Practical Tutorial

Why is Simulating Jets Hard?

- Typical AGN jet has $\gamma \sim 10$
- How do you get something to move that fast?
- You need energy! $$\frac{B^2}{8\pi} = \epsilon = \gamma \rho c^2$$
- Set $\frac{B^2}{8\pi} = 10,$ then $\rho c^2 = 1$
- 10% error in B^2 means $\Delta\epsilon = 1$, or 100% error in ρc^2!
- This is a *stiff* problem
- We need to minimize errors. How?

Equations of Motion in Conservative Form

Non-relativistic: $$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v_x)}{\partial x} = S$$

Gen. relativistic (GR): $$\frac{\partial(\sqrt{-g}\rho\gamma)}{\partial t} + \frac{\partial(\sqrt{-g}\rho\gamma v^x)}{\partial x} = S$$

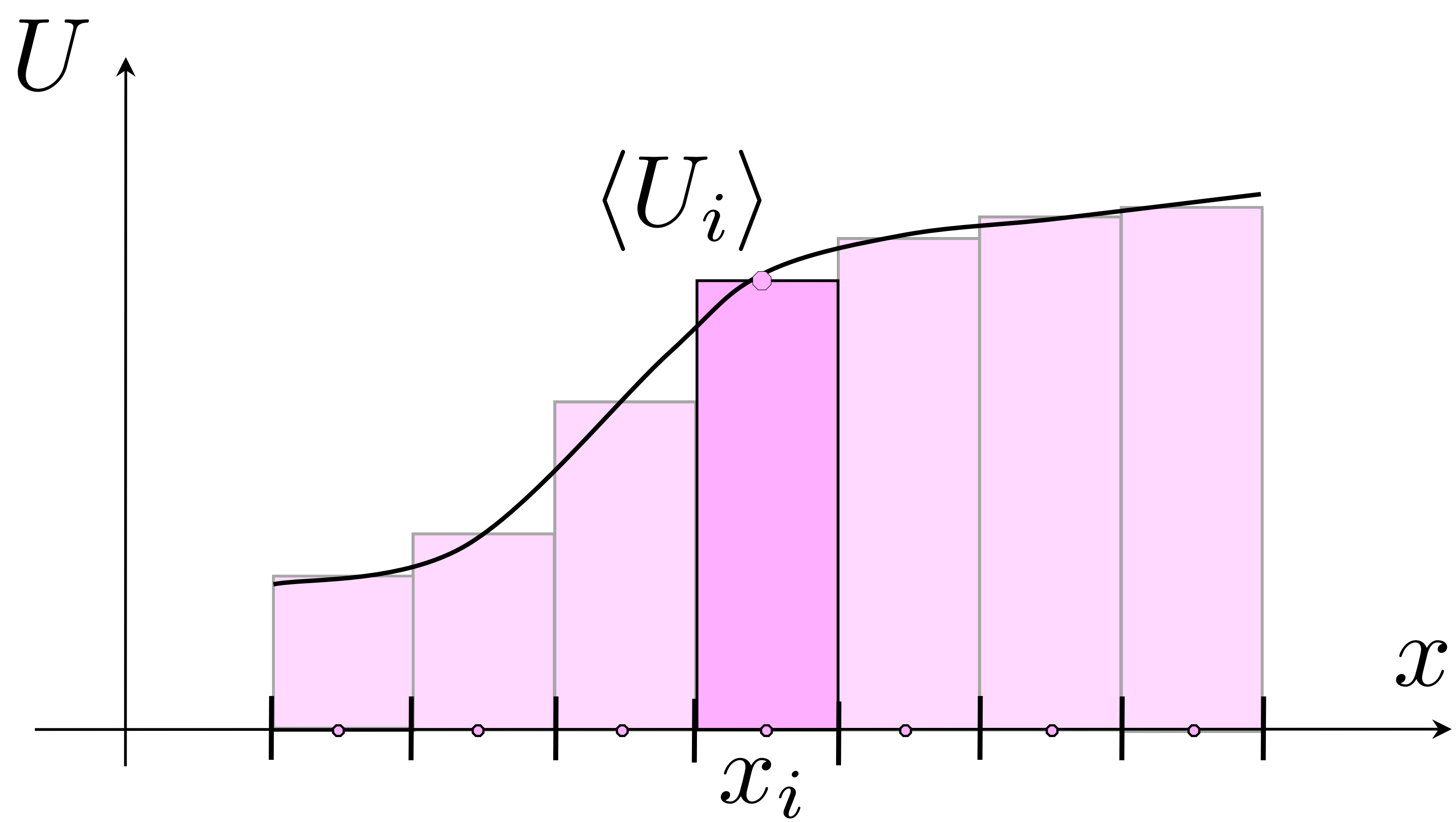
(g is the determinant of the metric)

Conservation law: $$\frac{\partial U}{\partial t} + \frac{\partial F^x}{\partial x} = S$$

The rest of equations of motion reduce to this form of conservation law as well.

How Do We Put Equations on the Grid?

Conservation law: $$\frac{\partial U}{\partial t} + \frac{\partial F^x}{\partial x} = S$$



How Do We Put Equations on the Grid?

Conservation law: $$\frac{\partial U}{\partial t} + \frac{\partial F^x}{\partial x} = S$$

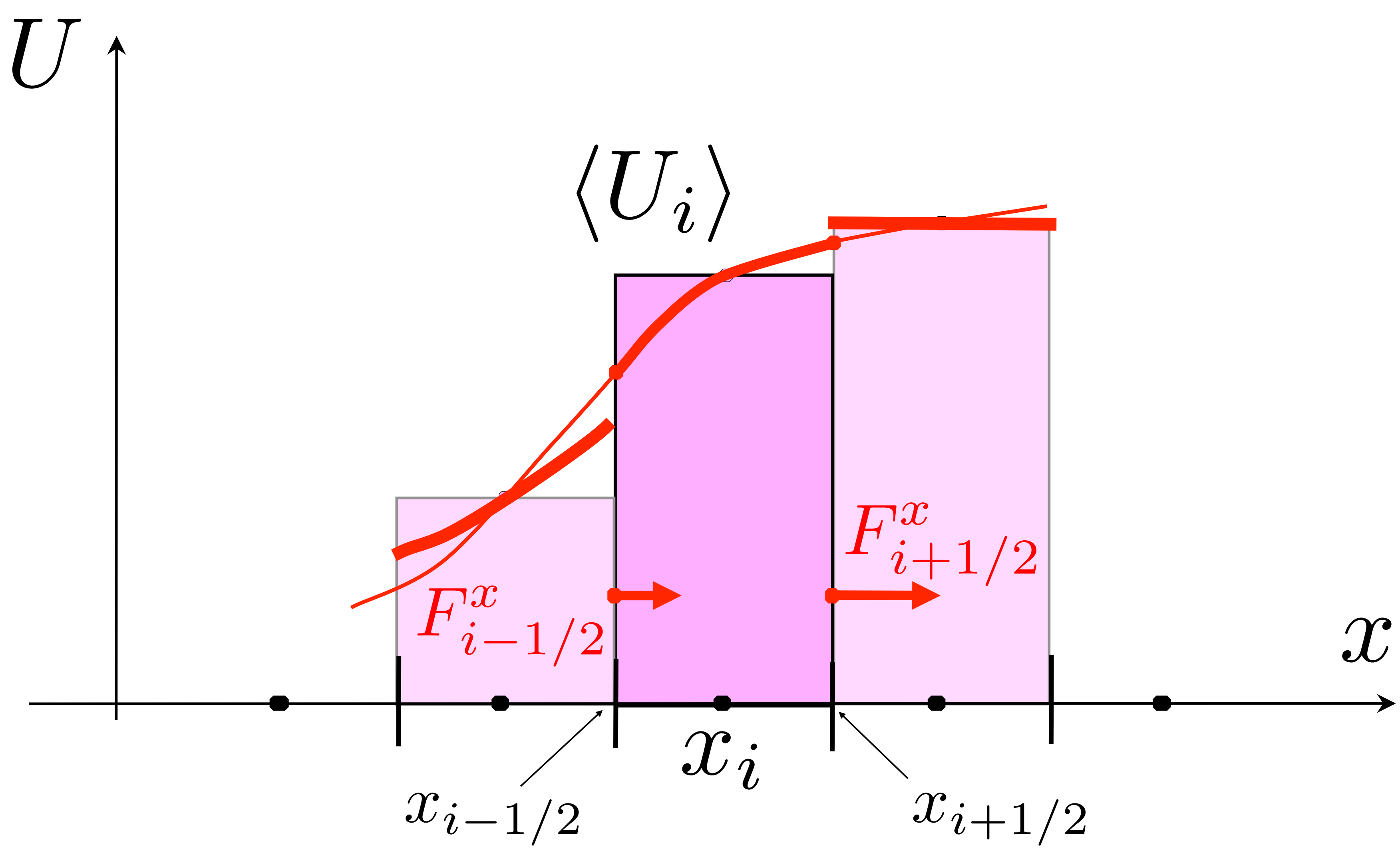
Integrate over the volume of a grid cell: $$\frac{\partial \langle U_i \rangle}{\partial t} + \frac{F^x_{i+1/2} - F^x_{i-1/2}}{\Delta x} = \langle S_i \rangle$$

Fit a high-order non-oscillatory polynomial

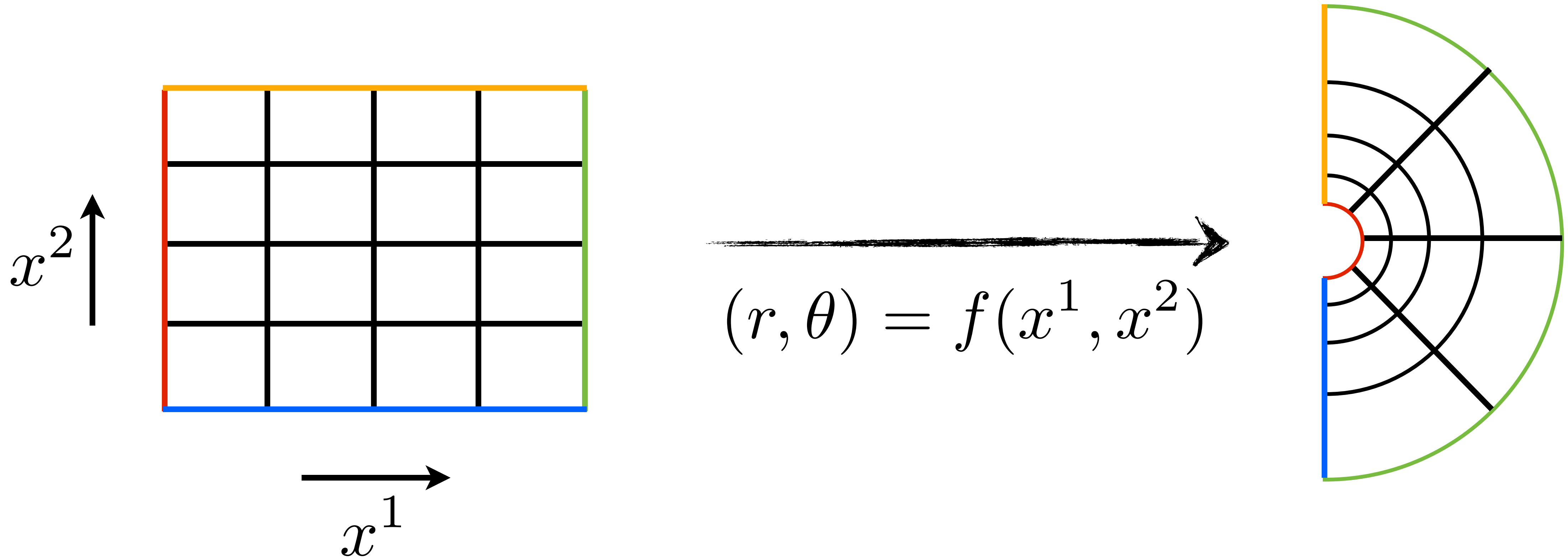
(e.g., high order schemes possible in GR, e.g., AT+2007)

Compute fluxes

Compute $\Delta \langle U_i \rangle$



Flexible Grid: Concentrate Resolution where Needed

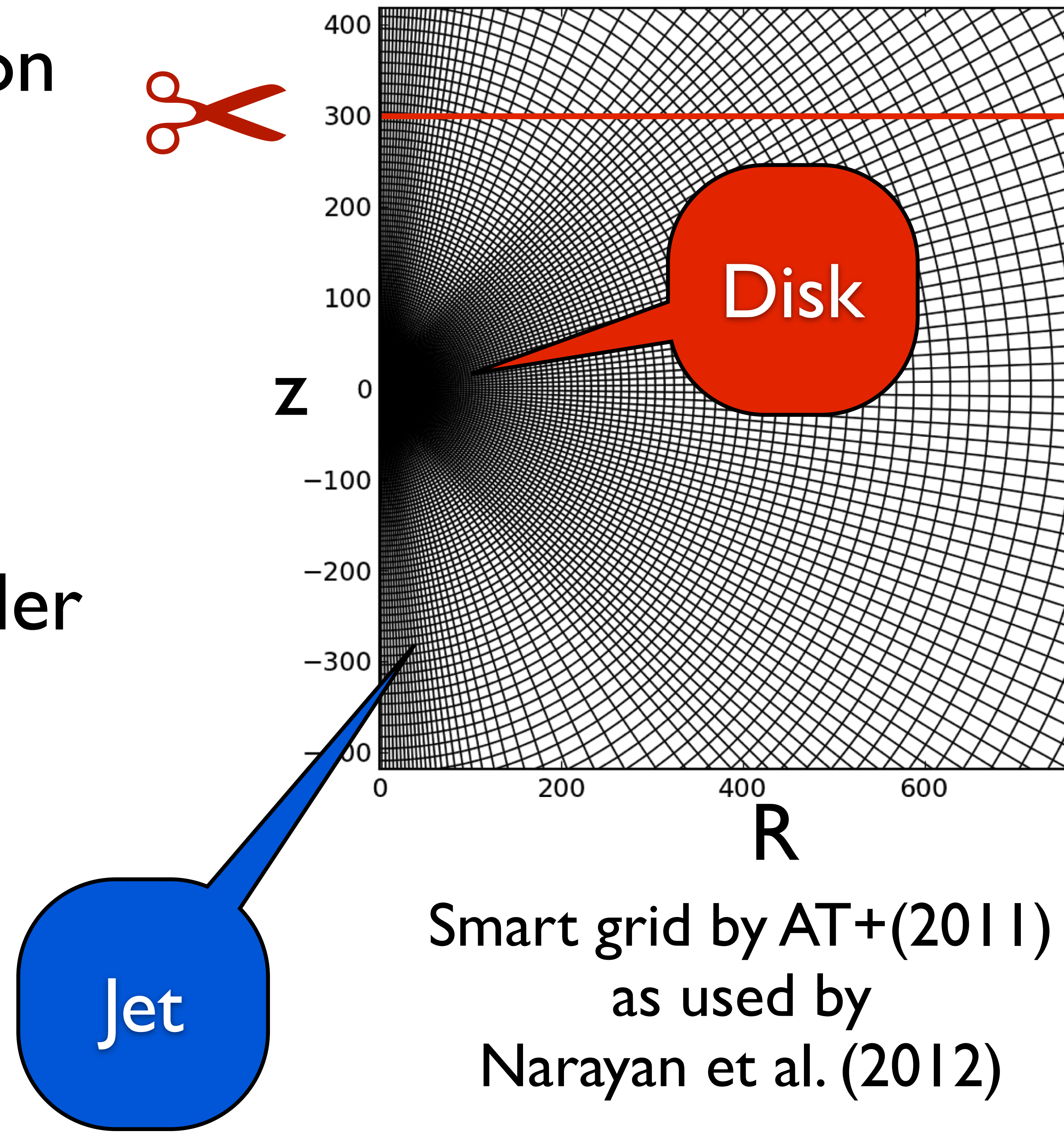


We can concentrate resolution in regions of interest by choosing an appropriate mapping f.

Literally flexible: grid can be curved or non-uniform, to conform to the shape of the boundary or geometry of the problem.

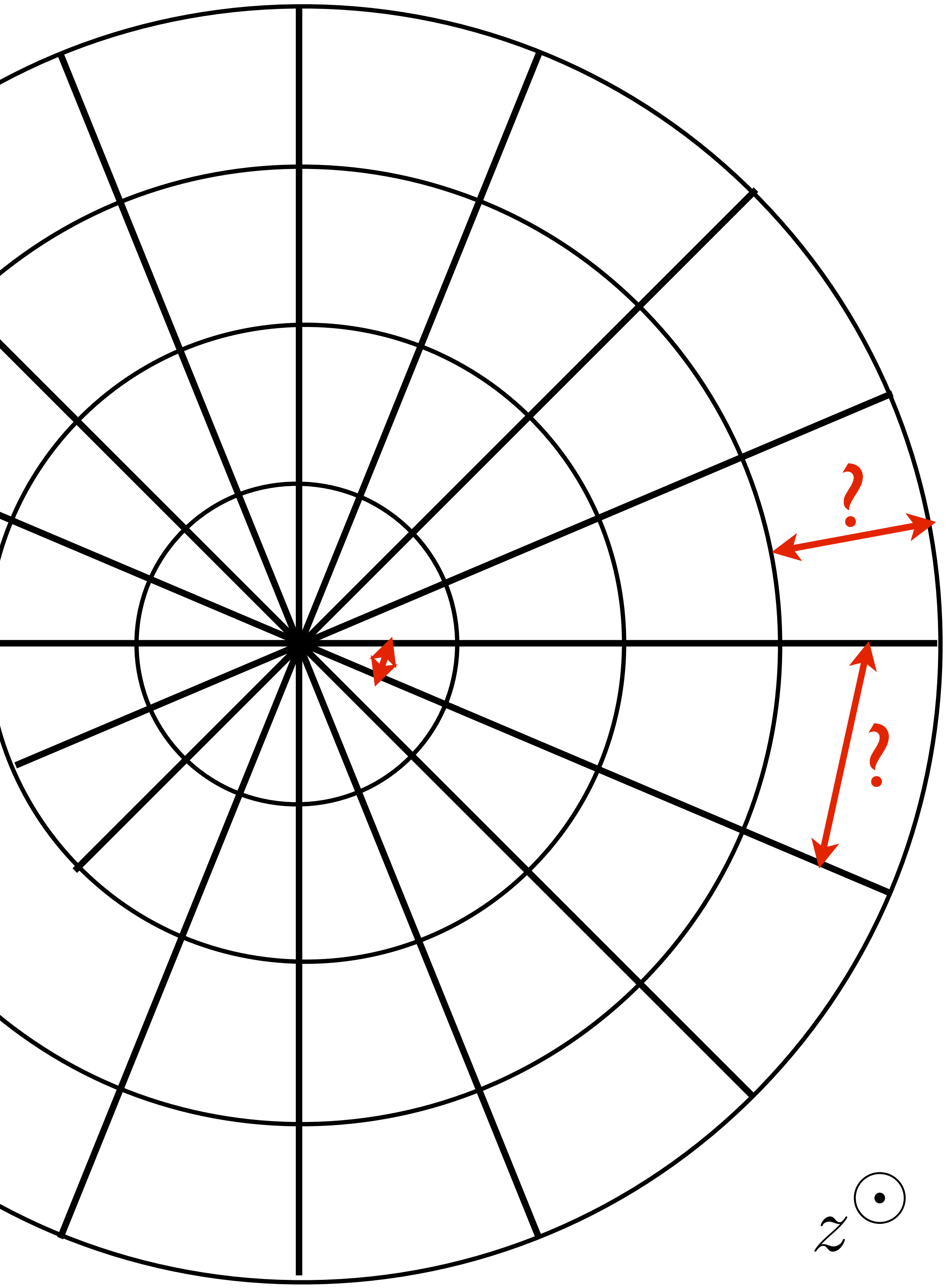
Smart Grid that Focuses Resolution on Disk and Jet

- Concentrates resolution where needed: jet and disk
  (AT et al. 2011)
- Follows collimating jet
- Allows the use of smaller resolutions
- *Question:* isn't the time step too small in 3D?



Smart grid by AT+(2011) as used by Narayan et al. (2012)

Advanced Approach to Polar Axis



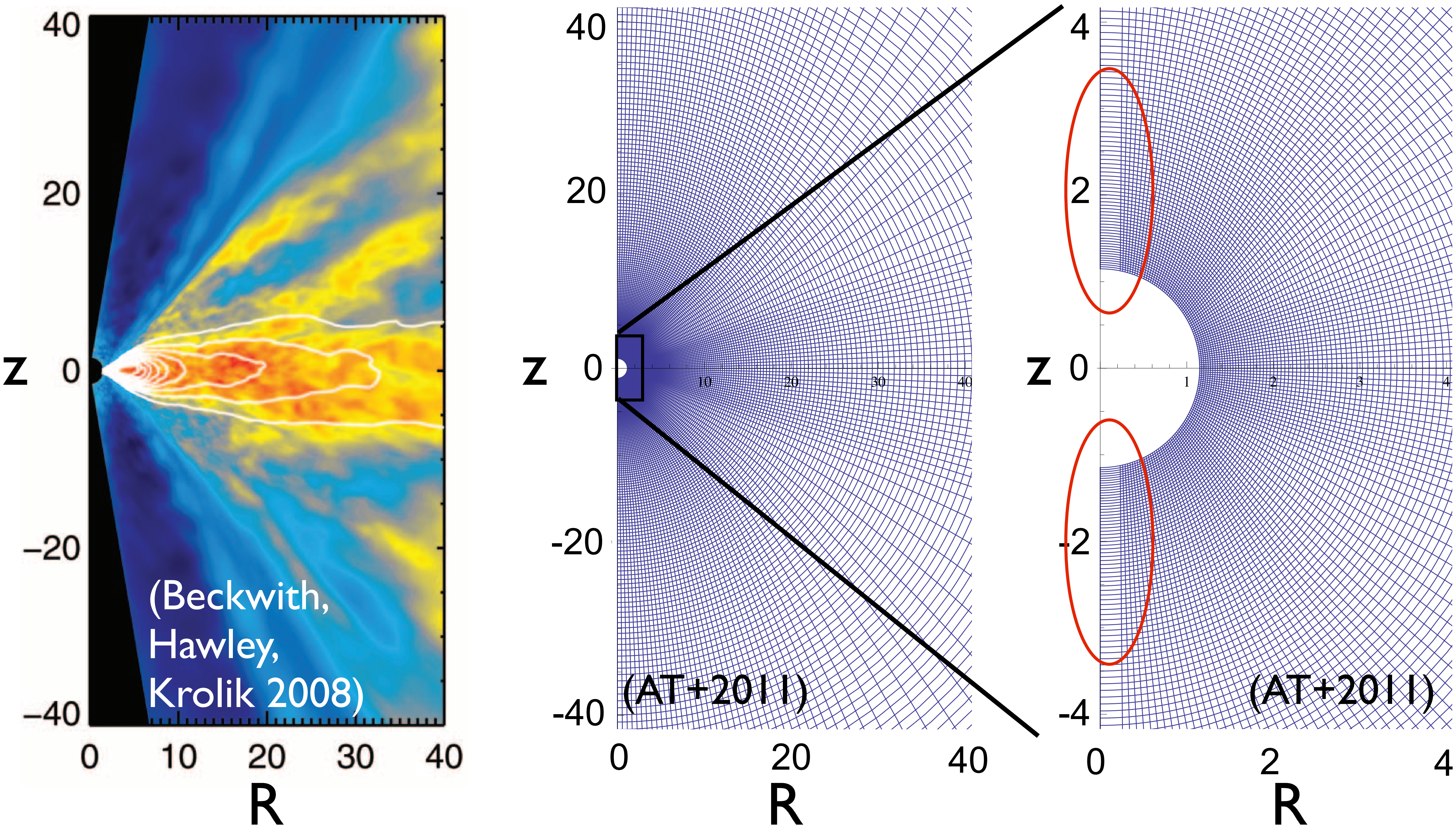
- Time step is the *smallest* light crossing time among all cells
- Small cell azimuthal extent can slow down a run by 10x
- This issue is of great importance for 3D performance

Advanced Approach to Polar Axis

1) Remove offending cells

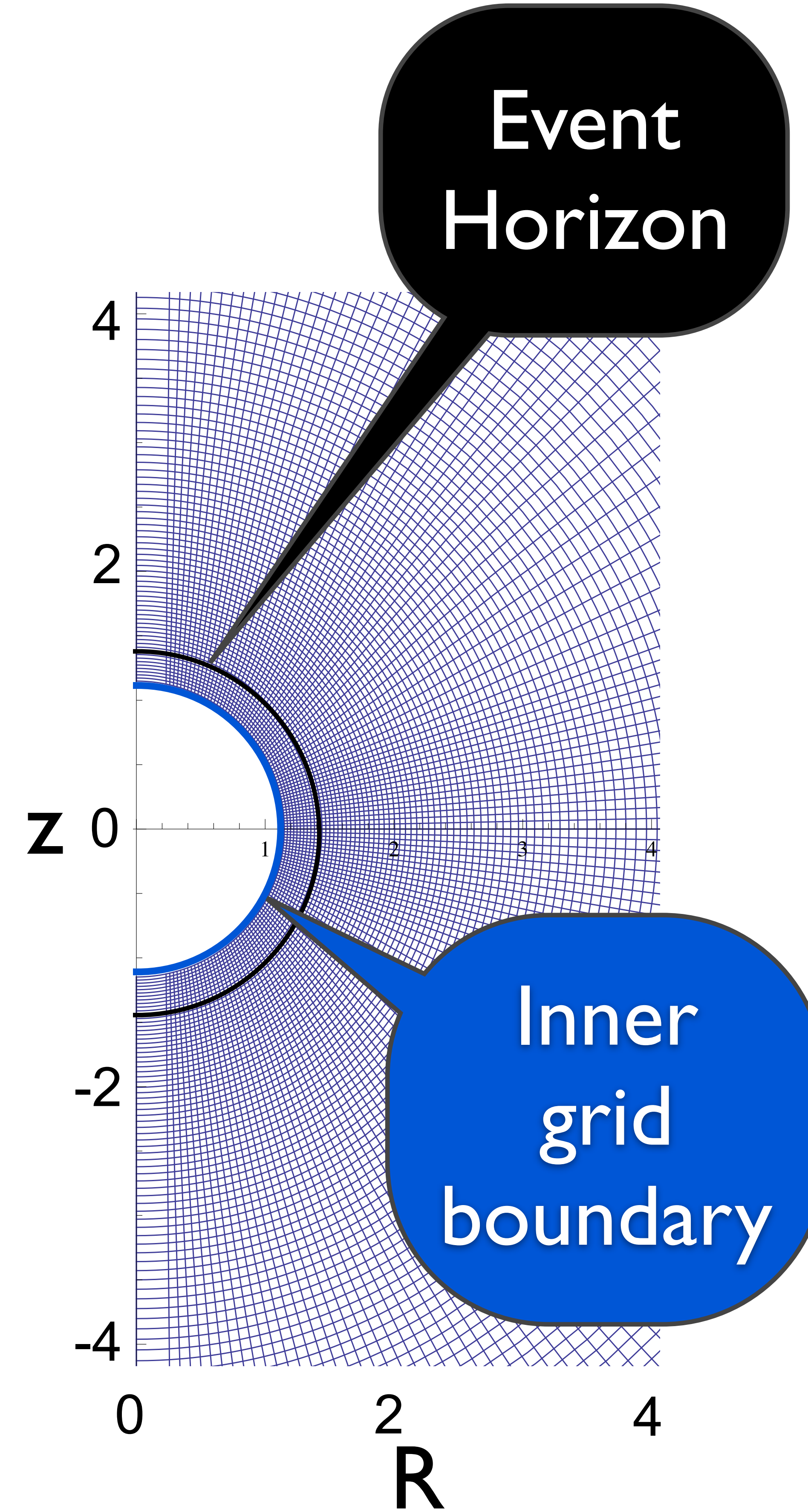
2) *Deform* offending cells

Speedup of 10x!



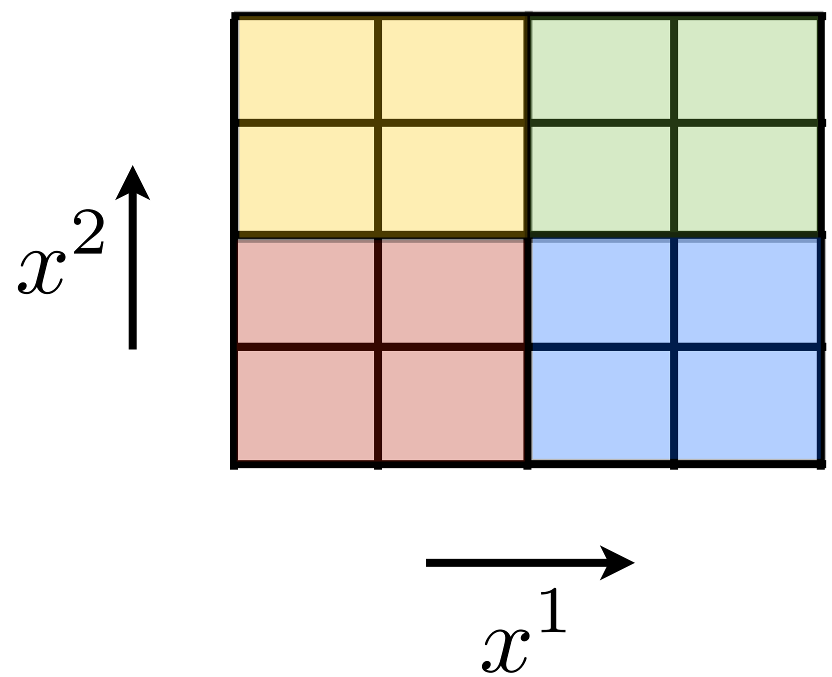
“Event Horizon” Boundary Condition

- Need to ensure that *numerically* no signals escape from the inner grid boundary
- We use horizon-penetrating (Kerr-Schild) coordinates
- Grid extends to the *interior* of the event horizon
- This ensures causal disconnect of the inner radial boundary from the rest of the grid

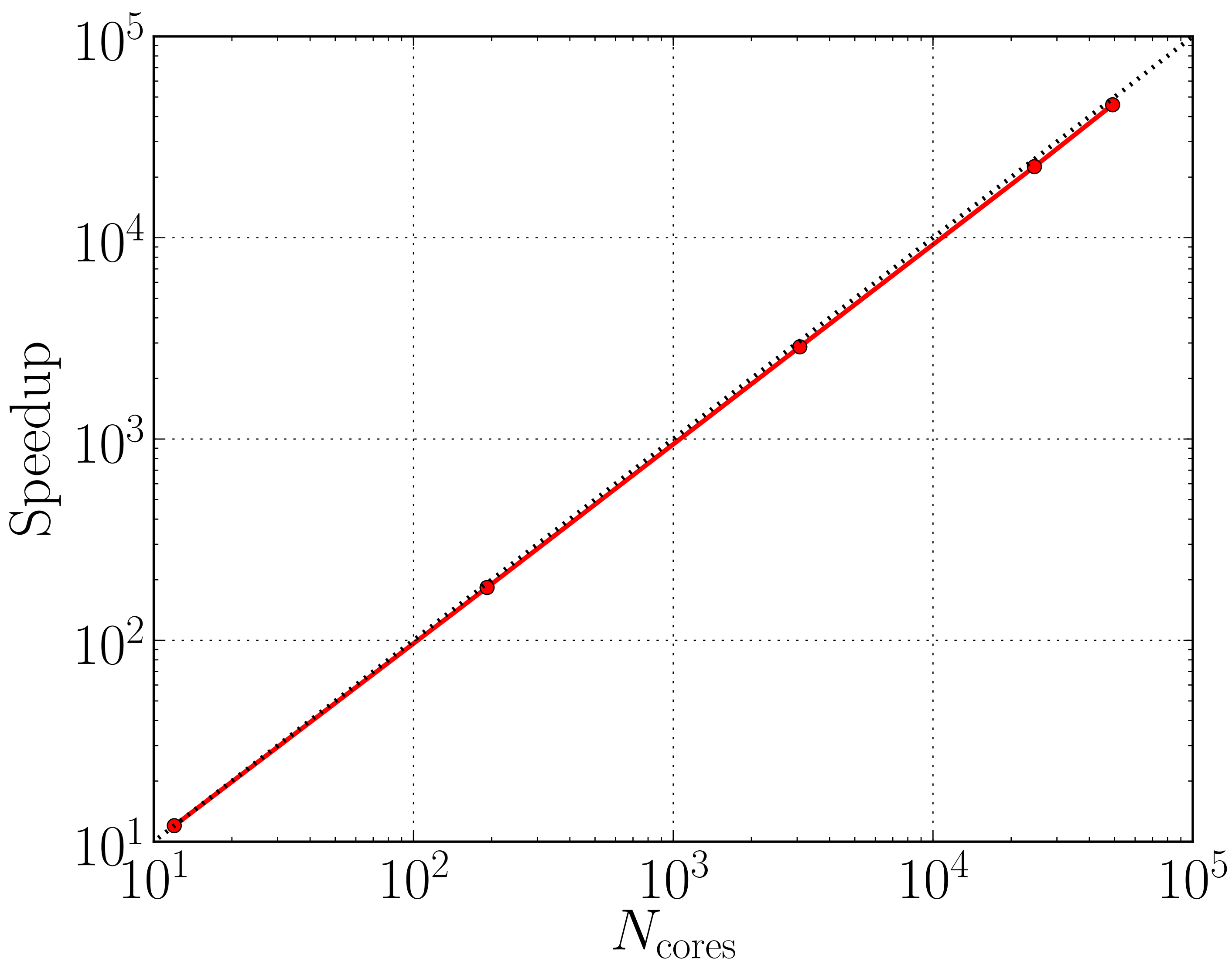


Code Parallelization and Scaling

- Both HARM and Athena Fully parallelized via domain decomposition (hybrid MPI+OpenMP)

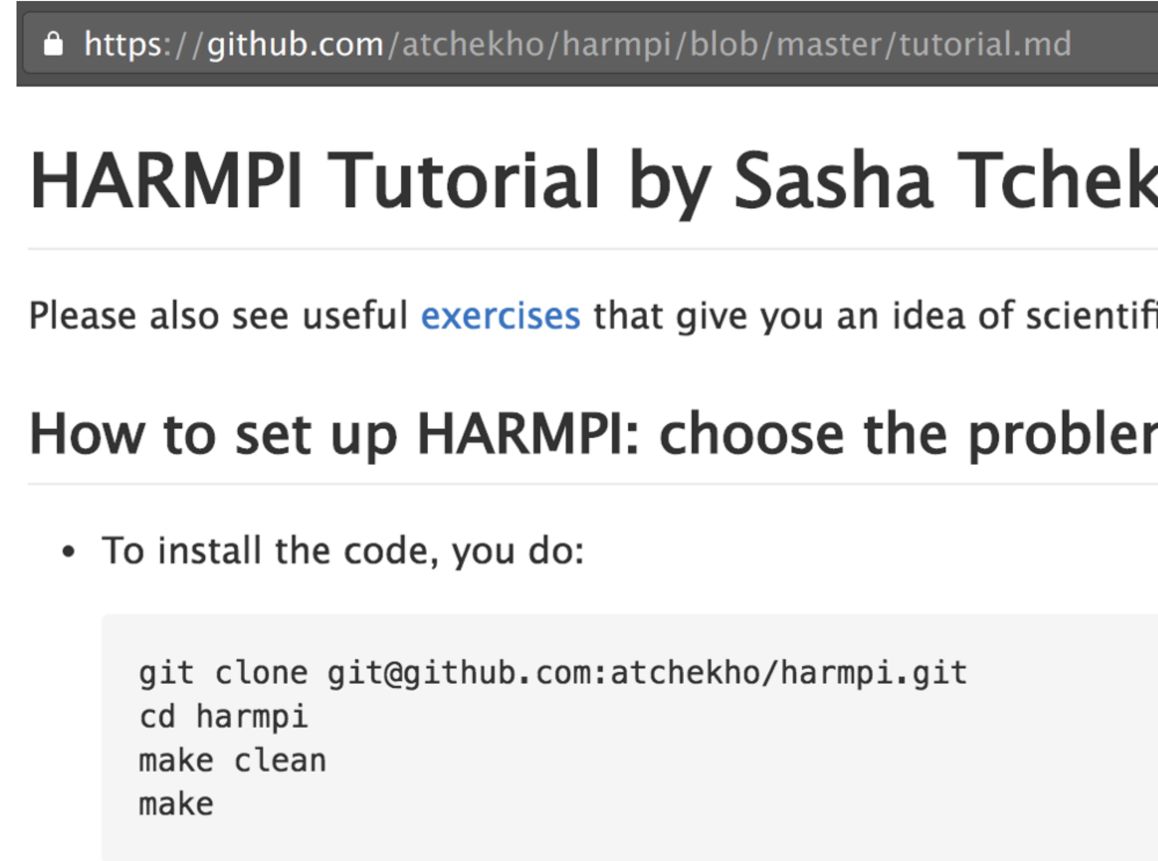


- Near-ideal scaling up to 50,000 cores (weak scaling, 32^3 tile, NICS Kraken, Cray XT5)



New Code HARMPI

- General Relativistic MHD code
- Based on serial, 2D code HARM2D (Gammie et al. 2003)
- Parallelized it via MPI
- Extended to 3D
- Kept it simple (graduate student startup time = hours)
- Made it open-source: github.com/atchekho/harmpi
- Added extra physics


https://github.com/atchekho/harmpi/blob/master/tutorial.md

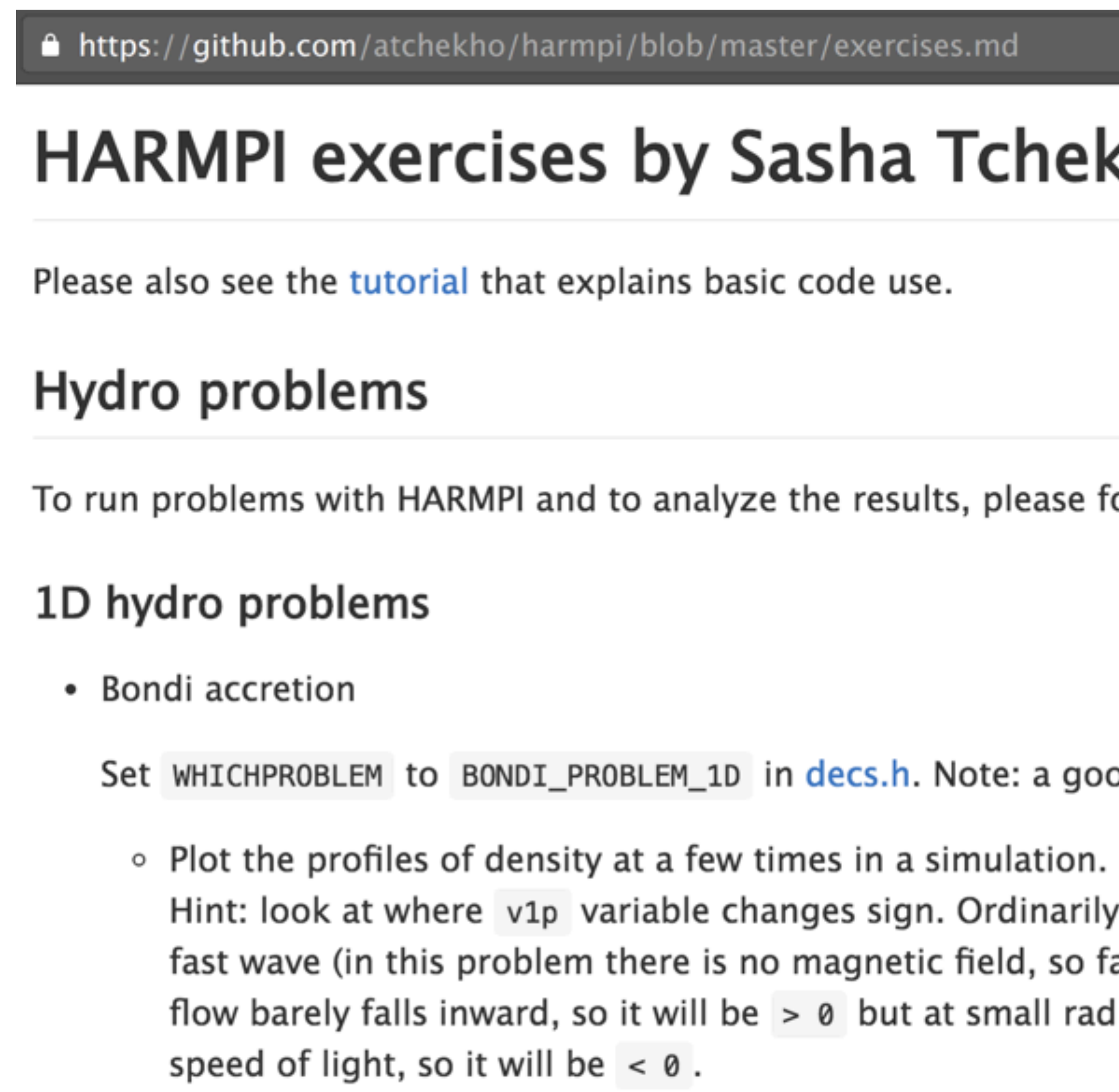
HARMPI Tutorial by Sasha Tchek

Please also see useful exercises that give you an idea of scientifi

How to set up HARMPI: choose the probler

- To install the code, you do:

```
git clone git@github.com:atchekho/harmpi.git
cd harmpi
make clean
make
```


https://github.com/atchekho/harmpi/blob/master/exercises.md

HARMPI exercises by Sasha Tchek

Please also see the tutorial that explains basic code use.

Hydro problems

To run problems with HARMPI and to analyze the results, please fo

1D hydro problems

- Bondi accretion

Set `WHICHPROBLEM` to `BONDI_PROBLEM_1D` in decs.h. Note: a goo

- Plot the profiles of density at a few times in a simulation. Hint: look at where `v1p` variable changes sign. Ordinarily fast wave (in this problem there is no magnetic field, so fa flow barely falls inward, so it will be `> 0` but at small rad speed of light, so it will be `< 0`.

Sasha Tchekhovskoy

How to get the code

- login onto Cartesius:

```
ssh -Y <user>@cartesius.surfsara.nl
```

- get the code:

```
cd ~/
cp -a /scratch-shared/ata2019/codes/harmpi .
```

- load modules:

```
module load mpi/openmpi/2.0.2 icc python
```

- compile the code:

```
make clean && make
```

- compile the code:

```
make clean && make
```

How to run the code

- copy the executable to scratch directory

```
mkdir $TMPDIR/myrun
cd $TMPDIR/myrun
cp ~/harmpi/harm .
```

- choose a problem of choice in decs.h

```
#define WHICHPROBLEM TORUS_PROBLEM
```

- Change resolution to be smaller

```
#define N1 (32)
#define N1 (32)
```

- get an interactive job:

```
srun -t 30 -N 1 -n 16 --pty bash -il
```

- get the interactive job:

```
mpirun ./harm 4 4 1
```

Analyzing the data

- start interactive python session:

```
ipython --pylab
```

- check if graphical windows work

```
plt.figure()
```

- look at the simulation results!

```
%run -i ~/harmpi/harm_script.py
rg("gdump")
rd("dump000")
plco(np.log10(rho),xy=1,xmax=100,ymax=50)
```

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