Radiative transfer and regulation of star formation in typical disk galaxies

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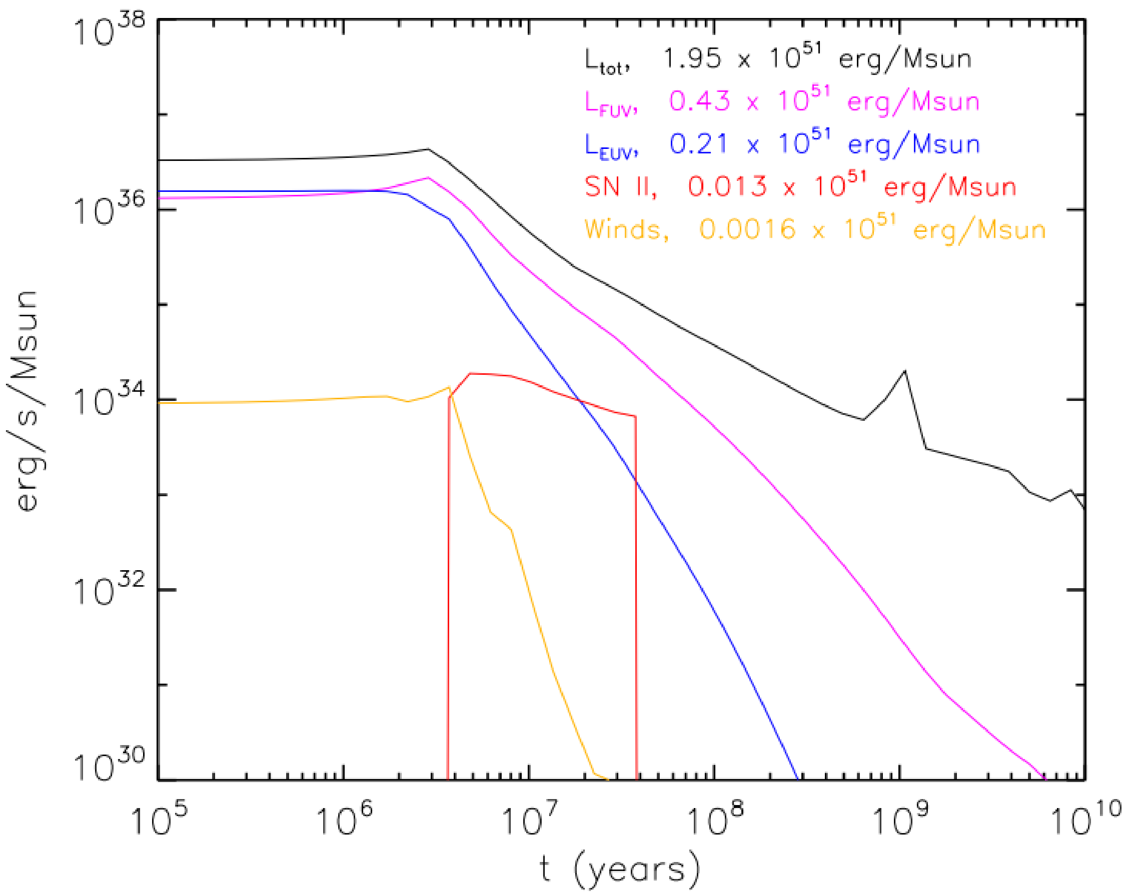
Energy per unit Stellar Mass

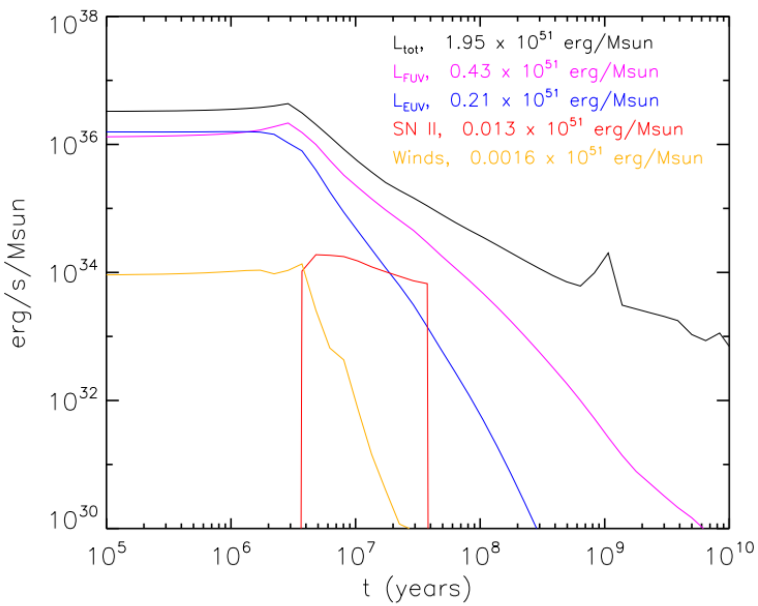
Chabrier (2003) IMF



Starburst 99 Leitherer+ 2014

Energy per unit Stellar Mass

Chabrier (2003) IMF

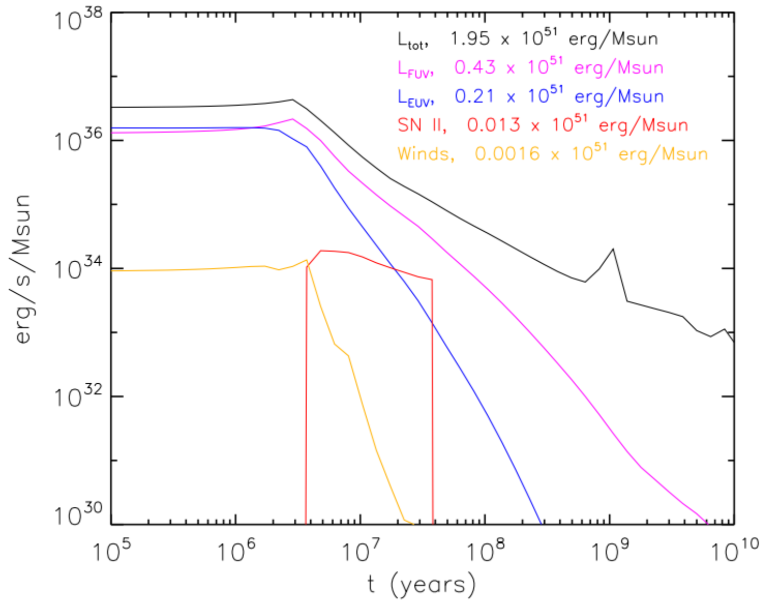


Radiative Stellar Feedback
~ 200 times as much energy as SN and Winds
Longer timescales
Long and short range effects
Peak temperatures limited < 20,000 K
Outflow speeds 10-30 km/s
Can act as an early feedback – cloud buster

Exception: Radiation Pressure
With photon-trapping if that works …
(see Springel yesterday,
Murray+ 2005, 2011, Krumholz & Thomspon 2012, David+ 2014)

Energy per unit Stellar Mass

Chabrier (2003) IMF



Radiation Bands

FUV

~ 6 eV-13.6 eV Photoelectric heating

Opacity: Dust ~ 300 cm^2/g (Z/Z_{solar})

11.2 eV- Lyman-Werner Dissociate H_2

Extra Opacity: H_2

Complicated: see Gnedin & Draine 2014

EUV

13.6 eV Ionize HI

Opacity: HI ~ 5,000,000 cm^2/g (HI/H)

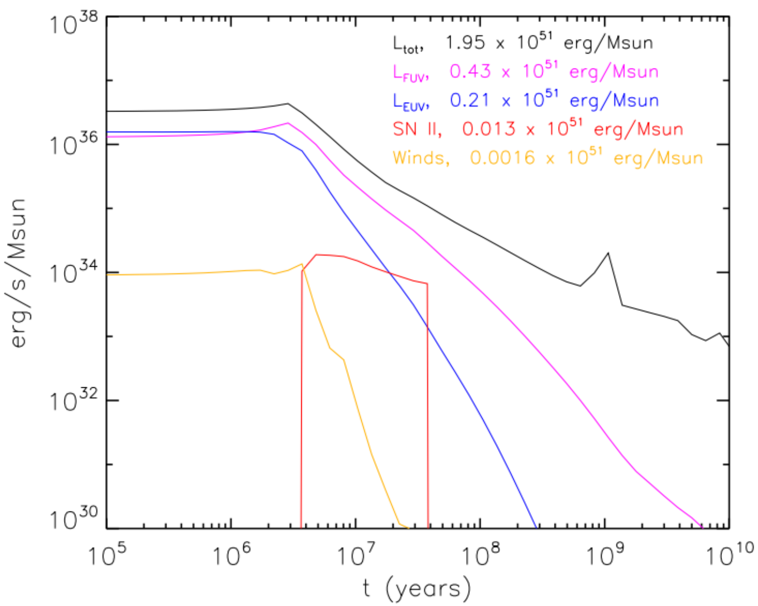
15.2 eV Ionize H_2

24.6 eV Ionize He

> 6 eV Ionize Metals, e.g. 11.2 eV Carbon

Energy per unit Stellar Mass

Chabrier (2003) IMF



Radiation Bands

FUV

- ~ 6 eV-13.6 eV Photoelectric heating
- Opacity: Dust ~ 300 cm^2/g (Z/Z_{solar})
- Length scale in ISM ~ 1 kpc
- Dominant heater of diffuse/neutral ISM
- Produced by recombinations
- Flux varies by factor ~ 100 across disk

EUV

- 13.6+ eV Ionize HI etc…
- Opacity: up to 5,000,000 cm^2/g
- Length Scale in ISM ~ 10 pc (HII regions)
  Few 100 pc in diffuse ISM
- Dominant heater, ionizer of IGM
- 40% recombinations – new ionizing photon
- Flux varies strongly w/ environment

Full Radiative Transfer Problem:

$$I(x, y, z, q, f, n, t)$$

- 3 spatial coordinate
- 2 angles
- Frequency
- Time
- Characteristic Speed c

Expensive

Radiative Transfer for Galaxy Formation

Approximate is better than constant

Considerations:

- For heating/chemical networks, only mean (angle averaged) intensity needed
- Scattering is common, (e.g. dust opacity ~ 50% scattering) – directional information lost
- Many sources, including recombinations in gas
- Often limited by front speed/chemistry not by speed of light

Classes of RT Methods

Flux Limited Diffusion/Moment Methods

- Treat radiation as continuous
- Good for diffussive regime/optically thick. e.g. IR
- Easy to have many sources
- Radiation bends around corners: poor shadows
- *Severe timestep limits*

Ray-tracing/ Characteristic Methods

- Adjustable angular accuracy: good shadows
- Can avoid timestep limits
- *Simple methods expensive for many sources*

Ray-tracing

Explicit characteristics (finite c)

N elements: Cost ($N_{directions}$ N)

Time steps: dt ~ L/$N^{1/3}$/c << dt_{Hydro}

e.g. Traphic (Pawlik & Schaye 2008), SPHRay (Altay+ 2008), ENZO RT (Reynolds+ 2009), C^2 -ray (Mellema+ 2006), FLASH

Full ray trace (c → Infinity)

N elements: Basic Cost ($N^{5/3}$)

Timesteps: dt ~ dt_{ionize} ~ dt_{Hydro}

e.g. TreeCol (Clarke+ 12), URCHIN (Altay & Theuns 2013)

Gasoline

Initial Code base for Radtiative Transfer method:
Gasoline parallel code (MPI) (Wadsley+ 2004)

- pkdgrav N-body Solver (Binary Tree, Hexadecapole) and Modern Smoothed Particle Hydrodynamics (see e.g. Keller+ 2014, Shen+ 2010)

Also implementing into CHANGA:
Rewrite of Pkdgrav2/Gasoline in Charm++ (Jetley, Quinn+ 2008)

- Faster Gravity: Fast-Multipole-like Tree
- Scales to > 100,000 cores
- All prior Gasoline physics modules now ported

Target: Fast RT for Cosmology Simulations/ Galaxy Formation

Primary Galaxy Formation approach:

Spatially uniform Ionization rates, $\Gamma(t)$

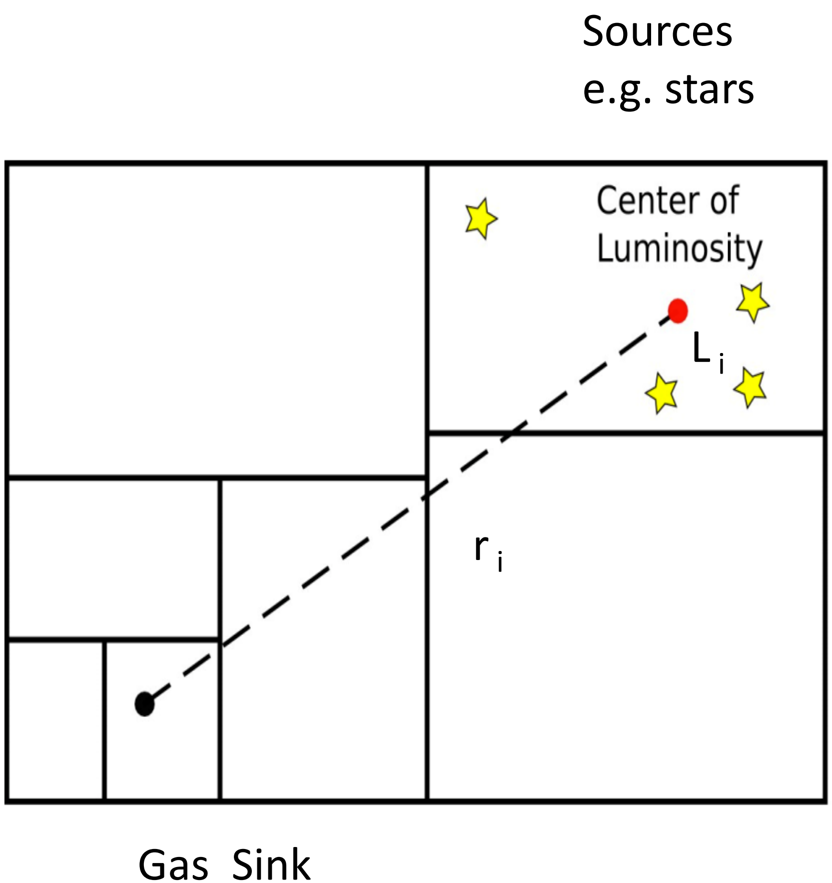
Goal: For similar cost to hydro+gravity:

Approximate Local $\Gamma(x,y,z,t)$

Tree approach $O(N \log N)$

see also URCHIN (Altay & Theuns 2013), C^2 -ray (Mellema+ 2006)

First approach: Tree Walk



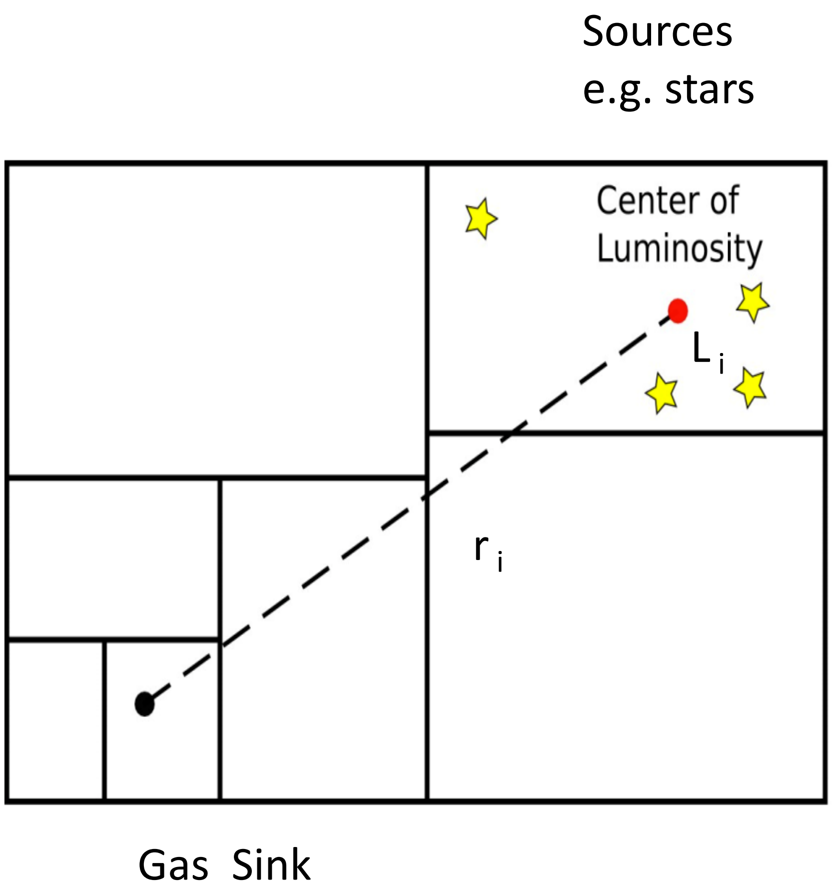
- Centre of mass

→ Centre of Luminosity

- Error control by opening angle $d_{cell}/r < \theta$
- $G \propto \sum_i \frac{L_i}{4\pi r_i^2}$
- Optically thin

Kannan, Woods, Wadsley+ 2014

First stage: Tree Walk



- Cost: $O(N_{sink} \log N_{source})$
- Multiple timesteps: $O(N_{active} \log N_{source})$
- Highly Parallelizable
- No RT timestep requirement
- Runtime < Tree Gravity

Kannan, Woods, Wadsley, et al. 2014
See also: Hu et al 2016 in prep

Second Stage: Absorption

Far from source/sink use Tree Cells

- Tree nodes carry opacity, density information, use geometric intersection to get length:

optical depth to traverse cell

Sub-cell Near source/sink use particles

- Similar to TRAPHIC/SPHRay:
  - Sort particles: Optical depth from 2d integral of Kernel, no self-optical depth

Note: Only approximate photon conservation, zero light travel time

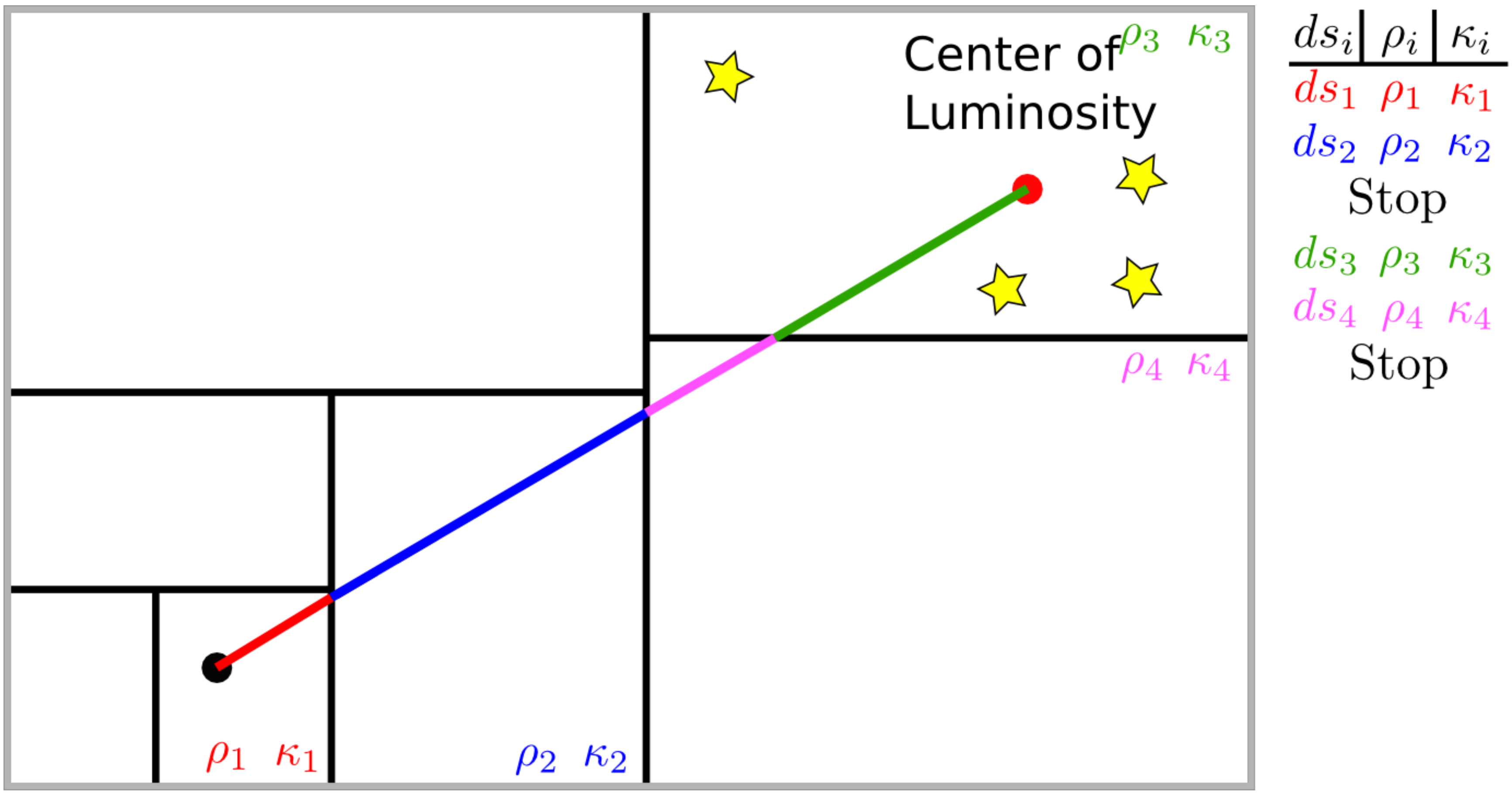
Woods, Wadsley & Couchman, in prep

Particle-Particle issues

- Particles treated as thin disks with column equal to integrated particle density $W_{2D}(b)$
- Both particles consider other to be in front on it. Solution: sort particles radially $r_1 < r_2$

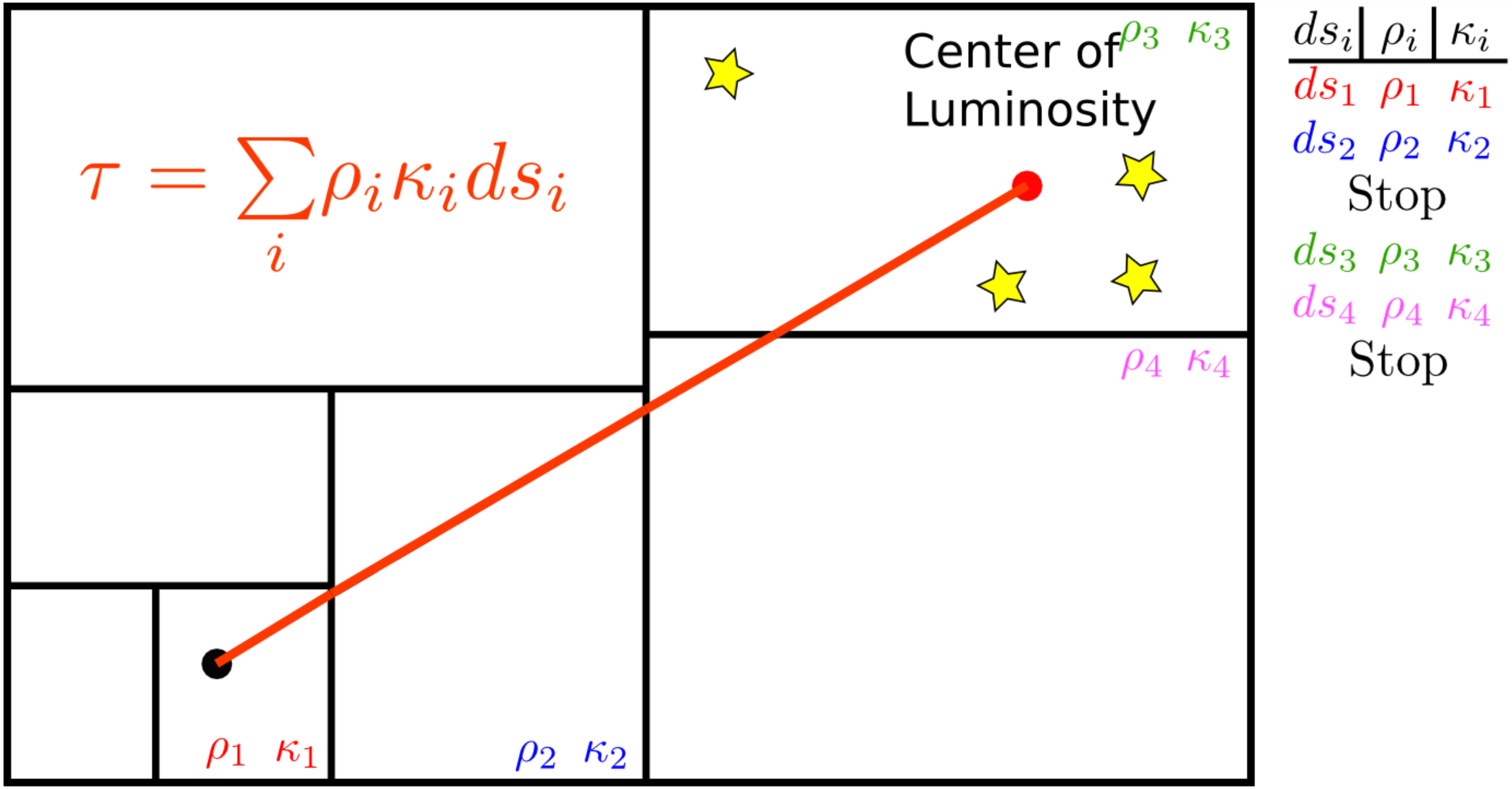
General issue: single cell/particle can have substantial optical depth –entire cell gas doesn't see the same radiation field

Second Stage: Absorption



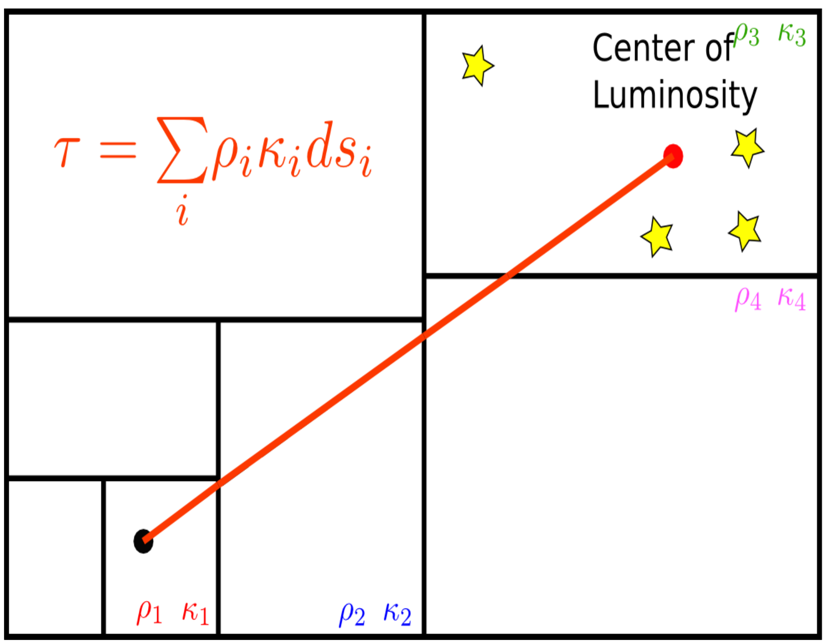
Woods, Wadsley & Couchman, in prep

Second Stage: Absorption



Woods, Wadsley & Couchman, in prep

Second Stage: Absorption



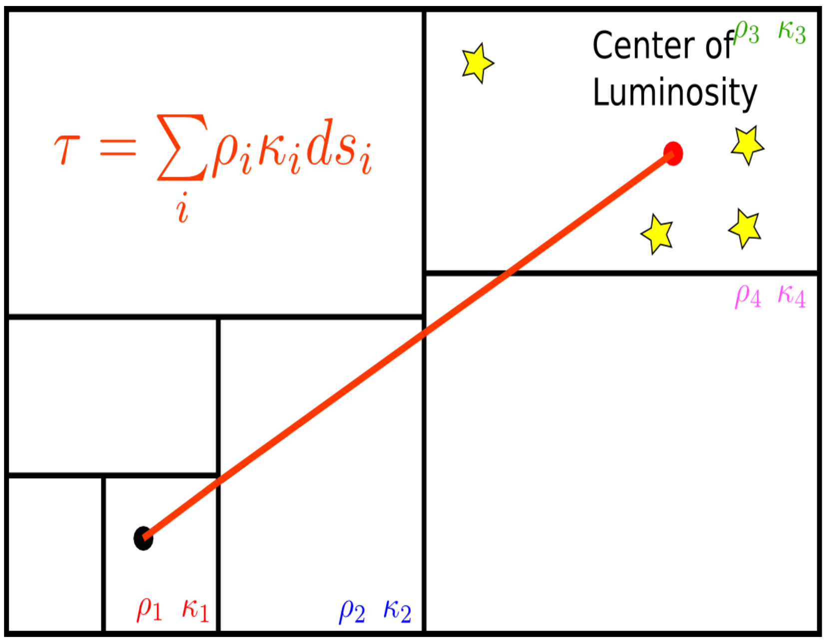
- Re-walk Tree source to sink
- Adaptive error control: opacity, angular size, current optical depth

  Default: Angular size

- $F \propto \sum_i \frac{L_i}{4\pi r_i^2} e^{-\tau}$

Woods, Wadsley & Couchman, in prep

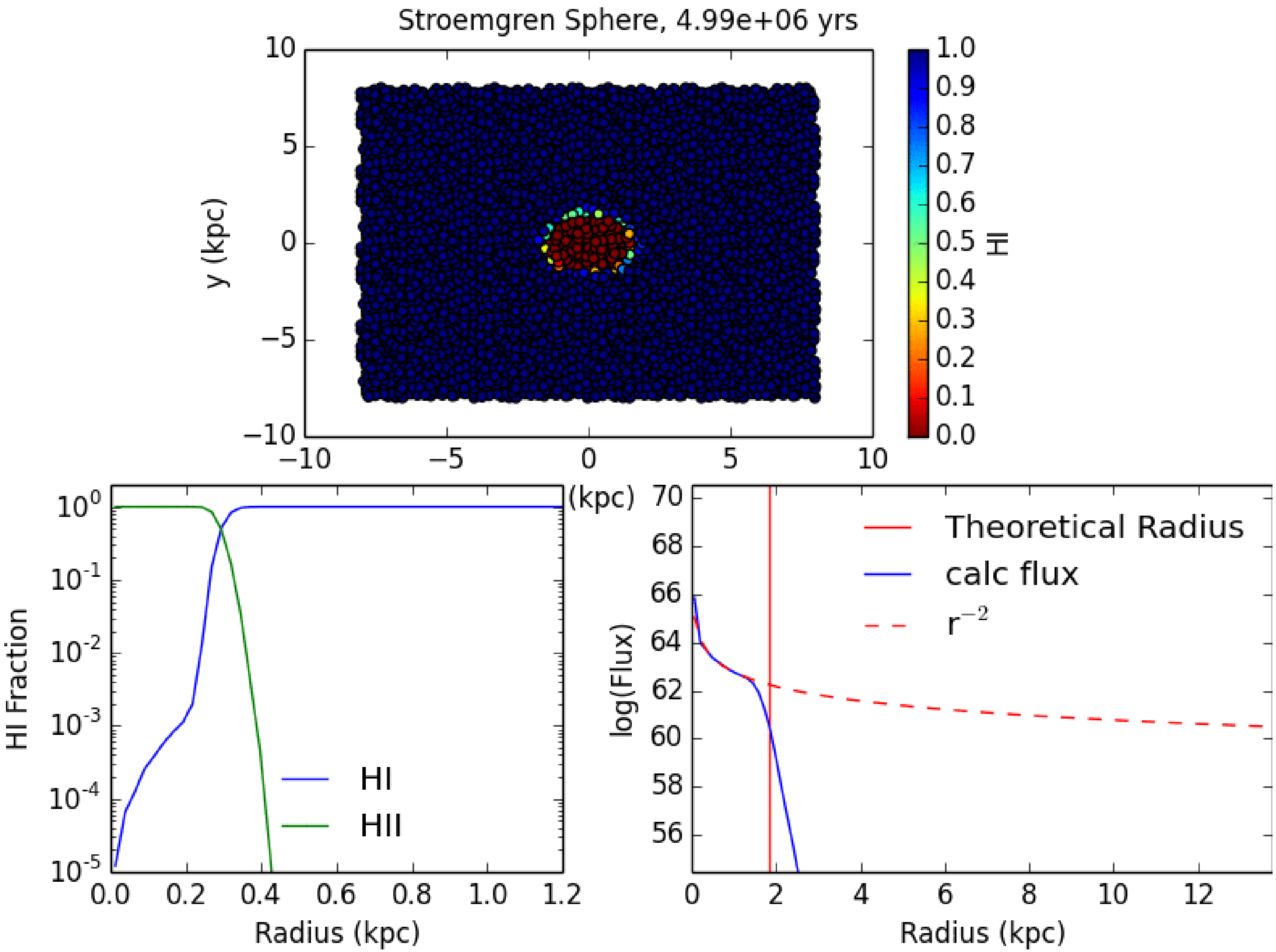
Second Stage: Absorption



- $O(N_{sink} \log N_{source} \log N)$
- Multiple timesteps: $O(N_{active} \log N_{source} \log N)$
- Highly Parallelizable
- No RT timestep requirement
- Runtime ~ Tree Gravity

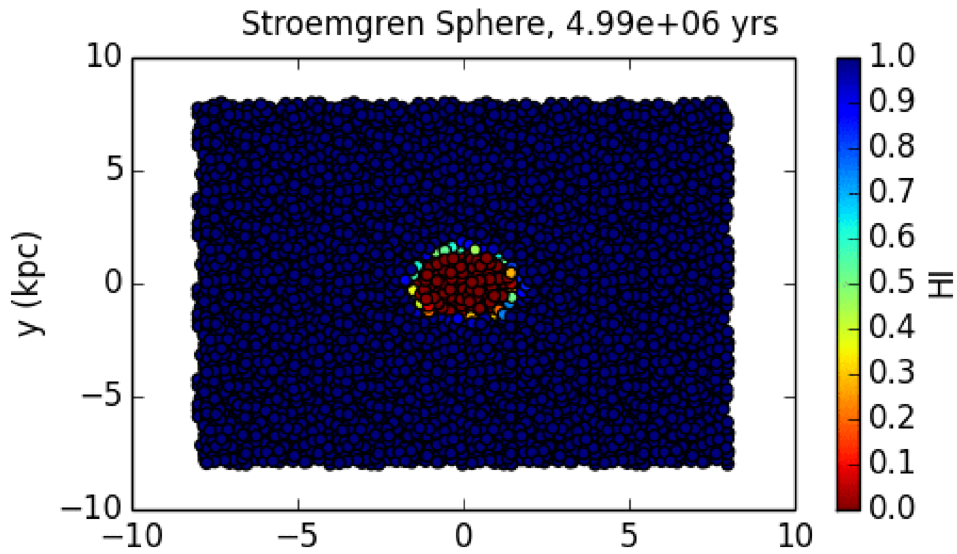
Woods, Wadsley & Couchman, in prep

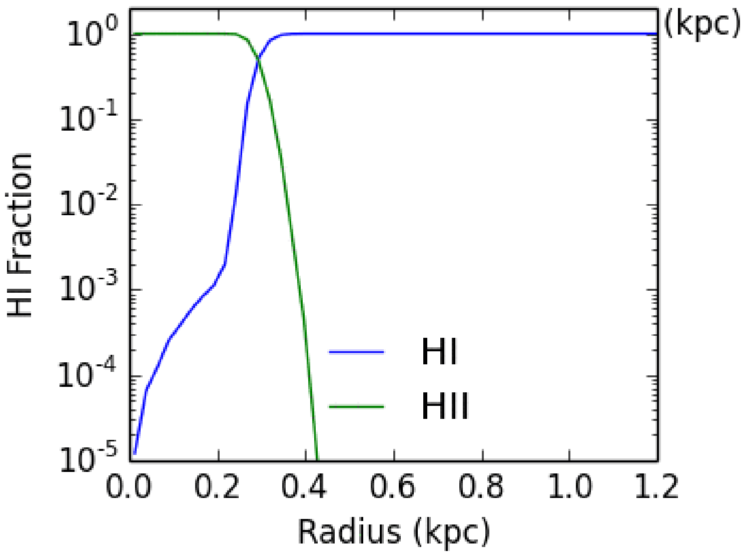
Code Tests: Strömgren Sphere

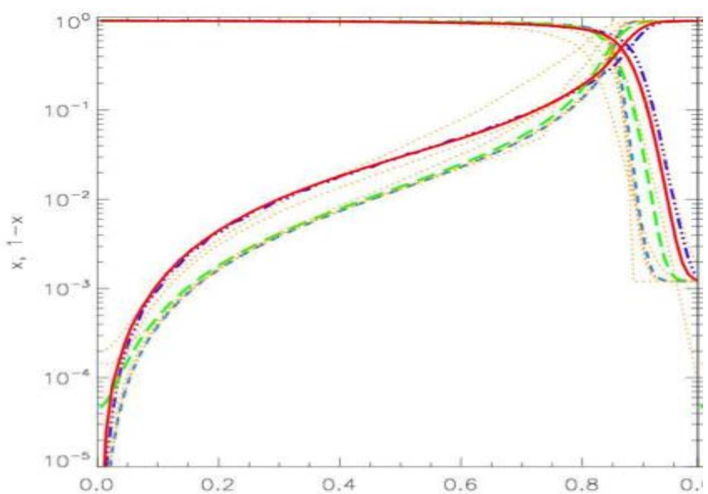


Thermal Strömgren Sphere, cf. Iliev+ 2006

Code Tests: Strömgren Sphere

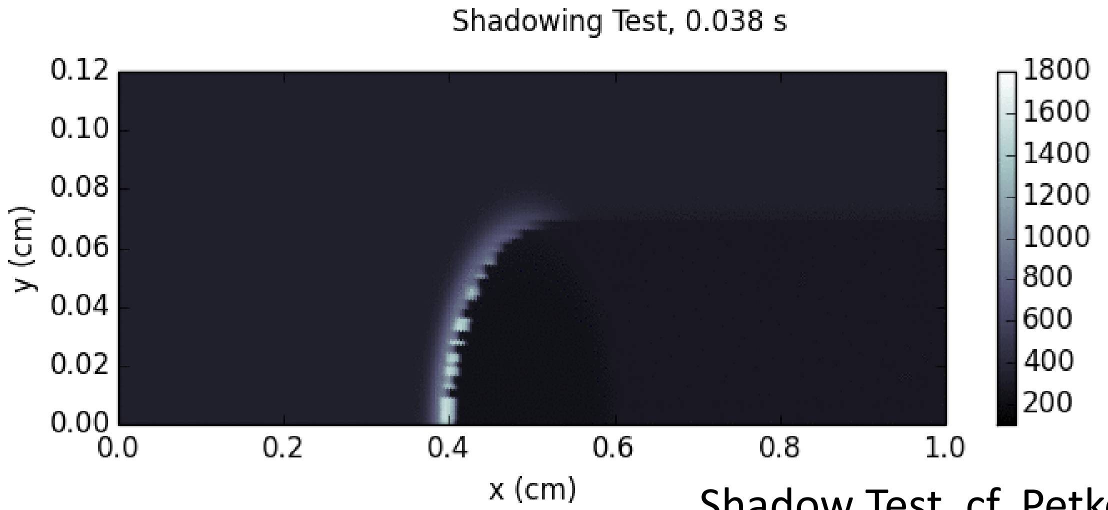




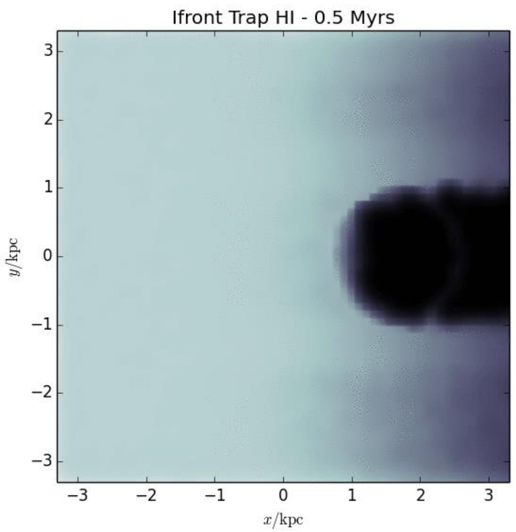


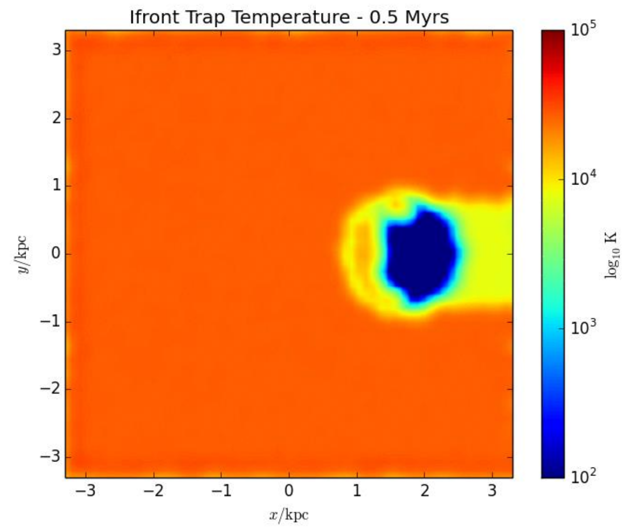
Strömgren Sphere, Altay+ 2008

Code Tests: Shadowing Test



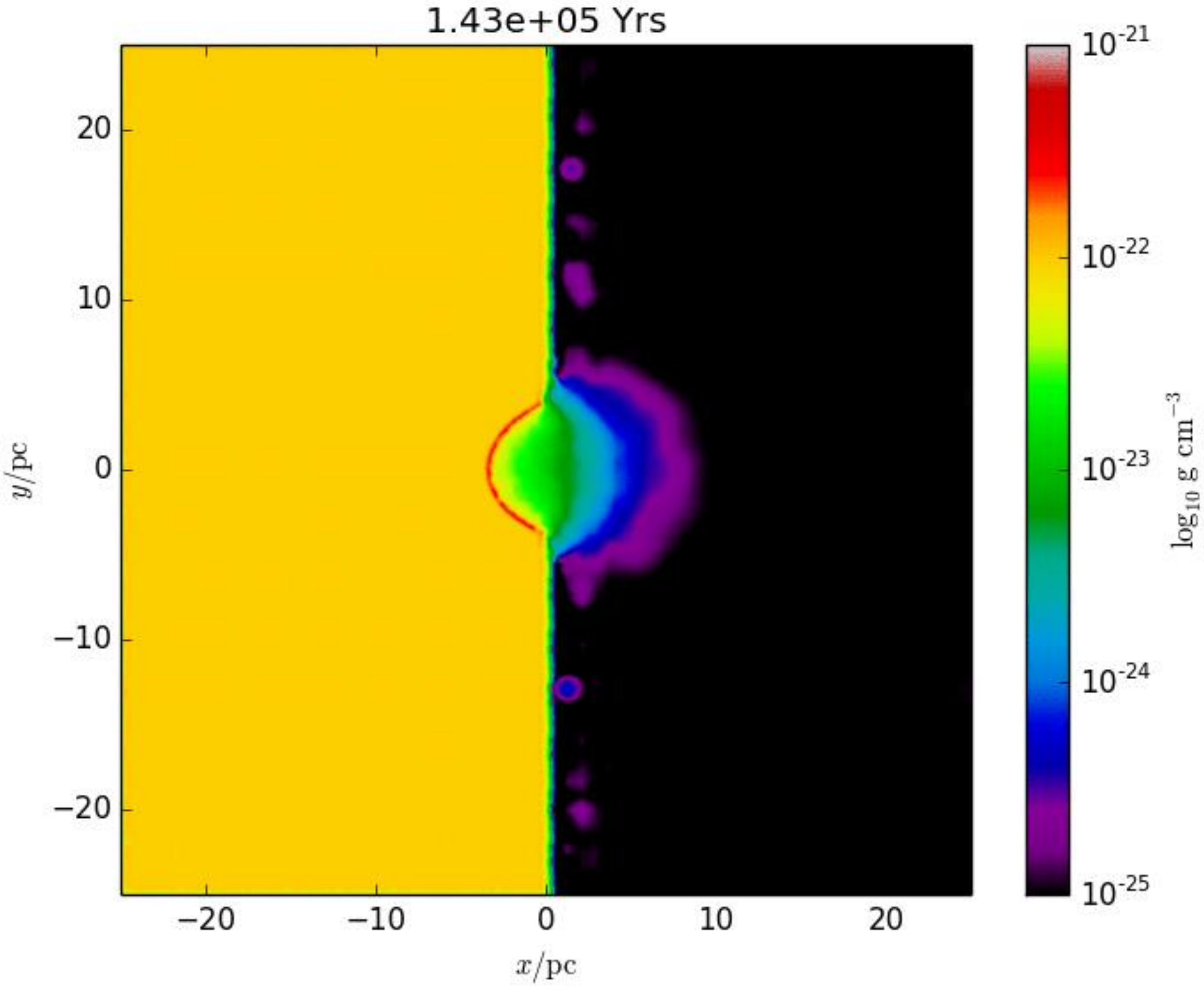
Shadow Test, cf. Petkova & Springel 2009





Trapped Ionization Front, cf. Iliev+ 2006

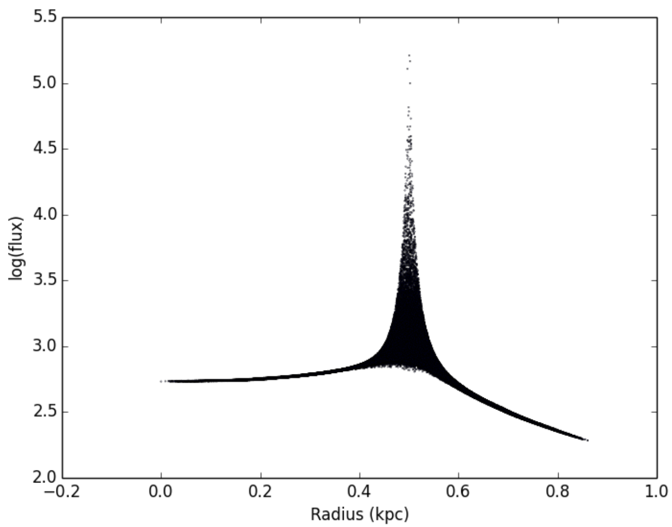
Hydrodynamic Test: Blister HII Region



Cosmic (UV) Background

Instead of periodic replicas of box sources, use background flux at fixed distance (cf. Altay & Theuns 2013)

Zoom in simulation: simpler, surround active region with shell of fixed surface flux



Shell approximation:
Uniform radiation field in inner shell
Field cuspy at shell radius

Radiative Transfer Summary

- Dynamic Radiative Transfer
- Applications: Lyman-Werner/H_2, UV/Ionization, X-ray, FUV Photoelectric/Heating, not IR
- Multi-band relatively cheap, knowledge of optical depth – detailed spectral shape changes
- Scales as number of active elements (multiple timesteps)
- Could allow gas to be sources – scattering
- No detailed photon conservation => front timing approximate
- No RT timestep required but can improve accuracy with ionization timestep

Preliminary

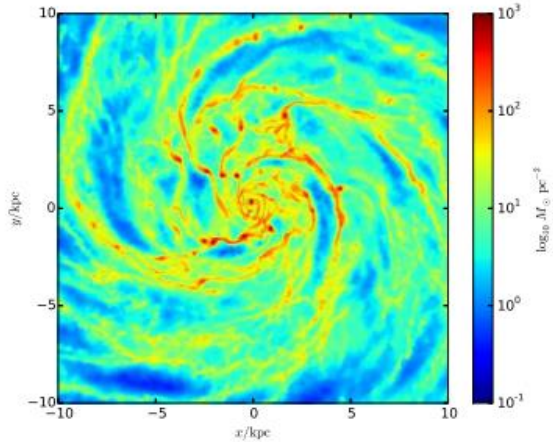
Test Case: FUV in a Disk Galaxy

FUV has long mean free paths, doesn't require high resolution
Note: only ~ 3% of absorptions result in gas heating
Also: Typically scatter ~ absorption (functions of wavelength, grains)
First attempt: just absorption

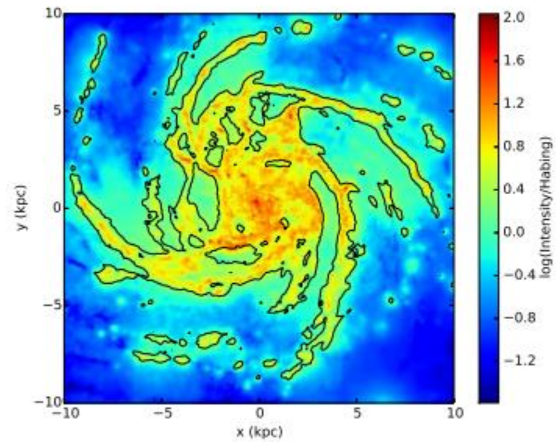
AGORA Isolated Galaxy IC

- 10^{12} M_{sun}, 10^{10} M_{sun} Gas, $4x10^{10}$ M_{sun} old stars
- Relaxed for 300 Myr first
- Gas resolution: m_gas =10^4 Msun, softening 80 pc, Jeans floor
- Single band: FUV
- Gasoline physics as in Keller+ 2014, 2015
- Star formation: Rho > 10 H/cc, T < 1000 K
- Superbubble feedback $10^{50\ erg}$/SN

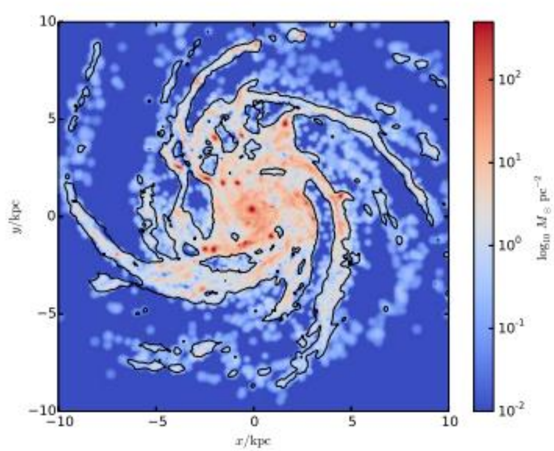
AGORA + FUV



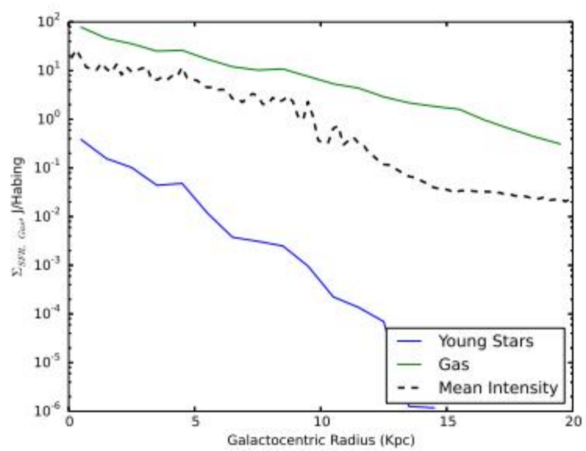
(a) Gas Surface Density



(b) Intensity

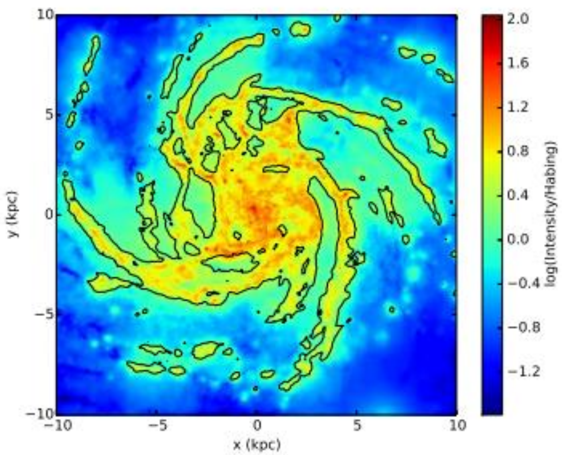


(c) Stellar Surface Density

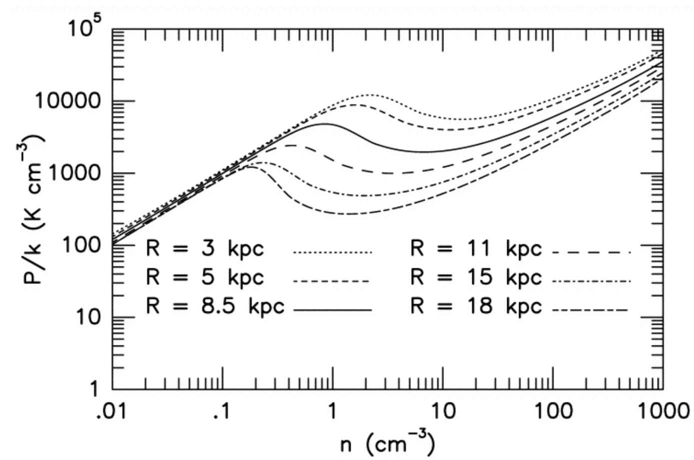


(d) Surface Density Profiles

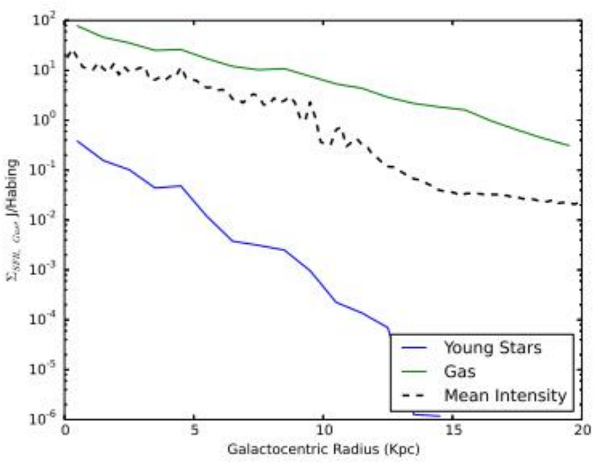
AGORA + FUV



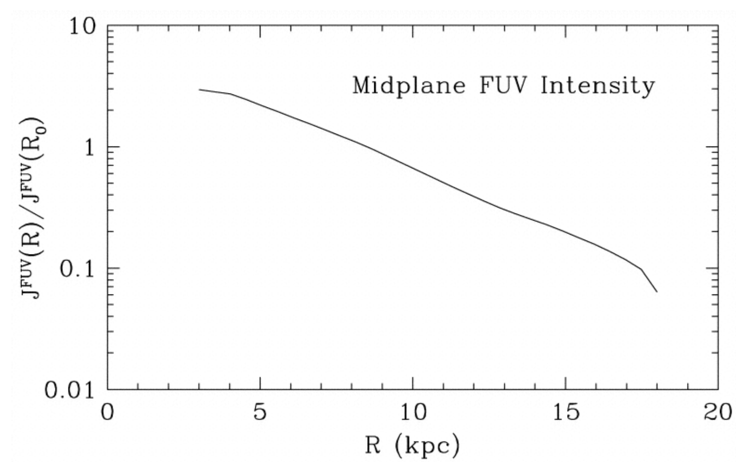
(b) Intensity



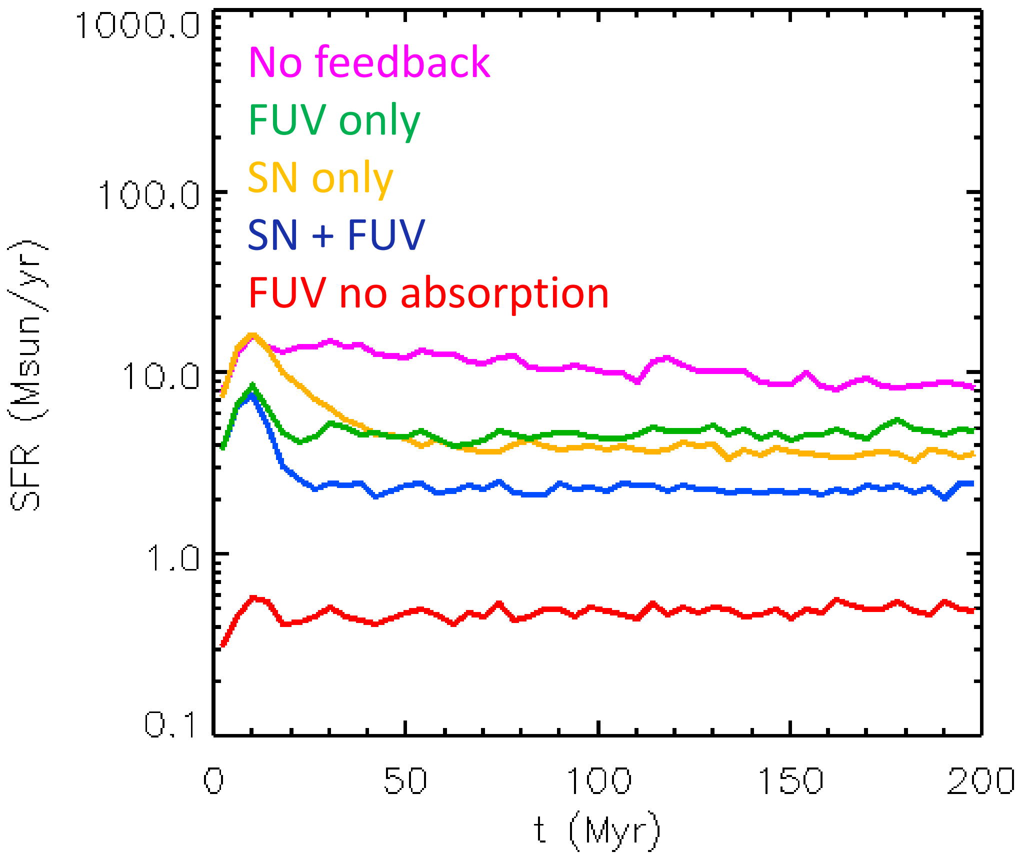
Wolfire+ 2003
(see also Benincasa+ 2016, Kim+ 2015)

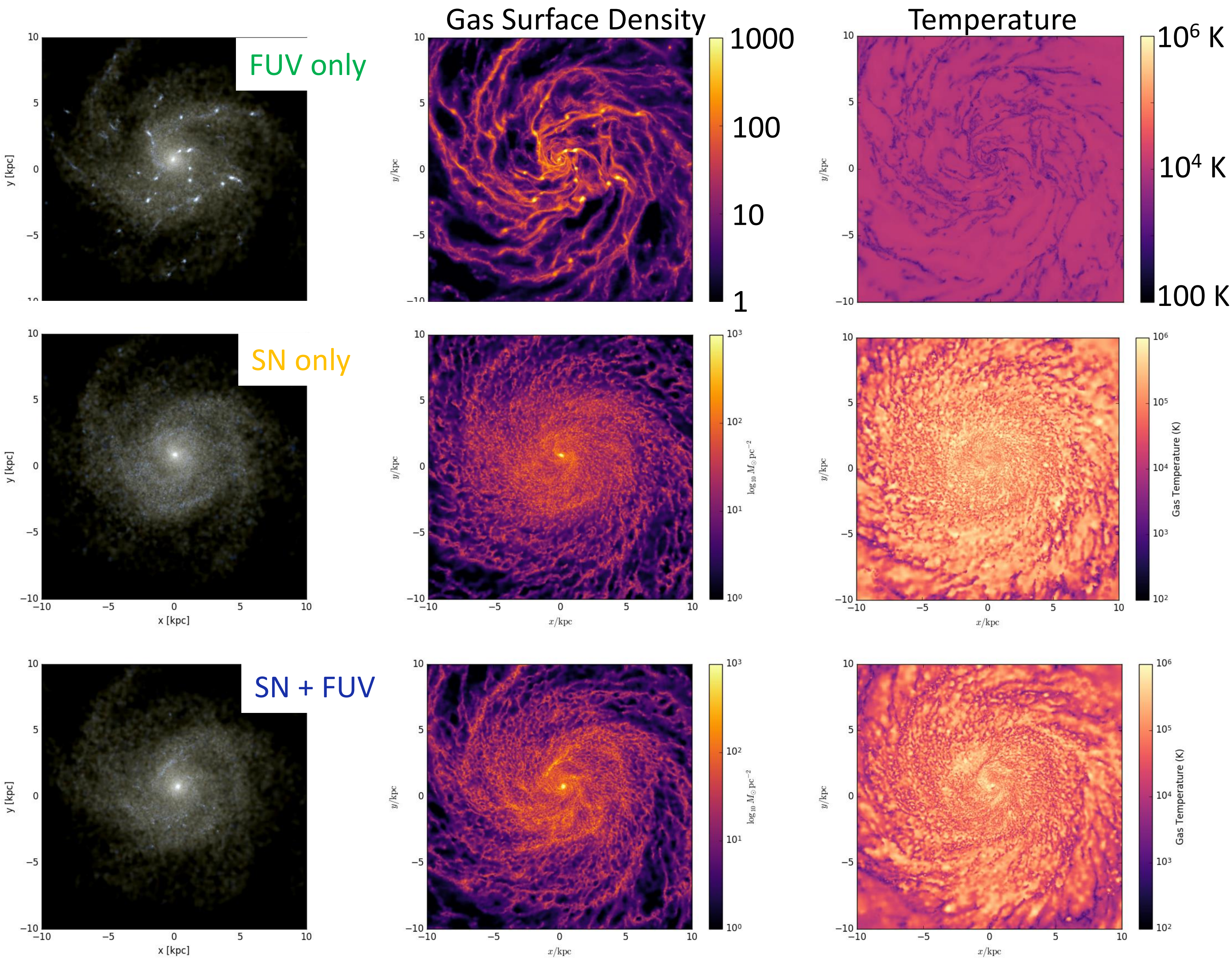


(d) Surface Density Profiles



Star Formation Rates with FUV

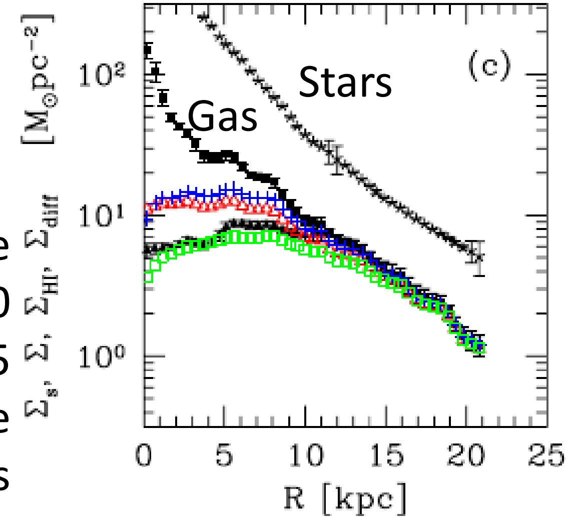




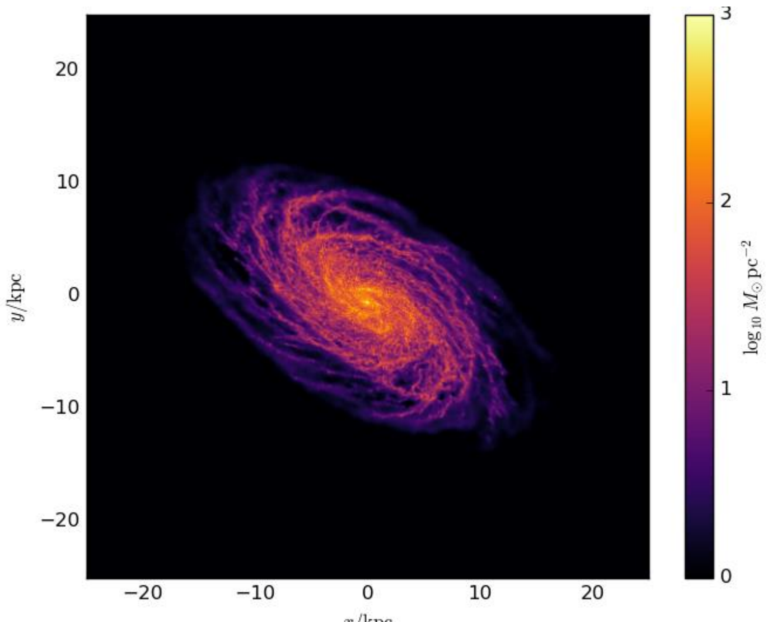
Gas Surface Density
Temperature
FUV only
SN only
SN + FUV
1000
100
10
1
10^6 K
10^4 K
100 K
y [kpc]
x [kpc]
y/kpc
x/kpc
log10 M⊙ pc^-2
Gas Temperature (K)

M63/ NGC 5055

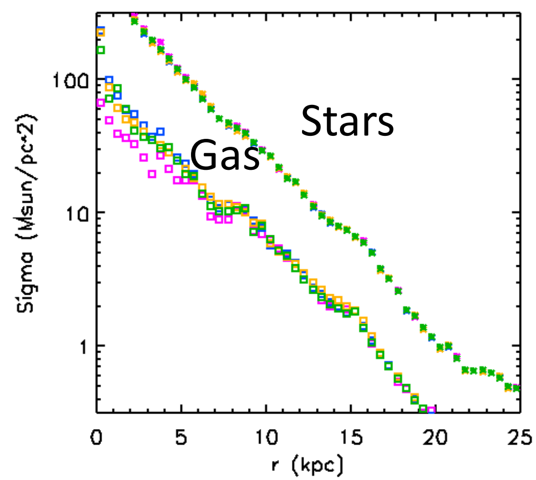
NGC 5055/ M63
“sunflower galaxy”
Spitzer Image



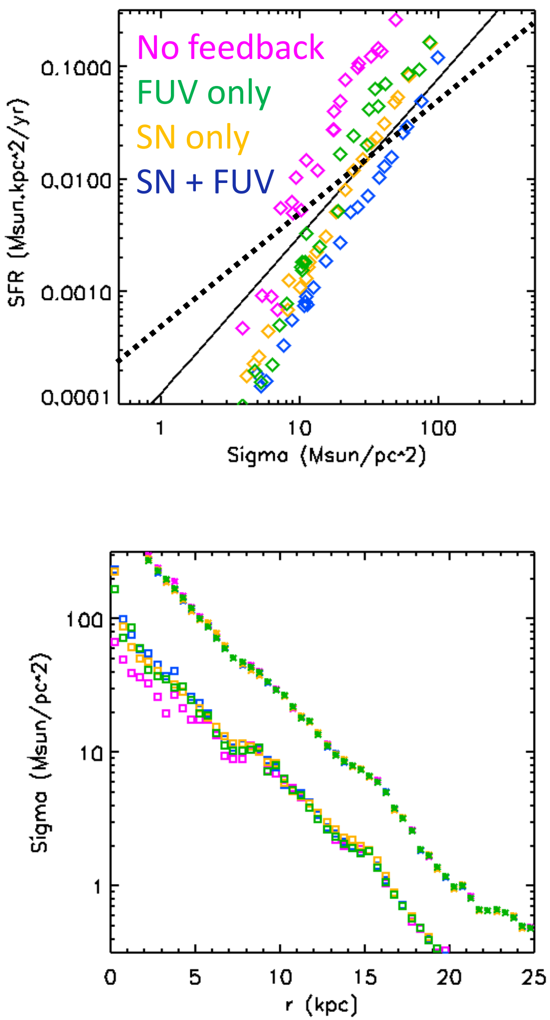
Ostriker, McKee
& Leroy 2010
THINGS NGC5055
surface
densities



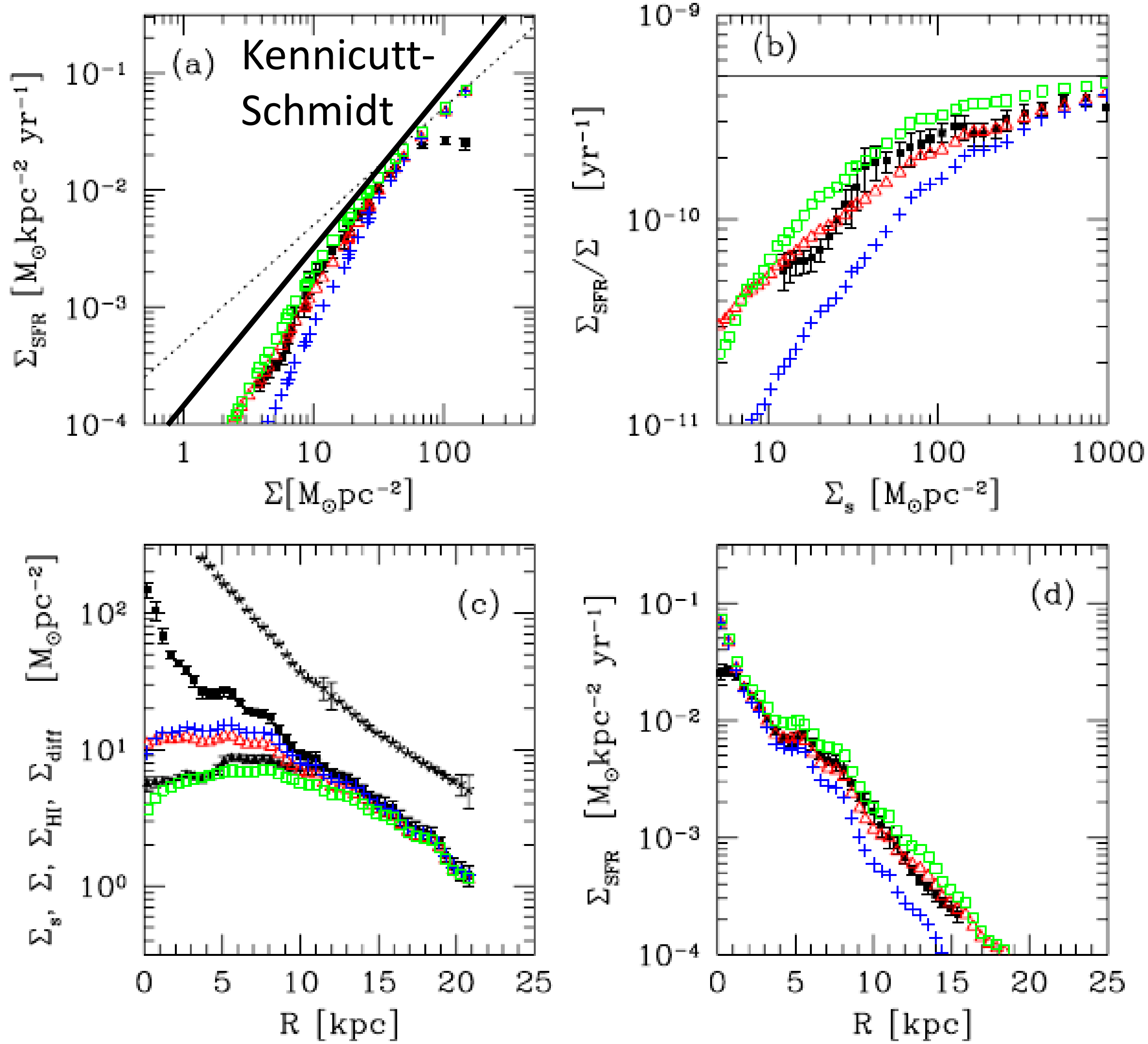
AGORA FUV+SN
(superbubble)



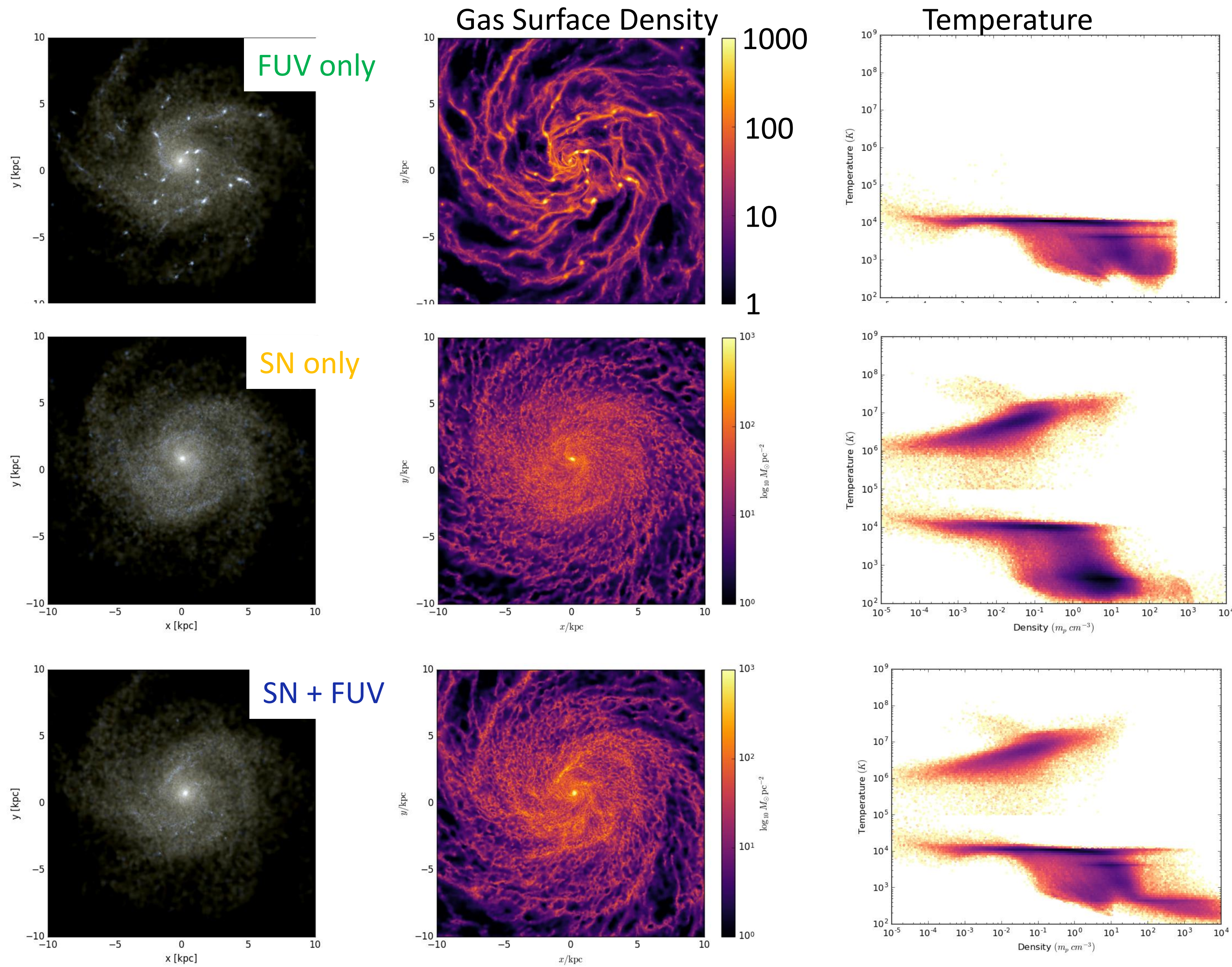
AGORA vs. NGC 5055



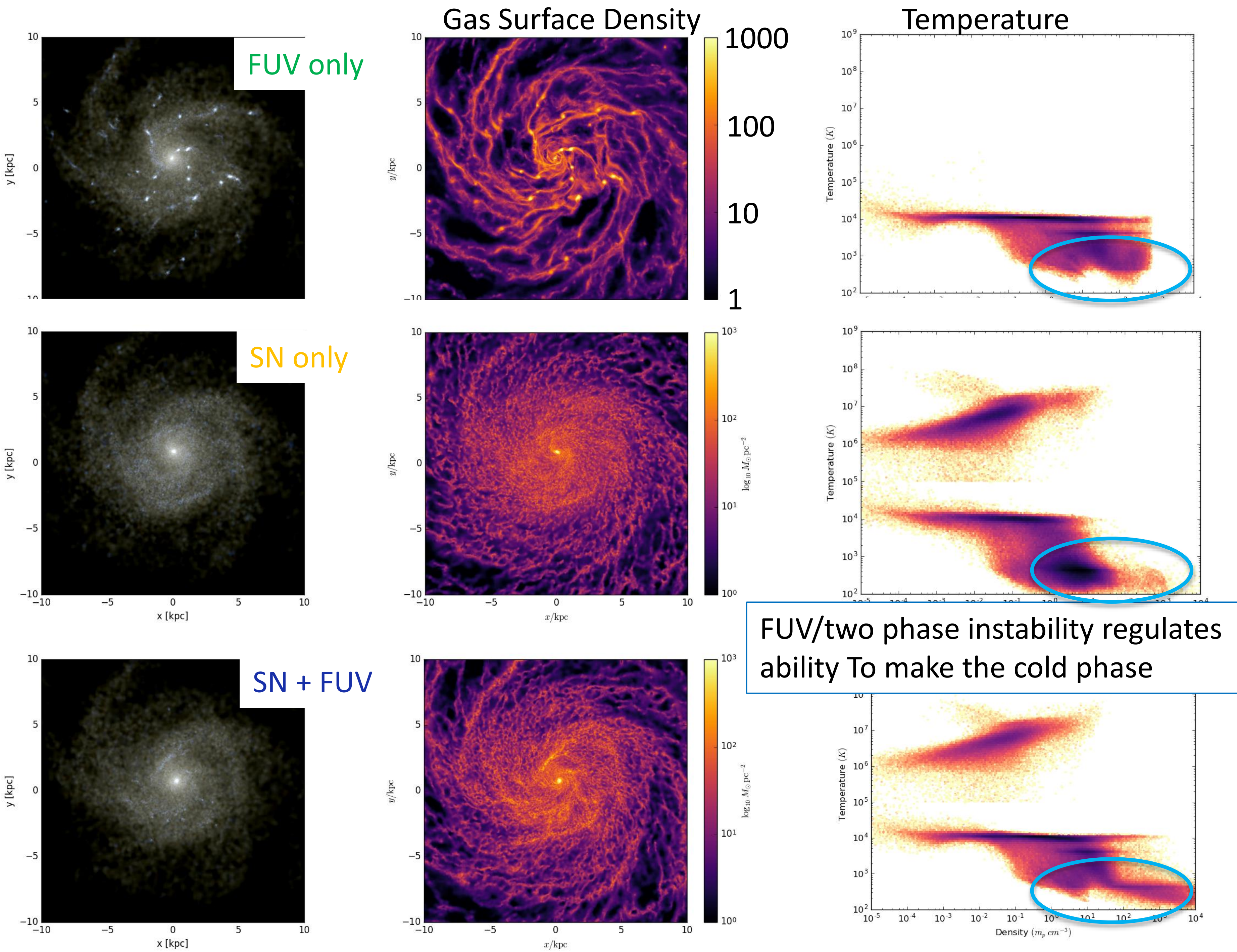
AGORA isolated disk



Ostriker, McKee & Leroy 2010



Gas Surface Density
Temperature
FUV only
SN only
SN + FUV
1000
100
10
1
y [kpc]
x [kpc]
y/kpc
x/kpc
$\log_{10} M_\odot\,pc^{-2}$
Temperature (K)
Density ($m_p\,cm^{-3}$)



Gas Surface Density
Temperature
FUV only
SN only
SN + FUV
x [kpc]
y [kpc]
x/kpc
y/kpc
1000
100
10
1
log10 M⊙ pc^-2
Temperature (K)
Density (m_p cm^-3)
FUV/two phase instability regulates ability To make the cold phase

Preliminary

FUV in Galaxies: Summary

Regulating Star formation with FUV has large impacts on observables, e.g. gas phases

Including FUV introduces greater sensitivity to star formation prescription: Work in progress

Next: Couple RT to molecular gas chemistry
(cf. Christensen+ 2012)
Can be used for post-processing
(SUNRISE type images)

AGORA edge on, (J. Grond)