"Show me [CII Lines],
You're getting better all the time,
And [mapping well past redshift 1],
Is an art that's hard to teach, …"
~ Bryan Keith Holland of The Offspring (paraphrased)

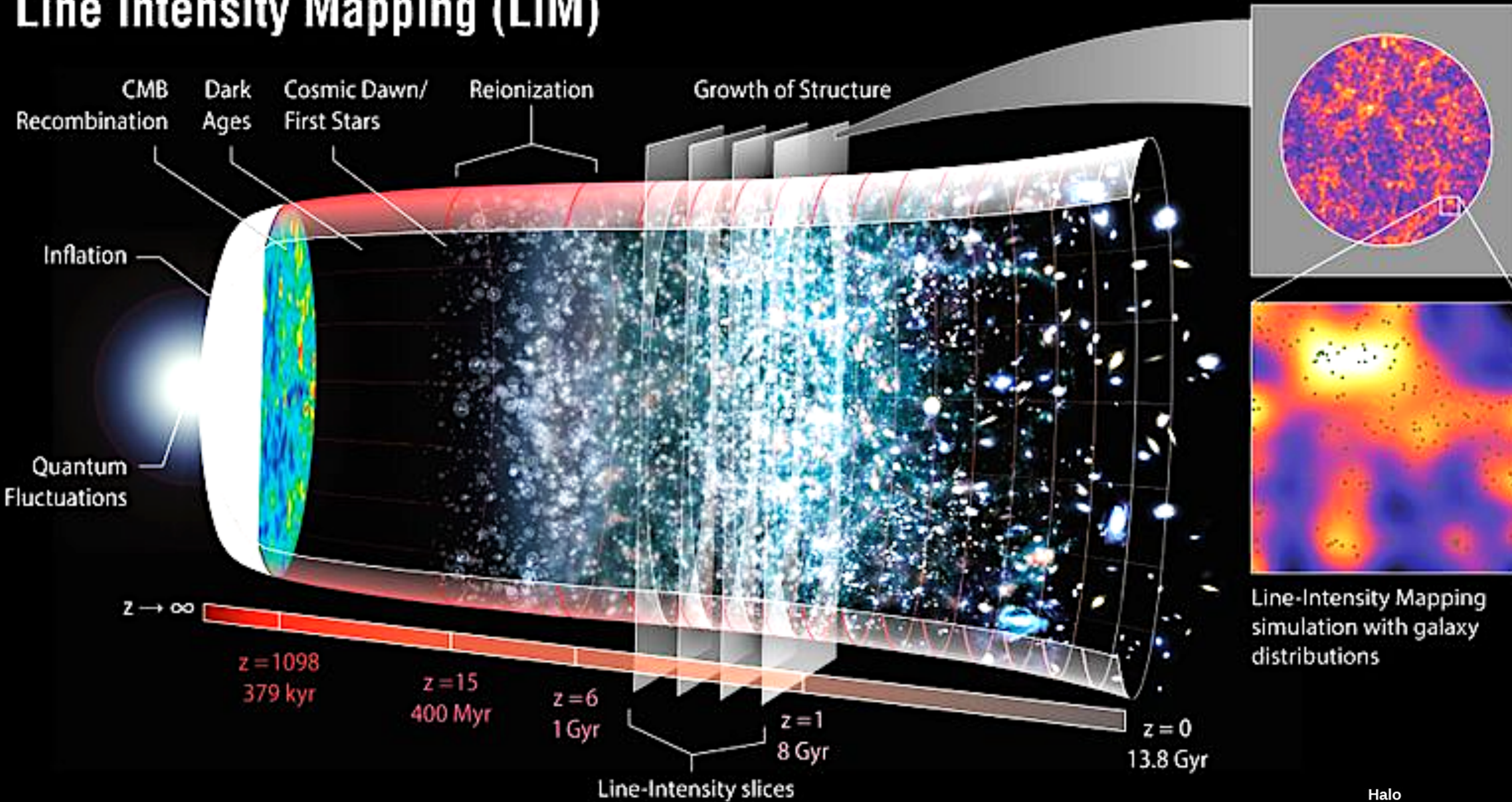
You're Gonna Go Far, KID

Cosmology with Kinetic Inductance Detectors on balloon- and space-based missions

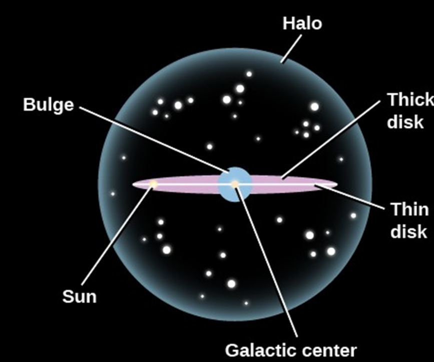
Trevor M. Oxholm
Timbie Group

October 27, 2020

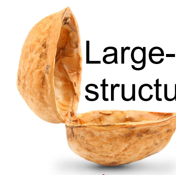
Line Intensity Mapping (LIM)



Dark matter halo growth

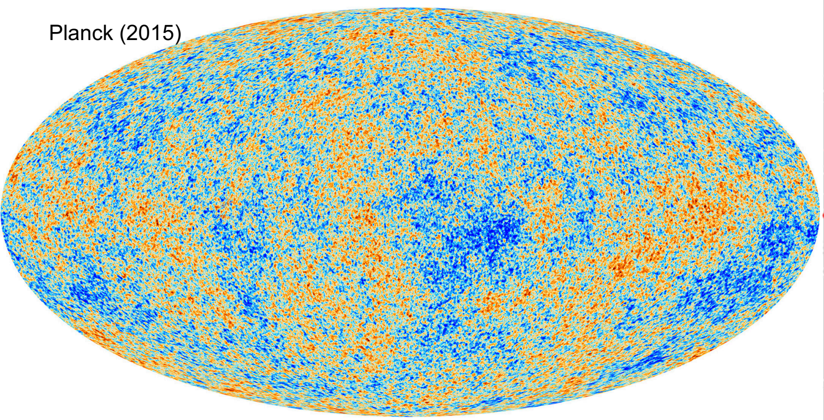


Mapping the structure of the universe

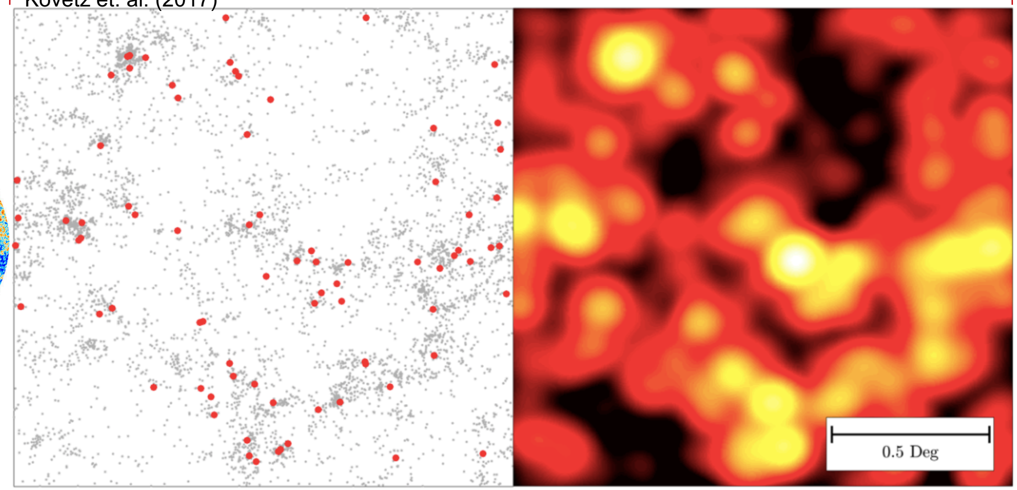


Large-scale structure

Planck (2015)



Kovetz et. al. (2017)



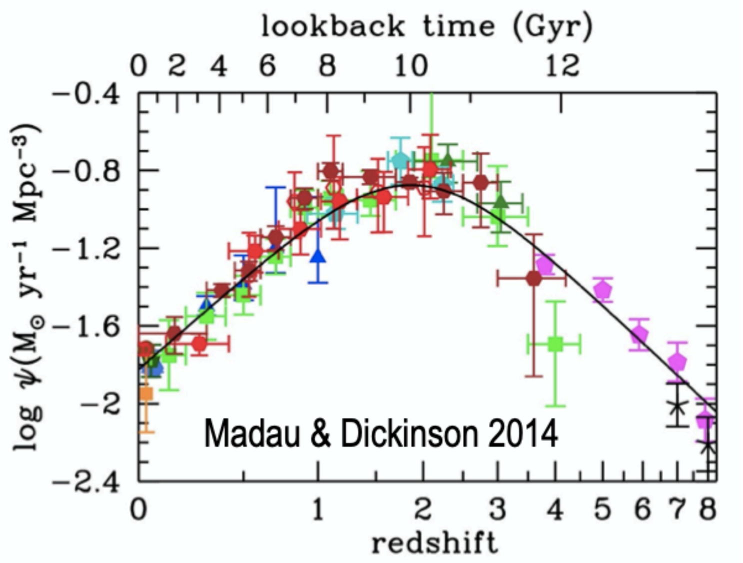
Cosmic microwave background:
- **Primary observable**: polarized temperature fluctuations
- **Pros**: unfettered by nonlinear matter evolution, closely tied to early-universe physics
- **Cons**: somewhat exhaustive research thus far -> challenging progress moving forward (though we are hopeful for continued discoveries!)

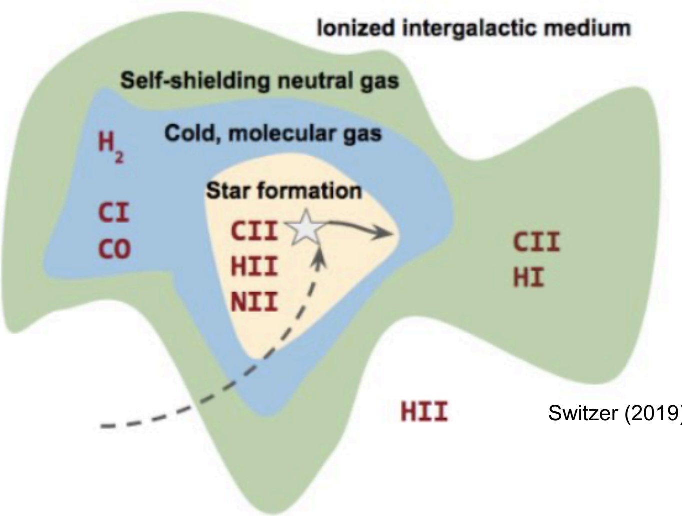
Galaxy redshift surveys
- **Primary Observable**: catalog of galaxy locations and shapes
- **Pros**: can map with visible light, precise angular scales
- **Cons**: imprecise redshift determination, only detects brightest galaxies

Line Intensity Mapping (LIM) Surveys
- **Primary Observable**: CMB-like map of the intensity of a specific emission line as a function of redshift/frequency
- **Pros**: precise redshift determination, 'Unbiased' (detects all emission in a given region), economical, can map beyond recombination era (in principle)
- **Cons**: huge galactic foreground signal, depends of line intensity models

Understanding cosmic star formation rates

- While underlying DM haloes have grown continuously, the **cosmic star formation rate has declined since z~2**
- **We need to line intensity models before we can infer underlying DM halo properties**
  - For our lines of interest, intensity models are closely intertwined with star formation
- Requires a **broad census of various gases over cosmic time**
  - Measurement of infrared dust (green) traces star formation rate density
  - Cold, molecular gas (blue) traces the “fuel” for star formation



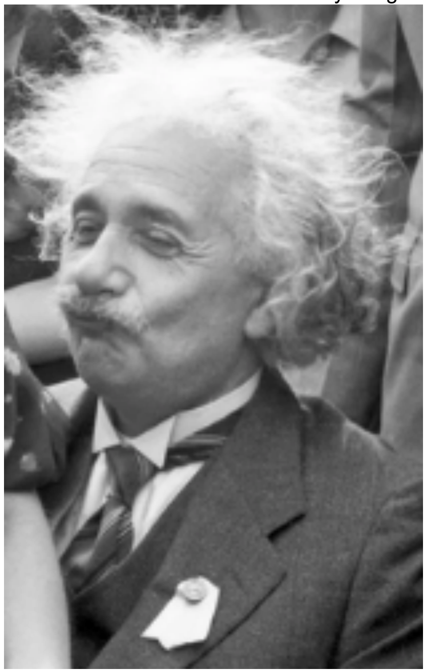


Switzer (2019)

Long-term scientific goals for LIM surveys

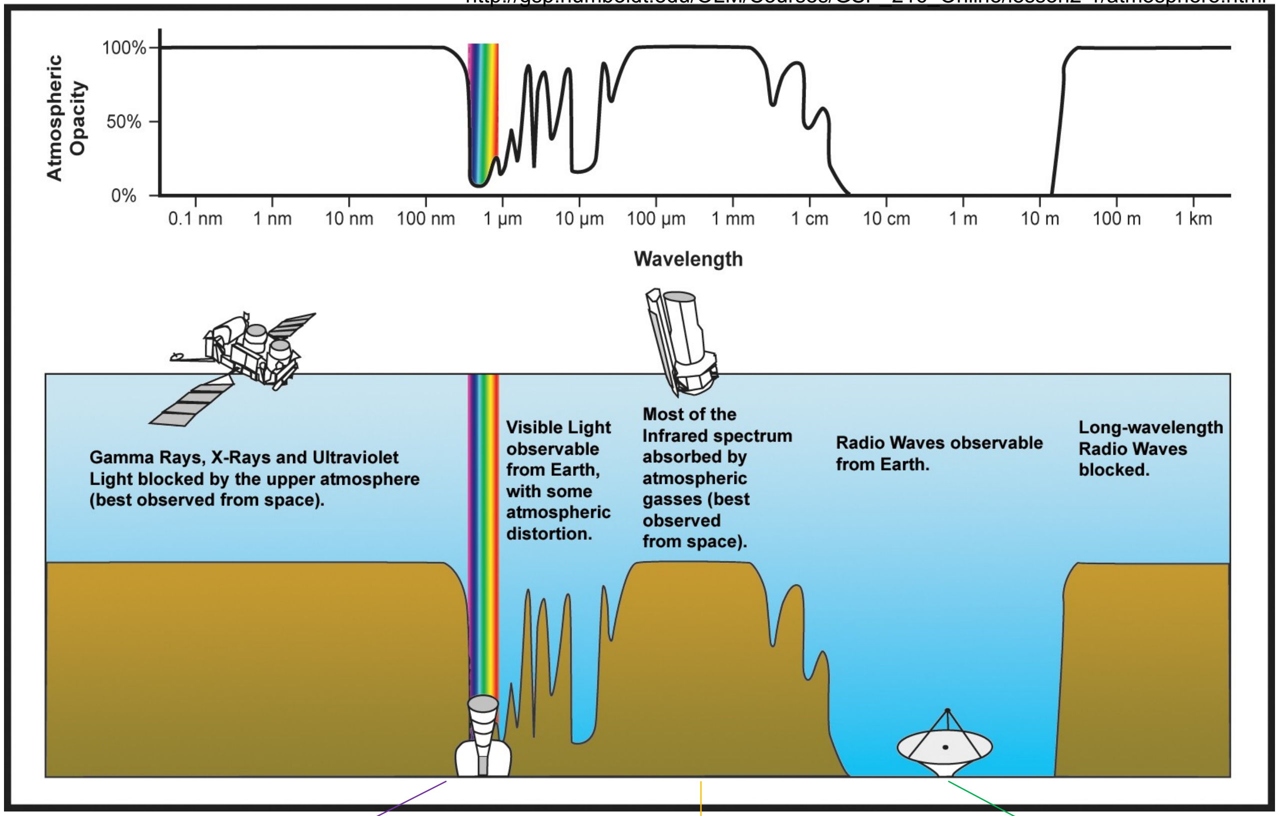
- **Largest maps ever created** -> huge census of galaxies, **lots of k-modes**!
  - Analogous to measuring a large phase space volume
- Lots of k-modes -> **low uncertainties**!
  - Signal-to-noise ~ $(N_{\text{k-modes}})^{1/2}$
- Opportunities are endless!
  - Competitive constraints on **cosmological parameters**
  - **Dark energy** equation of state
  - **Primordial non-Gaussianity** (new physics/inflation!)
  - **Epoch of reionization**
  - Mapping into the cosmic **"Dark Ages"**
- BUT first we need to learn how to deal with a lot of systematics and get funding for an ambitious experiment…

Underwood Archives/Getty Images



Barrier: atmospheric interference

http://gsp.humboldt.edu/OLM/Courses/GSP_216_Online/lesson2-1/atmosphere.html



~Visible
~eV

- Galaxy surveys
- Cosmology with transients

FIR – mm
~meV

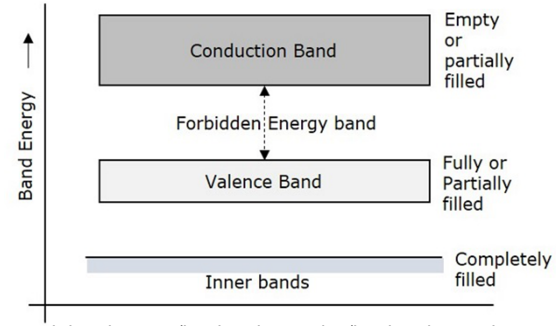
- CMB
- Star-formation history
- *Water on the moon! (SOFIA)*

21cm (HI)/radio
~µeV

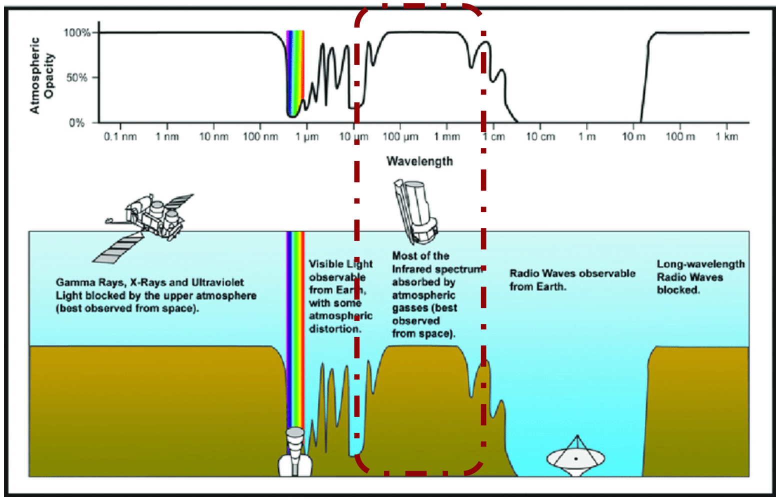
- Large-scale structure
- Reionization
- Synchrotron radiation

What’s so tough about mm – FIR astronomy?

- **Semiconductor detectors can not be used**
  - Semiconductor detection limited to E_g~1eV
- **Lack of low-noise amplifiers**
  - Need sensitive first-stage mixers
- **Need technology that can be fabricated into a large-scale array**
- **Atmosphere is opaque in the FIR-mm range**



https://www.tutorialspoint.com/basic_electronics/basic_electronics_energy_bands.htm



It’s tough enough to develop these technologies on the ground – but we also need to put them on balloons and satellites!

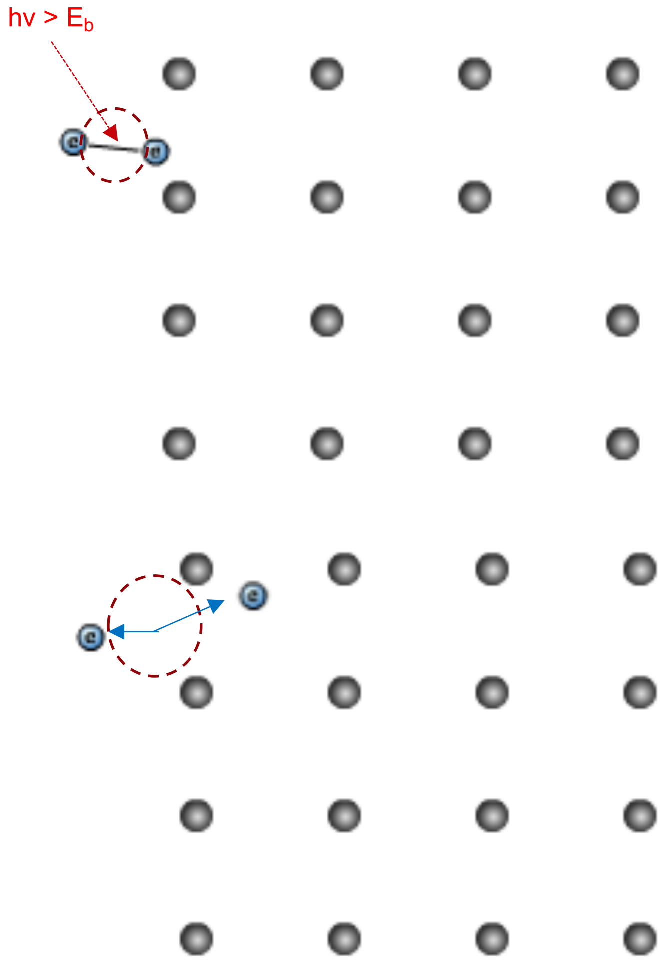
Superconducting pair-breaking detectors

How they work:

- Incoming photon directly breaks a Cooper pair
- We can detect the resulting change in electronic properties

Why they're useful:

- Can detect **lower-energy photons** than semiconductors
  - Semiconductors: E_g~1eV
  - Superconductors: E_b~1meV
- **Low-noise**
  - Ideally, detector noise is limited by incoming photon noise
- Highly **responsive** to changes in radiation
- Can be integrated into **large arrays**

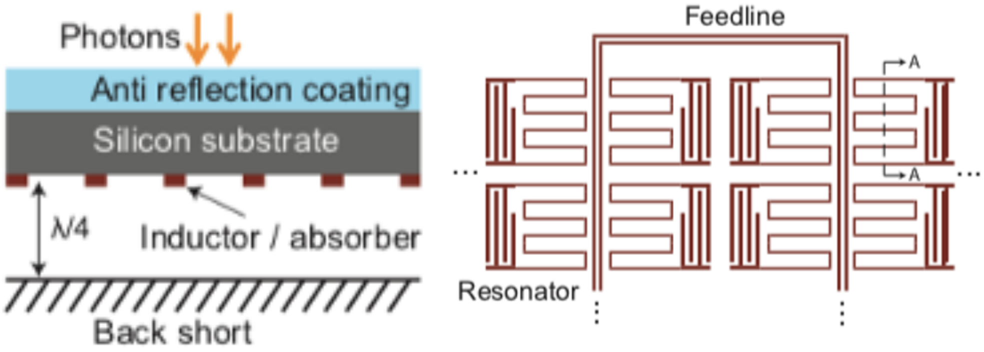


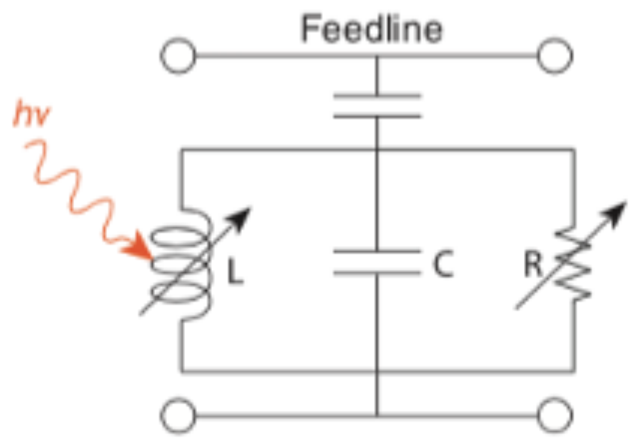
Kinetic Inductance Detectors (KIDs)

Array of superconducting resonators with resonance curves that track the amount of absorbed radiation – pair-breaking detectors

- Scalable to large arrays
- Low-noise over a wide dynamic range
- (Relatively) easily fabricated
- *But* the physics is really complicated…

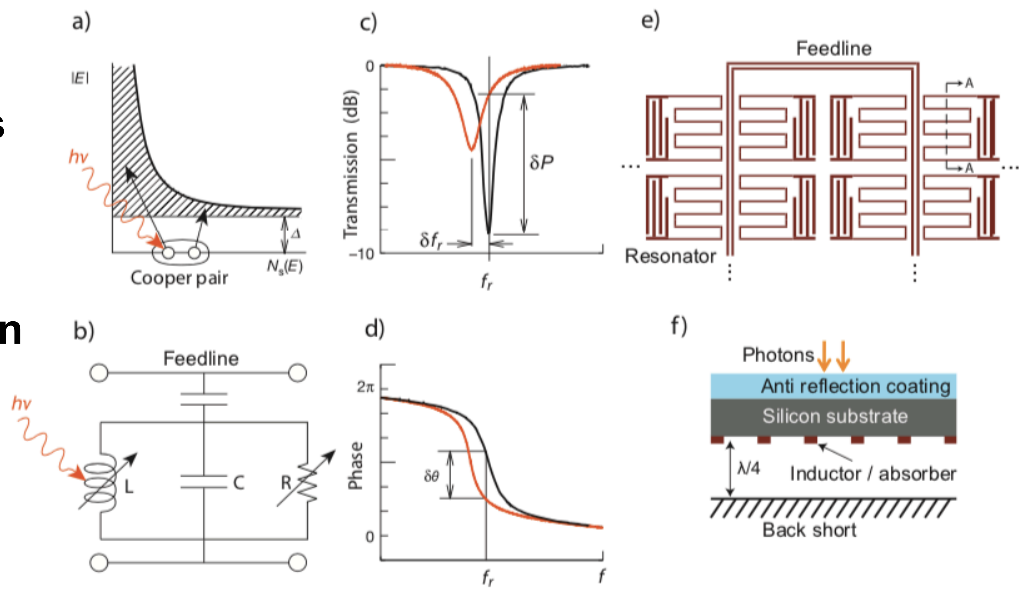
Day et. al. (2003)





KIDs – How a photon becomes a voltage

1. Incoming **photon** directly breaks a Cooper pair (a)
2. Distribution of broken pairs **changes the inductance and resistance** properties of the film (b)
3. Change in resonator inductance and resistance **change the transmission curve** (c,d)
4. We can directly measure **voltage** changes to the transmission curve over wide array of detectors.

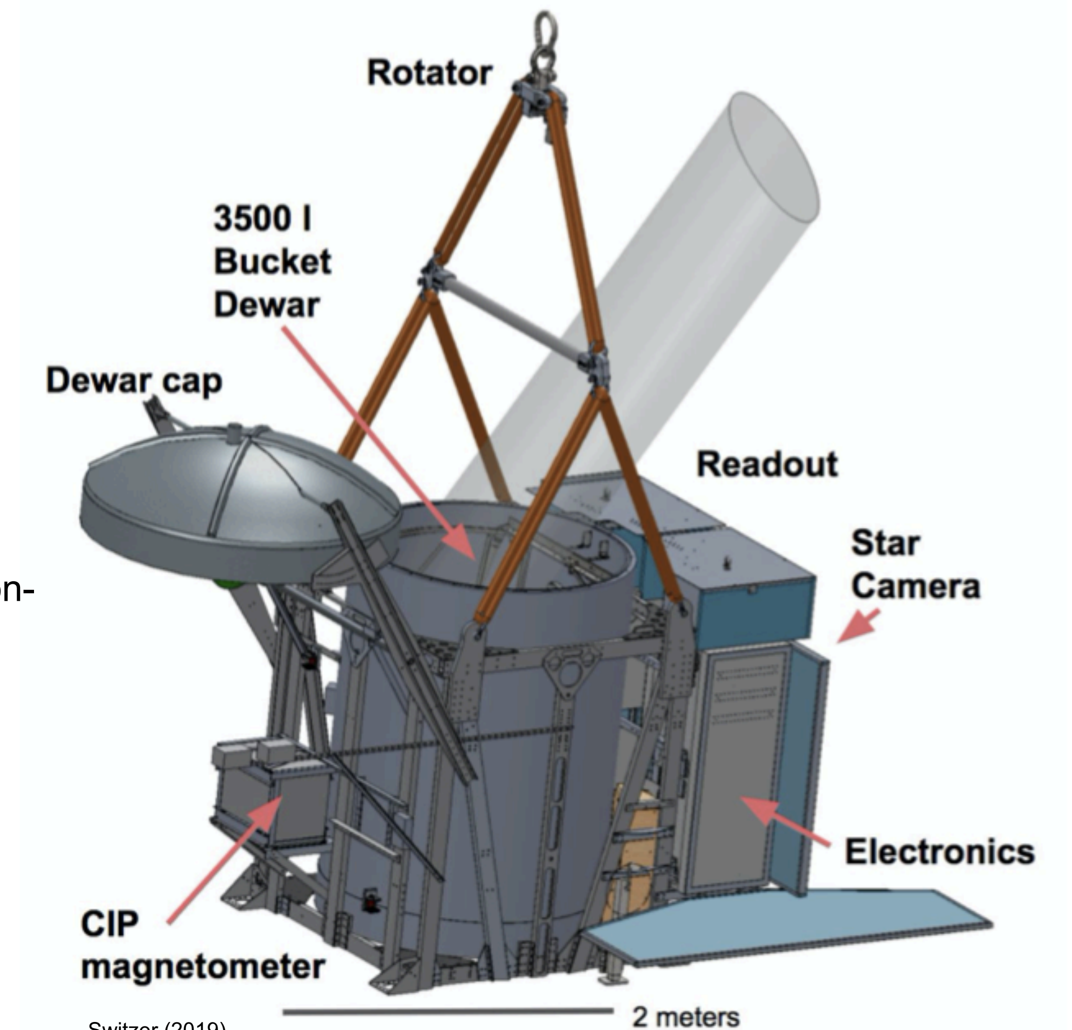


Day et. al. (2003)

EXCLAIM!

EXperiment for Large-Aperture Intensity Mapping:

- KID-equipped!
- Balloon-based NASA-GSFC mission
  - 36km elevation
  - Balloon expands to the size of a football field!
- 420-540 GHz band
- Dewar cooled to ~4K (including optics)
- Six 355-MKID Arrays integrated with an on-chip spectrometer at ~100mK
- 0.8m Primary Mirror
- Targeting 2022 Launch

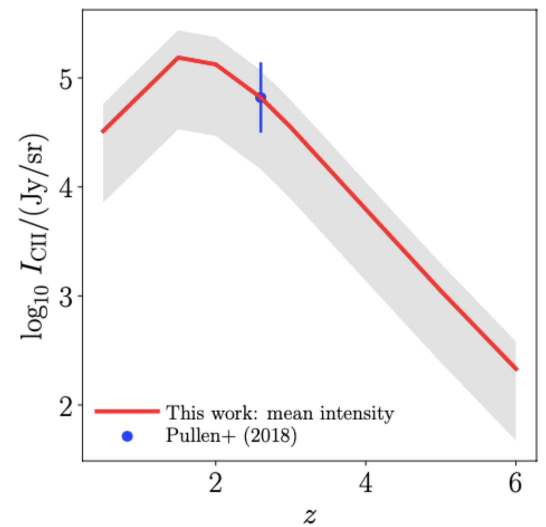


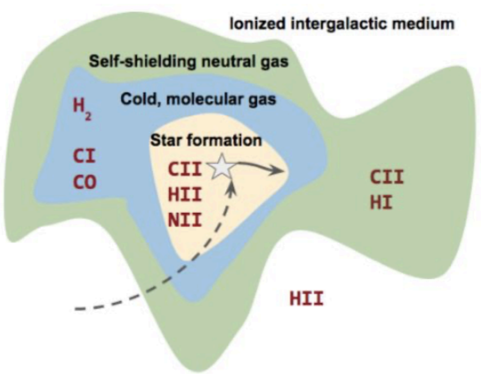
Switzer (2019)

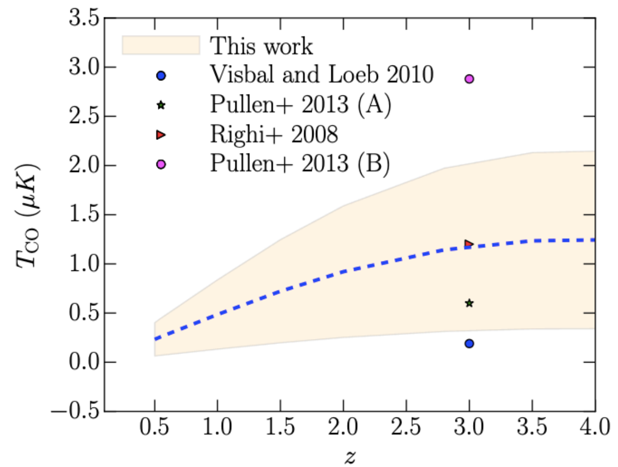
EXCLAIM: scientific targets

- Designed to cross-correlate with galaxy redshift surveys (BOSS or Hyper-Suprime Cam)
- CII traces star formation rate density
- CO ladder traces abundance of cold star-forming gas
- Line intensity mapping for:
  - CII - 2.5 < z < 3.5
  - CO(6-5) - 0.3 < z < 0.6
  - CO(5-4) - 0.08 < z < 0.35
  - CO(4-3) – 0 < z < 0.08

Padmanabhan (2019)





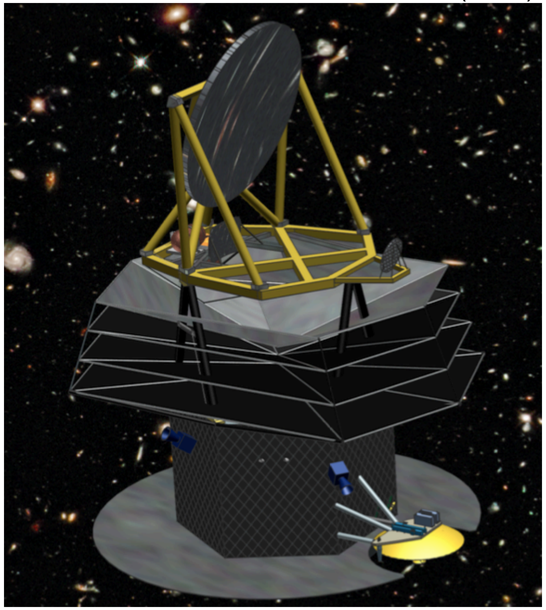


Padmanabhan (2017)

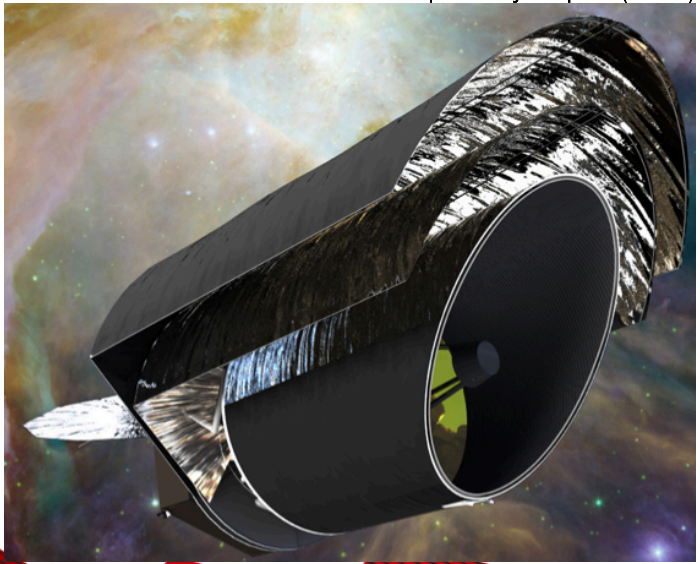
Future KID-equipped space missions?

- Galaxy Evolution Probe (proposed)
    - "Explorer-class" mission detecting ~20 - 200 µm emission
    - Scientific targets:
        - Relation between star formation rates and supermassive black hole growth
        - Growth of metals over cosmic time
        - History of SMBH accretion
    - Equipped with KID array
- Origins Space Telescope (future)
    - Proposed NASA "Flagship-class" mission detecting < ~1µm emission
    - Scientific targets:
        - Cosmic star & galaxy formation
        - Planetary formation/Protoplanetary disks
        - Supermassive black hole populations
        - Search for extraterrestrial life (M-dwarf-orbiting planets?)
    - May be equipped with KIDs or TESs

Glenn et. al. (2019)



OST Mission Concept Study Report (2019)



Advertisement (don't worry, non-political)

Nov 05, 2020

Eric Switzer, NASA/Goddard

"The Experiment for Cryogenic Large-aperture Intensity Mapping (EXCLAIM)"

The EXperiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM) is a cryogenic balloon-borne instrument that will survey galaxy and star formation history over cosmological time scales. Rather than identifying individual objects, EXCLAIM will be a pathfinder to demonstrate an intensity mapping approach, which measures the cumulative redshifted line emission. EXCLAIM will operate at 420-540 GHz with a spectral resolution R=512 to measure the integrated CO and [CII] in redshift windows spanning $0 < z < 3.5$. CO and [CII] line emissions are key tracers of the gas phases in the interstellar medium involved in star-formation processes. EXCLAIM will shed light on questions such as why the star formation rate declines at $z < 2$, despite continued clustering of the dark matter. The instrument will employ an array of six superconducting integrated grating-analog spectrometers (micro-spec) coupled to microwave kinetic inductance detectors (MKIDs). I will present an overview of the EXCLAIM instrument design and status.

Zoom URL: https://us02web.zoom.us/j/88513896776?pwd=Y1JtRE1KZllxWkFTamJBSGtGdm9yQT09

Meeting ID: 885 1389 6776
Passcode: 713070

EVENT DETAILS

Date:
Nov 05, 2020

Time:
3:45–5pm

Location:
Online Zoom meeting (see Abstract)

Notes:
Tea at 3:30 pm Talk begins at 3:45 pm

Speaker Host:
Peter Timbe, Physics Department UW Madison

Recommend Tweet

Acknowledgements

Research funding:

- Wisconsin Space Grant Consortium
- NASA OSSI Internship Program
- National Space Grant Internship Program

- Images from first page:
  - NASA-LAMBDA Archive (Line Intensity Mapping graphic)
  - https://evolution.calpoly.edu/milky-way-galaxy (Milky Way dark matter halo graphic)
- Image from this page:
  - Pixar Animation Studios - https://blog.sevenponds.com/lending-insight/film-review-up-2009/attachment/pixar-up-house