cdot\left[\left(p+\frac{B^2}{2}\right)I-\boldsymbol{B}\boldsymbol{B}\right]-\nabla\Phi+\frac{\kappa F}{c}$$

$$\rho\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\boldsymbol{B}}{\rho}\right) = (\boldsymbol{B}\cdot\nabla)\,\boldsymbol{v}+\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\text{non-ideal}}$$

$$\rho\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{E}{\rho}\right) = -\nabla\cdot\boldsymbol{F}-\nabla\boldsymbol{v}:\boldsymbol{P}+4\pi\kappa\rho B_{\mathrm{P}}-c\kappa\rho E$$

$$\rho\frac{\mathrm{d}u}{\mathrm{d}t} = -p\nabla\cdot\boldsymbol{v}-4\pi\kappa\rho B_{\mathrm{P}}+c\kappa\rho E+\rho\left.\frac{\mathrm{d}u}{\mathrm{d}t}\right|_{\text{non-ideal}}$$

$$\nabla^2\Phi = 4\pi G\rho$$

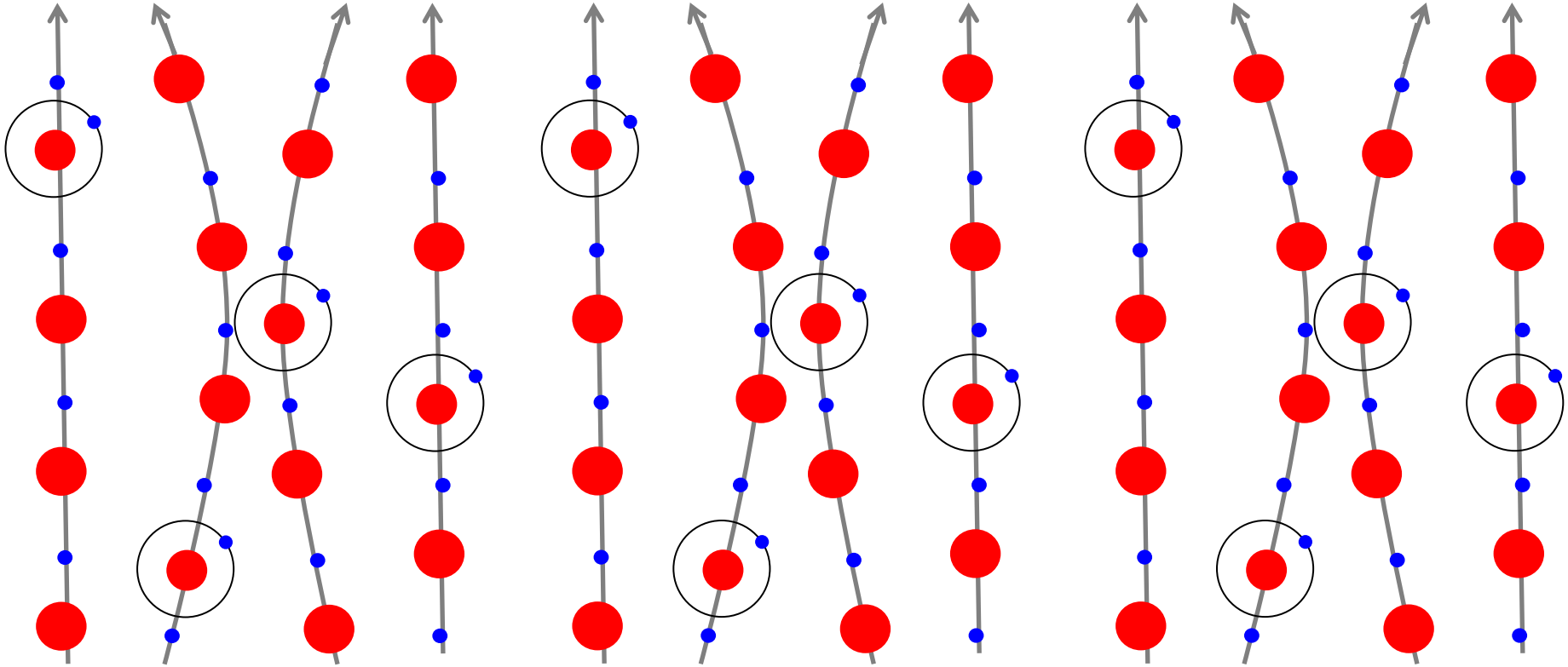
- Relevant processes:
  - Gas
  - Dust (self-consistent) [ignored]
  - Radiation
  - Kinematics
  - Magnetic fields
    - non-ideal MHD implicitly includes non-self-consistently evolved dust

Ideal magnetohydrodynamics

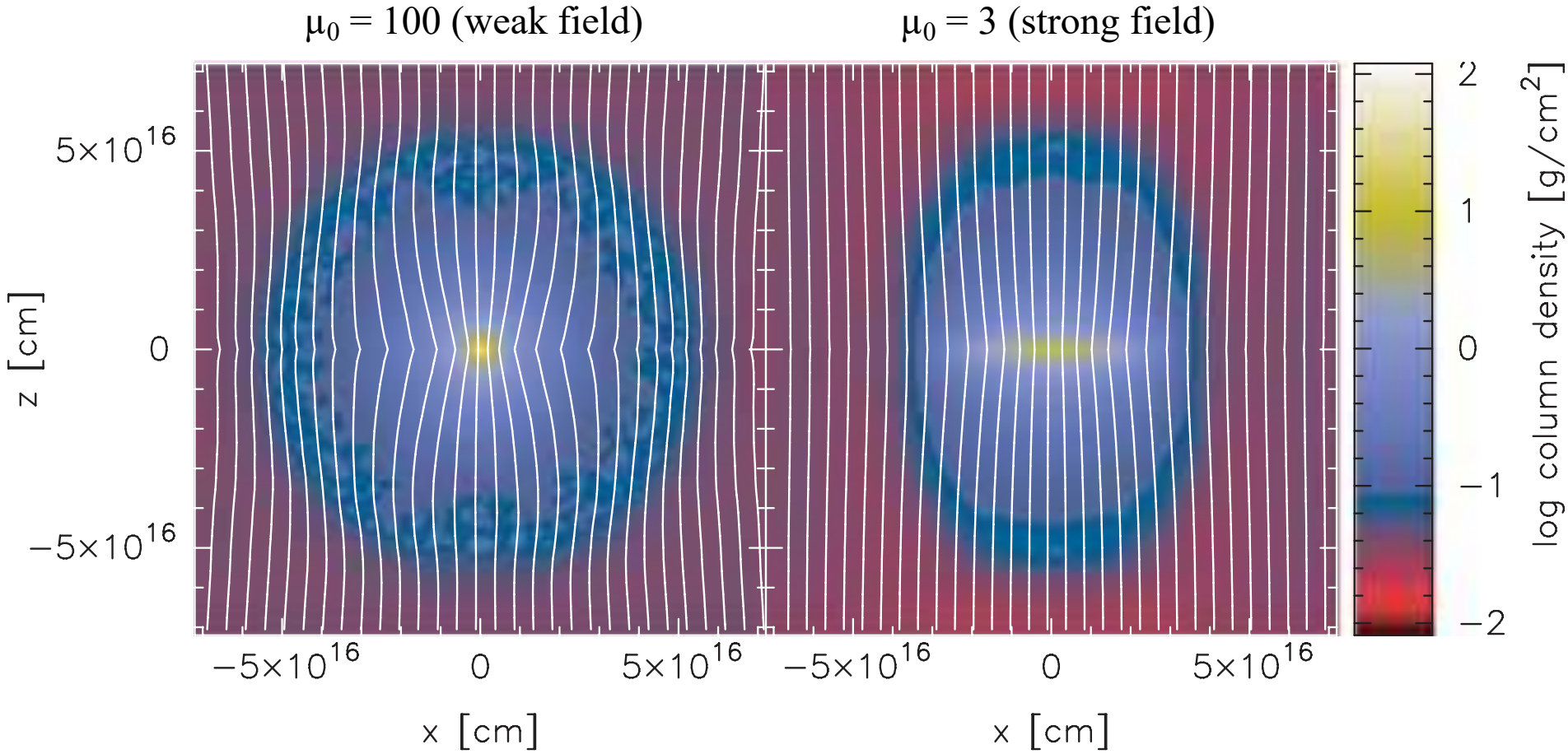
- Highly ionised plasma:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B})$$

- Zero resistivity & infinite conductivity
- Ions & electrons are tied to the magnetic field
- Neutral particles are tied to the magnetic field due to interactions with the ions & electrons



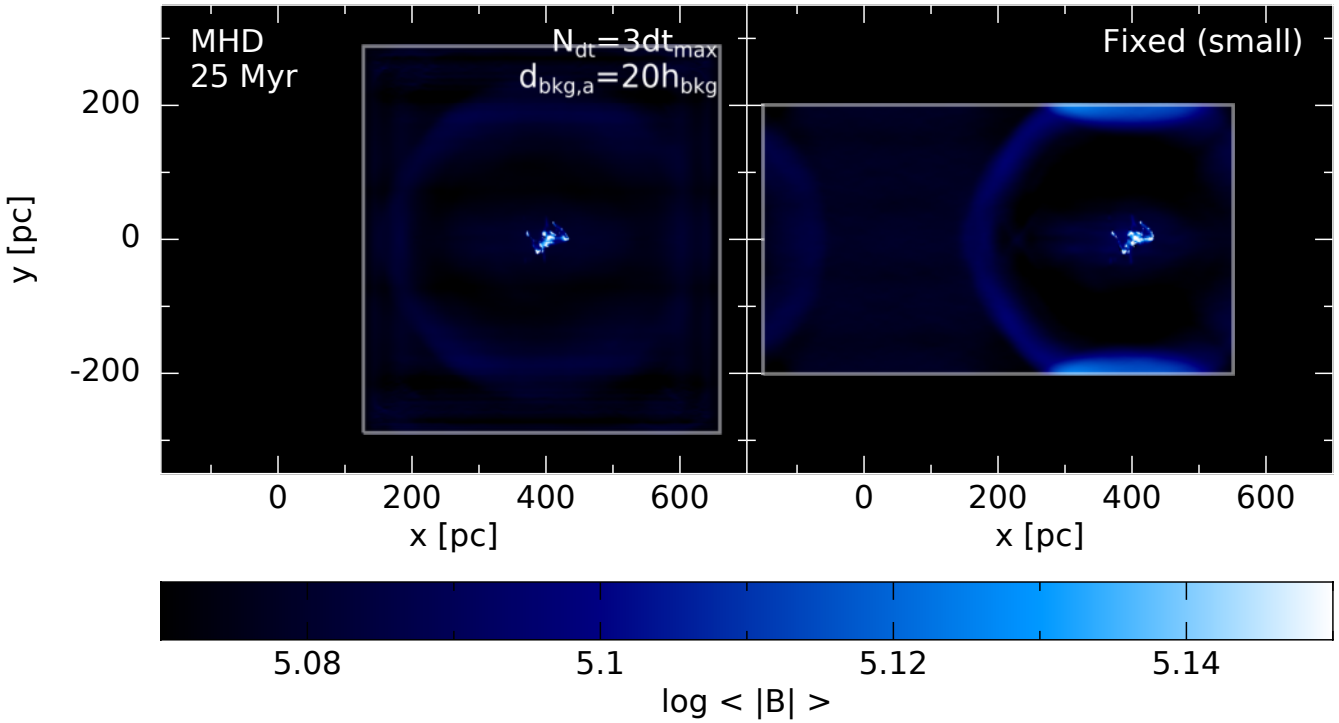
Ideal magnetohydrodynamics



Price & Bate (2007)

Aside: Magnetic boundary conditions

- Magnetic simulations *require* boundaries
- If not, simulations will
  - at best: Blow up and crash
  - at worst: Run to completion with the wrong answer
- How big of boundaries are needed?
- Not always easy to determine *a priori*:



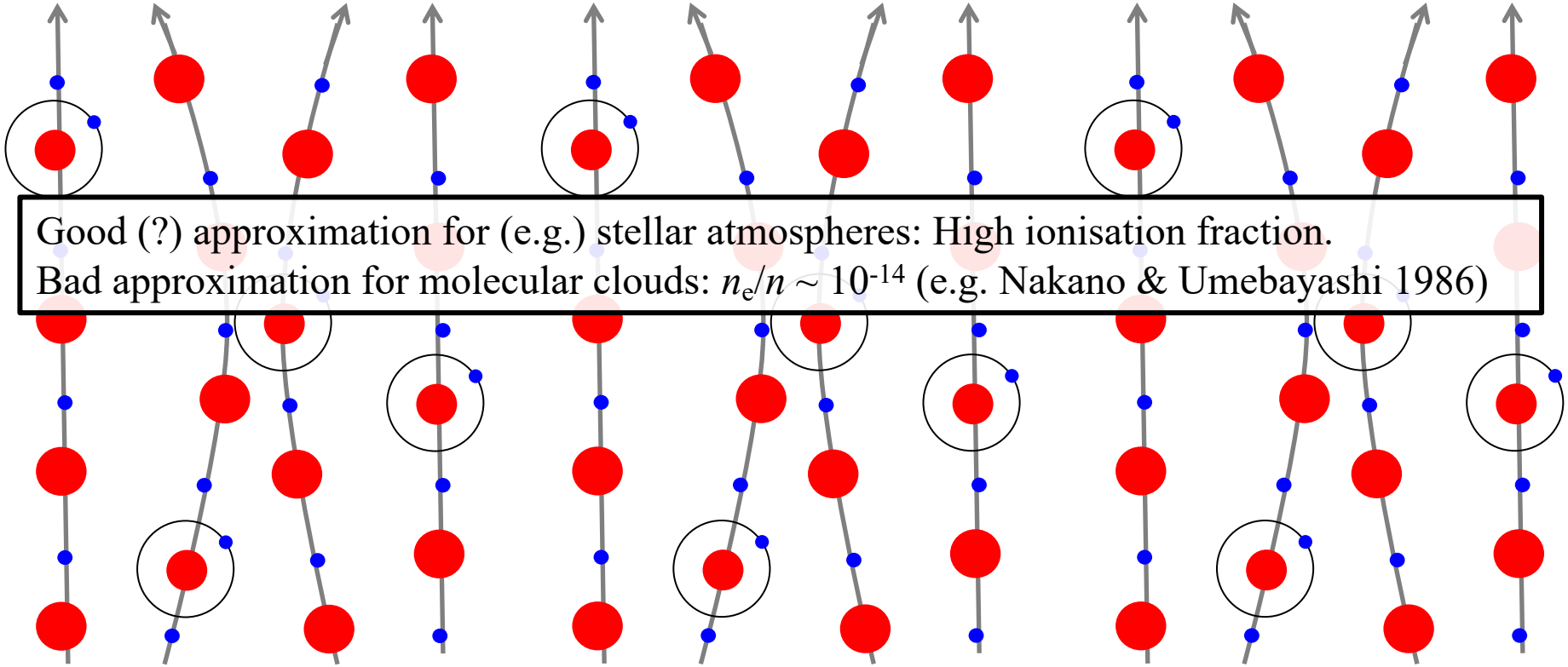
- See dynamic boundary conditions as introduced in Wurster & Bonnell (in prep)

Ideal magnetohydrodynamics

- Highly ionised plasma:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B})$$

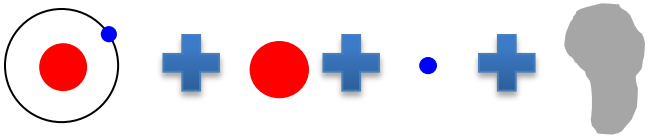
- Zero resistivity & infinite conductivity
- Ions & electrons are tied to the magnetic field
- Neutral particles are tied to the magnetic field due to interactions with the ions & electrons

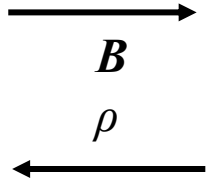


Good (?) approximation for (e.g.) stellar atmospheres: High ionisation fraction.
Bad approximation for molecular clouds: $n_e/n \sim 10^{-14}$ (e.g. Nakano & Umebayashi 1986)

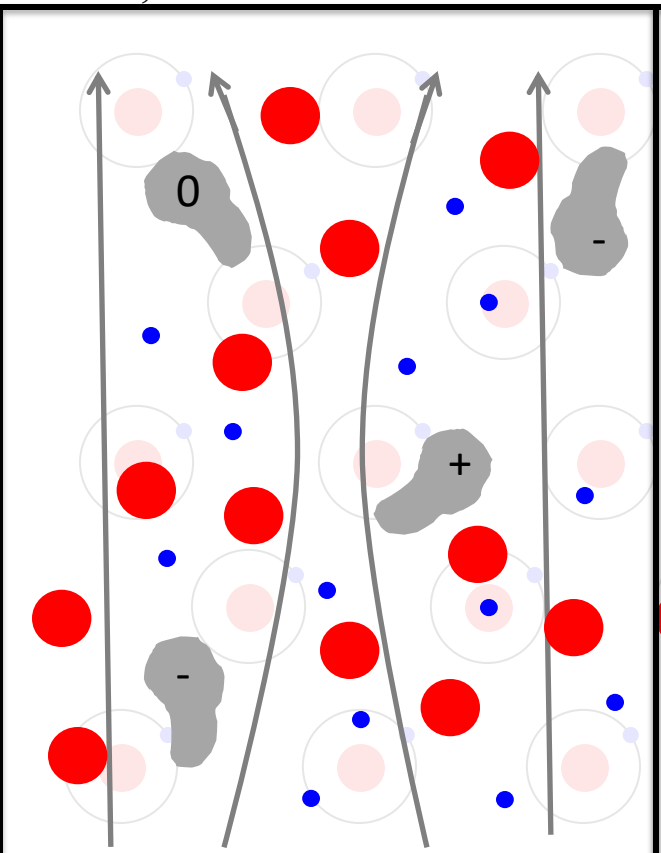
Non-ideal magnetohydrodynamics

- Partially ionised plasma and dust:

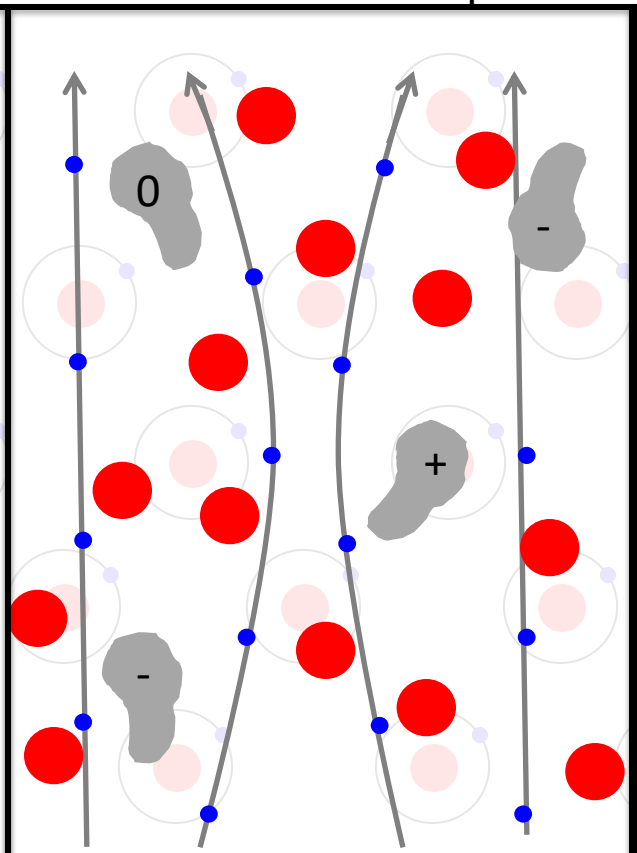




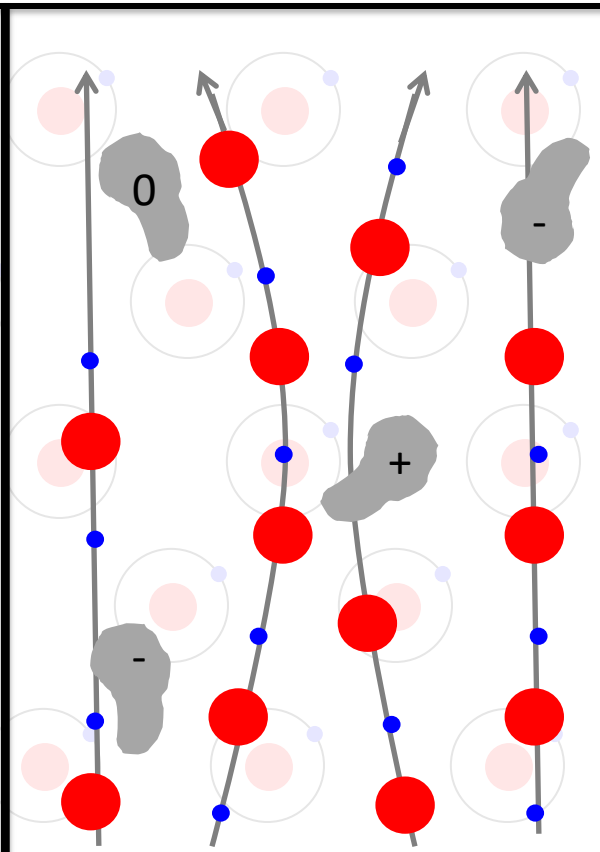
- Non-zero resistivity & conductivity
- Ions, electrons & neutrals behaviour is environment-dependent



Ohmic Resistivity
(diffusive)



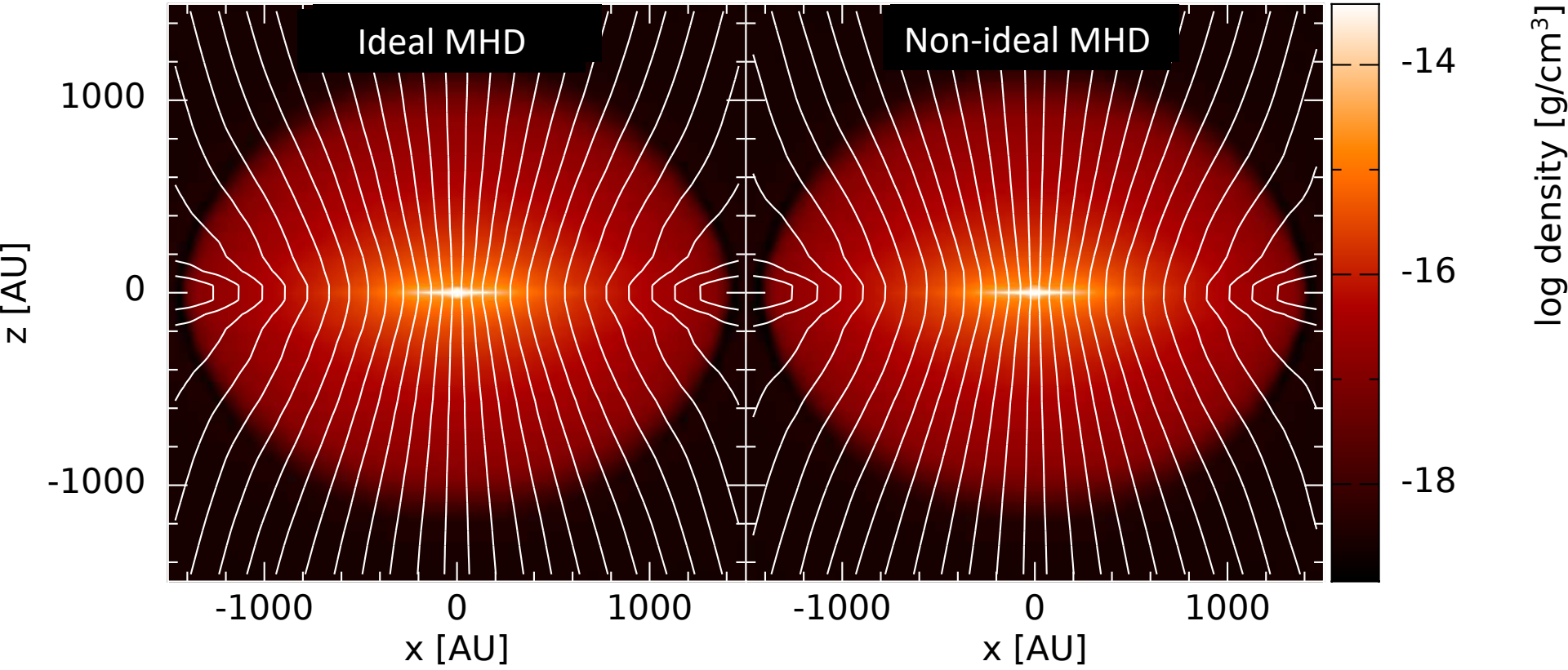
Hall Effect
(dispersive)



Ambipolar Diffusion
(diffusive)

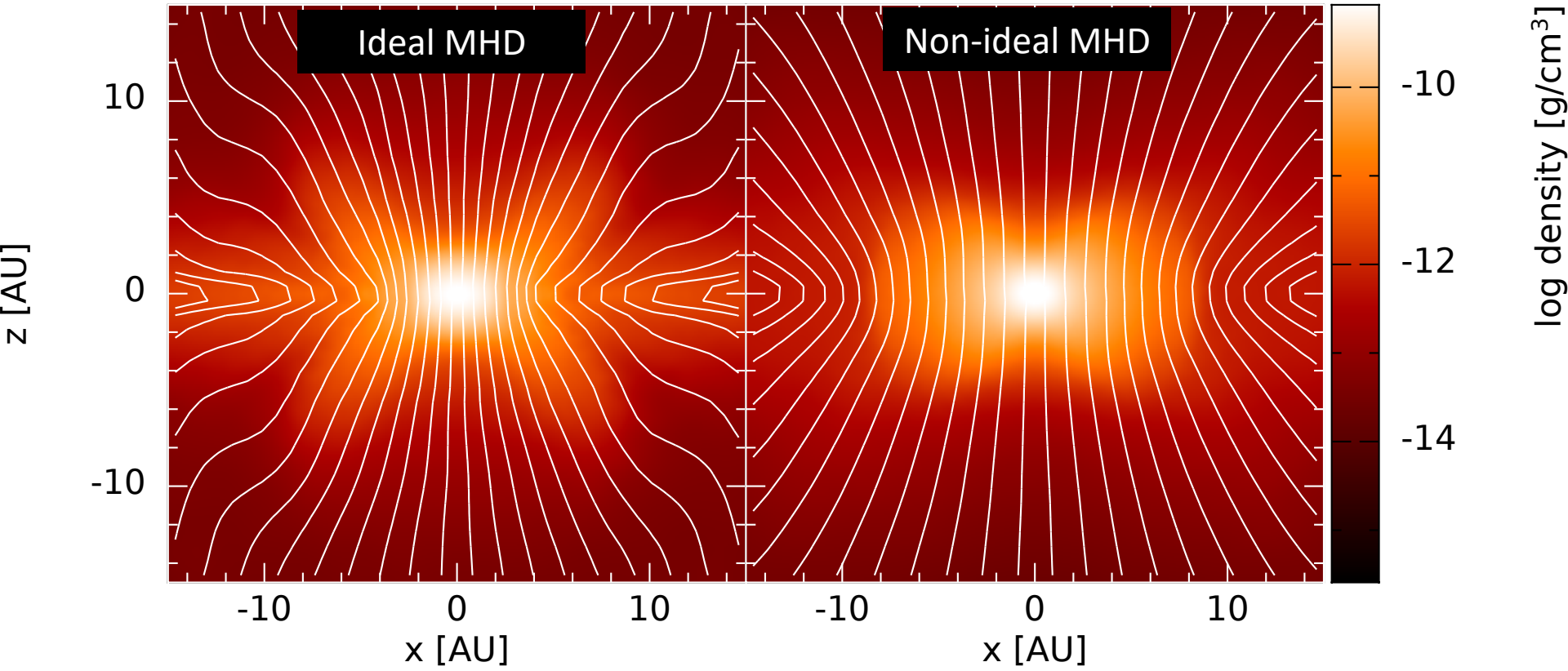
Non-ideal magnetohydrodynamics

- Strong field, initially vertical magnetic field
- Large scale structure



Non-ideal magnetohydrodynamics

- Strong field, initially vertical magnetic field
- Small scale structure



Non-ideal magnetohydrodynamics

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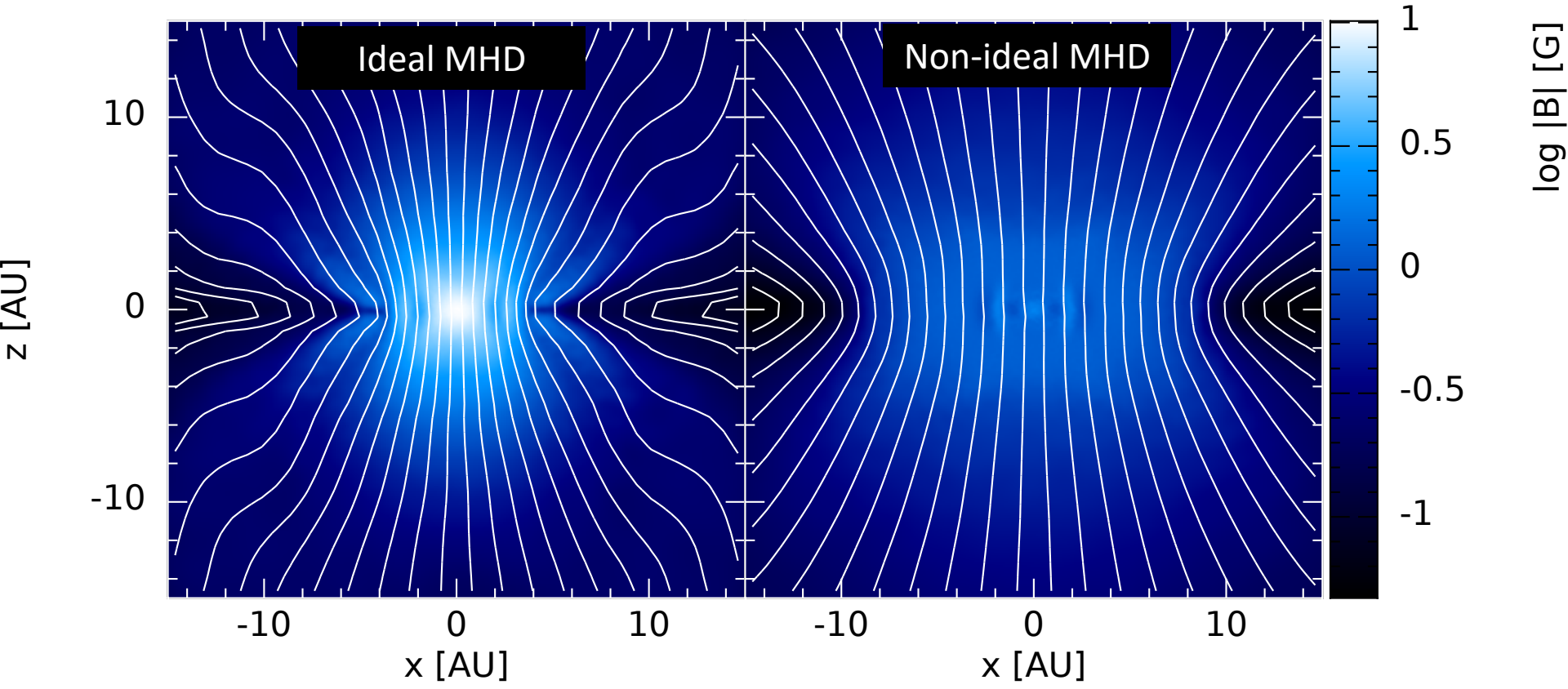
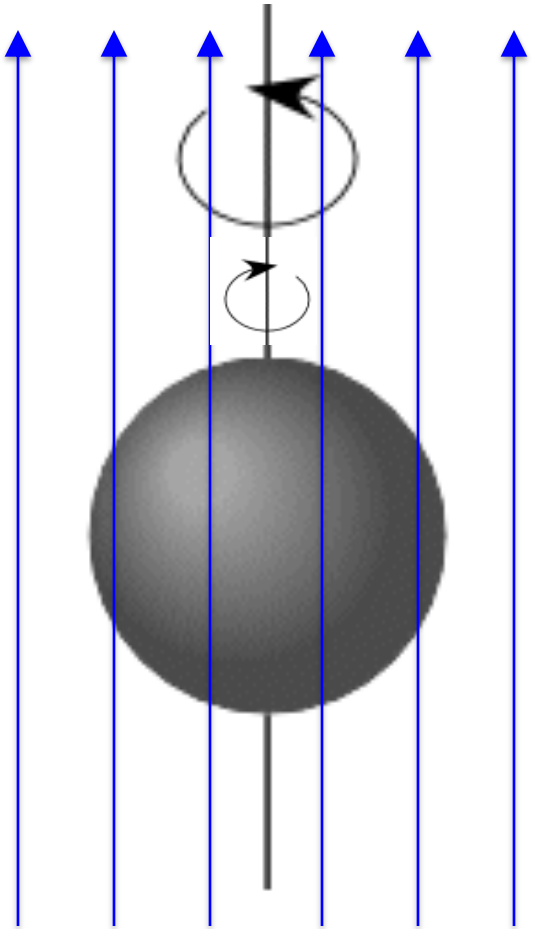


Non-ideal magnetohydrodynamics: Hall effect

➢Depending on the relative orientation of *L* & *B*, the Hall-induced rotation will contribute to or detract from the initial rotation

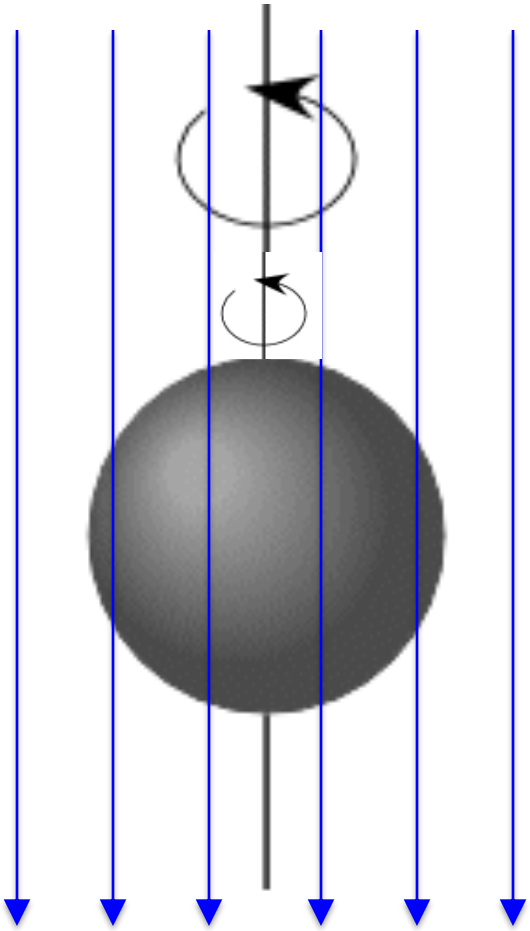
L & *B* are aligned



Direction of initial rotation

Hall-induced rotation

L & *B* are anti-aligned



see also: Braiding & Wardle (2012a,b)

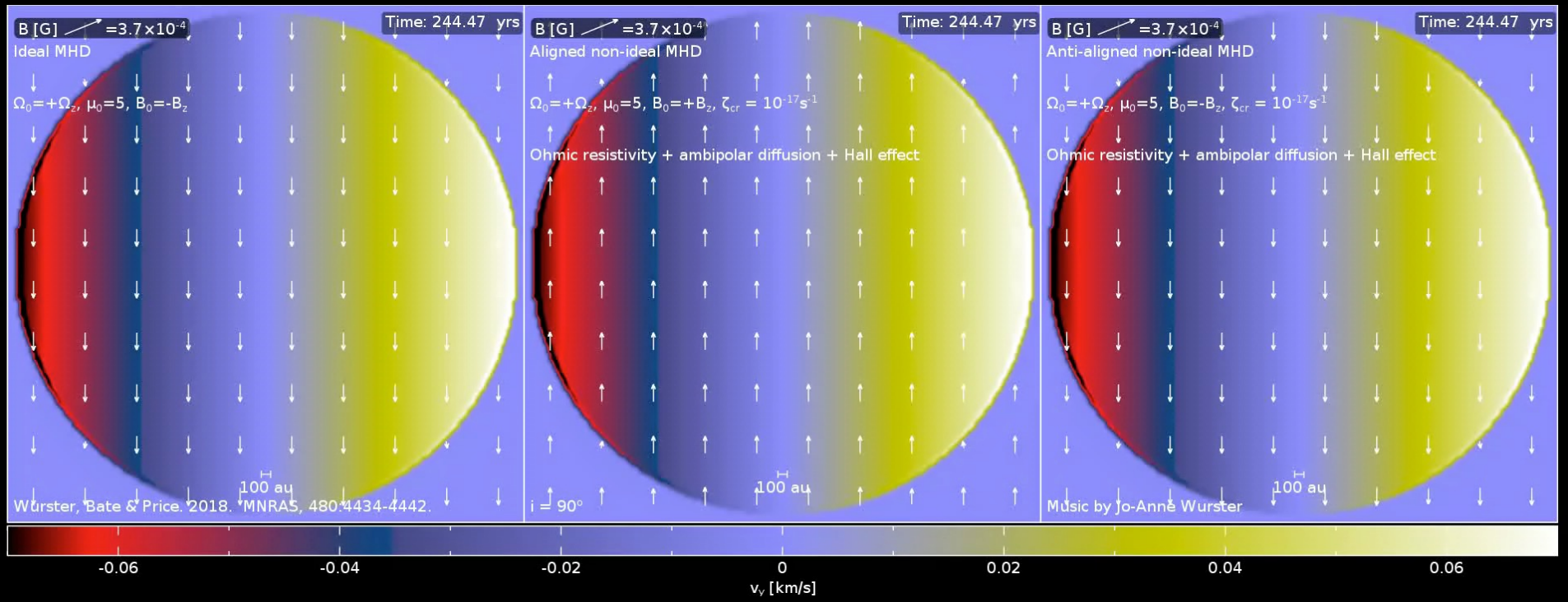
These simulations brought to you by...

- The smoothed particle radiation non-ideal magnetohydrodynamic code *sphNG* (Benz 1990)
  - These studies were performed prior to *Phantom* having radiation transport as flux limited diffusion

- Magnetic stability
  - artificial resistivity: Tricco & Price (2014)
  - divB cleaning: Tricco, Price & Bate (2016)
  - artificial resistivity: Price+ (2018)
  - divB cleaning stability: Dobbs & Wurster (2021)
    - to activate, set *hdivbmax_max* = 512 in the .in file
    (don't worry, a warning will appear if you need to do this)

- Non-ideal MHD (via *Nicil* Library)
  - version 1: Wurster (2016)
  - version 2: Wurster (2021)
    - v2 is in the current version of *Phantom*

Formation of a low-mass star



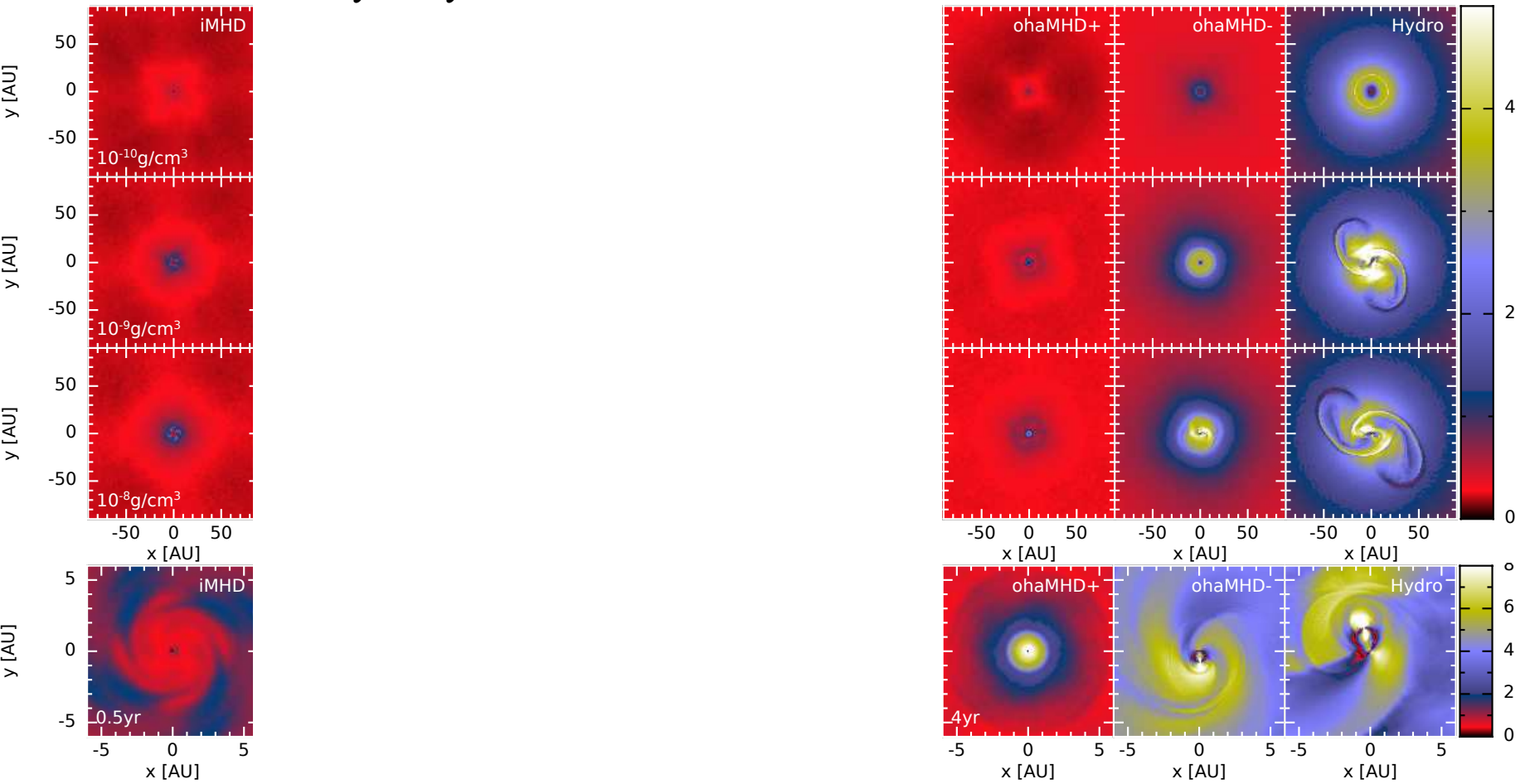
Wurster, Bate & Price (2018c)

https://www.youtube.com/watch?v=2SQxgXbdJyg&t=8s

Music: Jo-Anne Wurster

Rotationally supported discs

- Discs form in the hydrodynamics model and the non-ideal model with $-B_z$



- Discs form during the first hydrostatic core phase
- Similar disc structure obtained by Tsukamoto+ (2015a) with $\pm B_z$

Wurster, Bate & Bonnell (2021); Wurster, Bate & Price (2018a,c)

Rotationally supported discs

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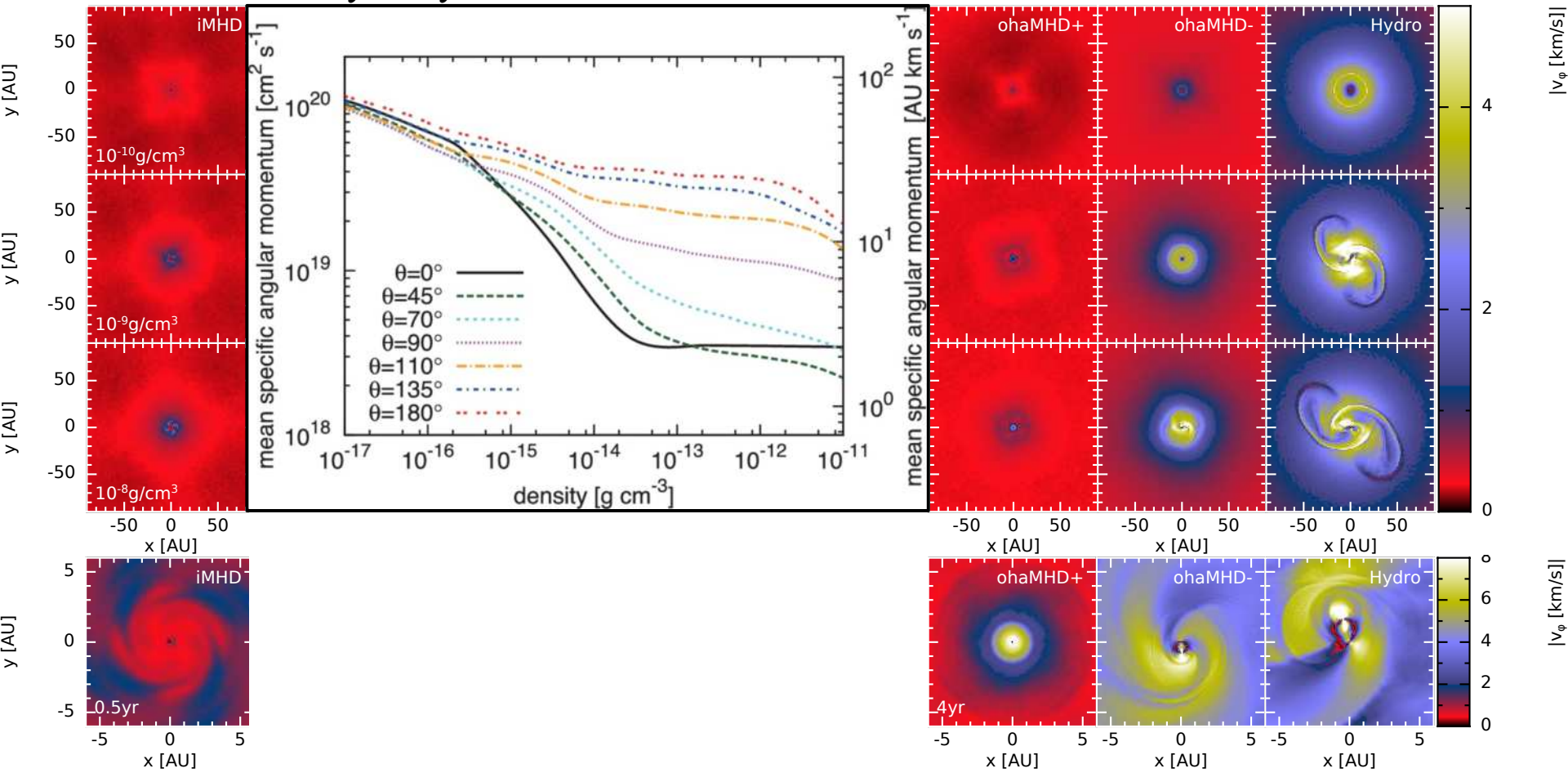

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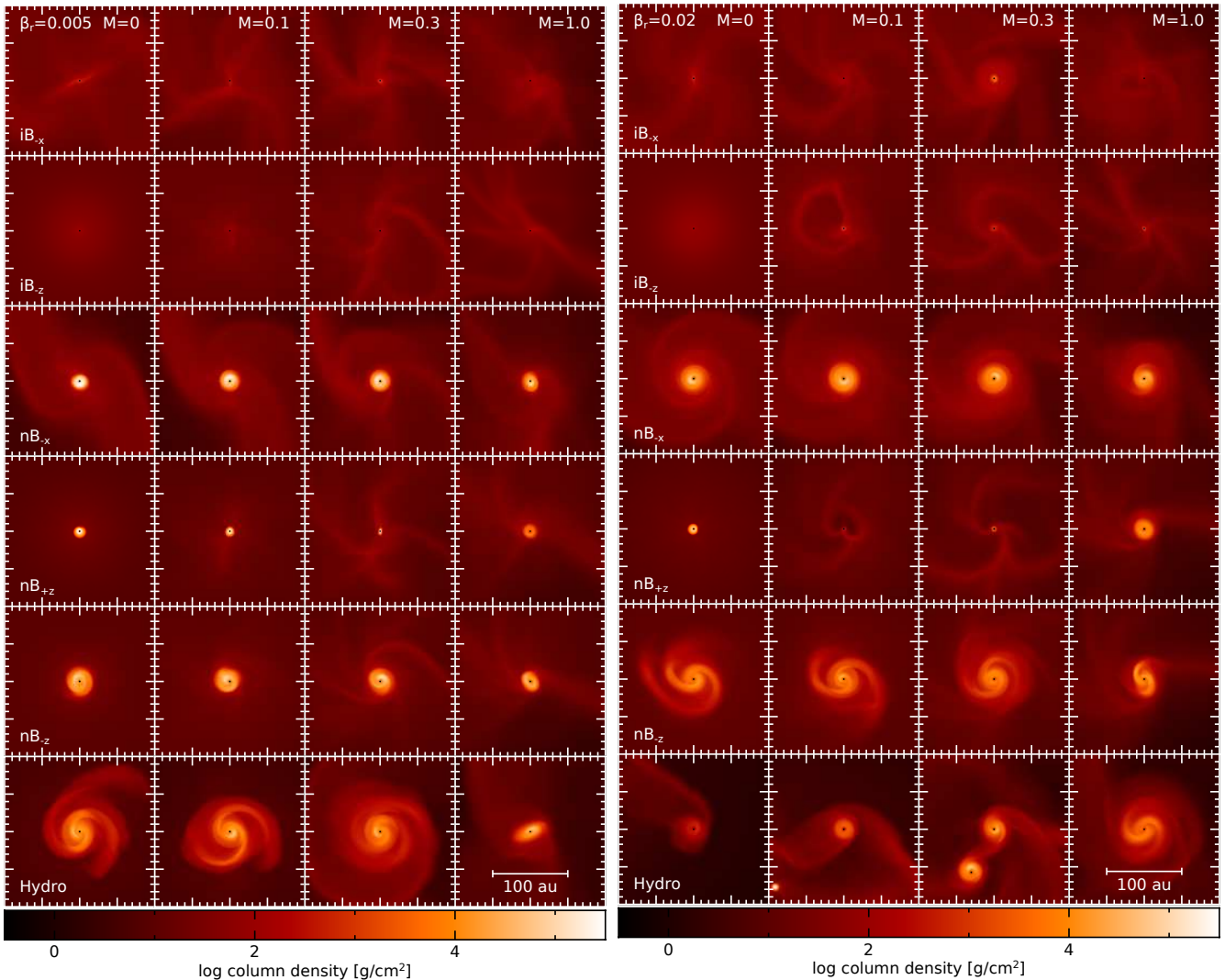
Wurster, Bate & Bonnell (2021); Wurster, Bate & Price (2018a,c); inset: Tsukamoto+ (2017)

Rotationally supported discs

➢Sub- and trans-sonic turbulence is not enough to permit the formation of rotationally supported discs when employing ideal MHD

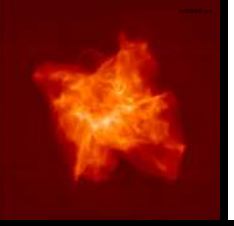


Wurster & Lewis (2020a)

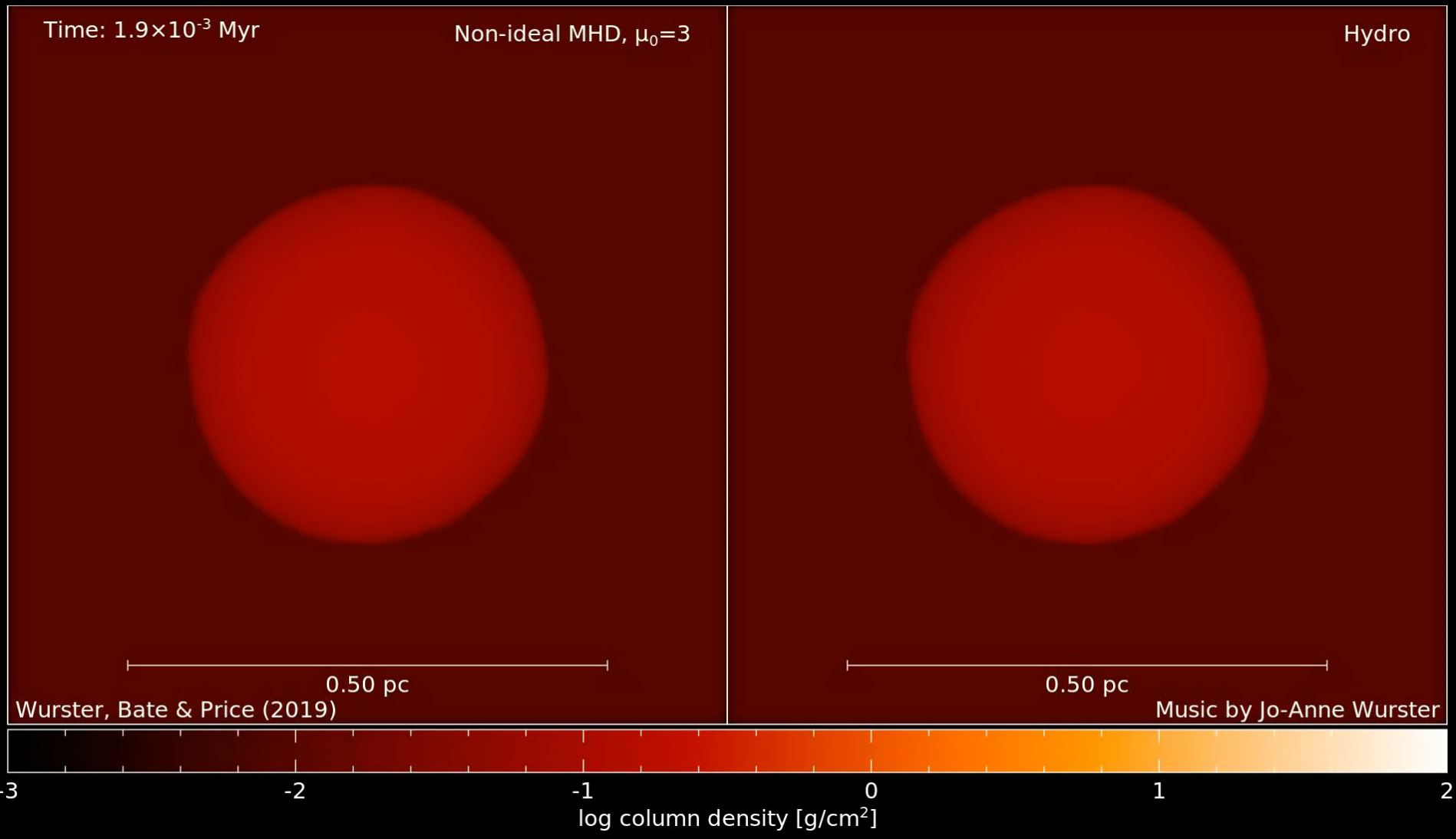
Star formation: From the beginning

- Stars do not form in isolation
- Star forming environments, on the large scale, are turbulent

Orion Molecular Cloud. (image credit: Drudis & Goldman via APOD)



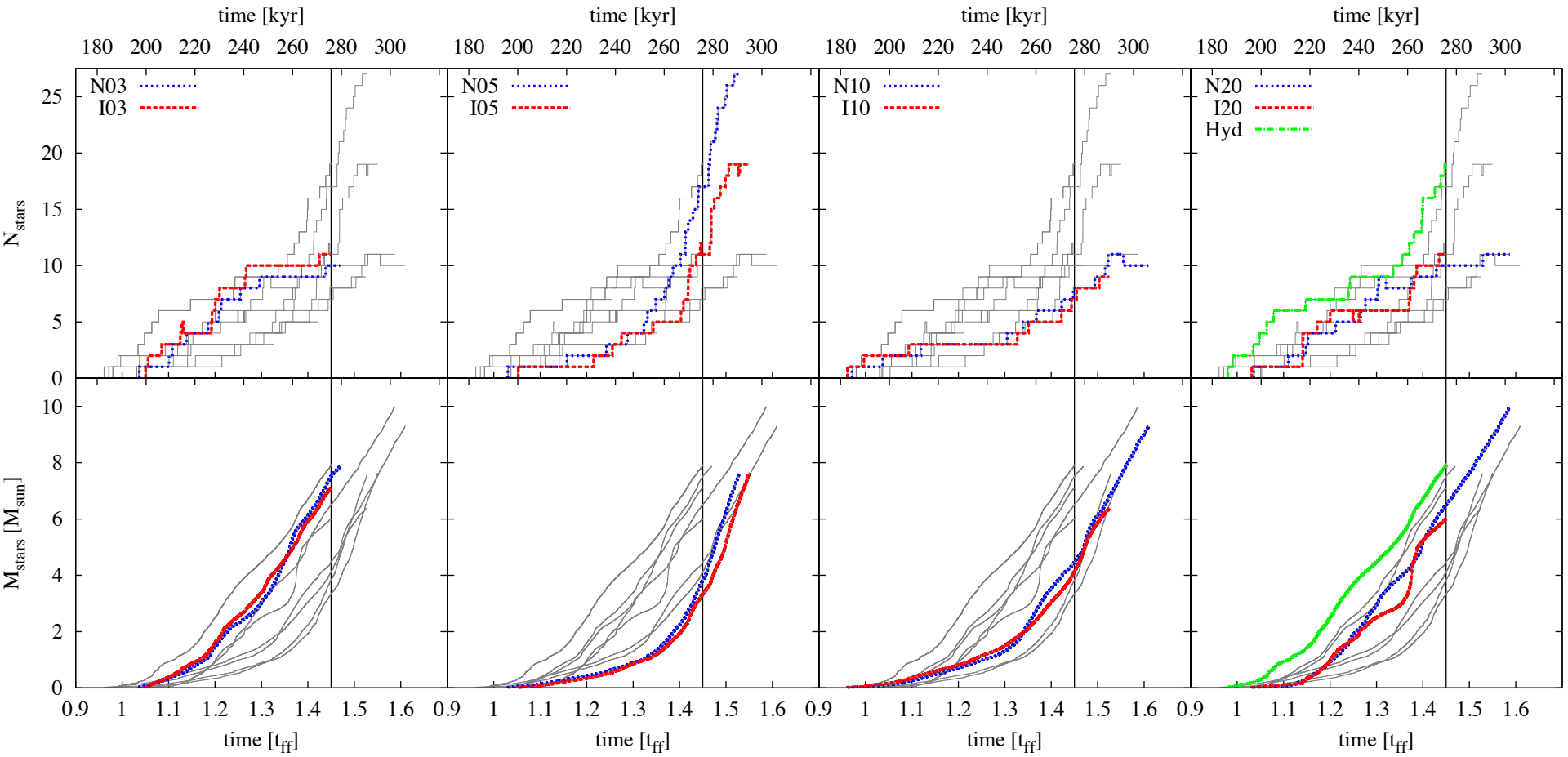
Cluster Formation: Effect of non-ideal MHD



Wurster, Bate & Price (2019) https://www.youtube.com/watch?v=VZixbkDMZO8&t=2s Music by Jo-Anne Wurster

Cluster Formation: Stellar Mass

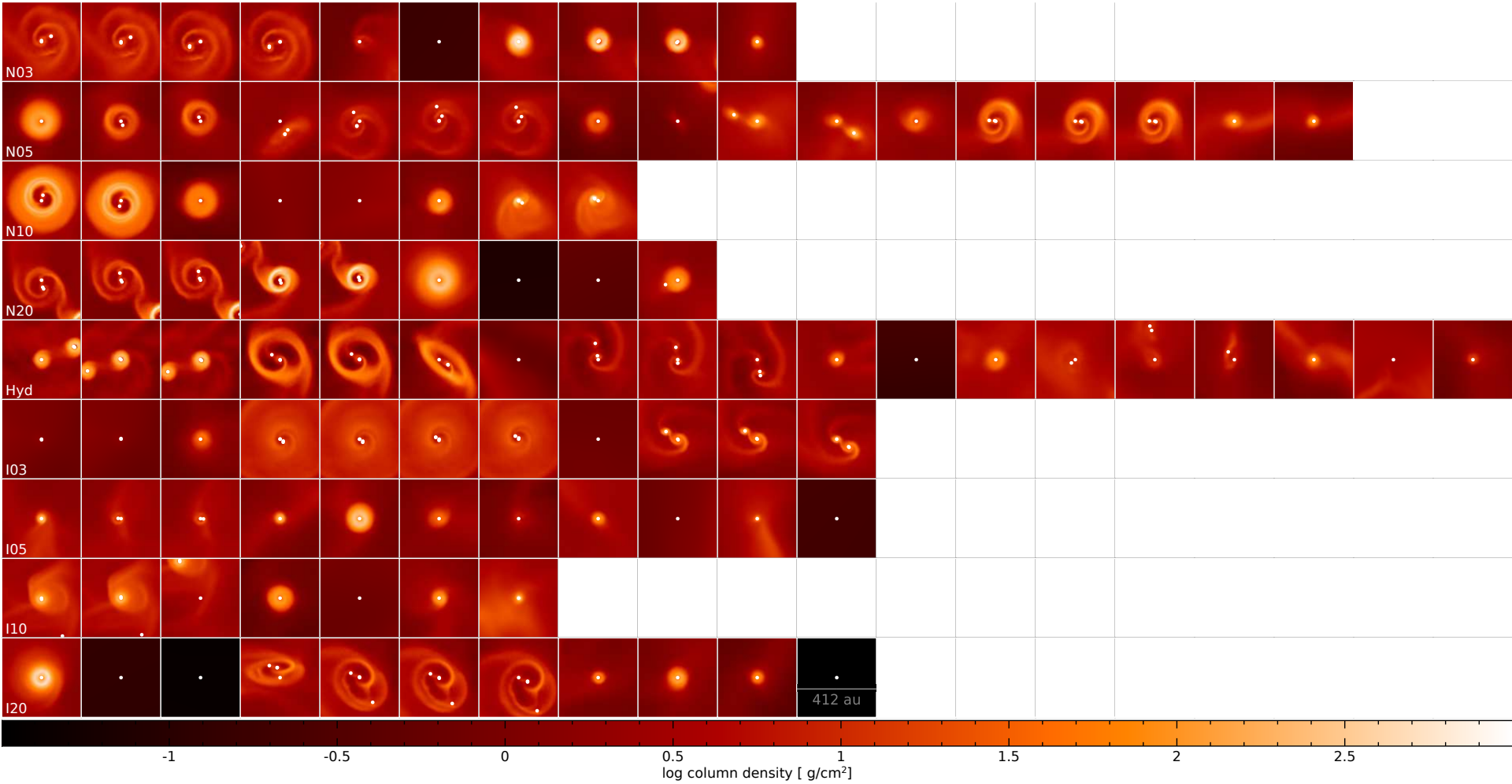
- No trend when stars form
- Excluding N03 & I03, there is more mass in stars with weaker initial magnetic field strengths



Wurster, Bate & Price (2019)

Cluster Formation: Protostellar discs

➢Large protostellar discs form in *all* our models



Wurster, Bate & Price (2019)

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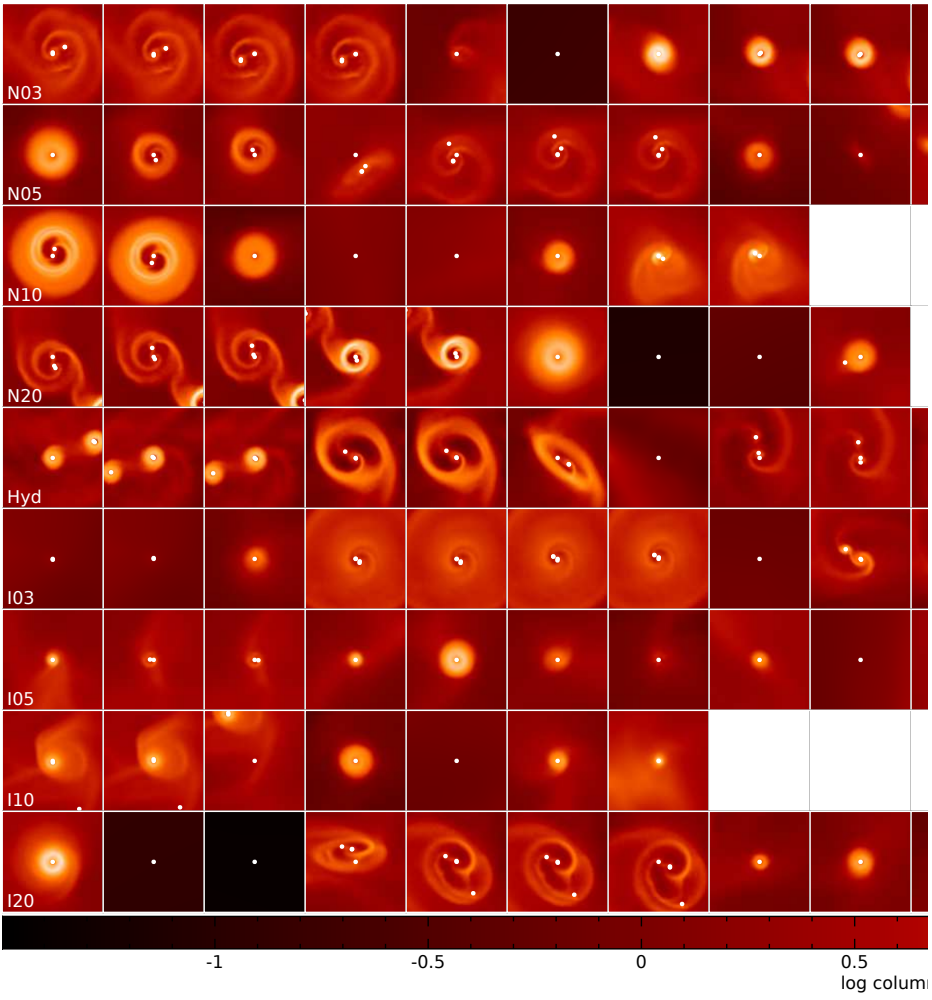
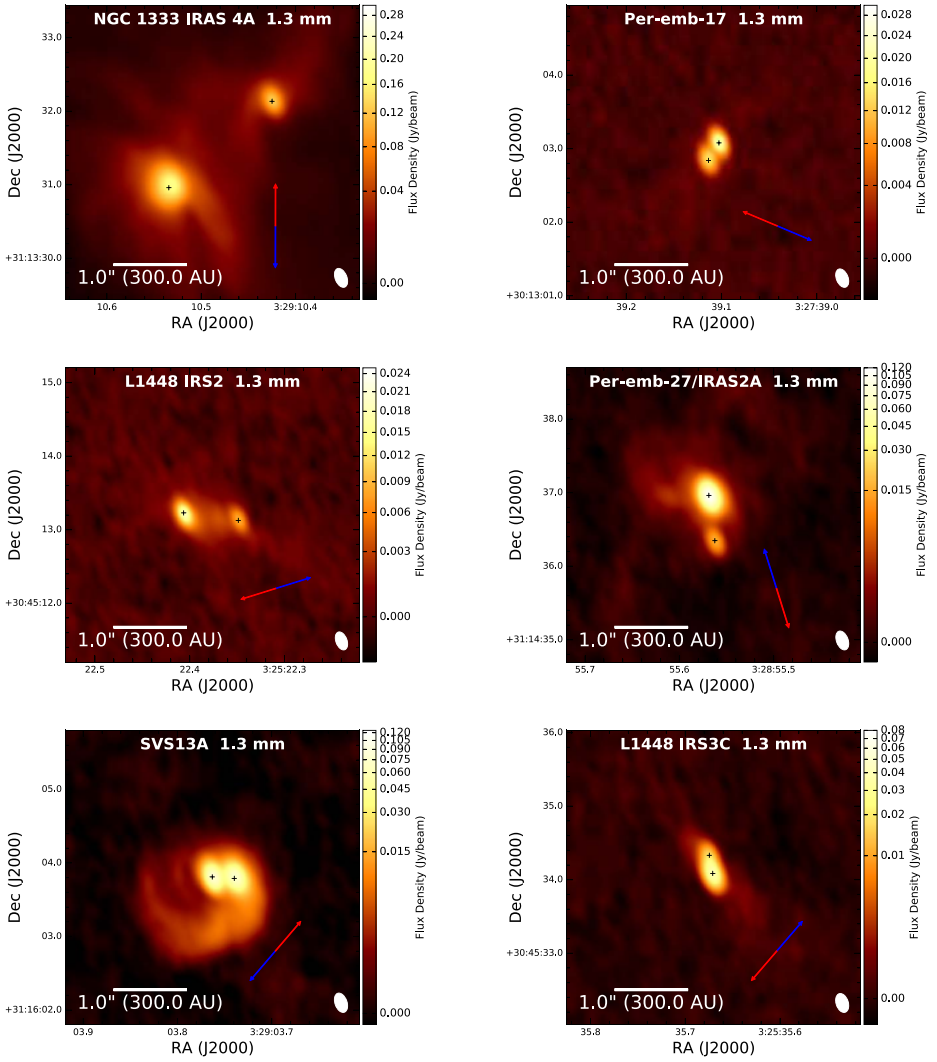


Wurster, Bate & Price (2019)



Discs in Perseus (Tobin+2018)

Cluster Formation: Protostellar discs

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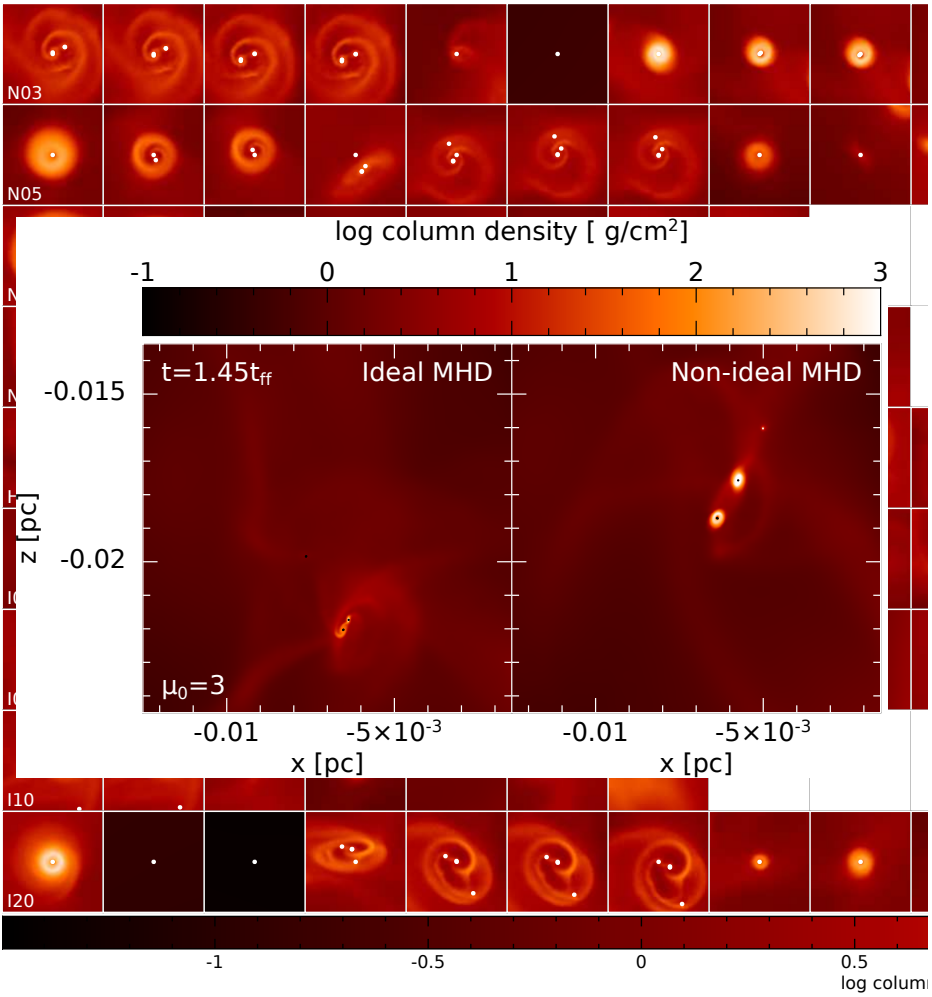
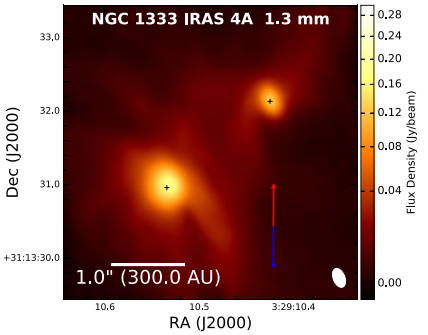
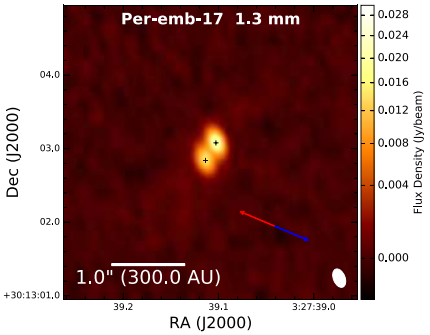
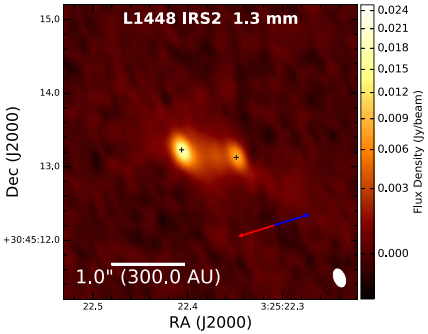
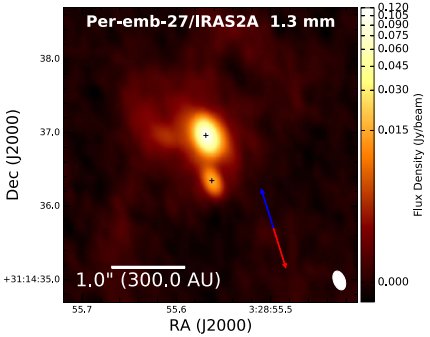
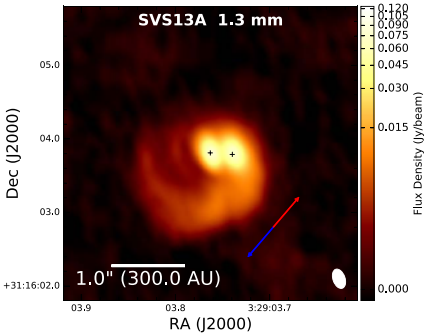


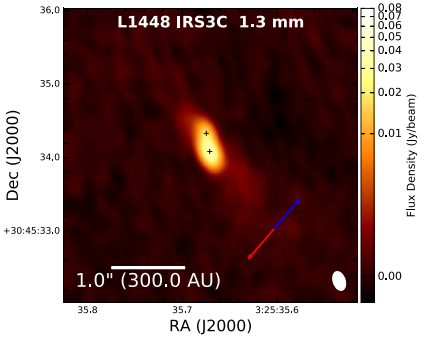






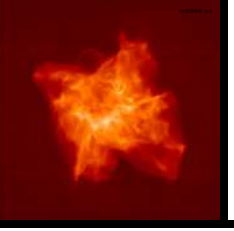






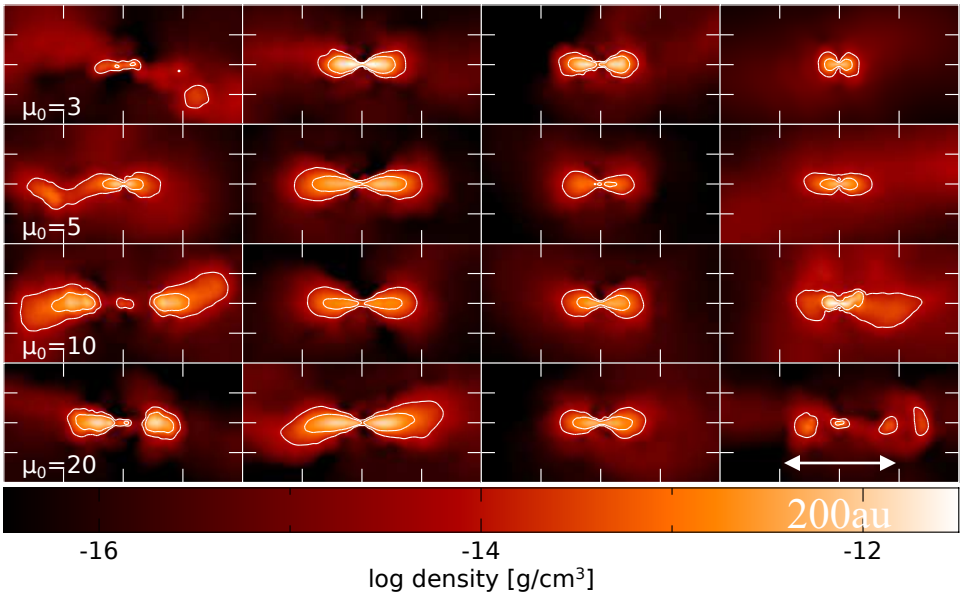
Wurster, Bate & Price (2019)

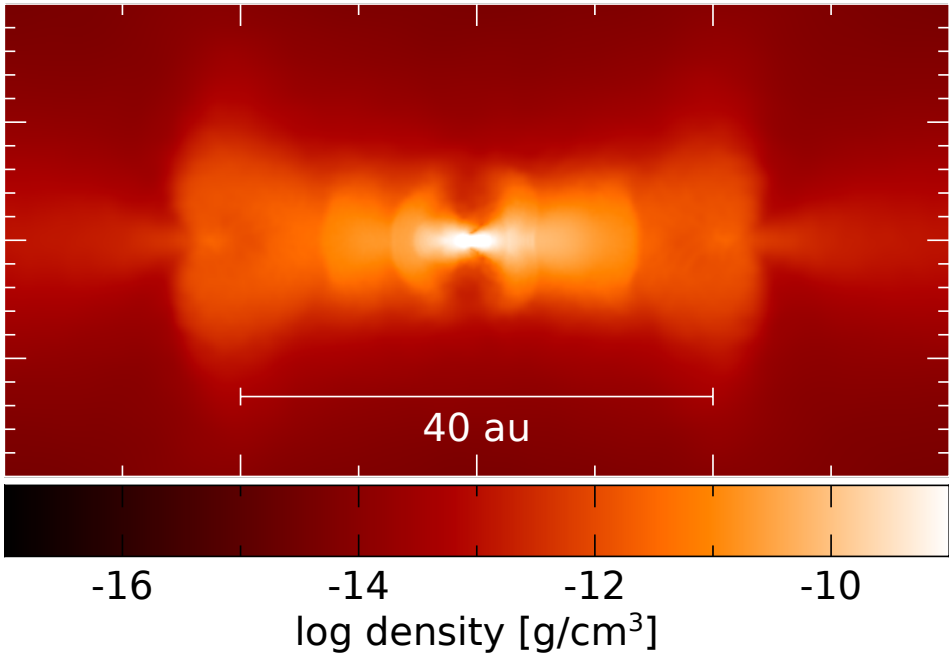
Discs in Perseus (Tobin+2018)



Cluster Formation: Protostellar discs

➢Discs are larger & more varied in these cluster simulations than the isolated simulations

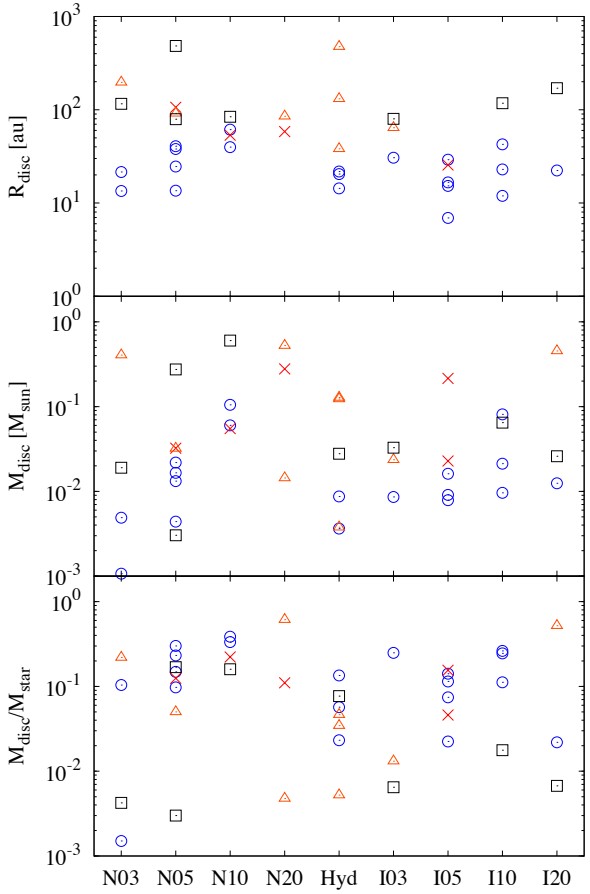


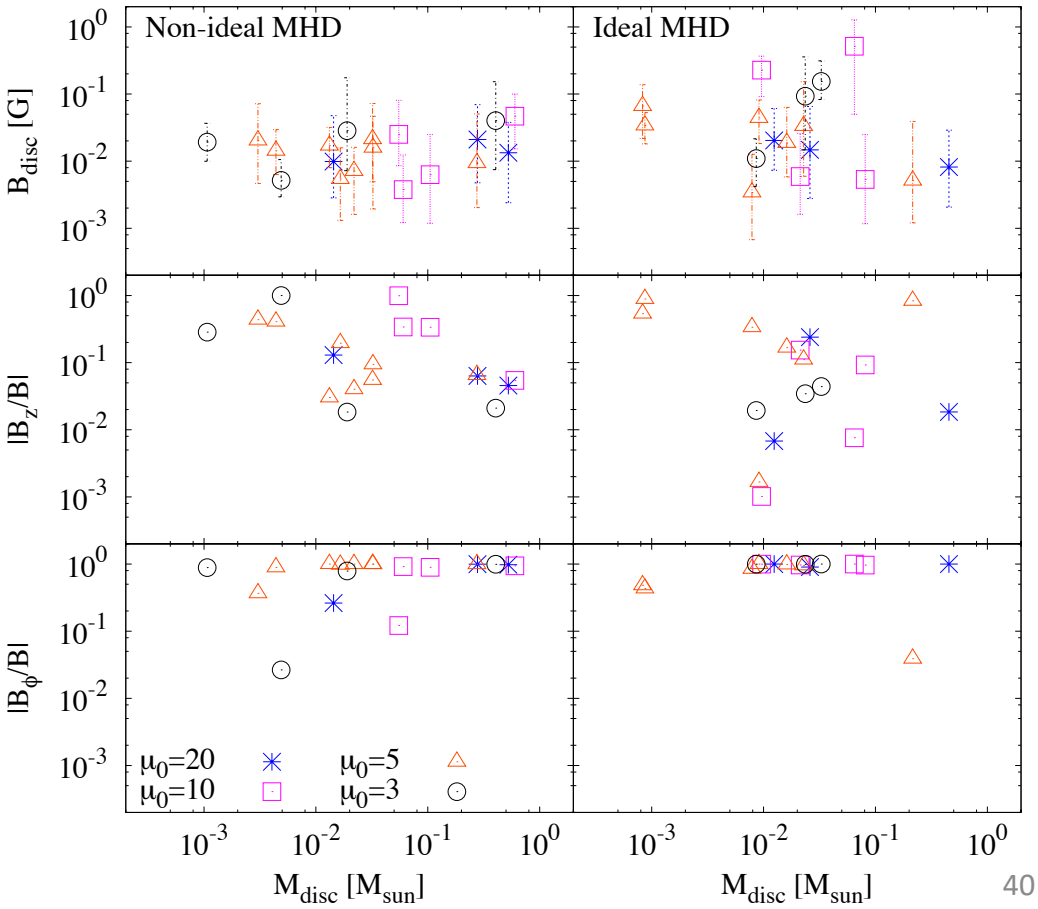


Wurster, Bate & Price (2018c, 2019); Wurster (2021)

Cluster Formation: Protostellar discs

- Stellar & disc hierarchy is continuously evolving
- There exist circumstellar discs, circumbinary discs, and circumsystem discs
- All discs are strongly magnetised
- Left: O = circumstellar disc; x = circumbinary disc; △ (□)= circumsystem discs about 3 (4) stars

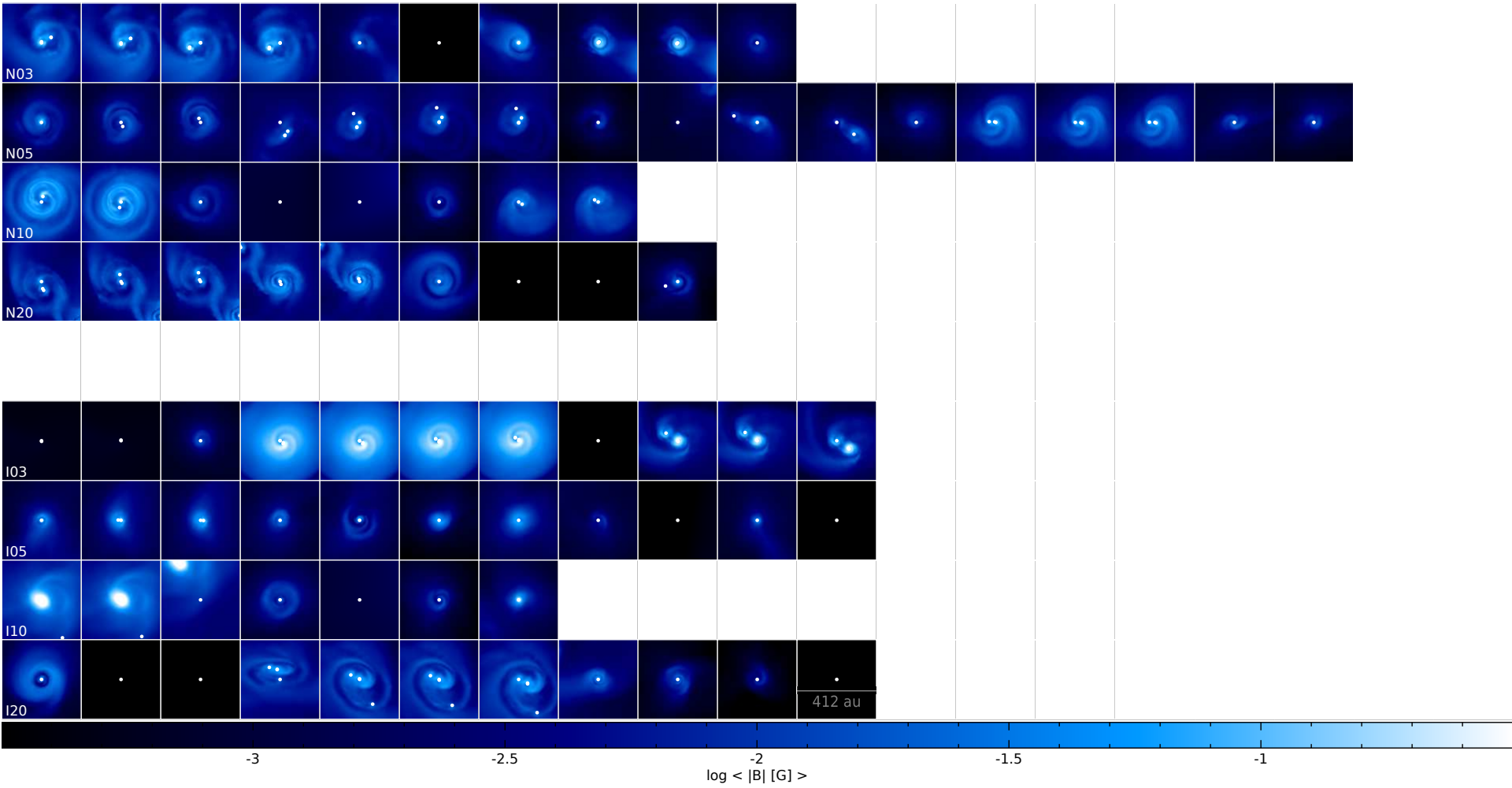




Wurster, Bate & Price (2019)

Cluster Formation: Protostellar discs

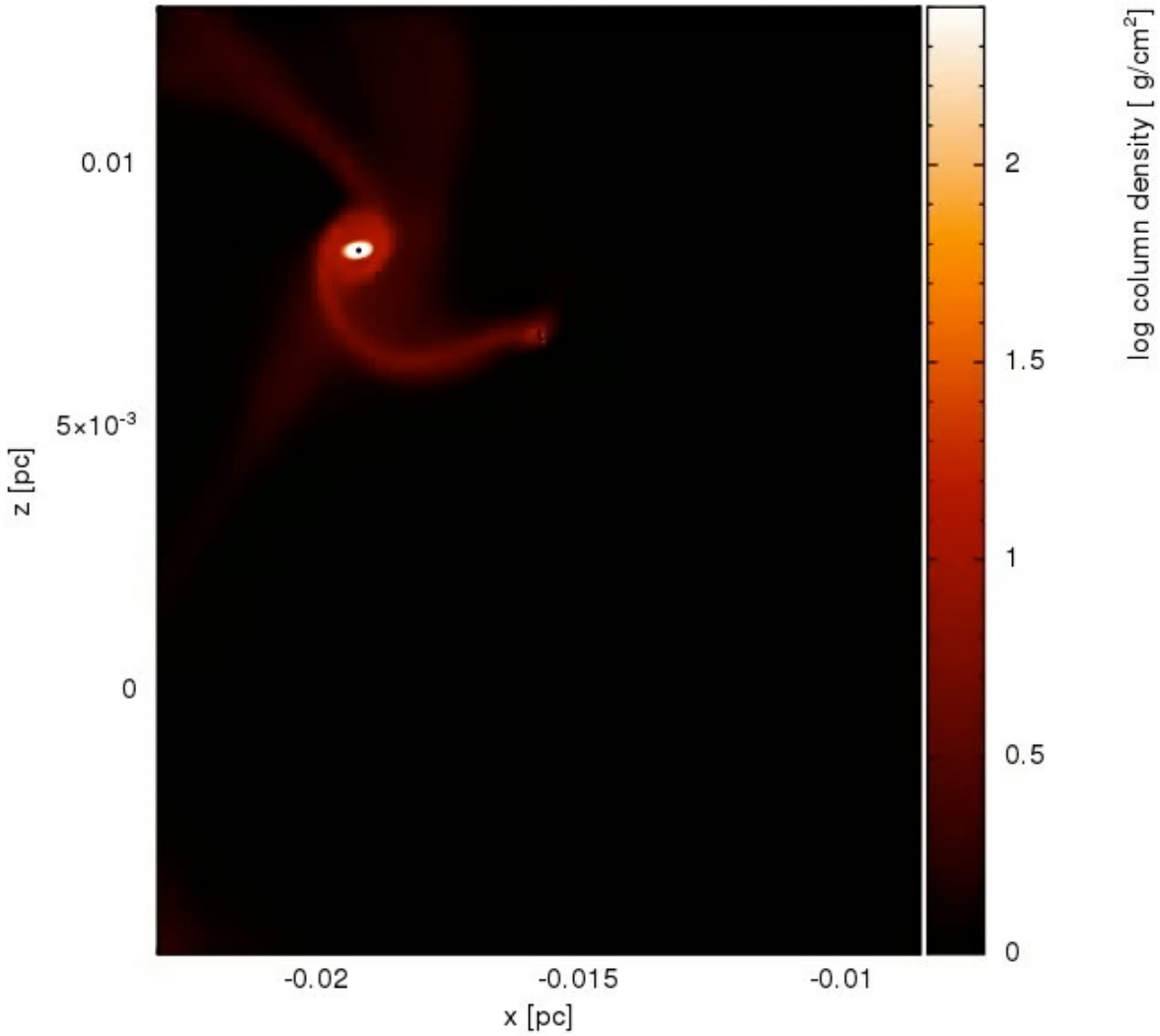
➢Large protostellar discs form in *all* our models



Wurster, Bate & Price (2019)

Cluster Formation: Protostellar discs

➢Large protostellar discs frequently form and interact



Wurster, Bate & Price (2019); see also Bate (2018) for a video the formation and evolution of 183 hydro discs

Conclusions

- Star forming molecular clouds are only weakly ionised
  - Ideal MHD is a poor description
- Isolated, low-mass star formation:
  - Large discs only form in the hydrodynamic model and weakly ionised model with $-B_z$.
    - *this resolved the magnetic braking catastrophe*
  - The Hall effect can cause counter rotating envelopes to form
  - When using non-ideal MHD, the maximum magnetic field strength is not coincident with the central magnetic field strength
- Star cluster formation:
  - No trends amongst most of our parameters
  - Discs form in all of our models, *suggesting that the magnetic braking catastrophe is a result of poor initial conditions*

- WARNING: *Microsoft* now considers BitBucket links to be malicious and blocks emails containing them

University of St Andrews · University of Exeter · erc · DiRAC · Monash University

James Wurster jhw5@st-andrews.ac.uk https://jameswurster.bitbucket.io/