Summary

PeV ~~SUSY~~ & GWs

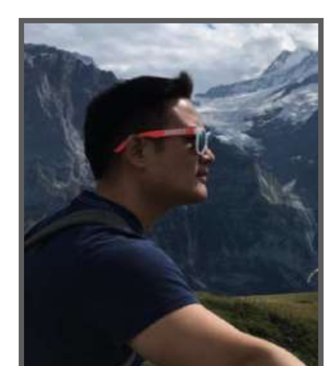
PeV ~~SUSY~~ & Small-scales

Introduction

Probing PeV scale SUSY breaking with satellite galaxies and primordial gravitational waves

Ryusuke Jinno (DESY→IFT)

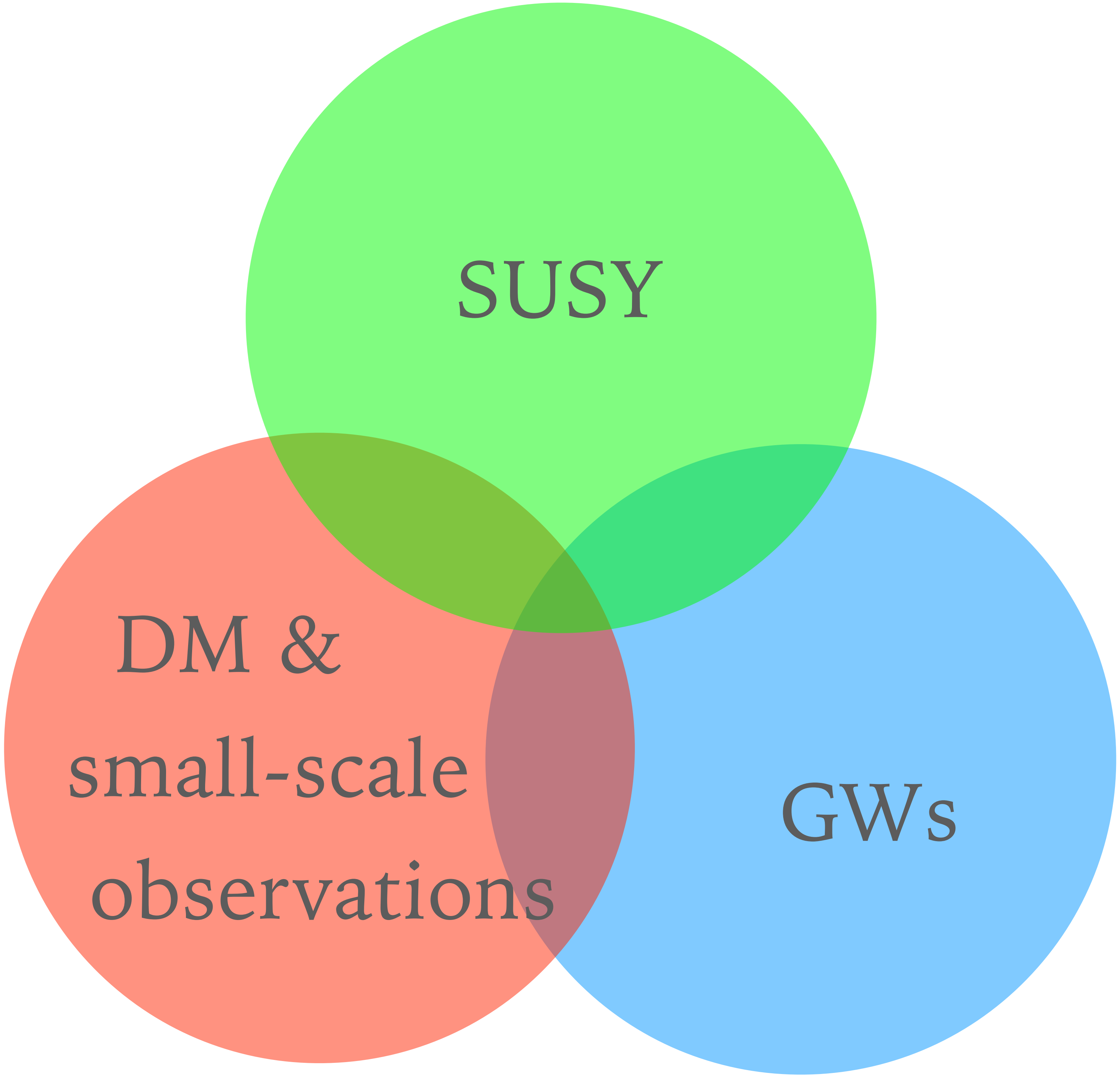
2021.11.30 @ KIAS



[Choi, Jinno, Yanagida, PRD 104 (2021) 2107.12804]

[Jinno, Moroi, Nakayama PRD 86 (2012) 1208.0184]

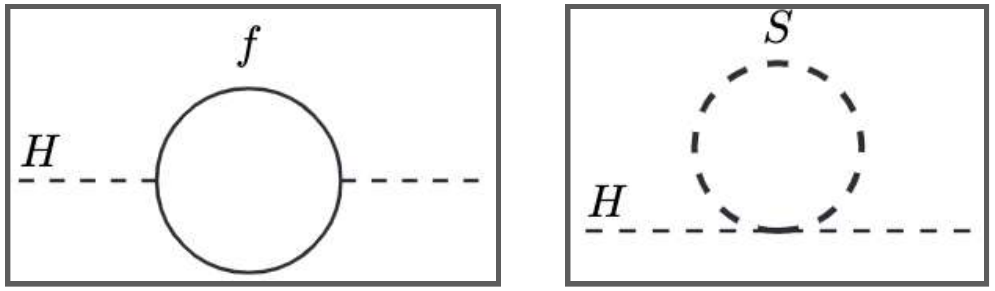
INTRODUCTION



INTRODUCTION: SUSY

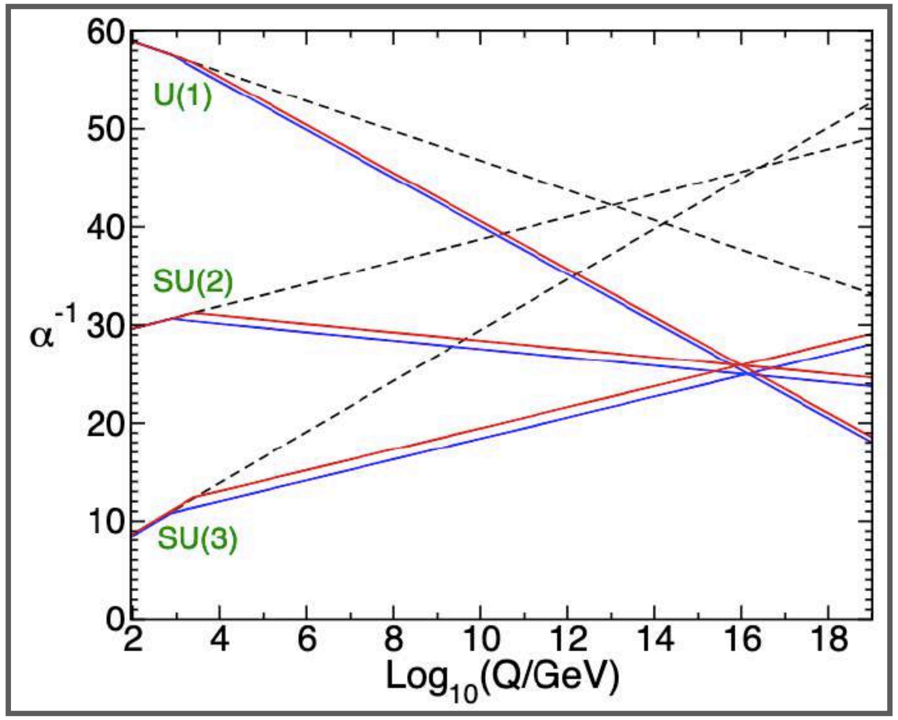
- SUSY
  - Symmetry btwn. bosons and fermions $\delta\phi = \epsilon\psi, \ \ \delta\psi = -i(\sigma^{\mu}\epsilon^{\dagger})\partial_{\mu}\phi$
  - Cancellation of quadratic divergence in higgs mass

    → solution to the hierarchy problem



[Martin 9709356]

  - Unification of the gauge forces strongly suggested



  - Viable dark matter candidates

    higgsino, bino, wino,

    gravitino,

    ...

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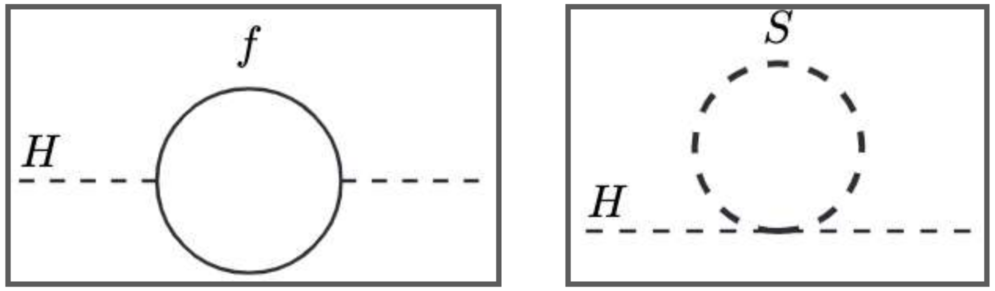

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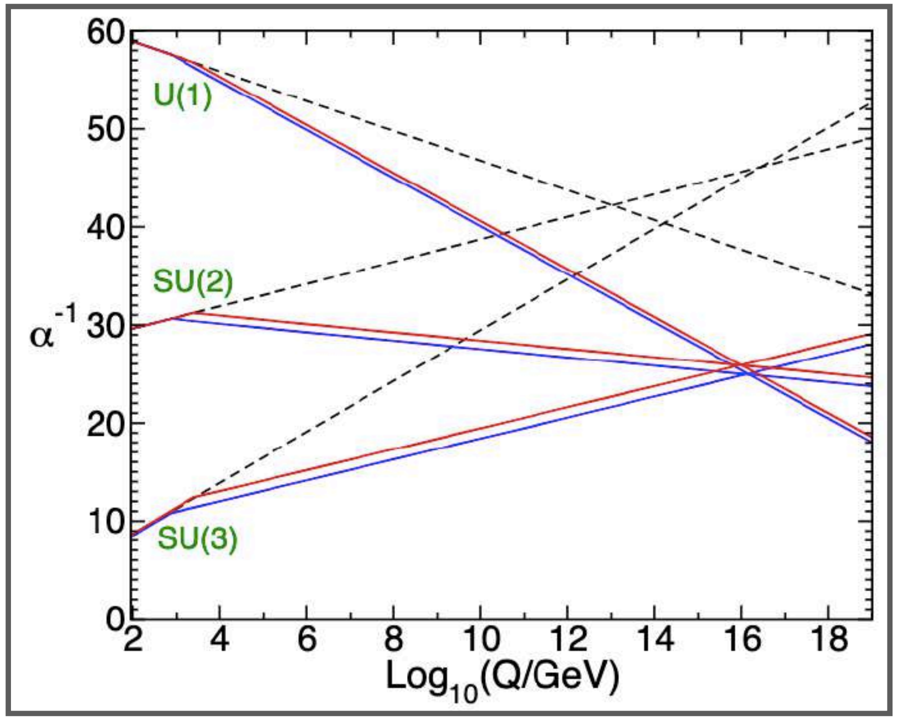

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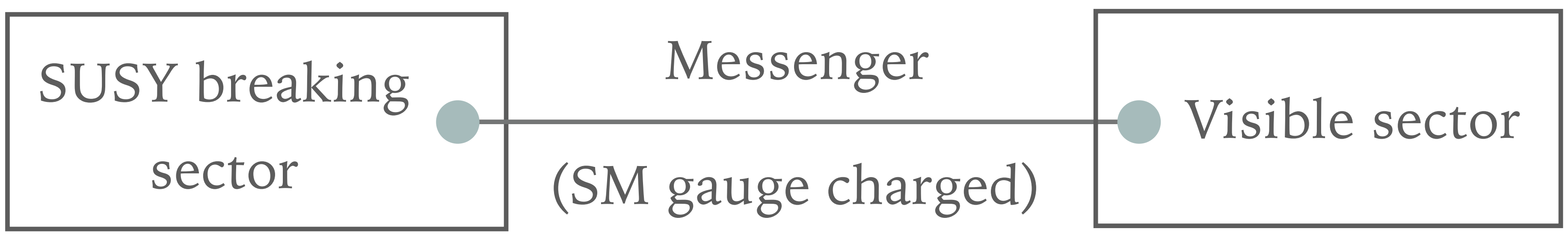
INTRODUCTION: SUSY

- ➤ Gravitino in PeV-scale SUSY breaking $\langle F \rangle \sim (10^6\ \mathrm{GeV})^2$

  - We assume that the visible sector receives masses through gauge mediation



$\langle F \rangle \neq 0$

Gluino mass $m_{\tilde{g}} \simeq N_{\mathrm{mess}} \frac{g_c^2}{(4\pi)^2} \frac{y \langle F \rangle}{M_{\mathrm{mess}}} \sim 10\,\mathrm{TeV}$

Note: The following story does not depend on the detailed mass spectrum

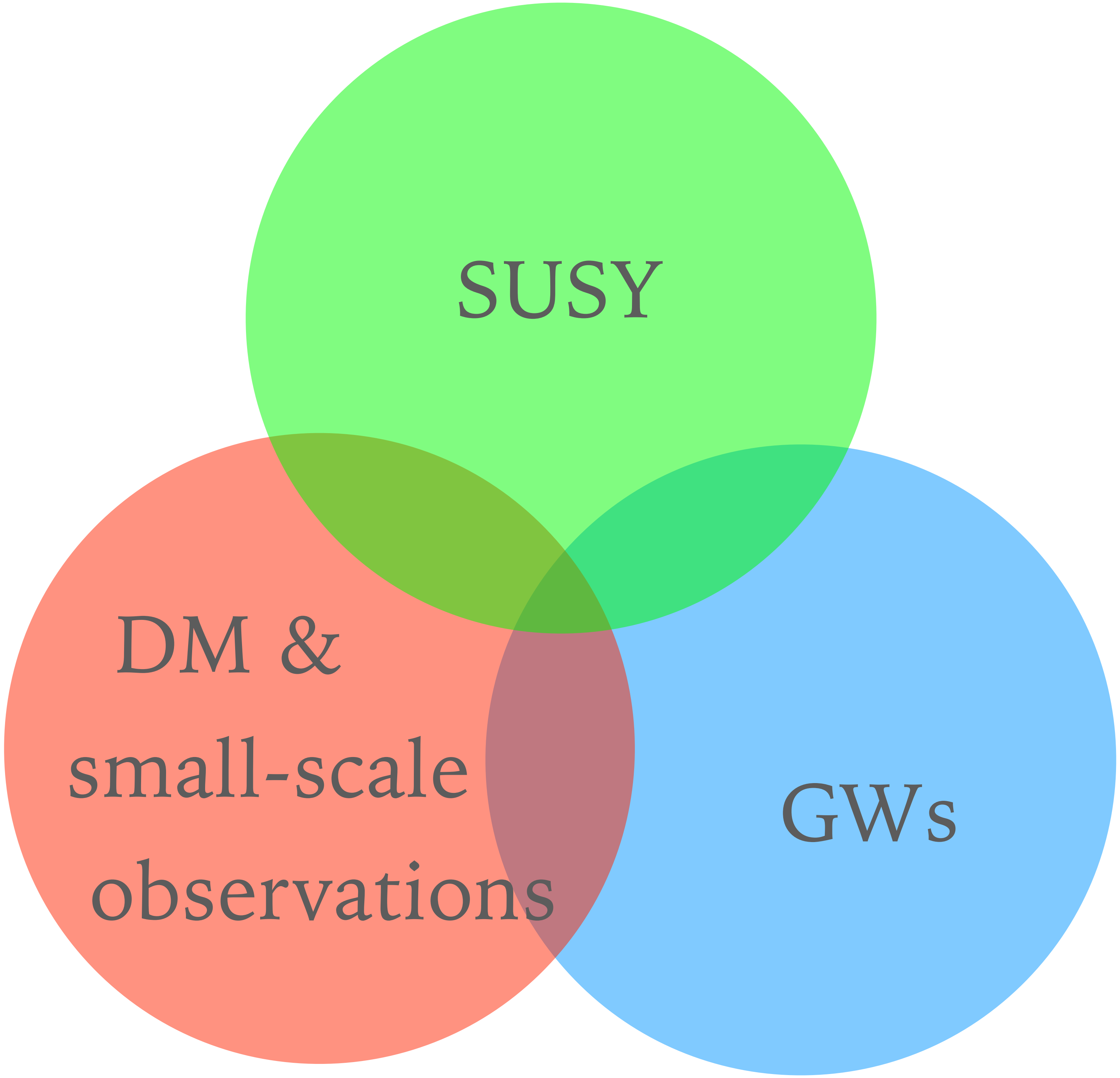
  - When SUSY is promoted to a local symmetry, the superpartner of graviton appears

$$\text{Gravitino:} \quad m_{3/2} \simeq \frac{\langle F \rangle}{\sqrt{3} M_P} \sim 100\,\mathrm{eV} - 1\,\mathrm{keV}$$

  - We consider cosmology with gravitino, and point out that

    inflatinoary GW spectrum has a distinct feature in PeV-scale ~~SUSY~~ scenarios

INTRODUCTION

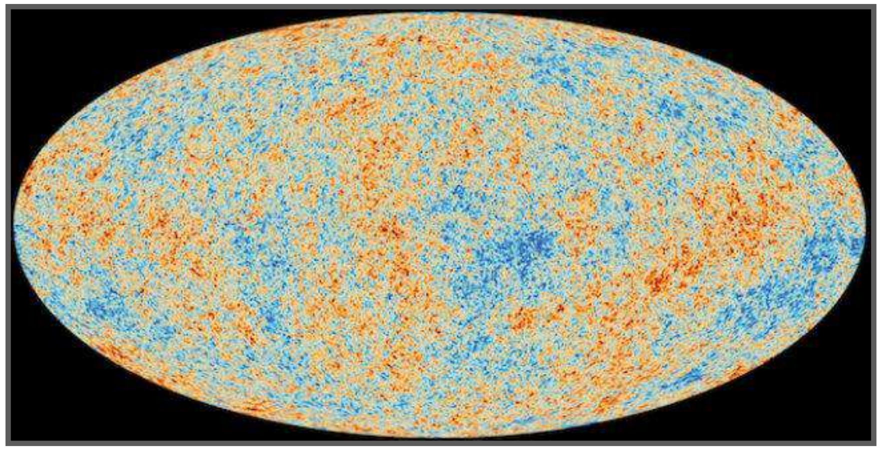


INTRODUCTION: DARK MATTER & SMALL-SCALES

➤ Dark matter & small-scale structures

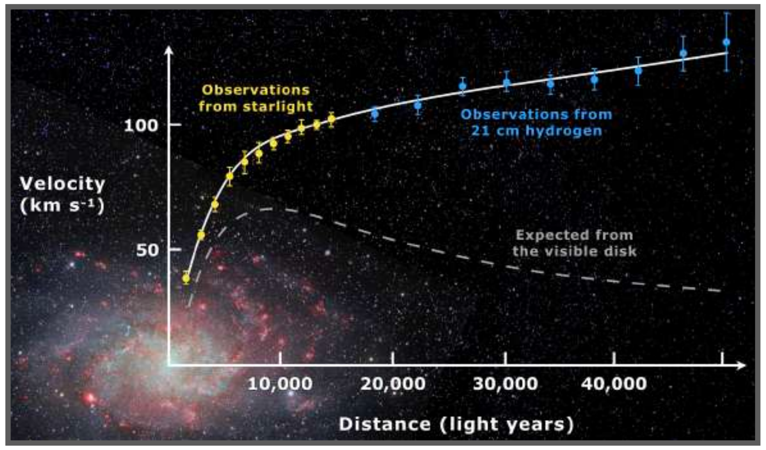
- Dark matter: unknown form of matter that accounts for ~25% of the energy budget

CMB



[Planck]

galaxy rotation curves



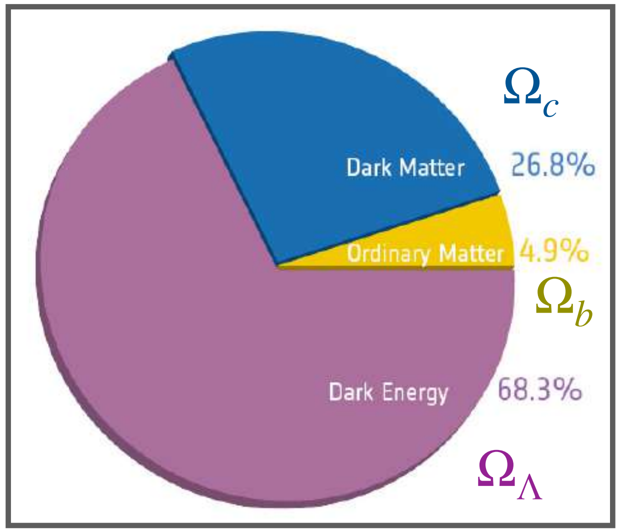
[Wikipedia]

bullet clusters

[ESA]

- Properties:

  - Long-lived
  - Feeble interactions with the ordinary matter
  - Not too much velocity (= not too hot)



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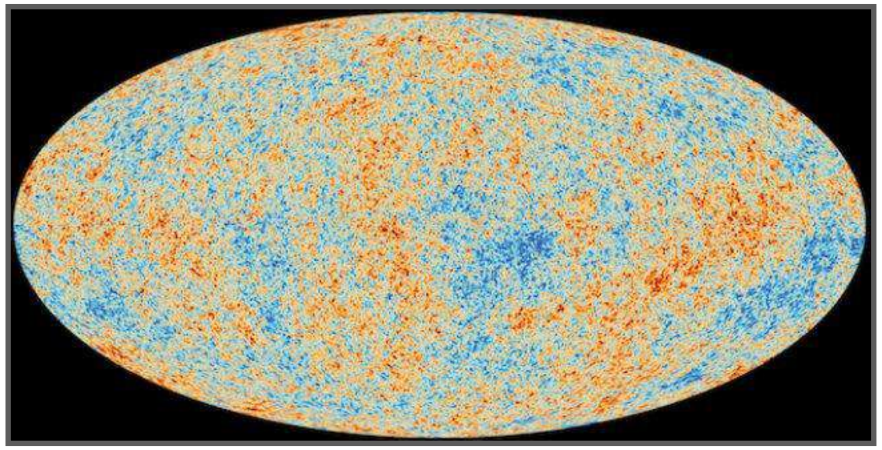

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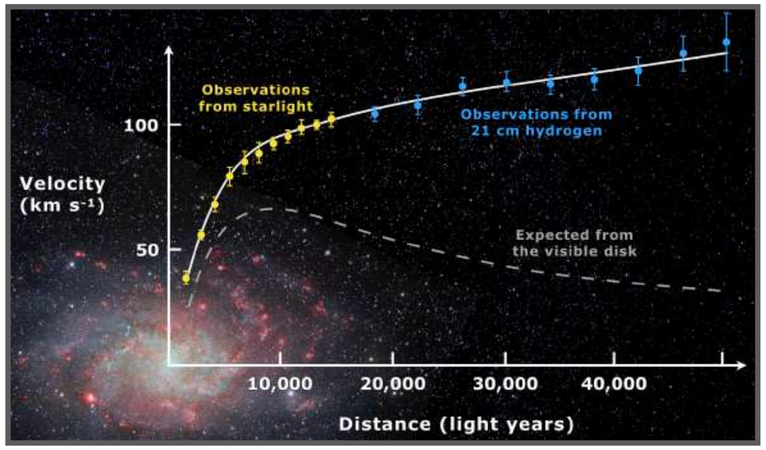

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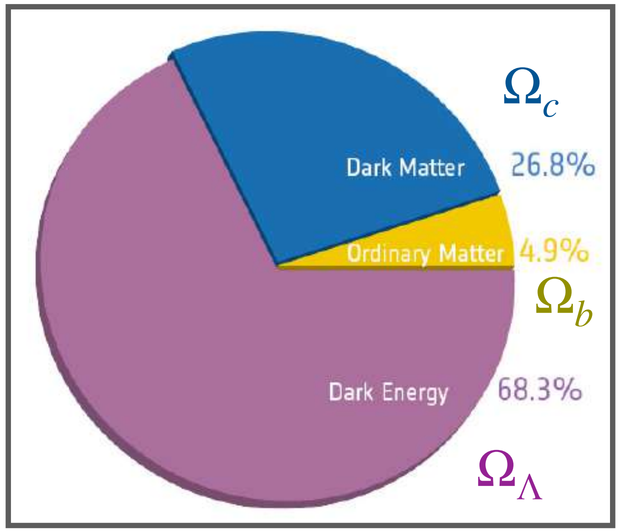


INTRODUCTION: DARK MATTER & SMALL-SCALES

- Dark matter & small-scale structures

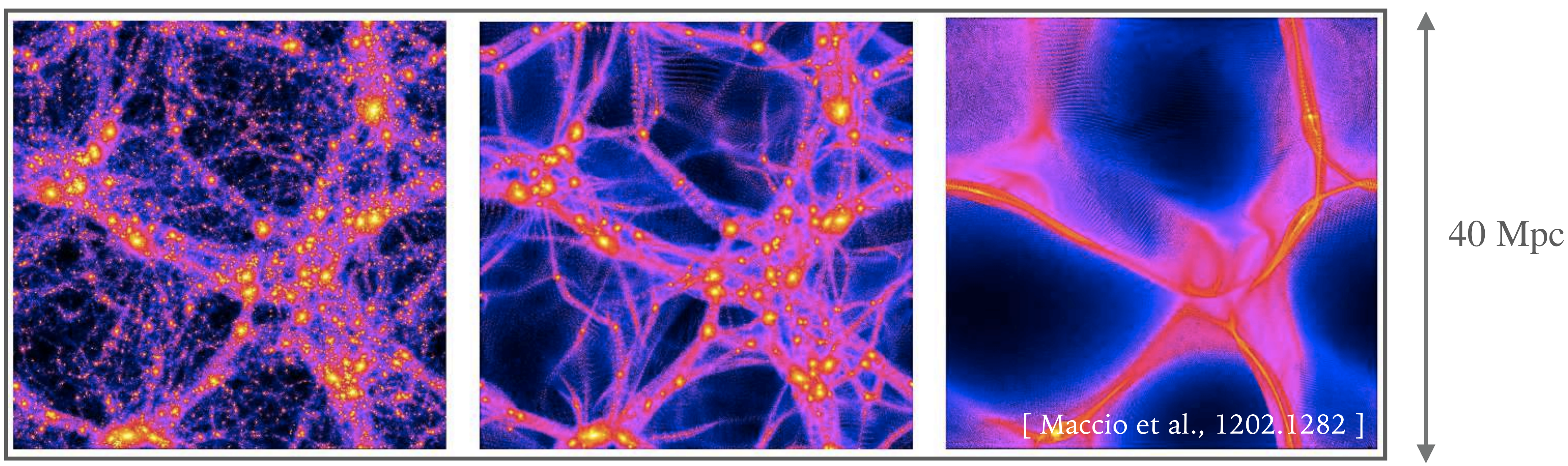
  - Cold DM (= zero velocity) vs. Warm DM (= nonnegligible velocity)

    In cosmology, CDM is very often assumed (e.g. ΛCDM model of cosmology)

    However, there is no a priori reason to assume that.

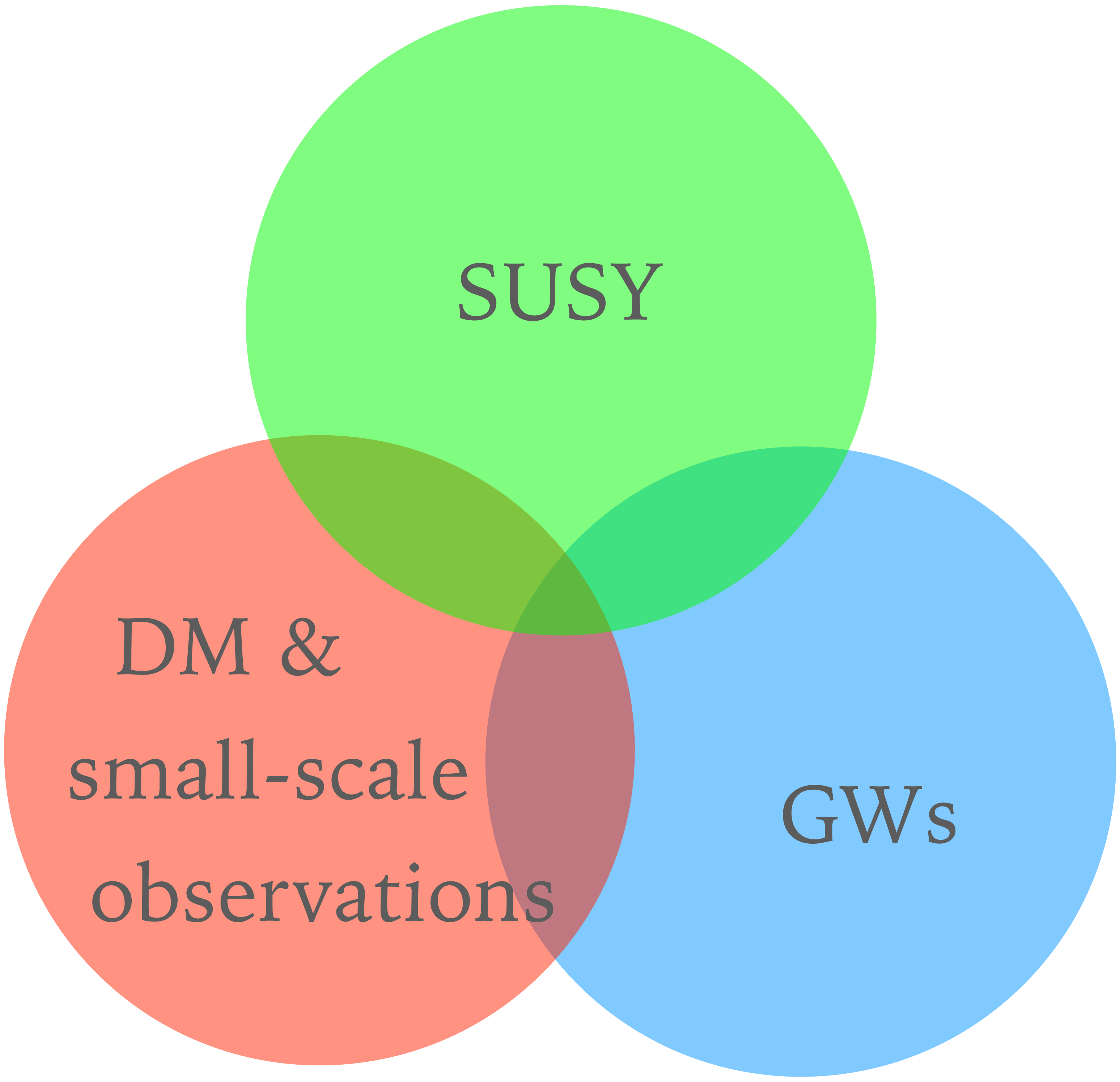
  - If DM has warmness, it smears out small-scale structures $v(z) \sim 0.012 \times (1+z) \times \left(\frac{\mathrm{keV}}{m}\right)^{4/3}$

CDM　　WDM $m = 0.2$ keV　　WDM $m = 0.05$ keV



  - Two observables will be explained as sensitive probes to the small-scale structure

INTRODUCTION



INTRODUCTION: GWS

- Gravitational waves (GWs)

- Transverse-traceless part of the metric $ds^2 = -dt^2 + a^2(\delta_{ij} + h_{ij})dx^i dx^j$

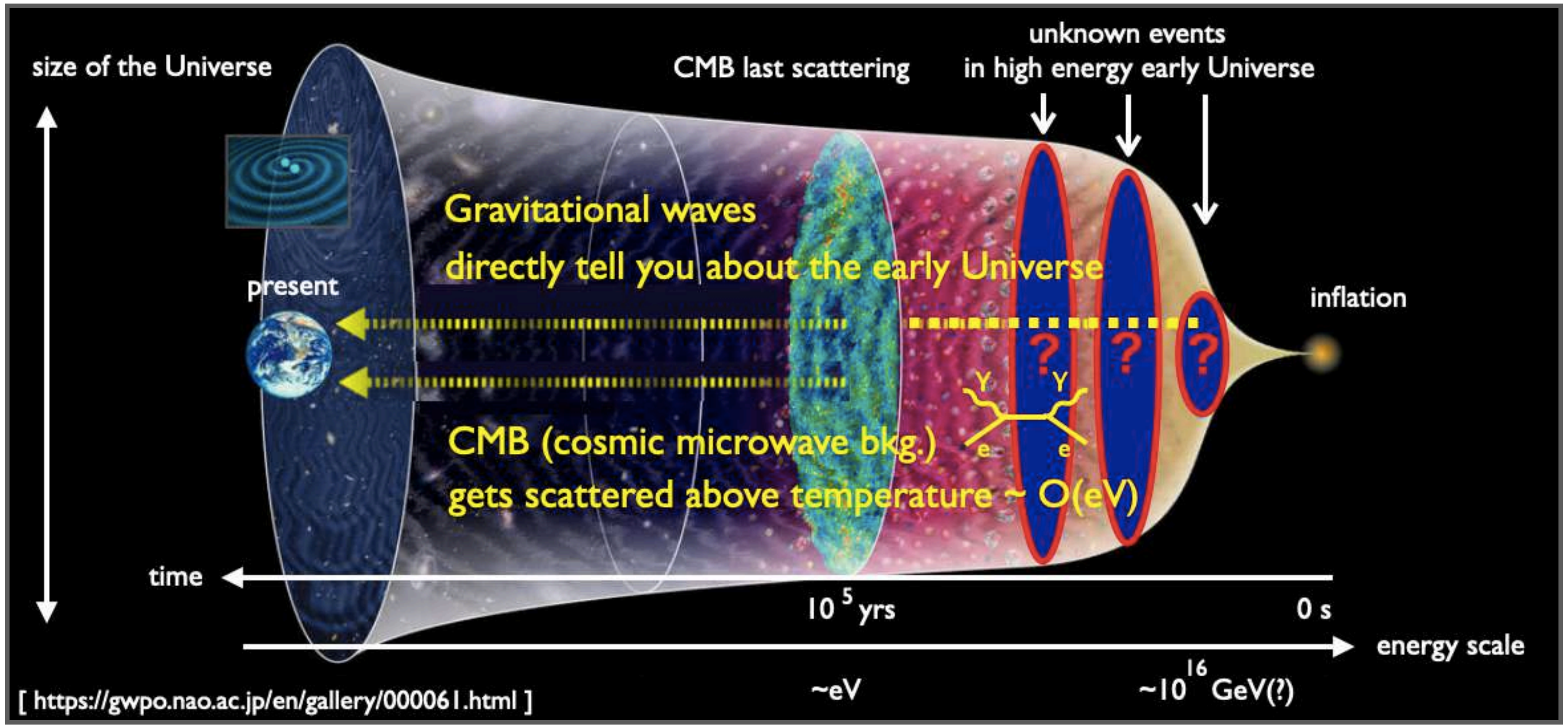
<u>massless action</u>

$$S_{\rm grav} \sim \frac{M_P^2}{8}\int d^4x\, a^3 \left[\dot{h}_{ij}^2 - \frac{1}{a^2}(\nabla h_{ij})^2\right]$$

<u>massless KG equation</u>

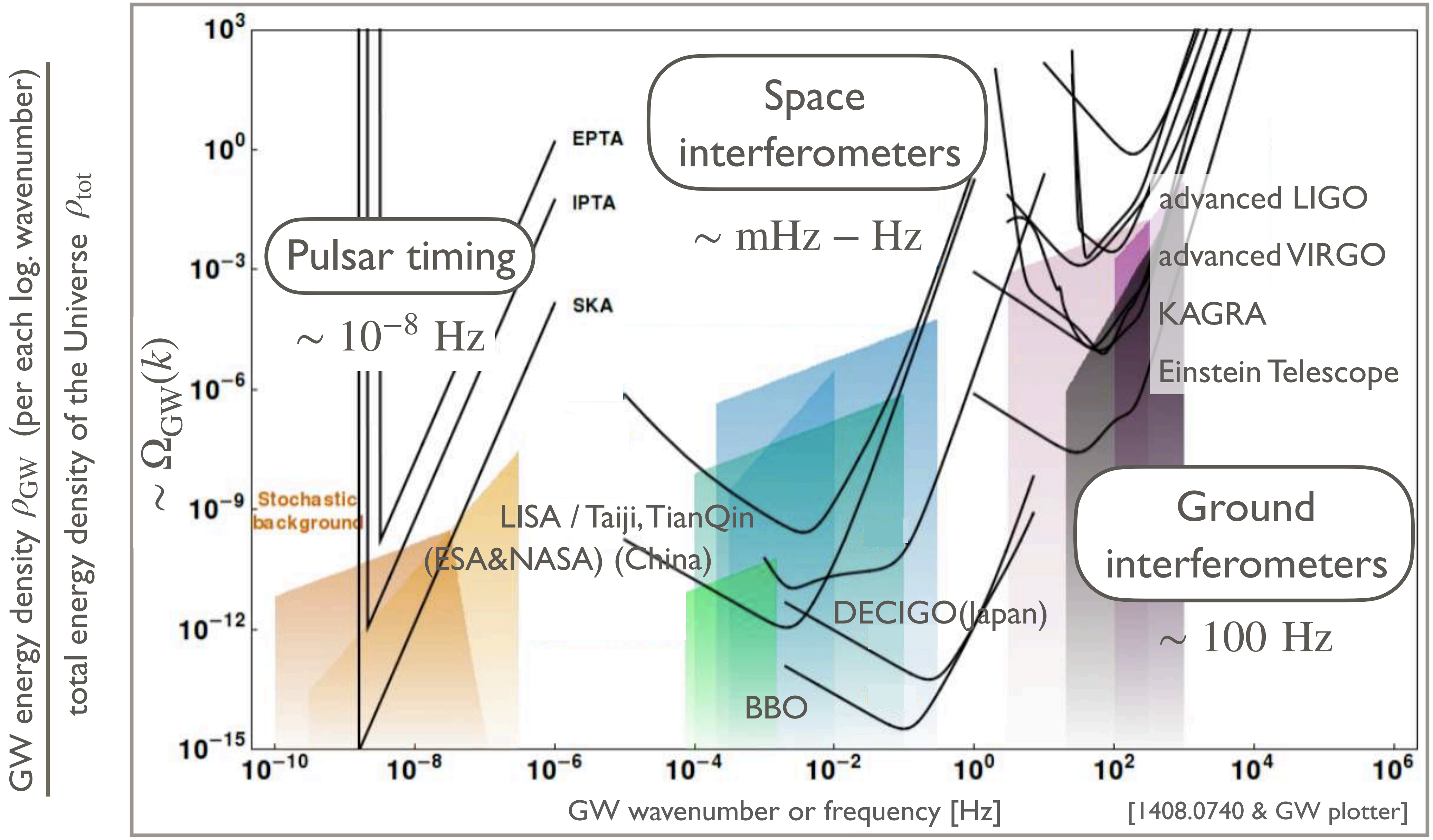
$$\Box h_{ij} \sim \frac{1}{M_P^2}\Lambda_{ij,kl}T_{kl}$$

- Thanks to M_P-suppressed interactions, GWs retain the original information



INTRODUCTION: GWS

- Summary of ongoing & future experiments



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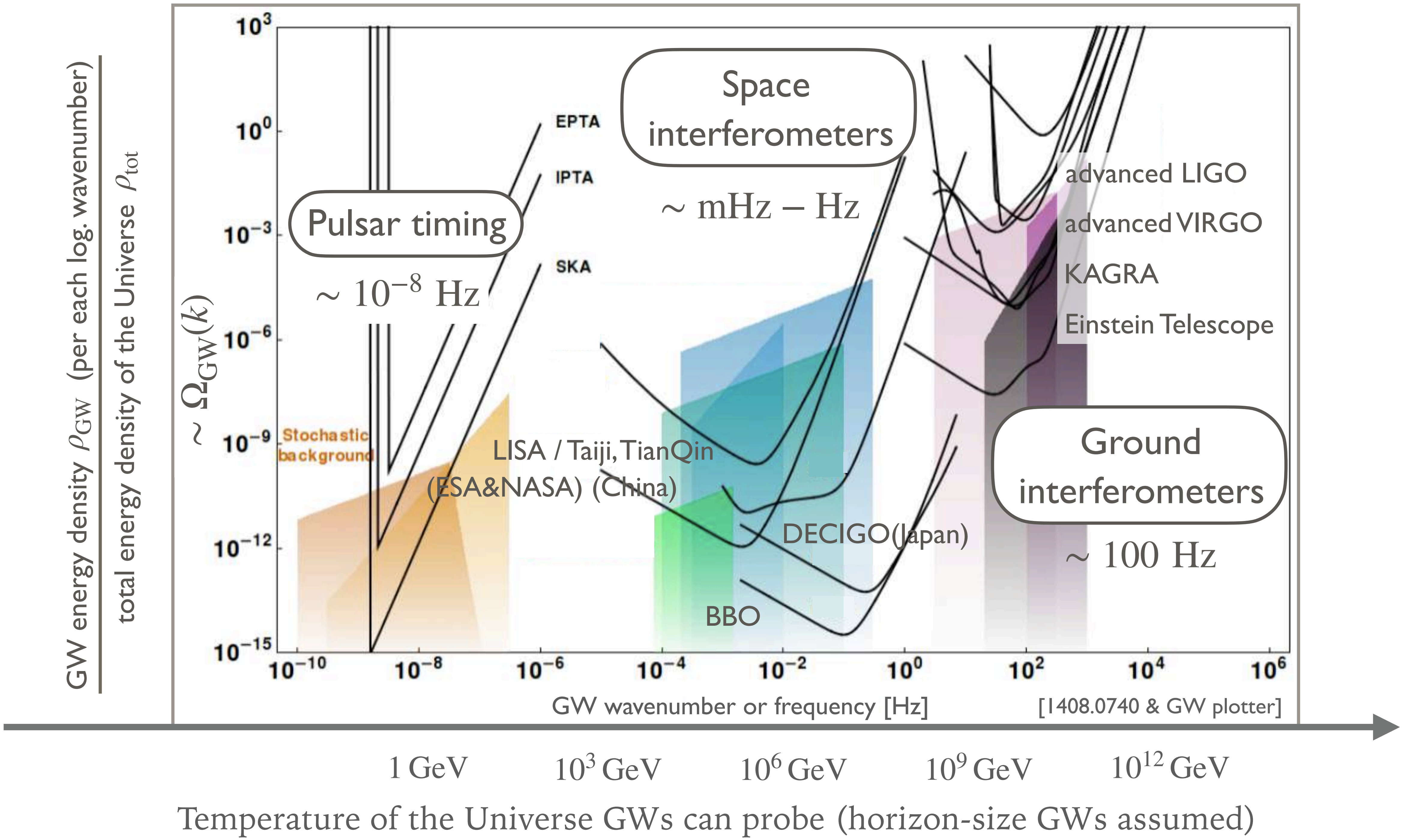
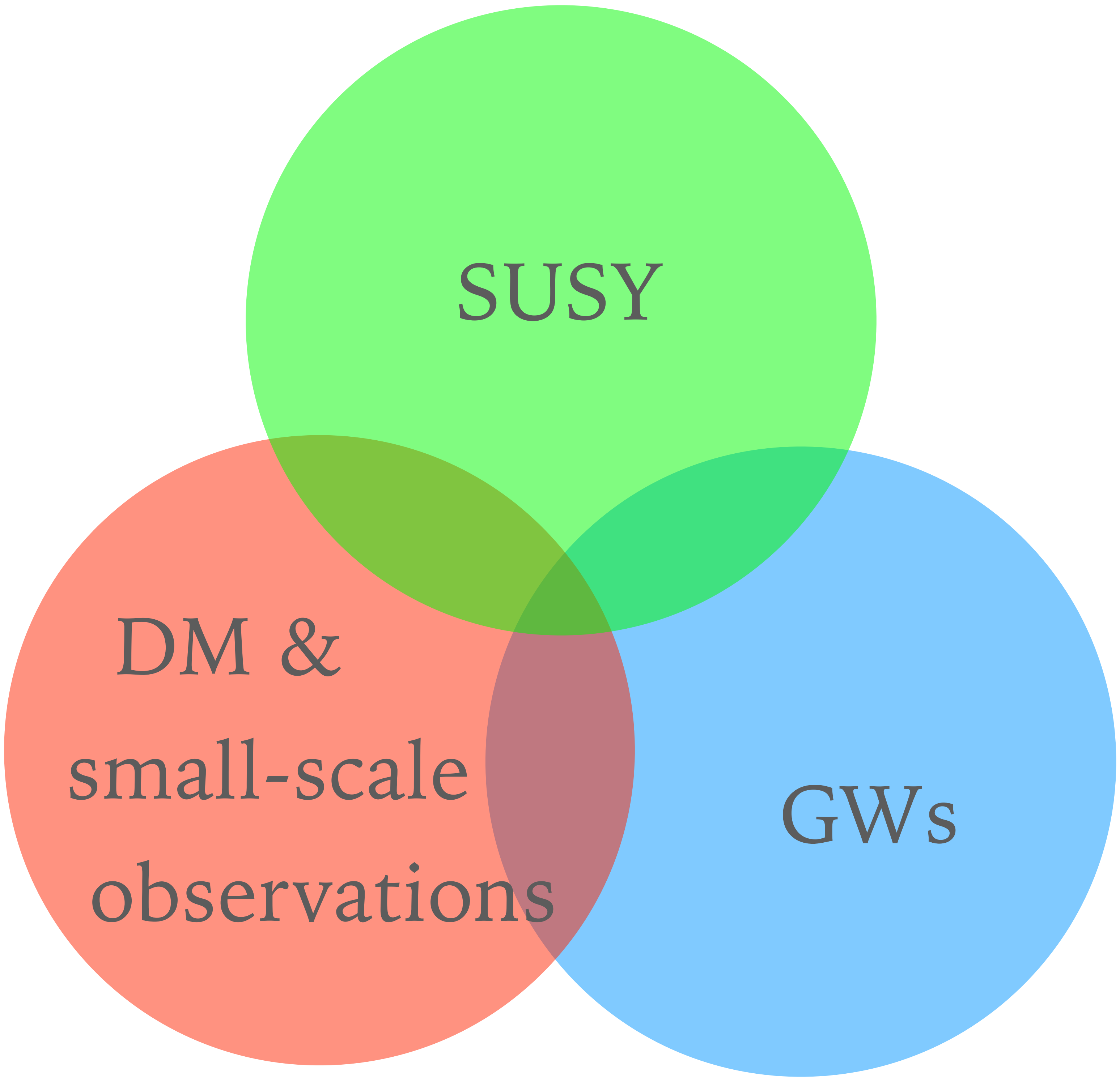


INTRODUCTION



SUMMARY

In PeV-scale SUSY breaking scenarios,

consideration on small-scale constraints implies

distinct features in the inflationary GWs

Punchline:

1. small-scale constraints on the warmness of gravitino requires entropy injection

2. entropy injection leaves an unavoidable imprint in the inflationary GW spectrum

Summary

PeV ~~SUSY~~
&
GWs

PeV ~~SUSY~~
&
Small-scales

Introduction

SMALL-SCALE OBSERVATIONS MEET PEV-SCALE SUSY BR.

➤ Overview of the cosmic history

- Inflation
- $T_{\rm RH}$ — Reheating $\rightarrow$ gravitinos thermalize

  gravitino = O(%) component of the thermal bath

- $T_{3/2,\rm dec}$ — Gravitino decoupling

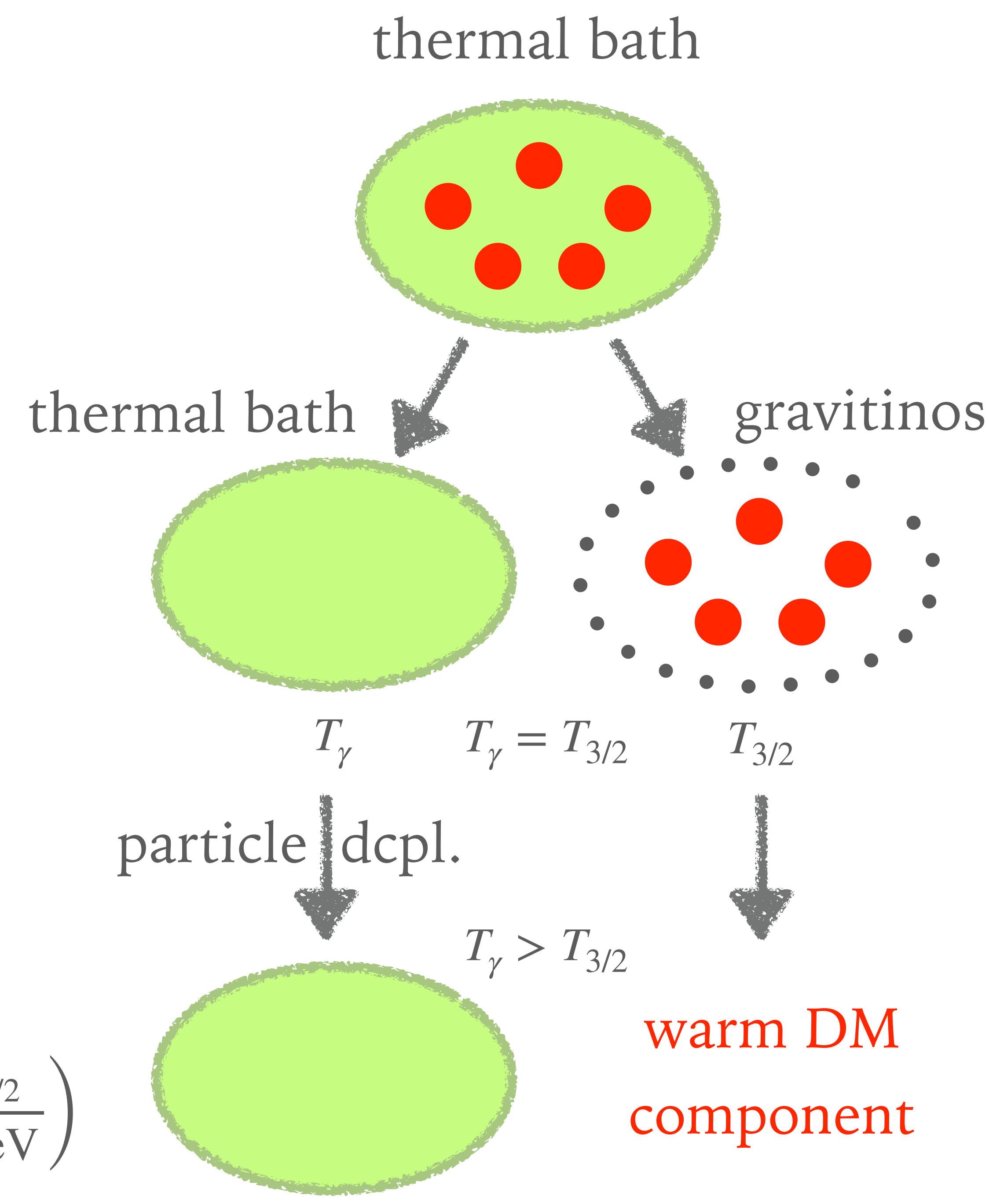
  occurs at $T_{3/2,\rm dec} \simeq m_{\tilde{g}} \simeq N_{\rm mess} \dfrac{g_c^2}{(4\pi)^2} \dfrac{yF}{M_{\rm mess}}$

- Now

  gravitino exists as a DM subcomponent

$$\Omega_{3/2}h^2 \simeq \left(\frac{T_{3/2,0}}{T_{\nu,0}}\right)^3 \left(\frac{m_{3/2}}{94\ \text{eV}}\right) \simeq \left(\frac{10.75}{g_{*s}(T_{3/2,\rm dec})}\right)\left(\frac{m_{3/2}}{94\ \text{eV}}\right)$$

T (decreasing), t (increasing)



SMALL-SCALE OBSERVATIONS MEET PEV-SCALE SUSY BR.

➤

$T_{\rm RH}$

$T_{3/2,\rm dec}$

1) For $m_{3/2} \sim 1\ \mathrm{keV}$, gravitino abundance should be diluted since $\Omega_{3/2} \gtrsim 1$.

This dilution (= entropy injection) must occur after gravitino decoupling.

2) Gravitino exists as a warm component:

Free-streaming length $\lambda \sim \frac{2\pi}{5}\left(\frac{m_{3/2}}{1\ \mathrm{keV}}\right)^{-1}\ \mathrm{Mpc}$

This also requires dilution from the viewpoint of small-scale observations.

particle dcpl.

Now

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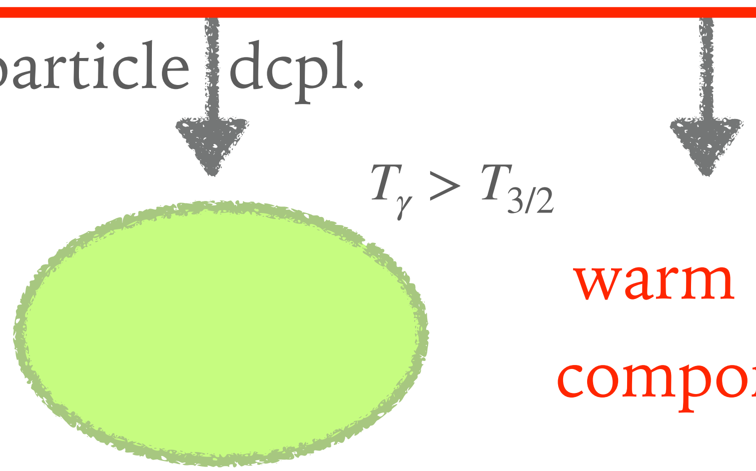

$T_\gamma > T_{3/2}$

warm DM component

T (decreasing), t (increasing)

SMALL-SCALE OBSERVATIONS MEET PEV-SCALE SUSY BR.

- Overview of the cosmic history

$T_{\rm RH}$

Inflation

Reheating → gravitinos thermalize

gravitino = O(1) component of the thermal bath

$T_{3/2,\rm dec}$

Gravitino decoupling

Heavy particle decay

Now

gravitino exists as a DM subcomponent

$$\Omega_{3/2}h^2 \simeq \left(\frac{T_{3/2,0}}{T_{\nu,0}}\right)^3 \left(\frac{m_{3/2}}{94\ \rm eV}\right) \simeq \left(\frac{10.75}{g_{*s}(T_{3/2,\rm dec})}\right)\left(\frac{m_{3/2}}{94\ \rm eV}\right)$$

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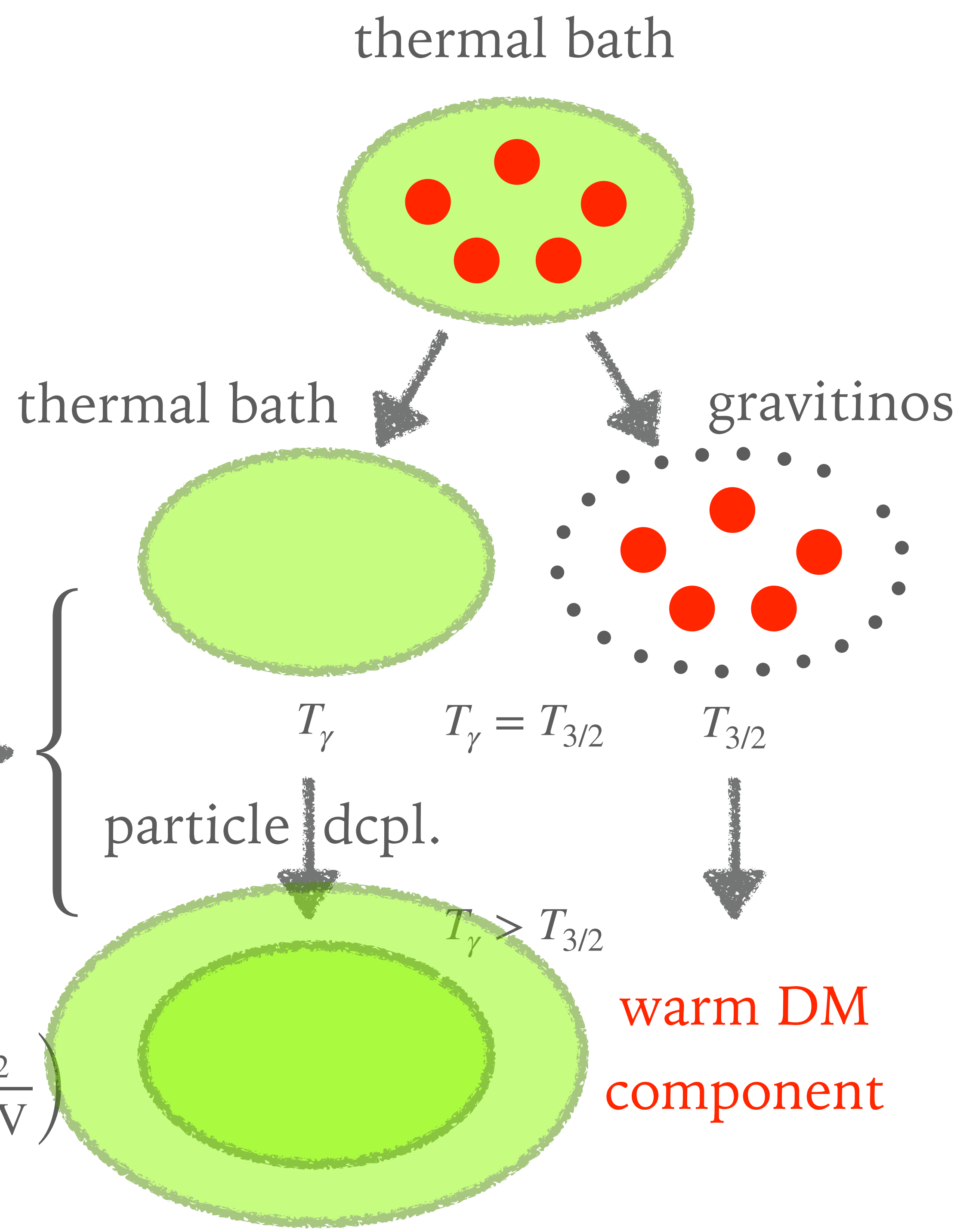

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How much dilution?

This also requires dilution from the viewpoint of small-scale observations.

T_{RH}

$T_{3/2,\mathrm{dec}}$

Now

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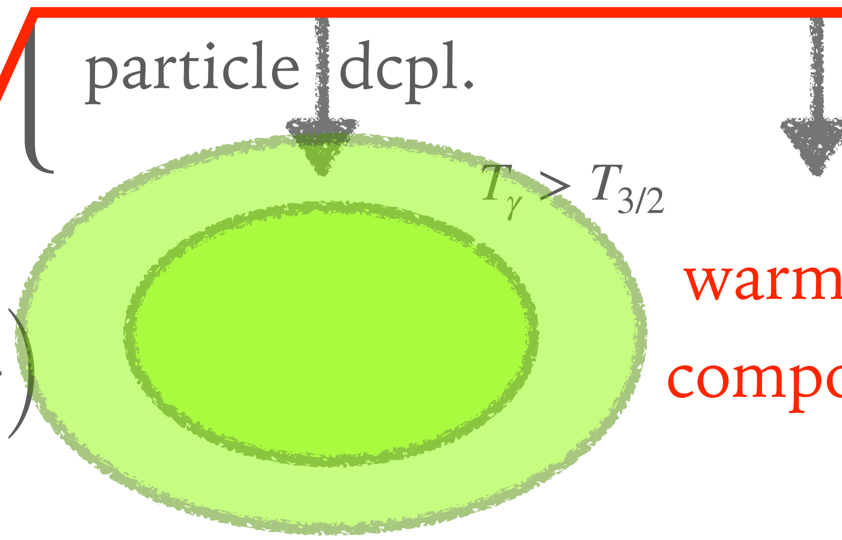


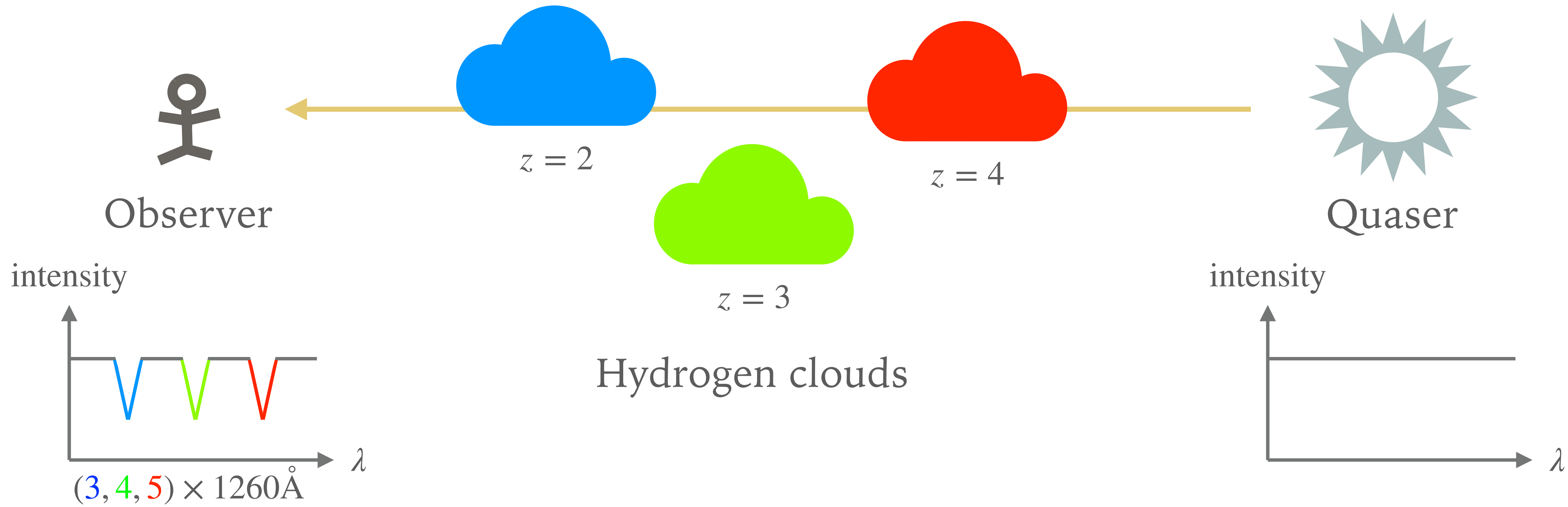
warm DM component

T (decreasing), t (increasing)

SMALL-SCALE OBSERVATIONS MEET PEV-SCALE SUSY BR.

➤ Small-scale observations: ① Lyman-α forest

- We observe the photon spectrum from quasers (also written as QSOs)
- Hydrogen clouds along the line of sight absorb photons with 1260Å at that time
- Since photons are constantly being redshifted,
  the absorption lines at different wavelengths correpond to different redshifts



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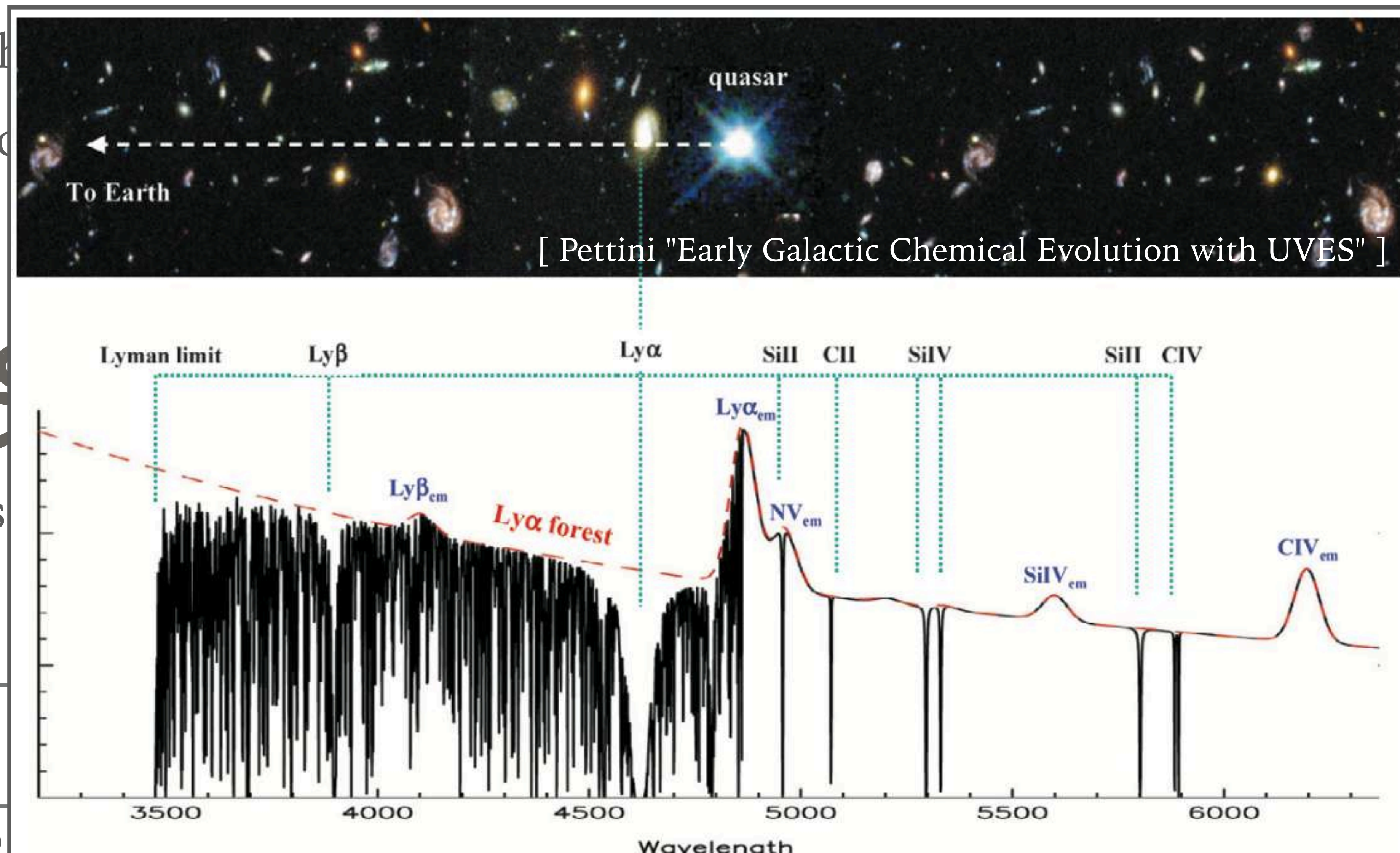
- Since ph

the abso … shifts



Obs … uaser

intensity

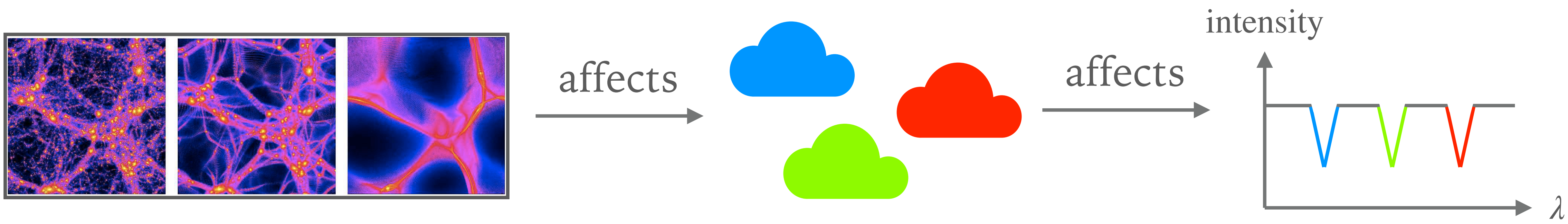
(3, 4, 5)

λ

SMALL-SCALE OBSERVATIONS MEET PEV-SCALE SUSY BR.

➤ Small-scale observations: ① Lyman-α forest

- Warmness affects the abundance of hydrogen clouds, and the amount of absorption



→ Constraints on warm DM can be derived

e.g. [Irsic et al. 1702.01764] [Murgia, Irsic, Viel 1806.08371] [Garzilli, Ruchayskiy, Magalich, Boyarsky 1912.09397]

- However, we do <u>not</u> use Lyman-α constraints

Why? Typically, people assume 100% WDM and derive constraints on mass.

But we need constraints on the allowed WDM fraction.

Anyway, Nsat (→ next slide) gives conservative bounds

SMALL-SCALE OBSERVATIONS MEET PEV-SCALE SUSY BR.

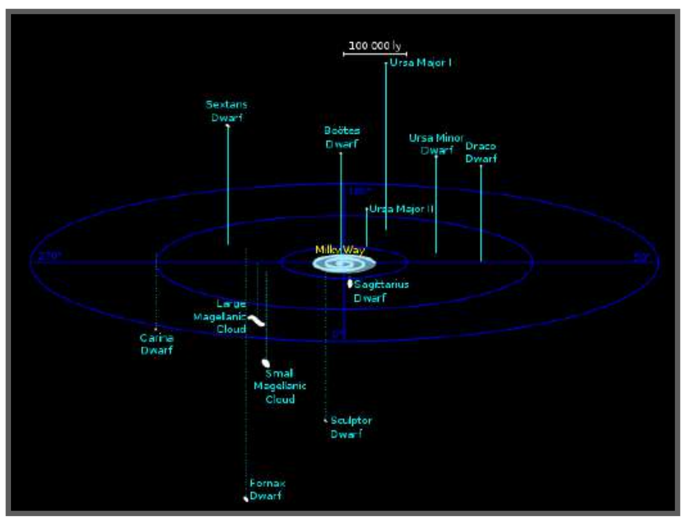
➤ Small-scale observations: ② Number of satellite galaxies

- Satellite galaxies of Milky Way (our Galaxy):

To take into account
SDSS sky coverage f=0.28

11 classical dwarf gal. + 15 ultra-faint dwarf gal. × 3.5 = 63 already 'observed'

So, any DM model should predict ≧63 satellite galaxies



Classical dwarf galaxies [Wikipedia]

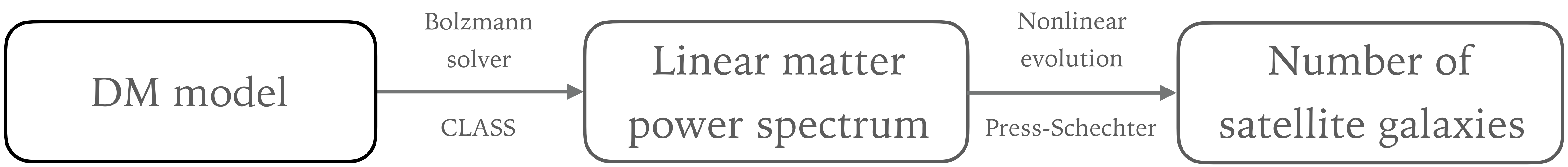
[Sloan Digital Sky Survey]

- We estimate the number of satellite galaxies in PeV-scale SUSY breaking scenarios using the Press-Schechter approach [Press-Schechter '74] [Polisensky, Ricotti 1004.1459] [Schneider 1412.2133]

SMALL-SCALE OBSERVATIONS MEET PEV-SCALE SUSY BR.

- Small-scale observations: ② Number of satellite galaxies

  - Pipeline



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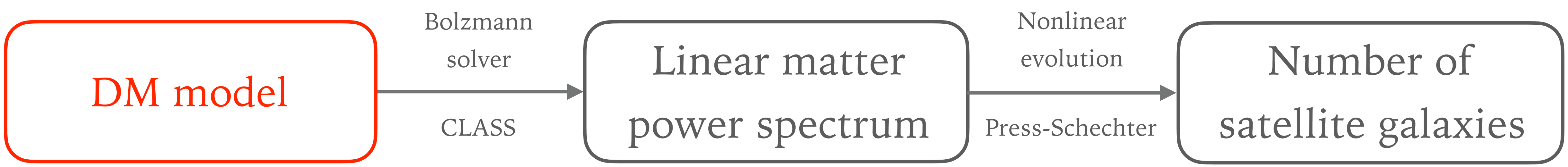


DM model?

MDM (Mixed DM) model = CDM (Cold DM) + WDM (Warm DM)

We do not specify who's this — Gravitino

Free parameters: WDM mass $m_{3/2}$ & WDM fraction $f_{3/2}$

SMALL-SCALE OBSERVATIONS MEET PEV-SCALE SUSY BR.

➤ Small-scale observations: ② Number of satellite galaxies

- Pipeline

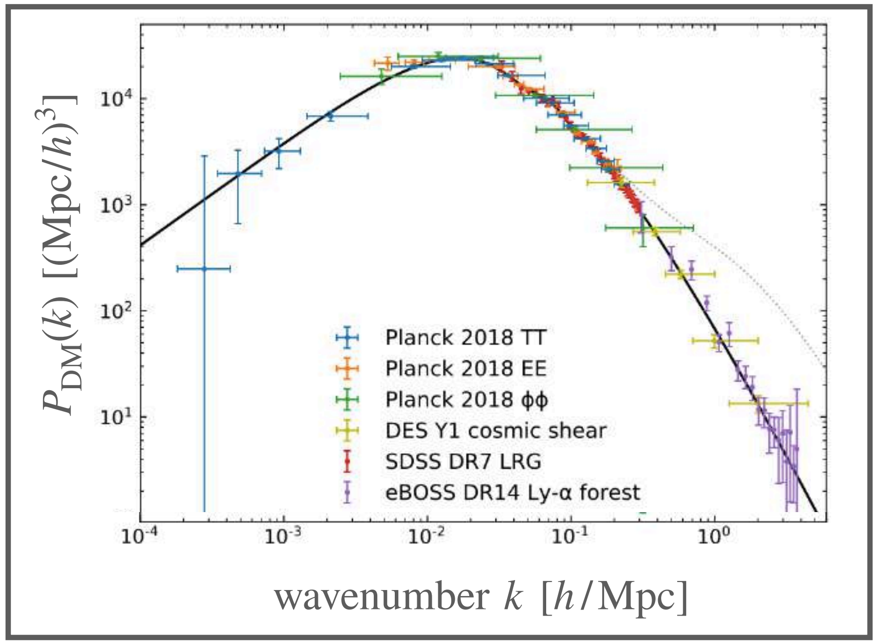
<u>Linear matter power spectrum?</u>

"Power spectrum (= 2-point ensemble average) of overdensity δ before complicated late-time nonlinear evolution sets in"

Define overdensity $\delta(\vec{x}) \equiv \dfrac{\rho(\vec{x})}{\bar{\rho}} - 1$

Fourier transform $\delta(\vec{k}) = \displaystyle\int \frac{d^3k}{(2\pi)^3}\, \delta(\vec{x})\, e^{i\vec{k}\cdot\vec{x}}$

Take 2-point average $\left\langle \delta(\vec{k})\delta^*(\vec{k}\,') \right\rangle = (2\pi)^3 \delta^{(3)}(\vec{k} - \vec{k}\,') P_{\mathrm{DM}}(k)$



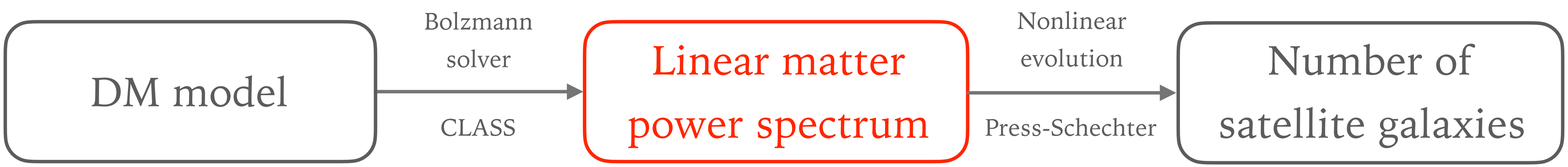
Q. Where's time label t?

A. These quantities are evaluated well after matter-radiation equality but before nonlinear evolution starts.
More precisely, these quantities are (fictitiously) extrapolated to the present time.

SMALL-SCALE OBSERVATIONS MEET PEV-SCALE SUSY BR.

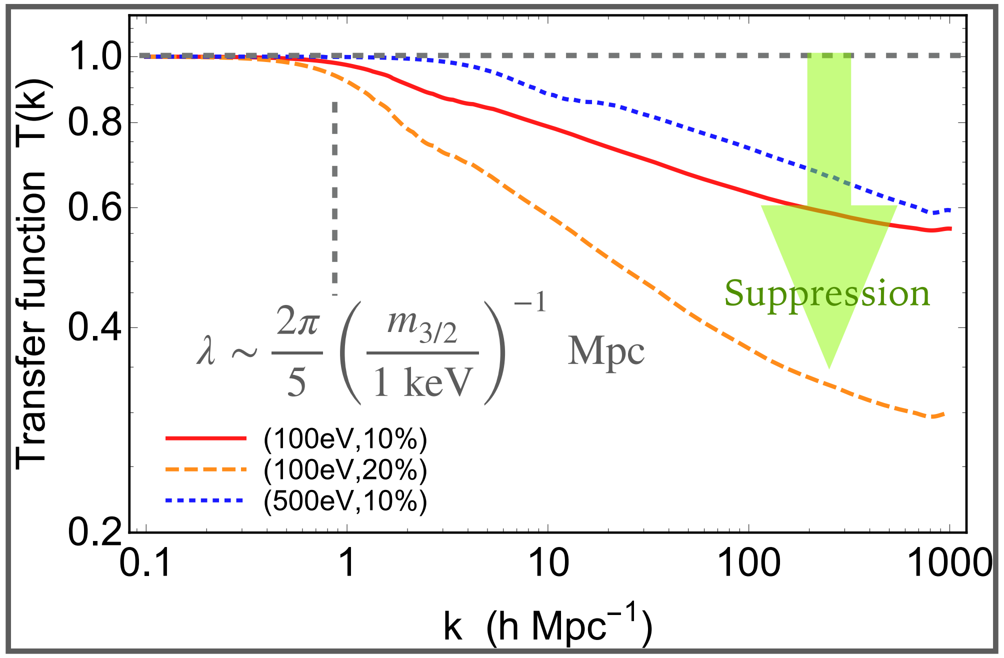
➤ Small-scale observations: ② Number of satellite galaxies

- Pipeline



Linear matter power spectrum?

We calculate the ratio of the linear matter power $T(k)^2 \equiv P_{\rm MDM}(k)/P_{\rm CDM}(k)$



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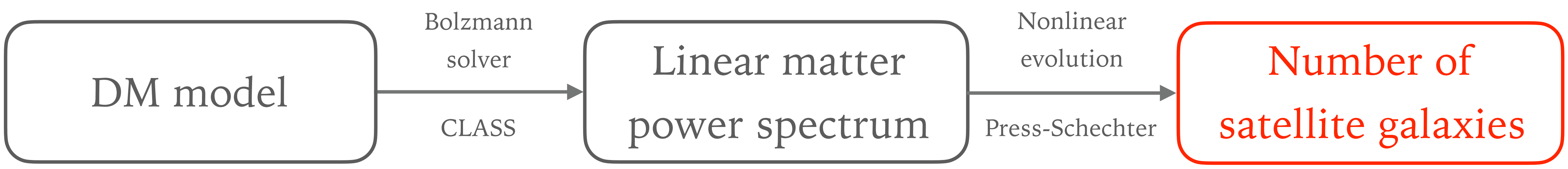
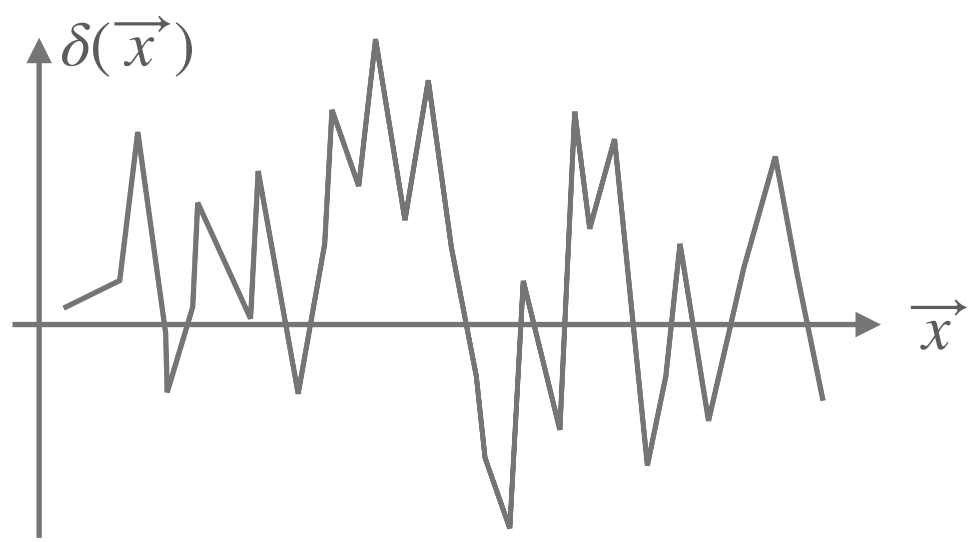


<u>Number of satellite galaxies?</u>

We use Press-Schechter approach [Press-Schechter '74] [Polisensky, Ricotti 1004.1459] [Schneider 1412.2133]

"For given overdensity $\delta(\vec{x})$, how many subhalos form in a Milky-way sized halo?"



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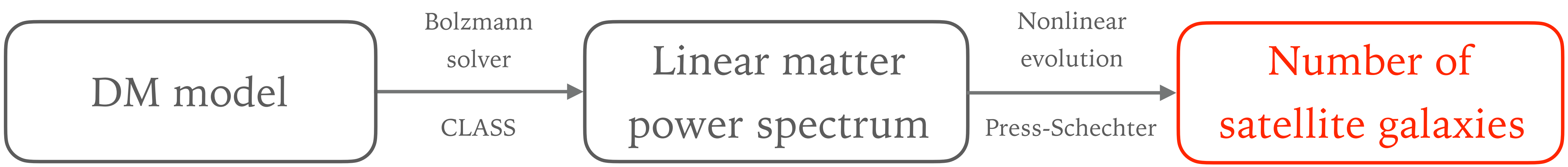

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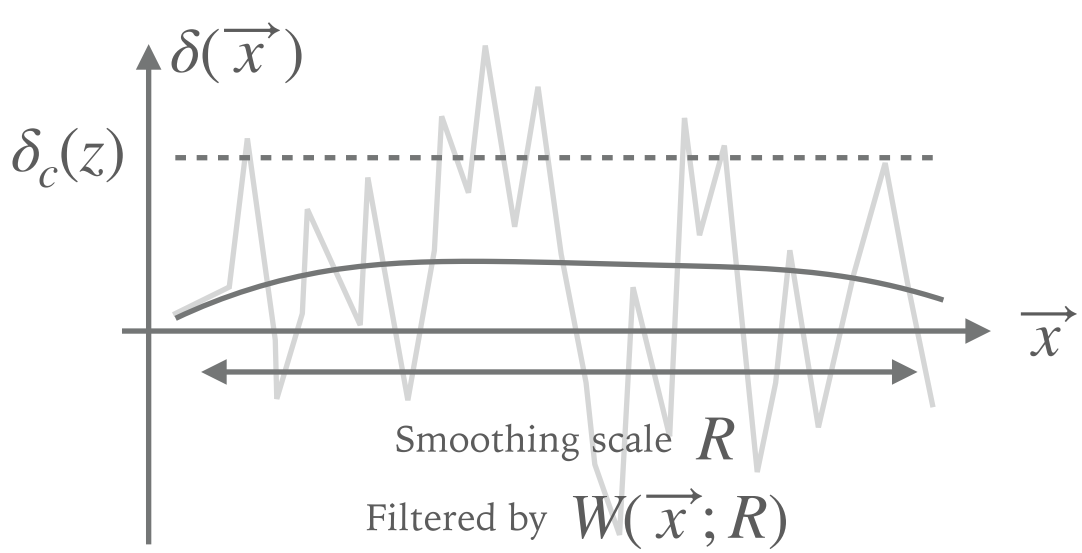

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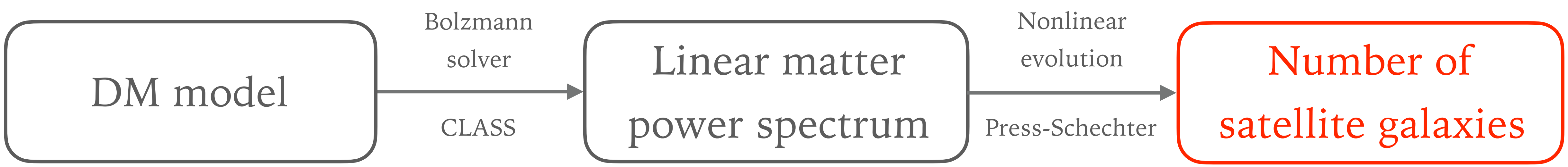

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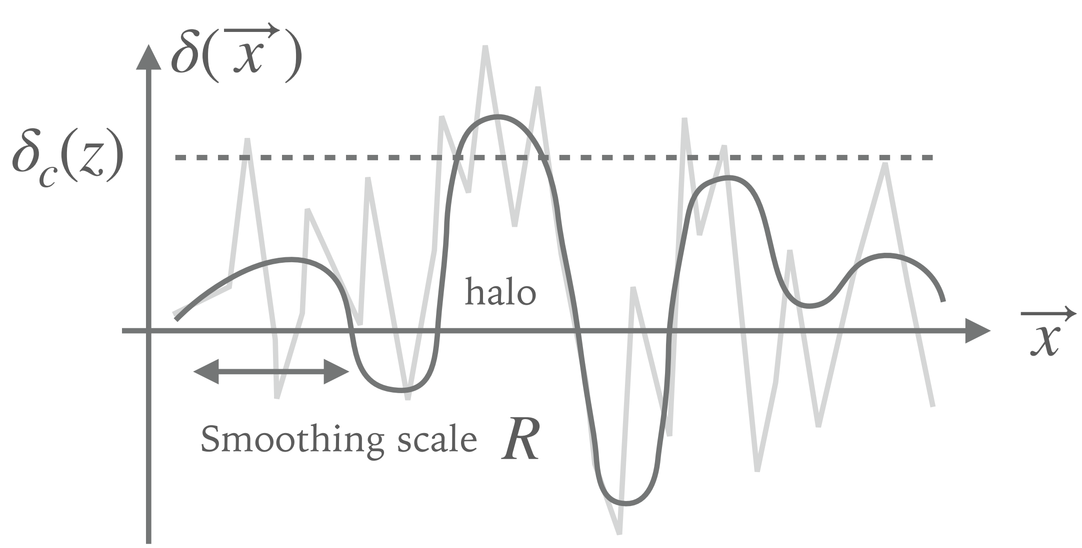
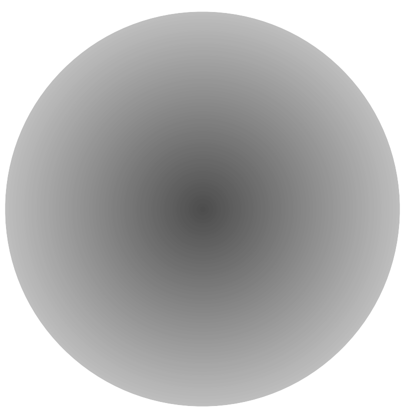


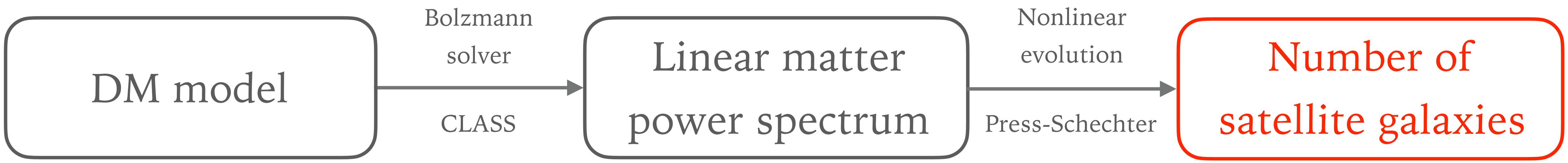


halo

SMALL-SCALE OBSERVATIONS MEET PEV-SCALE SUSY BR.

➤ Small-scale observations: ② Number of satellite galaxies

- Pipeline



Number of satellite galaxies?

We use Press-Schechter approach [Press-Schechter '74] [Polisensky, Ricotti 1004.1459] [Schneider 1412.2133]

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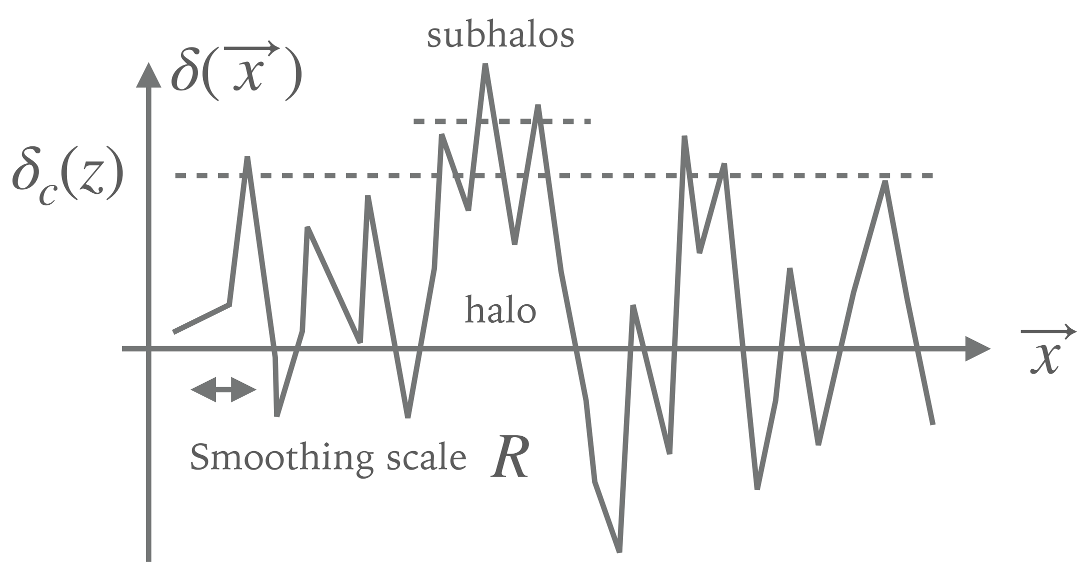

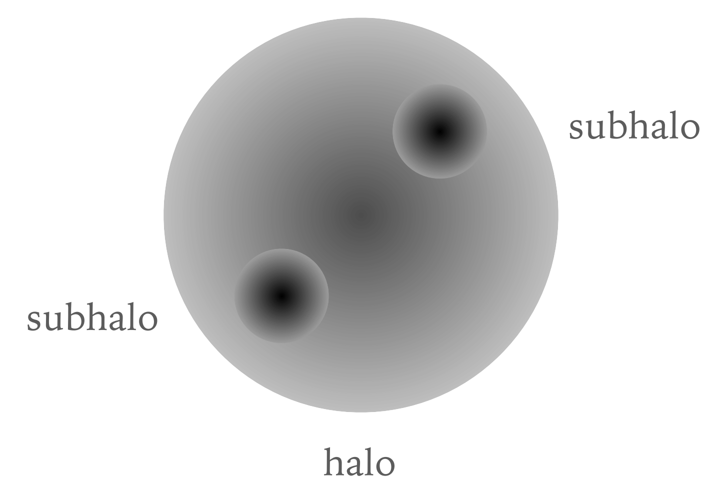

SMALL-SCALE OBSERVATIONS MEET PEV-SCALE SUSY BR.

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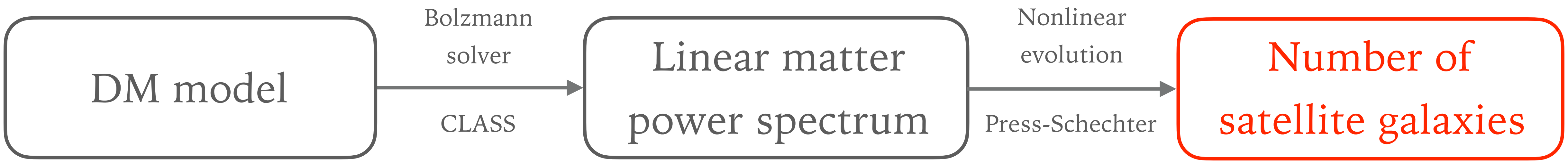

<u>Number of satellite galaxies?</u>

We use Press-Schechter approach [Press-Schechter '74] [Polisensky, Ricotti 1004.1459] [Schneider 1412.2133]

$$N_{\rm sat} = \int_{M_{\rm min}}^{M_h} dM_s \frac{1}{C_n} \frac{1}{6\pi^2} \frac{M_h}{M_s^2} \frac{P_{\rm MDM}(1/R_s)}{R_s^3 \sqrt{2\pi(S_s - S_h)}}$$

h = halo
s = subhalo

$M_{h,s}$: mass of the halo (h) or subhalo (s)

$c = 2.5,\ C_n = 44.5$: constants chosen to match with simulations

$$M_{h,s} = \frac{4\pi}{3} \times (cR_{h,s})^3 \times \rho_{m,0}$$

: relation between the filter scale $R_{h,s}$ and enclosed mass $M_{h,s}$

$$S_{h,s} = \frac{1}{2\pi^2} \int_0^{1/R_{h,s}} dk\, k^2 P_{\rm MDM}(k)$$

: variance of overdensity δ smoothed over the filter scale $R_{h,s}$

SMALL-SCALE OBSERVATIONS MEET PEV-SCALE SUSY BR.

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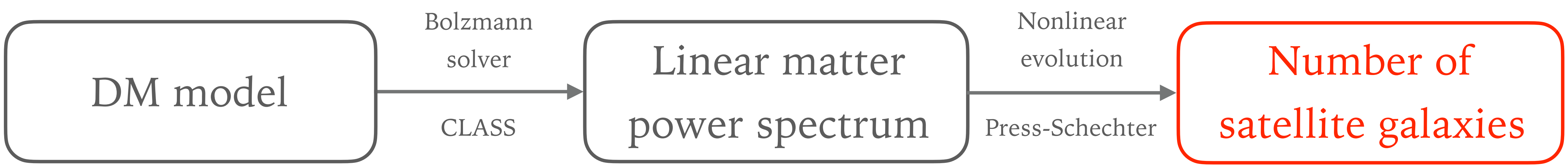

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For given initial density flucutations

$M_{h,s}$: mass of the halo (h) or subhalo (s) $c = 2.5,\ C_n$

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SMALL-SCALE OBSERVATIONS MEET PEV-SCALE SUSY BR.

➤ Small-scale observations: ② Number of satellite galaxies

- Pipeline

DM model → (Bolzmann solver, CLASS) → Linear matter power spectrum → (Nonlinear evolution, Press-Schechter) → Number of satellite galaxies

Number of satellite galaxies?

We use Press-Schechter approach [Press-Schechter '74] [Polisensky, Ricotti 1004.1459] [Schneider 1412.2133]

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h = halo

s = subhalo

$M_{h,s}$: mass of the halo (h) or subhalo (s)

$c = 2.5,\ C_n = 44.5$: constants chosen to match with simulations

We can estimate how many subhalos form between subhalo mass $[M_s, M_s + dM_s]$

$$M_{h,s} = \frac{4\pi}{3} \times (cR_{h,s})^3 \times \rho_{m,0}$$: rel

$$S_{h,s} = \frac{1}{2\pi^2}\int_0^{1/R_{h,s}} dk\, k^2 P_{\rm MDM}(k)$$: variance of overdensity δ smoothed over the filter scale $R_{h,s}$

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- Small-scale observations: ② Number of satellite galaxies

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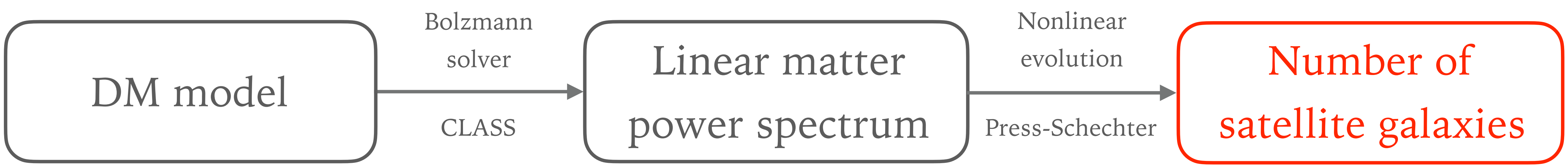

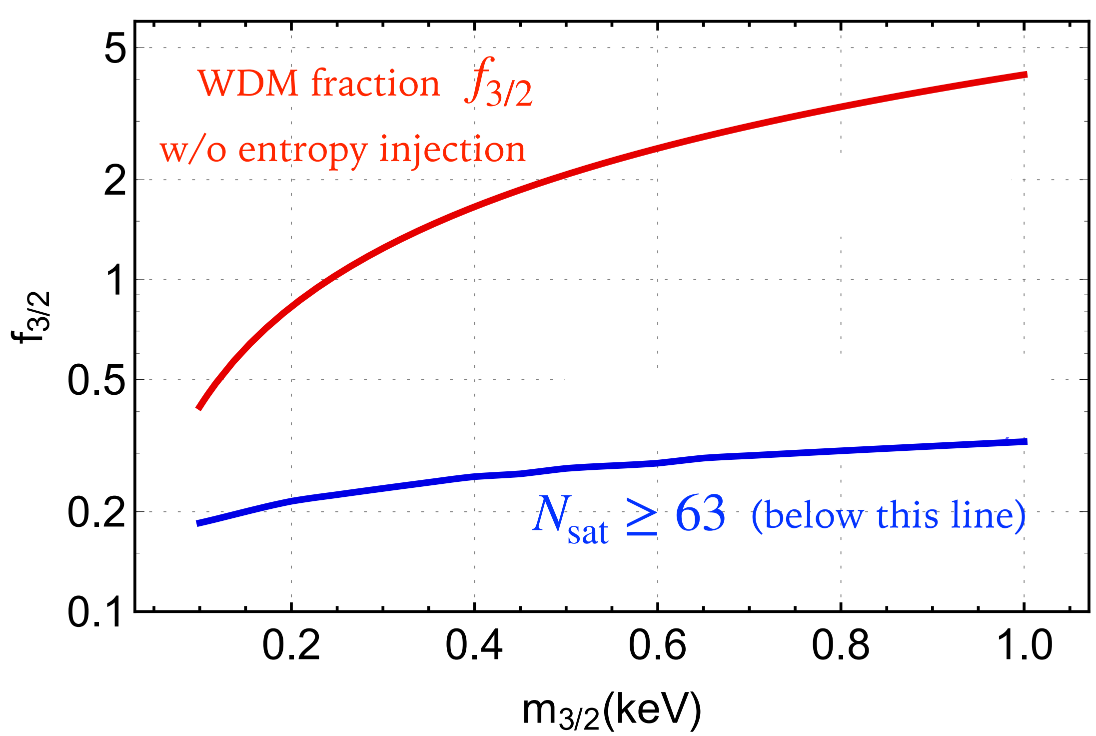

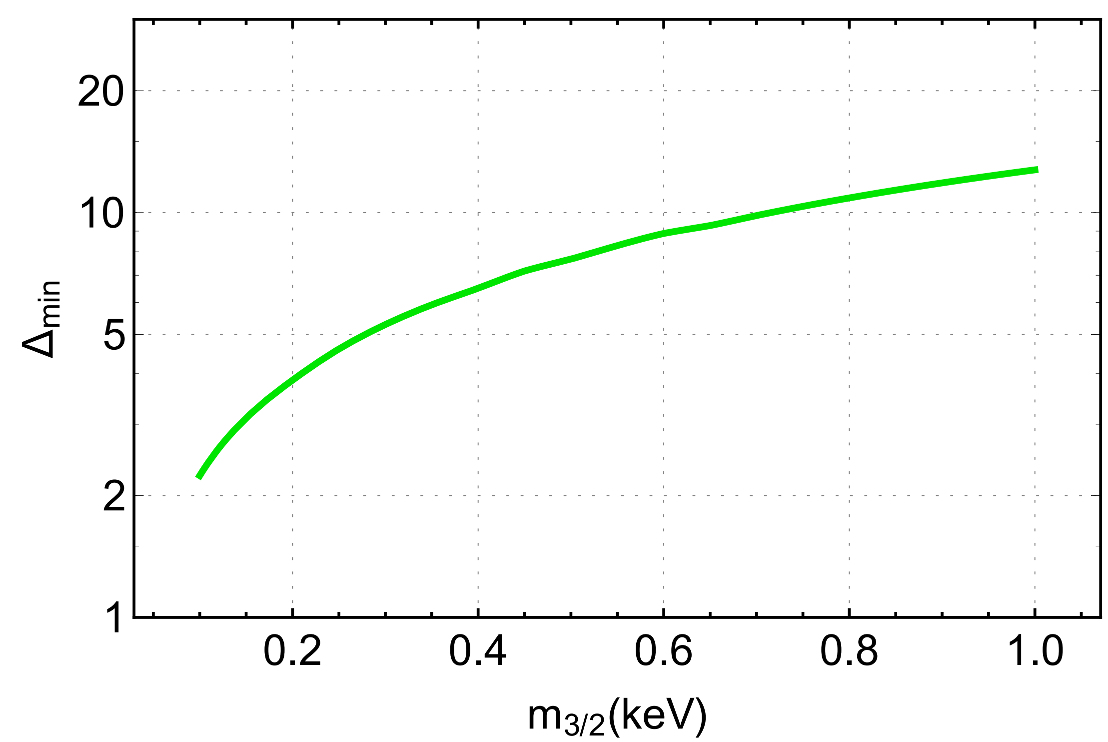

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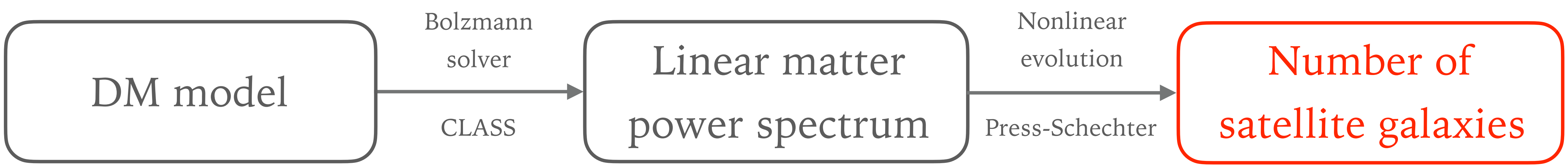
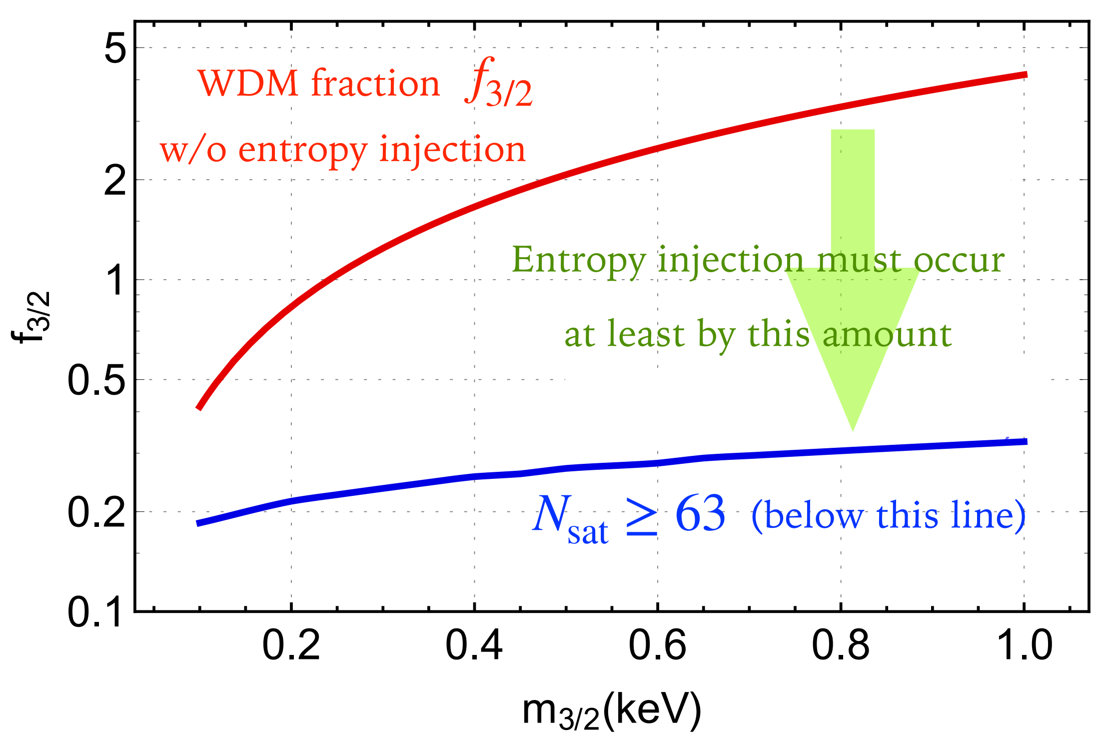
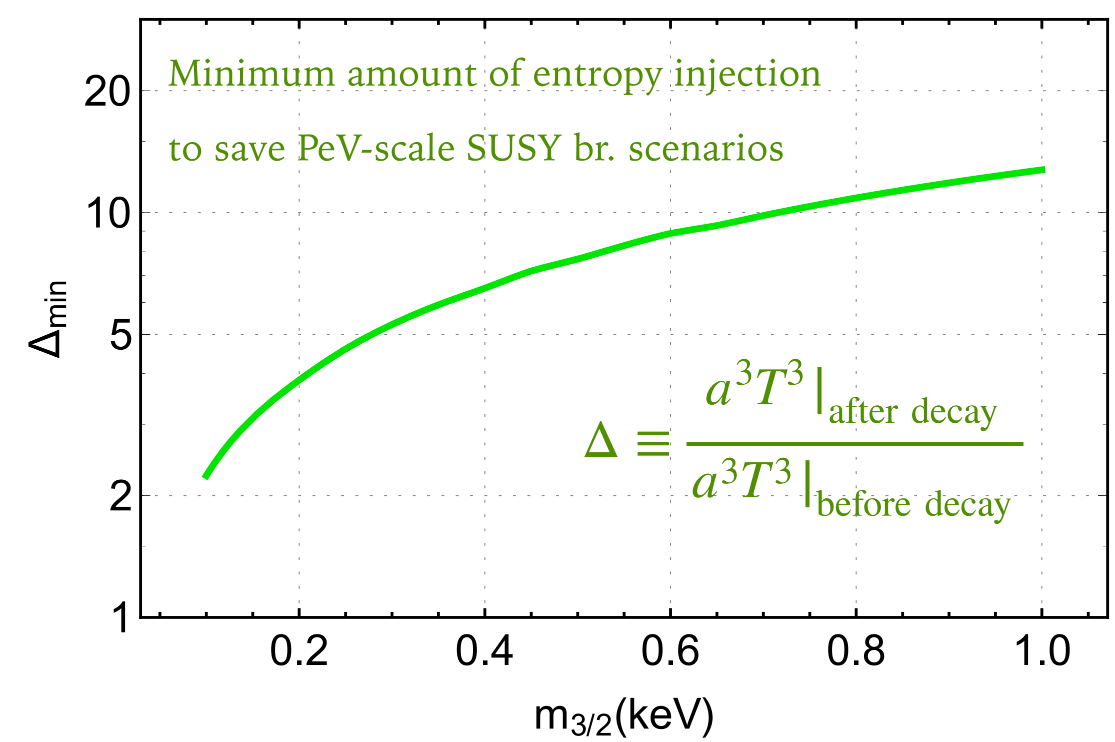






Summary

PeV ~~SUSY~~
&
GWs

PeV ~~SUSY~~
&
Small-scales

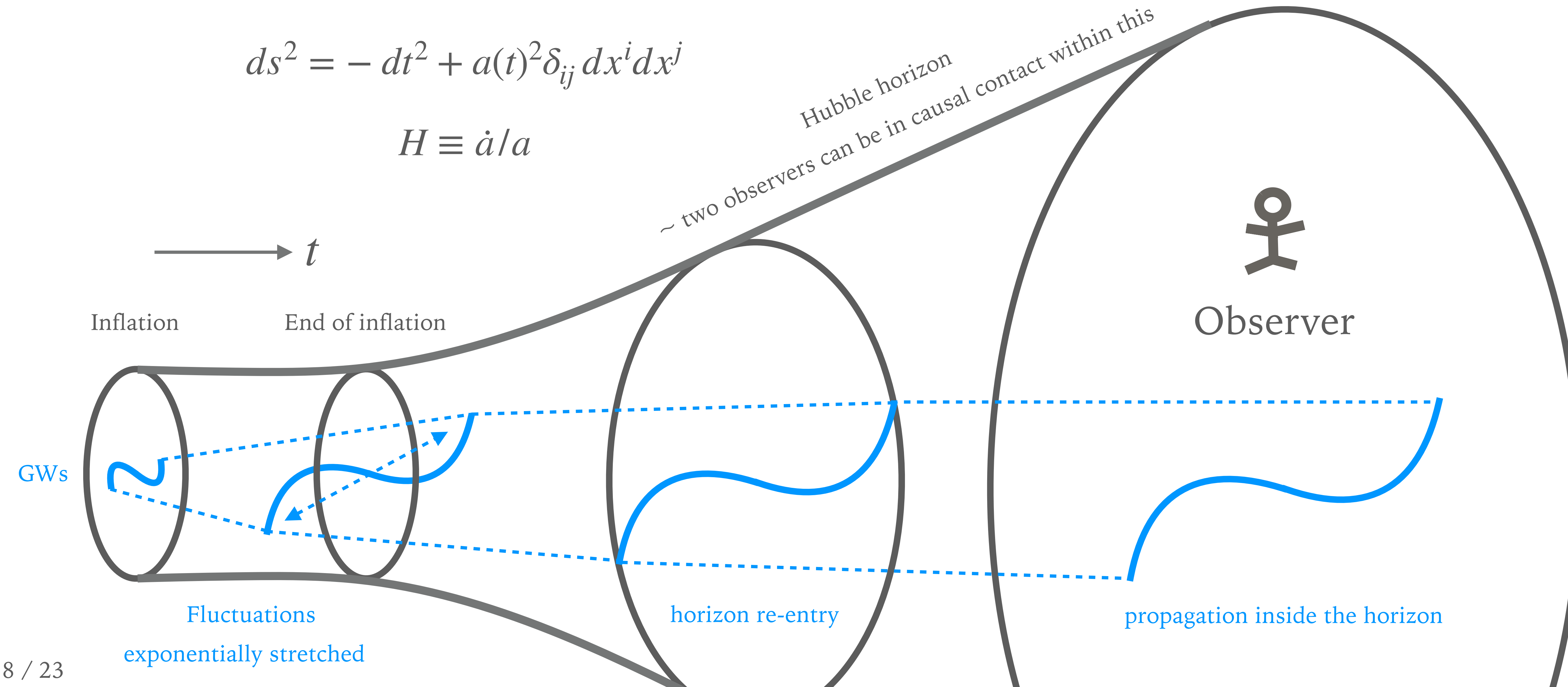
Introduction

IMPRINT OF PEV-SCALE SUSY BR. ON GRAVITATIONAL WAVES

- Inflationary GWs [Starobinsky '79]
  - During inflation, both scalar (= density) and tensor (= GWs) fluctuations are produced from quantum fluctuations, and stretched outside the horizon

$$ds^2 = -dt^2 + a(t)^2 \delta_{ij}\, dx^i dx^j$$

$$H \equiv \dot{a}/a$$



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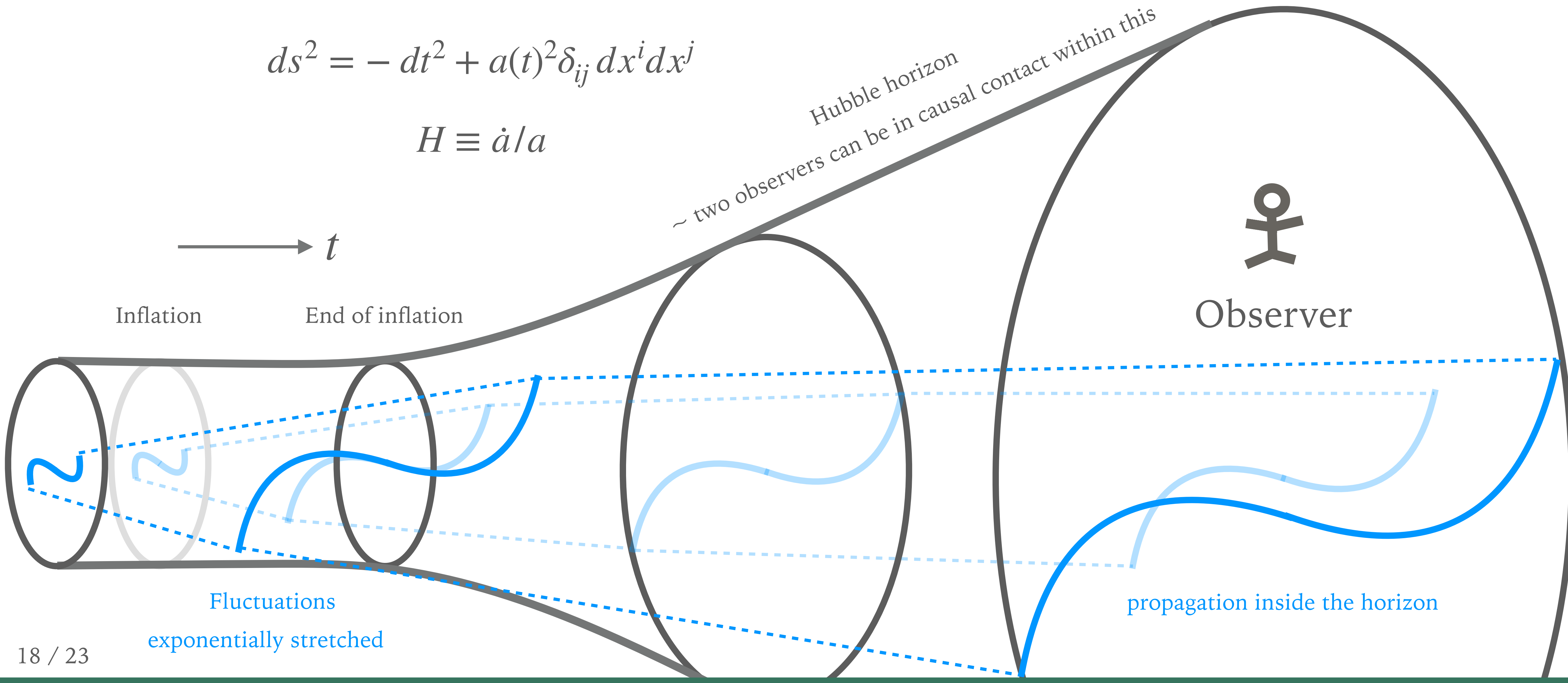
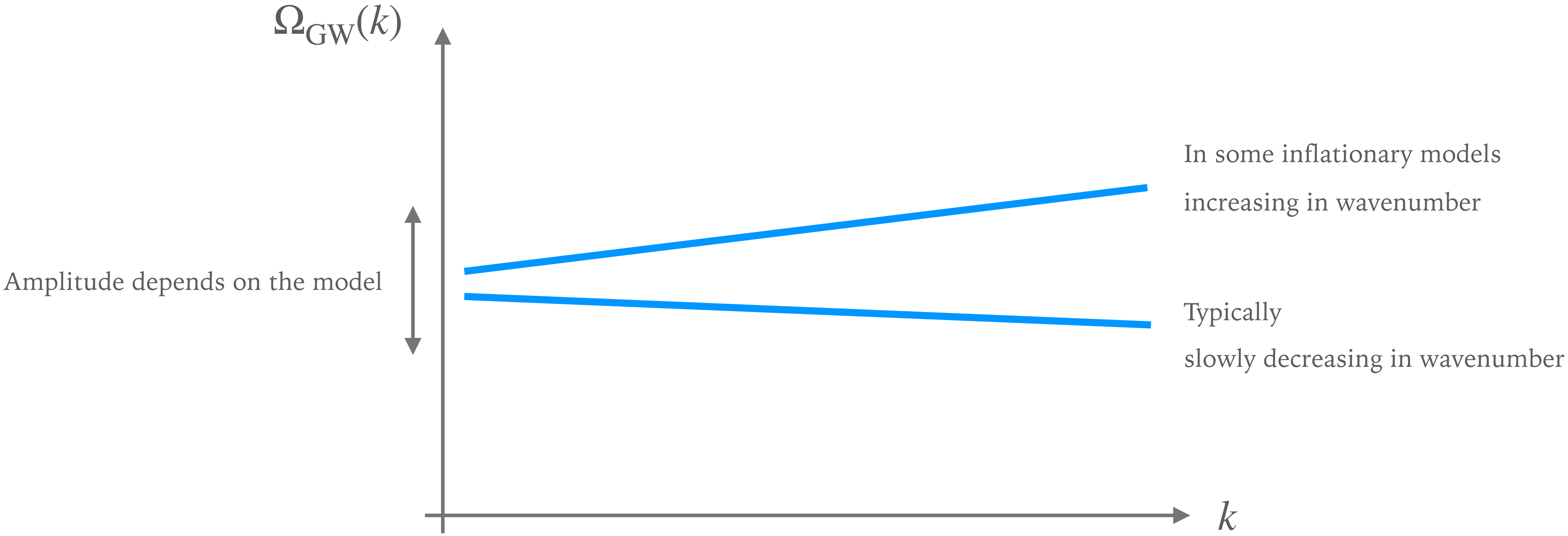


IMPRINT OF PEV-SCALE SUSY BR. ON GRAVITATIONAL WAVES

- Inflationary GWs [Starobinsky '79]
  - During inflation, both scalar (= density) and tensor (= GWs) fluctuations are produced from quantum fluctuations, and stretched outside the horizon
  - At present, GWs of various wavenumbers (theoretically) exist around us



IMPRINT OF PEV-SCALE SUSY BR. ON GRAVITATIONAL WAVES

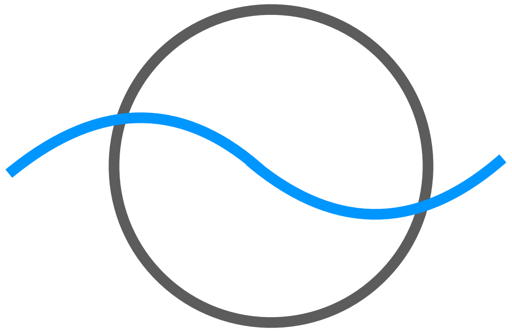
- Entropy injection leaves a distinct feature in the GW spectrum

  - Intuitively...

  GWs with **small k** (large wavelengths): get stuck outside the horizon

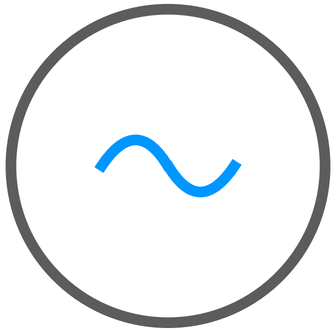
  why? Because of the equation of motion $\ddot{h}_{ij} + 3H\dot{h}_{ij} + \frac{k^2}{a^2}h_{ij} = 0$

  friction term!



  GWs with **large k** (short wavelengths): behaves as radiation within the horizon

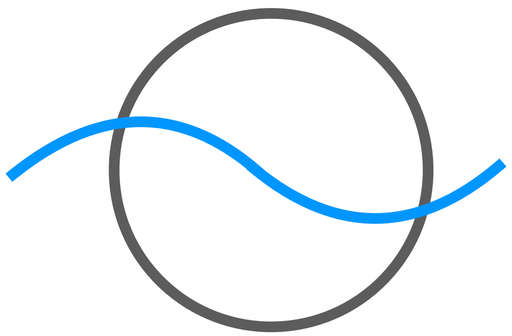
  why? Because they are massless fields $S_{\mathrm{grav}} \sim \int d^3x \, \frac{a^3}{2}\left[\dot{h}_{ij}^2 - \frac{1}{a^2}(\nabla h_{ij})^2\right]$



  - So, <u>entropy injection dilutes only GWs with **large k**</u>

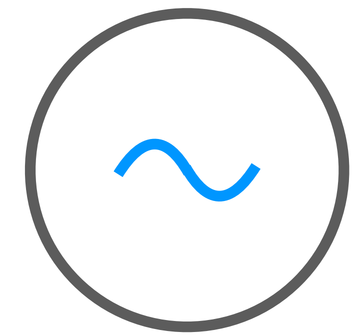
IMPRINT OF PEV-SCALE SUSY BR. ON GRAVITATIONAL WAVES

- Inflationary GW spectrum in PeV-scale SUSY breaking scenario

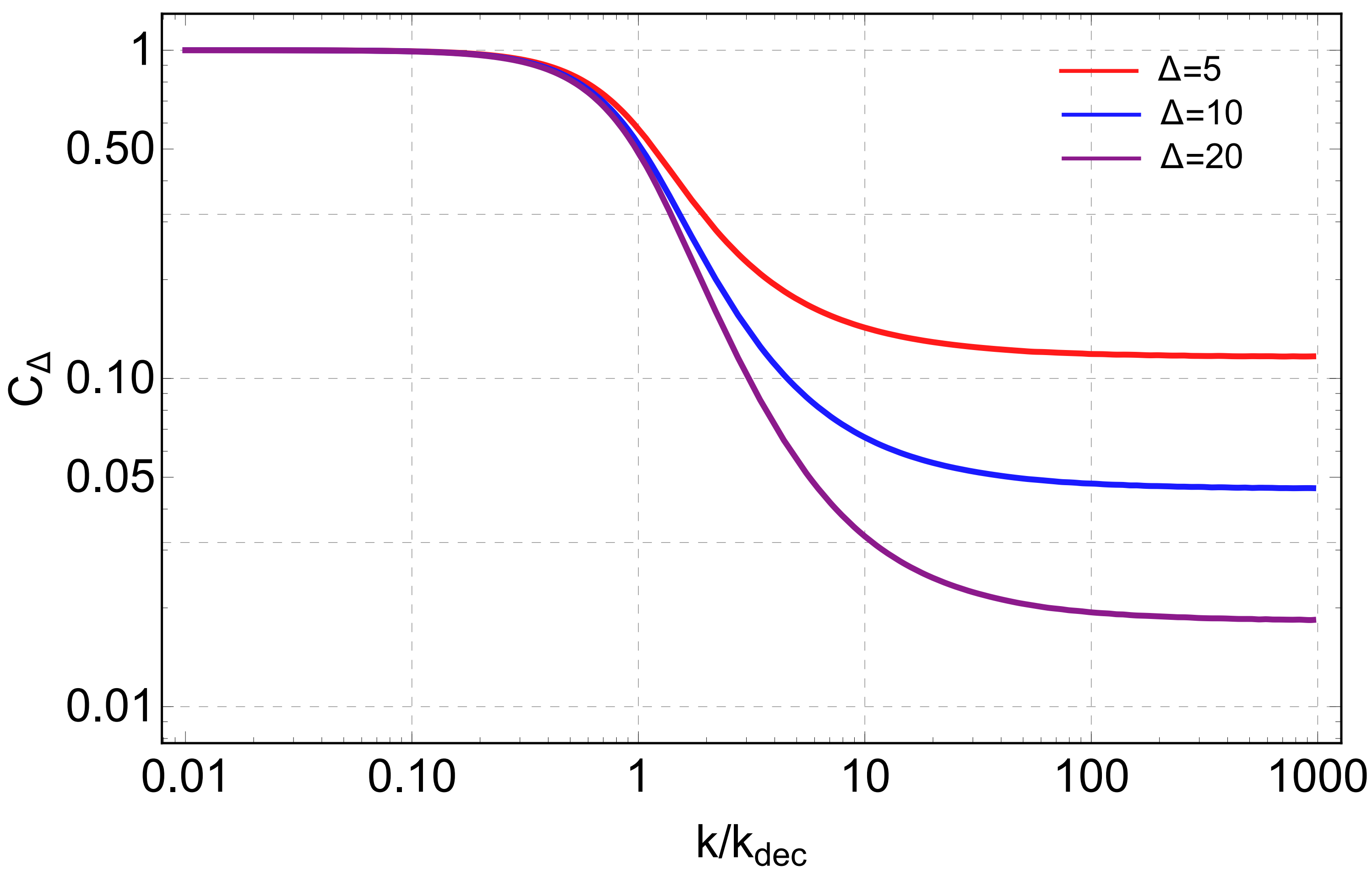


GWs outside the horizon when entropy injection occurs

GWs inside the horizon when entropy injection occurs



Ratio between $\Omega_{\rm GW}(k)$ w/ and w/o entropy injection



Suppression $\propto \dfrac{1}{\Delta^{4/3}}$

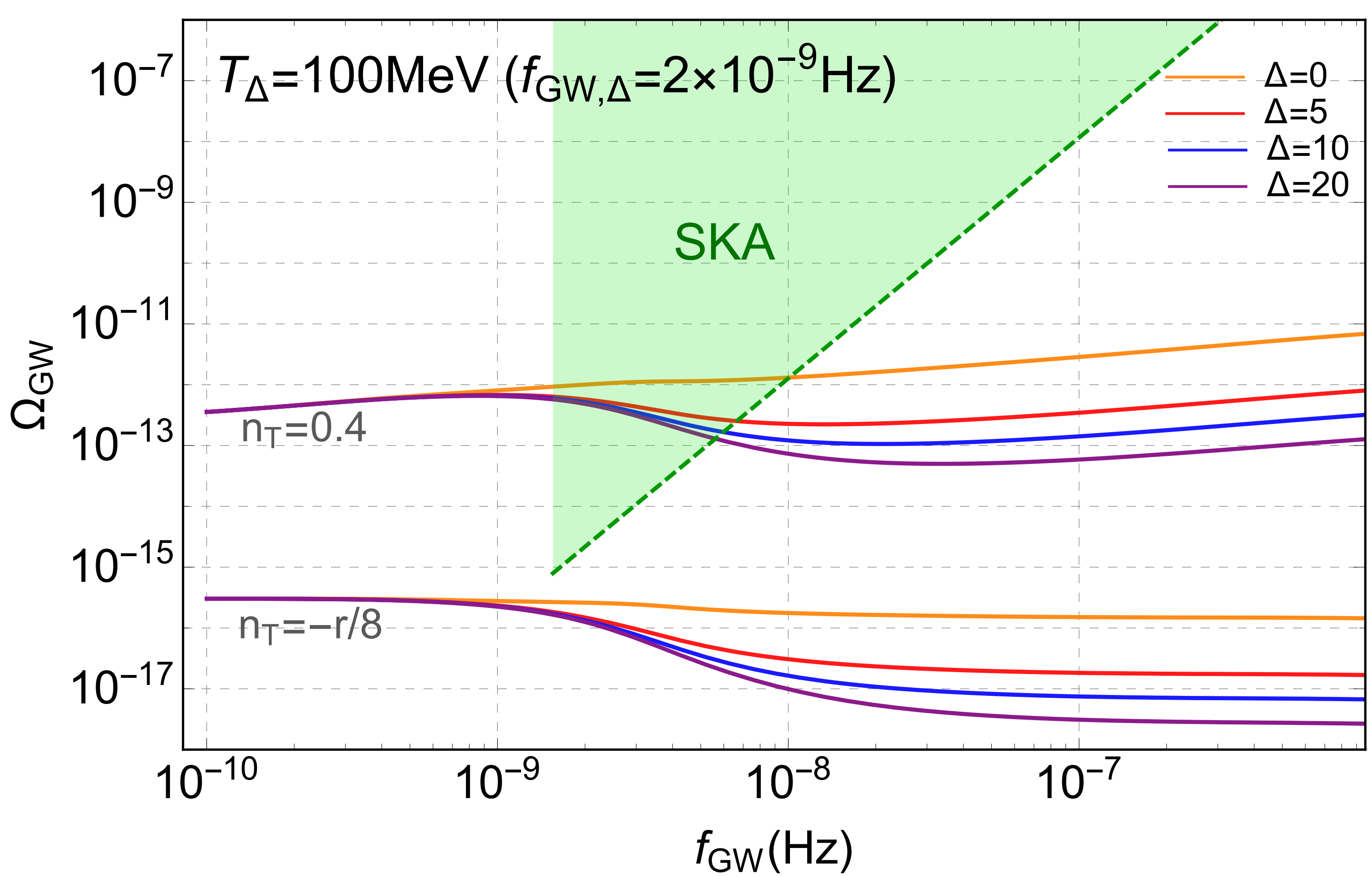
IMPRINT OF PEV-SCALE SUSY BR. ON GRAVITATIONAL WAVES

➤ Inflationary GW spectrum in PeV-scale SUSY breaking scenario

Entropy injection must occur between

(Big Bang Nucleosynthesis)$\sim$1MeV and (gravitino decoupling)$\sim$10TeV

$\to$ Frequency range of the feature is $[10^{-10}\,\mathrm{Hz},\ 10^{-5}\,\mathrm{Hz}]$ (SKA range)



Different inflationary models

IMPRINT OF PEV-SCALE SUSY BR. ON GRAVITATIONAL WAVES

- Inflationary GW spectrum in PeV-scale SUSY breaking scenario

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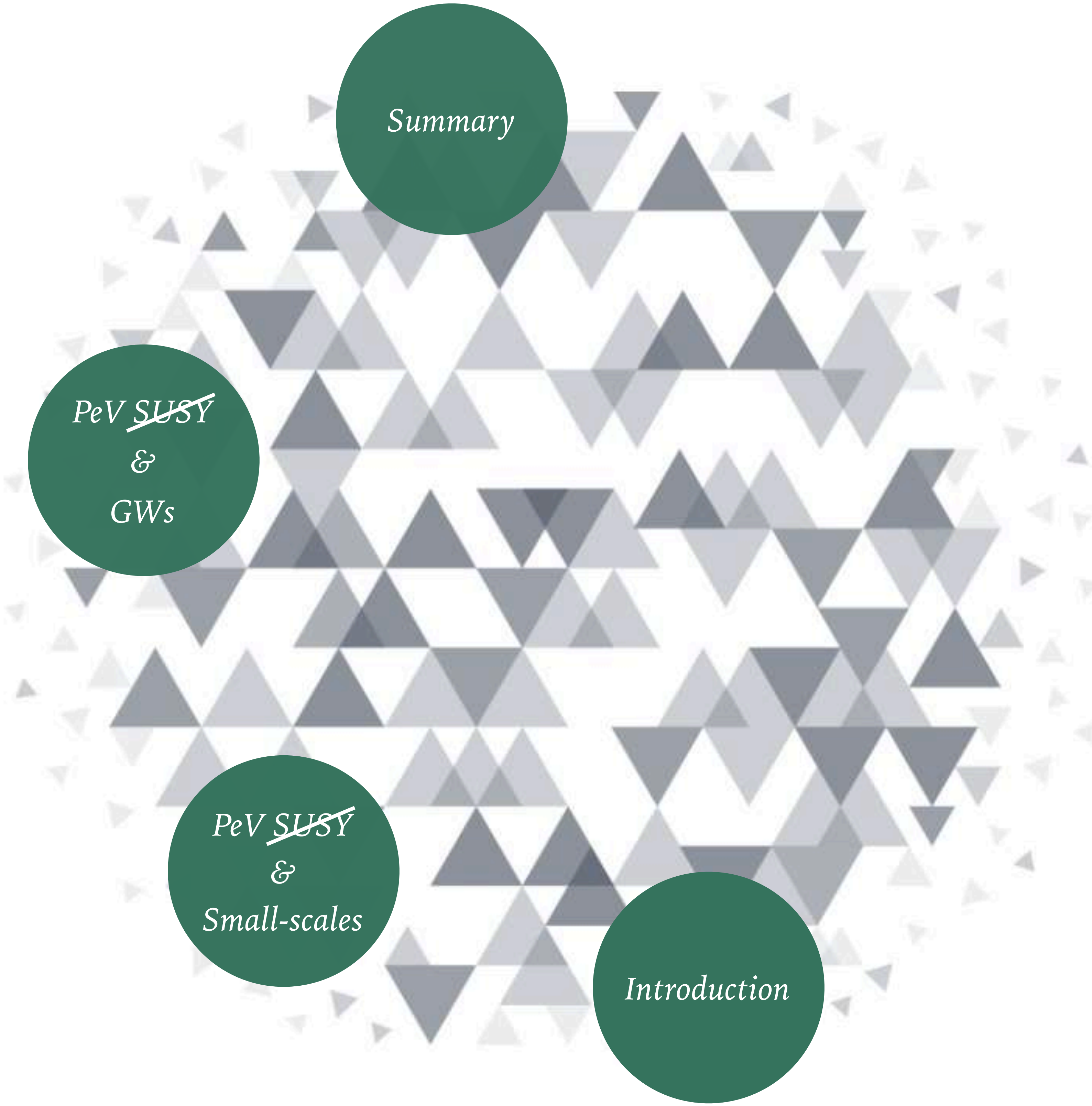
If we observe only featureless inflationary GWs between $[10^{-10}\,\mathrm{Hz},\, 10^{-5}\,\mathrm{Hz}]$,

then PeV-scale SUSY breaking scenarios are excluded.


Summary
PeV ~~SUSY~~ & GWs
PeV ~~SUSY~~ & Small-scales
Introduction

SUMMARY

- In PeV-scale SUSY breaking scenarios, light gravitinos can be a problem

$$\langle F \rangle \sim (10^6\ \mathrm{GeV})^2 \quad \rightarrow \quad m_{3/2} \simeq \frac{\langle F \rangle}{\sqrt{3} M_P} \sim 100\,\mathrm{eV} - 1\,\mathrm{keV}$$

Overclosure of the Universe / Small-scale structure

$$\Omega_{3/2} \gtrsim 1 \qquad\qquad \lambda \sim \mathcal{O}(\mathrm{Mpc})$$

- Solution to this problem requires entropy injection at some specific era

(Big Bang Nucleosynthesis $T \sim 1\,\mathrm{MeV}$) to (Gravitino decoupling $T \sim 10\,\mathrm{TeV}$)

- This in turn implies an unavoidable feature in the inflationary GW spectrum between a specific frequency range $[10^{-10}\,\mathrm{Hz},\ 10^{-5}\,\mathrm{Hz}]$