The Cosmic Dawn: Illuminating a Dark Universe

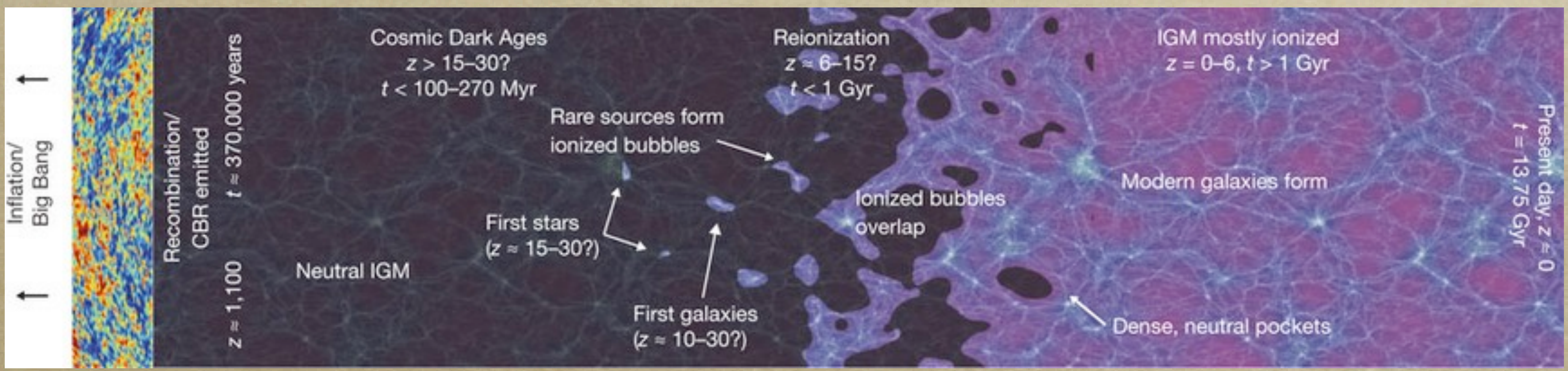
Steven Furlanetto
UCLA

Computational Astronomy: From Planets to Cosmos
June 26, 2012

Outline

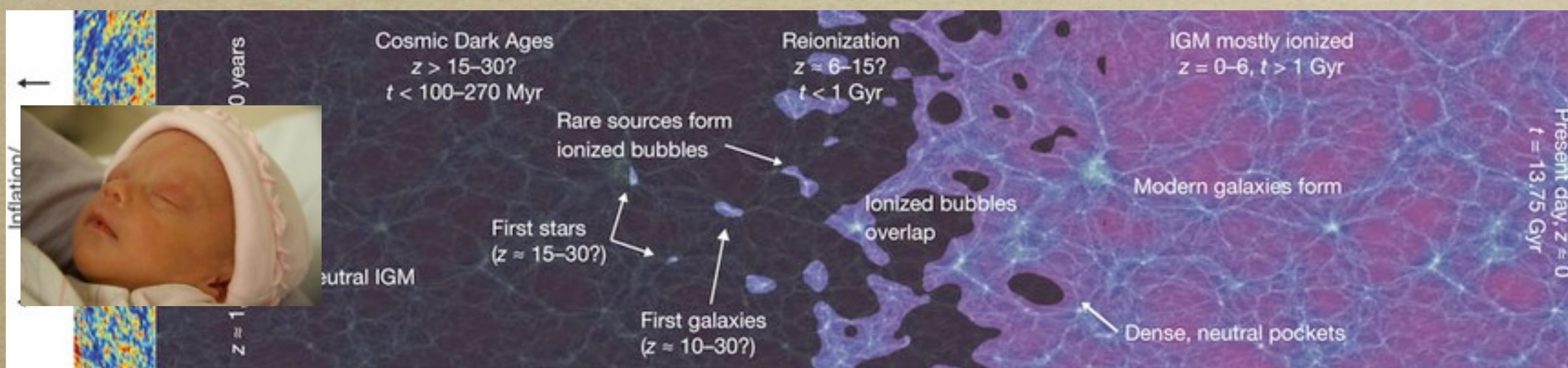
- *Who cares about the Cosmic Dawn?*
- *How do we study the unknown?*
- *How do we make it observable?*

A Brief History of Everything



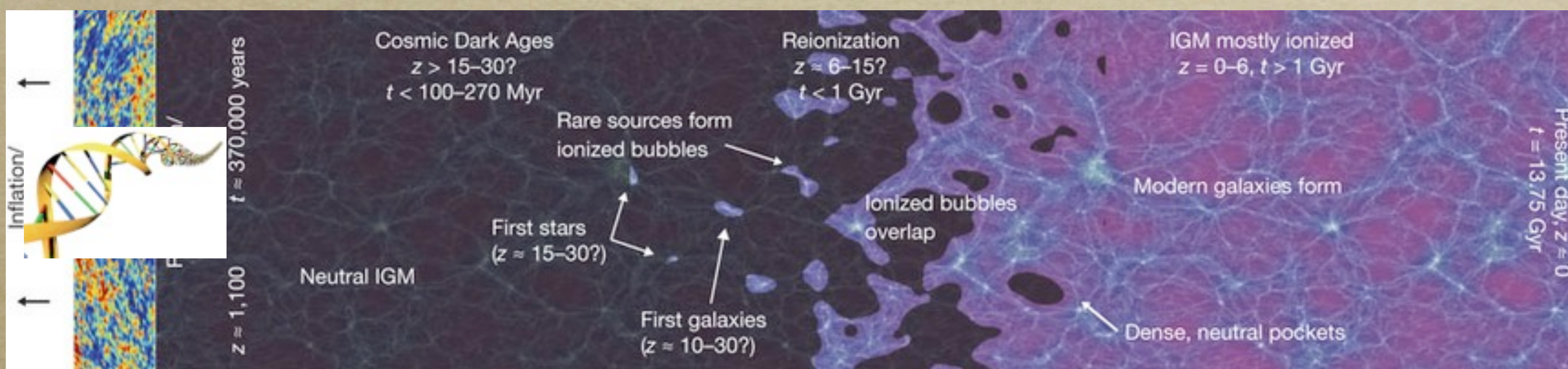
Robertson et al. 2010

A Brief History of Everything



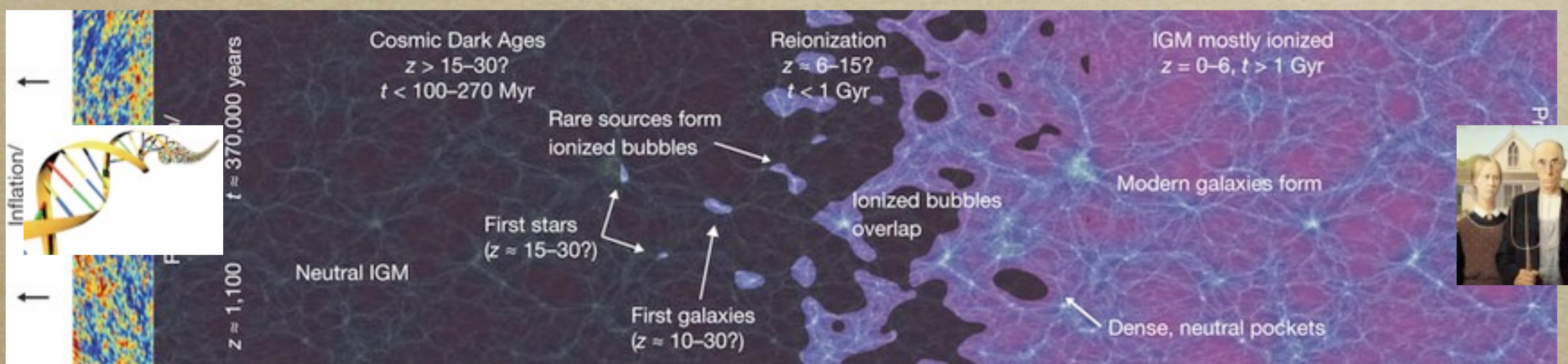
Robertson et al. 2010

A Brief History of Everything



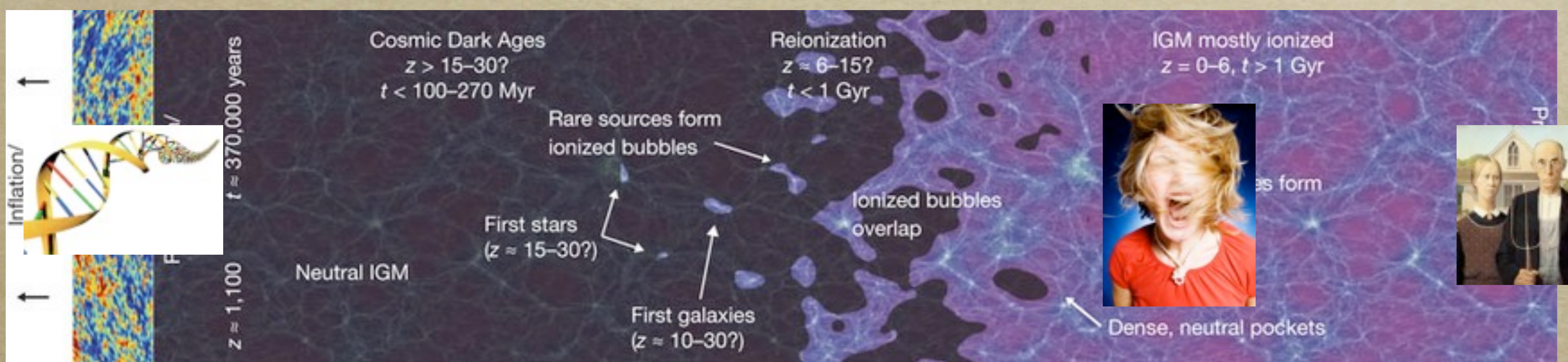
Robertson et al. 2010

A Brief History of Everything



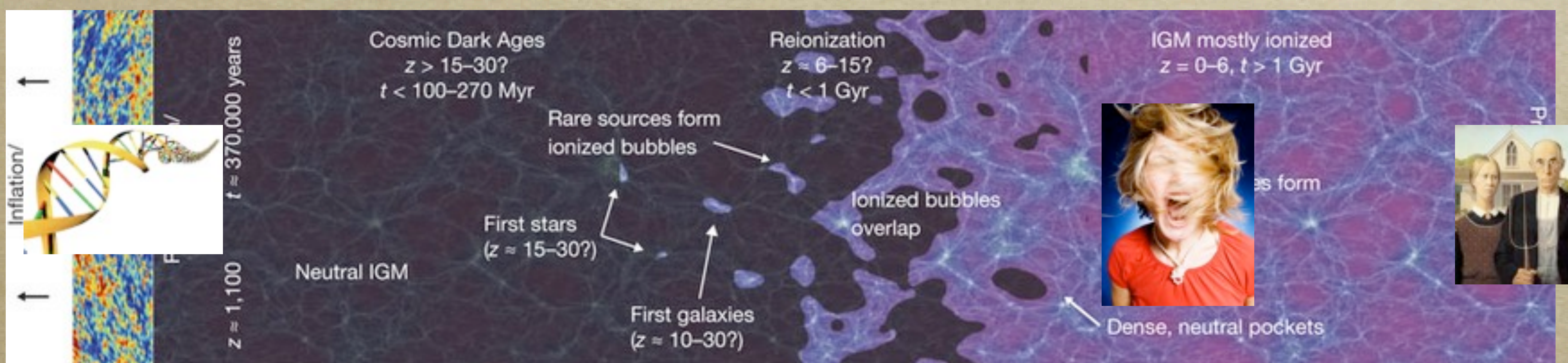
Robertson et al. 2010

A Brief History of Everything



Robertson et al. 2010

A Brief History of Everything



Robertson et al. 2010

- *What's so great about this "Cosmic Dawn"?*

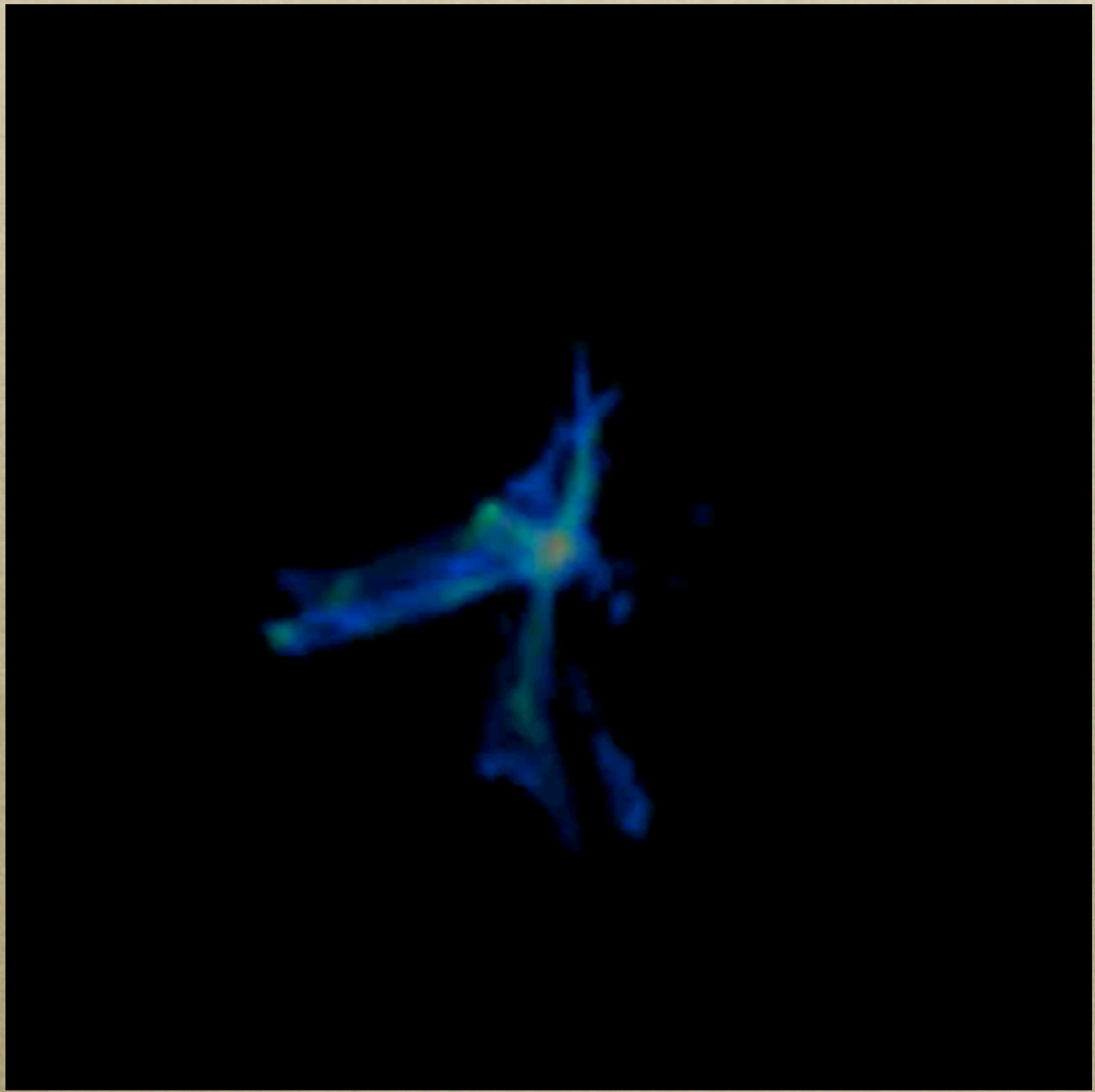
A Brief History of Everything

Robertson et al. 2010

- *What's so great about this "Cosmic Dawn"?*

The Birth of Complexity

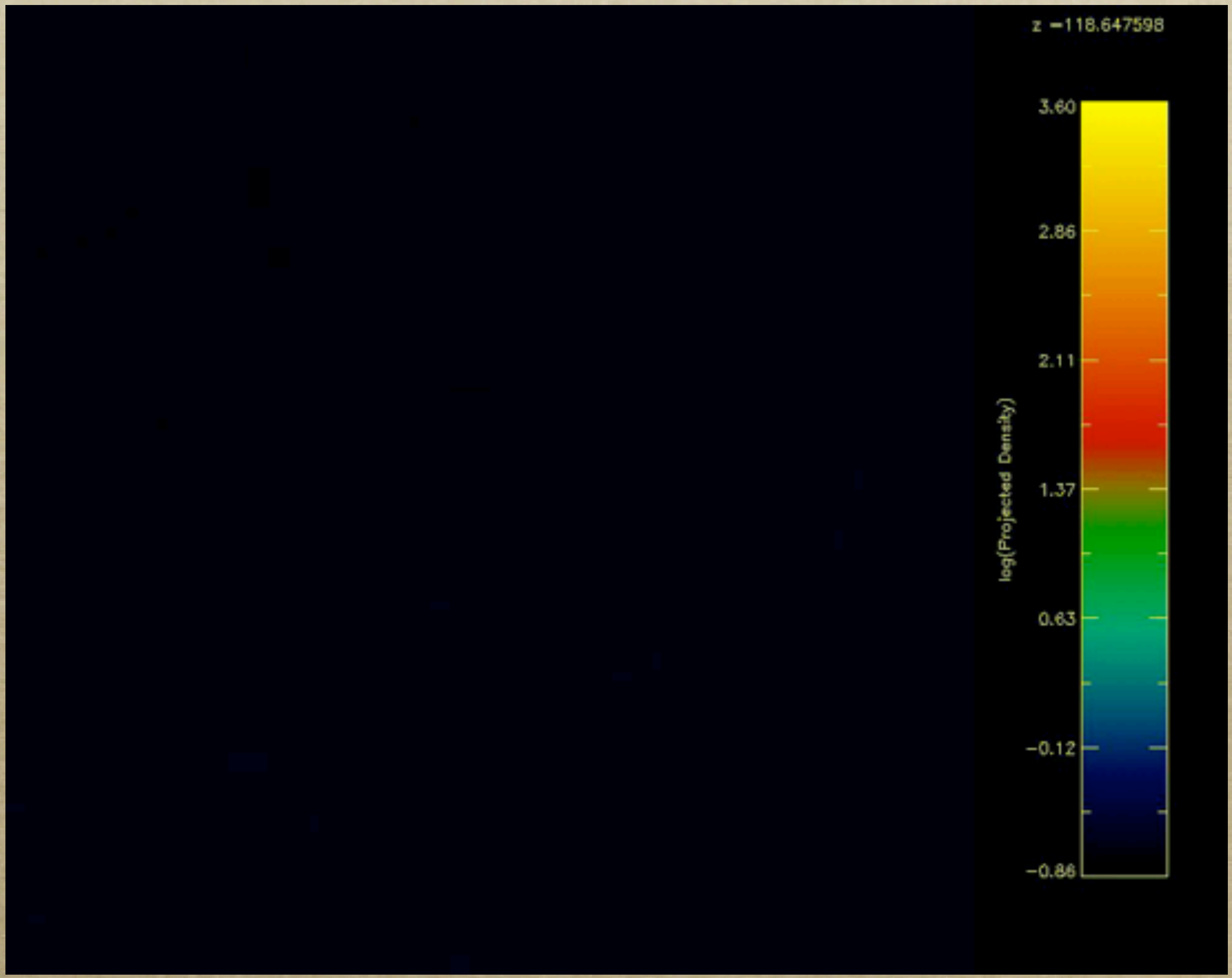
- *Start with a universe described by simple physics + a few numbers*
- *Then suddenly: radiation, chemistry, and kinetic feedback!*



Kahler & Abel (for PBS NOVA)

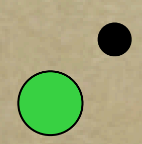
From Exotic to Normal

- *Population III stars*
  - *Form through H_2*
  - *May be very massive*
  - *Exceptionally luminous*
- *Heavy element production (and dispersal) seeds "normal" Population II star formation!*



Wise & Abel

Recombination and Reionization

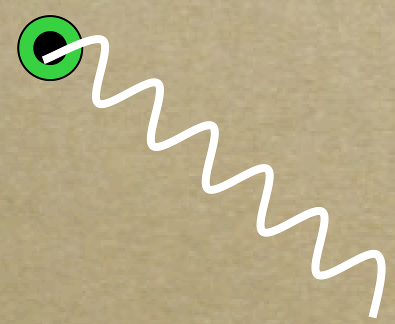


- *Recombination*
  - *Protons + electrons form hydrogen atoms*
  - *Occurs 400,000 years after Big Bang*
- *Reionization*
  - *Powerful photons rip electrons and protons apart*
  - *Requires sources like stars*

Recombination and Reionization

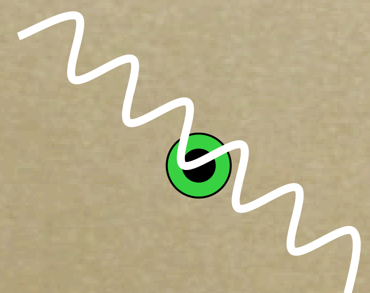
- *Recombination*
  - *Protons + electrons form hydrogen atoms*
  - *Occurs 400,000 years after Big Bang*
- *Reionization*
  - *Powerful photons rip electrons and protons apart*
  - *Requires sources like stars*

Recombination and Reionization



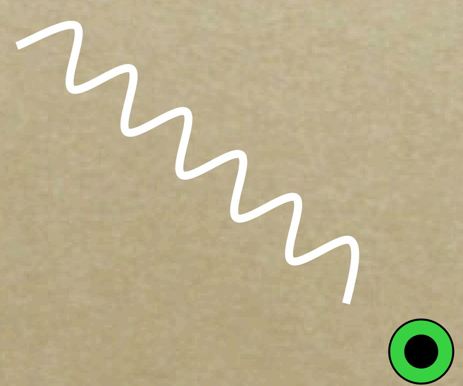
- *Recombination*
  - *Protons + electrons form hydrogen atoms*
  - *Occurs 400,000 years after Big Bang*
- *Reionization*
  - *Powerful photons rip electrons and protons apart*
  - *Requires sources like stars*

Recombination and Reionization



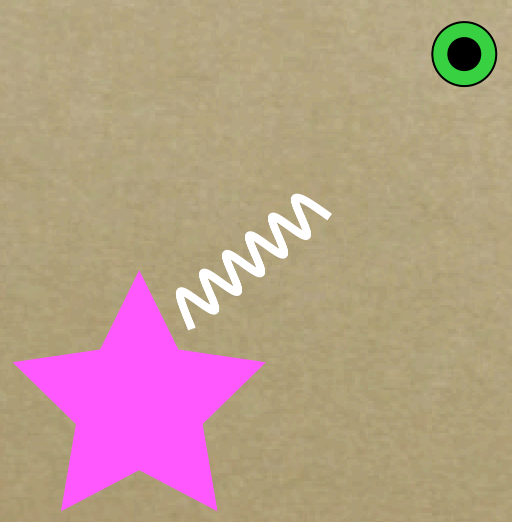
- *Recombination*
  - *Protons + electrons form hydrogen atoms*
  - *Occurs 400,000 years after Big Bang*
- *Reionization*
  - *Powerful photons rip electrons and protons apart*
  - *Requires sources like stars*

Recombination and Reionization



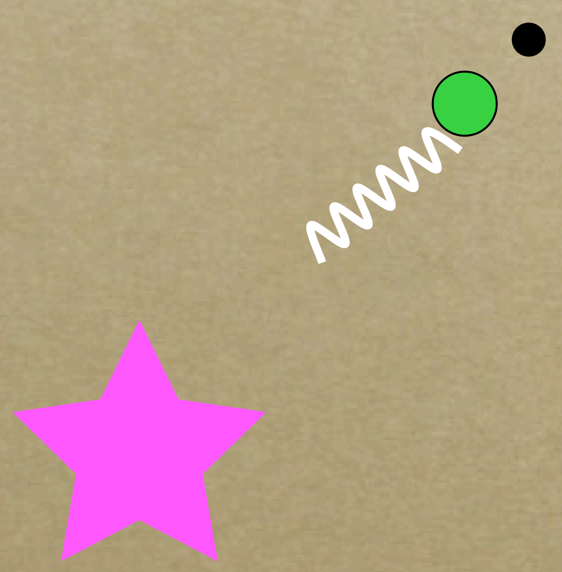
- *Recombination*
  - *Protons + electrons form hydrogen atoms*
  - *Occurs 400,000 years after Big Bang*
- *Reionization*
  - *Powerful photons rip electrons and protons apart*
  - *Requires sources like stars*

Recombination and Reionization



- *Recombination*
  - *Protons + electrons form hydrogen atoms*
  - *Occurs 400,000 years after Big Bang*
- *Reionization*
  - *Powerful photons rip electrons and protons apart*
  - *Requires sources like stars*

Recombination and Reionization



- *Recombination*
  - *Protons + electrons form hydrogen atoms*
  - *Occurs 400,000 years after Big Bang*
- *Reionization*
  - *Powerful photons rip electrons and protons apart*
  - *Requires sources like stars*

Feedback, Glorious Feedback

Alvarez, Kahler, & Abel

The First Black Holes

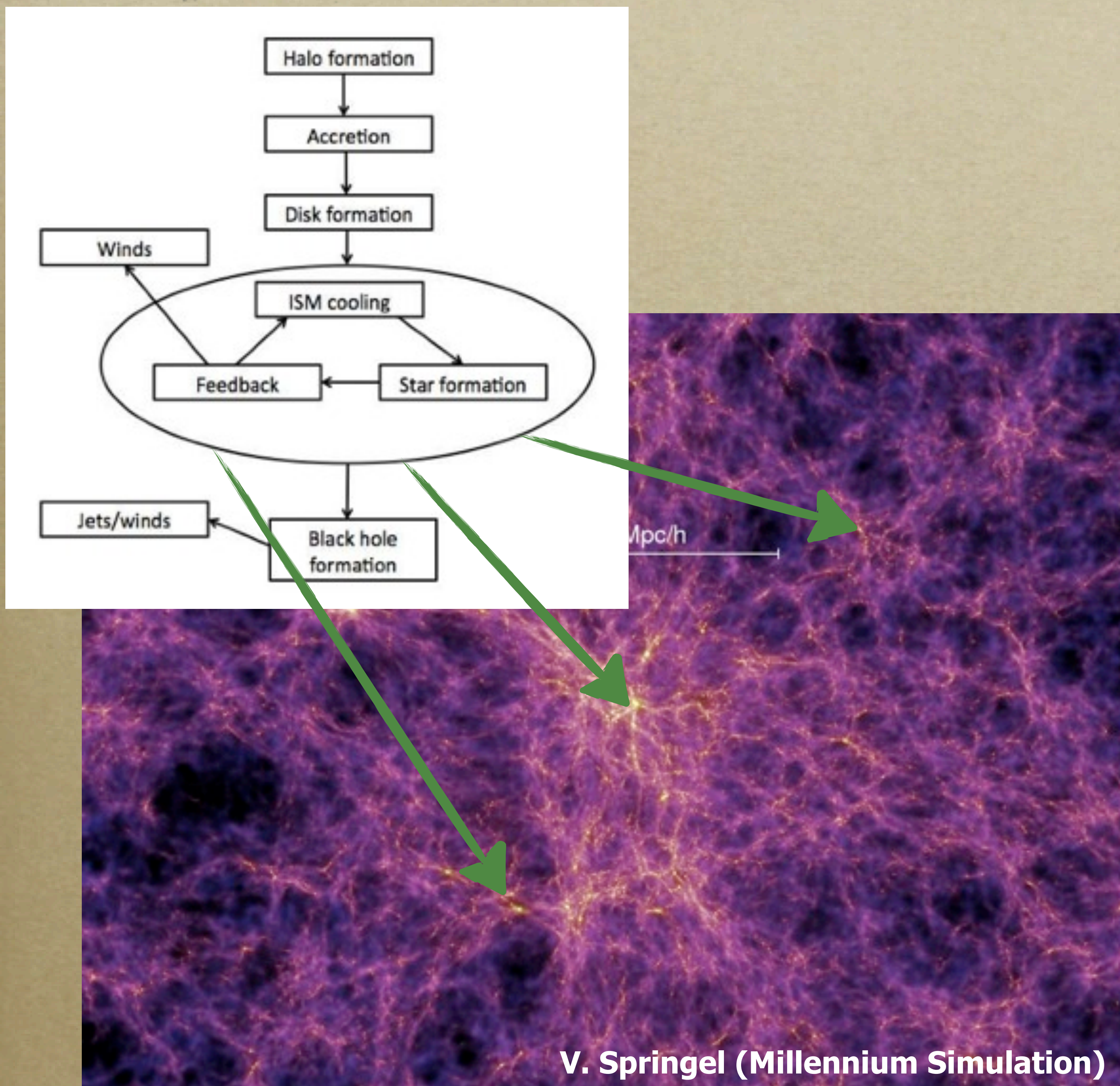
T. di Matteo et al.

- *Black holes appear at the same time (or slightly later)*
- *How do they affect galaxy formation?*
- *How do they affect the intergalactic medium?*

He thinks too much:
Such men are dangerous.

- *How do we study the unknown?*

Grand Unified Galaxy Formation



- *Goal is a physically-grounded model of star and black hole formation within galaxies, including all relevant physical processes, and their relation to underlying dark matter structures (on small and large scales)*

Method #1: Computational Astrophysics

- *Precise numerical calculations from first principles*

Method #1: Computational Astrophysics

- *Precise numerical calculations from first principles*
- *When the first star forms:*

Method #1: Computational Astrophysics

- *Precise numerical calculations from first principles*
- *When the first star forms:*
  - *The universe is defined by simple initial conditions*

Method #1: Computational Astrophysics

- *Precise numerical calculations from first principles*
- *When the first star forms:*
  - *The universe is defined by simple initial conditions*
  - *The physics is known*

Method #1: Computational Astrophysics

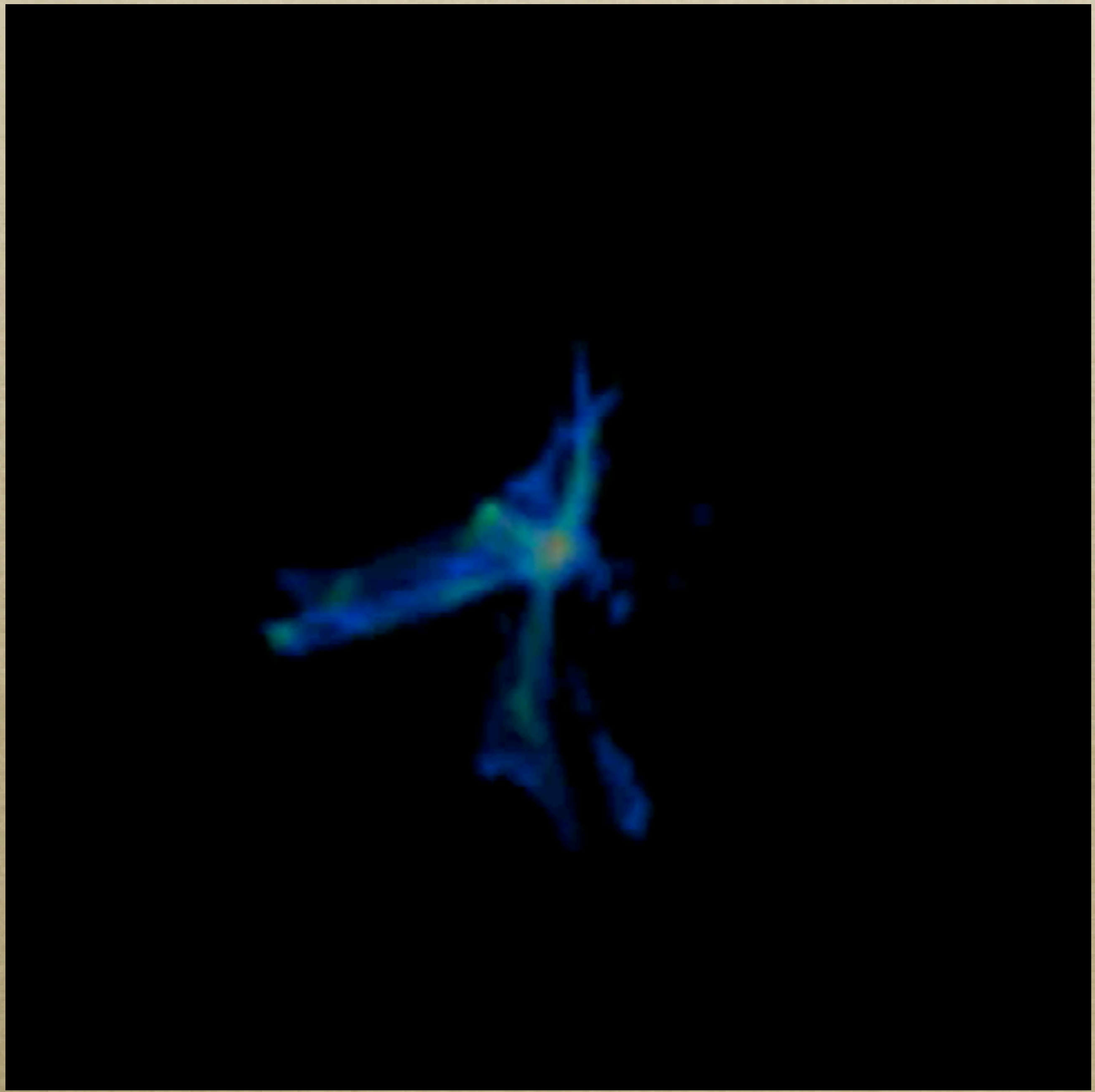
- *Precise numerical calculations from first principles*
- *When the first star forms:*
  - *The universe is defined by simple initial conditions*
  - *The physics is known*
  - *So its formation is a well-posed problem!*

Method #1: Computational Astrophysics

- *Precise numerical calculations from first principles*
- *When the first star forms:*
  - *The universe is defined by simple initial conditions*
  - *The physics is known*
  - *So its formation is a well-posed problem!*
- *GOAL: understand first steps in detail*

Simulating The First Stars: Lessons

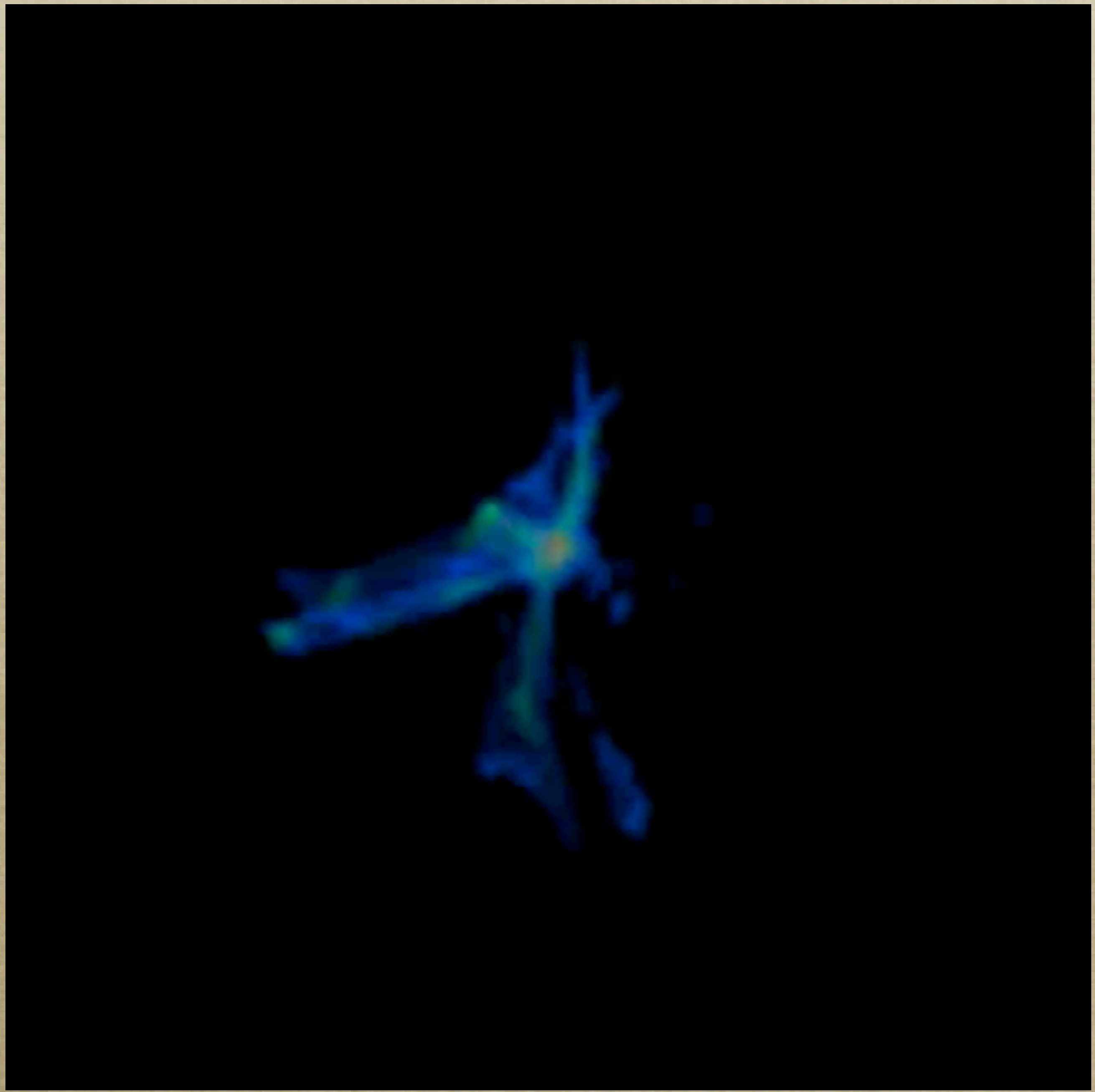
- *Stars form in small dark matter clumps*



Kahler & Abel (for PBS NOVA)

Simulating The First Stars: Lessons

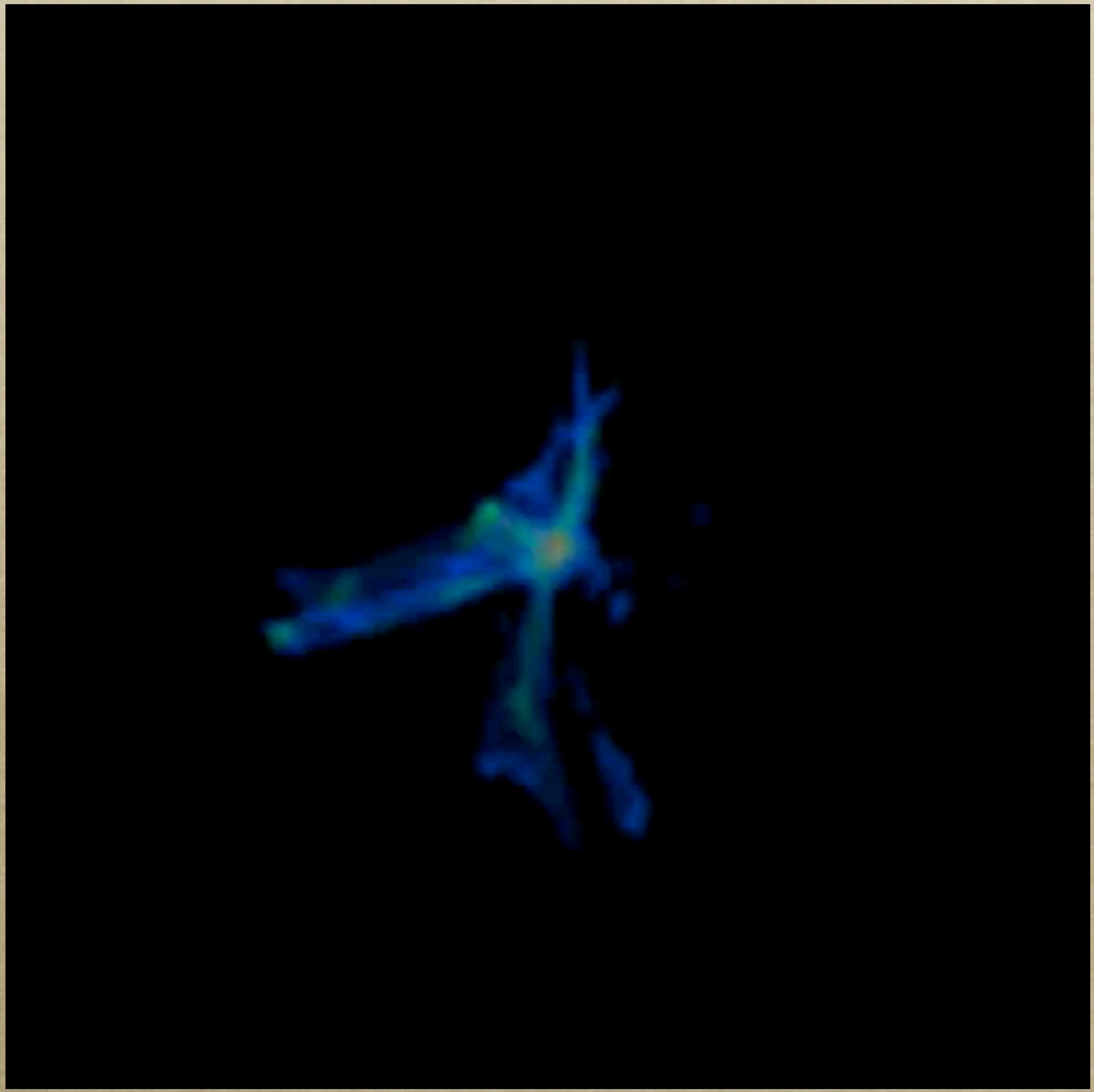
- *Stars form in small dark matter clumps*
- *Gas heats as it falls onto clump*



Kahler & Abel (for PBS NOVA)

Simulating The First Stars: Lessons

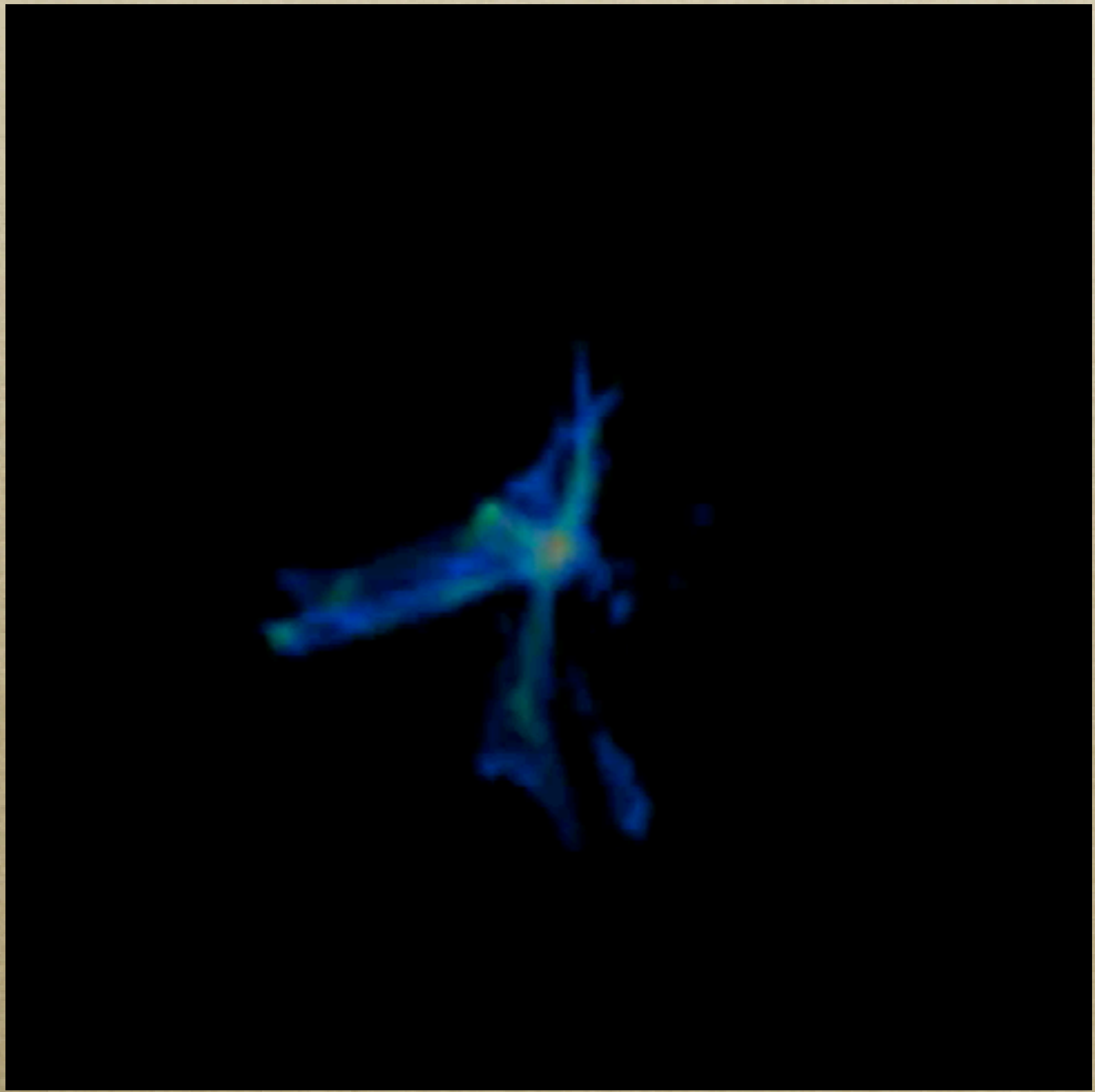
- *Stars form in small dark matter clumps*
- *Gas heats as it falls onto clump*
- *Cools through radiation from molecular hydrogen*



Kahler & Abel (for PBS NOVA)

Simulating The First Stars: Lessons

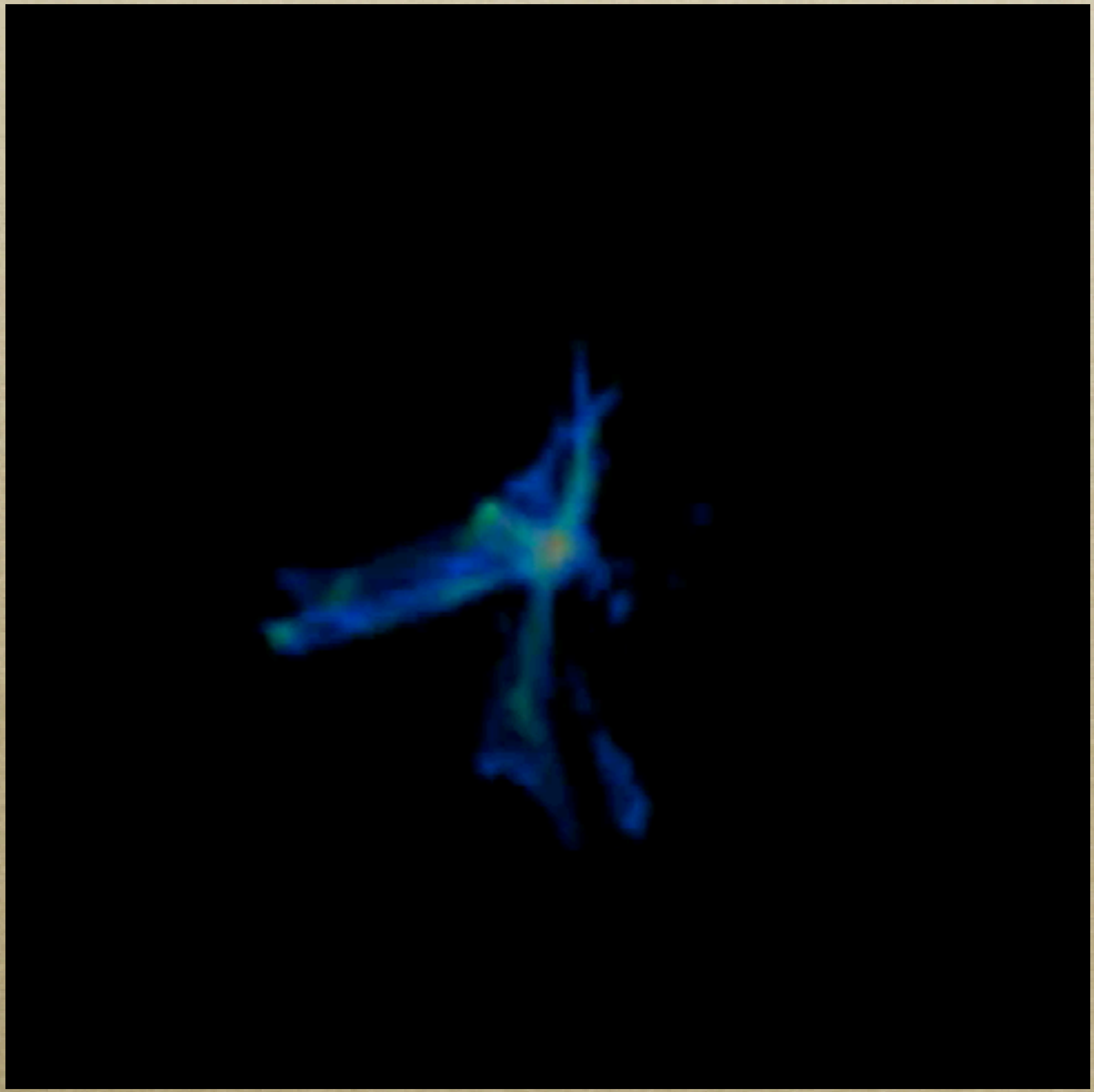
- *Stars form in small dark matter clumps*
- *Gas heats as it falls onto clump*
- *Cools through radiation from molecular hydrogen*
- *Left with gas clump several hundred times larger than Sun*



Kahler & Abel (for PBS NOVA)

Simulating The First Stars: Lessons

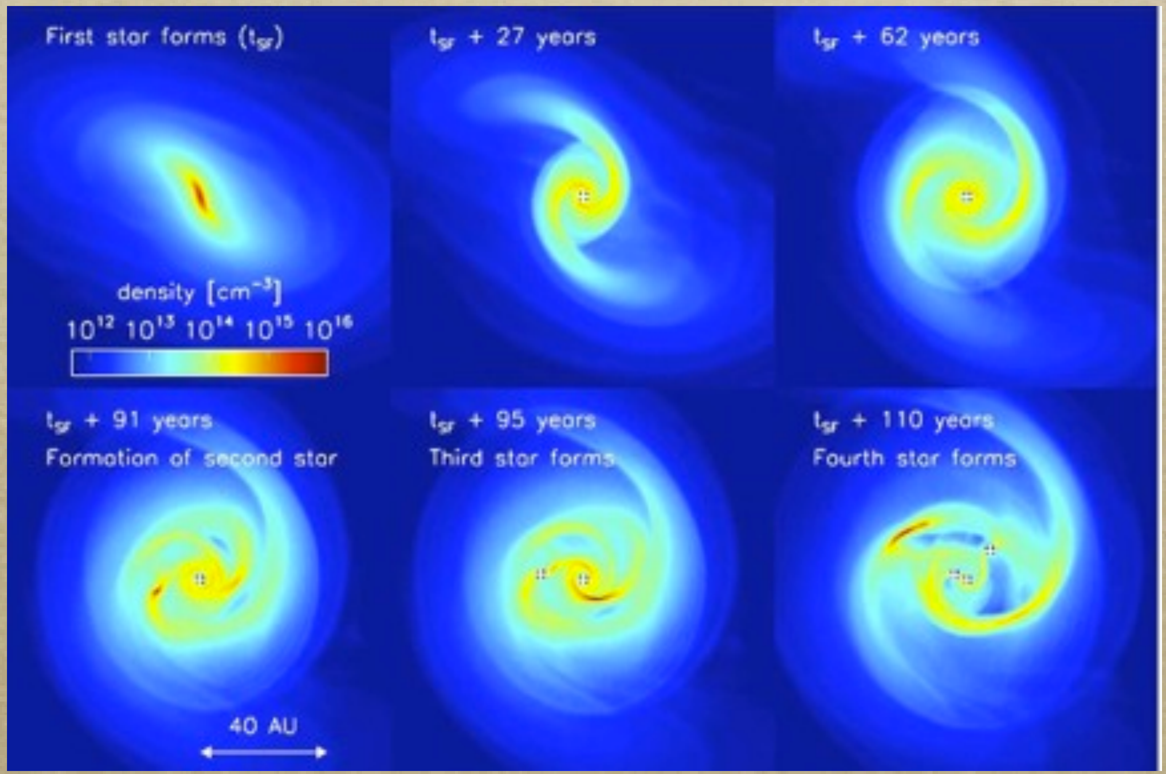
- *Stars form in small dark matter clumps*
- *Gas heats as it falls onto clump*
- *Cools through radiation from molecular hydrogen*
- *Left with gas clump several hundred times larger than Sun*
- *If left alone, it will contract to form first star!*



Kahler & Abel (for PBS NOVA)

Challenge #1: Computational Power

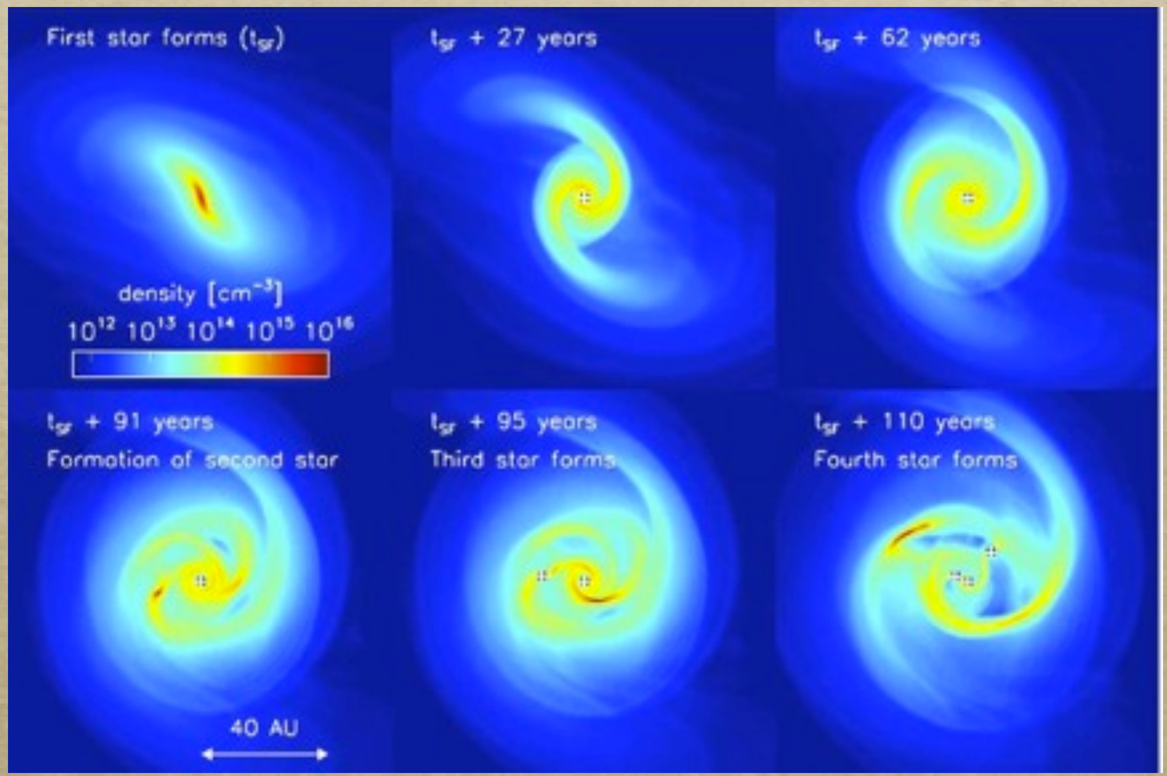
- *Key Question: How massive are the first stars?*
- *Original answer: ~100-500 solar masses*



Clark et al. (2011)

Challenge #1: Computational Power

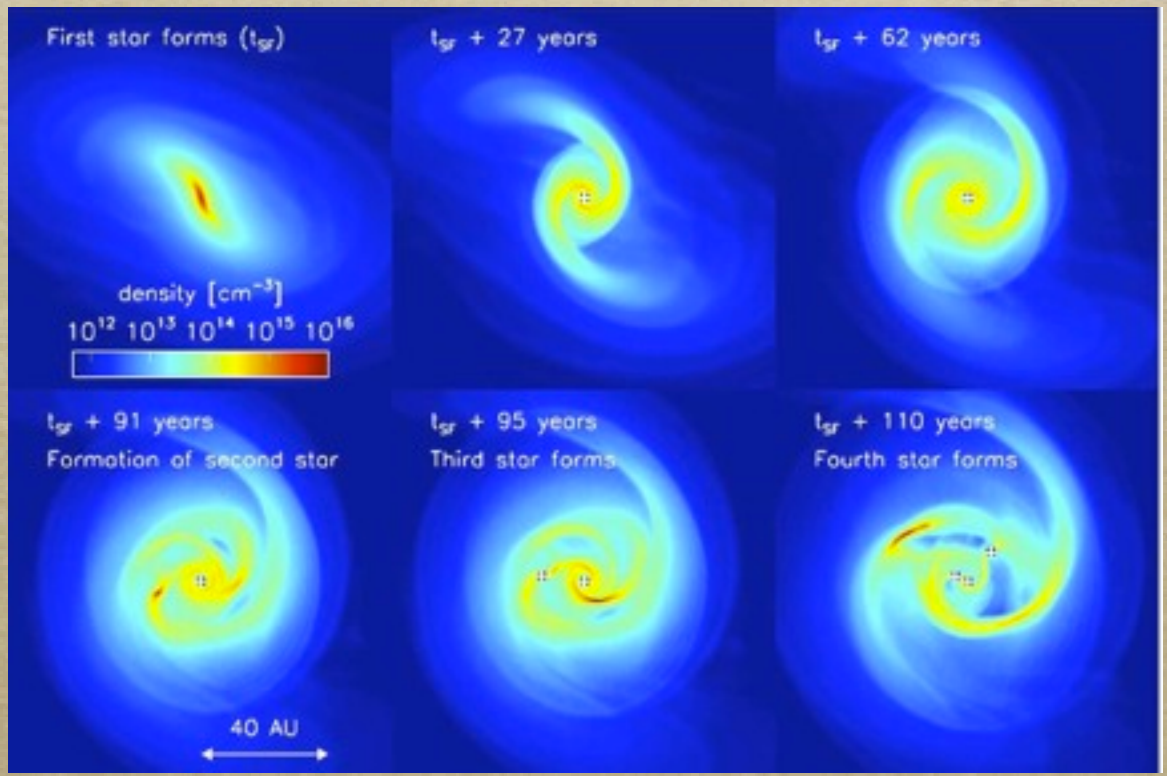
- *Key Question: How massive are the first stars?*
- *Original answer: ~100-500 solar masses*
- *More recently:*



Clark et al. (2011)

Challenge #1: Computational Power

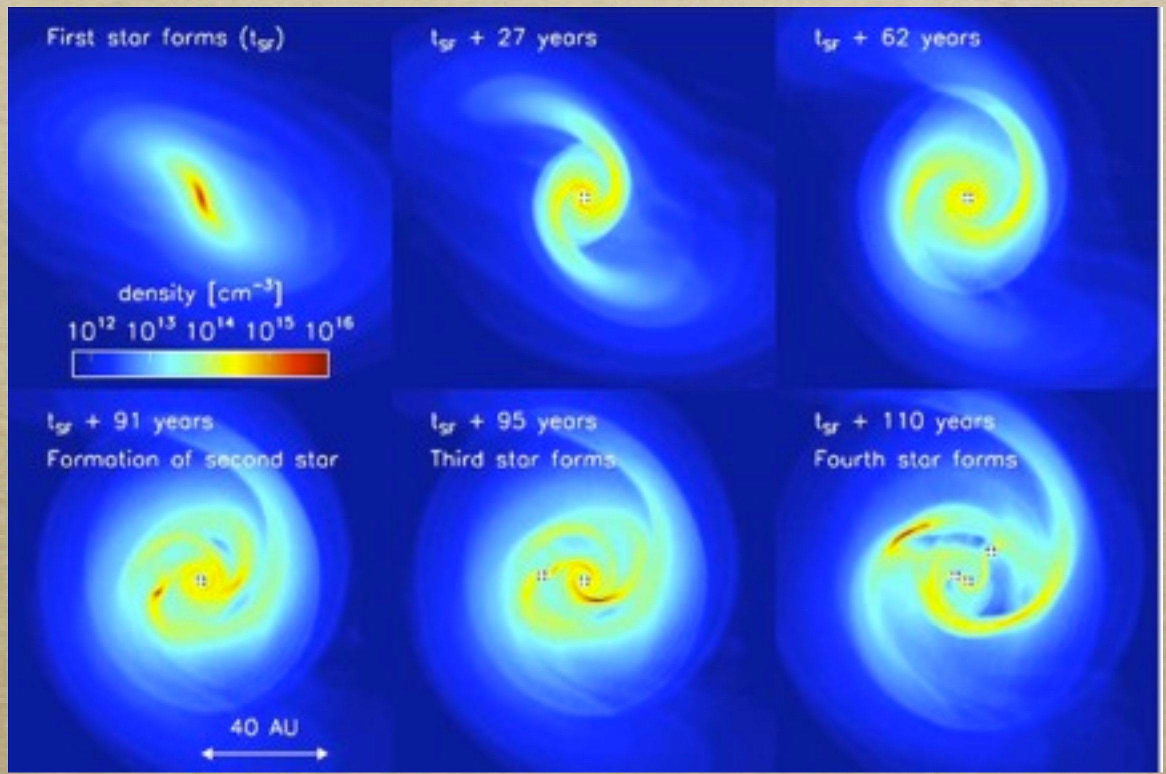
- *Key Question: How massive are the first stars?*
- *Original answer: ~100-500 solar masses*
- *More recently:*
  - *Disk forms around first star, possibly causing fragmentation*



Clark et al. (2011)

Challenge #1: Computational Power

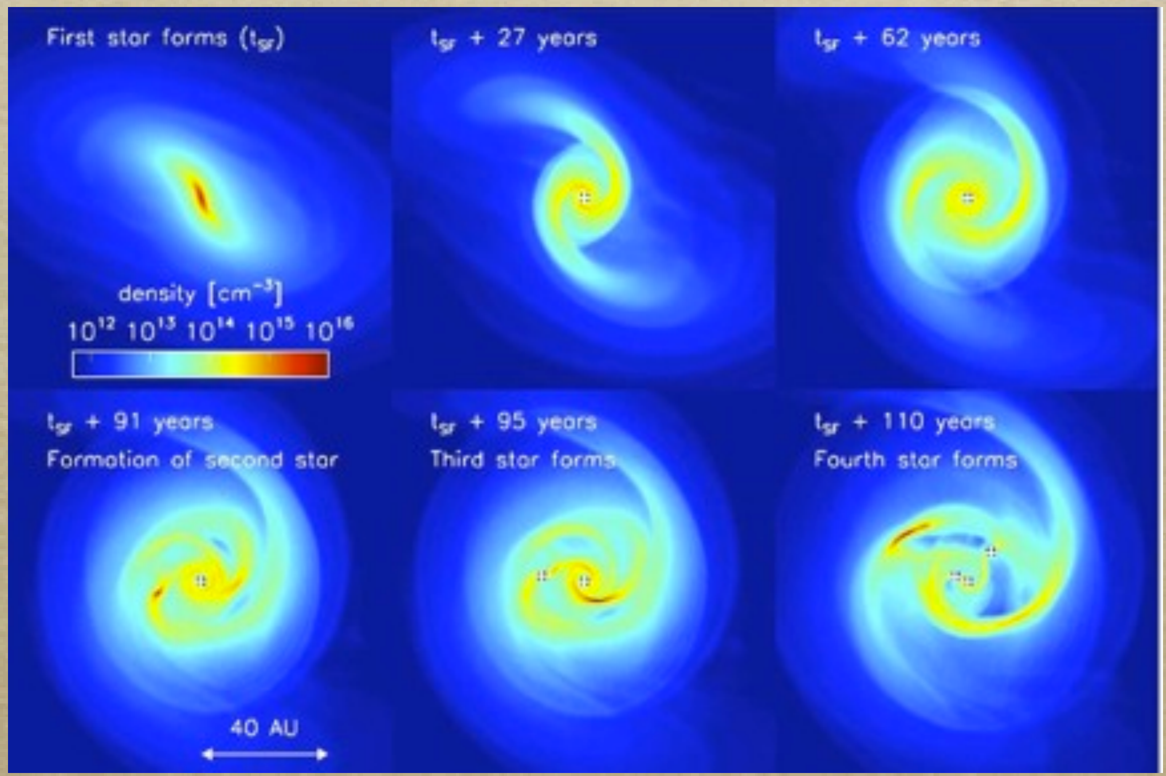
- *Key Question: How massive are the first stars?*
- *Original answer: ~100-500 solar masses*
- *More recently:*
  - *Disk forms around first star, possibly causing fragmentation*
  - *Chemo-thermal effects may also cause fragmentation*



Clark et al. (2011)

Challenge #1: Computational Power

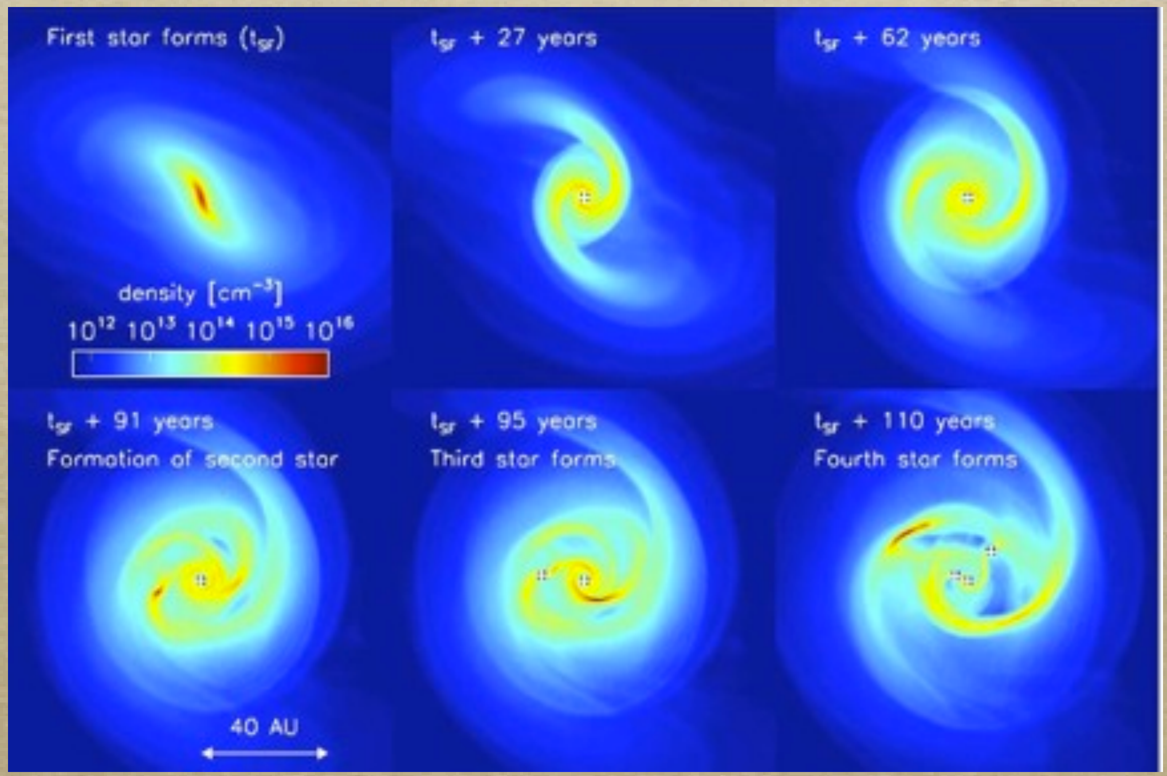
- *Key Question: How massive are the first stars?*
- *Original answer: ~100-500 solar masses*
- *More recently:*
  - *Disk forms around first star, possibly causing fragmentation*
  - *Chemo-thermal effects may also cause fragmentation*
  - *Unresolved turbulence in the clouds can cause fragmentation*



Clark et al. (2011)

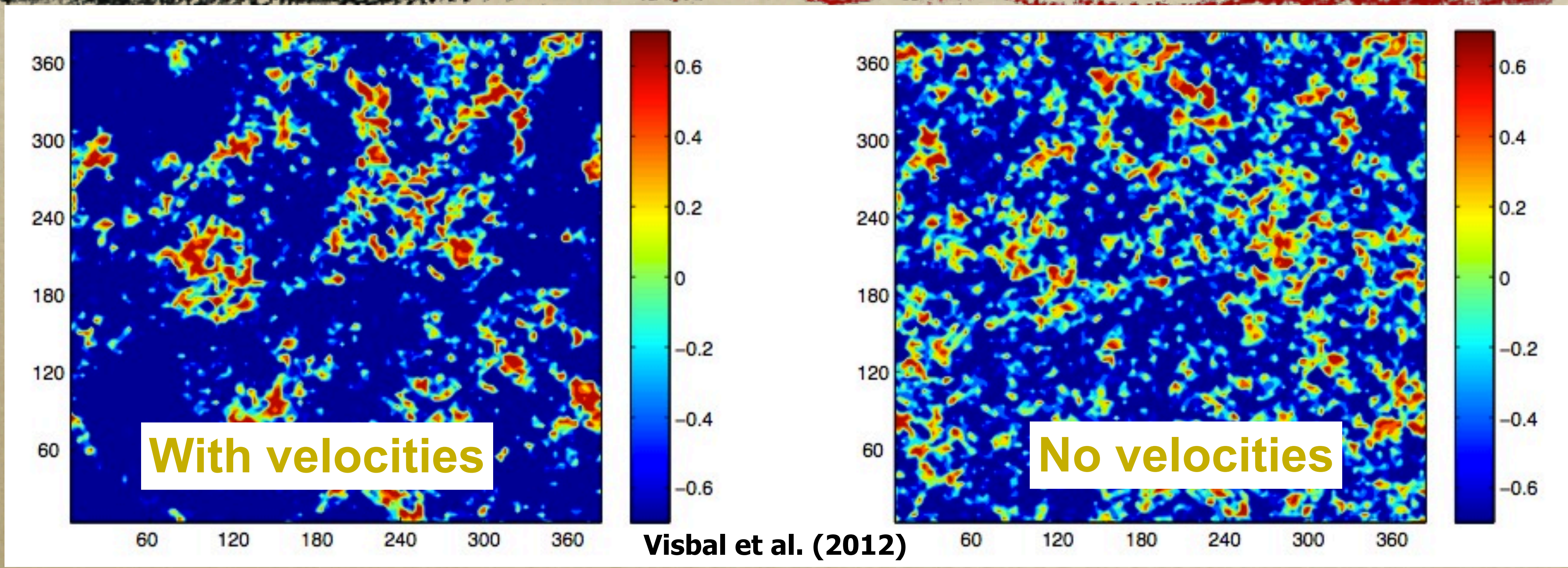
Challenge #1: Computational Power

- *Key Question: How massive are the first stars?*
- *Original answer: ~100-500 solar masses*
- *More recently:*
  - *Disk forms around first star, possibly causing fragmentation*
  - *Chemo-thermal effects may also cause fragmentation*
  - *Unresolved turbulence in the clouds can cause fragmentation*
- *Current answer: ???? solar masses*



Clark et al. (2011)

Challenge #2: The Right Physics



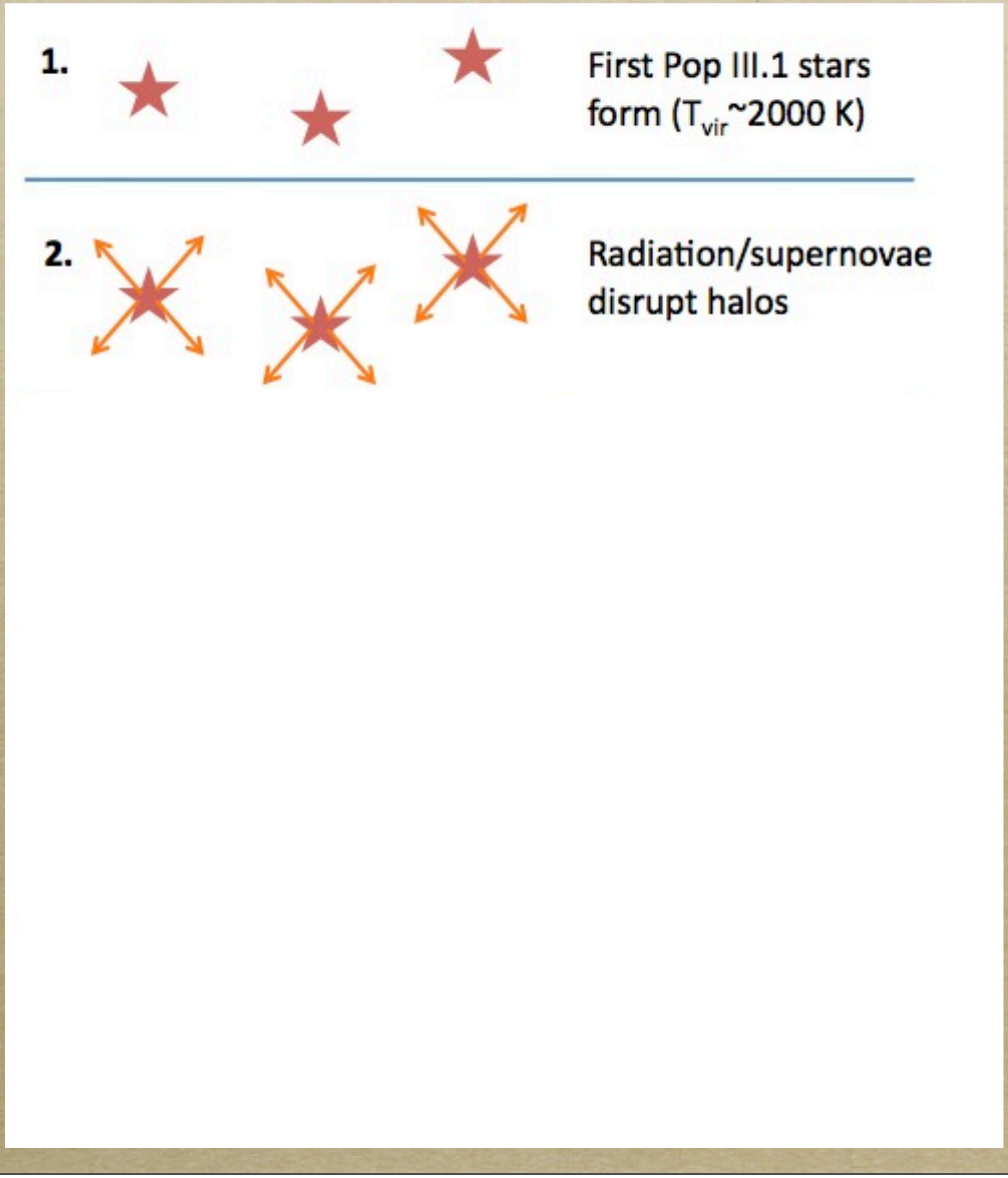
- *Acoustic oscillations at recombination imprint bulk velocities on the gas relative to dark matter*
- *These prevent gas from accreting onto dark matter clumps, delaying structure formation!*

Challenge #3: Too much physics!

- *Unlike the local Universe, distant galaxies strongly affect the fuel supply at high redshifts!*

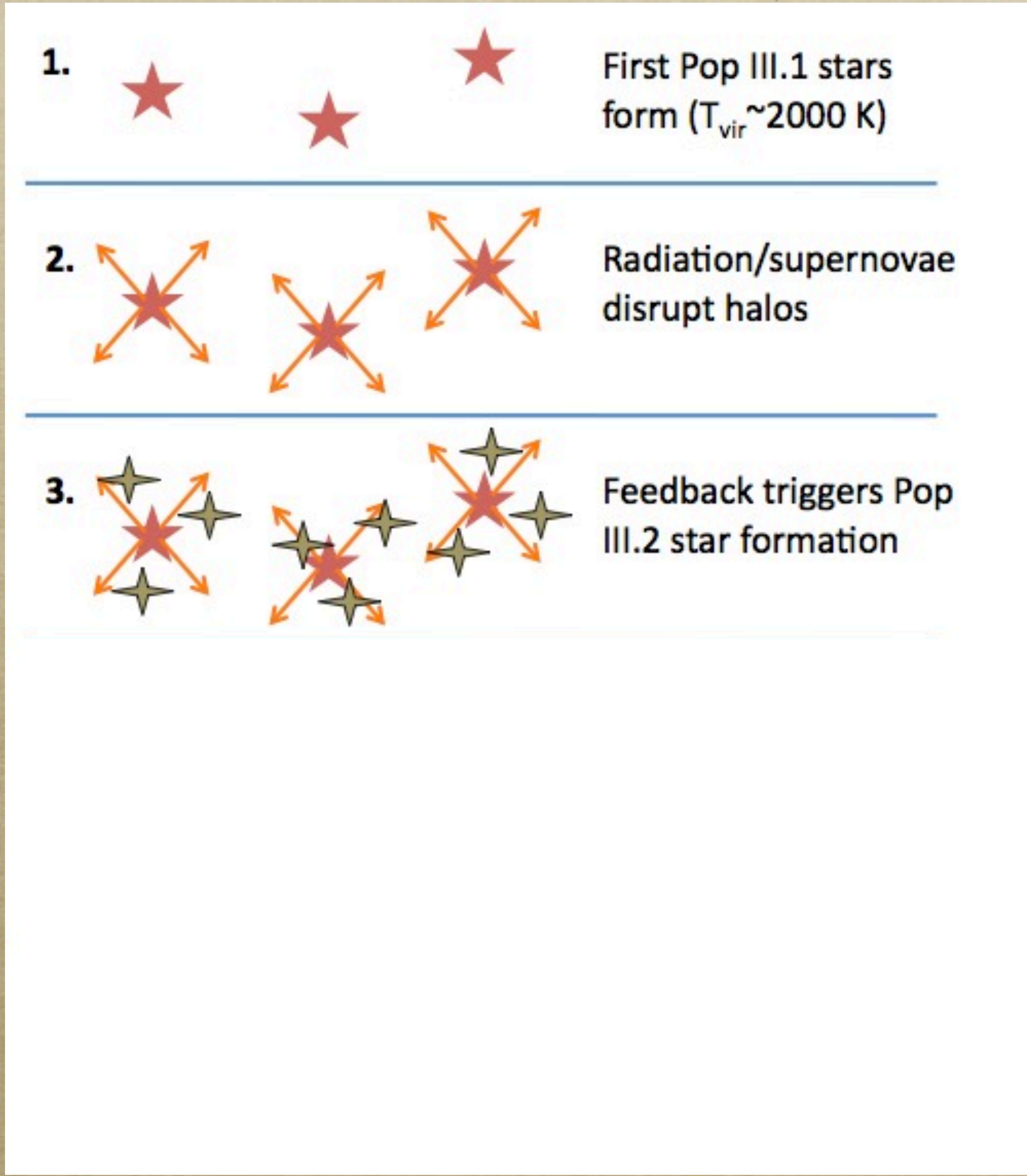
Challenge #3: Too much physics!

- *Unlike the local Universe, distant galaxies strongly affect the fuel supply at high redshifts!*
    - *Gas flows and winds*
    - *Heavy element enrichment*



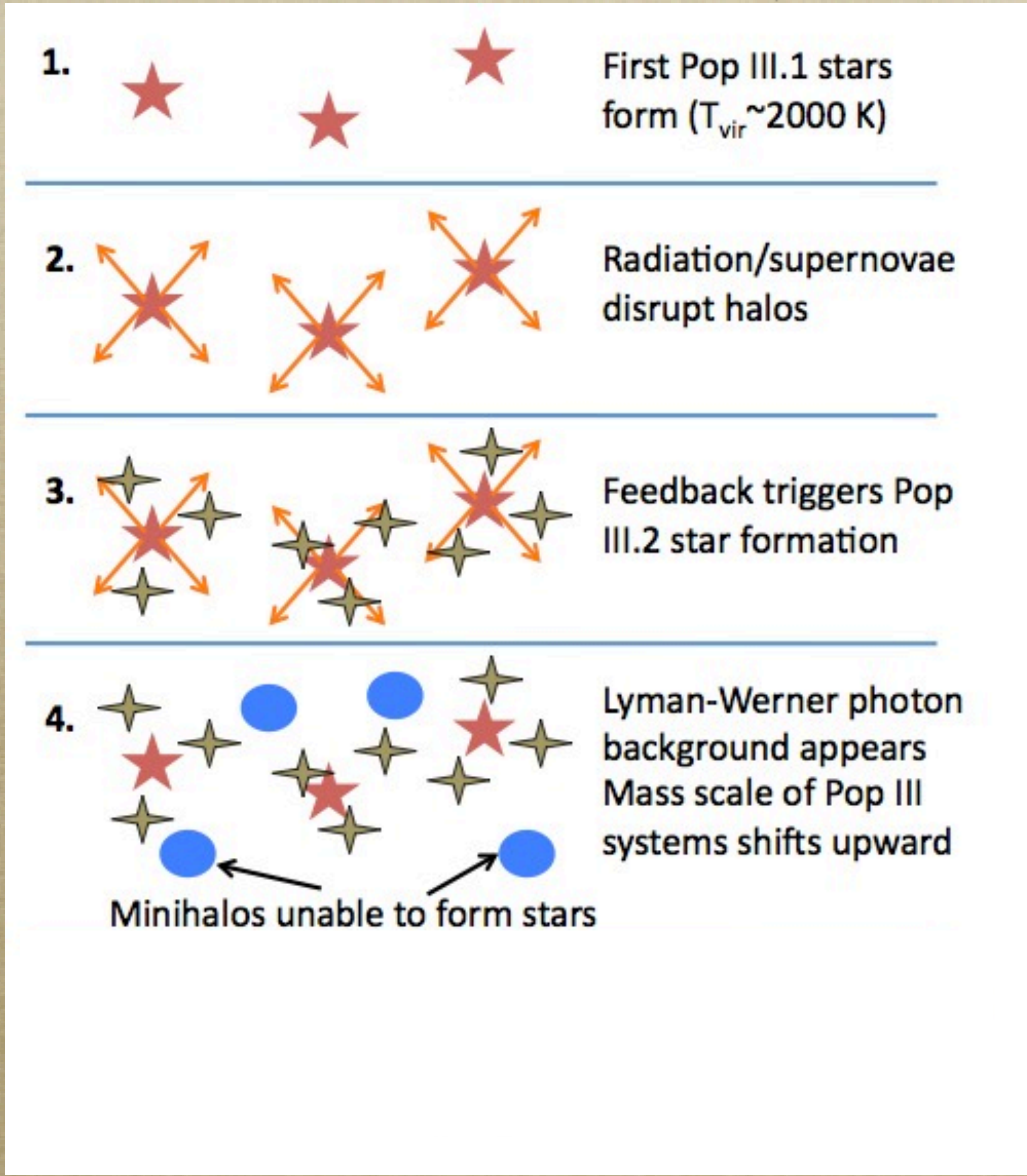
Challenge #3: Too much physics!

- *Unlike the local Universe, distant galaxies strongly affect the fuel supply at high redshifts!*
  - *Gas flows and winds*
  - *Heavy element enrichment*



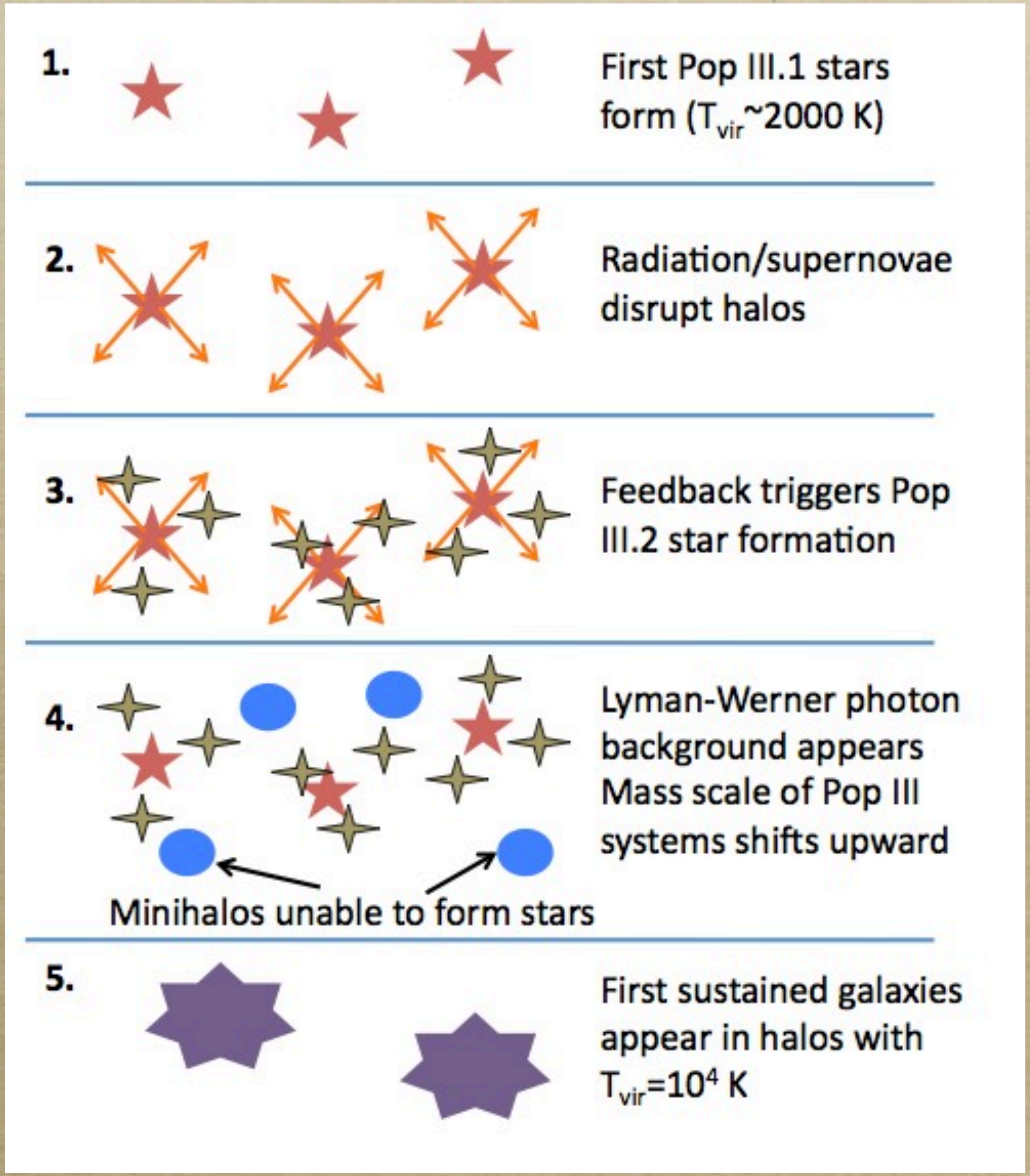
Challenge #3: Too much physics!

- *Unlike the local Universe, distant galaxies strongly affect the fuel supply at high redshifts!*
  - *Gas flows and winds*
  - *Heavy element enrichment*
  - *Ultraviolet photons*



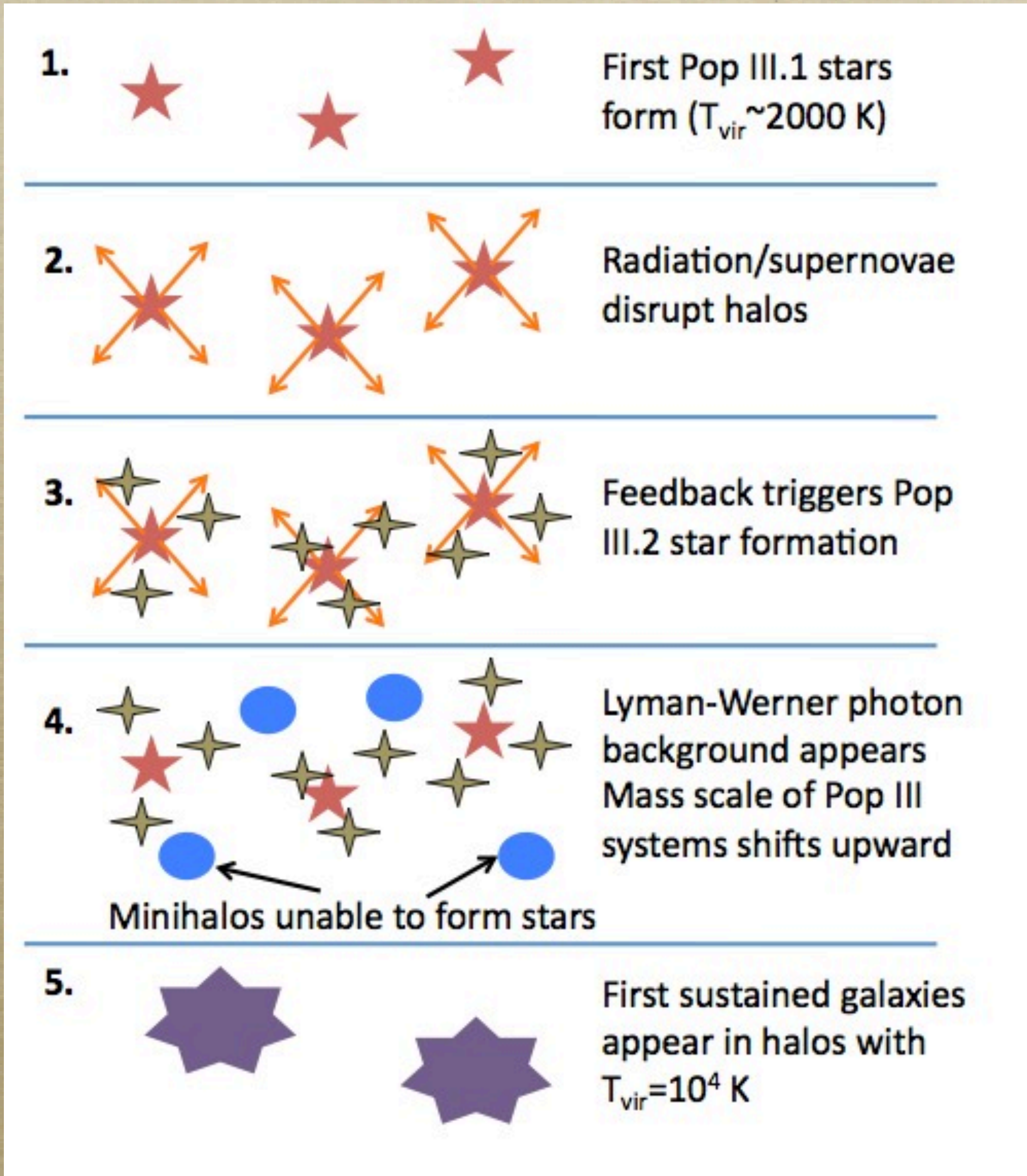
Challenge #3: Too much physics!

- *Unlike the local Universe, distant galaxies strongly affect the fuel supply at high redshifts!*
  - *Gas flows and winds*
  - *Heavy element enrichment*
  - *Ultraviolet photons*
  - *Ionizing photons*
  - *X-rays*

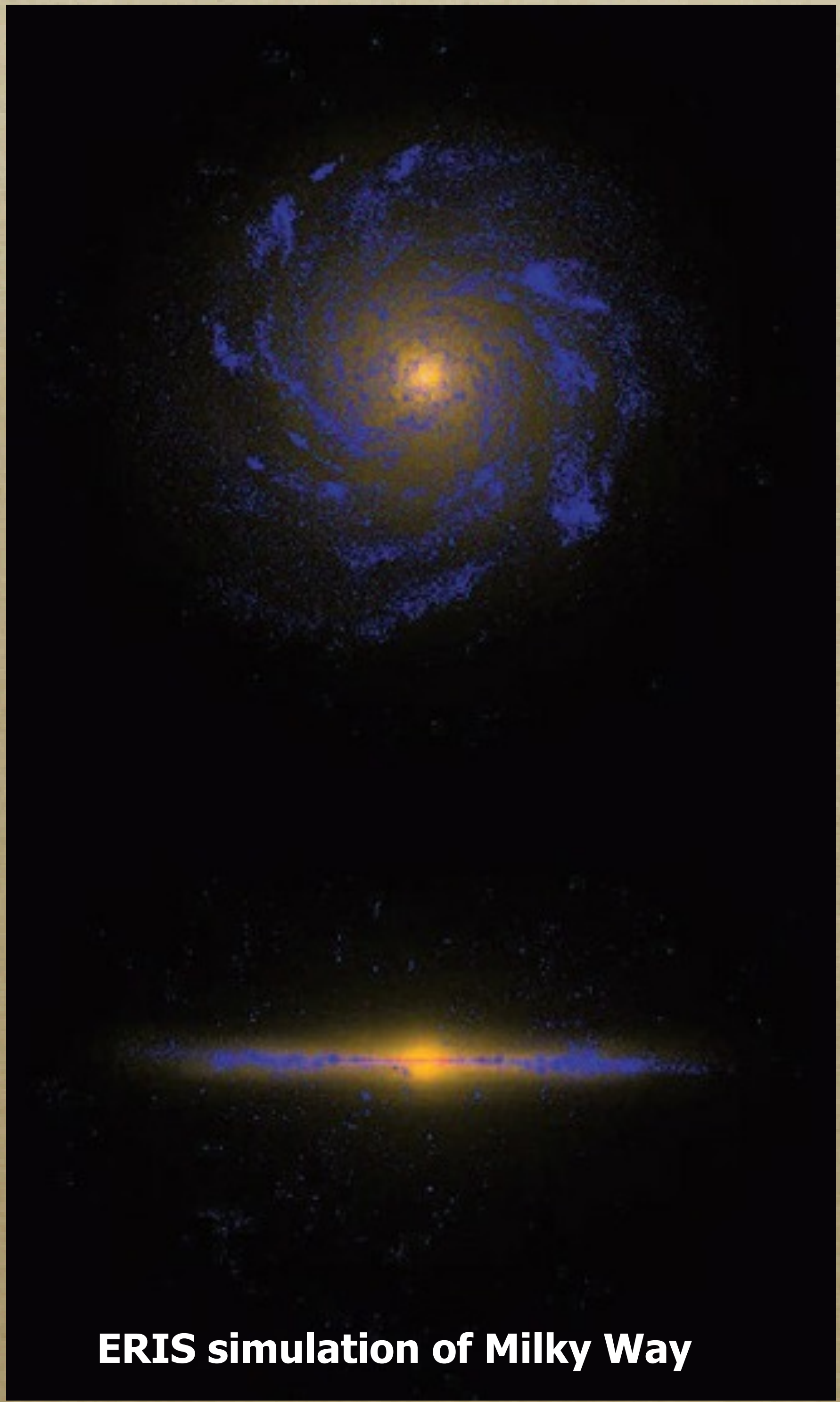


Challenge #3: Too much physics!

- *Unlike the local Universe, distant galaxies strongly affect the fuel supply at high redshifts!*
  - *Gas flows and winds*
  - *Heavy element enrichment*
  - *Ultraviolet photons*
  - *Ionizing photons*
  - *X-rays*
- *Detailed simulations require enough resolution to see an individual star AND simultaneously include large-scale feedback*



External Processes and Galaxy Formation



- *At late times, external inputs are:*
  - *Nearly uniform*
  - *Slowly evolving*
  - *Known!*
- *At early times, they are half the process!*

Numerical Simulations of the Early Universe

- *Most successful with carefully chosen problems*
  - *Formation of the first stars*
  - *Explosions of the first stars*
  - *Radiation from the first stars…*

Method #2: Parameterized Analytic Models

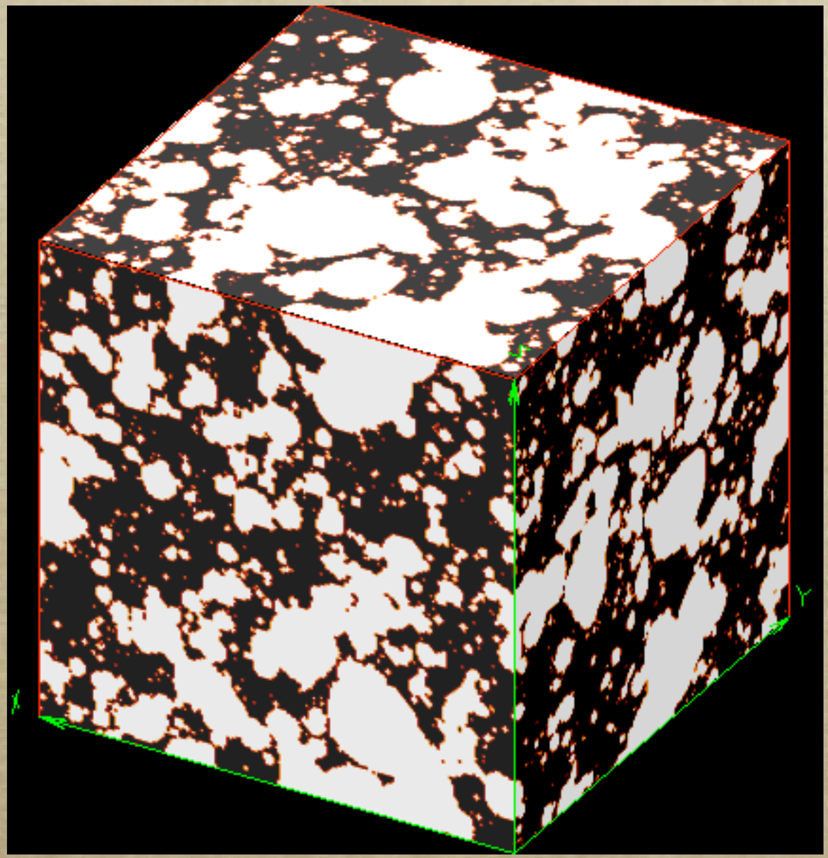
- *Galaxies are just machines that accrete gas and churn out stars*
- *Crudely parameterize the physics, e.g.*

Method #2: Parameterized Analytic Models

- *Galaxies are just machines that accrete gas and churn out stars*
- *Crudely parameterize the physics, e.g.*
  - *Star formation efficiency*
- *GOAL: understand robust aspects of paradigm, identify key physical inputs*

Example: Photon Counting and Reionization

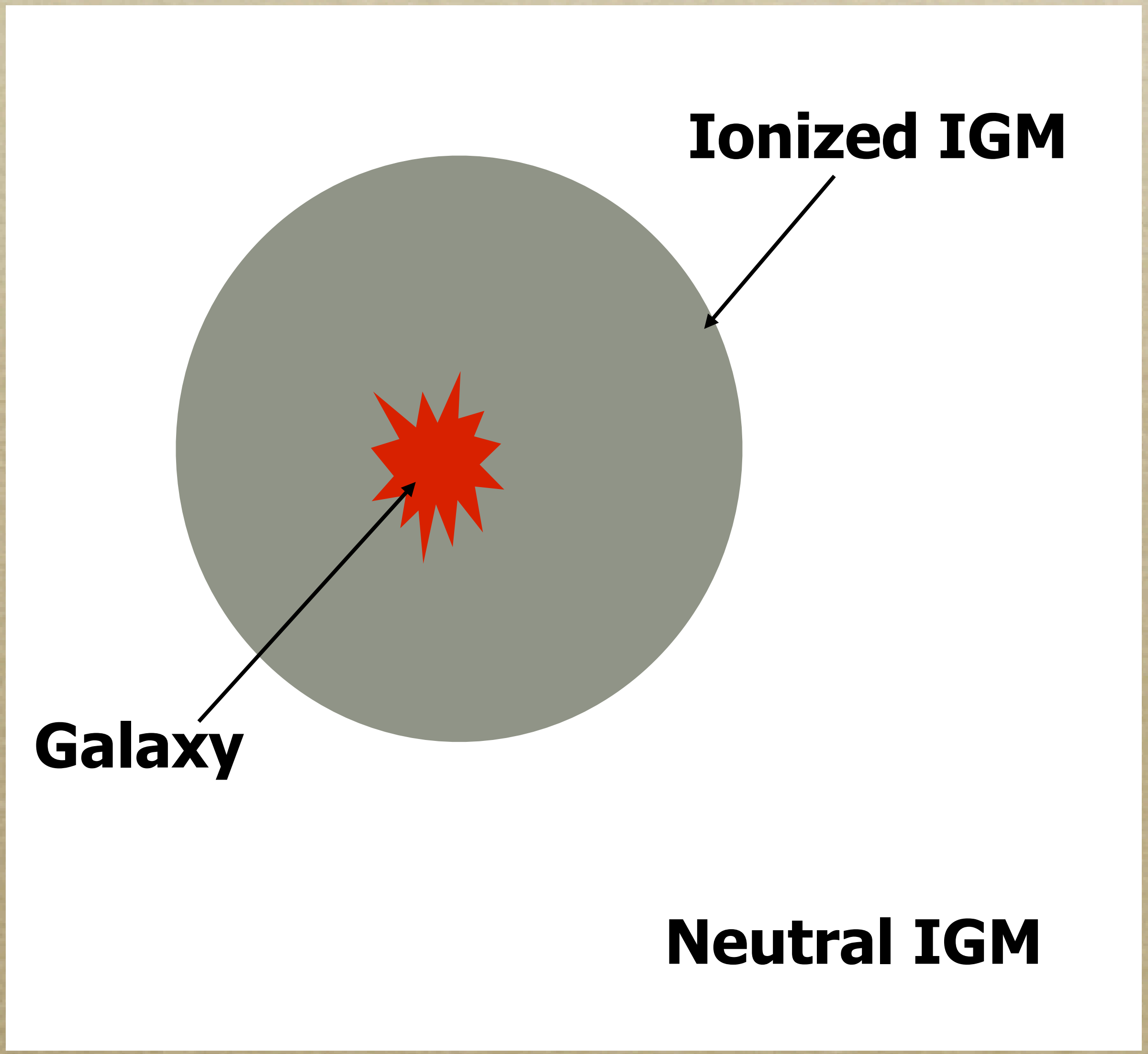
- *Goal: a simple model for the morphology of the ionized gas*
    - *Assume we know galaxy distribution*



Mesinger & Furlanetto (2007)

Example: Photon Counting and Reionization

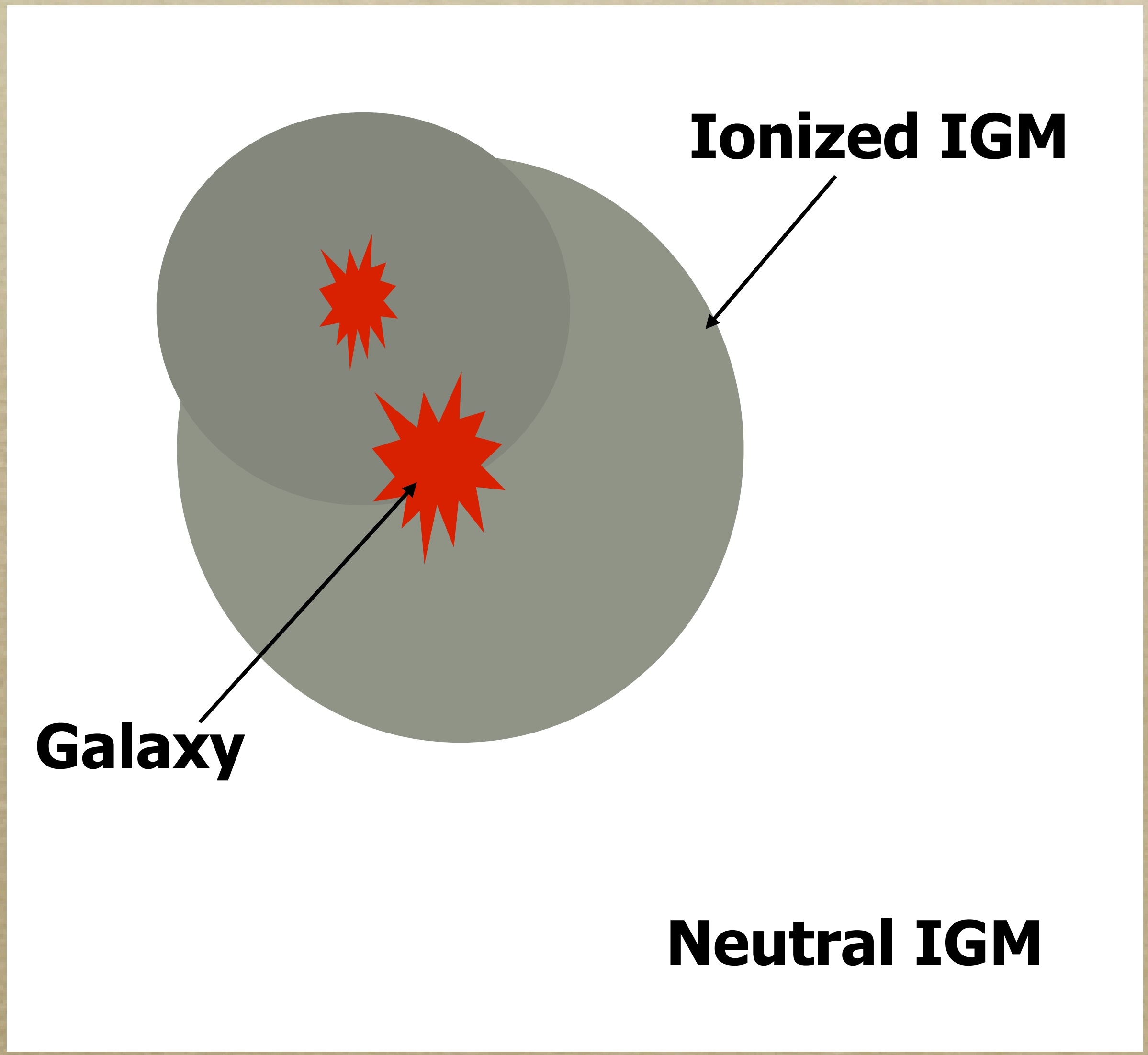
- *Compare (# ionizing photons) to (# atoms)*
- *First ionized bubble is easy...*



Furlanetto et al. (2004)

Example: Photon Counting and Reionization

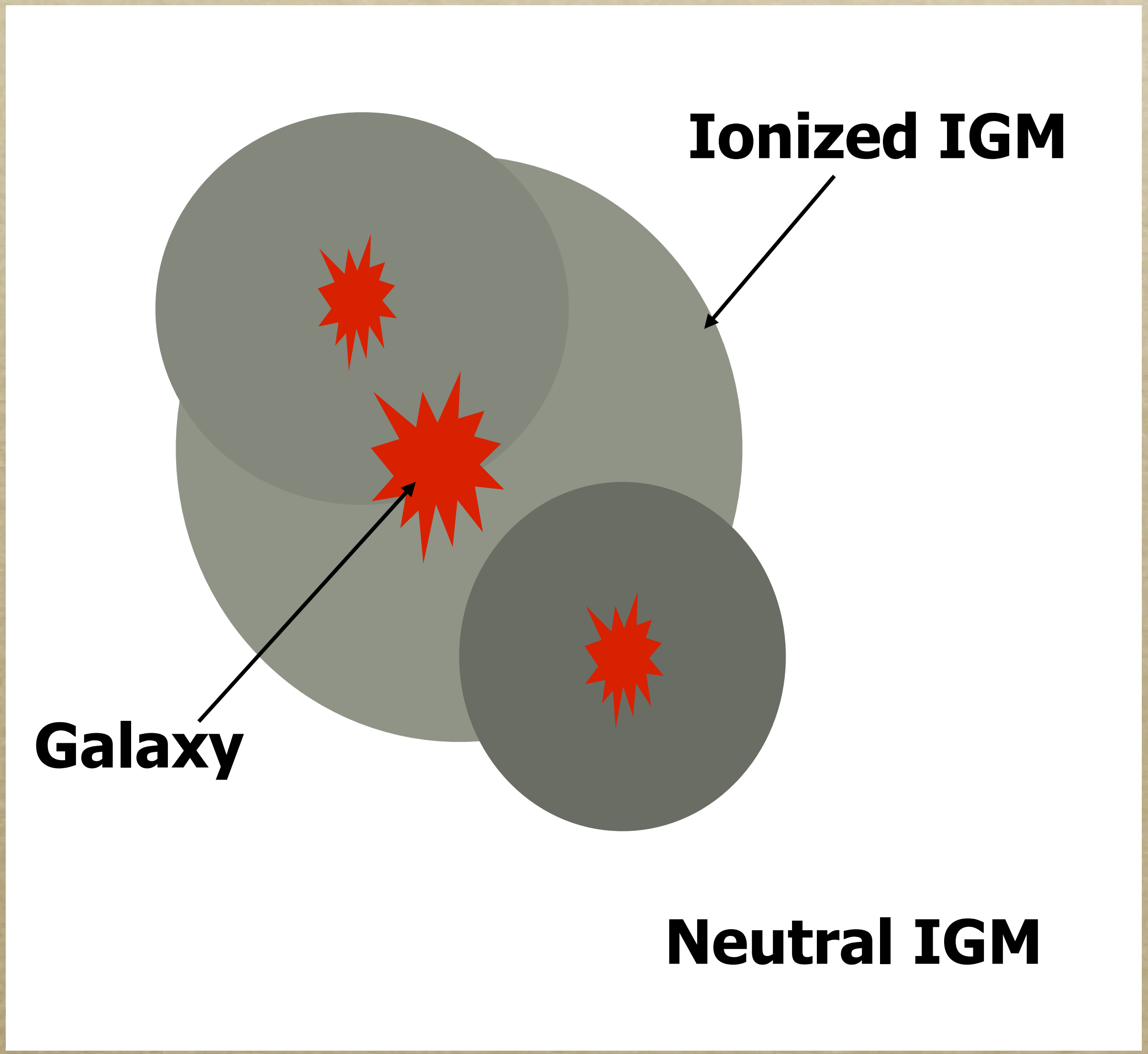
- *Compare (# ionizing photons) to (# atoms)*
- *First ionized bubble is easy...*
- *But what if that bubble overlaps another galaxy?*
    - *Early galaxies are highly clustered and bubbles are big!*



Furlanetto et al. (2004)

Example: Photon Counting and Reionization

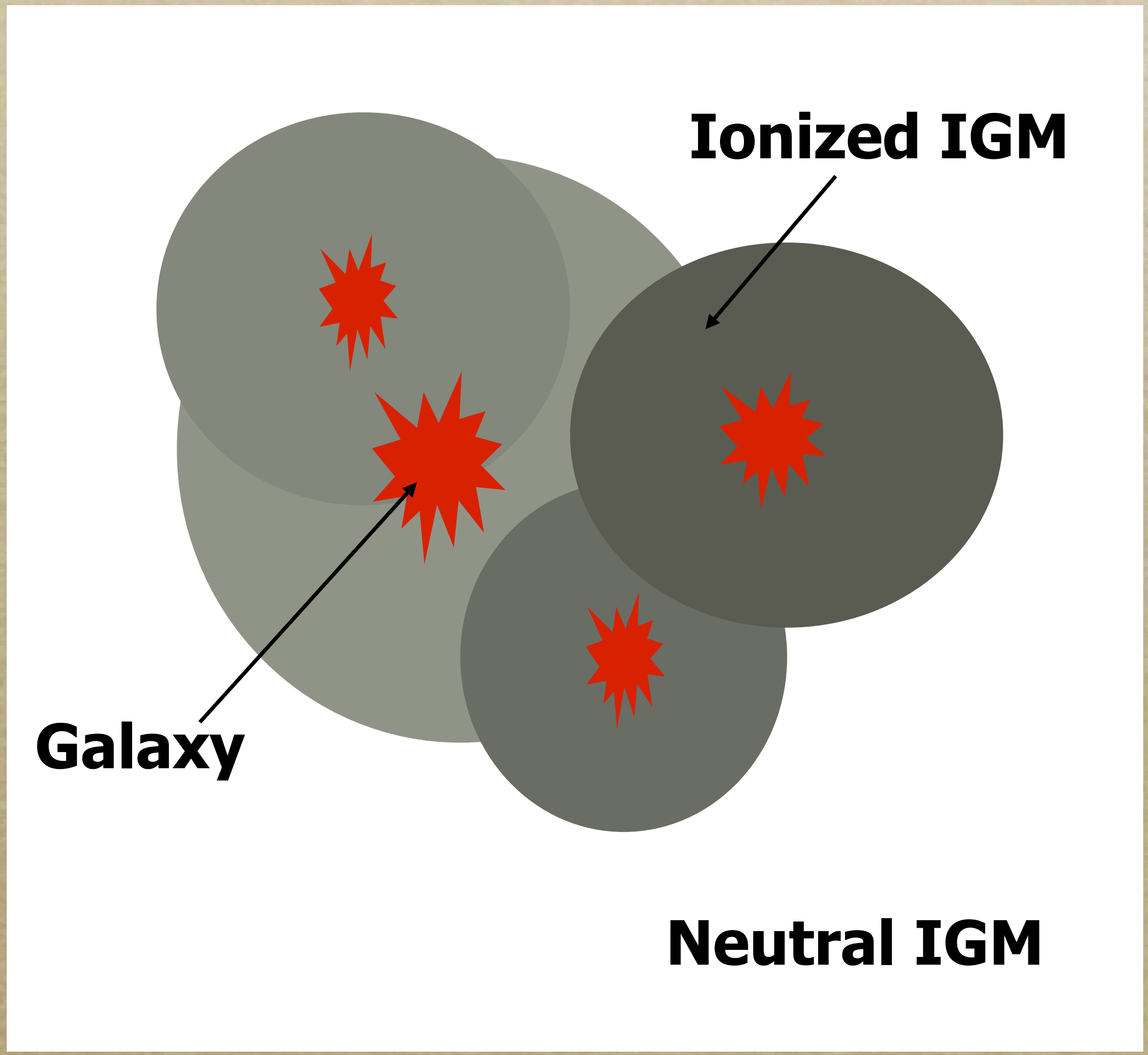
- *Compare (# ionizing photons) to (# atoms)*
- *First ionized bubble is easy...*
- *But what if that bubble overlaps another galaxy?*
  - *Early galaxies are highly clustered and bubbles are big!*



Furlanetto et al. (2004)

Example: Photon Counting and Reionization

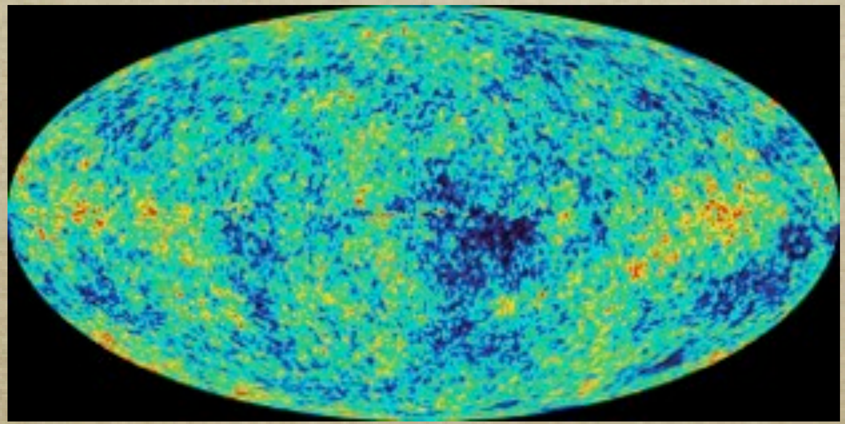
- *Compare (# ionizing photons) to (# atoms)*
- *First ionized bubble is easy...*
- *But what if that bubble overlaps another galaxy?*
    - *Early galaxies are highly clustered and bubbles are big!*



Furlanetto et al. (2004)

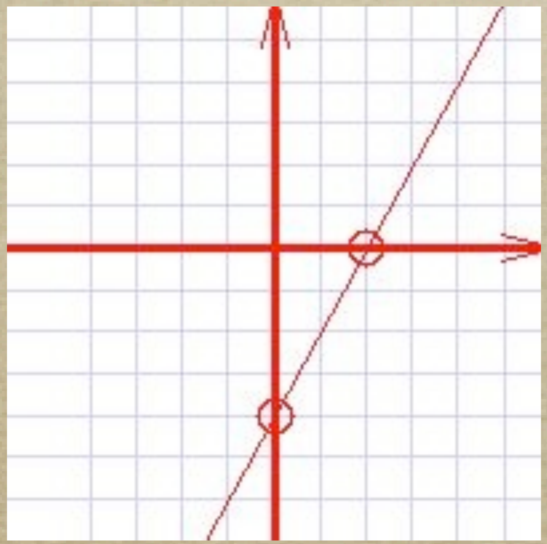
“Semi-Numeric” Approaches

- *Step 1: Begin with initial conditions of simulation*



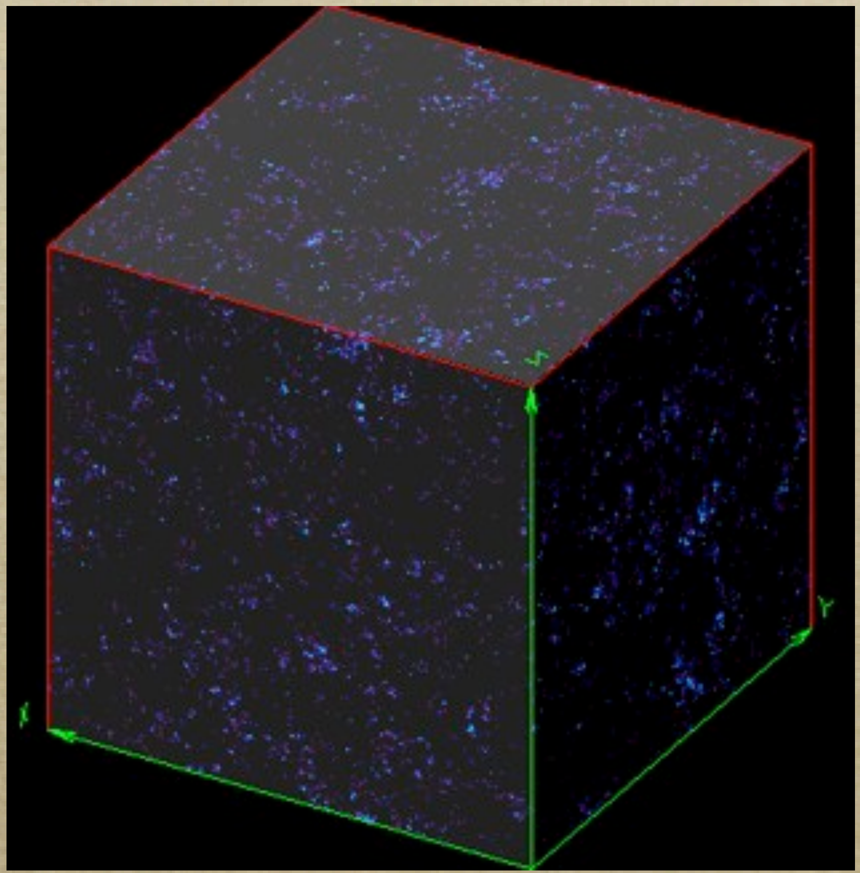
“Semi-Numeric” Approaches

- *Step 1: Begin with initial conditions of simulation*
- *Step 2: Evolve the box using simple physics (“linear theory”)*



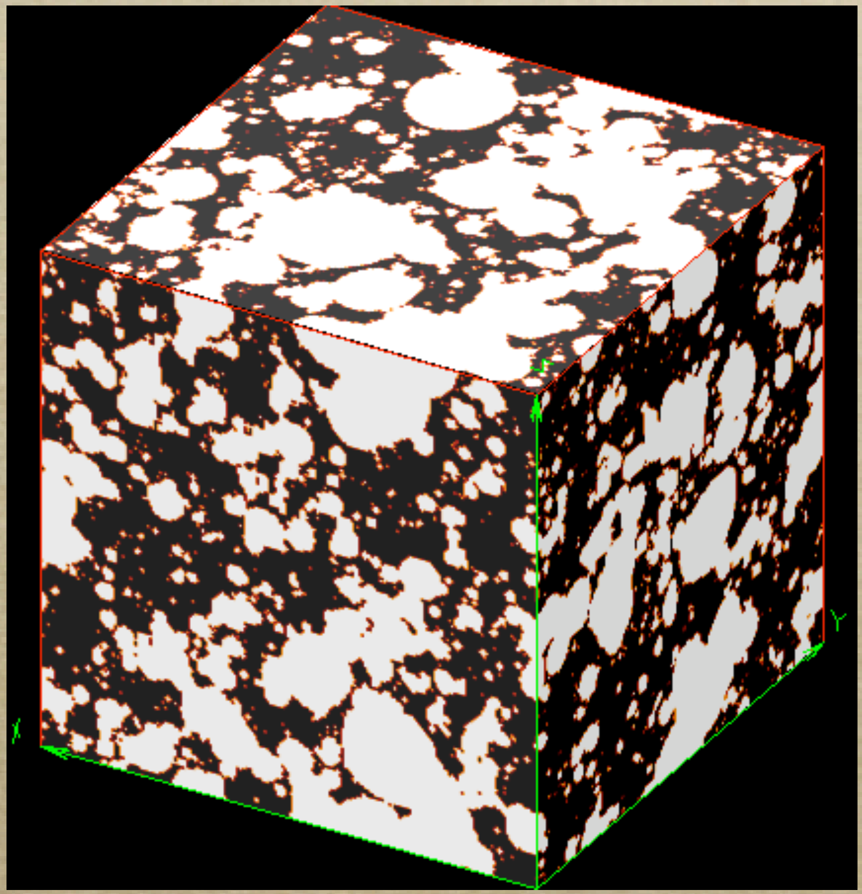
“Semi-Numeric” Approaches

- *Step 1: Begin with initial conditions of simulation*
- *Step 2: Evolve the box using simple physics (“linear theory”)*
- *Step 3: Use analytic arguments to identify sites of galaxies*



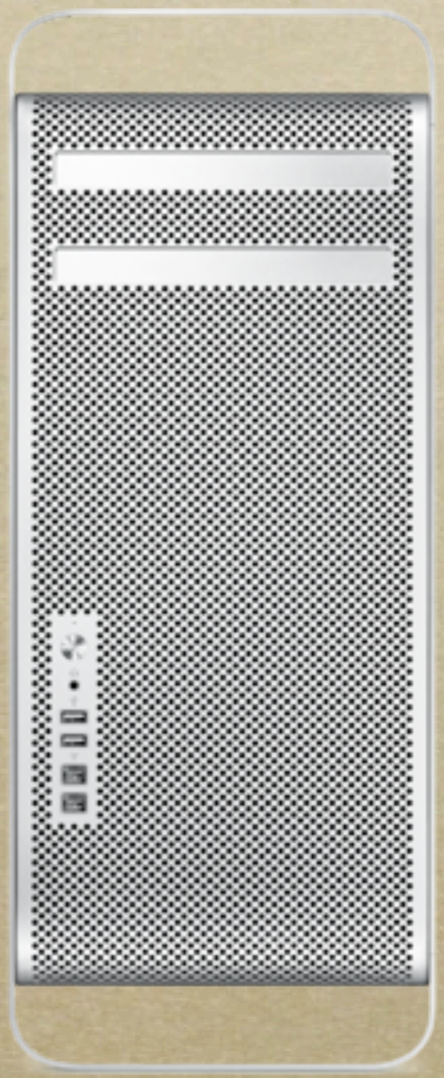
"Semi-Numeric" Approaches

- *Step 1: Begin with initial conditions of simulation*
- *Step 2: Evolve the box using simple physics ("linear theory")*
- *Step 3: Use analytic arguments to identify sites of galaxies*
- *Step 4: Use photon-counting to paint on ionized bubbles*



“Semi-Numeric” Approaches

- *Step 1: Begin with initial conditions of simulation*
- *Step 2: Evolve the box using simple physics (“linear theory”)*
- *Step 3: Use analytic arguments to identify sites of galaxies*
- *Step 4: Use photon-counting to paint on ionized bubbles*
- *Computing requirements: fancy desktop rather than custom cluster!*



Example: Semi-Numeric Models of Reionization

Alvarez, Kahler, & Abel

Can we all just get along?

- *Neither approach is satisfactory*
  - *Computational: only part of the story*
  - *Analytic: missing physics*

Can we all just get along?

- *Neither approach is satisfactory*
  - *Computational: only part of the story*
  - *Analytic: missing physics*
- *Problem: how can we do better?*

Data!

- *Hubble Ultra-Deep Field contains hundreds of early galaxies!*
- *Real data let us narrow down our models*
- *Just beginning to get there!*

Where next?

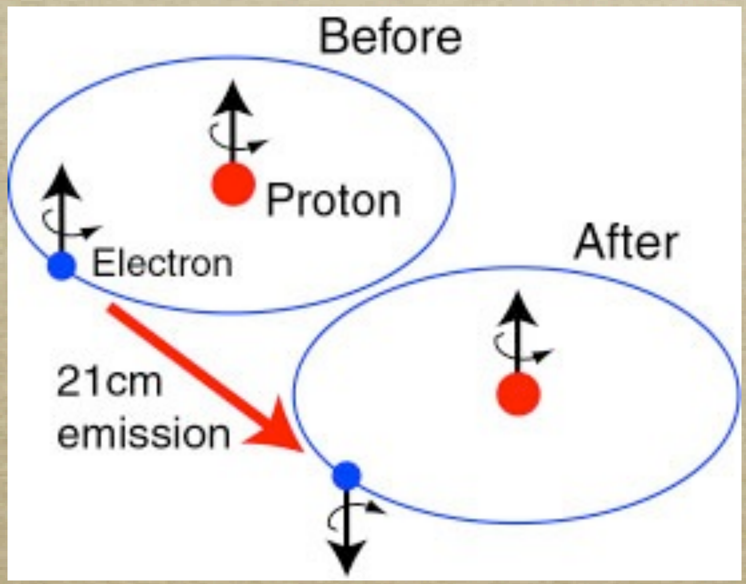
- *How do we make it observable?*

Methods to Study The Cosmic Dawn

- *Galaxies*
  - *Deeper and/or wider and/or different surveys!*
  - *Detailed spectroscopy*
- *Reionization*
  - *The spin-flip background*
  - *The Lyman-α line*
  - *CMB*
  - *Diffuse line backgrounds*
- *The first generations*
  - *The spin-flip background*
  - *Diffuse line backgrounds*

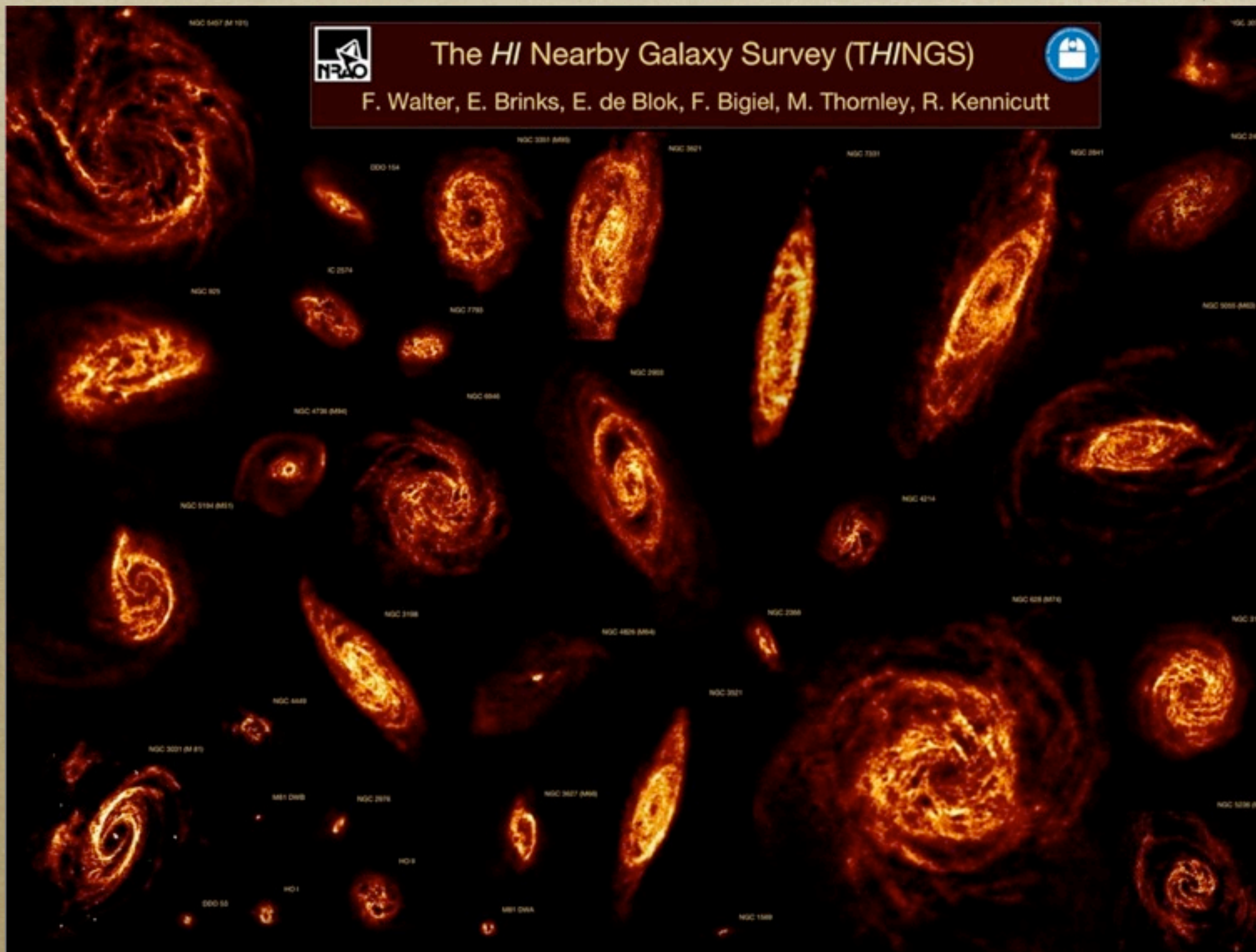
The Spin-Flip Background

- *Protons and electrons both have spin and hence magnetic moments*
- *The 21 cm hyperfine spin-flip transition (ν~1.4 GHz)*

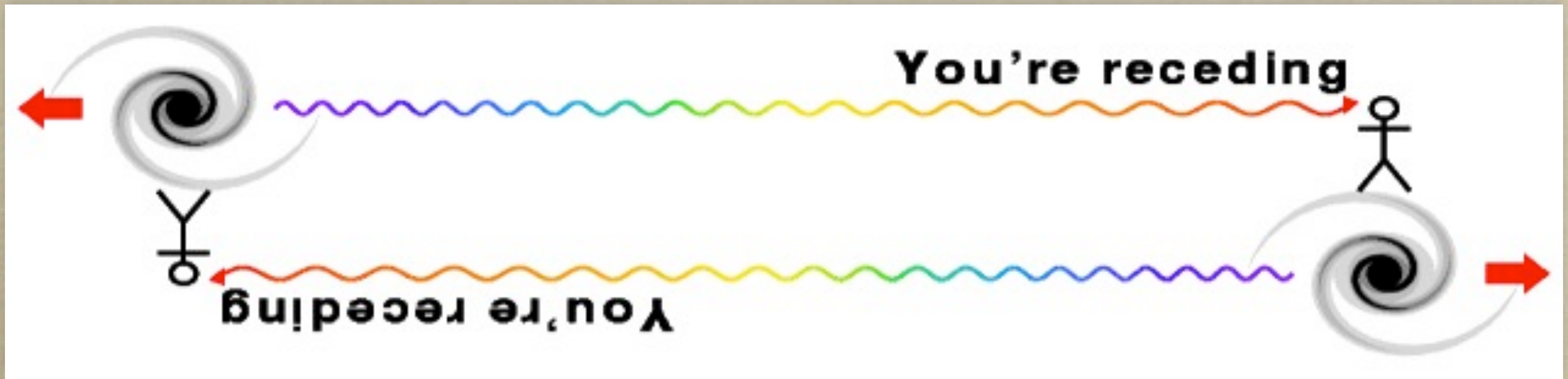


Jodrell Bank

The 21 cm Line In Astronomy



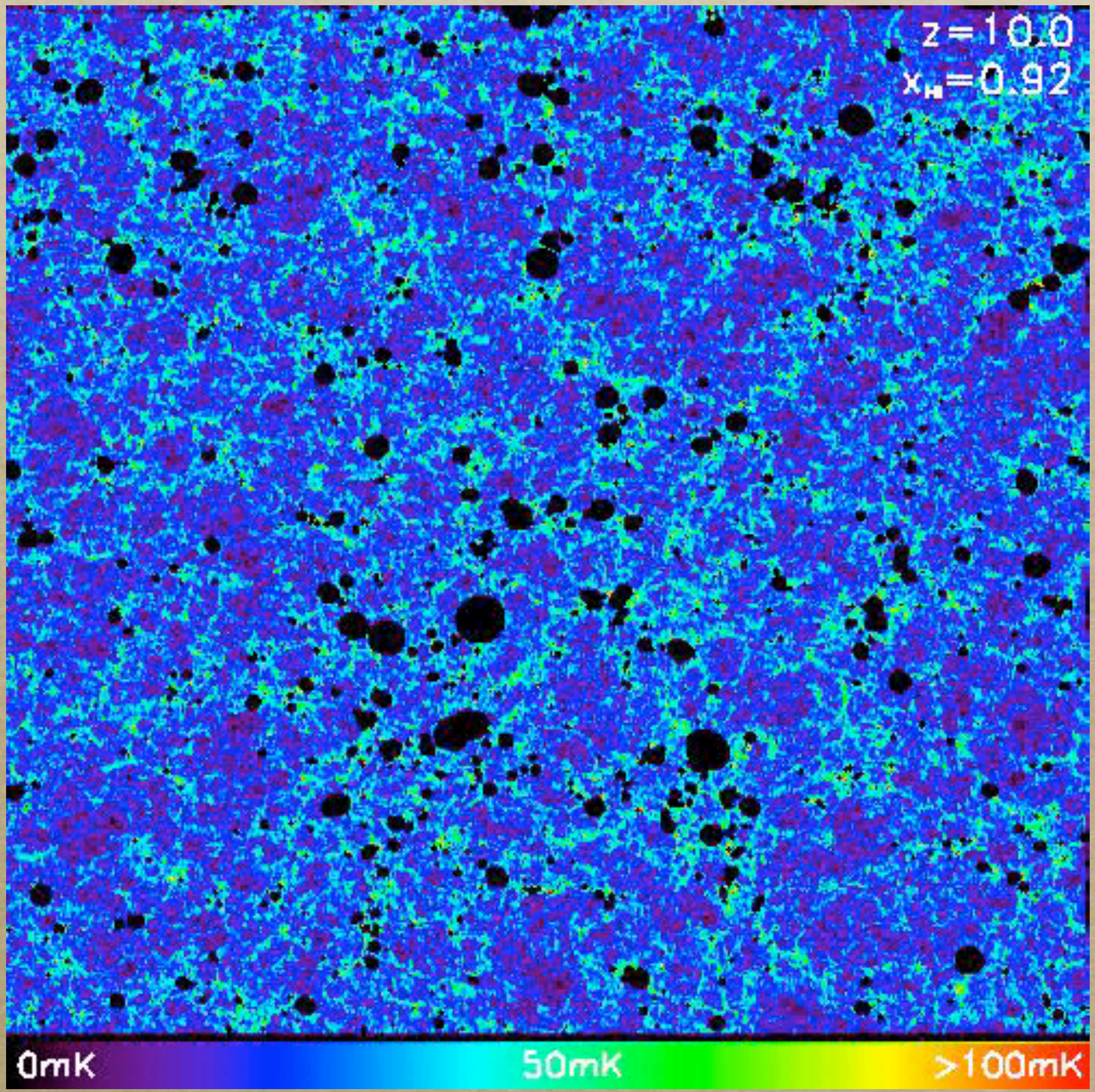
The Cosmological Redshift



E. Wright

- *Photons get stretched as they travel*
- *Become more "red" and less energetic*

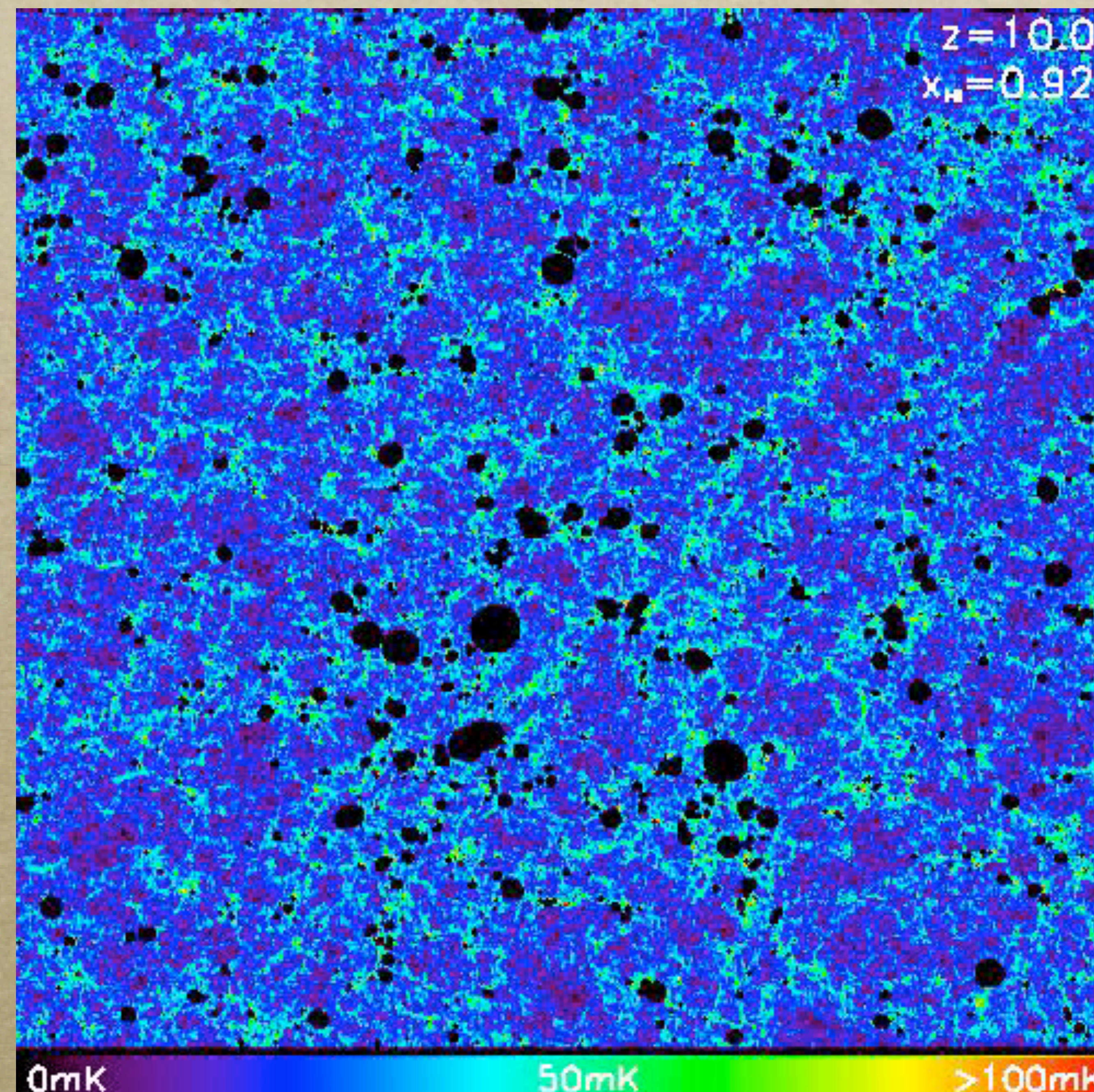
Advantages of the Spin-Flip Background



Mesinger & Furlanetto

Advantages of the Spin-Flip Background

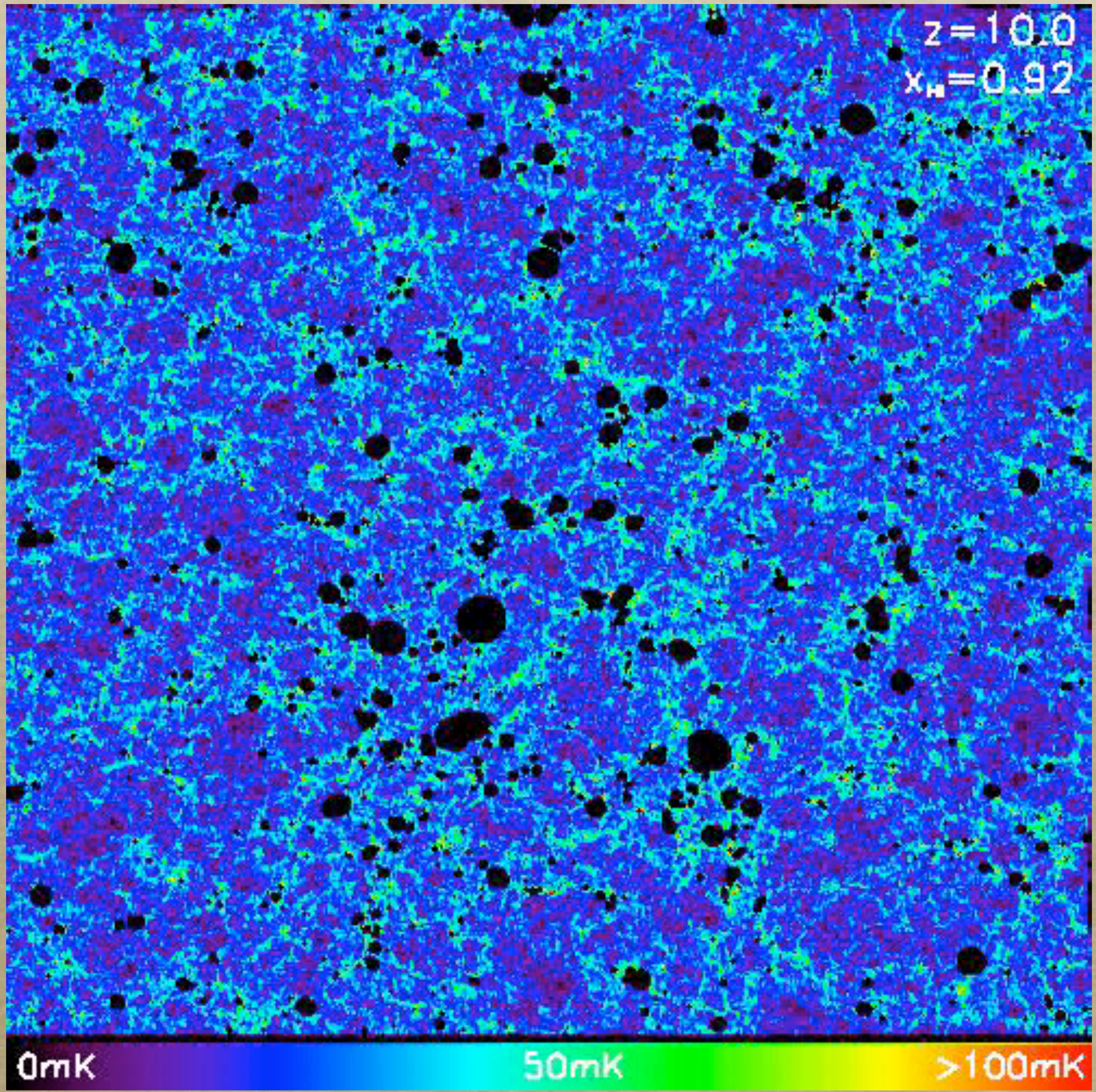
- *Spectral line measures entire history*



Mesinger & Furlanetto

Advantages of the Spin-Flip Background

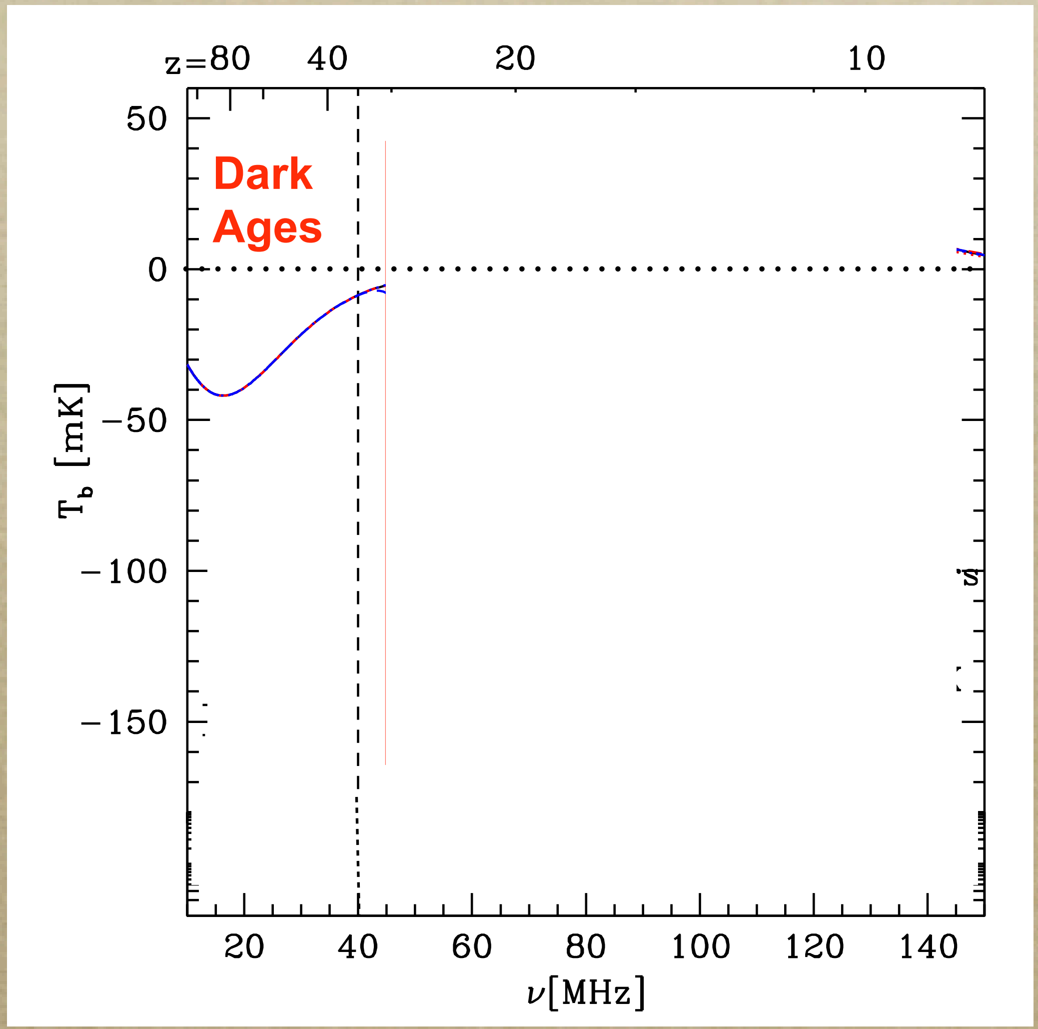
- *Spectral line measures entire history*
- *Directly measures intergalactic gas (radiation backgrounds)*



Mesinger & Furlanetto

The Spin-Flip Background Through Time

- *Four Phases to the spin-flip background* *(Furlanetto 2006, Pritchard & Loeb 2010, McQuinn & O'Leary 2012)*
  - *Dark Ages*



J. Pritchard

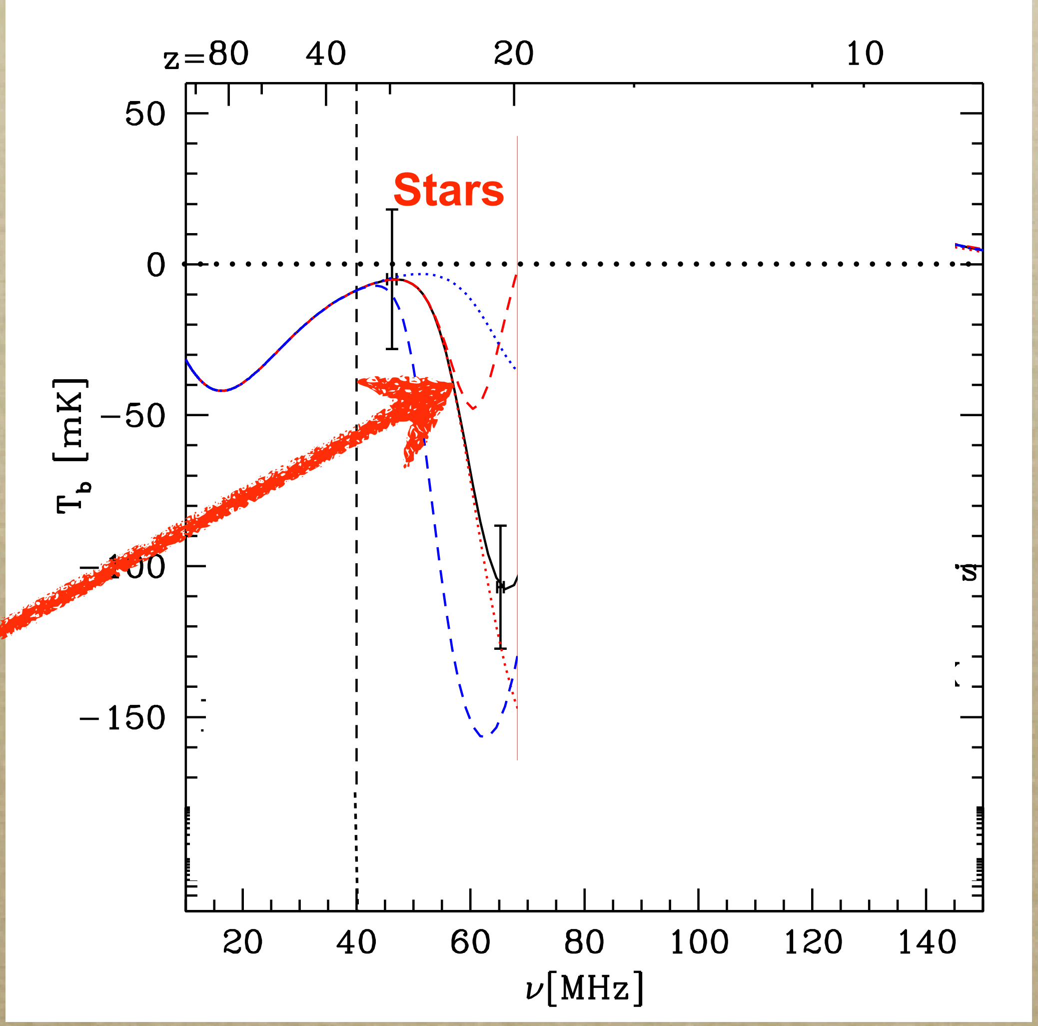
What light through yonder window breaks?

- *First stars and galaxies produce ultraviolet photons*
- *Light up the spin-flip background by scattering off of intergalactic gas*

J-J Milan (Wikipedia)

The Spin-Flip Background Through Time

- *Four Phases to the spin-flip background*
  (Furlanetto 2006, Pritchard & Loeb 2010, McQuinn & O'Leary 2012)
  - *Dark Ages*
  - *First Stars*



J. Pritchard

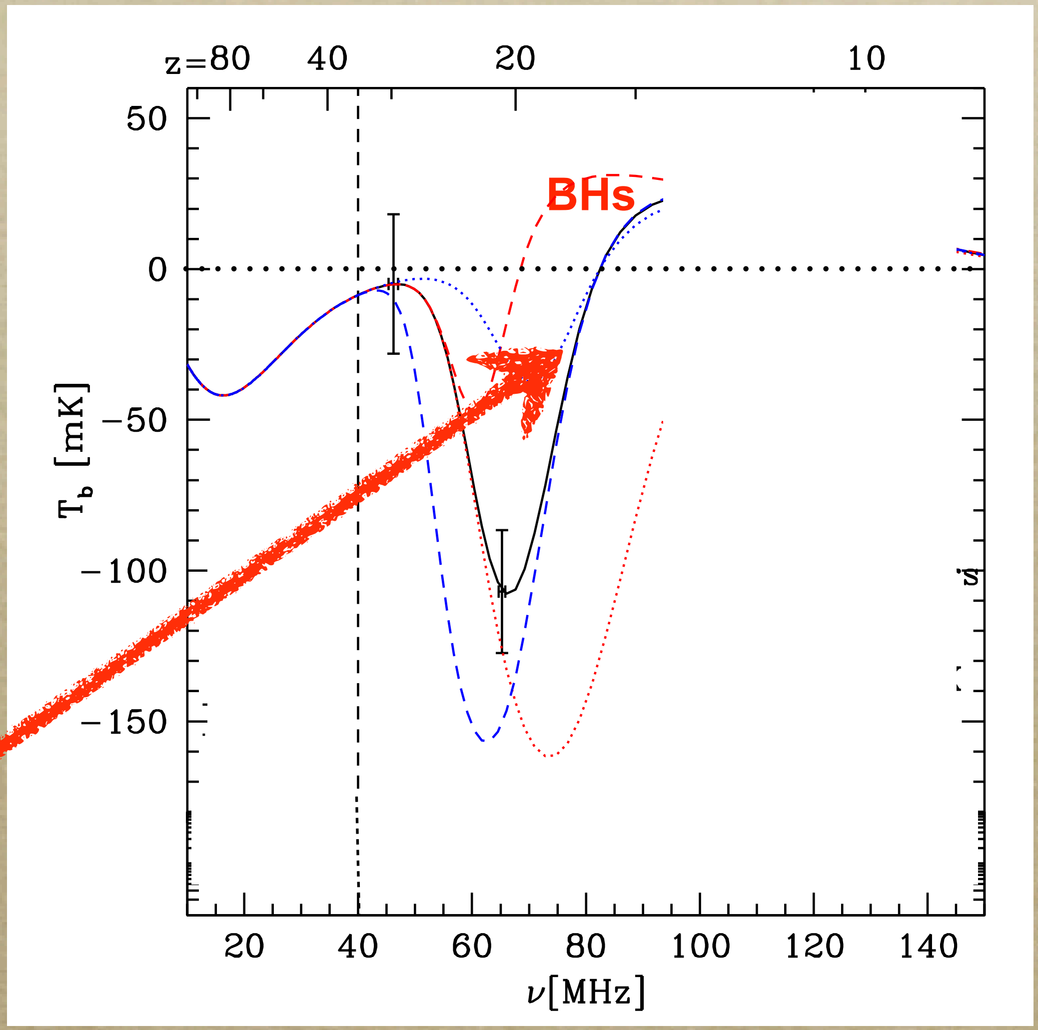
O! She doth teach the torches to burn bright

D. Dixon

- *Gas falling onto black holes produces intense radiation*
  - *Stellar remnants*
  - *Quasars*
- *X-rays heat the intergalactic gas, changing spin-flip background*

The Spin-Flip Background Through Time

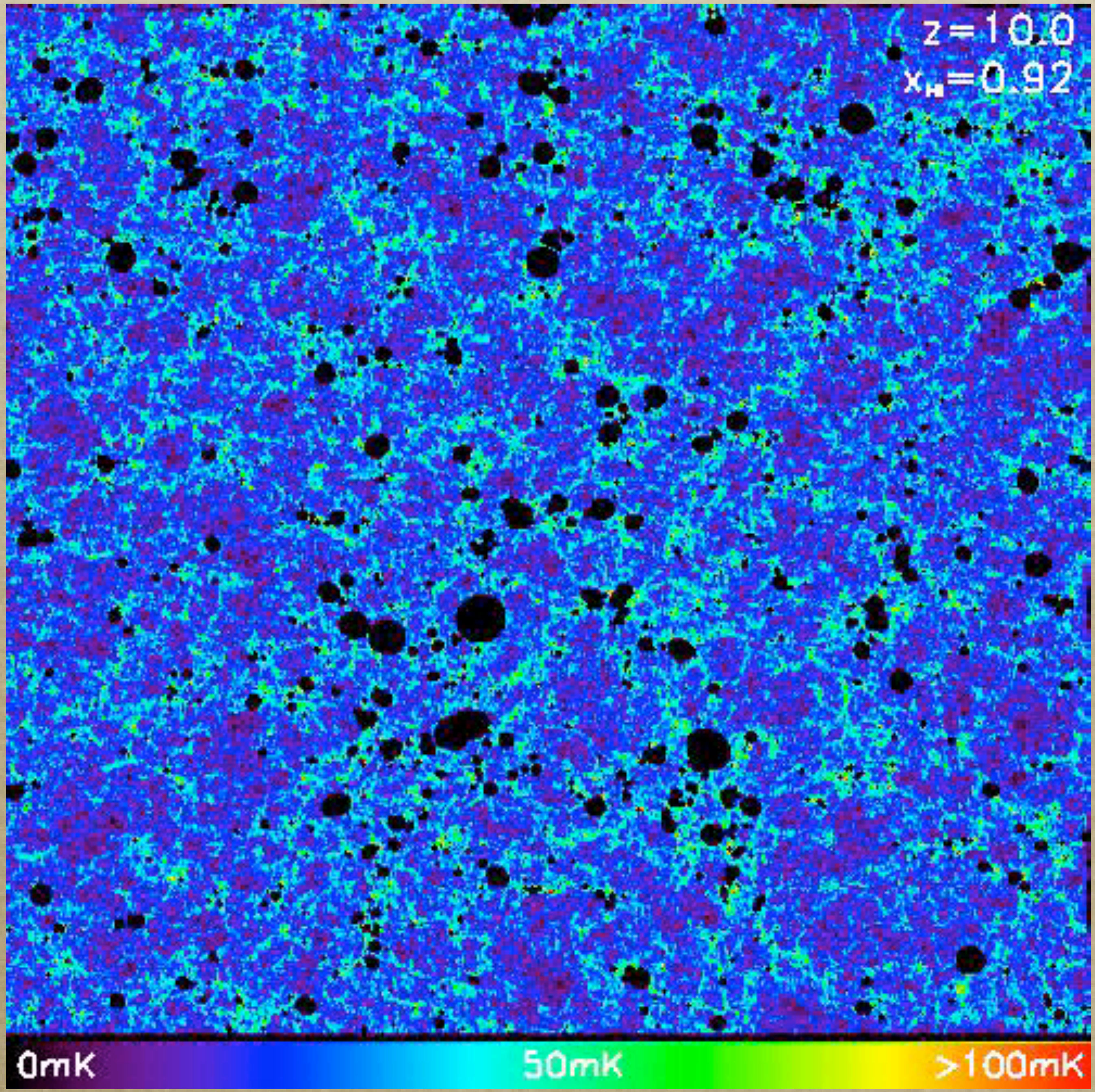
- *Four Phases to the spin-flip background*
  (Furlanetto 2006, Pritchard & Loeb 2010, McQuinn & O'Leary 2012)
  - *Dark Ages*
  - *First Stars*
  - *First Black Holes*



J. Pritchard

Reionization

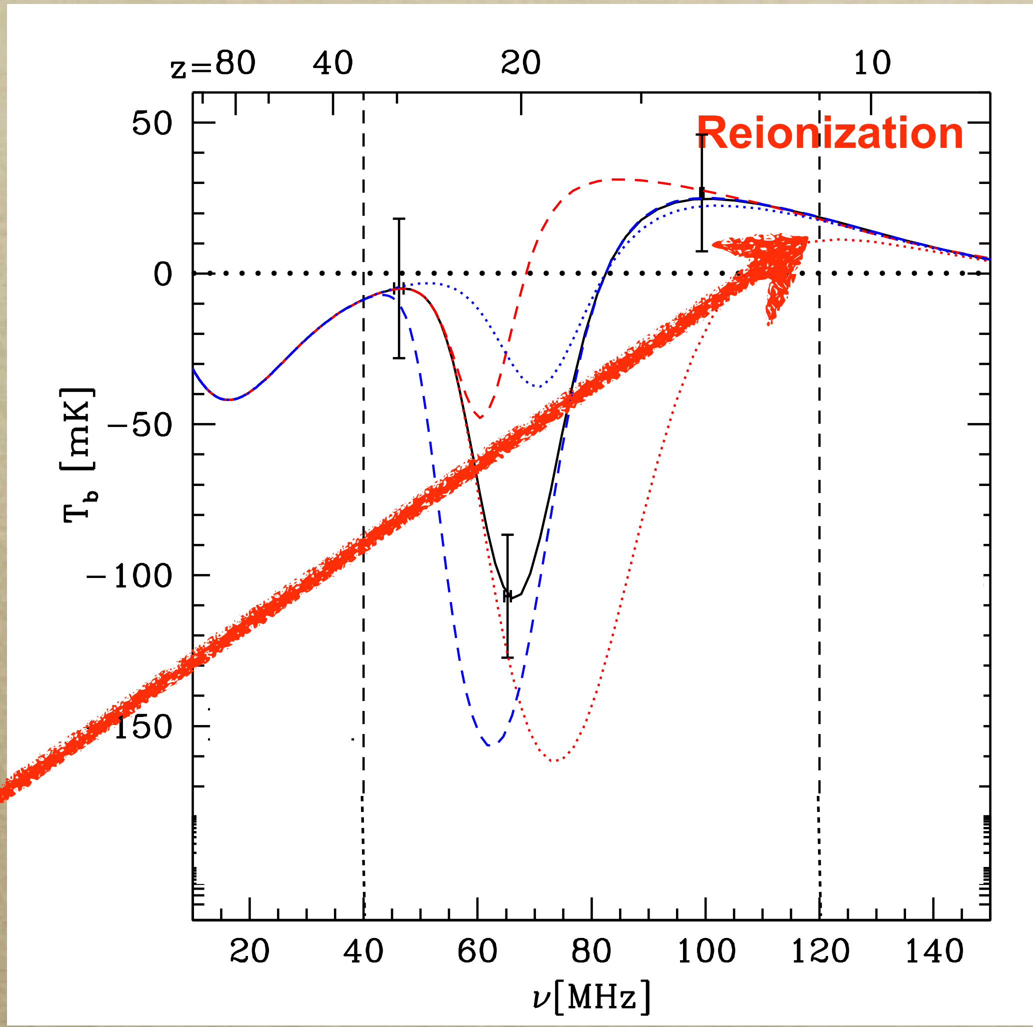
- *Early stars and galaxies produce ionizing photons*
- *Ionized bubbles grow and merge*



Mesinger & Furlanetto (2007)

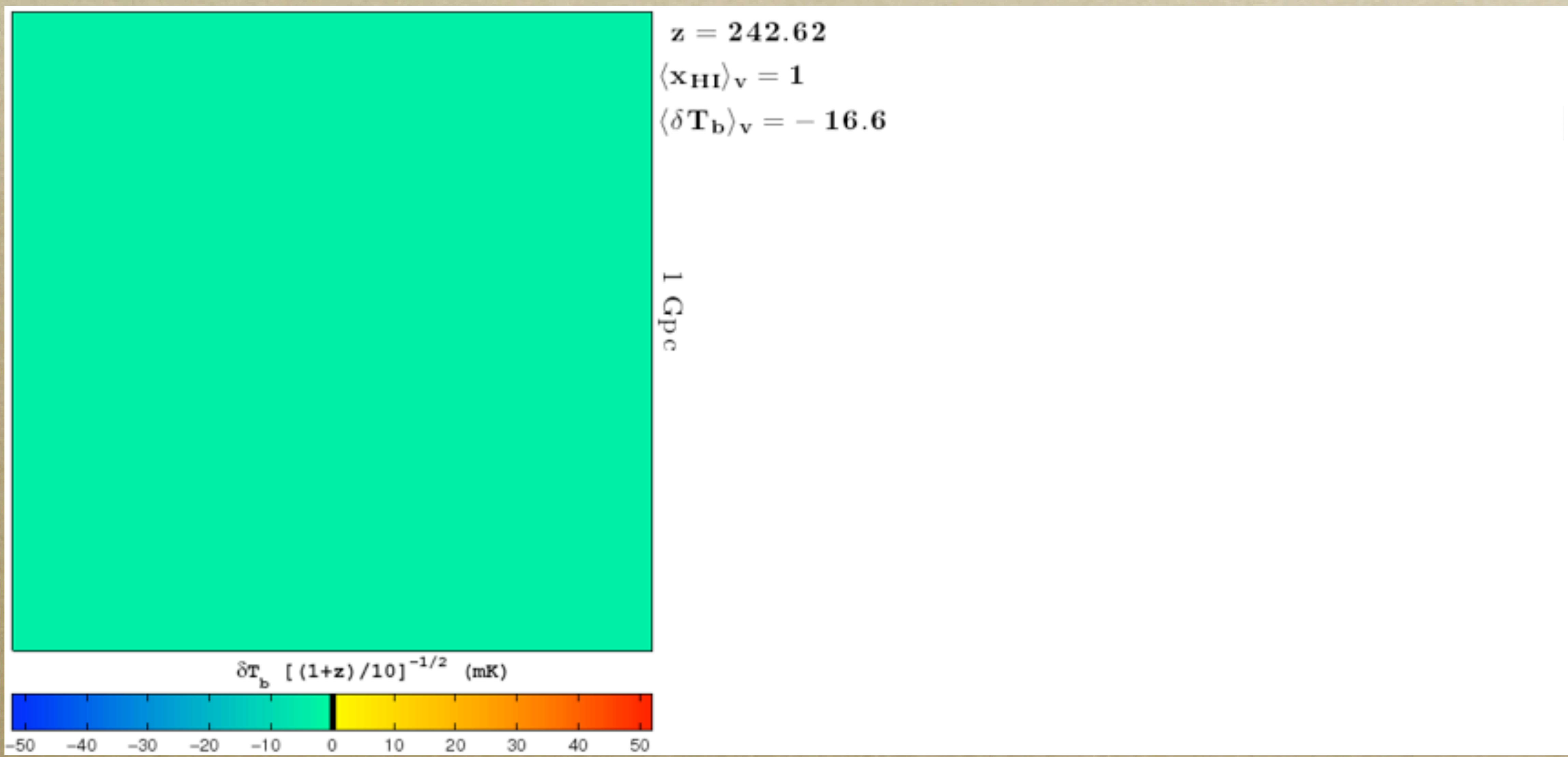
The Spin-Flip Background Through Time

- *Four Phases to the spin-flip background*
  (Furlanetto 2006, Pritchard & Loeb 2010, McQuinn & O'Leary 2012)
  - *Dark Ages*
  - *First Stars*
  - *First Black Holes*
  - *Reionization*



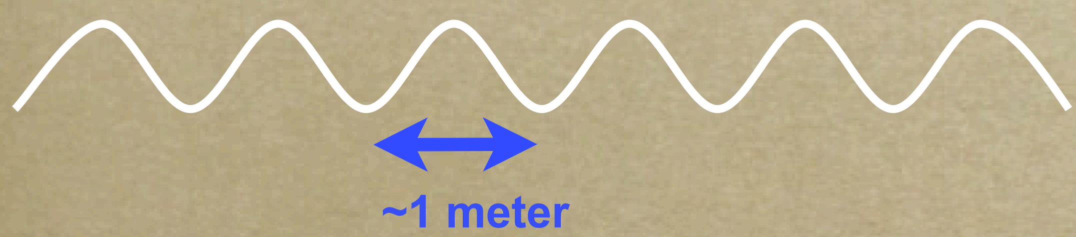
J. Pritchard

The Complete Picture

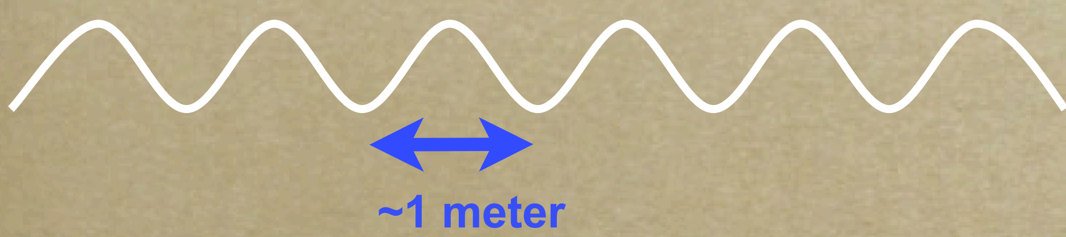


Mesinger, Furlanetto, & Cen (2010)

Low-Frequency Radio Telescopes

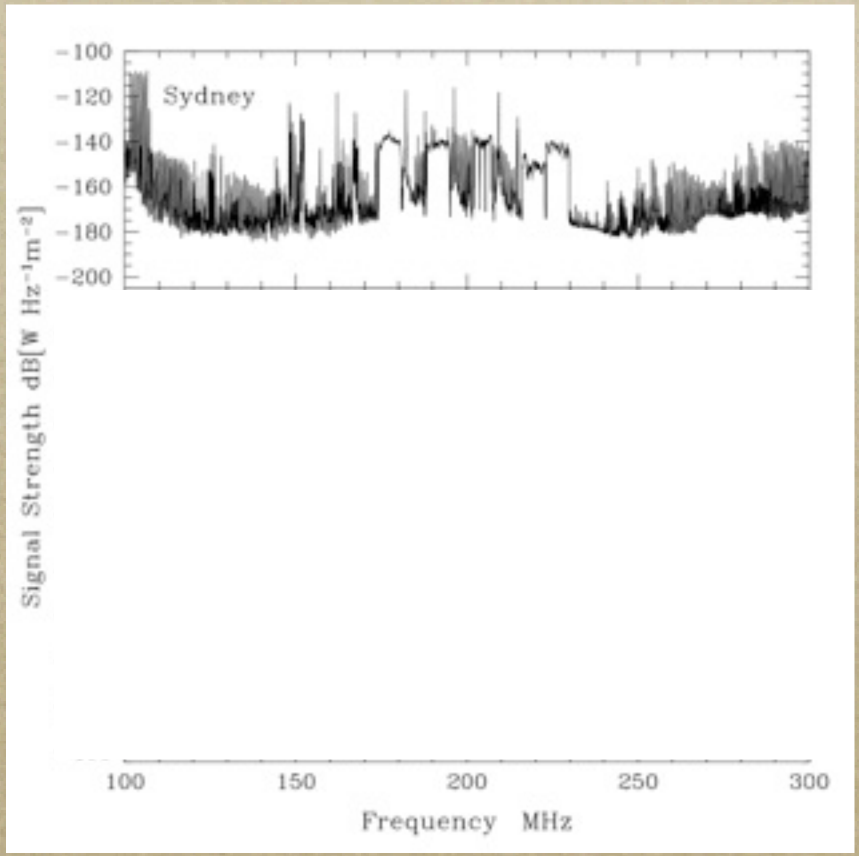


Low-Frequency Radio Telescopes



Problem #1: Terrestrial Interference

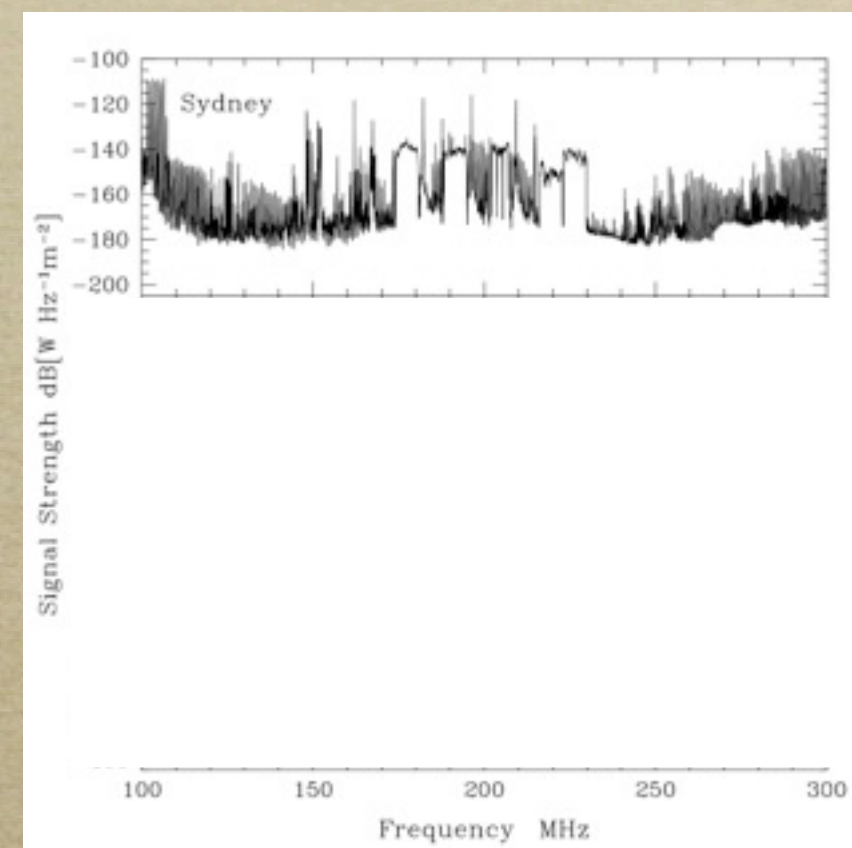
- *Spin flip photons begin at 21 cm; end at ~1-2 m*
  - *This is <200 MHz*
- *The usual answer: Distance*



Furlanetto et al. (2006)

Problem #1: Terrestrial Interference

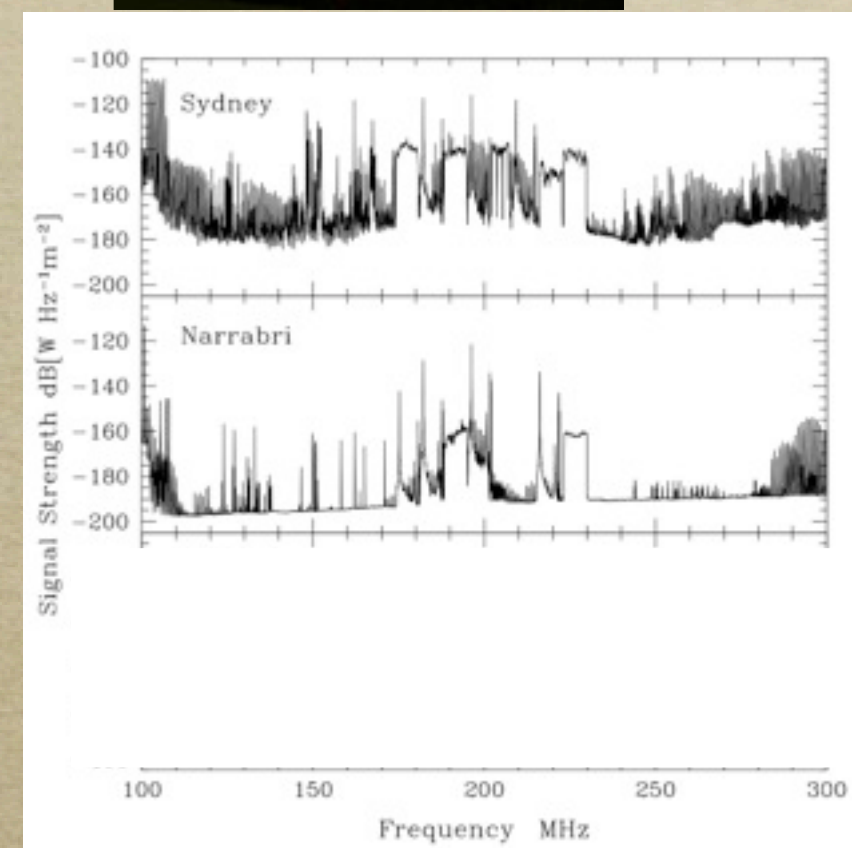
- *Spin flip photons begin at 21 cm; end at ~1-2 m*
  - *This is <200 MHz*
- *The usual answer: Distance*



Furlanetto et al. (2006)

Problem #1: Terrestrial I nce

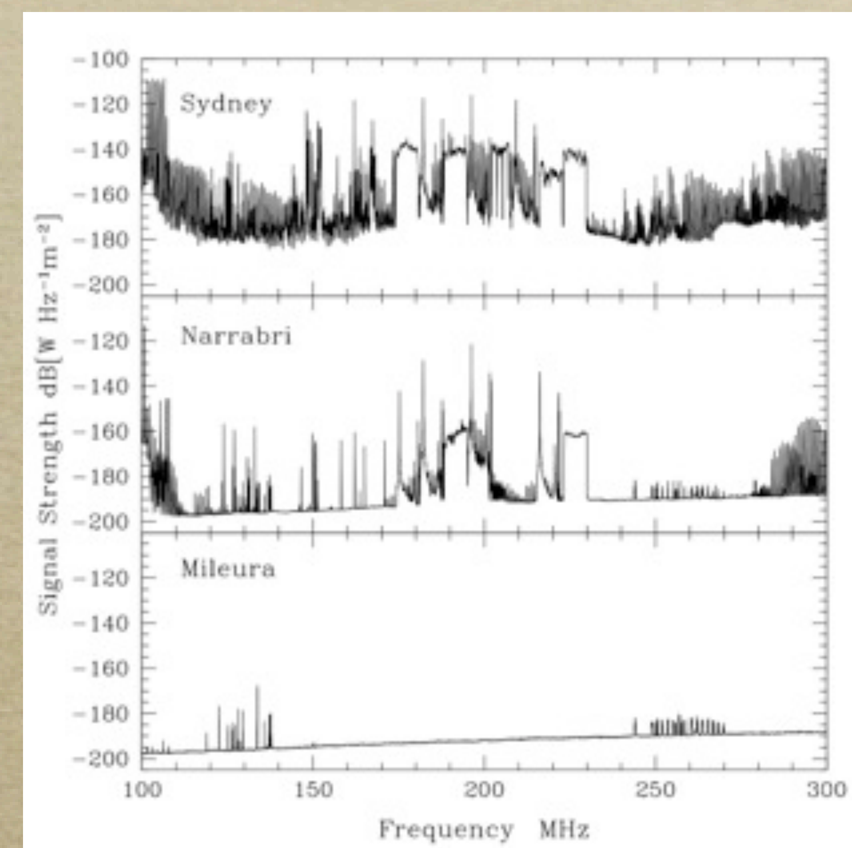
- *Spin flip photons* *begin at 21 cm; end at ~1-2 m*
  - *This is <200 MHz*
- *The usual answer: Distance*



Furlanetto et al. (2006)

Problem #1: Terrestrial Interference

- *Spin flip photons begin at 21 cm; end at ~1-2 m*
    - *This is <200 MHz*
- *The usual answer: Distance*



(2006)

Problem #2: The Ionosphere

- *For radio waves, the ionosphere acts just like an optical seeing layer*
  - *But slower (seconds) and over wider scales (degrees)*
- *Computing essential to correct distortions*

Problem #3: Astronomical Foregrounds

Problem #3: Astronomical Foregrounds

The spin-flip background is 10,000 times fainter than our Galaxy!!!

Implications for Spin-Flip Measurements

- *Need huge telescope and high angular resolution to measure structures*

Implications for Spin-Flip Measurements

- *Need huge telescope and high angular resolution to measure structures*
- *Requires an interferometer*

Implications for Spin-Flip Measurements

- *Need huge telescope and high angular resolution to measure structures*
- *Requires an interferometer*
  - *Many telescopes combined into one: requires substantial computing*

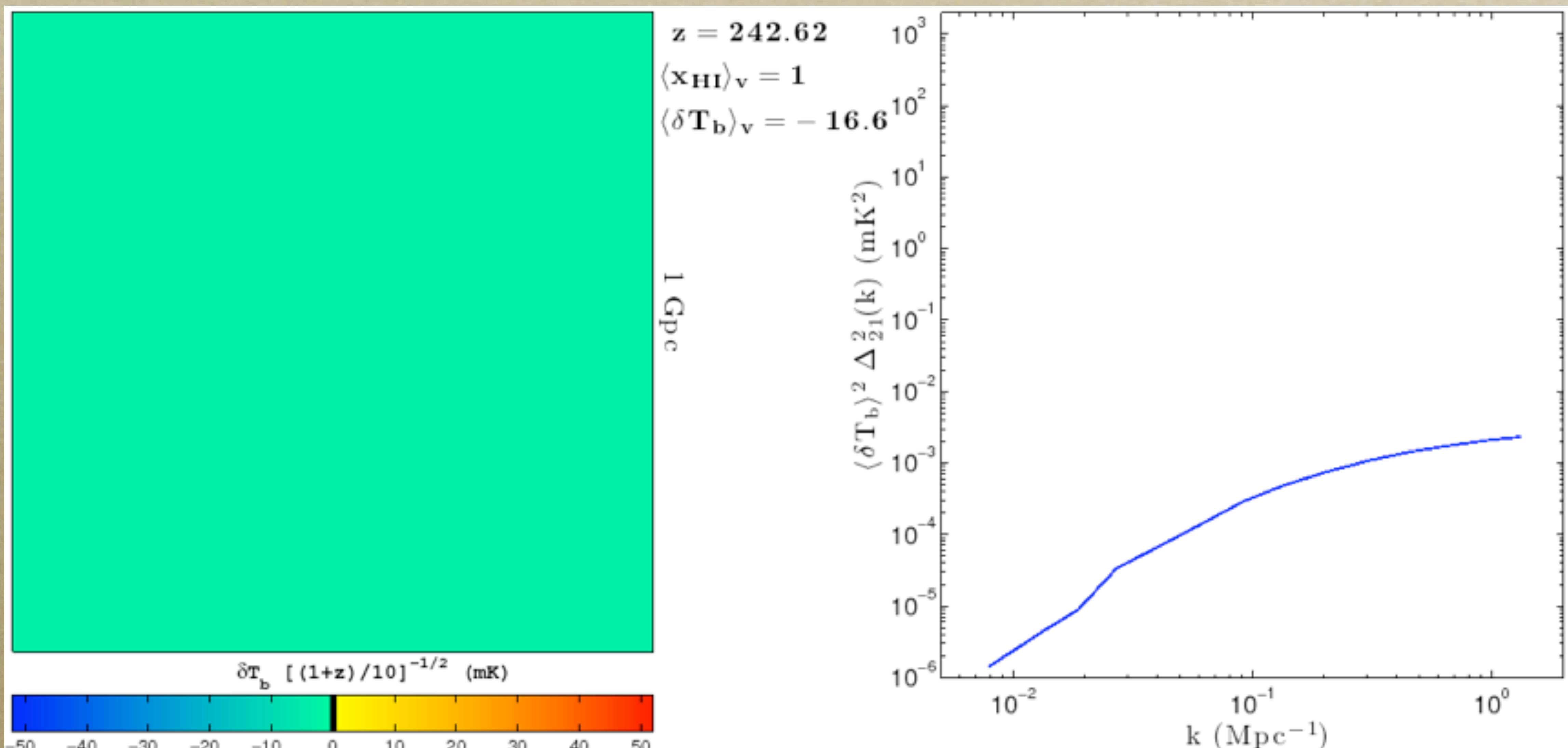
Implications for Spin-Flip Measurements

- *Need huge telescope and high angular resolution to measure structures*
- *Requires an interferometer*
  - *Many telescopes combined into one: requires substantial computing*
- *Map-making is very difficult: beyond current capabilities except on largest scales*

Implications for Spin-Flip Measurements

- *Need huge telescope and high angular resolution to measure structures*
- *Requires an interferometer*
    - *Many telescopes combined into one: requires substantial computing*
- *Map-making is very difficult: beyond current capabilities except on largest scales*
- *Current experiments focus on statistics*

The Complete Picture



Mesinger, Furlanetto, & Cen (2010)

Implications for Spin-Flip Measurements

- *Need huge telescope and high angular resolution to measure structures*
- *Requires an interferometer*
  - *Many telescopes combined into one: requires substantial computing*
- *Map-making is very difficult: beyond current capabilities except on largest scales*
- *Current experiments focus on statistics*
  - *Rather than zoom in on a small area seen in detail, can measure statistics from a large area seen crudely*

Implications for Spin-Flip Measurements

- *Need huge telescope and high angular resolution to measure structures*
- *Requires an interferometer*
  - *Many telescopes combined into one: requires substantial computing*
- *Map-making is very difficult: beyond current capabilities except on largest scales*
- *Current experiments focus on statistics*
  - *Rather than zoom in on a small area seen in detail, can measure statistics from a large area seen crudely*
- *Can use simple antennae rather than dishes to be sensitive to wide areas*

Implications for Spin-Flip Measurements

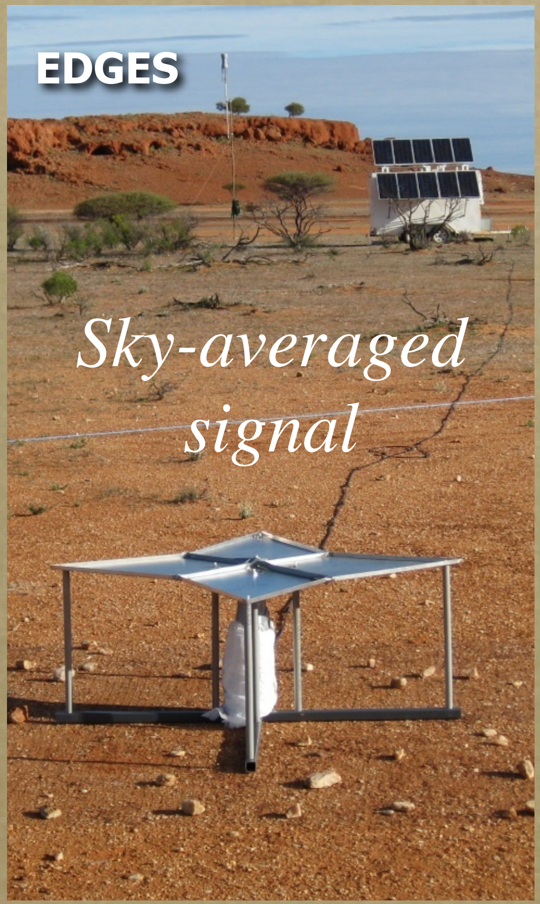
- *Need huge telescope and high angular resolution to measure structures*
- *Requires an interferometer*
  - *Many telescopes combined into one: requires substantial computing*
- *Map-making is very difficult: beyond current capabilities except on largest scales*
- *Current experiments focus on statistics*
  - *Rather than zoom in on a small area seen in detail, can measure statistics from a large area seen crudely*
- *Can use simple antennae rather than dishes to be sensitive to wide areas*
  - *Use interferometer + digital tools to get resolution*

Implications for Spin-Flip Measurements

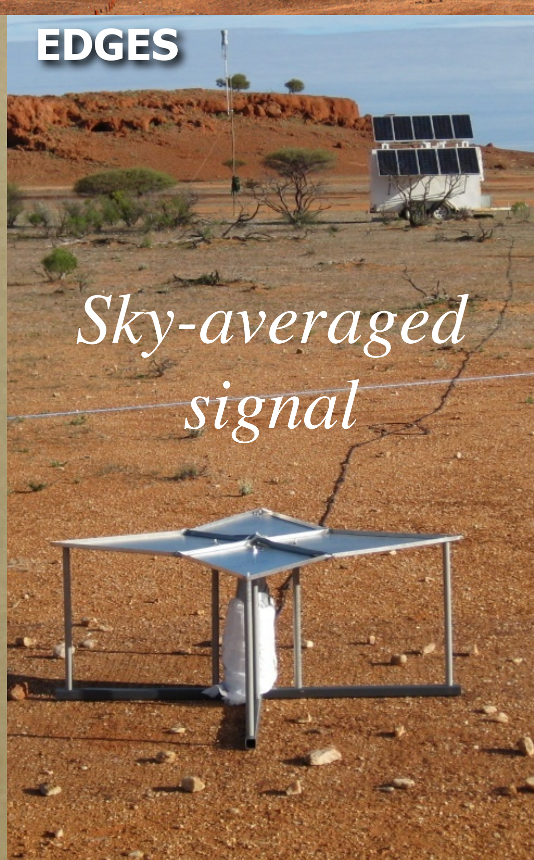
- *Need huge telescope and high angular resolution to measure structures*
- *Requires an interferometer*
  - *Many telescopes combined into one: requires substantial computing*
- *Map-making is very difficult: beyond current capabilities except on largest scales*
- *Current experiments focus on statistics*
  - *Rather than zoom in on a small area seen in detail, can measure statistics from a large area seen crudely*
- *Can use simple antennae rather than dishes to be sensitive to wide areas*
  - *Use interferometer + digital tools to get resolution*
  - *Requires HUGE arrays (100+ elements): huge computing*

Approaches to the Spin-Flip Background

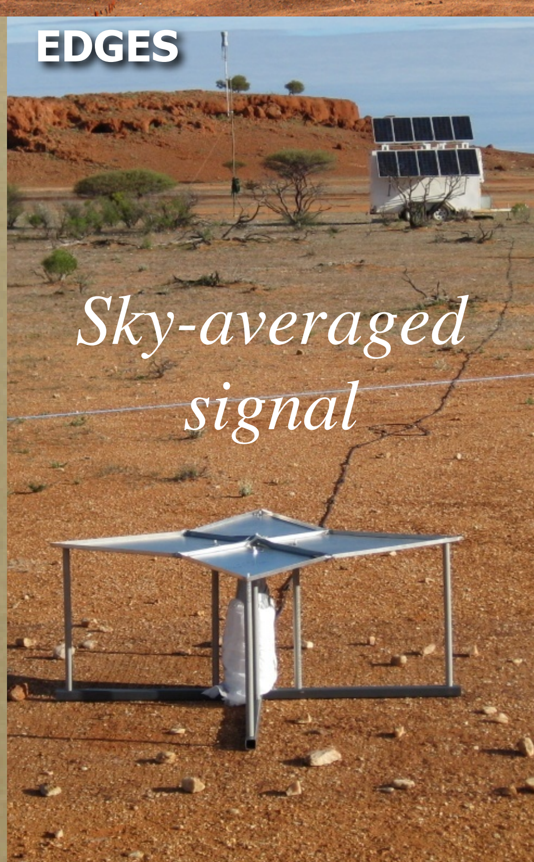
Approaches to the Spin-Flip Background



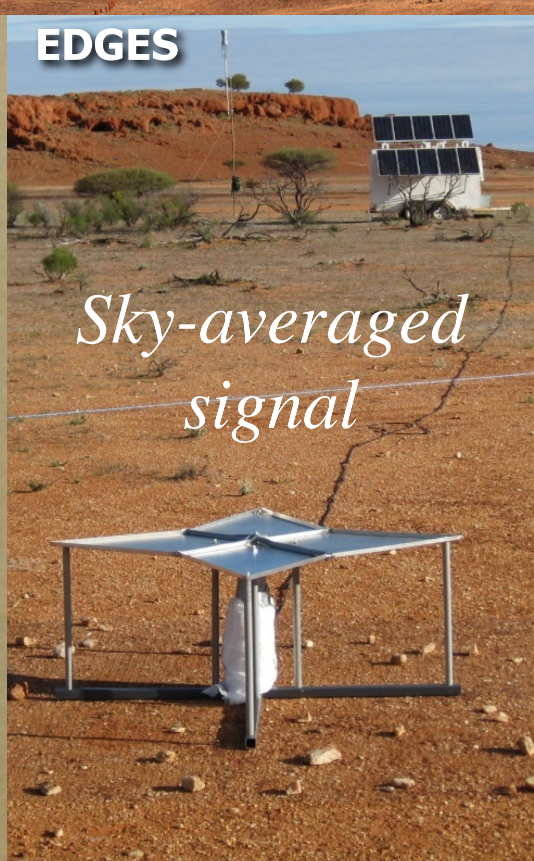
Approaches to the Spin-Flip Background

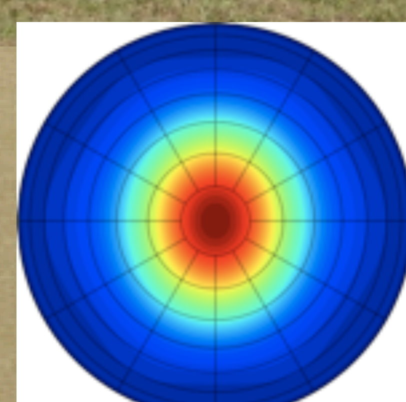


Approaches to the Spin-Flip Background

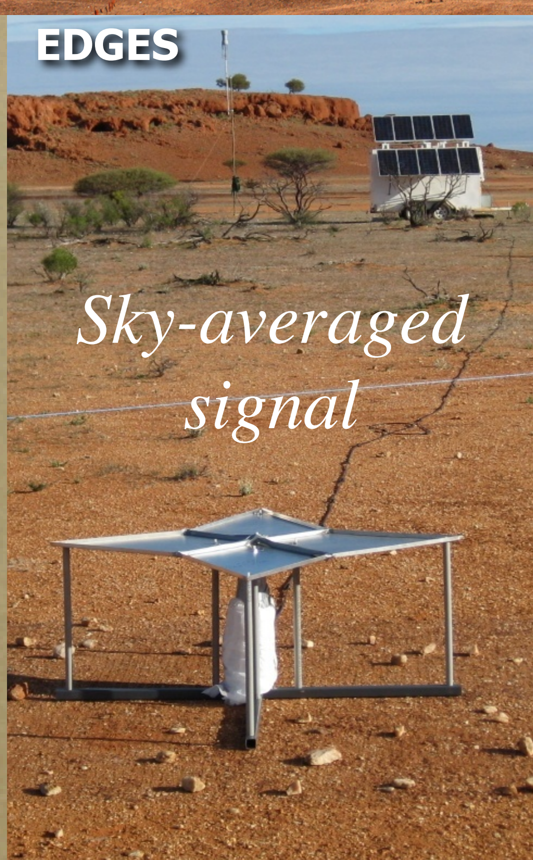


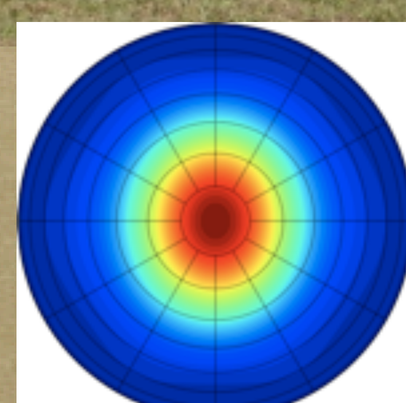
Approaches to the Spin-Flip Background



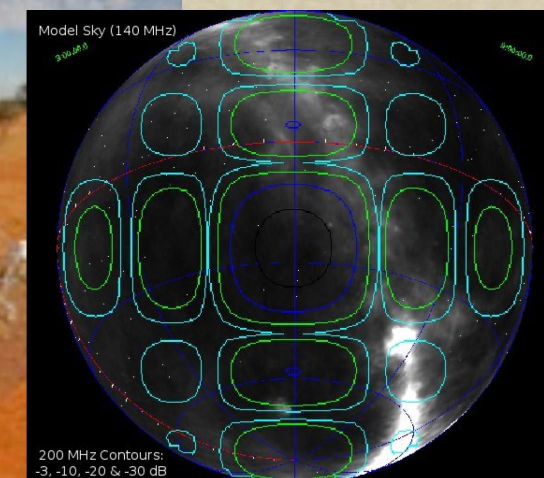


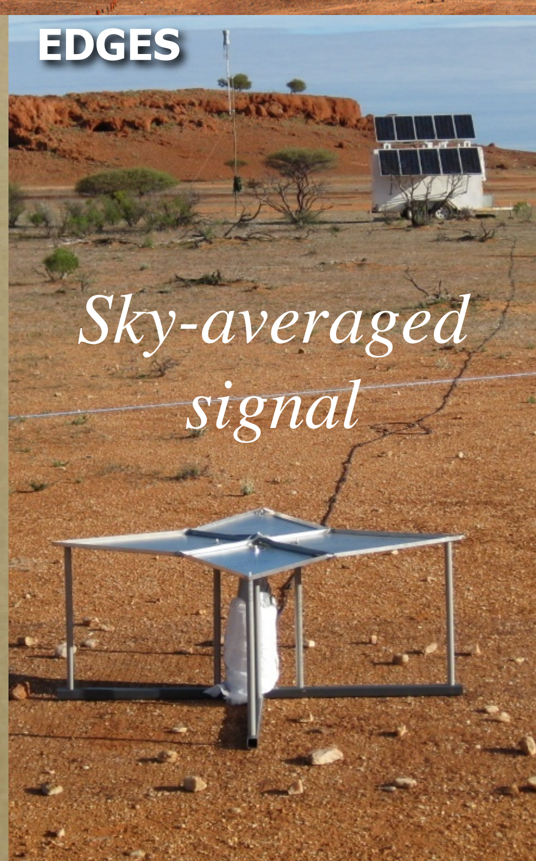
Approaches to the Spin-Flip Background

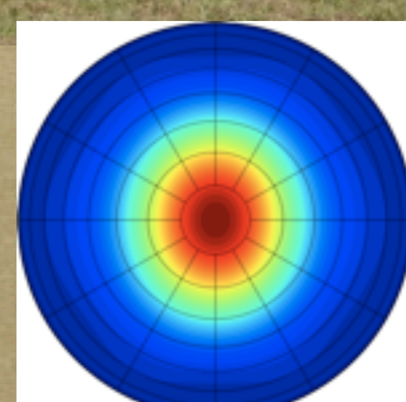




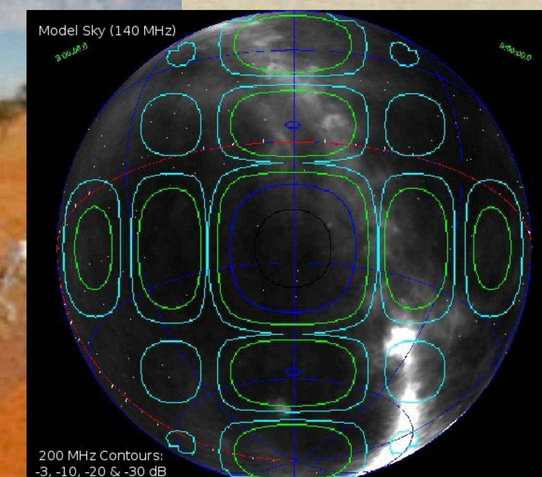
Approaches to the Spin-Flip Background

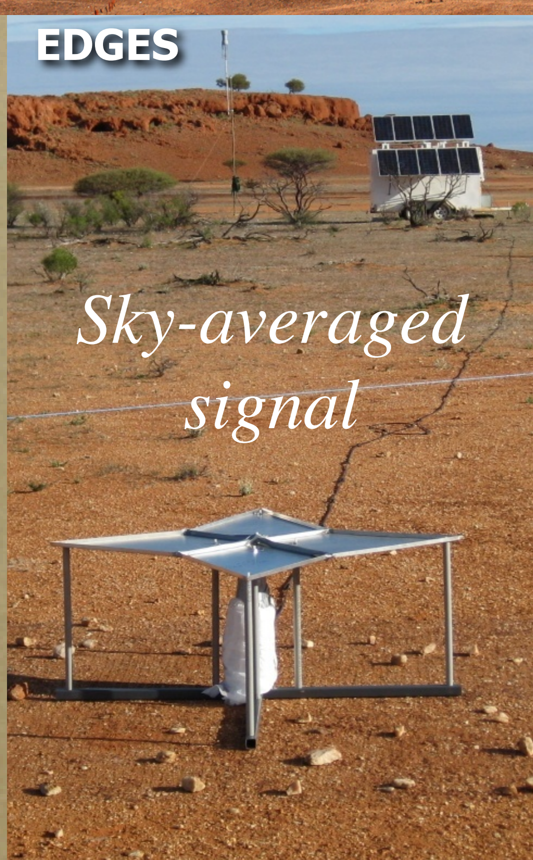


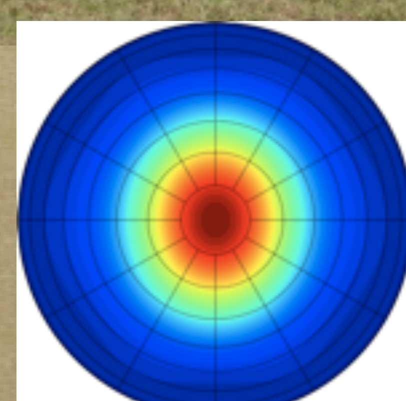




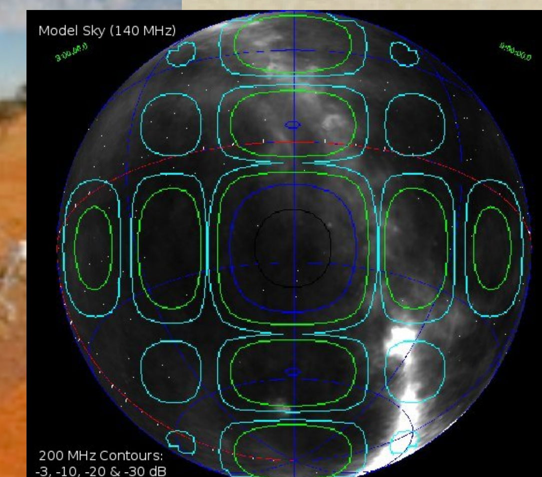
Approaches to the Spin-Flip Background

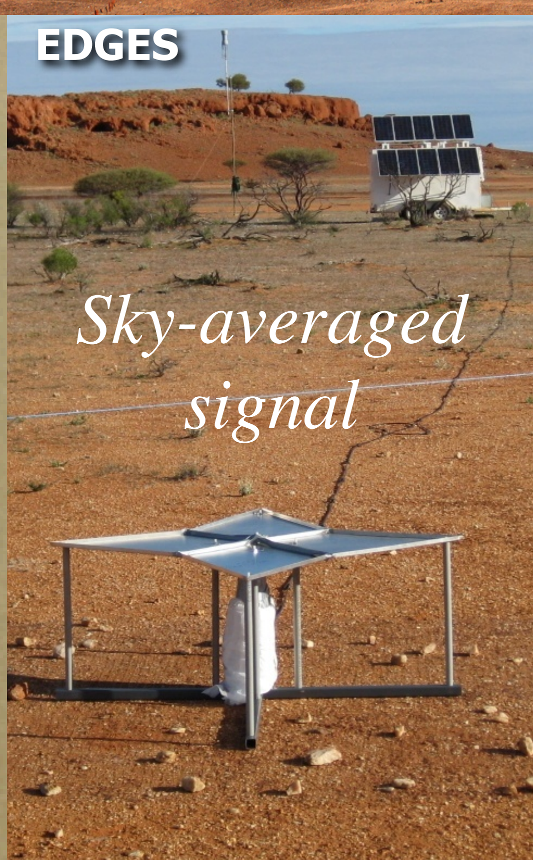


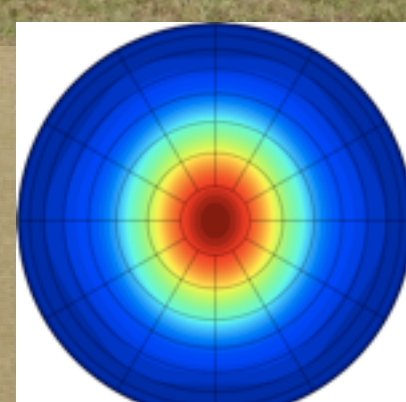




Approaches to the Spin-Flip Background



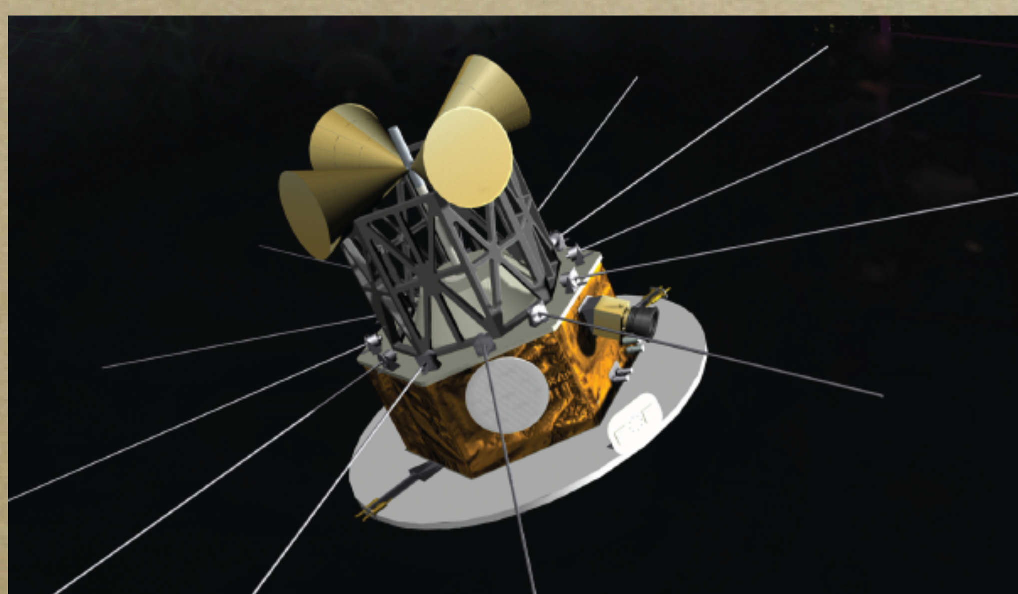


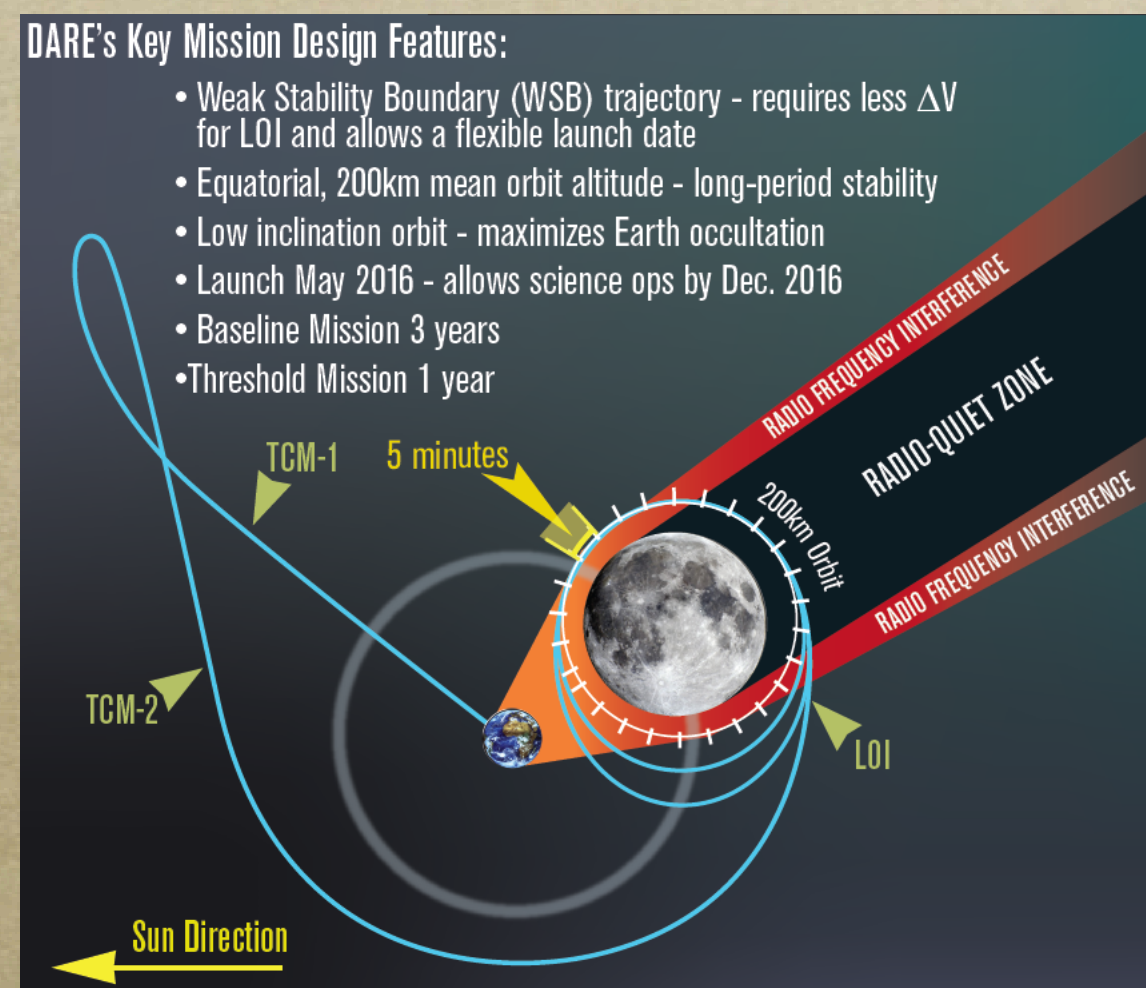


To The Moon!

DARE

DARK AGES RADIO EXPLORER





Summary

- *Computational astrophysics is one tool in understanding the Cosmic Dawn - but it still requires us to be clever!*
- *The spin-flip background is an exciting (though not yet useful) probe of the Cosmic Dawn*
  - *Computing is essential to this observing strategy*