Radiative transfer and regulation of star formation in typical disk galaxies

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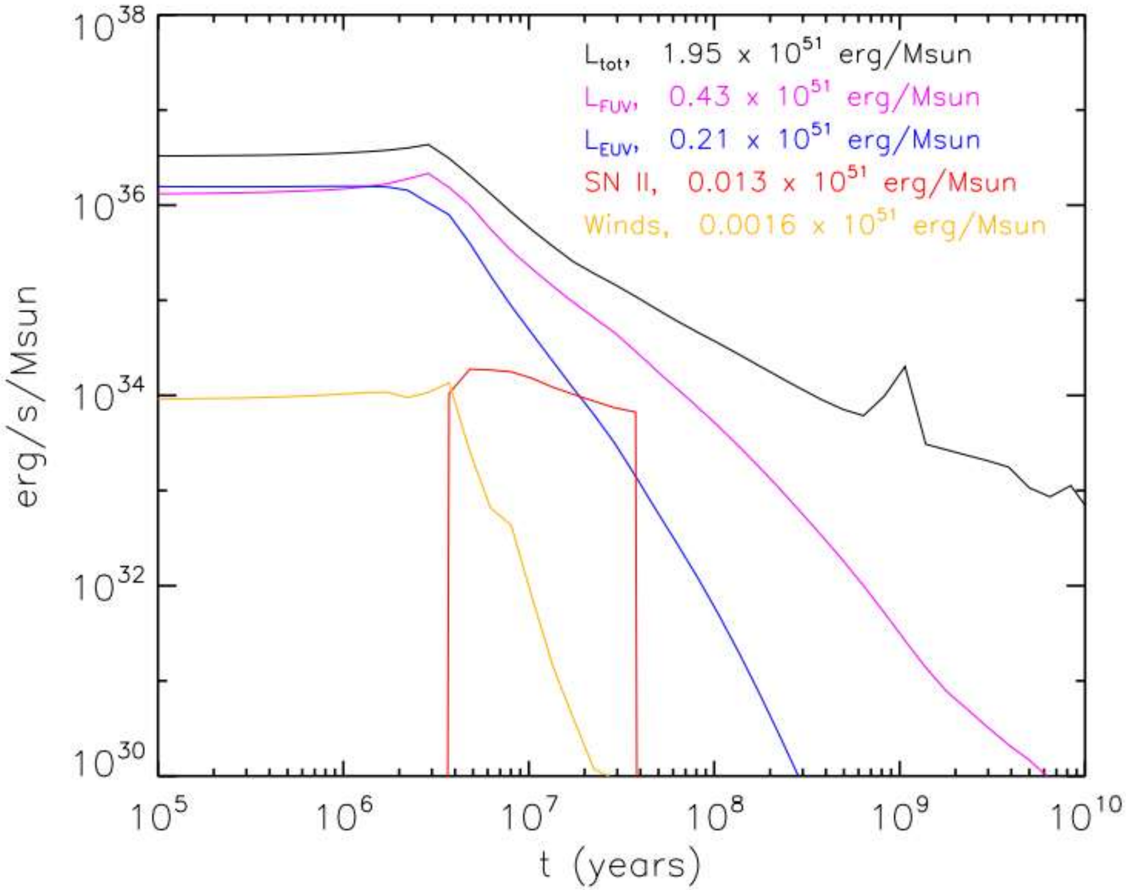
Feedback Energy per unit Stellar Mass

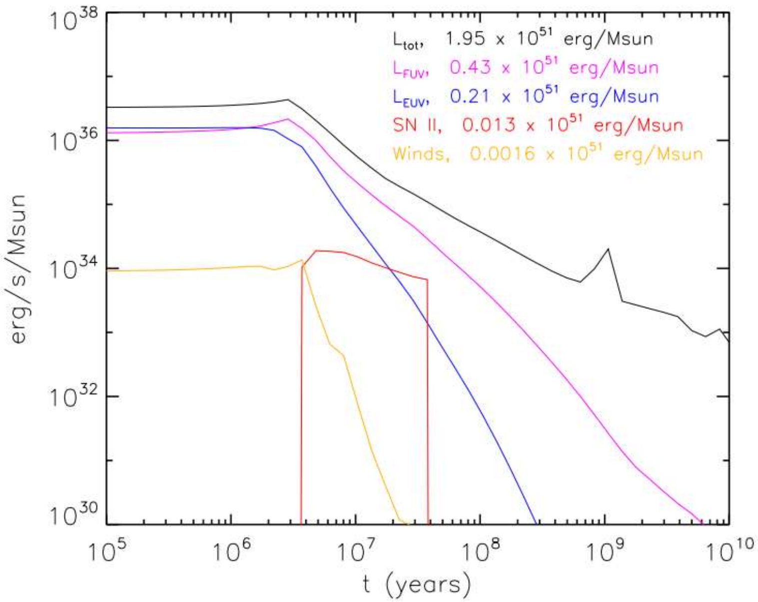
Chabrier (2003) IMF



Starburst 99 Leitherer+ 2014

Feedback Energy per unit Stellar Mass

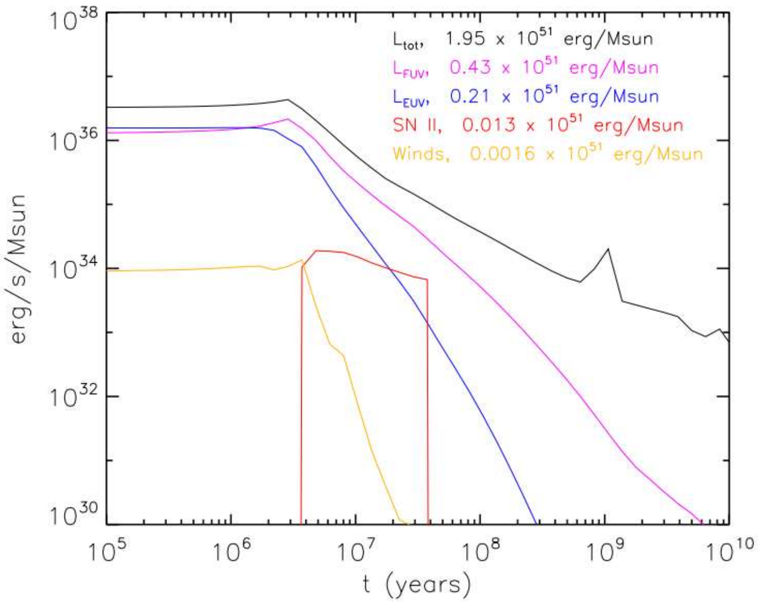
Chabrier (2003) IMF



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
Limited direct feedback – cloud busting only

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

Feedback 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

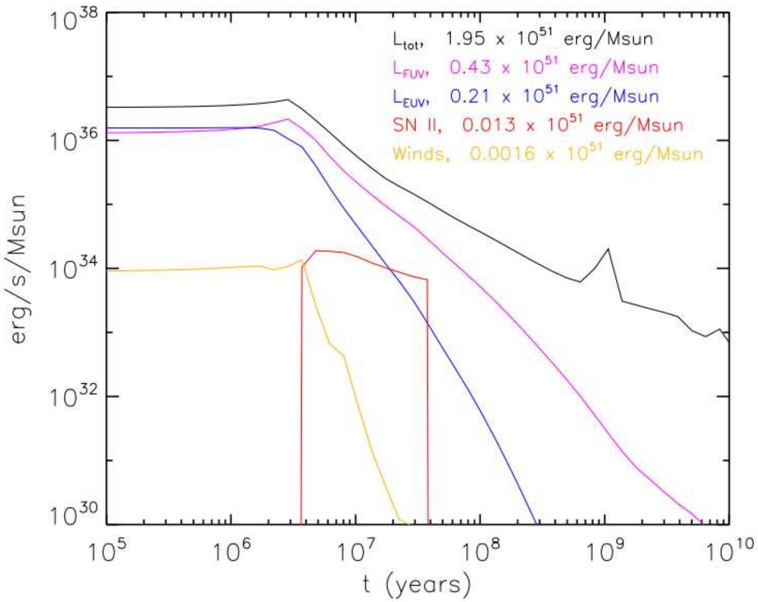
Opacity: HI ~ 5,000,000 cm^2/g (HI/H)

15.2 eV Ionize H_2

24.6 eV Ionize He

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

Feedback 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

Also produced by recombinations

Flux varies by factor ~ 100 across galaxy 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)

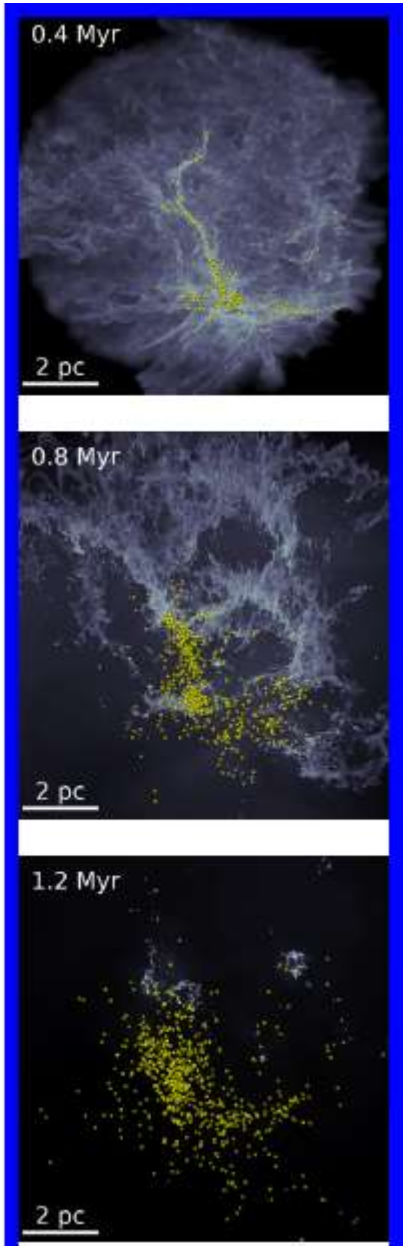
Few 100 pc in diffuse ISM

Dominant heater, ionizer of IGM

40% recombinations – new ionizing photon

Flux varies strongly w/ environment

Numerical Issue: Feedback Double-counting



Galvagnin+ 2015

- Primary role of EUV radiation is to disperse the molecular cloud (e.g. Dale+ 2012, Galvagnin+ 2015)
- Feedback models that add radiation as "just more energy" are wrong
- EUV radiation only strongly couples close to the source, i.e. low escape fraction
- Adding "Extra" feedback is only valid **IF** you resolve the dense molecular gas and/or the model halts once the cloud is dispersed
- Codes with SF threshold <= 100 cm^{-3} probably should not add full EUV -- clouds already low density (see also Naab+Ostriker 2017, Keller+ 2016, Semenov – gas supported by Pressure floor, numerics)

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 diffusive regime/optically thick. e.g. IR
- Easy to have many sources
- FLD: Radiation bends around corners: poor shadows
- *Severe timestep limits*

Improvements: OTVET (Gnedin&Abel 2001), M1-methods (e.g. Rosdahl+ 2013)

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) per step

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

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

Optimization – combine rays/packets

e.g. Traphic (Pawlik & Schaye 2008)

$O(N\, N_{ray}\, N_{iter})$ for fixed time interval t, Iterations: $N_{iter} \sim t\, N^{1/3}/L/c$

Full ray trace (c → Infinity)

N elements: Basic Cost $O(N_{source}\, N^{4/3})$

Monte-Carlo-like: Multiple rays per cell

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

e.g. TreeCol (Clarke+ 12), URCHIN (Altay & Theuns 2013), Abel&Wandelt 2002, MORAY (Wise&Abel 2011)

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

Reverse Ray Trace: Tree approach $O(N \log N)$
Only trace radiation to elements that need it

see also URCHIN (Altay & Theuns 2013), C^2 -ray (Mellema+ 2006), Kannan+ 2014, Hu, Naab+ 2017

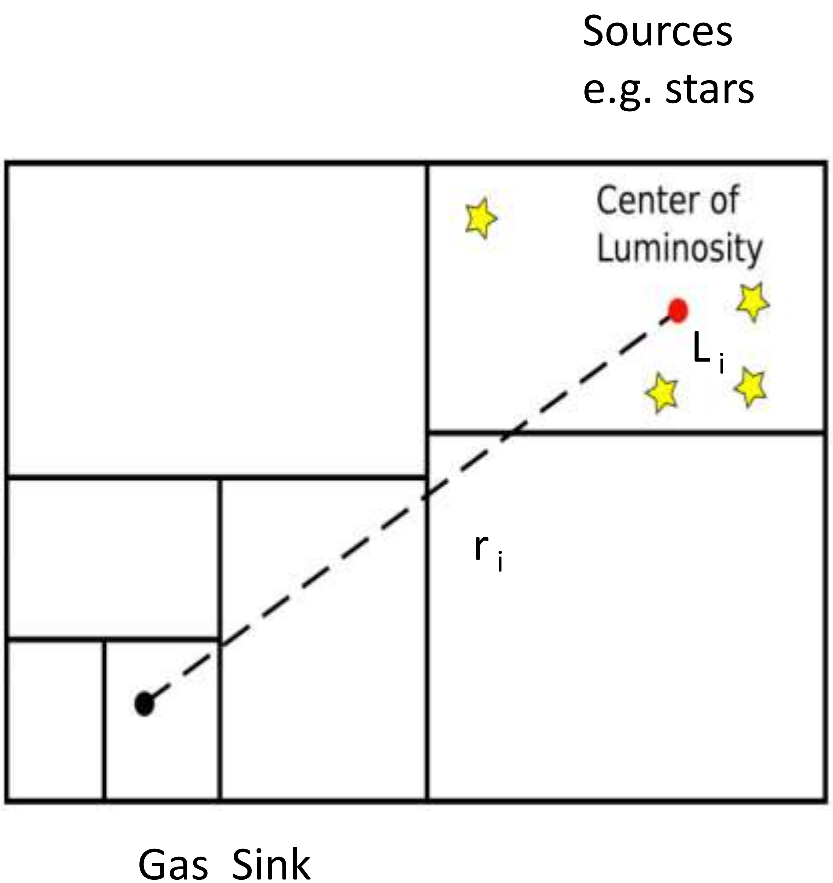
Gasoline

Initial Code base for Radiative Transfer method:
Gasoline parallel code (MPI) (Wadsley+ 2004)
• pkdgrav N-body Solver (Binary Tree, Hexadecapole) and Modern Smoothed Particle Hydrodynamics (see e.g. Wadsley+ 2017)

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

First Stage: Tree Walk

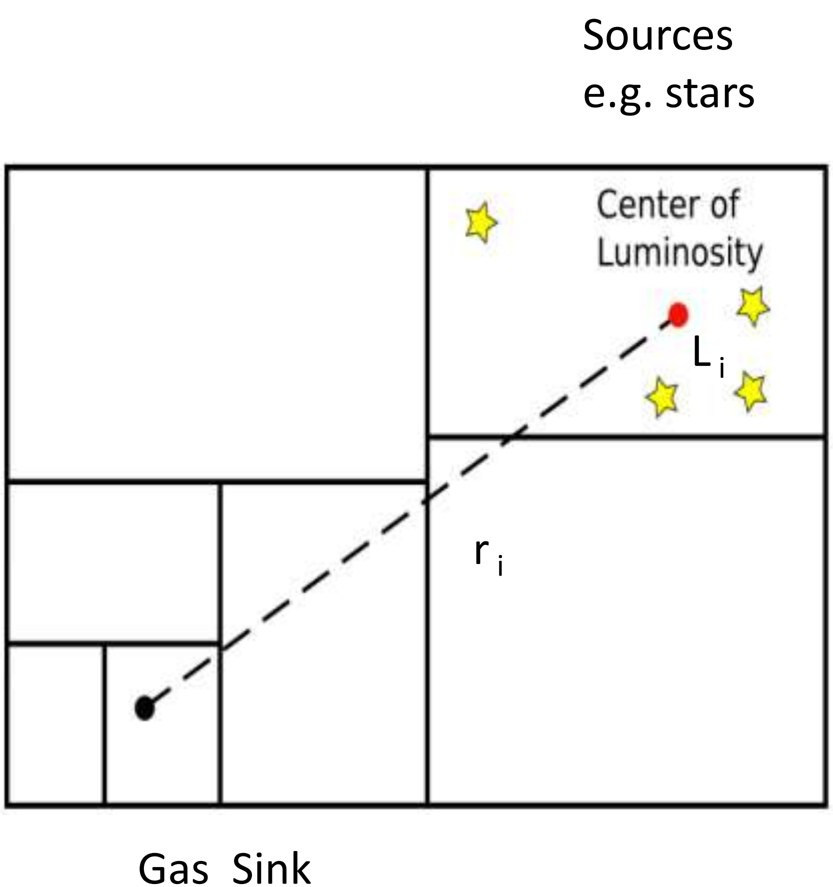


- Centre of mass

→ 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

First Stage: Tree Walk



- Cost: $O(N_{sink} \log N_{source})$
- Multiple timesteps: $O(N_{active} \log N_{source})$
  Typical $N_{active} < 0.01\ N$
- Highly Parallelizable
- No RT timestep requirement
- Runtime < Tree Gravity

Second Stage: Absorption

Far from source/sink use Tree Cells

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

  → record optical depth to traverse cell

Near source/sink use particles

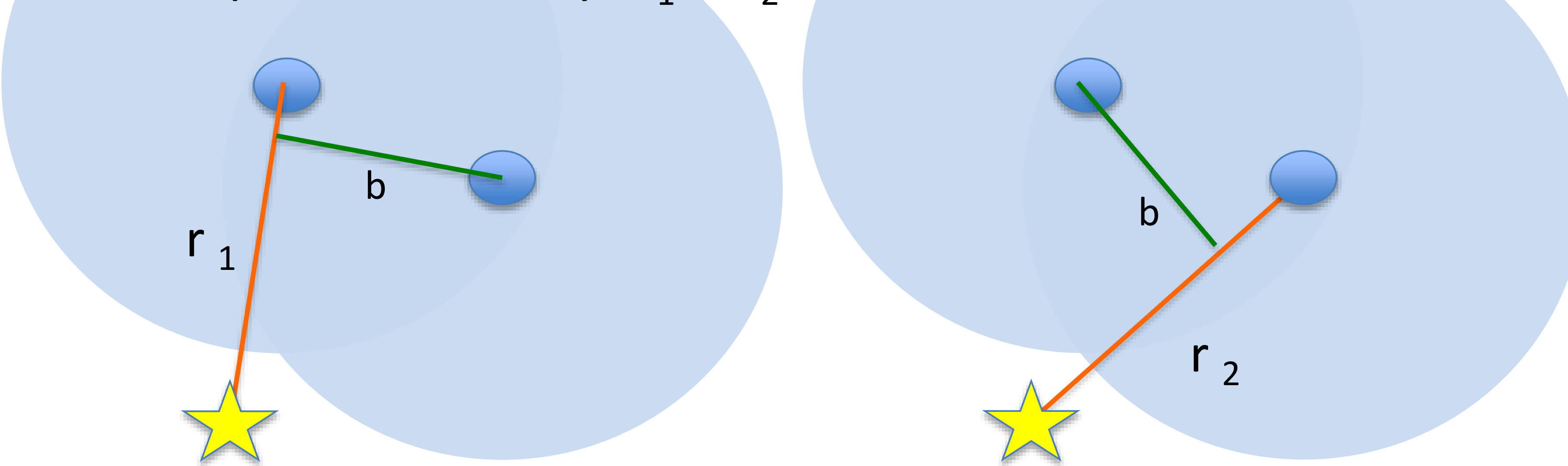
- Similar to TRAPHIC/SPHRay:
  → Sort particles: Optical depth from 2d integral of Kernel, no self-optical depth

Note: Only approximate photon conservation, zero light travel time

Woods, Wadsley, Grond & Couchman, in prep

Particle-Particle issues

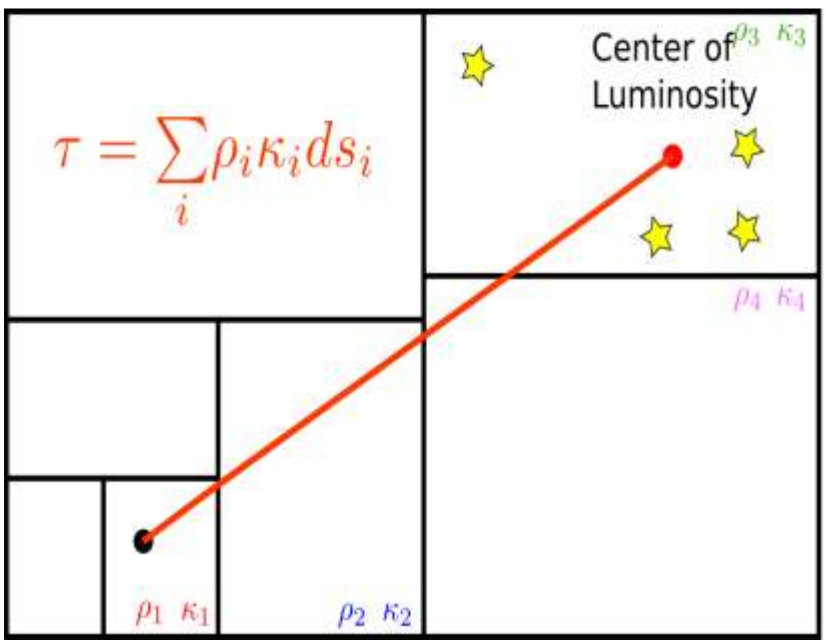
- Particles treated as thin disks with column equal to integrated particle density $W_{2D}(b)$
- Both particles consider other to be in front on it. Solution: sort particles radially $r_1 < r_2$



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

Fixes, see Mellema+ 2006, Pawlik+Schaye 2011

Second Stage: Absorption

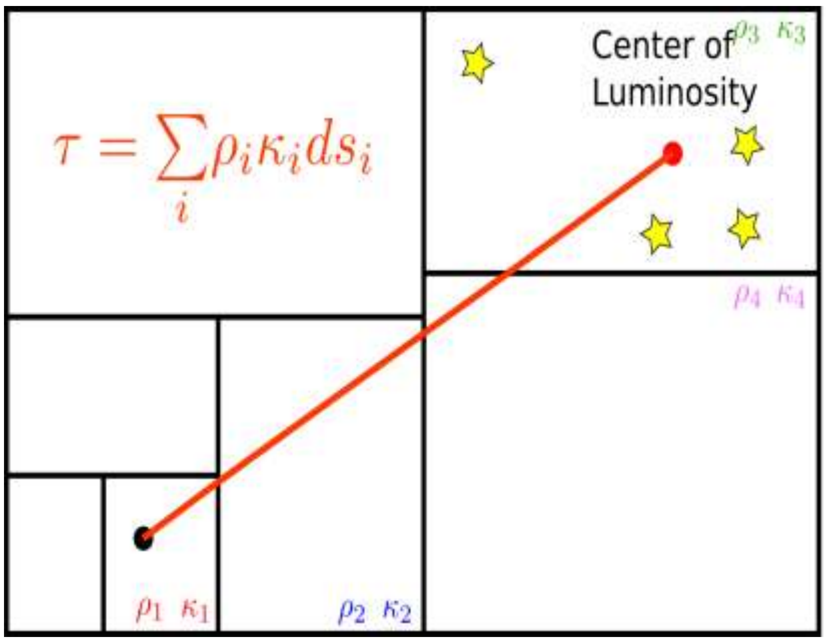


- Re-walk Tree source to sink
- Adaptive error control: opacity, angular size, current optical depth

  Default: Angular size
- $$\Gamma \propto \sum_i \frac{L_i}{4\pi r_i^2} e^{-\tau}$$

Woods, Wadsley, Grond & Couchman, in prep

Overall Method Scaling



- Multiple timesteps: $O(N_{active} \log N_{source} \log N)$
  Typical $N_{active} < 0.01$ N
- Highly Parallelizable
- No RT timestep requirement
- Runtime ~ Tree Gravity

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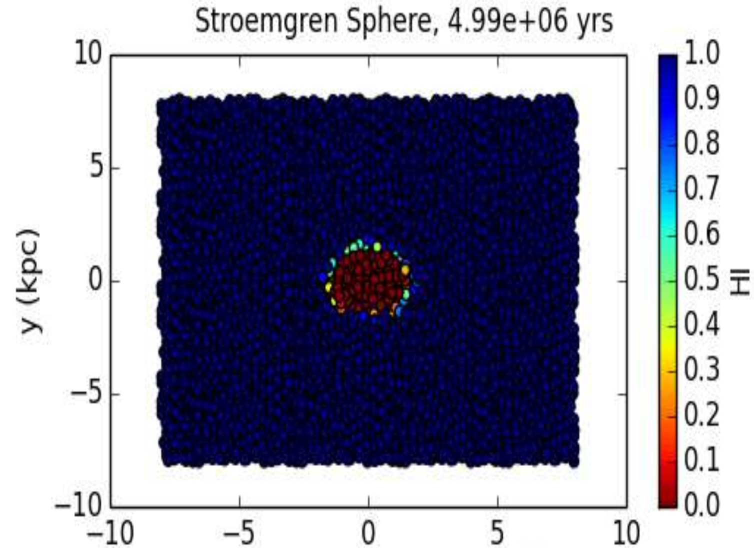
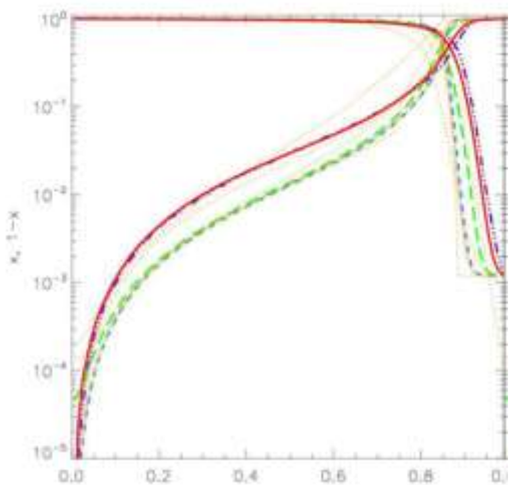
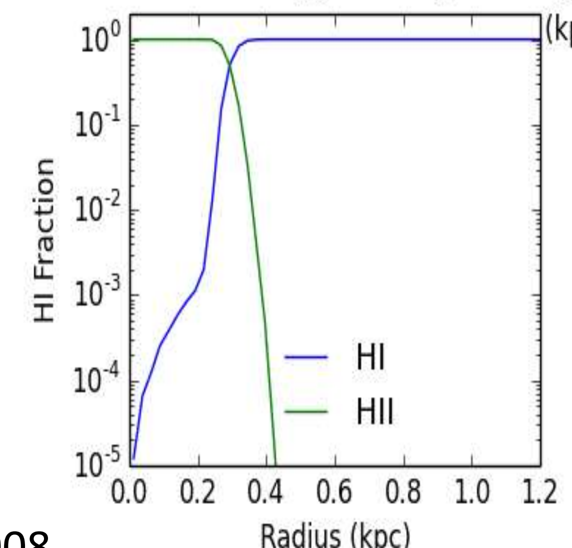
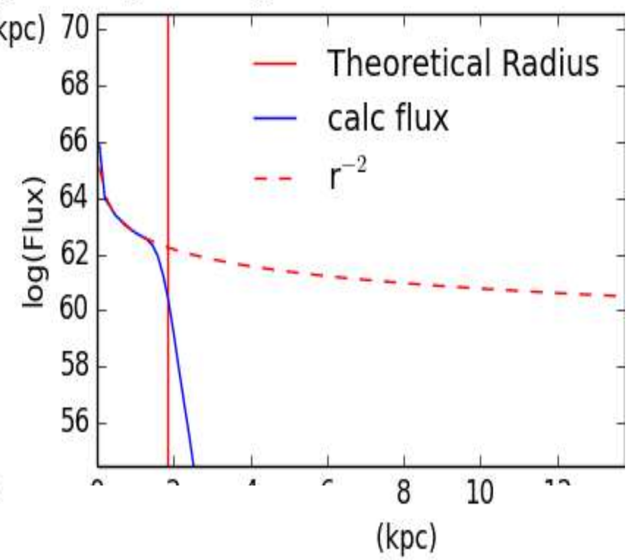
Code Tests: Strömgren Sphere





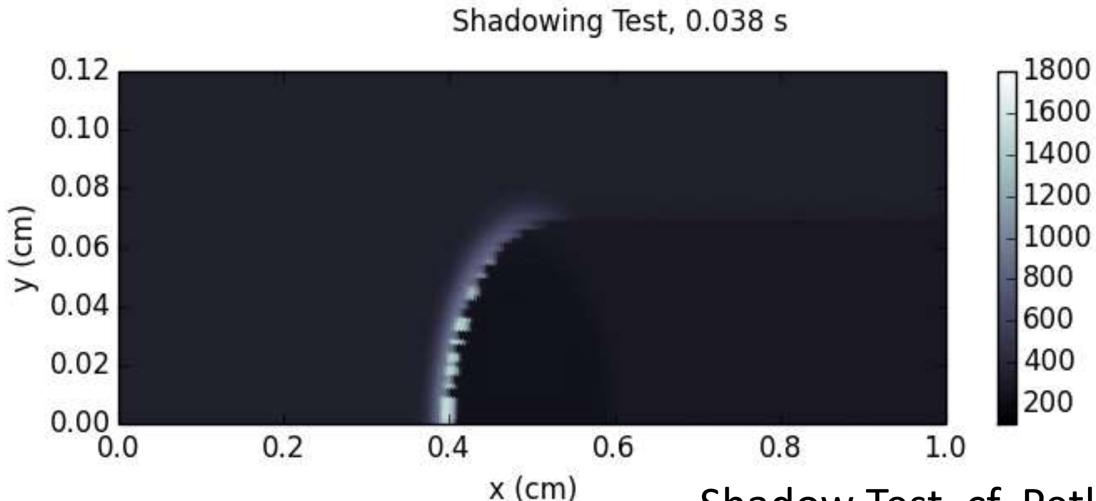
Strömgren Sphere, Altay+ 2008



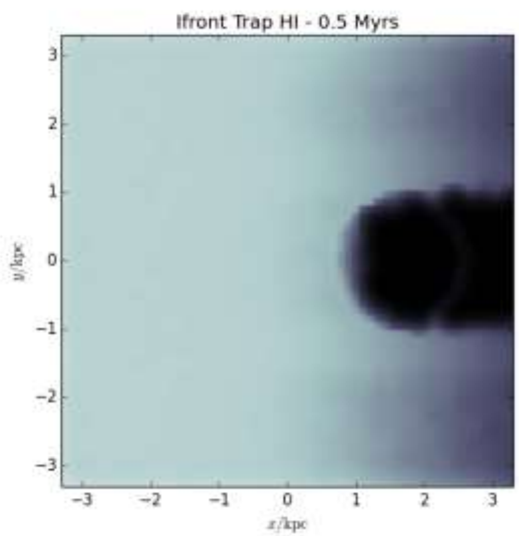


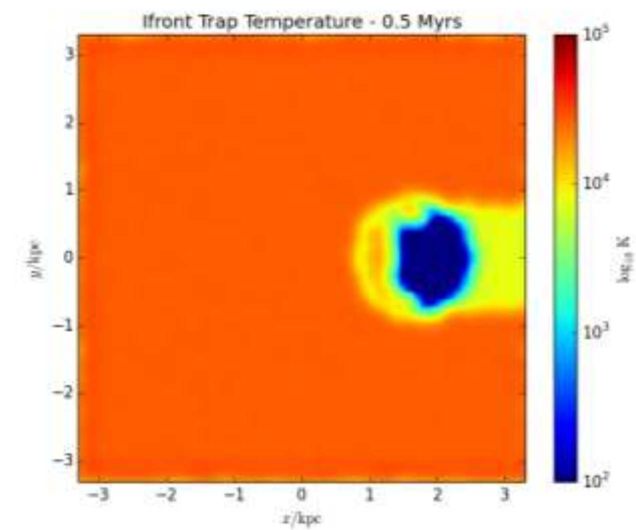
Thermal Strömgren Sphere, cf. Iliev+ 2006

Code Tests: Shadowing Test



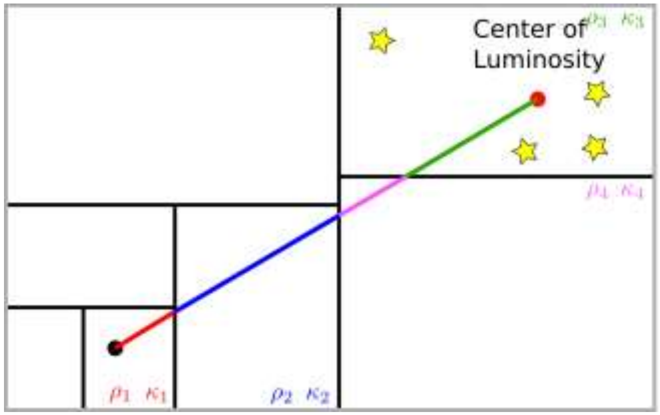
Shadow Test, cf. Petkova & Springel 2009





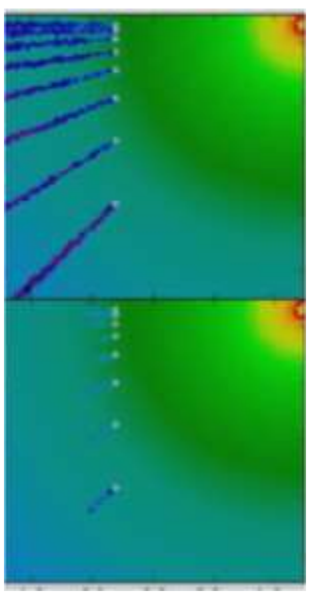
Trapped Ionization Front, cf. Iliev+ 2006

Pathological case: High opacity far from receiver



Simple ionization fronts (e.g. Stroemgren Sphere) are easy – default scheme refines close to elements being ionized
Opacity closer to source is low

For small, dense absorbers in between, added refinement needed

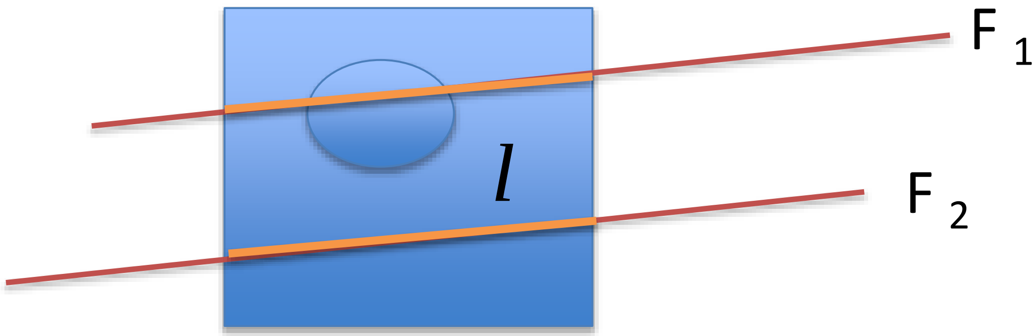


Full refinement: $O(N_{active} \log N_{source} \; N^{1/3})$
(Ray Tracing)

Default refinement: $O(N_{active} \log N_{source} \log N)$

Absorption Refinement Strategy

- Consider two paths through large cell



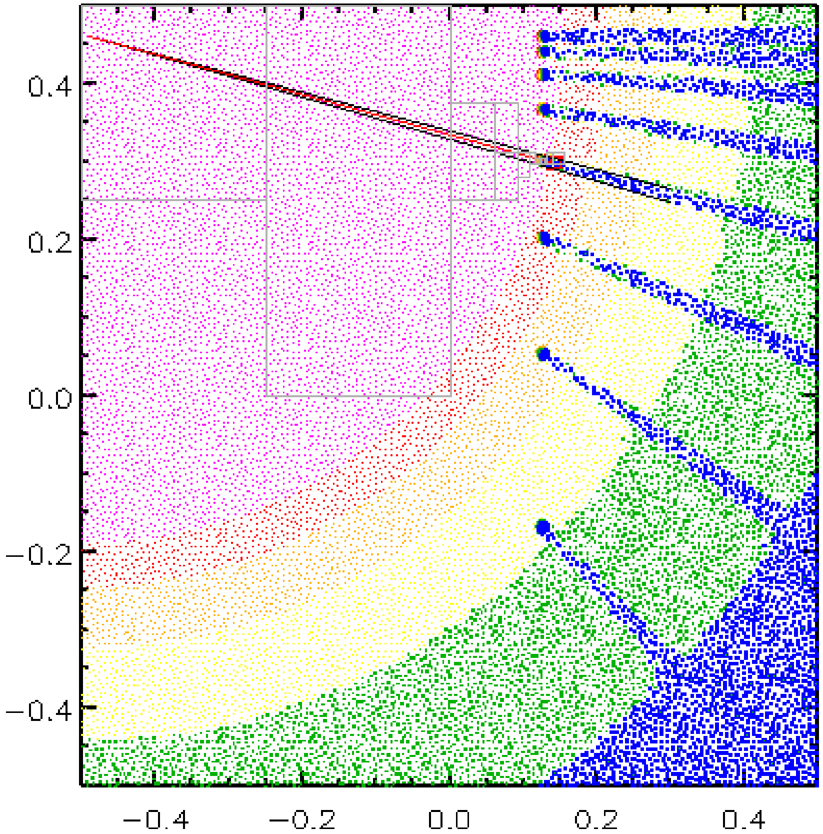
- Calculate minimum/maximum absorption coefficient (α=ρκ) through cells (during tree build)

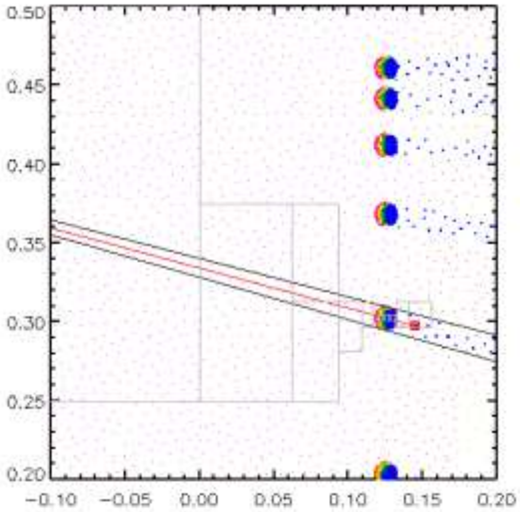
$$\tau_{\max} = l\alpha_{\max} \qquad \tau_{\min} = l\alpha_{\min}$$

- Refine if $\tau_{\max} - \tau_{\min} > \tau_{refine}$

$$\text{Fractional Error} = \frac{F_1 - F_2}{F_1} \leq 1 - e^{-(\tau_{\max} - \tau_{\min})} < \tau_{refine} \ (\text{small}\ \tau)$$

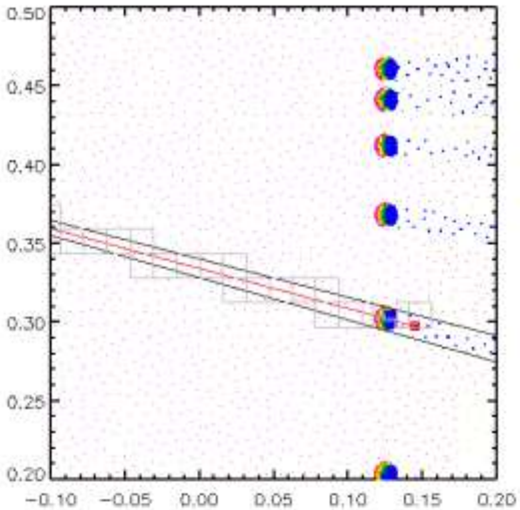
Absorption Refinement Strategy





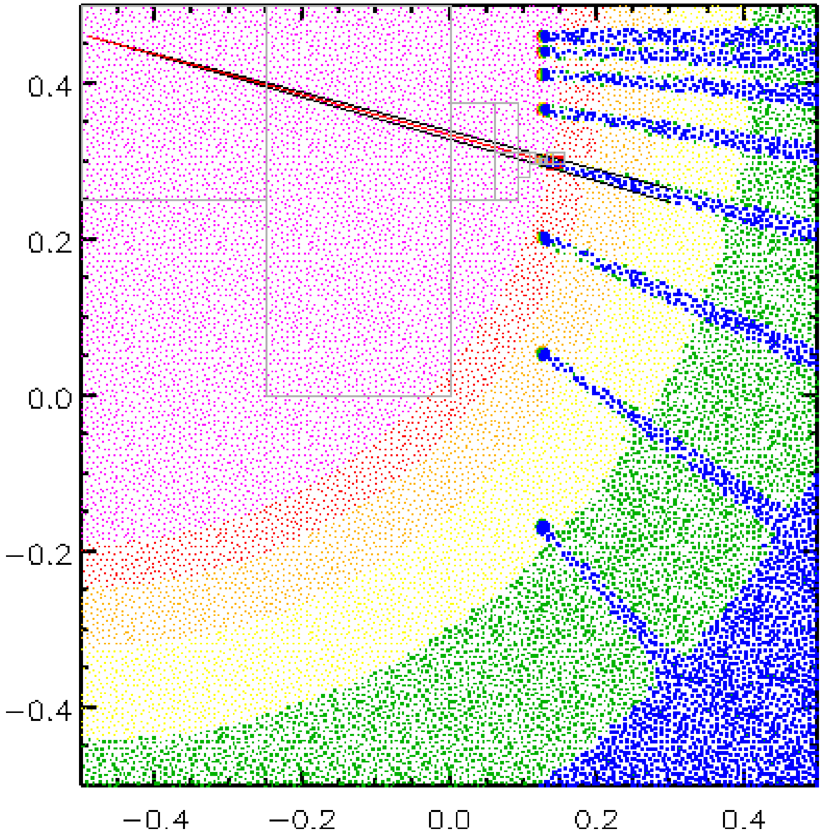
Adaptive Refinement

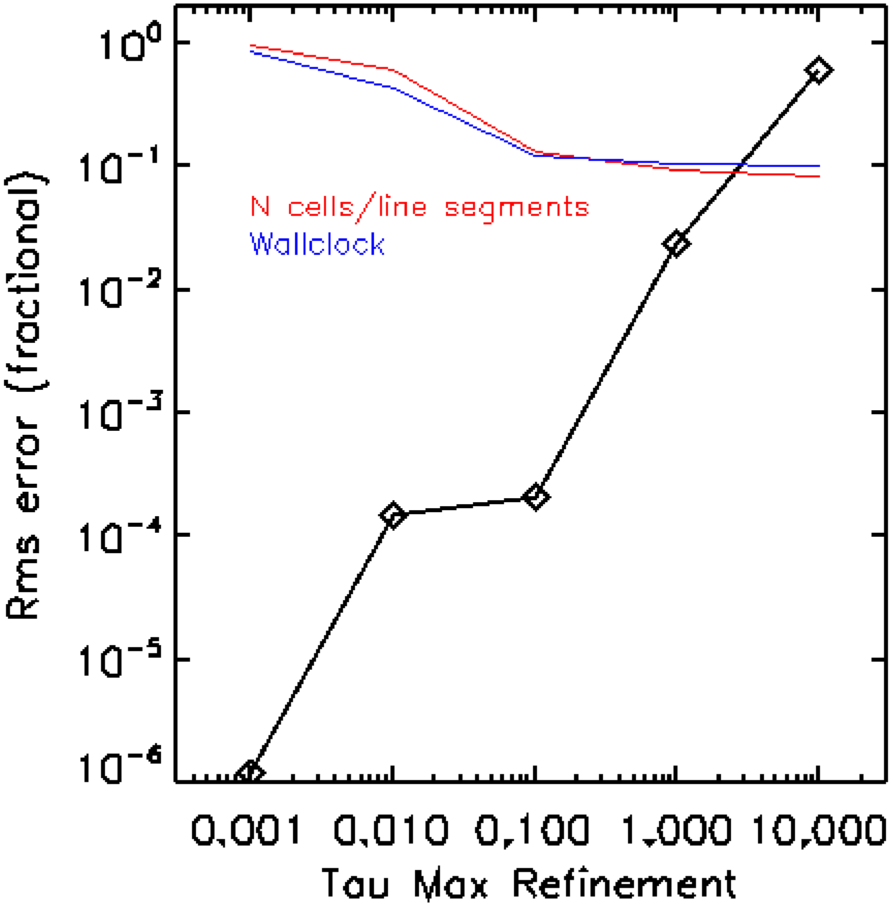
$\tau_{refine} = 0.1$



Full Refinement

Absorption Refinement Strategy



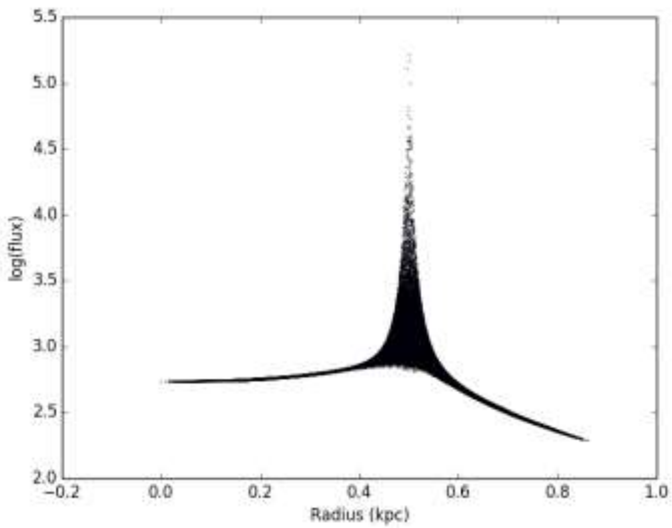


Woods, Wadsley, Grond & Couchman, in prep

Cosmic (e.g. UV) Backgrounds

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) – lots of info to use to adapt cost because total flux known
- Could allow gas to be sources – scattering
- No detailed photon conservation => front timing approximate but no Monte-Carlo type noise
- No RT timestep required but can improve accuracy with ionization timestep

Woods, Wadsley, Grond & Couchman, in prep

Preliminary

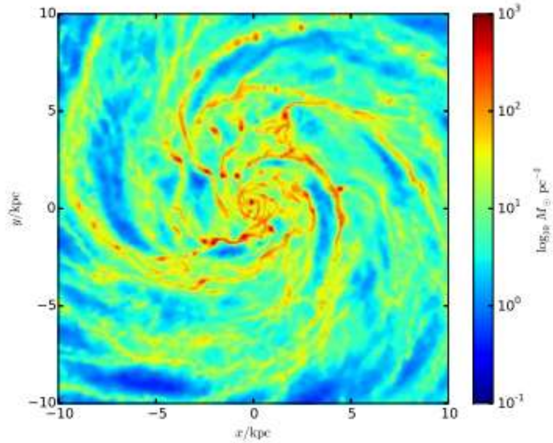
Test Case: FUV in a Disk Galaxy

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

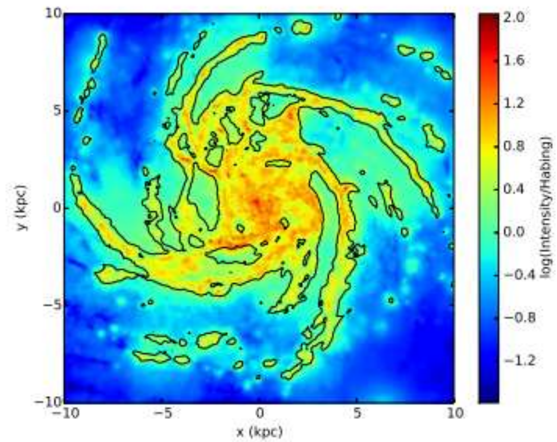
AGORA Isolated Galaxy IC

- 10^{12} M_{sun}, 10^{10} M_{sun} Gas, 4×10^{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: Density > 10 H/cc, T < 1000 K
- Superbubble feedback 0.5×10^{51} erg/SN (Keller+ 2014)

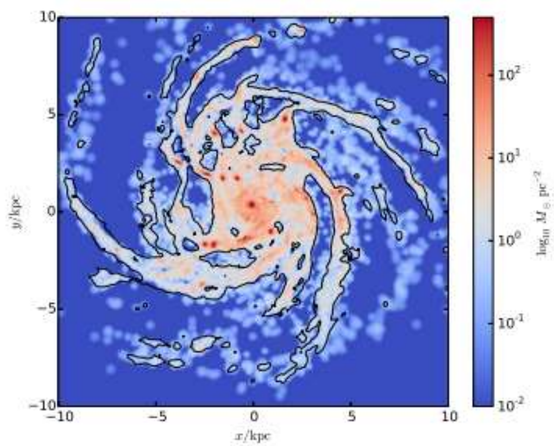
AGORA + FUV



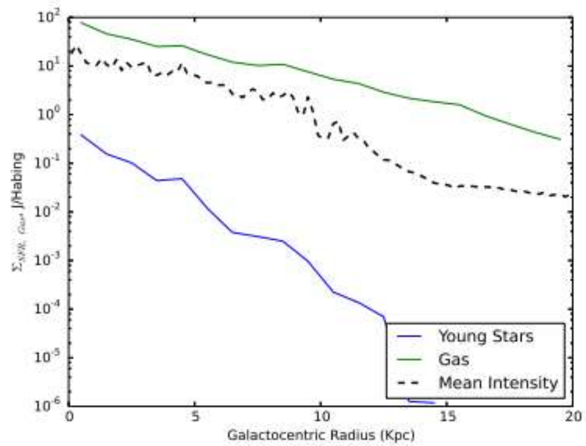
(a) Gas Surface Density



(b) Intensity

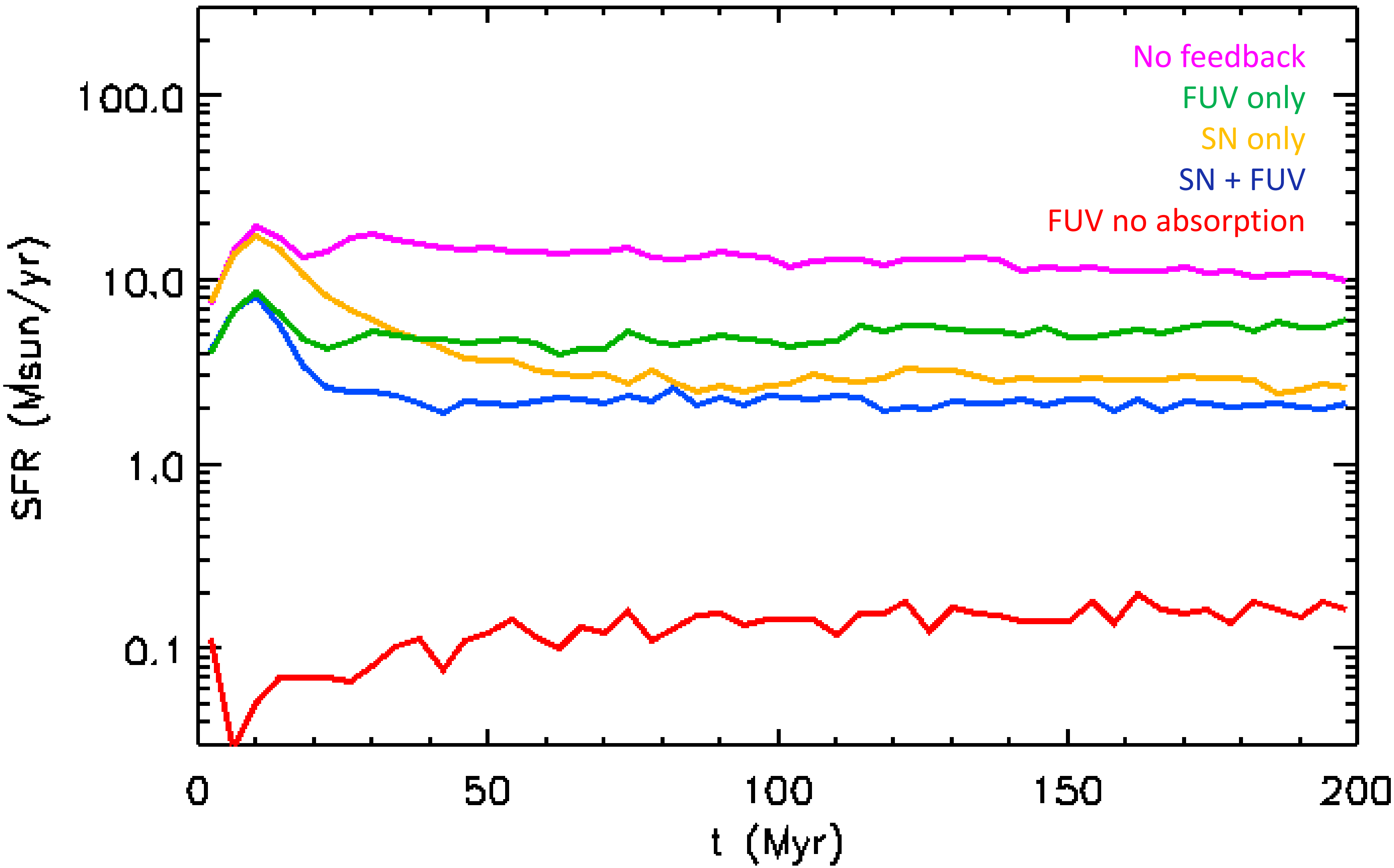


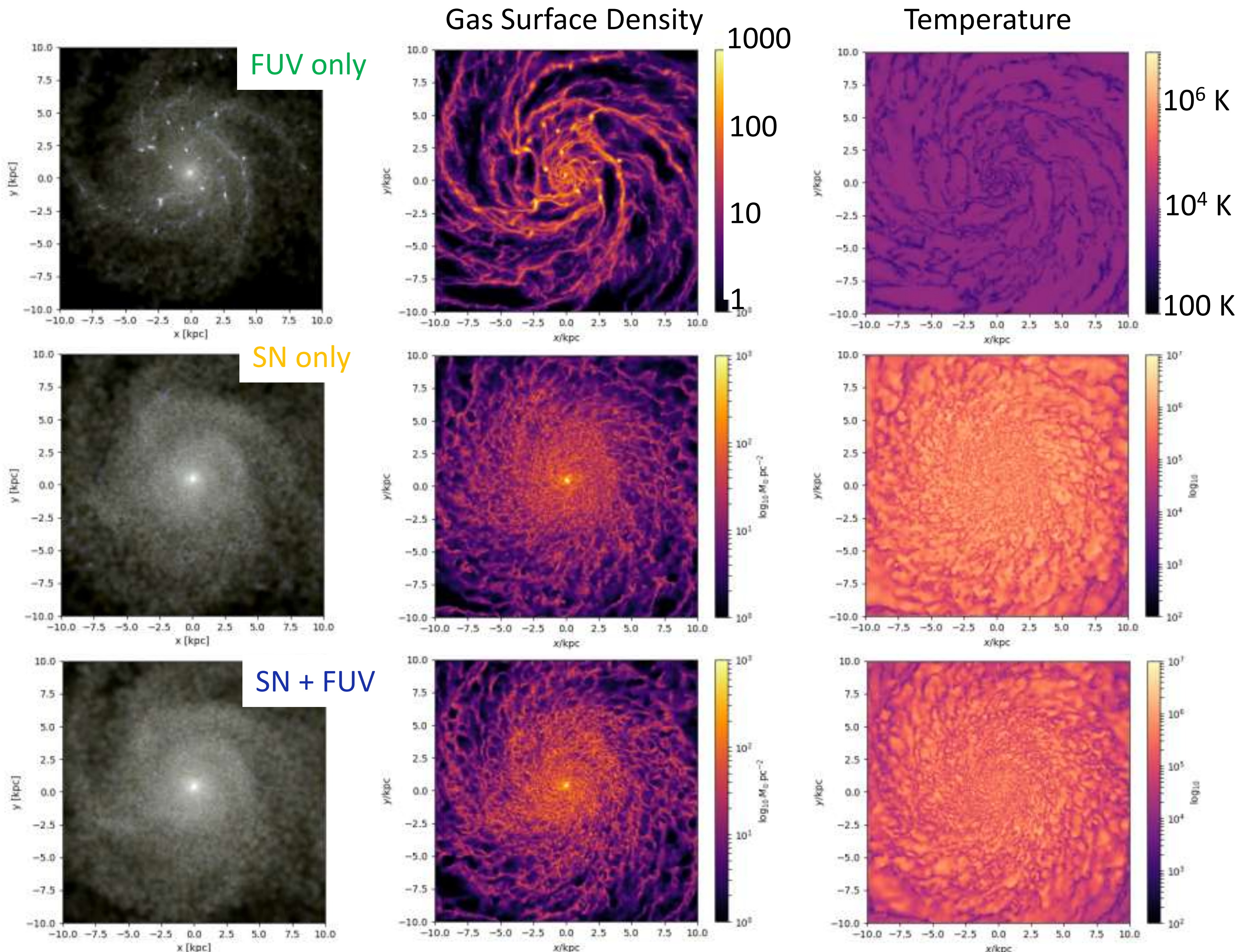
(c) Stellar Surface Density



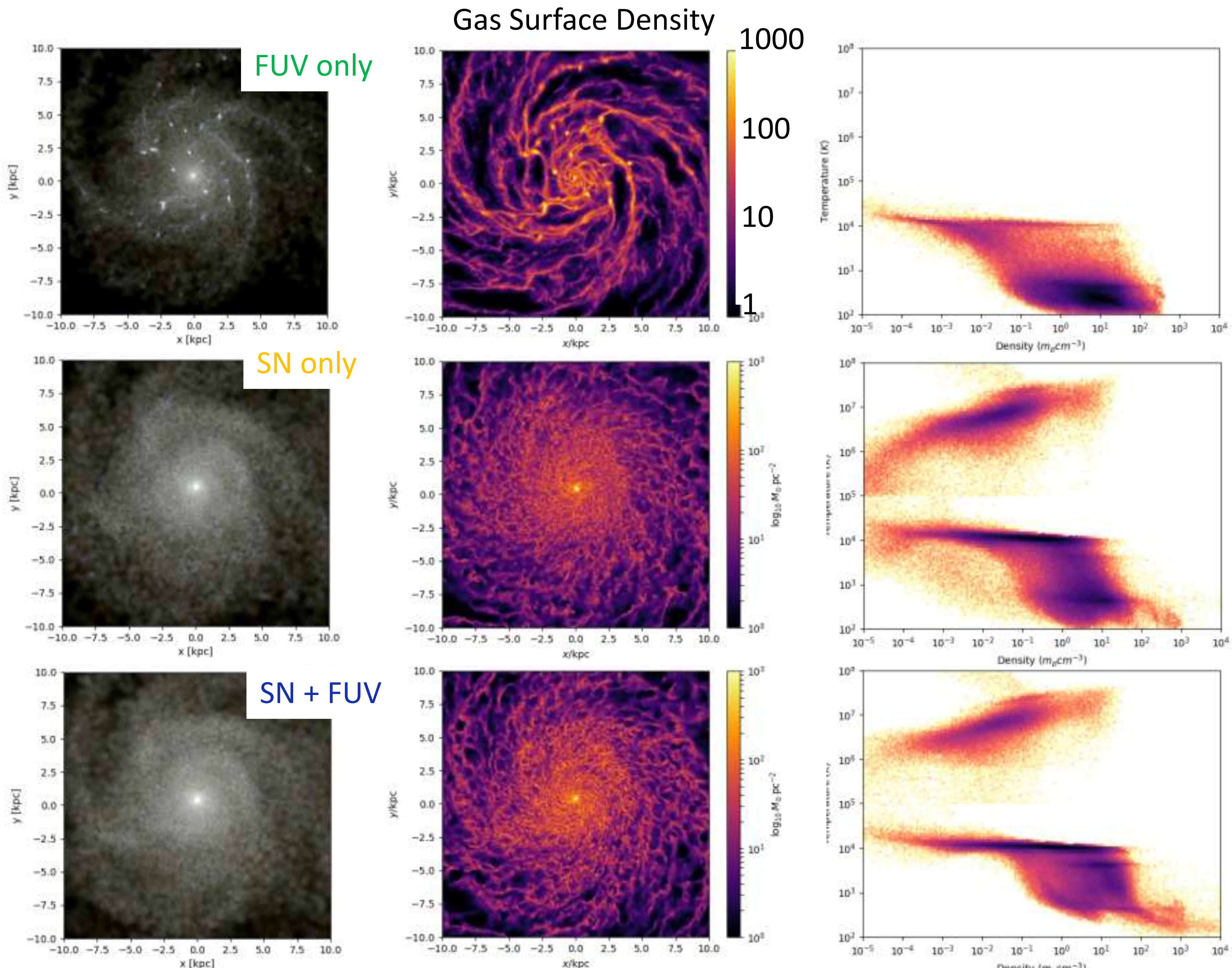
(d) Surface Density Profiles

Star Formation Rates with FUV





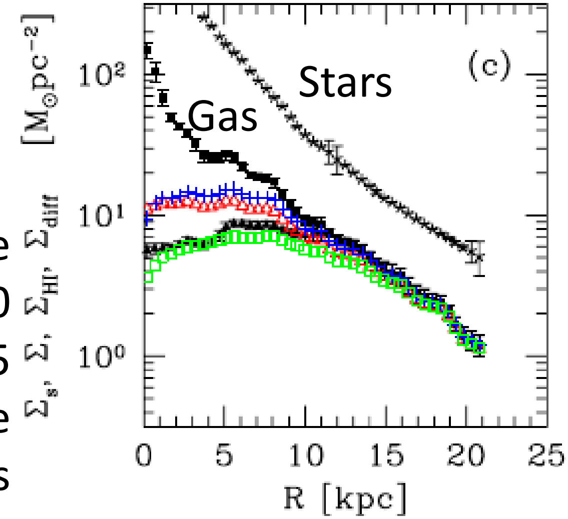
Gas Surface Density
Temperature
FUV only
SN only
SN + FUV
1000
100
10
1
10^6 K
10^4 K
100 K
x [kpc]
y [kpc]
x/kpc
y/kpc
log10 M⊙ pc^-2
log10



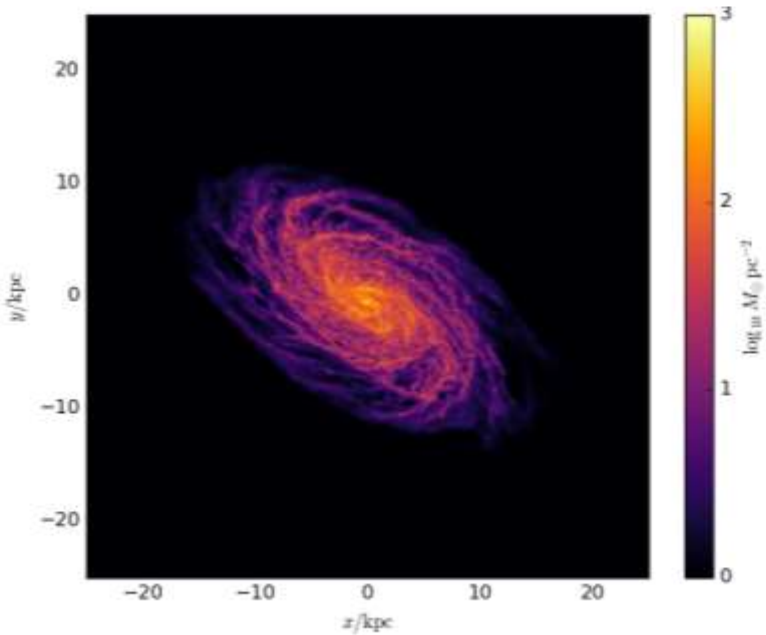
Gas Surface Density
FUV only
SN only
SN + FUV
1000
100
10
1
x [kpc]
y [kpc]
x/kpc
y/kpc
Temperature (K)
Density ($m_p cm^{-3}$)
$\log_{10} M_\odot\, pc^{-2}$

M63/ NGC 5055

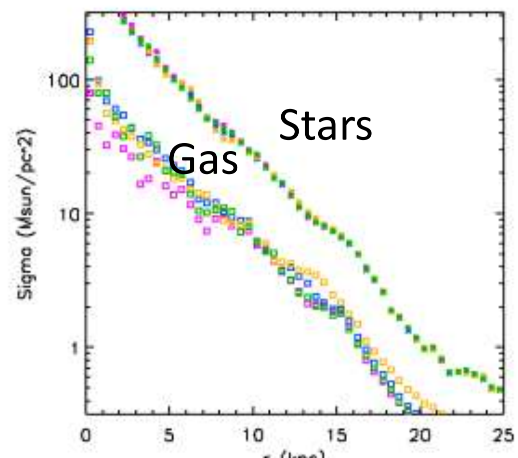
NGC 5055/ M63
“sunflower galaxy”
Spitzer Image



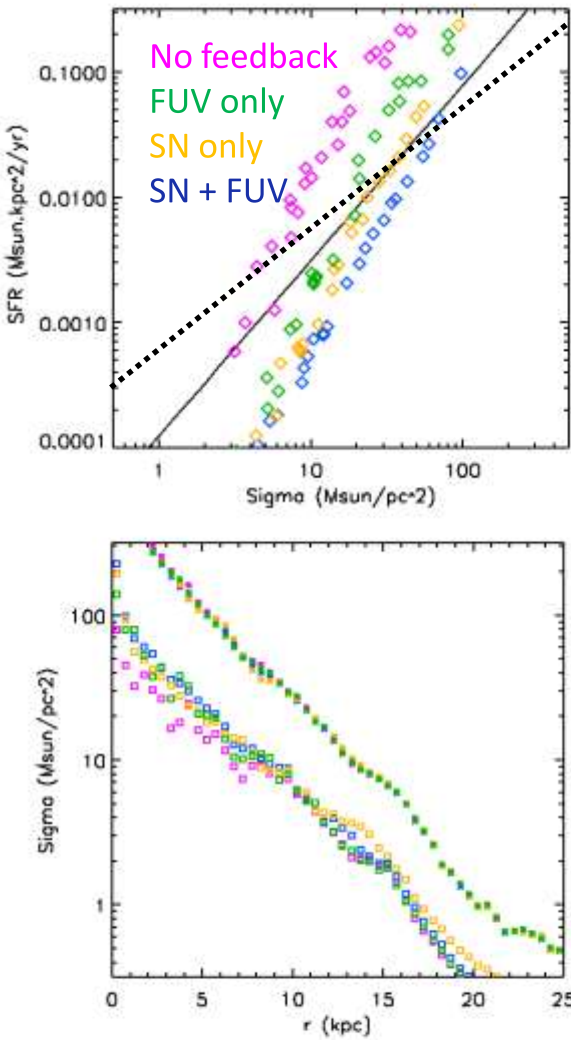
Ostriker, McKee & Leroy 2010
THINGS NGC5055 surface densities



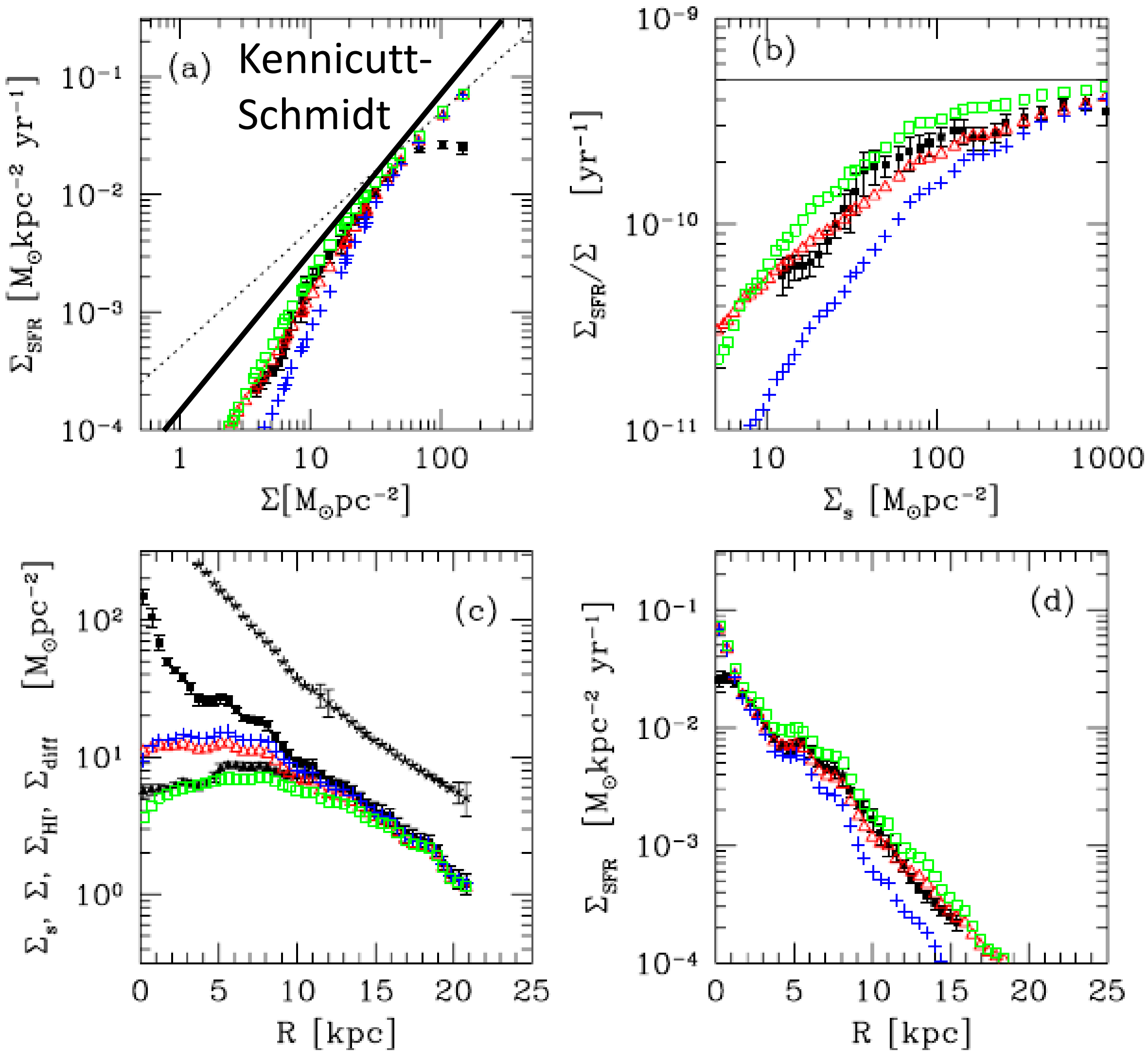
AGORA FUV+SN
(superbubble)



AGORA vs. NGC 5055



AGORA isolated disk



Ostriker, McKee & Leroy 2010

RT in Galaxies Summary

Work in progress

FUV has large impacts on observables, e.g. gas phases

FUV can regulate star formation – added dimension for Kennicutt-Schmidt relation

Note: Prior work (e.g. Ostriker+ 2010) overstated impact of FUV (assumed $P_{SN} = 5 \times P_{FUV}$)

Tricky considerations: unresolved structure, escape fractions (see e.g. Kravtsov+Gnedin 2011 resolution independent subgrid approaches)

More detailed simulations in progress…

Thanks