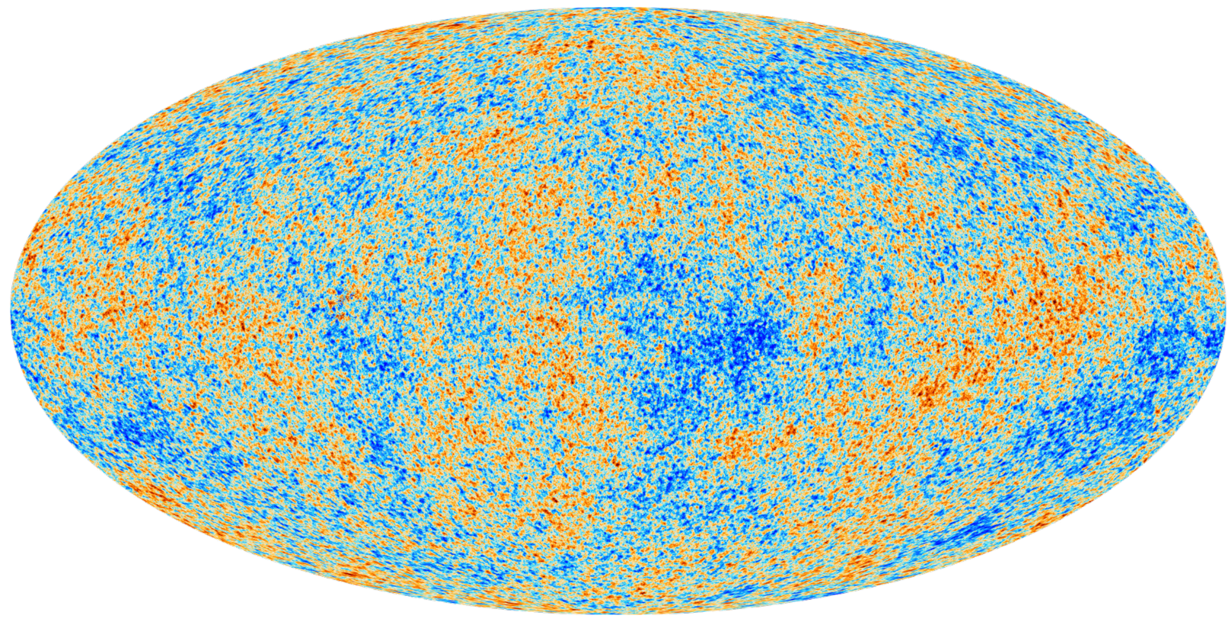
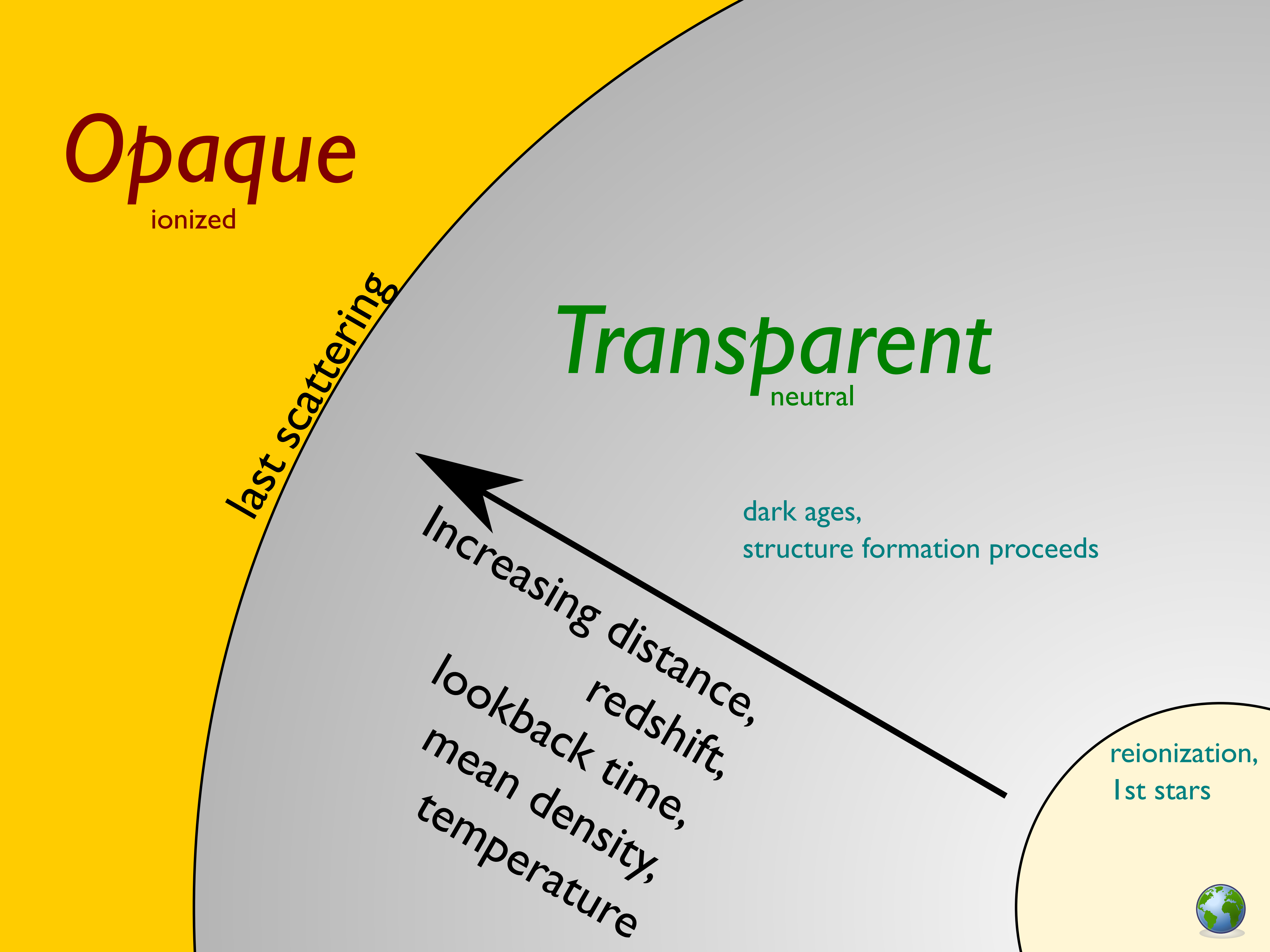
Physics from the Cosmic Microwave Background and the Road to CMB-S4



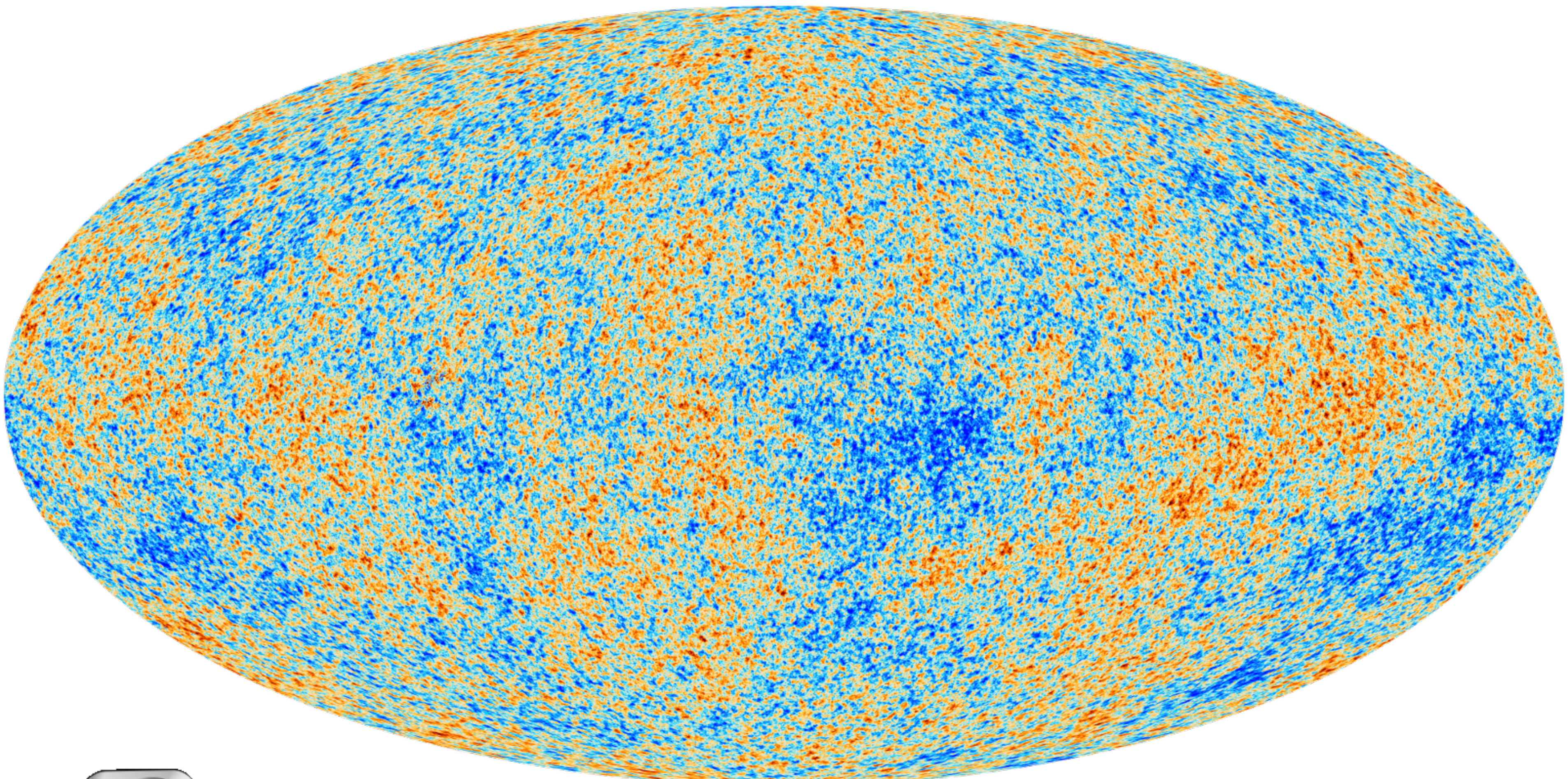
Kevin Huffenberger
Florida State University

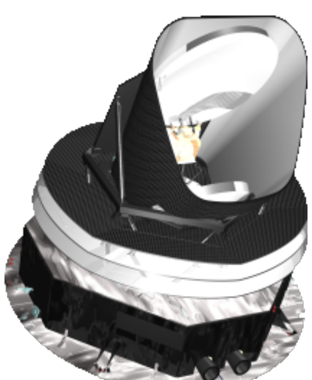
Co-spokesperson,
CMB-S4 collaboration

CIPANP-2022, Lake Buena Vista, Florida


Opaque
ionized
last scattering
Transparent
neutral
dark ages,
structure formation proceeds
Increasing distance,
redshift,
lookback time,
mean density,
temperature
reionization,
1st stars

CMB fluctuations

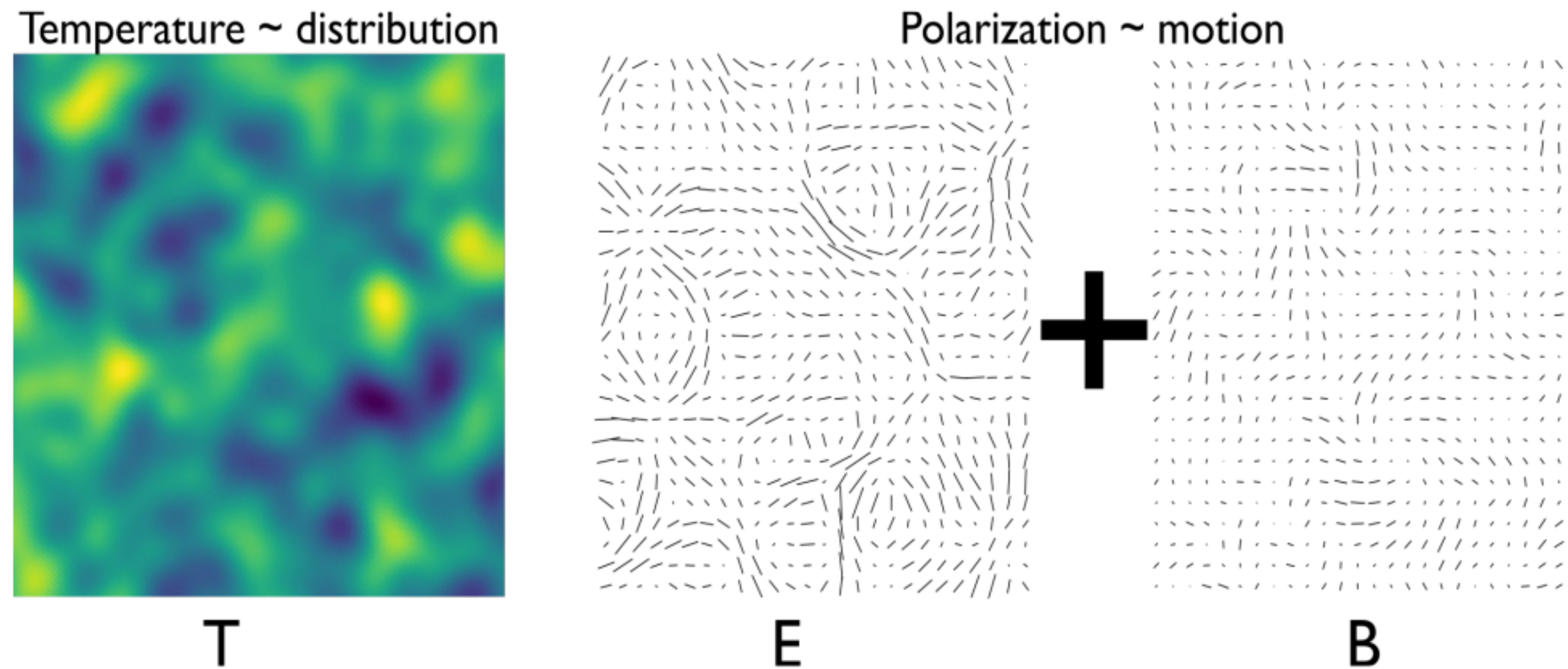




~ few hundred μK around mean *T*

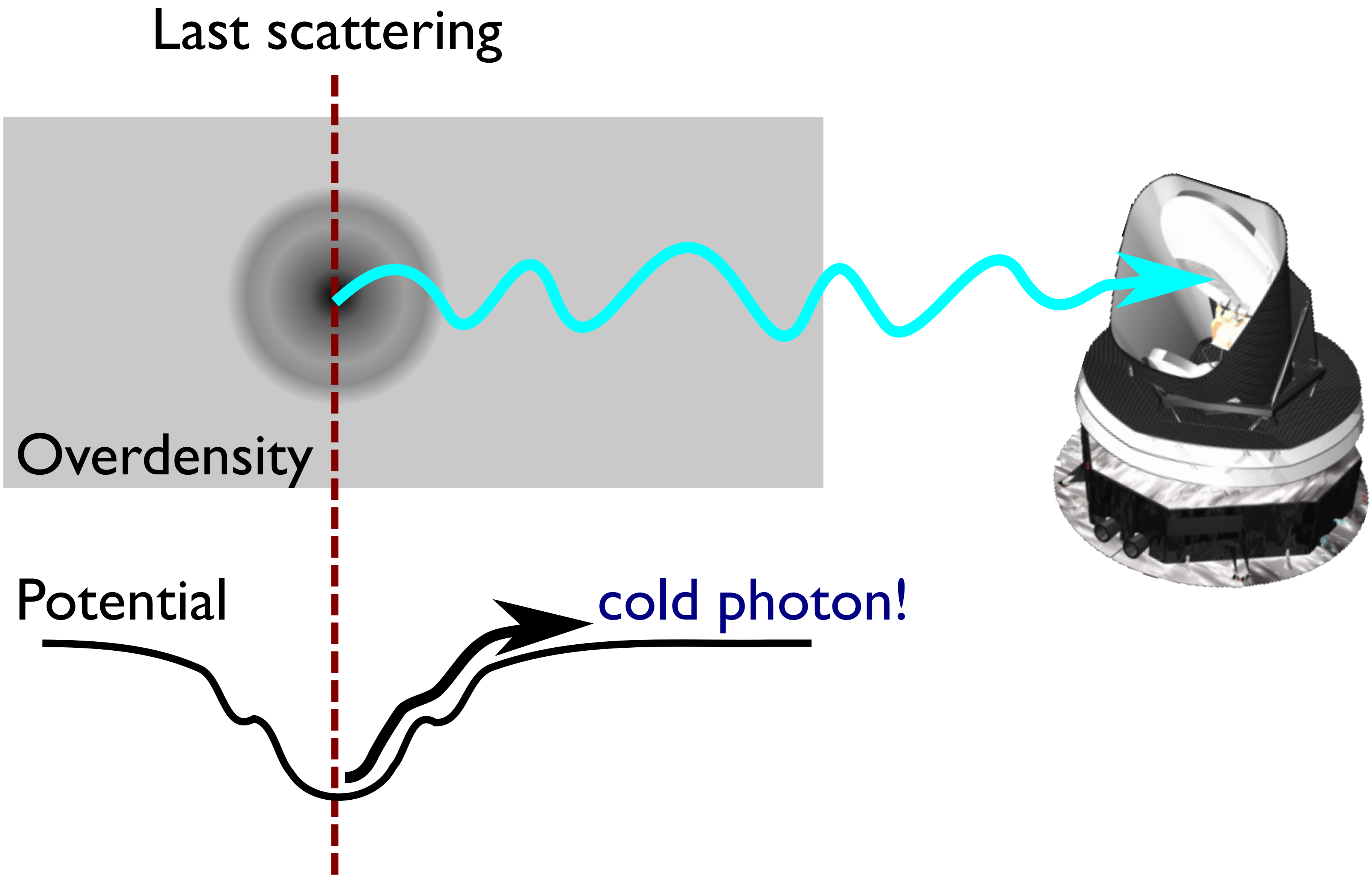
Information in CMB

Snapshot of the primordial plasma when the Universe became transparent



… plus the effects (lensing, scattering, emission) of everything in front.

Probing gravitational potential

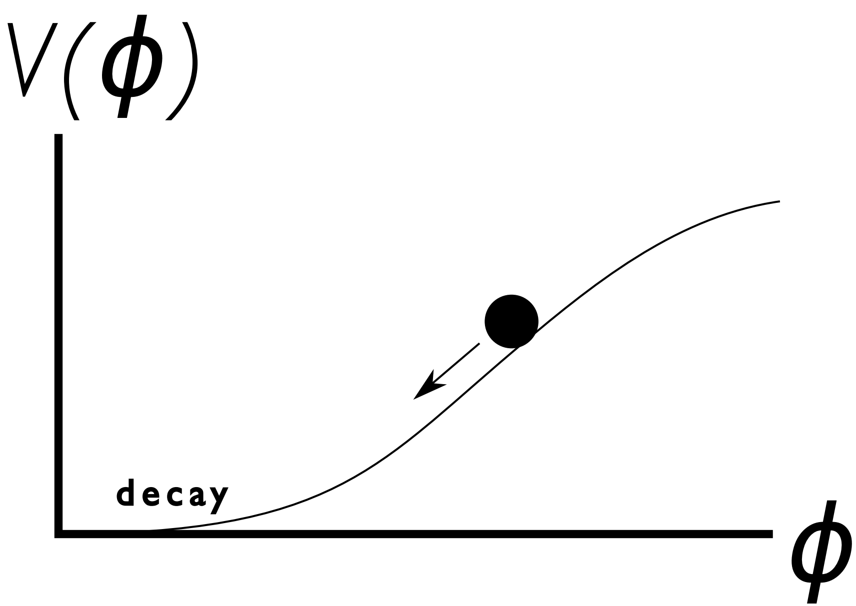


Inflation and initial fluctuations

Unknown physics at high energies causing exp(60)-fold expansion could explain:

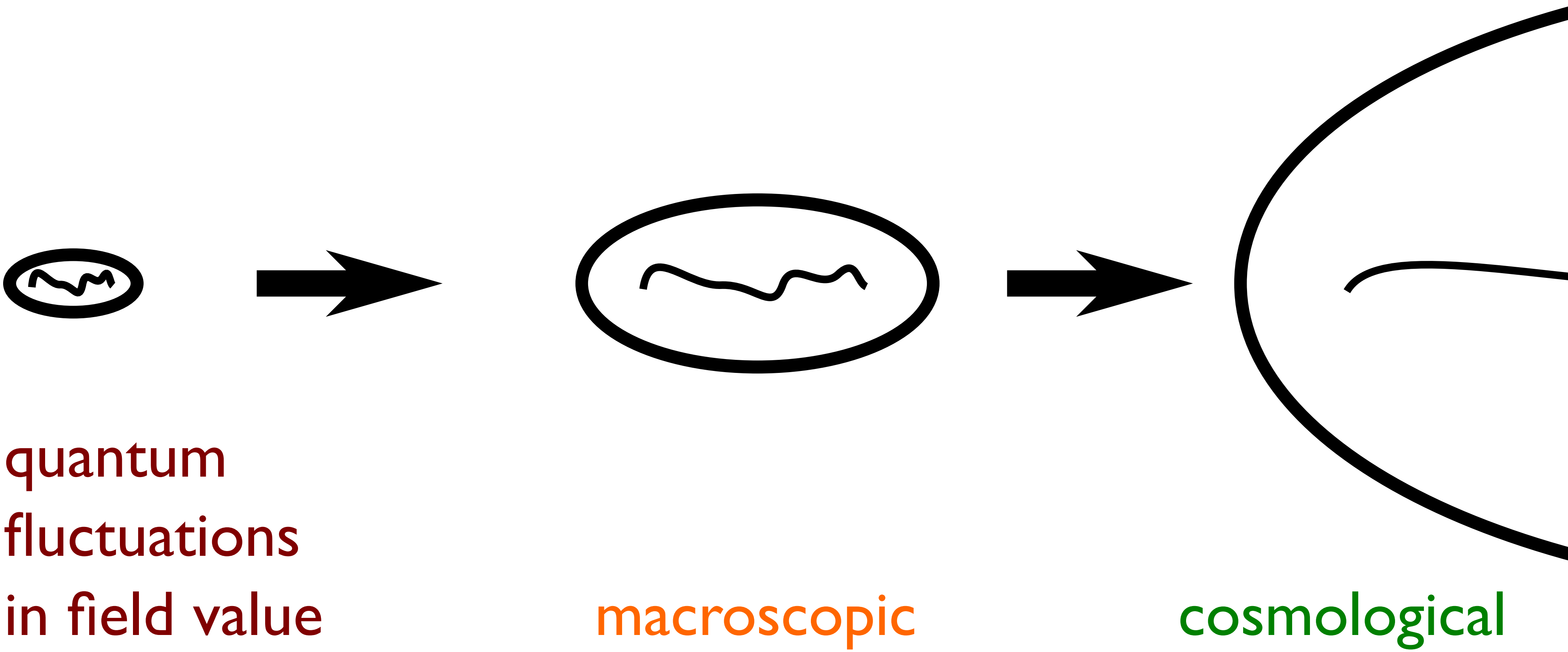
- spatial flatness
- rarity of magnetic monopoles
- uniformity of CMB sky

Expand by 10^{26} in 10^{-32} s (!) driven by a scalar field (?)



Inflaton field

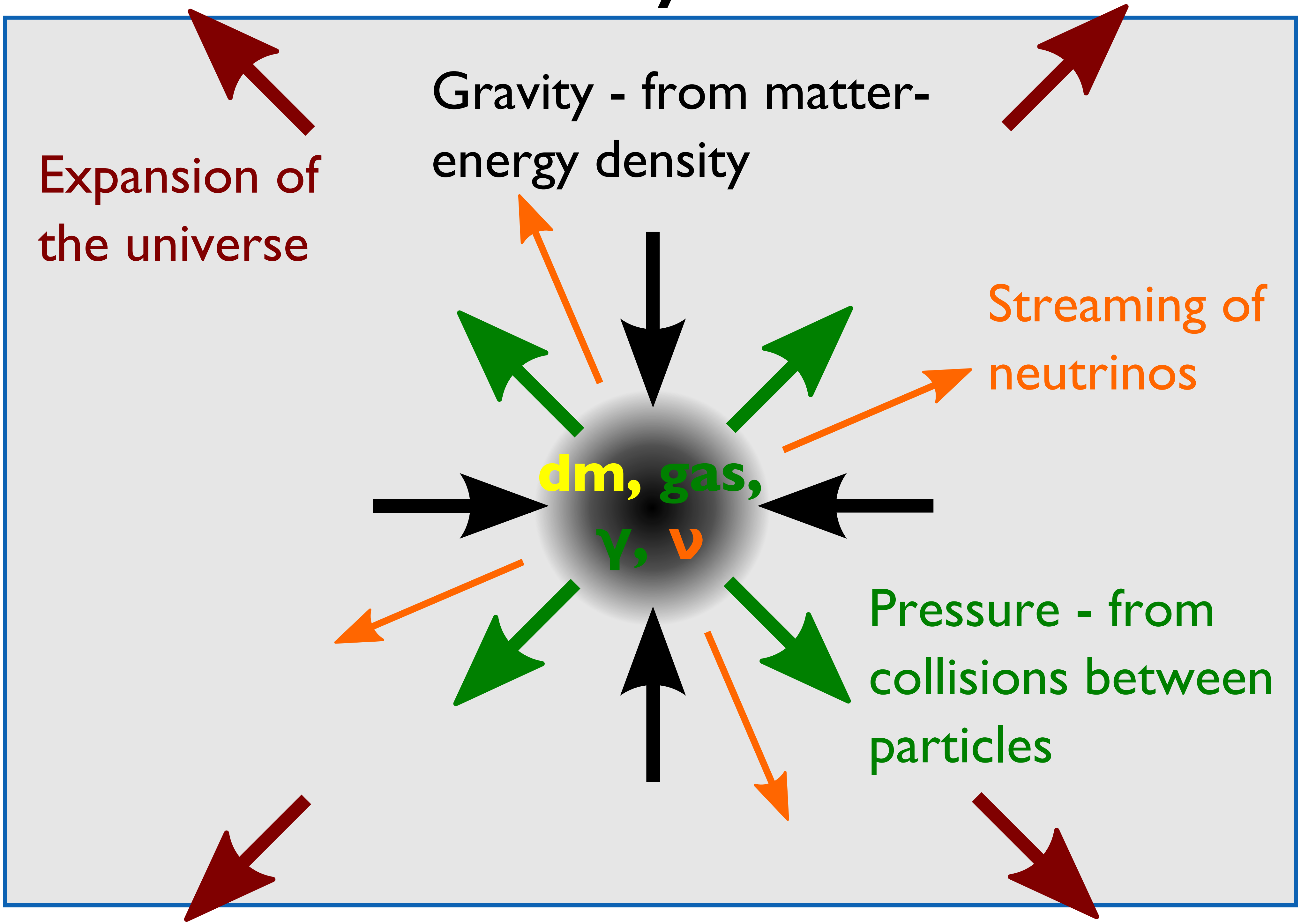
Inflation and initial fluctuations



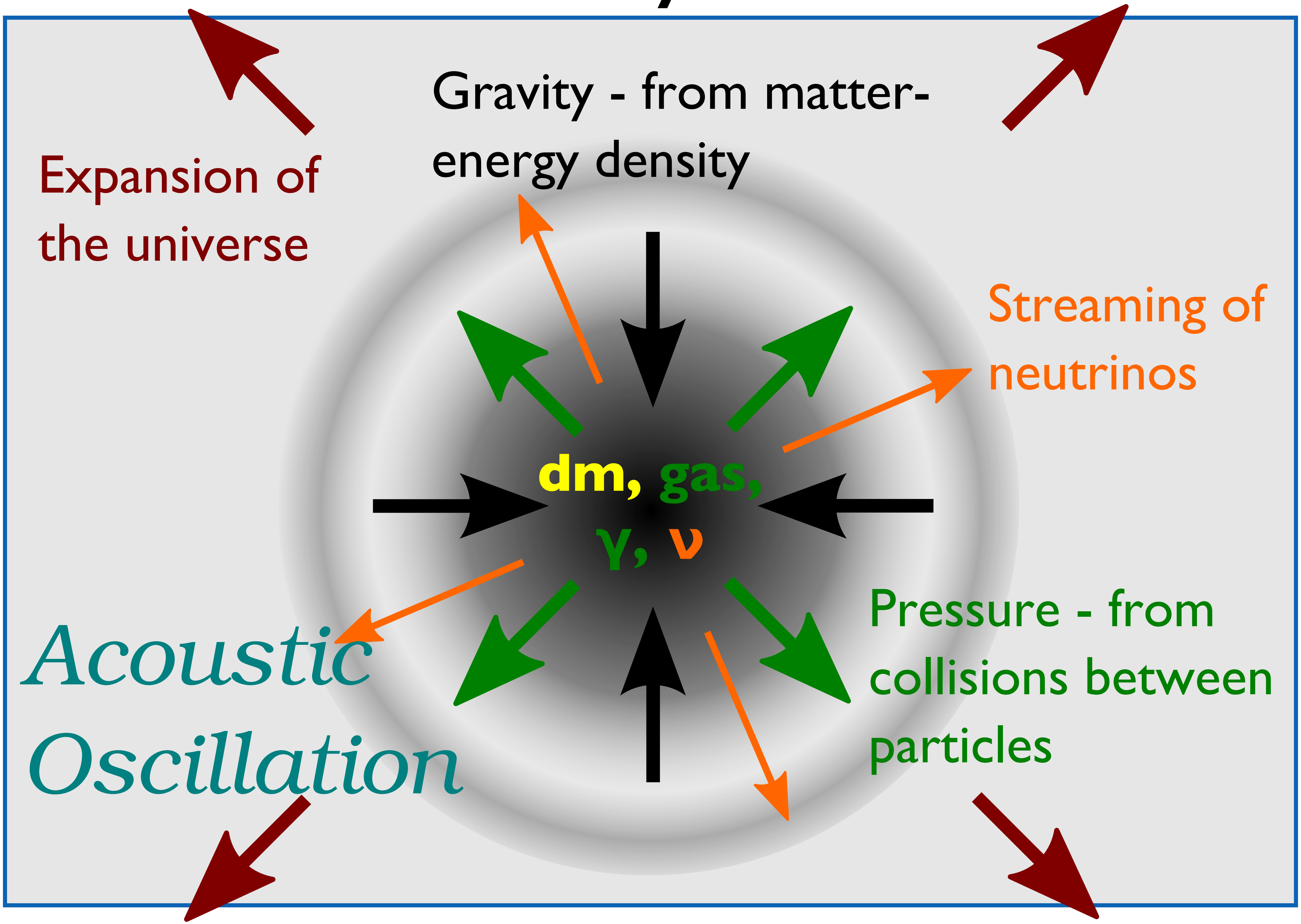
Nearly scale-free spectrum of initial fluctuations

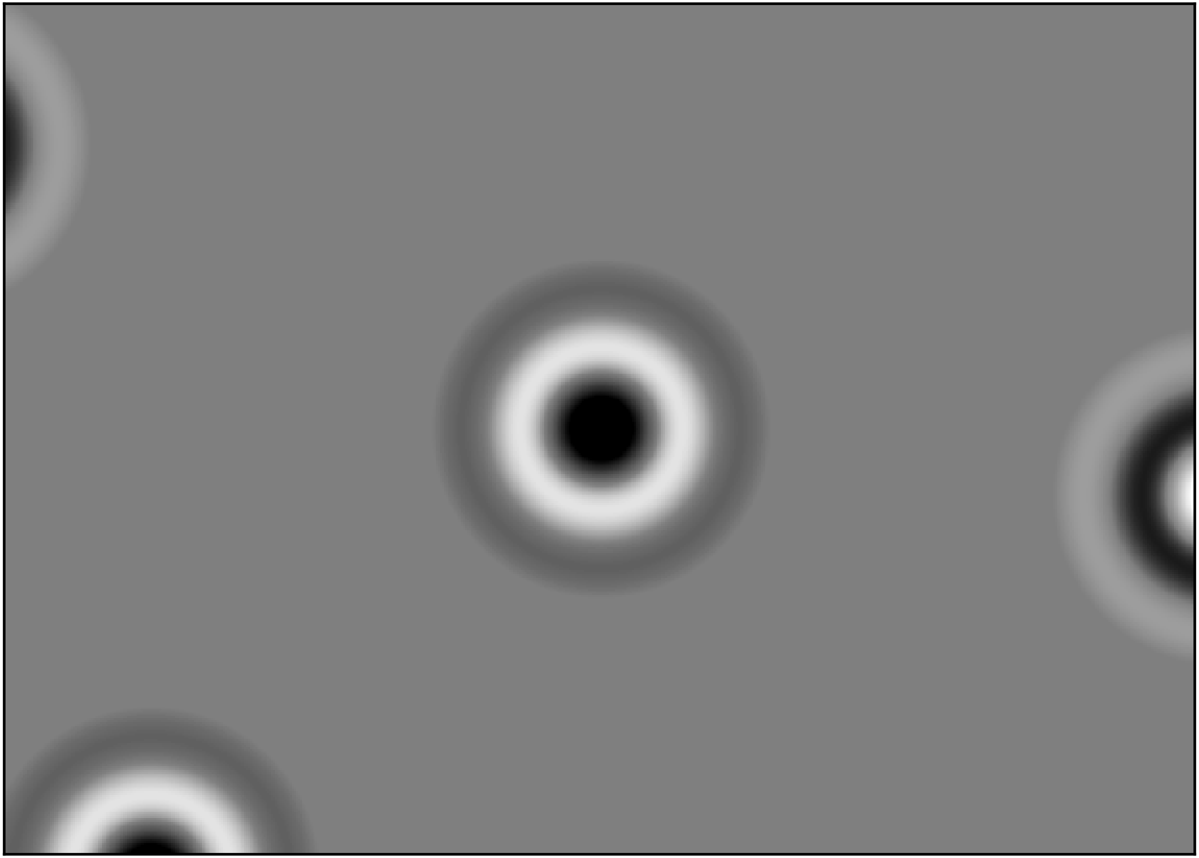
Tensor perturbations (gravitational waves)

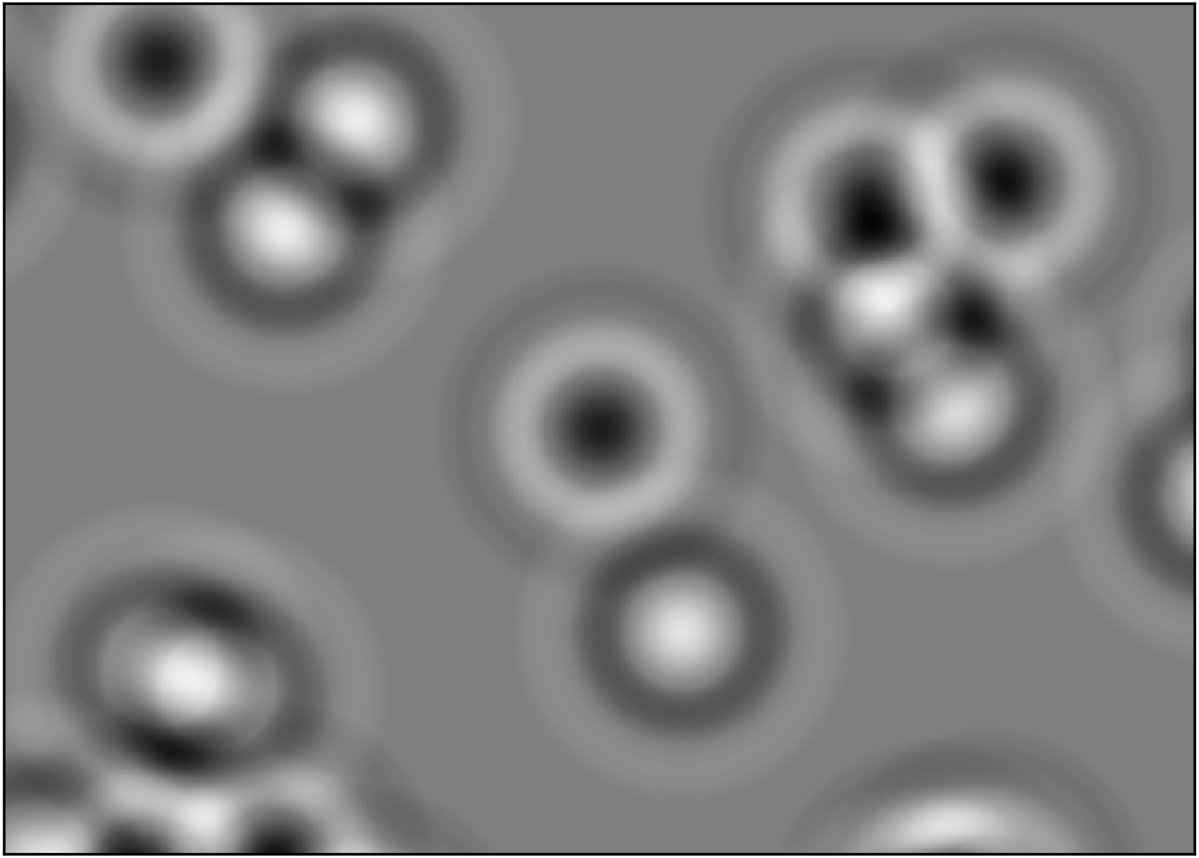
Evolution of overdensity

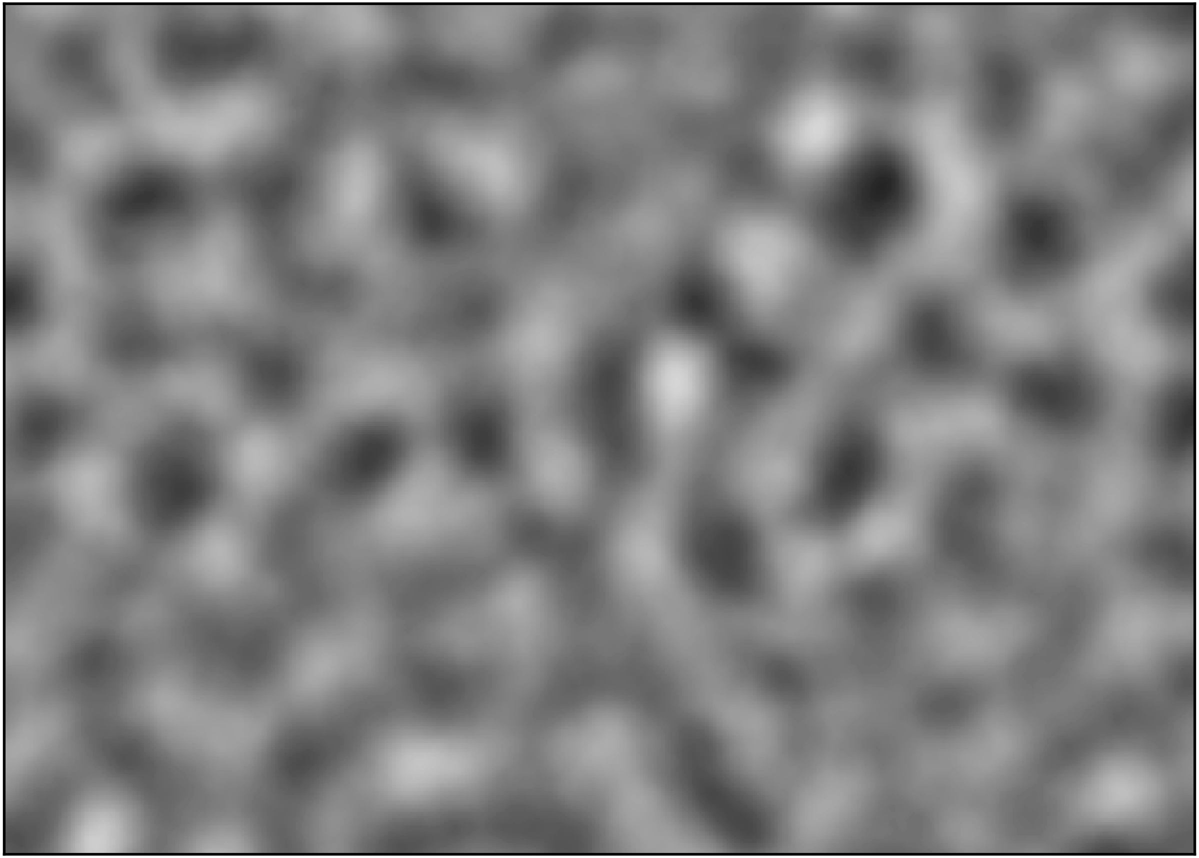


Evolution of overdensity

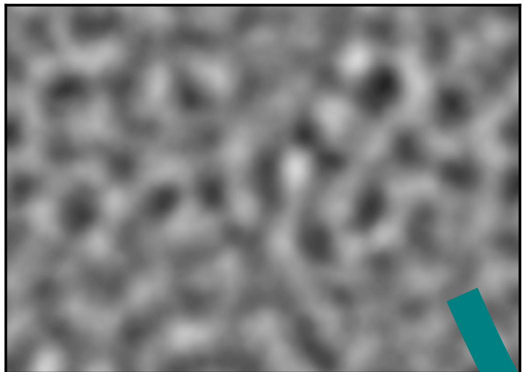






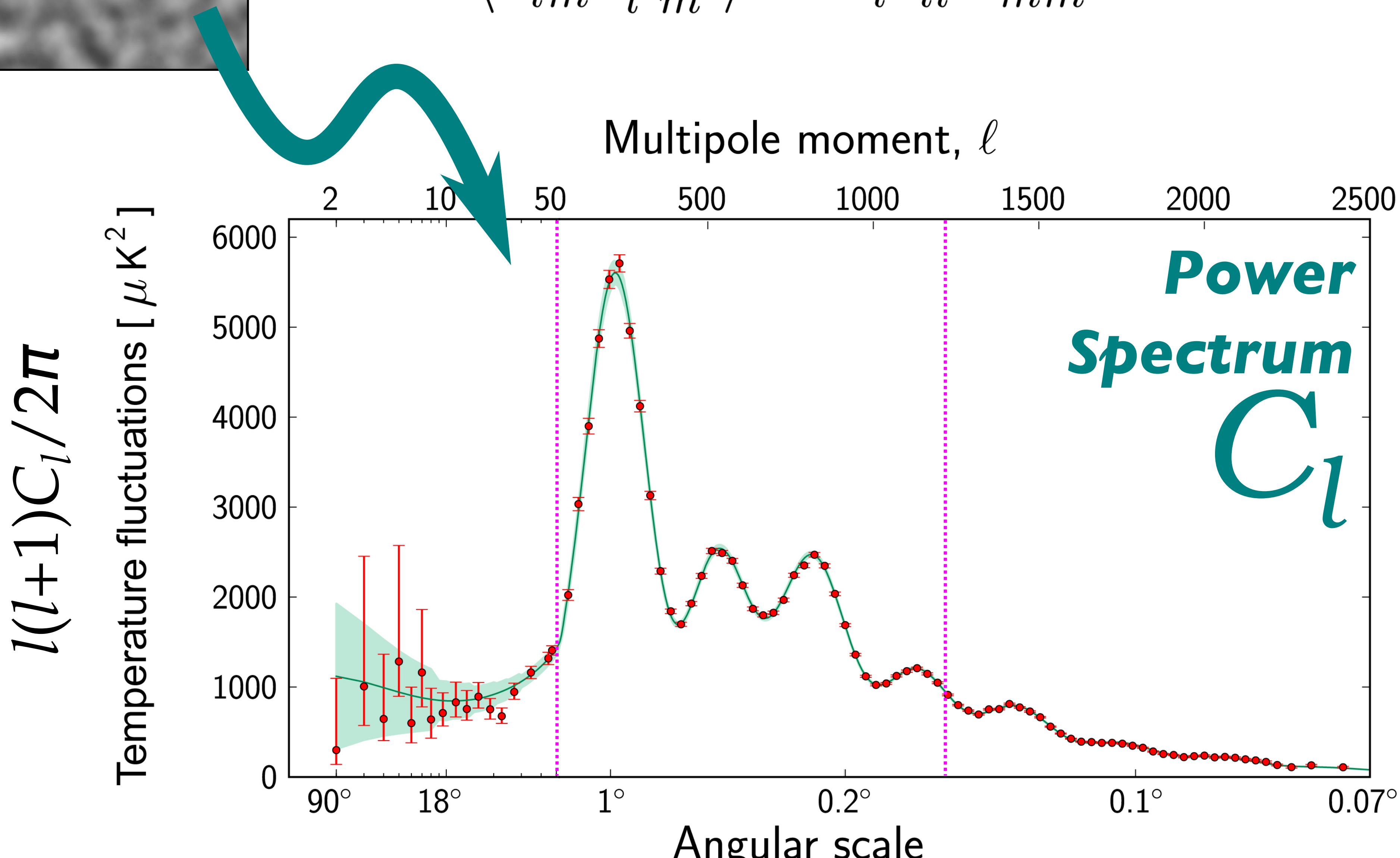


Correlations in harmonic space



$$a_{lm} = \int d\Omega\, T(\theta,\phi) Y^*_{lm}(\theta,\phi)$$

$$\langle a_{lm} a^*_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$



Power spectra provide...

Big picture of ΛCDM cosmology:

5% baryons

27% dark matter

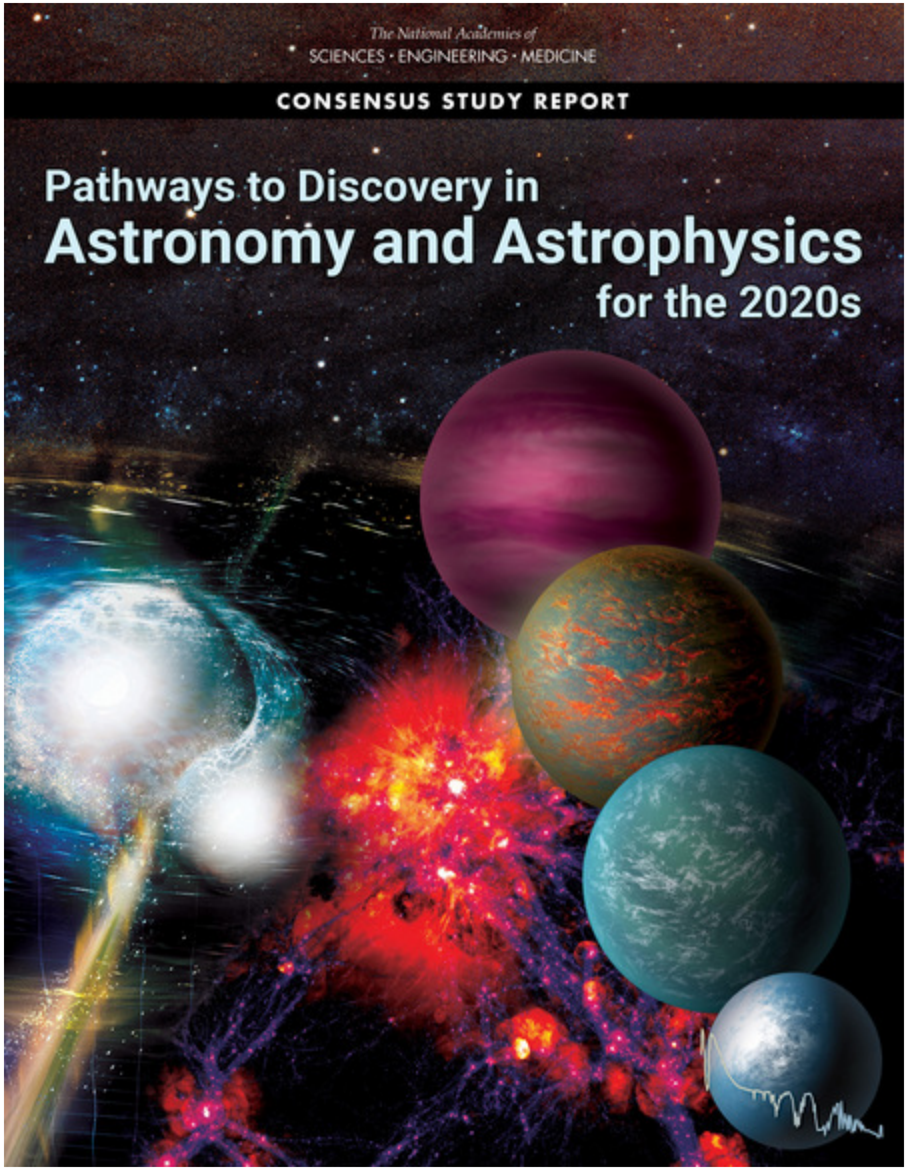
68% dark energy

Spatial flatness

Inflationary spectral tilt $n_s = 0.9649 \pm 0.0042$

... with ~ percent-level precision

Much more to discover...



National Academies Decadal Survey

[G]iven technical and scientific progress over the last decades, ground-based cosmic microwave background (CMB) studies are poised in the next decade to make a major step forward, and the CMB Stage 4 (CMB-S4) observatory (with support from NSF and DOE) will have broad impact on cosmology and astrophysics.

The Survey is also excited by the breadth of science, including time-domain and transient studies, and the potential engagement of a community well beyond traditional CMB cosmologists.

Recommendation: The National Science Foundation and the Department of Energy should jointly pursue the design and implementation of the next generation ground-based cosmic microwave background experiment (CMB-S4).

https://nap.nationalacademies.org/catalog/26141/pathways-to-discovery-in-astronomy-and-astrophysics-for-the-2020s

Snowmass cosmic frontier plenary, Seattle July 2022

The Cosmic Frontier strategy

In order to completely fulfill its science mission:

- CF's top project priority is to complete the construction of CMB-S4, launch new efforts to delve deep and search wide for dark matter, and to aim high in advancing dark energy and cosmic acceleration research.

- CF seeks increased research support to execute the science goals of all projects in its portfolio, including new funding mechanisms to support cross-survey science and theory, and to leverage projects such as DESI, LSST, and CMB-S4.

https://indico.fnal.gov/event/22303/contributions/246084/subcontributions/8621

What is the excitement about?

Primordial gravitational waves ★

Light relic particles beyond-the-standard-model ★

Neutrino mass

Integrated maps of gas pressure to high redshift (incl. galaxy clusters)

Integrated (lensing) maps of total mass to high redshift

Time-domain millimeter-wave astronomy ★

... and more!

Gravitational Waves

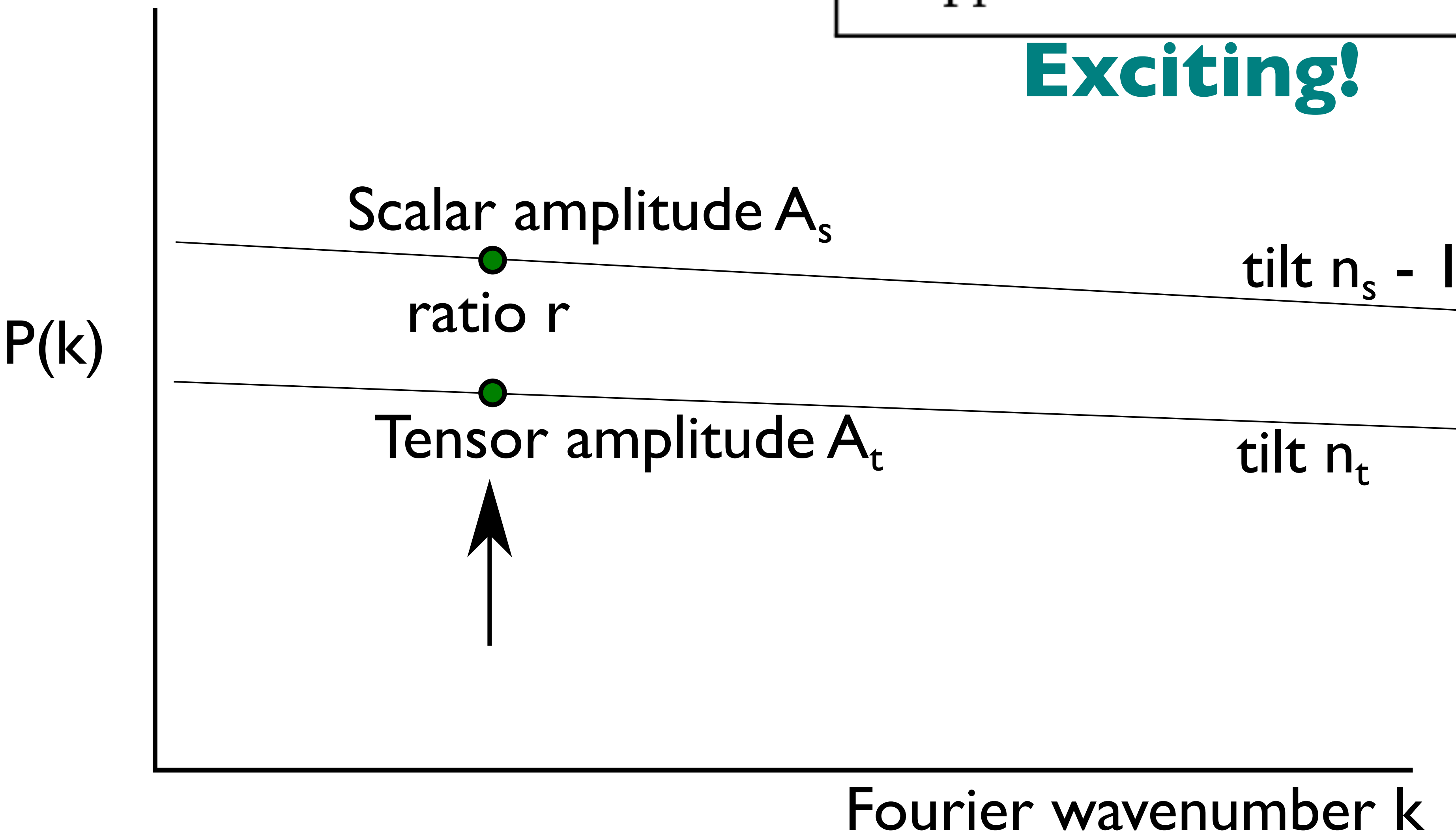
Polarization

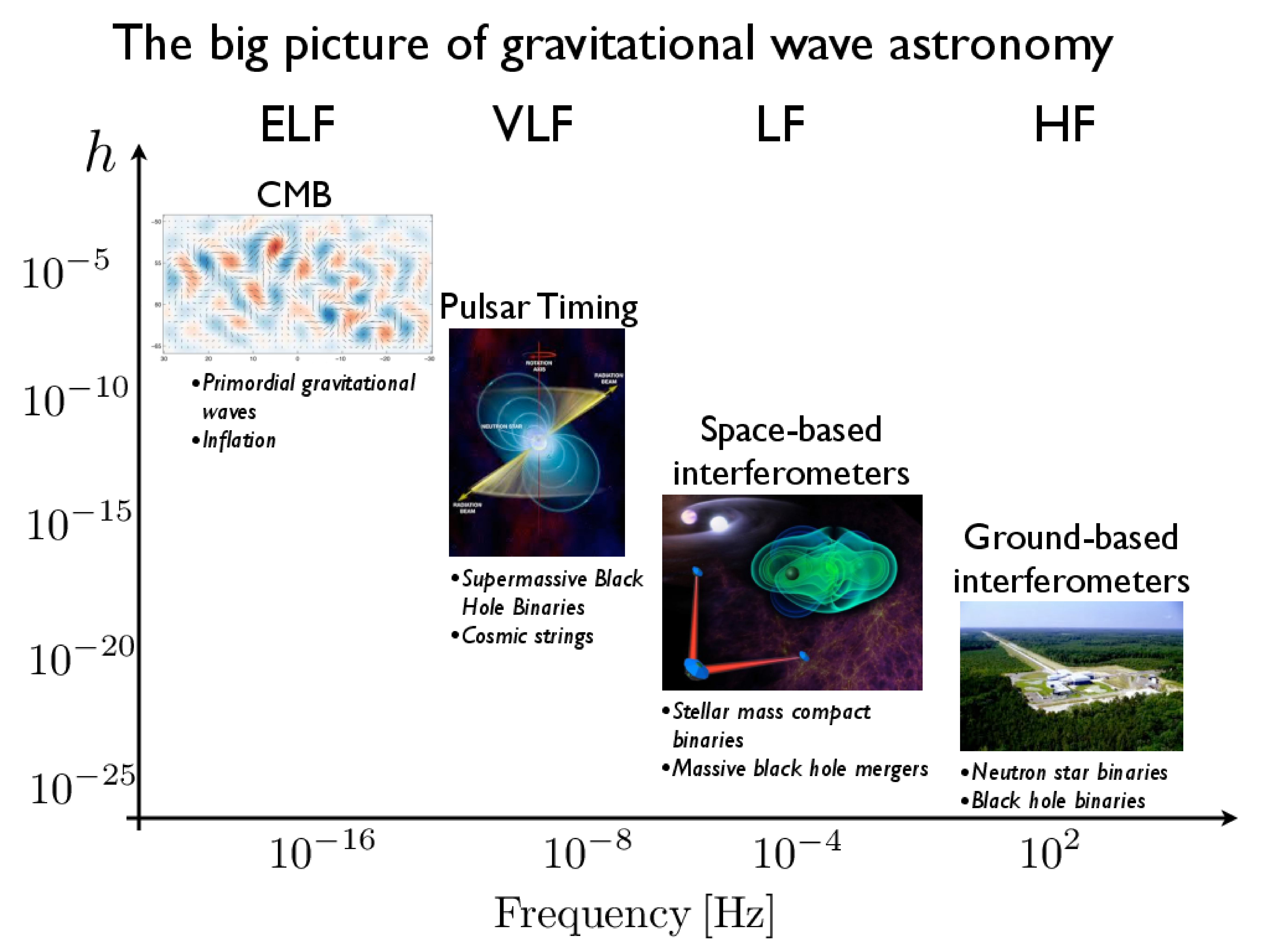
B modes

inflaton potential

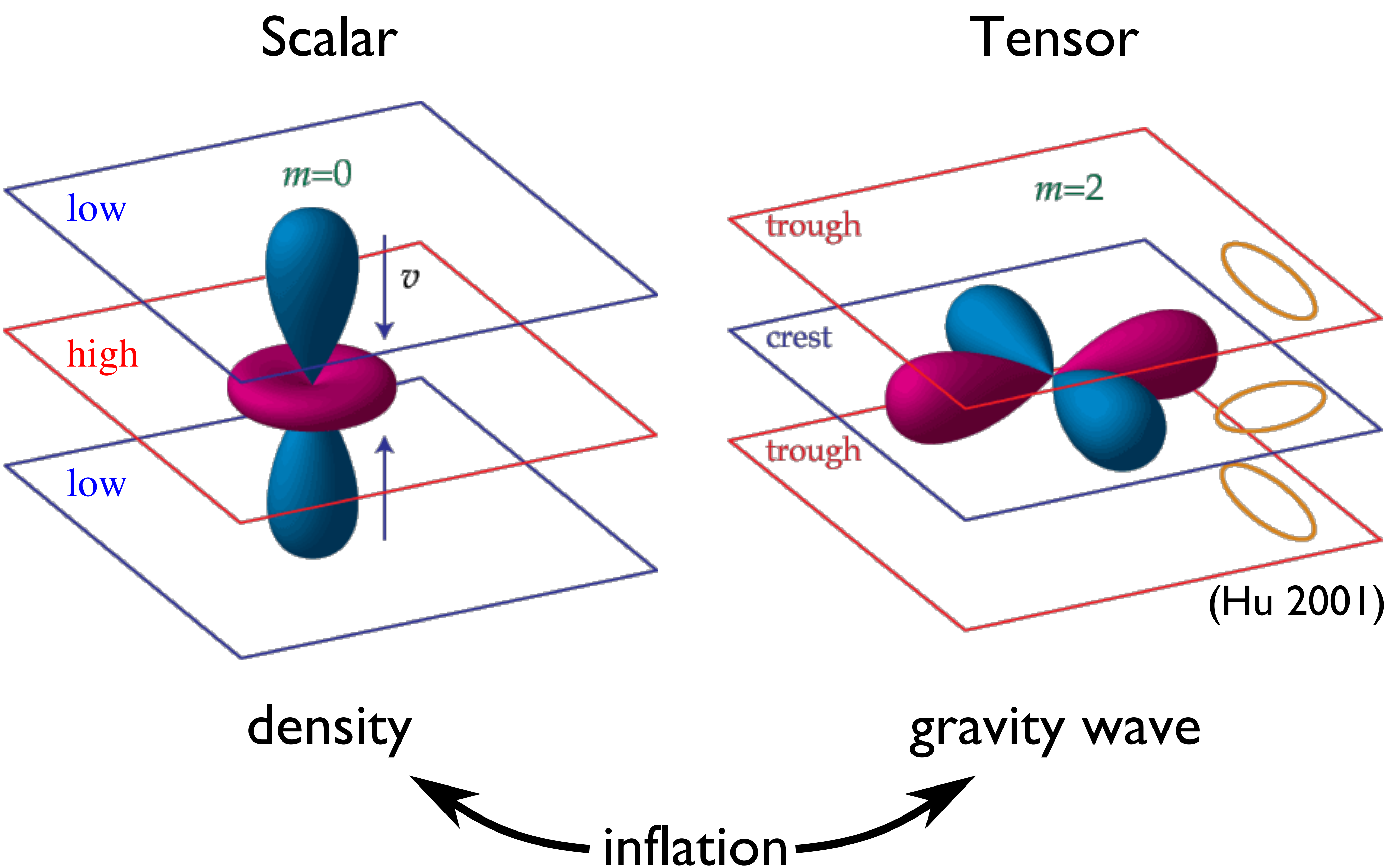
$$r = \frac{8}{M_{\rm Pl}^2}\left(\frac{d\phi}{dN}\right)^2 \longrightarrow \boxed{\frac{\Delta\phi}{M_{\rm Pl}} = \mathcal{O}(1)\sqrt{\frac{r}{0.01}}.}$$

Exciting!

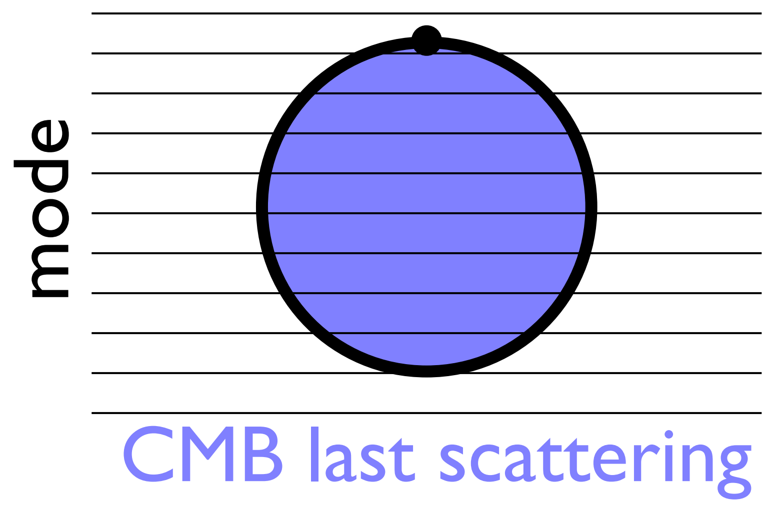


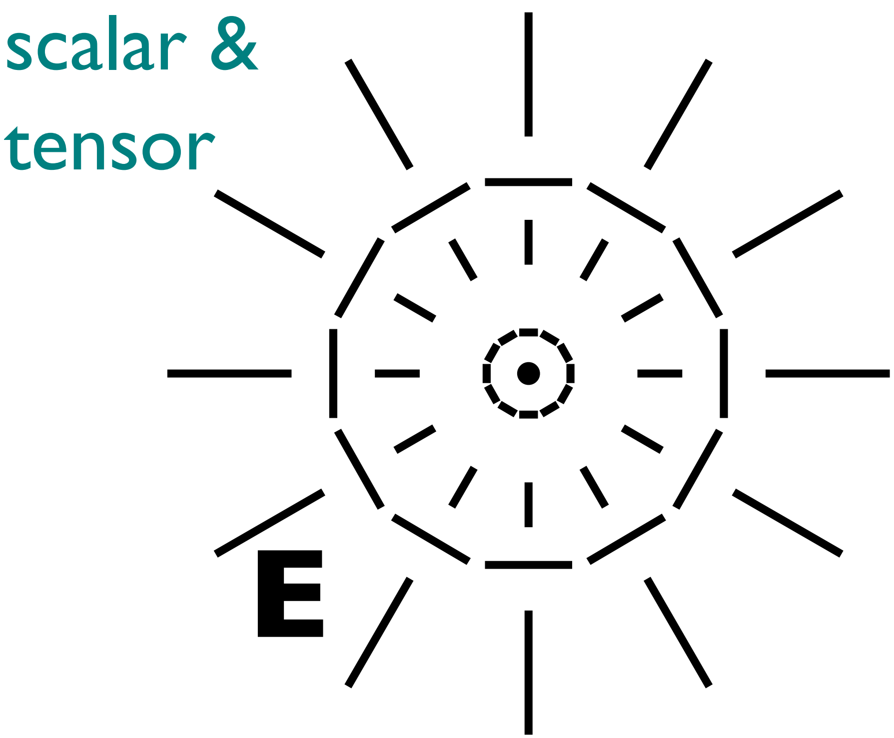

The big picture of gravitational wave astronomy
ELF
VLF
LF
HF
h
CMB
•Primordial gravitational waves
•Inflation
Pulsar Timing
•Supermassive Black Hole Binaries
•Cosmic strings
Space-based interferometers
•Stellar mass compact binaries
•Massive black hole mergers
Ground-based interferometers
•Neutron star binaries
•Black hole binaries
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-16}
10^{-8}
10^{-4}
10^{2}
Frequency [Hz]

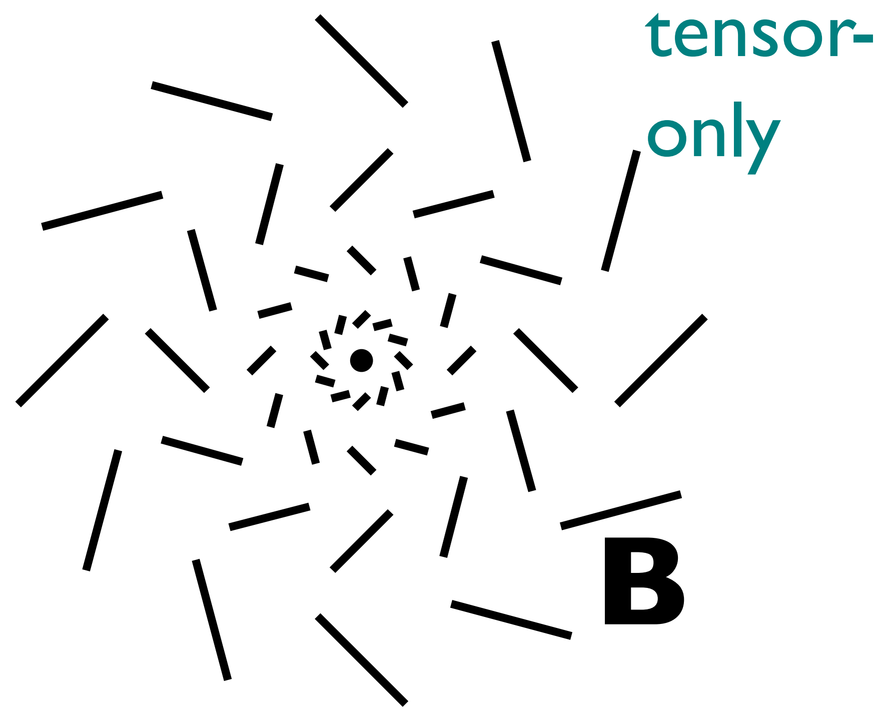
Perturbations generating quadrupoles



Types of polarization patterns



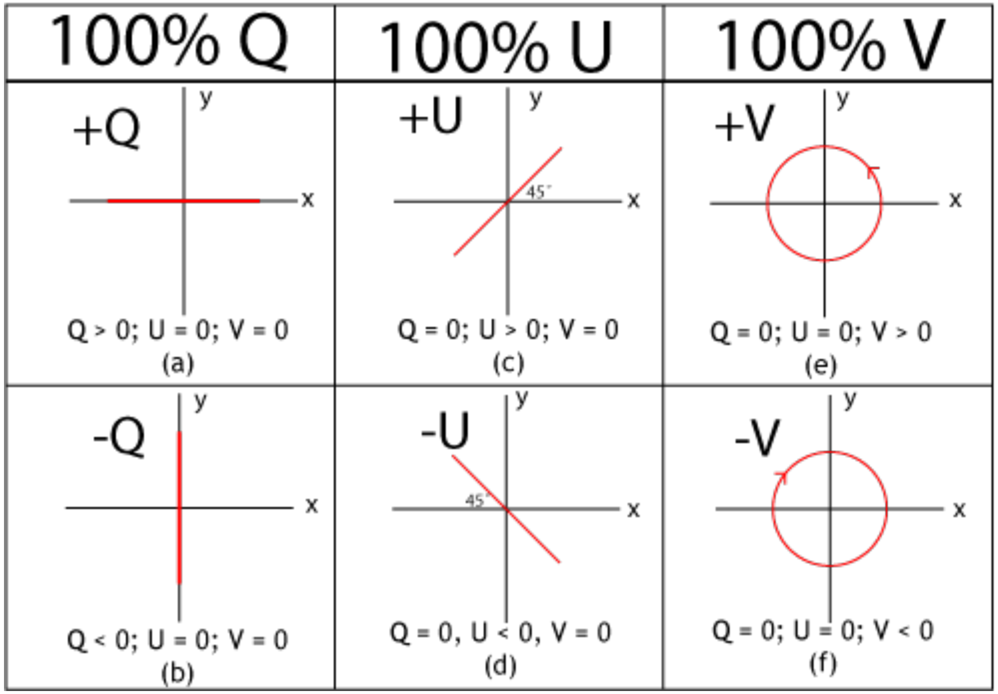




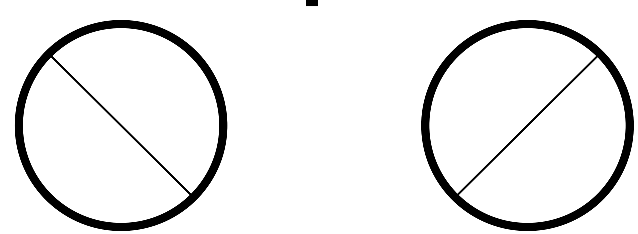
Polarization analysis

Step 1: decompose incoming E field into Stokes parameters:

T, Q, U, V



projected in polarized 3d



Polarization analysis

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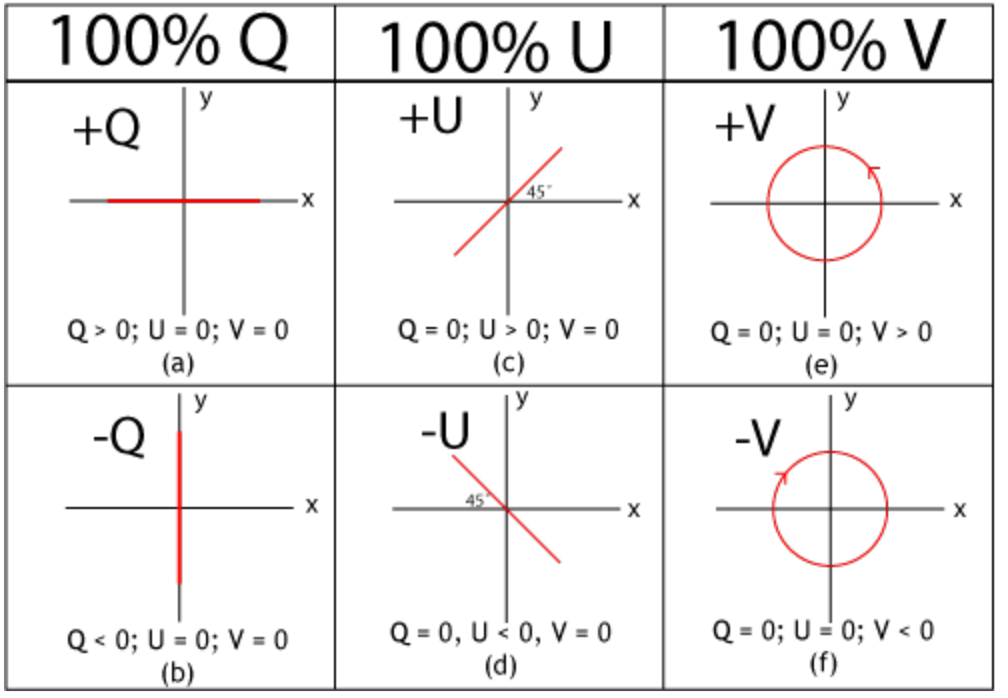


Step 2: rewrite in spin-0 and spin-2 sph. harm. basis:

$$T(\mathbf{n}) = \sum_{lm} a_{T,lm} Y_{lm}(\mathbf{n})$$

$$(Q+iU)(\mathbf{n}) = \sum_{lm} a_{2,lm}\ {}_2Y_{lm}(\mathbf{n})$$

$$(Q-iU)(\mathbf{n}) = \sum_{lm} a_{-2,lm}\ {}_{-2}Y_{lm}(\mathbf{n})$$

Polarization analysis

Step 3: Take even and odd parity combinations.

$$a_{E,lm} = -(a_{2,lm} + a_{-2,lm})/2 \qquad \text{even}$$
$$a_{B,lm} = -(a_{2,lm} - a_{-2,lm})/2i, \qquad \text{odd}$$

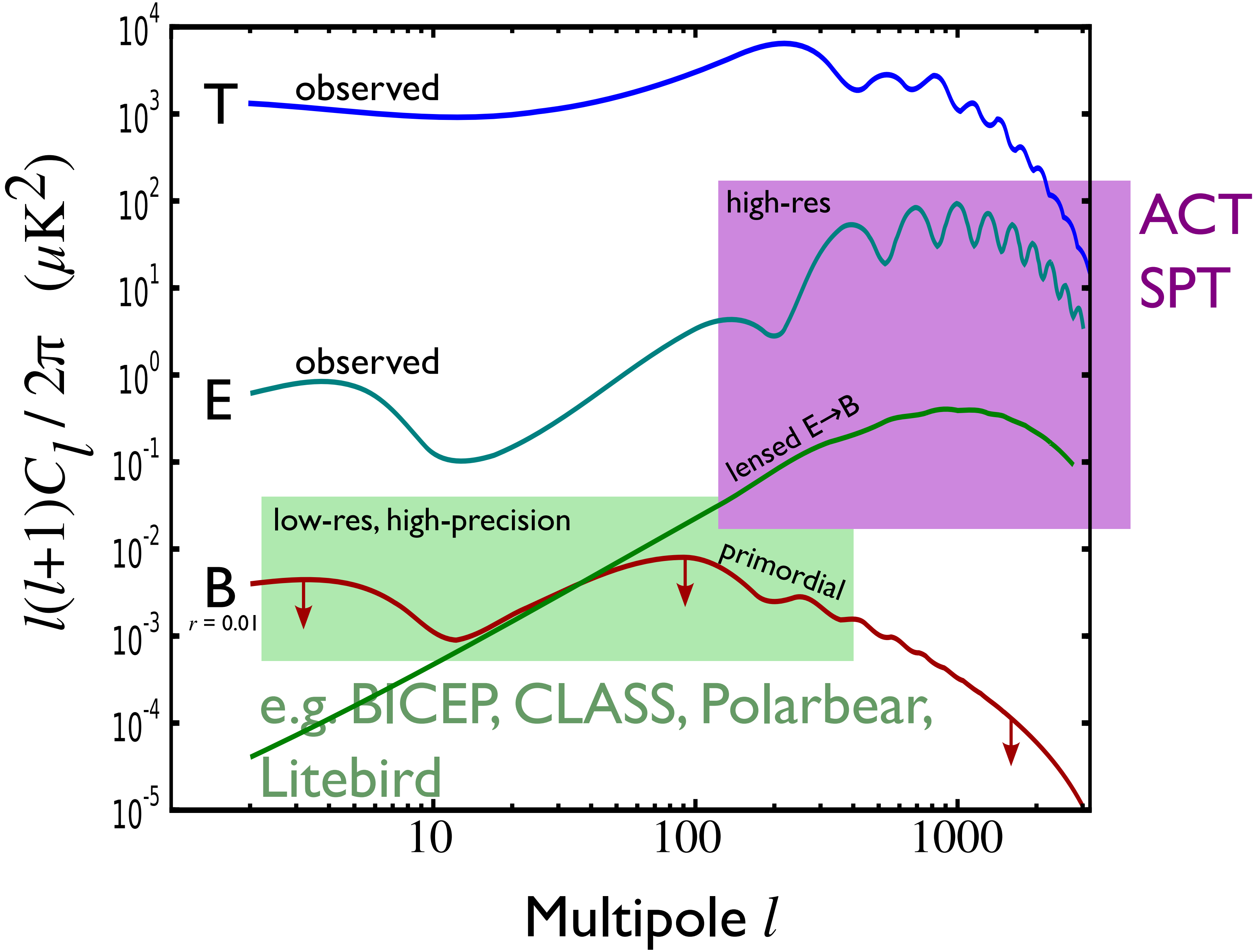
Variance of a_{lm}s are "easy" to compute from theory for T, E, B.

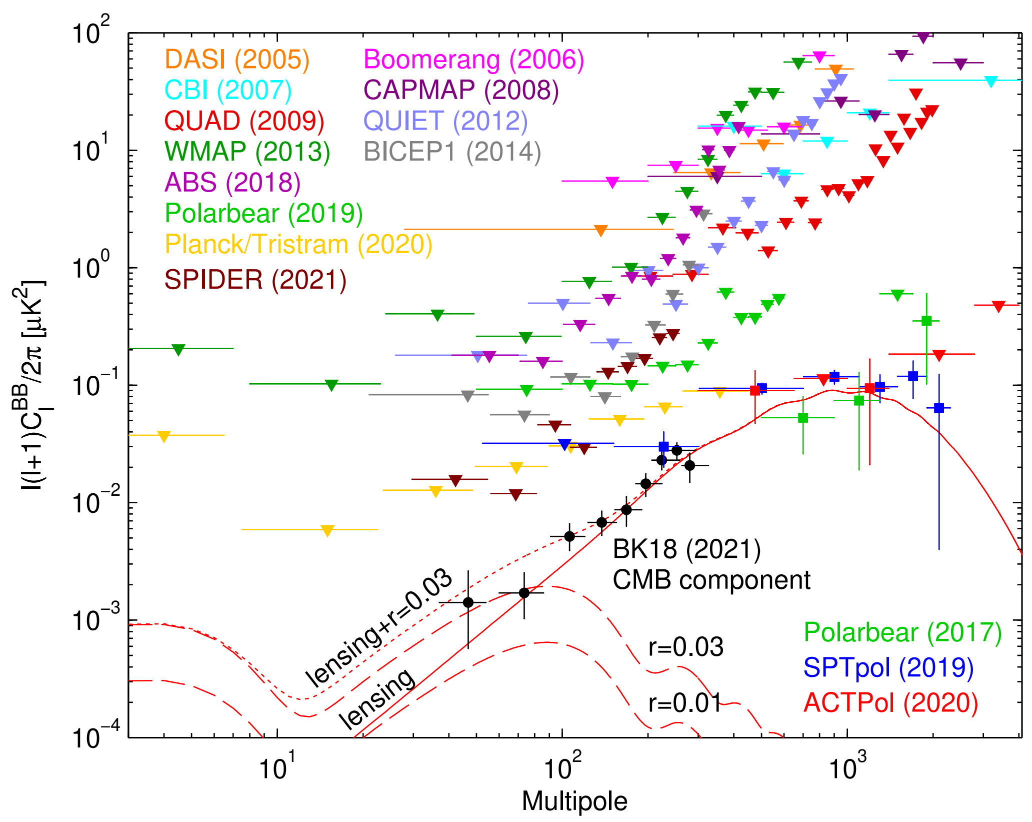
e.g.

$$\langle a^B_{lm} a^{B*}_{lm} \rangle = \delta_{mm'} C^{BB}_l$$

Theory: init'l 3d P(k) for fluct. from infl. (scal., tens.)
composition (gives expansion history and growth)

Polarization power spectra





DASI (2005)
Boomerang (2006)
CBI (2007)
CAPMAP (2008)
QUAD (2009)
QUIET (2012)
WMAP (2013)
BICEP1 (2014)
ABS (2018)
Polarbear (2019)
Planck/Tristram (2020)
SPIDER (2021)
BK18 (2021)
CMB component
lensing+r=0.03
lensing
r=0.03
r=0.01
Polarbear (2017)
SPTpol (2019)
ACTPol (2020)
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
Multipole
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3

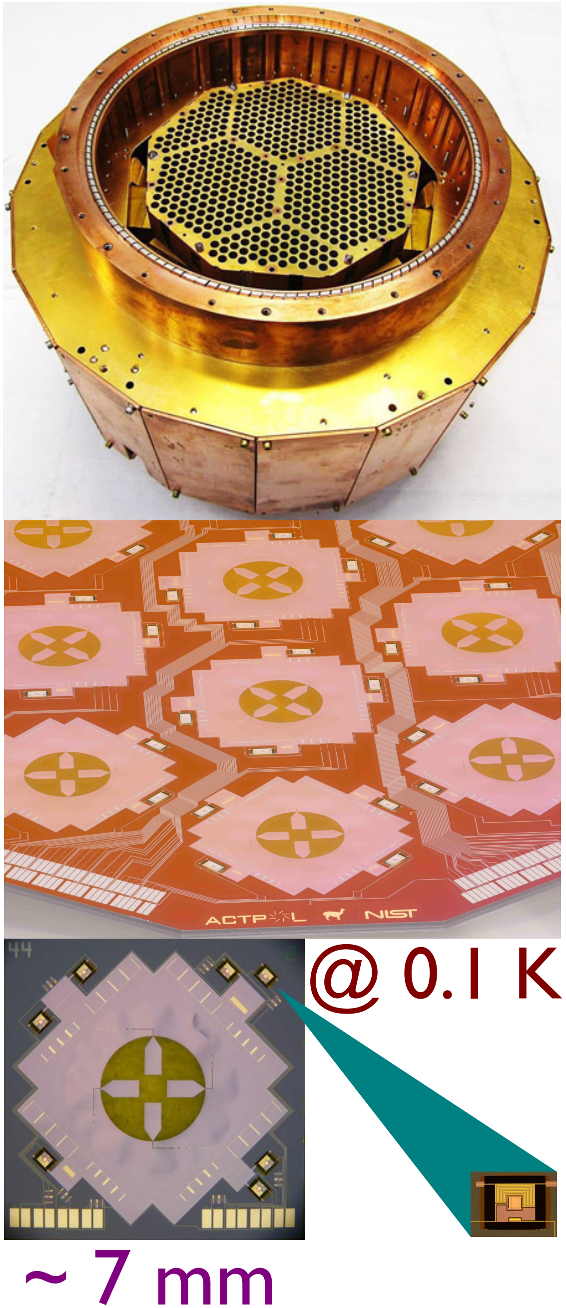
CIPANP plenary

Wednesday Morning, 10:30 am

Zeeshan Ahmed

BICEP 3 results

CMB Detector Technology



Transition Edge Sensor coupled to a polarized bolometer

Major noise source (from ground) is photon shot noise from atmospheric glow

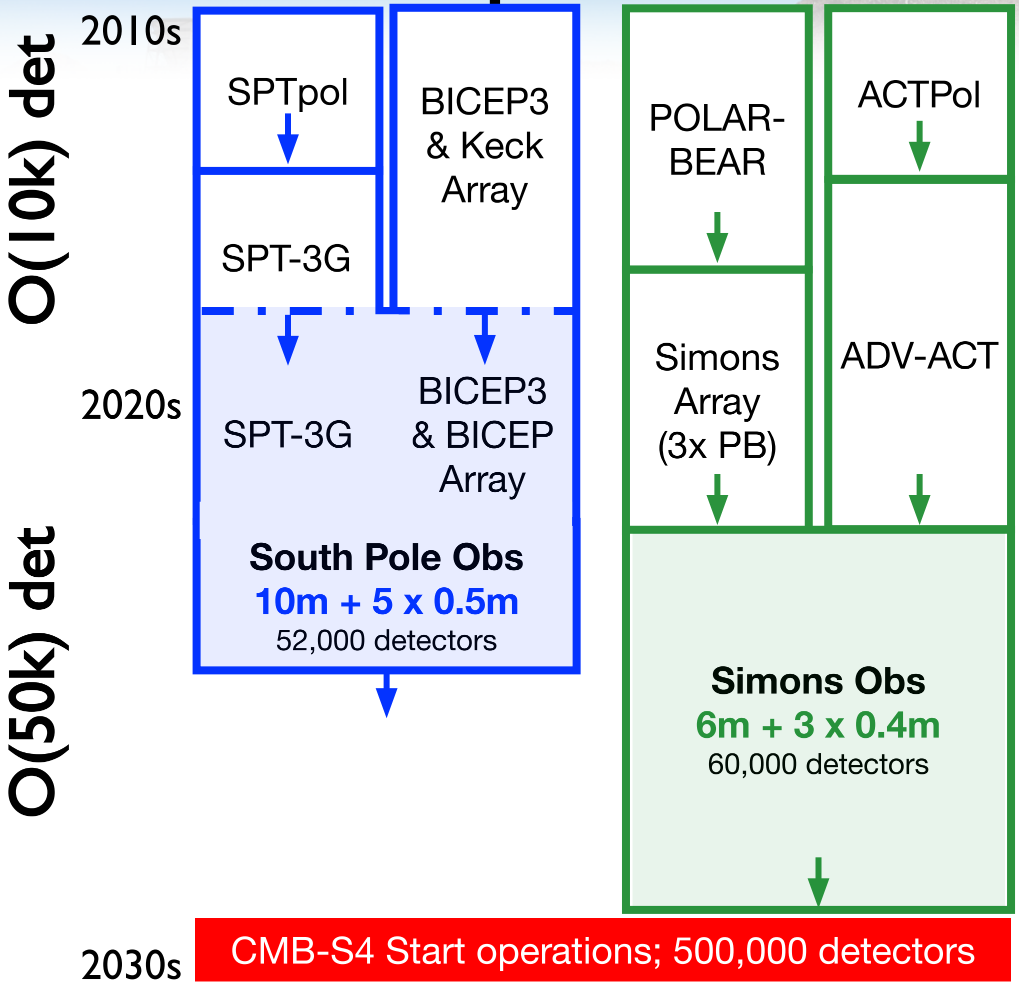
Go to the best atmosphere (South Pole, Atacama in Chile)

Need more detectors, not necessarily better detectors

Trend to big projects. Helpful to have Nat'l Lab resources

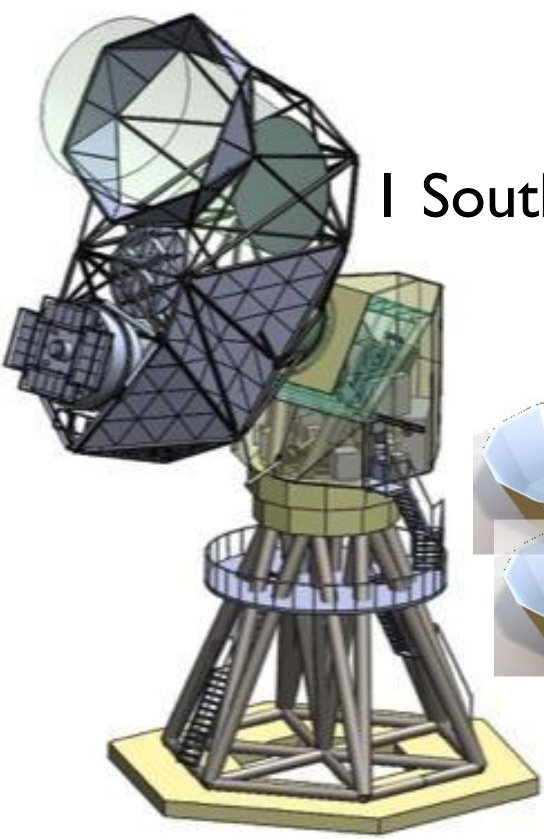
Evolution of Ground-Based CMB Experiments

Simons Obs.

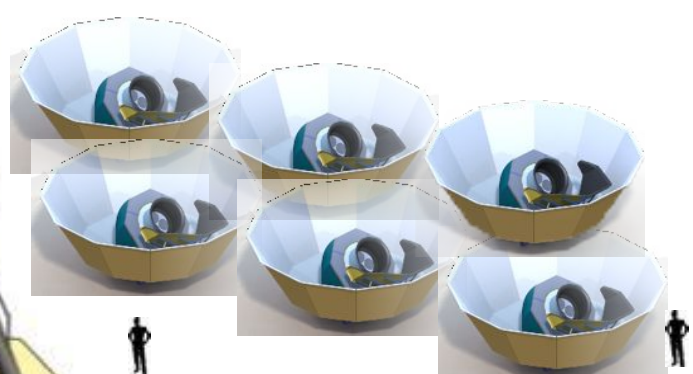


CMB-S4 project - reference design

2 Chile large telescopes (6m)



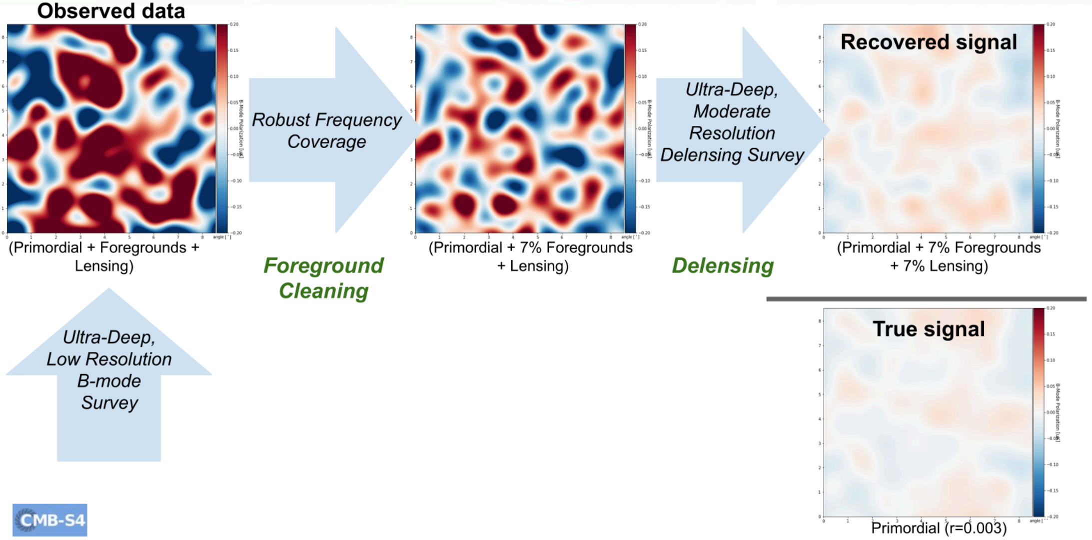
1 South Pole large telescope (5m)



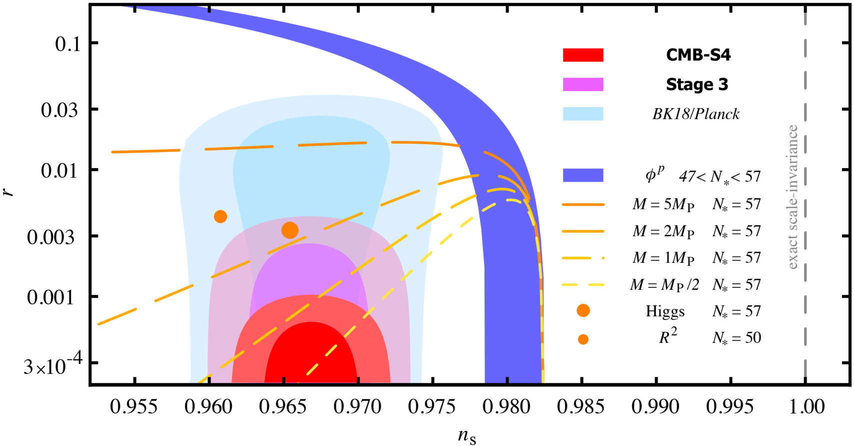
~$600? million cost

18? South Pole small telescopes

Simons Observatory large aperture telescope under construction



Observed data
(Primordial + Foregrounds + Lensing)
Robust Frequency Coverage
Foreground Cleaning
(Primordial + 7% Foregrounds + Lensing)
Ultra-Deep, Moderate Resolution Delensing Survey
Delensing
Recovered signal
(Primordial + 7% Foregrounds + 7% Lensing)
True signal
Primordial (r=0.003)
Ultra-Deep, Low Resolution B-mode Survey
CMB-S4

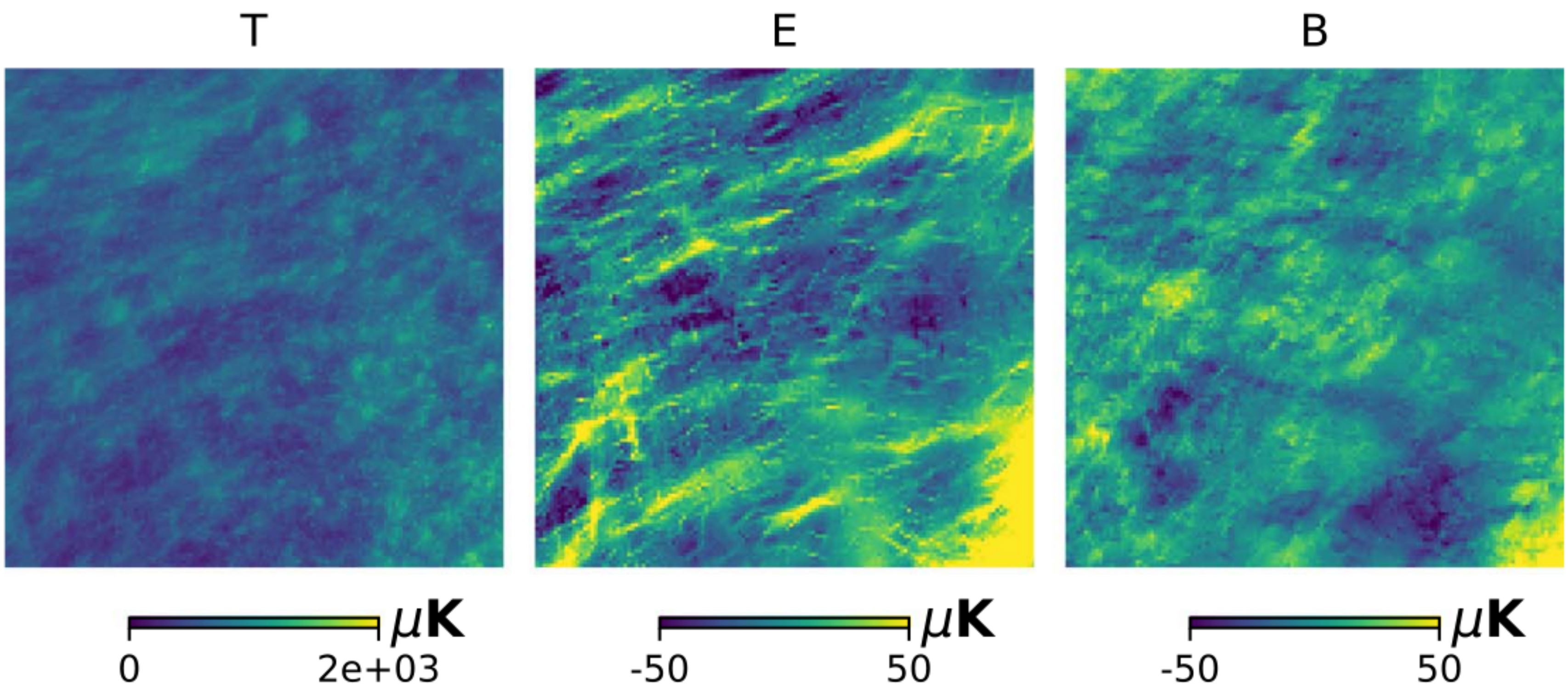


CMB-S4
Stage 3
BK18/Planck
ϕ^p 47< N_*< 57
$M = 5M_P$ $N_* = 57$
$M = 2M_P$ $N_* = 57$
$M = 1M_P$ $N_* = 57$
$M = M_P/2$ $N_* = 57$
Higgs $N_* = 57$
R^2 $N_* = 50$
exact scale-invariance
0.1
0.03
0.01
0.003
0.001
3×10^{-4}
r
0.955
0.960
0.965
0.970
0.975
0.980
0.985
0.990
0.995
1.00
n_S

Foreground challenge

The primordial B-mode signal is smaller than Milky Way foregrounds and lensing

At FSU we have made several studies of the relationships between the filamentary interstellar medium and the power spectral properties of the foreground polarization



Rotti & Huffenberger 2019, Huffenberger et al 2020, **Hervias-Caimapo & Huffenberger 2022**

Light Relic Particles

Light relic particles

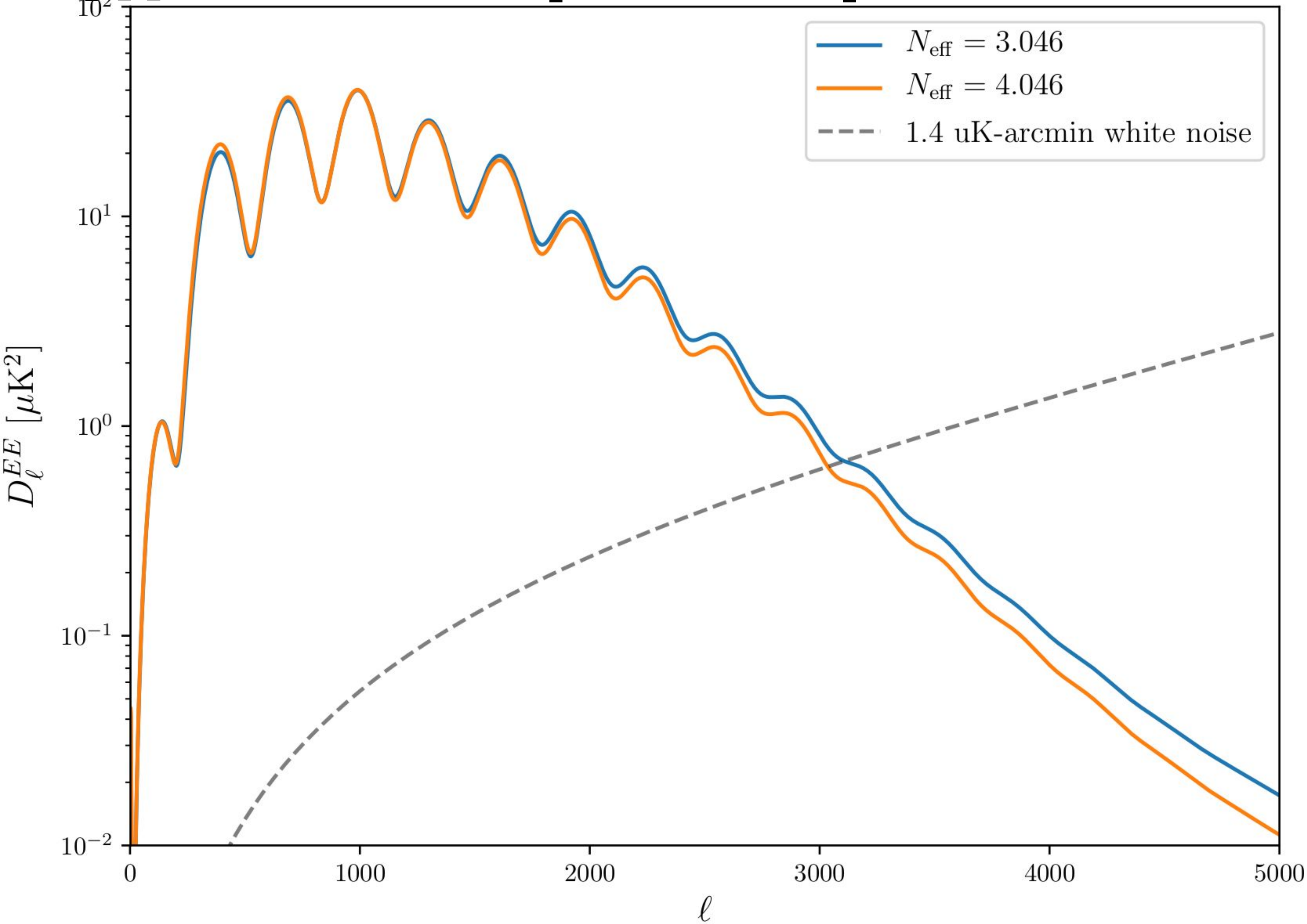
Once they decouple/freeze out, relativistic, free-streaming particles move mass-energy density out of overdensities

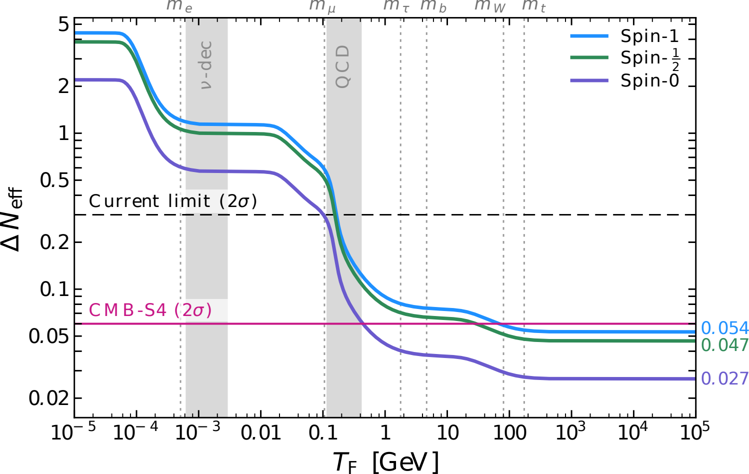
SM has only ν, but any BSM light particle acts similarly: axions, sterile neutrinos, etc.

$$N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma} \qquad N_{\rm eff}^{\rm SM} = 3.044$$

*would be exactly 3 for instant ν decoupling

N_{eff} effect on power spectrum



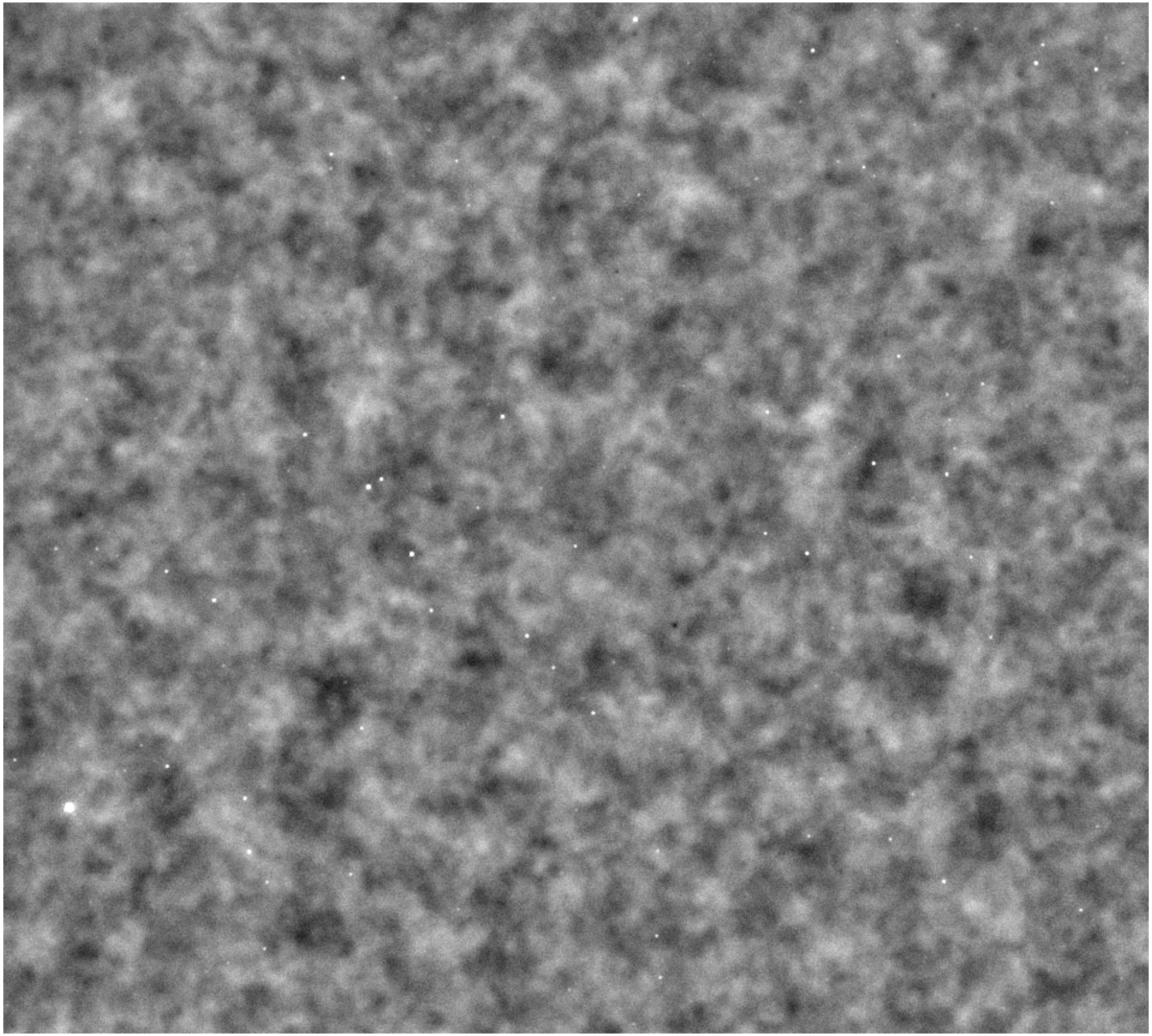


m_e
m_μ
m_τ
m_b
m_W
m_t
ν-dec
QCD
Spin-1
Spin-$\frac{1}{2}$
Spin-0
Current limit (2σ)
CMB-S4 (2σ)
0.054
0.047
0.027
$\Delta N_{\rm eff}$
5
2
1
0.5
0.2
0.1
0.05
0.02
10^{-5}
10^{-4}
10^{-3}
0.01
0.1
1
10
100
10^3
10^4
10^5
$T_{\rm F}$ [GeV]

Mass (eV)
10-30
10-27
10-24
10-21
10-18
10-15
10-12
10-9
10-6
10-3
1
103
106
109
1012
1015
Light Relics
DM annihilation
Ultralight Axions
Axion DM photon coupling
Neutrino Mass & Warm DM
Axion DM Isocurvature
DM-baryon scattering
Primary CMB
Low-ℓ CMB
CMB lensing
CMB modulation
B-modes

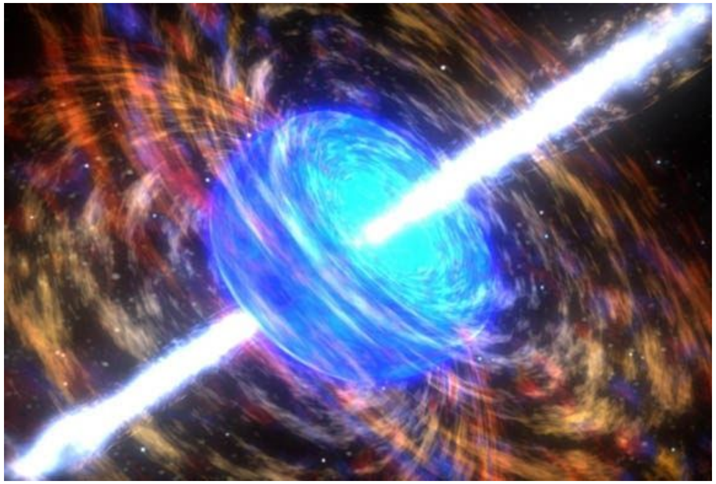
Time domain mm-wave astronomy

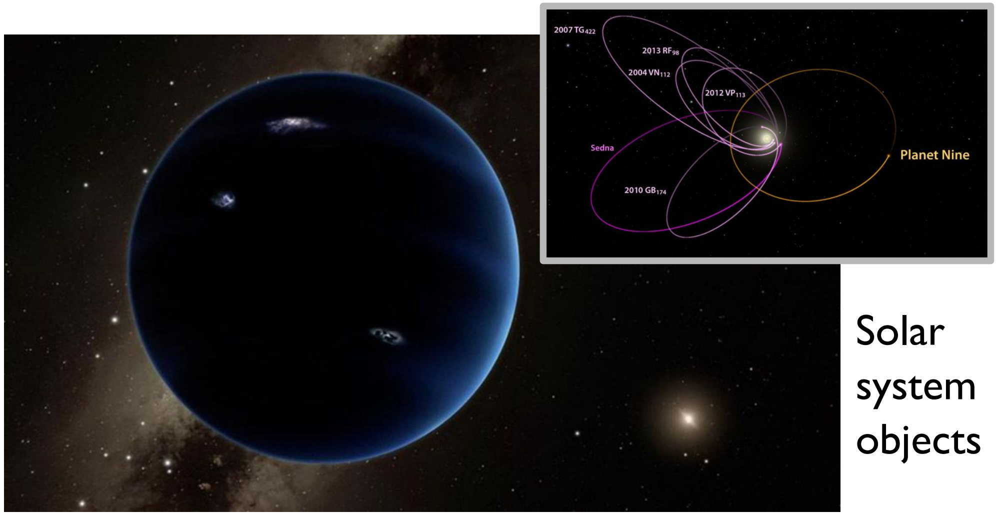
Emissive Sources



Transients in the millimeter

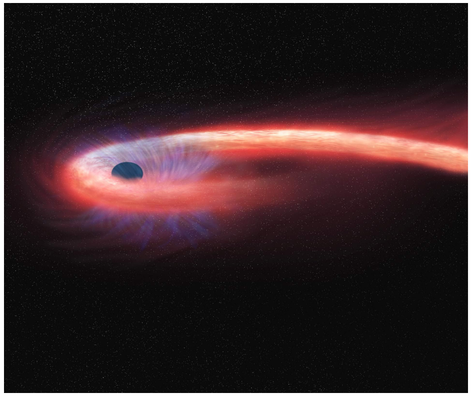
Gamma ray bursts

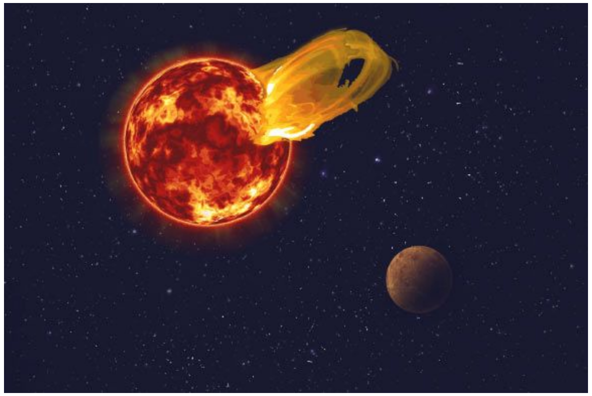




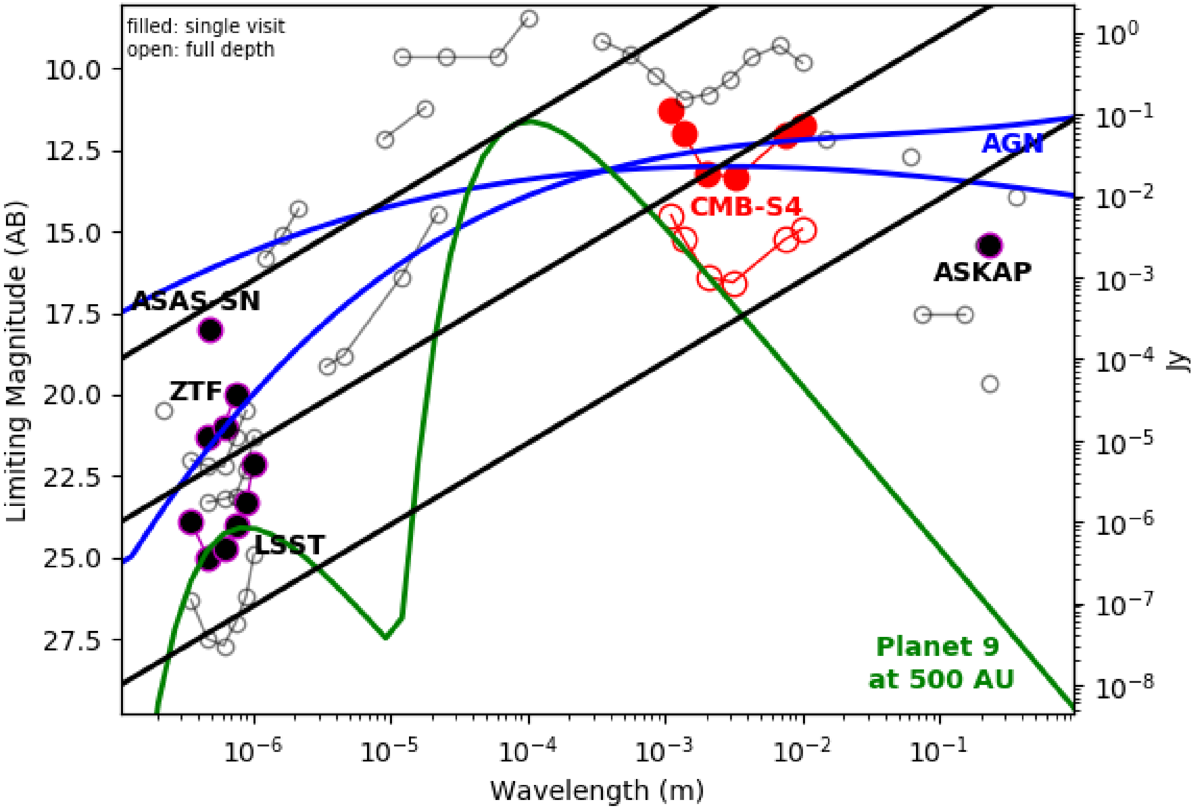
Solar system objects

Tidal disruption events





Stellar flares

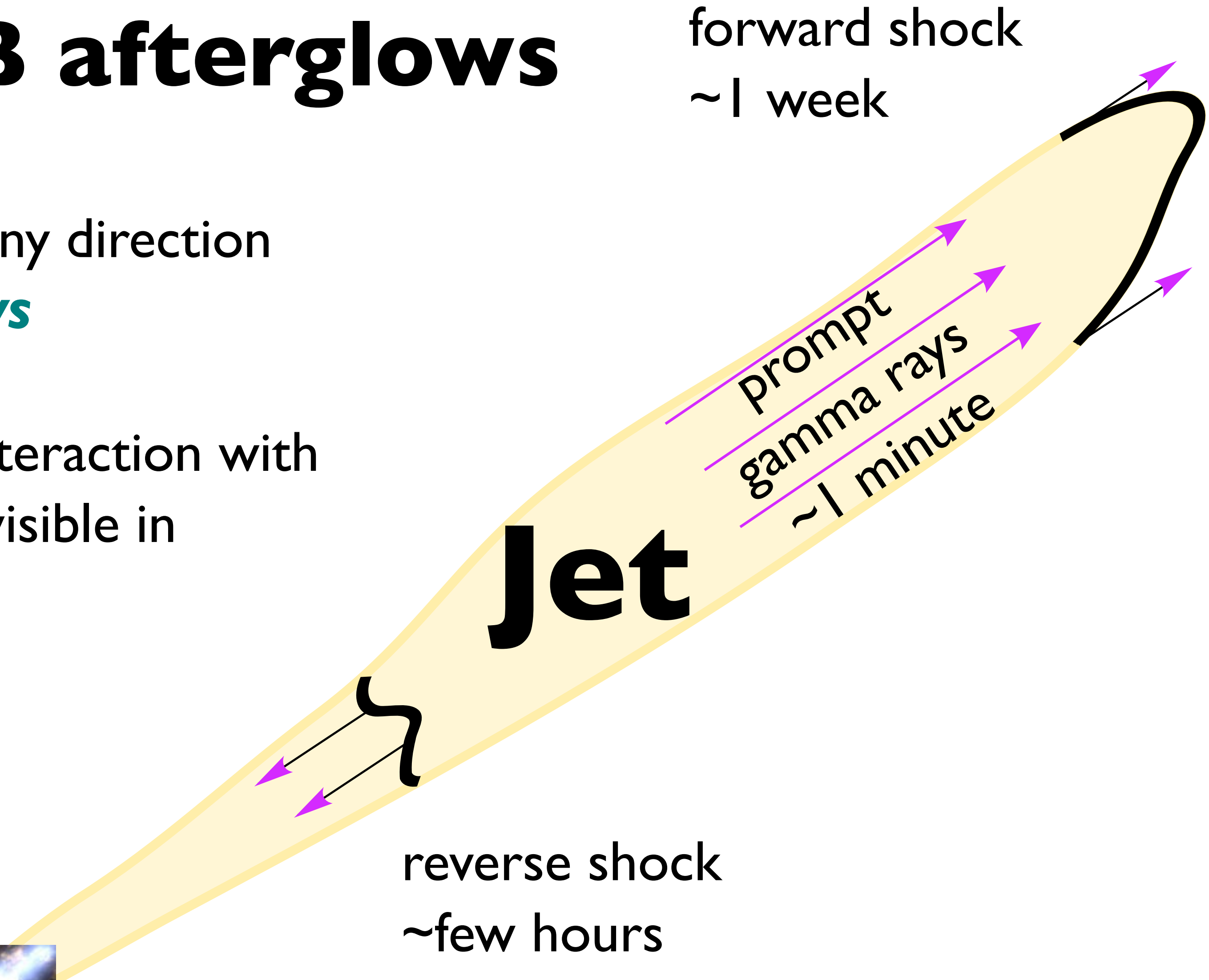


filled: single visit
open: full depth
Limiting Magnitude (AB)
10.0
12.5
15.0
17.5
20.0
22.5
25.0
27.5
Wavelength (m)
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Jy
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
ASAS-SN
ZTF
LSST
CMB-S4
AGN
ASKAP
Planet 9
at 500 AU

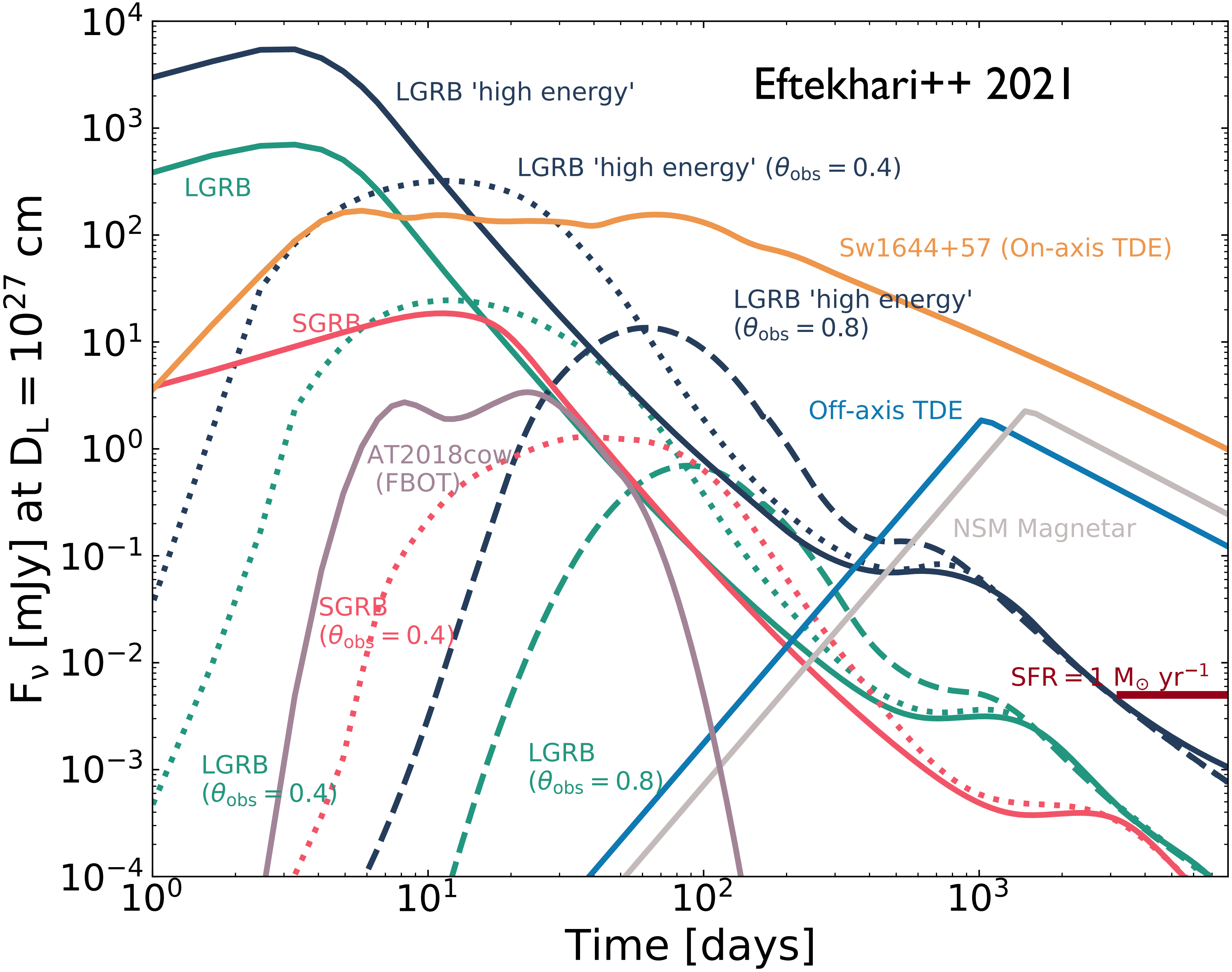
Long-GRB afterglows

afterglow visible in any direction
orphan afterglows

synchrotron from interaction with
ambient medium is visible in
mm waveband



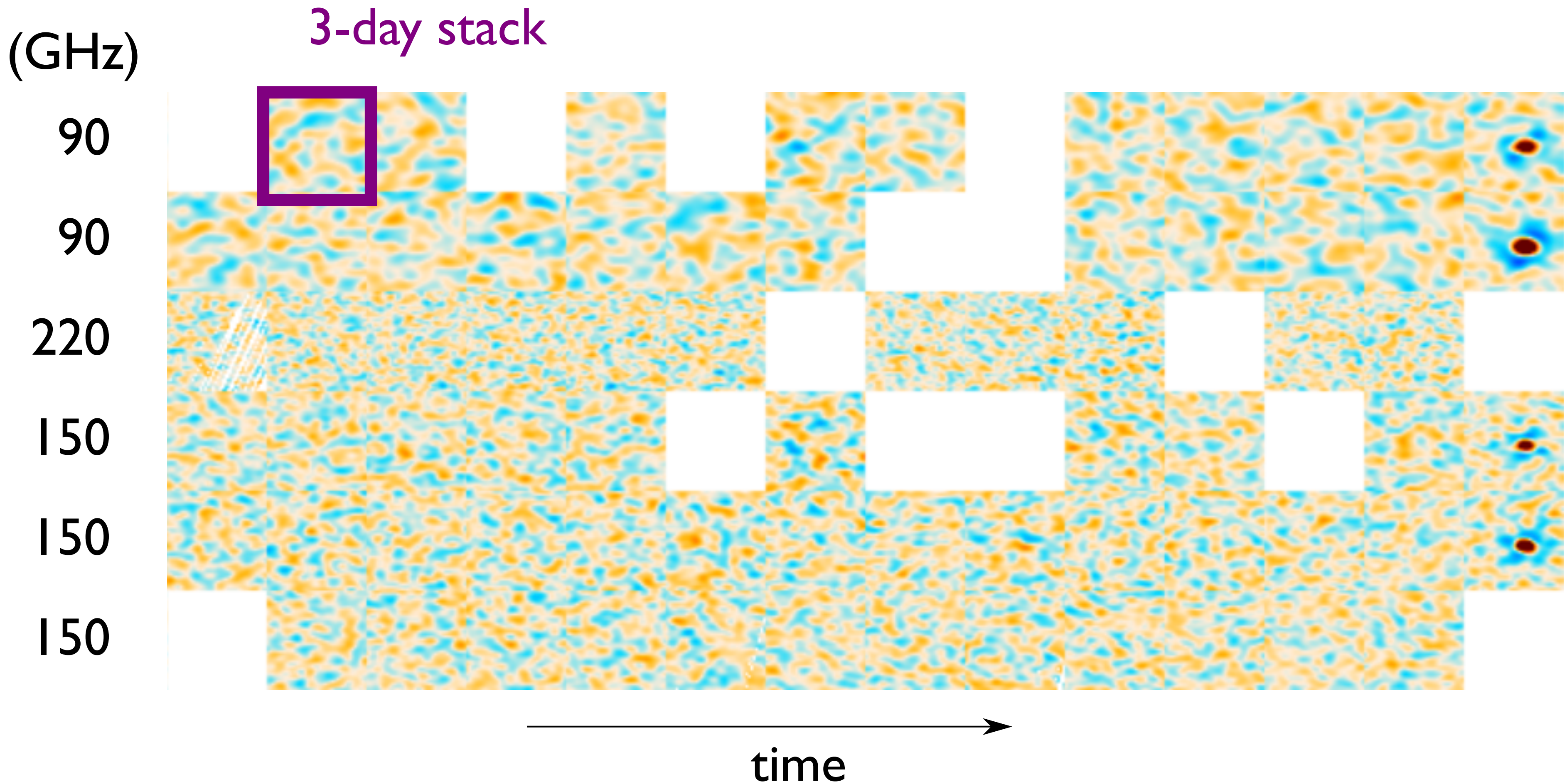
"collapsar/hypernova" direct collapse to black hole + accretion disk



Eftekhari++ 2021
LGRB 'high energy'
LGRB 'high energy' ($\theta_{obs} = 0.4$)
LGRB
Sw1644+57 (On-axis TDE)
LGRB 'high energy' ($\theta_{obs} = 0.8$)
SGRB
Off-axis TDE
AT2018cow (FBOT)
NSM Magnetar
SGRB ($\theta_{obs} = 0.4$)
SFR = 1 $M_\odot$ yr^{-1}
LGRB ($\theta_{obs} = 0.4$)
LGRB ($\theta_{obs} = 0.8$)
F_ν [mJy] at $D_L = 10^{27}$ cm
Time [days]

ACT stellar transients

Naess++ 2021 (ACT)
Guns++ 2021 (SPT)



Diverse, young, main-sequence, magnetically active, binary

Conclusions

CMB is rich in information about physics, astrophysics, and cosmology.

Multifrequency analysis, wide/deep coverage, high-/low-resolution all important (= ACT, SO, CMB-S4 for me)

Primordial B-modes, light relics are among several fundamental physics drivers.

Filament models for polarization foregrounds