Berkeley
UNIVERSITY OF CALIFORNIA

Gravitational Wave Gastronomy

New Observational Windows on High-Scale Physics Workshop, IPMU

David Dunsky, Anish Ghoshal, Hitoshi Murayama, Yuki Sakakihara, and Graham White

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arXiv: 2111.08750

Gravitational Wave Gastronomy

Definition:

- *A savory variation of **Gravitational Wave Astronomy**.*
- *The search for gravitational wave signatures from the "eating" of one topological defect by another. Observed to occur in hybrid topological defects (i.e. domain walls bounded by strings, and strings bounded by monopoles.)*
- *Seasoned with equal parts of gravitational wave physics, early universe cosmology, and grand unification.*

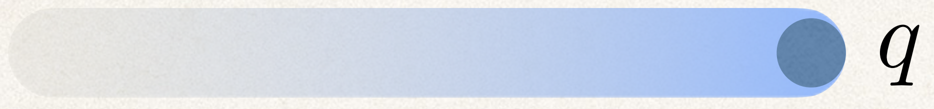
Outline

- ***Appetizers***: Gravitational Wave (GWs) basics, as probes of the early universe, and relationship to Grand Unified Theories (GUTs)
- ***Entree***: Dynamics and the GW signatures from hybrid topological defects
- ***Dessert:*** Outlook for distinguishing GUT symmetry breaking chains by such GW signatures

Gravitational Wave Basics: Emission

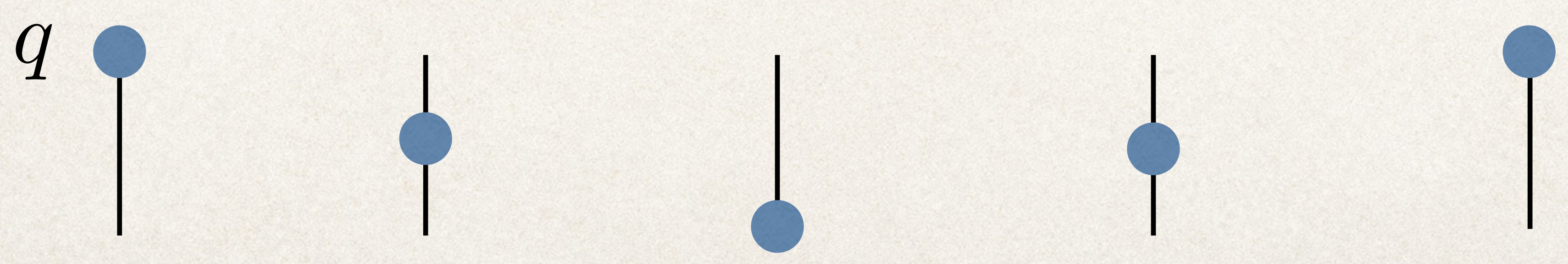
Electromagnetism

- Accelerated electric charges → Electromagnetic radiation



- If q & γ increase → Emitted power increases

- Electromagnetic waves oscillate charges up and down

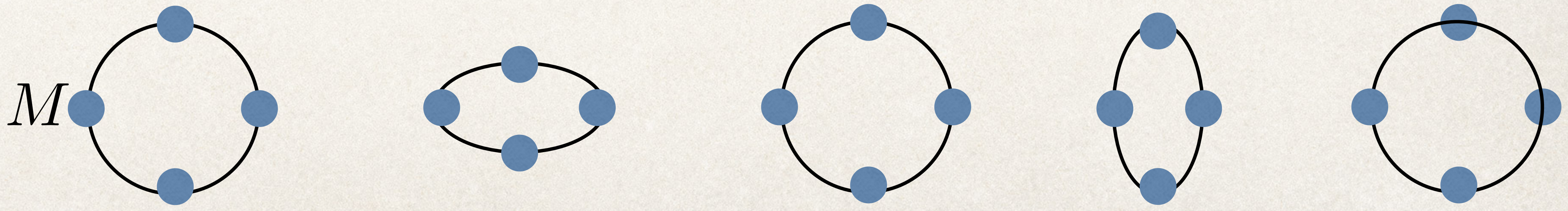


Gravity

- Accelerated masses → Gravitational radiation

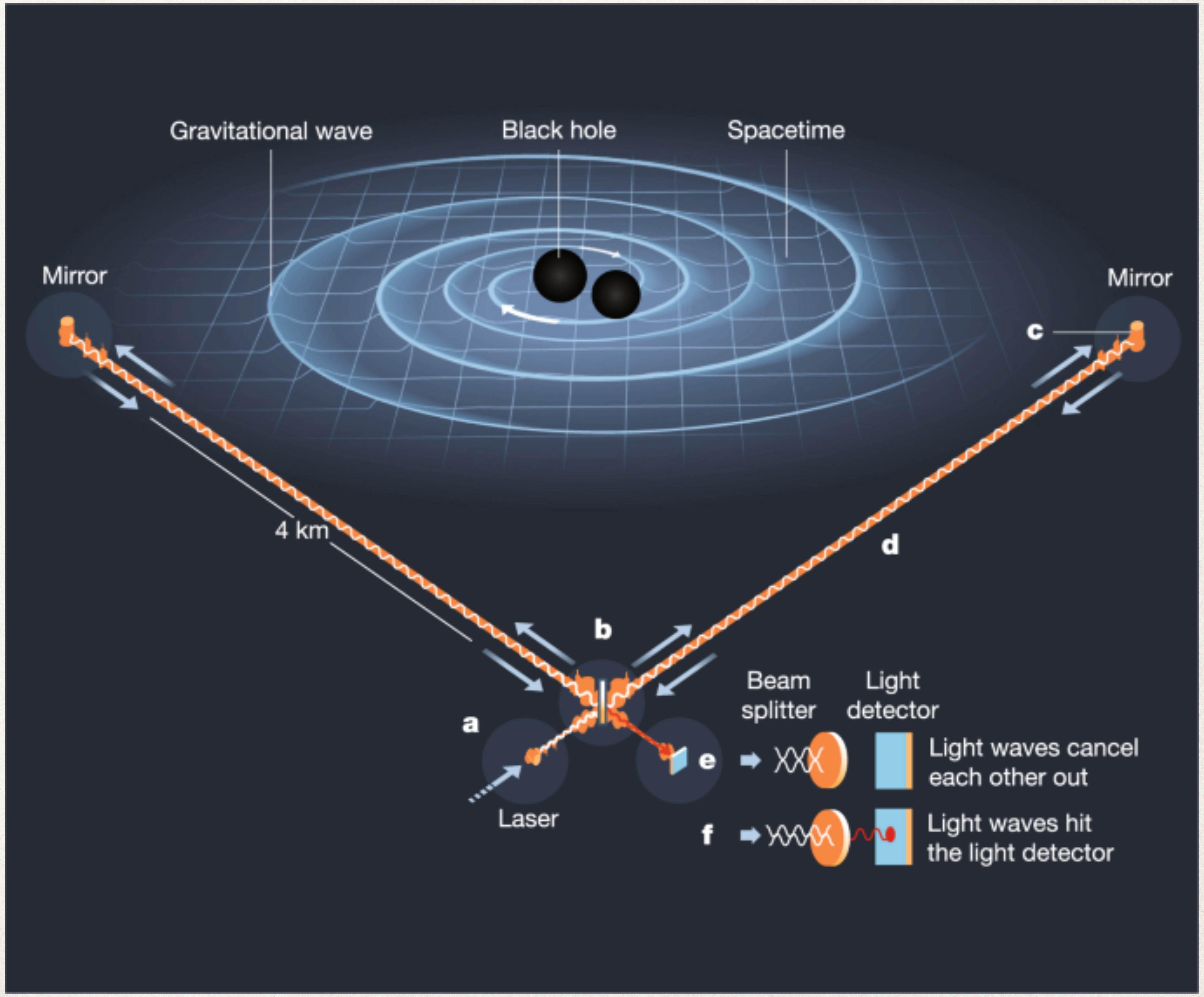
- If M & γ increase → Emitted power increases

- Gravitational waves stretch and squeeze space



Gravitational Wave Basics: Detection

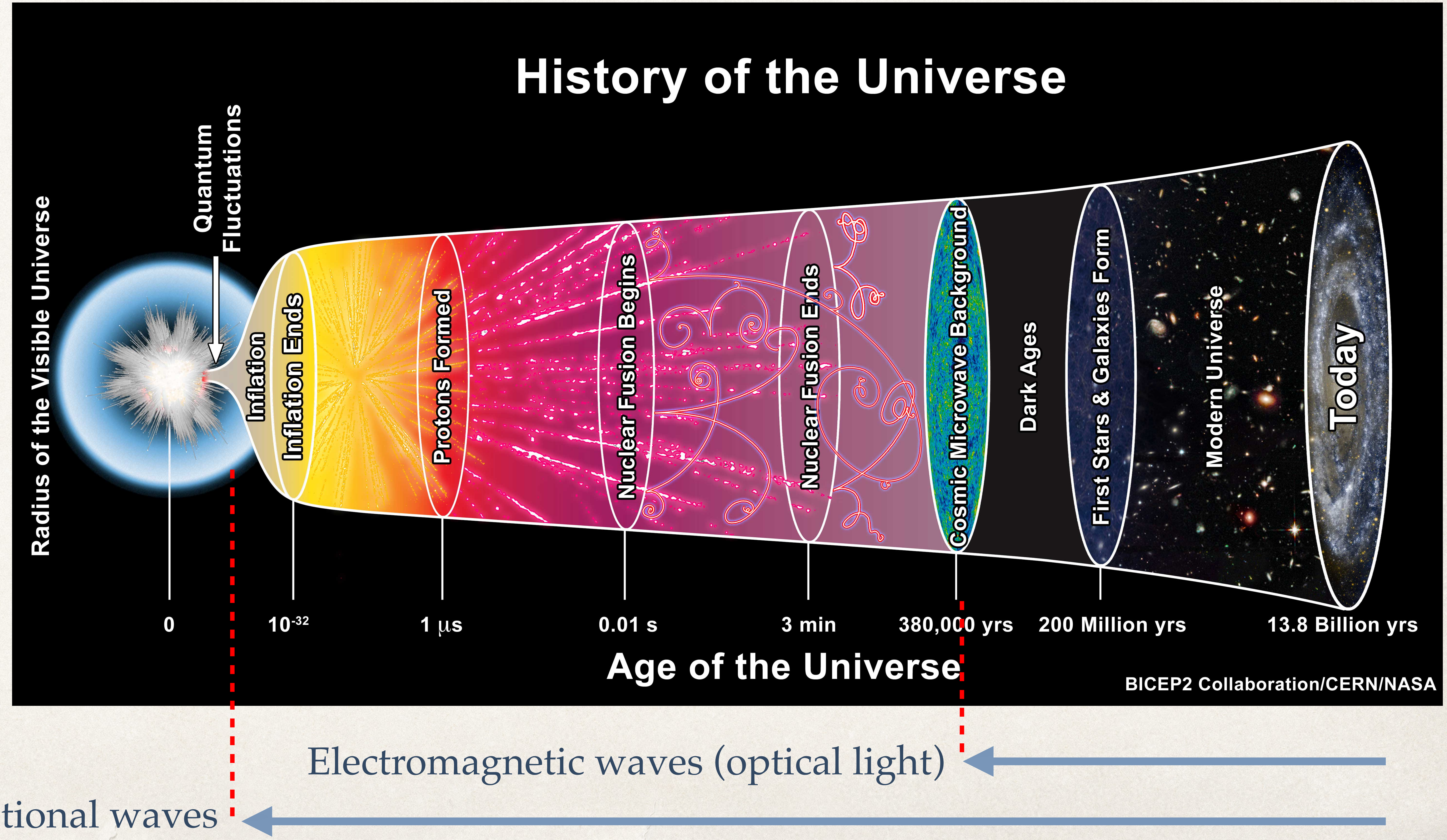
- Most GW detectors take advantage of this incredibly small stretch and squeeze of space via laser interferometry
    - For ex, Laser Interferometer Gravitational-Wave Observatory (LIGO)



Nature

Gravity Waves as Probes of the Early Universe

- Early universe transparent to GWs
- Potentially remarkable probe of moments after Big Bang



History of the Universe

BICEP2 Collaboration/CERN/NASA

Electromagnetic waves (optical light)

Gravitational waves

Gravity Waves as Probes of the Early Universe

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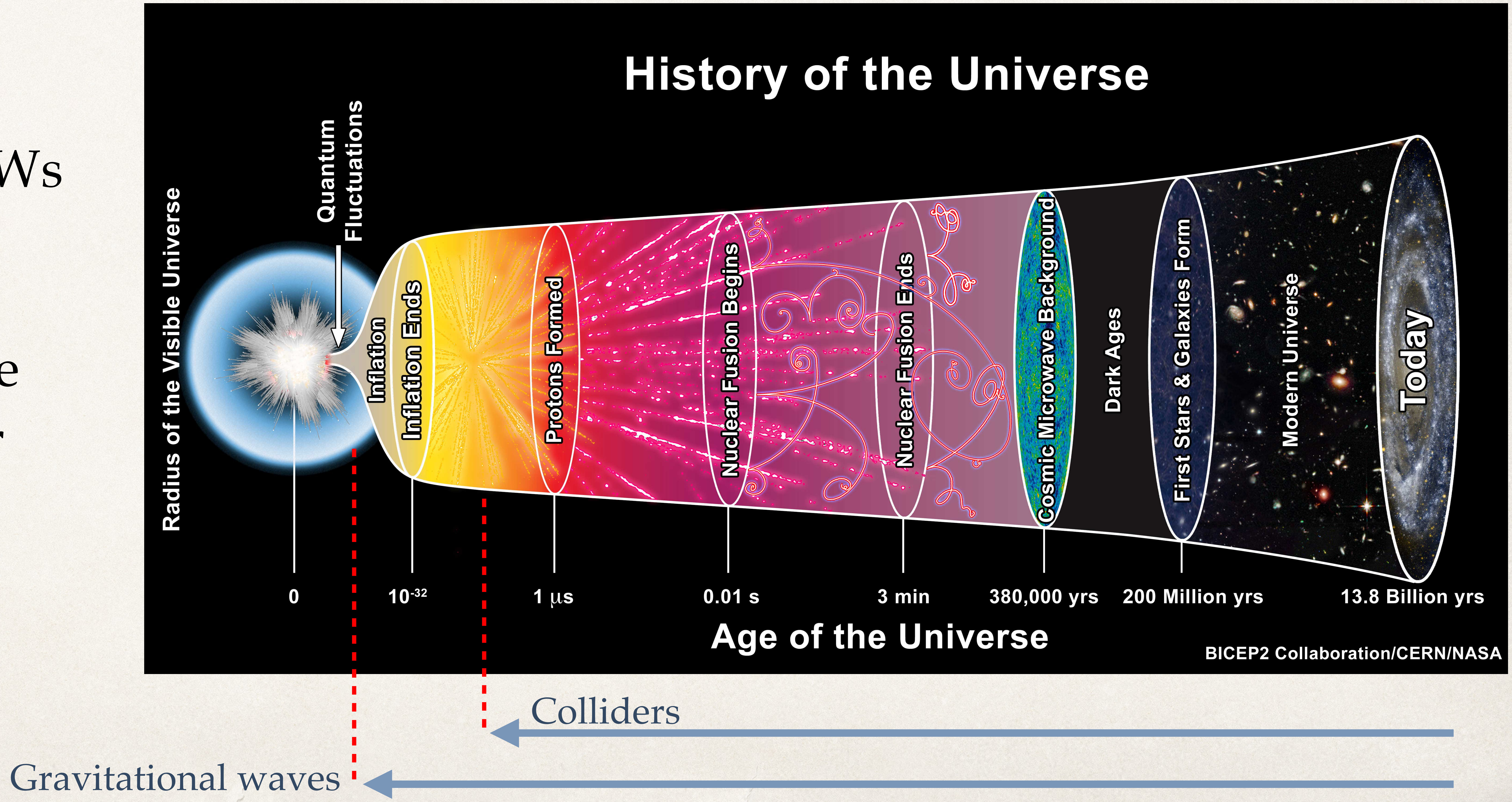
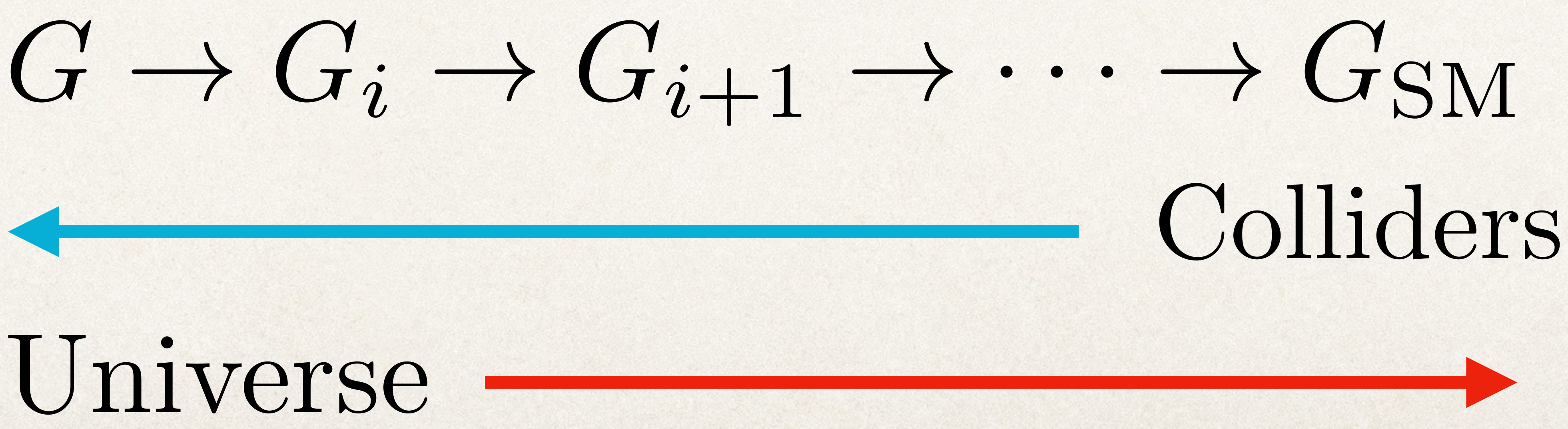


BICEP2 Collaboration/CERN/NASA

Gravitational Waves and GUTs

- Grand Unified Theories (GUTs) intimately tied to gravitational waves:
  - True symmetries of nature are restored at high temperatures in early universe
  - As the universe expands and cools, gauge symmetries describing nature spontaneously break



$$G \to G_i \to G_{i+1} \to \cdots \to G_{\mathrm{SM}}$$

Gravitational Waves and GUTs

- Grand Unified Theories (GUTs) intimately tied to gravitational waves:
  - When breaking, many gauge groups leave behind topological relics if non-trivial vacuum

$$\pi_{2-D}(G_j/G_{j+1}) \neq 0$$

  - $D = 0 \rightarrow \text{Monopoles form}$ $\quad D = 1 \rightarrow \text{Cosmic Strings form}$ $\quad D = 2 \rightarrow \text{Domain Walls form}$

- Topological defects massive and can accelerate to relativistic speeds → source of GW!

Hybrid Topological Defects

- For some chains, strings bounded by monopoles, or walls bounded by strings

Hybrid Topological Defects

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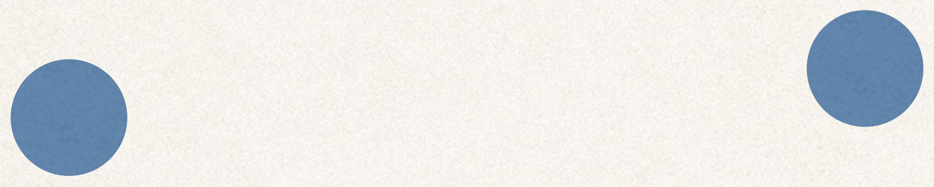
$$G \xrightarrow{\text{monopoles}} H \times U(1)$$



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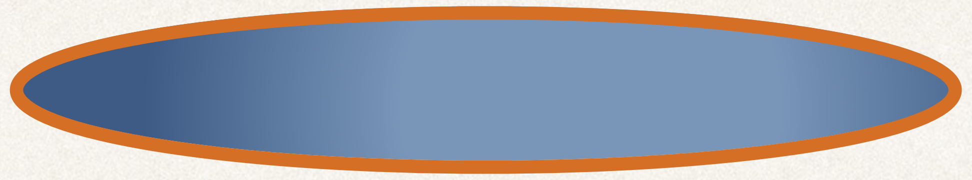

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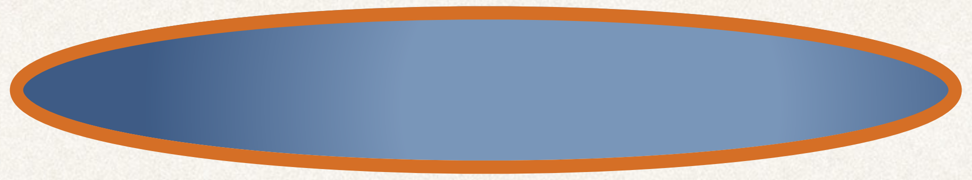

- Tension force of string or wall causes (relativistic) oscillations

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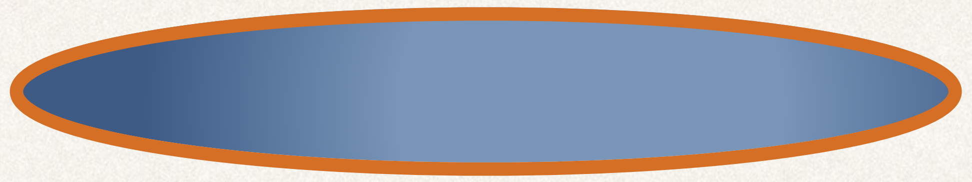

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↓

Gravitational radiation (Unique fingerprints of chains)

Hybrid Topological Defects

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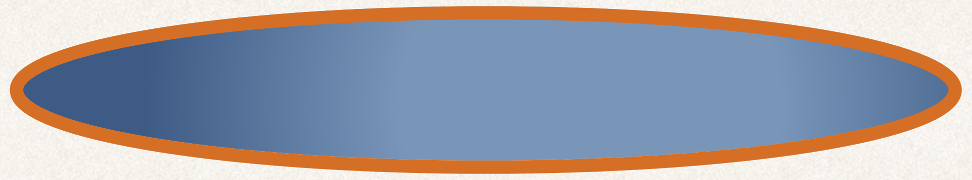

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Gravitational radiation (Unique fingerprints of chains)

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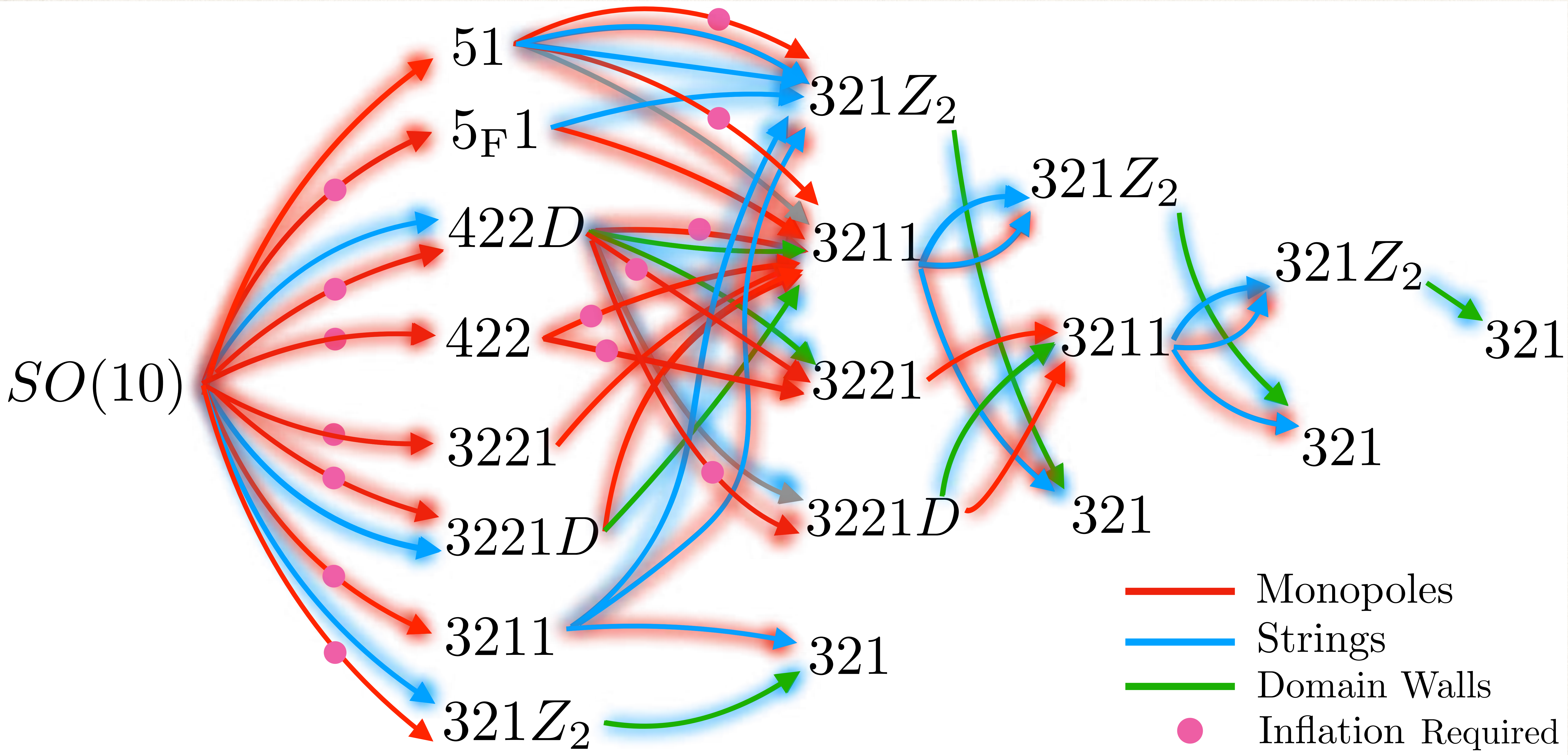
Decay

Four Course Menu

- Monopoles eating strings (nucleation) ← See previous talk by Valerie Domcke!
- Strings eating monopoles (collapse)
- Strings eating walls (nucleation)
- Walls eating strings (collapse)

Symmetry Breaking Chains



$SO(10)$

51

$5_{\mathrm{F}}1$

$422D$

422

3221

$3221D$

3211

$321Z_2$

$321Z_2$

3211

3221

$3221D$

321

$321Z_2$

3211

321

$321Z_2$

3211

321

$321Z_2$

321

🟥 Monopoles

🟦 Strings

🟩 Domain Walls

● Inflation Required

Group abbreviations

$51 = SU(5) \times U(1)_X$

$5_{\mathrm{F}}1 = SU(5)_{\text{flipped}} \times U(1)_{\text{flipped}}$

$422 = SU(4)_c \times SU(2)_L \times SU(2)_R$

$3221 = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$3211 = SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

$321 = SU(3)_c \times SU(2)_L \times U(1)_Y$

$D =$ D-Parity

Gravitational Wave Basics: Computing Signal

- Measure strain through $\Omega_{\rm GW} \equiv \frac{d\rho_{\rm GW}}{d\ln f}\frac{1}{\rho_{\rm crit}} \propto \text{Strain}^2$
- Recipe:

Estimate: $P_{\rm GW} \sim G\langle \dddot{Q}^2 \rangle \longrightarrow \rho_{\rm GW} \sim P_{\rm GW} \times \Delta t \times n_{\rm sources} \longrightarrow \Omega_{\rm GW} \sim \left.\frac{\rho_{\rm GW}}{\rho_{\rm BG}}\right|_{\text{Emission}} \times \Omega_{\rm rad}$

$$f \sim \text{scale size of system}\Big|^{-1}_{\text{Emission}} \times \text{Redshift}$$

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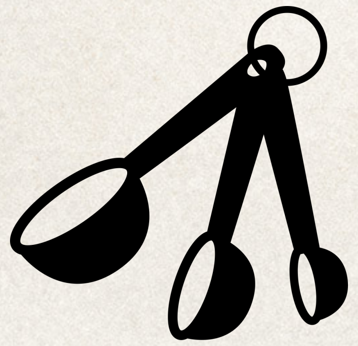
$$f \sim \left.\text{scale size of system}^{-1}\right|_{\text{Emission}} \times \text{Redshift}$$

Exact:



$$P_{\rm GW}(f) \sim G|T^{T}_{\mu\nu}(f)|^2 \longrightarrow \frac{d\rho_{\rm GW}(t)}{df} = \int dt' \underset{\underset{\text{Expansion}}{\uparrow}}{\frac{a(t')^4}{a(t)^4}} \int dl \underset{\underset{\text{Source Density}}{\uparrow}}{\frac{dn(l,t')}{dl}} \underset{\underset{\text{Power}}{\uparrow}}{\frac{dP(l,t')}{df'}} \underset{\underset{\text{Redshift}}{\uparrow}}{\frac{df'}{df}}$$

Weinberg '72

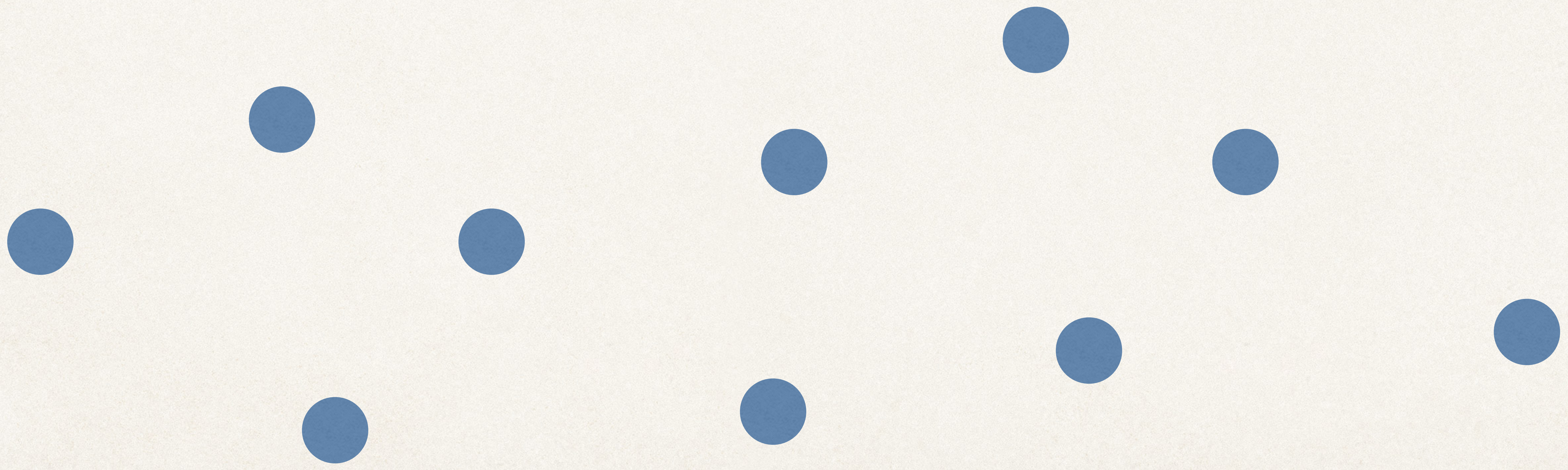
Strings Bounded by Monopoles

Monopoles Eating Strings (Nucleation)

See previous talk by Valerie Domcke!

- Occurs in following scenario

Monopole formation



Monopoles Eating Strings (Nucleation)

- Occurs in following scenario

Monopole formation → Inflation

Monopoles Eating Strings (Nucleation)

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Monopole formation → Inflation → String formation

Monopoles Eating Strings (Nucleation)

- Occurs in following scenario

Monopole formation → Inflation → String formation → Wait…

Monopoles Eating Strings (Nucleation)

- Occurs in following scenario

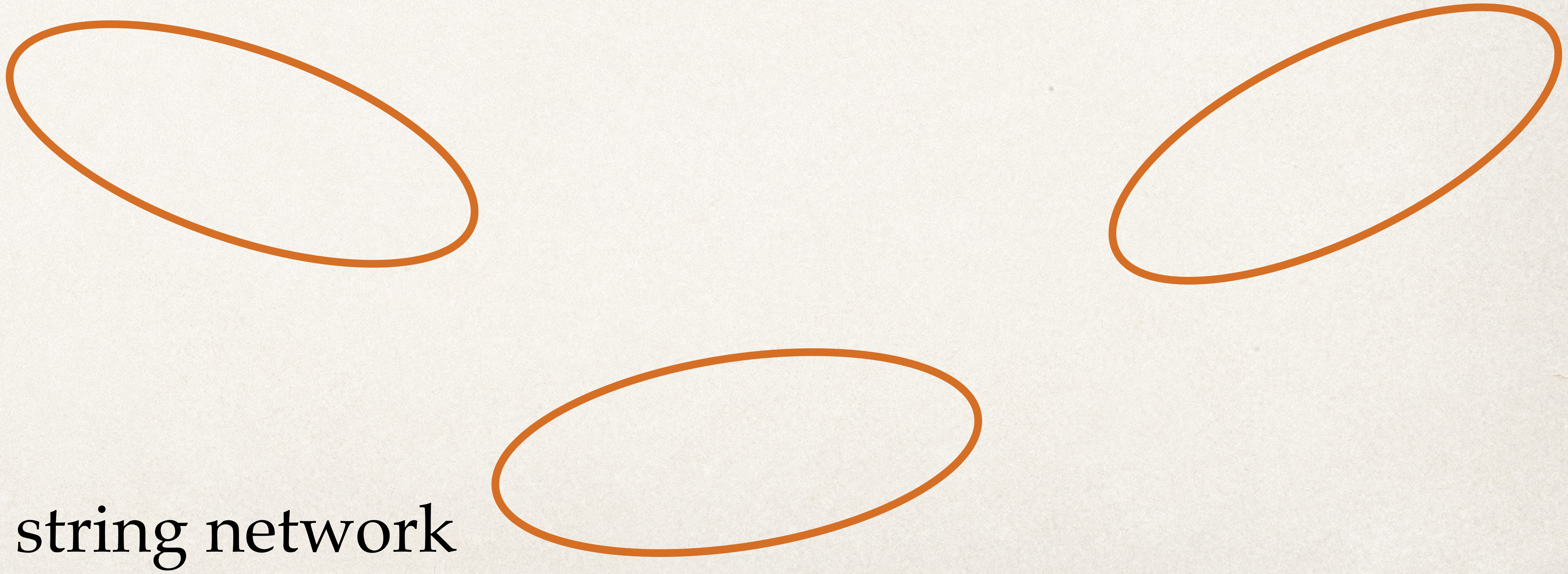
Monopole formation → Inflation → String formation → Nucleation

- String rest mass converted to monopole kinetic energy

↓

Decay via gravitational radiation

- Before nucleation, strings evolve as pure string network



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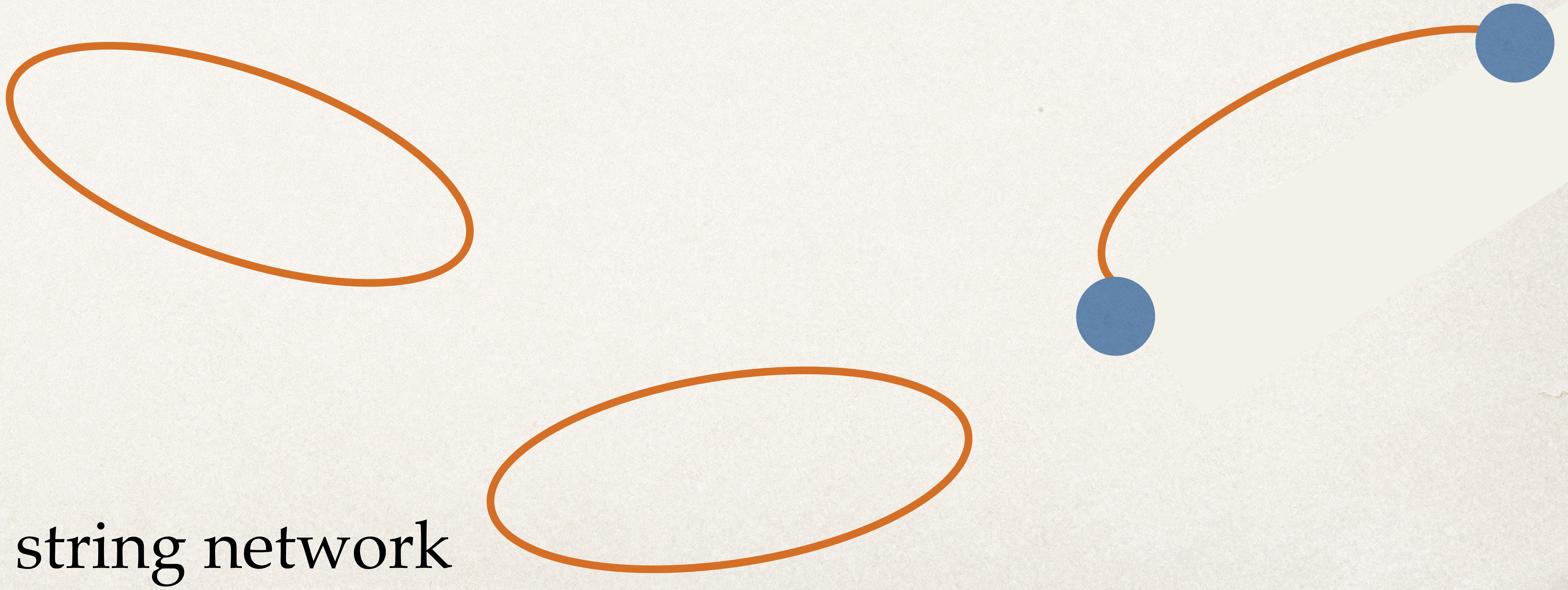

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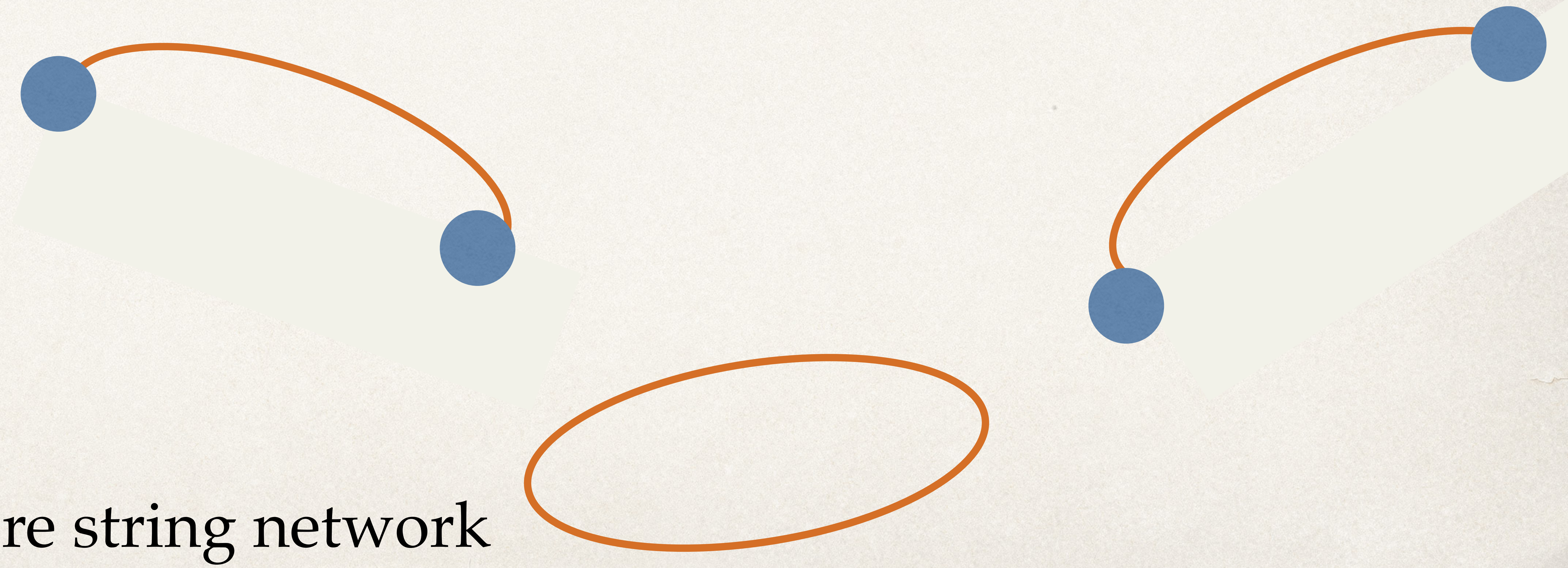

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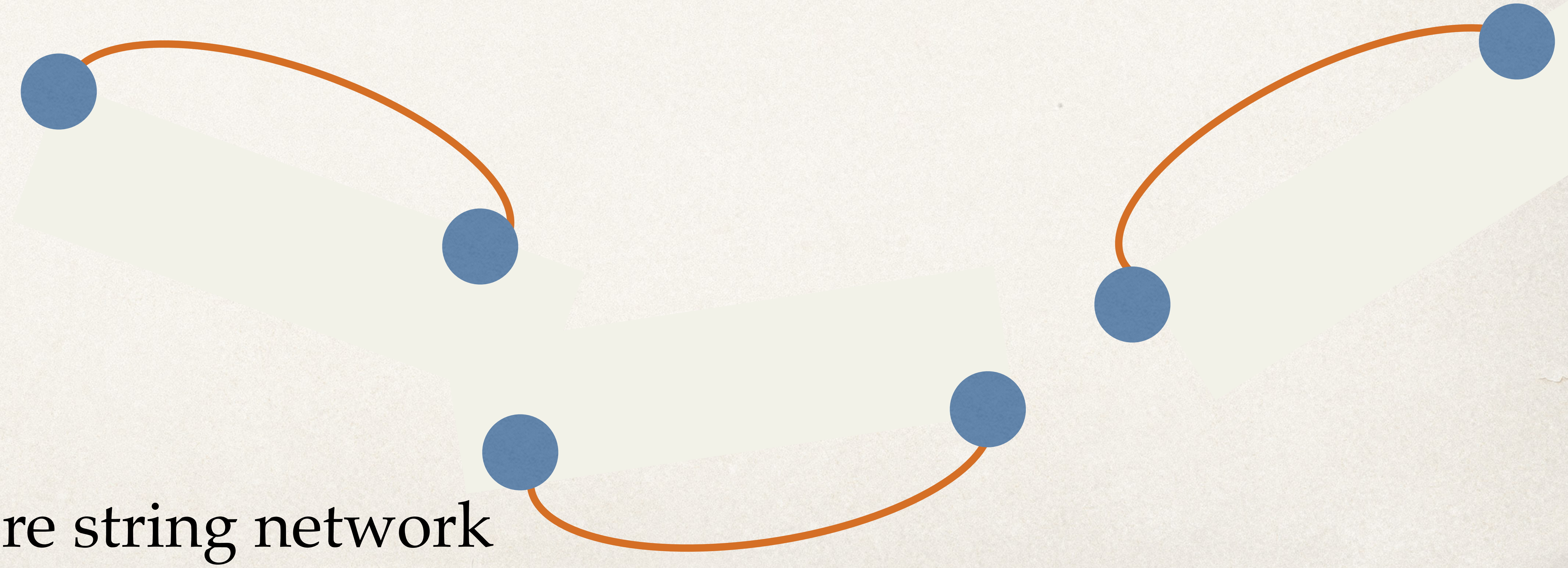
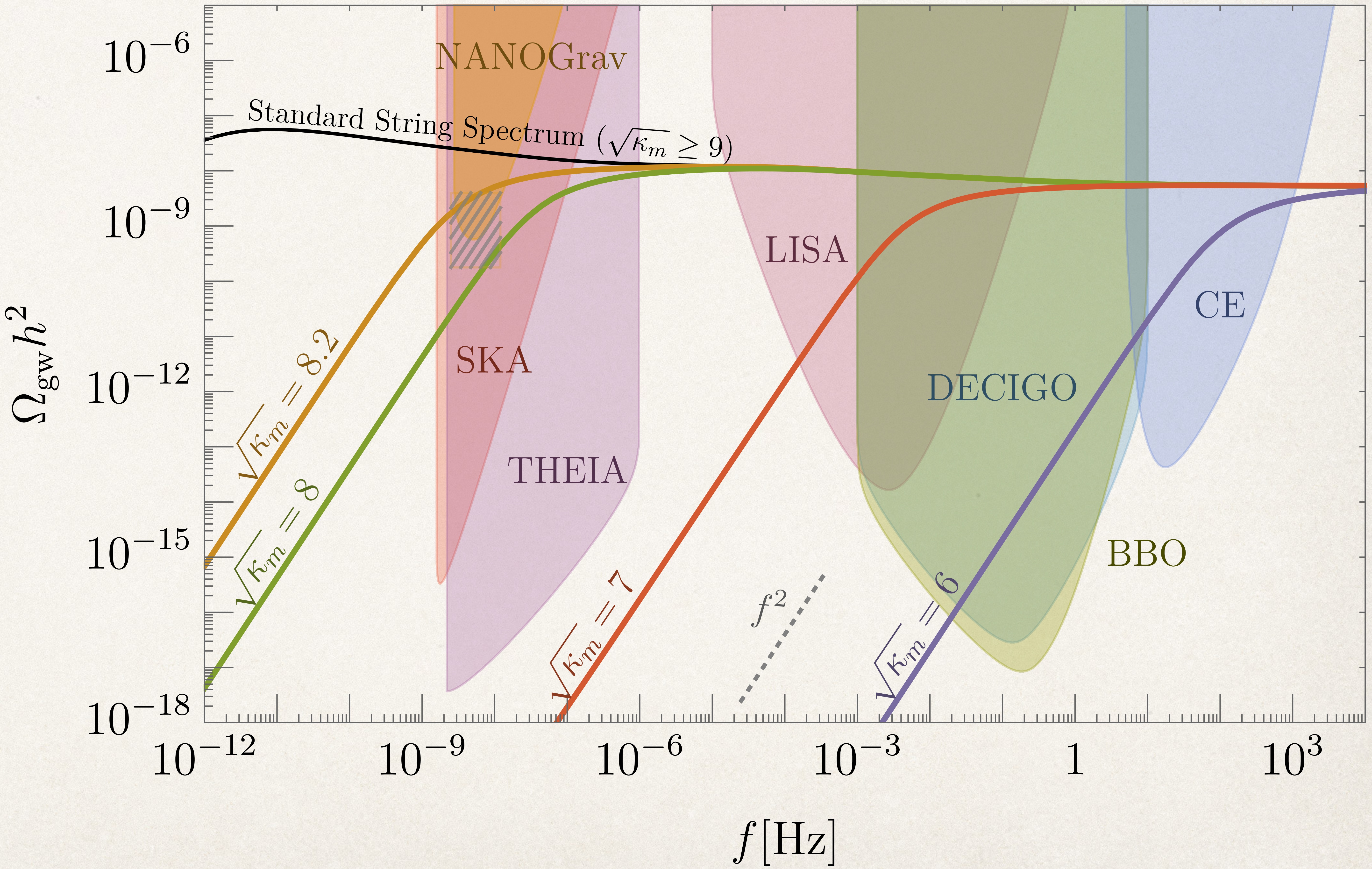


- Before nucleation, strings evolve as pure string network

Monopole Nucleation Spectrum

- Standard, flat, string spectrum at high frequencies, f^2 decaying spectrum at lower frequencies



See also Dror '19, Buchmuller '21

Strings Eating Monopoles (Collapse)

- New menu items: 1) Enhanced Kibble-Zurek mechanism, 2) Monopole-antimonopole annihilation, and 3) GW spectrum

Langacker-Pi '80, Holman '92, Vilken '96 and '97

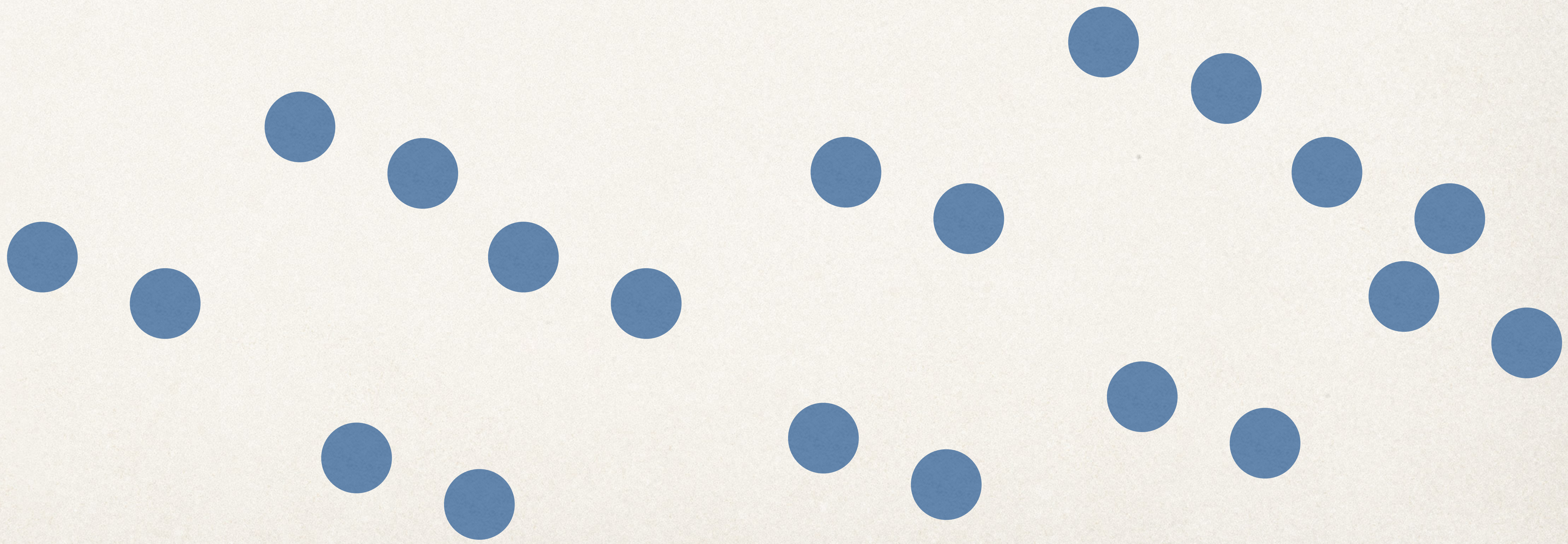
- Occurs in following scenario

Inflation ⟶ Monopole formation

$$n_m \sim H^3 \times \left(\frac{M_{\rm Pl}}{v_m}\right)^2$$

Originally estimate by Kibble

Zurek's Enhancement



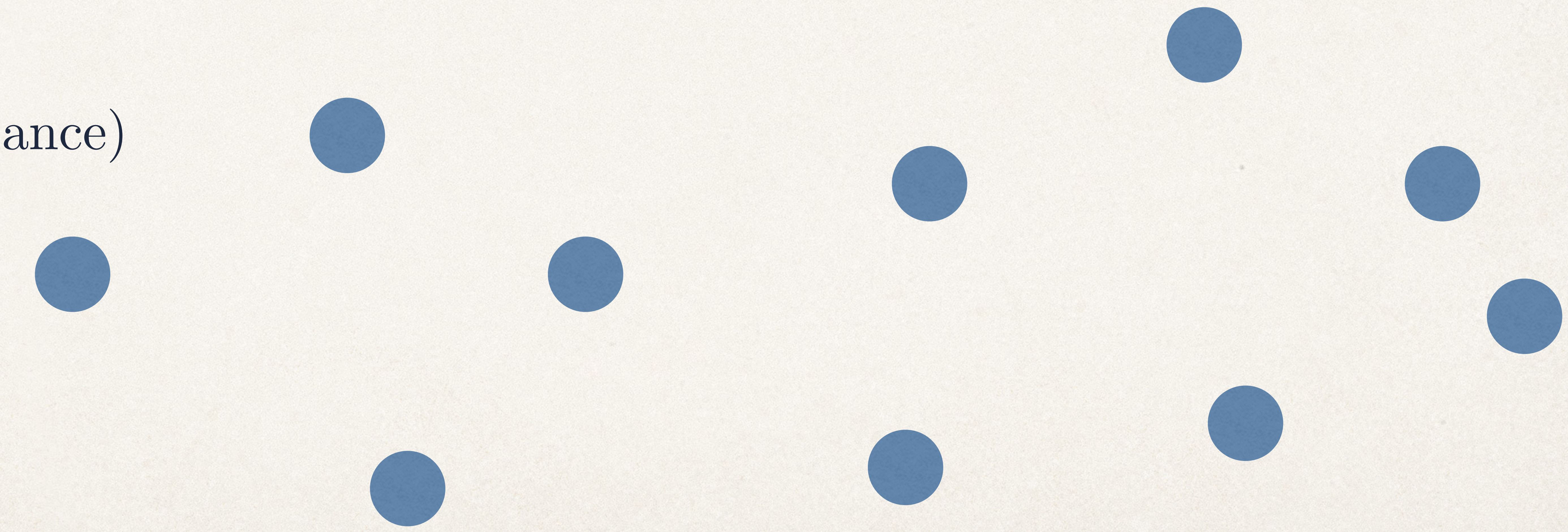
Zurek '85, Murayama '09

Strings Eating Monopoles (Collapse)

- Occurs in following scenario

Inflation → Monopole formation

$$n_m(T) \approx 10^{-5} \frac{v_m}{M_{\mathrm{Pl}}} T^3 \quad \text{(Freeze-Out Abundance)}$$



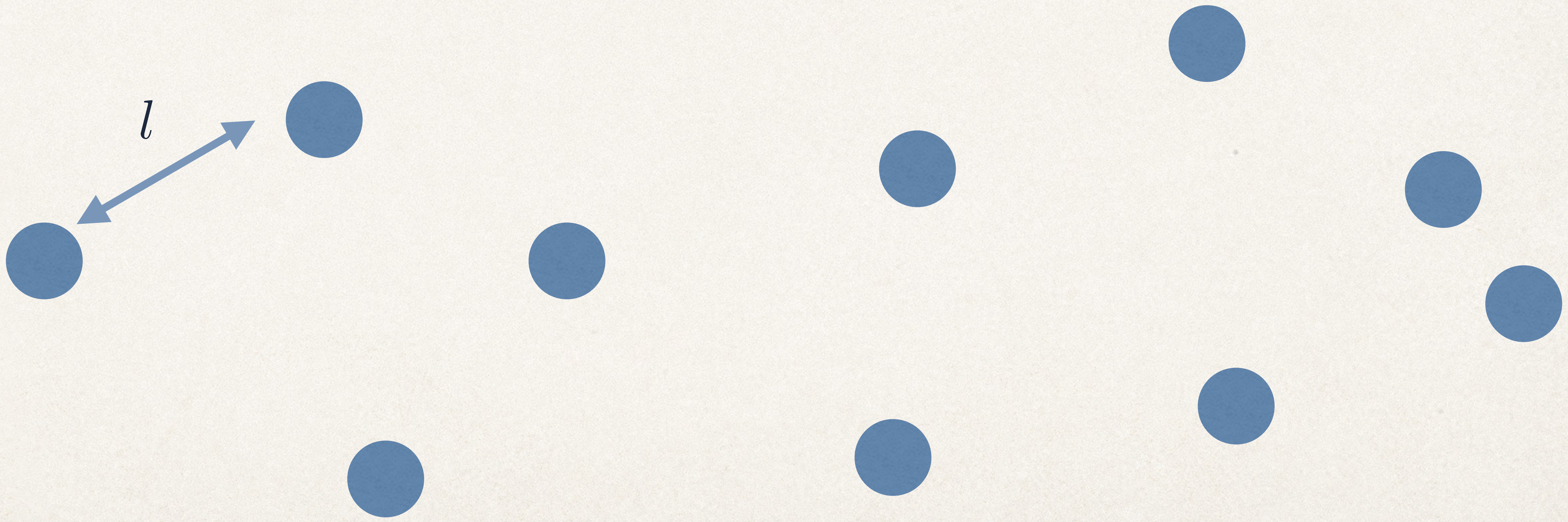
Strings Eating Monopoles (Collapse)

- Occurs in following scenario

Inflation ⟶ Monopole formation ⟶ String formation ⟶ Annihilation

$$l \approx \frac{1}{n_m(T = v_\mu)^{1/3}}$$

- String rest mass converted to monopole kinetic energy



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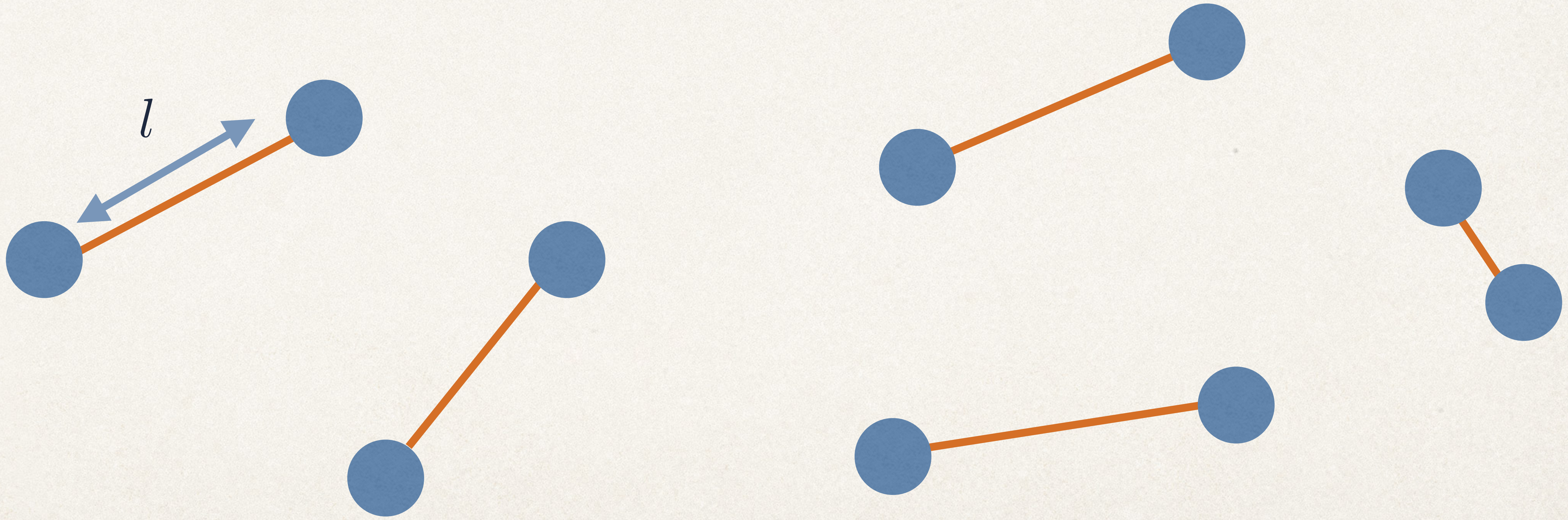


- String rest mass converted to monopole kinetic energy

Monopole Network Evolution

- String rest mass converted to monopole kinetic energy → Decay via friction & gravitational radiation

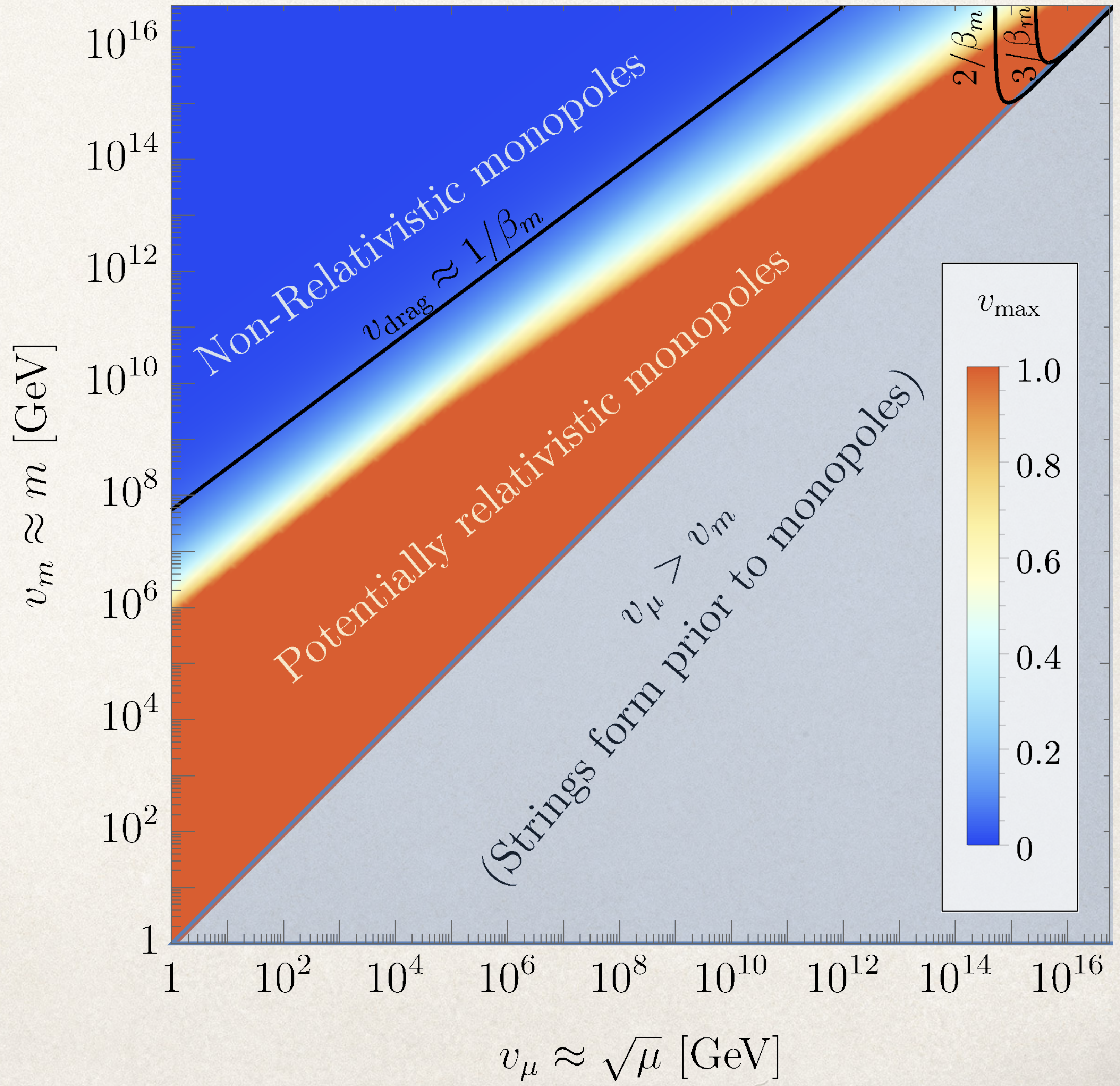
$$\mu l \approx 2 \times \frac{1}{2} m v_{\mathrm{max}}^2$$

- Potential gravitational wave signal if $v_{\mathrm{max}} \sim 1$
- String induced monopole motion generates friction with plasma

$$F_{\mathrm{string}} \sim \mu \quad \xleftrightarrow{\text{balance}} \quad F_{\mathrm{friction}} \sim T^2 v \quad \longrightarrow \quad v_{\mathrm{drag}} \sim \frac{\mu}{T^2}$$

Vilenkin '82

$$\tau \approx \frac{E}{|P_f|} \approx \frac{\mu l}{\beta T^2 v^2} \quad \text{(Monopole-bounded string lifetime)}$$



Monopole Burst Spectrum

- $\rho_{\mathrm{GW,burst}} \approx n_m(v_\mu) \times P_{\mathrm{GW}} \times \tau$

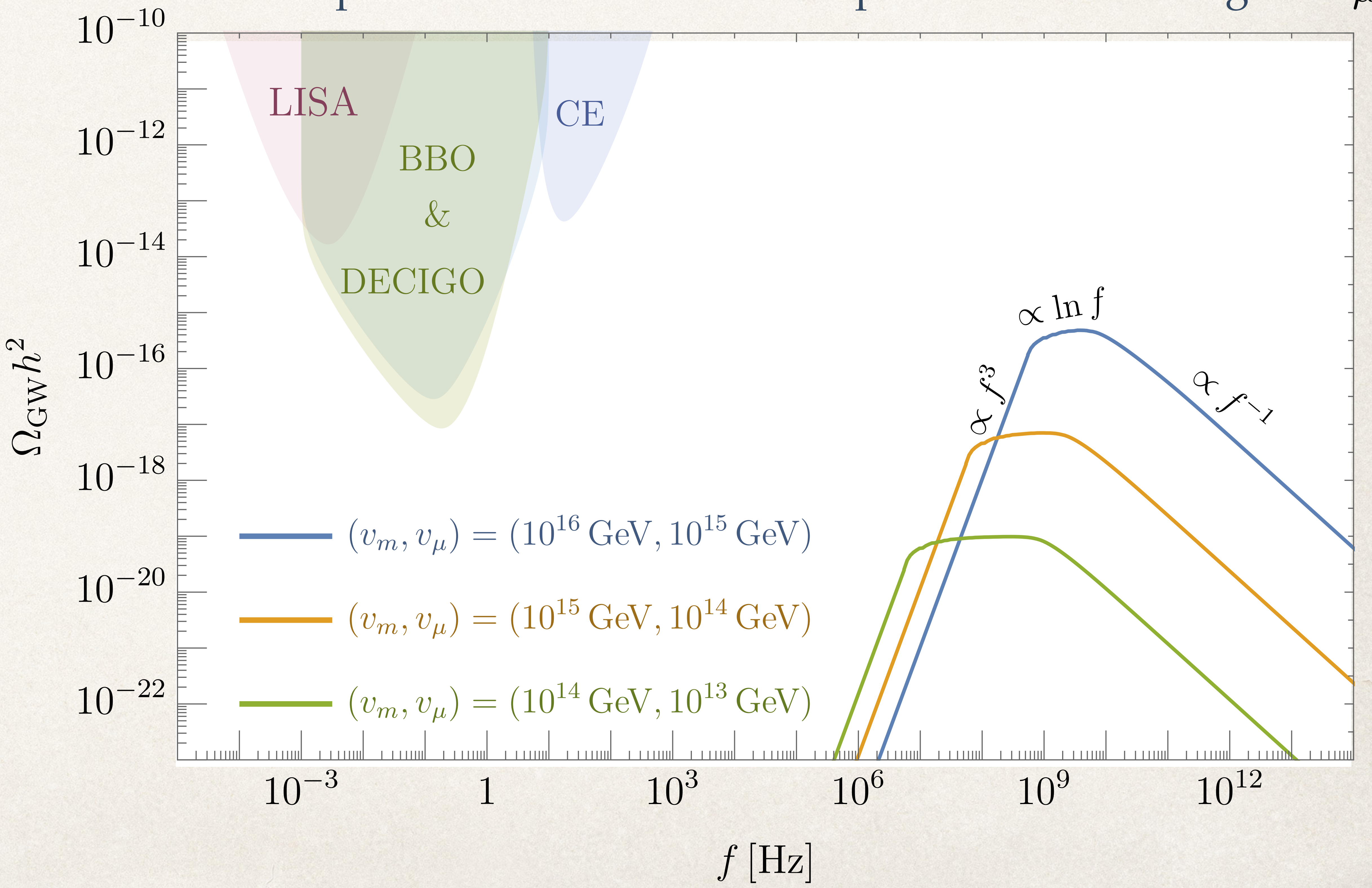
  $\sim G\mu^2$ (Roughly same as pure strings)
  Leblond '09

- $\Omega_{\mathrm{GW,burst}} \approx \dfrac{\rho_{\mathrm{GW,burst}}}{\rho_{\mathrm{BG}}(v_\mu)} \times \Omega_{\mathrm{rad}} \sim 10^{-4}\,(G\mu)^{4/3}$

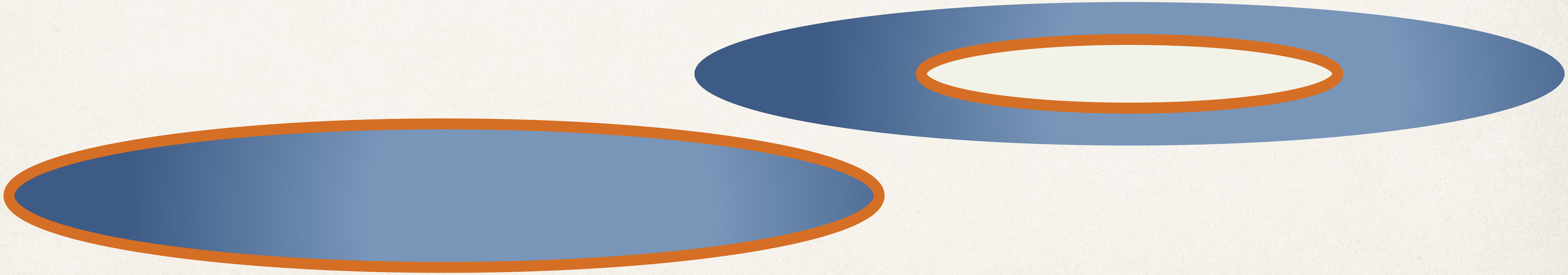
  $$f_{\mathrm{burst}} \sim \frac{1}{l}\frac{a(v_\mu)}{a(t_0)} \sim 10^8\mathrm{Hz}\left(\frac{v_m}{10^{15}\mathrm{GeV}}\right)^{1/3}$$

- $\Omega_{\mathrm{GW}} \propto$ f^{-1} and $\ln f$ at high frequencies,
  f^3 at lower frequencies

Exact recipe with $\delta-$source of monopole-bounded strings at v_μ



Domain Walls Bounded by Strings



Kibble '82, Everett '82

Strings Eating Domain Walls (Nucleation)

- Occurs in following scenario

String formation

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String formation ⟶ Inflation

Strings Eating Domain Walls (Nucleation)

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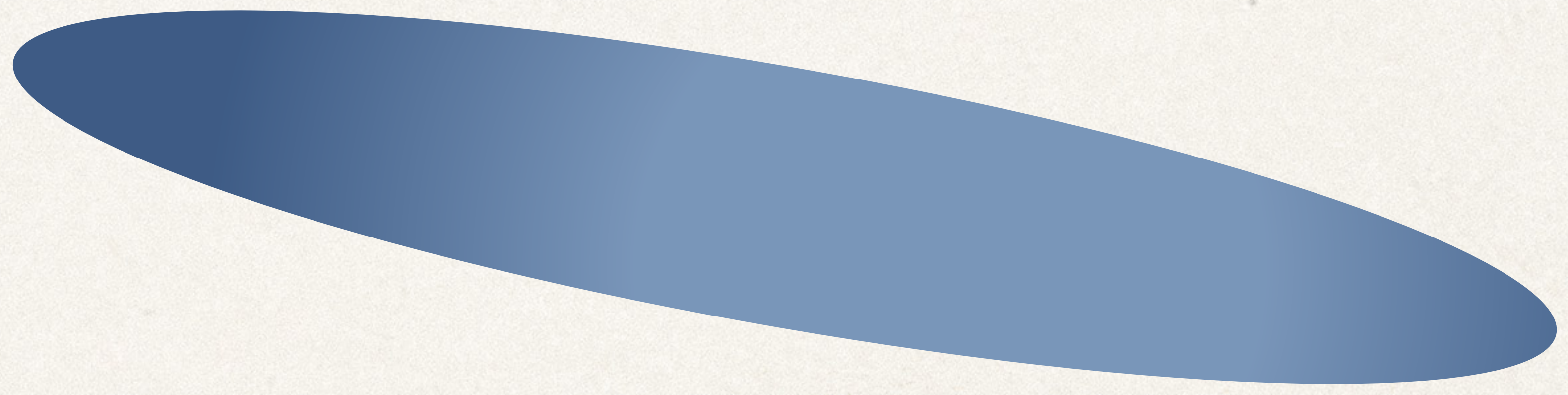
String formation → Inflation → Wall formation



Strings Eating Domain Walls (Nucleation)

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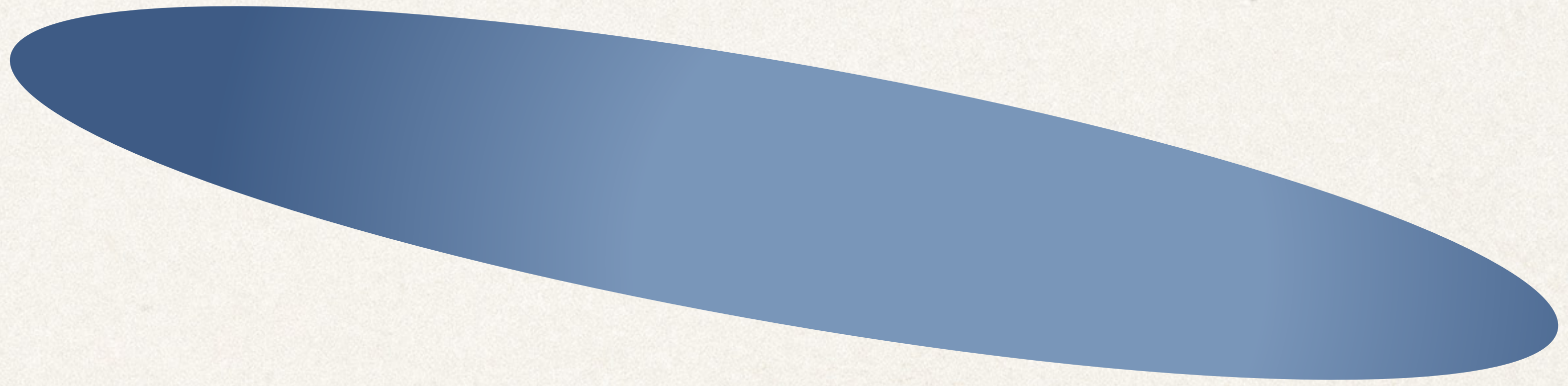
String formation → Inflation → Wall formation → Wait…



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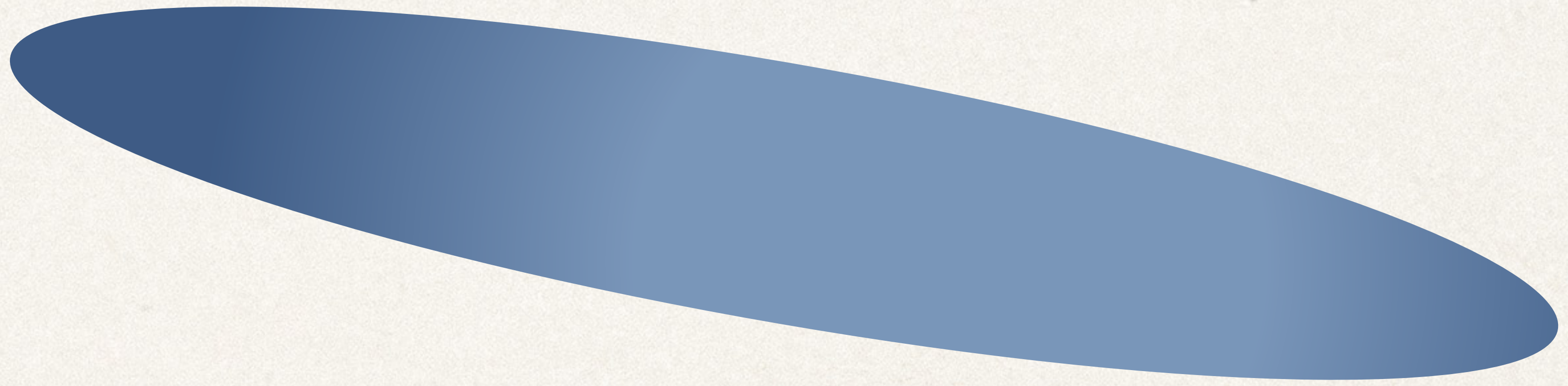
String formation → Inflation → Wall formation → Nucleation

- Wall rest mass converted to string kinetic energy (string expands and eats wall)



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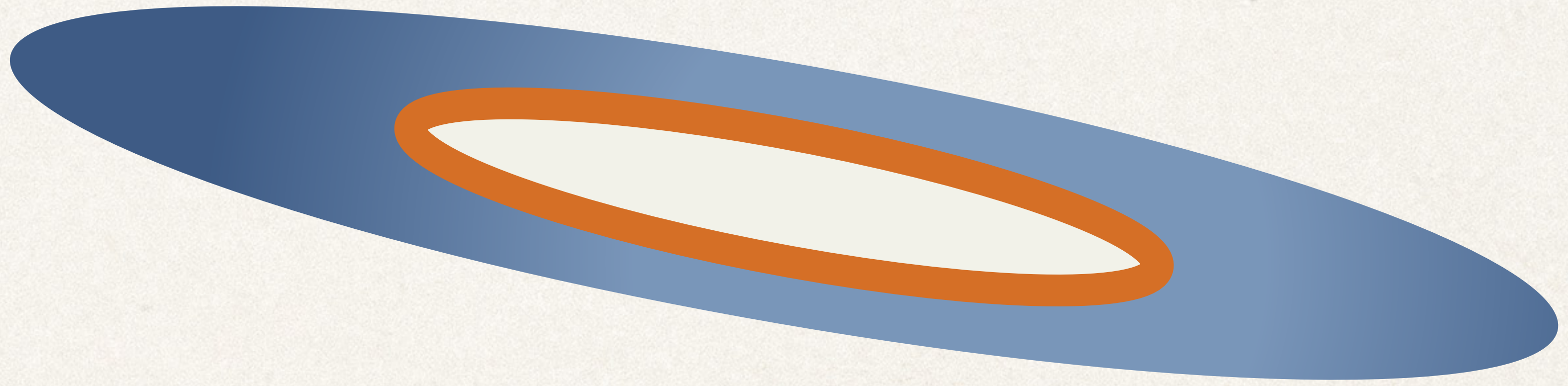


- Before nucleation, walls evolve as pure wall network

Pure Wall Network Evolution

- One-scale model and "infinite" (superhorizon) wall network

Typical separation and wall curvature same scale R ⟶ $\rho_\infty \sim \frac{\sigma R^2}{R^3} = \frac{\sigma}{R}$

$\sigma \approx v_w^3$ (Wall mass per unit area)

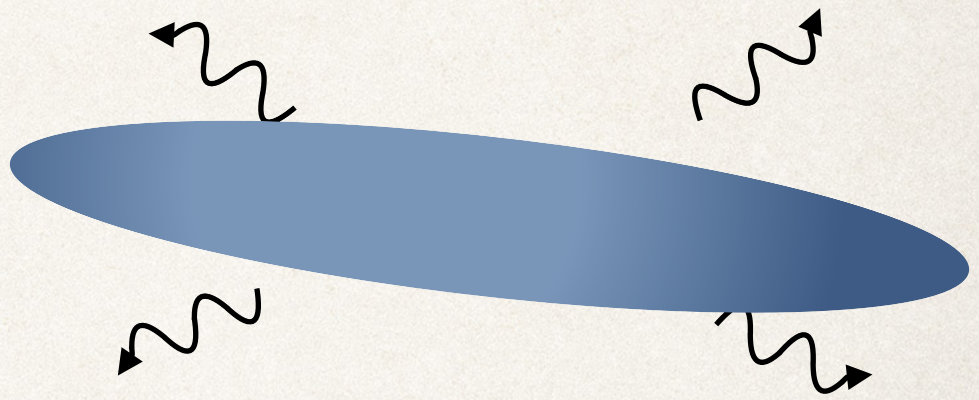
- Network reaches scaling regime, similar to infinite string network $R/t = \mathcal{O}(1)$ constant

- Domain wall energy density grows with respect to background energy density!

(Leads to "domain wall problem")

Domain Wall Gravitational Wave Amplitude

- Gravitational wave power sets amplitude of spectrum



$$P_{\rm GW} \approx G \sum_{i,j} \langle \dddot{Q}_{ij} \dddot{Q}_{ij} \rangle \sim G(M_w R^2\, \omega^3)^2 = \mathcal{B}\, G\sigma M_w .$$

$\uparrow$

$\mathcal{B} \sim 1$ for walls in scaling regime *Hiramatsu 2014*

$$\frac{d\rho_{\rm GW}}{dt} + 4H\rho_{\rm GW} = -n_{\rm DW} P_{\rm GW} \simeq \frac{G\sigma^2}{t}\theta(t_\Gamma - t) \longrightarrow \rho_{\rm GW}(t) \approx \begin{cases} G\sigma^2 & t \leq t_\Gamma \\ G\sigma^2 \left(\dfrac{a(t_\Gamma)}{a(t)}\right)^4 & t > t_\Gamma \end{cases}$$

$$\Omega_{\rm GW,max} \approx \frac{\rho_{\rm GW}(t_\Gamma)}{\rho_c(t_\Gamma)}\Omega_{\rm rad} \sim (G\sigma t_\Gamma)^2 \Omega_{\rm rad}$$

$$f_{\rm peak} \approx \frac{1}{t_\Gamma}\frac{a(t_\Gamma)}{a(t_0)} \quad \text{(Observed peak frequency)}$$

String Nucleation Rate

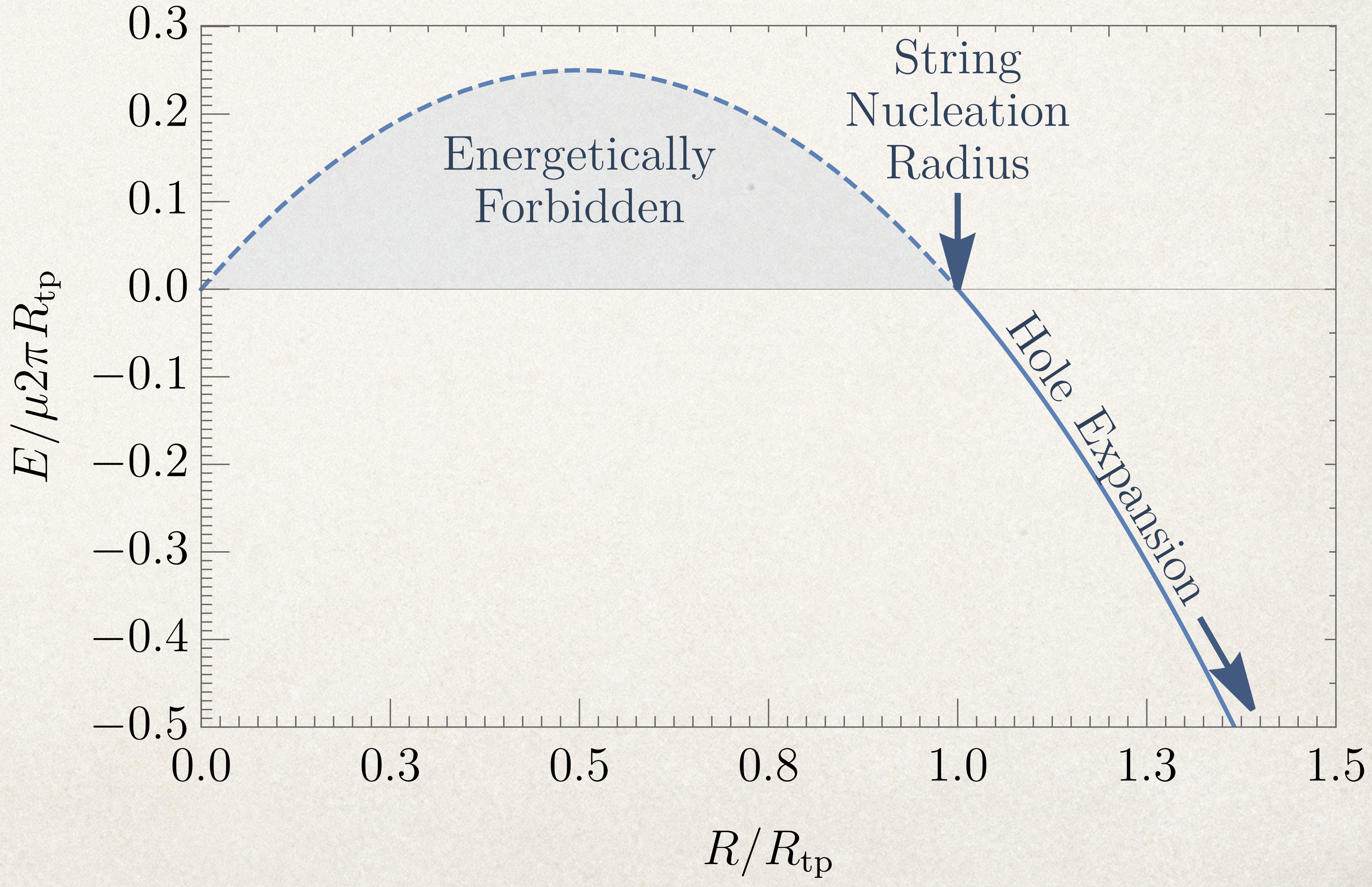
- We saw domain wall size grows with time $R^2 \sim t^2$

- Eventually, energetically favorable to lose wall mass and nucleate strings

$$E = \mu 2\pi R - \sigma\pi R^2$$

- WKB tunneling rate per unit area

$$\Gamma_d \propto \sigma e^{-S_E}\ , \qquad S_{\mathrm{E}} = \int_0^{R_{\mathrm{tp}}} dr\sqrt{\mu r E} \propto \frac{\mu^3}{\sigma^2}$$



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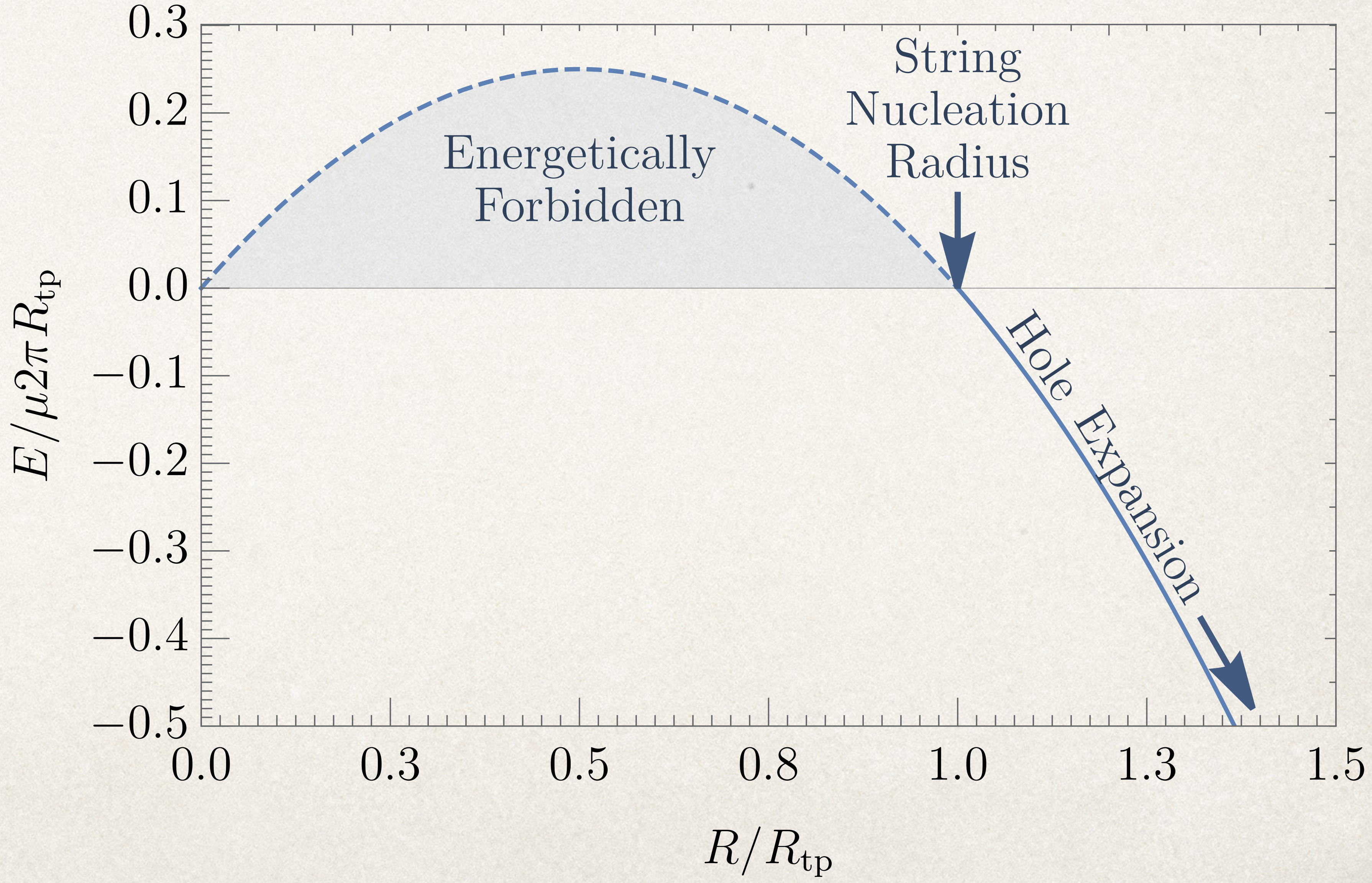


- Bounce action formalism

$$\Gamma_d \sim \sigma \exp(-\frac{16\pi}{3}\kappa_s) \qquad \kappa_s = \frac{\mu^3}{\sigma^2}$$

- Exponentially sensitive! Large separation of string and domain wall scales → long-lived wall network

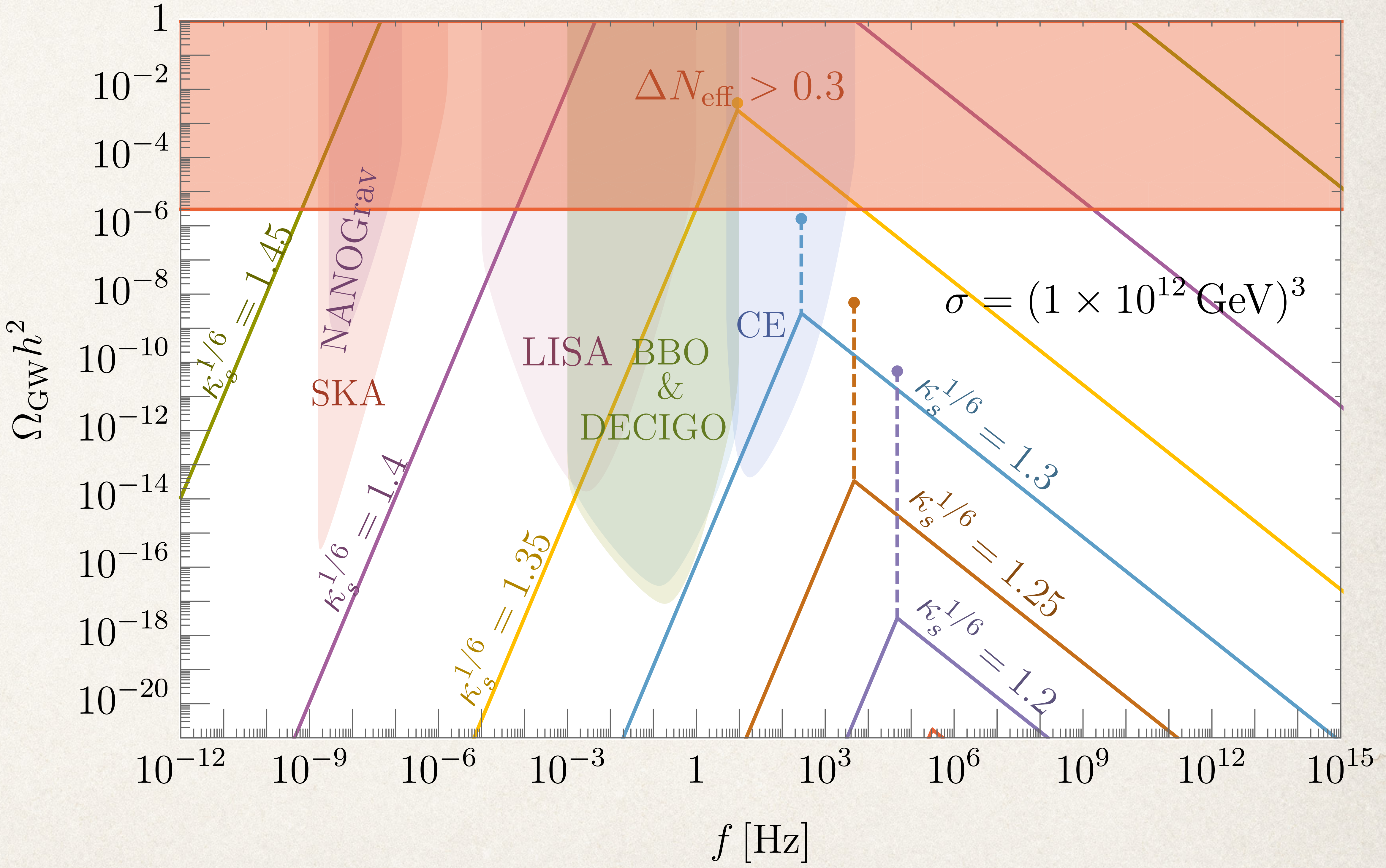
String Nucleation on Walls Spectrum

- Walls eaten when $A > A_{\max} \sim \Gamma_d t^2$

$$t_\Gamma \sim \frac{1}{A \times \Gamma_d} \sim \frac{1}{\sigma^{1/3}} \exp \frac{16\pi\kappa_s}{9}$$

$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c}\frac{d\rho_{\mathrm{GW}}(t_0, f)}{df}$$

$$\approx \Omega_{\mathrm{GW,max}} \begin{cases} \left(\dfrac{f}{f_{\mathrm{peak}}}\right)^{-1} & f > f_{\mathrm{peak}} \\ \left(\dfrac{f}{f_{\mathrm{peak}}}\right)^{3} & f \leq f_{\mathrm{peak}} \end{cases}$$



- f^{-1} spectrum at high frequencies,
  f^3 decaying spectrum at lower frequencies

Hiramatsu 2014

Walls Eating Strings (Collapse)

- Occurs in following scenario

Inflation → String formation

Walls Eating Strings (Collapse)

- Occurs in following scenario

Inflation → String formation → Wall formation → Eventual collapse

- Wall rest mass converted to string kinetic energy

↓

Wall-bounded strings oscillate and decay via gravitational radiation

$$\begin{aligned} f_{\text{string}} &\approx \mu \\ f_{\text{DW}} &\approx \sigma R \end{aligned} \longrightarrow R_c \equiv \frac{\mu}{\sigma}$$

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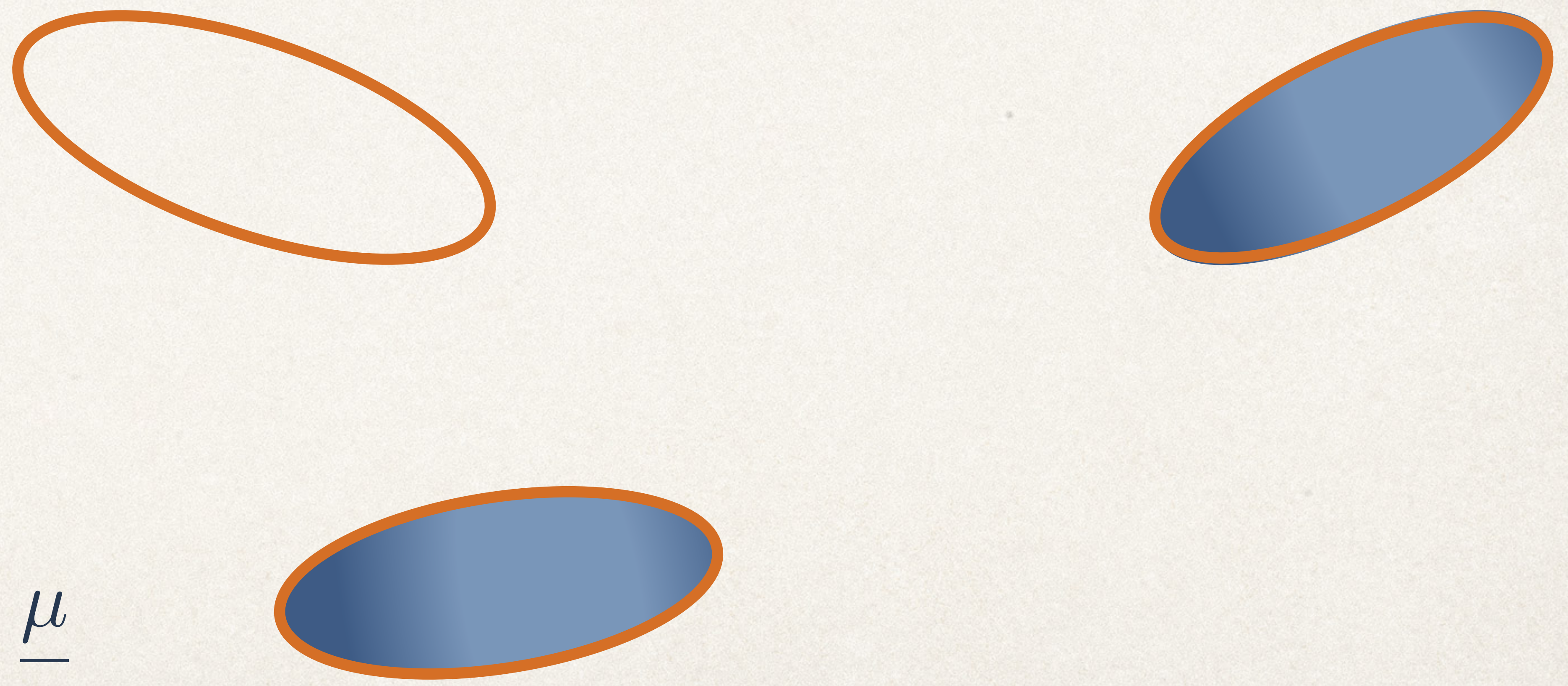

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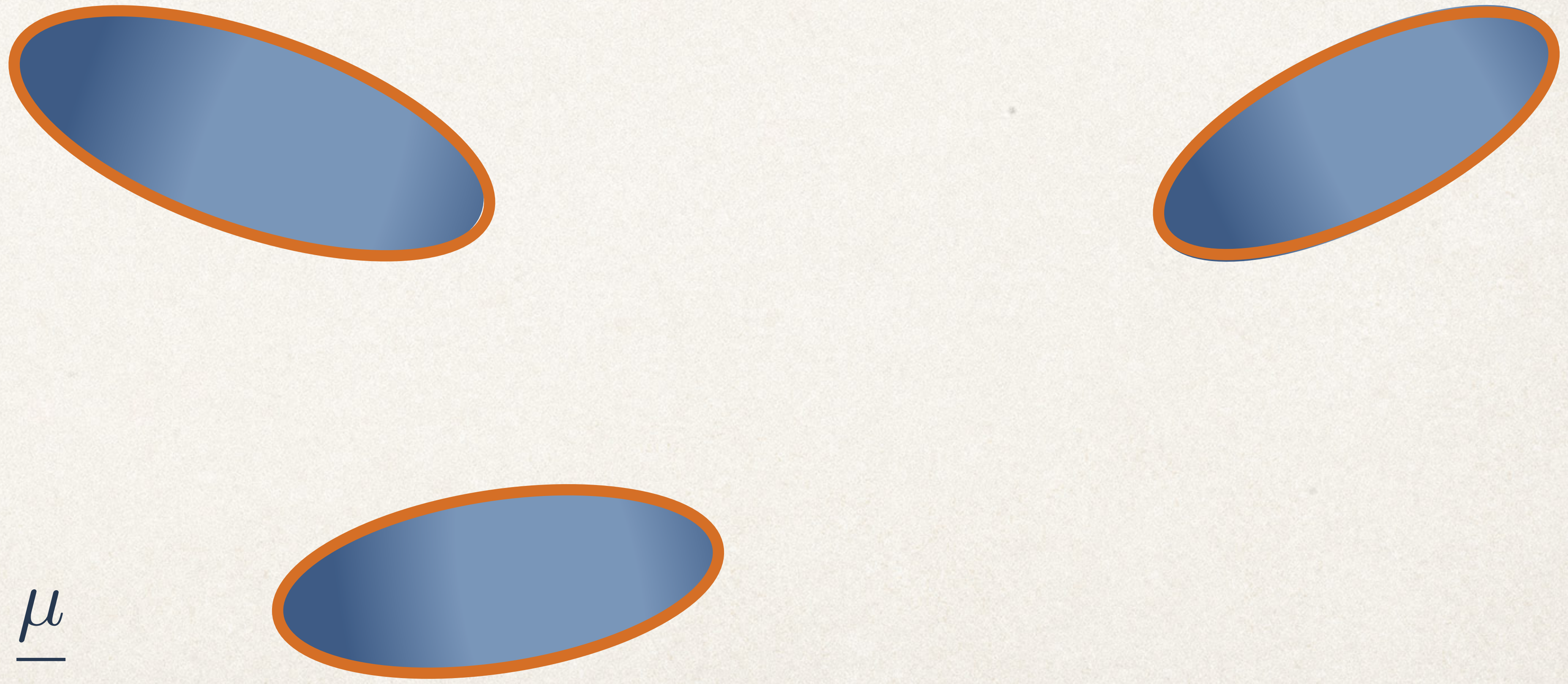


Dynamics of Domain Wall Bounded Strings

- Combine domain wall and string Nambu-Goto actions

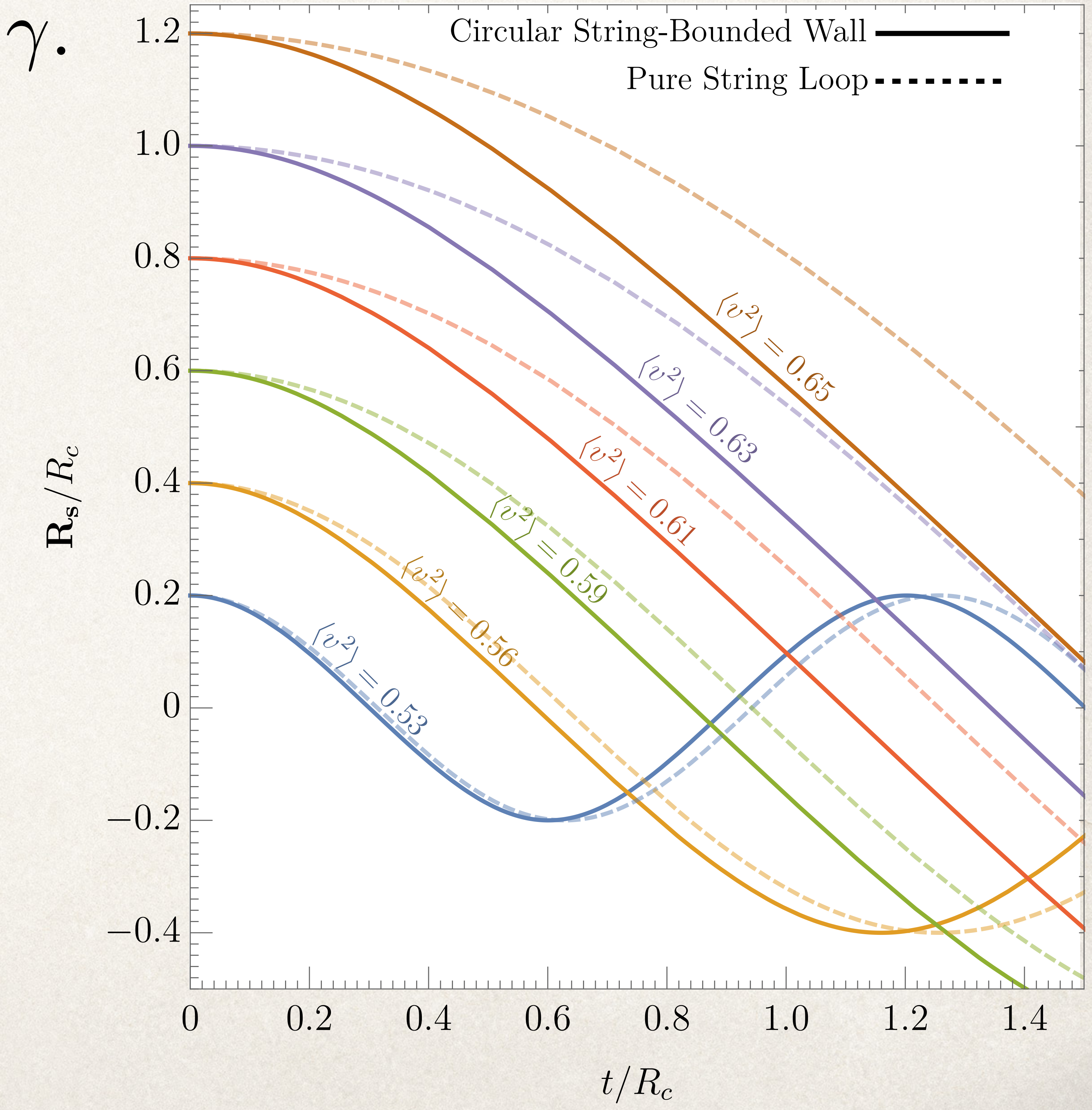
$$S = -\mu \int d^2\xi \sqrt{-\gamma} - \sigma \int d^3\xi \sqrt{-\gamma}.$$

- Identify boundary of domain wall with string radius

E.O.M. of circular string boundary

String dominates dynamics for $|\mathbf{r}_s| < R_c$

Domain wall dominates dynamics for $|\mathbf{r}_s| > R_c$



Evolution of String-Wall Network

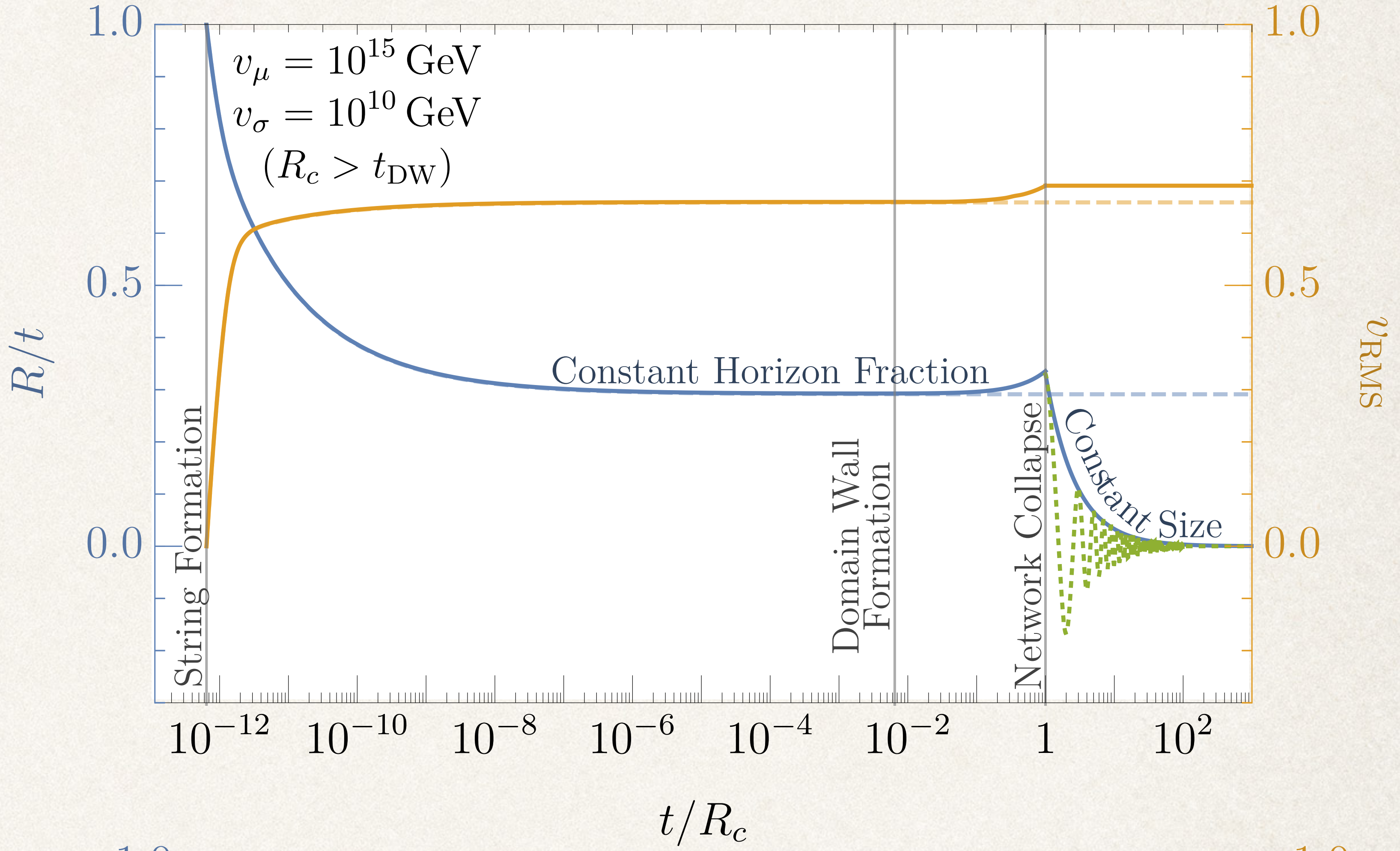
- Effect of wall tension on the infinite string network?
- Recipe:

1a) Solve velocity averaged Nambu-Goto E.O.M one-scale model ($\rho_\infty = \frac{\mu R}{R^3} = \frac{\mu}{R^2}$)
Martins, Shellard '96

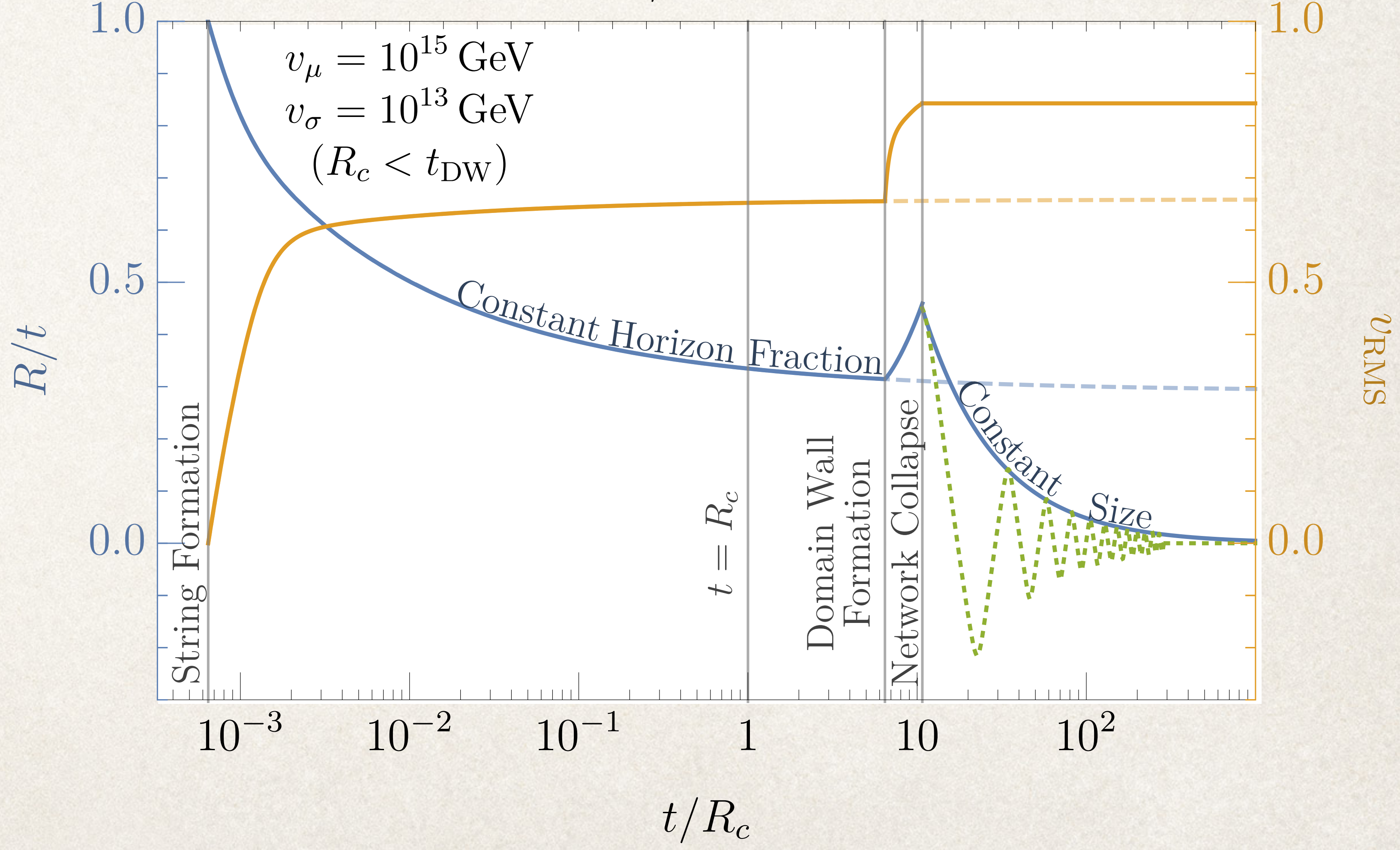
1b) Once wall tension begins affecting evolution, infinite strings of curvature radius R behave like wall bounded strings of radius R

2) Piecewise connect with solution of circular string-bounded wall

Case 1:
$t_{\mathrm{DW}} < R_c$



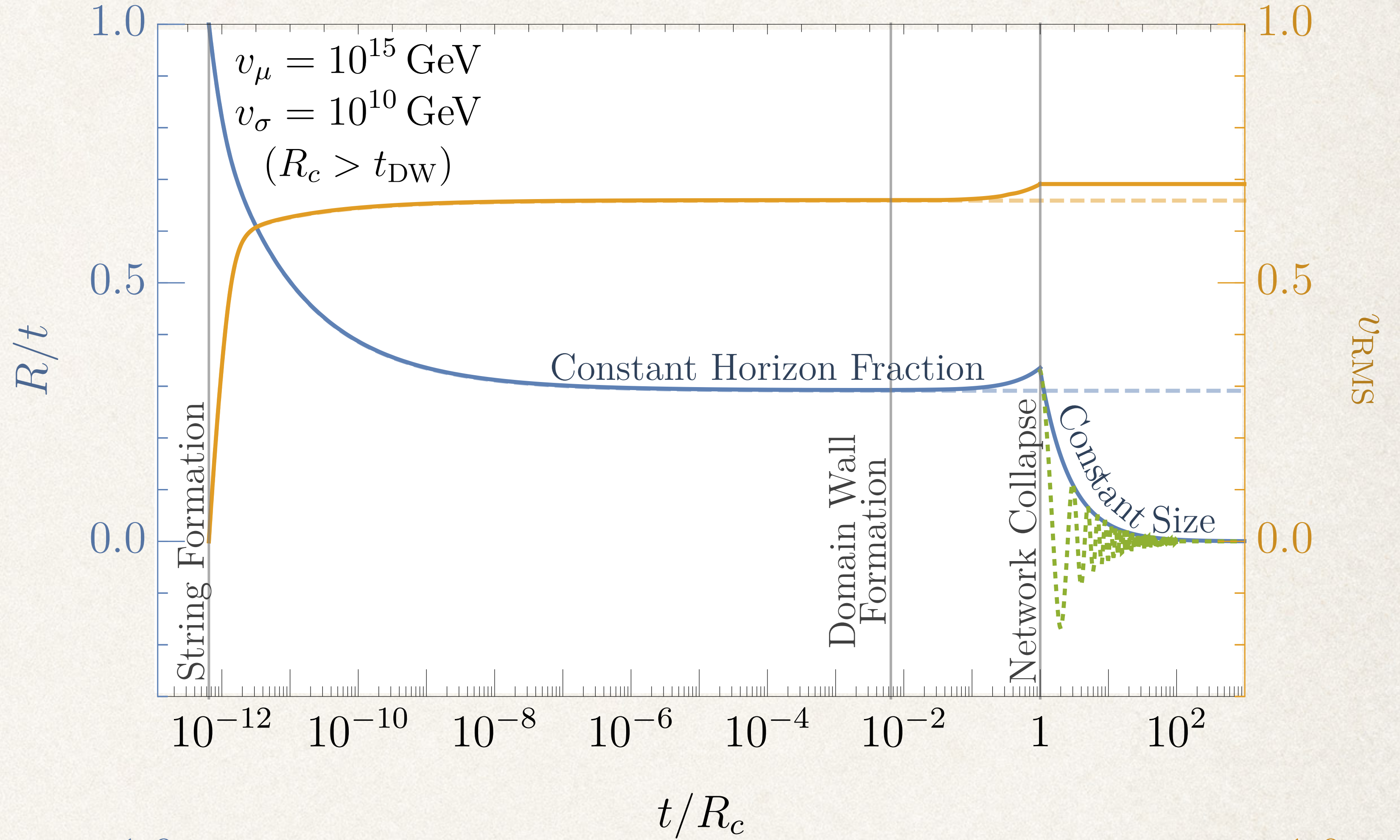
Case 2:
$t_{\mathrm{DW}} > R_c$



Evolution of String-Wall Network

- After attaching to strings, network evolves like usual string network if $R < R_c$
- After $R > R_c$, domain wall tension dominates, collapses (eating begins)
- Network collapse at $t_* \approx \mathrm{Max}(R_c, t_{\mathrm{DW}})$, as first proposed by *Everett, Vilenkin '82* and *Martin, Vilenkin '96*
- Domain wall bounded strings oscillate with constant mass before decaying via GW

Case 1:
$t_{\mathrm{DW}} < R_c$



Case 2:
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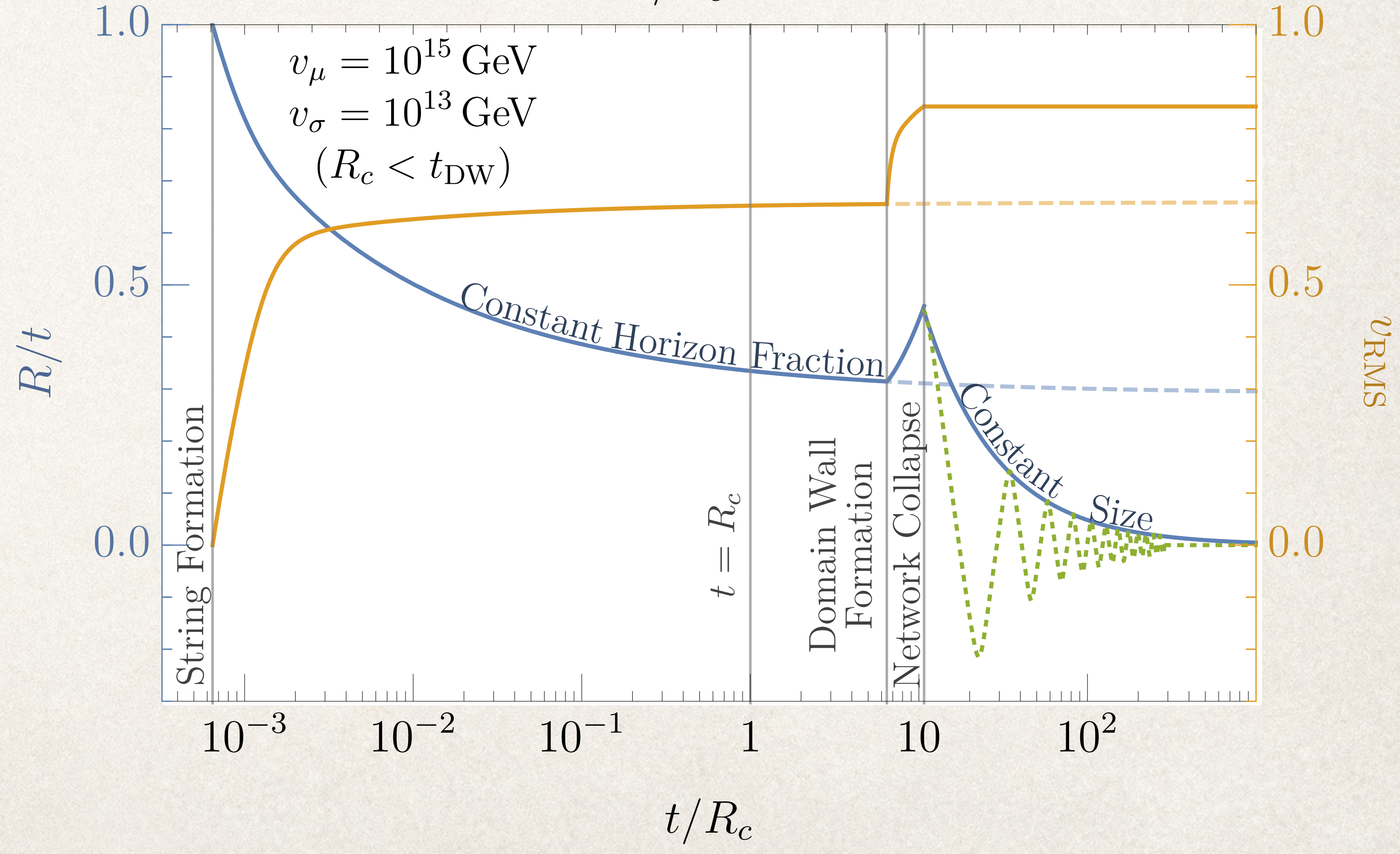


Gravitational Power of String-Bounded Wall

- Quadrupole formula, $P_{\rm GW} \approx \frac{G}{45}\langle \dddot{Q}_{ij}\dddot{Q}_{ij}\rangle$, for string loop $P^{(\rm string)}_{\rm GW} \sim G\mu^2$ and wall $P^{(\rm wall)}_{\rm GW} \sim G\sigma M_{\rm DW}$

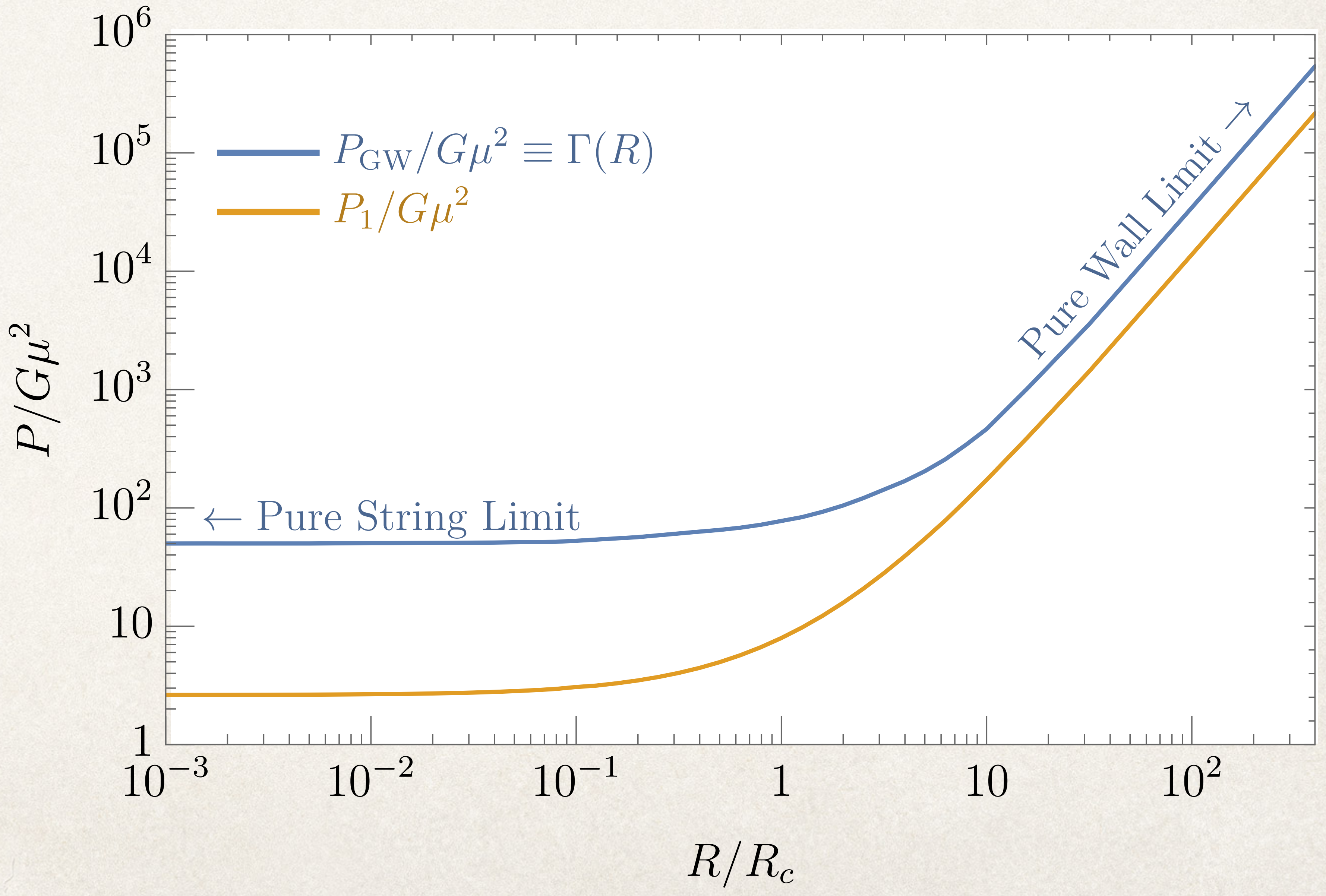
$$\downarrow$$

$$P^{(\rm wall)}_{\rm GW} \gtrsim P^{(\rm string)}_{\rm GW} \quad \text{when} \quad R > R_c$$

- In reality, expect highly relativistic string to dominate GW emission

- Numerically compute $P_n = \frac{G\omega_n^2}{\pi}\int d\Omega |T^T_{\mu\nu}(\mathbf{k},\omega_n)|^2$ for circular string-bounded wall solution

Weinberg '72



Gravitational Wave Amplitude

- Can estimate $\Omega_{\rm GW}$ and frequency of GW spectrum similar to strings

- Energy density of largest wall bounded strings after collapse evolves as

$$\rho_{\rm DW}(t) = \rho(t_*)_{\rm DW} \left(\frac{a(t*)}{a(t)}\right)^3 \longrightarrow \qquad \Omega_{\rm DW} \approx \frac{\rho_{\rm DW}(t_{\rm decay})}{\rho_{\rm BG}(t_{\rm decay})}\Omega_{\rm rad} \qquad t_{\rm decay} \approx \frac{M_{\rm DW}}{\Gamma(R)G\mu^2} \xrightarrow{R \gtrsim R_c} \sim \frac{1}{G\sigma}$$

$$\frac{\Omega_{\rm DW}}{\Omega_{\rm strings}} \sim \sqrt{\frac{t_*}{R_c}}$$

(Growth over string spectrum requires $t_{\rm DW} \gg R_c$)

$$f_{\rm decay} \sim \frac{1}{R(t_*)}\frac{a(t_\Gamma)}{a(t_0)} \sim 10^3\,{\rm Hz}\left(\frac{t_*}{R_c}\right)^{-1}\left(\frac{\sigma}{(10^7{\rm GeV})^3}\right)^{1/2}\left(\frac{\mu}{(10^{14}{\rm GeV})^2}\right)^{-1}$$

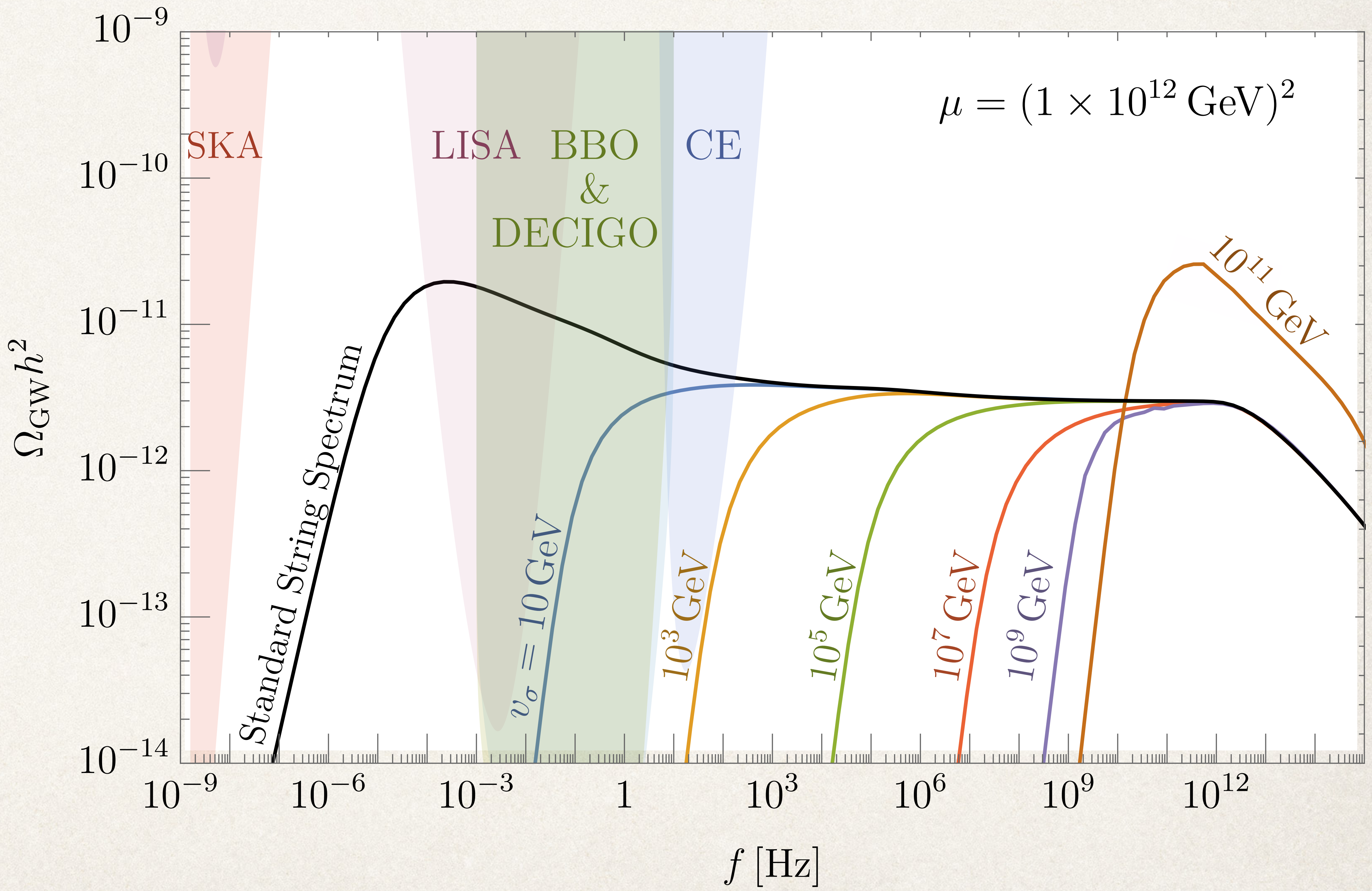
(Relatively high frequencies)

Gravitational Wave Amplitude

- Can confirm simple estimates more precisely

$$\Omega_{\mathrm{GW}} h^2 = f \frac{d\rho_{\mathrm{GW}}}{df} \frac{h^2}{\rho_c}$$

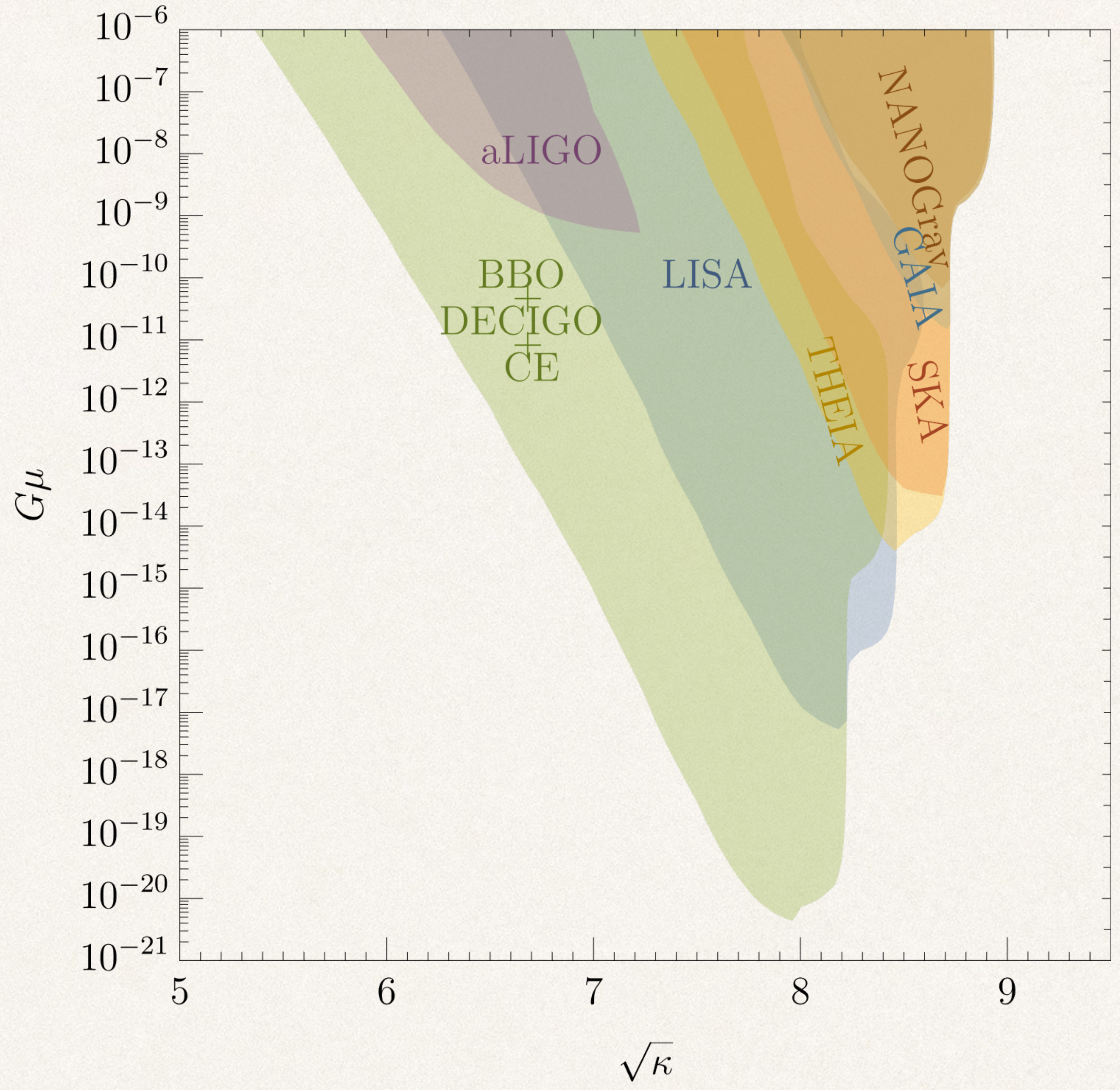
$$\frac{d\rho_{\mathrm{GW}}(t)}{df} = \int_{t_{\mathrm{sc}}}^{t} dt' \underset{\substack{\uparrow \\ \text{Expansion}}}{\frac{a(t')^4}{a(t)^4}} \int dl \underset{\substack{\uparrow \\ \text{One-scale model}}}{\frac{dn(l,t')}{dl}} \underset{\substack{\uparrow \\ \text{Power}}}{\frac{dP_l(l,t')}{df'}} \underset{\substack{\uparrow \\ \text{Redshift}}}{\frac{df'}{df}}$$



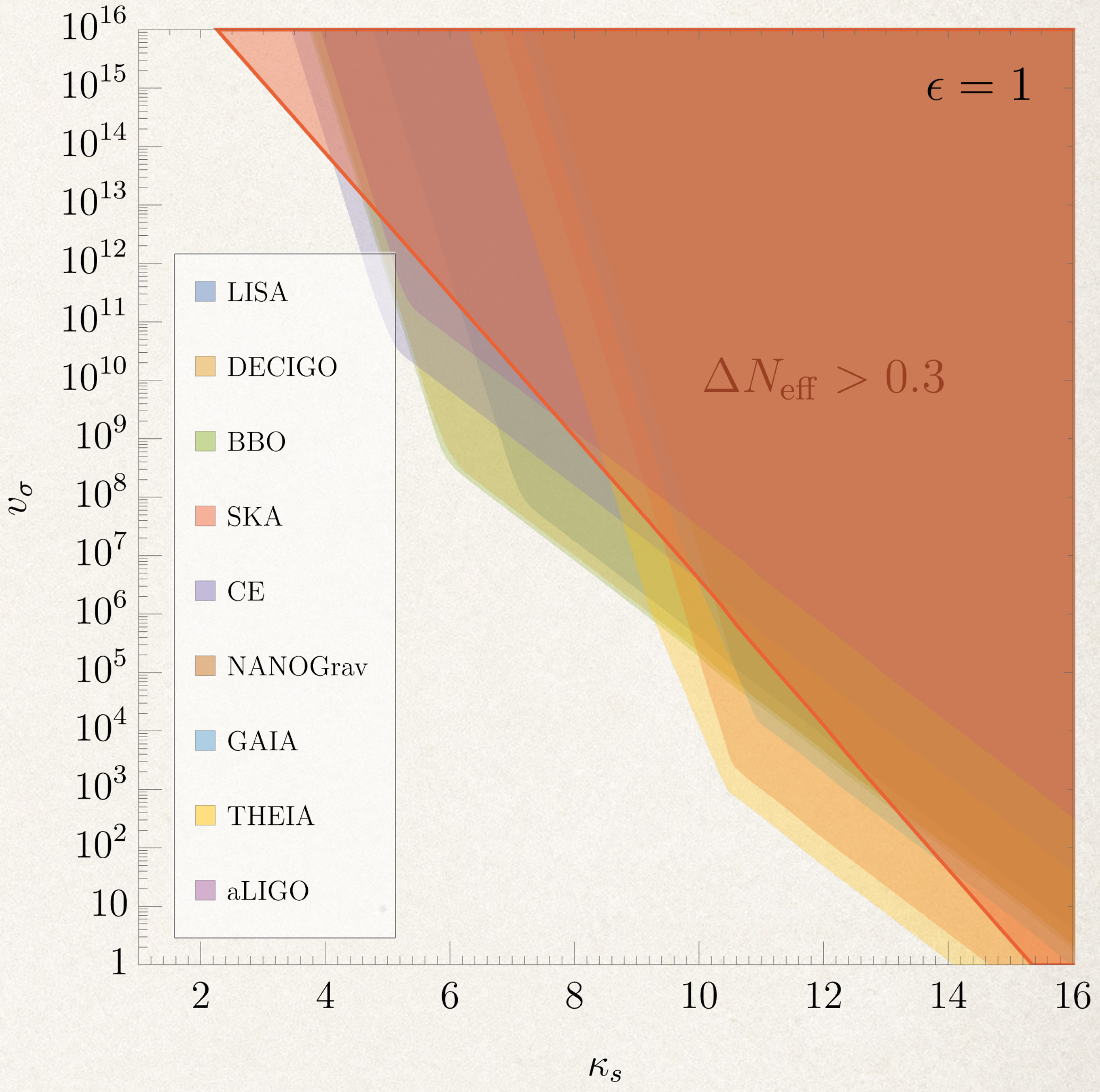
- Standard, flat, string spectrum at high frequencies, f^3 decaying spectrum at lower frequencies
- Domain wall "bump" before decay if $t_{\mathrm{DW}} \gg R_c$

Overview of Spectra

	IR	UV	Generally high frequency signal?
Monopoles eating strings (Nucleation)	f^2	f^0	
Strings eating monopoles (Collapse)	f^3	$\ln f \to f^{-1}$	🟦
Strings eating domain walls (Nucleation)	f^3	f^{-1}	
Domain walls eating strings (Collapse)	f^3	f^0	🟦



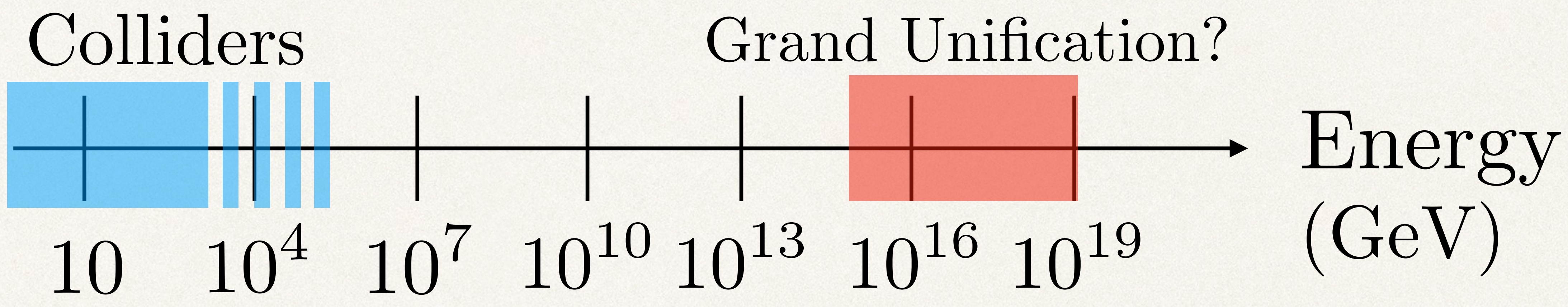
Monopole nucleation on strings



String nucleation on monopoles

Conclusions

- Gravitational waves provide amazing view into early universe and high energy physics



- GUT symmetry chains with hybrid topological defects produce unique gravitational wave fingerprints upon being "eaten"

- These signatures may allow us to understand our universe at a fundamental level

Thank you!