What Gravitational Waves might tell us about Dark Matter

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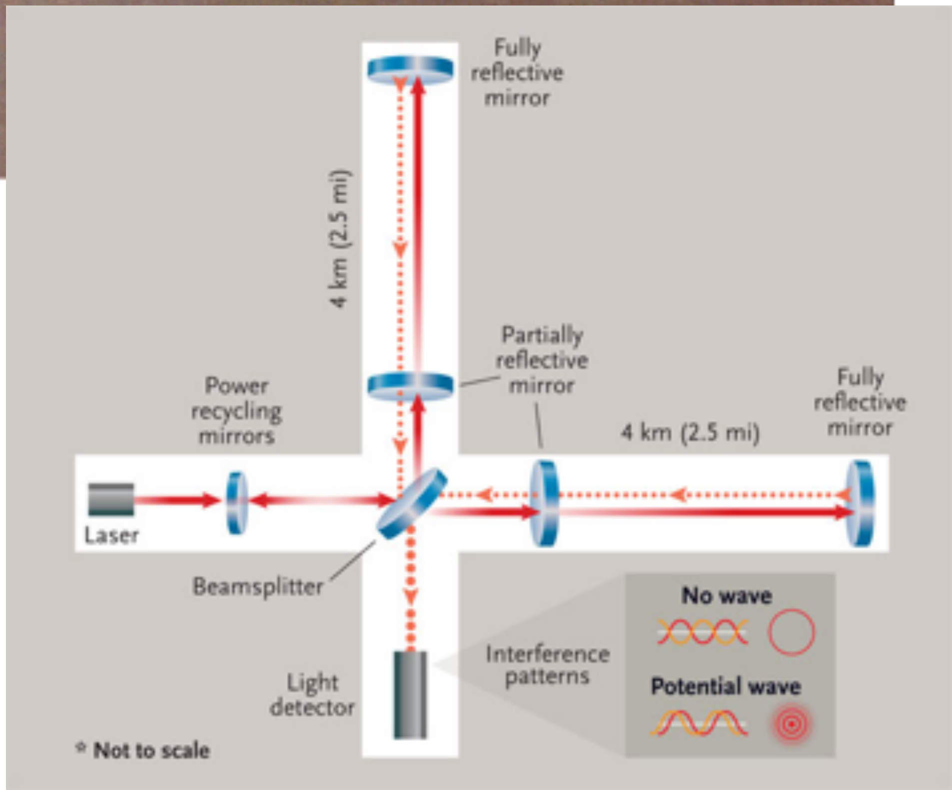
Aachen - Bonn - Heidelberg - Mainz RU Meeting
MITP Mainz
Dec. 16, 2016

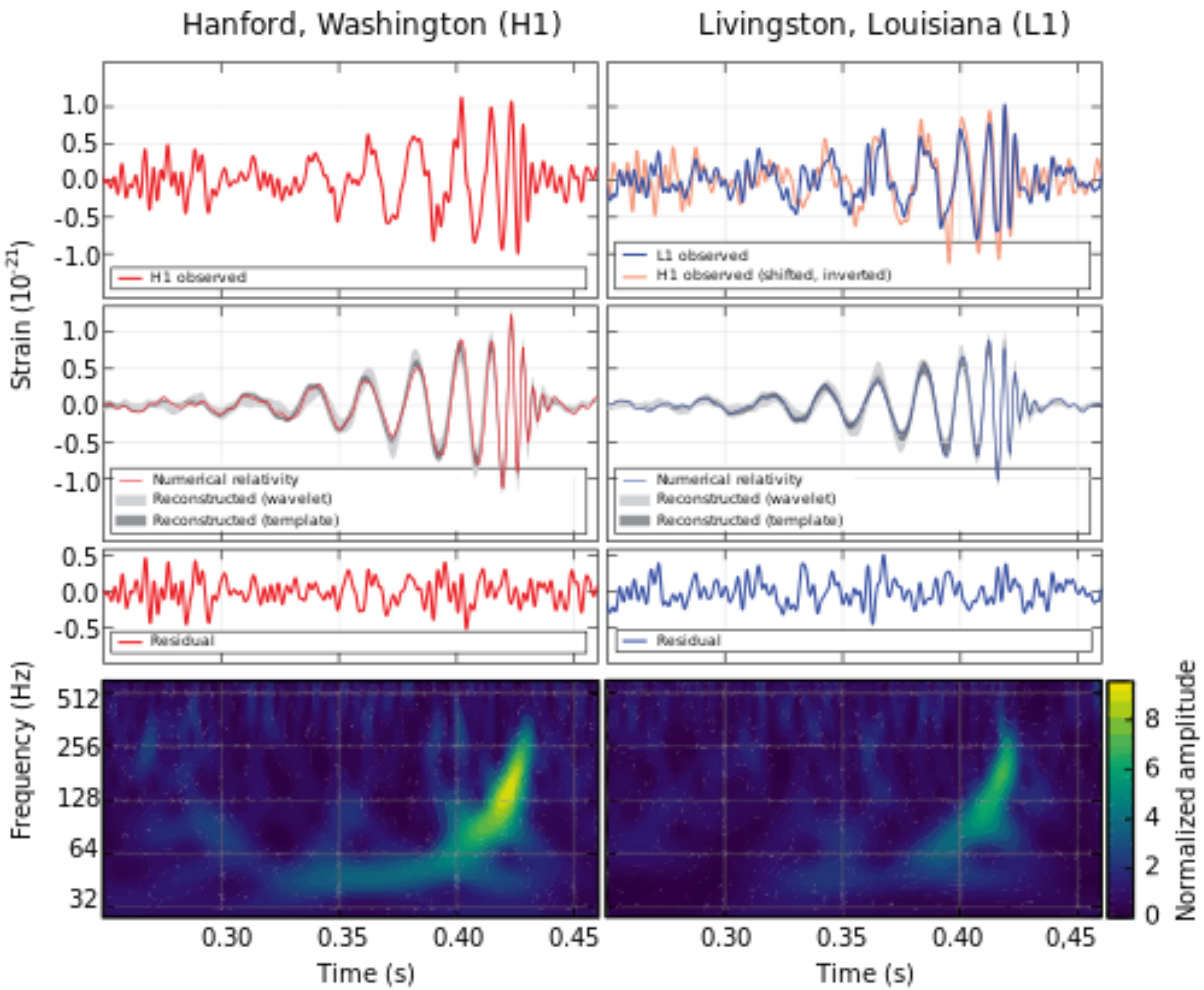
Physics Highlight 2016

LIGO



Hanford, Washington, USA

Signal



Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized amplitude
Time (s)

Great!

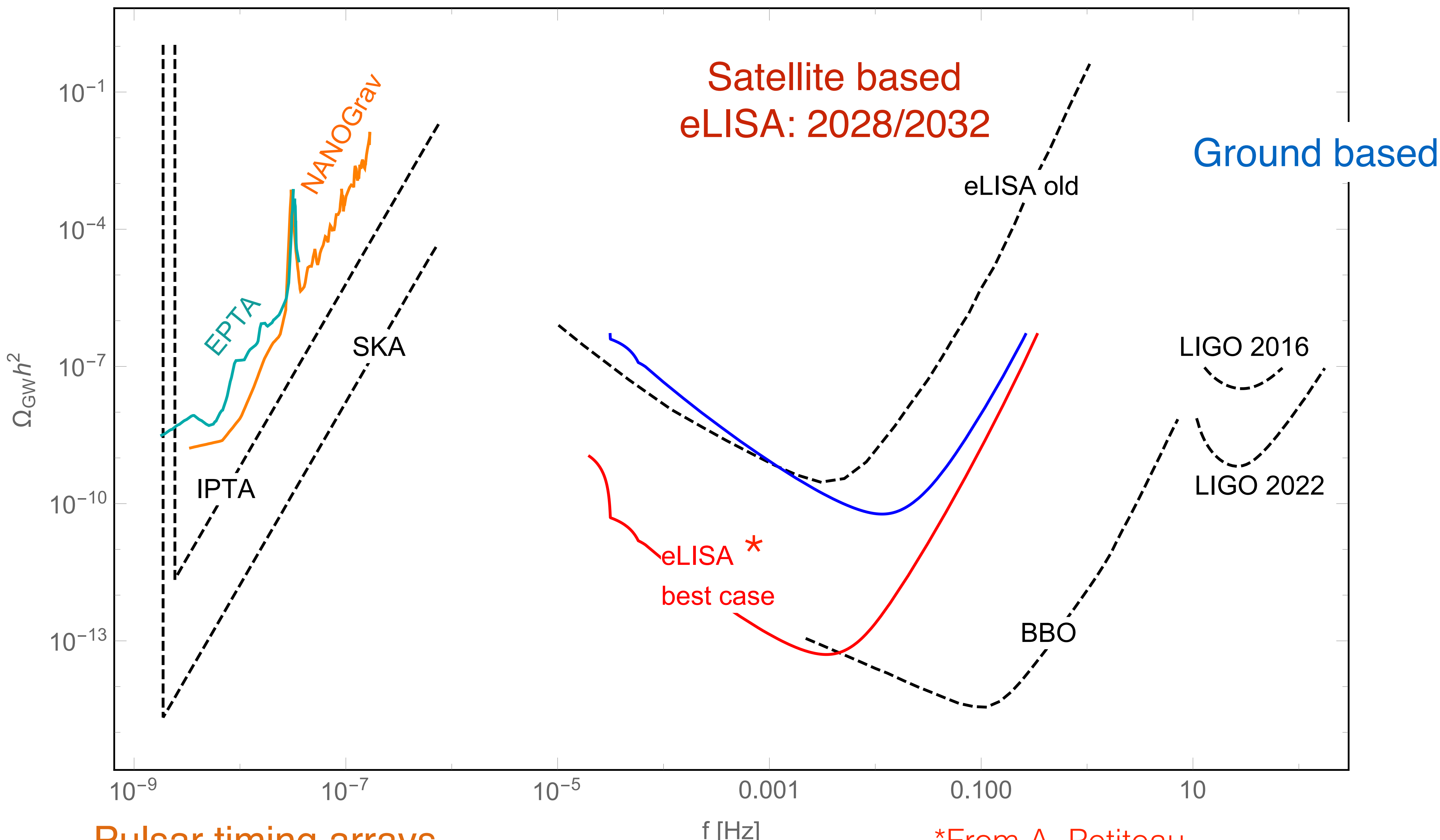
But why should
we (particle physicists) care?

Outline

- The GW Soundscape
- GWs as windows into the early universe
  - Signal from a dark (matter) sector PT
- GWs from massive compact (DM) objects
- Constraining DM interactions with GW expts

Ligo is not the only game in town

Experiments

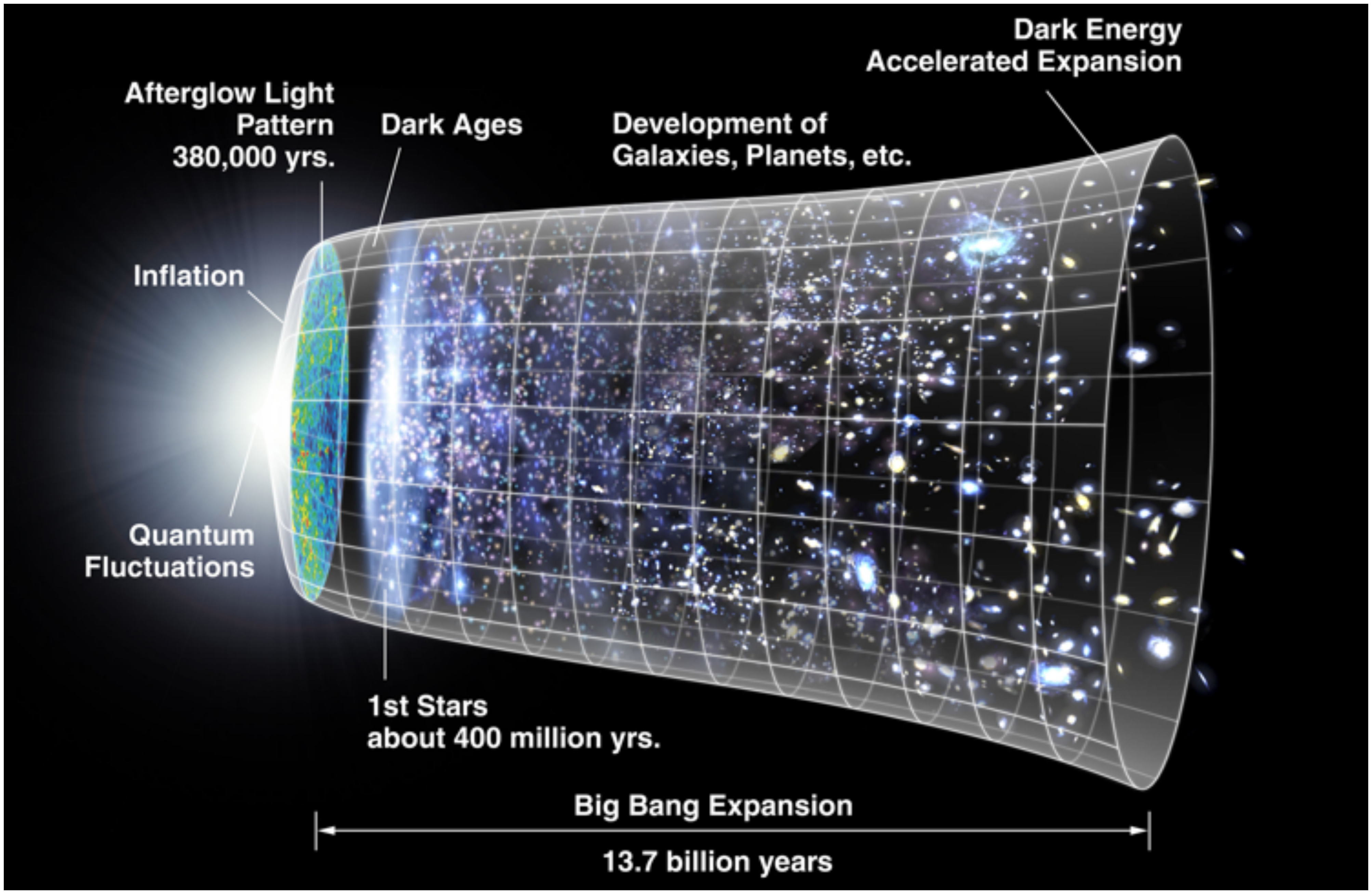


Pulsar timing arrays
Data already available

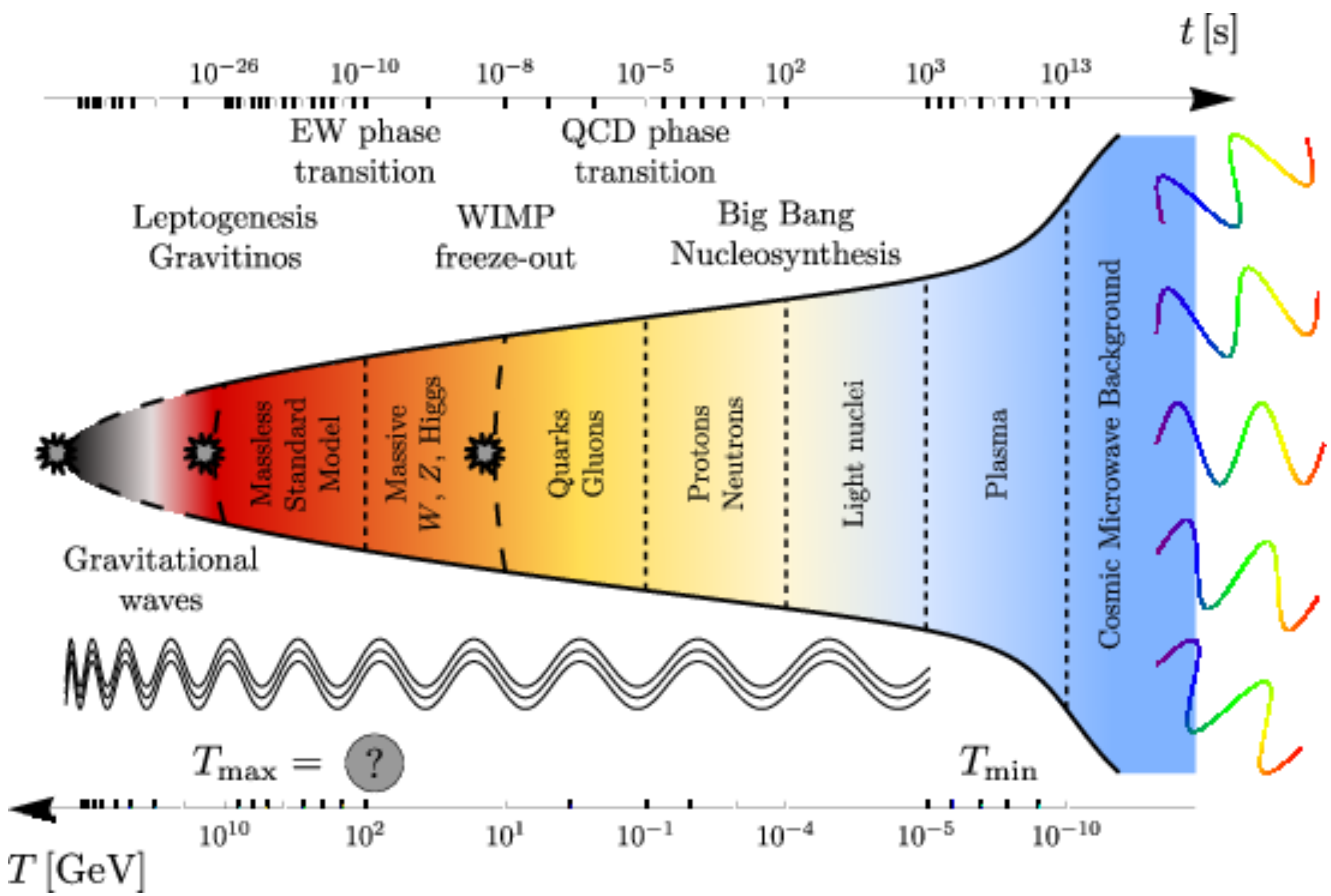
*From A. Petiteau
This is now realistic thanks to the success of Pathfinder!

GWs as window into the early universe

Thermal History



Thermal History



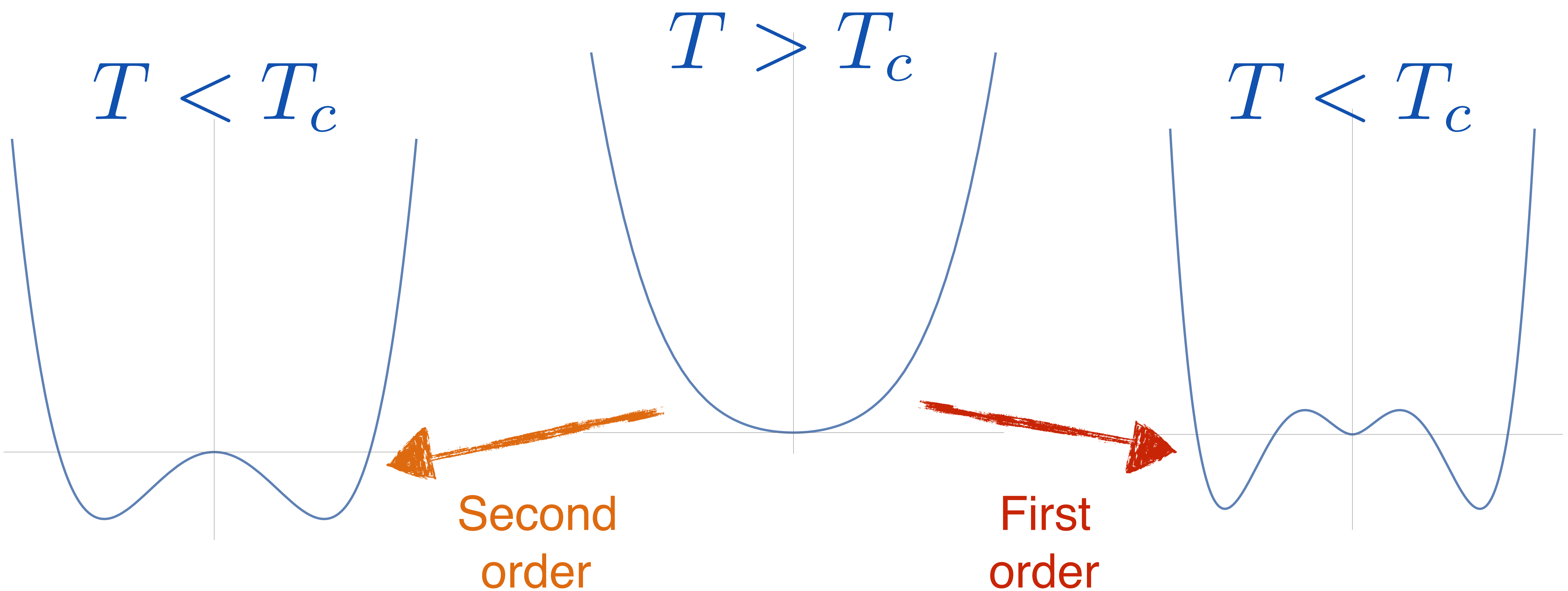
GWs are unique direct messengers from this era!

But also difficult to detect

need a strong signal!

Cosmological Phase Transitions

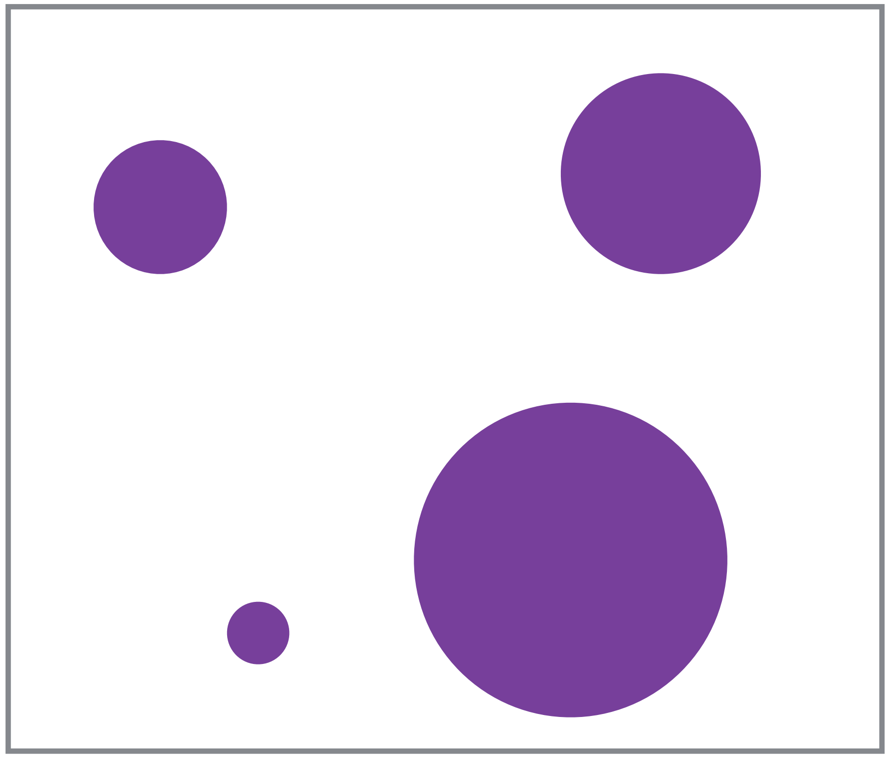
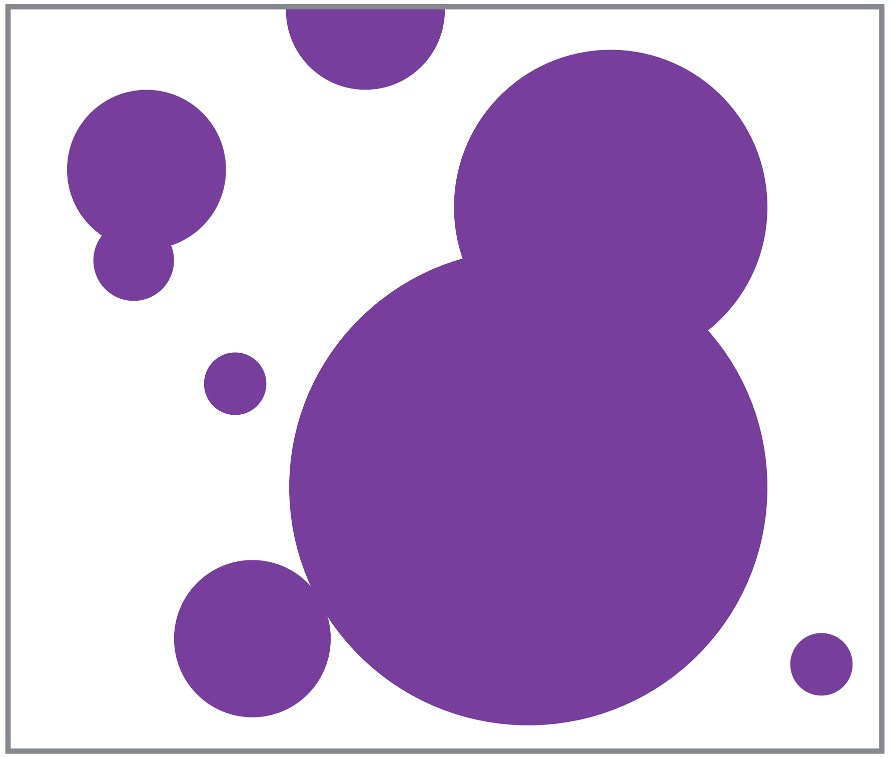
- Early Universe in symmetric phase (e.g. unbroken electroweak symmetry)



GWs from PTs

First order PT → Bubbles nucleate, expand

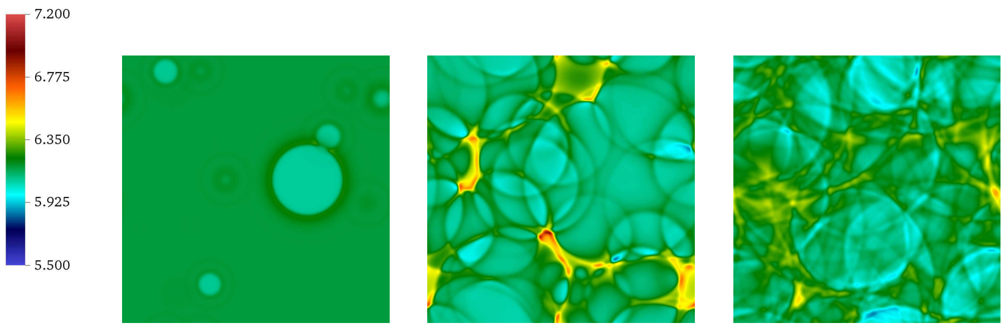
Bubble collisions → Gravitational Waves

Signal is Universal

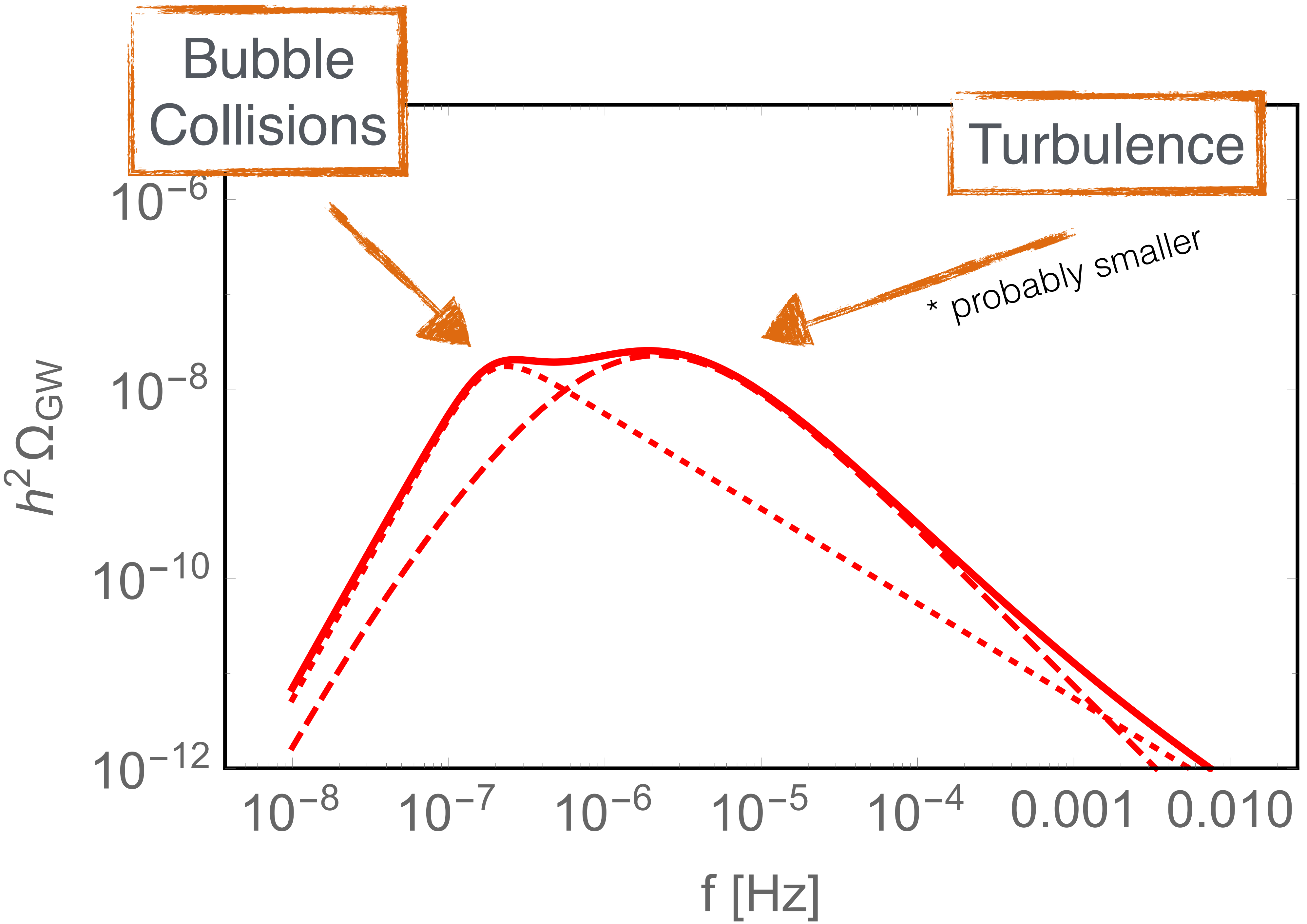
- PT characterised by few parameters:
  - Latent heat $\alpha \approx \frac{\Omega_{\text{vacuum}}}{\Omega_{\text{rad}}}$
  - Bubble wall velocity v
  - Bubble nucleation rate β
  - PT temperature T_*
- Three physical contributions
  - Bubble wall collisions
  - Turbulence
  - Sound waves

Extensive numerical simulations. Recently e.g. Hindmarsh et al:
Sound wave contributions



Phenomenological Parameterisations:
Caprini et al, 1512.06239

GW signal


Bubble Collisions
Turbulence
* probably smaller
$h^2\Omega_{GW}$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
0.001
0.010
f [Hz]

Peak Frequency

- Redshift:

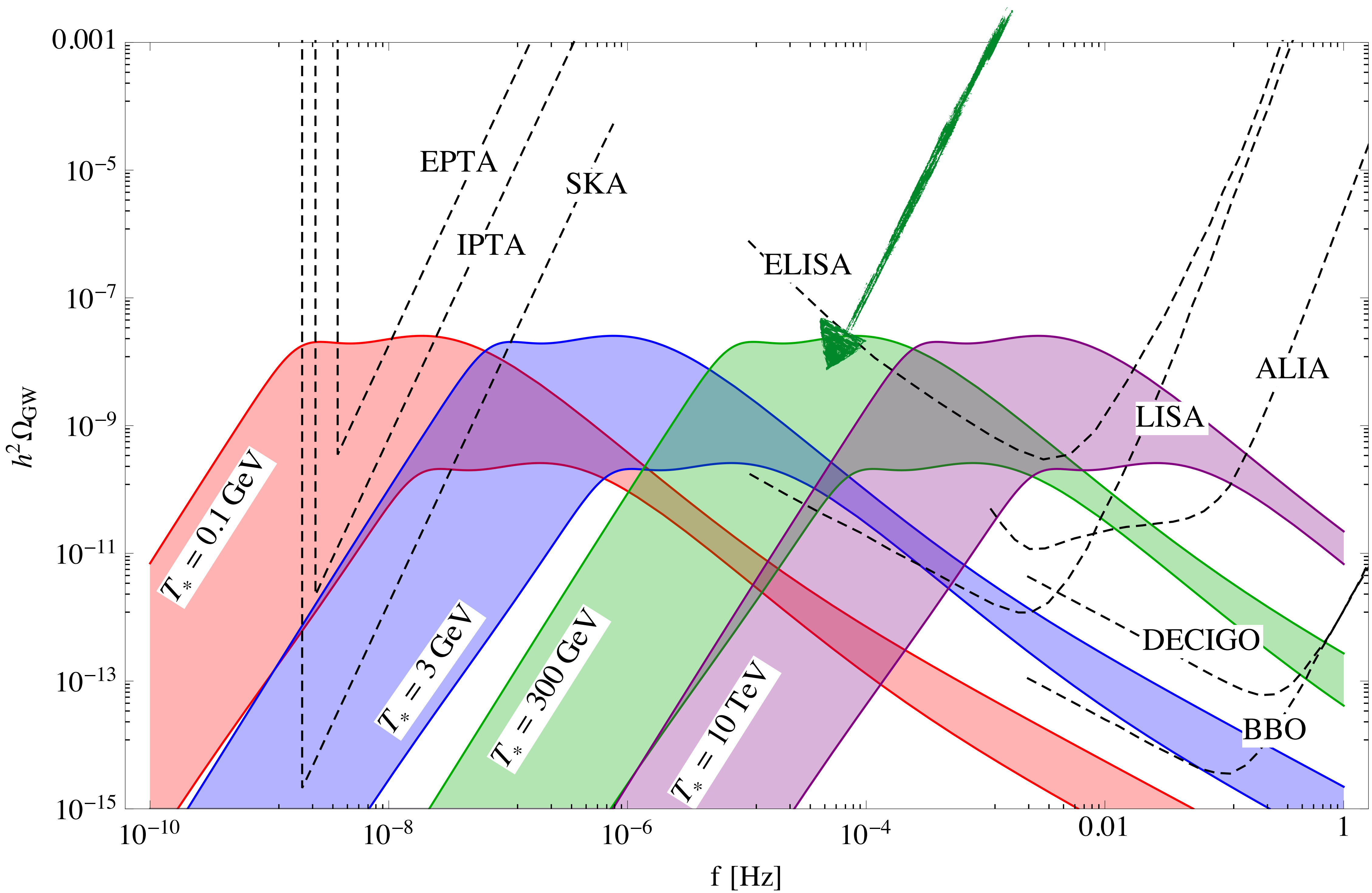
$$f = \frac{a_*}{a_0} H_* \frac{f_*}{H_*} = 1.59 \times 10^{-7}\ \mathrm{Hz} \times \left(\frac{g_*}{80}\right)^{\frac{1}{6}} \times \left(\frac{T_*}{1\ \mathrm{GeV}}\right) \times \frac{f_*}{H_*}$$

PT Temperature
~ DM Mass

- Peak regions: $k/\beta \approx (1 - 10)$

$$f_{\mathrm{peak}}^{(B)} = 3.33 \times 10^{-8}\ \mathrm{Hz} \times \left(\frac{g_*}{80}\right)^{\frac{1}{6}} \left(\frac{T_*}{1\ \mathrm{GeV}}\right) \left(\frac{\beta}{\mathcal{H}_*}\right)$$

Example: Strong EWPT



PS, 2016

SM: PTs are weak

PT in a dark sector?

Composite DM

- Alternative to elementary WIMP models
- Phenomenologically viable, “generic” possibility in presence of hidden sectors
- Some nice features:
  - DM stability, mass scale
  - Symmetric component annihilation for ADM
  - Self-interactions

Dark QCD

- Models I'm interested in here:
- Nonabelian SU(N) dark sector, confinement scale Λ_d
- n_f light/massless flavours

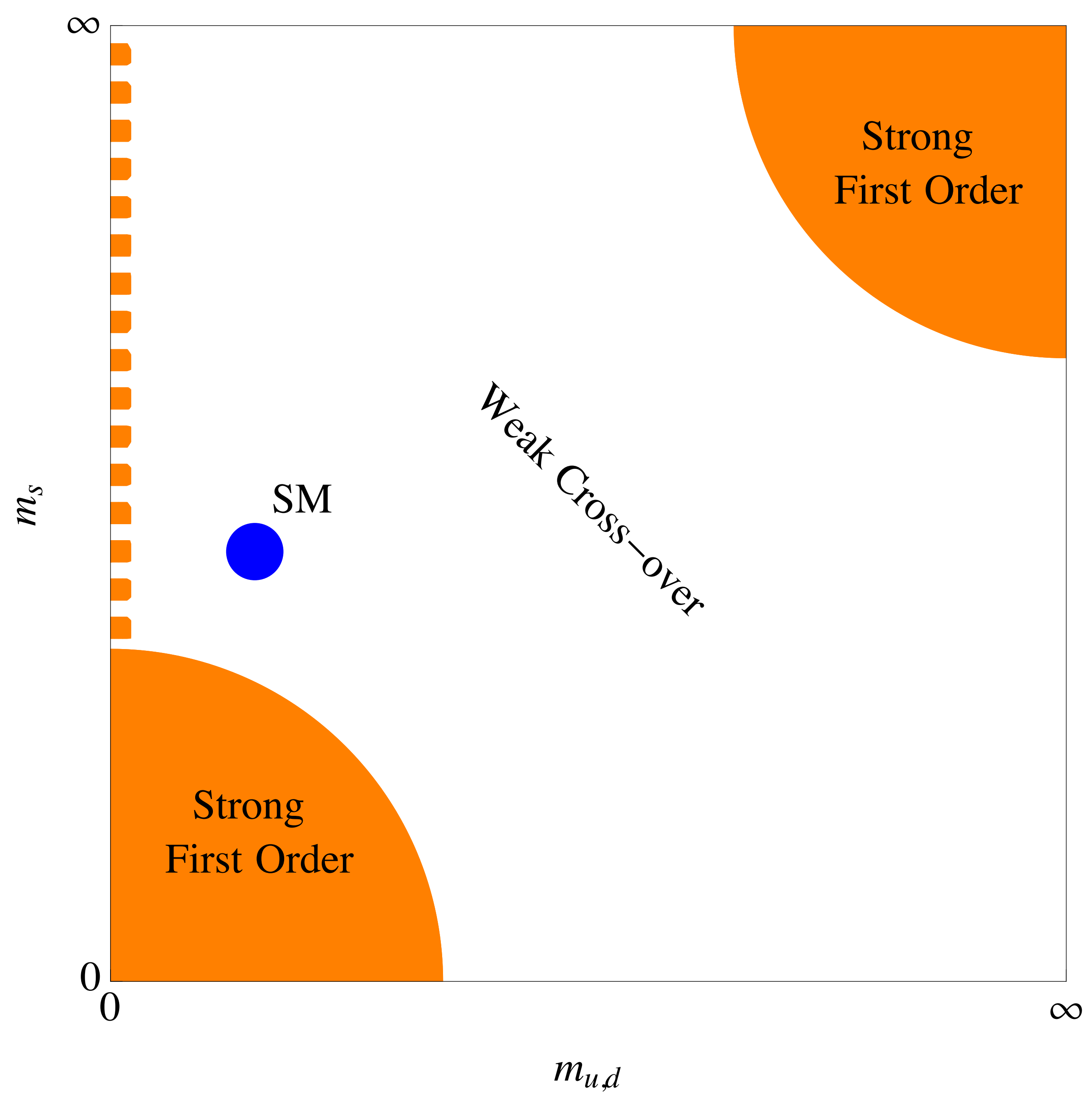
$n_f = 0$	$n_f > 0$
Glueball DM	Dark Baryons or Dark Pions
PT from center symmetry restoration	Chiral Symmetry Breaking

The Dark Phase Transition

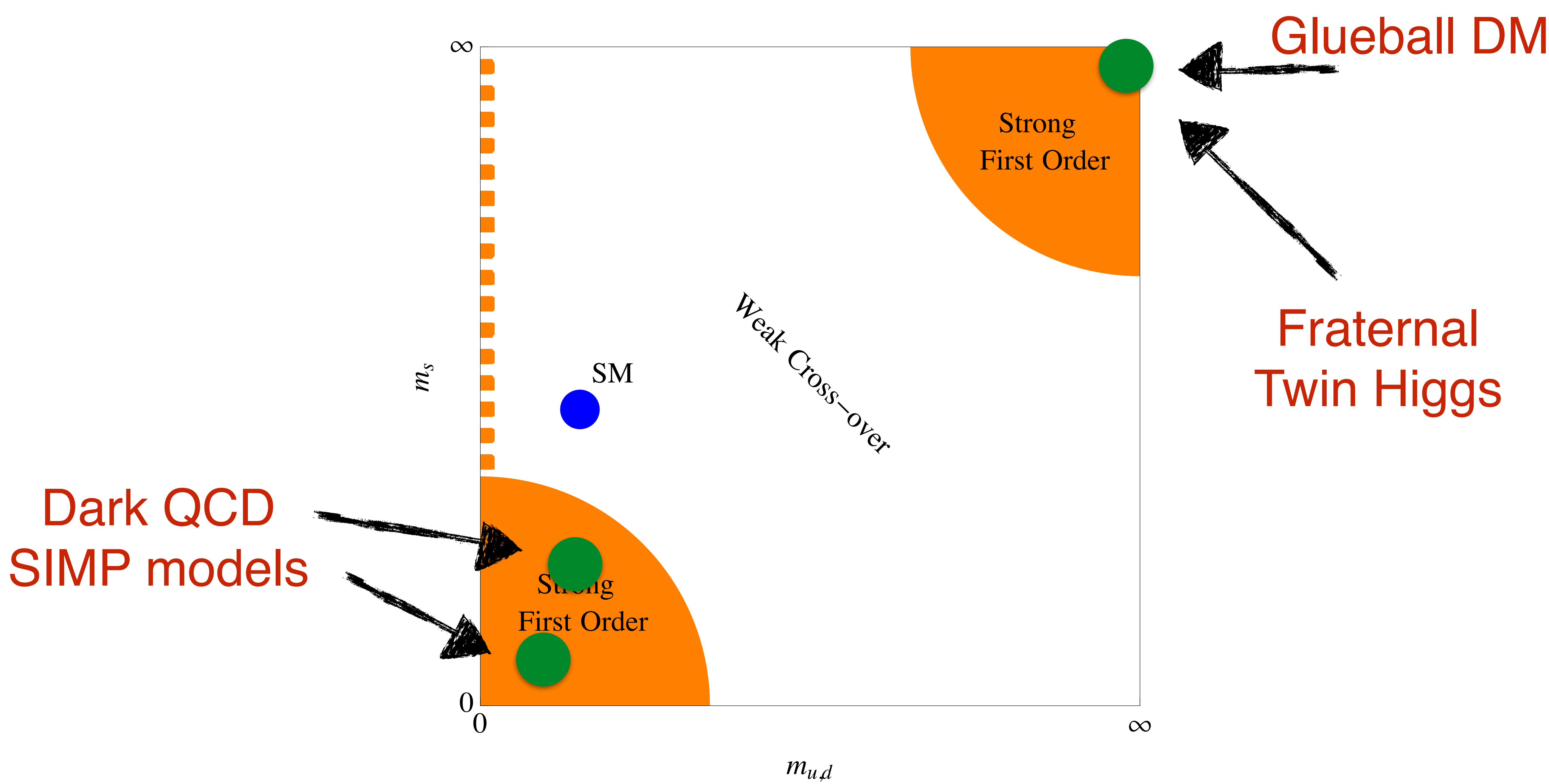
Phase Transition

- SU(N) dark sectors well motivated
- Confinement/chiral symmetry breaking phase transition at scale Λ_d
  - DM: $\Lambda_d \sim M_{\rm DM}$ (MeV - 100 TeV)
  - Naturalness: $\Lambda_d \sim \text{few} \times \Lambda_{\rm QCD}$
- First order PT in large class of models
- Still possible if LHC finds no new physics

QCD Phase Diagram



Phase Diagram II



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SU(N) - PT

- Consider $SU(N_d)$ with n_f massless flavours

- PT is first order for
  - $N_d \geq 3 \quad , \quad n_f = 0$ — Svetitsky, Yaffe, 1982; M. Panero, 2009
  - $N_d \geq 3 \quad , \quad 3 \leq n_f < 4N_d$ — Pisarski, Wilczek, 1983

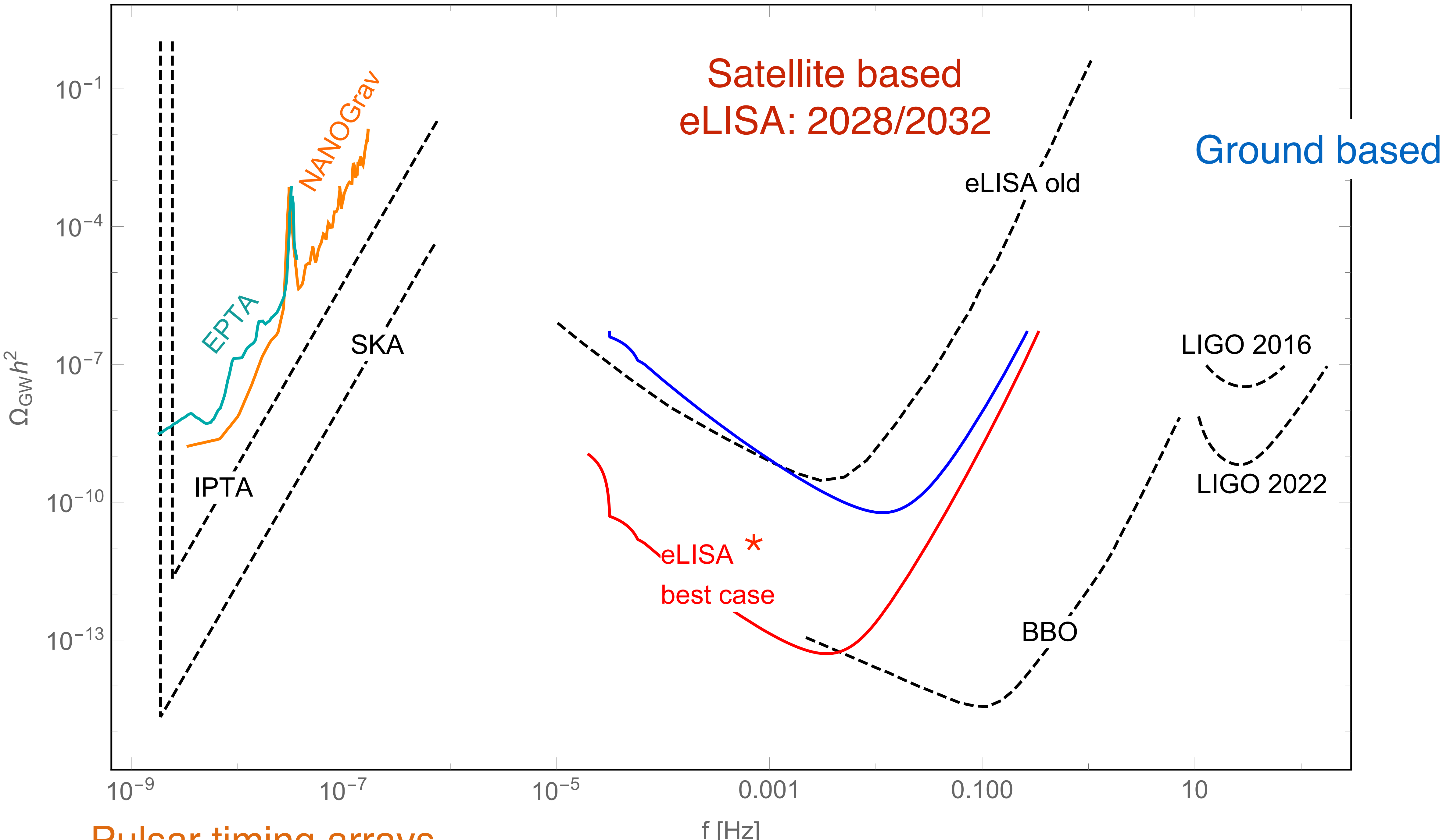
- Not for:
  - $n_f = 1$ (no global symmetry, no PT)
  - $n_f = 2$ (not yet known)

Models span full mass range:

few 100 MeV (SIMP) to

~100 TeV (strong annihilation, saturating unitarity bound)

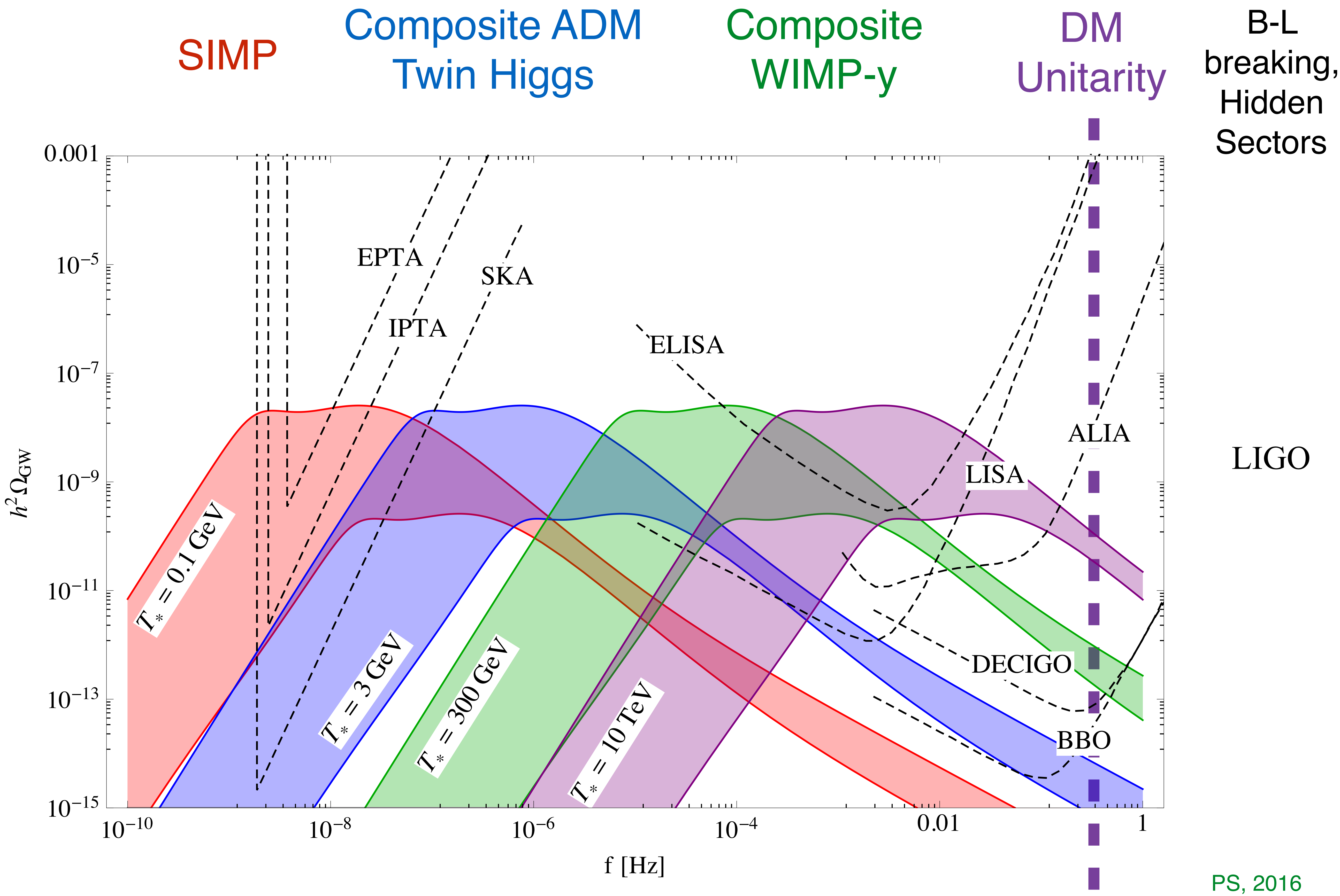
Experiments



Pulsar timing arrays
Data already available

PS, 2016

* From A. Petiteau


SIMP
Composite ADM
Twin Higgs
Composite
WIMP-y
DM
Unitarity
B-L
breaking,
Hidden
Sectors
0.001
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
$h^2\Omega_{GW}$
EPTA
IPTA
SKA
ELISA
ALIA
LISA
LIGO
DECIGO
BBO
$T_* = 0.1$ GeV
$T_* = 3$ GeV
$T_* = 300$ GeV
$T_* = 10$ TeV
10^{-10}
10^{-8}
10^{-6}
10^{-4}
0.01
1
f [Hz]
PS, 2016

GWs from Exotic Compact Objects (ECO)

Exotic Compact Objects

- Two SM objects can produce binary inspiral signal:
  - Black Holes
  - Neutron Stars
- Dark sector particles may form ECOs:
  - boson stars (e.g. axions)
  - fermion stars
  - DM stars

based on Giudice, Mccullough, Urbano, 2016

Characteristics

- LIGO: Wave-form gives information about masses and radii
- Mass:
  - Neutron stars $M < 3.6\ M_{\odot}$
  - Any heavier objects must be a BH (in SM)
- Compactness: $C = M/R$
  - Black hole has $C = 1/2$, NS are below 1/4 typically

based on Giudice, Mccullough, Urbano, 2016

ECOs

- Free field boson stars

$$M_{\rm max} = 0.633\,\frac{M_P^2}{m_B} \approx \left(\frac{10^{-10}\ {\rm eV}}{m_B}\right) M_\odot \qquad (M/R)_{\rm max} = 0.16$$

- Self-interacting boson stars

$$M_{\rm max} = 0.06\sqrt{\lambda}\,\frac{M_P^3}{m_B^2} \approx \sqrt{\lambda}\left(\frac{100\ {\rm MeV}}{m_B}\right)^2 10\ M_\odot \qquad (M/R)_{\rm max} = 0.08$$

based on Giudice, Mccullough, Urbano, 2016

ECOs

- Free field boson stars

$$M_{\rm max} = 0.633\,\frac{M_P^2}{m_B} \approx \left(\frac{10^{-10}\ {\rm eV}}{m_B}\right) M_\odot \qquad (M/R)_{\rm max} = 0.16$$

Axion mass range

- Self-interacting boson stars

$$M_{\rm max} = 0.06\sqrt{\lambda}\,\frac{M_P^3}{m_B^2} \approx \sqrt{\lambda}\left(\frac{100\ {\rm MeV}}{m_B}\right)^2 10\ M_\odot \qquad (M/R)_{\rm max} = 0.08$$

Dark pions?

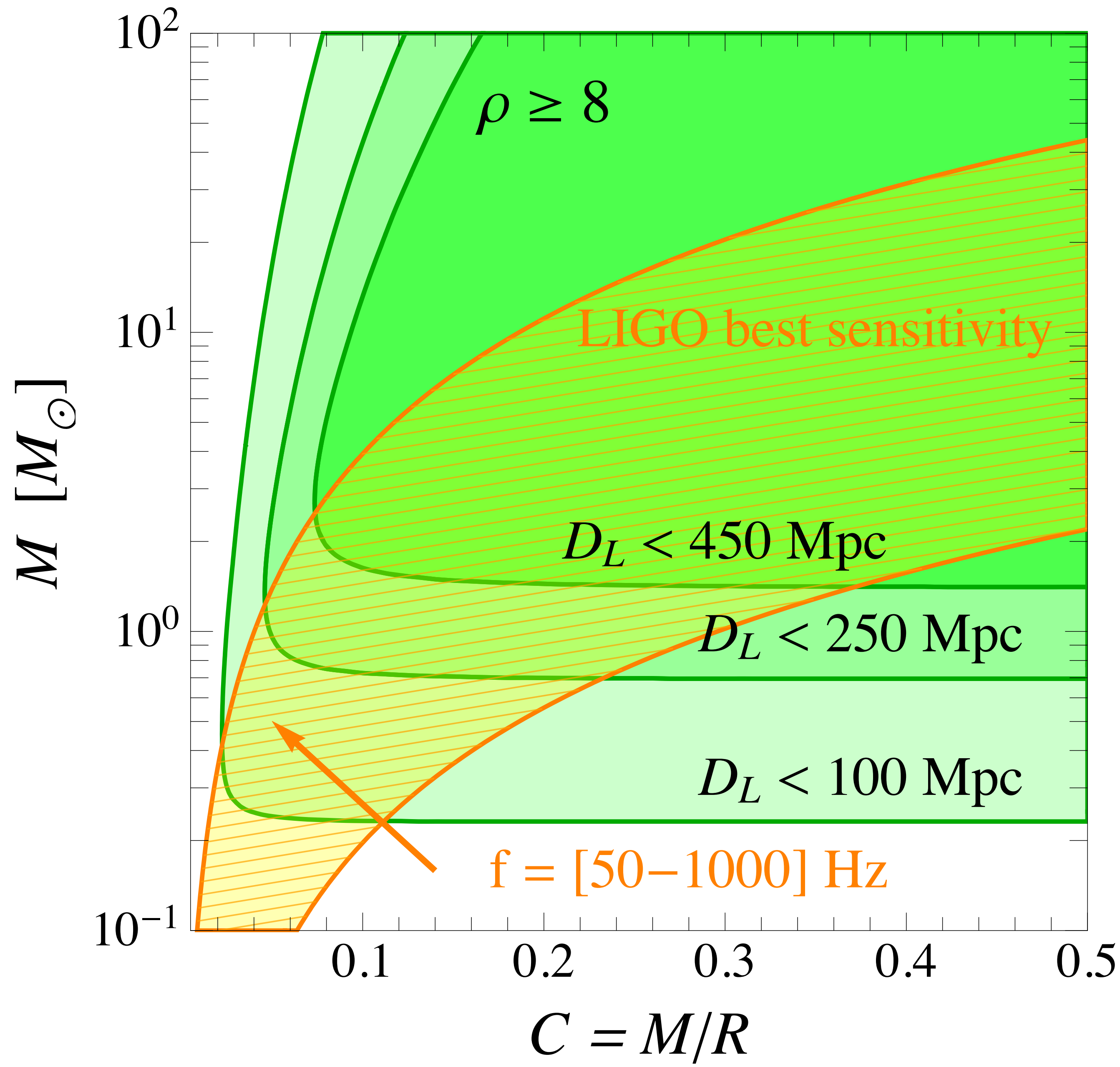
based on Giudice, Mccullough, Urbano, 2016

Detectability

- Peak frequency

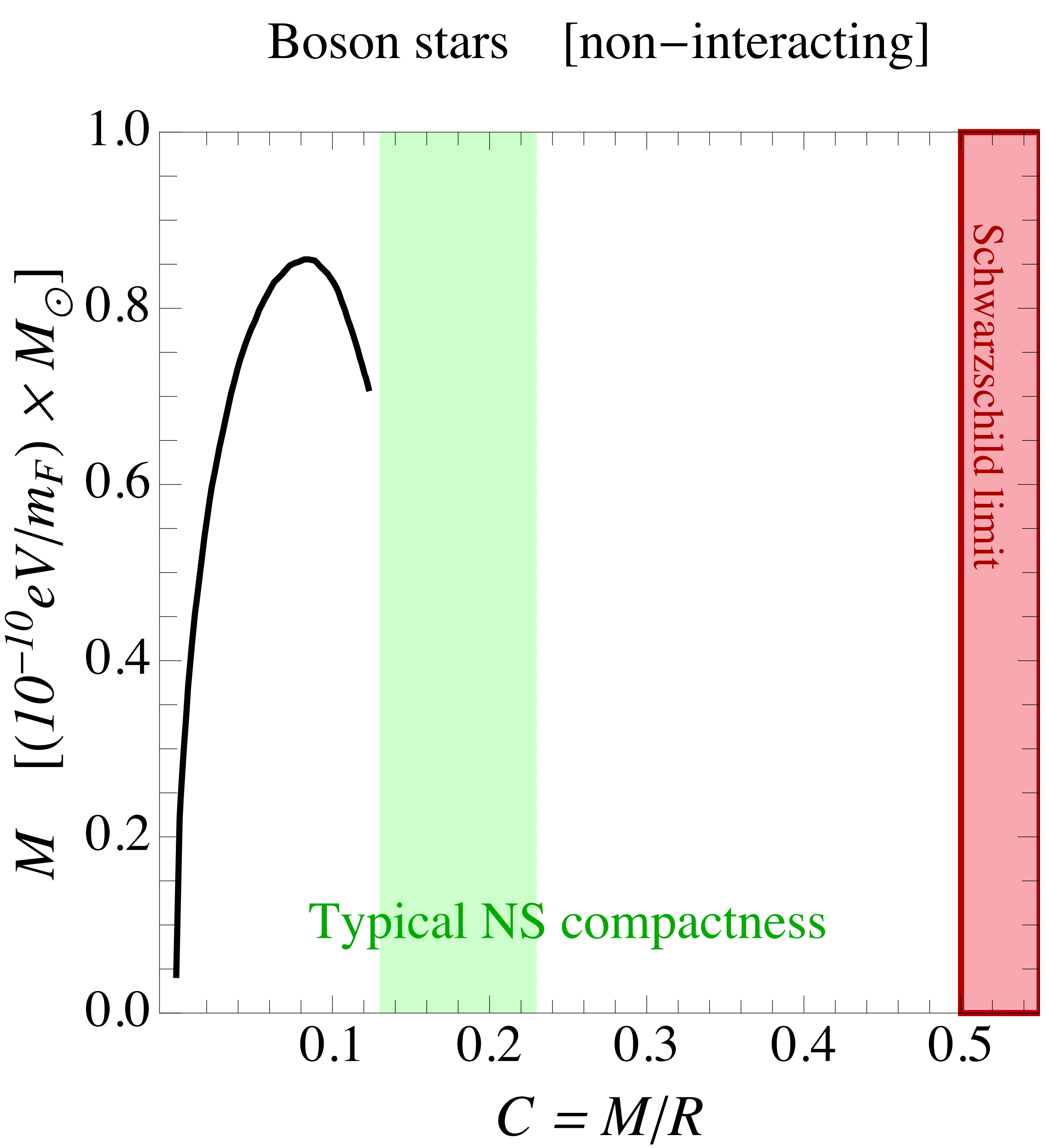
$$f_{BH}^{\mathrm{ISCO}} = \frac{1}{6^{3/2}\pi M_{\mathrm{tot}}}$$

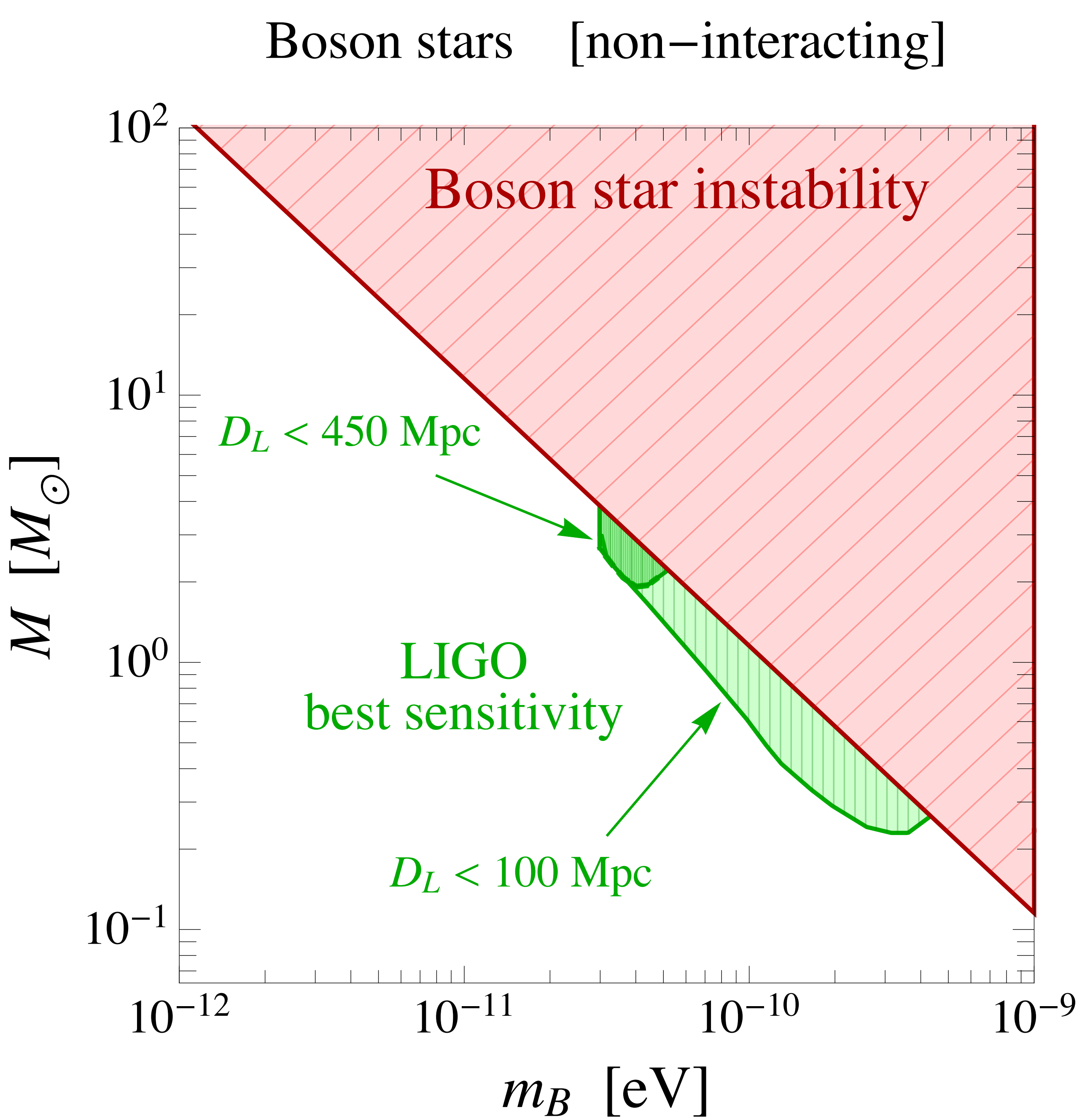
$$f_{ECO}^{\mathrm{ISCO}} = \frac{C^{3/2}}{3^{3/2}\pi M_{\mathrm{tot}}}$$



based on Giudice, Mccullough, Urbano, 2016

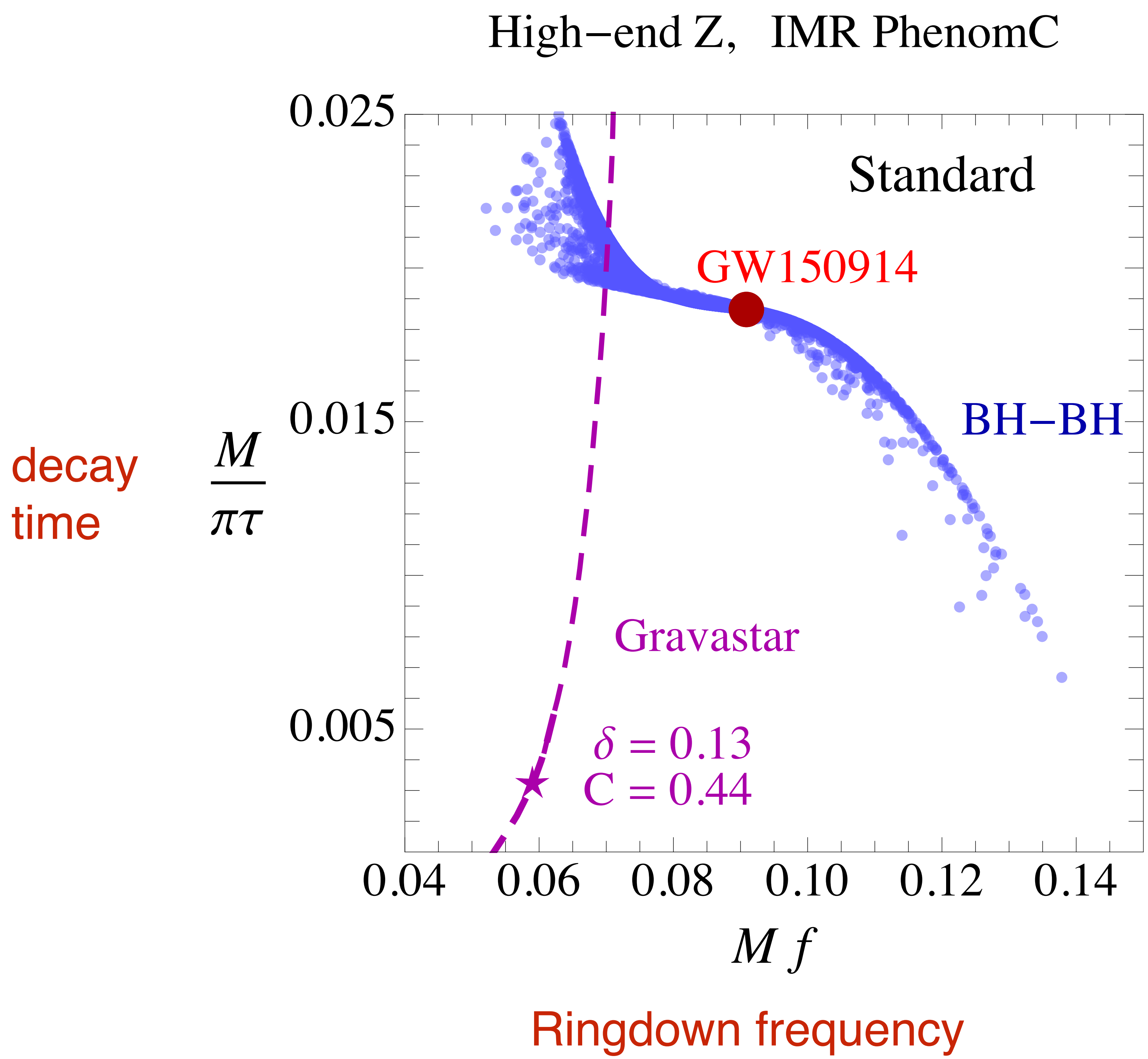
Detectability





based on Giudice, Mccullough, Urbano, 2016

Waveforms



based on Giudice, Mccullough, Urbano, 2016

Using GW experiments to constrain DM

based on M. Pospelov's talk at DESY workshop on
Gravitational Waves and Cosmology, 2016

Topological Defects

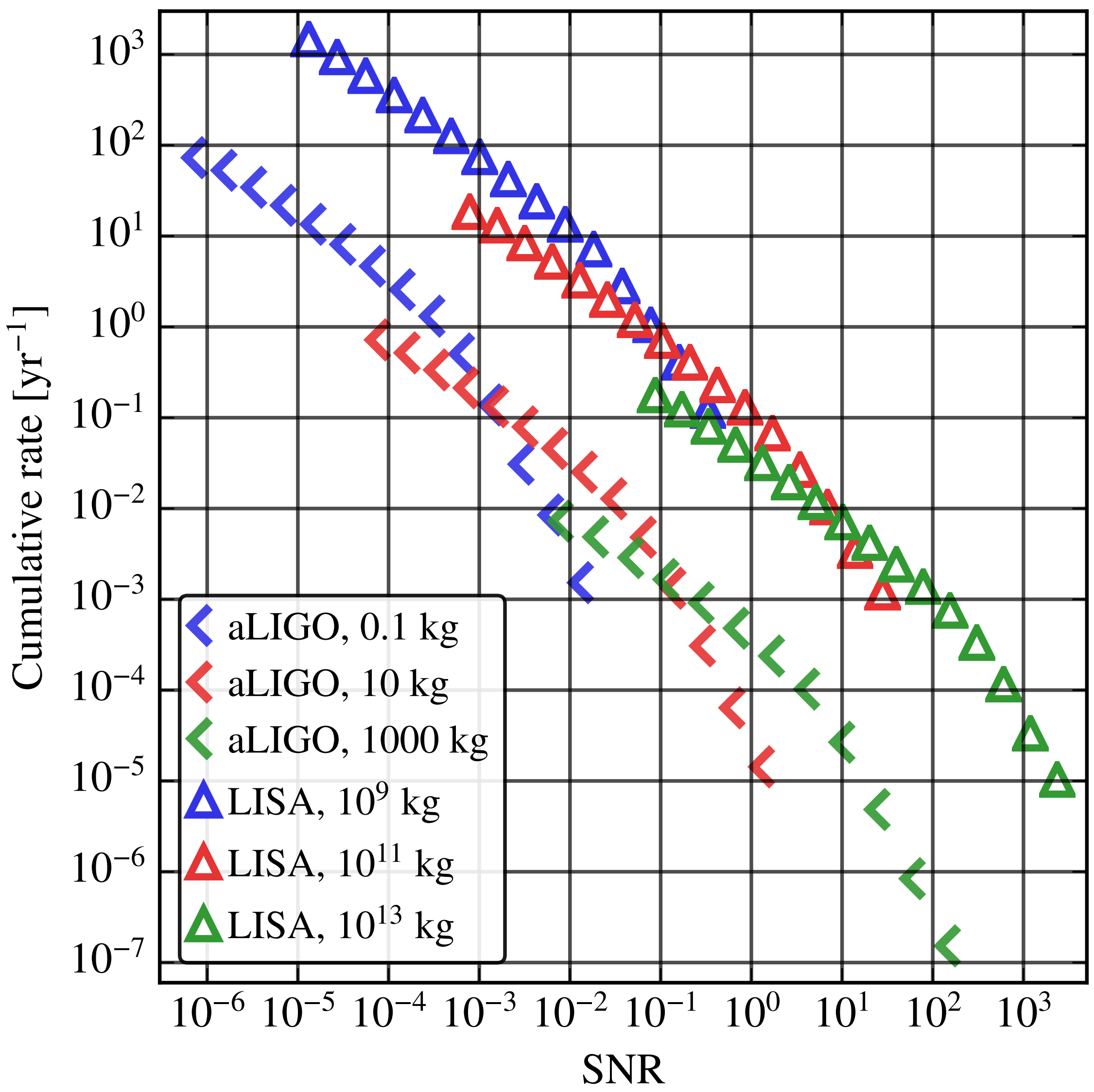
- Again consider scalar field with e.g. $V(\phi) = \lambda(\phi^2 - v^2)^2$
- If $\phi = \pm v$ at $\pm$ infinity, then stable domain wall will form that connects the two
- Typical "size" $1/m_\phi$ and energy per area $v^2 m_\phi$
- A network of such topological defects could contribute to DM density

Macroscopic DM

Signals

- Defect could pass through detector
  - Transient (finite duration) signal
- GW detectors are very sensitive to tiny variations
  - Can hope to detect signal there

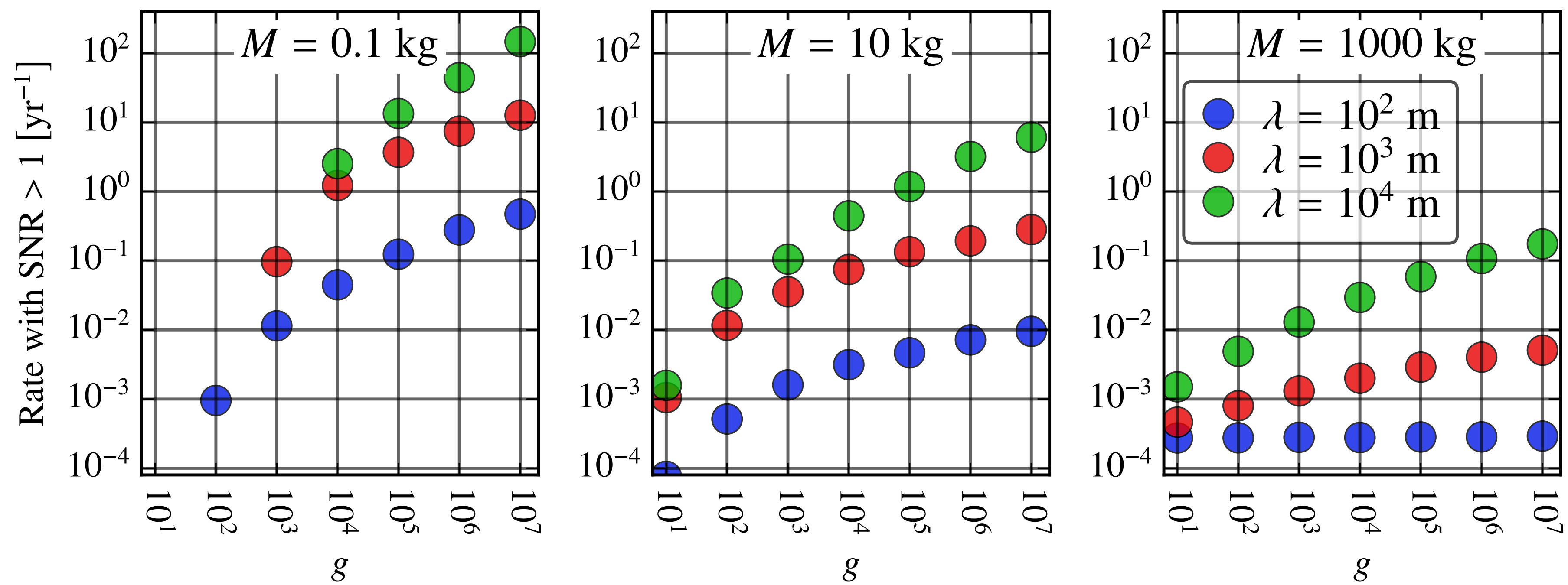
Gravitational Interaction only



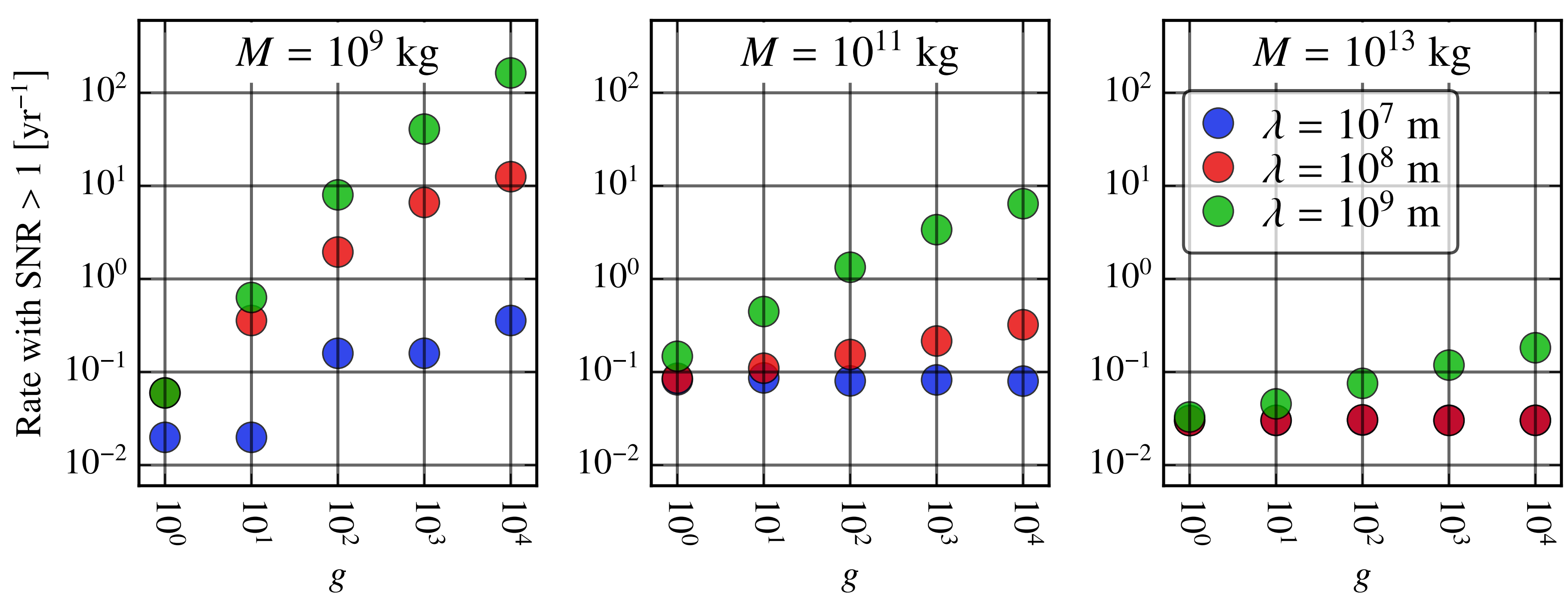
Almost good enough

New Yukawa Interaction

- LIGO



- LISA



Magnetic force

- Domain walls with axion like couplings will apply force to nuclear spins as wall passes through
- Detectable with network of magnetometers
- People actually do this! Here!


The GNOME Experiment
Collaboration website
Live Data
News
Download
Notebook
Internal
Current date: 2016/12/15 23:35:11 GPS
Show Map Legend
Mainz
Institution: JG-University of Mainz
Sensor type: Atomic Magnetometer
Sensor: Rubidium atomic magnetometer with NMOR probe
Contacts: Dmitry Budker, Samer Afach, Arne Wickenbrock, Hector Masia Roig
Coordinates: 49.9929 N, 8.2473 E

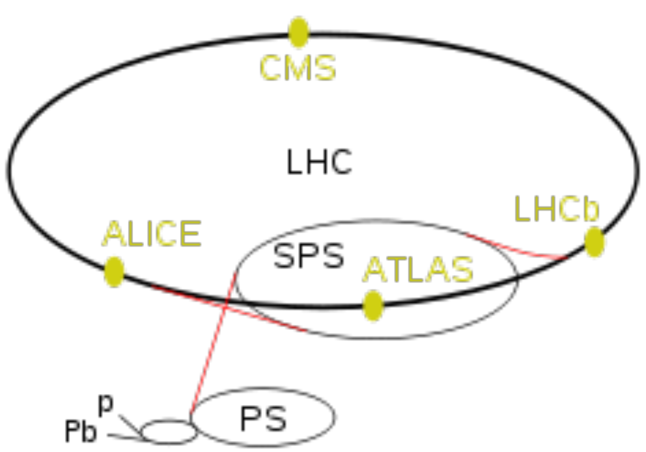
Summary

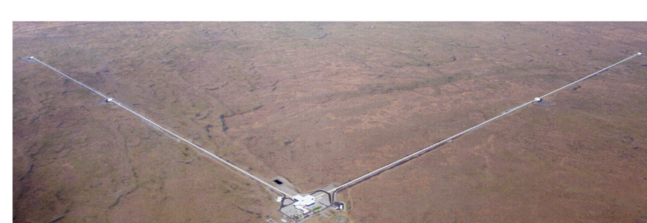
- Gravitational Waves offer unique window into the early universe
- Possible to observe GWs from phase transitions, possibly from dark (matter) sectors
- More exotic DM objects might directly (through mergers) or indirectly (through their interactions) show up in GW detectors
- Also Inflation, Supernovas, tests of GR, etc… worth spending some time thinking about GWs

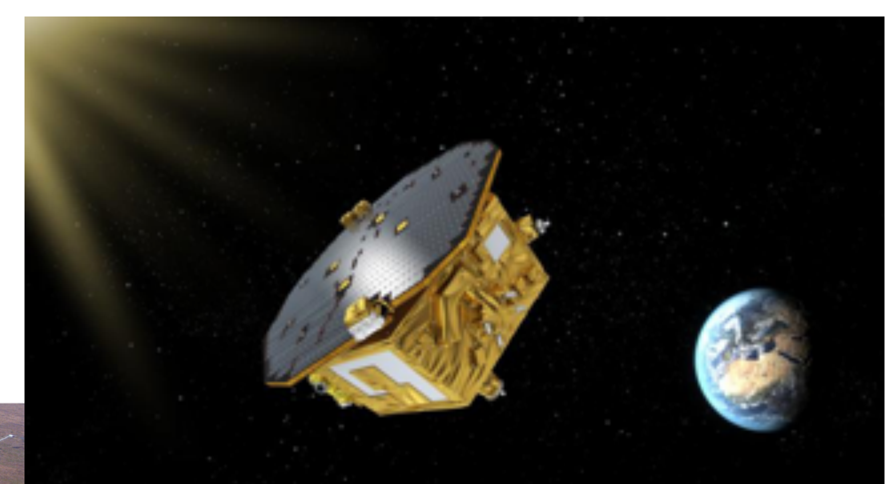
Summary

- We are used to looking for new physics under the lamppost

- Sometimes it is useful to remember that there is more than one lamp

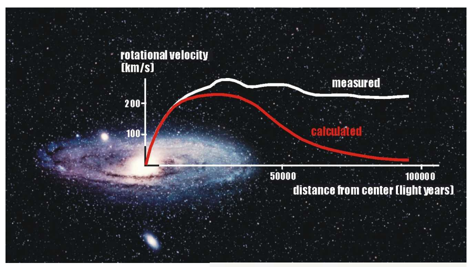


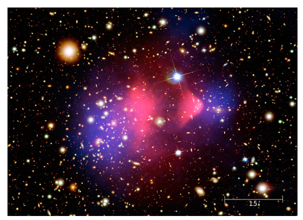


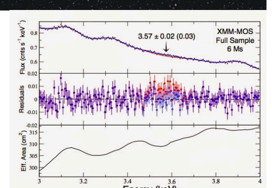


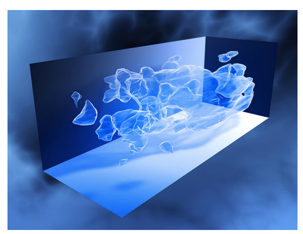
Dark Matter

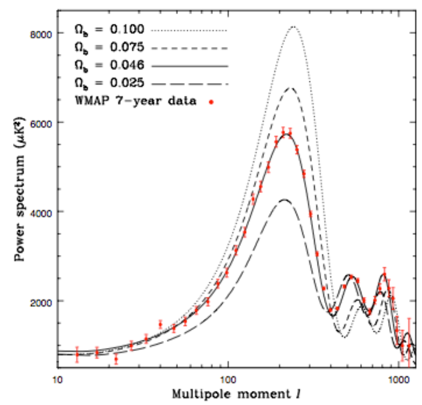
We have seen DM in the sky:



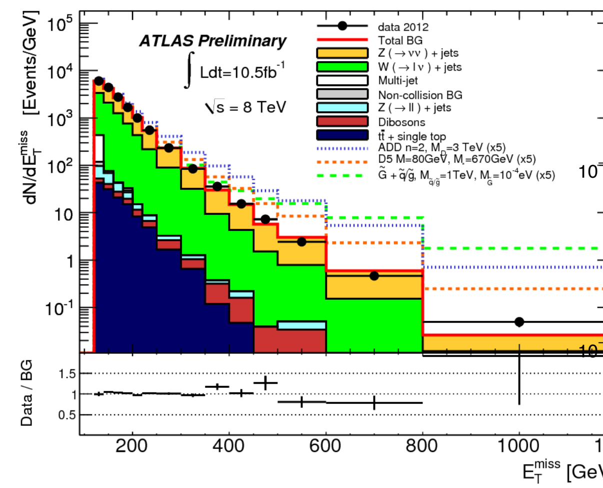


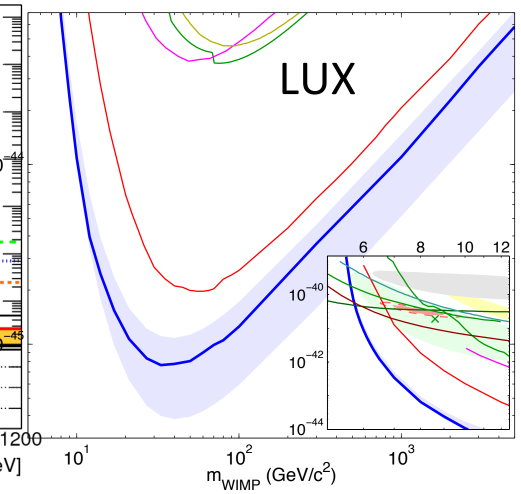






But no direct observation

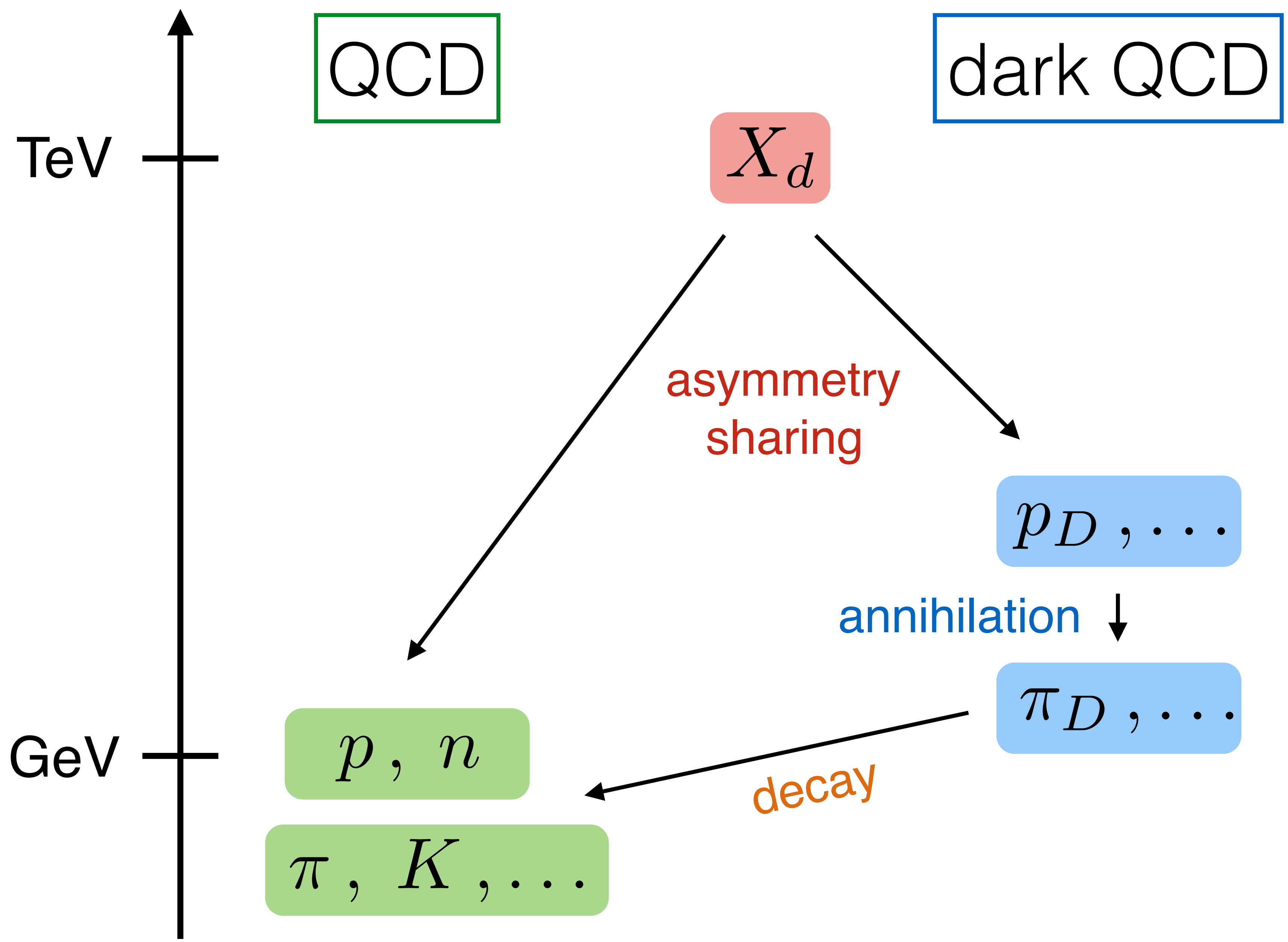




Maybe DM is just part of a larger dark sector

- Example: Proton is massive, stable, composite state
- DM self interactions solve structure formation problems
- New signals, new search strategies!

Composite DM



- SU(N) dark sector with neutral "dark quarks"
- Confinement scale

$$\Lambda_{\rm darkQCD}$$

- DM is composite "dark proton"

Bai, PS, PRD 89, 2014
PS, Stolarski, Weiler, JHEP 2015

many other works!
Similar setup e.g.: Blennow et al; Cohen et al; Frandsen et al;
Reviews: Petraki & Volkas, 2013; Zurek, 2013;

DM Motivation

- New mechanisms for relic density, extend mass range:
  - Asymmetric DM - GeV-TeV scale
  - Strong Annihilation - 100 TeV scale
  - SIMP - MeV scale
    Hochberg, Kuflik, Volansky, Wacker, 2014; + Murayama, 2015
- Advantages of Composite
  - DM mass scale and stability
  - Fast annihilation for ADM
  - Self-interactions for structure formation

GW spectra

- Lot of work on GW from 1st order PT
    - Still difficult to simulate or model

See talks by Hindmarsh, Weir for more details

- Here in addition:
    - Transition is non-perturbative
    - Parameters not known - take an optimistic guess

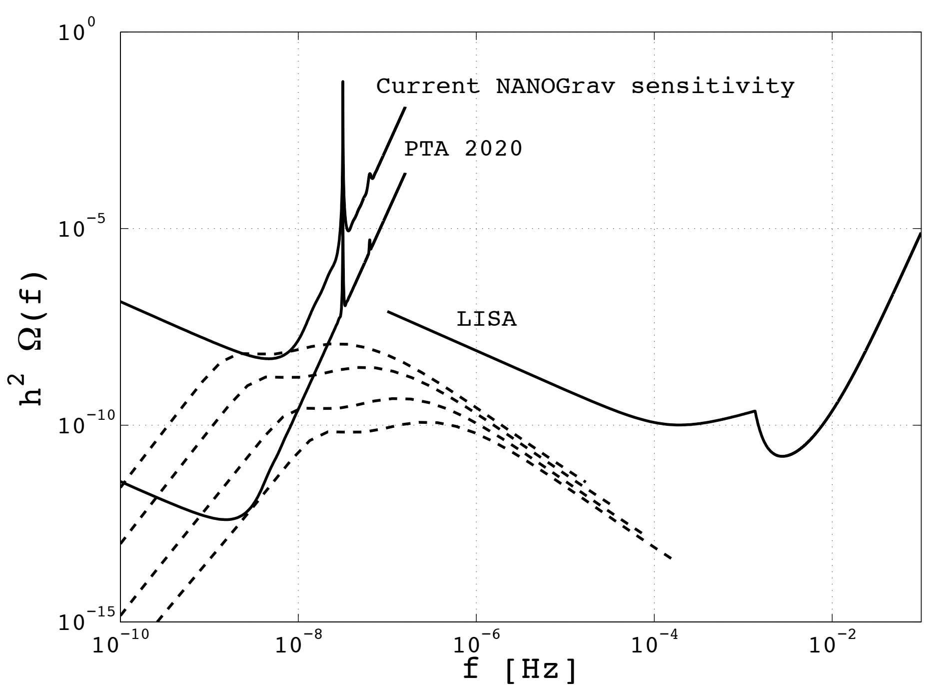
$$\beta/H_* = 1 - 100$$

$$v = 1$$

$$\frac{\kappa\alpha}{1+\alpha} = 0.1$$

SU(N) - PT 2

- One more parameter: Θ angle
- Effect on PT not well studied — M. Anber, 2013; Garcia-Garcia, Lasenby, March-Russell, 2015
- $N_d,\ n_f$ dependence of PT strength? — Panero, 2009
- Finite density/chemical potentials?
    - QCD FOPT? — Schwarz, Stuke, 2009
    - GW signal: — Caprini, Durrer, Siemens, 2009



Questions for Lattice

- Dynamics of PT known from lattice?
  - Latent heat
  - Bubble nucleation rate
  - Dependence on $N_d, \; n_f$
  - theta param, chem. potentials?
- At least some of this is known AFAIK
- For Cosmology: $T < T_C$ relevant

I'd be happy to collaborate!